~~Spatial~~ Avalanches in magnetization dynamics

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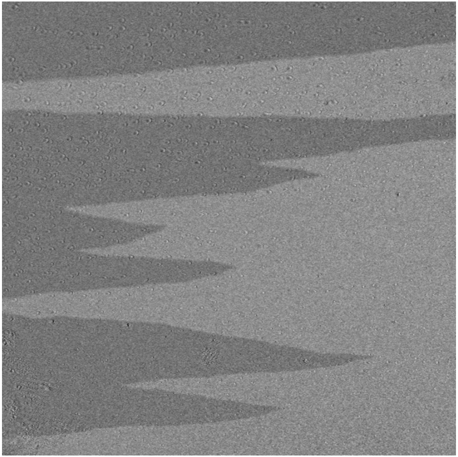
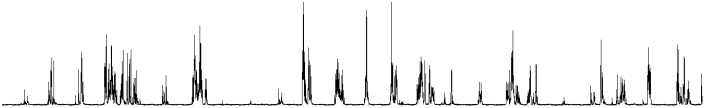
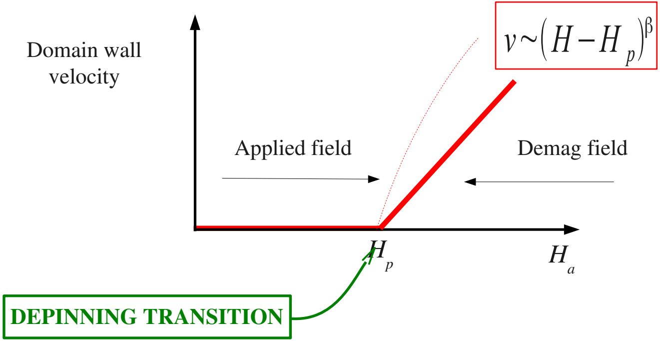
Magnetization dynamics: motion of domain walls



Pinning and depinning of domain walls





Outline

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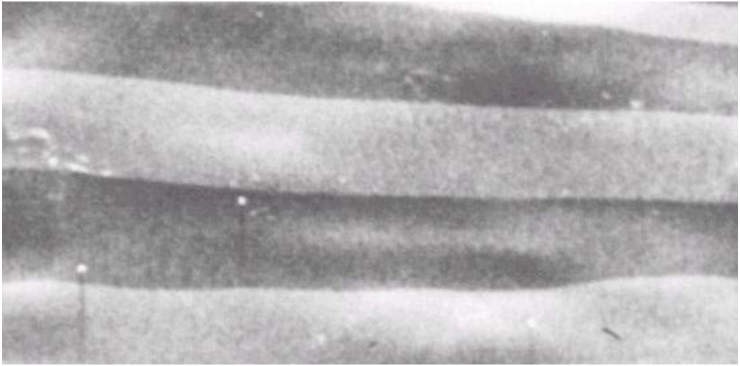
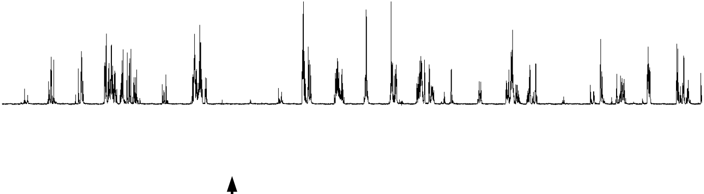
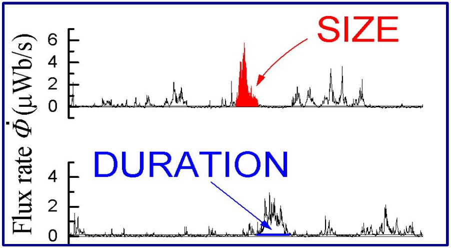
1. Magnetization dynamics: temporal structure
   - Universality and depinning transition
   - Asymmetry in the avalanche average shape
   - Simmetric avalanches in thin films
2. Magnetization dynamics: spatial structure
   - Spatial avalanches in a window
   - Searching for the universality classes
   - Experimental avalanches from MOKE
3. Domain walls for spintronics devices
   - Future DW devices
   - Role of disorder in DW dynamics
   - Creep and DW structure

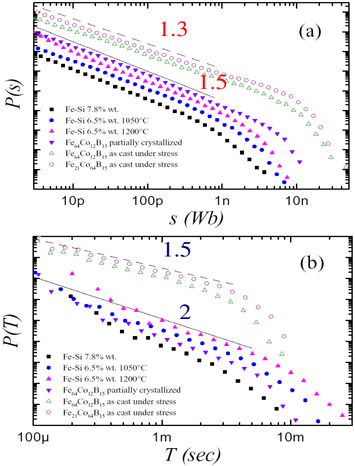
Bulk systems: extended domain walls





Avalanches, power laws, and universality classes





Power law distributions

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

UNIVERSALITY CLASSES

The origin of the universality classes in 3D systems

$$\frac{\partial h(\boldsymbol{r},t)}{\partial t} = H(t) - k M_s^2 \bar{h} + \gamma \nabla^2 h(\boldsymbol{r},t) + \int d^2 r\, K(\boldsymbol{r}'-\boldsymbol{r})\left(h(\boldsymbol{r}',t) - h(\boldsymbol{r},t)\right) + \eta(\boldsymbol{r},h)$$

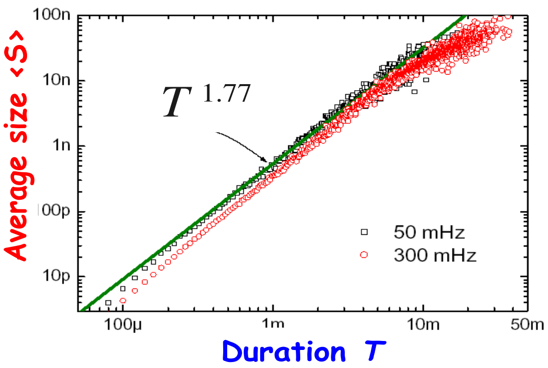
Range of interactions: J(q) = |q|$^{\mu}$

Stray fields LONG RANGE (μ = 1)		Surface tension SHORT RANGE (μ = 2)
3	Upper critical dimension	5
1.5	$P(S) \sim S^{-\tau}$	1.3
2	$P(T) \sim T^{-\alpha}$	1.5

The $\gamma = 1/\sigma\nu z$ exponent

Average size
& duration

$$\langle S(T)\rangle \sim T^{1/\sigma \nu z}$$



Universal scaling function: the average shape

$$\langle S(T)\rangle \sim T^{1/\sigma \nu z} \Rightarrow V \sim \frac{\langle S\rangle}{T}$$

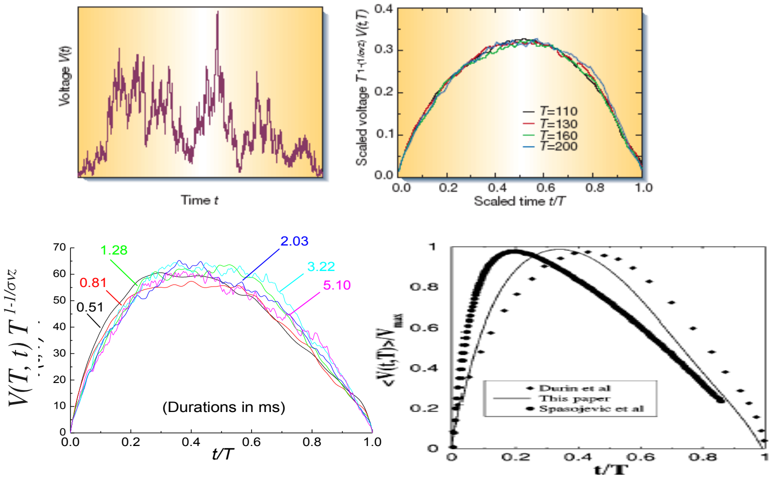
Average avalanche shape

$$V(t,T) = T^{1/\sigma \nu z - 1} g_{shape}(t/T)$$

$V \sim \langle S\rangle / T$

Universal scaling functions

Asymmetry in the avalanche average shape

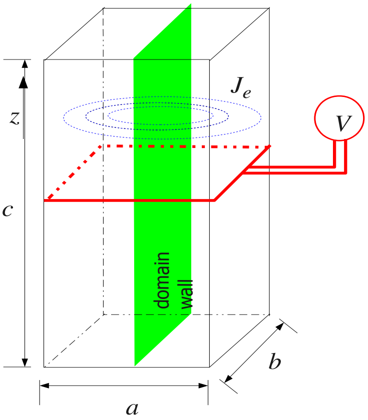


Theory

Experiments

Marked time asymmetry

The delay of the eddy currents



$$\mathbf{H_e} = H_e(x, y, t)\hat{z}$$

$$\nabla^2 H_e = \sigma \mu \frac{\partial H_e}{\partial t}$$

Usual approximation:

No time delay between the magnetization change and the eddy current field

We need to calculate the mean pressure integrating H_e over the thickness

A negative mass for domain walls!

$$\Gamma v = H_a(t) - H_{dem} + H_p(x)$$

$$\Gamma v + \Gamma_0 \int^t e^{-(t-t')/\tau_0} v(t') dt'/\tau_0$$

Non - local damping

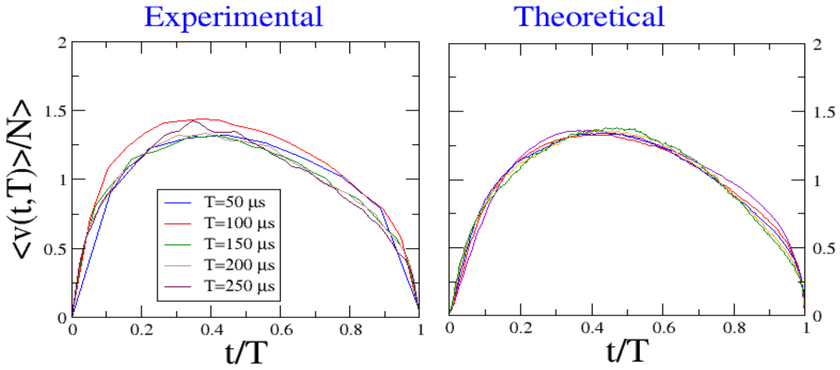
In Fourier space:

$$\tilde{P}_e = [(\Gamma + \Gamma_0) + i\omega \bar{M}]\tilde{v}$$

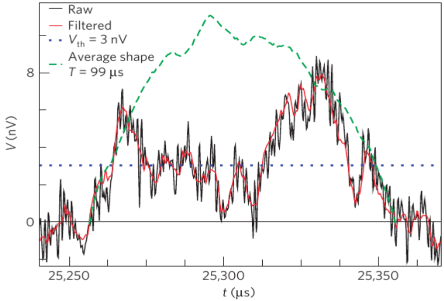
Negative mass!

$$\bar{M} \sim -I_s \Gamma \tau_0$$

Shapes in experiments and in the model



Detection of avalanches in thin films



in thin films (Py, 1 µm),
the signal to noise is too low
→ a threshold splits avalanches

we need a good
filtering technique

Wiegner filter

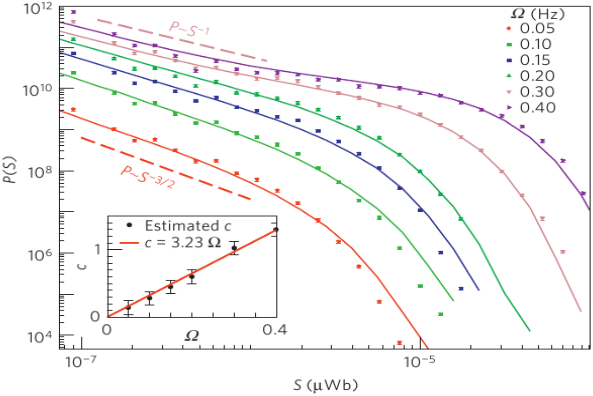
$$\tilde{V}(f) = \frac{\tilde{V}_{out}(f)}{\tilde{h}(f)} \frac{|\tilde{v}(f)|^2}{|\tilde{n}(f)|^2 + |\tilde{v}(f)|^2}$$

guess of signal spectrum

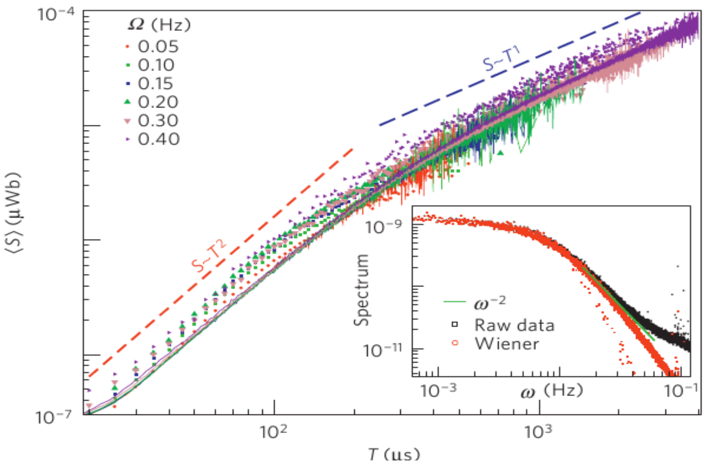
impulse response

background noise spectrum

Size distributions in a ’long range’ film (3D)



The $1/\sigma\nu z$ again

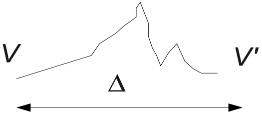


it perfectly follows the model (and no eddy currents)!

Universal scaling function revisited

$$G_{c,k}(V,t;V',t+\Delta)$$

c: field rate
k: demagnetizing factor



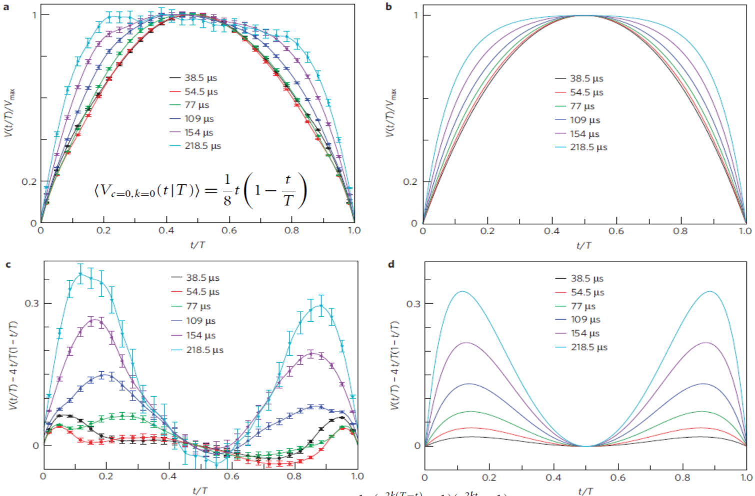
$$\langle V_{c,k}(\Delta|T)\rangle = \frac{\int dV' V' G_{c,k}(0^+,0;V',\Delta)G_{c,k}(V',\Delta;0,T)}{\int dV' G_{c,k}(0^+,0;V',\Delta)G_{c,k}(V',\Delta;0,T)}$$

$$= T^x \mathcal{V}(\Delta/T,(k/k_0)T^w, c/c_0T^y)$$

relevant

marginal

Universal scaling function: results



$$\langle V_{c=0,k}(t|T)\rangle = \frac{1}{2k}\frac{(e^{2k(T-t)}-1)(e^{2kt}-1)}{e^{2kT}-1}$$

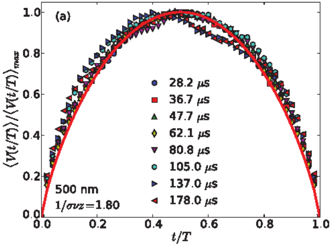
Just published on PRE: short range films

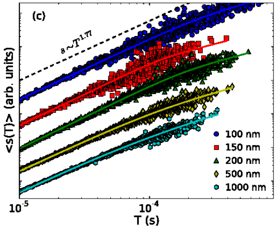
General scaling forms

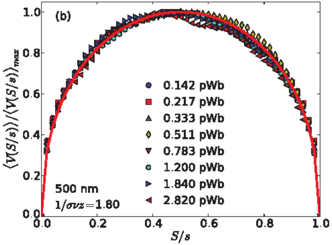
$$\langle V(t|T)\rangle \propto \left[\frac{t}{T}\left(1-\frac{t}{T}\right)\right]^{1/\sigma\nu z-1}$$

$$\langle V(S|s)\rangle \propto \left[\frac{S}{s}\left(1-\frac{S}{s}\right)\right]^{1-\sigma\nu z}$$

see Laurson et al, Nat. Com. 4, 2927 (2013)







with $1/\sigma\nu z = 1.80$. See Bohn et al, 90, 032821 (2014)

Something more... from Pierre and Kay

Using normalized units:

- S/S_m, with $S_m = \frac{\langle S^2 \rangle}{2\langle S \rangle}$
- T/τ_m, with τ_m to be determined

the average shape for avalanches of given size S follows:

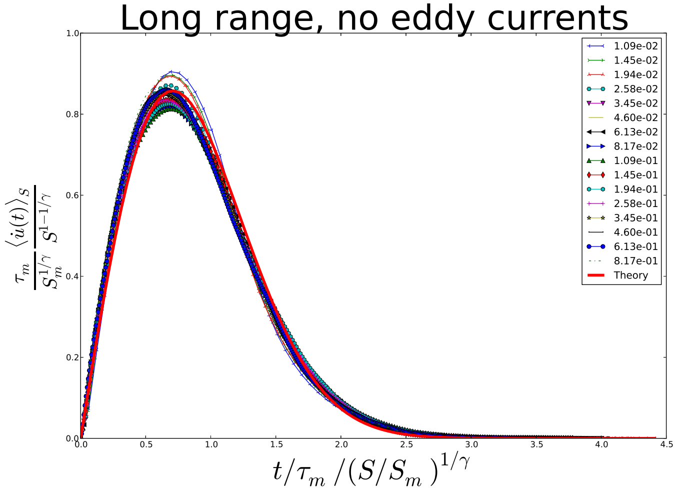
$$\langle v(t) \rangle_S = \frac{S}{\tau_m} \left(\frac{S}{S_m} \right)^{-1/\gamma} F(\tilde{t})$$

with: $\tilde{t} = \frac{t}{\tau_m} / \left(\frac{S}{S_m} \right)^{1/\gamma}$, $\int dt \langle v(t) \rangle_S = S$, $\int d\tilde{t} F(\tilde{t}) = 1$.

In the ABBM mean field model, one has:

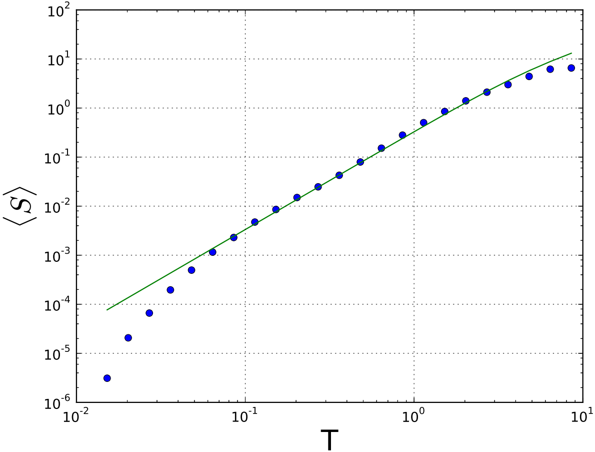
$$F(\tilde{t}) = 2\tilde{t}e^{-\tilde{t}^2}, \gamma = 2$$

Comparison with experiments (1)



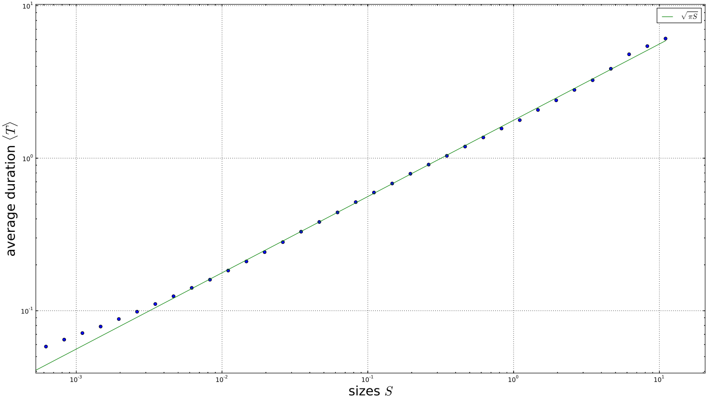
Comparison with experiments (2)

$$\langle S \rangle = 2T coth(T/2) - 4$$



Comparison with experiments (3)

$$\langle T \rangle = \sqrt{\pi S}$$



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Visualization of DW dynamics in thin films

Tunable scaling behaviour observed in Barkhausen criticality of a ferromagnetic film

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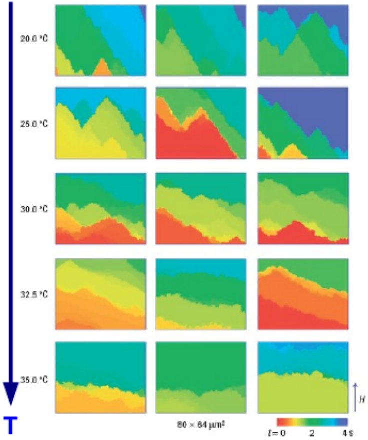
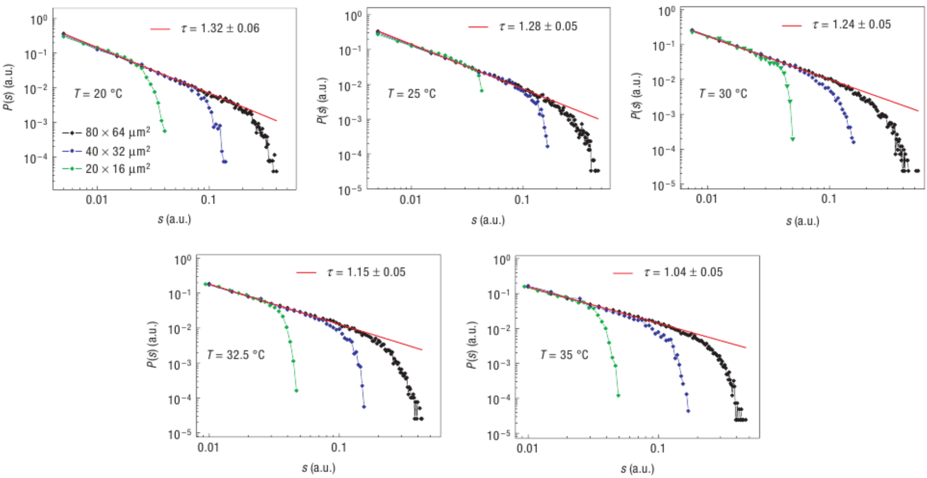
[2]Nanotechnology Research Institute, National Institute of Advanced Industrial Science and Technology, 1-1-1 Higashi, Tsukuba, Ibaraki 305-8562, Japan

- FM MnAs 50 nm film on GaAs(001)
- Fixed field at 99% H_c
- Different spot sizes
- Local magnetization changes
- $T_c \sim 40\ ^\circ C$
- Distribution of avalanche sizes $P(S)$



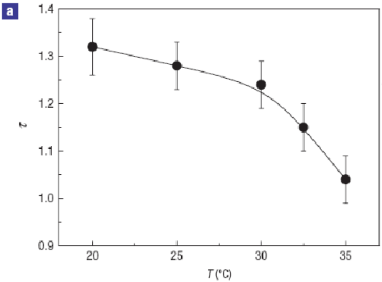
Barkhausen avalanche distributions



Cross-over between two universality classes(?)

Zigzag walls

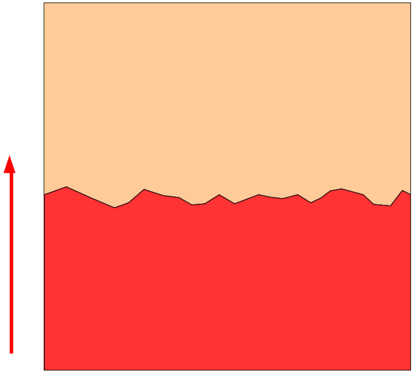
Low temperature / high dipolar forces



High temperature / low dipolar forces

Rough walls

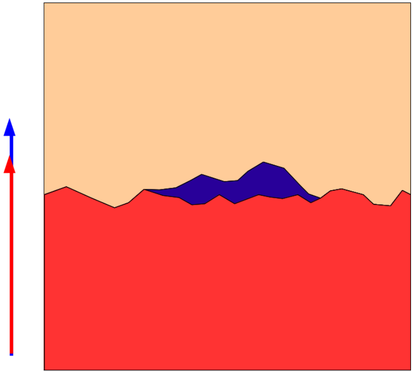
Avalanches in a window frame



The effect of the frame

- Front in the full system
- Avalanche in the full system
- Avalanche in the window
- Avalanche cut by smaller windows

Avalanches in a window frame



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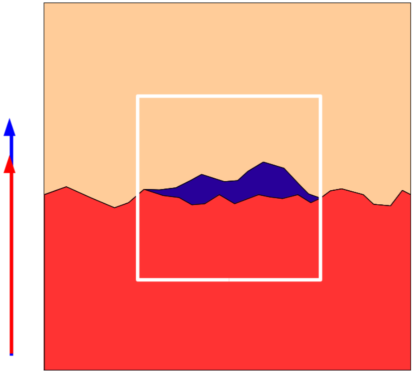

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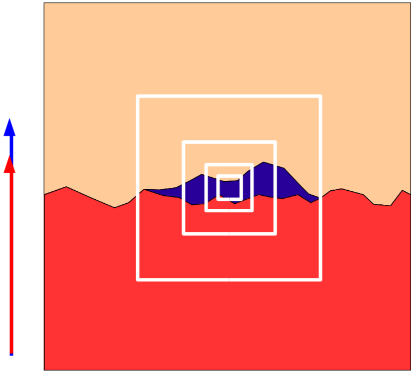

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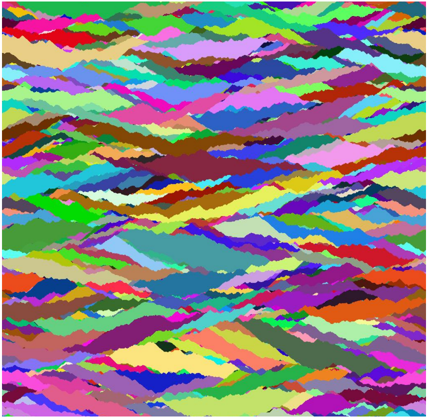
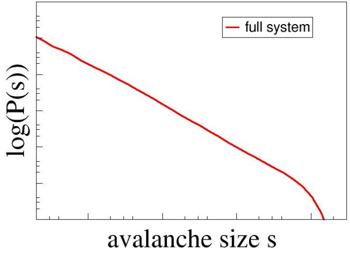
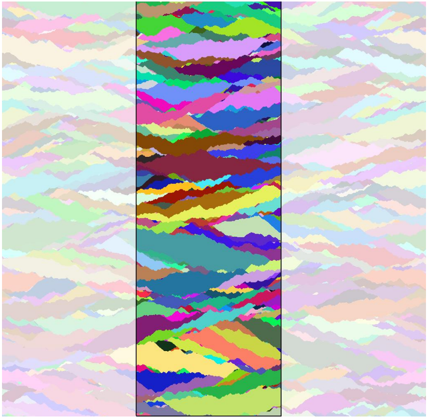


Distribution of avalanches

In the Full System

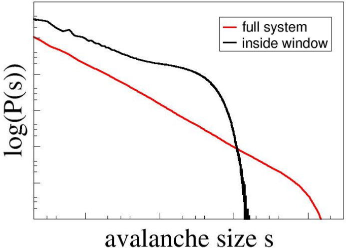


Avalanches in a window frame

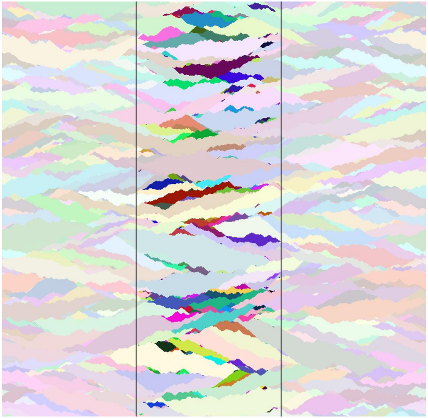


Distribution of avalanches

Within the Window frame

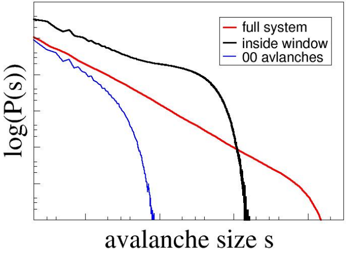


Avalanches in a window frame

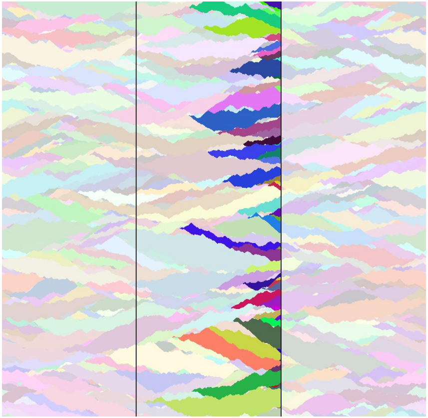


Distribution of avalanches

No touching any edge (00)

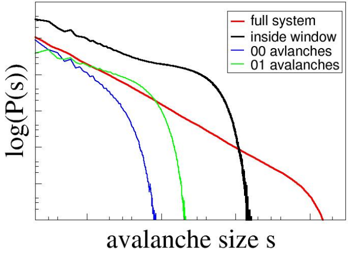


Avalanches in a window frame



Distribution of avalanches

Touching the right edge(01)



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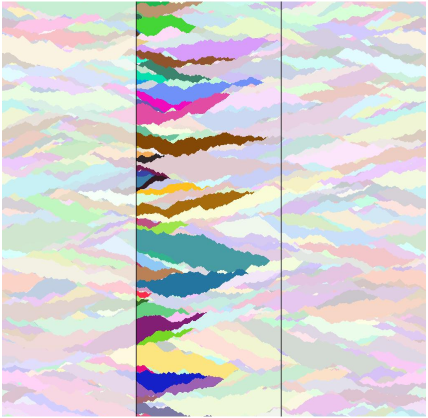
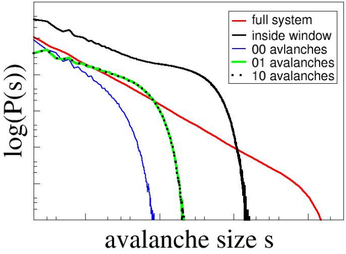
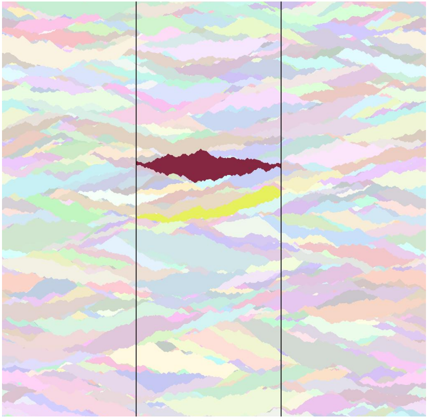


Distribution of avalanches

Touching the left edge (10)

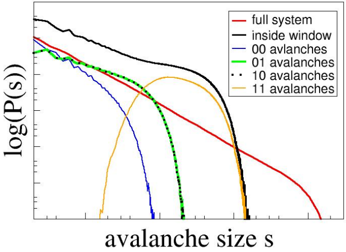


Avalanches in a window frame

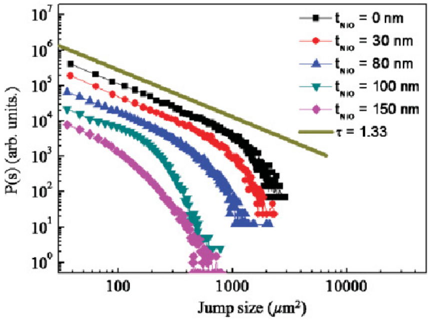


Distribution of avalanches

Touching both edges (11)

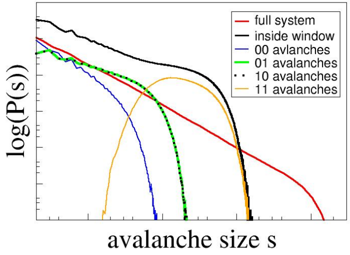


Avalanches in a window frame



Distribution of avalanches

Sound familiar?



Spatial structure of avalanches in DPD

Directed Percolation Depinning: the quenched KPZ model

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

- $h(x,t)$: height of the front
- F: the driving force
- k: the “demagnetization field”
- γ, λ: linear and non-linear terms
- η: gaussian random noise.

Critical exponents are well known

- size exponent: $\tau = 1.24$
- roughness exponent: $\zeta = 0.63$

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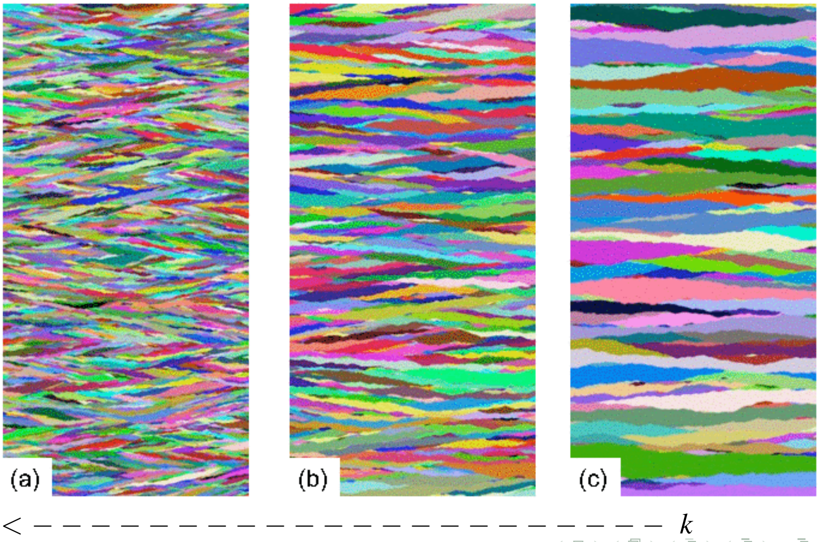
Effect of the demag field



Area-weighted size distributions in the full system

Traditional size distributions

$$P(S|L_k) = S^{-\tau}\mathcal{P}(S/L_k^{1+\zeta}), \text{ where } L_k \sim k^{-\nu_k}$$

Problem: normalization depends on lattice space!

$$N^{-1} = \int_{a^2}^{\infty} P(S|k)\, dS \sim \int_{a^2}^{L_k^{1+\zeta}} S^{-\tau}\, dS \sim a^{2(1-\tau)} - L_k^{(1-\tau)(1+\zeta)}$$

The area-weighted size distribution

$$A(S) = S \cdot P(S)$$

$$A(S|L_k) = L_k^{(\tau-2)(1+\zeta)} S^{1-\tau} \mathcal{A}_{Sk}(S/L_k^{1+\zeta})$$

$$= (S/L_k^{1+\zeta})^{2-\tau} \mathcal{A}_{Sk}(S/L_k^{1+\zeta})/S = S_k^{2-\tau} \mathcal{A}_{Sk}(S_k)/S$$

This is the fraction of the full system area covered by avalanches with sizes between S and $S + dS$.

Theoretical avalanche distributions in the window

Internal (00) avalanches

$$A_{00}(s|W,L_k) = L_k^{(\tau-2)(1+\zeta)} s^{1-\tau} \mathcal{A}_{00}\left(\frac{s}{L_k^{1+\zeta}}, \frac{W}{L_k}\right)$$

Split (01-10) avalanches

$$A_{10}(s|W,L_k) = \frac{1}{W} L_k^{(\tau-2)(1+\zeta)} s^{1-\tau+1/(1+\zeta)} \mathcal{A}_{10}\left(\frac{s}{L_k^{1+\zeta}}, \frac{W}{L_k}\right)$$

Spanning (11) avalanches

$$A_{11}(s|W,L_k) = \frac{1}{s}\left(\frac{s}{WL_k^{\zeta}}\right)^{(2-\tau)(1+\zeta)/\zeta} \mathcal{A}_{11}\left(\frac{s}{WL_k^{\zeta}}, \frac{W}{L_k}\right)$$

SloppyScaling environment

The goal

Fitting A_{00}, A_{10}, A_{11} together, with a functional form of the $\mathcal{A}_{00}, \mathcal{A}_{10}, \mathcal{A}_{11}$ universal functions *plus* corrections to scaling.

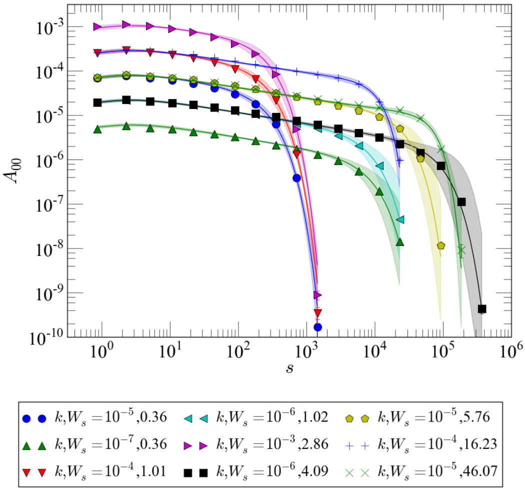
Functional forms of $\mathcal{A}_{xy}$ universal functions

$$\mathcal{A}_{00} = \exp(-(U_{00}s_k^{1/2} + Z_{00}s_k^{\delta_{00}} + C_{00}(\frac{s_k}{W_k^{n_{00}}})^{m_{00}})$$
$$\mathcal{A}_{10} = \exp(-(U_{10}s_k^{1/2} + Z_{10}s_k^{\delta_{10}} + C_{10}(\frac{s_k}{W_k^{n_{10}}})^{m_{10}})$$
$$\mathcal{A}_{11} = \exp(-(U_{11}s_k^{1/2} + Z_{11}s_k^{\delta_{11}} + D_{11}(\frac{s_k}{W_k})^{m1} + C_{11}(\frac{s_k}{W_k^{n_{11}}})^{-m2})$$

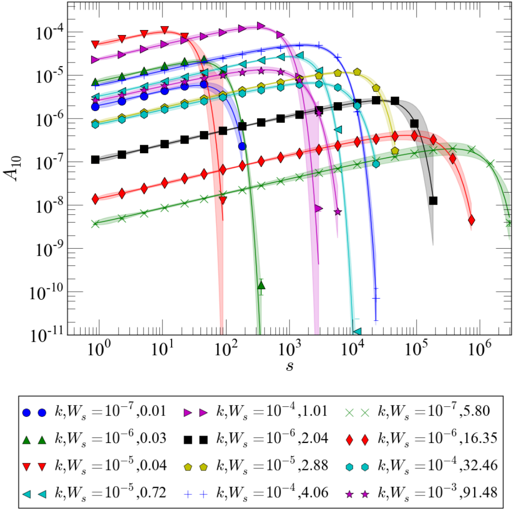
In sum

3 functions, 27 fitting parameters, 24 data sets (for different L_k and W), 133 + 167 + 60 = 360 points

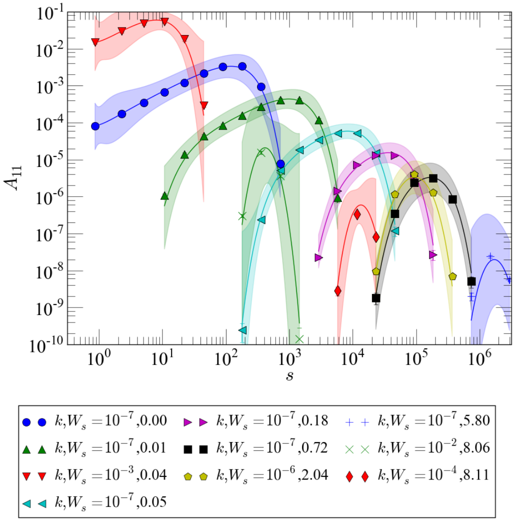
Multiple data fits



Multiple data fits



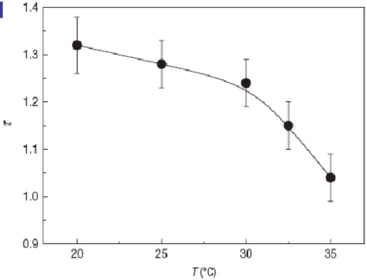
Multiple data fits



Cross-over between two universality classes(?)

Zigzag walls a

Low temperature / high dipolar forces



High temperature / low dipolar forces

Rough walls

A simple front propagation model

Eq. of motion of DW segment along the vertical direction

$$\Gamma \frac{\partial h_i}{\partial t} = \frac{1}{\cos\theta_i}\Big[\gamma_w \frac{\partial^2 h_i}{\partial x^2} + \qquad \text{elastic}$$

$$2M_s\mu_0 H_a + \qquad \text{field}$$

$$\eta(i, h_i) + \qquad \text{noise}$$

$$4\ \mu_0 M_s^2 \Delta_z^2 \sum_{j\neq i} \frac{h_i - h_j}{[\Delta_z^2 (i-j)^2 + (h_i - h_j)^2]^{3/2}}\Big] \qquad \text{dipolar}$$

Laurson, L.; Durin, G. Zapperi, S. PRB 89, 104402 (2014)

A simple front propagation model

Eq. of motion of DW segment along the vertical direction

$$\Gamma \frac{\partial h_i}{\partial t} = \frac{1}{\cos\theta_i}\left[\gamma_w \frac{\partial^2 h_i}{\partial x^2} + 2M_s\mu_0 H_a + \eta(i,h_i) + 4\ \mu_0 M_s^2 \Delta_z^2 \sum_{j\neq i} \frac{h_i - h_j}{[\Delta_z^2(i-j)^2 + (h_i-h_j)^2]^{3/2}}\right]$$

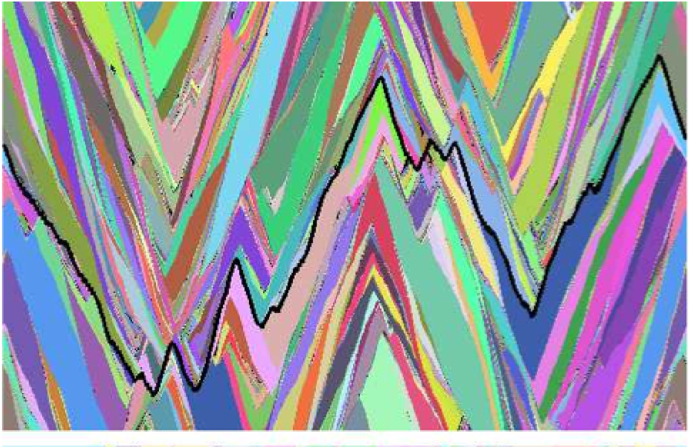
Eq. of motion in dimensionless units

$$\frac{\partial h_i}{\partial t} = \frac{1}{\cos\theta_i}\left[\lambda \frac{\partial^2 h_i}{\partial x^2} + F_{ext} + \eta(i,h_i) + 4 \sum_{j\neq i} \frac{h_i - h_j}{[(i-j)^2 + (h_i-h_j)^2]^{3/2}}\right]$$

where $\lambda = l_D/\Delta_z$, with $l_D = \gamma_w/(\mu_0 M_s^2)$ the “domain formation”

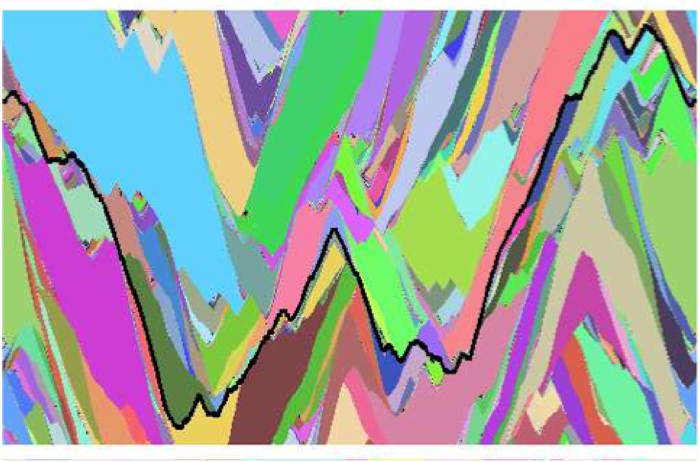
A simple front propagation model

The effect of lenght λ



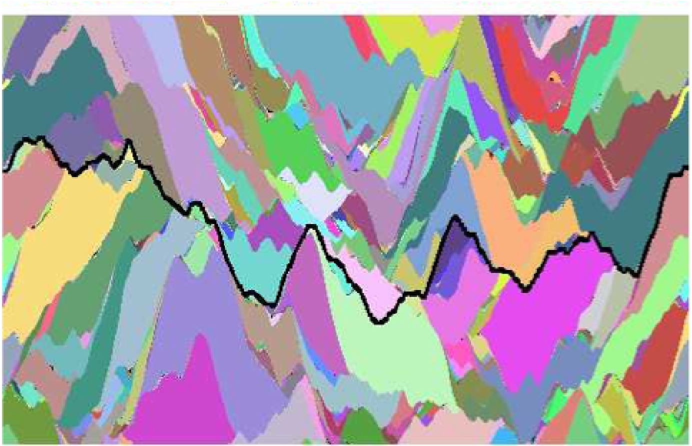
$\lambda = 1$

The effect of lenght λ



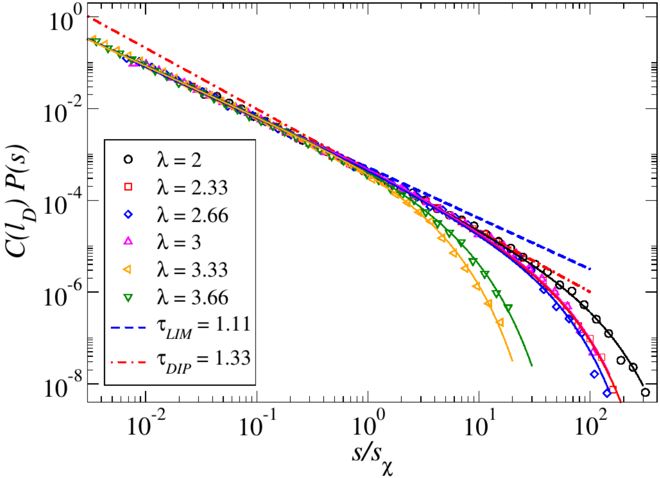
$\lambda = 2$

The effect of lenght λ

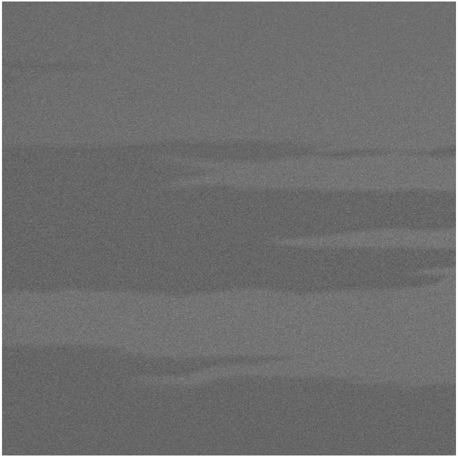


$\lambda = 4$

The real crossover: elastic vs. dipolar

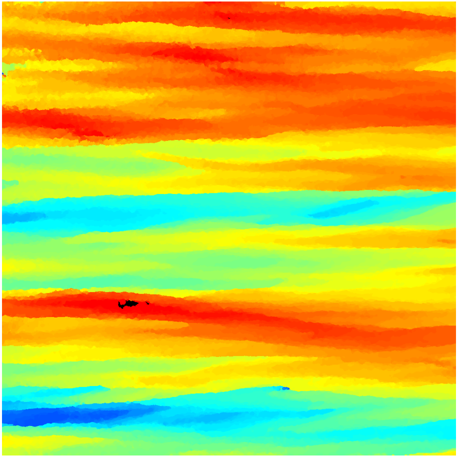


Getting avalanches from MOKE experiments



- Domain wall dynamics in a $NiO(t_{NiO})/Fe(30nm)$ with $t_{NiO} = 80nm$
- Fixed field applied in the horizontal direction
- Magnification: 10x (values: 5, 10, 20, 50)
- Area: 900 x 900 μm^2
- Camera Speed: 2.5 frames/s

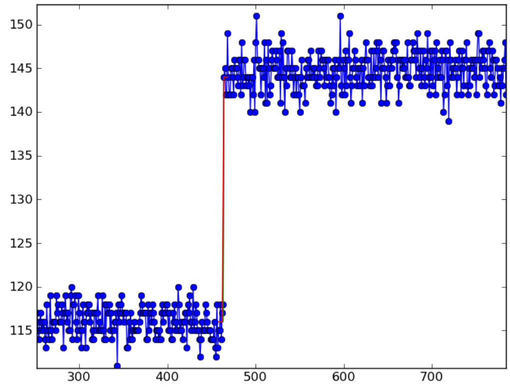
Getting avalanches from MOKE experiments



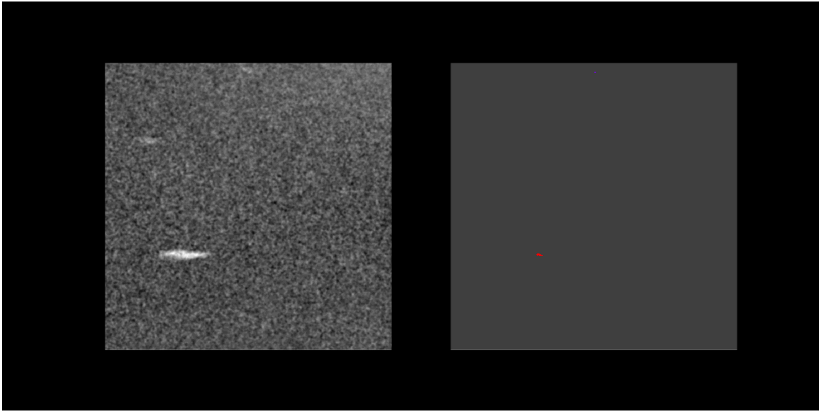
- Domain wall dynamics in a $NiO(t_{NiO})/Fe(30nm)$ with $t_{NiO} = 80nm$
- Fixed field applied in the horizontal direction
- Magnification: 10x (values: 5, 10, 20, 50)
- Area: 900 x 900 μm^2
- Camera Speed: 2.5 frames/s

Pixel analysis

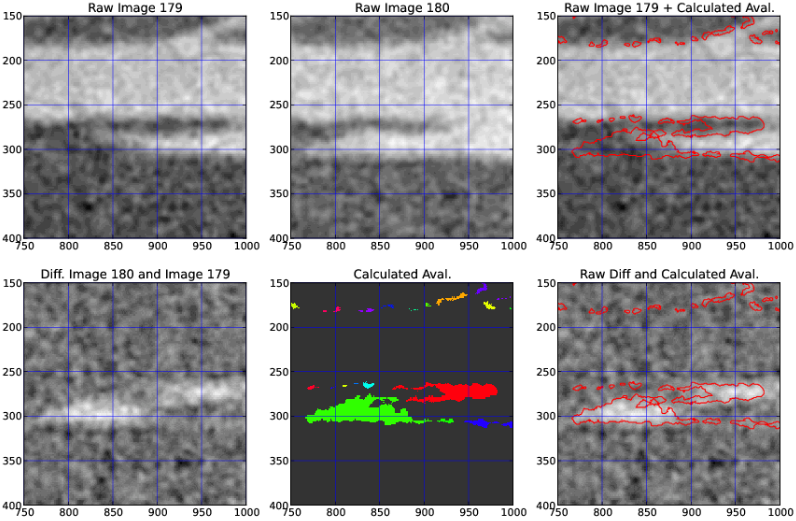
Detect grey level change for each pixel



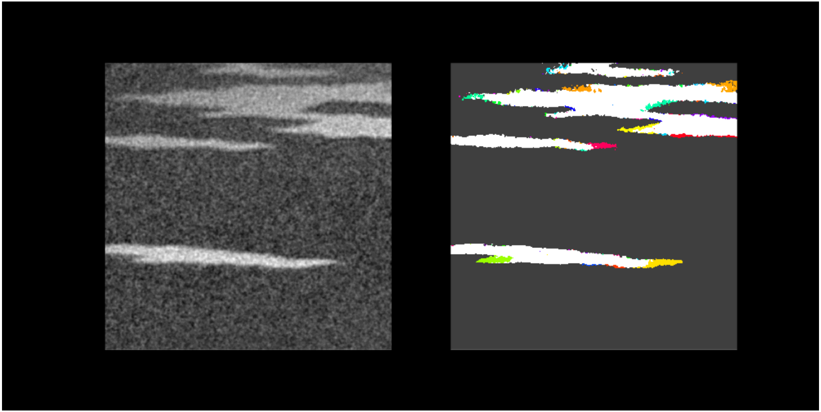
Pixel analysis



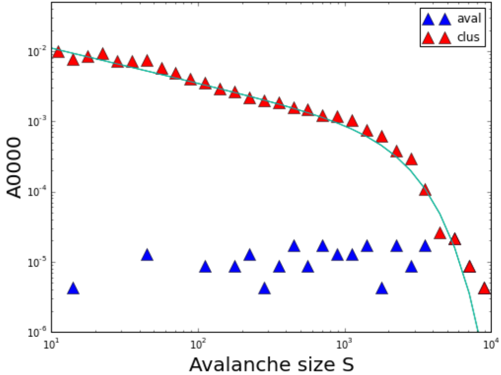
Pixel analysis



Avalanches or clusters?

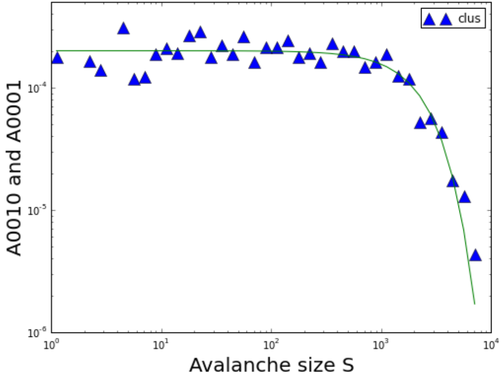


Not yet exaustive



For clusters: $A_{00}(S) \sim S^{1-\tau} \mathcal{A}_{00}(S/S_o)$ with $\tau \sim 1.5$

Not yet exaustive

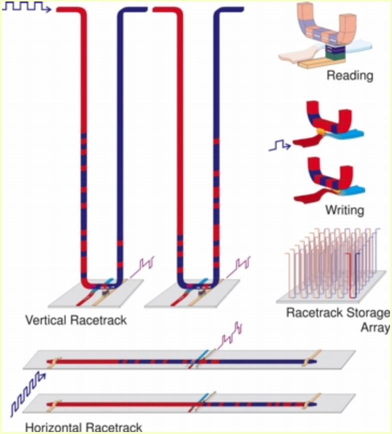


For clusters: $A_{01}(S) \sim S^{1-\tau+1/(1+\zeta)} \mathcal{A}_{01}(S/S_o)$

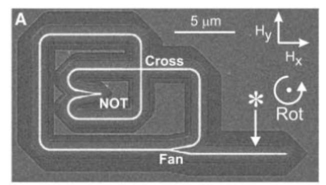
Outline

DW for spintronics devices

Racetrack memory (2008)



Magnetologic memory (2005)



DW oscillator (2008)

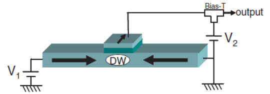


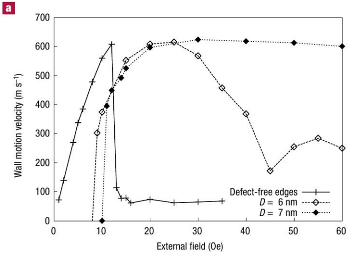
Fig. 3. Schematic illustration of a three-terminal device that produces microwaves by utilizing the current-induced DW rotation.

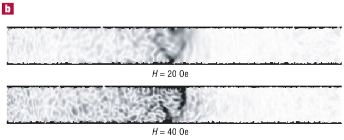
Role of disorder in DW dynamics: rough edges

LETTERS

Faster magnetic walls in rough wires

YOSHINOBU NAKATANI[1,2], ANDRÉ THIAVILLE*[1] AND JACQUES MILTAT[1]



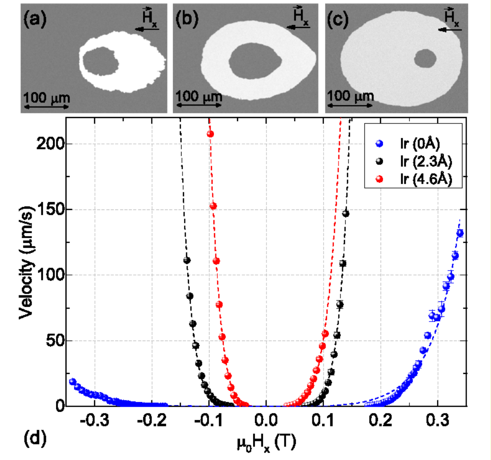


Turbolent DW motion:
no Walker breakdown

Main conclusion...

Roughness should rather be engeneered than avoided

Creep and DW structure



Thank you very much for your attention