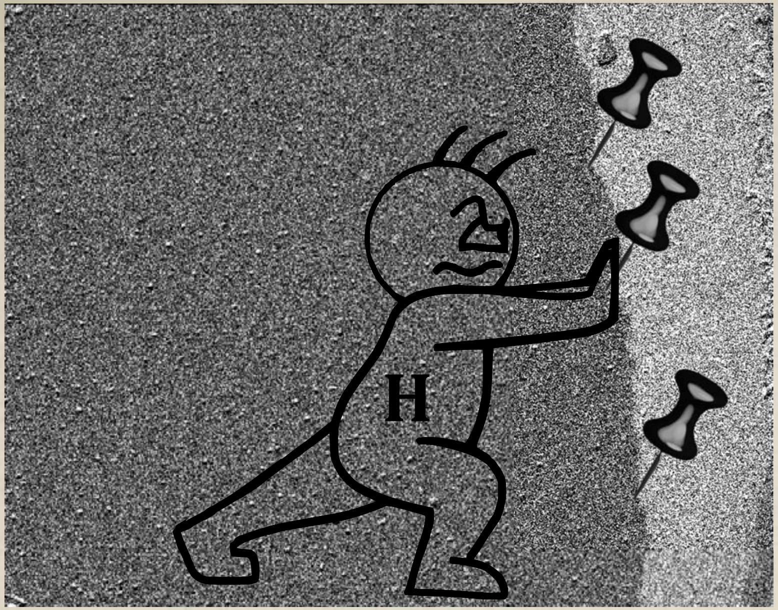


Laboratoire de Physique des Solides
(Université Paris-Sud, Orsay)

V. Jeudy, J. Ferré, J. Gorchon, A. Mougin, J.-P. Jamet,
P. Metaxas, V. Repain, M. Bauer, S. Lemerle,

Collaborations:
V. Baltz, B. Rodmacq (Inst. L. Néel, Grenoble)

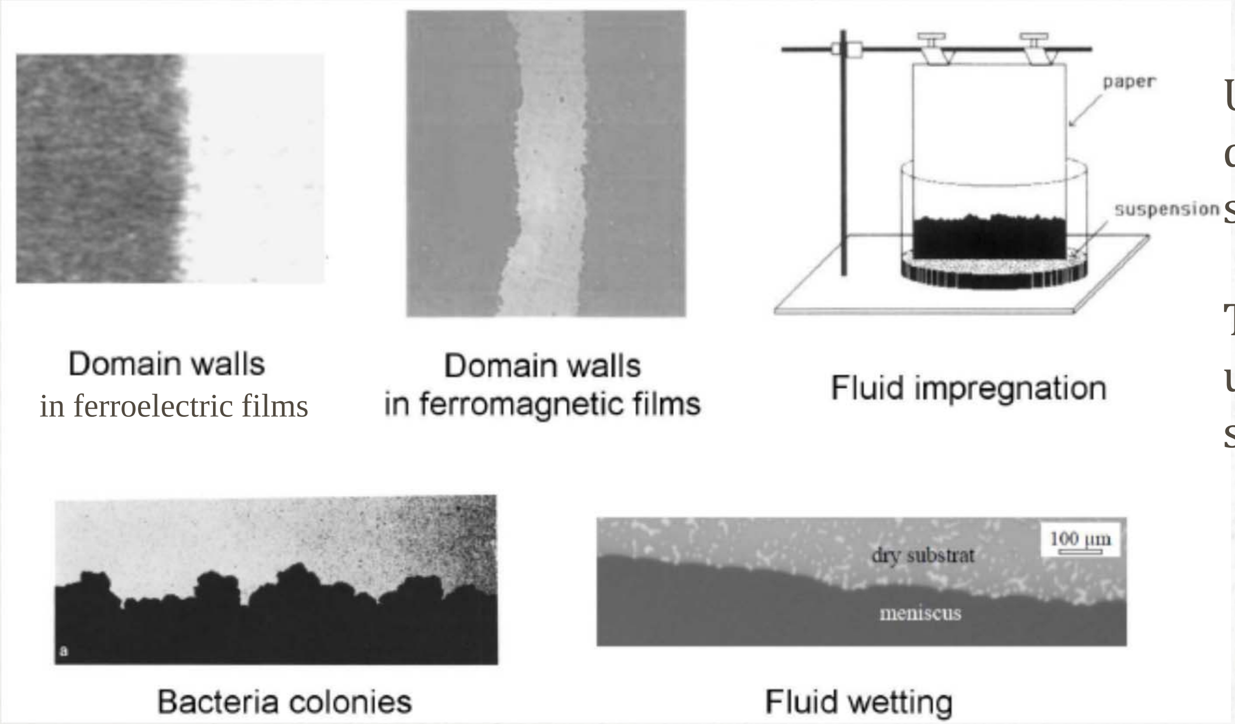
S. Bustingorry, A. Kolton (C.A. Bariloche)

T. Giamarchi (Univ. Geneva)

FIELD-DRIVEN DOMAIN WALL MOTION

IN FERROMAGNETIC FILMS WITH WEAK DISORDER

MOTION OF AN ELASTIC INTERFACE IN A WEAKLY DISORDERED SYSTEMS

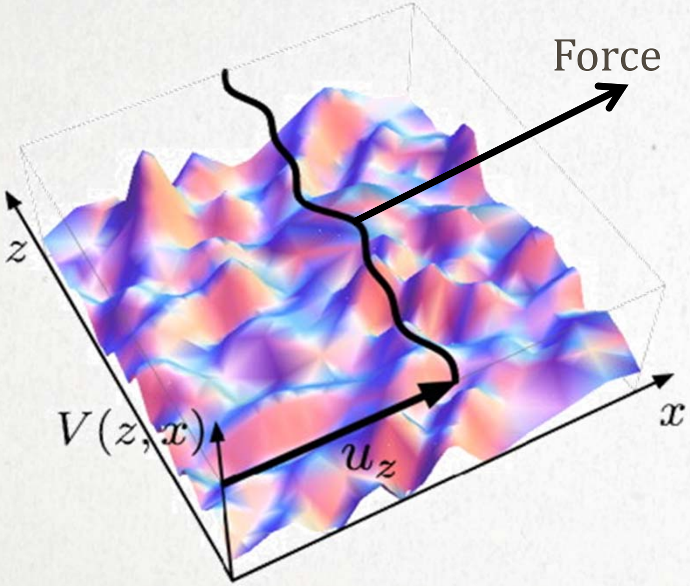


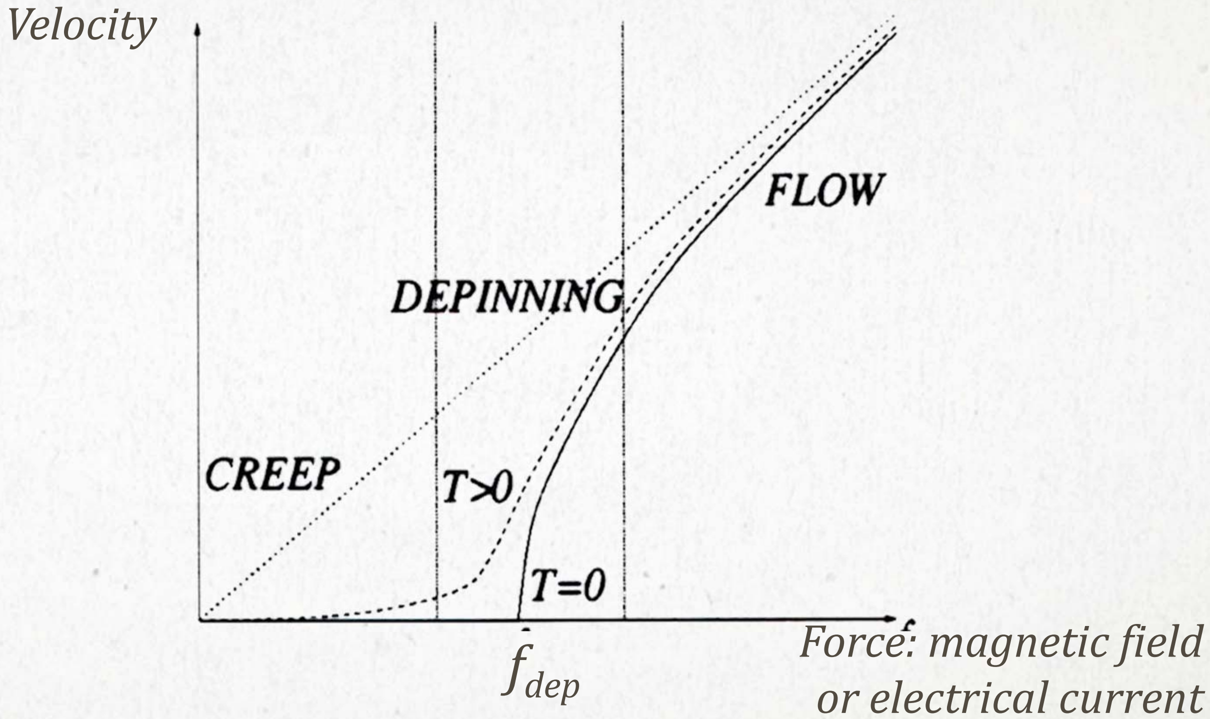
1D interface, 2D medium; similar

Universal behavior:
different physics at the microscopical scale,
same description at the macroscopical level ?

To what extends interface motion can be used to address some general problems in statistical physics ?

FORCE DRIVEN MOTION OF AN INTERFACE: BASIC IDEAS





Magnetization reversal, depinning, current

P. Chauve et al., PRB (2000), T. Giamarchi et al., Lect. Notes Phys. (2006),
E. Agoristsas et al. Physica B (2012)

OUTLINE

1- MAGNETIZATION REVERSAL IN FERROMAGNETIC THIN FILMS

2- THE CREEP REGIME AT CONSTANT TEMPERATURE

3- THERMAL STUDY OF PINNING DEPENDENT REGIMES

4- DOMAIN WALL MOTION DRIVEN BY AN ELECTRIC CURRENT

1- MAGNETIZATION REVERSAL IN FERROMAGNETIC THIN FILMS

- Pinning strength
- Magnitude of the driving force
- Method for DW velocity measurement
- DW dynamical regimes

STRONG PINNING DISORDER: NUCLEATION

Polar MOKE image:
FePt thin film

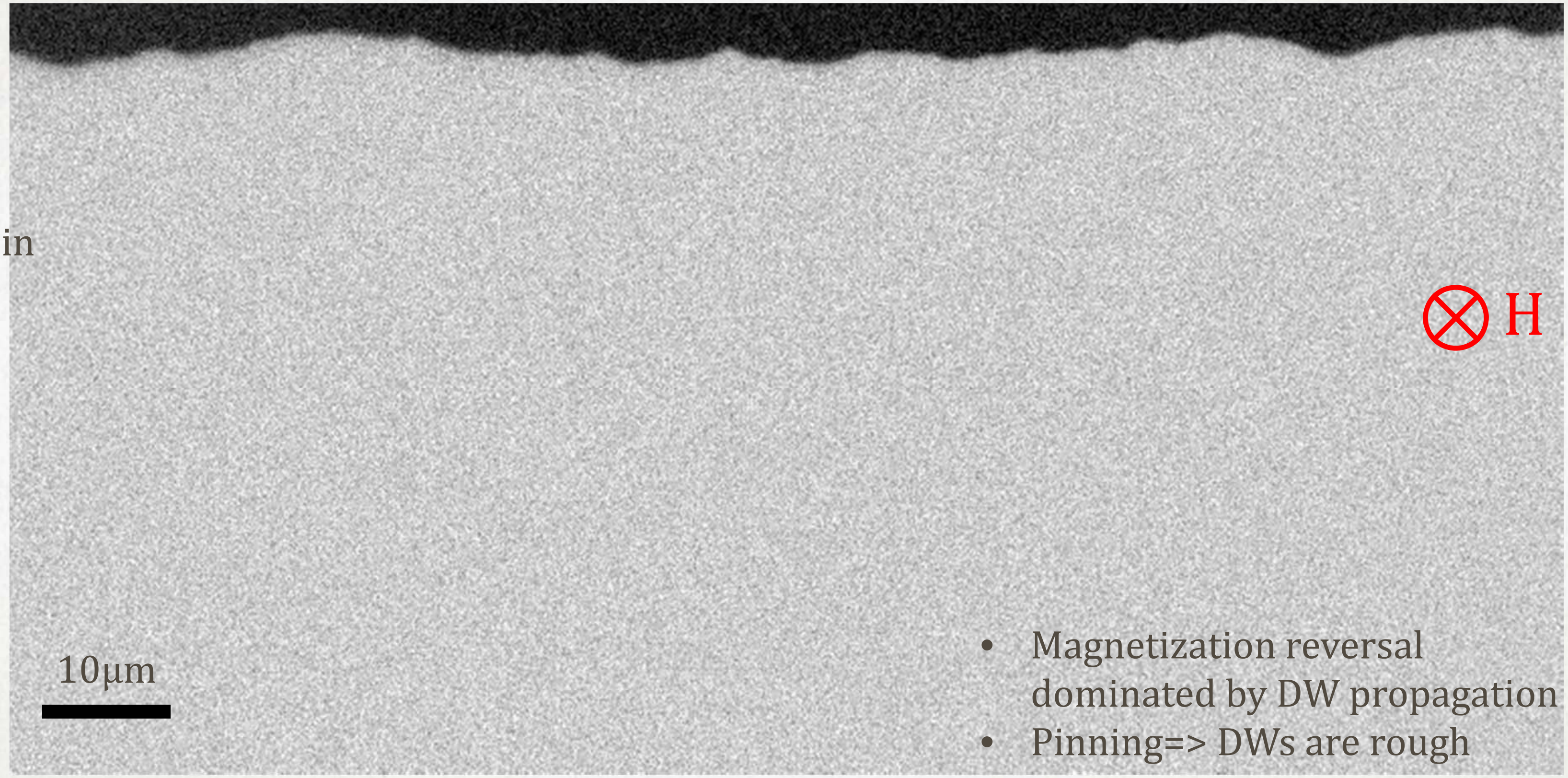
⊗ H

- DW propagation impeded by DW pinning
- Magnetization reversal dominated by nucleation

J.P. Attané et al., PRB (2010)

WEAK PINNING DISORDER: INTERFACES PROPAGATION

Polar MOKE
Pt/Co/Pt film thin
H=0.06H_{dep}



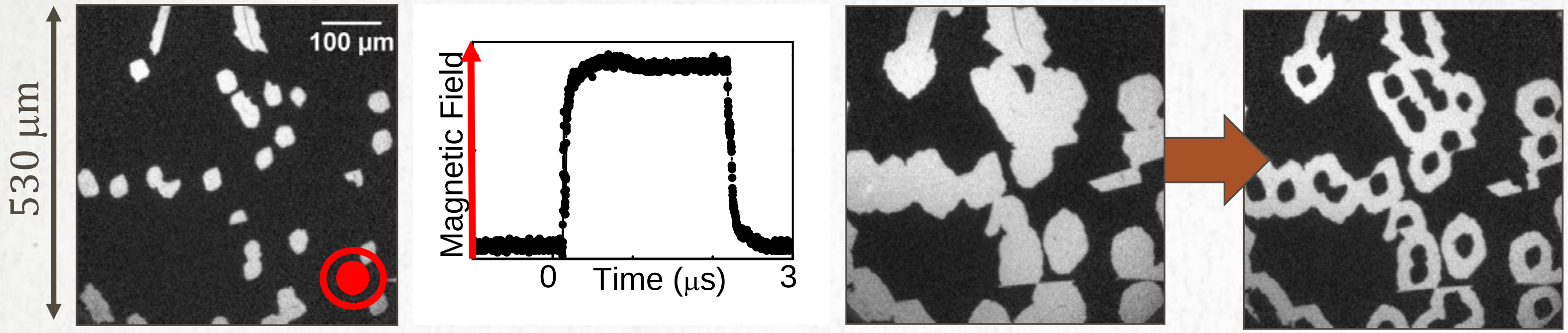
DW thickness
$\Delta \approx 1 - 10nm$

- Magnetization reversal dominated by DW propagation
- Pinning=> DWs are rough

M. Bauer et al., Phys. Rev. Lett. (2005)

MEASUREMENT OF DW VELOCITY

Magneto-optical Kerr microscopy and magnetic field pulses

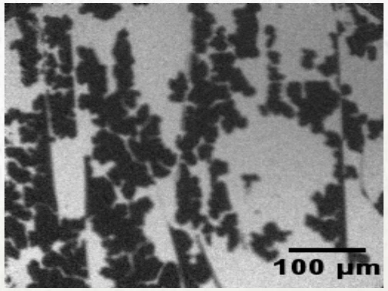


Before Pulse field After Displacement

Average velocity= DW displacement/pulse duration

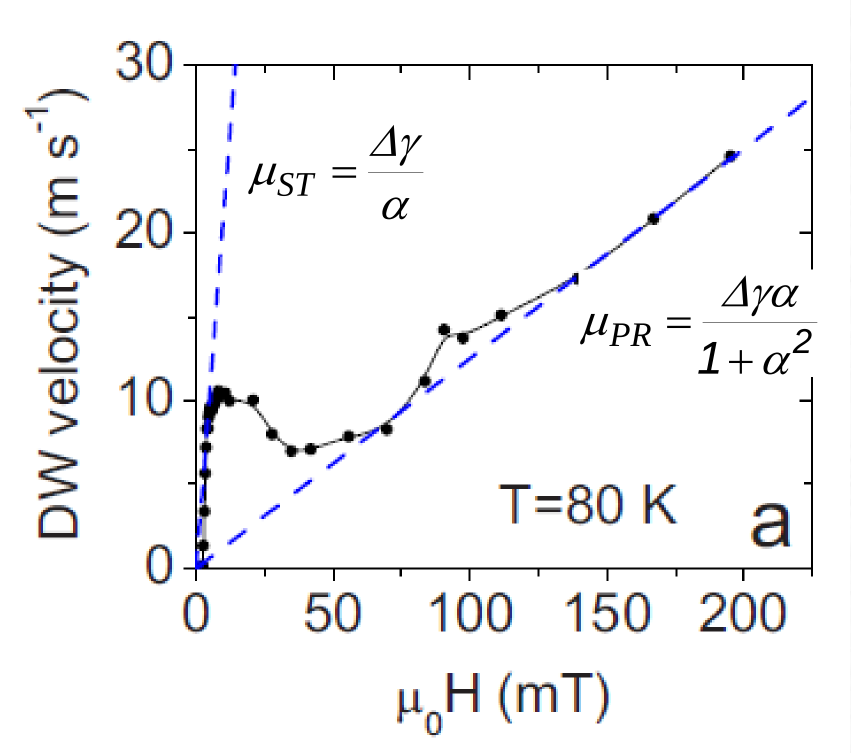
Limits :

- multiple nucleation at high field
- Strong and extended pinning defects



GaMnAs T=40 K

VERY WEAK PINNING DISORDER : FLOW REGIMES



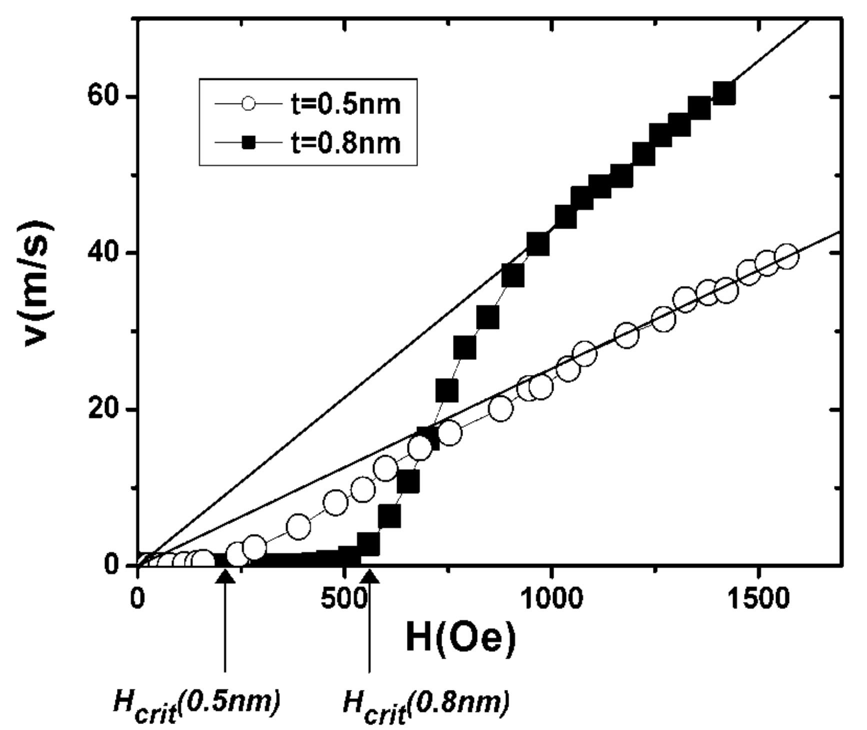
(Ga,Mn)As 50nm thick film with PMA

Dynamics
- Controlled by dissipation
- Depends on the magnetic structure of the domain wall

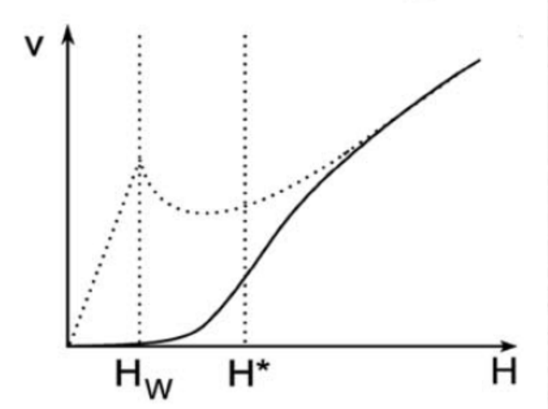
Different regimes
- Steady : fixed direction of magnetization $\vec{M}$
- Precessionnal : rotation of $\vec{M}$

A. Dourlat et al., Phys. Rev. B. (2008)

WEAK PINNING DISORDER : HIGH FIELD FLOW REGIME



Pt/Co/Pt ultrathin film with PMA



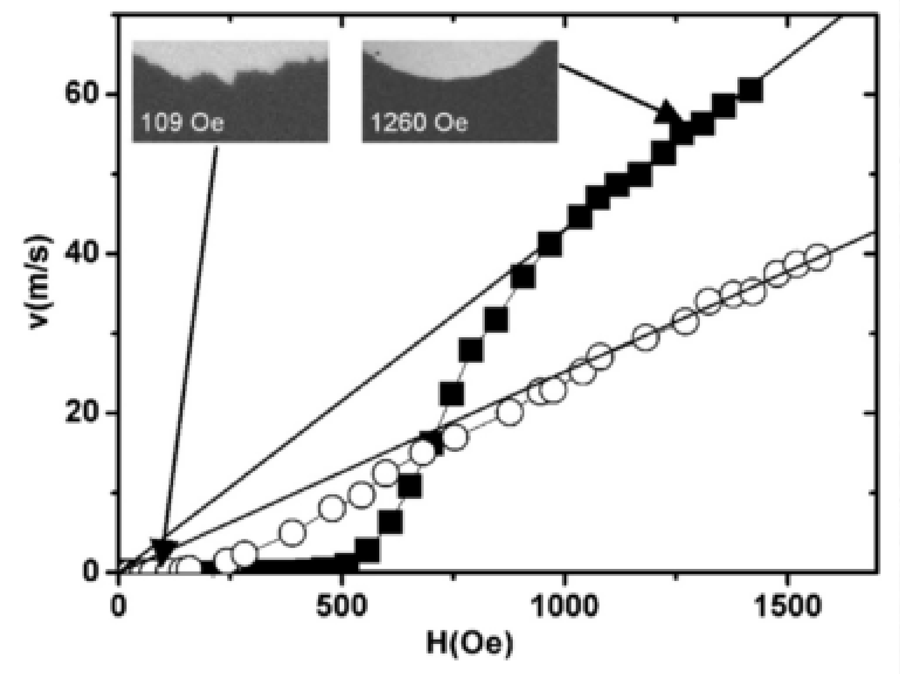
Larger pinning strength ⇒
The steady flow regime is hidden by pinning depend motion.

P. Metaxas et al., Phys. Rev. Lett. (2007)

ROUGHTNESS AND VELOCITY

Pt/Co/Pt
ultrathin films

Creep Flow



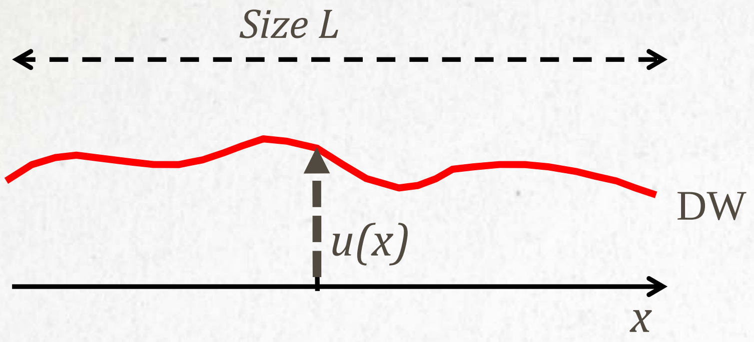
Creep: rough domain walls
Flow: smooth domain walls

P. Metaxas et al., Phys. Rev. Lett. (2007)

2- THE CREEP REGIME AT CONSTANT TEMPERATURE

- Theoretical predictions and experimental results
- Controlling domain wall creep

CREEP REGIME: BASIC MODEL AND PREDICTIONS



Free energy of a DW segment of size L

$$F(L,u) = \underbrace{\epsilon_{el}\frac{u^2}{L}}_{\text{elastic}} - \underbrace{\epsilon_{pin} u\sqrt{n_i \xi L}}_{\text{pinning}} - \underbrace{M_s H t L u}_{\text{Zeeman}}$$

ξ : *correlation length of the disorder*

n_i: *density of pinning centers*

$\boldsymbol{\epsilon}_{\mathbf{el}} \approx 4\sqrt{AKt}$: *elastic energy*

$\Delta = \sqrt{A/K}$: *domain wall thickness*

Pinning control parameters

Larkin length $\mathbf{L_c} \Leftarrow F_{elastic}(L_c, \xi) = F_{pinning}(L_c, \xi)$

Depinning field $\mathbf{H_{dep}} \Leftarrow F_{pinning}(L_c, \xi) = F_{Zeeman}(L_c, \xi)$

Depinning temperature $\mathbf{k_B T_{dep}} \approx F_{pinning}(L_c, \xi)$

Predictions

Velocity: $v_{creep} = v_{creep}{}^{0}\ e^{-\frac{T_{dep}}{T}\left(\frac{H_{dep}}{H}\right)^{\mu}}$

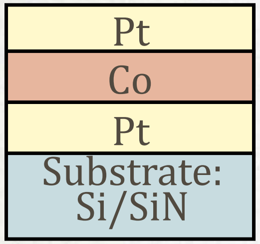
Roughness:

$$w(L) = \langle\langle (u(x+L) - u(x))^2 \rangle\rangle \alpha \left(\frac{L}{L_c}\right)^{2\zeta}$$

with $\mu = 1/4$ and $\zeta = 2/3$

S. Lemerle et al., Phys. Rev. Lett. (1998)

CREEP REGIME : DW MOTION IN Pt/Co/Pt ULTRATHIN FILMS



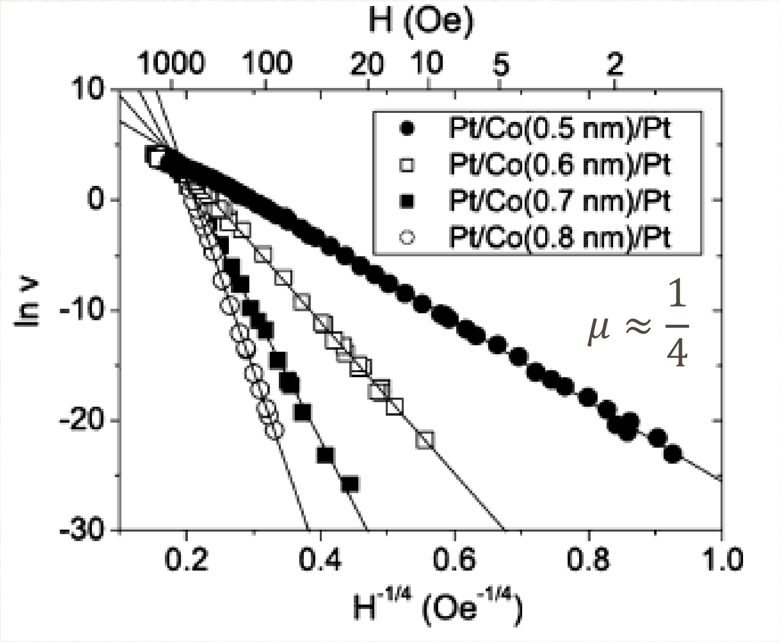
Pt

Co

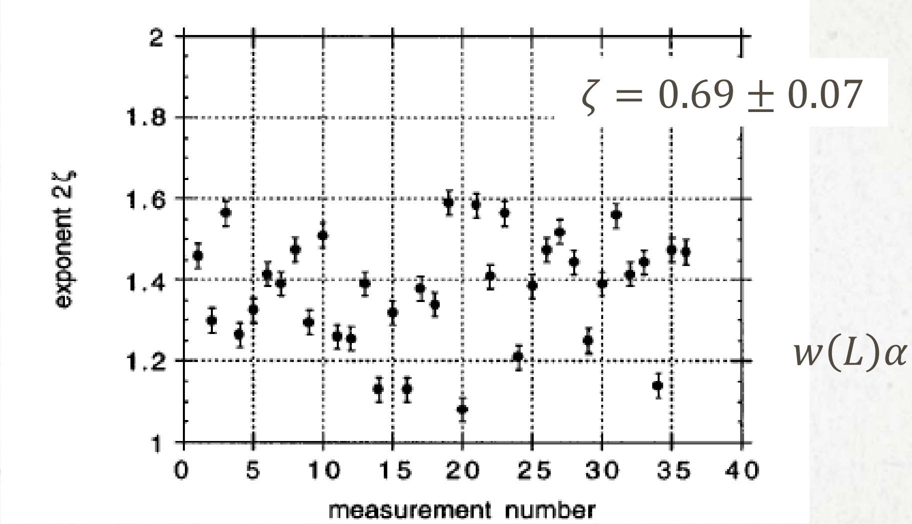
Pt

Substrate: Si/SiN

Creep exponent



Roughness exponent



$$w(L) \alpha \left(\frac{L}{L_c}\right)^{2\zeta}$$

Both scaling laws are compatible with theoretical predictions

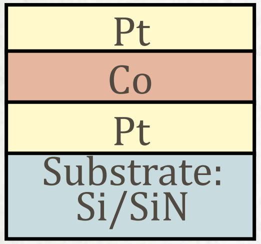
Ultrathin Pt/Co/Pt films:
experimental model system to investigate the elastic interface motion in a weakly disordered systems

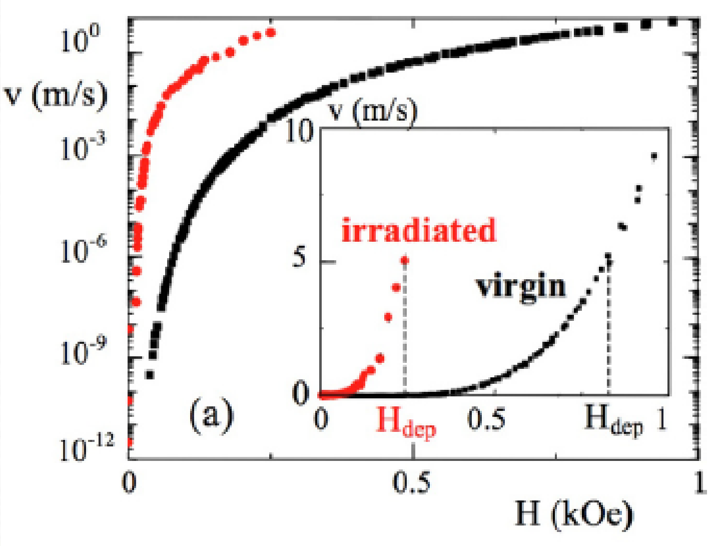
S. Lemerle et al., Phys. Rev. Lett. (1998), P. Metaxas et al., Phys. Rev. Lett. (2007)

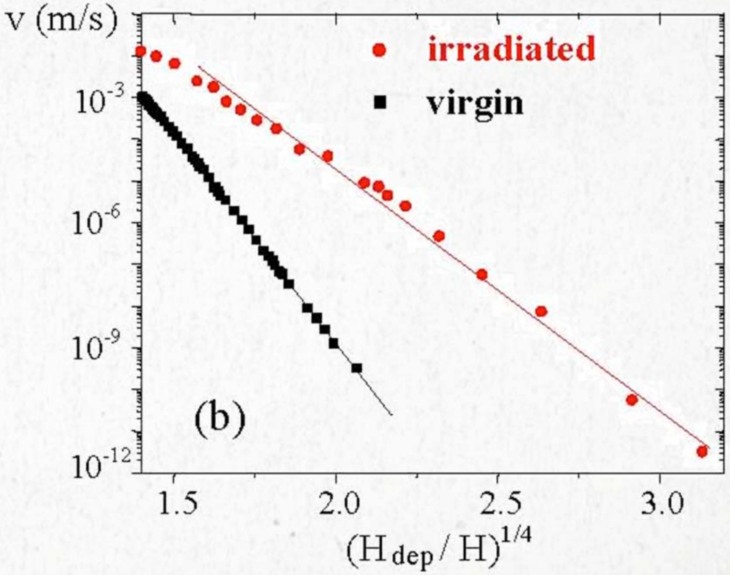
CONTROLLING DOMAIN WALL CREEP

Irradiations by ion beam

Pt/Co(0.5 nm)/Pt


Pt
Co
Pt
Substrate: Si/SiN





Low dose He^+ irradiation

⇒ Co and Pt intermixing at the interface: alloying of the Co and smoothing of the nano-irregularities

⇒ reduction of the pinning strength

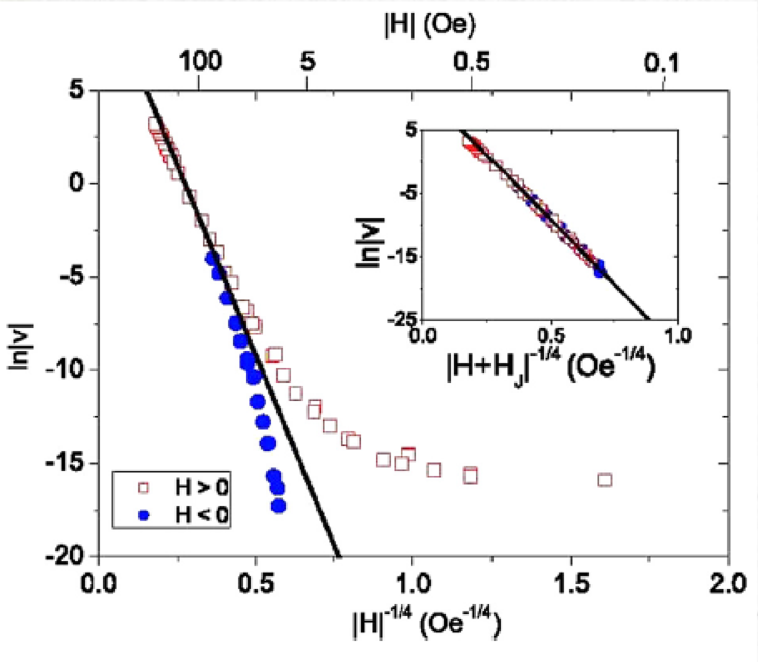
J. Ferré et al., phys. stat. sol. (a) (2004),
J. Ferré et al. J. Phys. D (2003)

P. Metaxas et al., JAP (2012)

CONTROLLING DOMAIN WALL CREEP

Creep in presence of an interlayer coupling


Pt
Hard Co
Pt
Soft Co
Pt
Si/SiO2



Other studies at the LPS:

- *Periodic pinning potential*
- *DW deroughening due to dipolar interactions*

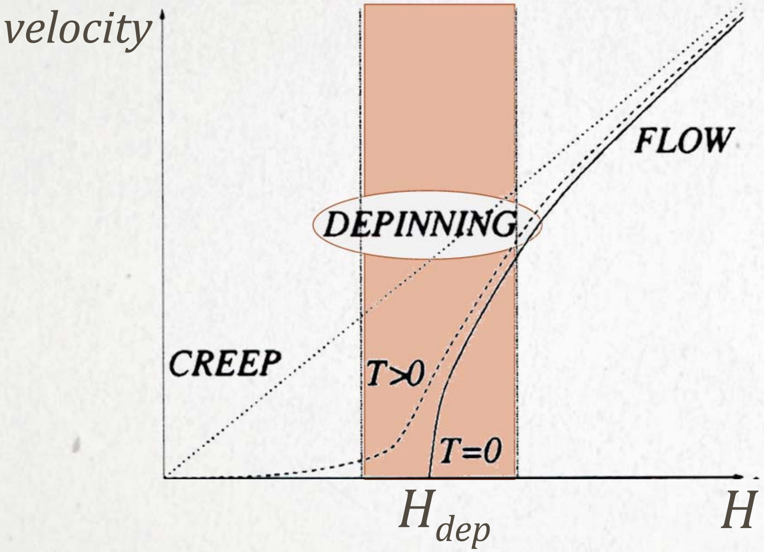
- Coupling between the two Co layers (RKKY, dipolar interaction)
- Effective coupling field: $H_J = \frac{J}{M_s t}$

P. Metaxas et al. J. Mag. Mag. Mat. (2008),

P. Metaxas et al., JAP (2012)

3- THERMAL STUDY OF PINNING DEPENDENT REGIMES

COULD WE BRIDGE THE GAP BETWEEN THE CREEP AND THE FLOW REGIME ?



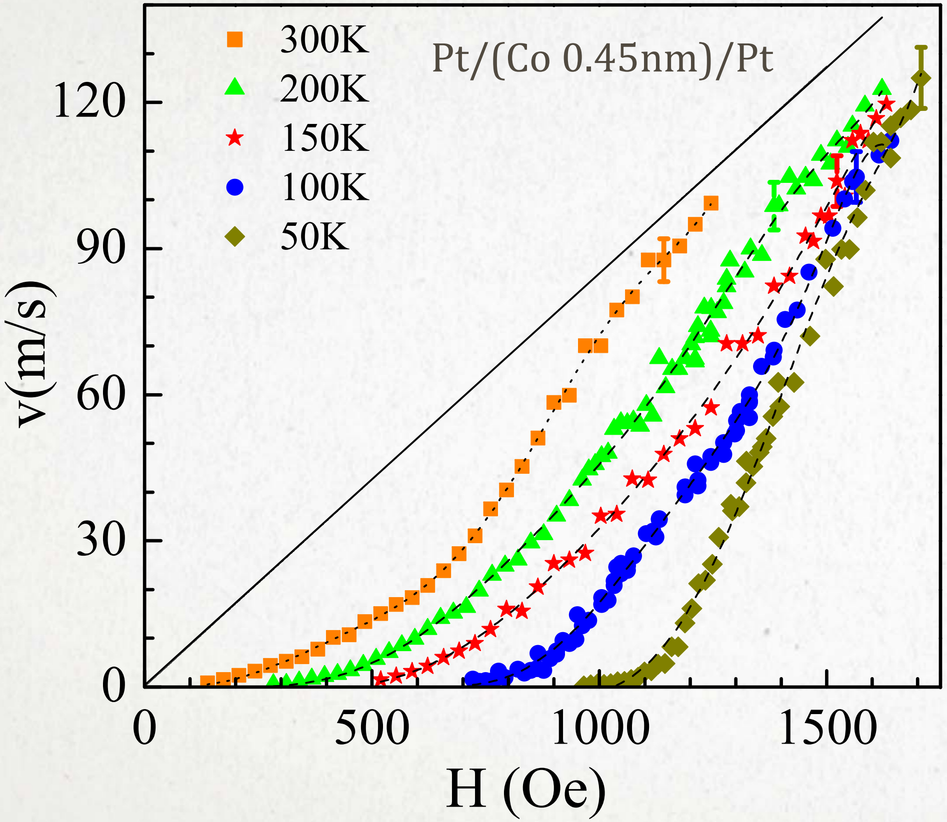
- Single or different regimes?
- Universality?
- Prediction for the depinning transition :

$$v \sim (H - H_{dep})^{\beta} \text{ and } v(H_{dep}) \sim T^{\psi}$$

-

S. Bustingorry et al., Euro Phys. Lett. (2008)

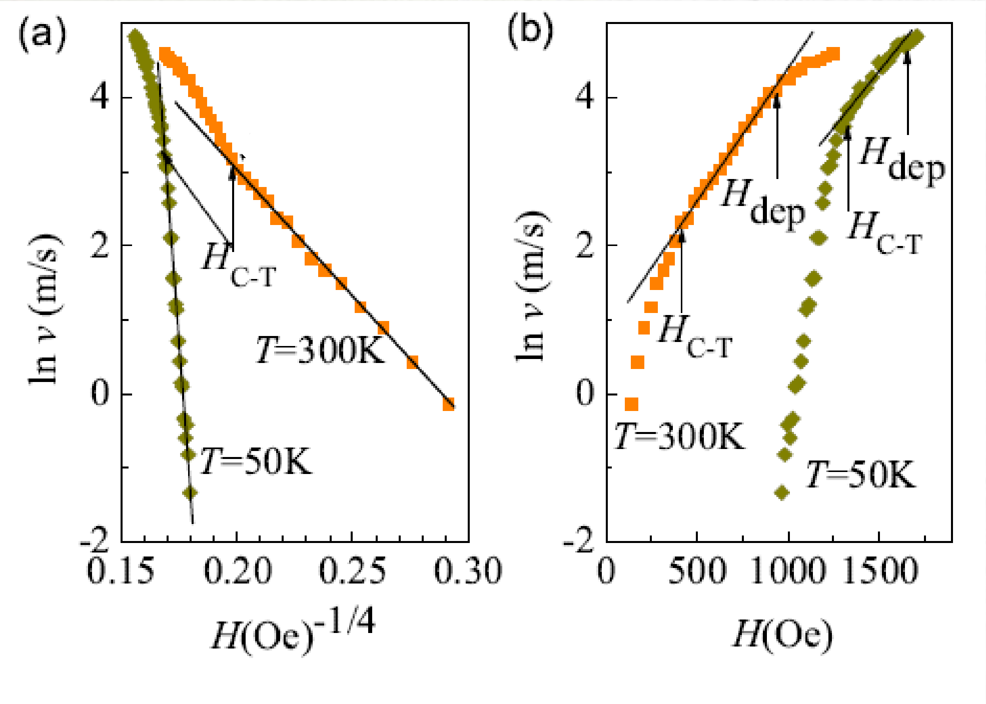
FIELD DRIVEN DOMAIN WALL DYNAMICS FOR DIFFERENT TEMPERATURES



- *T* ↘ ⇒ shifts of the curves towards the high field region.
- Nature of the dynamical regimes ?

J. Gorchon et al., submitted to Phys. Rev. Lett.

IDENTIFICATION OF PINNING DEPENDENT REGIMES



Cross over fields: $H_{C-T}(T)$ and $H_{dep}(T)$
Fit of the creep law ⇒ $T_{dep}(T)$ and $v_{creep}{}^0\,(T)$

- **Creep : $\boldsymbol{H < H_{C-T}}$**

$$v_{creep}(H,T) = v_{creep}{}^0\,(T)\, e^{-\frac{T_{dep}}{T}\left(\frac{H_{dep}}{H}\right)^{1/4}}$$

- **TAFF : $\boldsymbol{H_{C-T} < \mathrm{H} < H_{dep}}$** Thermally Activated Flux Flow

$$v_{TAFF}(H,T) = v_{TAFF}{}^0\,(T)\, e^{-\frac{T_{dep}}{T}\left(1-\frac{H}{H_{dep}}\right)}$$

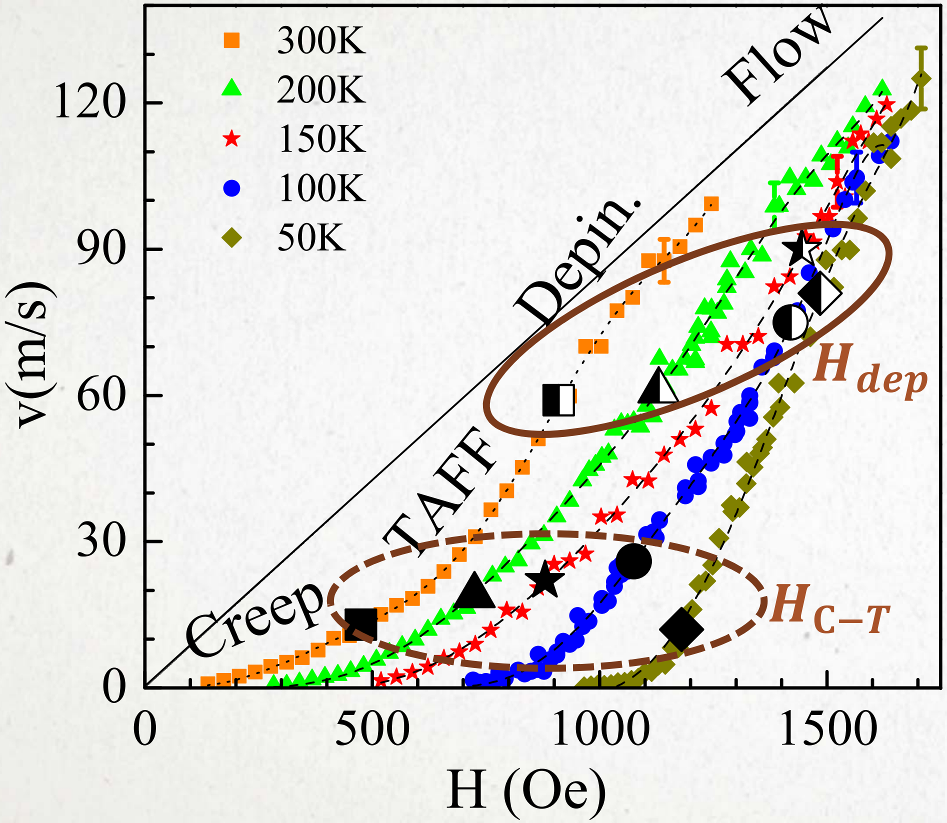
- **Depinning : $\boldsymbol{\mathrm{H} \geq H_{dep}}$**

- **Flow : $\boldsymbol{\mathrm{H} \gg H_{dep}}$**

$$m = \frac{v}{H} - DH^{-4}$$ *L.W. Chen et al. PRB 51 (1995)*

J. Gorchon et al., submitted to Phys. Rev. Lett.   P.W. Anderson and Y.B. Kim, Rev. Mod. Phys. (1964)

IDENTIFICATION OF PINNING DEPENDENT REGIMES



⇒ 3 pinning dependent dynamical regimes

Parameters controlling DW dynamics

- $H_{dep}(T), T_{dep}(T)$

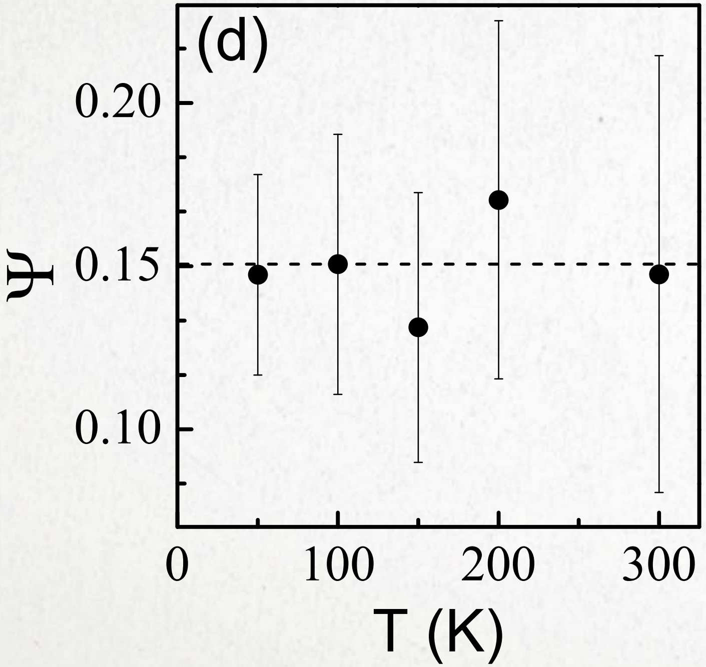
Velocities

- Mobility in the flow regime: m
- Creep prefactor : $v_{creep}{}^{0}\ (T)$
- Velocity at the depinning transition: $\mathrm{v}\big(H_{dep}(T)\big)$

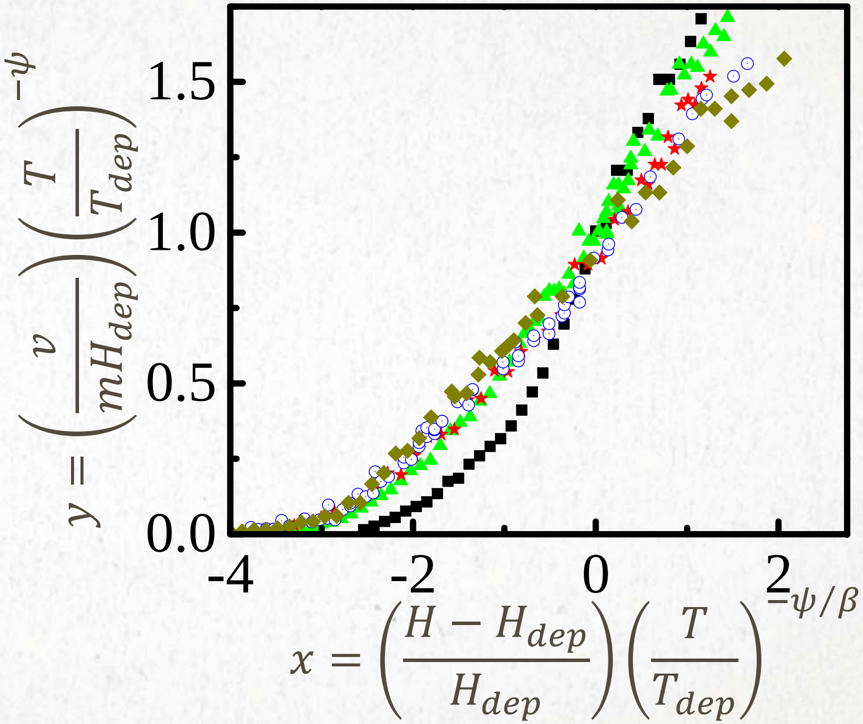
DEPINNING TRANSITION

- Prediction $v(H_{dep}) = mH_{dep}\left(\frac{T}{T_{dep}}\right)^{\psi}$

with $\psi = 0.15$



Rescaling with $\beta = 0.25$



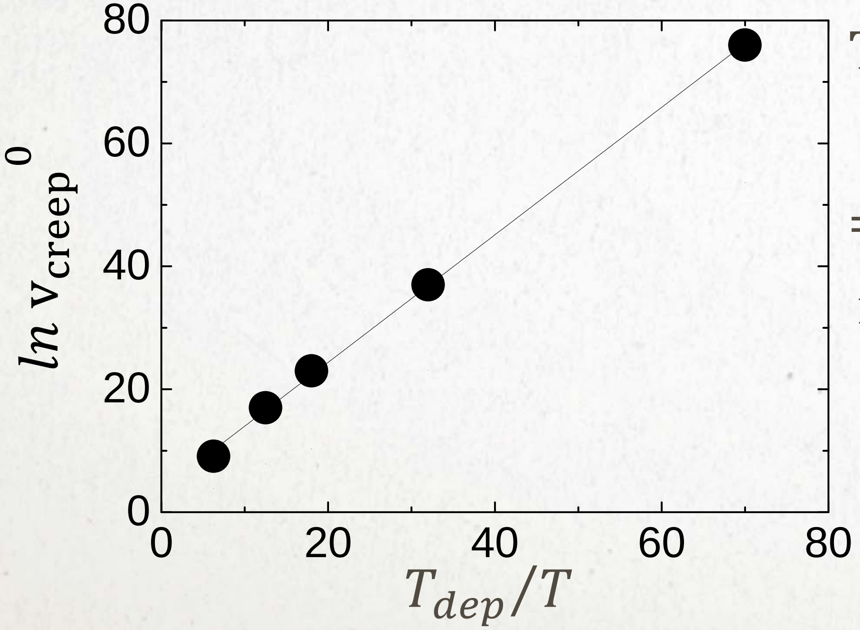
⇒ Universality of the depinning transition

S. Bustingorry et al., Phys. Rev. B. (2012)

CREEP PREFACTOR

Creep law

$$v_{creep}(H,T) = \boldsymbol{v_{creep}}^{\mathbf{0}}\ (\boldsymbol{T})\ e^{-\frac{T_{dep}}{T}\left(\frac{H_{dep}}{H}\right)^{1/4}}$$



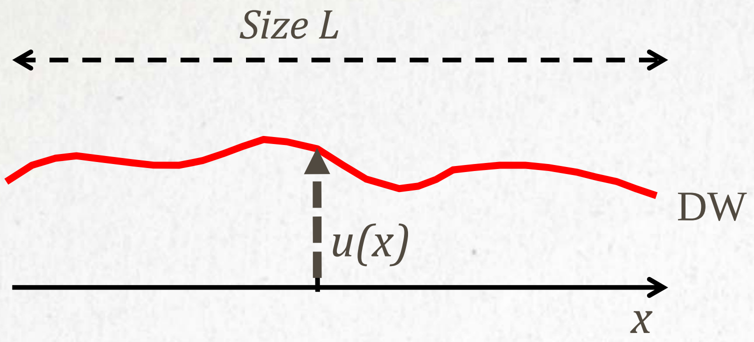
The creep pre-factor is temperature dependent.

$\Rightarrow v_{creep}{}^{0}\ (T) = \frac{\xi}{\tau} e^{C\frac{T_{dep}}{T}}$ with $C \approx 1.04 \pm 0.02$
for $\xi = 19nm, \tau = 1ns$ close to typical relaxation time.

$\Rightarrow$ Effective attempt frequency : $\frac{1}{\tau_{eff}} = \frac{1}{\tau} e^{C\frac{T_{dep}}{T}}$

T_{dep} ↘ ⇒ more time is spent for the exploration of surrounding pinning sites

MICROSCOPIC PARAMETERS CONTROLING DW PINNING



Free energy of a DW segment of size *L*

$$F(L,u) = \underbrace{\epsilon_{el}\frac{u^2}{L}}_{\text{elastic}} - \underbrace{\epsilon_{pin} u\sqrt{n_i \xi L}}_{\text{pinning}} - \underbrace{M_s H t L u}_{\text{Zeeman}}$$

$$\left.\begin{array}{r}\text{Larkin length } L_c\\ \text{Depinning field } H_{dep}\\ \text{Depinning temperature } k_B T_{dep}\end{array}\right\} \Rightarrow \begin{cases} \epsilon_{el} = \left(k_B T_{dep}\right)^2/\left(M_S H_{dep} t\right)\xi^3 \\ {\epsilon_{pin}}^2 = \left[\left(k_B T_{dep}\right)\left(M_S H_{dep} t\right)\xi\right]/\Delta \\ L_c = \left(k_B T_{dep}\right)/\left[\left(M_S H_{dep} t\right)\xi\right] \end{cases}$$

- Sample characterization ⇒ elastic energy $\boldsymbol{\epsilon}_{\mathbf{el}}$ and magnetization at saturation M_S
- Eq. 1⇒ corelation length of the disorder $\xi(300\text{ K}) = 19\text{ nm}$

  ≈ lateral size of Pt crystallites determined by AFM ⇒ ξ is T-independent.

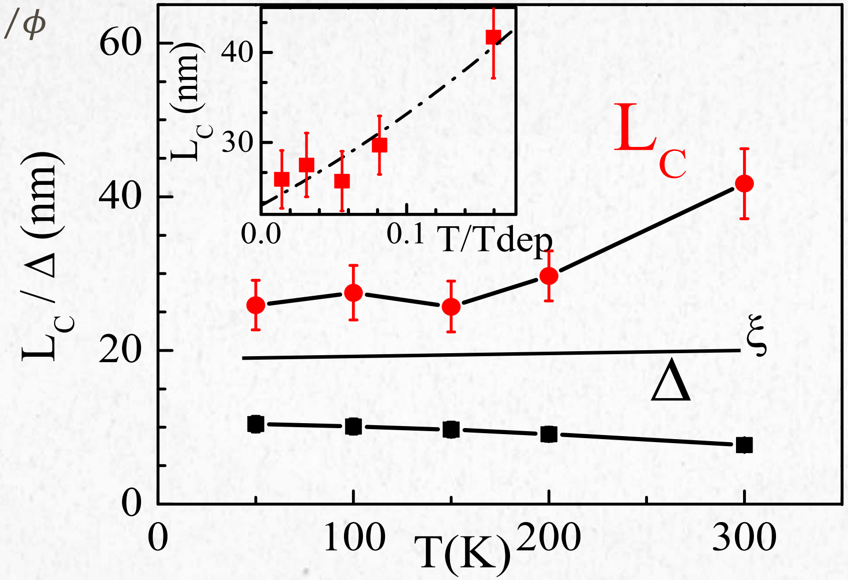
THERMAL SCALING OF THE LARKIN LENGTH

Predictions :

$$L_c(T) = L_c{}^0\left(1 + \frac{T}{T_{dep}}\right)^{1/\phi}$$

with $\phi = 0.20$

Thermal crossover exponent



$T_{dep}(T)$and $H_{dep}(T) \Rightarrow L_c\,(T)$

Fit $\Rightarrow L_c{}^0 = 25 \pm 2nm\ \ and$

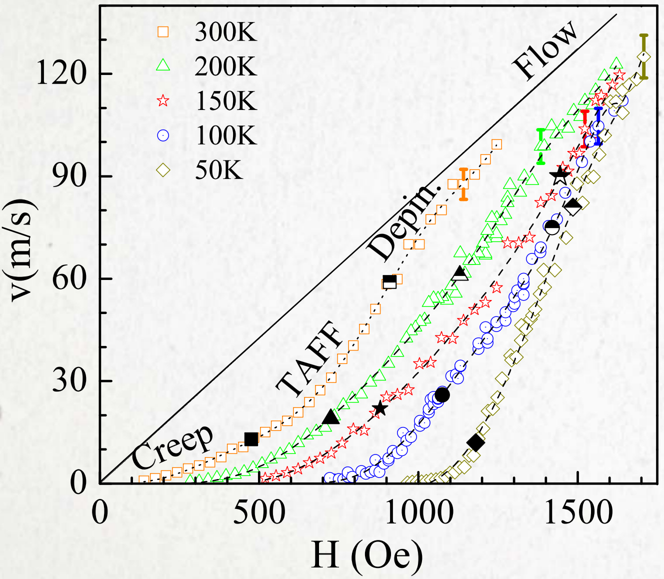
$\phi = 0.24 \pm 0.05$

good agreement ⟹ universal thermal dependence of the Larkin length

T. Nattermann et al. PRB **42** (1990), S. Bustingorry et al. PRB **82** (2012),
E. Agoritsas et al. PRE **87**(2013).

CONCLUSION ON THERMAL STUDIES AND OPEN QUESTIONS

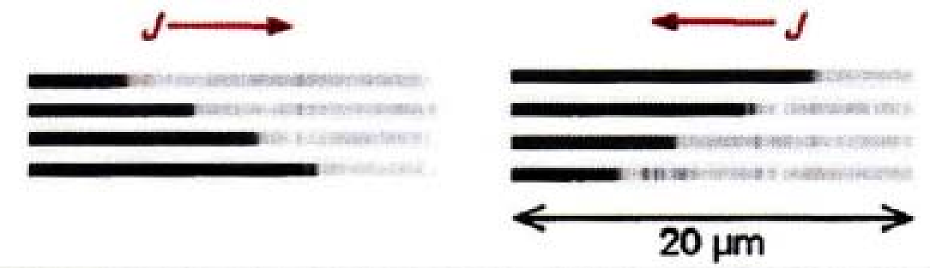
- 3 pinning dependent regimes :
  creep, TAFF and depinning

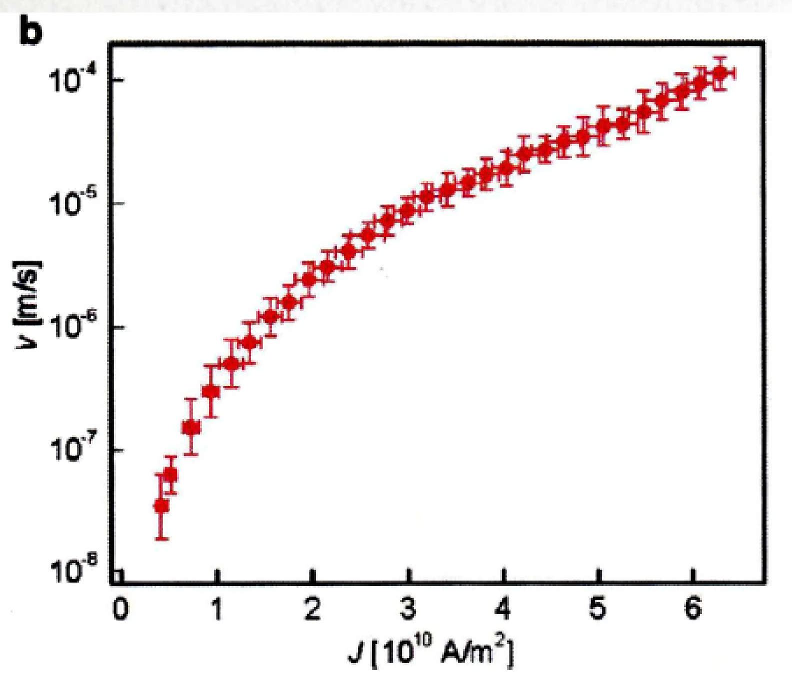


- The creep pre-factor is temperature dependent. Origin ?
- Depinning transition: universal thermal scaling exponent $\psi = 0.15$
- Larkin length: universal thermal exponent $\varphi = 0.24$
- TAFF regime : universal? Origin ?
- and…

4- DOMAIN WALL MOTION DRIVEN BY AN ELECTRIC CURRENT

CURRENT DRIVEN DW MOTION IN A TRACK





DW motion due to a spin transfer torque between the spin of the carriers and the local magnetization.

$$v = v_0 e^{-\left[\frac{T_{dep}}{T+aJ^2}\left(\frac{H_{dep}}{H}+bJ\right)^{\mu}\right]} \text{ with } \mu \approx \frac{1}{4}$$

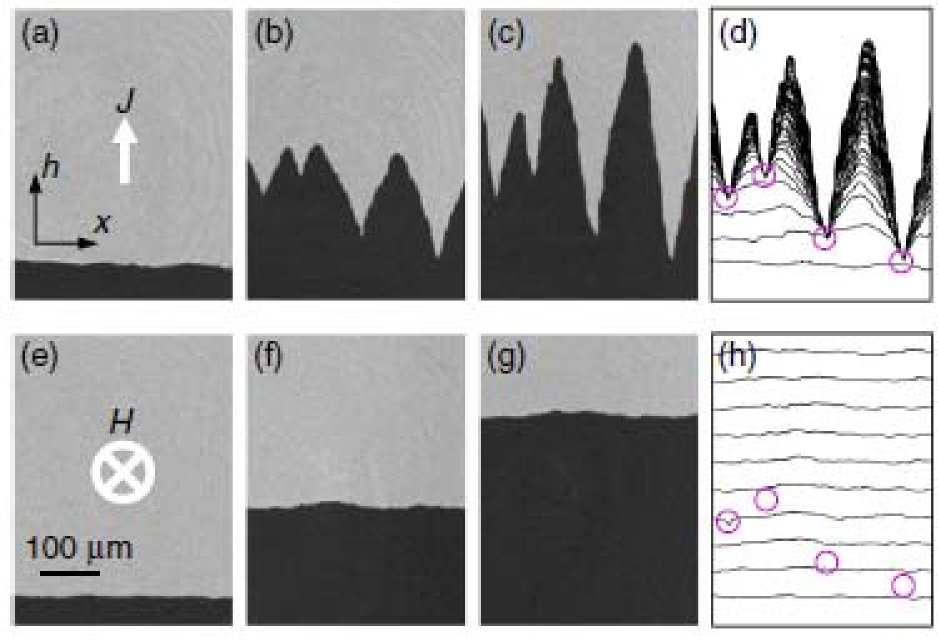
Same creep exponent as for field-driven DW motion

K.-J. Kim et al., Current Appl. Phys. 13, 228 (2013)

CURRENT DRIVEN DW MOTION IN EXTENDED GEOMETRY

t=0s 20min 4hr Δt =3min

$J = 10^{10} A/m^2$



$H = 1mT$

t=0s 10min 20min

Pt/Co(0.3)/Pt

- Correlation between the DW velocity and its shape
- Different roughness exponent: $\zeta_H = 0.68 \pm 0.04$ $\zeta_J = 0.99 \pm 0.01$
- Physics of the formation of the montains ?

K.-W. Moon et al., Phys. Rev. Lett. 110, 107203(2013)

CONCLUSION

- **Ultrathin Pt/Co/Pt films:**
  Model system to investigate the elastic interface motion in a weakly disordered systems

- **Thermal study:**
  - **Evidence of 3 distinct** pinning dependent regimes : creep, TAFF, and depinning
  - Determination of the **universal scaling laws for the depinning transition**
  - **Extraction of (non-universal) microscopic length and energy scales**

PERSPECTIVES

- **Transient creep regime**
- **Current induced DW motion**