Motion of interfaces with an internal degree of freedom

Vivien Lecomte[1], Stewart Barnes[2,3], Jean-Pierre Eckmann[4], Thierry Giamarchi[2]

[1]Laboratoire Probabilités et Modèles Aléatoires, Paris
[2]Department of Quantum Matter Physics, Université de Genève
[3]Physics Department, University of Miami
[4]Département de Physique Théorique et Section de Mathématiques, Genève

Grenoble – Journée K – 6th July 2016

Motion of interfaces with an internal degree of freedom

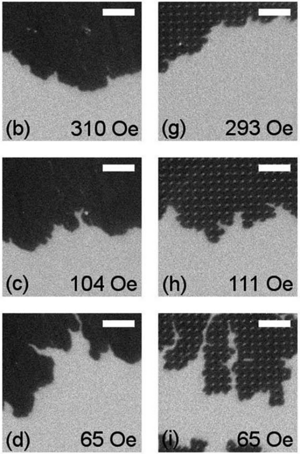
Vivien Lecomte[1], Stewart Barnes[2,3], Jean-Pierre Eckmann[4], Thierry Giamarchi[2]
Sebastian Bustingorry[5], Alejandro Kolton[5]

[1]Laboratoire Probabilités et Modèles Aléatoires, Paris
[2]Department of Quantum Matter Physics, Université de Genève
[3]Physics Department, University of Miami
[4]Département de Physique Théorique et Section de Mathématiques, Genève
[5]CNEA, Bariloche, Argentina

Grenoble – Journée K – 6th July 2016

Interfaces

Interfaces in magnetic films



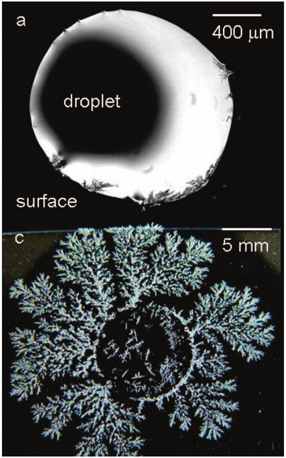
from Metaxas *et al.*

APL **94** 132504 (2009)

Large range of physical scales

Wide spectrum of phenomena

Crystal growth



from Shahidzadeh-Bonn *et al.*

Langmuir **24** 8599 (2008)

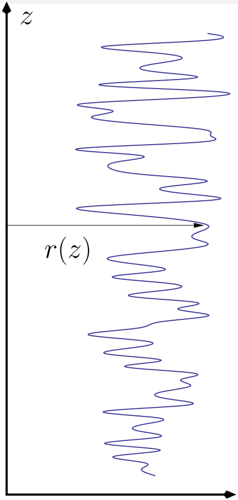
Disordered elastic systems

- Elasticity: tends to flatten the interface

$$\frac{c}{2}\int dz\,(\nabla r(z))^2$$

- Disorder: tends to bend it

$$\int dz\, V(r(z),z)$$



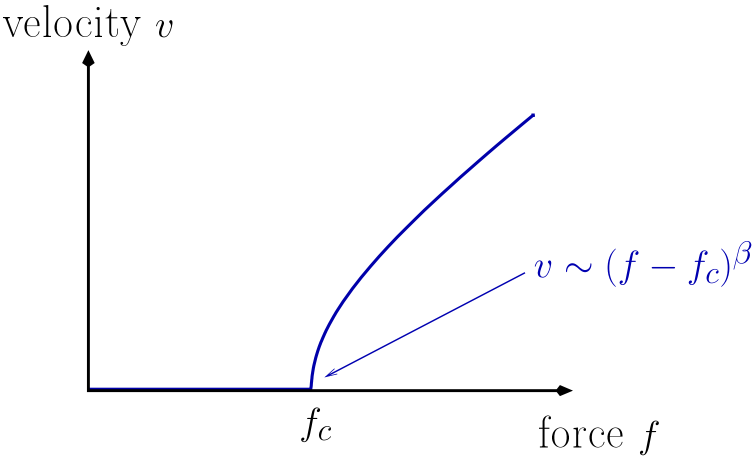
Competition btw “order” and “disorder”

Is the knowledge of $r(z)$ sufficient?

$\rightarrow$ Have a look to the dynamics in simple examples.

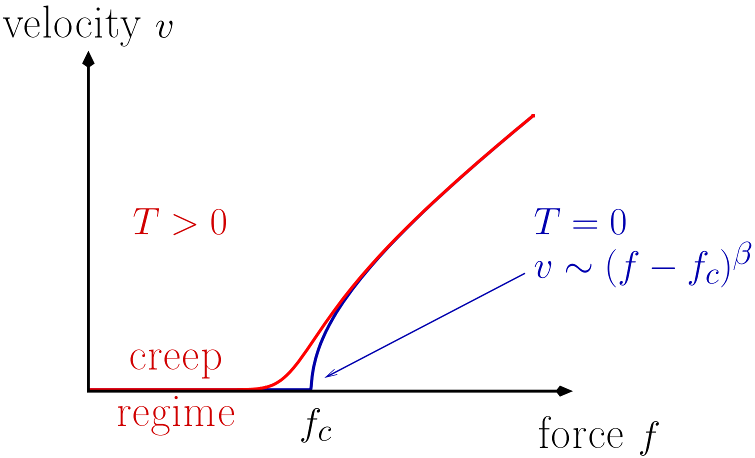
Depinning transition @ zero temperature

threshold force f_c



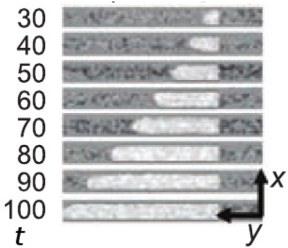
Depinning transition @ finite temperature

thermal rounding



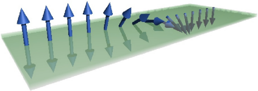
Outline

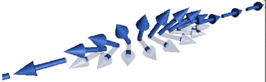
1. Interface Physics
   - Systems
   - Depinning transition
2. Depinning with internal degree of freedom ←
   - Modelisation
   - Dynamics

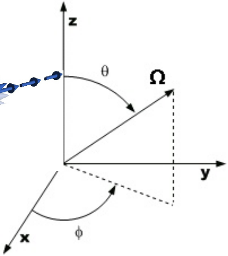


from Yamanouchi *et al.*, Science **317** 1726 (2007)

From bulk model to effective description

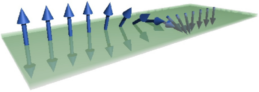


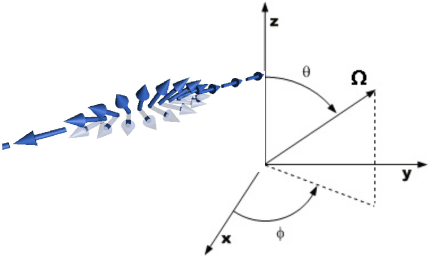




from Tatara *et al.*, J. Phys. Soc. Jap **77** 031003 (2008)

From bulk model to effective description





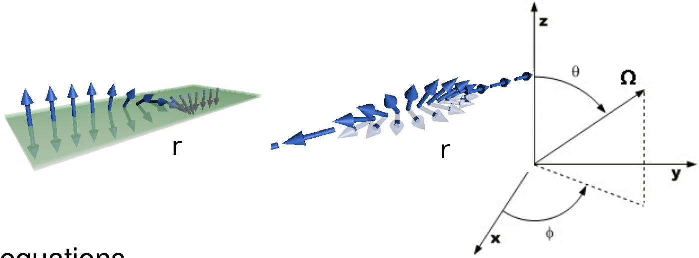
- Bulk energy

$$E = \int d^d x \left\{ J \left[(\nabla\theta)^2 + \sin^2\theta (\nabla\phi)^2 \right] + K \sin^2\theta + K_\perp \sin^2\theta \cos^2\phi \right\}$$

- Equation of motion (Landau-Lifshitz-Gilbert)

$$\partial_t \Omega = \Omega \times \left(\frac{\delta E}{\delta \Omega} + f + \eta \right) - \Omega \times \left(\alpha \partial_t \Omega \right)$$

From bulk model to effective description

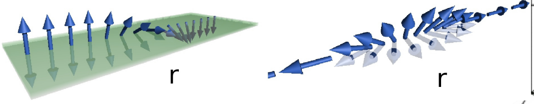


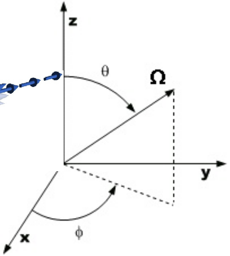
- Effective equations

$$\alpha\partial_t r - \partial_t\phi = J(\nabla r)^2 + F_{\text{pinning}} + f_{\text{ext}} + \eta_1$$

$$\underbrace{\alpha\partial_t\phi + \partial_t r}_{\text{damping}} = \underbrace{J(\nabla\phi)^2 + -\frac{1}{2}K_\perp \sin 2\phi}_{\text{forces}} \underbrace{+\ \eta_2}_{\text{thermal noise}}$$

From bulk model to effective description





- Case of a rigid wall (no elasticity)

$$\alpha\partial_t r - \partial_t\phi = \overbrace{-\cos\kappa r}^{\text{pinning}} + \overbrace{f}^{\text{external}} + \eta_1$$

$$\alpha\partial_t\phi + \partial_t r = -\frac{1}{2}K_\perp \sin 2\phi + \eta_2$$

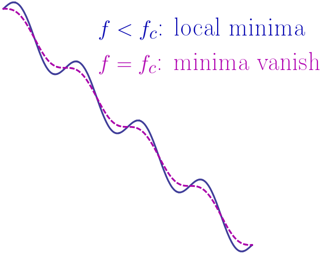
- Effective model: collective degrees of freedom

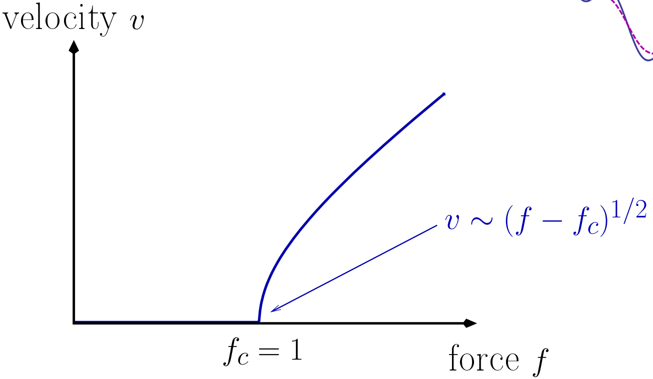
Position $r(t)$ coupled to phase $\phi(t)$

Depinning @ zero temperature

(1st case) Large $K_\perp$: ϕ decouples from r

$$\alpha \partial_t r = \underbrace{f - \cos \kappa r}_{\text{total force}}$$

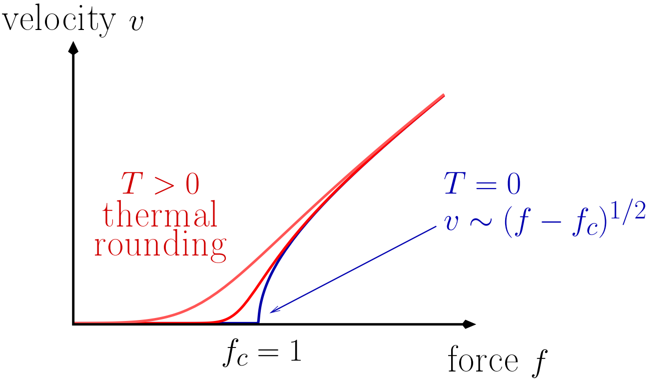




Depinning @ finite temperature

(1st case) Large $K_\perp$: ϕ decouples from r

$$\alpha \partial_t r = \underbrace{f - \cos \kappa r}_{\text{total force}} + \eta$$



Depinning @ zero temperature

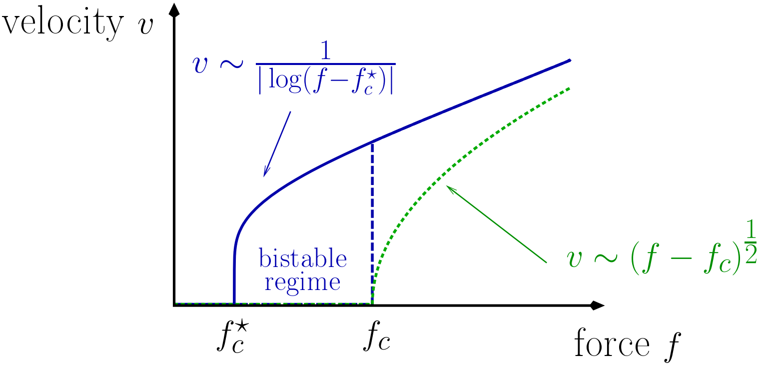
(2nd case) Small $K_\perp$: ϕ matters

$$\alpha\partial_t r - \partial_t\phi = f - \cos\kappa r$$
$$\alpha\partial_t\phi + \partial_t r = -\frac{1}{2}K_\perp \sin 2\phi$$

Depinning @ zero temperature

(2nd case) Small $K_\perp$: ϕ matters

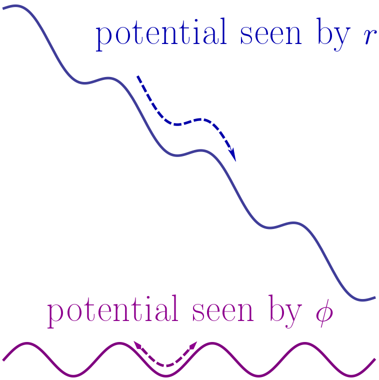
- Dramatic change in the depinning law: $v \sim \frac{1}{|\log(f - f_c^\star)|}$



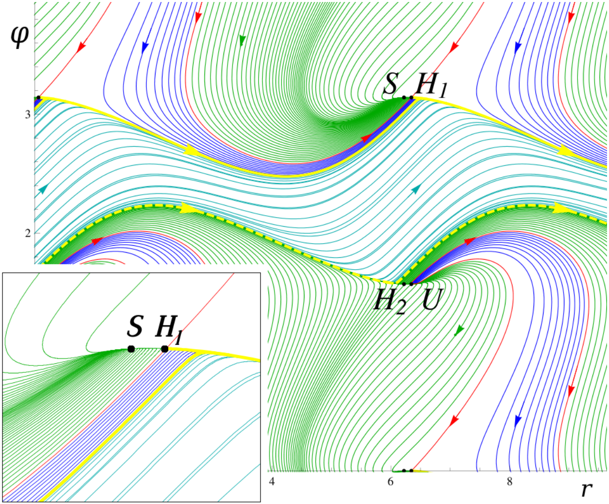
- Depinning at lower critical force: $f_c^\star < f_c$
- Bistability

Physical interpretation

In the bistable regime $f_c^\star < f < f_c$: ϕ helps r to cross barriers



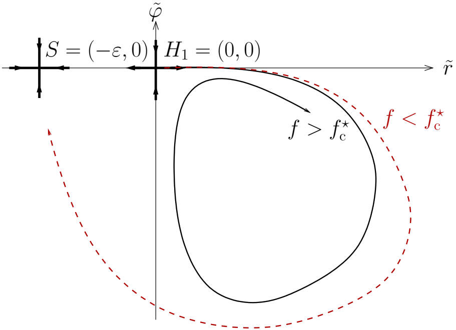
Phase space



In the bistable regime ($f_c^\star < f < f_c$)

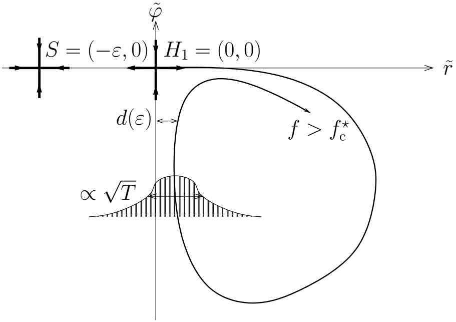
Phase space

Homoclinic bifurcation: $(\epsilon \propto f_c - f)$



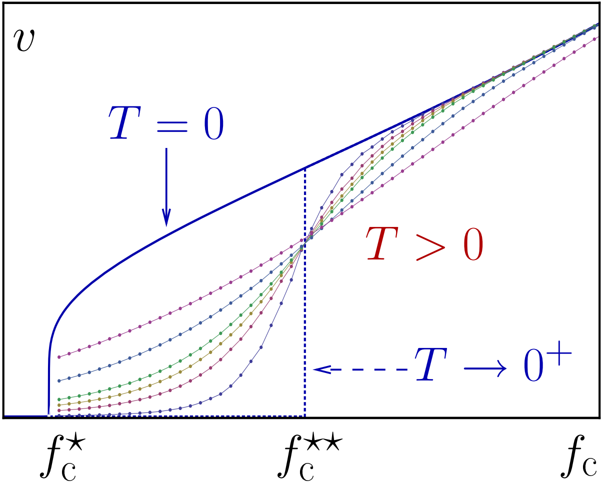
Phase space: $T > 0$

Homoclinic bifurcation with noise: $(\epsilon \propto f_c - f)$



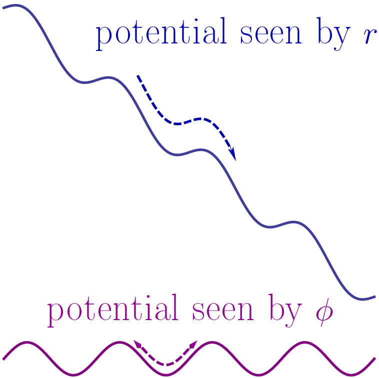
$$\text{escape time} \sim \underbrace{\exp\left(\frac{\epsilon^3}{T}\right)}_{\text{Arrhenius}} \underbrace{\exp\left(-\frac{A}{T} d(\epsilon)^2\right)}_{\text{Trapping probability}}$$

Finite temperature



Force-velocity characteristics

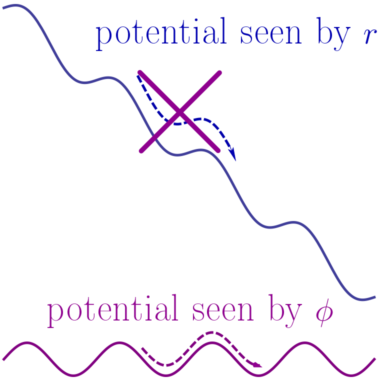
This is not the end of the story



The phase ϕ plays the role of inertia: helps to cross barriers

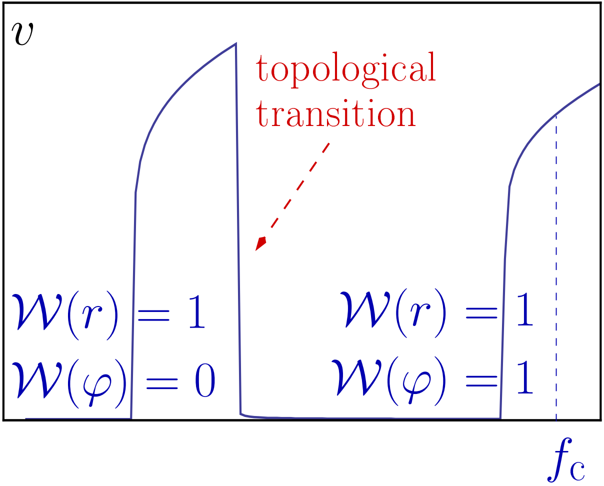
This is not the end of the story

(3rd case) Even smaller $K_\perp$



inertia is unbounded whereas ϕ is bounded and periodic

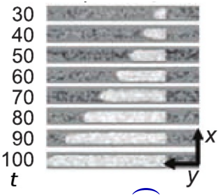
Topological transition



Successive regimes characterized by winding numbers $\mathcal{W}$

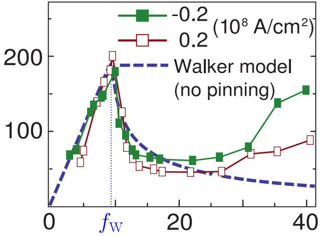
Experiment (i)

SPINTRONICS



DW velocity (m/s)

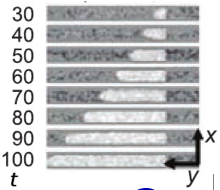
experiment from Parkin *et al.*, Science **320** 190 (2008)



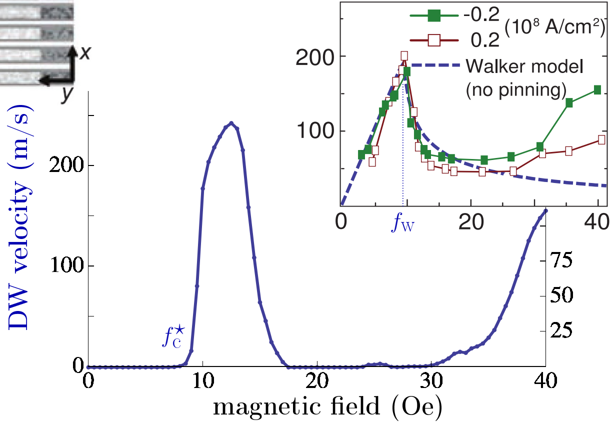
magnetic field (Oe)

Experiment (i)

SPINTRONICS

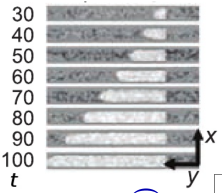


experiment from Parkin *et al.*, Science **320** 190 (2008)

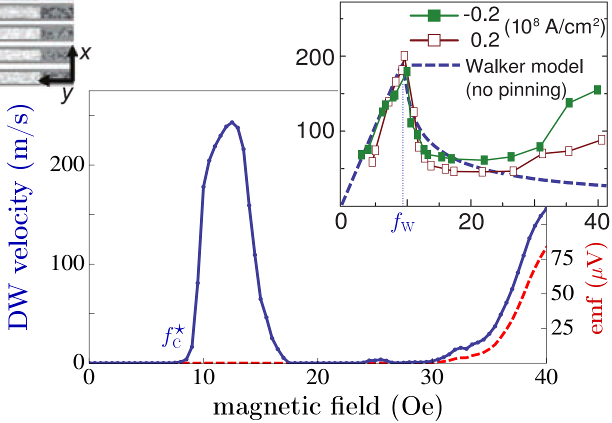


Experiment (i)

SPINTRONICS



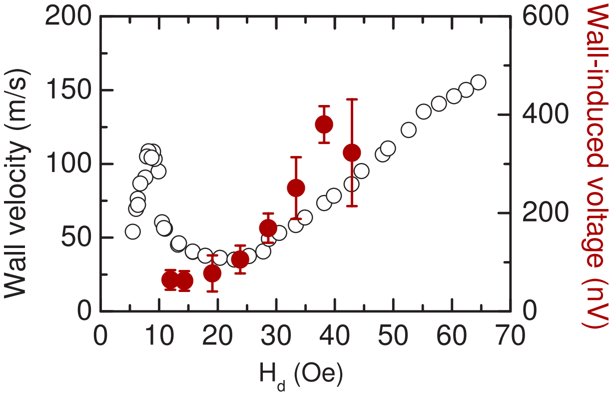
experiment from Parkin *et al.*, Science **320** 190 (2008)



emf $=$ wall induced voltage $\propto \langle \partial_t \phi \rangle$

Experiment (ii) SPINTRONICS

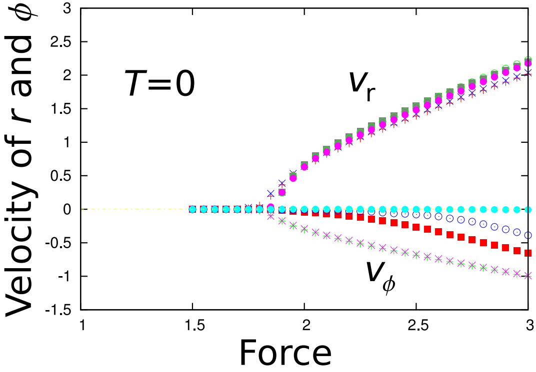
experiment from Yang, Beach *et al.*, PRL **102** 067201 (2009)



$\propto \langle \partial_t \phi \rangle$

Including elasticity: numerical approach

[On-going work with S. Bustingorry, A. Kolton]



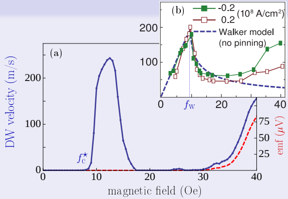
$T = 0$ creep-like motion of ϕ induced by $v_r > 0$

Outlook

PRB **80** 054413 (2009)

Internal degree of freedom

- unusual depinning law
- bistability
- non-monotonous $v(f)$ at finite T
- link with experiments



Perspective

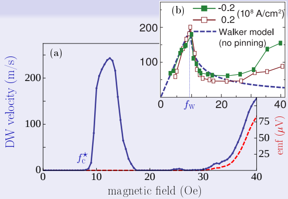
- Interface with elasticity ⟷ modified creep law?
- Current-driven wall ⟷ spintronics?
- Experiments ⟷ periodic patterning?
- Other internal degrees ⟷ coupled interfaces?

Outlook

PRB **80** 054413 (2009)

Internal degree of freedom

- unusual depinning law
- bistability
- non-monotonous $v(f)$ at finite T
- link with experiments



Perspective

- Interface with elasticity ⟷ modified creep law?
- Current-driven wall ⟷ spintronics?
- Experiments ⟷ periodic patterning?
- Other internal degrees ⟷ coupled interfaces?