Domain wall in a ferromagnetic Ising Co thin film

Lemerle, Ferre, Chappert, Mathe, Giamarchi, PLD (Phys. Rev. Lett. 1998)

D =1+1 interface (d=1,N=1)

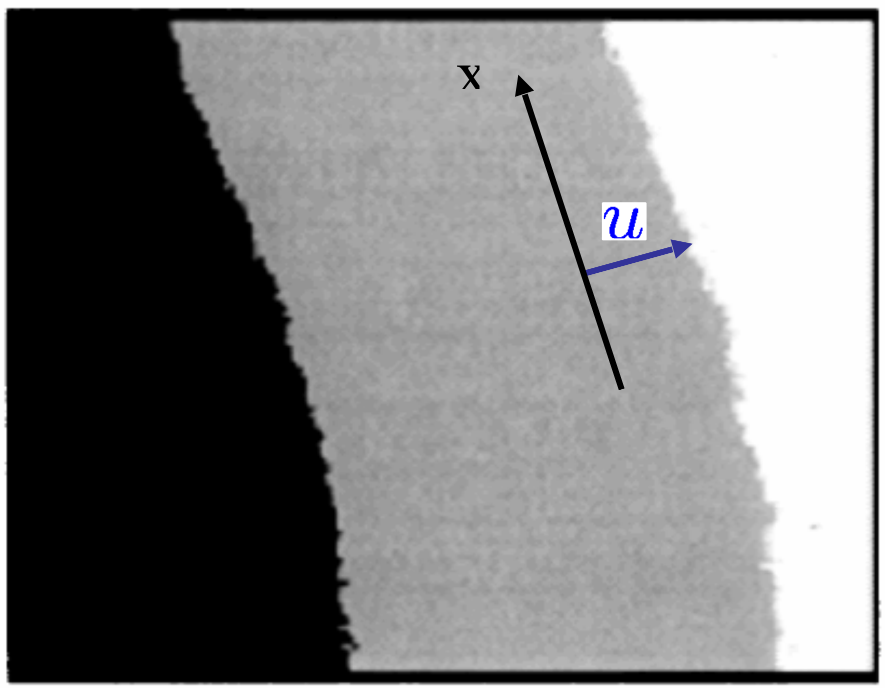
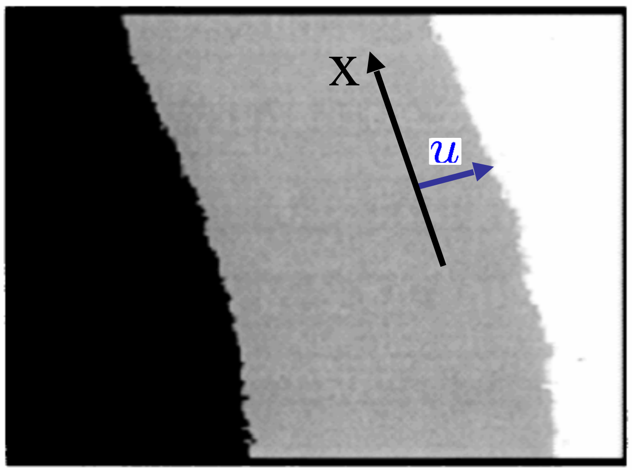


FIG. 1. Typical magneto-optical image (size $90 \times 72\ \mu\mathrm{m}^2$, $\lambda = 638.1$ nm). The gray part corresponds to the surface swept by the domain wall during 111 μs at 460 Oe ($T = 23\,^\circ$C). The dark part is the original domain.



D =1+1 interface (d=1,N=1)

short-range disorder

$$\langle\langle [u(x+L) - u(x)]^2 \rangle\rangle \propto u_c^2 \left(\frac{L}{L_c} \right)^{2\zeta}$$

thermally equilibrated

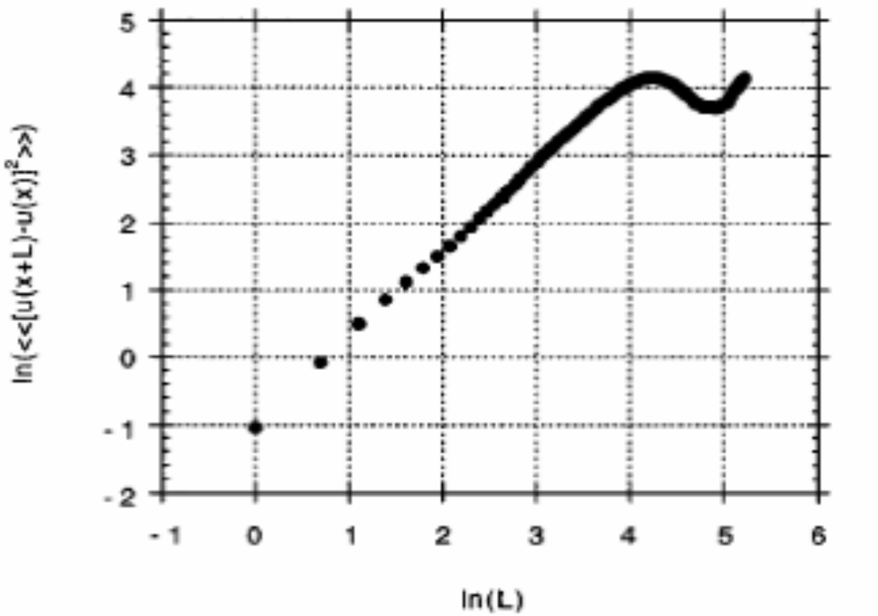


FIG. 4. Typical correlation function drawn in a ln-ln plot. The unit of L is the pixel of the CCD camera, i.e., 0.28 μm.

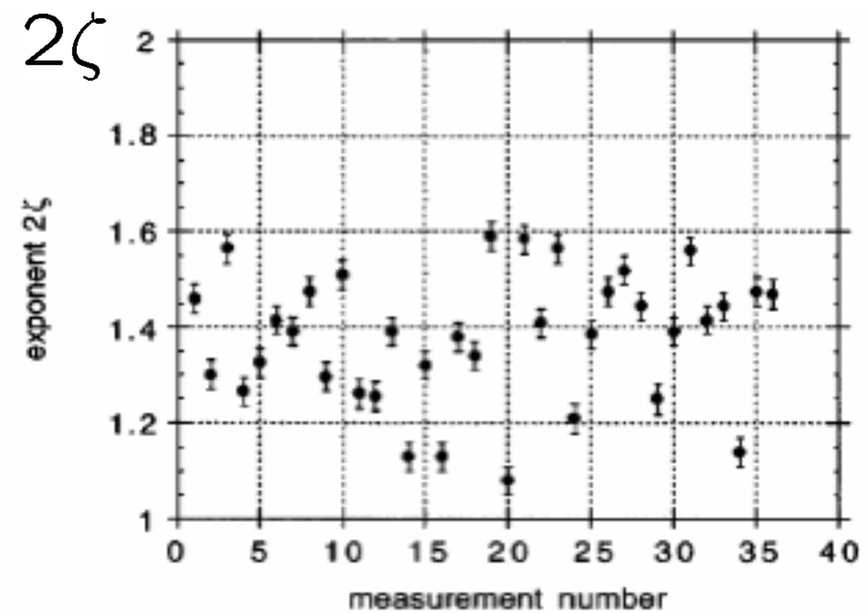


FIG. 5. Wandering exponent 2ζ. Measurements on different MDW driven at $H = 50$ Oe during 20–45 min and then frozen ($T = 300$ K, estimated error on 2ζ for a given image: ± 0.03).

(a)

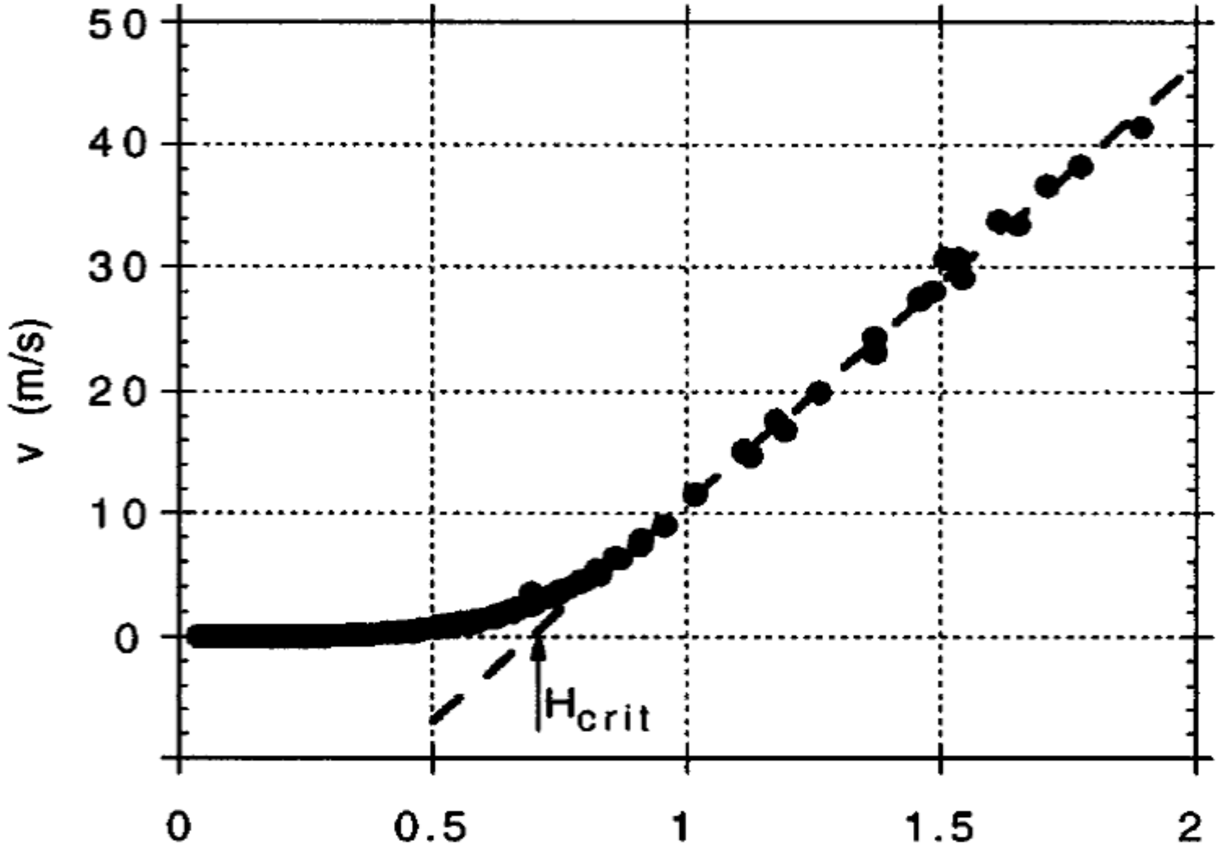


FIG. 2. (a),(b): MDW velocity versus applied magnetic field at room temperature (v in m/s). The dashed line in (a) is the linear fit of the high field part ($H > 0.86$ kOe) and the arrow marks its intersection with the line $v(H) = 0$. This is the definition of $H_{\rm crit}$.

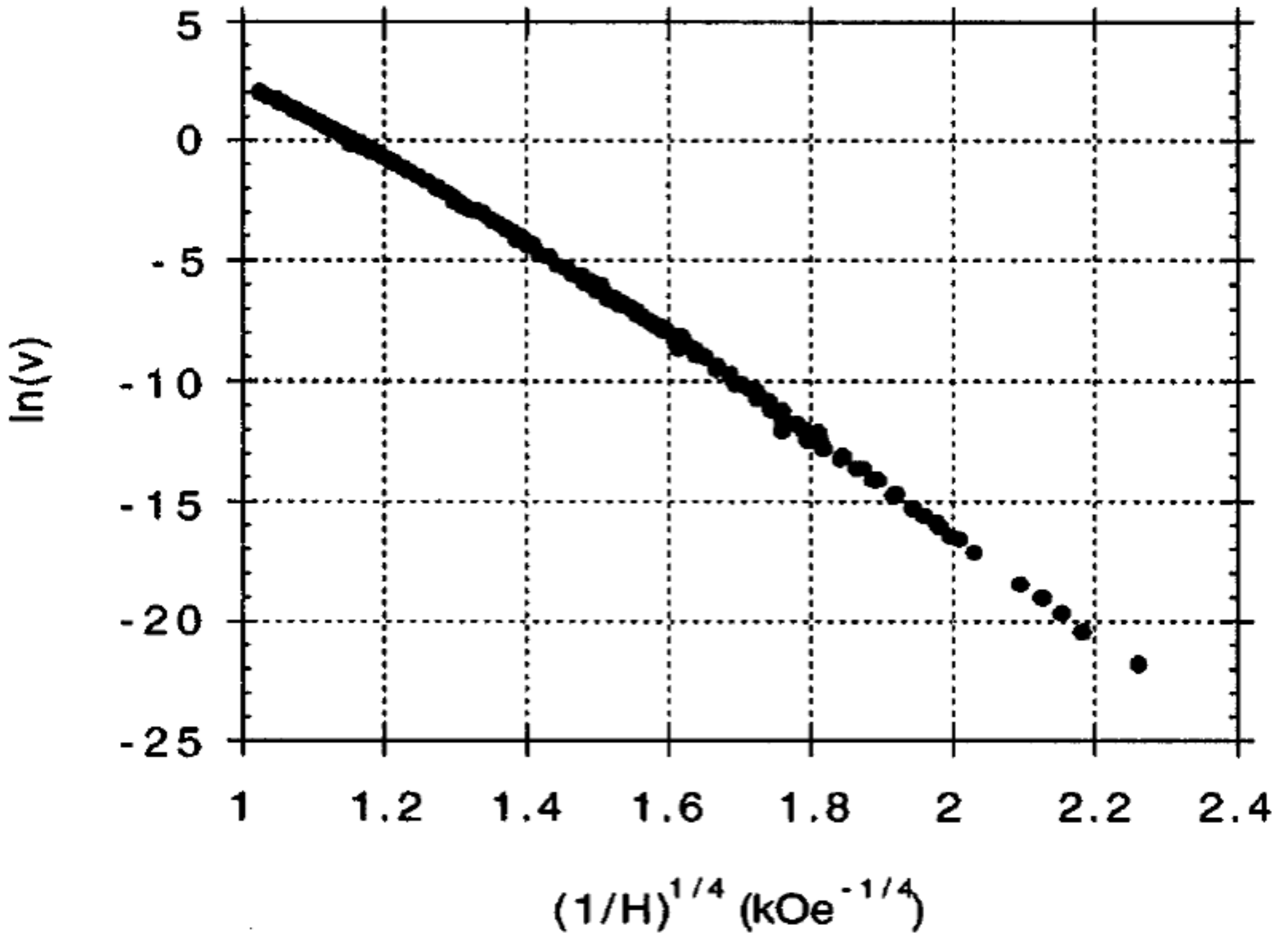


FIG. 3. Natural logarithm of MDW velocity as a function of $(1/H)^{1/4}$ (room temperature, $H \leq 955$ Oe).

Contact line of a fluid

quasi-static depinning

E. Rolley et al. (ENS)

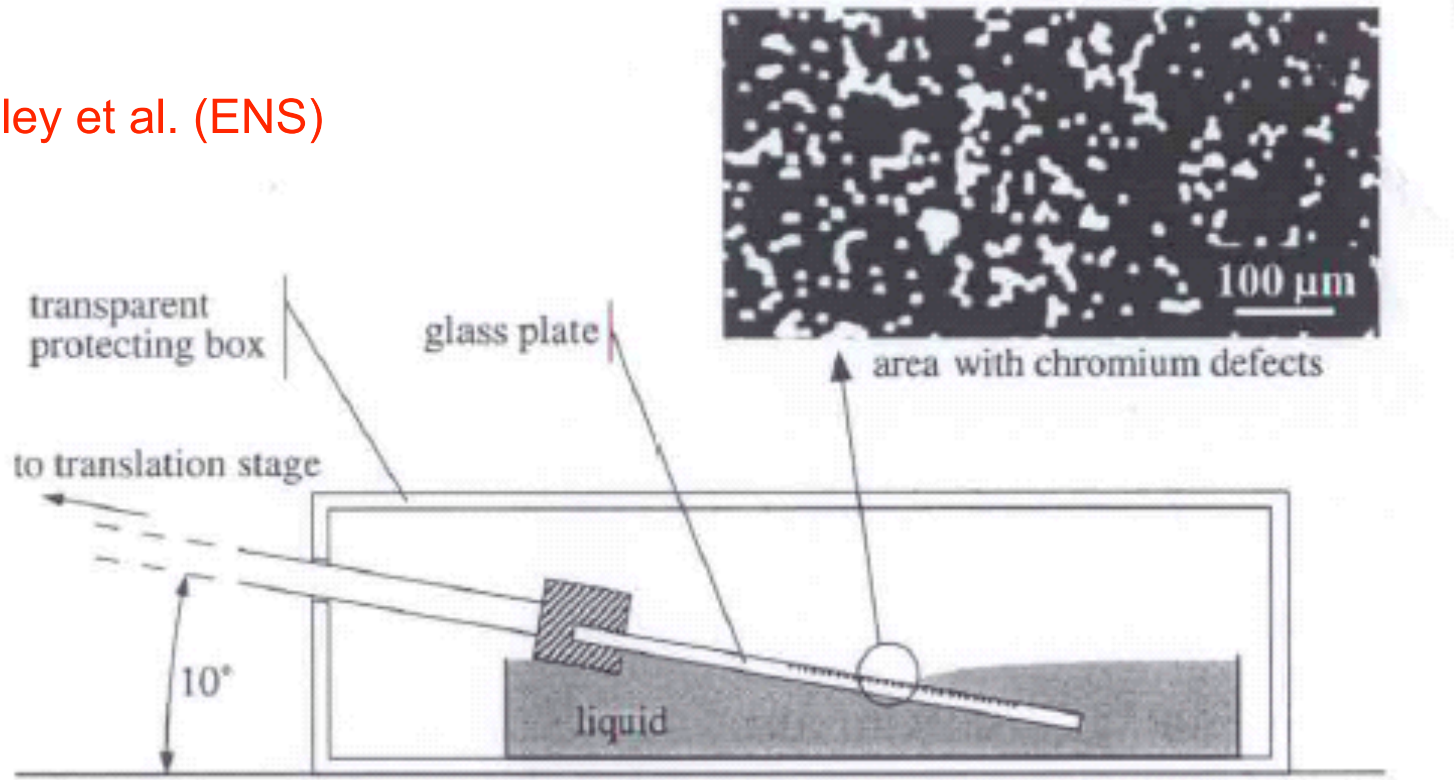


Fig. 2. Sketch of the experimental setup. Inset: photograph of the disordered substrate, the chromium defects appear as white square spots.

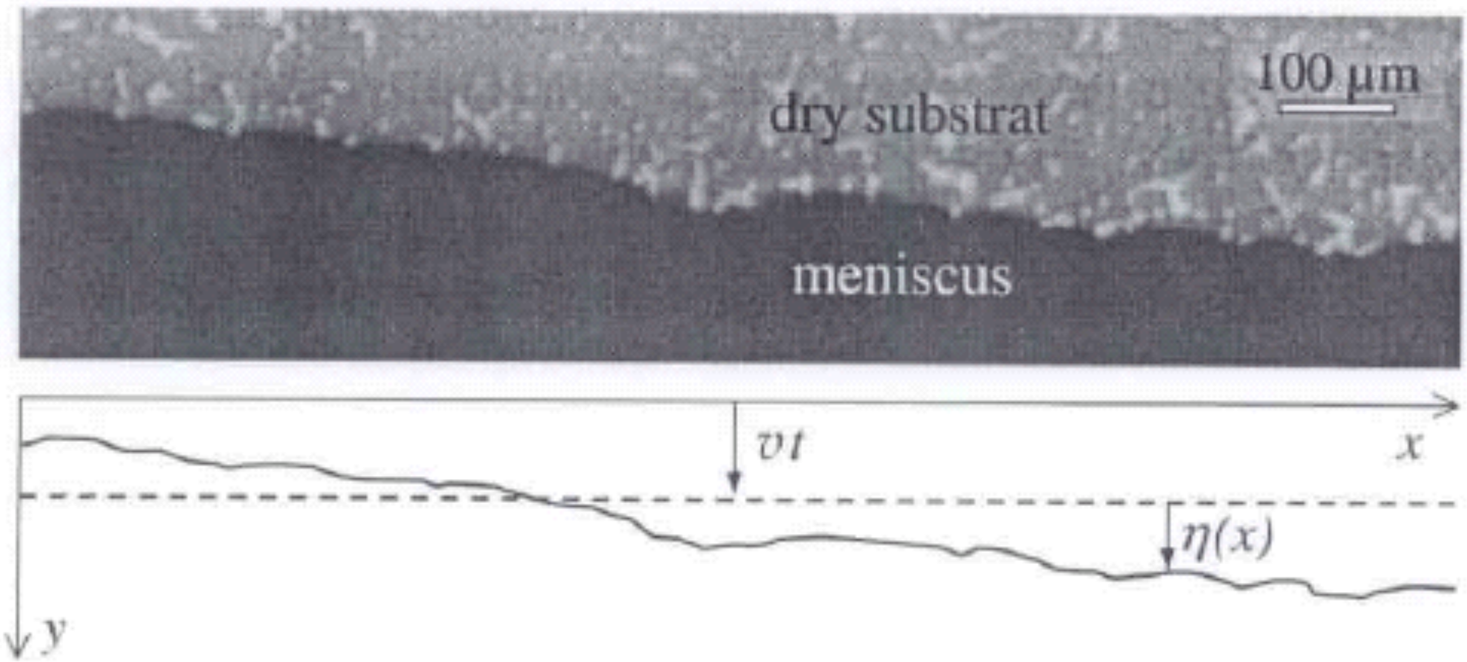
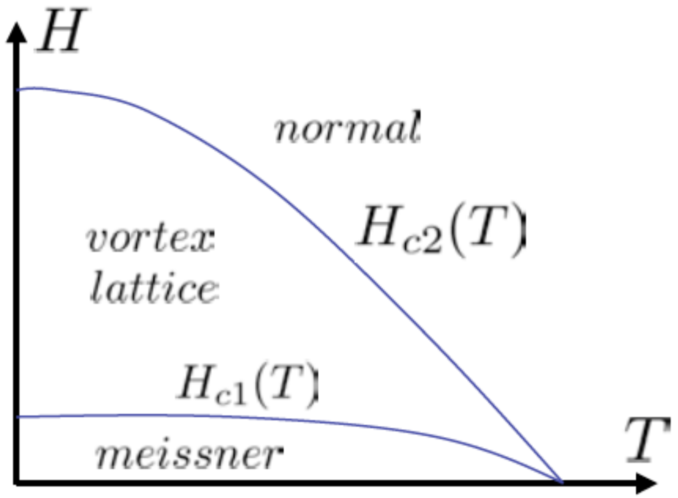
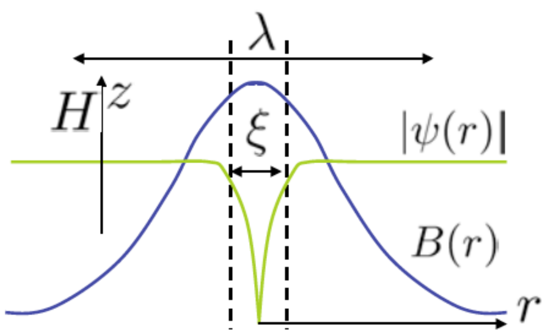


Fig. 1. Upper part: image of the contact line obtained with an ordinary CCD camera. Lower part: the position $\eta(x,t) \equiv y(x,t) - vt$ of the CL is defined with respect to its average position vt.

Abrikosov vortex lattice (type II superconductors)

Mean-field phase diagram





The vortex solution

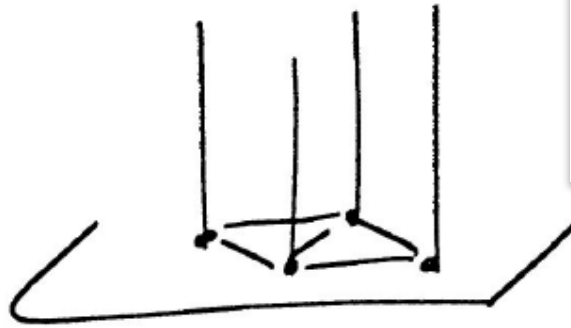
vortex lattice = many parallel vortex lines aligned external field

which order into a triangular lattice

Elasticity of a lattice of vortex lines

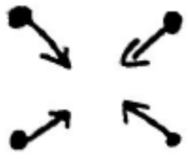
Q: what are d,N ?

$\longrightarrow$ line lattice $\vec{u}(\vec{x}, z)$



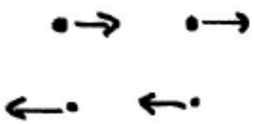
triangular in plane

bulk C_{11}



$\partial_\alpha u_\alpha$

shear C_{66}



$\partial_y u_x$

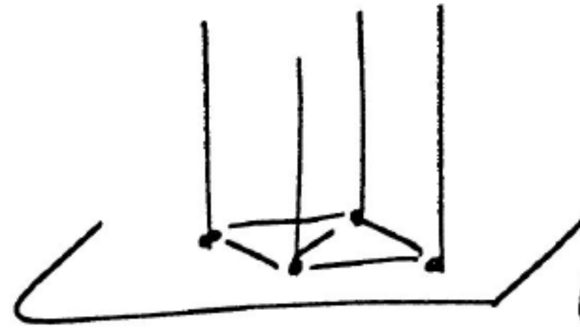
$\partial_z u_z$

tilt C_{44}

$$E_{el} = \frac{1}{2} \int_{q=(q_\perp, q_z)} \left[\left(C_{11} q_\perp^2 + c_{44} q_z^2 \right) P^L_{\alpha\beta}(q_\perp) + \left(c_{66} q^2 + c_{44} q_z^2 \right) P^T_{\alpha\beta}(q_\perp) \right] u^\alpha_{-q} u^\beta_q$$

Elasticity of a lattice of vortex lines

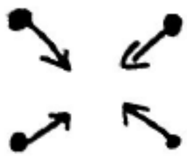
$\longrightarrow$ line lattice $\qquad \vec{u}(\vec{x}, z)$



$N = 2$
$d = 3$

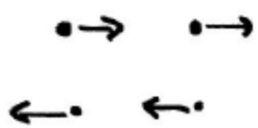
triangular in plane

bulk C_{11}



$\partial_\alpha u_\alpha$

shear C_{66}



$\partial_y u_x$

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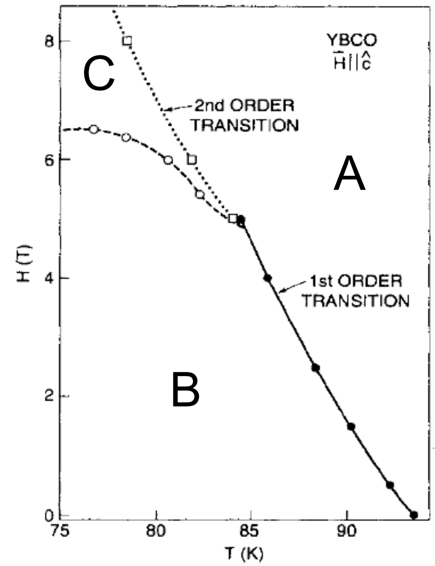
Vortex Lattice + Thermal fluctuations + quenched impurities

3 phases - phase diagram

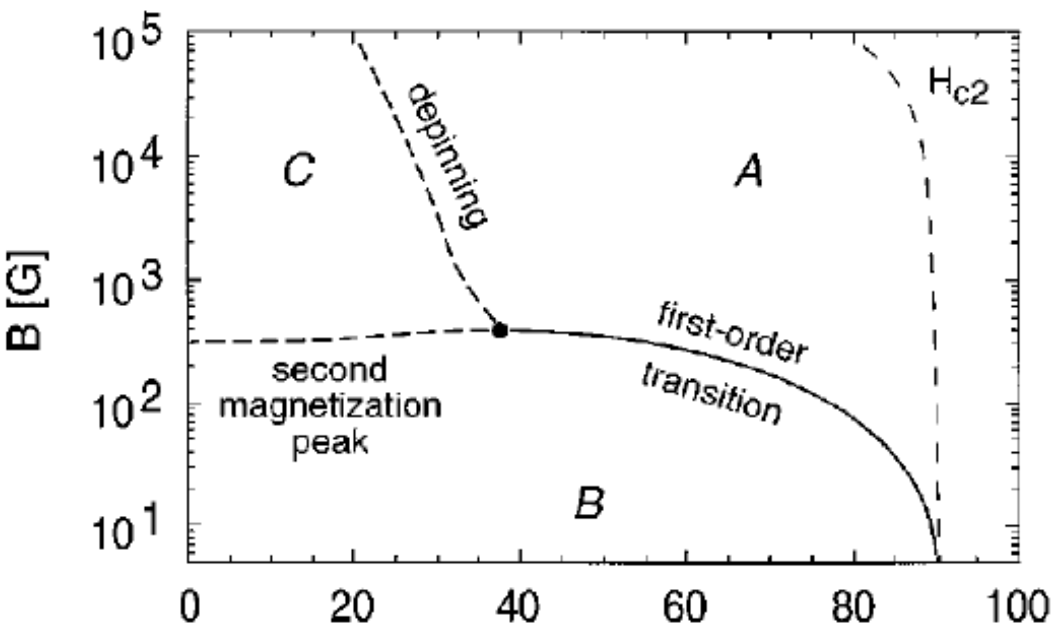
A: Vortex Liquid

C: Vortex glass strongly pinned amorphous

B: Bragg glass weakly pinned - quasi-LR transl order
- no dislocations

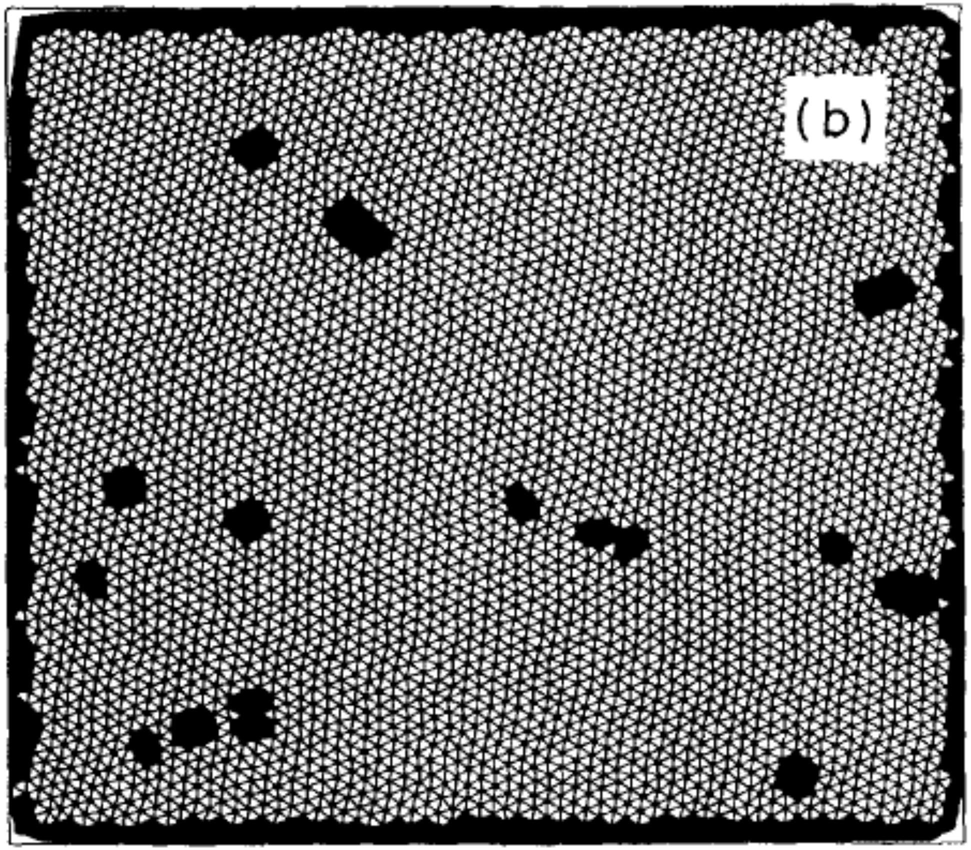


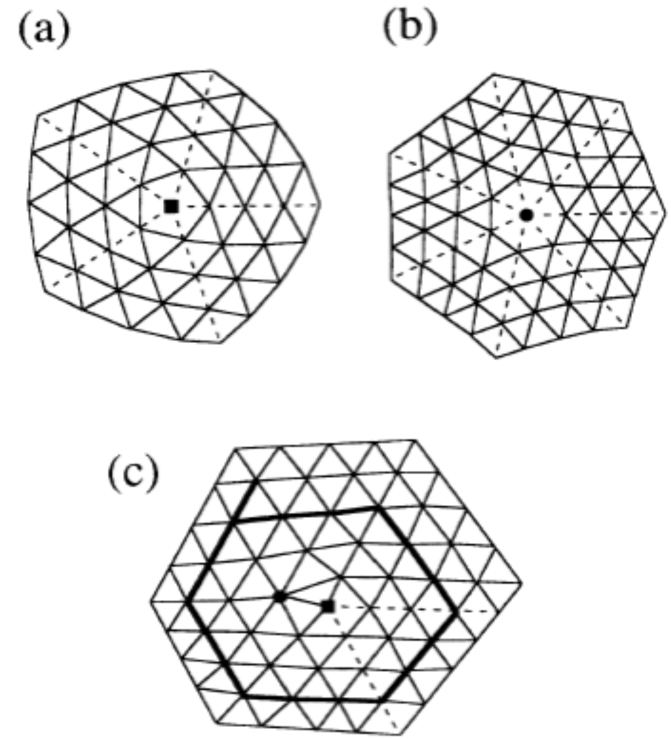
YBaCuO



BiSCCO

early decoration images of vortex lattice(seen from top)
+ delaunay triangulation





dislocations and disclinations

Periodic object + weak disorder

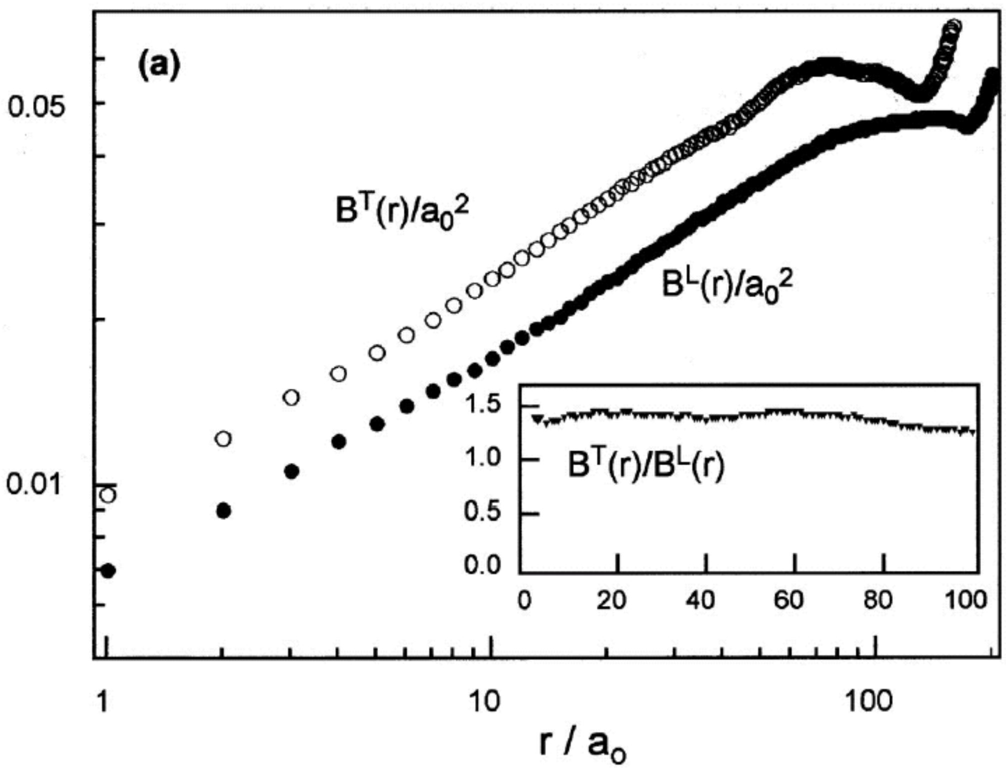
Abrikosov vortex lattice

Bragg Glass: No dislocation

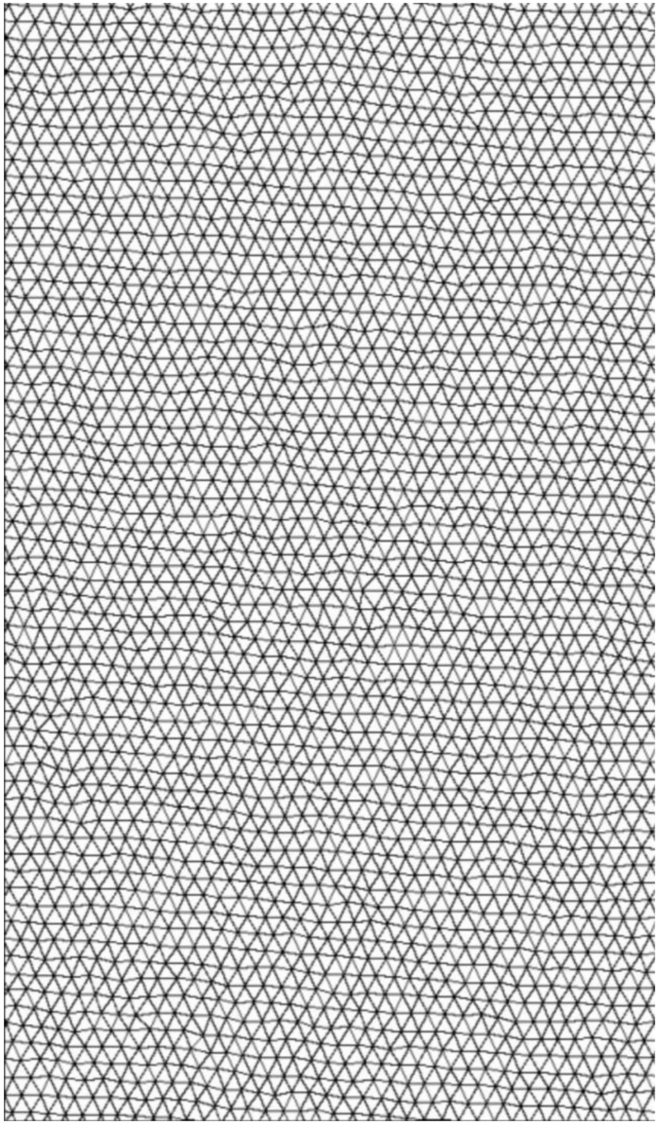
$$B(r) = \overline{(u(r) - u(0))^2}$$

$$B(r) \sim |r|^{2\zeta} \ll a_0^2 \qquad \zeta \approx .22$$

$$d = 3, N = 2$$



decoration



$$B(r) \sim A_d \ln |r| \geq a_0^2$$

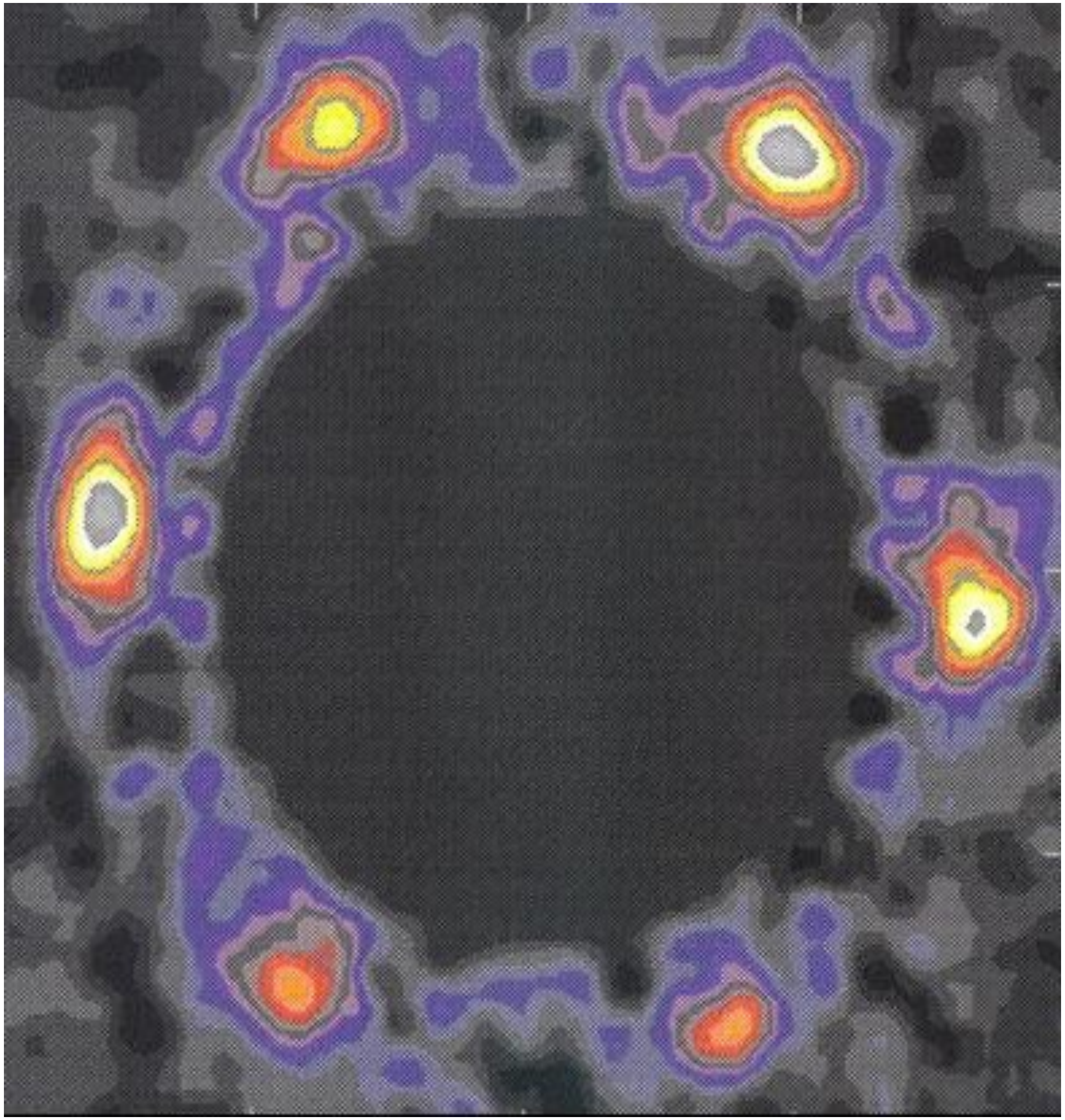
divergent Bragg peaks

$$\rho_K(x) = \rho_0 e^{iKu(x)}$$

$$\overline{\rho_K(x)\rho_K^*(0)} \sim |x|^{-\eta}$$

Klein et al. KBaBiO

Neutron diffraction



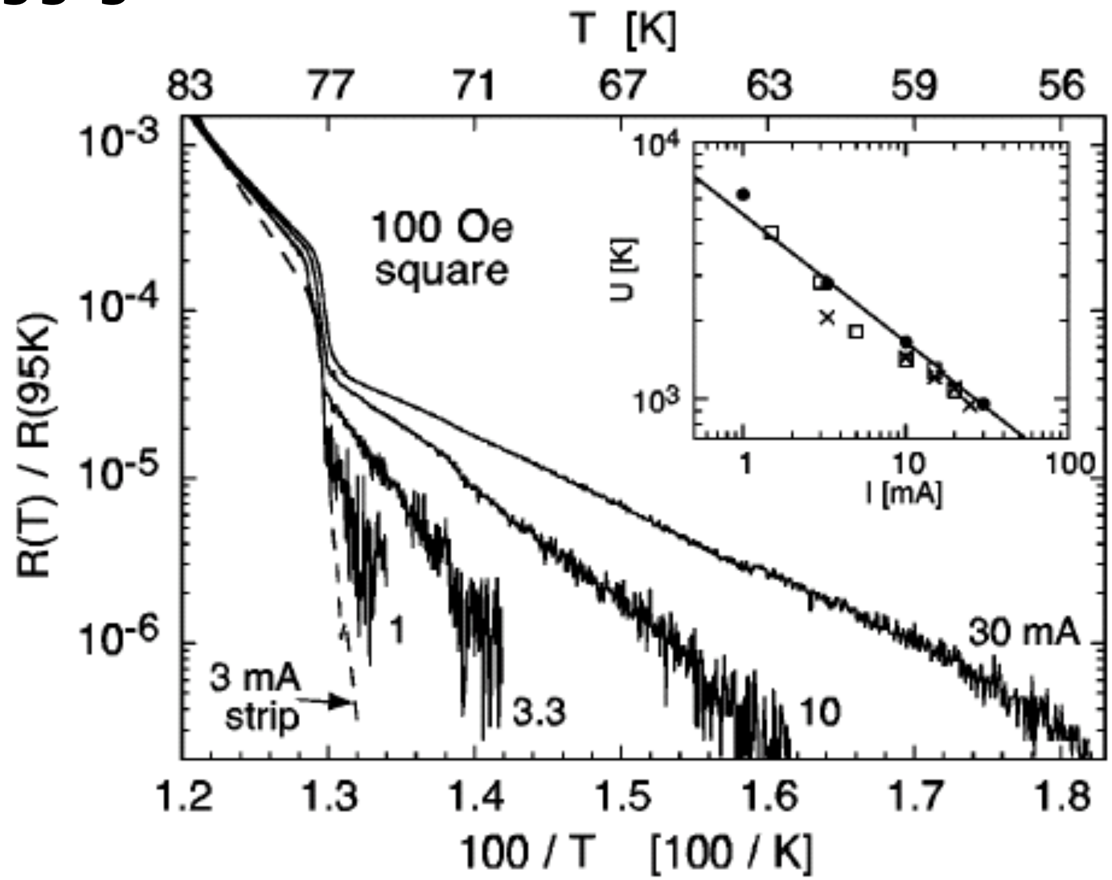
Vortex creep in the Bragg glass

Zeldov et al. BSCCO

$$R \sim v \sim e^{-U(j)/T}$$

$$U(j) \sim j^{-\mu}$$

$$\mu = 1/2$$



velocity of vortex v <=> electric field E

(Lorentz) force acting on vortex f <=> j super-current

creep => zero linear resistivity
= true superconductivity !

Reviews

- Pinning of elastic manifolds

  Blatter et al. Rev. Mod. Phys. 66 (1994) 1125.

  Nattermann and Scheidl Adv. Phys. 49 (2000) 607 cond-mat/0003052.

  Giamarchi and PLD, in book "Spin glasses and random fields" cond-mat/9705096

  PLD in book BCS: 50 years, and Int. J. of Mod. Phys. B, **24** 20-21, 3855 (2010).

  (with more applications to superconductors)

- Functional RG

  PLD, K. Wiese, cond-mat/0611346, Markov Proc. Relat. Fields **13** (2007) 777.

  P. Le Doussal, arXiv:0809.1192, Annals of Physics **325** 1, 49-150 (2010).

Avalanches

Avalanches

Review PhD thesis (2013), A. Dobrinevski, arXiv1312.7156

ABBM model

B. Alessandro, C. Beatrice, G. Bertotti, and A. Montorsi, J. Appl. Phys. **68**, 2901 (1990).

Nonstationary dynamics of the ABBM model
A. Dobrinevski, PLD, K. Wiese, PRE 85, 031105 (2012).

BFM and beyond mean-field

Avalanche dynamics of elastic interfaces
PLD, K. Wiese, arXiv:1302.4316, PRE 88 (2013) 022106.

Size distributions of shocks and static avalanches from the FRG
PLD, K. Wiese, arXiv:0812.1893, PRE, 79, 5 051106, (2009)

Universality in the mean spatial shape of avalanches
T. Thiery, PLD, EPL 114 36003 (2016).

Contact line of a fluid

quasi-static depinning

E. Rolley et al. (ENS)

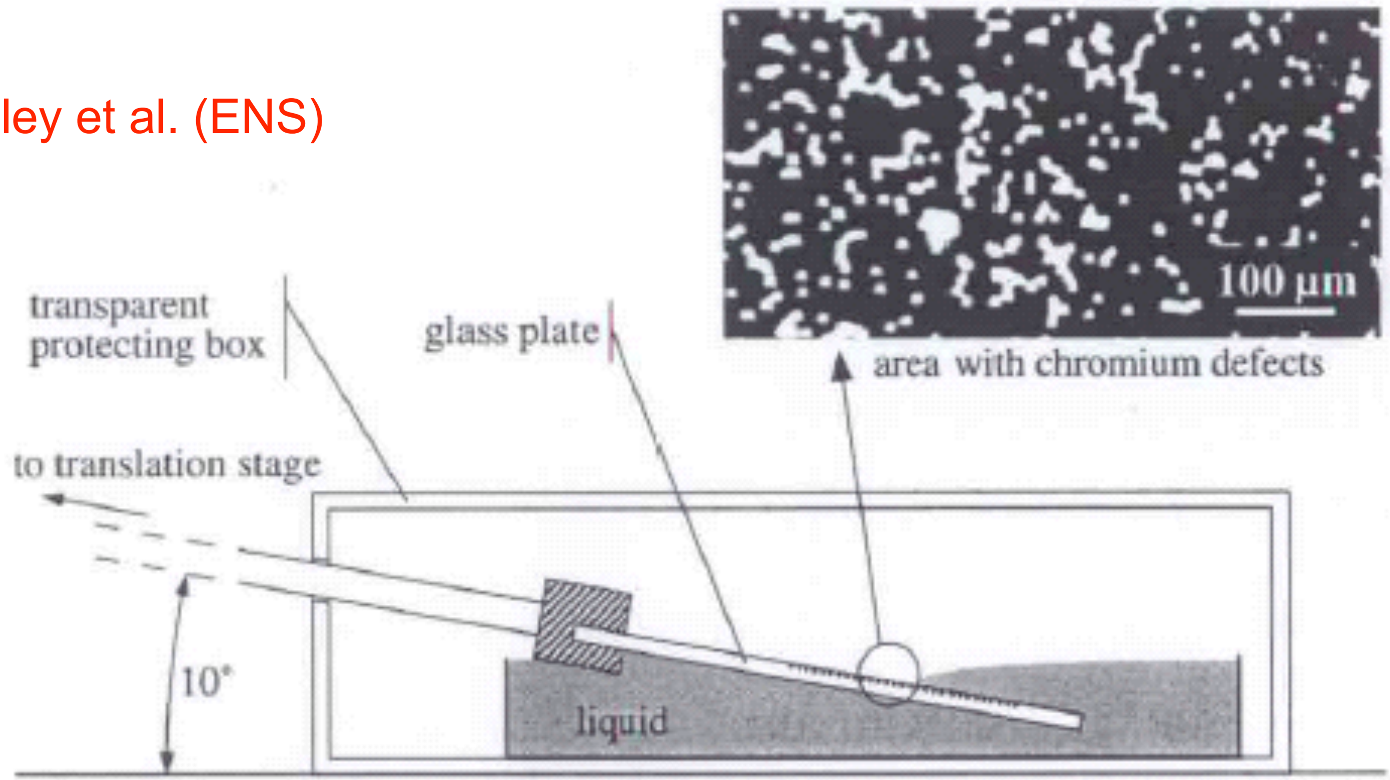


Fig. 2. Sketch of the experimental setup. Inset: photograph of the disordered substrate, the chromium defects appear as white square spots.

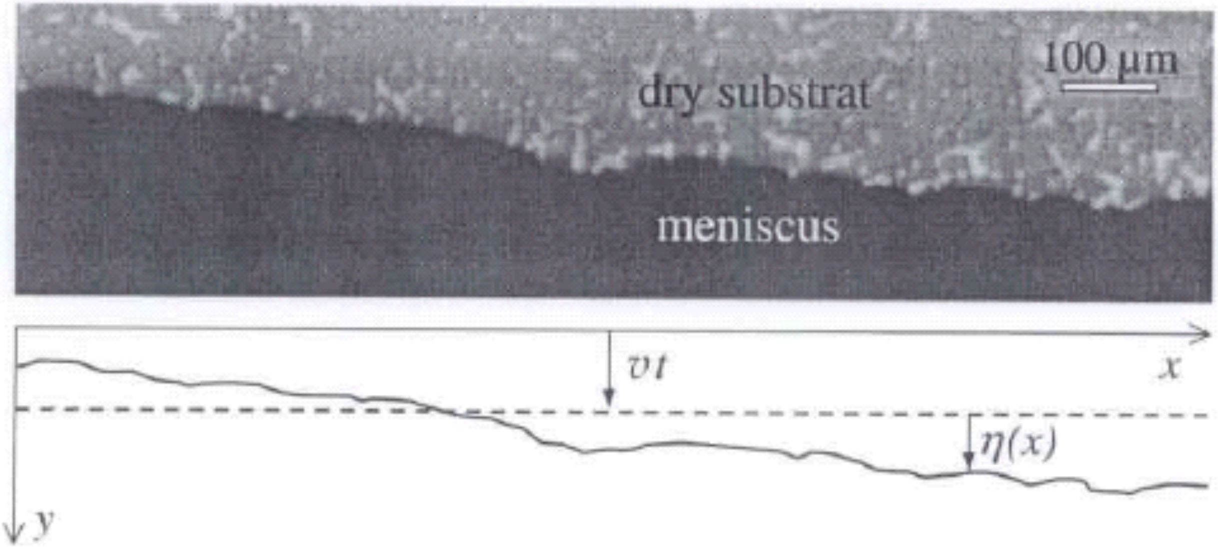


Fig. 1. Upper part: image of the contact line obtained with an ordinary CCD camera. Lower part: the position $\eta(x,t) \equiv y(x,t) - vt$ of the CL is defined with respect to its average position vt.

friction (overdamped dynamics)

$w(t) = vt$

$$\eta_0 \partial_t u(x,t) = \nabla_x^2 u(x,t) + m^2 (w(t) - u(x,t)) + F(u(x,t), x)$$

elastic restoring force
(here non-local)

driving

(quenched) substrate disorder

contact line: gravity (capillary length)

magnetic interface: demag. field

crack line: loading

Avalanches: reproducible

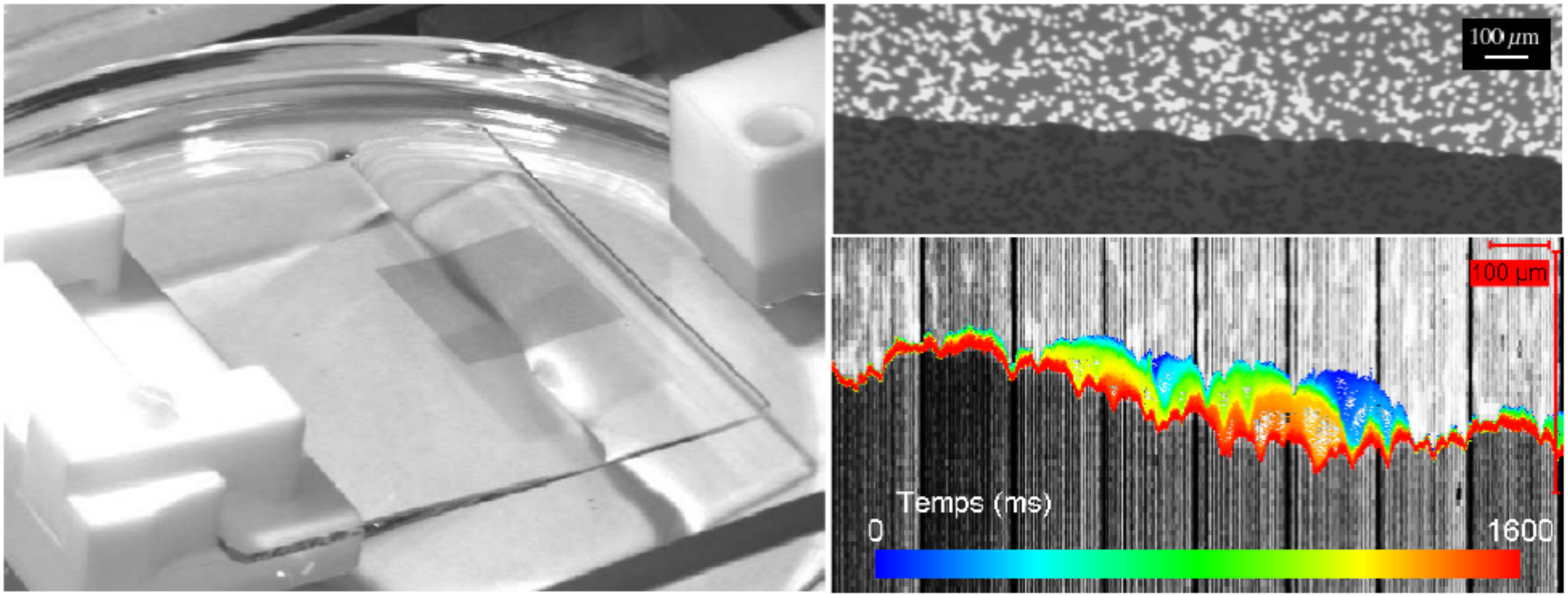
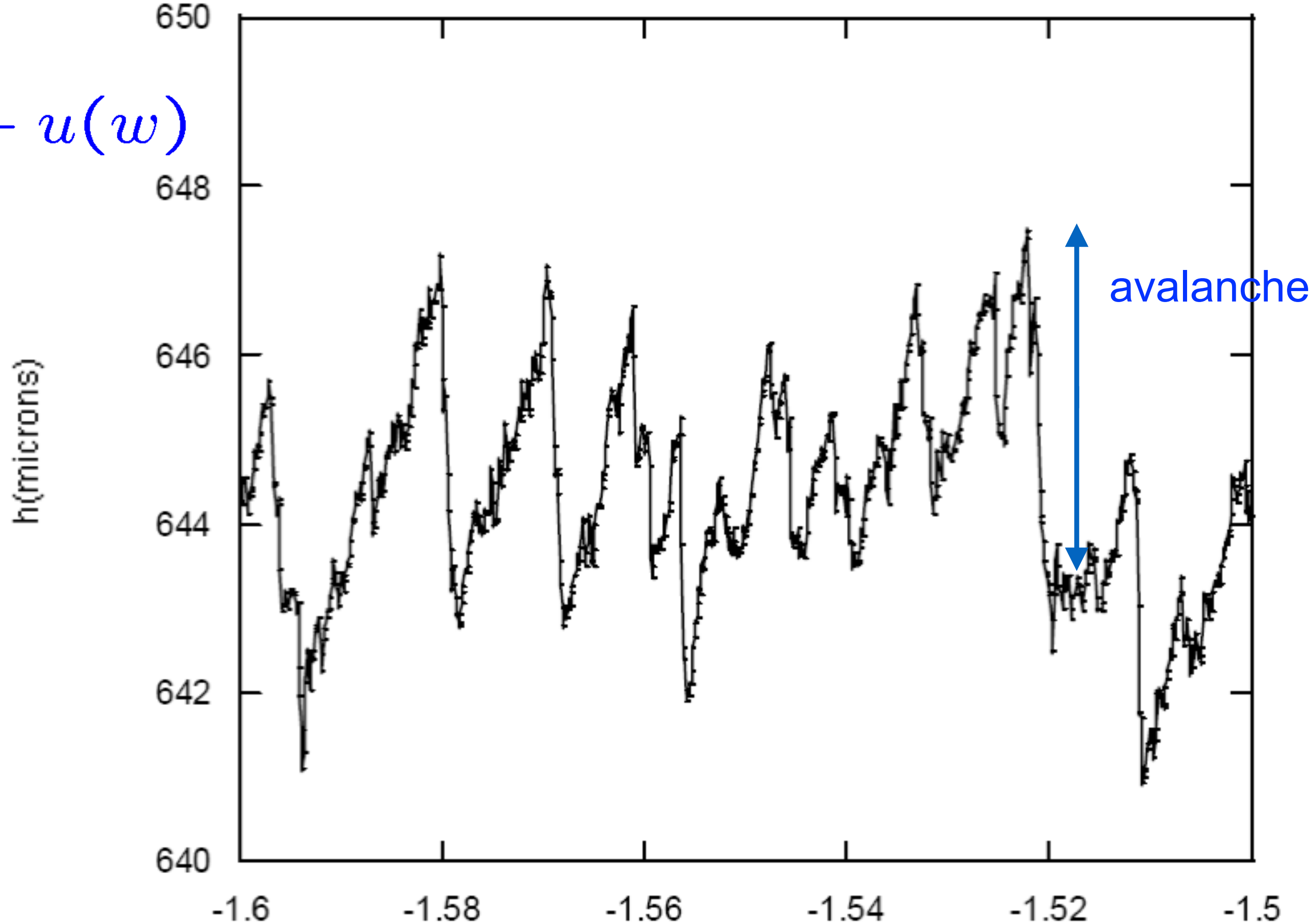


Figure 2: A contact line for the wetting of a disordered substrate by Glycerine [7]. Experimental setup (left). The disorder consists of randomly deposited islands of Chromium, appearing as bright spots (top right). Temporal evolution of the retreating contact-line (bottom right). Note the different scales parallel and perpendicular to the contact-line. Pictures courtesy of S. Moulinet, with kind permission.

u(w) = center of mass of the contact line (over 2 Lc)

$$w - u(w)$$



$w = vt$

Barkhausen (magnetic) noise

G. Durin (Torino) F. Bohn (Brazil)

area proportional to total avalanche size S

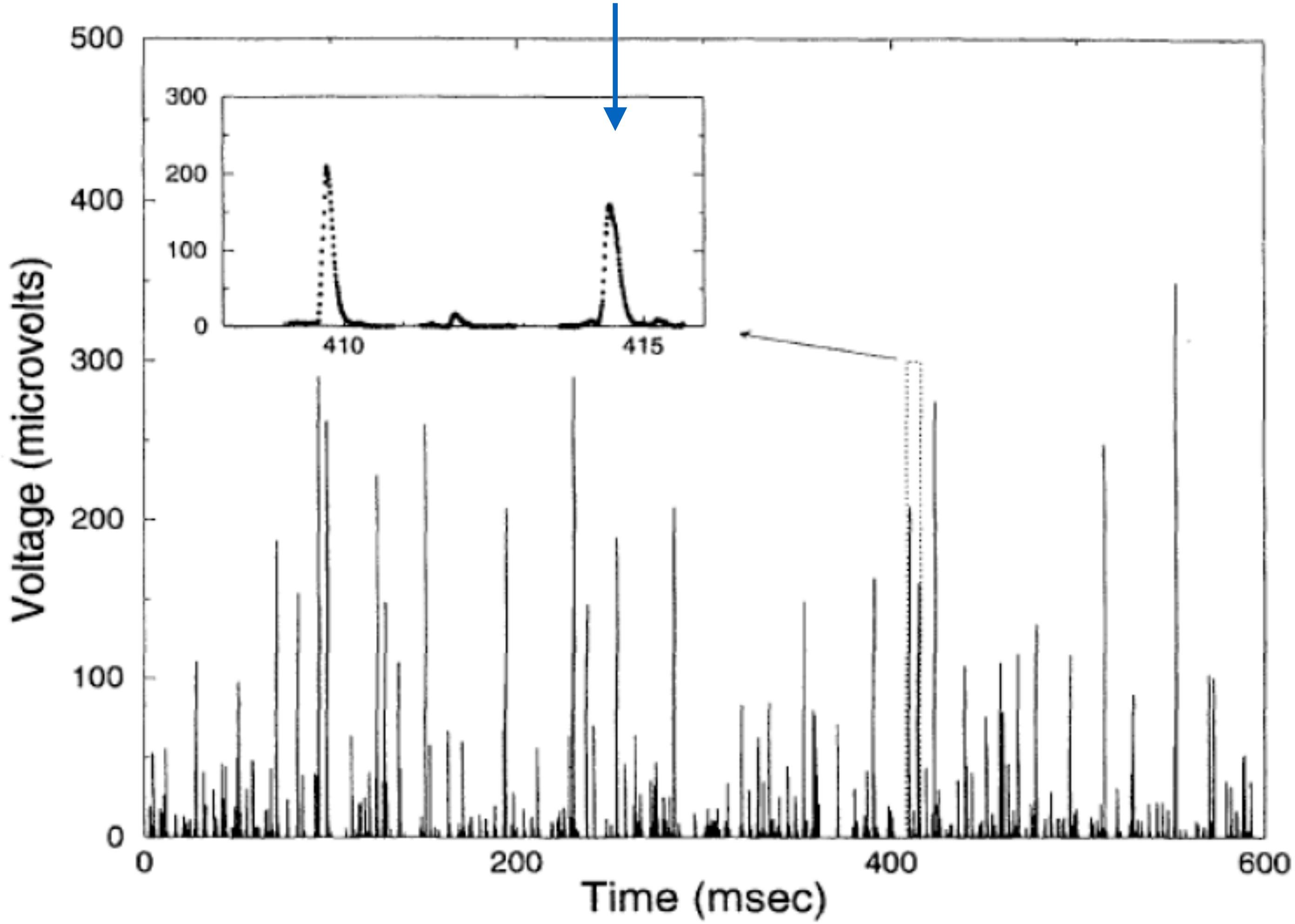
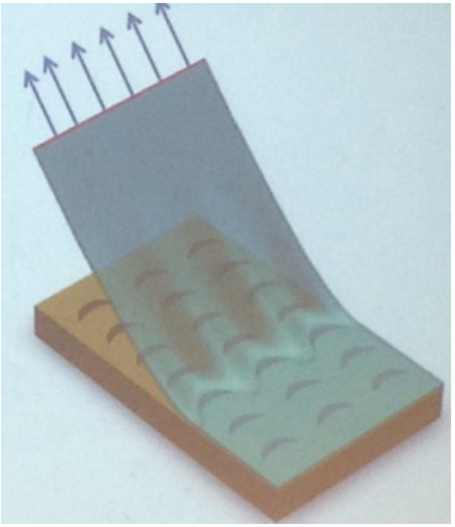


FIG. 1. Experimental Barkhausen signal (voltage produced from a pickup coil around a ferromagnet subjected to a slowly varying applied field).

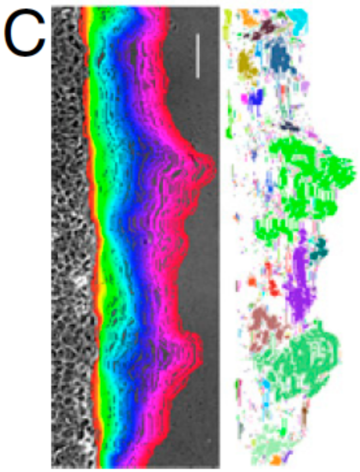
- Fracture: peeling

L. Ponson (UPMC-Paris)

J. Chopin



- Bursts of activity in collective cell migration



Chepizhko et al. (Santucci, Zapperi..) PNAS 113 11408 (2016)

Here we show that collective cell migration occurs in bursts that are similar to those recorded in the propagation of cracks, fluid fronts in porous media and ferromagnetic domain walls

Functional RG and field theory

how to measure/define it?

PLD, EPL (2006), AnnalsPhys. (2010) PLD, KW, EPL (2007)

$$\overline{(u(w) - w)(u(w') - w')}^c = m^{-4} L^d \Delta(w - w')$$

central object is renormalized disorder correlator $\Delta(w) \equiv \Delta_m(w)$

it obeys differential FRG equation as m is varied

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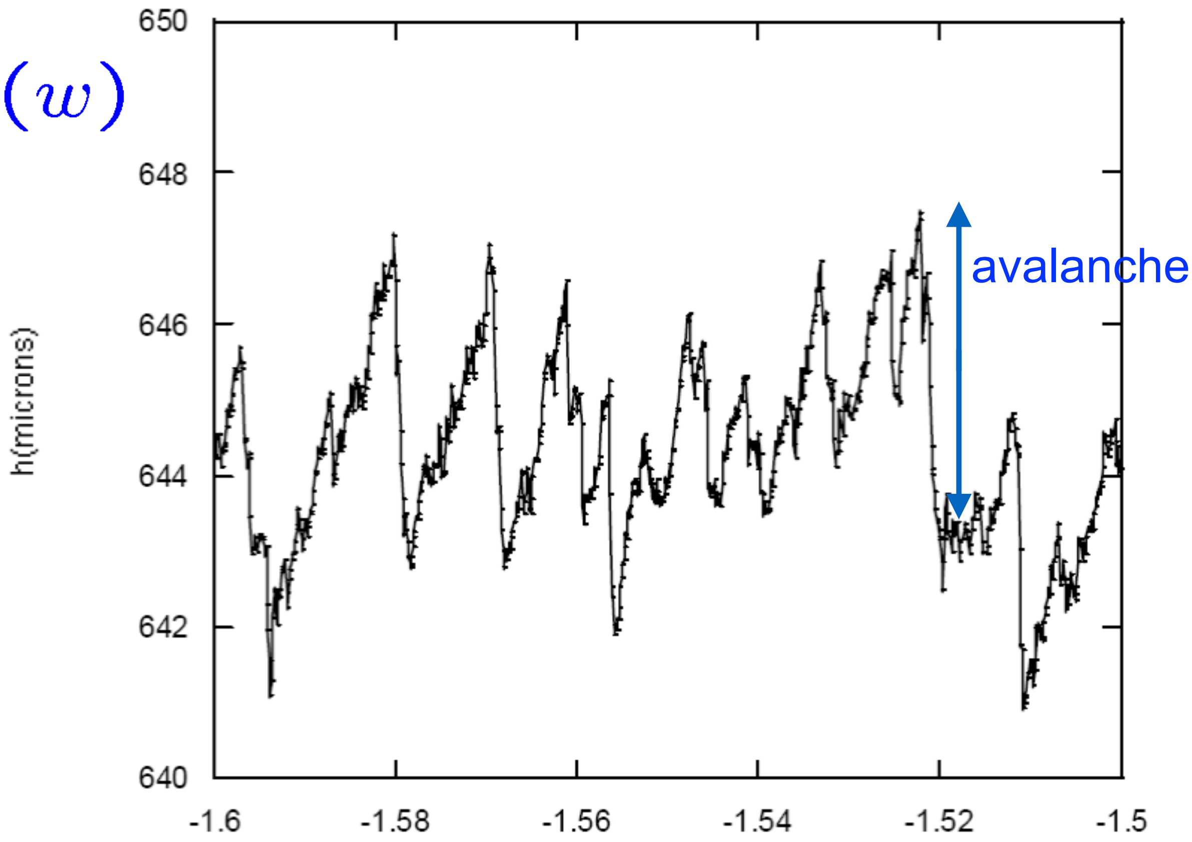
$w - u(w)$



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$$\overline{(u(w)-w)(u(w')-w')}^c = m^{-4} L^d \Delta(w-w')$$

$$\Delta_m(w) \simeq_{m\to 0} m^{\epsilon-2\zeta} \tilde{\Delta}^*(w m^{\zeta})$$

$$-m\partial_m \Delta = (\epsilon - 2\zeta)\Delta + \zeta\Delta' - (\frac{\Delta^2}{2} + \Delta\Delta(0))''$$

$$+\frac{1}{2}(\Delta'^2(\Delta - \Delta(0))'' + \frac{\lambda}{2}\Delta'(O^+)^2\Delta''(u)$$

$\lambda_{stat} = -1$

$\lambda_{dep} = 1$

2-loop Chauve, PLD, KW, PRL (2000) 3-loop Huseman, PLD, KW unpub.

- analytic correlator => Larkin
- develops a cusp at Lc (Larkin length)

$$S_m := \frac{\langle S^2 \rangle}{2\langle S \rangle} = \frac{|\Delta'(0^+)|}{m^4}$$

Functional RG and field theory

central object is renormalized disorder correlator $\Delta(w) \equiv \Delta_m(w)$

how to measure/define it?

PLD, EPL (2006), AnnalsPhys. (2010) PLD, KW, EPL (2007)

$$\overline{(u(w)-w)(u(w')-w')}^c = m^{-4} L^d \Delta(w-w')$$

it obeys differential FRG equation as m is varied

FRG fixed point: $\Delta_m(w) \simeq_{m\to 0} m^{\epsilon-2\zeta} \tilde{\Delta}^*(w m^\zeta)$ $\quad \epsilon = d_{uc} - d$

$$\tilde{\Delta}^*(u) = \epsilon d_1(u) + \epsilon^2 d_2(u) + ..$$

All universal observables can be obtained in perturbation in $\tilde{\Delta}^*(u)$ i.e. in ϵ

Allows to calculate depinning critical exponents: two independent exponents

$u \sim x^\zeta$ SR $\zeta = \frac{\epsilon}{3}(1 + 0.1433\epsilon)$ $\quad \epsilon = 4 - d$

LR 0.39735ϵ $\quad \epsilon = 2 - d$

$x \sim t^z$

$z = 2 - \frac{2}{9}\epsilon - 0.0432\epsilon^2$

$-0.1133\epsilon^2$

Ferrero (2013)

SR d=1 $\zeta = 1.250 \pm 0.005$

$z = 1.433 \pm 0.007$

LR d=1 predicts 0.4 confirmed numerics

Rosso, Krauth $\zeta = 0.39..$

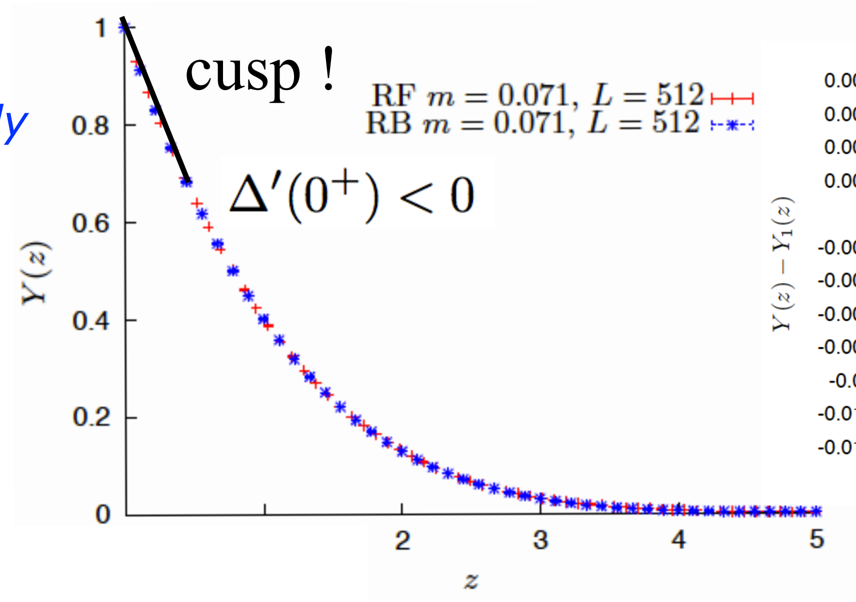
fracture: Ponson, Santucci,..

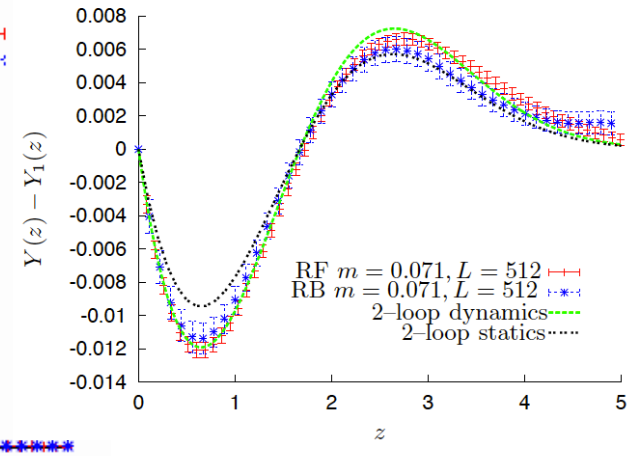
FRG fixed point at depinning: numerics and experiments

numerics: interface driven quasi-statically by quadratic well

A. Rosso, PLD, KW

condmat/0610821





contact line experiment:

E. Rolley, S. Moulinet, PLD, KW

EPL, 87 (2009) 56001

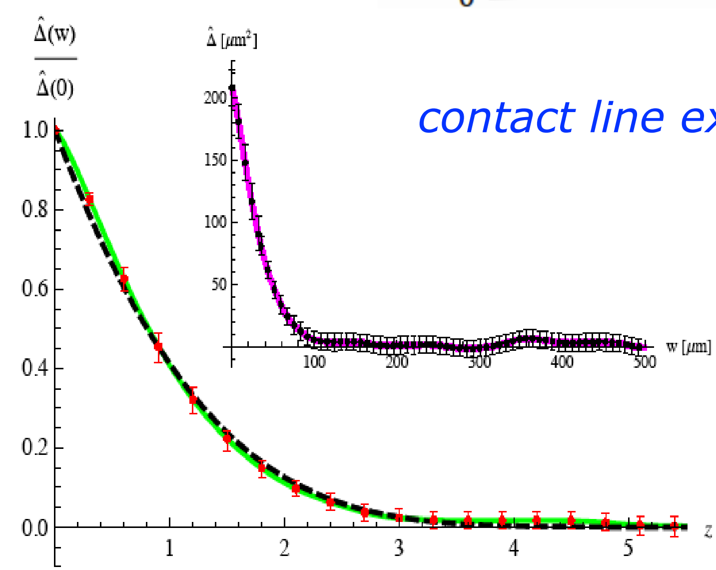


Fig. 6: Inset: The disorder correlator $\hat\Delta(w)$ for iso/Si at $v = 1\mu\mathrm{m/s}$ up to $w = 35\mu\mathrm{m}$, and then at $v = 10\mu\mathrm{m/s}$ for $w > 35\mu\mathrm{m}$, with error-bars as estimated from the experiment. Main plot: The rescaled disorder correlator $\hat\Delta(w)/\hat\Delta(0)$ (green/solid) with error bars (red). The dashed line is the 1-loop result from equation (6).

$$\hat\Delta(w - w') := \langle \overline{\mathsf{h}}_l(w)\overline{\mathsf{h}}_l(w')\rangle$$

$$\bar h_l(t) := \frac{1}{l}\int_0^l h(x,t)\,\mathrm{d}x$$

$$\mathsf{h}(x,w) := h(x,w/v) - h_0$$

Quantitative scaling of magnetic avalanches

Barkhausen noise

G. Durin,[1,2] F. Bohn,[3] M. A. Corrêa,[3] R. L. Sommer,[4] P. Le Doussal,[5] and K. J. Wiese[5]

Phys. Rev. Lett. (2016)

LR elasticity samples, comparison with MF

LR polycrystalline $Ni_{81}Fe_{19}$ Permalloy (Py)

200 nm thick

$\tau_m = 39\,\mu s$ is ONLY parameter!

$$\langle \dot{u}(t)\rangle_S = \frac{S}{\tau_m}\left(\frac{S}{S_m}\right)^{-\frac{1}{\gamma}} f\left(\frac{t}{\tau_m}\left(\frac{S_m}{S}\right)^{\frac{1}{\gamma}}\right)$$

$$S_m := \frac{\langle S^2\rangle}{2\langle S\rangle} \qquad f_0(t) = 2te^{-t^2} \quad , \quad \gamma = 2$$

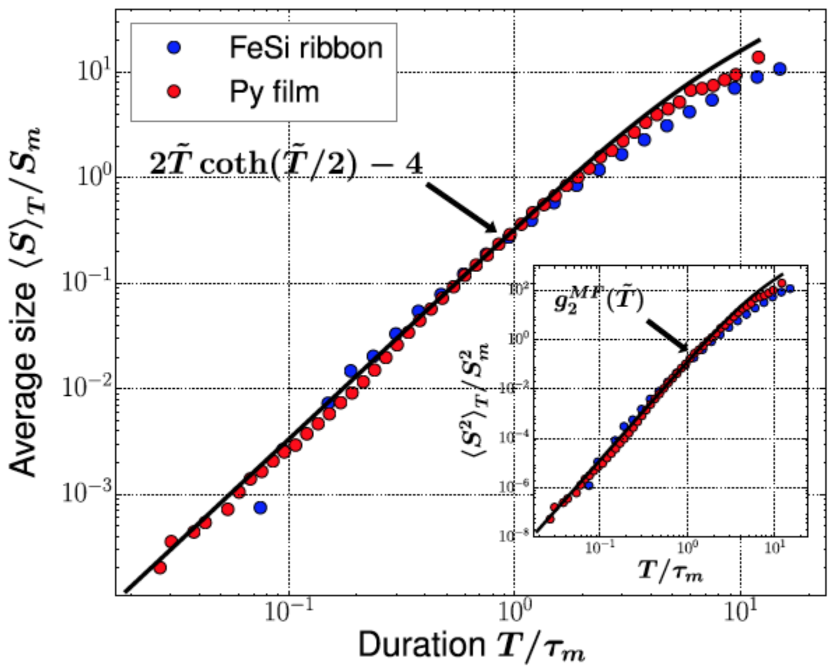


Figure 1. Normalized average size $\langle S\rangle_T/S_m$ of Barkhausen avalanches in the FeSi ribbon (blue dots) and the Py thin film (red dots) as a function of the normalized duration $\tilde{T} = T/\tau_m$. The continuous line is the theoretical prediction $g_1^{\rm MF}$ of Eq. (4). For the ribbon, the deviation at large durations is more evident due to effect of the eddy currents. The inset shows the second moment $\langle S^2\rangle_T/S_m^2$ compared to the prediction $g_2^{\rm MF}$ of Eq. (4).

m = k0 demag. field

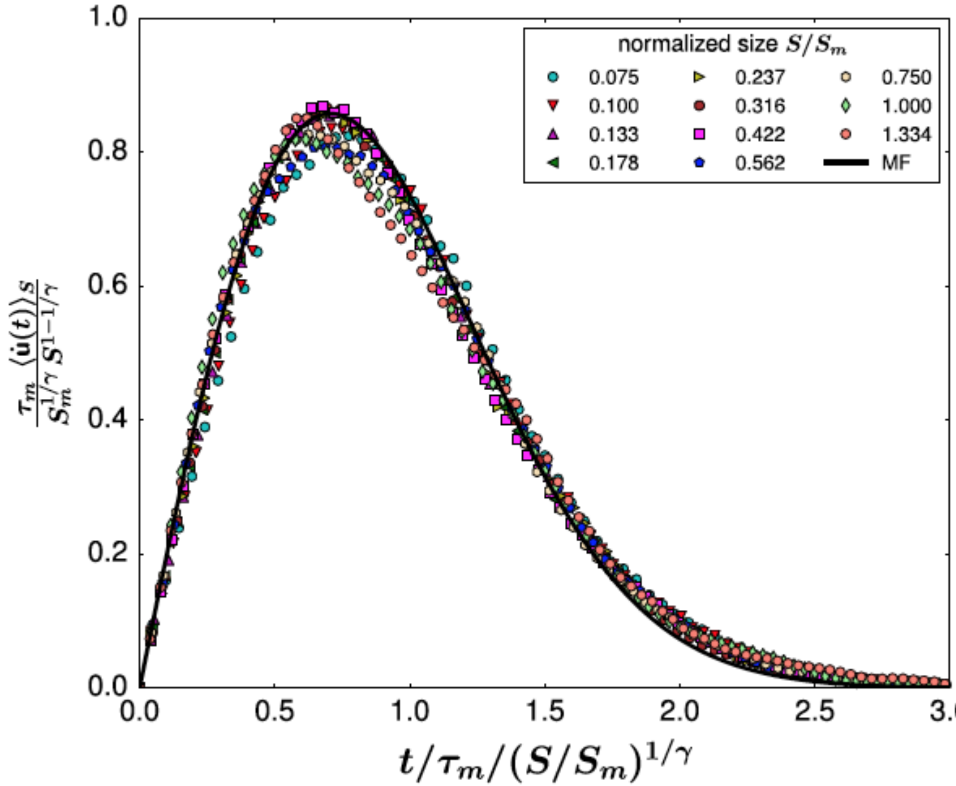


Figure 4. Scaling collapse of the average shapes at fixed avalanche sizes $\langle \dot{u}(t)\rangle_S$, according to Eq. (7), in the Py thin film. The continuous line is the mean-field universal scaling function in Eq. (8).

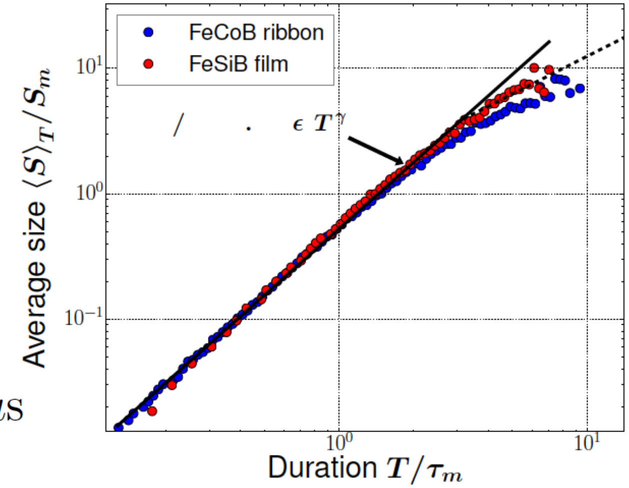
avalanche shape at fixed size: beyond mean-field

samples with SR elasticity

SR amorphous $Fe_{75}Si_{15}B_{10}$ (FeSiB) alloy 1000 nm

comparison with theory with epsilon=2

$\tau_m = 38\,\mu s$



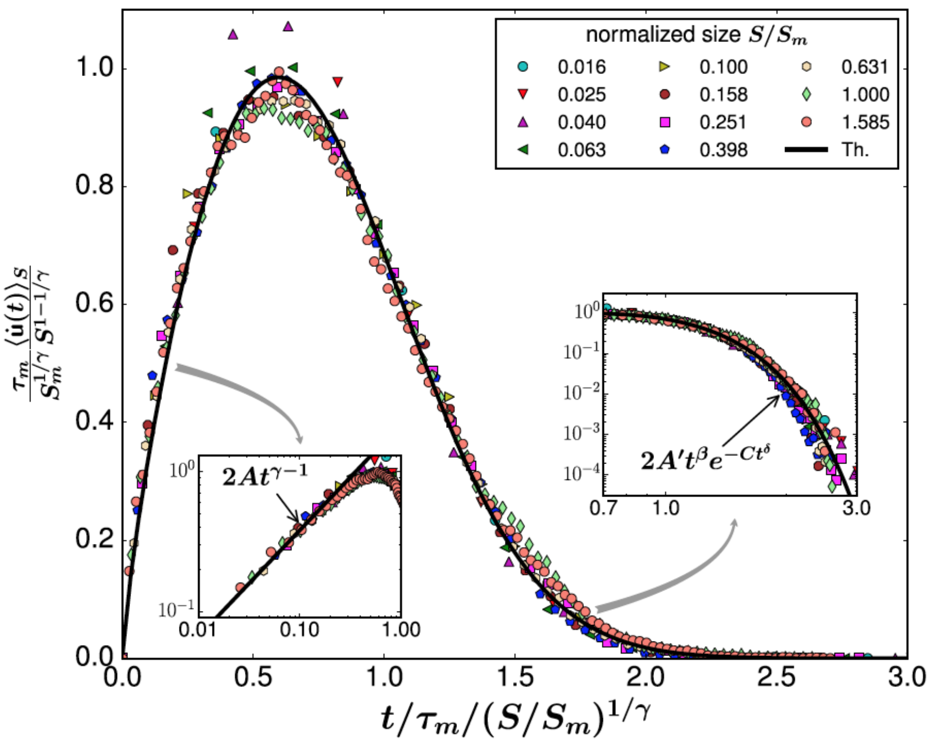
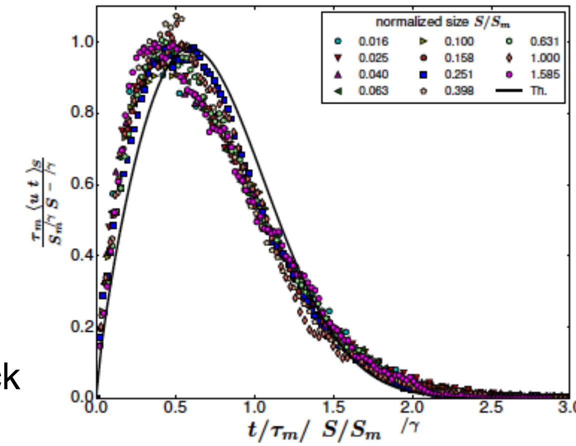


Figure 5. Scaling collapse of the average shape at fixed avalanche sizes $\langle \dot{u}(t)\rangle_S$, according to Eq. (7), in the FeSiB thin film. The continuous line is the prediction for the universal SR scaling function of Eq. (9). The insets show comparisons of the tails of the data with the predicted asymptotic behaviors of Eqs. (10) and (11), setting $\epsilon = 2$, with $A = 1.094, A' = 1.1, \beta = 0.89, C = 1.15$, and $\delta = 2.22$.

eddy currents

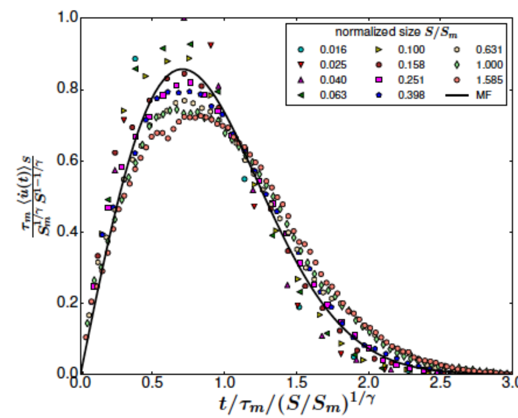
ribbons

$20\,\mu m$ thick



attempt to fit MF

$\gamma = 1.76$



Avalanche size distribution beyond mean-field

$$P(S) = \frac{\langle S\rangle}{S_m^2} p(S/S_m)$$

recall: $d = d_{uc}$ $\quad p_{MF}(s) = \frac{1}{2\sqrt{\pi} s^{3/2}} e^{-s/4}$

$$\rho(S) = \rho_0 P(S)$$

$$S_m := \frac{\langle S^2\rangle}{2\langle S\rangle}$$

$d = 4 - \epsilon$

$$\boxed{p(s) = \frac{A}{2\sqrt{\pi}} \frac{1}{s^\tau} e^{C s^{1/2} - \frac{B}{4} s^\delta}}$$

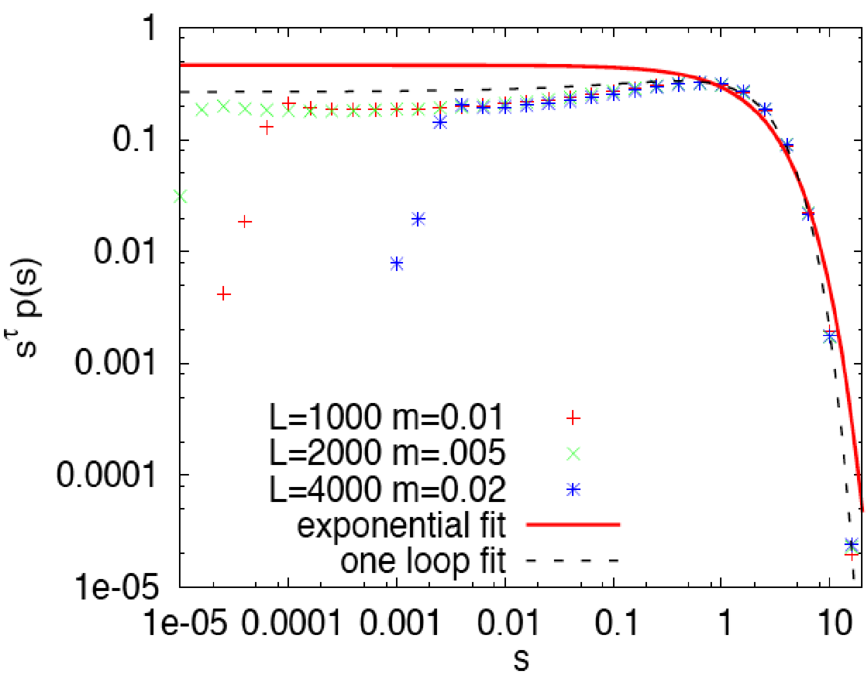
$$\gamma_E = 0.577216$$

$$A = 1 - \frac{2 - 3\gamma_E}{36}\epsilon$$

$$B = 1 + \frac{2}{9}(1 + \frac{\gamma_E}{4})\epsilon$$

$$C = \frac{\sqrt{\pi}}{9}\epsilon$$

$d = 1$



avalanche exponent:

$$\tau = \frac{3}{2} - \frac{\epsilon}{12}$$

$$\delta = 1 + \frac{\epsilon}{6}$$

agrees to $O(\epsilon)$ with Narayan-Fisher conjecture

$$\tau_{\text{conj}} = 2 - \frac{2}{d + \zeta}$$

$$\tau_{\text{num}}^{d=1} = 1.08 \pm 0.02$$

NF = 1.11

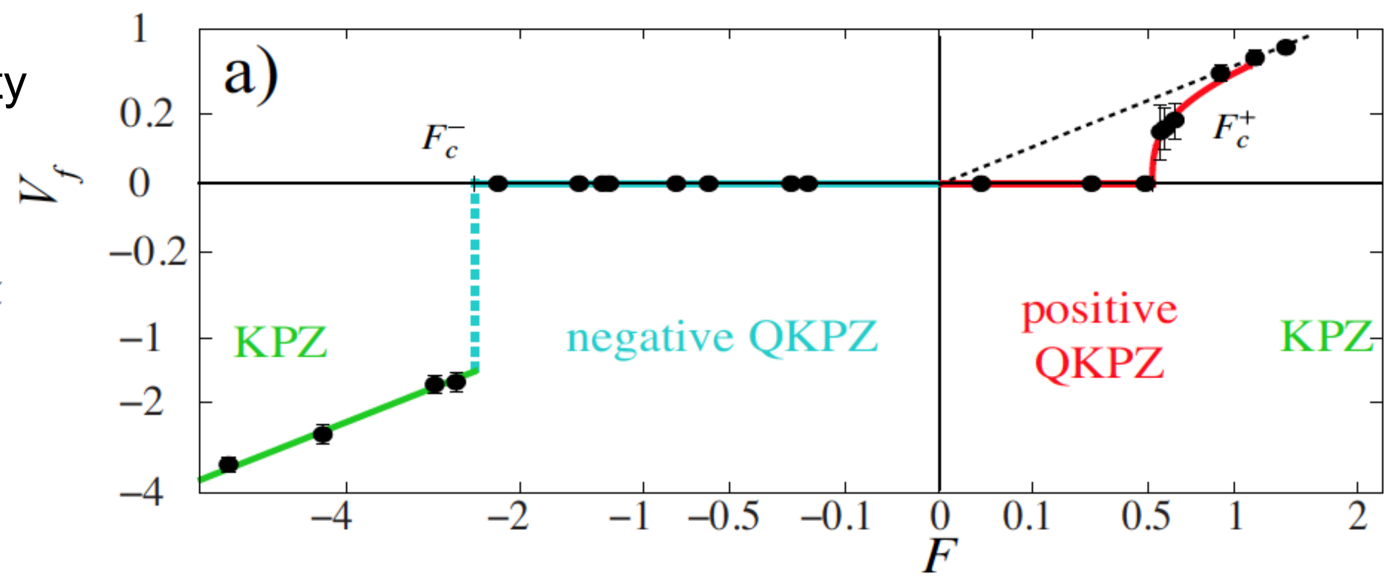
Additional topics

Experimental evidence for three universality classes for reaction fronts in disordered flows

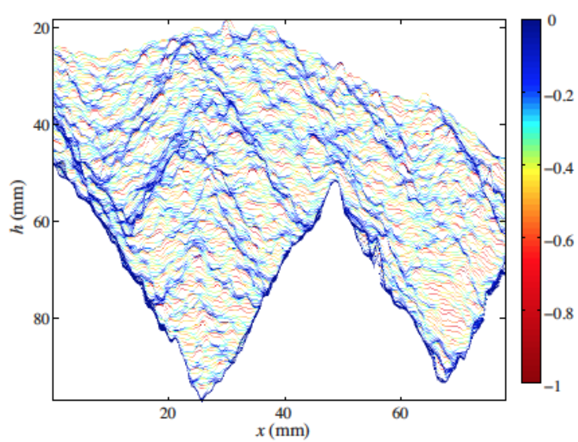
Séverine Atis,[1] Awadhesh Kumar Dubey,[1] Dominique Salin,[1]
Laurent Talon,[1] Pierre Le Doussal,[2] and Kay Jörg Wiese[2]

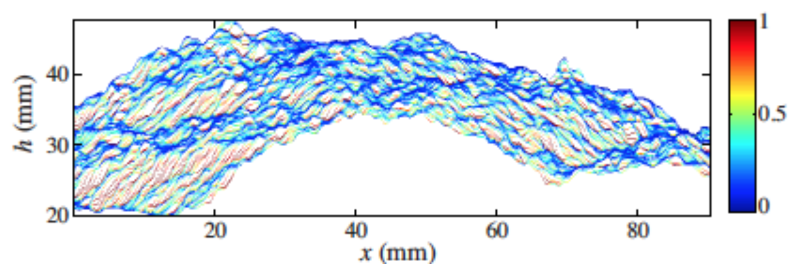
Front velocity

$$v = V_f / V_\chi$$



$$F = (\overline{U} + V_\chi)/V_\chi \; + \; 0.38$$





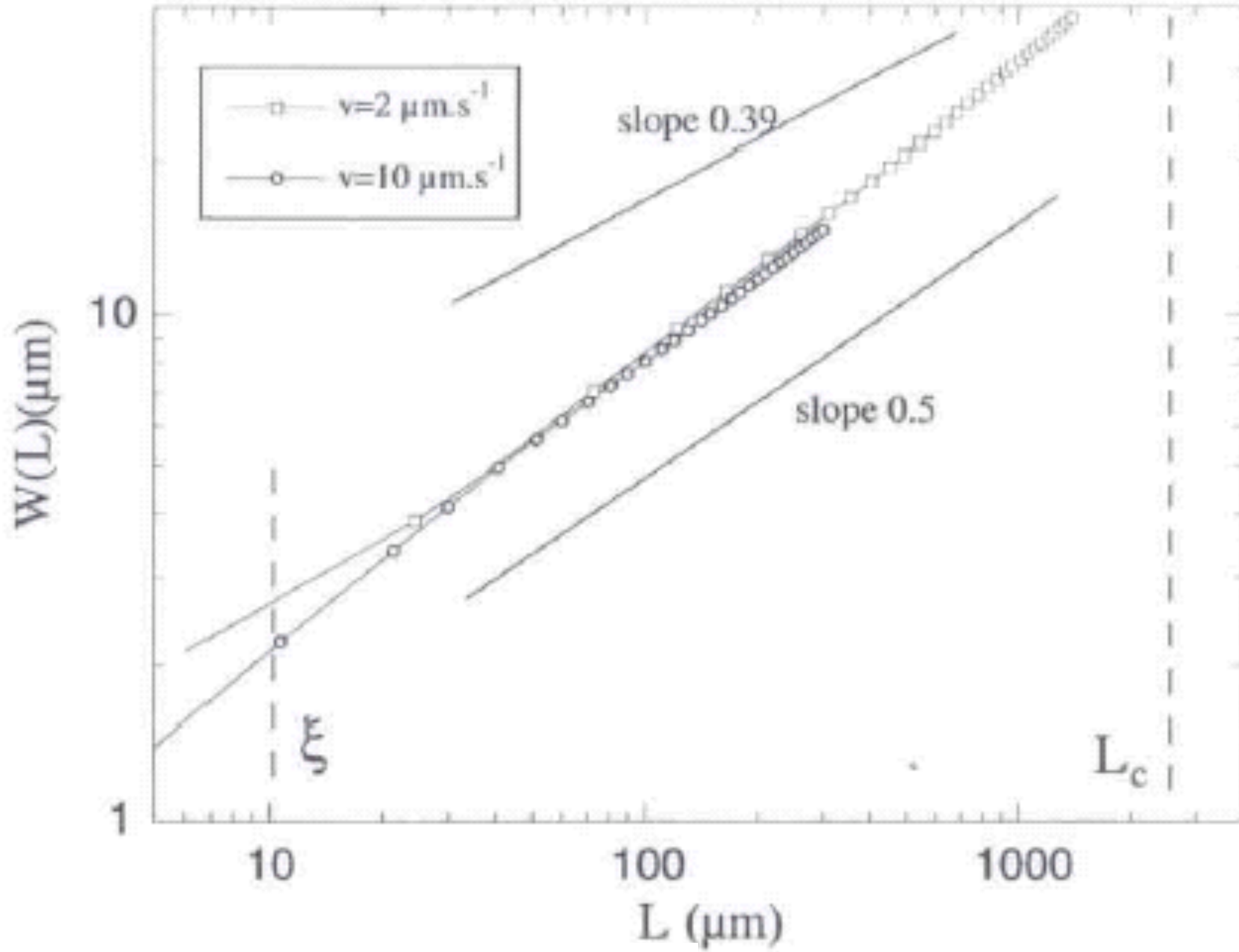


Fig. 3. Roughness W as a function of distance L for different drift velocities. The upper (respectively, lower) graph corresponds to data obtained with water (respectively, water-glycerol mixture). For both graphs, the data ∘ have been obtained with a larger magnification (resolution 2.1 μm) than the others (resolution 6.1 μm).

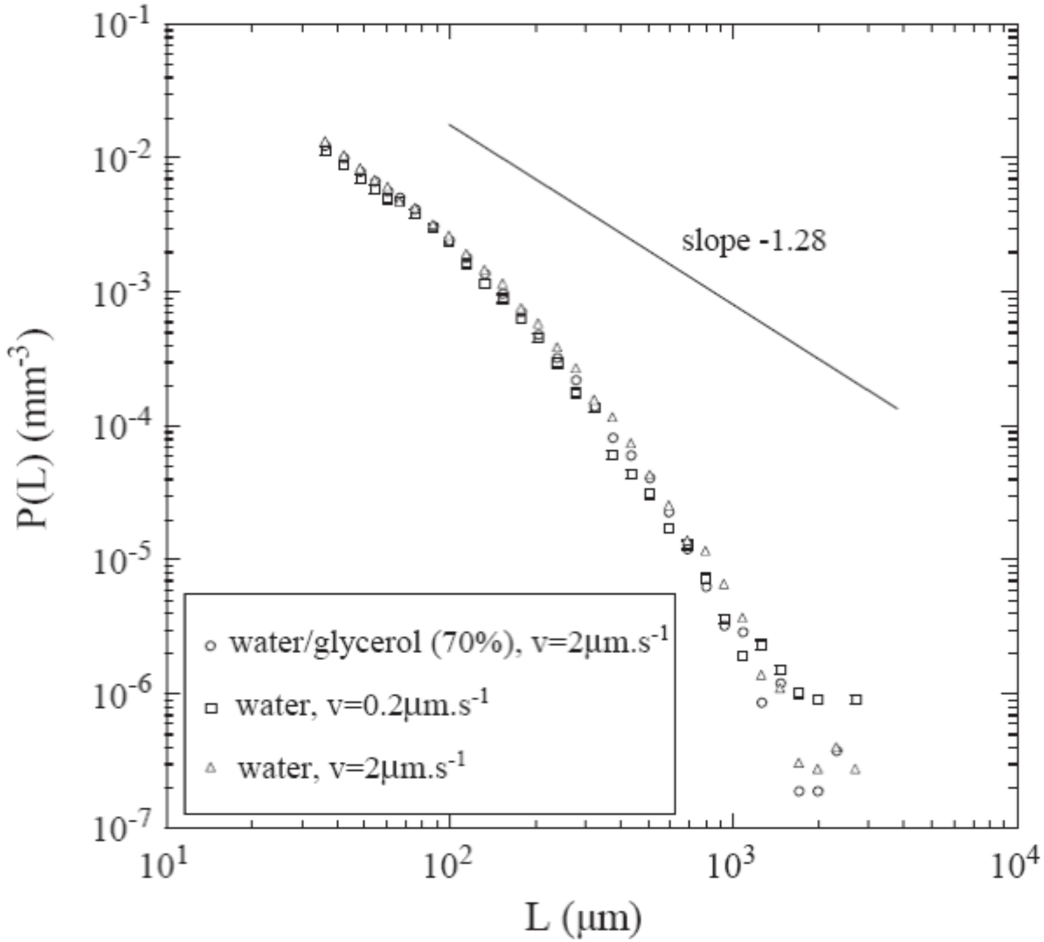


Fig. 7. Probability $P(L)$ of occurrence of an avalanche of length L for different drift velocities and different viscosities. P is the number of avalanches divided by the effective area swept by the CL and by the effective pixel size. This curves are obtained with the same magnification of the microscope; other magnifications lead to the same curves. The solid line is the power law dependence expected from numerical simulation.

Q: is there translational order in the moving lattice ?

Q: is there translational order in the moving lattice ?

"Moving glass effect"

In lattice moving along principal axis direction x

the Fourier modes (0, K_y) of the disorder are NOT averaged out by motion !

=> transverse displacements u_y still see static disorder !

Moving glass equation

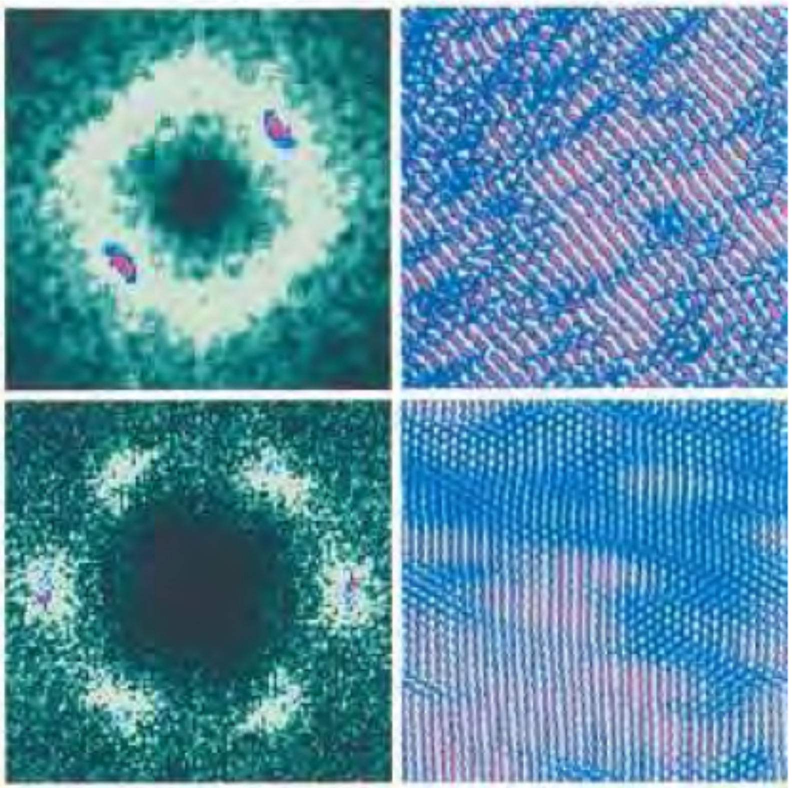
$$\eta\partial_t u^y(x,t)+\eta v\cdot\nabla u^y(x,t) = c\nabla^2 u^y(x,t)+U(x)\rho_0\sum_{K^y} iK^y e^{iK^y(y-u^y(x,t))}$$

is a pinning equation with additional convective term

- upper critical dimension is d_uc=3 instead of 4

- there is a transverse pinning f_c

Moving Bragg glass and moving smectic



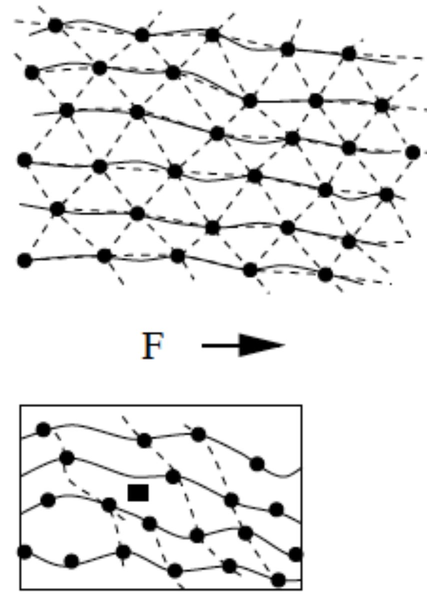


Fig. 18. Left: Decoration in motion images in $NbSe_2$ at 4 K from Ref. 170. Right column: Real space image (Fourier filtered) which shows the static channels along direction of motion. Left column: Its Fourier transform, which shows transverse order (two peaks) or full triangular lattice order (six peaks). Top: Moving smectic (low-field, higher-velocity). Bottom: Moving Bragg glass (high-field, lower-velocity). Right: (top) Moving Bragg glass on static channels, (bottom) moving smectic, channels are decoupled by dislocations (black square).