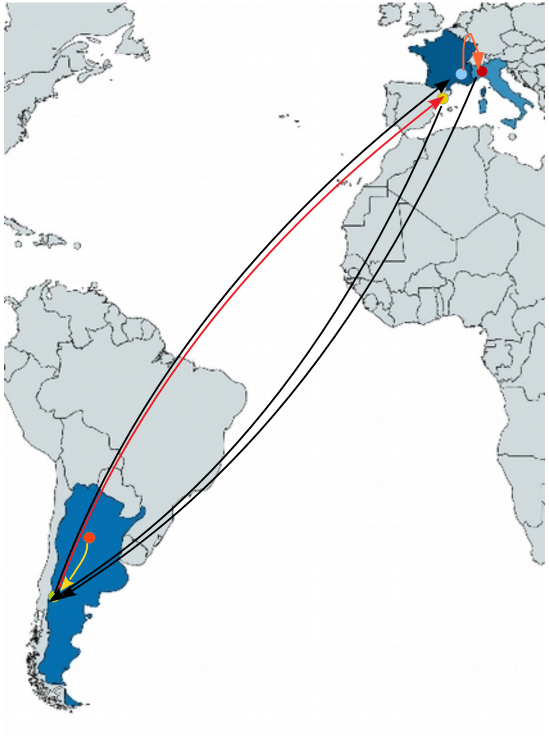
Ezequiel Ferrero - Academic path





Córdoba (ARG)→ Bariloche (ARG) → Grenoble (FRA) → Milano (ITA) …→ ... Barcelona (ESP)



- Córdoba National University
  2006-2011 Physics PhD. Advisor: Prof. S.A. Cannas
  Statistical Mechanics of classical spin models

- Bariloche Atomic Center (+stay at LPTMS Orsay)
  2011-2013 postdoc. Drs. A.B. Kolton, S. Bustingorry, A. Rosso
  Disordered elastic systems (depinning)

- Grenoble Alpes University
  2013-2016 postdoc. Prof. J-L Barrat
  Amorphous solids (yielding)

- University of Milan
  2017 postdoc. Prof. S. Zapperi
  Glass failure (brittle-ductile transition in nano-rods)

- Bariloche Atomic Center
  2018-... Researcher CONICET
  StatMech of materials (yielding, depinning, etc.)

- University of Barcelona
  2022-2024 María Zambrano researcher. Prof. Carmen Miguel

Driven Disordered Systems

$$\hbar = 0$$

Ezequiel Ferrero

Bariloche Atomic Centre

São Paulo School of Advanced Science on Disordered Systems
ICTP - SAIFR, São Paulo, 05/05/2025

Driven Disordered Systems

Agenda

L1. The **depinning** transition of elastic interfaces driven in disordered media and the **creep** motion at low driving

L2. The **yielding** transition of amorphous solids under deformation and associated **criticality** and **avalanche** statistics

L3. **Common framework** for depinning and yielding, analogies and **recent endeavors** in the field

L1. The depinning transition of elastic interfaces driven in disordered media

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ICTP - SAIFR, São Paulo, 05/05/2025

L1. The depinning transition of elastic interfaces driven in disordered media

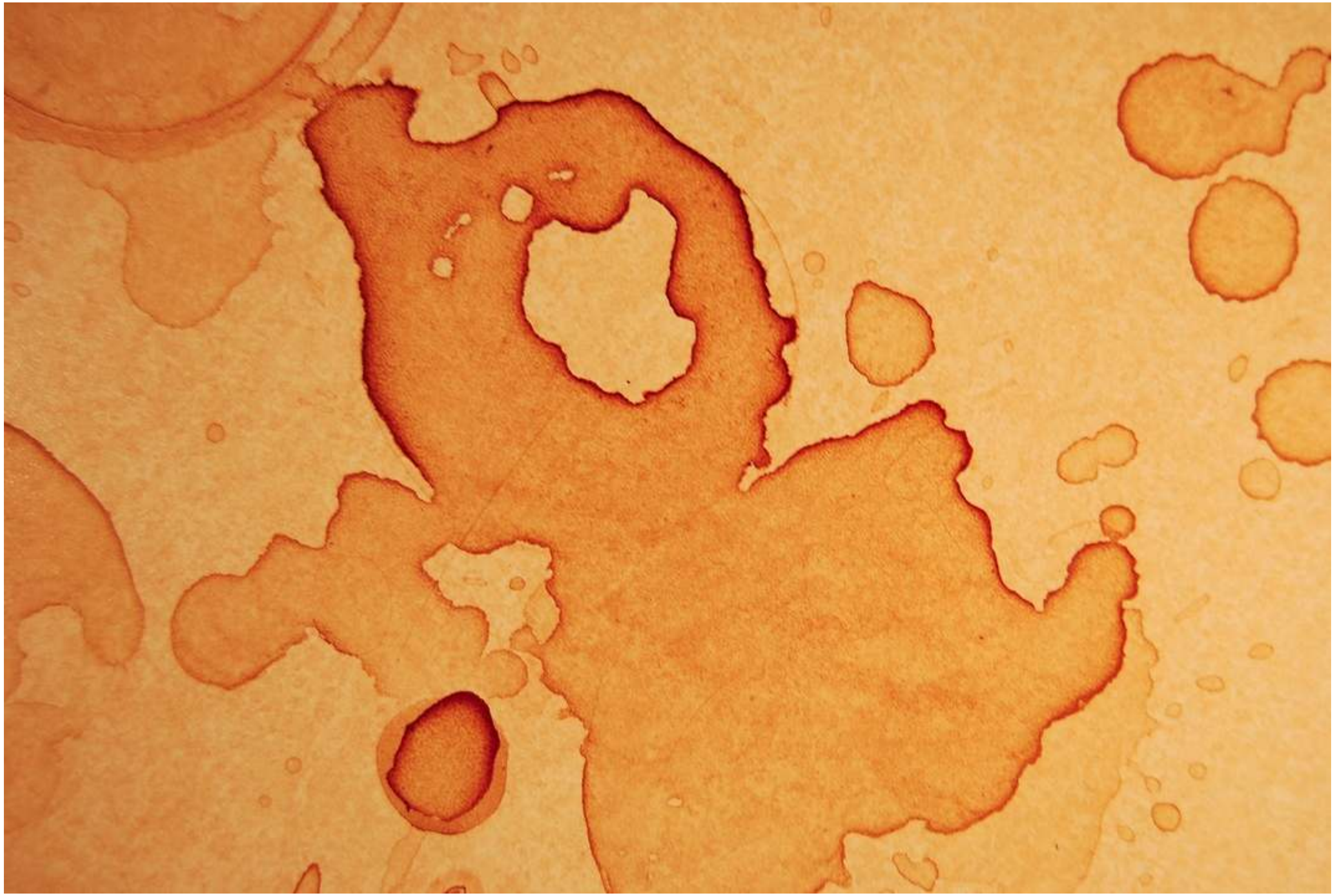
Ezequiel Ferrero

*Alejandro **Kolton**, Alberto **Rosso**, Sebastián Bustingorry,*
Eduardo Jagla, Nirvana Caballero, Laura Foini, Thierry Giamarchi,
Javier Curiale, Lucas Albornoz, Vincent Jeudy, ...

São Paulo School of Advanced Science on Disordered Systems
ICTP - SAIFR, São Paulo, 05/05/2025

Pinning everywhere

Pinning everywhere



Pinning everywhere

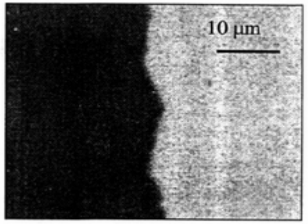
The leading edge of a lava flow destroys a road on 8 February 2024 near the town of Grindavík, Iceland.

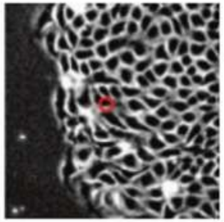
Photo by Mike Mezeul II, edited by Charlie Borst

Pinning everywhere

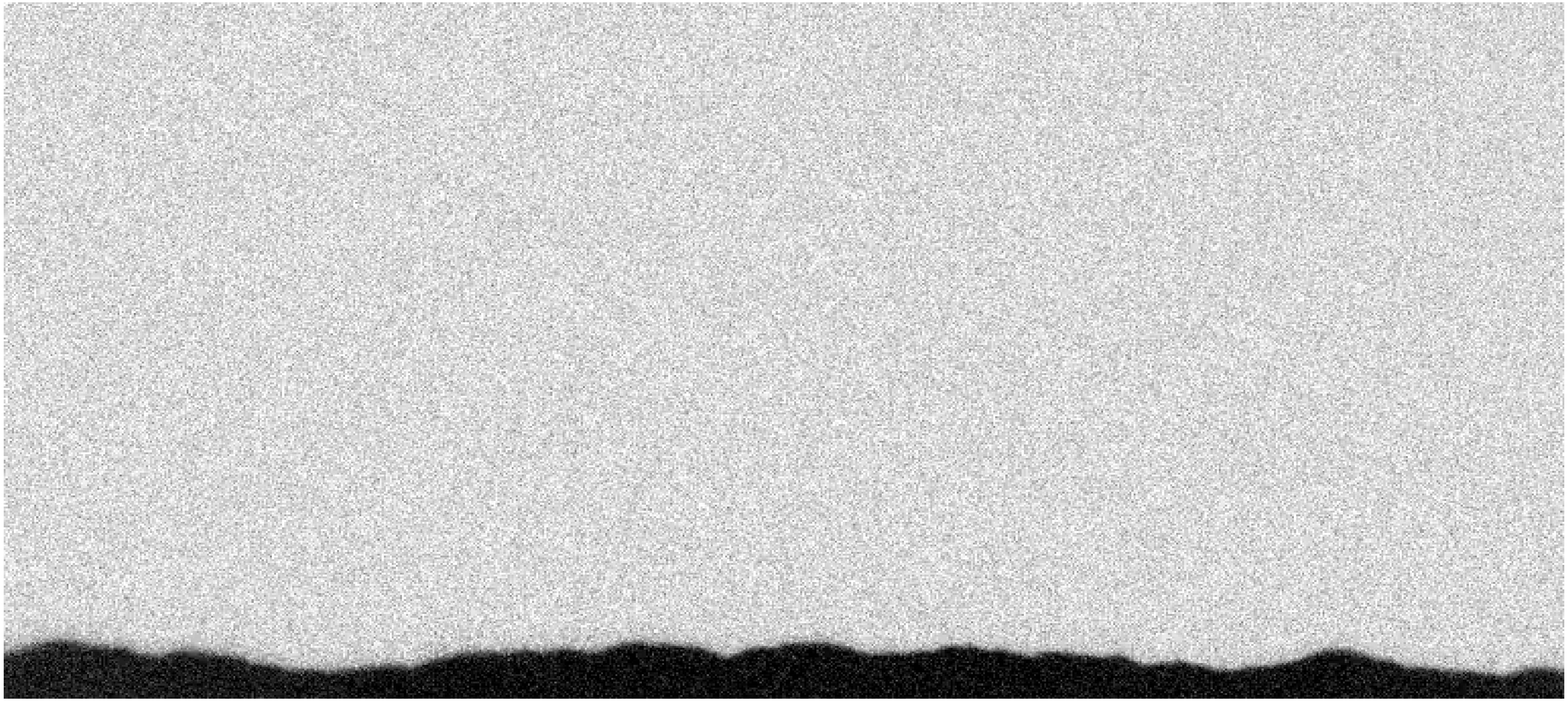
Photo art by
Elisabeth Agoritsas

A LARGE VARIETY OF PHYSICAL SYSTEMS





Magnetic domain walls

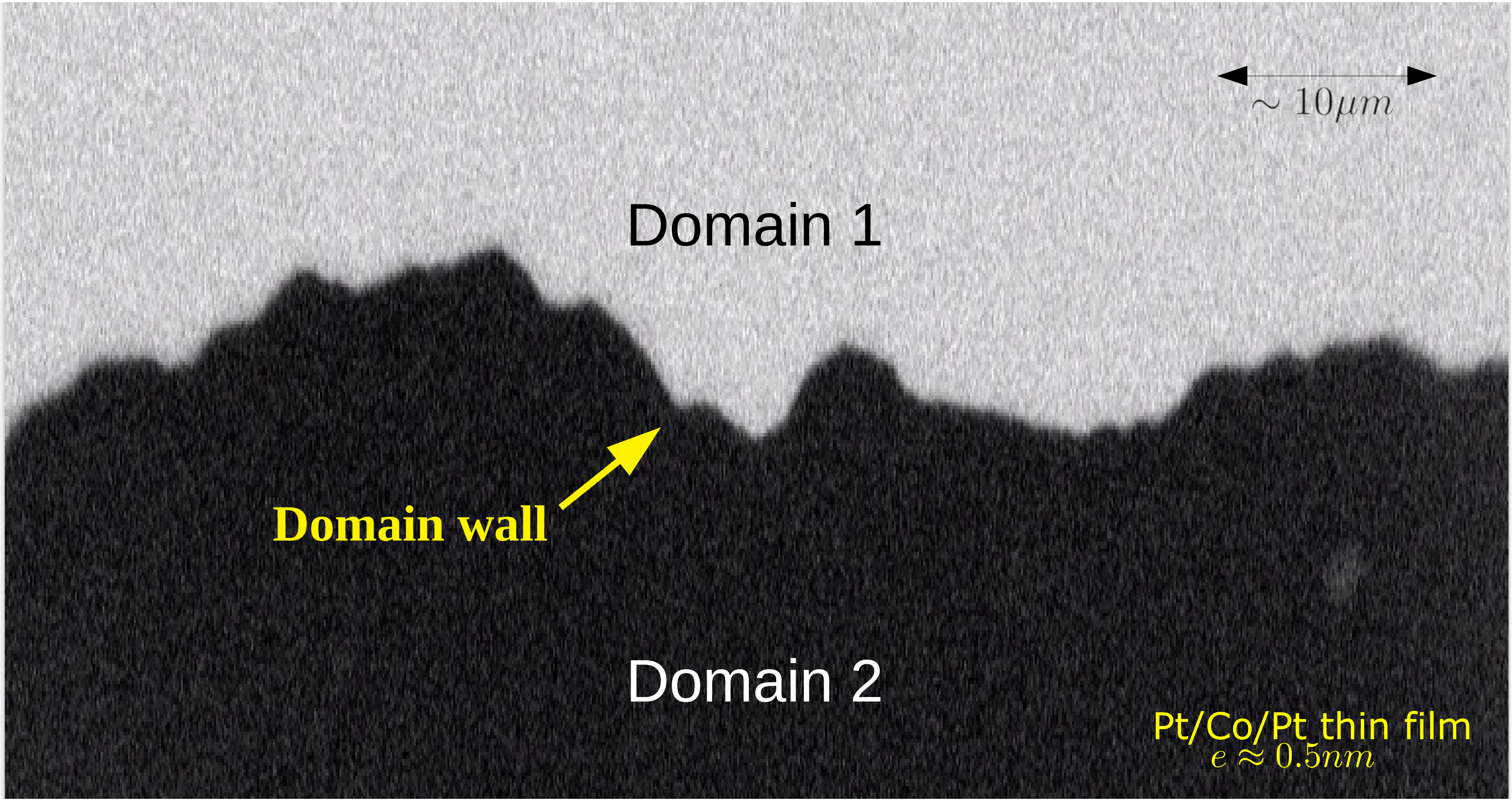


Polar Magneto-Optic Kerr effect (PMOKE) microscopy

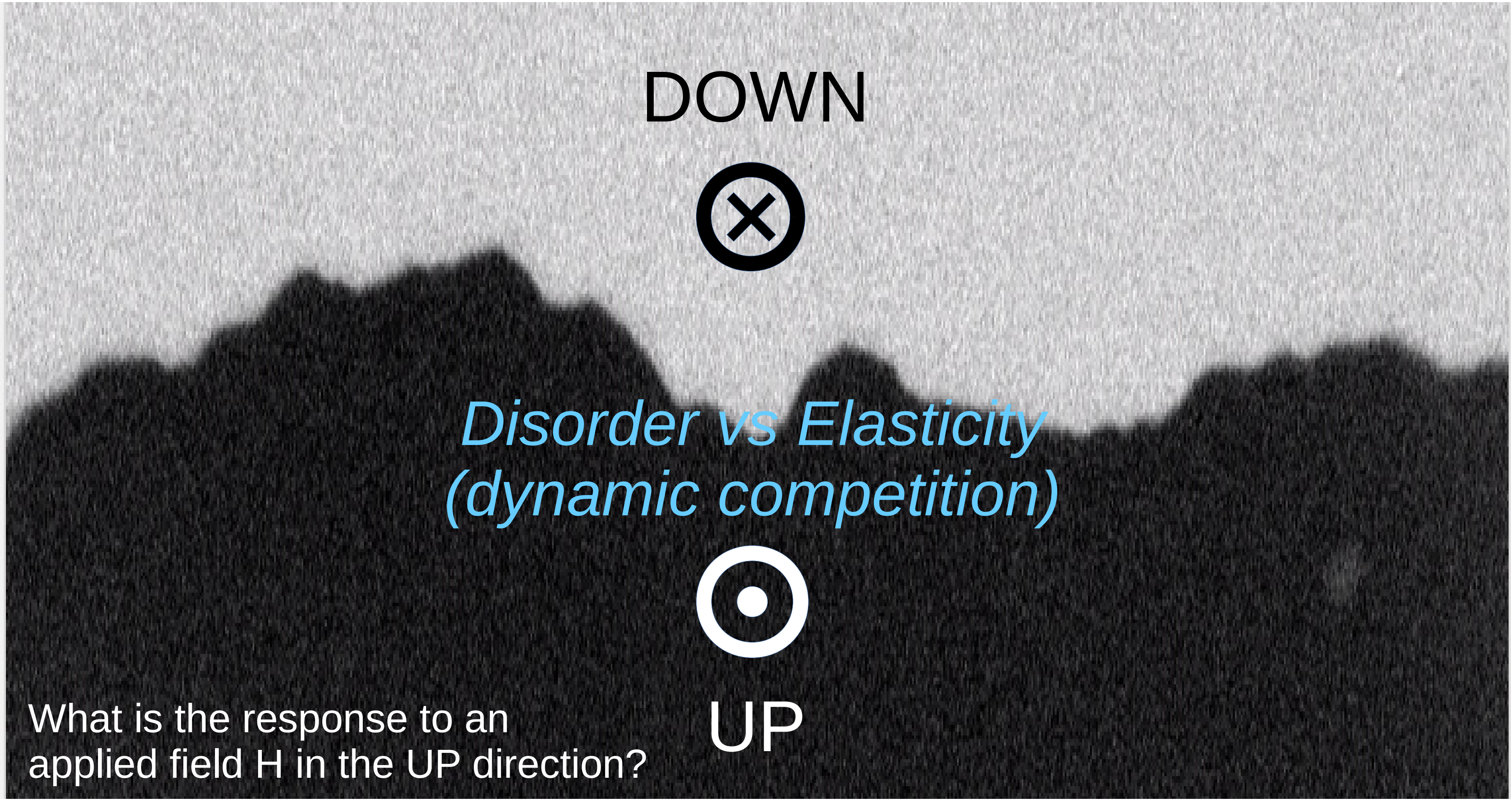
DW in a Pt/Co/Pt thin film in the creep regime

Lemerle, Jamet, Ferre, et al (LPS Orsay)

Magnetic domain walls

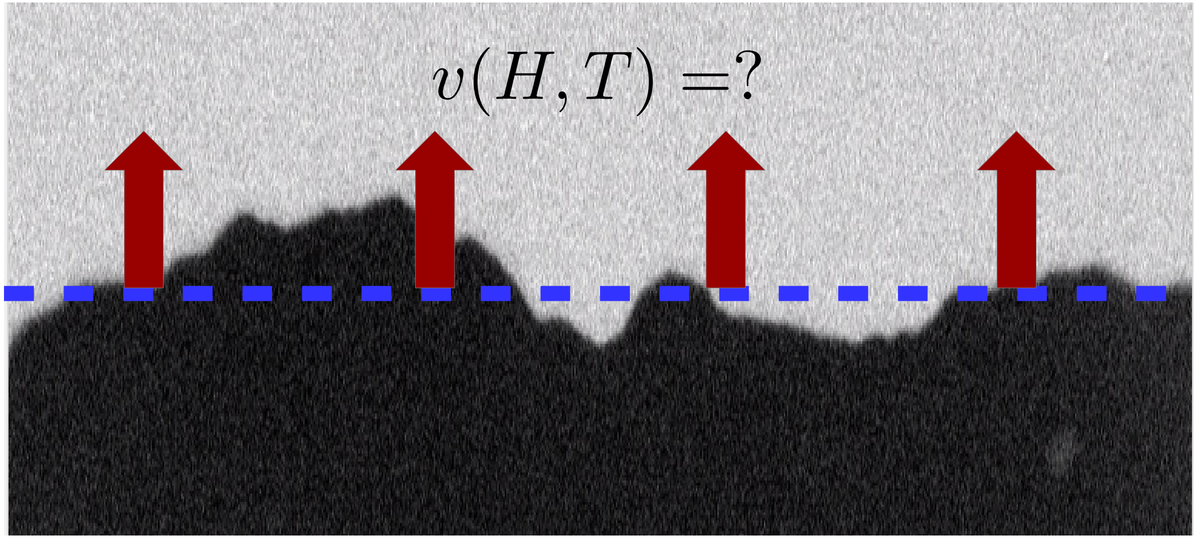


Magnetic domain walls



Magnetic domain walls

A transport problem Interfaces Motion control → Applications (e.g. racetrack memories)



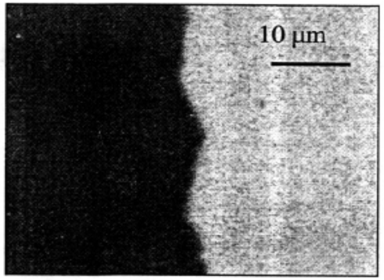
What is the mean velocity *v* for given applied field *H* and temperature *T* ?

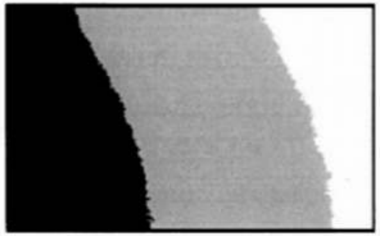
Is the interface flat or twisty?

Is the movement smooth, continuous? When?
When is it jerky, intermittent?

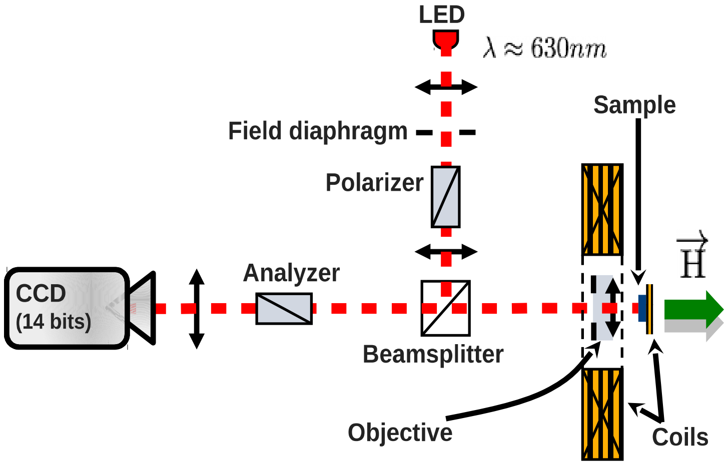
Statistical physics of **driven disordered elastic systems** → **Universality**

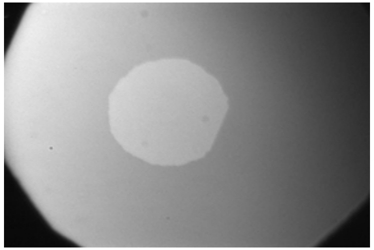
Magnetic Domain Walls

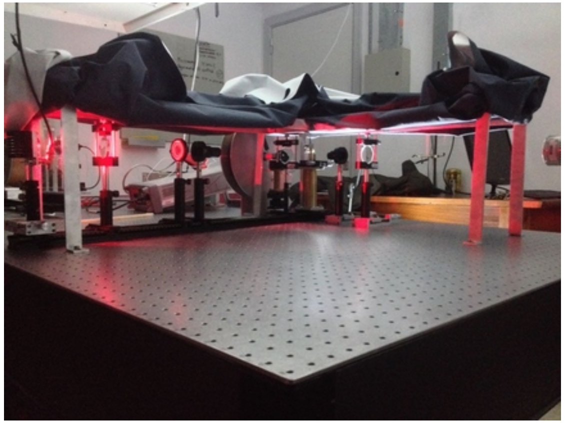


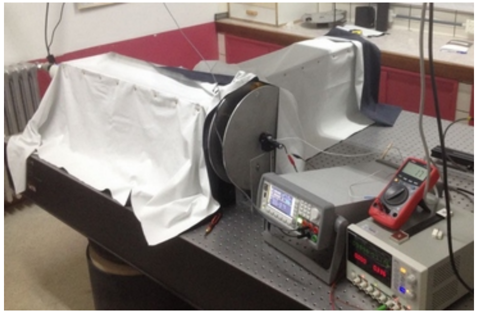


Magnetic domain walls
(Paris)
J. Ferré, J.P. Jamet,
A. Mougin, V. Jeudy
(Bariloche)
J. Curiale, S. Bustingorry





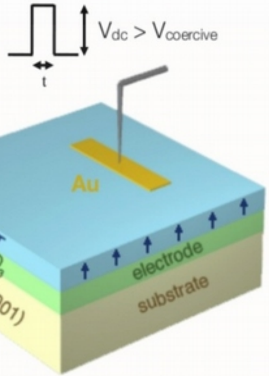




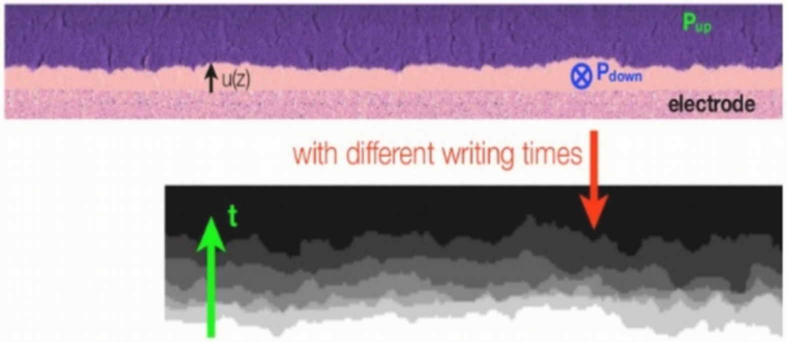
PMOKE @Bariloche

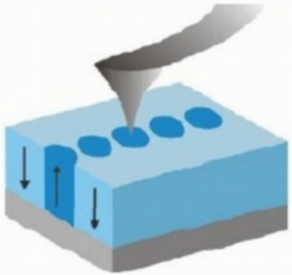
Ferroelectric domain walls

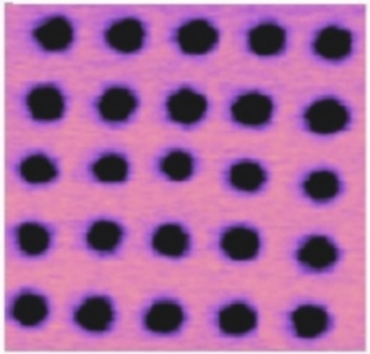
Ferroelectric Domain Walls
(Geneva)
P. Paruch, J. Guyonnet

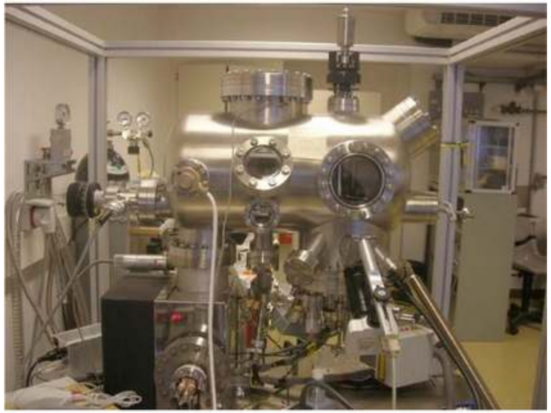


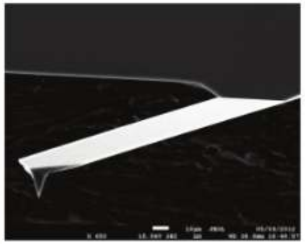
Pinning → rough walls

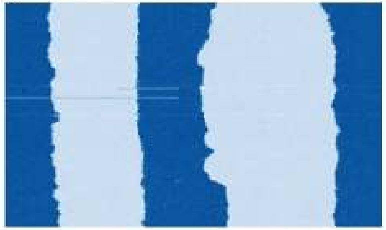










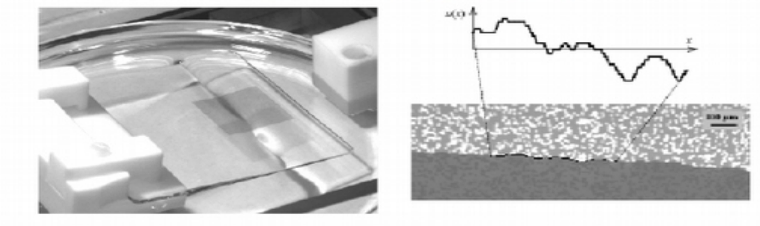


Atomic Force Microscope (AFM)
piezoresponse force microscopy

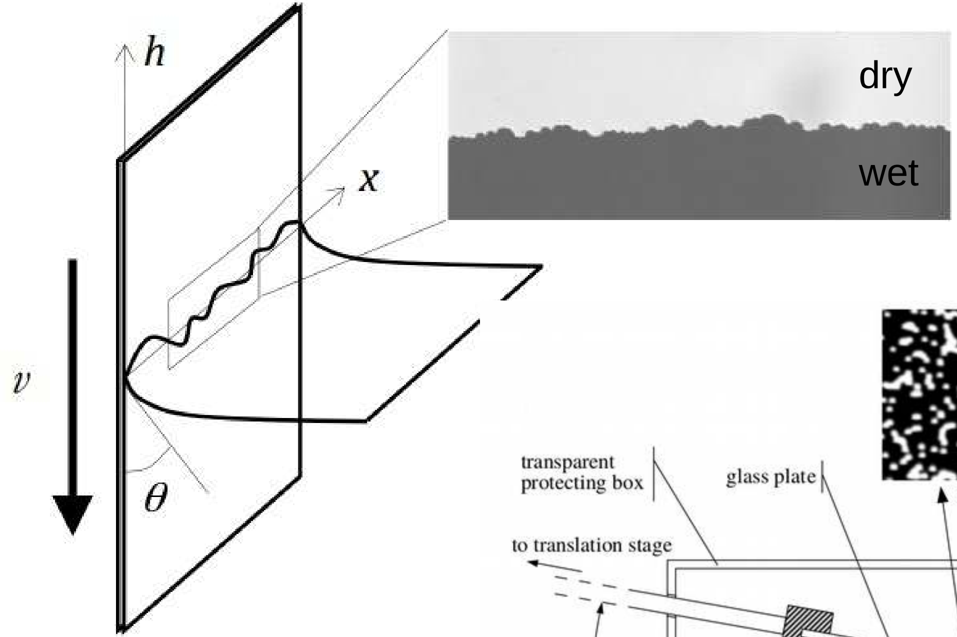
Contact lines in partial wetting

Contact lines in partial wetting
(Paris) Moulinet, Rolley.

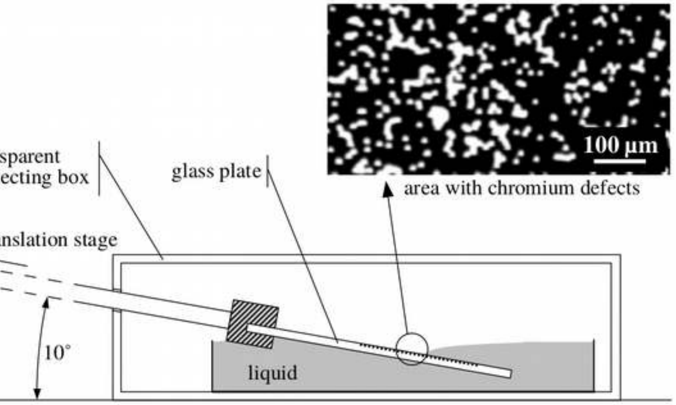
Roughness



Liquids with different viscosity:
water, aqueous glycerol solutions, etc.



Avalanches!



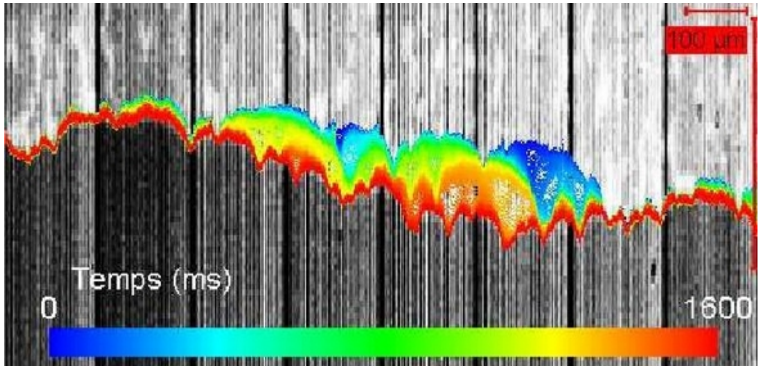


Plate moves up, interface “down”

Contact lines in partial wetting

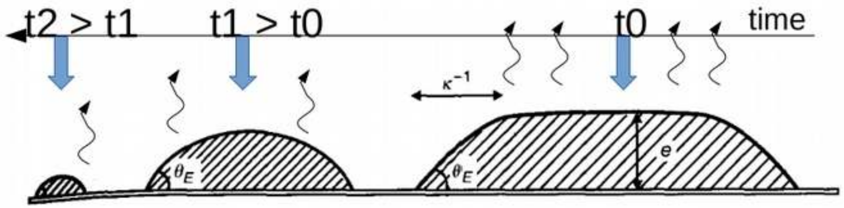
Evaporating drops: Do this at home!

credit: A.B. Kolton

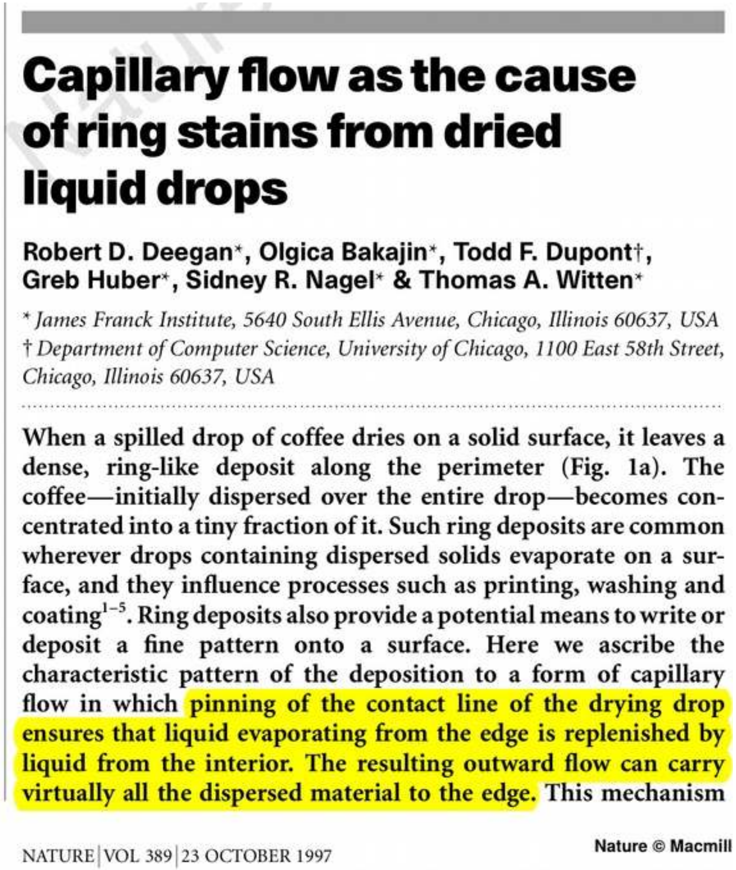
Before After

Why do solutes accumulate in the borders?

Why don't they just shrink like this?



"Capillarity and Wetting Phenomena"
Pierre-Gilles de Gennes, Françoise Brochard-Wyart and David Quéré



Capillary flow as the cause of ring stains from dried liquid drops

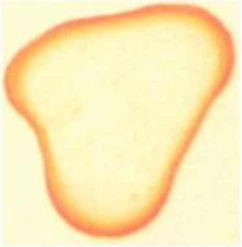
Robert D. Deegan*, Olgica Bakajin*, Todd F. Dupont†, Greb Huber*, Sidney R. Nagel* & Thomas A. Witten*

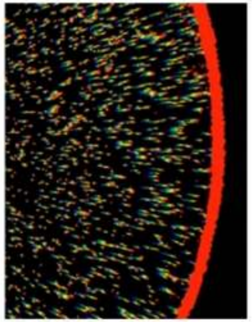
* *James Franck Institute, 5640 South Ellis Avenue, Chicago, Illinois 60637, USA*
† *Department of Computer Science, University of Chicago, 1100 East 58th Street, Chicago, Illinois 60637, USA*

When a spilled drop of coffee dries on a solid surface, it leaves a dense, ring-like deposit along the perimeter (Fig. 1a). The coffee—initially dispersed over the entire drop—becomes concentrated into a tiny fraction of it. Such ring deposits are common wherever drops containing dispersed solids evaporate on a surface, and they influence processes such as printing, washing and coating[1–5]. Ring deposits also provide a potential means to write or deposit a fine pattern onto a surface. Here we ascribe the characteristic pattern of the deposition to a form of capillary flow in which pinning of the contact line of the drying drop ensures that liquid evaporating from the edge is replenished by liquid from the interior. The resulting outward flow can carry virtually all the dispersed material to the edge. This mechanism

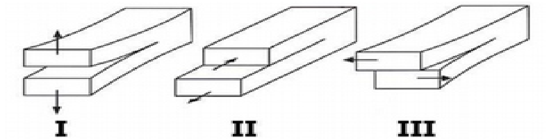
NATURE | VOL 389 | 23 OCTOBER 1997

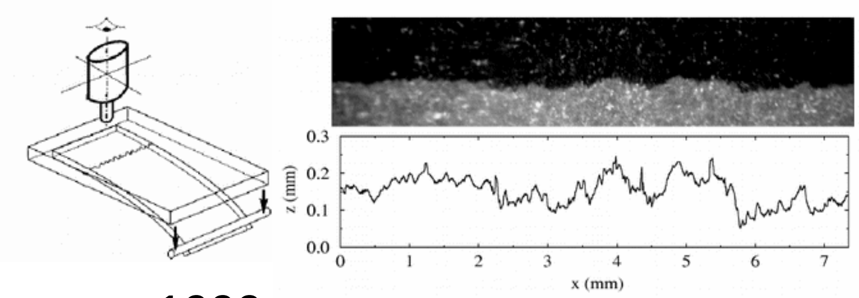
Nature © Macmill





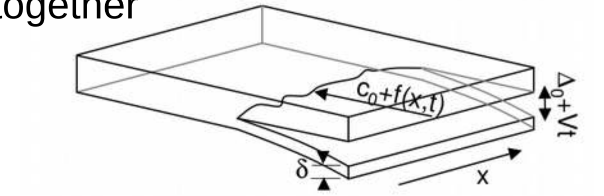
Fracture lines: crack propagation

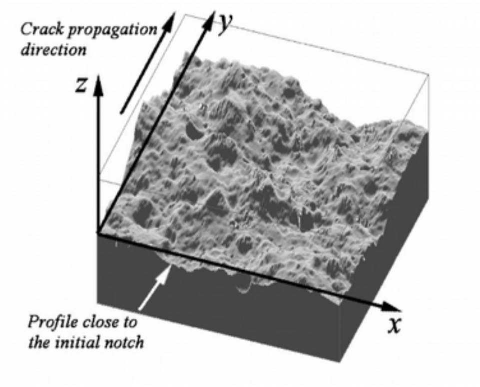


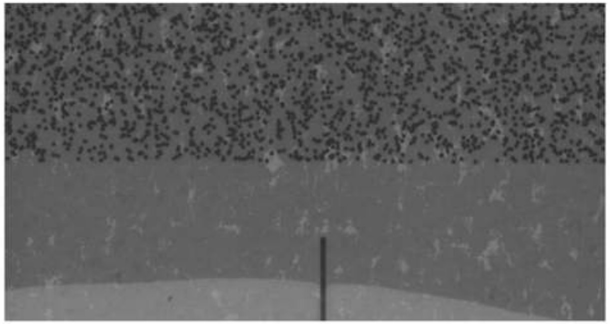


~1999

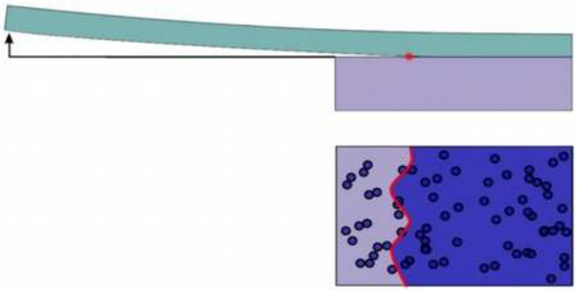
Transparent plates of Plexiglas sandblasted and annealed together







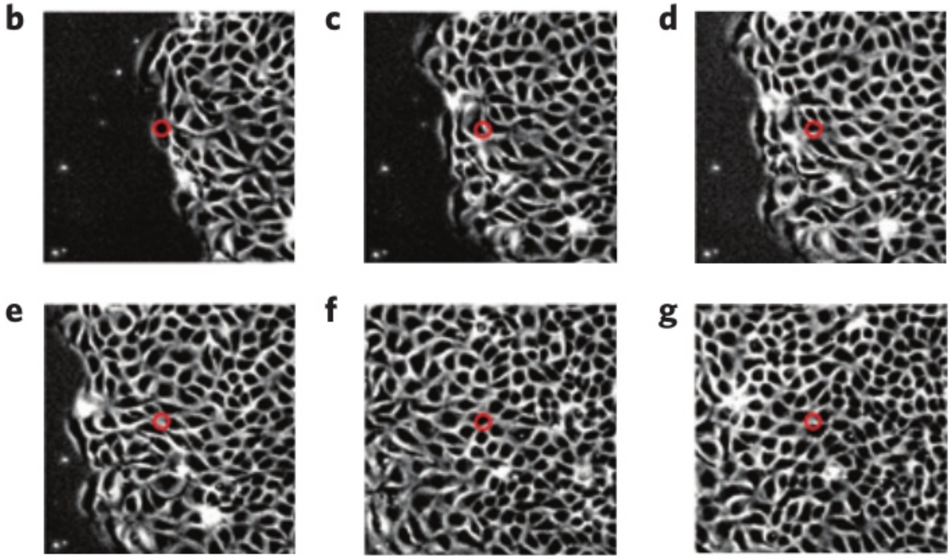
~2020s

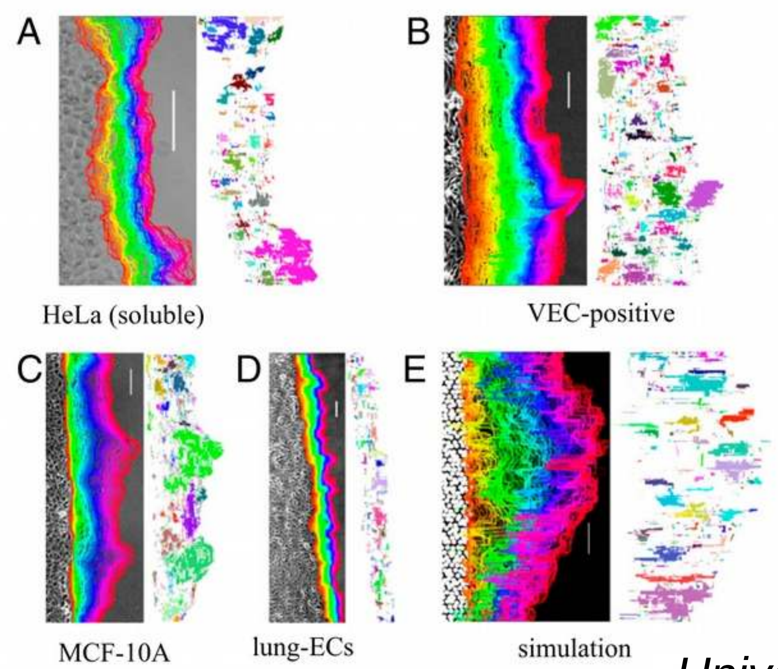


5 mm thick PMMA detached from a 20 mm thick PDMS. Disorder is introduced by printing ink dots of diameter 100µm

Fracture lines
(Lyon, Oslo, Paris)
Bonamy, Ponson, Santucci

Tissue growth: collective cell migration





Universality?

Collective cell migration
(Barcelona) X. Trepat

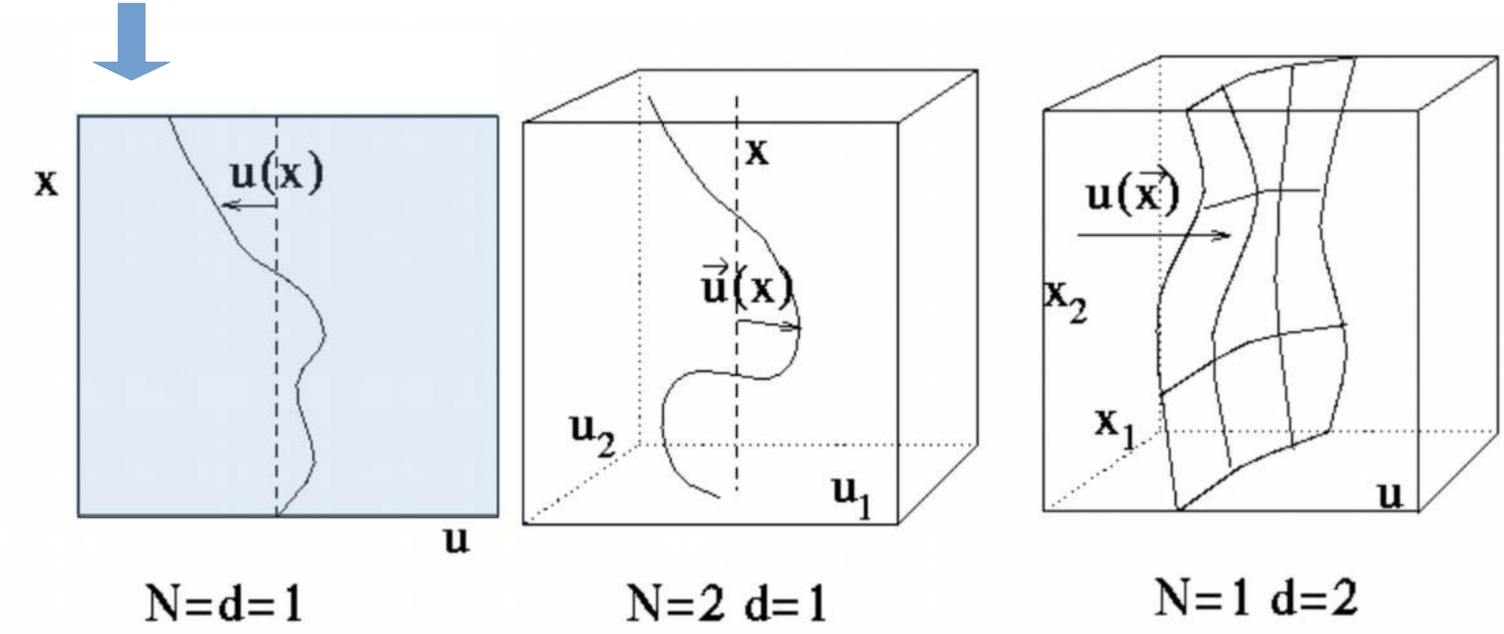
Trends Cell Biol. 2011

Burst of activity in collective cell migration
(Milan) S. Zapperi, C. La Porta

PNAS 2016

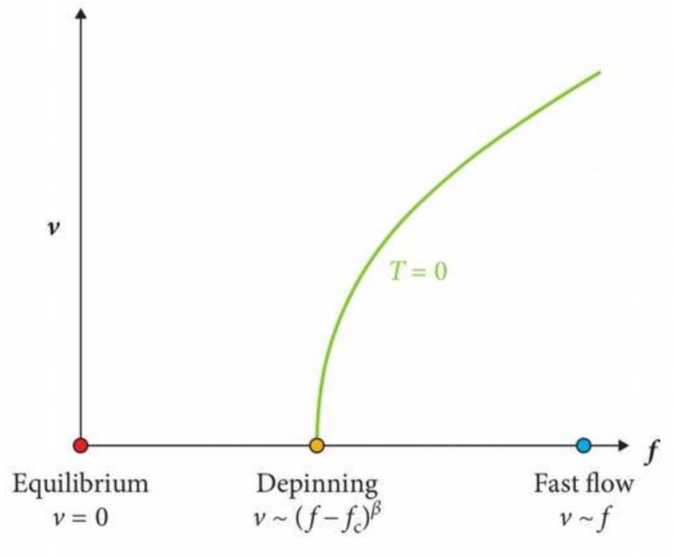
Disordered elastic manifolds

All examples so far: d=1 dimensional interfaces moving in a D=2 dimensional random media



d: manifold dimension N: degrees of freedom

THE DEPINNING TRANSITION



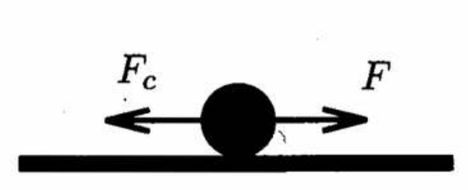
Toy example: motion of a particle with friction

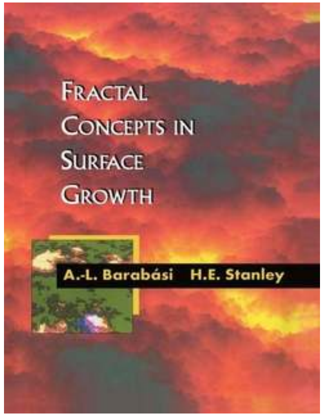
Particle of mass *m* on a plane, driven by an external force *F*.
Two **friction forces**: static friction F_c and dynamic friction $\rho\, dr/dt$.

For $F<F_c$: $v=0$.

For $F>F_c$ the e.o.m. is:

$$m\frac{d^2r}{dt^2} = F - F_c - \rho\frac{dr}{dt} \qquad [F > F_c]$$





After a transient a constant velocity *v* is reached

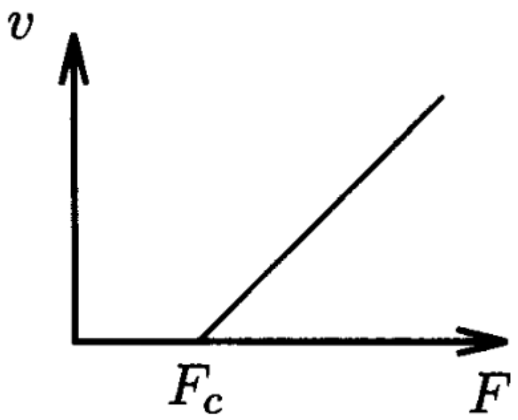
$$v = (F - F_c)/\rho$$

$$v \sim (F - F_c)^\beta \qquad \beta = 1$$

Two regimes:

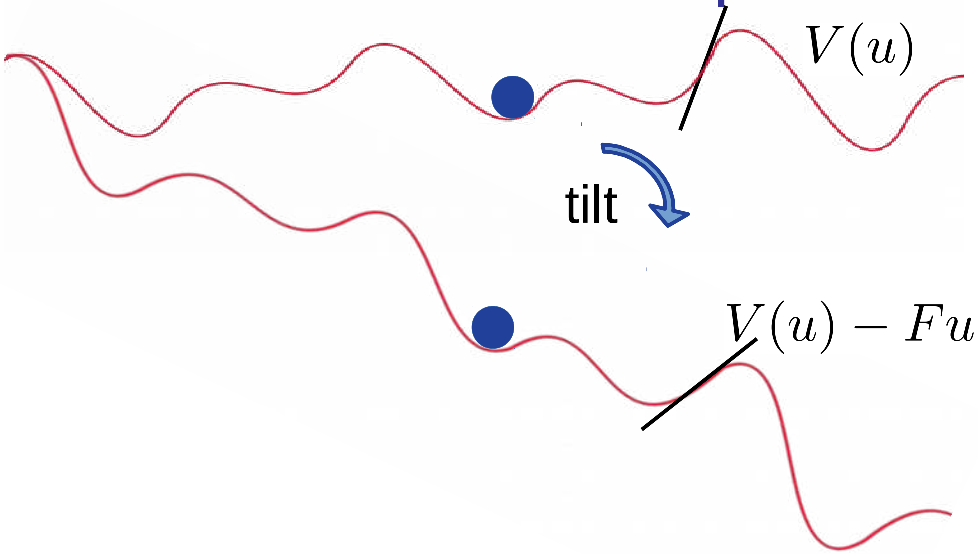
Pinned phase: $F<F_c$

Moving phase: $F>F_c$



A.-L. Barabási, H.E. Stanley “Fractal Concepts in Surface Growth” (1995)

Particle on a random potential



$$\mathcal{H} = V(u) - Fu$$

Overdamped e.o.m

$$\gamma \partial_t u = -\partial_u \mathcal{H} = F - \partial_u V(u)$$

To have a finite velocity $\partial_t u > 0 \Rightarrow F > \partial_u V$

Then the onset of sustained movement is

$$F_c = \max_u \partial_u V(u)$$

Close to the critical position (last arrested point):

$$F_V \approx F_c + \underbrace{\partial_u F|_{u_c}}_{\partial_u^2 V|_{u_c} = 0} \delta u + \partial_u^2 F|_{u_c} \delta u^2$$

$$\gamma \partial_t u = F - F_V \approx \delta f + c\delta u^2$$

$\delta f = F - F_c$ distance to criticality

Particle on a random potential (cont.)

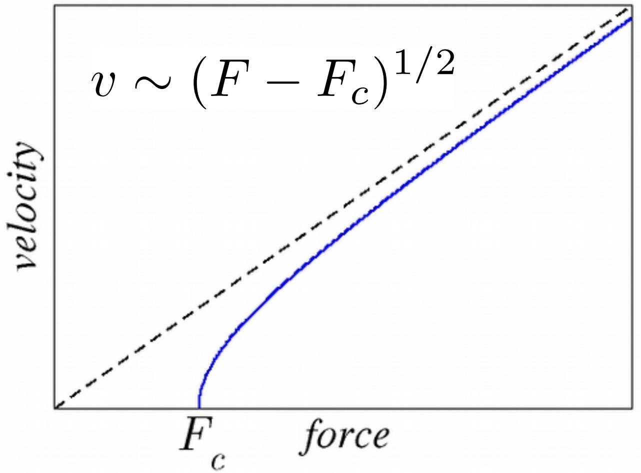
$$\gamma \frac{\partial u}{\partial t} \approx \delta f + c\delta u^2$$

Typical time spent close to the critical position

$$\tau = \gamma \int \frac{du}{\delta f + c\delta u^2} = \frac{\gamma}{2c\sqrt{\delta f}} \int \frac{d\tilde{u}}{\sqrt{\tilde{u}}(1+\tilde{u})} \sim \frac{1}{\sqrt{\delta f}}$$

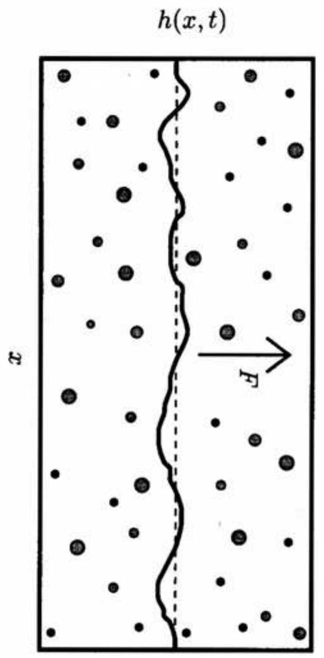
Then $v \sim \tau^{-1} \sim \delta f^{1/2}$ $\qquad \beta = \frac{1}{2}$

velocity-force characteristics sufficiently close to F_c:



What about extended elastic lines, beyond one particle?

Interface: collective motion

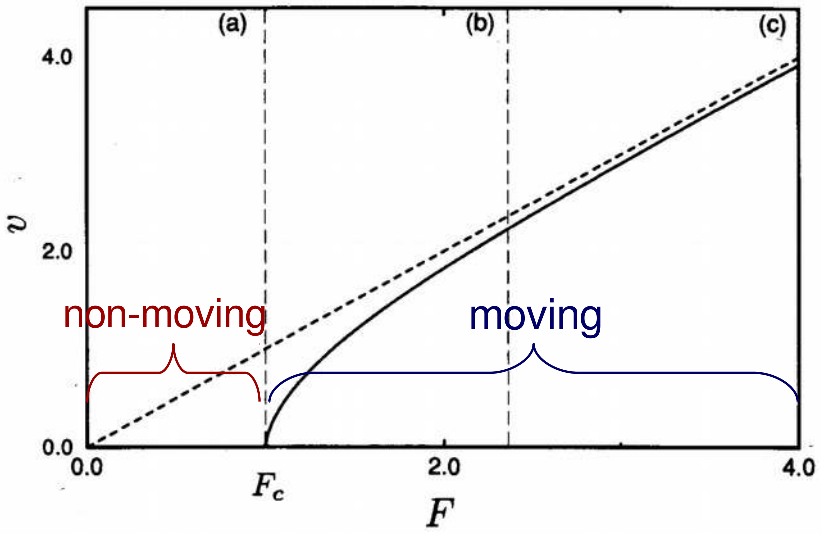


A critical force F_c emerges and **depends on details** as the disorder strength, disorder type, the elastic constant, ...

Phase transition:
-Below F_c: non-moving
-Above F_c: moving

Close to $F=F_c$ mean velocity behaves as

$$v \sim (F - F_c)^{\beta} \qquad \beta < 1$$



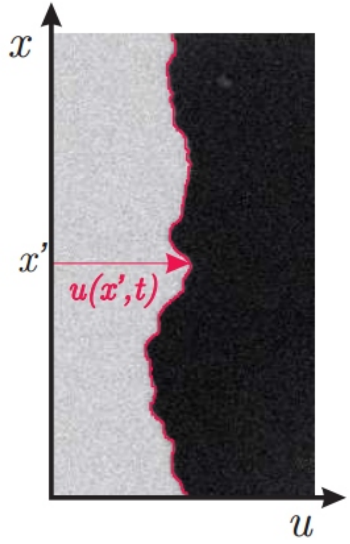
As we approach F_c from above the dynamics becomes tortuous, punctuated. The line is **blocked in larger and larger segments**

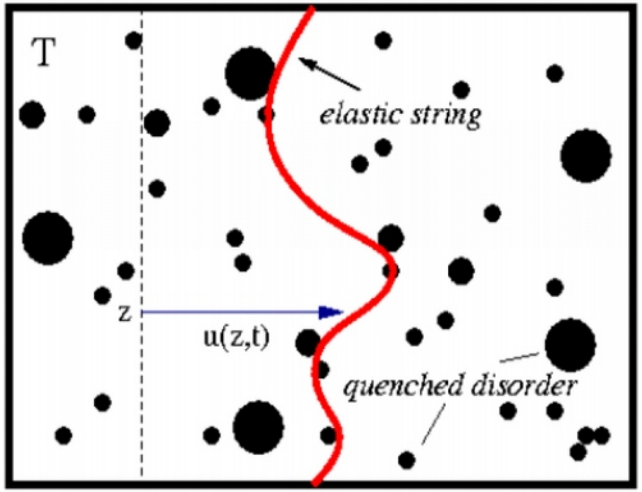
Correlation length: size of the pinned regions: $\xi \sim (F - F_c)^{-\nu}$

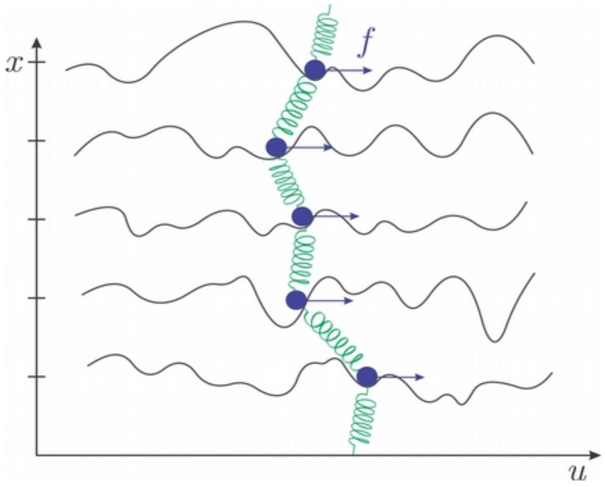
A.-L. Barabási, H.E. Stanley "Fractal Concepts in Surface Growth" (1995)

Extended elastic interface in a disordered medium

Dynamics governed by the *interplay between disorder and elasticity*

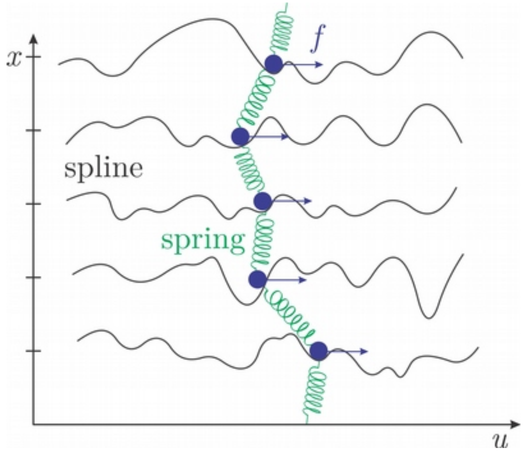






- Elastic restoring forces: try to smooth the interface
- Quenched disorder forces: pins and distort the interface
- Driving force: pushes/pulls the interface
- Thermal noise: agitates stochastically & allows for activated jumps

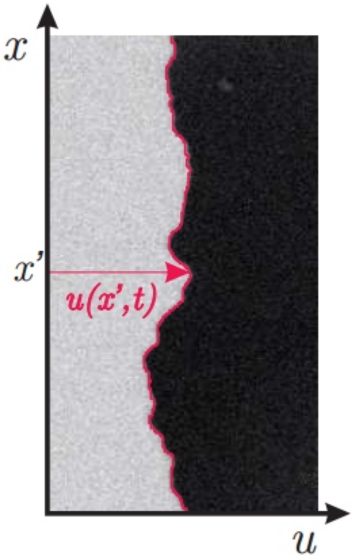
MODELING DEPINNING



Model: The Quenched Edwards-Wilkinson elastic line

Assumptions: overdamped, uni-valued interface *u(x)*

$$\gamma \partial_t u(x,t) = \underbrace{c\nabla^2 u(x,t)}_{\text{local force due to elastic interactions}} + \underbrace{F_{\mathrm{p}}(x,u)}_{\text{pinning force}} + \underbrace{f}_{\text{external force}} + \underbrace{\eta(x,t)}_{\text{thermal noise}}$$



$F_p = -\partial_u V_p(x,u)$ $\quad V_p(x,u)$ disorder potential, with correlator:

$$\overline{[V_p(x,u) - V_p(x',u')]^2} \propto \delta(x-x')R(u-u')$$

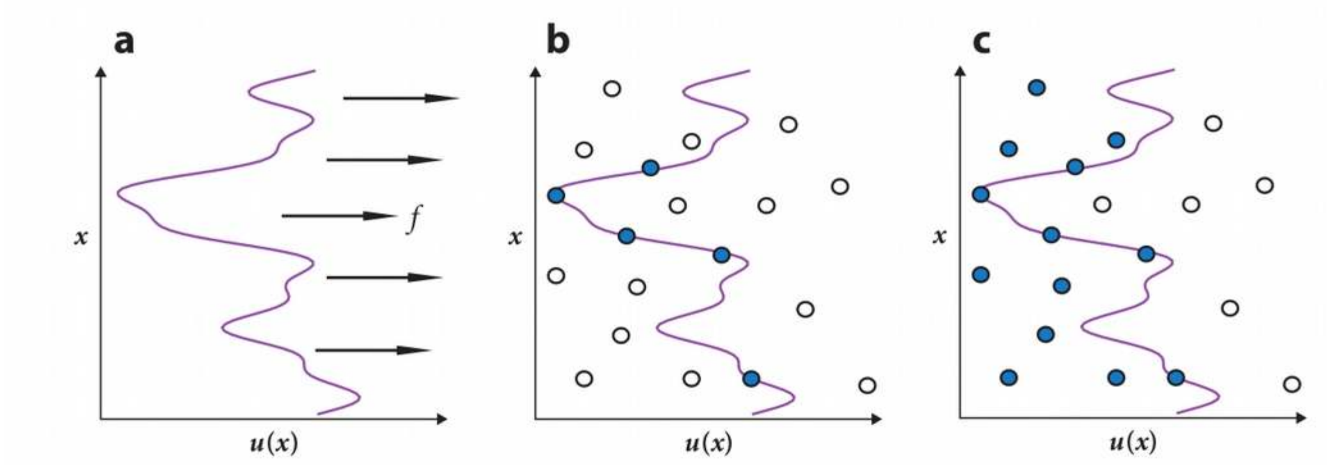
Langevin term, introduces a finite temperature T, white noise

$$\langle \eta(x,t) \rangle = 0 \qquad \langle \eta(x,t)\eta(x',t') \rangle = 2\gamma k_B T \delta(t-t')\delta(x-x')$$

Disorder types: RB RF

$$F_p = -\partial_u V_p(x,u) \qquad \overline{[V_p(x,u) - V_p(x',u')]^2} = \Delta_0 \delta(x-x') R(u-u')$$

RB case RF case



Random-bond (RB)

$R(s)$ is short ranged $\sim e^{-s/r_f}$

Random-field (RF)

$R(s)$ is long ranged $\sim |s|$

Yet, the disorder force is short-range correlated in both cases

Filled circles are the impurities that contribute to the pinning energy of the interface

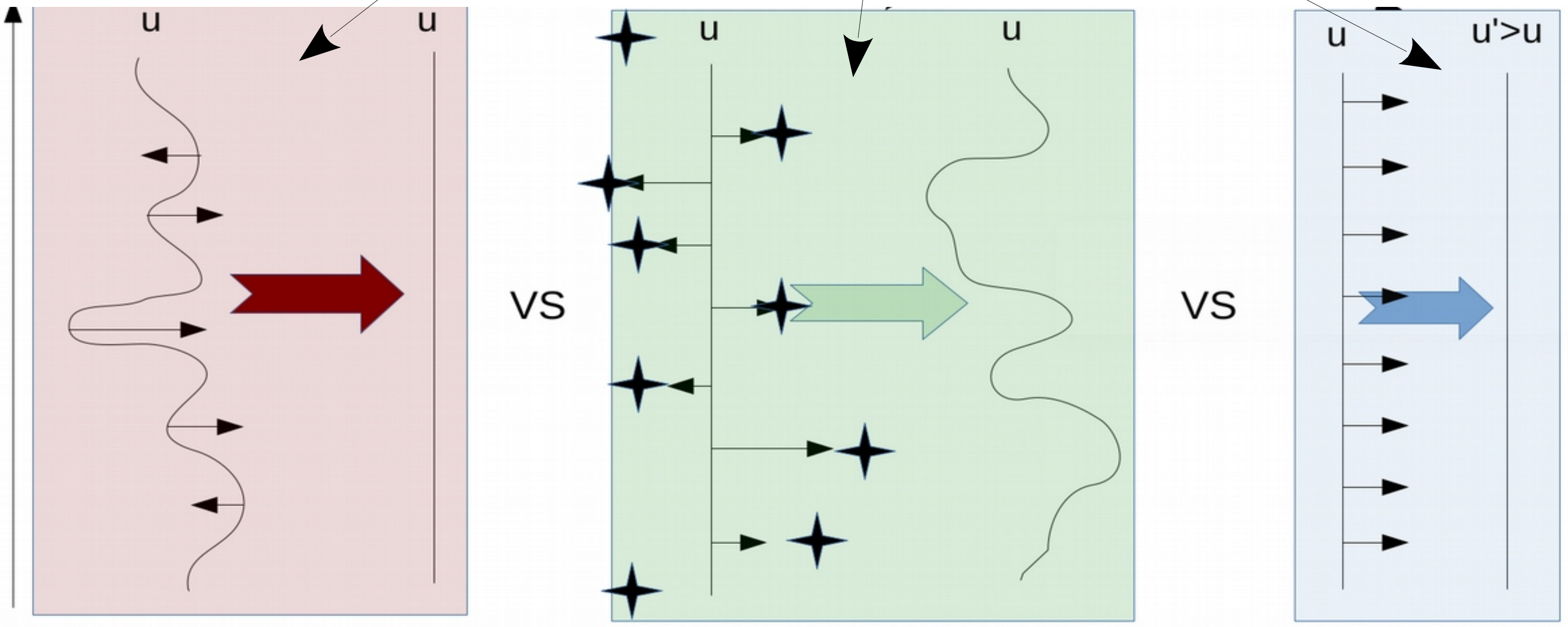
RF saves memory

EEF, L Foini, T Giamarchi, AB Kolton, A Rosso, Annu. Rev. Condens. Matter Phys. 12, 111 (2021)

The Quenched Edwards-Wilkinson elastic line

$$\gamma \partial_t u(x,t) = c\partial_x^2 u(x,t) + F_p(x,u) + f + \eta_T(x,t)$$

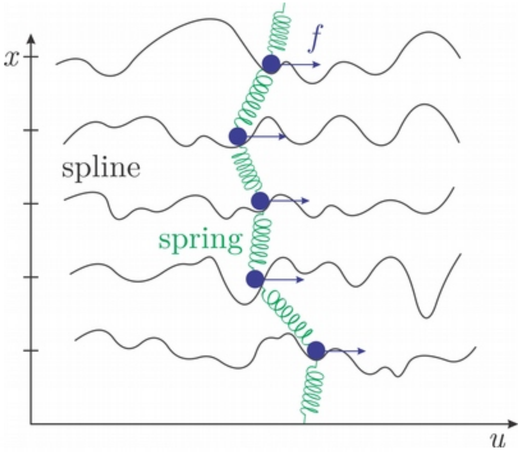
shakes



smoothes ***distorts and pins*** ***pushes***

Typical numerical approach

- Line of size ***L***
  - discretize *x*=0...(*L*-1)
  - keep *u(x,t)* as a *real* variable
  - periodic boundary conditions (*u*[0] coupled with *u*[*L*-1])



- Different disorder schemes
  - Continuous splines (cubic or linear)
  - Either presorted (with p.b.c. also in *u*) or dynamically generated.
  - With or without memory (RF-RB)

We want to solve:

$$\gamma \partial_t u(x,t) = c\partial_x^2 u(x,t) + F_p(u,x) + f + \eta(x,t)$$

one discretizes $x = i\Delta x$ $t = n\Delta t$ keeping $u(x,t)$ as a continuum variable

And do Euler integration

$$u(x,t+\Delta t) = u(x,t) + \left[\tilde{c}\,(u(x-1,t) + u(x+1,t) - 2u(x,t)) + F_p(u(x,t),x) + f + \sqrt{2T\eta_x(t)/\Delta t}\right]\Delta t$$

Play with the line 👇

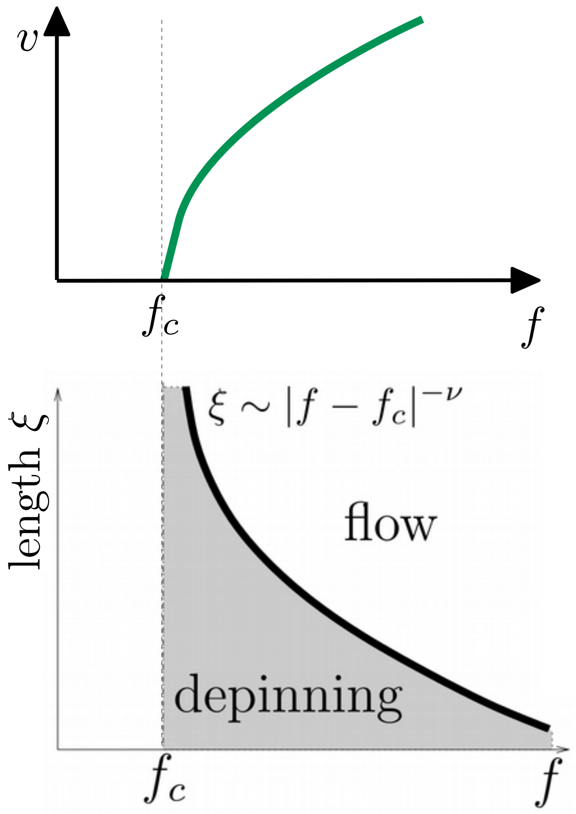
https://editor.p5js.org/droyktton/full/kfhajdpOk

Massively parallel implementations on GPUs

EEF, S. Bustingorry, A.B. Kolton, PRE **87**, 032122 (2013) sup.mat.

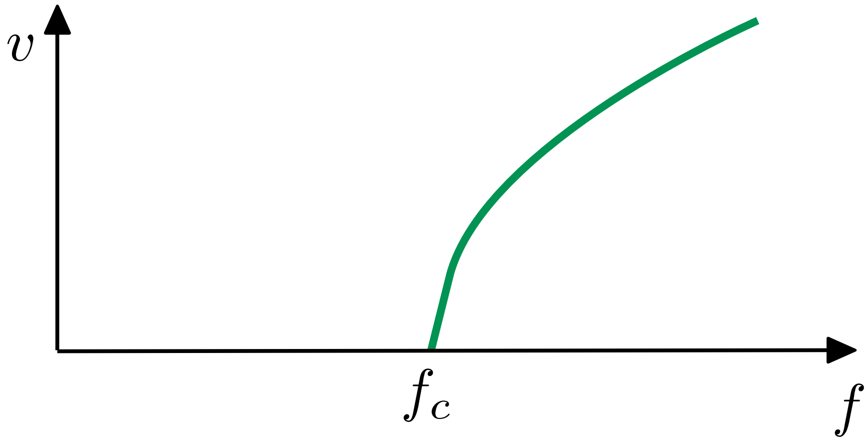
Play with the elastic line!

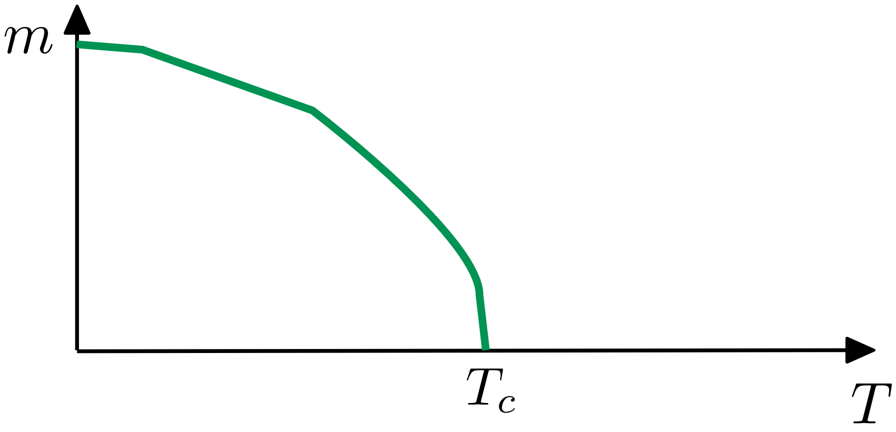
Let’s see who gets the best estimate of F_c



CRITICAL PHENOMENA IN DRIVEN PHASE TRANSITIONS

Analogy with equilibrium critical phenomena



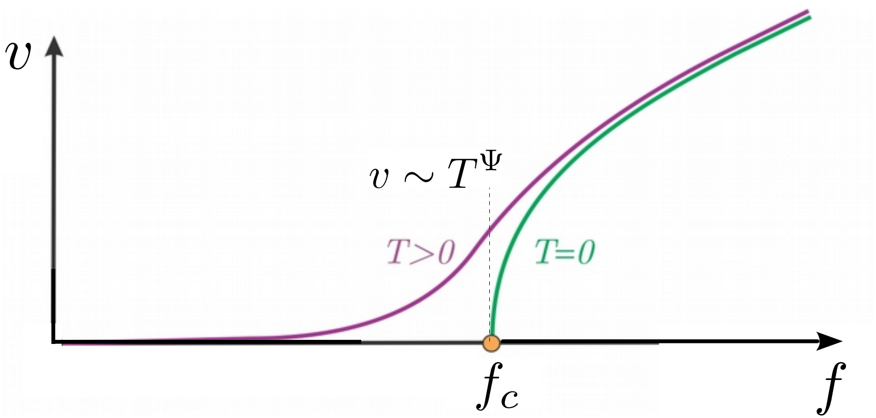


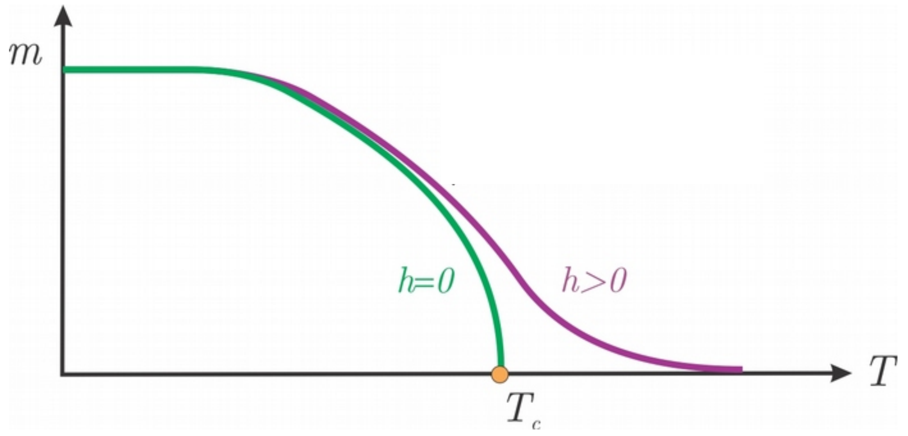
$v \sim (f - f_c)^\beta$	order parameter	$m \sim (T_c - T)^\beta$
$\xi \sim (f - f_c)^{-\nu}$	divergent length scale	$\xi \sim \lvert T_c - T\rvert^{-\nu}$
$\tau \sim \xi^z \sim (f - f_c)^{-z\nu}$	divergent time scale	$\tau \sim \xi^z \sim \lvert T_c - T\rvert^{-z\nu}$

[Daniel S. Fisher, “Sliding Charge Density Waves as a Dynamic Critical Phenomenon”, Phys. Rev. B 31, 1396 (1985)]

Transition thermal rounding

(recap on Friday L3)

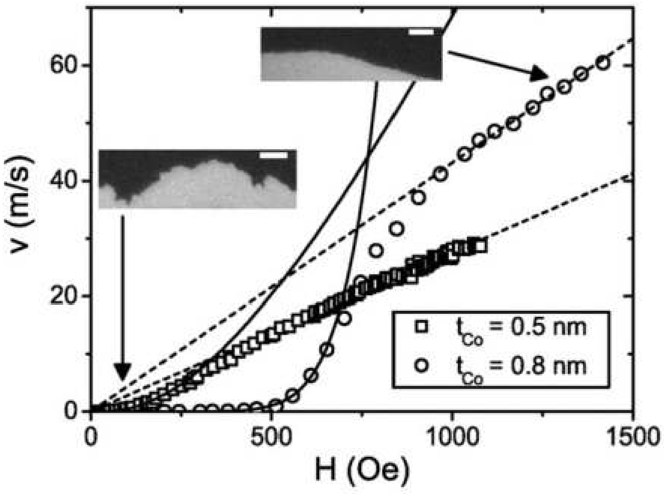




$v \sim (f - f_c)^{\beta}$	order parameter	$m \sim (T_c - T)^{\beta}$
$\xi \sim (f - f_c)^{-\nu}$	divergent length scale	$\xi \sim \lvert T_c - T\rvert^{-\nu}$
$\tau \sim \xi^z \sim (f - f_c)^{-z\nu}$	divergent time scale	$\tau \sim \xi^z \sim \lvert T_c - T\rvert^{-z\nu}$
$v(F_c) \sim T^{\psi}$	temperature/field rounding	$m(T_c) \sim h^{1/\delta}$

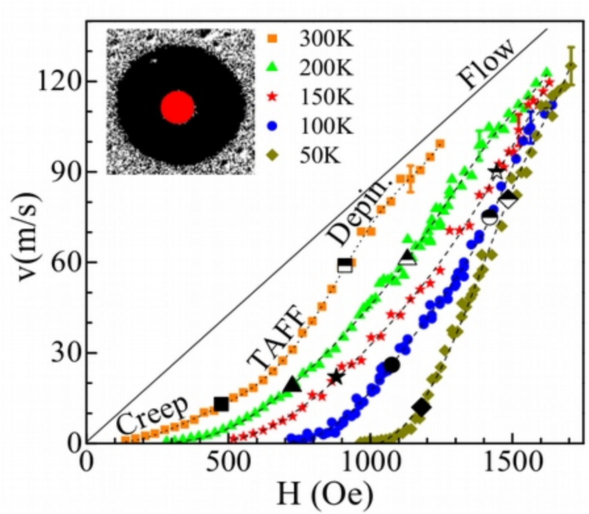
Depinning transition: experimentally tested

[P.J. Metaxas et al.
PRL, 99, 217208 (2007)]

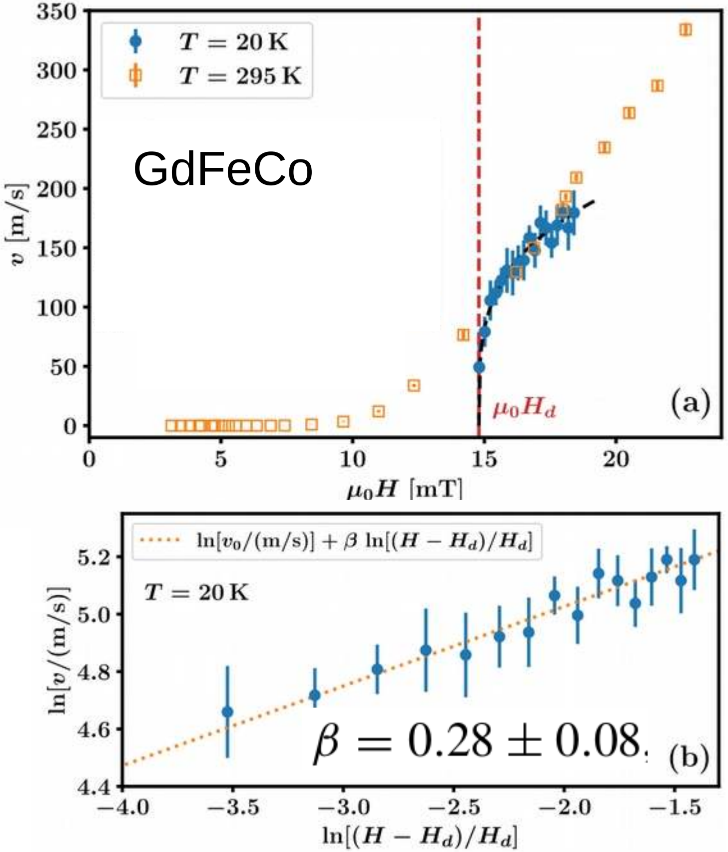


Pt/Co/Pt

[J. Gorchon et al,
PRL 113, 027205 (2014)]

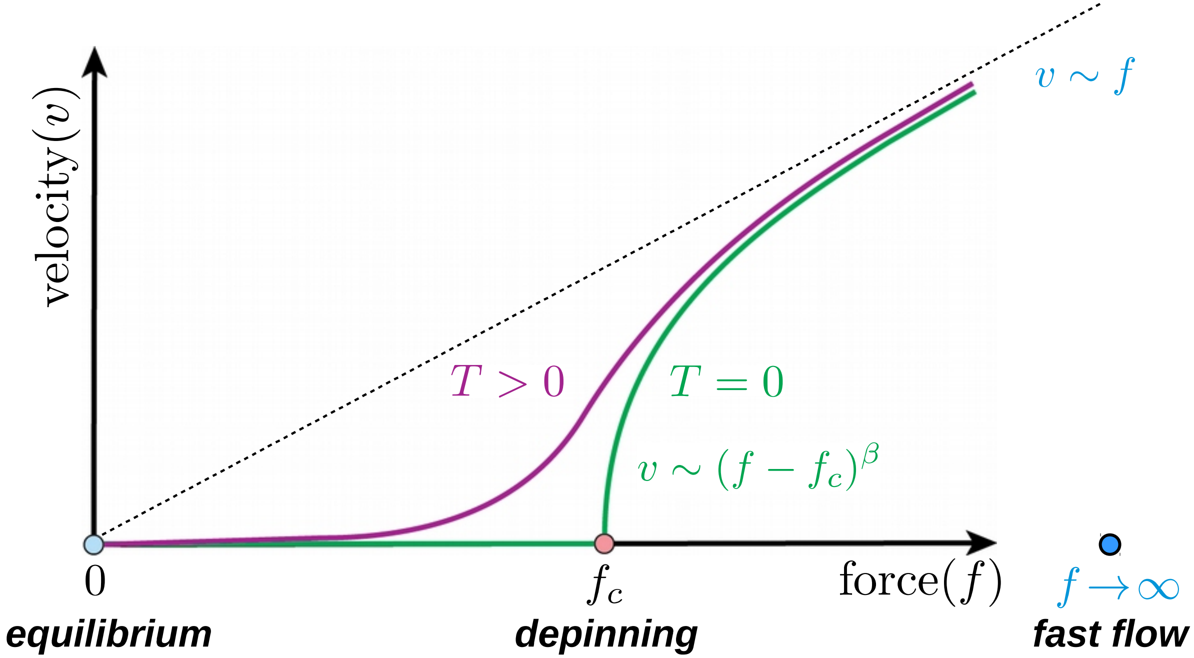


LPS, Paris-Sud ⟶ CAB, Bariloche



[L.J. Albornoz et al, PRB 104, L060404 (2021)]

Three reference states: line's geometry!



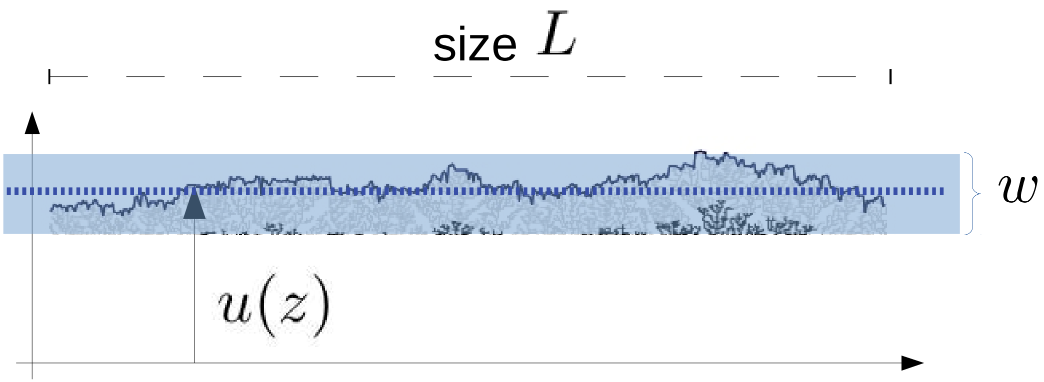
At the reference points interface is rough and self-affine $w \sim \ell^\zeta$

$$\zeta_{\mathtt{eq}}^{\mathtt{RB}} = 2/3 \qquad \zeta_{\mathtt{dep}} = 1.25 \qquad \zeta_{\mathtt{ff}} = 1/2$$

$$\zeta_{\mathtt{eq}}^{\mathtt{RF}} = 1$$

EEF, S. Bustingorry, A.B. Kolton, A. Rosso, CRP **14** 641 (2013)

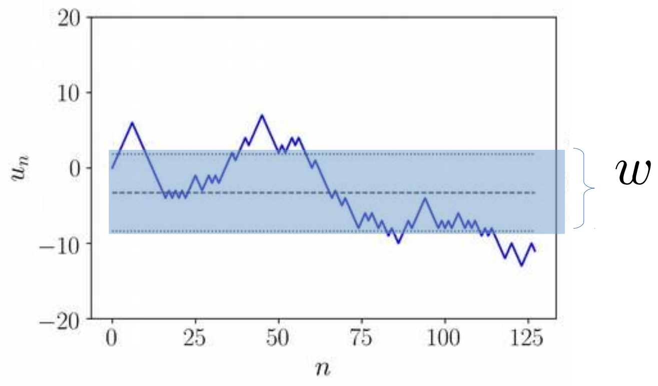
Critical interfaces: fluctuations - roughness



$$\langle u(z)\rangle = \frac{1}{L}\sum_{z=0}^{L-1} u(z)$$ mean position

$$w^2 = \frac{1}{L}\sum_{z=0}^{L-1}\left[u(z) - \langle u(z)\rangle\right]^2$$ width (roughness)

Mapping to random-walk (Directed polymer)



For a random-walk of the polymer:

interface fluctuations $\overline{\sigma_L^2} = \frac{L}{6} - \frac{1}{6L} \sim L$

interface width $w_L = \sqrt{\overline{\sigma_L^2}} \sim \sqrt{L}$

In general: (beyond RW) $\boxed{w \sim L^{\zeta}}$ $\zeta \rightarrow$ *roughness exponent*

Critical interfaces: time and finite size scaling

Starting from a flat interface:

$$w(t) \sim t^{\gamma} \quad \gamma: \textit{growth} \text{ exponent}$$

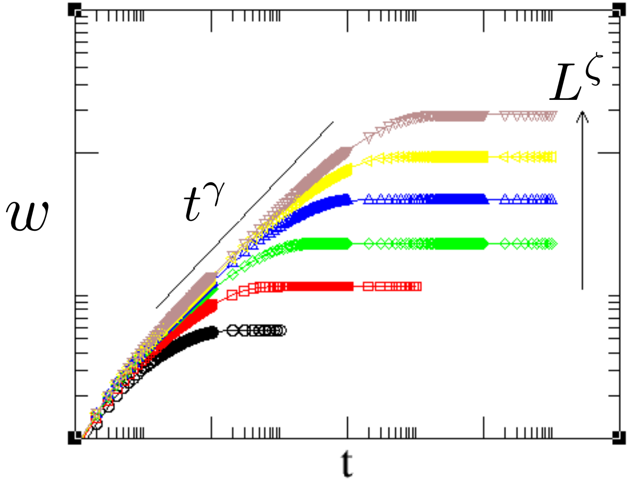
$$w(L)_{\texttt{sat}} \sim L^{\zeta} \quad \zeta: \textit{roughness} \text{ exponent}$$

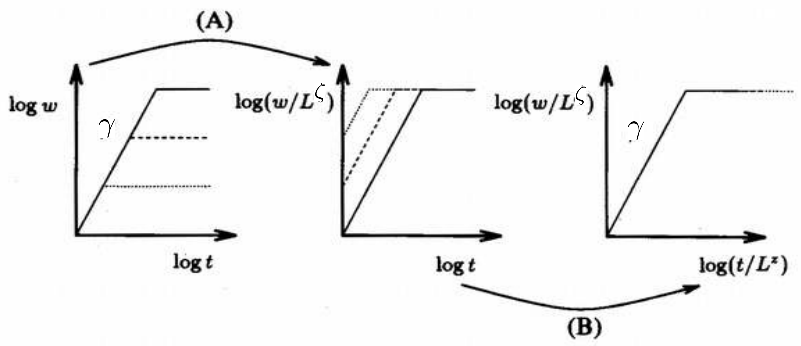
The crossover time depends on the system size

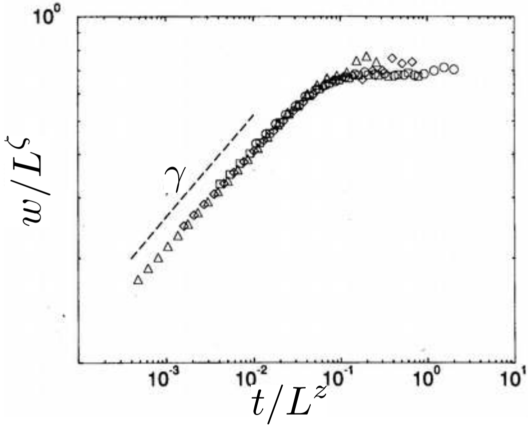
$$t_x \sim L^z \qquad z: \textit{dynamical} \text{ exponent}$$

Since at saturation $\quad L^{\zeta} \sim t_x^{\gamma} \sim L^{z\gamma}$

we have the scaling relation $\quad z = \zeta/\gamma$







A.-L. Barabási, H.E. Stanley "Fractal Concepts in Surface Growth" (1995)

Critical interfaces: rough "self-affine" geometry

Given piece of line of length ℓ in a critical configuration, its width would be $w \sim \ell^\zeta$

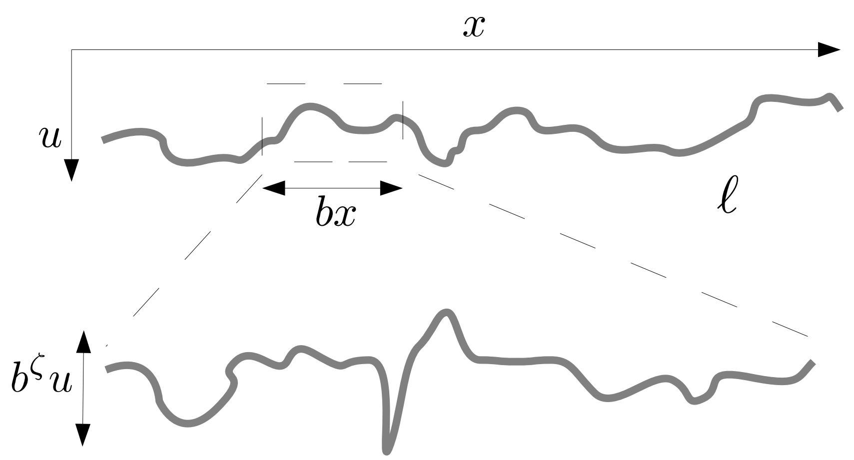
Interface is self-affine, statistically invariant under the anisotropic rescaling:

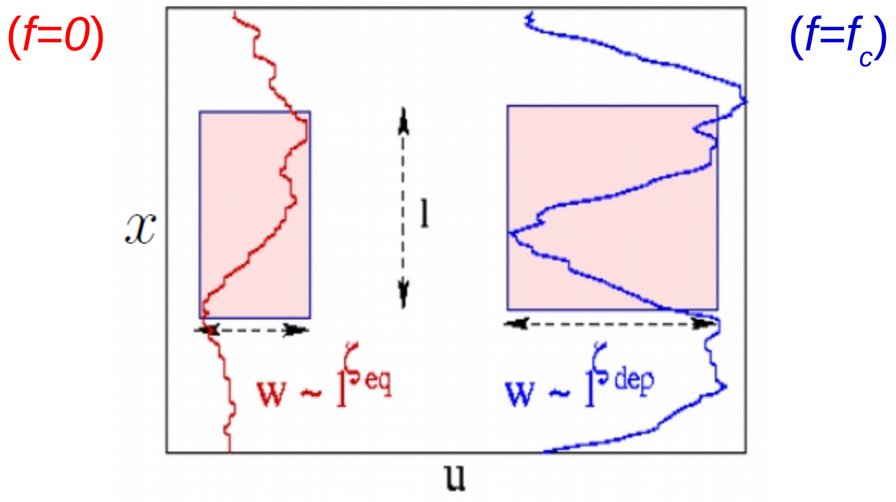
$$x \to bx \qquad u \to b^\zeta u \qquad u(bx) \sim b^\zeta u(x)$$

$\zeta = 1$: fractal

$\zeta \neq 1$: self-affine

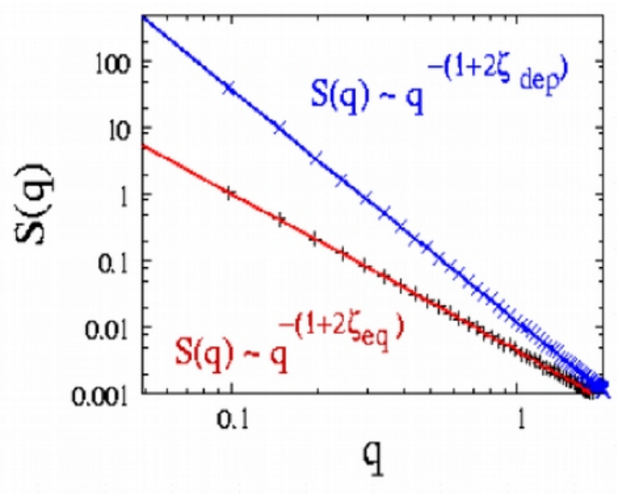
ζ Hölder or self-affine exponent, or the 'roughness' of *u(x)*





Rough geometry: Structure factor

Another way to measure roughness: **interface structure factor**



$$S(q,t) = \langle \hat{u}(q,t)\hat{u}(-q,t)\rangle$$

with $\quad \hat{u}(q,t) = \int dx\ u(x,t)e^{-ixq}$

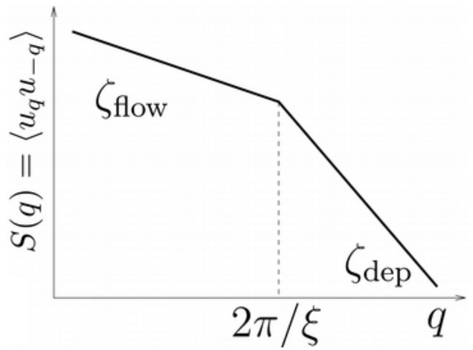
$$\text{small } q \to \text{large } \ell$$

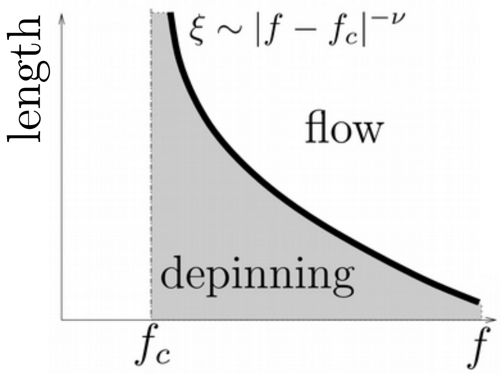
$$\text{large } q \to \text{small } \ell$$

Essentially *at the critical points*:

$$S(q,t) \sim q^{-(1+2\zeta)}F\left(qt^{1/z}\right)$$

For a given $F > F_c$



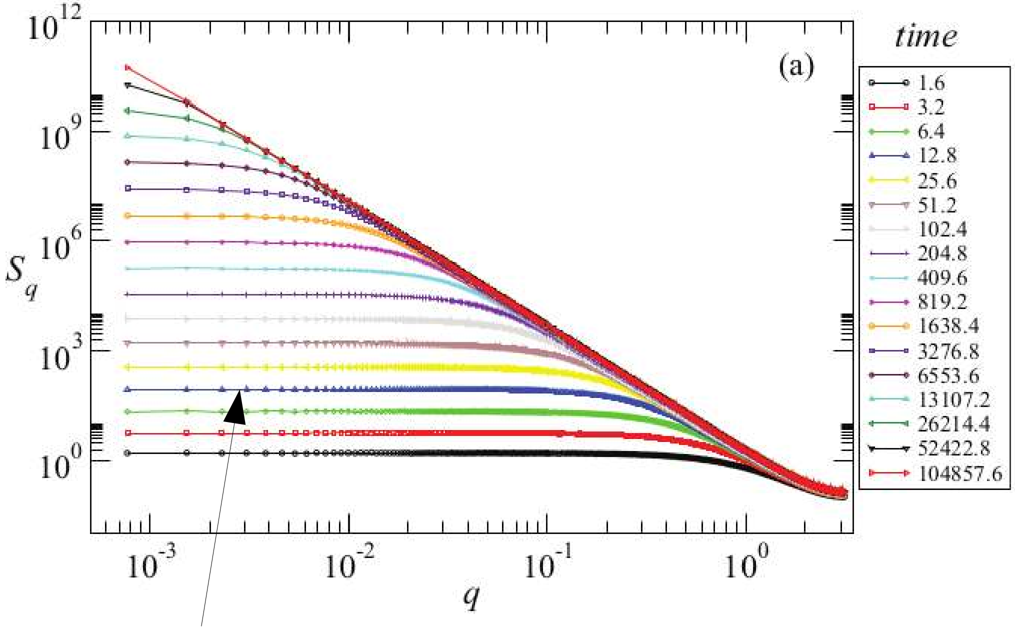


Rough geometry: Structure factor

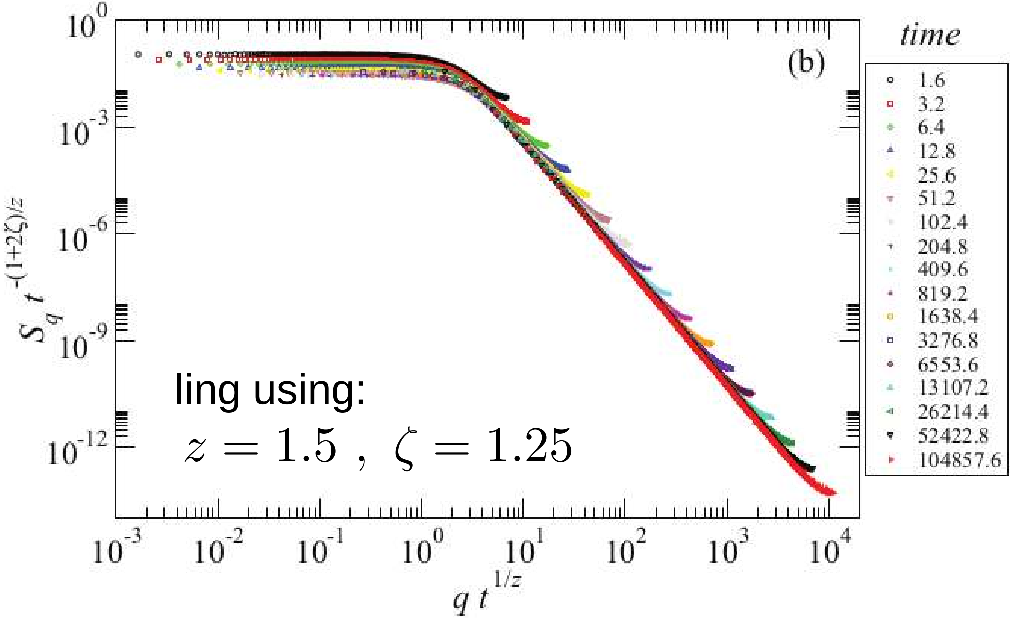
Starting from a flat line at $f=f_c$ $\quad \xi(t) \sim t^{1/z}$

$$S(q,t) \sim q^{-(1+2\zeta)} F\left(q t^{1/z}\right)$$

$$F(y) \sim \begin{cases} y^{(1+2\zeta)} & \text{for} \quad y \ll 1 \ (q \ll 1/\xi) \\ 1 & \text{for} \quad y \gg 1 \ (q \gg 1/\xi) \end{cases}$$



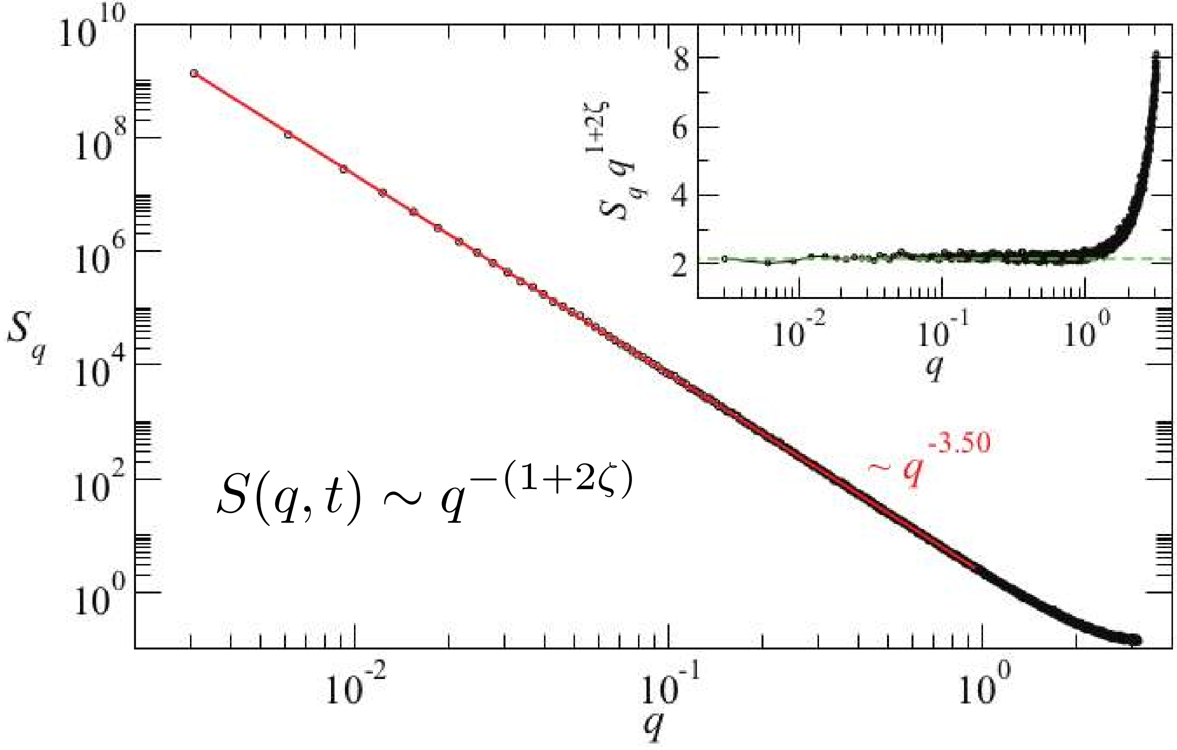
memory of the initial condition



EEF, S. Bustingorry, A.B. Kolton, PRE **87**, 032122 (2013)

Rough geometry: Structure factor

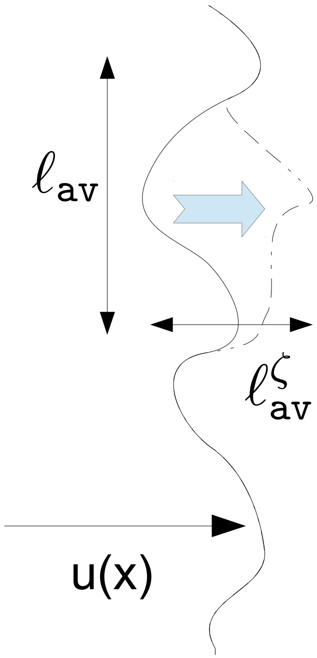
In the steady state at $f=f_c$



$$\zeta = 1.250 \pm 0.005$$

EEF, S. Bustingorry, A.B. Kolton, PRE **87**, 032122 (2013)

Critical interface: critical exponents



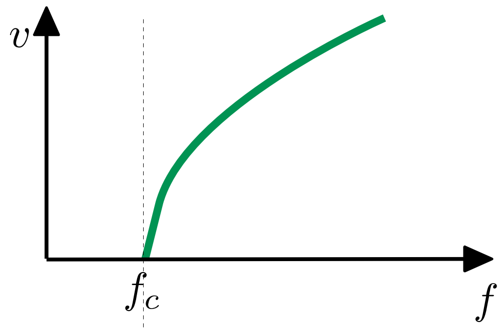
Velocity force characteristics: $v \sim (F - F_c)^{\beta}$

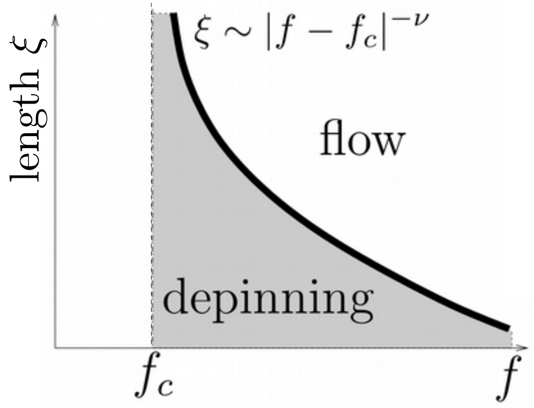
Correlation length: $\xi \sim (F - F_c)^{-\nu}$

Correlation time: $\tau \sim \xi^{z}$

Critical fluctuations, roughness: $w \sim \xi^{\zeta}$

Four critical exponents: β, ν, ζ, z
Not all independent!





e.g., at depinning the movement is dominated by avalanches

$\ell_{\mathtt{av}} \propto \xi$

$$v \sim \frac{\texttt{normal displacement}}{\texttt{time}} \sim \frac{\Delta u}{\tau} \sim \frac{\ell_{\mathtt{av}}^{\zeta}}{\ell_{\mathtt{av}}^{z}} \sim (F - F_c)^{\nu(z-\zeta)}$$

Hiperscaling relation

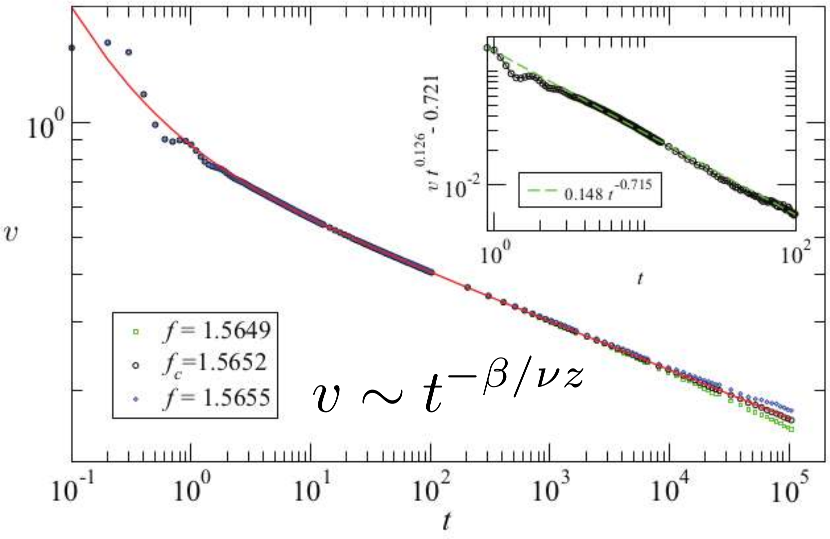
$$\boxed{\beta = \nu(z - \zeta)}$$

qEW critical exponents (from non-steady critical relaxation)

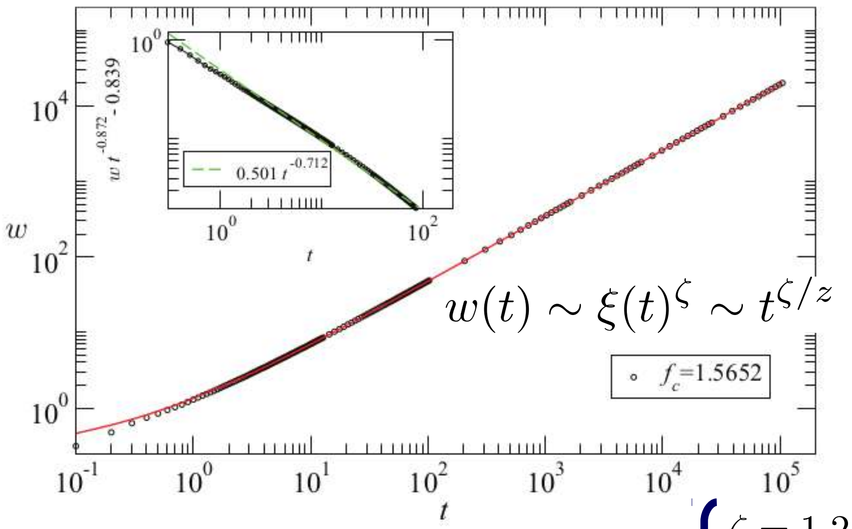
Using yet another analogy with equilibrium critical phenomena $v(t,h,L) = b^{-\beta/\nu}\tilde{v}(b^{-z}t, b^{1/\nu}h, b^{-1}L)$

$h = (f - f_c)/f_c$

After a quench from f→∞ (flat line) Using $b \equiv t^{1/z}$ $v(t) \simeq t^{-\beta/\nu z} G(t^{1/\nu z} h)$



$v \sim t^{-\beta/\nu z}$



$w(t) \sim \xi(t)^{\zeta} \sim t^{\zeta/z}$

$L = 2^{25} = 33554432$

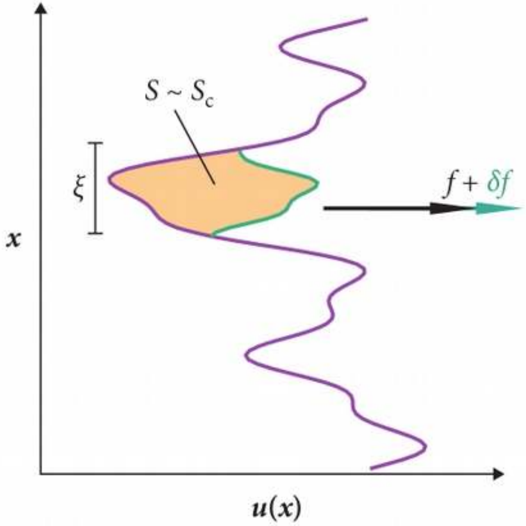
+ Statistical-tilt symmetry relation $\boxed{\nu \sim \dfrac{1}{2-\zeta}}$

$$\begin{cases} \zeta = 1.250 \pm 0.005 \\ z = 1.433 \pm 0.007 \\ \nu = 1.333 \pm 0.007 \\ \beta = 0.245 \pm 0.006 \end{cases}$$

EEF, S. Bustingorry, and A. B. Kolton PRE **87**, 032122 (2013)

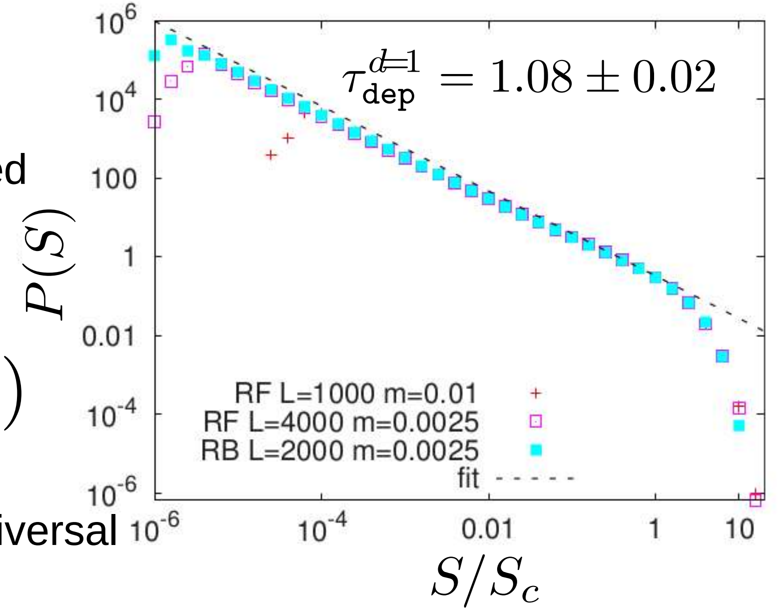
Avalanches at the depinning transition

Quasistatic protocol to measure avalanches: starting with $f \sim< f_c$ progressively push the line by tiny amounts



- Avalanche location cannot be predicted
- Avalanche size statistics is scale-free

$$P(S) \propto S^{-\tau_{\rm dep}} g\left(S/S_c\right)$$



- Gutenberg–Richter exponent $\tau_{\rm dep}$ is universal
- S_c is the clear manifestation of the divergent correlation length

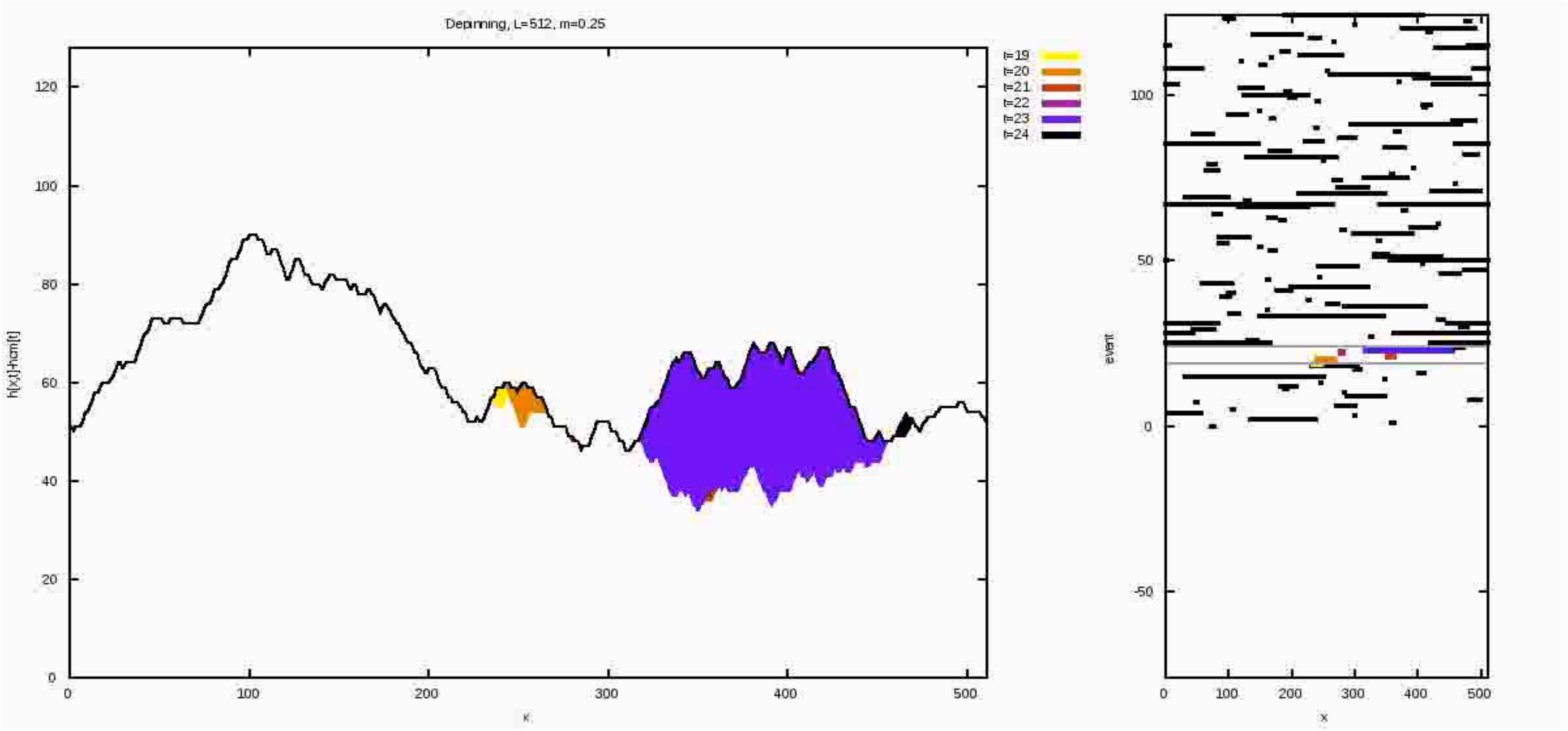
$$S_c \simeq \xi^{d+\zeta_{\rm dep}} \simeq |f-f_c|^{-\nu_{\rm dep}(d+\zeta_{\rm dep})}$$

Narayan-Fisher relation

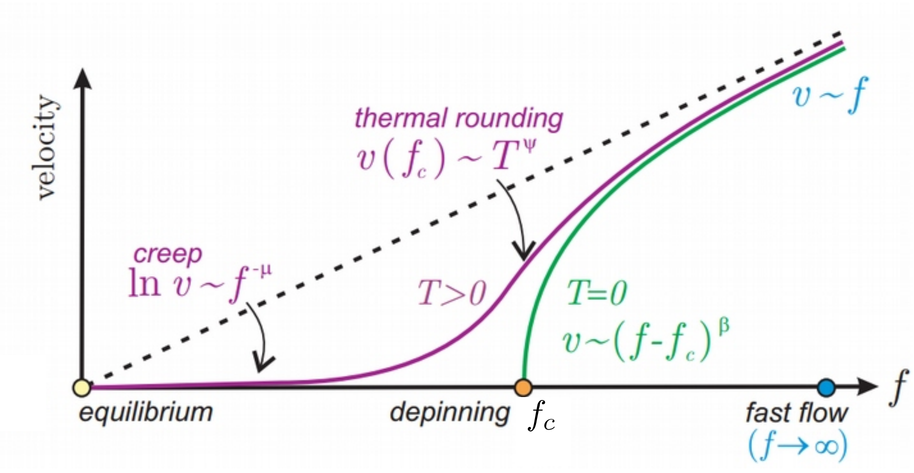
$$\boxed{\tau = 2 - \frac{2}{d+\zeta}}$$

A. Rosso, P. Le Doussal, K. Wiese, PRB 80, 144204 (2009)
K. Wiese Rep. Prog. Phys. 85 (2022) 086502

Depinning avalanches



Global picture depinning summary (QEW model in d=1)



$$\zeta_{\tt eq}^{\rm RB} = 2/3 \quad \zeta_{\tt dep} = 1.25 \quad \zeta_{\tt ff} = 1/2$$

$$\zeta_{\tt eq}^{\rm RF} = 1$$

At equilibrium, mean velocity is zero and the dynamics is glassy (highly degenerated GS): in order to observe a rearrangement of size *l* we need to overcome a barrier $E_b(l)$ growing as $E_b \sim l^{\theta}$. The resulting roughness ζ depends on the type of disorder

At the **zero temperature depinning** transition, the velocity vanishes as $v(f,T=0) \sim (f-f_c)^{\beta}$ for $f > f_c$, while $v=0$ for $f<f_c$. **At finite temperature**, this sharp transition is rounded and the velocity behaves as $v(f_c,T) \sim T^{\psi}$. A thermal creep is observed even at f<<fc.

At large force, $f>>f_c$, in the **fast-flow regime**, we recover the linear response *v~f*. Here impurities generate an *effective thermal noise* on the interface with $T_{eff} - T \sim \Delta/v$ (Δ being the disorder strength). The fast-flow roughness corresponds to the Edwards–Wilkinson roughness

$$\zeta_{\tt ff} = \zeta_{\tt EW} = 1/2$$

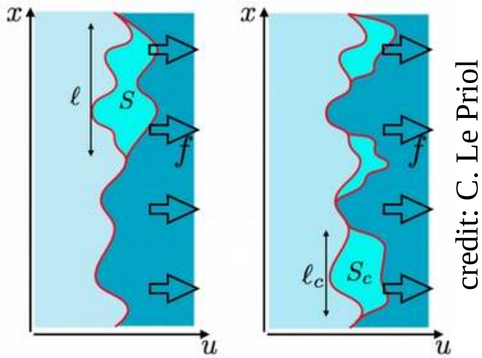
EEF, S. Bustingorry, A.B. Kolton, A. Rosso, CRP **14** 641 (2013)

Beyond qEW: Long range elasticity

For the case of a contact line of a liquid meniscus as well as the crack front of a brittle material, the local elastic force is replaced by a long-range one

$$c\nabla^2 u \to c \int \frac{[u(x',t) - u(x,t)]}{|x' - x|^{\alpha+d}} \mathrm{d}^d x'$$

$$\gamma \partial_t u(x,t) = c \int \frac{[u(x',t) - u(x,t)]}{|x' - x|^{\alpha+d}} d^d x' + F_{\mathtt{p}}(x,u) + f$$



credit: C. Le Priol

Qualitative phenomenology is similar to the qEW, but the universal properties are different. However, for α ≥ 2, one recovers the short-range universality class

Table 1 Depinning exponents: mean-field and finite dimension[a]

Depinning exponent	Observable	Mean field $d \geq 2\alpha$	$d = 1$ $\alpha = 2$	$d = 1$ $\alpha = 1$	$d = 2$ $\alpha = 2$
z	$t(L) \sim L^z$	α	1.433	0.77	1.56
ζ_{dep}	$u(x) \sim x^{\zeta_{\mathrm{dep}}}$, $w^2 \sim L^{2\zeta_{\mathrm{dep}}}$	0	1.250	0.39	0.75
τ_{dep}	$P(S) \sim S^{-\tau_{\mathrm{dep}}}$	3/2	$\tau_{\mathrm{dep}} = 2 - \alpha/(d + \zeta_{\mathrm{dep}})$		
ν_{dep}	$\xi \sim \lvert f - f_c \rvert^{-\nu_{\mathrm{dep}}}$	α^{-1}	$\nu_{\mathrm{dep}} = 1/(\alpha - \zeta_{\mathrm{dep}})$		
β	$v \sim \lvert f - f_c \rvert^{\beta}$	1	$\beta = \nu_{\mathrm{dep}}(z - \zeta_{\mathrm{dep}})$		

EEF, L Foini, T Giamarchi, AB Kolton, A Rosso, Annu. Rev. Condens. Matter Phys. 12, 111 (2021)

Beyond qEW: quenched KPZ (Kardar–Parisi–Zhang) model

In the presence of *anisotropies* in the disorder or in the elastic interaction, a non-linearity becomes relevant for short-range elasticity. An anharmonic term comes in

$$\gamma \partial_t u(x,t) = c\nabla^2 u(x,t) + \lambda[\nabla u(x,t)]^2 + F_{\mathrm{p}}(x,u) + f$$

At depinning, the motion remains intermittent with large avalanches but with different exponents. Statistical tilt symmetry relation is no longer valid and we need to measure 3 independent exponents

Table 3 Exponents of the quenched Kardar–Parisi–Zhang (qKPZ) depinning universality class[a]

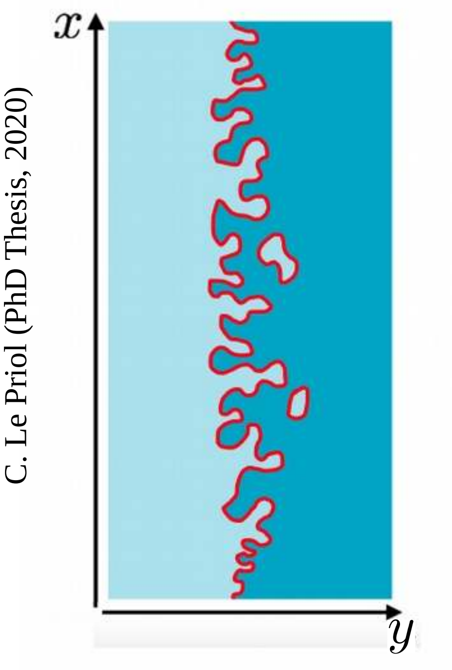
qKPZ exponent	$d = 1 \quad \alpha = 2$	$d = 2 \quad \alpha = 2$
z	1	1.1
ζ_{dep}	0.63	0.45
ν_{dep}	1.733	1.05
τ_{dep}	$\tau_{\mathrm{dep}} = 2 - (\zeta_{\mathrm{dep}} + 1/\nu_{\mathrm{dep}})/(d + \zeta_{\mathrm{dep}})$	
β	$\beta = \nu_{\mathrm{dep}}(z - \zeta_{\mathrm{dep}})$	

Kardar, Parisi, Zhang, PRL. **56**, 889 (1986)

EEF, L Foini, T Giamarchi, AB Kolton, A Rosso, Annu. Rev. Condens. Matter Phys. 12, 111 (2021)

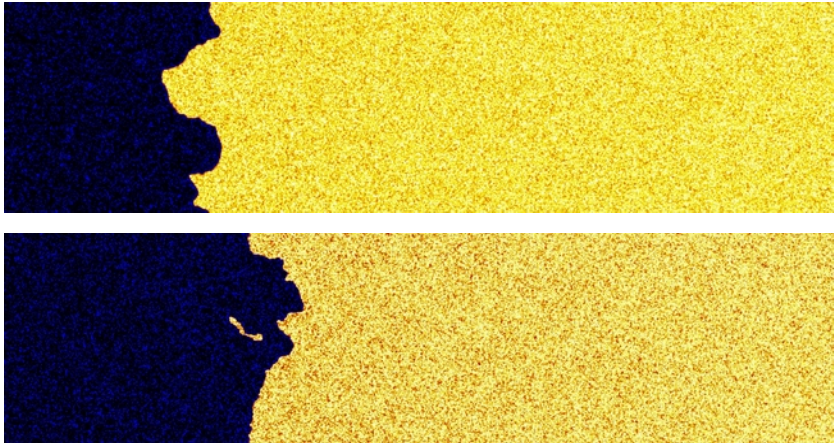
Beyond qEW: Not uni-valued interface? → ϕ^4 model

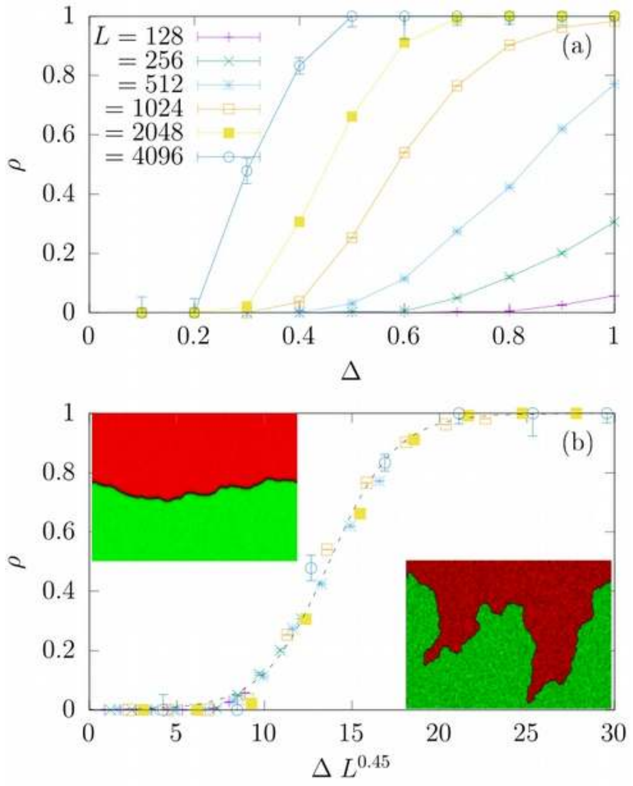
$$\gamma\, \partial_t \phi = c\nabla^2\phi + \epsilon_0[(1 + r(x, y))\phi - \phi^3] + h$$



C. Le Priol (PhD Thesis, 2020)

Ginzburg-Landau equation for a scalar order parameter field $\phi(x, y)$



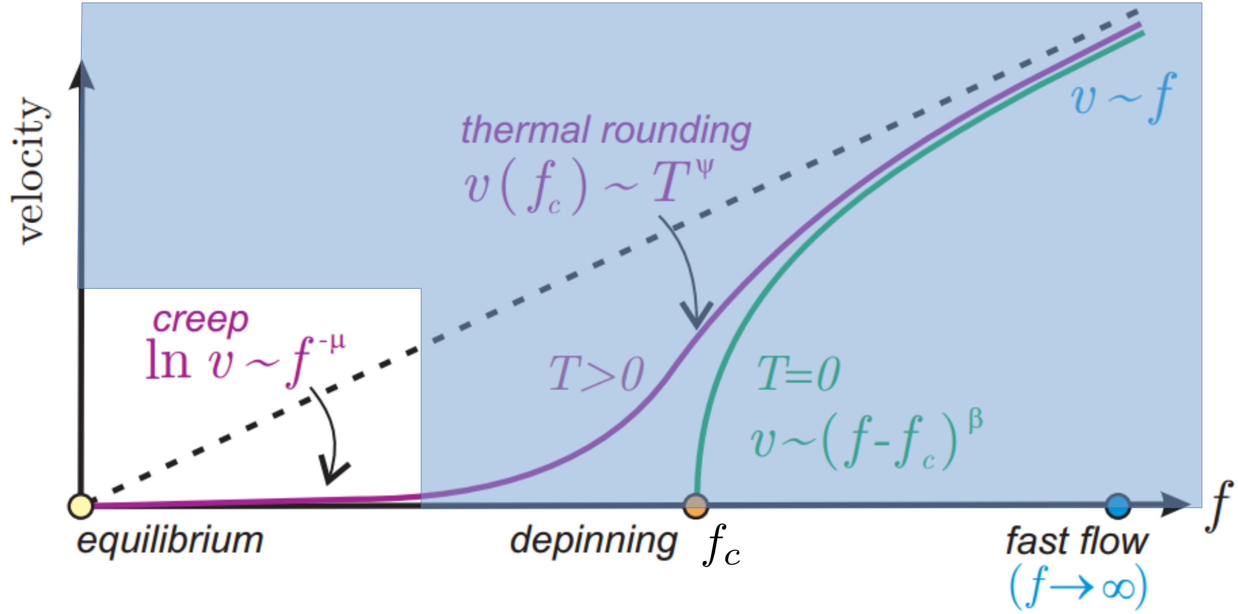


In general: overhangs, fingers and bubbles

video

AB Kolton, EEF, A Rosso PRB 108, 174201 (2023)

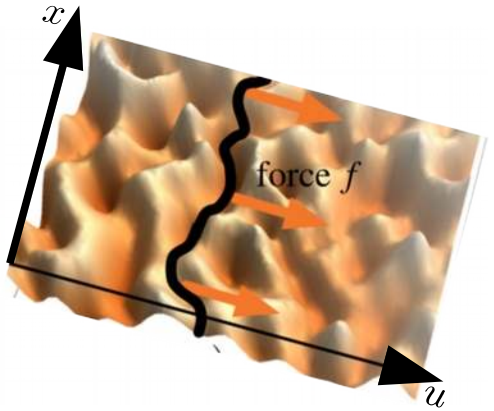
CREEP

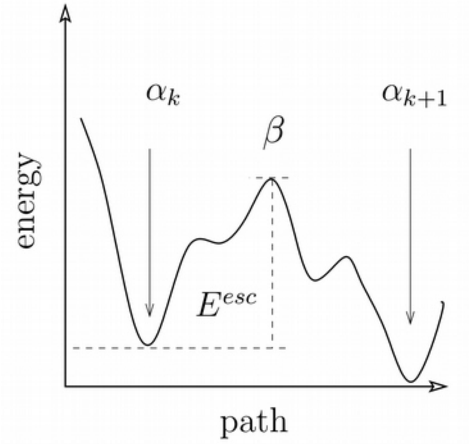


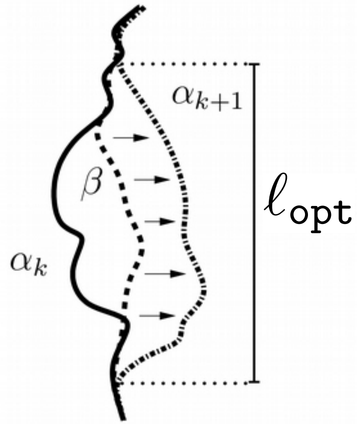
velocity
thermal rounding
$v(f_c) \sim T^{\psi}$
$v \sim f$
creep
$\ln v \sim f^{-\mu}$
$T>0$
$T=0$
$v \sim (f-f_c)^{\beta}$
equilibrium
depinning
f_c
fast flow
$(f \to \infty)$
f

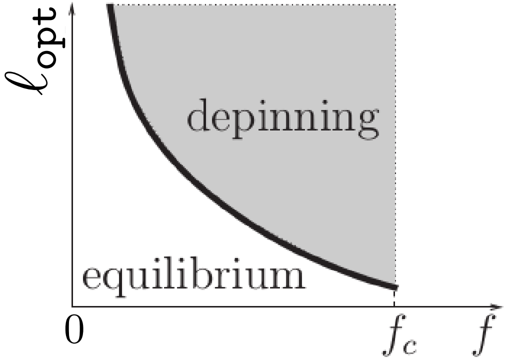
Creep motion $f \ll f_c \; , \; T \ll 1$

- Ultra-slow dynamics ruled by activation
- Velocity dominated by collective forward motion









From scaling arguments:

Required rearrangement for barrier jump

$$\boxed{\ell_{\mathrm{opt}} \sim f^{-\nu_{\mathrm{eq}}}} \; , \; \nu_{\mathrm{eq}} = \frac{1}{2-\zeta_{\mathrm{eq}}}$$

Divergent barriers as f→0 (glassy dynamics)

$$E^{\mathrm{esc}}(\ell_{\mathrm{opt}}) \sim \ell_{\mathrm{opt}}^{\theta} \sim f^{-\mu} \; , \; \mu = \theta \nu_{\mathrm{eq}}$$

Assumptions

- Static (as-equilibrium) description of the interface at f>0 *. $\theta = \theta_{\mathrm{eq}}, \zeta = \zeta_{\mathrm{eq}}, \nu = \nu_{\mathrm{eq}}$
- Forward motion delivered by independent jumps over “typical” barriers…..

*true below certain scale, FRG [Chauve et al. PRB 2000]

Creep: Ultra-slow activated dynamics

$$f \ll f_c \;,\; T \ll 1$$

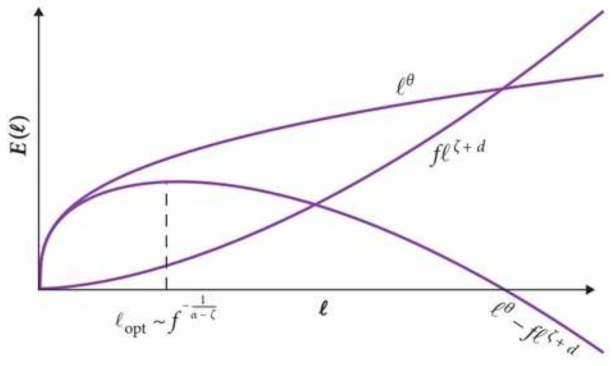
Scaling Arguments

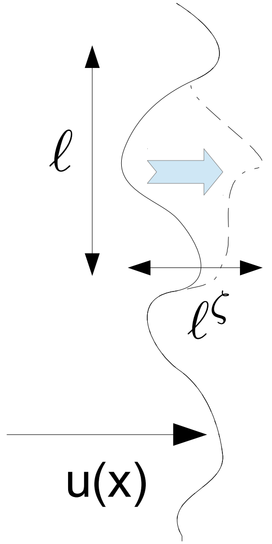
(Ioffe-Vinokur 1987, Feigel'man 1989, Nattermann 1990)

$$H[u] = \frac{c}{2}\int d^dx\, (\nabla u)^2 + \int d^dx\, V_p(u,x) - f\int d^dx\, u$$

Barriers (or sample to sample fluctuations)

$$E_{\rm p}(\ell) \sim \ell^{\theta_{eq}} \sim \ell^{d-2+2\zeta_{\rm eq}}$$





Energy gain of an avalanche of size $\ell \times \ell^\zeta$: $f\ell^{d+\zeta_{\rm eq}}$

Balancing $\Rightarrow$ $\ell = \ell_{\rm opt} \sim f^{-\frac{1}{2-\zeta_{\rm eq}}} \sim f^{-\nu_{\rm eq}}$

Assuming an Arrhenius time for barrier jump

$$v = \frac{\Delta u}{\Delta t} \sim \ell_{\rm opt}^{\zeta_{\rm eq}} e^{-\frac{\ell_{\rm opt}^{\theta_{\rm eq}}}{K_B T}} \sim \exp\left[-\frac{U_0}{k_B T}\left(\frac{f_0}{f}\right)^\mu\right] \qquad \mu = \nu_{\rm eq}\theta_{\rm eq}$$

Creep law

Creep formula

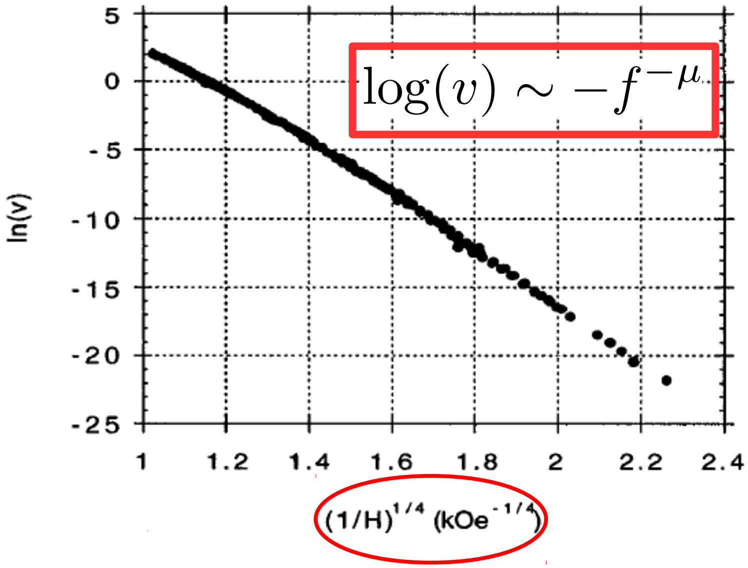
$$\boxed{v \sim \exp\left[-\frac{U_0}{k_B T}\left(\frac{f_0}{f}\right)^{\mu}\right]}$$

Creep exponent

$$\mu = \theta_{\text{eq}} \nu_{\text{eq}} = \frac{d - 2 + 2\zeta_{\text{eq}}}{2 - \zeta_{\text{eq}}}$$

$$d = 1, \ \zeta_{\text{eq}}^{\text{RB}} = 2/3 \qquad \boxed{\mu = 1/4}$$

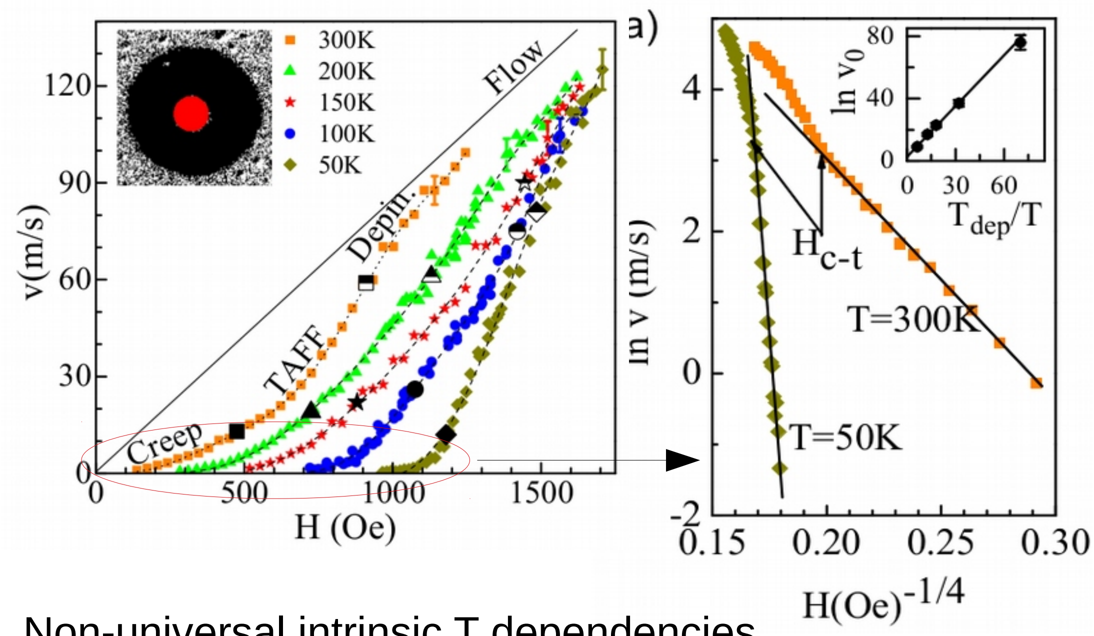
Experimental success!

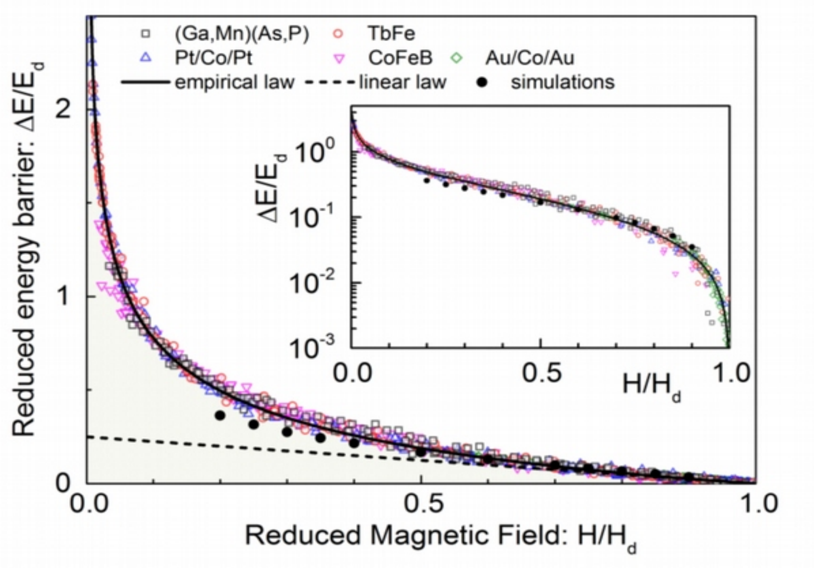


S. Lemerle, J. Ferré et al. PRL 80, 849 (1998)

and later on elsewhere…
[K.-J. Kim et al Nature 2009]
[J. Gorchon et al. PRL 2014]
[V. Jeudy et al. PRL 2016]
[M. Grassi et al. PRB 2018]

Creep experiments: First in 1998 and many after





Non-universal intrinsic T dependencies

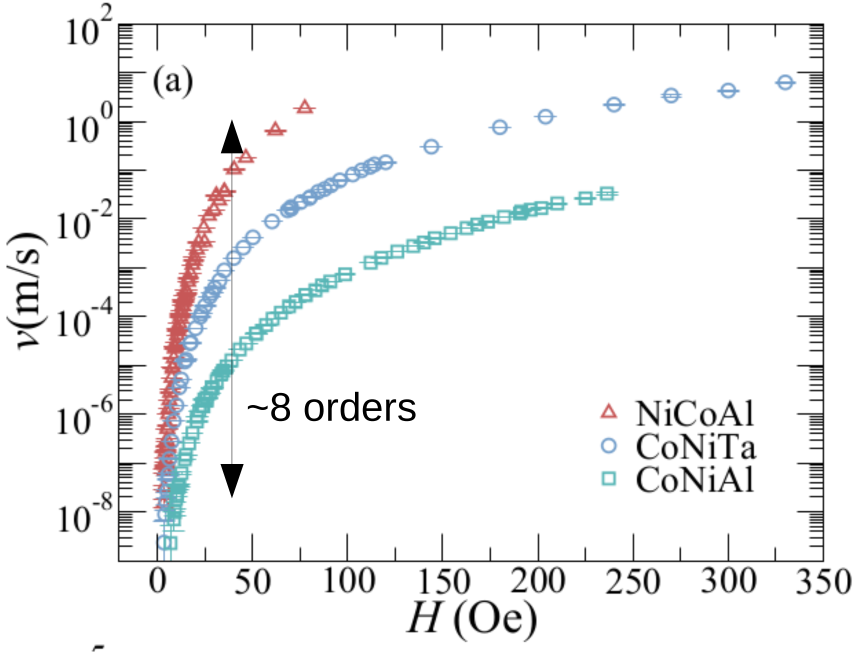
$$v = v_0 e^{-\frac{T_{\text{dep}}}{T}\left(\frac{H_{\text{dep}}}{H}\right)^{1/4}} \quad T_{\text{dep}}(T),\ H_{\text{dep}}(T),\ v_0(T)$$

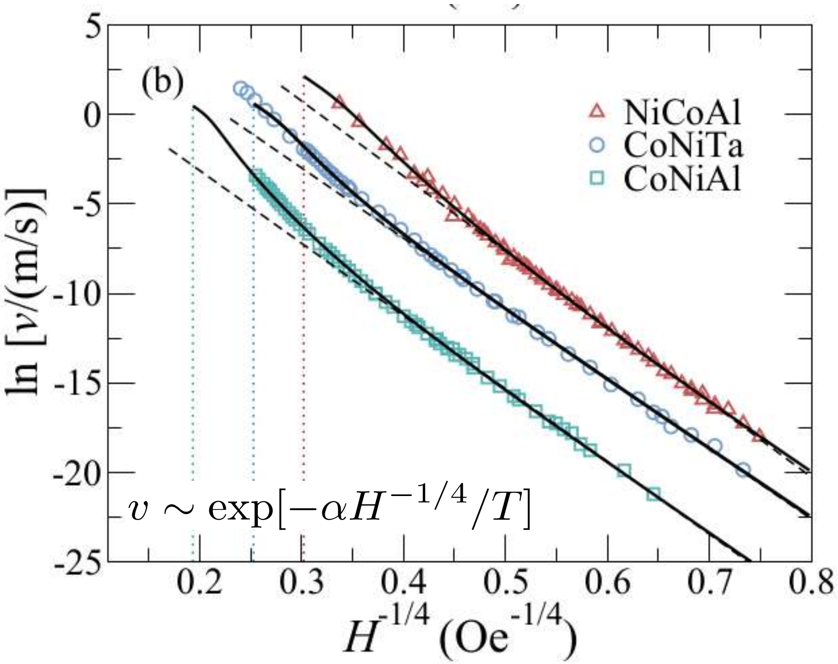
$$v(H,T) \sim \exp\left[-\frac{\Delta E(H)}{T}\right]$$

[J. Gorchon et al, PRL 113, 027205 (2014)]

V. Jeudy et al PRL 117, 057201 (2016)

Creep experiments @Bariloche





~8 orders of magnitude of creep law !

From walking velocities to finger-nails growth velocity

N.B. Caballero et al. Phys. Rev. B 96, 224422 (2018)

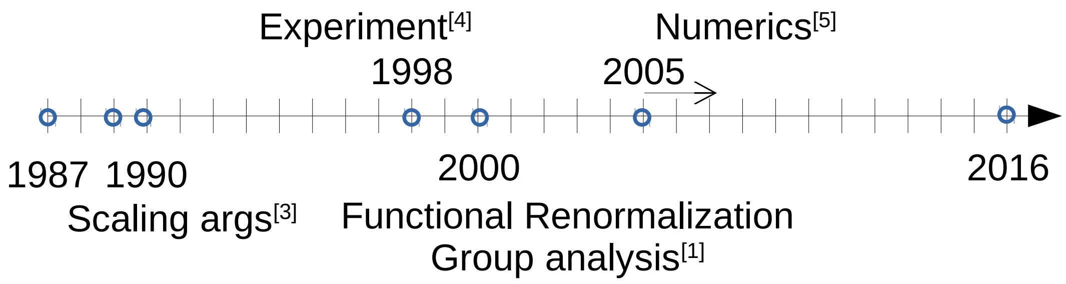
Creep motion

Phenomenological law works well, but:

- Are there “typical” creep events?
- How is the size distribution of those activated events?
- What is their organization in space and time?

Can we simulate creep?

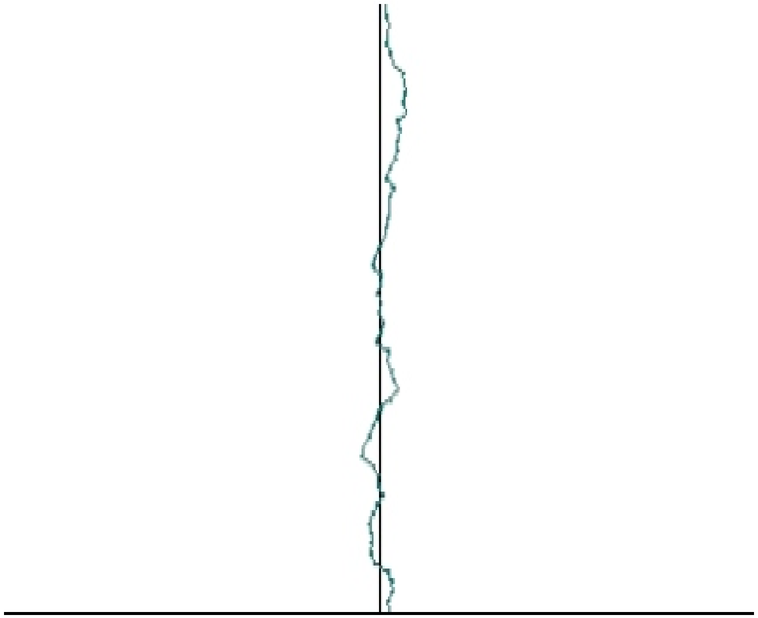
Historic timeline



The futility problem for $f<f_c$ at $T>0$

$$\gamma\partial_t u(x,t) = c\partial_x^2 u(x,t) + F_p(u,x) + f + \eta(x,t)$$

Langevin dynamics fails to study creep



f~0.5 f_c and non-negligible *T*

- "**Useless**" local back and forth futile motion, vibrations at finite *T* (acceptance is not the issue)

- Arrhenius limit: the line advances only due to **rare events** (very slow motion)

$$v \sim \exp[-\alpha f^{-1/4}/T]$$

- **Barriers diverge** when *f→0*, the regime of interest.

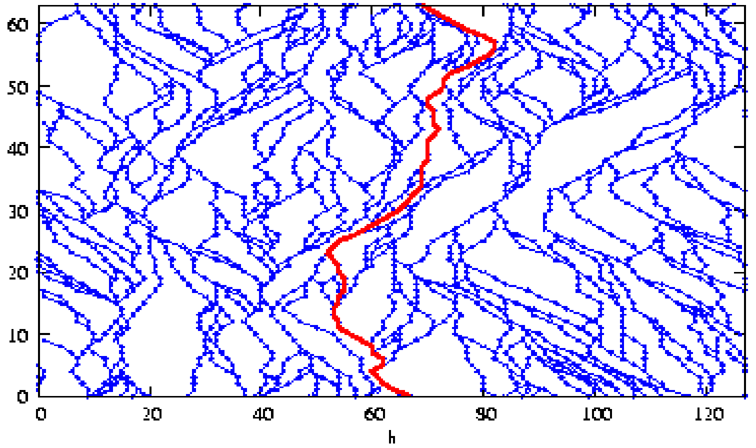
Modeling Transition pathways algorithm for T=0+

Kolton et al. PRL **97** 057001 (2006), PRB **79** 18207 (2009)

Discrete polymer of size *L defined by:* $\{u_i\}\ (i = 0, ..., L-1)$

$$E = \sum_i \frac{c}{2}(u_{i+1}-u_i)^2 + \sum_i V_p(i,u_i) - \sum_i f u_i$$

- **hard** metric **constraint** $|u_i - u_{i-1}| \leq K = 1 \quad \forall i$

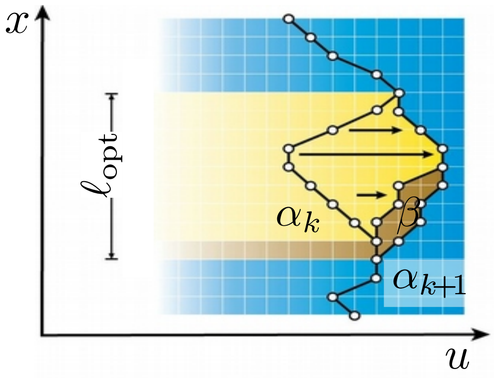


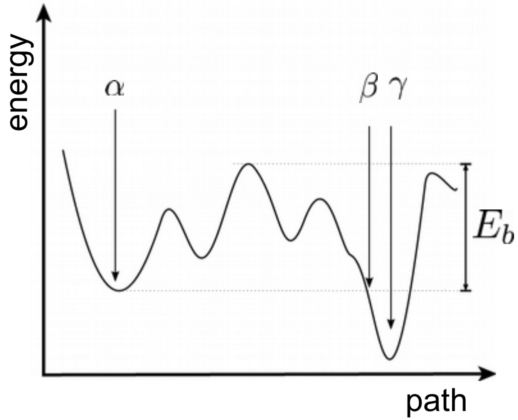
Exact algorithm: **successive** (forward) **search** of new **metastable** states connected by **minimal barriers**.

- Exponential cost in $\ell_{\text{opt}}(f)$
- Limited to $L = 32, f \approx 0.2$

Proposed **approximation**:
look for ~~minimal barrier~~ → **smallest** favorable **move**

$$E_b \sim \ell_{opt}^{\theta}$$





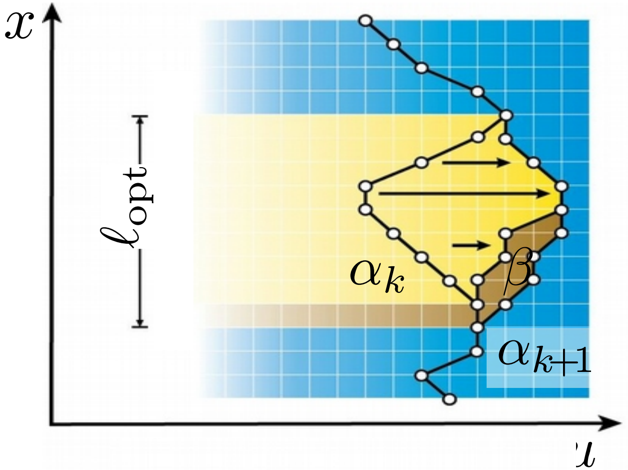
Modeling: Two steps creep algorithm (T=0$^+$)

“Creep events” connect one metastable state and the next one.

Each **event**, composed by **two steps**:

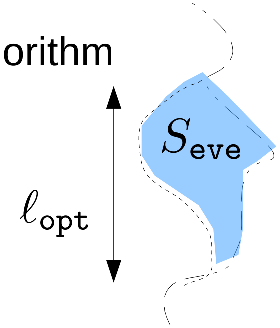
“Activated” part: *Dijkstra's search** (*O(L log L)*)
to find the smallest rearrangement that decreases E
Start with l_{nuc}=*1* and increase it until we find a favorable ***nucleus***.

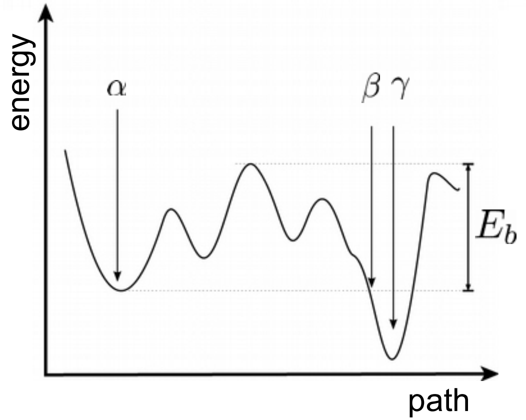
Deterministic part: simple relaxation to the local minimum.
Polymer follows the energy gradient by ***elementary moves***.



+ both steps implemented in parallel on GPUs

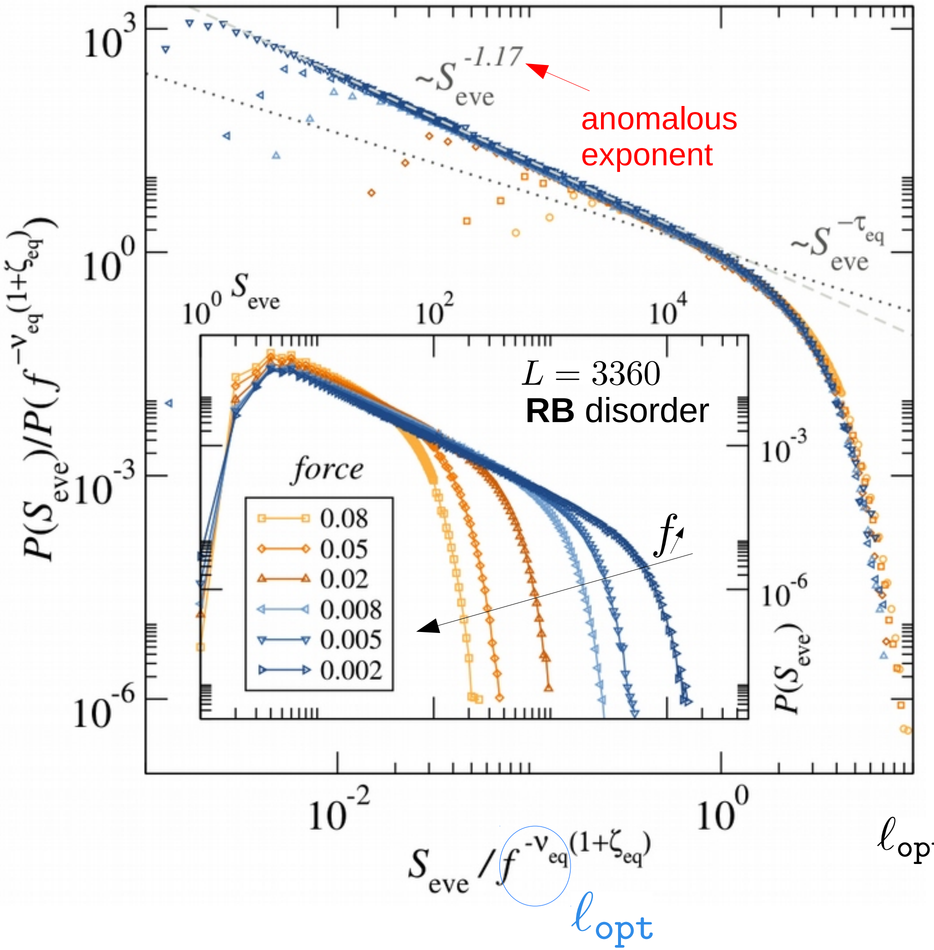
Two orders of magnitude **improvement** respect to exact algorithm
(system sizes *L=3360* and driving forces *f~0.002* reached)





*also called “transfer matrix method”

Creep events size distribution



- Power-law distributed when $f \to 0$

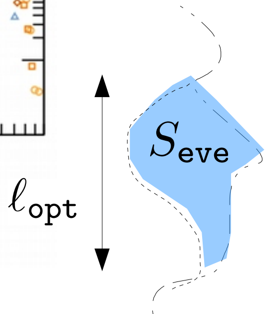
Event sizes are not distributed around a “typical” value

- Collapse with $S_c^{eve} \sim \left(\ell_{opt}(f)\right)^{1+\zeta_{eq}}$

Creep law is safe! :^)

- Anomalous $\tau > \tau_{eq}$

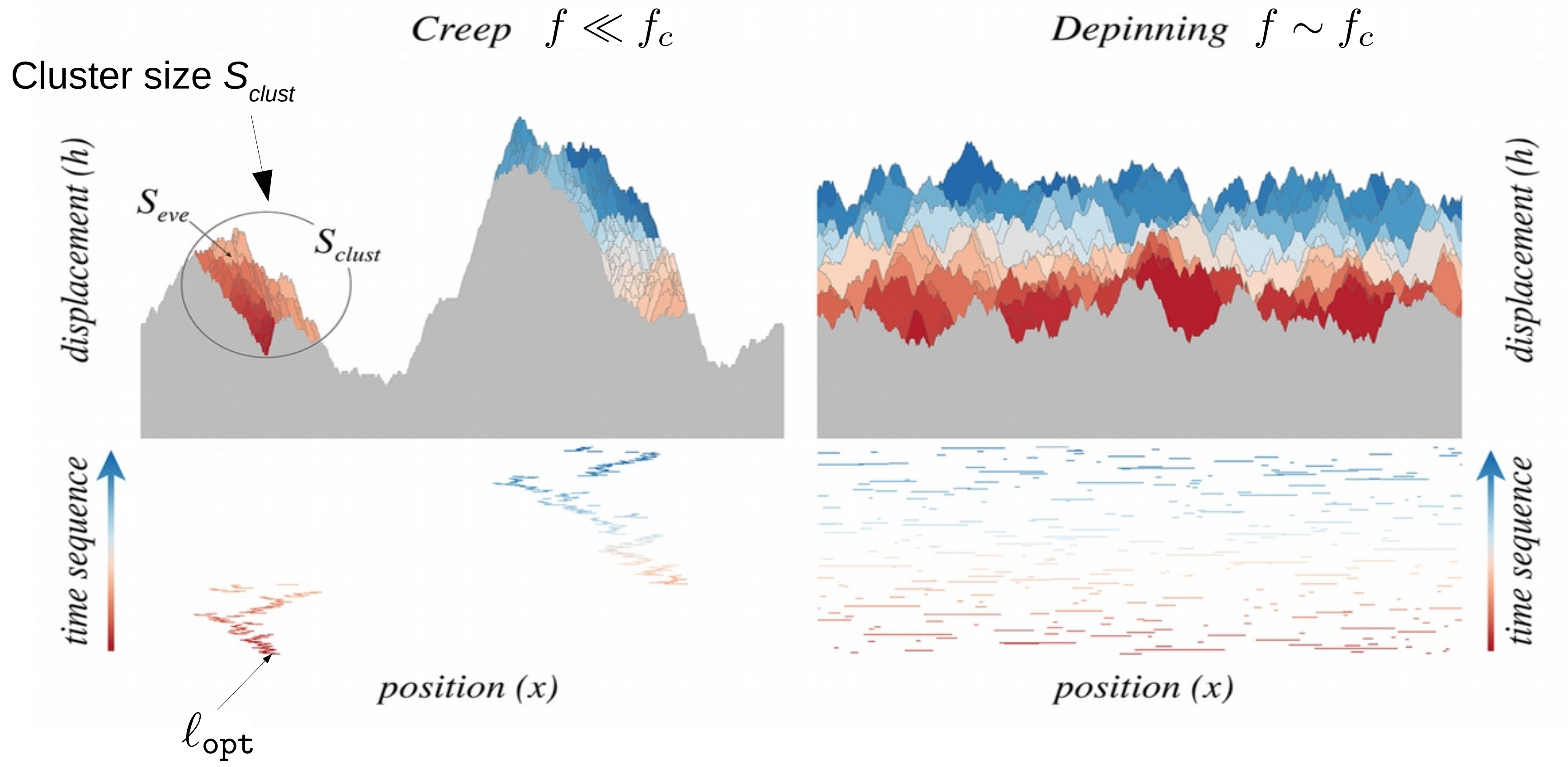
$$\tau_{eq} = 2 - \frac{2}{d + \zeta_{eq}} = 4/5 \quad (\text{for } d=1)$$



Reason? events are not uncorrelated

Similar to **Gutenberg-Richter** exponent anomaly in **earthquakes models**

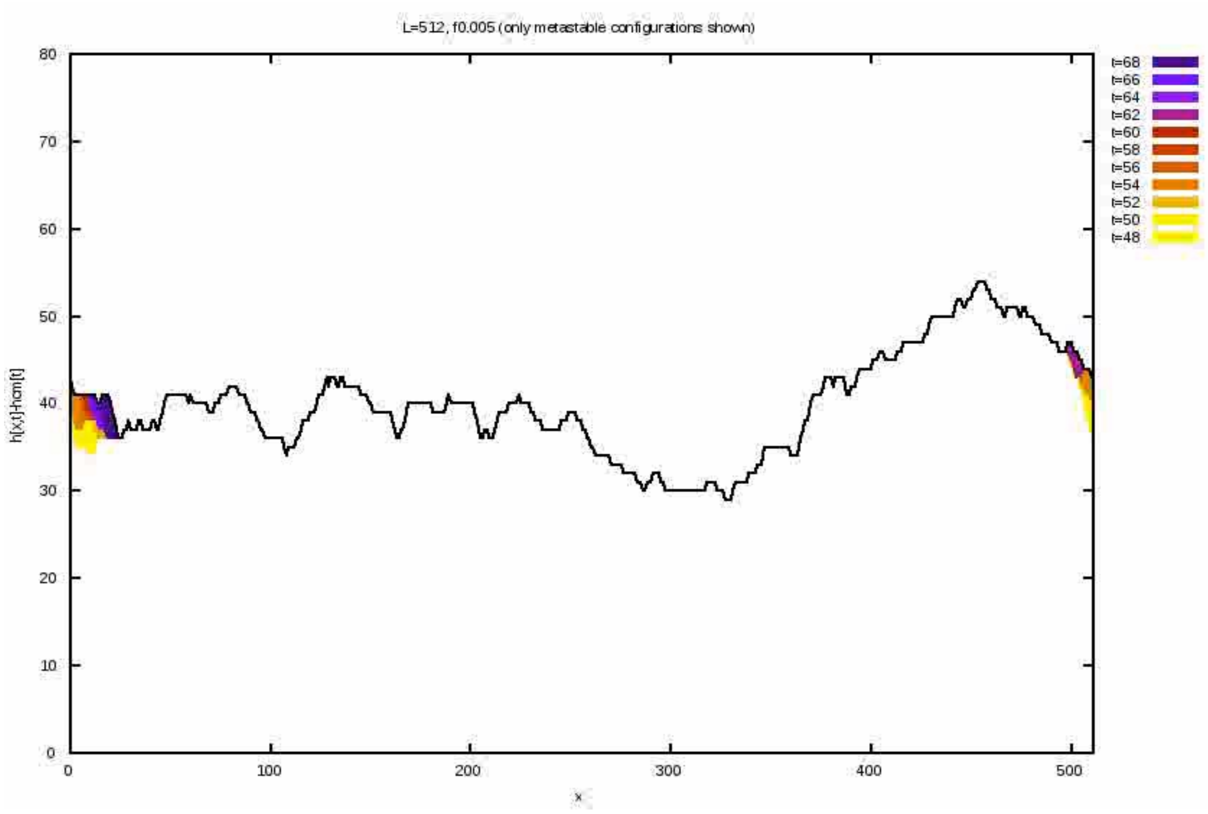
Event patterns and activity maps

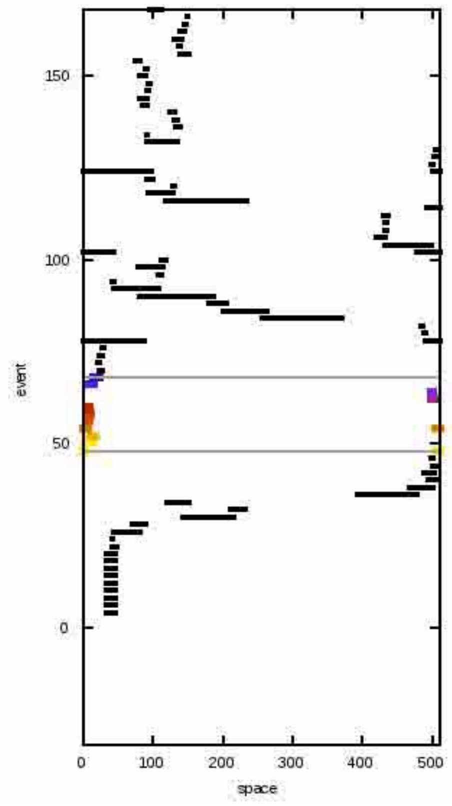


Events like “aftershocks”

Uncorrelated avalanches

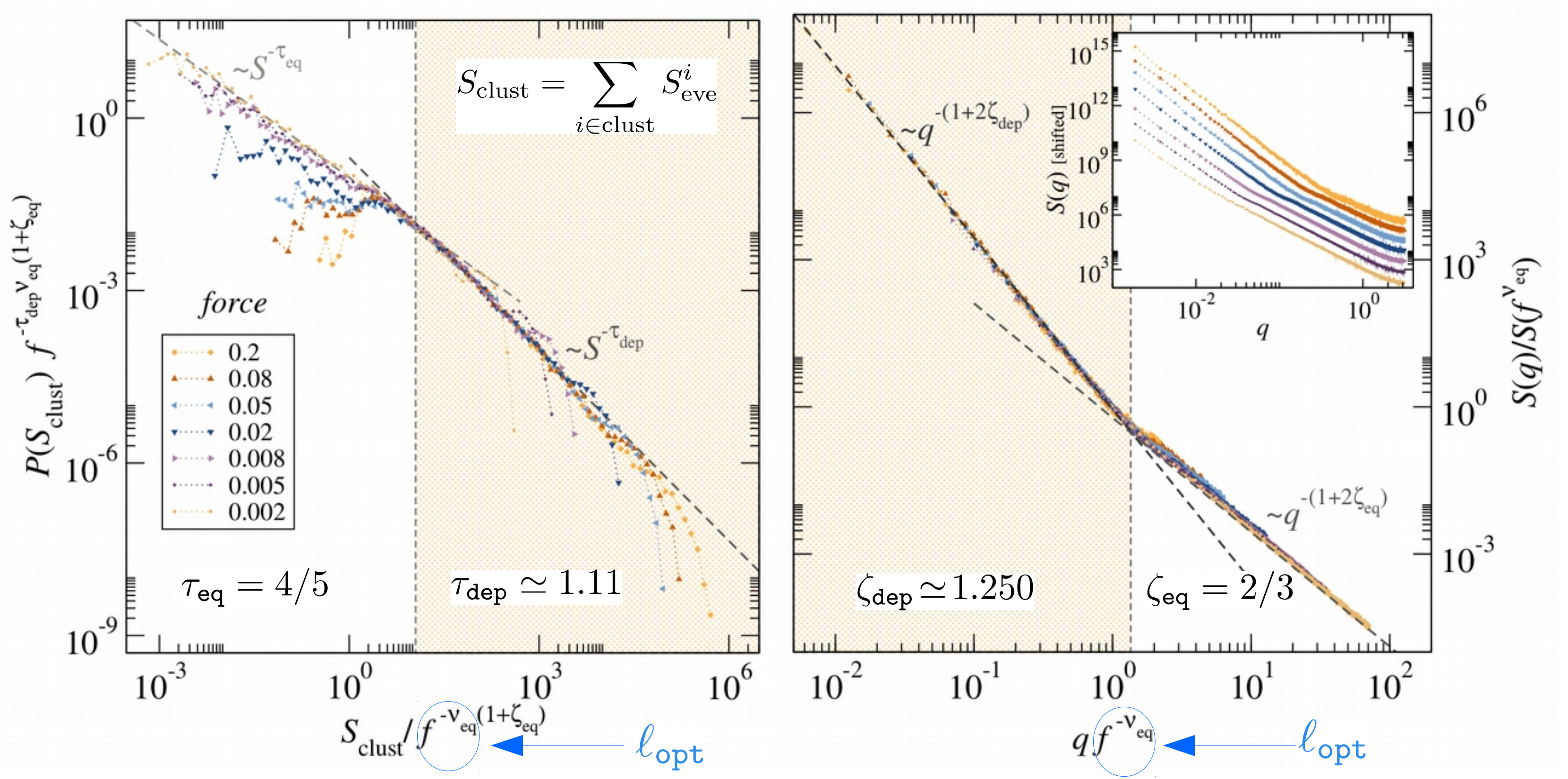
Creep events





Clusters size distribution

Structure factor



Small size → **equilibrium**-exponent
Large size → **depinning**-exponent
→ **Upper cutoff** controlled by **system size**.

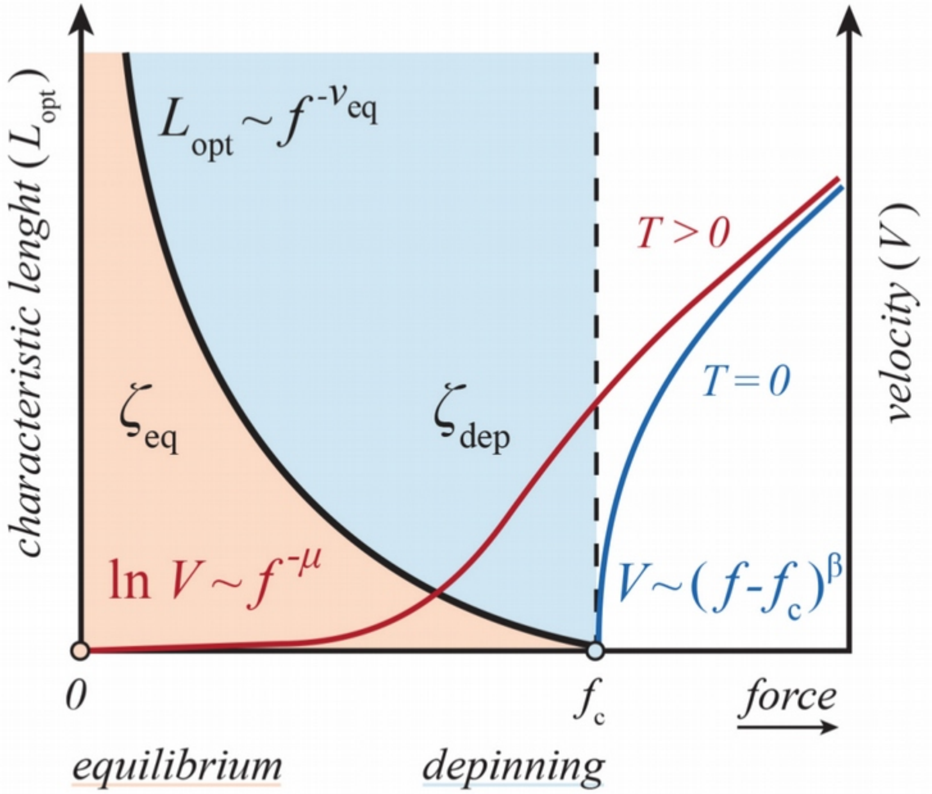
$\zeta_{\rm eq}$ **at short length**-scales

$\zeta_{\rm dep}$ **at large length**-scales

Creep prediction & phase diagram

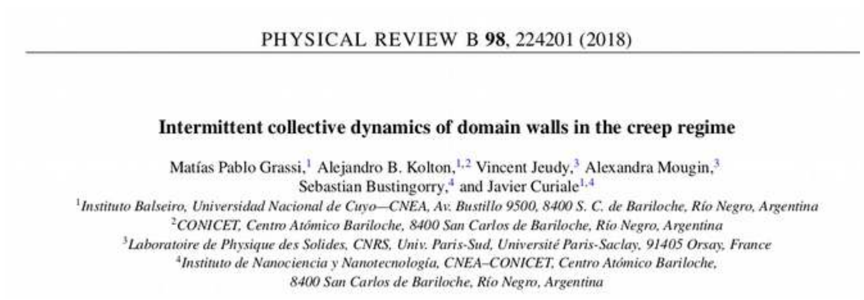
- Distribution of creep events is power-law with cutoff characterized by $\ell_{\texttt{opt}} \sim f^{-\nu_{\texttt{eq}}}$
- Creep events are correlated in space and time sequence.
- Large clusters of events behave like depinning avalanches at the far away critical point.

Geometry ↔ Transport!! deduce velocity from the structure factor and vice versa



E.E.Ferrero, L. Foini, T. Giamarchi, A.B. Kolton, A. Rosso PRL **118**, 147208 (2017)

Experimental realizations of spatiotemporal patterns


PHYSICAL REVIEW B **98**, 224201 (2018)

Intermittent collective dynamics of domain walls in the creep regime

Matías Pablo Grassi,[1] Alejandro B. Kolton,[1,2] Vincent Jeudy,[3] Alexandra Mougin,[3]
Sebastian Bustingorry,[4] and Javier Curiale[1,4]
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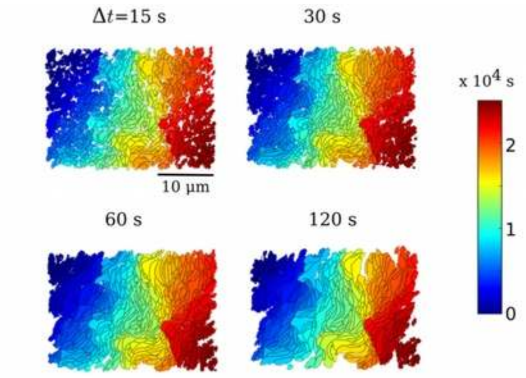
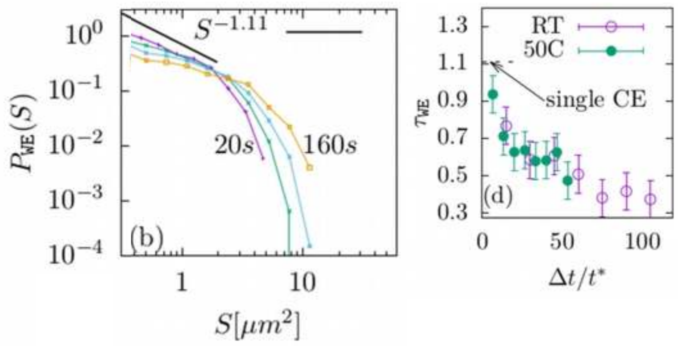
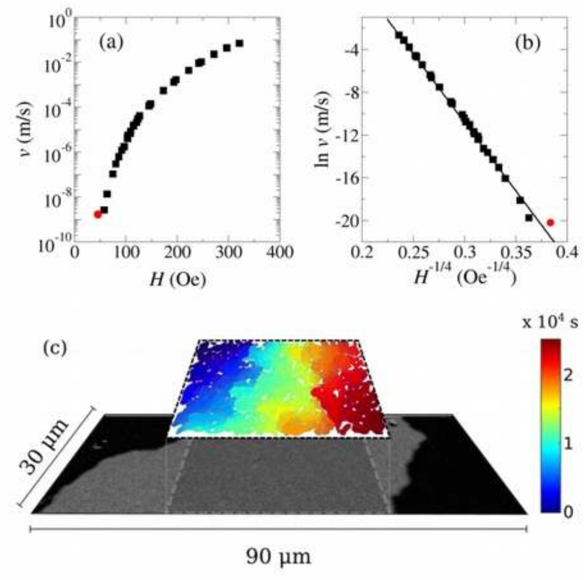
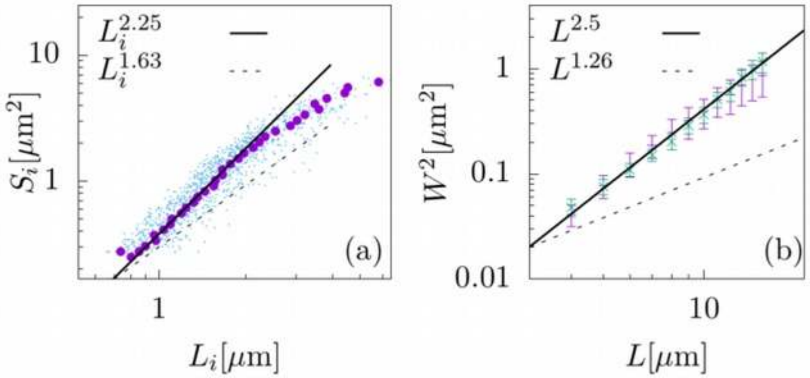
8400 San Carlos de Bariloche, Río Negro, Argentina







Creep events accumulate in depinning clusters!



Evidence favors
qEW over qKPZ

$$\zeta_{\mathtt{qEW}} = 1.25$$

$$\zeta_{\mathtt{qEW}} = 0.63$$

Experimental realizations of spatiotemporal patterns


PHYSICAL REVIEW B **110**, L020405 (2024)

Letter

Earthquakelike dynamics in ultrathin magnetic films

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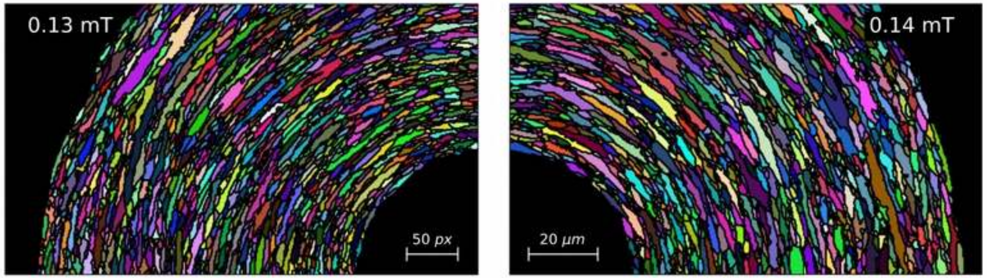
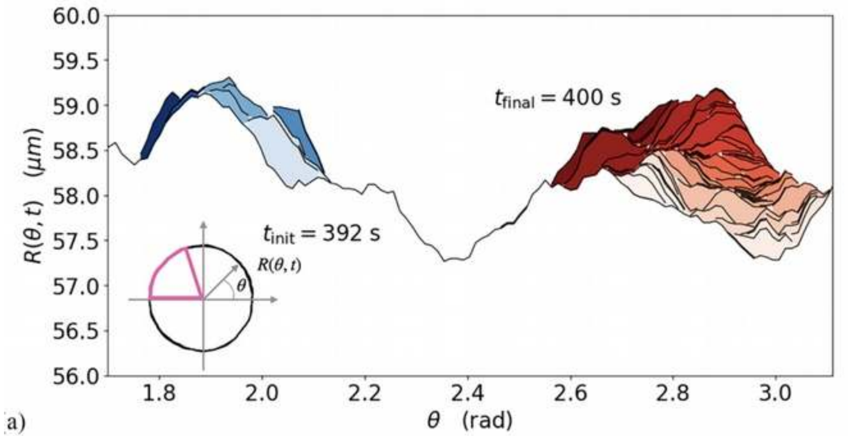
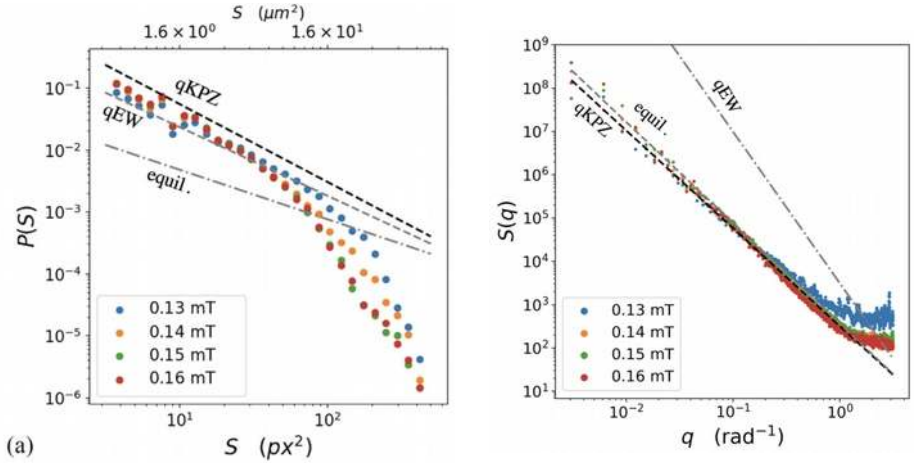
[7] *Institut de Physique Théorique, Université Paris-Saclay, CNRS, 91191 Gif-sur-Yvette, France*







Creep events accumulate in depinning clusters

Evidence favors qKPZ over qEW !!!

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"Depinning free of the elastic approximation"
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"Soil creep facilitated by cyclic variations of environmental conditions"
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Thanks!

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Alejandro Kolton, Alberto Rosso, Sebastián Bustingorry,
Eduardo Jagla, Nirvana Caballero, Laura Foini, Thierry Giamarchi,
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