# Dynamics of domain walls with an internal degree of freedom

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Courmayeur – 31th January 2011

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[5]CNEA, Bariloche, Argentina

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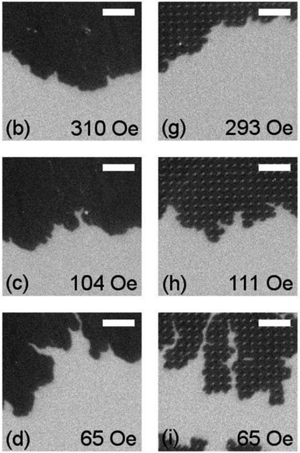
# Interfaces

Interfaces in magnetic films



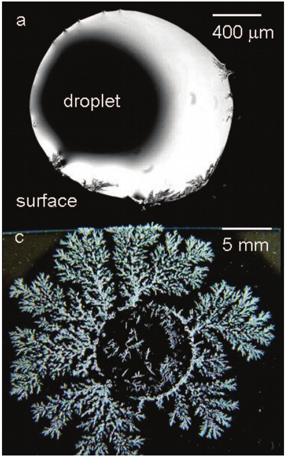

from Metaxas *et al.*

APL **94** 132504 (2009)

Large range of physical scales

Wide spectrum of phenomena

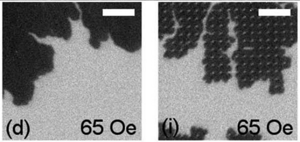
Crystal growth




from Shahidzadeh-Bonn *et al.*

Langmuir **24** 8599 (2008)

# Interfaces

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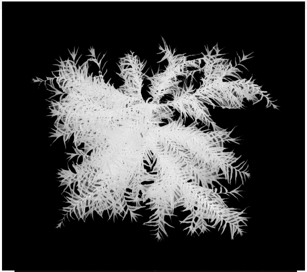
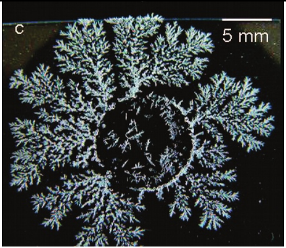
Wide spectrum of phenomena



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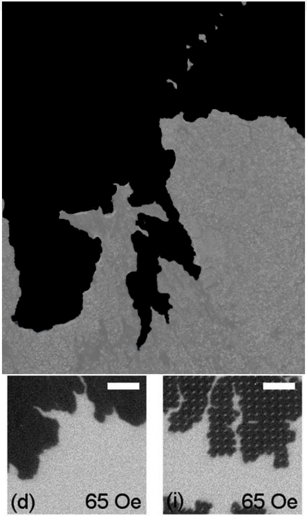


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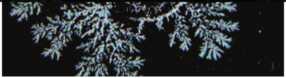
APL **94** 132504 (2009)



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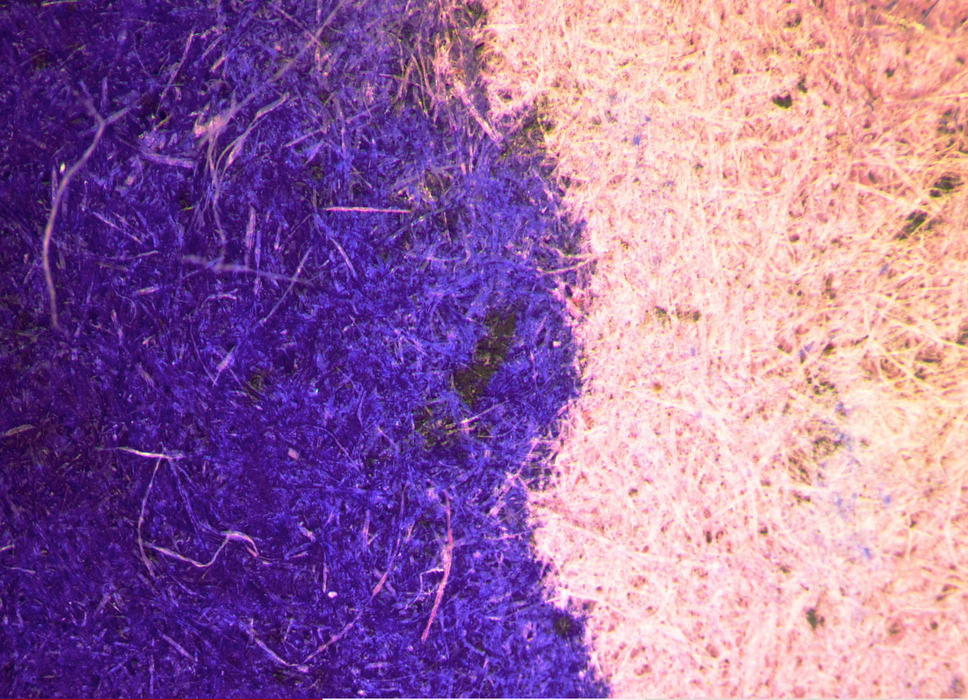


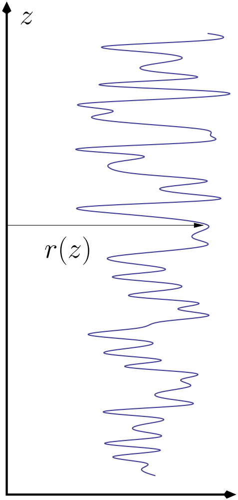
# Disordered elastic systems

- Elasticity: tends to flatten the interface

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

- Disorder: tends to bend it

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



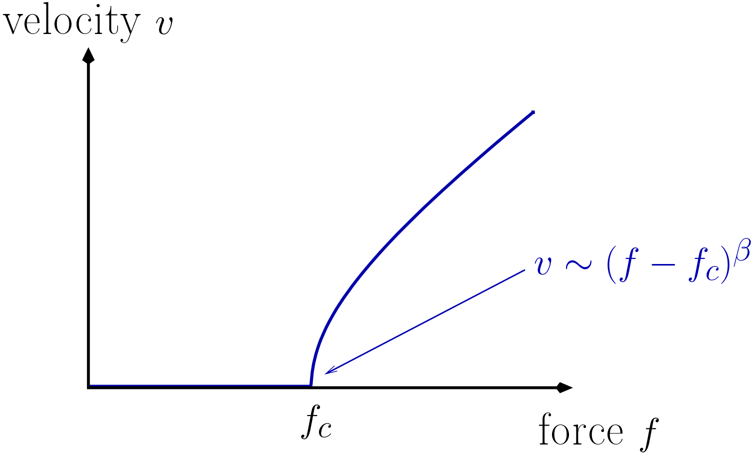

Competition btw “order” and “disorder”

# Is $r(z)$ enough?

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

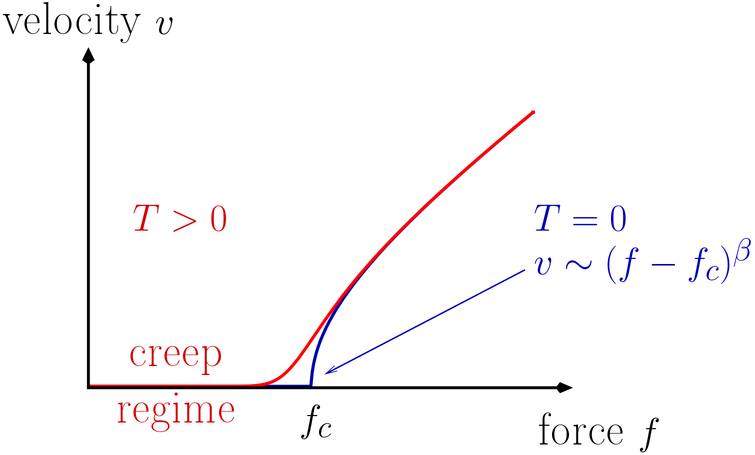
# Depinning transition @ zero temperature

threshold force



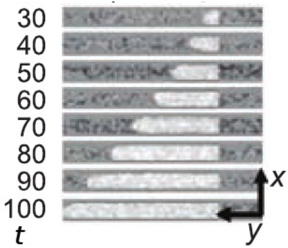
# Depinning transition @ finite temperature

thermal rounding



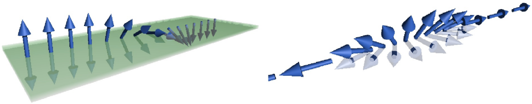
# Outline

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

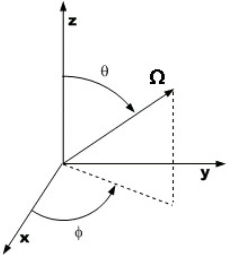



from Yamanouchi *et al.*, Science **317** 1726 (2007)

# Bulk model



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



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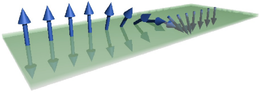
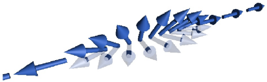
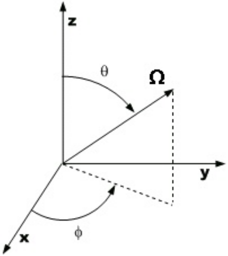






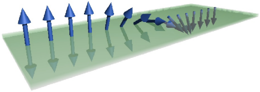

- Bulk energy

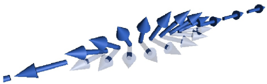
$$E = \int d^d x \left\{ J \left[ (\nabla\theta)^2 + \sin^2\theta (\nabla\phi)^2 \right] + K \sin^2\theta + K_\perp \sin^2\theta \cos^2\phi \right\}$$

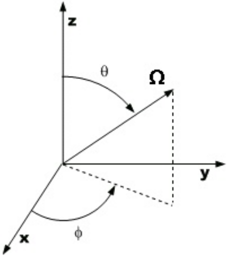
- Equation of motion (Landau-Lifshitz-Gilbert)

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

# Bulk model





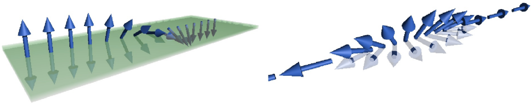


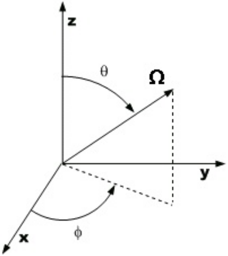

- Effective equations

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

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

# Bulk model






- Rigid wall approximation

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

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

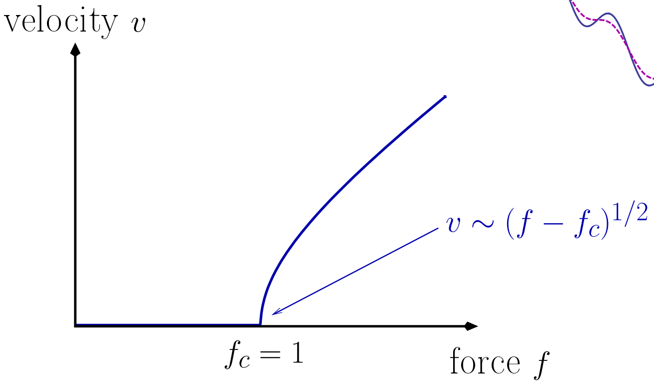
- Effective model

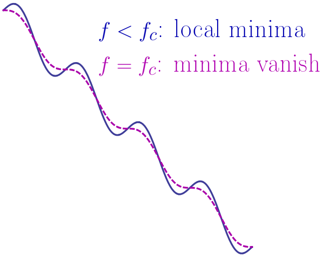
Position $r(t)$ coupled to phase $\phi(t)$

# Depinning @ zero temperature

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

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

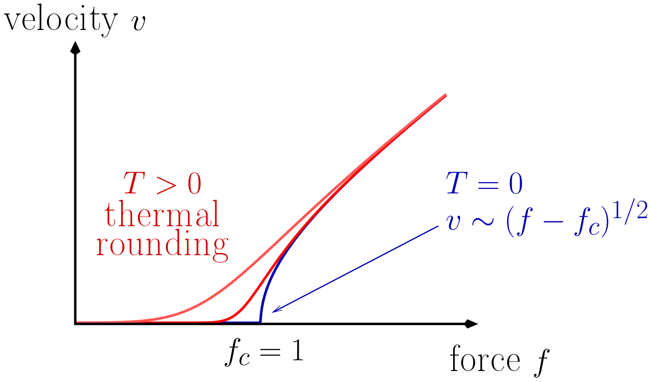


# Depinning @ finite temperature

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

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



# Depinning @ zero temperature

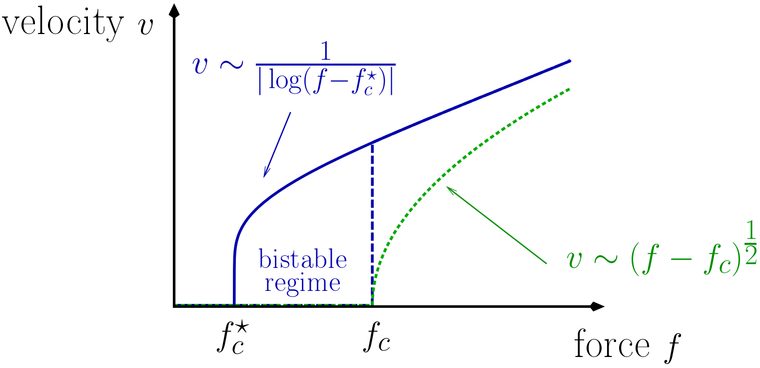
**(2nd case)** Small $K_\perp$: $\phi$ matters

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

# Depinning @ zero temperature

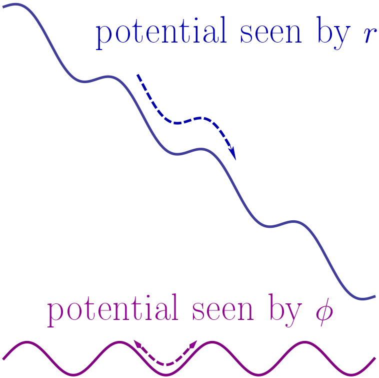
**(2[nd] case)** Small $K_\perp$: $\phi$ matters

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

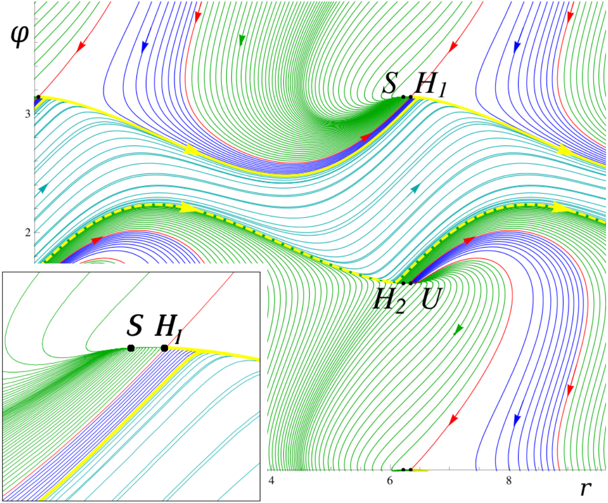



- Depinning at lower critical force: $f_c^\star < f_c$
- Bistability

# Physical interpretation



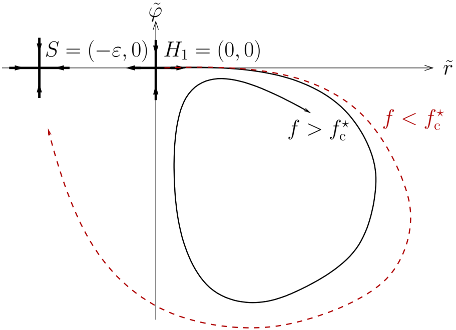
# Phase space




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

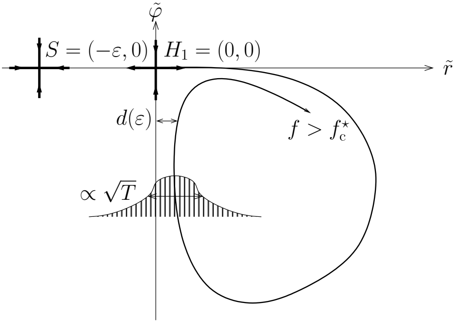
# Phase space

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



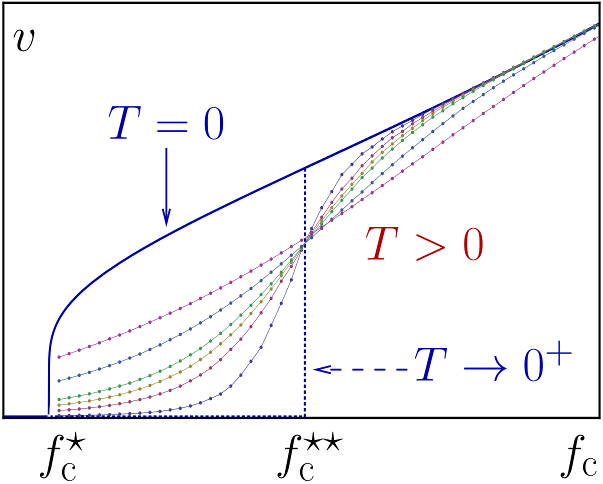
# Phase space: $T > 0$

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



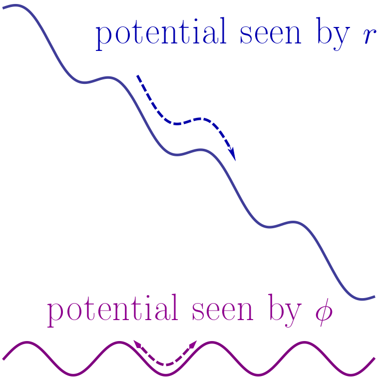

$$\text{escape time} \sim \underbrace{\exp\left(\frac{\epsilon^3}{T}\right)}_{\text{Arrhenius}} \underbrace{\exp\left(-\frac{A}{T} d(\epsilon)^2\right)}_{\text{Trapping probability}}$$

# Finite temperature




Force-velocity characteristics

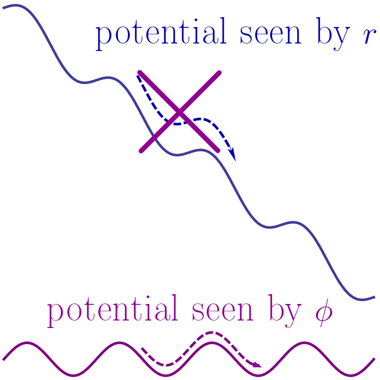
# This is not the end of the story




The phase $\phi$ plays the role of inertia: helps to cross barriers

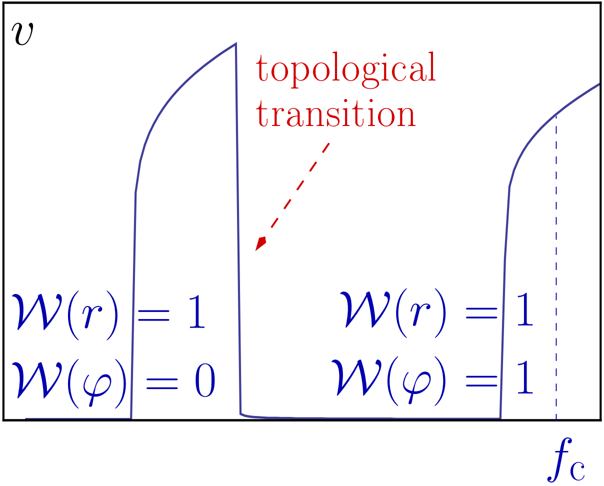
# This is not the end of the story

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



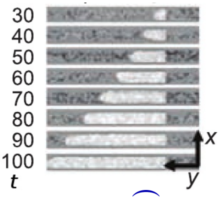

inertia is unbounded whereas $\phi$ is bounded and periodic

# Topological transition



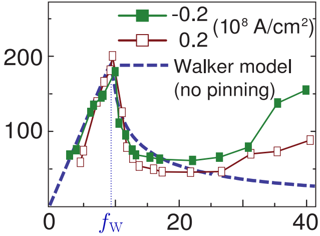

Successive regimes characterized by winding numbers $\mathcal{W}$

# Experiment (i) SPINTRONICS




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

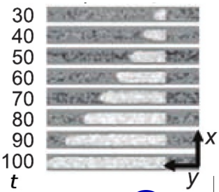
DW velocity (m/s)



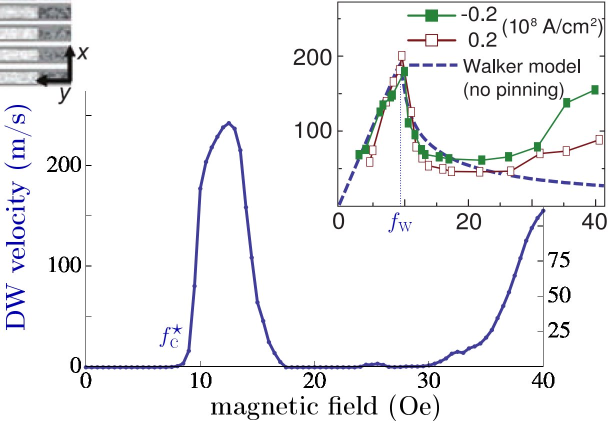

magnetic field (Oe)

# Experiment (i)

## SPINTRONICS




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



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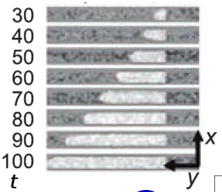
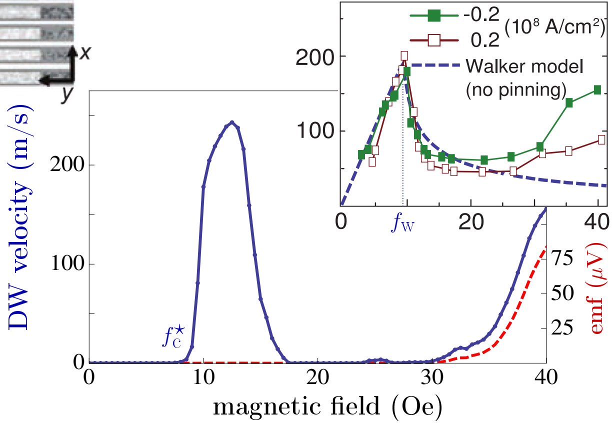


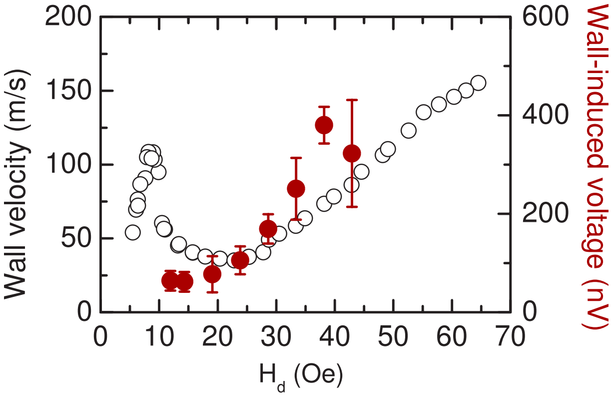

experiment from Parkin *et al.*, Science **320** 190 (2008)




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

# Experiment (ii) SPINTRONICS

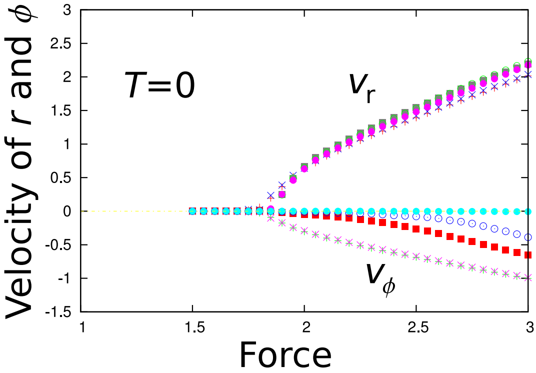
experiment from Yang, Beach *et al.*, PRL **102** 067201 (2009)




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

# Numerics: including elasticity

on-going work with S. Bustingorry, A. Kolton



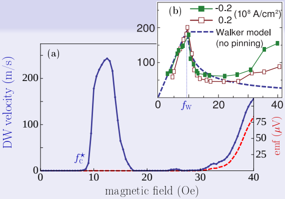

$T = 0$ creep-like motion of $\phi$ induced by $v_r > 0$

# 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
- Experiments ↔ periodic patterning?
- Other internal degrees ↔ coupled interfaces?

# Outlook

PRB **80** 054413 (2009)

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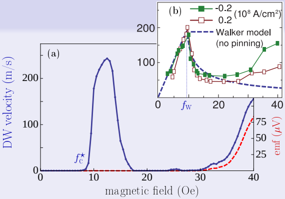


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