Depinning transition for domain walls with an internal degree of freedom

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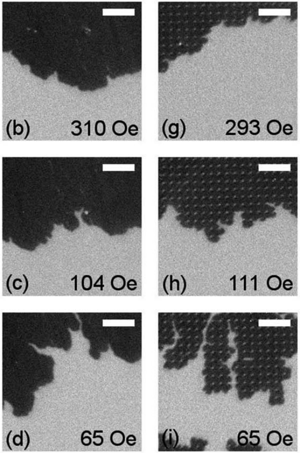
Interfaces

Interfaces in magnetic films



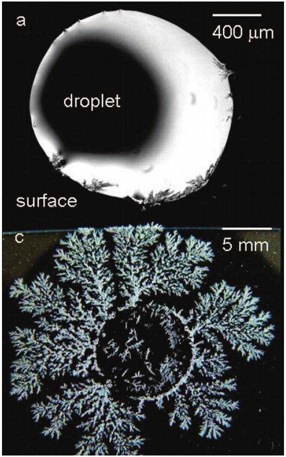
from Metaxas *et al.*

APL **94** 132504 (2009)

Large range of physical scales

Wide spectrum of phenomena

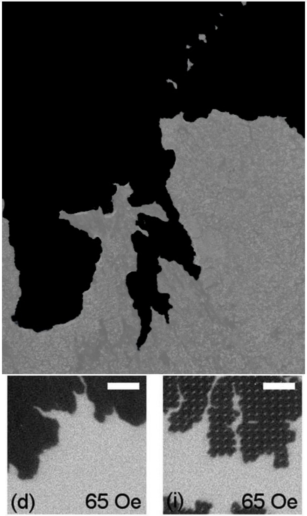
Crystal growth



from Shahidzadeh-Bonn *et al.*

Langmuir **24** 8599 (2008)

Interfaces



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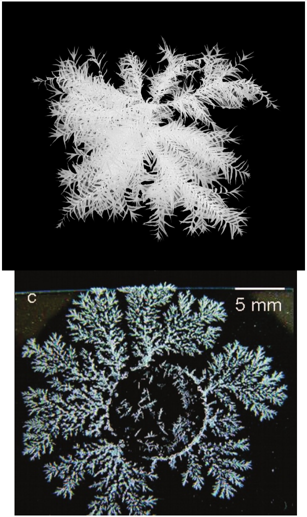

from Shahidzadeh-Bonn *et al.*

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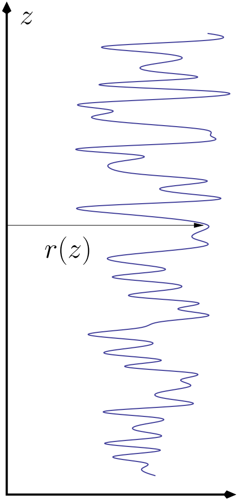
Disordered elastic systems

- Elasticity: tends to flatten the interface

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

- Disorder: tends to bend it

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



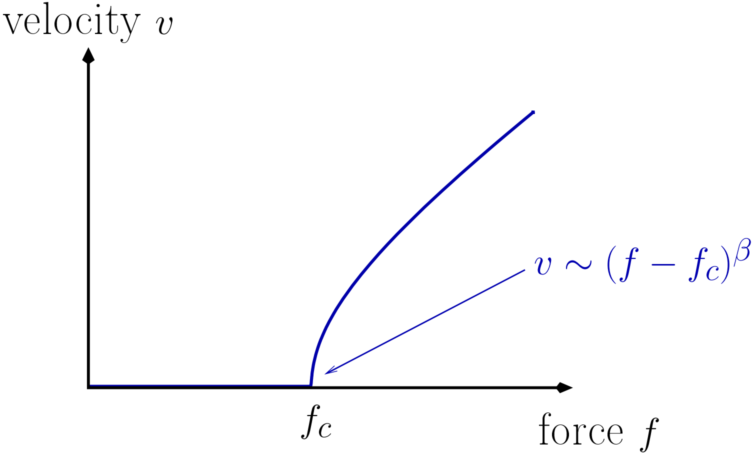
Competition btw “order” and “disorder”

Is $r(z)$ enough?

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

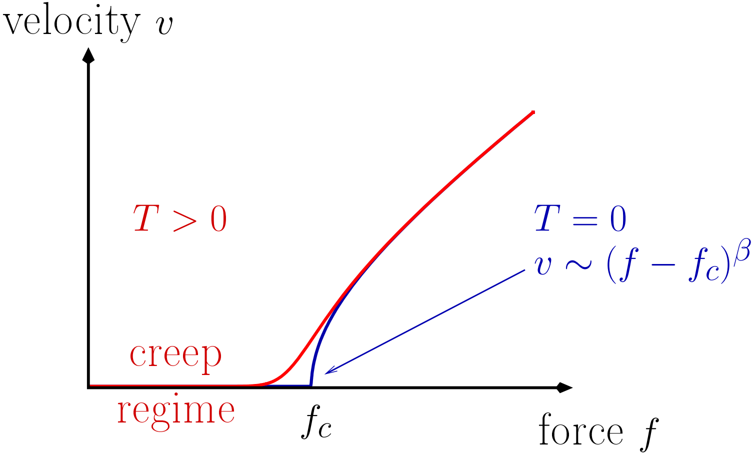
Depinning transition @ zero temperature

threshold force



Depinning transition @ finite temperature

thermal rounding

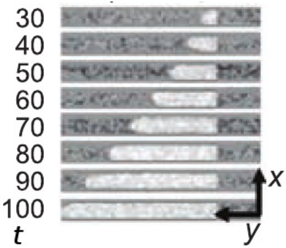


A case with internal degrees: ferromagnetic wire

$$v(f) \sim \exp\left[-\frac{U_c}{T}\left(\frac{f_c}{f}\right)^{\mu}\right] \qquad \text{(creep)}$$

	Field drive		Current drive	
	μ^*	σ^*	μ	σ
Experiment	1.2 ± 0.1	1.4 ± 0.1	0.33 ± 0.06	2.0 ± 0.2
Theory	1.0	1.5	0.5	1.25

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

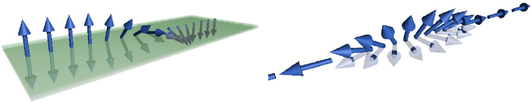


driving the wall with a current:
coupling with a phase

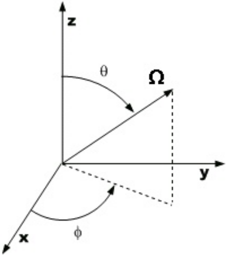
Outline

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

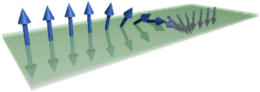
Bulk model

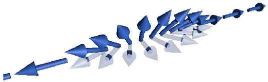


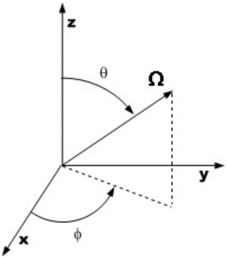
from Tatara *et al.*, J. Phys. Soc. Jap **77** 031003 (2008)



Bulk model







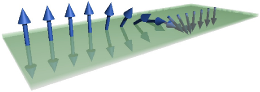
- Bulk energy

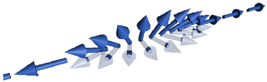
$$E = \int d^d x \left\{ J \left[(\nabla\theta)^2 + \sin^2\theta (\nabla\phi)^2 \right] + K \sin^2\theta + K_\perp \sin^2\theta \cos^2\phi \right\}$$

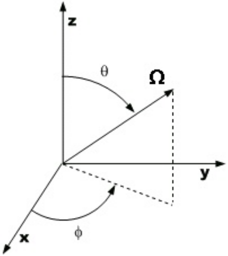
- Equation of motion (Landau-Lifshitz-Gilbert)

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

Bulk model





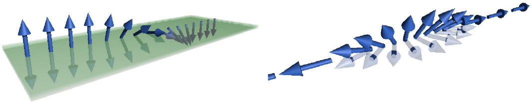


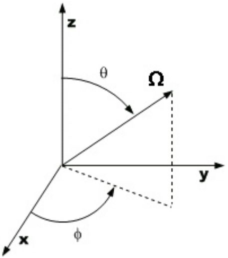
- Effective equations

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

$$\alpha\partial_t\phi + \partial_t r = J(\nabla\phi)^2 \ + \ -\frac{1}{2}K_{\perp}\sin 2\phi \qquad\qquad + \ \eta_2$$

Bulk model





- Rigid wall approximation

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

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

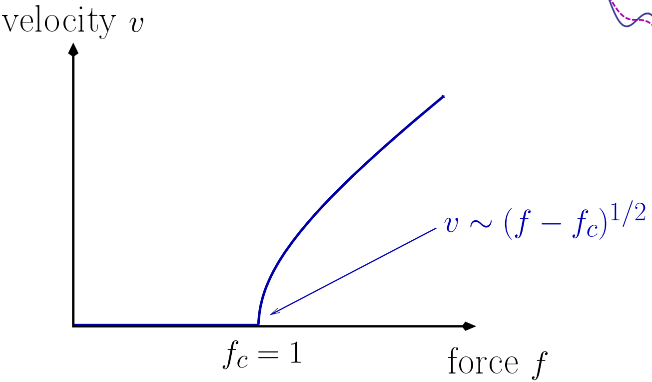
- Effective model

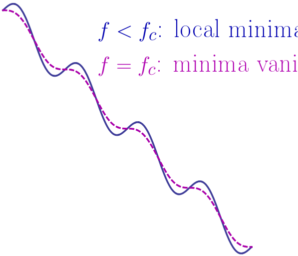
Position $r(t)$ coupled to phase $\phi(t)$

Depinning @ zero temperature

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

$$\alpha \partial_t r = f - \cos \kappa r$$

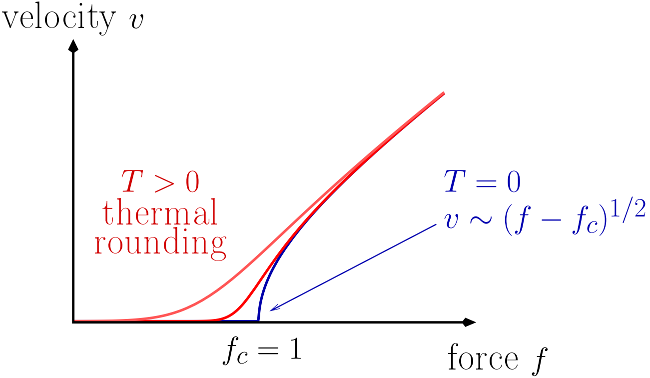




Depinning @ finite temperature

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

$$\alpha \partial_t r = f - \cos \kappa r + \eta$$



Depinning @ zero temperature

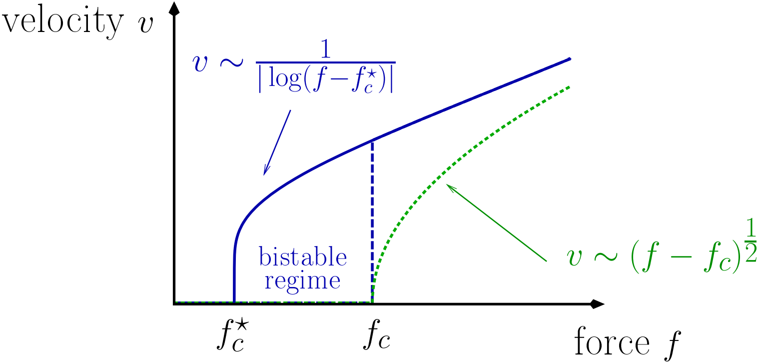
(2nd case) Small $K_\perp$: ϕ matters

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

Depinning @ zero temperature

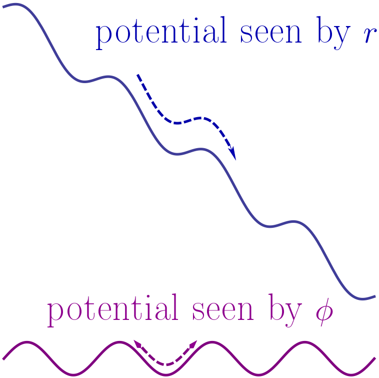
(2nd case) Small $K_\perp$: ϕ matters

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

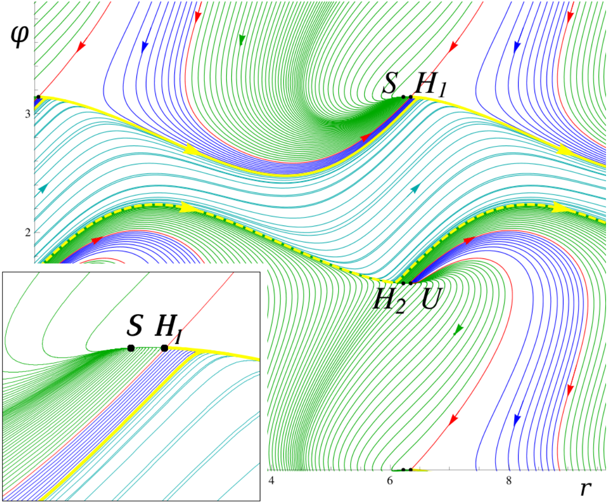


- Depinning at lower critical force: $f_c^\star < f_c$
- Bistability

Physical interpretation



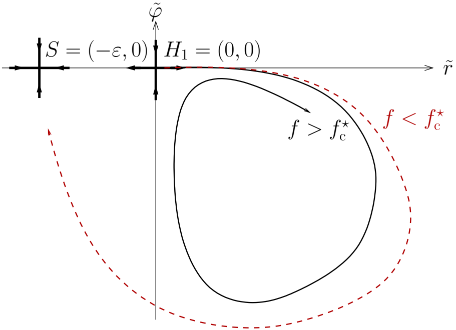
Phase space



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

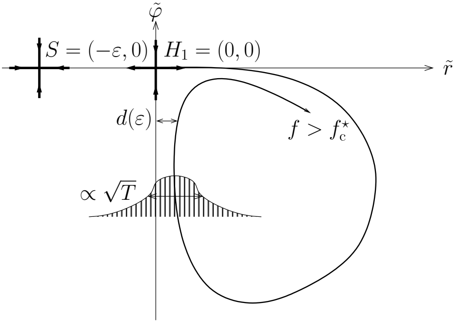
Phase space

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



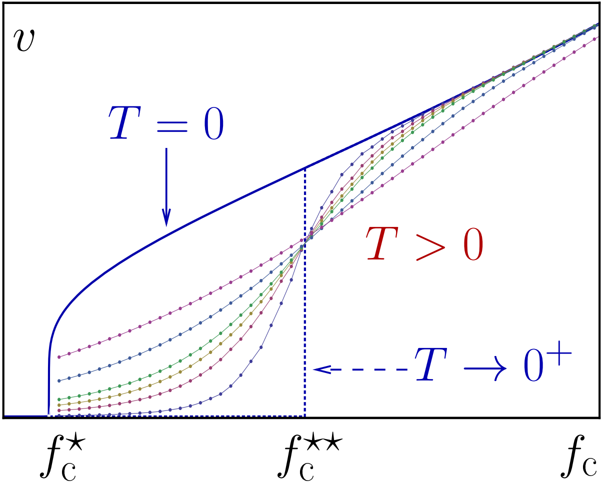
Phase space: $T > 0$

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



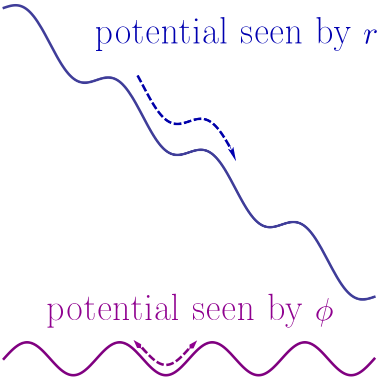
$$\text{escape time} \sim \underbrace{\exp\left(\frac{\epsilon^3}{T}\right)}_{\text{Arrhenius}} \underbrace{\exp\left(-\frac{A}{T} d(\epsilon)^2\right)}_{\text{Trapping probability}}$$

Finite temperature



Force-velocity characteristics

This is not the end of the story

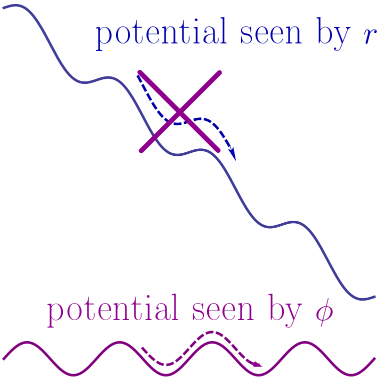


The phase ϕ plays the role of inertia: helps to cross barriers

[see also Risken chap.11]

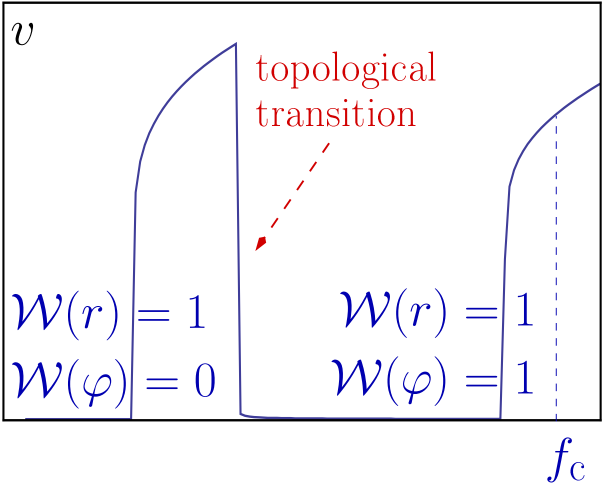
This is not the end of the story

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



inertia is unbounded whereas ϕ is bounded and periodic

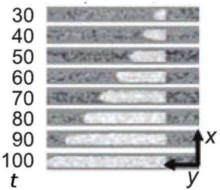
Topological transition



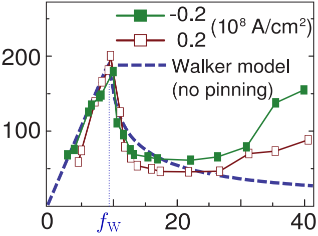
Successive regimes characterized by winding numbers $\mathcal{W}$

Experiment

SPINTRONICS



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



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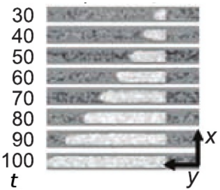

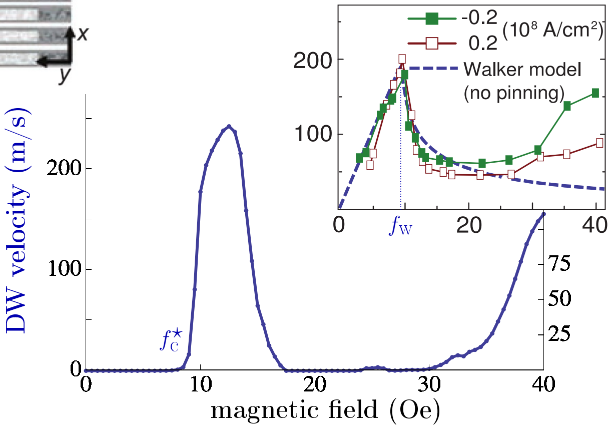

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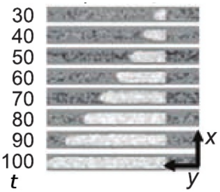

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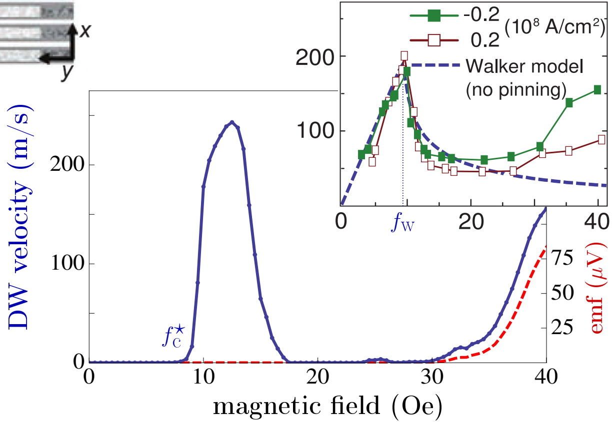
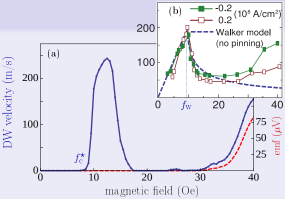


Outlook

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 $\leftrightarrow$ modified creep law?
- Current driven wall
- Experiments $\leftrightarrow$ periodic patterning?
- Other internal degrees $\leftrightarrow$ coupled interfaces?

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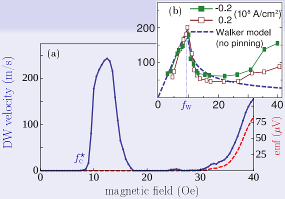

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