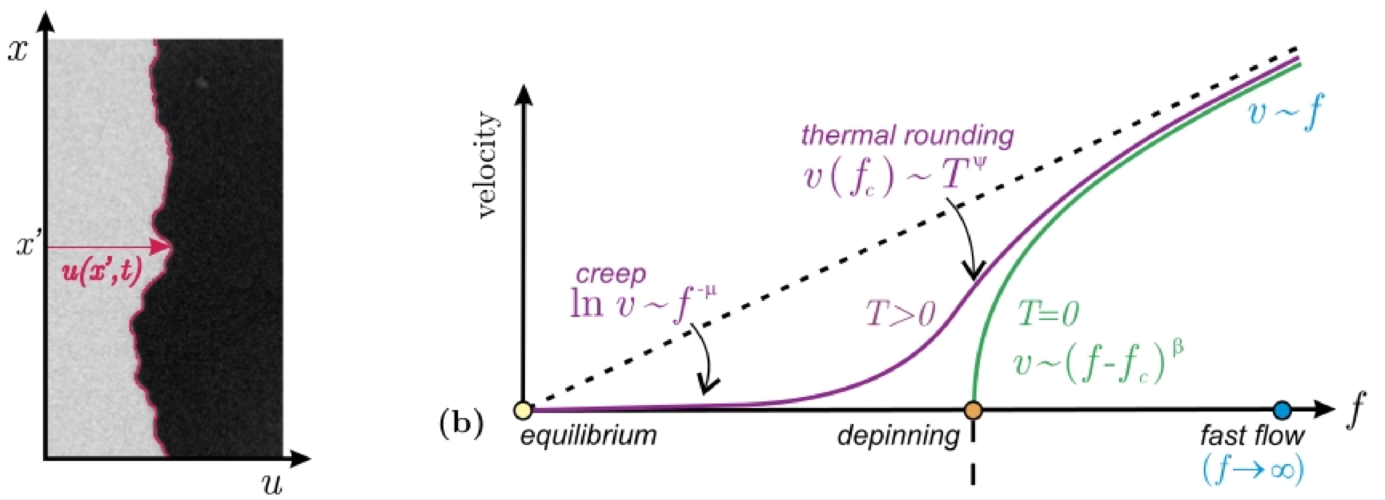
April 2014 – Paris

THERMAL ROUNDING OF THE DEPINNING TRANSITION



Sebastian Bustingorry

CONICET – Centro Atómico Bariloche – Argentina

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THERMAL ROUNDING OF THE DEPINNING TRANSITION

Alejandro Kolton, Thierry Giamarchi
Jon Gorchon, Vincent Jeudy, Jacques Ferré

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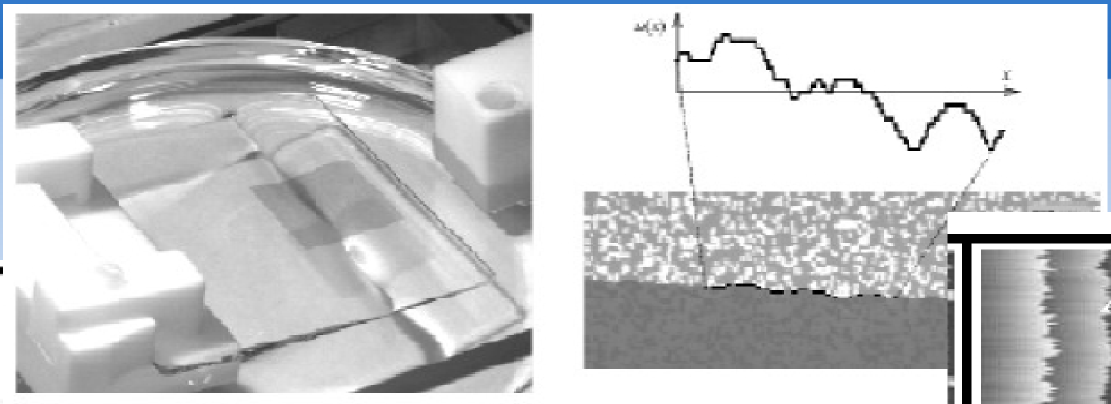
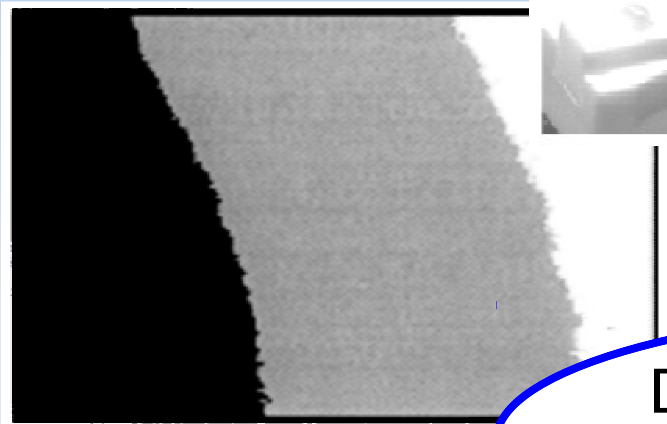
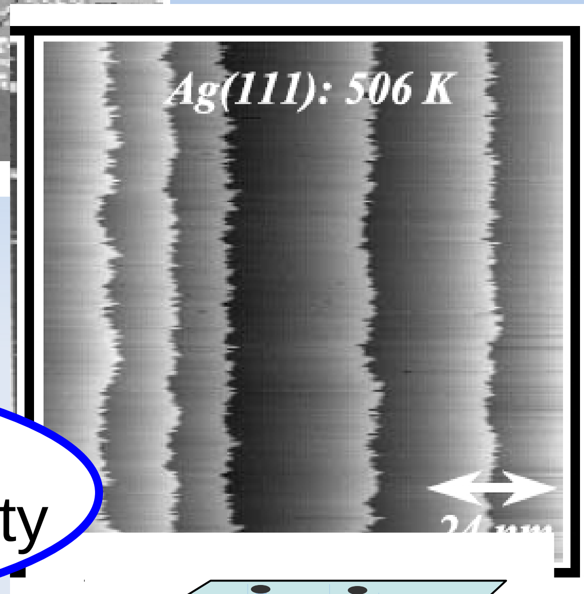
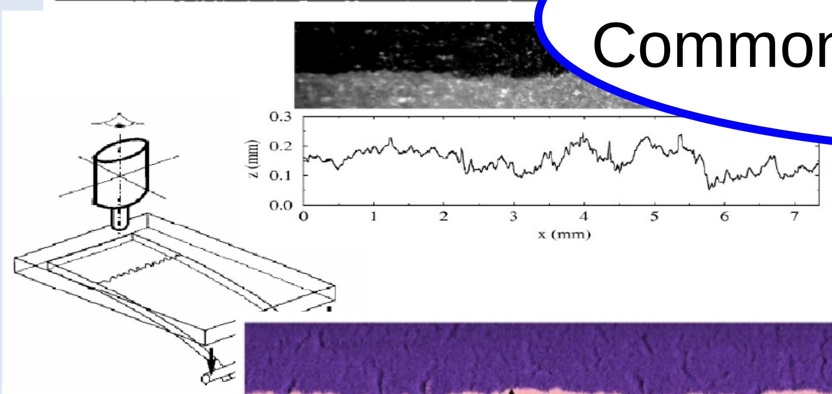
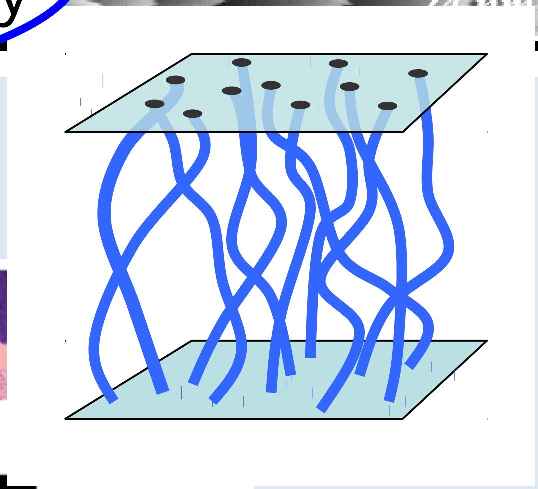


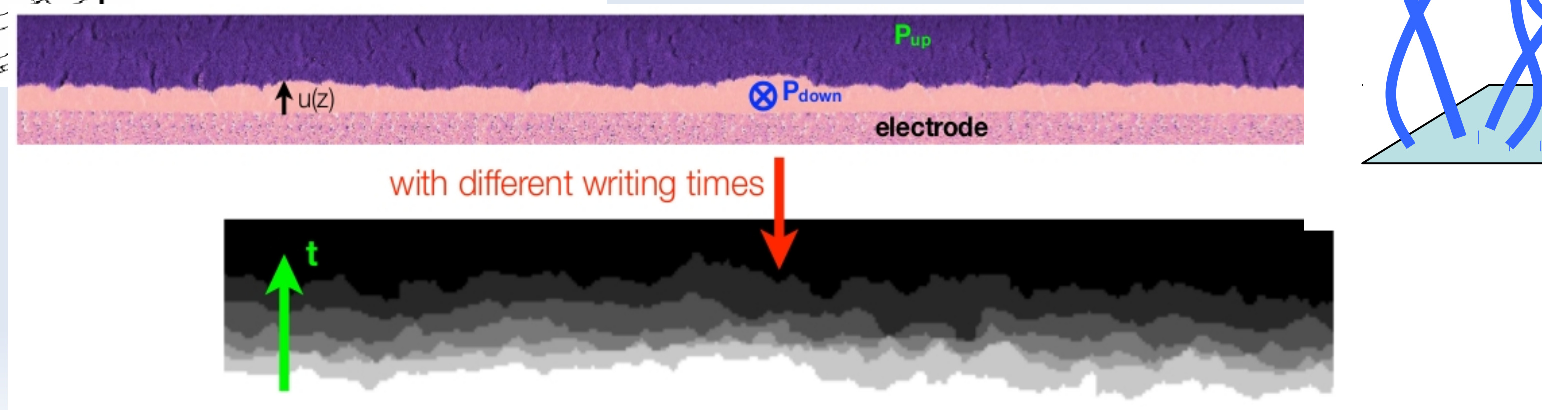




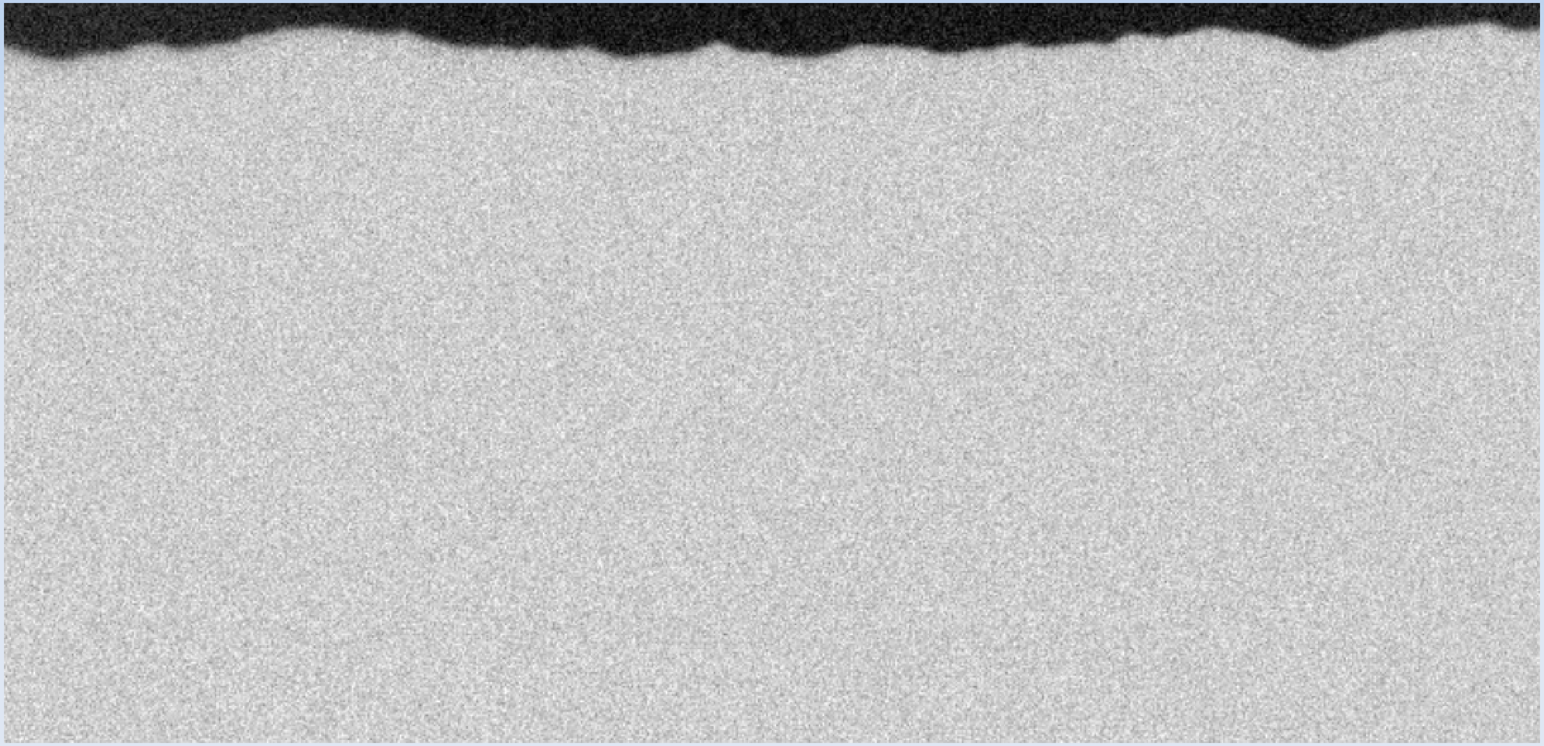
Disordered Elastic Sistems
Common Framework: Universality







Depinning transition



A. Mougin et al, LPS, Orsay – PT/Co/PT film – Kerr microscopy

Depinning transition

A. Mougin et al, LPS, Orsay – PT/Co/PT film – Kerr microscopy

Depinning transition

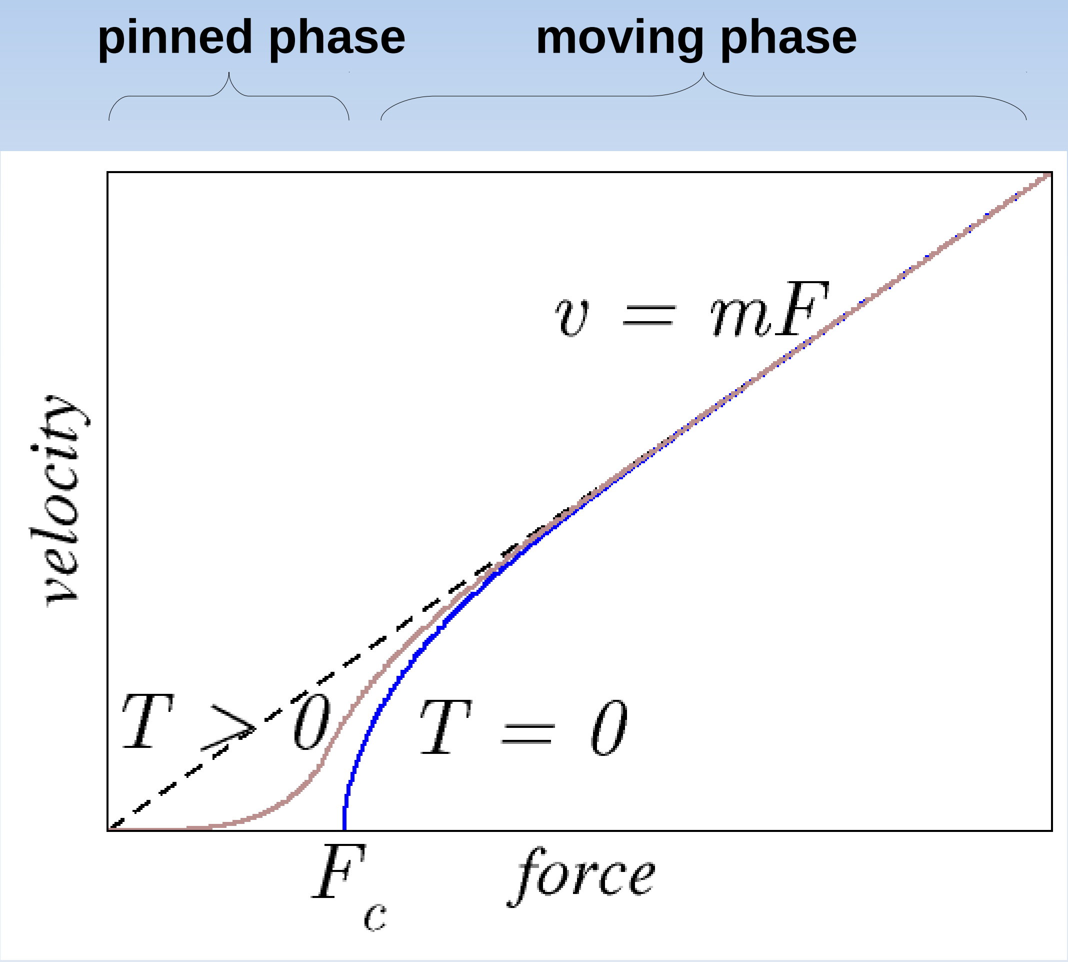
Ferromagnets
- out-of-plane anisotropy
- semiconductors

Ferroelectrics
Vortex lattices in High Tc
Charge density waves
Friction – sliding surfaces
- earthquakes

…

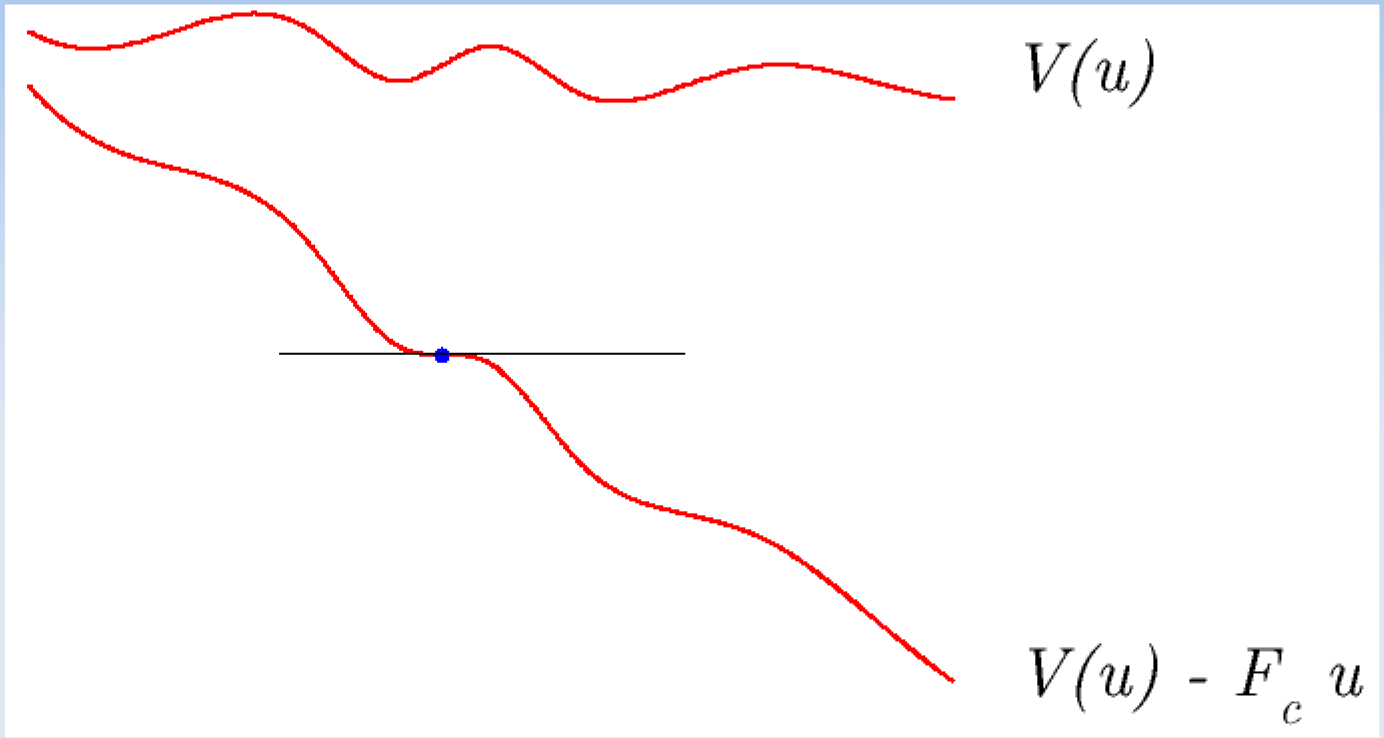
Common ingredients:
- ✔ interface degrees of freedom
- ✔ underlaying disorder
- ✔ driving force

Others:
- thermal fluctuations
- long-range forces
- dimensionality
- non-harmonic effects
- ...



Depinning transition

One dimension



particle in a random potential

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

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

$$\partial_t u > 0 \Rightarrow F > \partial_u V$$

$$F_c = \max_u \partial_u V$$

critical force

close to the critical position:

$$F \approx (F - F_c) + c\delta u^2$$

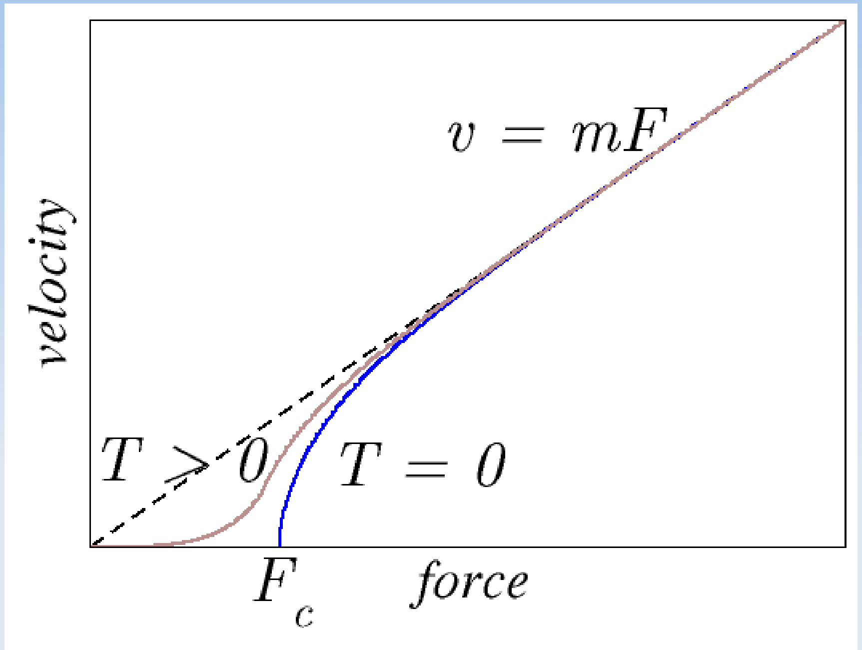
$$\gamma \partial_t u = \delta f + c\delta u^2$$

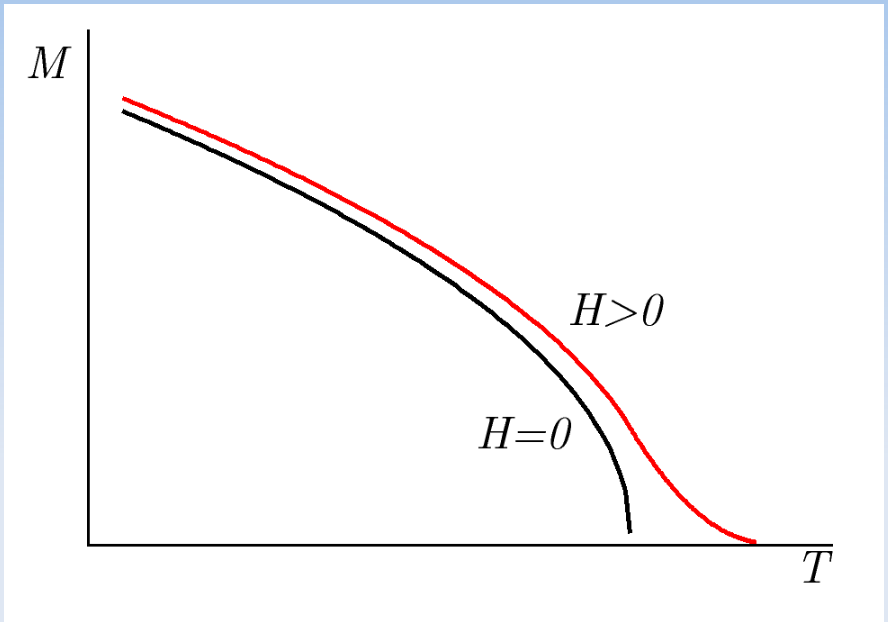
$$\tau = \gamma \int \frac{du}{\delta f + c\delta u^2} = \frac{\gamma}{2c\sqrt{\delta f}} \int \frac{d\tilde{u}}{\sqrt{\tilde{u}}(1 + \tilde{u}^2)} \sim \frac{1}{\sqrt{\delta f}}$$

typical time spent close to the critical position

Depinning transition

Critical phenomena

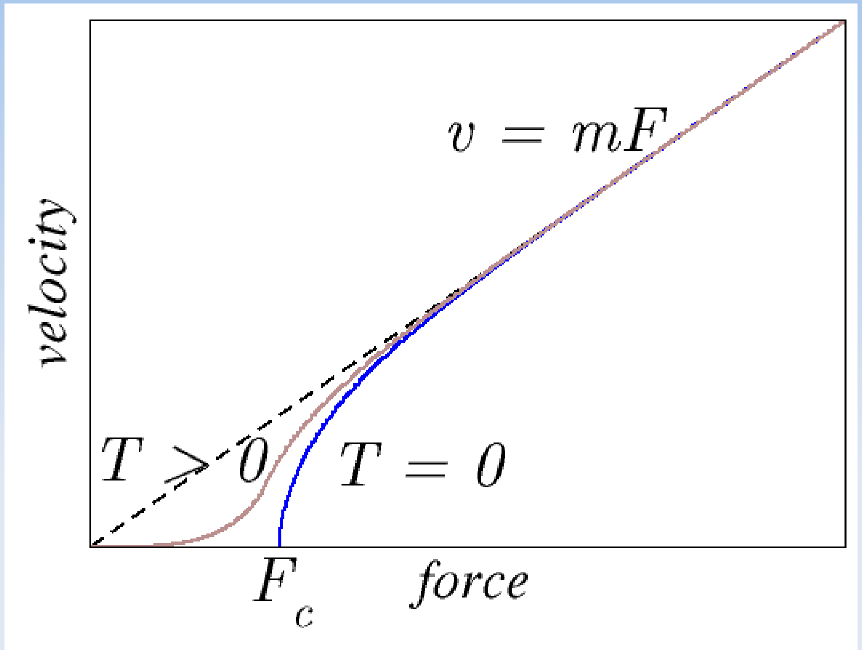


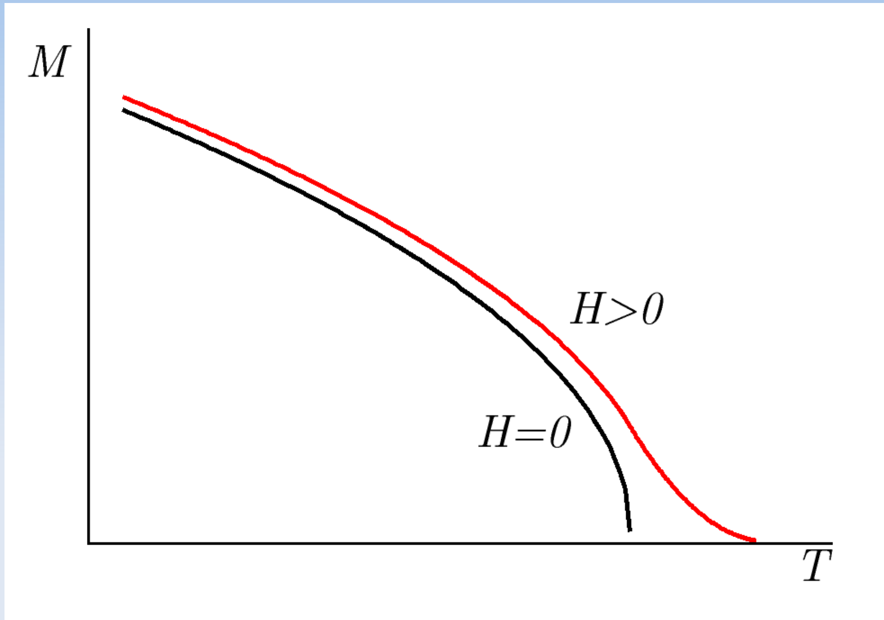


$V \sim (F - F_c)^{\beta}$	order parameter	$M \sim (T - T_c)^{\beta}$
$\xi \sim (F - F_c)^{-\nu}$	divergent correlation length	$\xi \sim (T - T_c)^{-\nu}$
$V \sim T^{\psi}$	field rounding	$M \sim h^{1/\delta}$

Depinning transition

Critical phenomena





scaling hypotesis:
the order parameter is a homogeneous function of the state variables
(universality, scaling relations among exponents)

$$V = \lambda f \left[\frac{F - F_c}{F_c} \lambda^{-1/\beta}, T \lambda^{-1/\psi} \right]$$

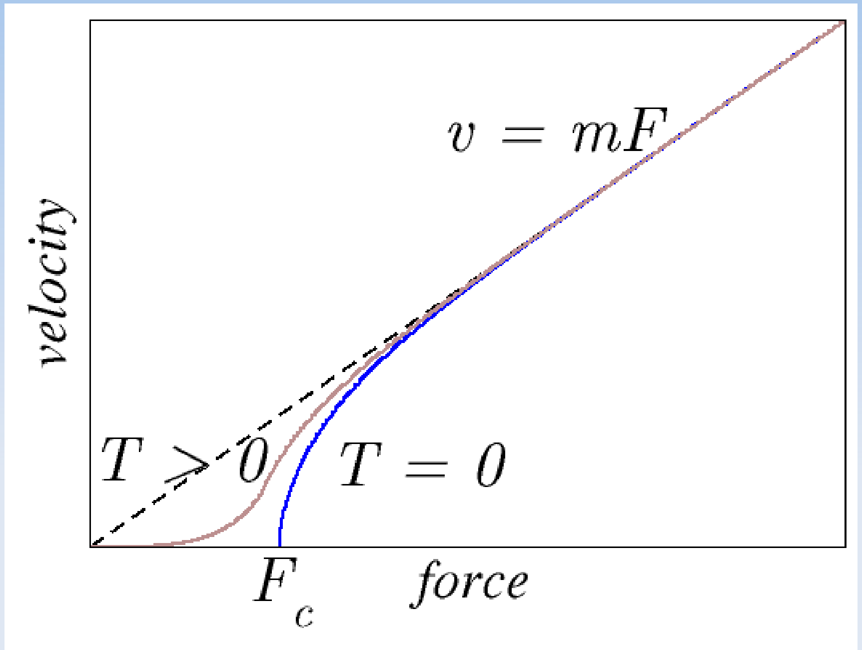
$$M = \lambda f \left[\frac{T_c - T}{T_c} \lambda^{-1/\beta}, H \lambda^{-\delta} \right]$$

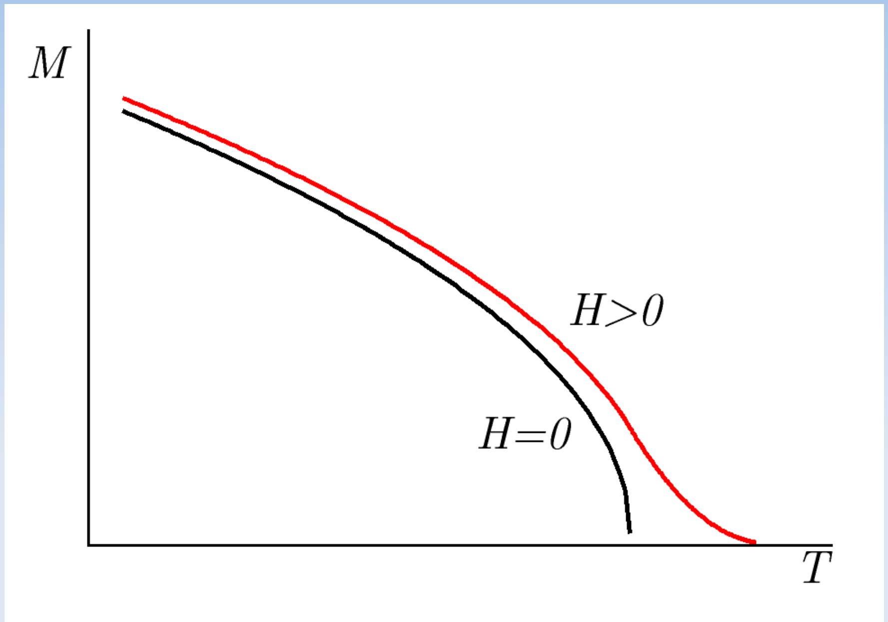
$$\Rightarrow V = T^{\psi} f \left[\frac{F - F_c}{F_c} T^{-\psi/\beta}, 1 \right]$$

$$\Rightarrow M = H^{1/\delta} f \left[\frac{T_c - T}{T_c} H^{-1/\beta\delta}, 1 \right]$$

Depinning transition

Critical phenomena

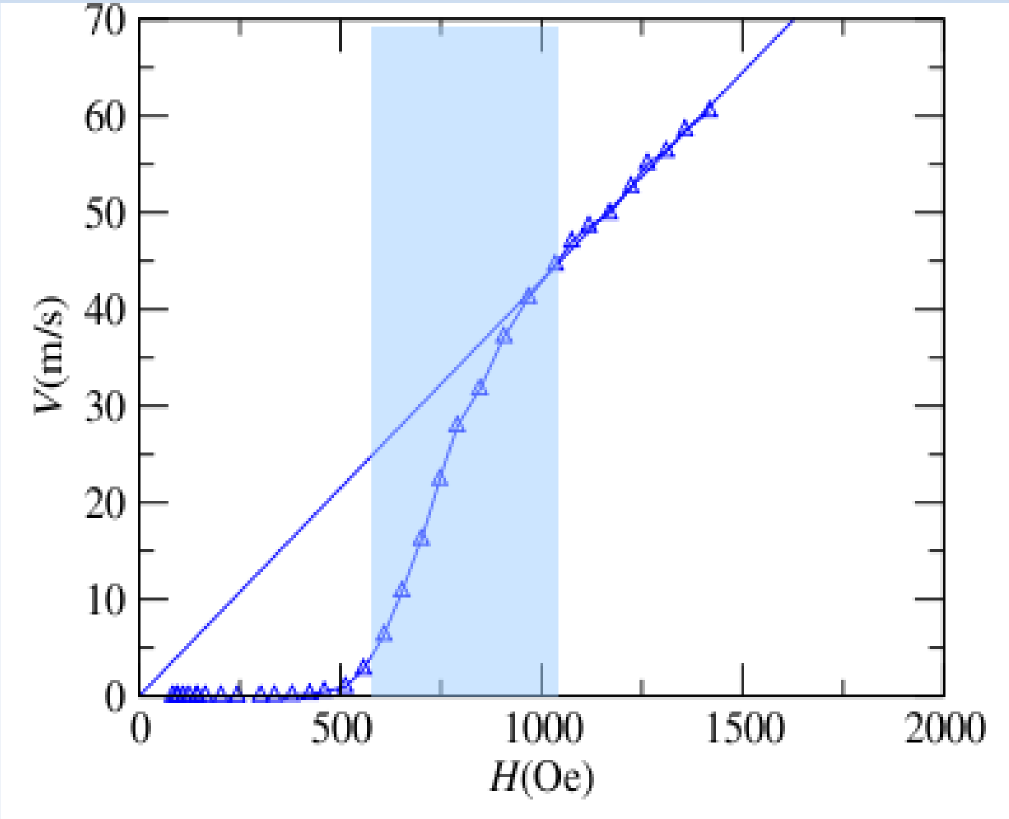


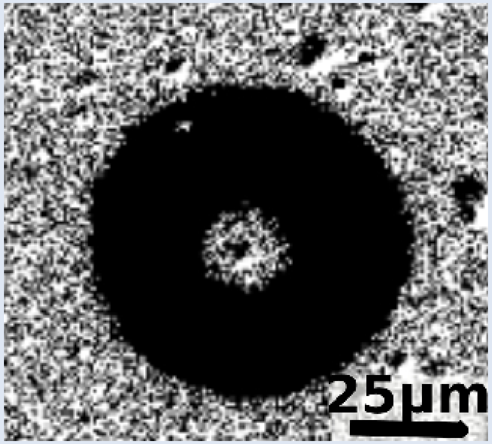


How far can this analogy be taken?

Depinning transition

creep depinning fast-flow





Minimum ingredients:

- interface degrees of freedom
- underlaying disorder
- driving force
- thermal fluctuations

experimental data, Pt/Co/Pt thin films, P. Metaxas et al 2007

Depinning transition

Disorder elastic system

Minimum ingredients:

- interface degrees of freedom
- underlaying disorder
- driving force
- thermal fluctuations

$$\mathcal{H}[u] = \int_L dz \left[\frac{c}{2} \left(\frac{\partial u}{\partial z} \right)^2 + V(u,x) + Fu \right]$$

Hamiltonian

$$\gamma \frac{\partial u(z,t)}{\partial t} = -\frac{\delta \mathcal{H}[u(z,t)]}{\delta u(z,t)} + \eta(z,t)$$

overdamped equation of motion

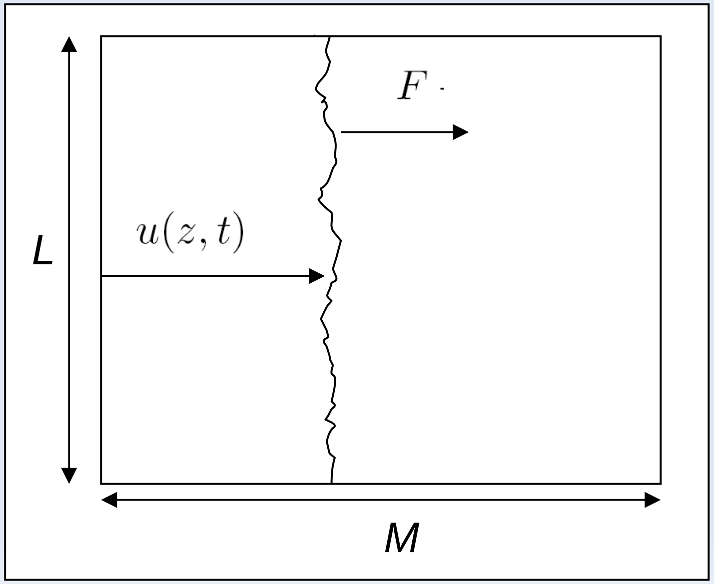
$$\frac{\partial u(z,t)}{\partial t} = \nu \frac{\partial^2 u(z,t)}{\partial z^2} + \xi(u,z) + \eta(z,t)$$

uncorrelated Random bond disorder

$$\begin{aligned} \overline{V(u,z)} &= 0 \\ \overline{V(u,z)V(u',z')} &= D_{\mathrm{RB}} \delta(u-u')\delta(z-z') \end{aligned}$$

uncorrelated thermal noise

$$\begin{aligned} \langle \eta(z,t) \rangle &= 0 \\ \langle \eta(z,t)\eta(z',t') \rangle &= 2\gamma T \delta(z-z')\delta(t-t') \end{aligned}$$

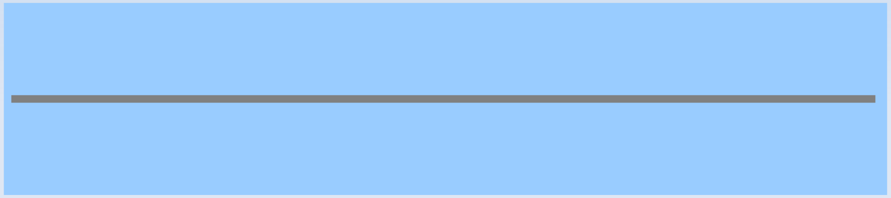


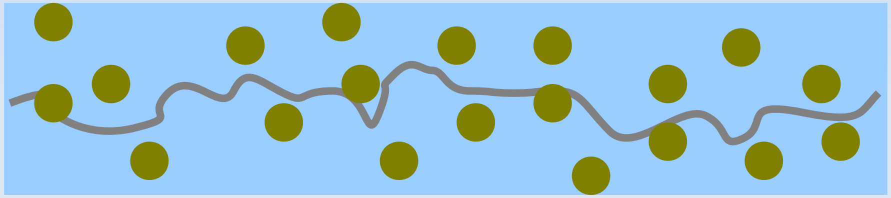
Depinning transition

Geometrical regimes

$$\mathcal{H}[u] = \int_L dz \left[\frac{c}{2} \left(\frac{\partial u}{\partial z} \right)^2 + V(u,x) \right]$$

competition between elasticity and disorder





roughness function
(heigh-heigh correlation)

$$B(r) = \overline{\left\langle [u(z,r) - u(z)]^2 \right\rangle}$$

$B(r) \sim r^{2\zeta}$ with ζ the **roughness exponent**

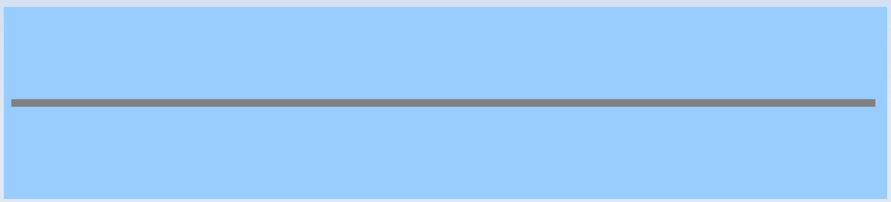
power-law behavior, signature of self-affine properties

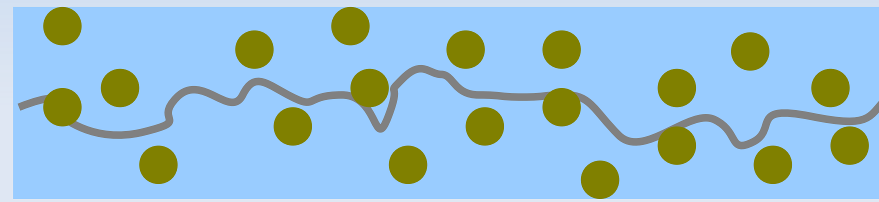
Depinning transition

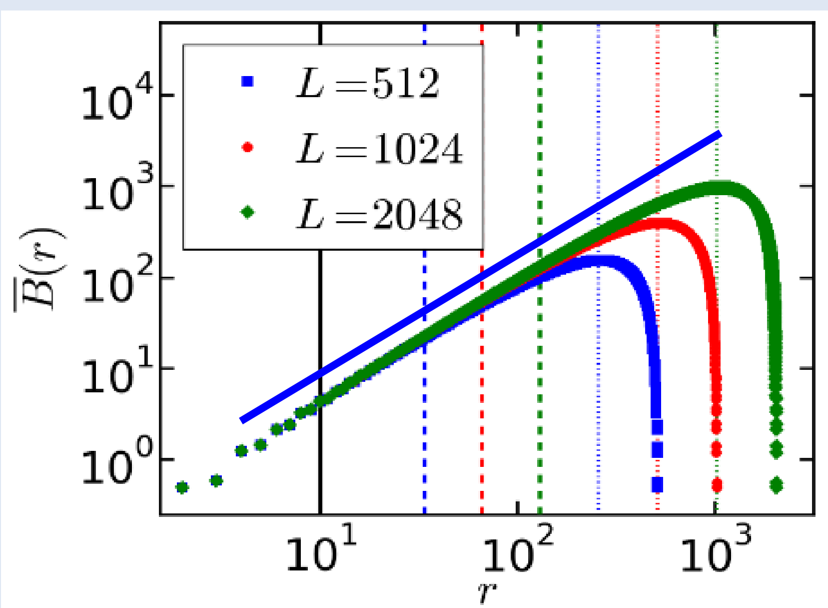
Geometrical regimes

$$\mathcal{H}[u] = \int_L dz \left[\frac{c}{2} \left(\frac{\partial u}{\partial z} \right)^2 + V(u,x) \right]$$

competition between elasticity and disorder







$$B(r) = \overline{\left\langle [u(z,r) - u(z)]^2 \right\rangle}$$

$B(r) \sim r^{2\zeta}$ with ζ the **roughness exponent**

power-law behavior, signature of self-affine properties

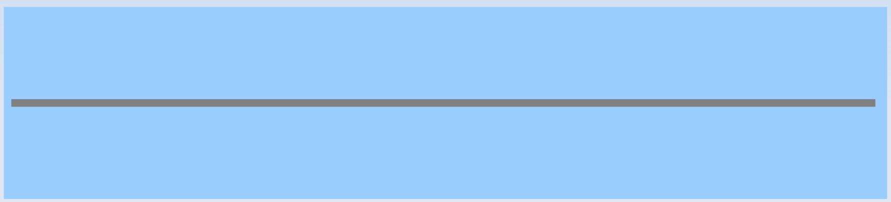
random matrix numerical simulation

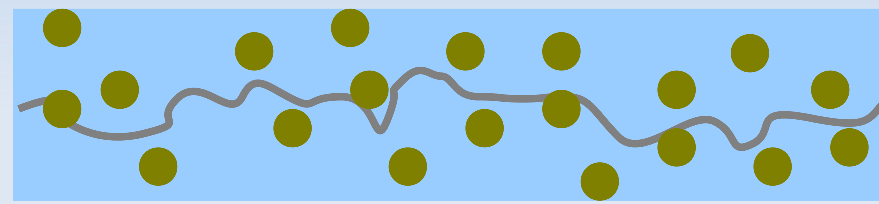
Depinning transition

Geometrical regimes

$$\mathcal{H}[u] = \int_L dz \left[\frac{c}{2} \left(\frac{\partial u}{\partial z} \right)^2 + V(u,x) \right]$$

competition between elasticity and disorder





$$\zeta_{eq} = 2/3$$

equilibrium roughness exponent
(zero force and zero temperature)

$$\zeta_{eq} > \zeta_{\mathrm{random-walk}} = 1/2$$

$$B(r) = \overline{\left\langle [u(z,r) - u(z)]^2 \right\rangle}$$

$B(r) \sim r^{2\zeta}$ with ζ the **roughness exponent**

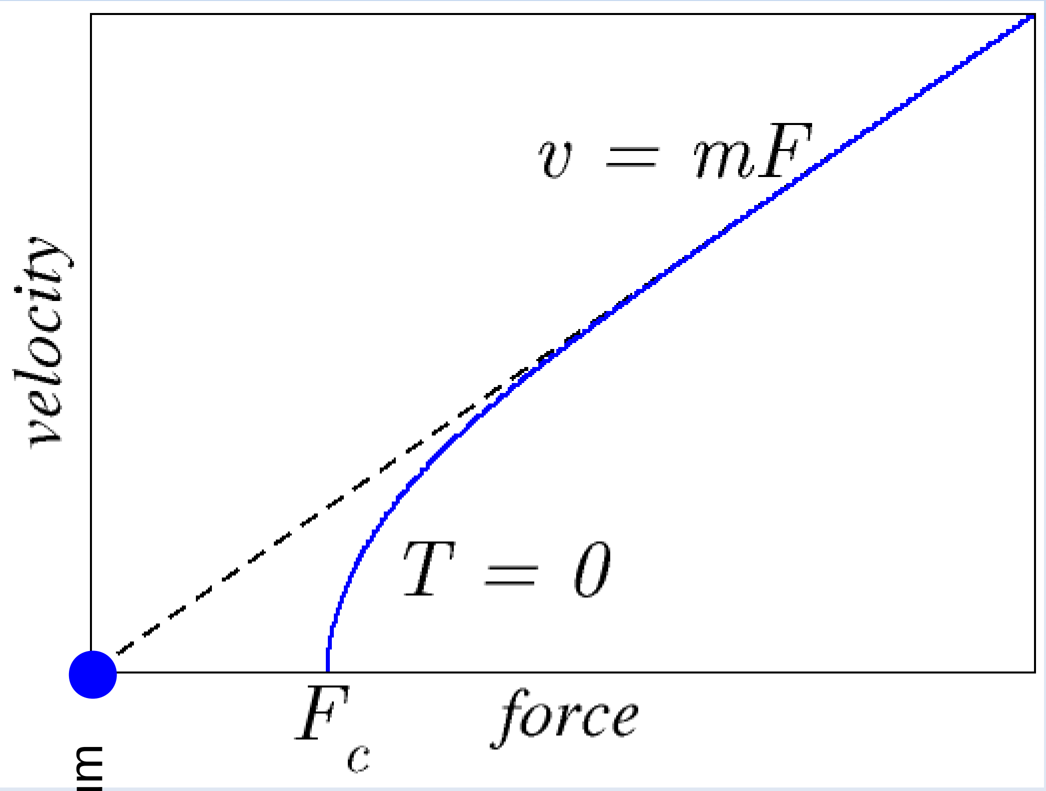
power-law behavior, signature of self-affine properties

the interface adjust to the disorder
environment and roughens

Depinning transition

Geometrical regimes

equilibrium $\zeta_{eq} = 2/3$



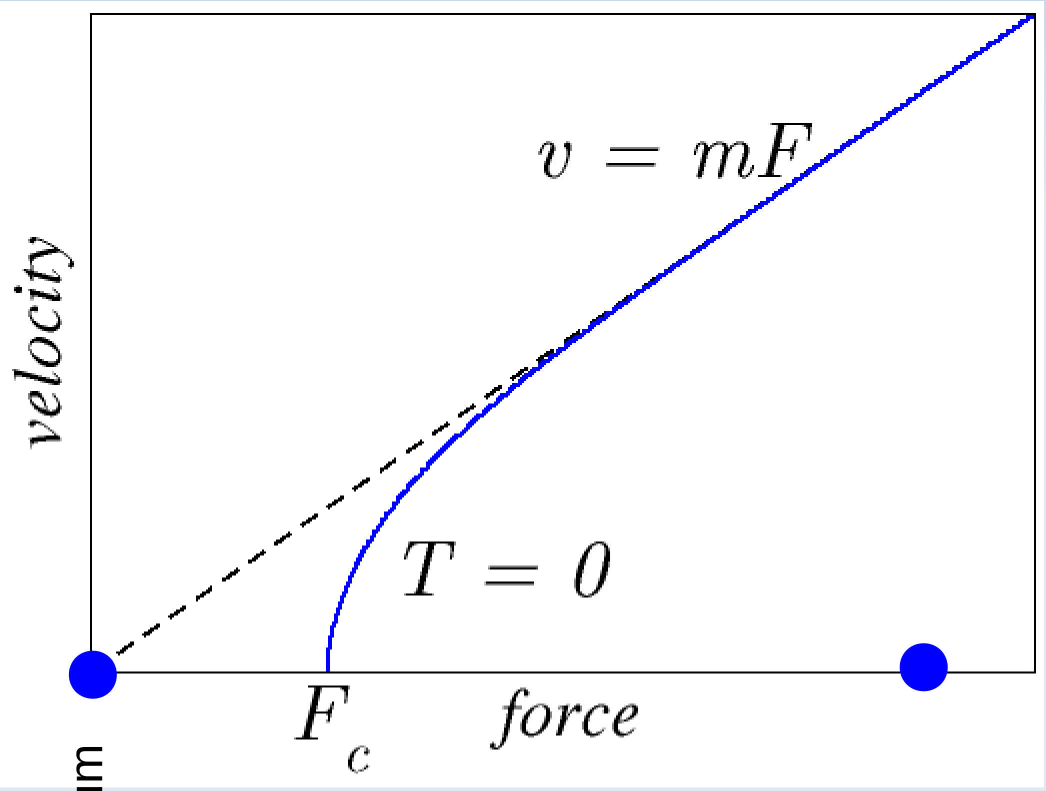
equilibrium

Depinning transition

Geometrical regimes

equilibrium $\zeta_{eq} = 2/3$

fast flow



equilibrium

fast flow

Depinning transition

Geometrical regimes

fast flow

$$\partial_t u(z,t) = \nu \partial_z^2 u(z,t) + \xi(u,z) = \nu \partial_z^2 u(z,t) + \xi(vt,z)$$

$$\begin{aligned} \overline{\tilde{\xi}(t,z)} &= \xi(vt,z) \\ \overline{\tilde{\xi}(t,z)\tilde{\xi}(t',z')} &= \frac{D}{v}\delta(t-t')\delta(z-z') \end{aligned}$$

disorder becomes an effective “thermal” noise of intensity $\frac{D}{v}$

$$\zeta_{FF} = \zeta_{\text{thermal}} = \zeta_{\text{random-walk}}$$

$$\boxed{\zeta_{FF} = 1/2}$$

Depinning transition

Geometrical regimes

fast flow

$$\partial_t u(z,t) = \nu \partial_z^2 u(z,t) + \xi(u,z) = \nu \partial_z^2 u(z,t) + \xi(vt,z)$$

$$\begin{aligned} \overline{\tilde{\xi}(t,z)} &= \xi(vt,z) \\ \overline{\tilde{\xi}(t,z)\tilde{\xi}(t',z')} &= \frac{D}{v}\delta(t-t')\delta(z-z') \end{aligned}$$

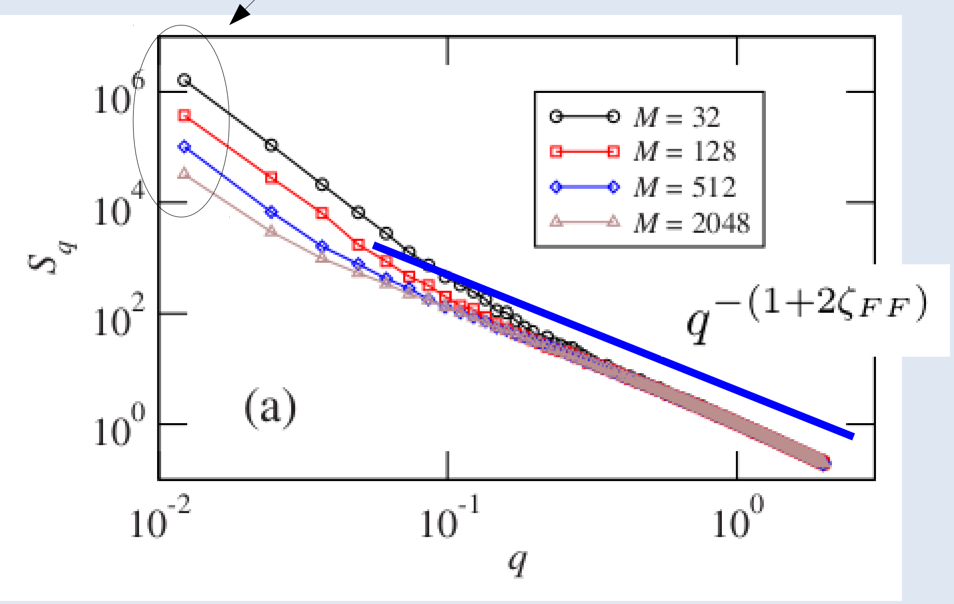
$$\zeta_{FF} = 1/2$$

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

$$B(r,t) = \int \frac{dq}{\pi}\,[1-\cos(qr)]\,S(q)$$

same information if $\zeta < 1$

finite size effects

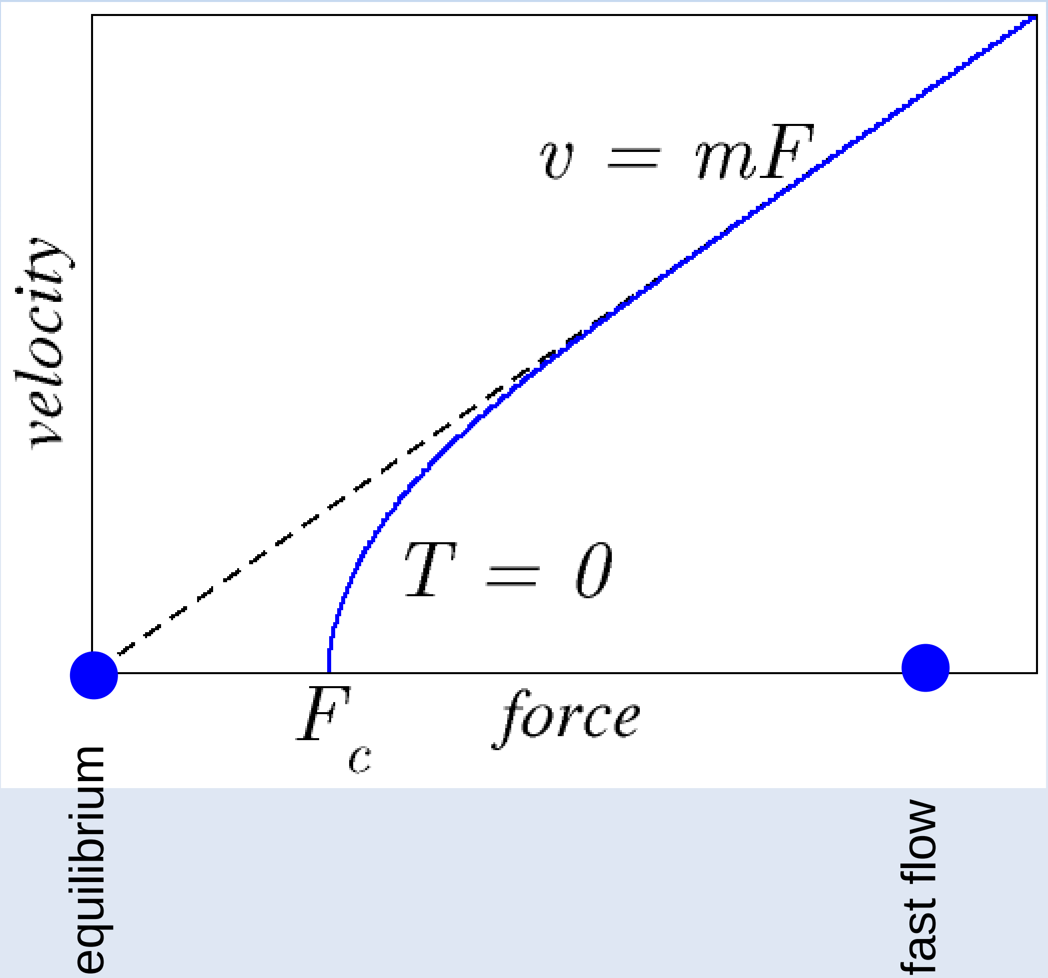


Depinning transition

Geometrical regimes

equilibrium $\zeta_{eq} = 2/3$

fast flow $\zeta_{FF} = 1/2$



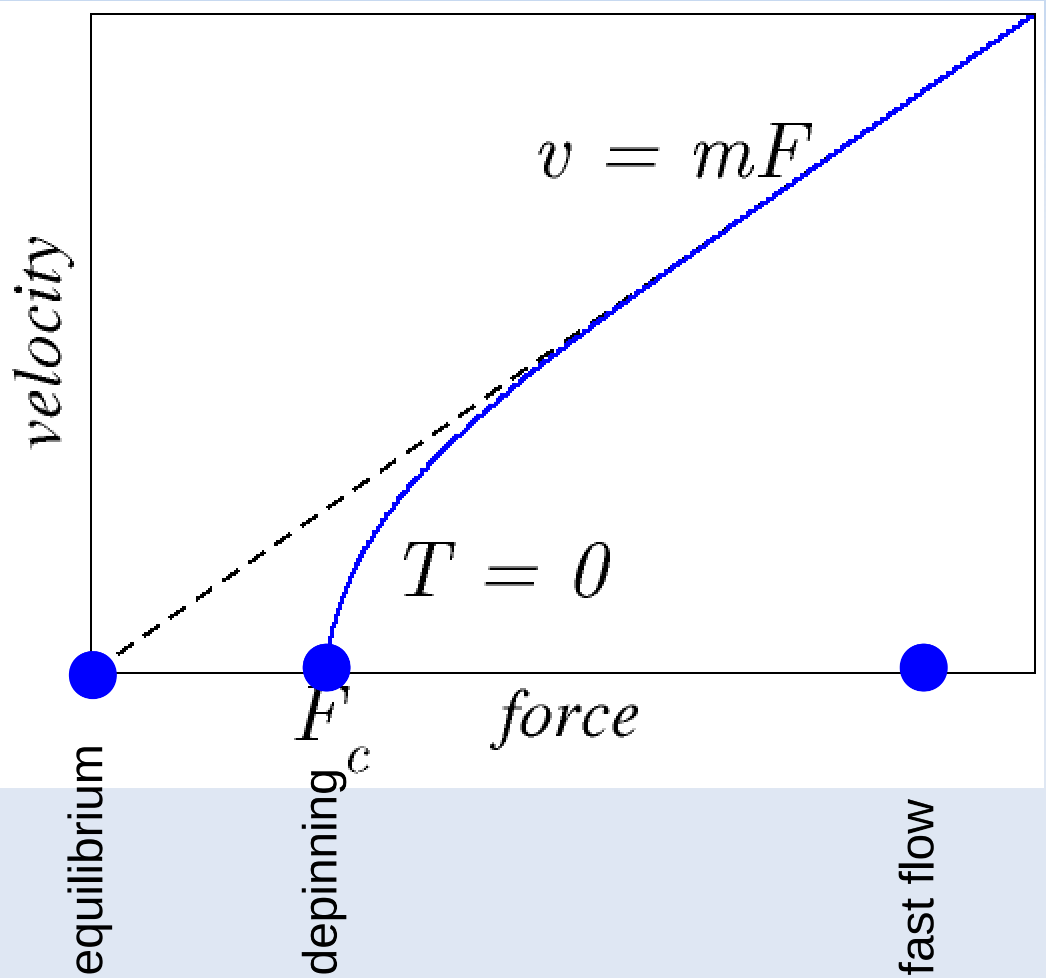
Depinning transition

Geometrical regimes

equilibrium $\zeta_{eq} = 2/3$

depinning

fast flow $\zeta_{FF} = 1/2$



Depinning transition

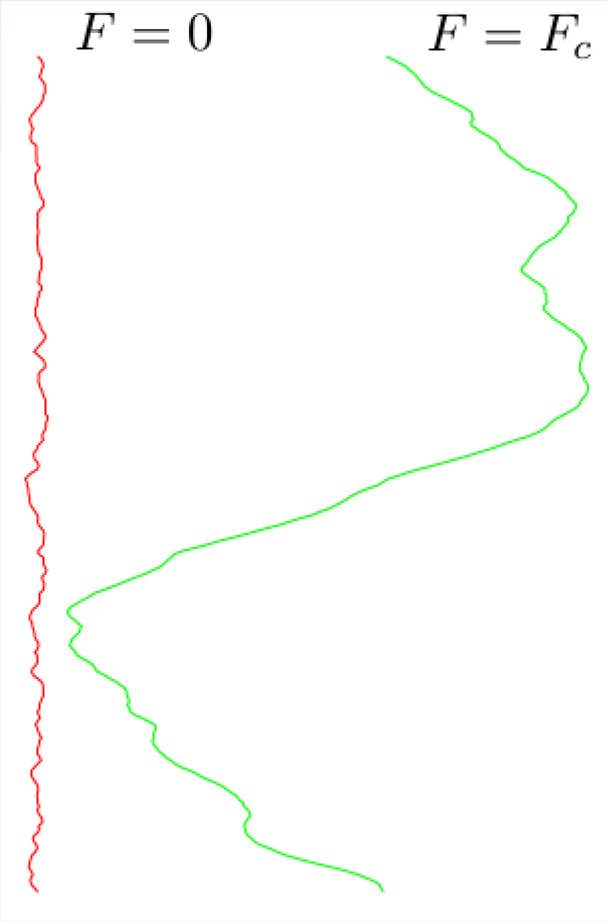
Geometrical regimes

depinning configuration

the interface becomes rougher: it is ready to move but stand still

"infinite" avalanche ready to move

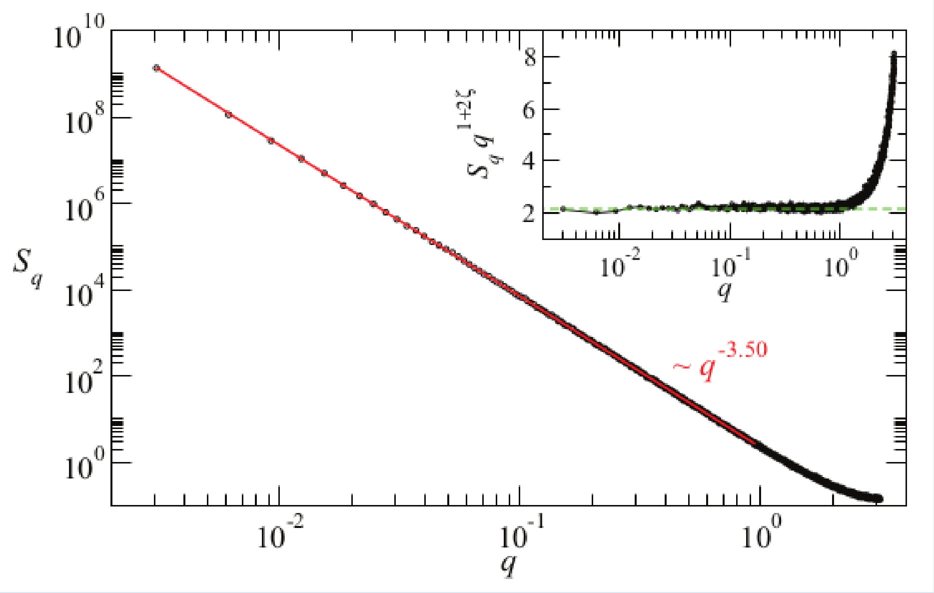
$$\xi \sim (F - F_c)^{-\nu}$$



$$S(q) \sim q^{-(1+2\zeta_{dep})}$$

$$\zeta_{dep} = 1.25$$

$$B(r) \sim r$$ (anomalous scaling)



Rosso, Krauth, PRE, 2001
Ferrero, Bustingorry, Kolton, PRE 2013

Depinning transition

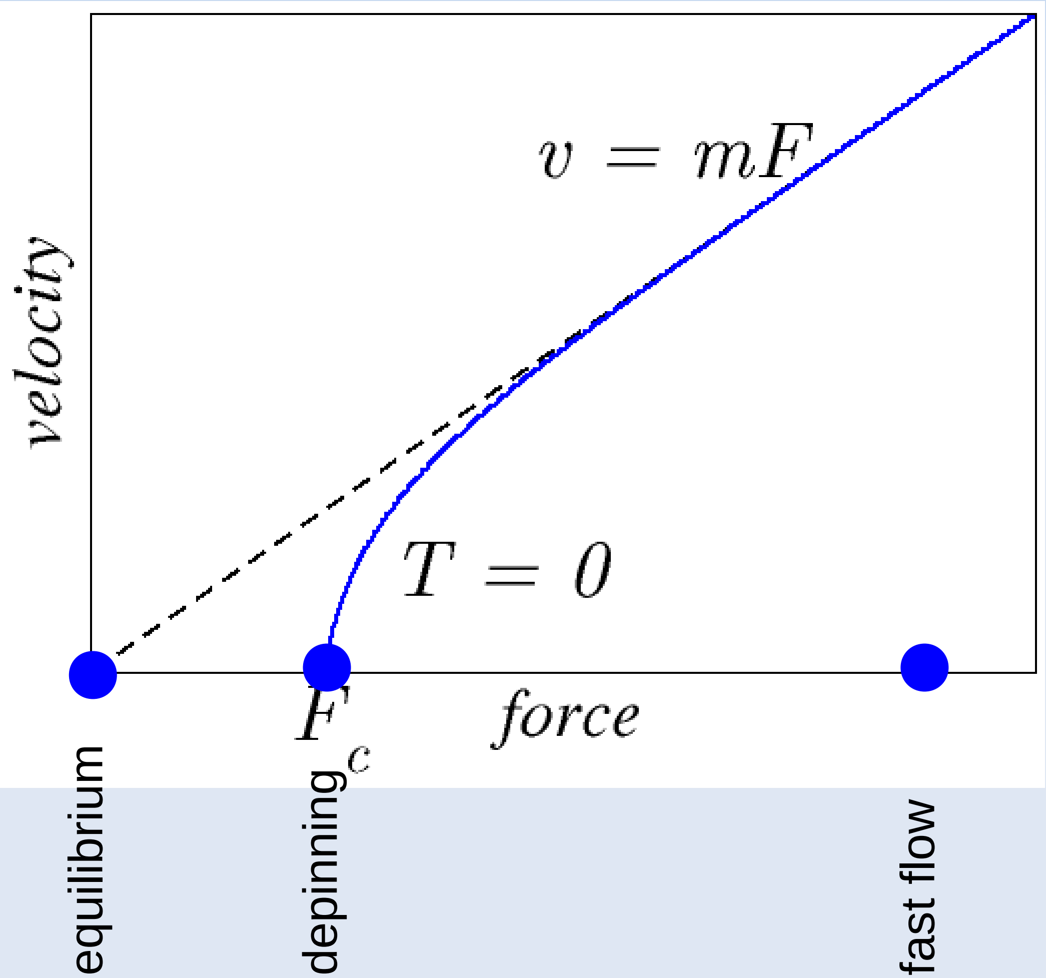
Geometrical regimes

equilibrium $\zeta_{eq} = 2/3$

depinning $\zeta_{dep} = 1.25$

fast flow $\zeta_{FF} = 1/2$

three geometrical “fixed points”
describing all length scales
(harmonic, RB)



Depinning transition

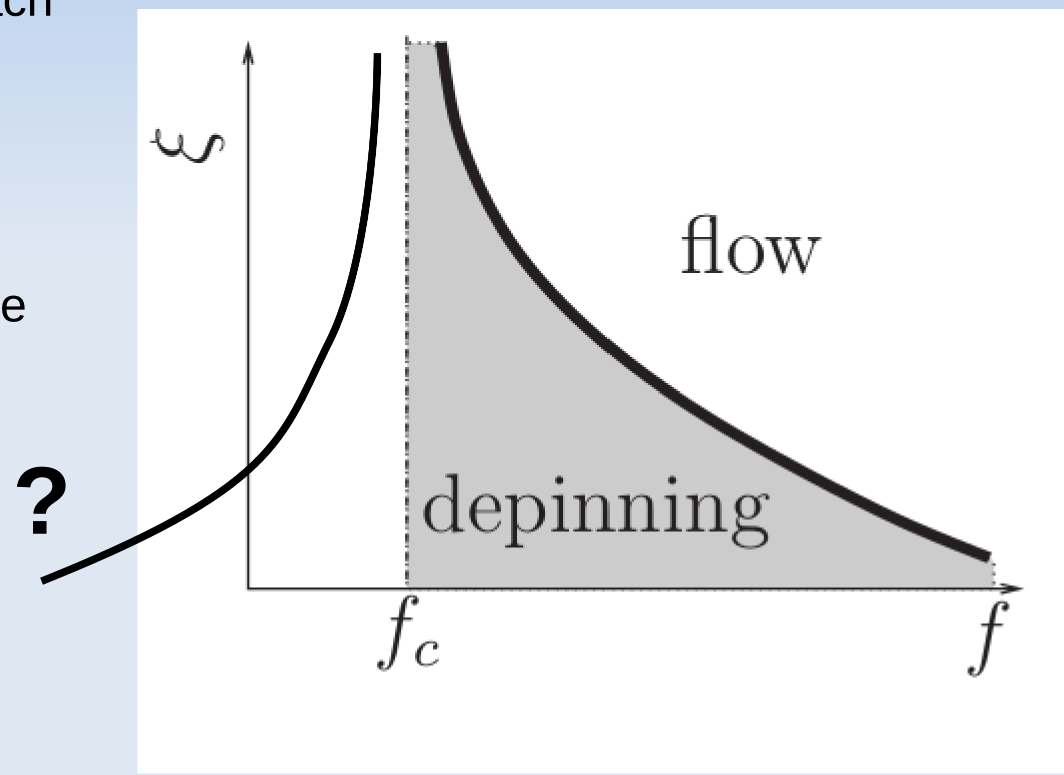
Geometrical regimes

typical size of an “avalanche”
which is critically pinned and detach

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

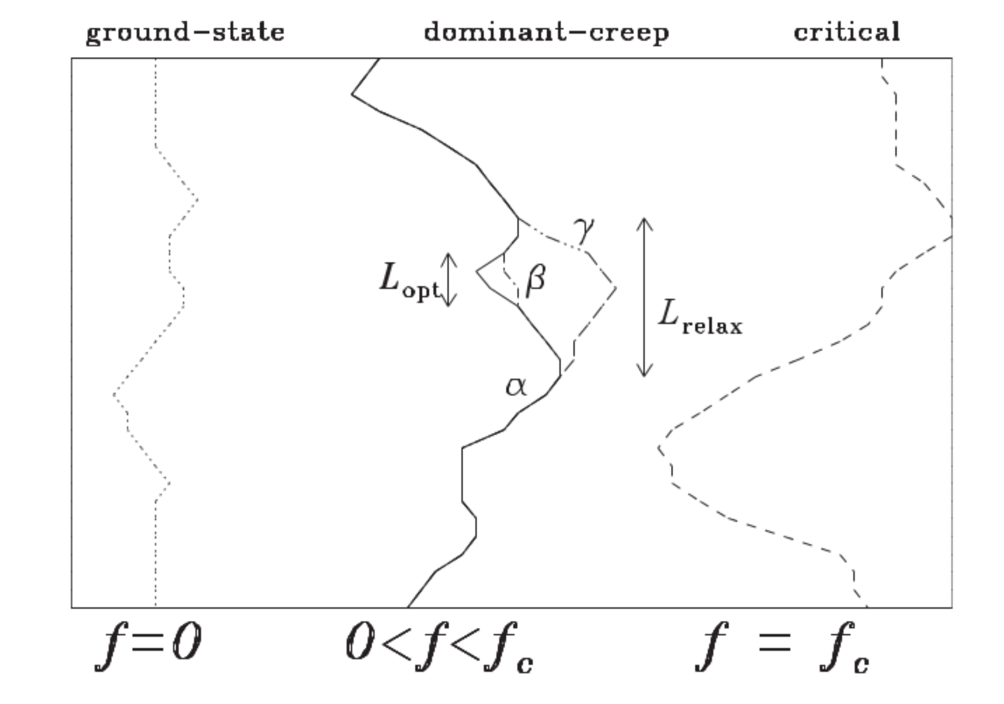
divergent correlation length from above

Is there a divergent correlation
length from below?

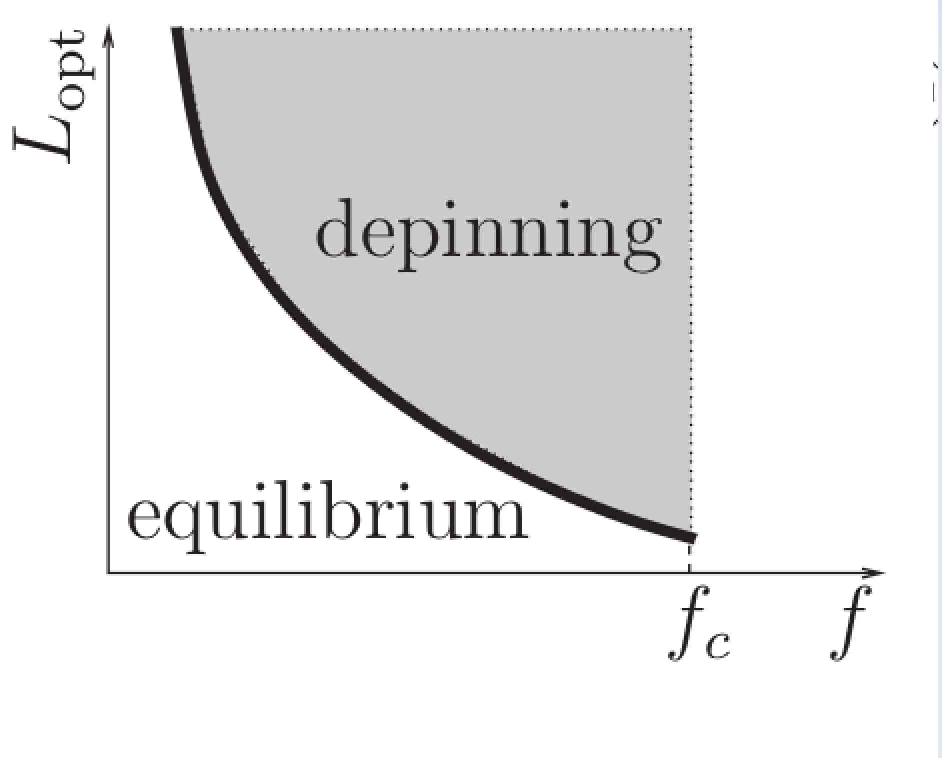


Depinning transition

Geometrical regimes



$L_{opt} \sim F^{-\nu_{eq}}$ $\nu_{eq} = 3/4$



sequence of metastable states

L_{opt} optimal size of the interface, necessary to excite to go to the next metastable state (steady state property)

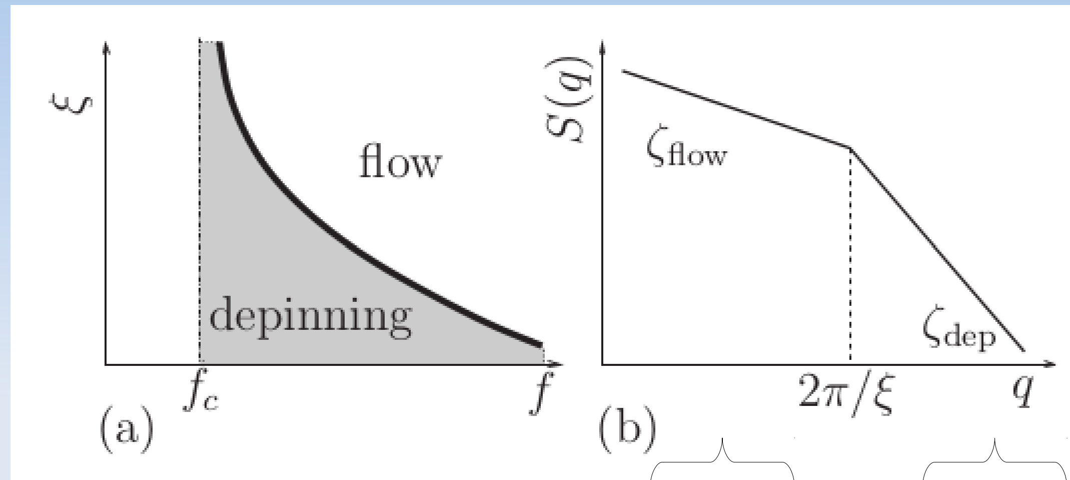
L_{relax} relaxed size of the next metastable state (transient dynamics)

Kolton et al, PRL, 2006; PRB 2009

Depinning transition

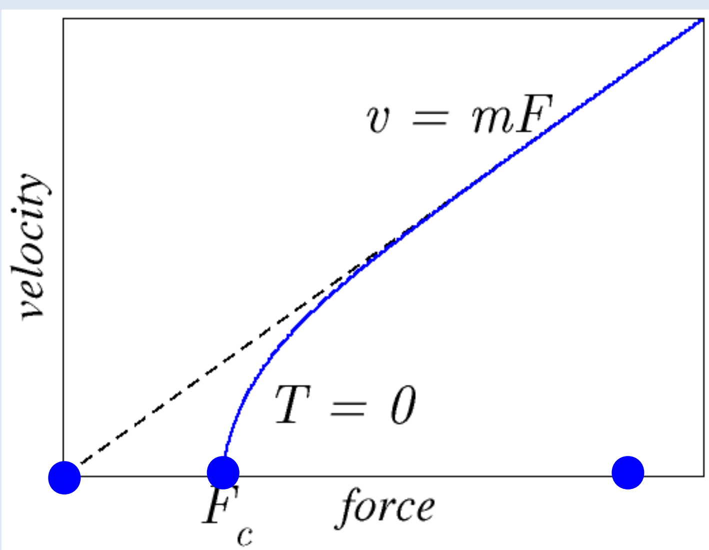
Geometrical regimes

separation between length scales with different geometrical properties



large length scale

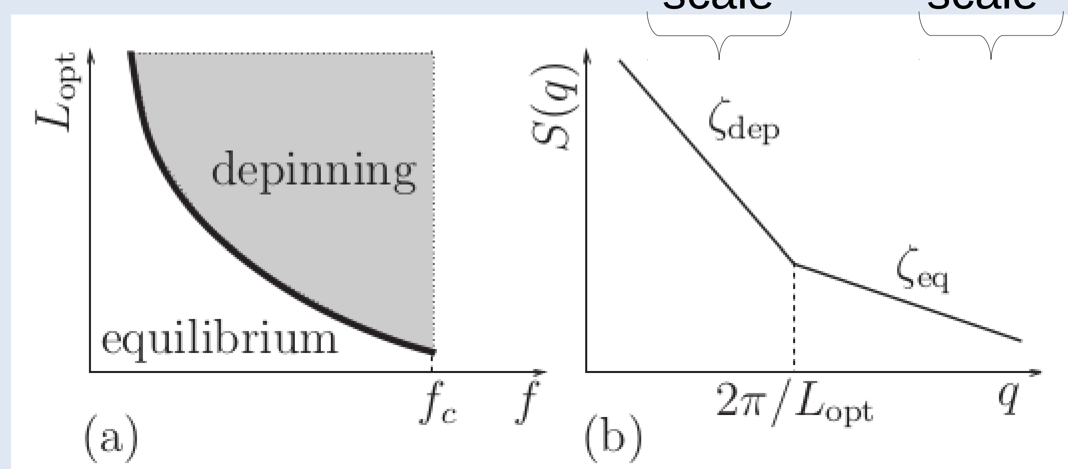
small length scale



eq

dep

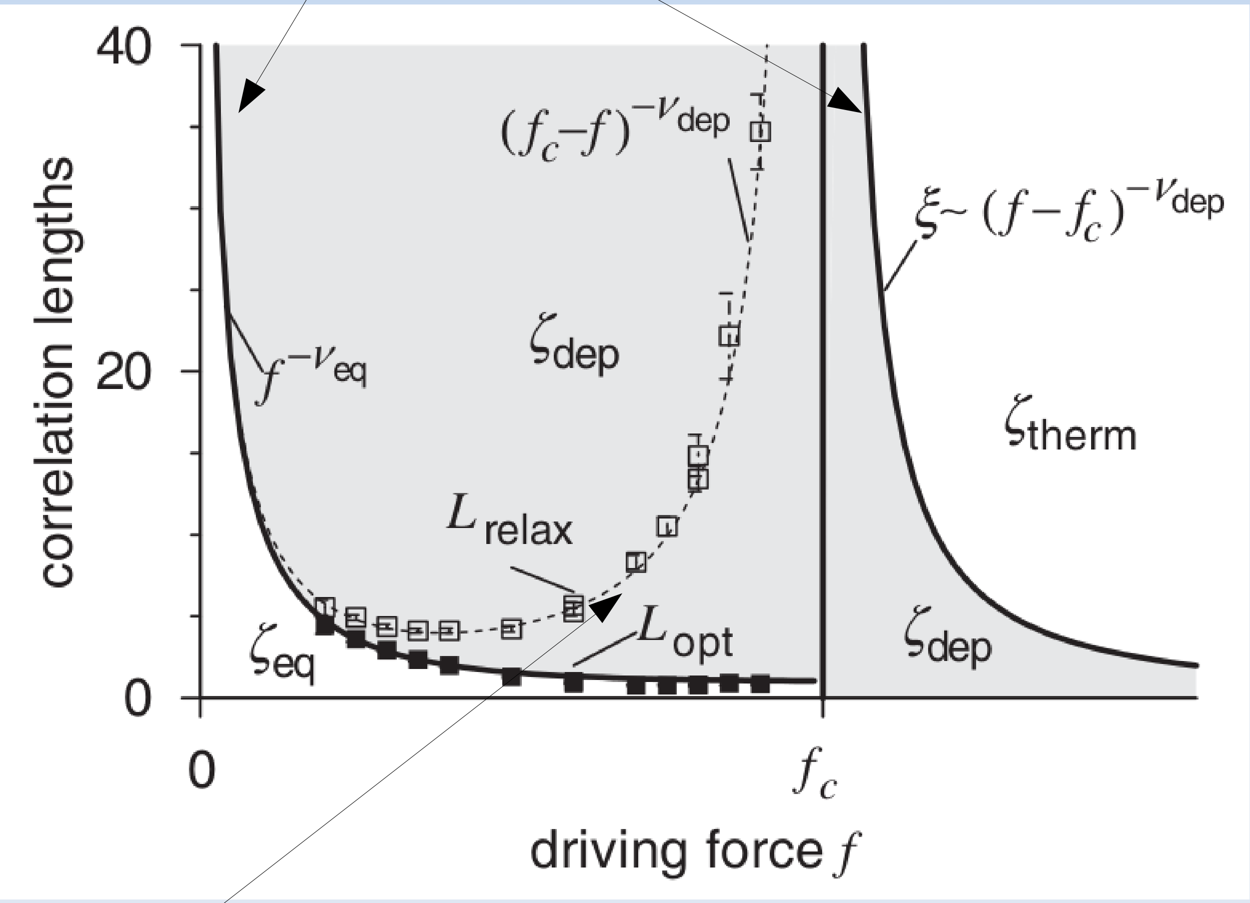
FF



Depinning transition

Geometrical regimes

divergent steady state length scales



dynamic length

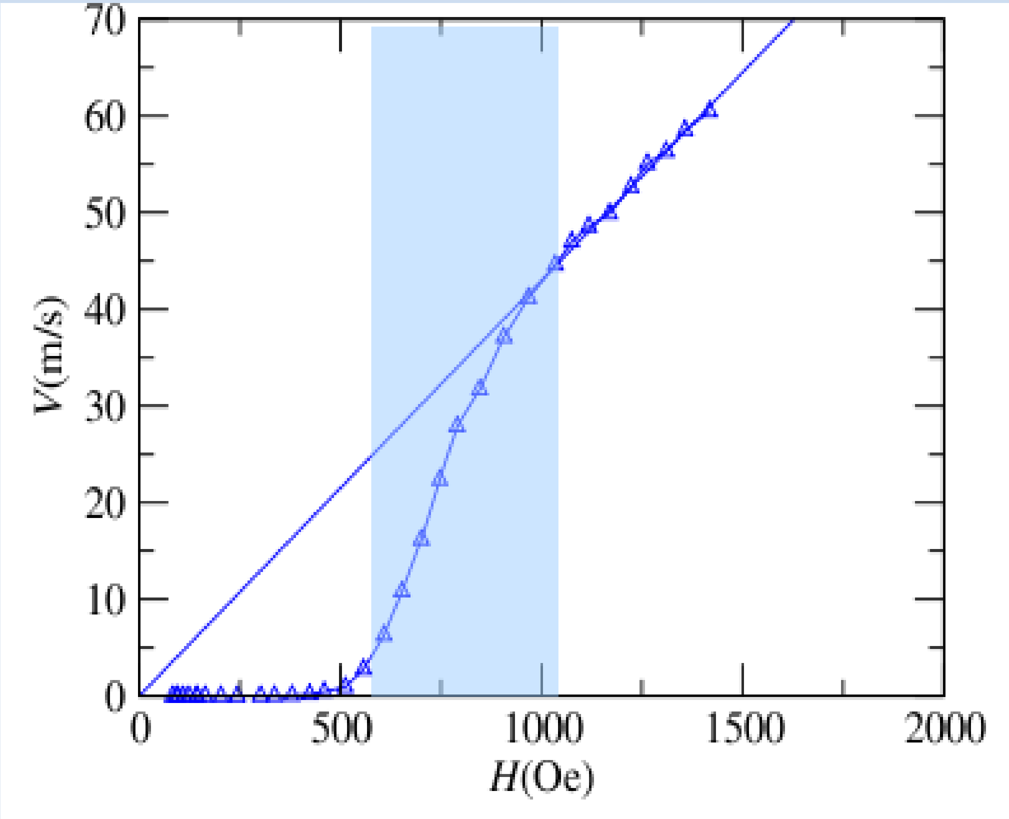
not as in standard critical phenomena

Kolton et al, PRL, 2006; PRB 2009

Depinning transition

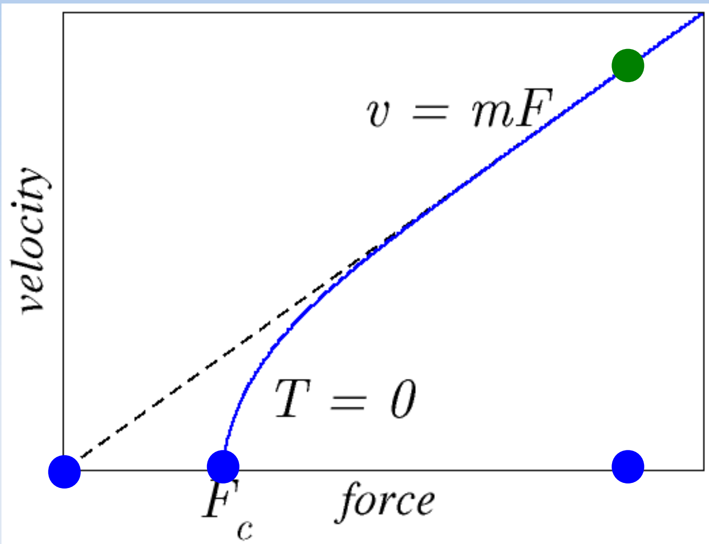
Dynamical regimes

creep depinning fast-flow



Depinning transition

Dynamical regimes



fast flow

$$V = mF$$

mobility

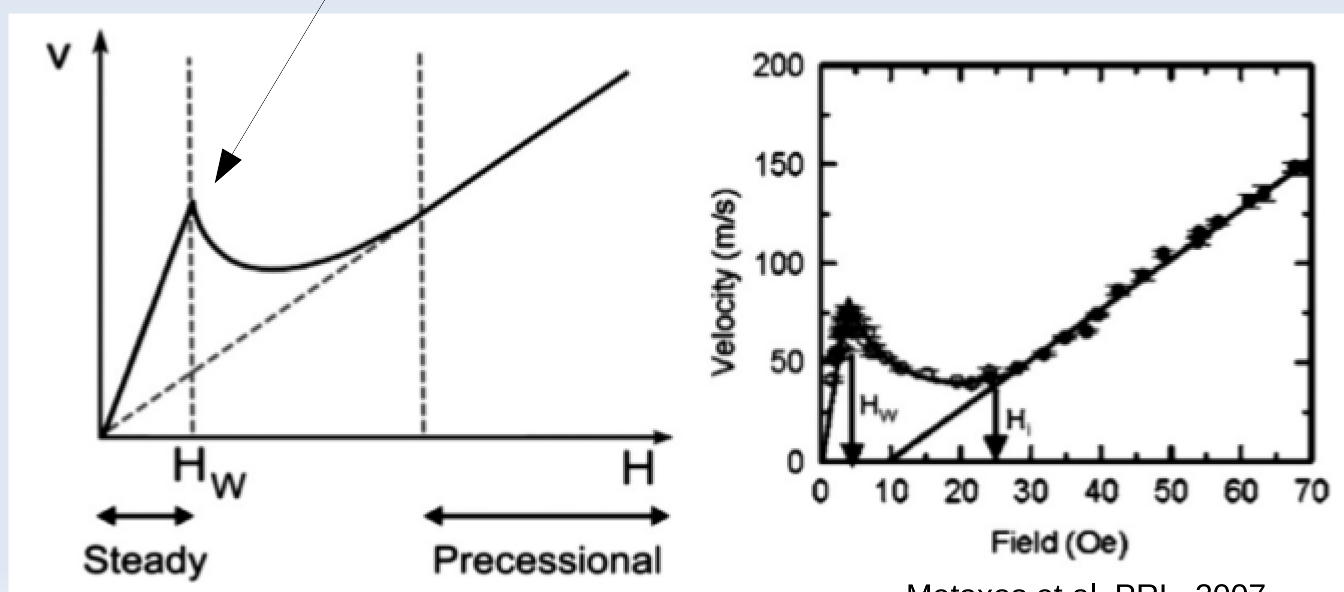
it seems simple.... but not so simple

Walker field

internal degree of freedom of de domain wall

not considered in the simple disordered elastic system model

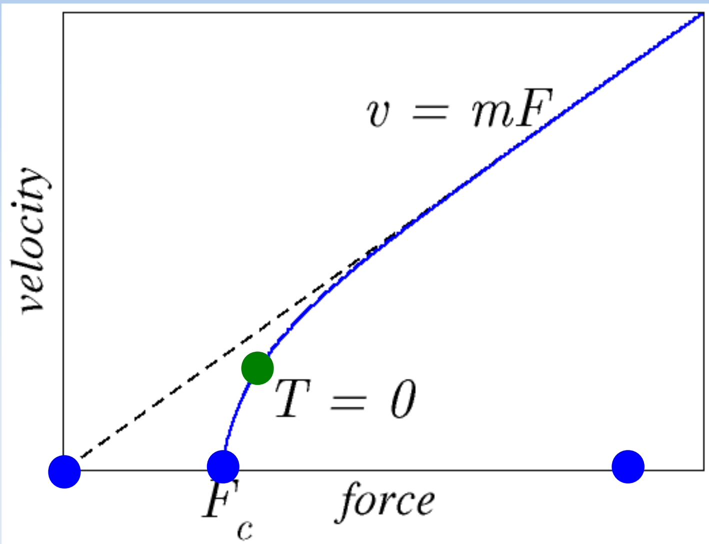
either H_W is too high or too small



Metaxas et al, PRL, 2007
Beach et al, Nat Mat, 2005

Depinning transition

Dynamical regimes



zero temperature depinning

$$F \leq F_c \quad \Rightarrow \quad V = 0$$

$$F \gtrsim F_c \quad \Rightarrow \quad \begin{cases} V \sim (F - F_c)^{\beta} \\ \xi \sim (F - F_c)^{-\nu} \end{cases}$$

$\beta = 0.25$:depinning exponent

$\nu = 4/3$:correlation length exponent

$$\beta = 0.245 \pm 0.006$$
$$\nu = 1.333 \pm 0.007$$

numerical studies of relaxation properties in extremely large elastic line systems

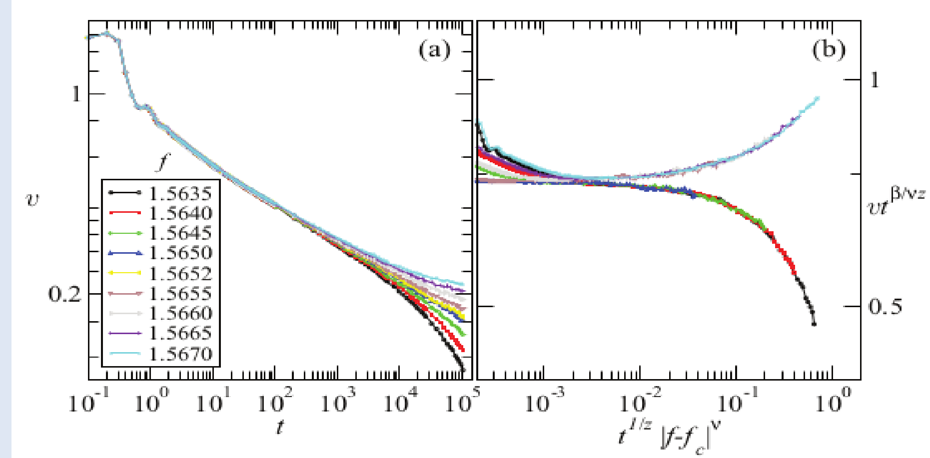
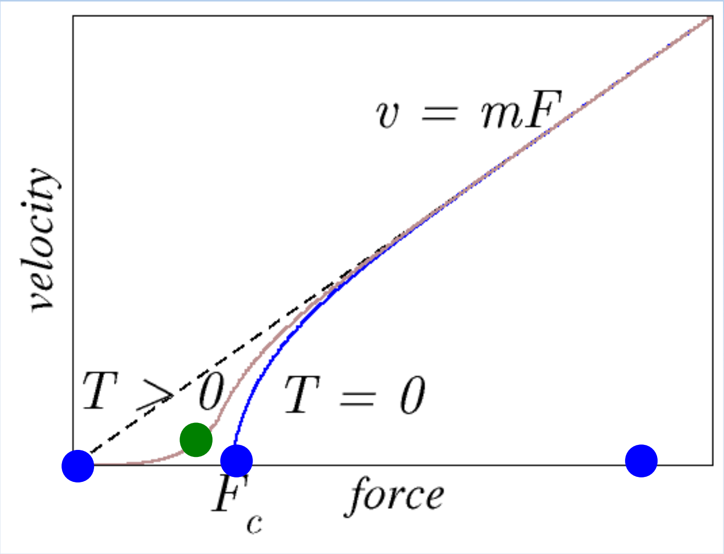


FIG. 13. (Color online) String velocity $v(t)$ as a function of time for the RB case with uniformly distributed disorder for which $f_c = 1.5652$ using $\delta t = 0.1$. The system size is $L = 4\,194\,304$. In (a) we present the raw data, and in (b) $v(t,f)$ has been rescaled to $vt^{\beta/\nu z}$ and t to $t^{1/z}|f - f_c|^{\nu}$.

Ferrero, Bustingorry, Kolton, PRE 2013

Depinning transition

Dynamical regimes



creep: simple scaling argument

energy scale

$$\mathcal{H} \sim \int dz(\partial_z u)^2 \Rightarrow U \sim \ell^{2\zeta+d-2} \sim \ell^\theta$$

energy exponent $\theta = 2\zeta_{eq} + d - 2$

the movement is achieved by overcoming the barriers associated to the optimal length

$$U \sim L_{opt}^\theta \sim F^{-\theta\nu}$$

velocity is given by Arrhenius activation over this characteristic energy scale

$$U(F) = U_c \left(\frac{F}{F_c}\right)^{-\mu}$$

$$V = V_0 \exp\left(-\frac{U}{k_B T}\right) = V_0 \exp\left[-\frac{U_c}{k_B T}\left(\frac{F}{F_c}\right)^{-\mu}\right]$$

creep exponent

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

$(d = 1)$ $\mu = 1/4$

Nattermann, PRL 1990
Chauve, Giamarchi, Le Doussal, PRB 2002

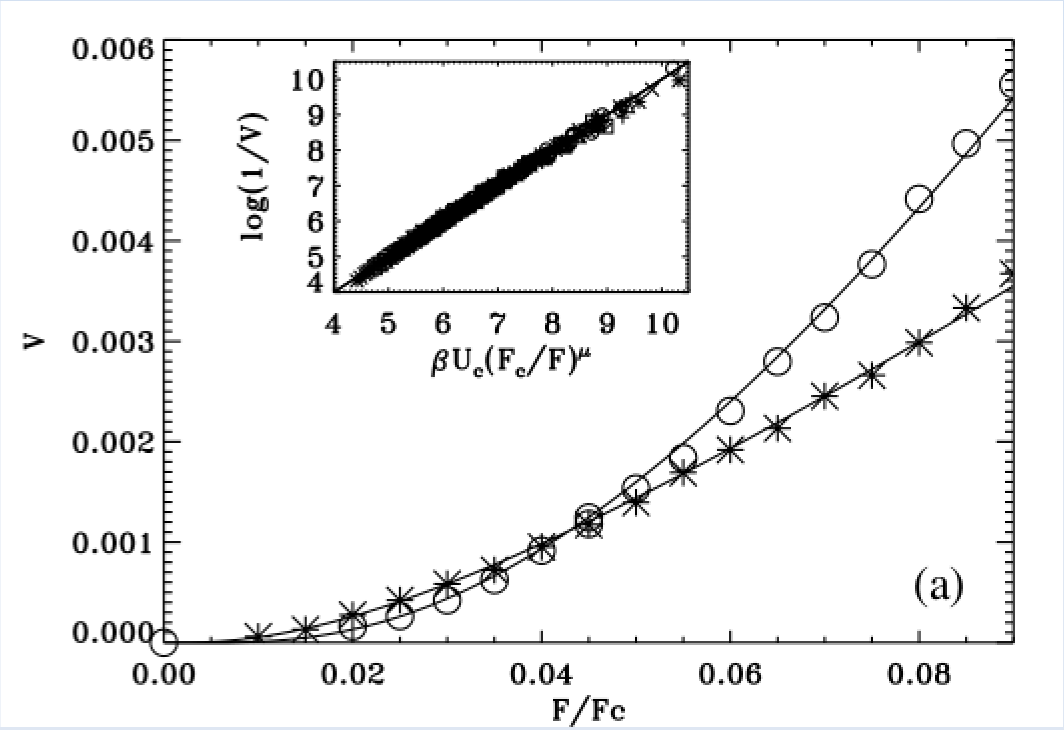
Depinning transition

Dynamical regimes

$$V = V_0 \exp\left(-\frac{U}{k_B T}\right) = V_0 \exp\left[-\frac{U_c}{k_B T}\left(\frac{F}{F_c}\right)^{-\mu}\right]$$

$\mu = 1/4$

robust exponent!



Numerically,
disorder elastic system
Kolton, Rosso, Giamarchi, PRL, 2005

Depinning transition

Dynamical regimes

$$V = V_0 \exp\left(-\frac{U}{k_B T}\right) = V_0 \exp\left[-\frac{U_c}{k_B T}\left(\frac{F}{F_c}\right)^{-\mu}\right]$$

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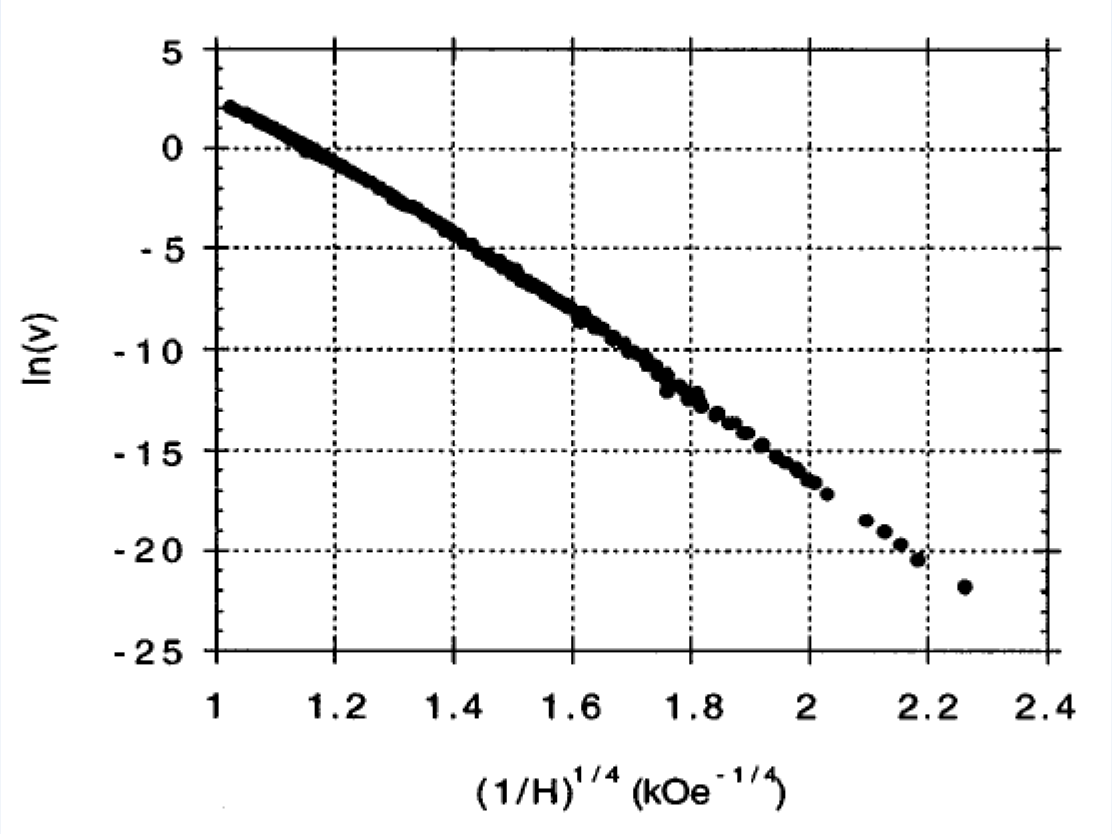
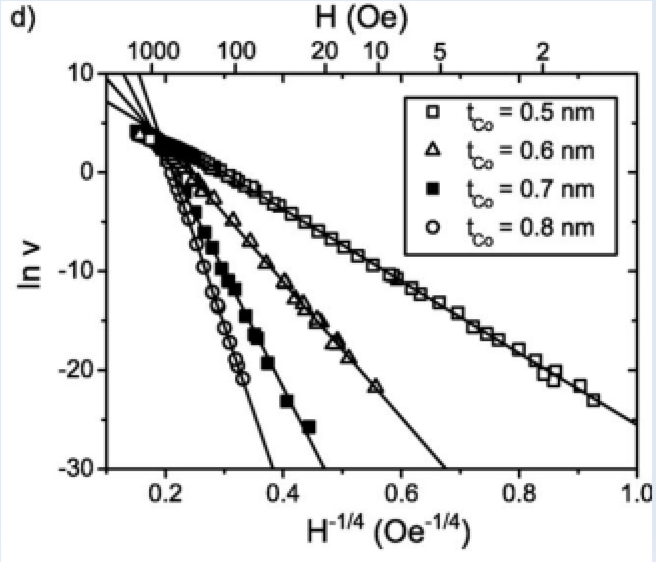


Pt/Co/Pt
ferromagnetic ultrthin film (0.5nm)
LPS, Orsay
Lemerle et al, PRL, 1998



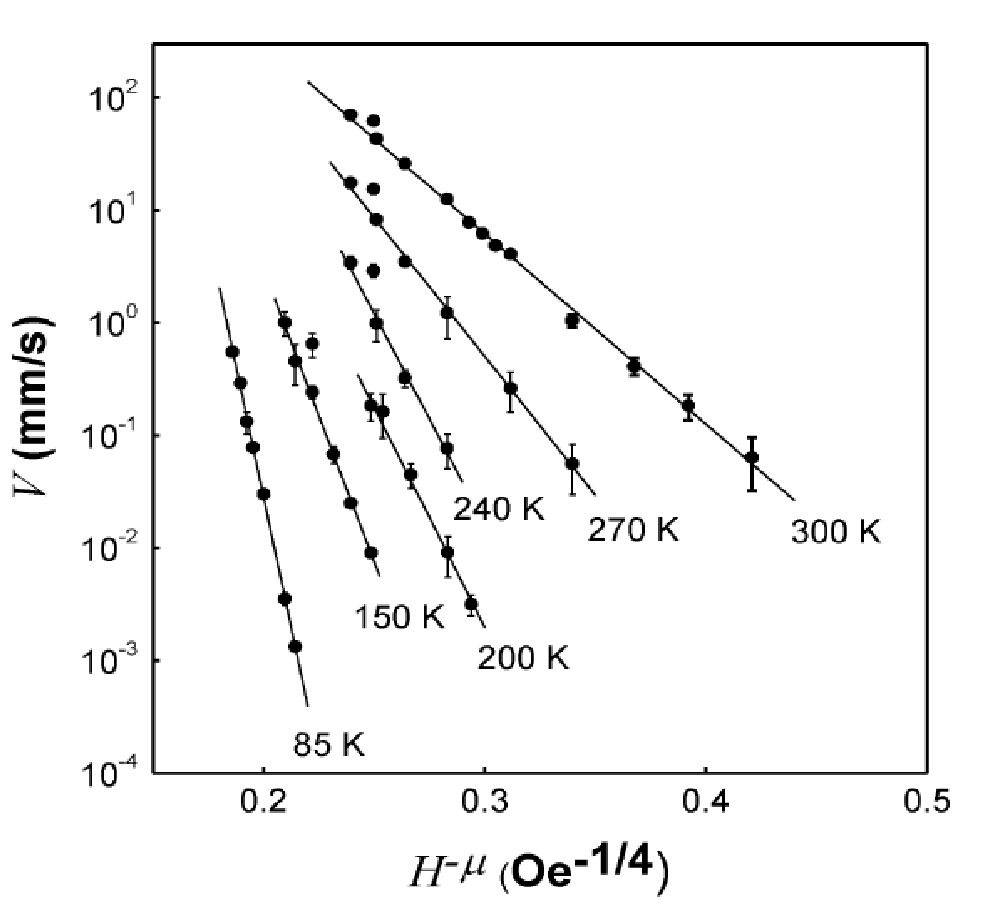
Metaxas et al, PRL, 2007

Depinning transition

Dynamical regimes

$$V = V_0 \exp\left(-\frac{U}{k_B T}\right) = V_0 \exp\left[-\frac{U_c}{k_B T}\left(\frac{F}{F_c}\right)^{-\mu}\right]$$

$\mu = 1/4$ robust exponent!



Pt/CoFe/Pt
ferromagnetic ultrthin film (0.3nm)
Kim, Kim, Choe, IEEE TMag.,2009

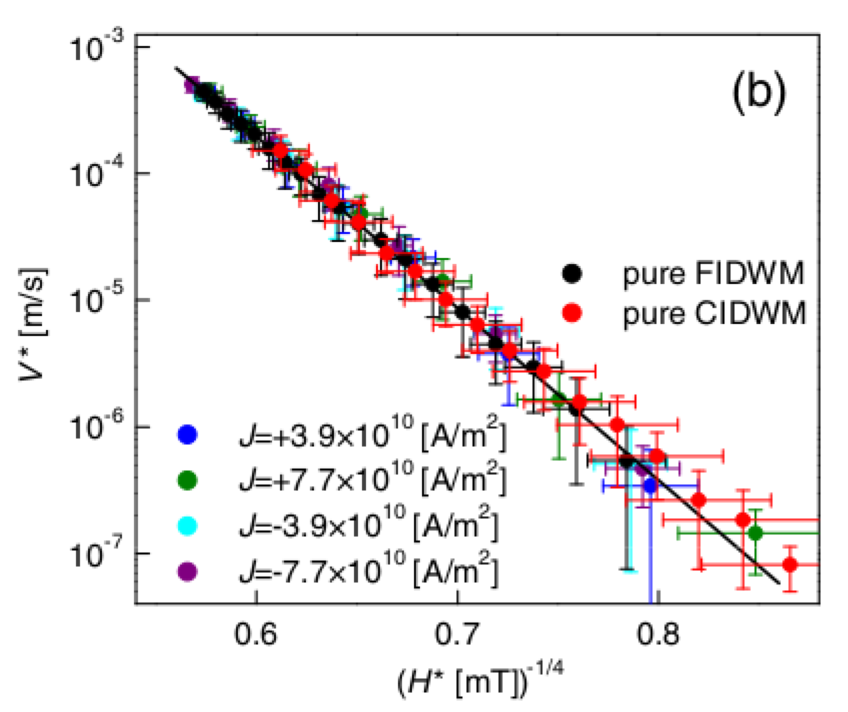
different temperatures

Depinning transition

Dynamical regimes

$$V = V_0 \exp\left(-\frac{U}{k_B T}\right) = V_0 \exp\left[-\frac{U_c}{k_B T}\left(\frac{F}{F_c}\right)^{-\mu}\right]$$

$\mu = 1/4$ robust exponent!



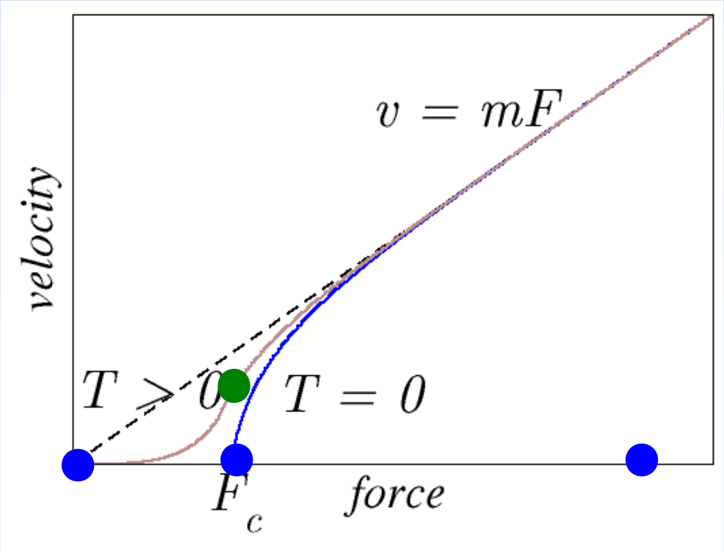
Pt/Co/Pt
ferromagnetic nanowire
Lee et al, PRL,2011

effective field including
current induced velocity

$$H^*_{\rm th} = H - \varepsilon_{\rm th} J - \eta_{\rm th} J^2 \sqrt{H - \varepsilon_{\rm th} J} + \frac{2}{5}\eta_{\rm th}^2 J^4$$

Depinning transition

Dynamical regimes

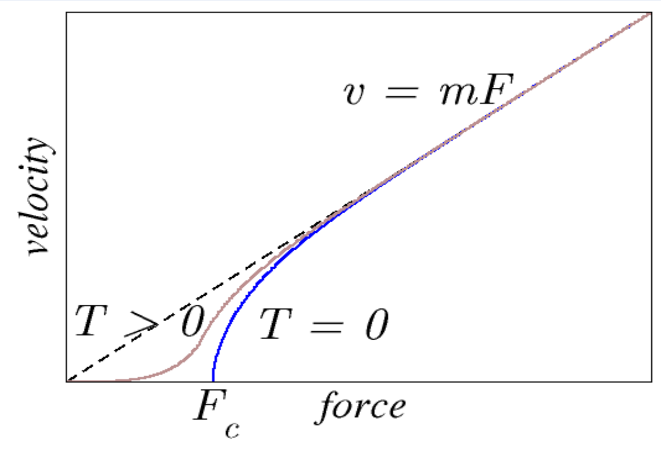


finite temperature depinning: **Thermal rounding**

from standard critical phenomena

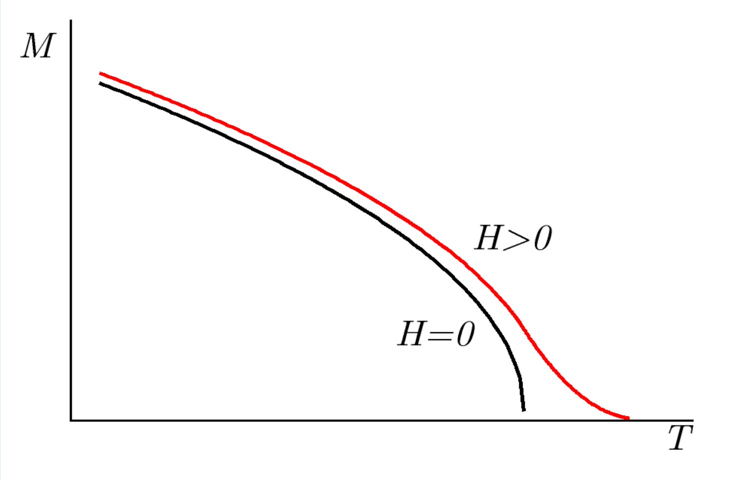
$$F = F_c \Rightarrow V \sim T^{\psi}$$

ψ **:thermal rounding exponent**



$V \sim T^{\psi}$

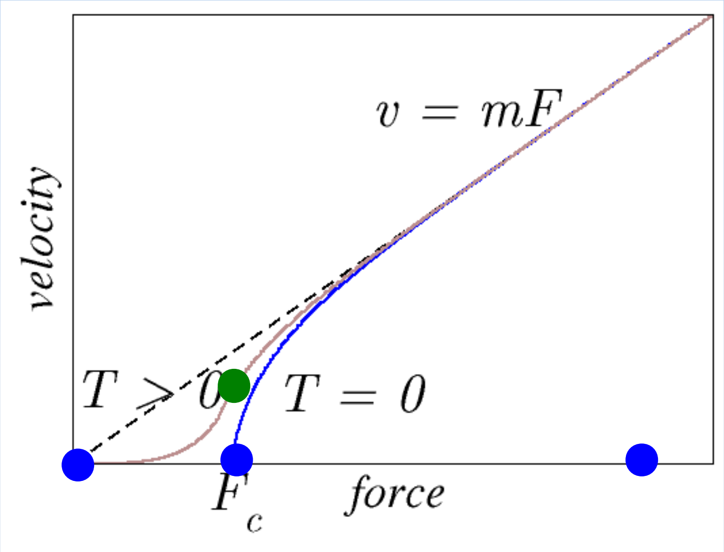
field rounding



$M \sim h^{1/\delta}$

Depinning transition

Dynamical regimes



finite temperature depinning: **Thermal rounding**

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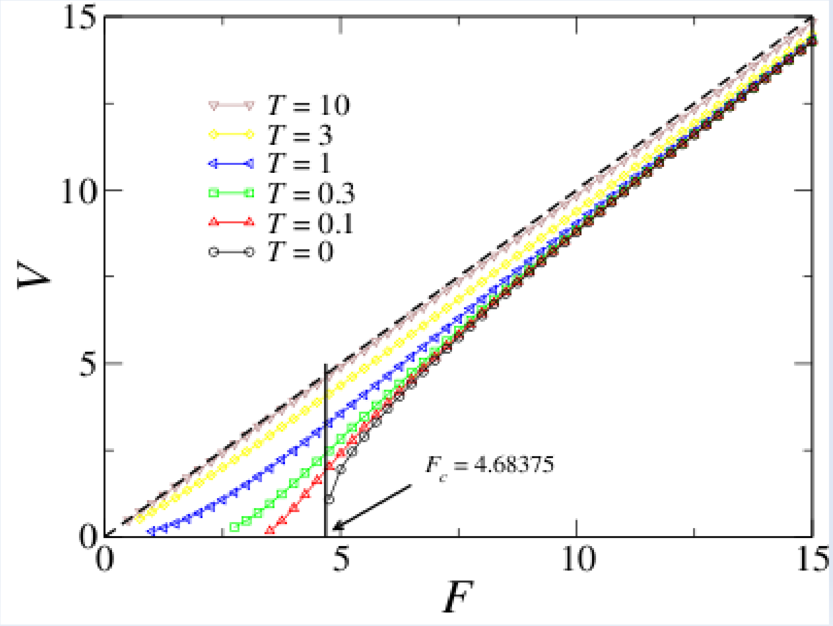
ψ **:thermal rounding exponent**

$$\psi = 0.15 \pm 0.01$$

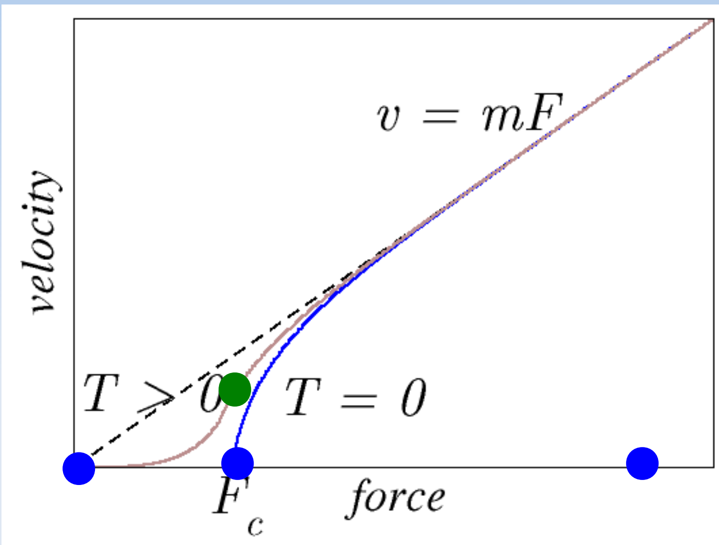
numerical simulation
disodered elastic system



Bustingorry, Kolton, Giamarchi, PRE 2012

Depinning transition

Dynamical regimes



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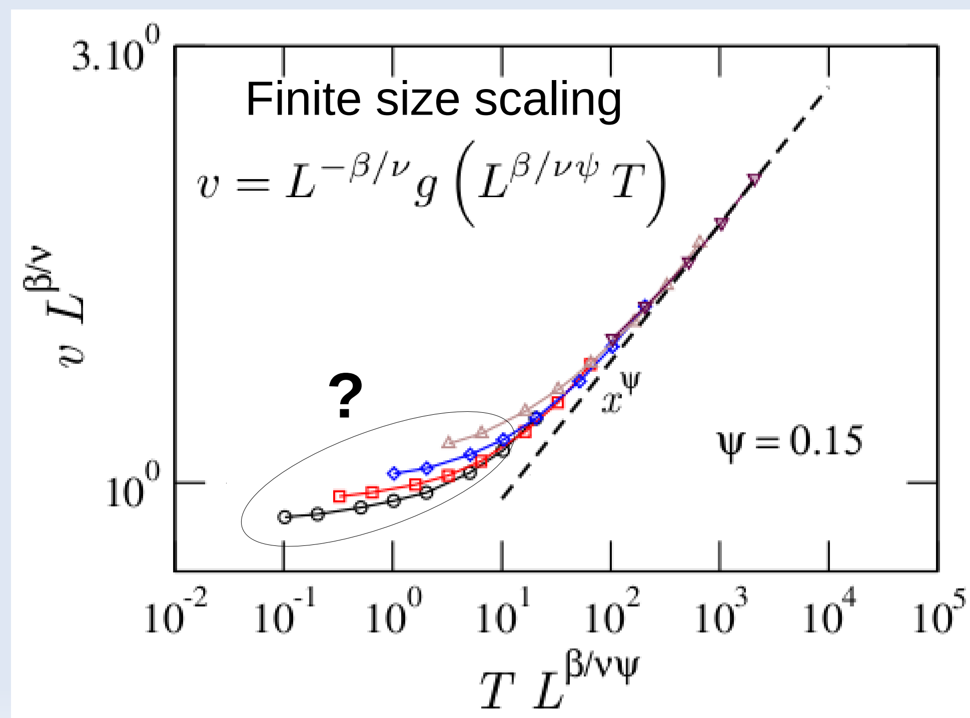


numerical simulation
disodered elastic system

Bustingorry, Kolton, Giamarchi, PRE 2012

Depinning transition

Dynamical regimes

finite temperature depinning: **Thermal rounding**

$$F = F_c \Rightarrow V \sim T^{\psi}$$

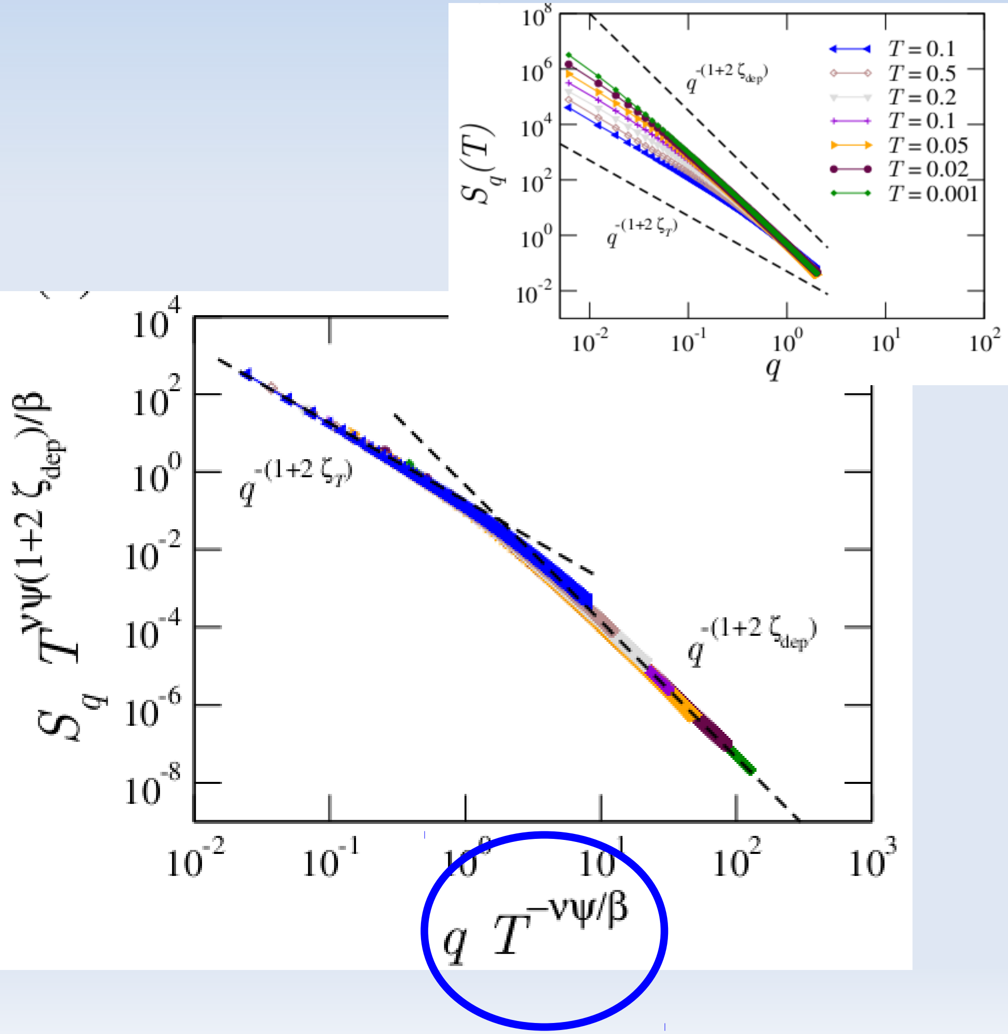
$$F = F_c \Rightarrow \xi \sim T^{\psi\nu/\beta}$$

$$\xi \sim (F - F_c)^{-\nu} \sim V^{-\nu/\beta}$$

geometrical properties

$$\psi = 0.15 \pm 0.01$$

numerical simulation
disodered elastic system



Bustingorry, Kolton, Giamarchi, PRE 2012

Depinning transition

Dynamical regimes

$$F = F_c \Rightarrow V \sim T^{\psi}$$

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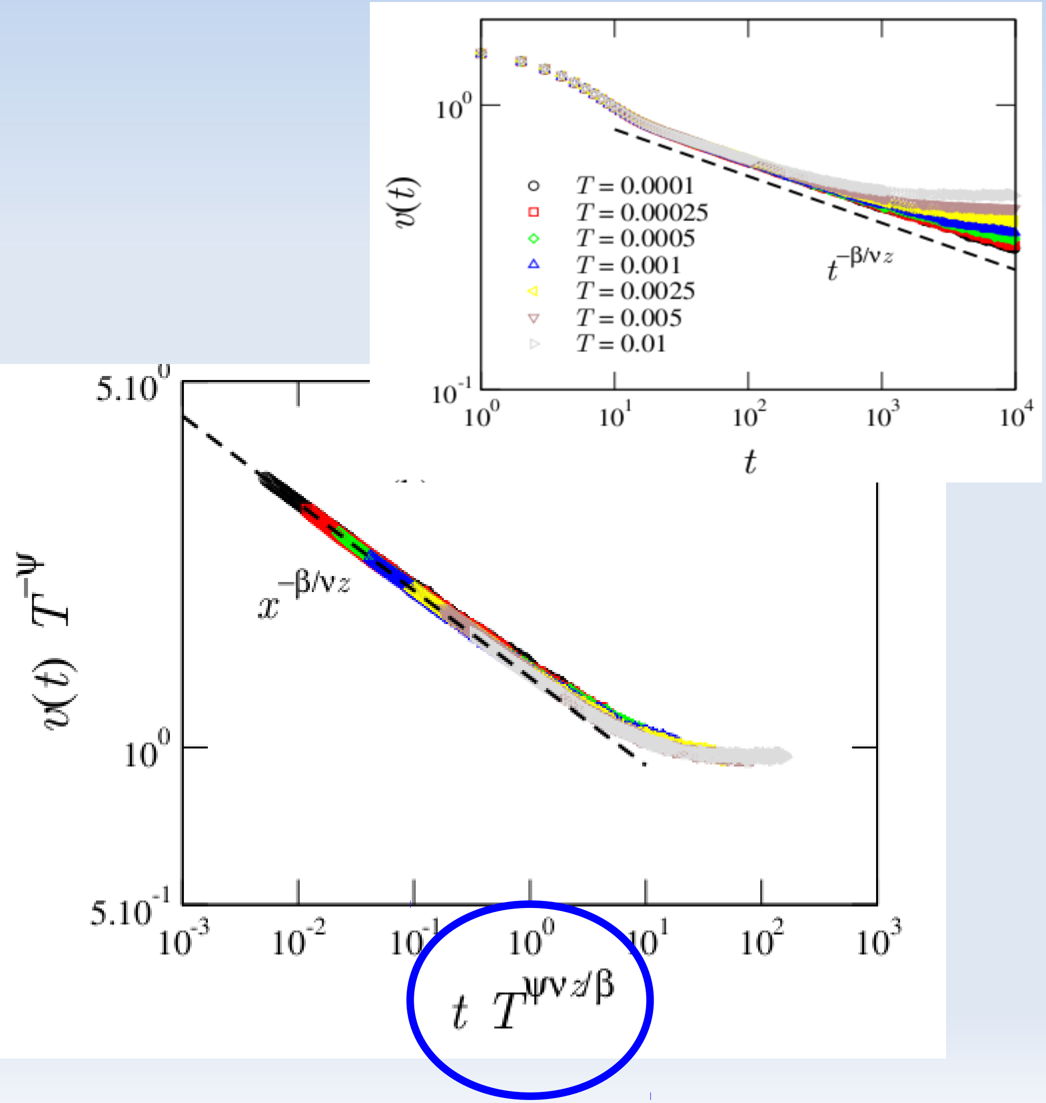
$$\xi \sim (F - F_c)^{-\nu} \sim V^{-\nu/\beta}$$

short time dynamics

$$\psi = 0.15 \pm 0.01$$

numerical simulation
disodered elastic system

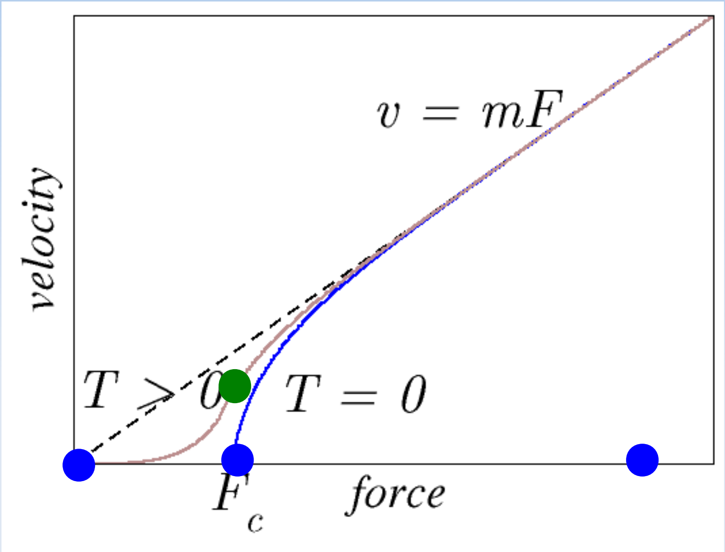
finite temperature depinning: **Thermal rounding**



Bustingorry, Kolton, Giamarchi, PRE 2012

Depinning transition

Dynamical regimes



finite temperature depinning: **Thermal rounding**

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$$F = F_c \Rightarrow V \sim T^{\psi}$$

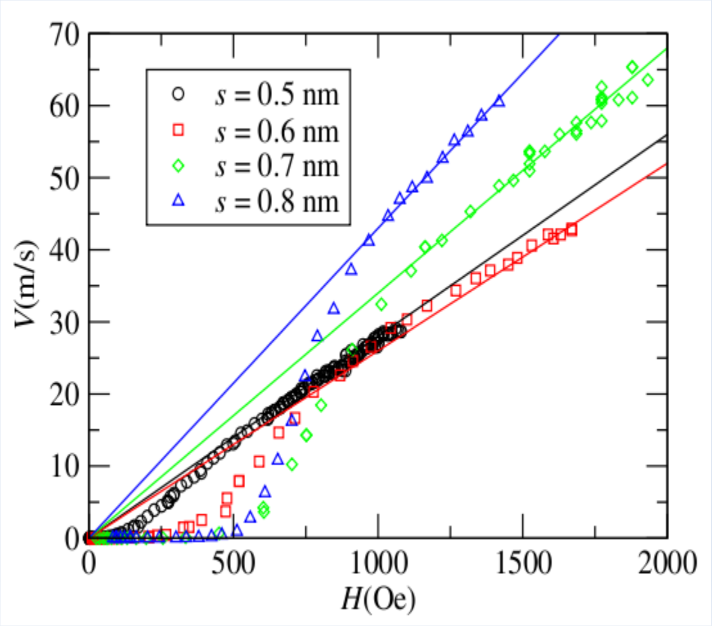
ψ **:thermal rounding exponent**

$$\psi = 0.20(6)$$

Pt/Co/Pt ultrathin fimls of thickness *s*
Metaxas et al, PRL 2007 (LPS, Orsay)

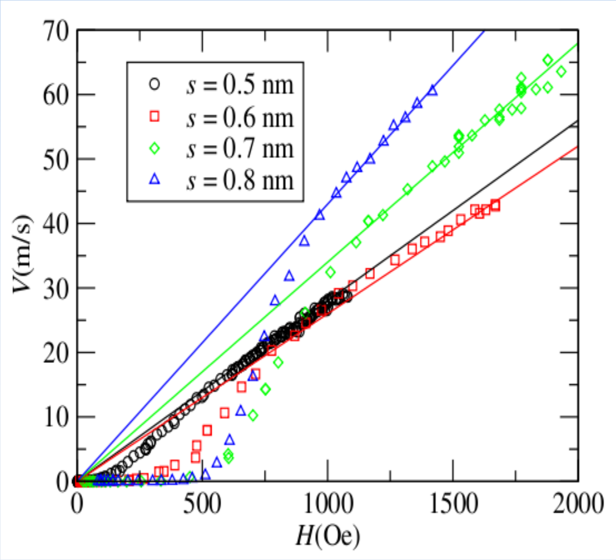
first experimental data with the full three regimes

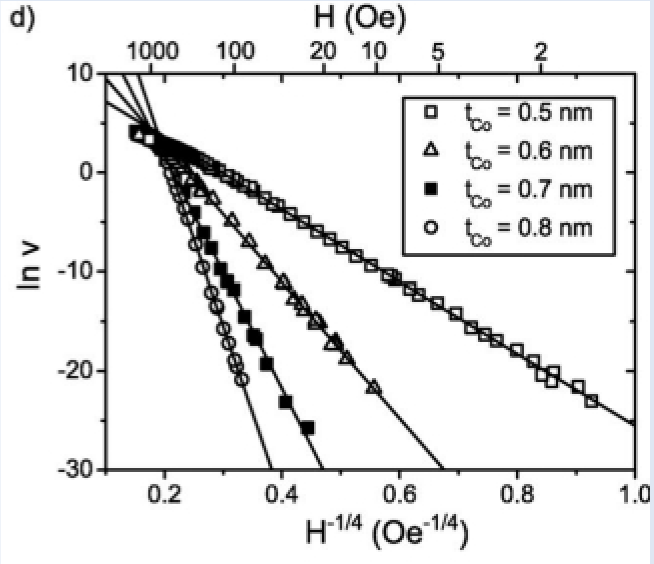
SCALING ANALISYS!



Depinning transition

Dynamical regimes





Metaxas et al, PRL 20007

$$V = V_0 \exp\left[-\frac{U_c}{k_B T}\left(\frac{H_c}{H}\right)^{\mu}\right]$$

$$\mu = \frac{d - 2 + 2\zeta}{2 - \zeta}$$

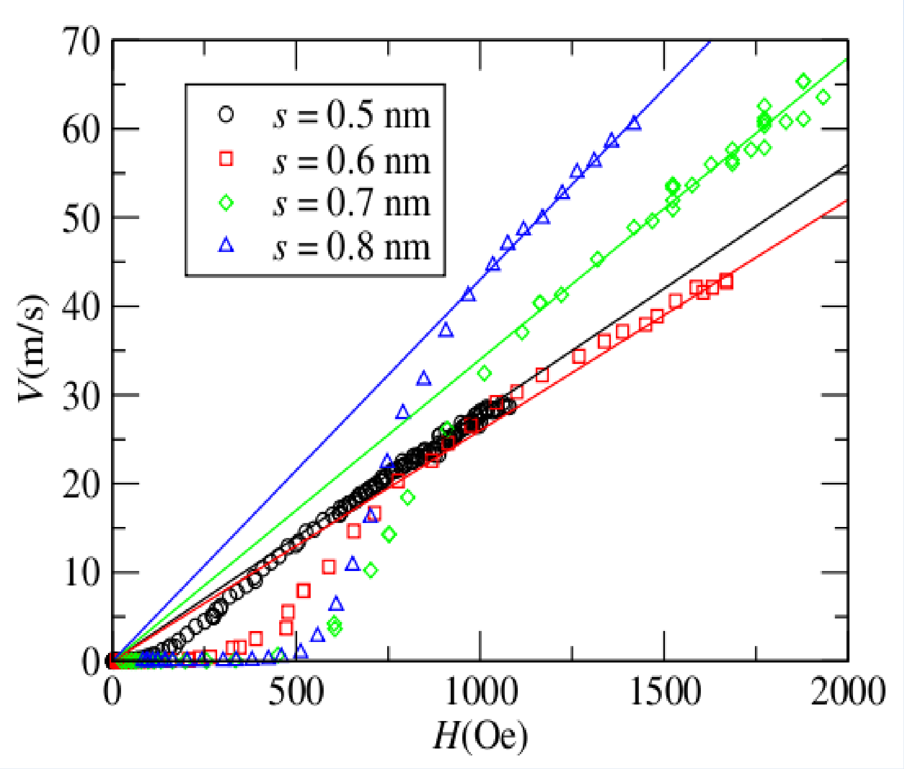
s[nm]	0.5	0.6	0.7	0.8
M_S[erg/(G.cm^3)]	910	1130	1200	1310
K_{eff}[Merg/cm^3]	3.2	4.5	3.2	2.0
A[μerg/cm]	1.4	1.6	1.8	2.2
δ[nm]	6.2	5.5	6.7	8.6
m[m/(Oe.s)]	0.028	0.026	0.034	0.043
H^*(Oe)	230	590	750	650
T_{dep}/T	9	14	22	35

H_c y T_{dep} has been originally obtained using the creep regime

Depinning transition

Dynamical regimes

$$\psi = 0.20(6)$$



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H_c(Oe)	330	660	800	730
T_c/T	9.85	14.4	22.36	36.03

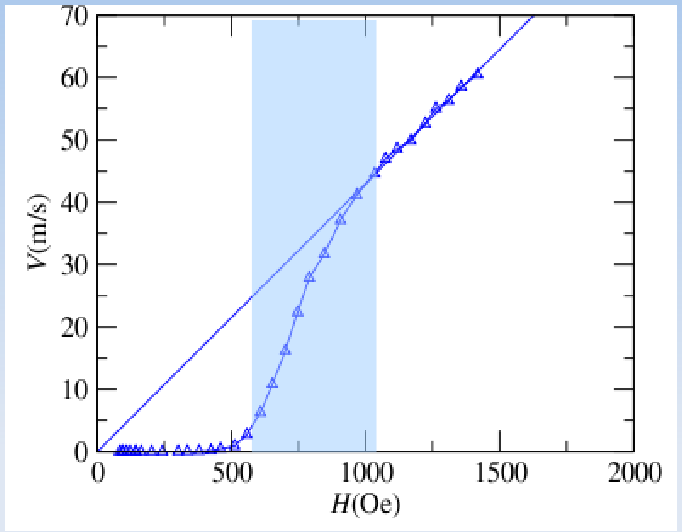
- Mobility from the fast-flow regime

The critical field is now determined from the depinning regime

The depinning temperature is obtained from the creep law

Depinning transition

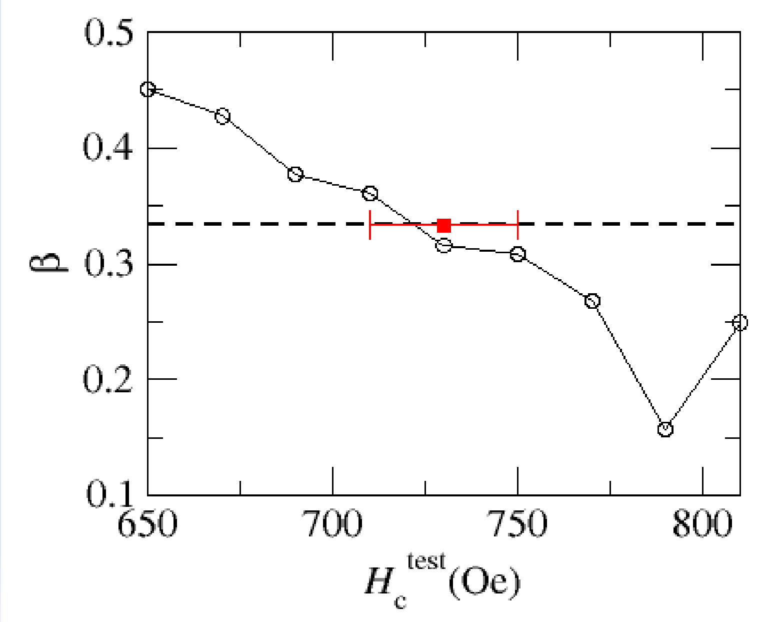
Dynamical regimes

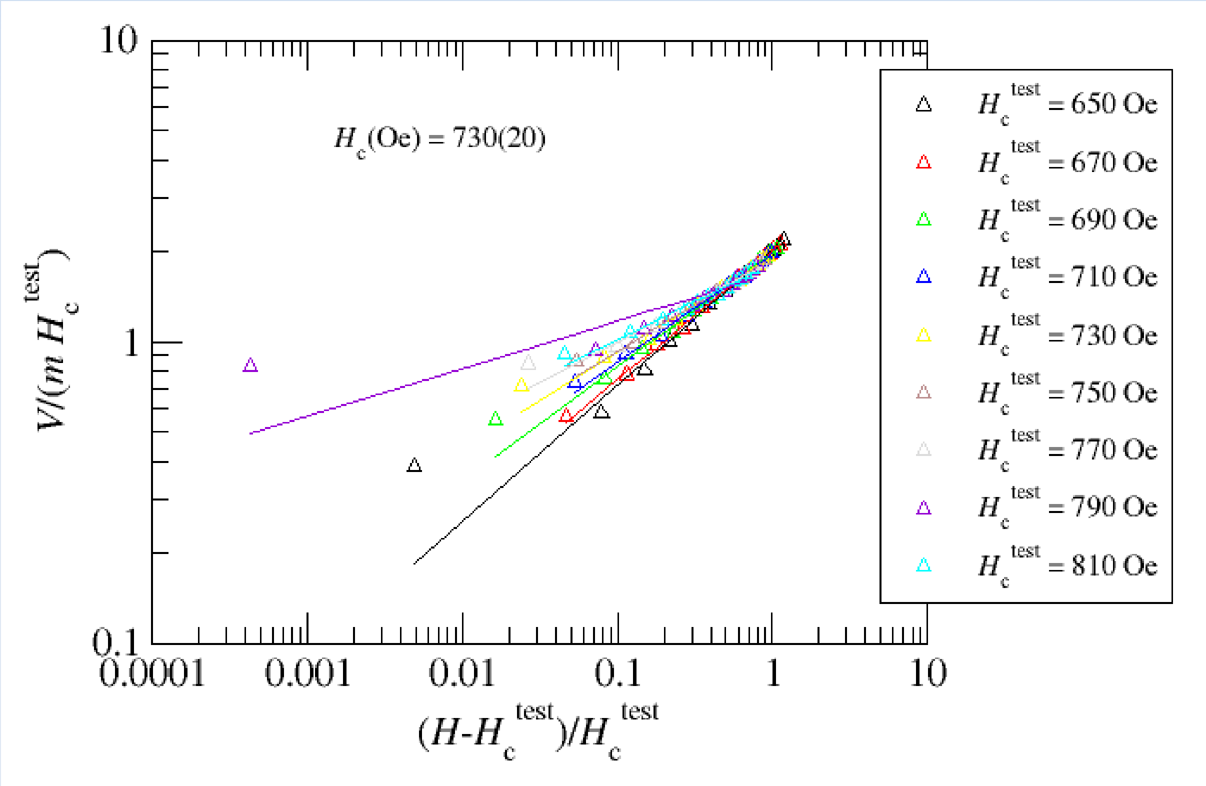


$$V \sim (F - F_c)^\beta$$

$$\frac{V}{mH_c} \sim \left(\frac{H - H_c}{H_c}\right)^\beta$$

experiment:
scaled variables





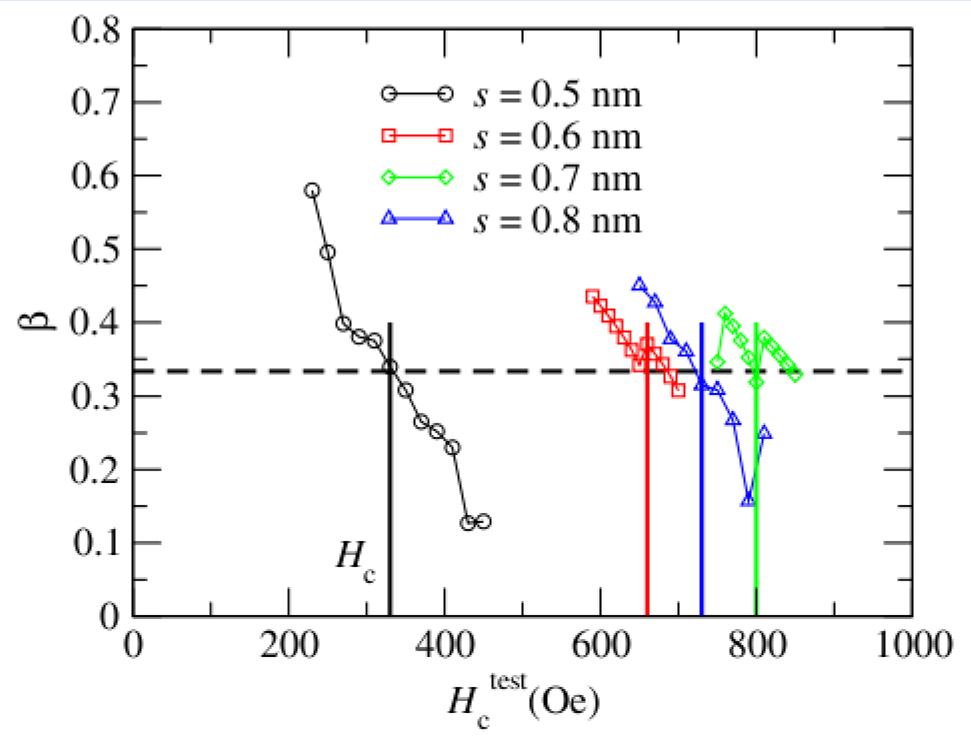
Search for the value of H_c which better ajust to $\beta = 1/3$

Bustingorry, Kolton, Giamarchi, PRB 2012

Depinning transition

Dynamical regimes

$\psi = 0.20(6)$



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Bustingorry, Kolton, Giamarchi, PRB 2012

Depinning transition

Dynamical regimes

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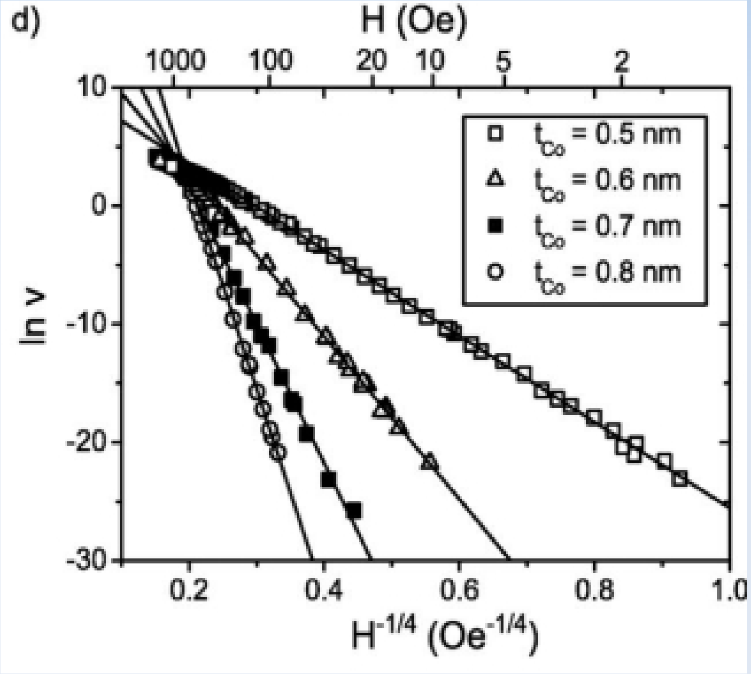

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thickness

↓

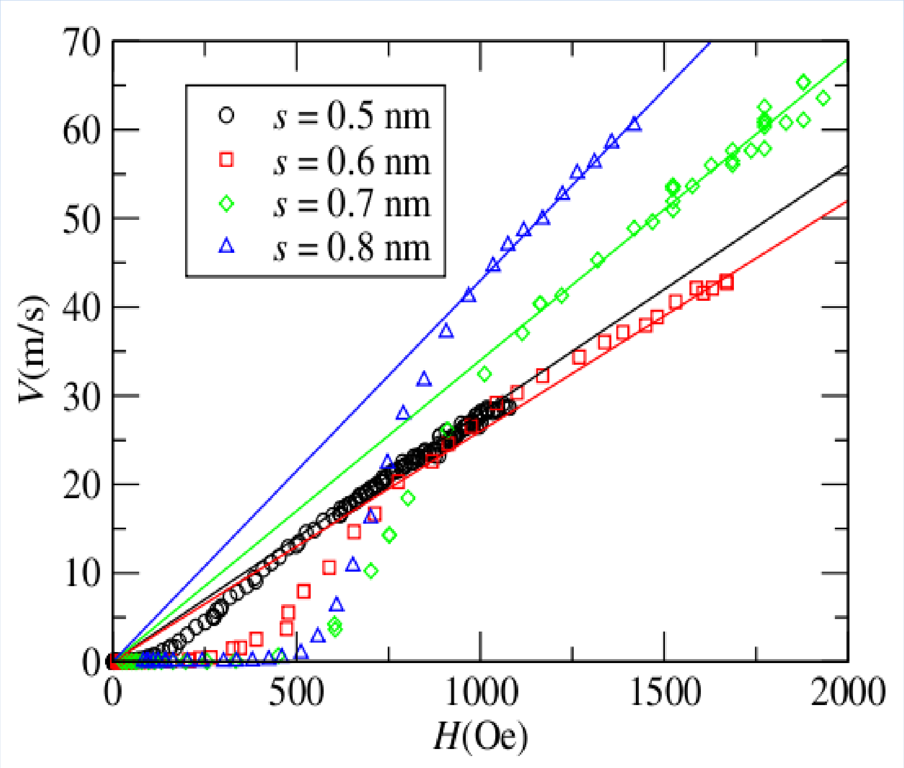
effective temperature

Bustingorry, Kolton, Giamarchi, PRB 2012

Depinning transition

Dynamical regimes

$$\psi = 0.20(6)$$



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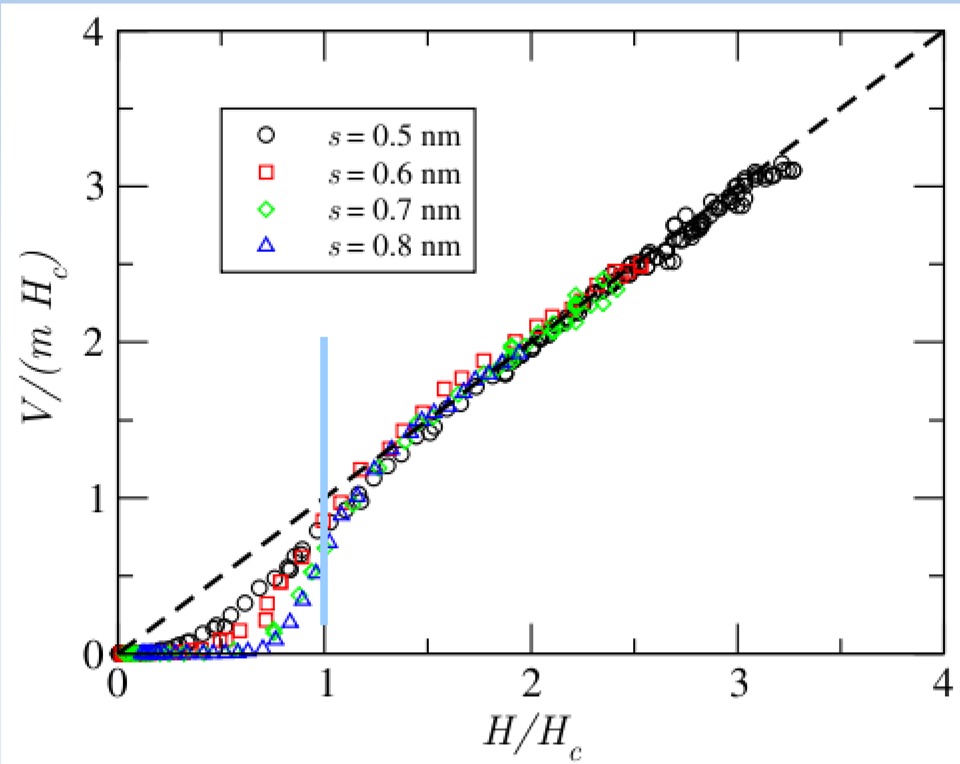
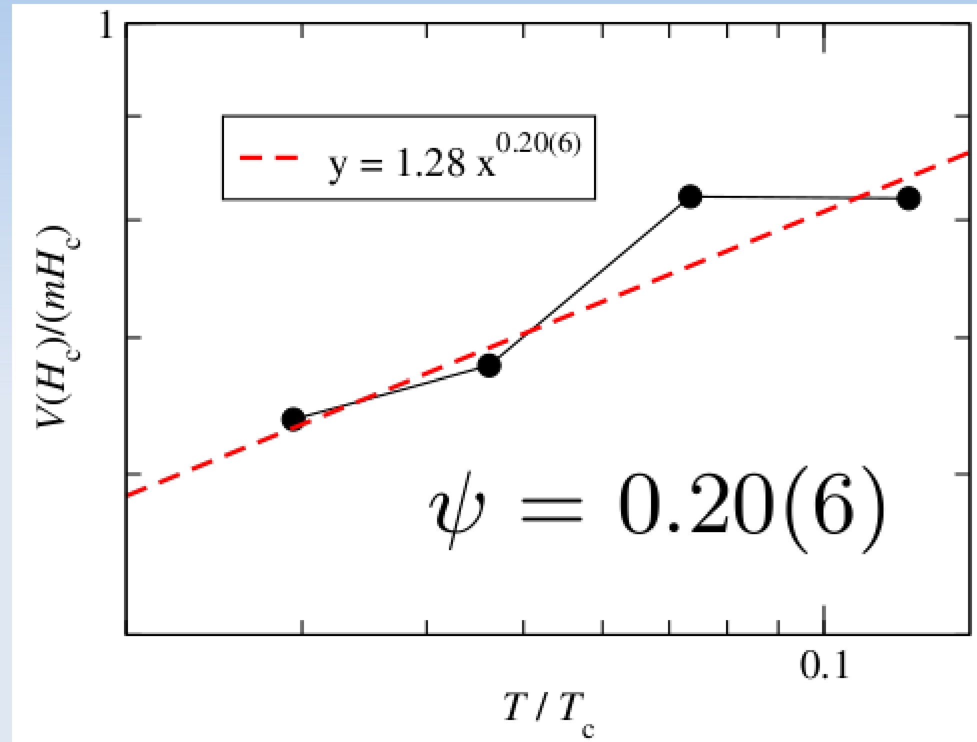
Depinning transition

Dynamical regimes



scaled variables



thermal rounding exponent

small value of the thermal rounding exponent consistent with numerical simulations

Bustingorry, Kolton, Giamarchi, PRB 2012

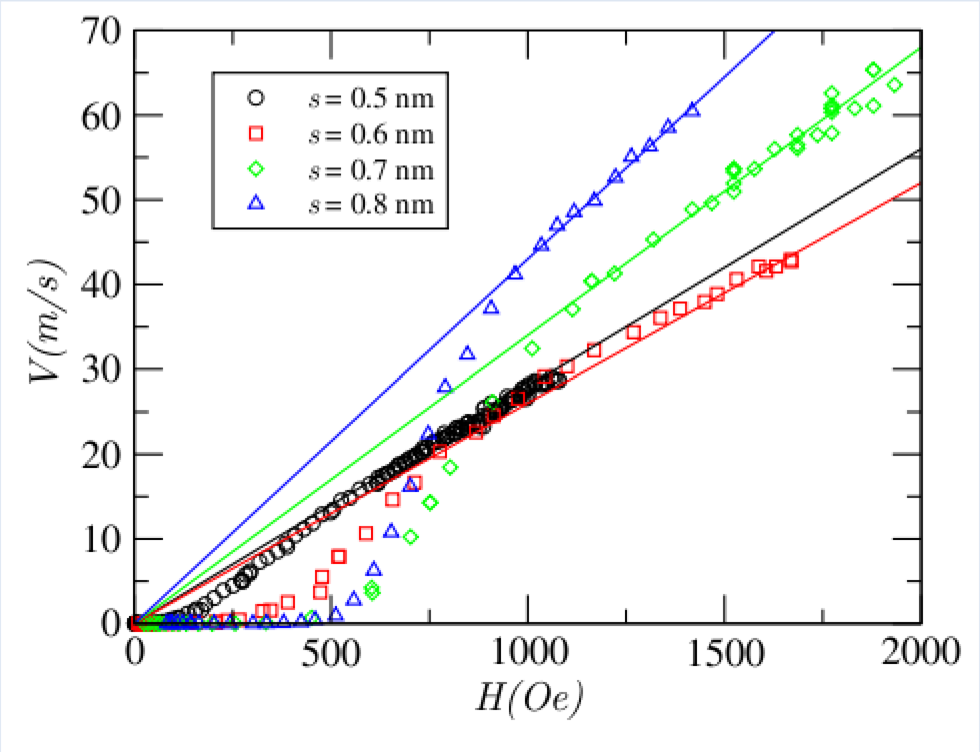
Depinning transition

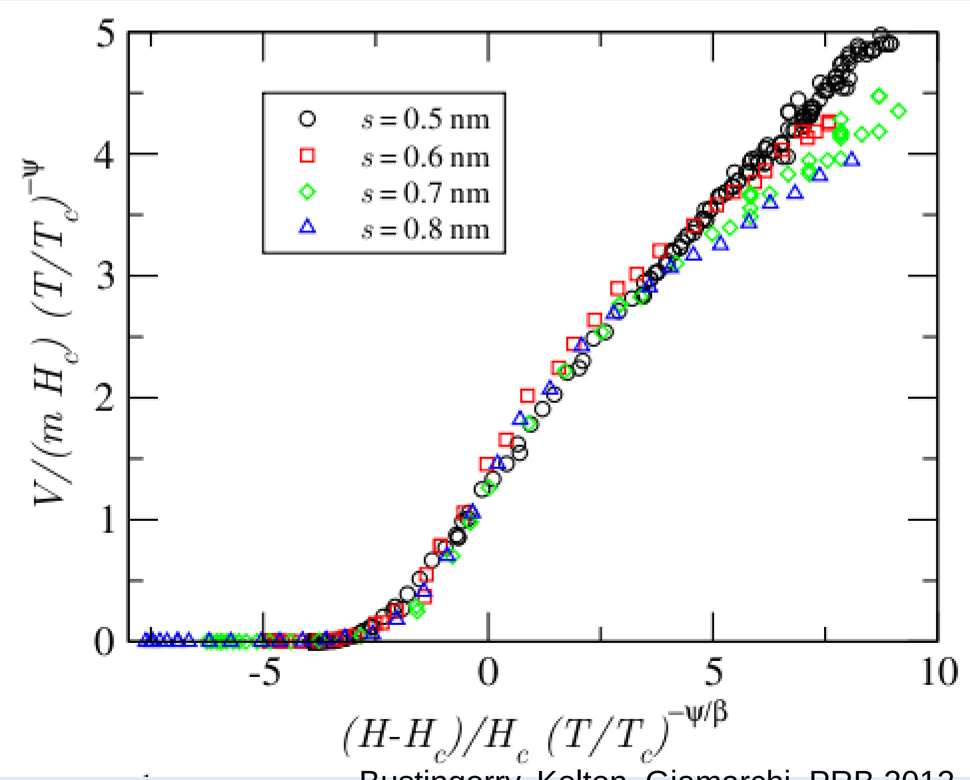
Dynamical regimes

Universal scaling function

$$\frac{V}{mH_c} \sim \left(\frac{T}{T_c}\right)^{\psi} G\left[\frac{H-H_c}{H_c}\left(\frac{T}{T_c}\right)^{-\psi/\beta}\right]$$

(as in standard critical phenomena)



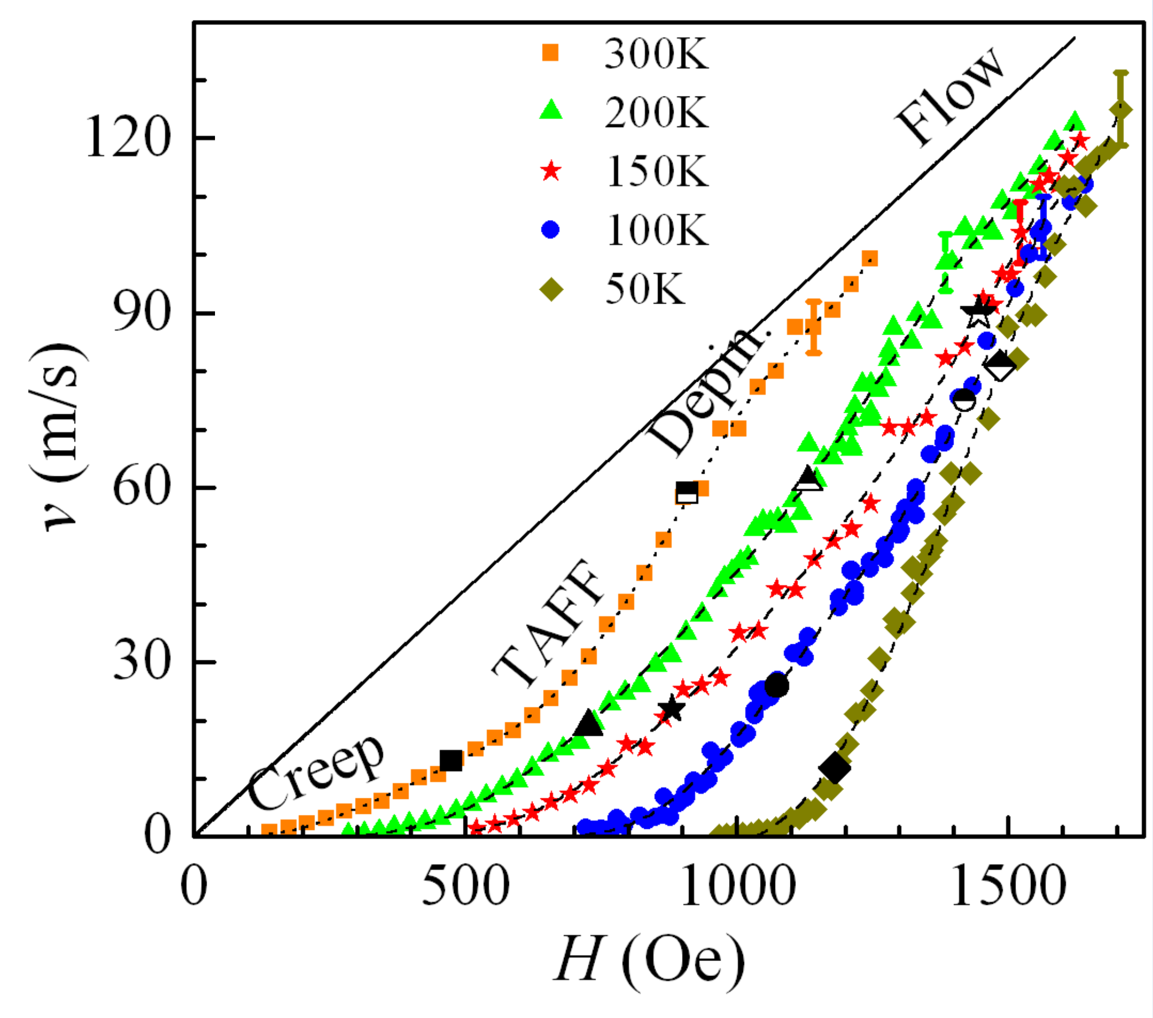


Bustingorry, Kolton, Giamarchi, PRB 2012

Depinning transition

Dynamical regimes

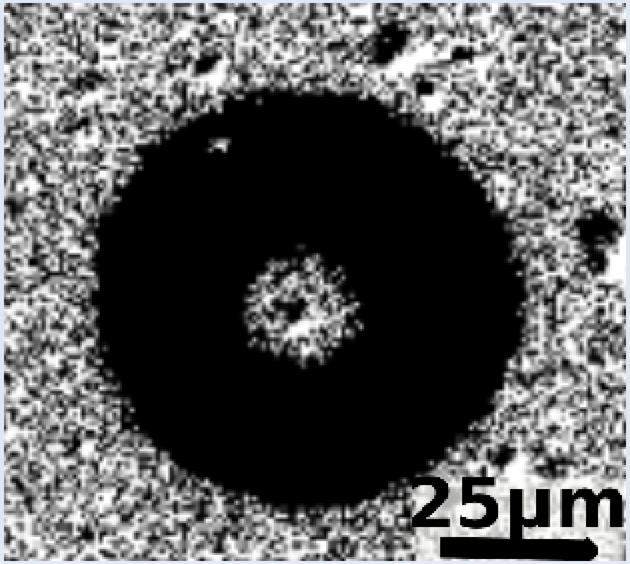
New experimental results: **Pt/Co/Pt at low temperatures**



thickness s = 0.45nm
KERR microscopy
LPS, Orsay
J. Gorchon, V. Jeudy, J. Ferré

temperature control

$$50 < T < 300$$



Depinning transition

Dynamical regimes

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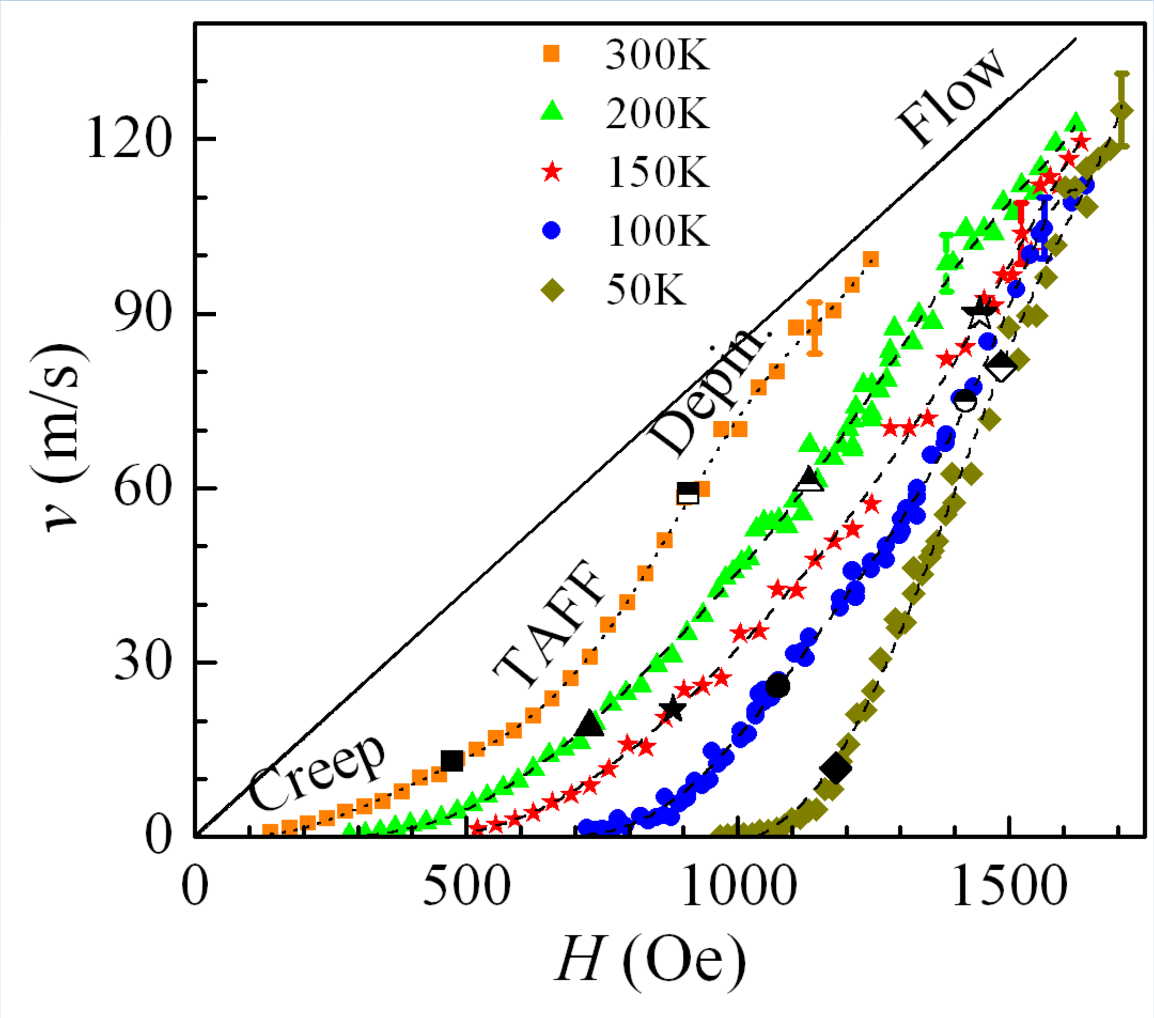

thickness *s* = 0.45nm
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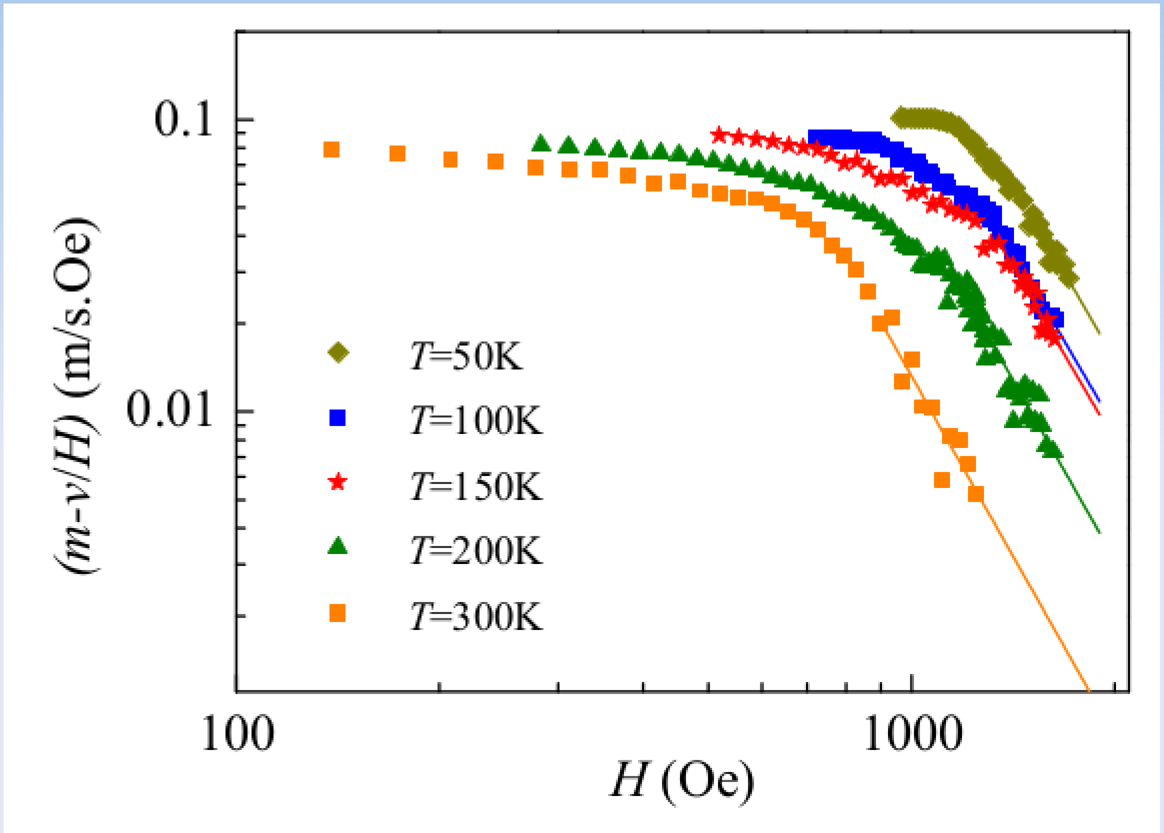
$$50 < T < 300$$

the fast-flow regime
is not well reached $\rightarrow$ *m*??

Depinning transition

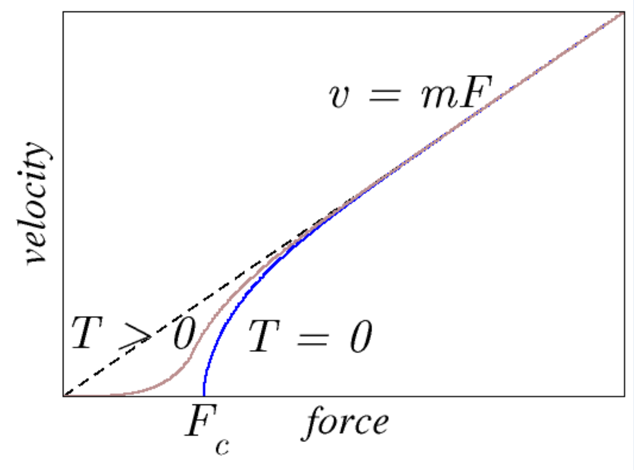
Dynamical regimes



$$m - v/H \equiv DH^{-c}$$

Chen et al, PRB 1995

experimental data gives $c = 4$



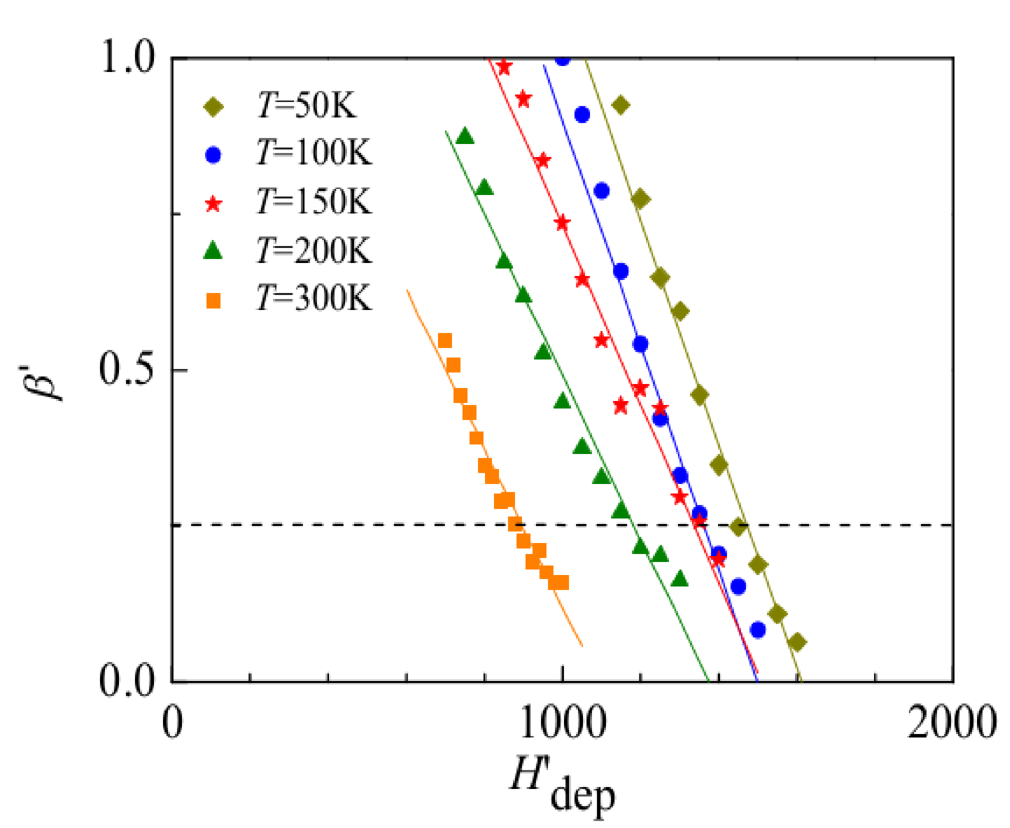
T (K)	300	200	150	100	50
M_s (erg/G.cm^3)	800(40)	1120(50)	1260(60)	1370(70)	1470(80)
m(m/s.Oe)	0.085(0.04)	0.083(0.05)	0.091(0.05)	0.089(0.06)	0.102(0.07)
$H_{C-T}(creep)$ (Oe)	480(20)	720(30)	870(40)	1080(40)	1170(40)
$H_{C-T}(TAFF)$ (Oe)	470(20)	730(30)	890(40)	1070(40)	1190(40)
$H_{dep}(TAFF)$ (Oe)	920(30)	1060(50)	1360(30)	1480(50)	1500(40)
$H_{dep}(depin.)$ (Oe)	900(40)	1190(40)	1335(50)	1360(50)	1470(50)
T_{dep} (K)	1880(110)	2500(150)	2700(160)	3200(190)	3500(210)

Depinning transition

Dynamical regimes

extracting the critical field by fixing β

$$\frac{V}{mH_c} \sim \left(\frac{H - H_c}{H_c}\right)^{\beta}$$



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Depinning transition

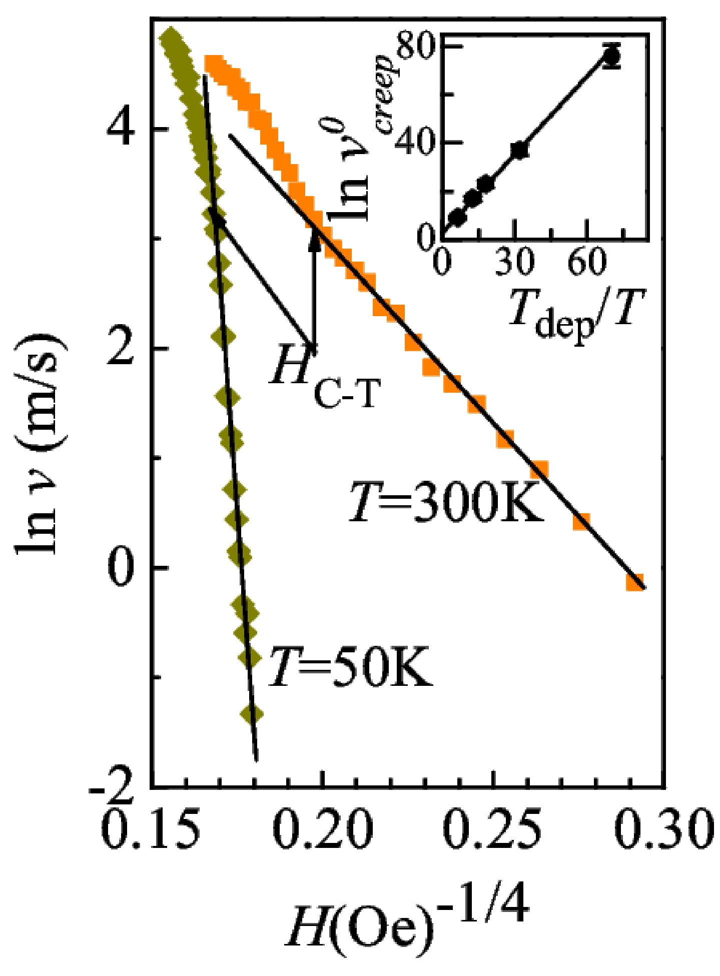
Dynamical regimes

creep

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

$$v^0_{creep} = v'^0_{creep}e^{CT_{dep}/T}$$

$$v'^0_{creep} = \xi/\tau = 35 \pm 15 m/s$$



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Depinning transition

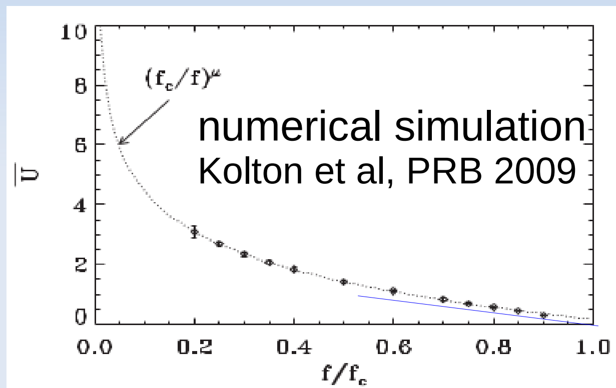
Dynamical regimes

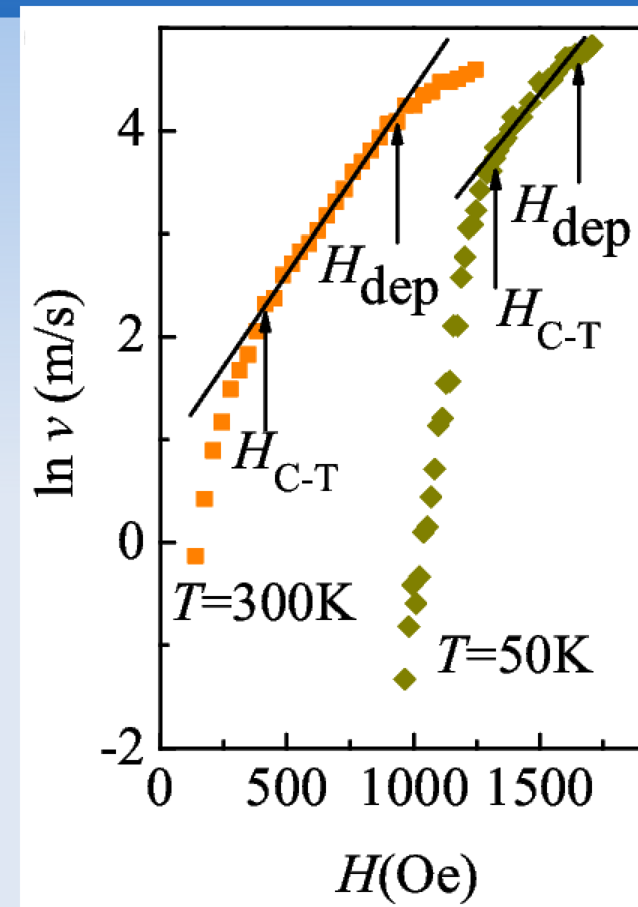
TAFF

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

$$U \sim \frac{H_{dep} - H}{H_{dep}}$$

linearly





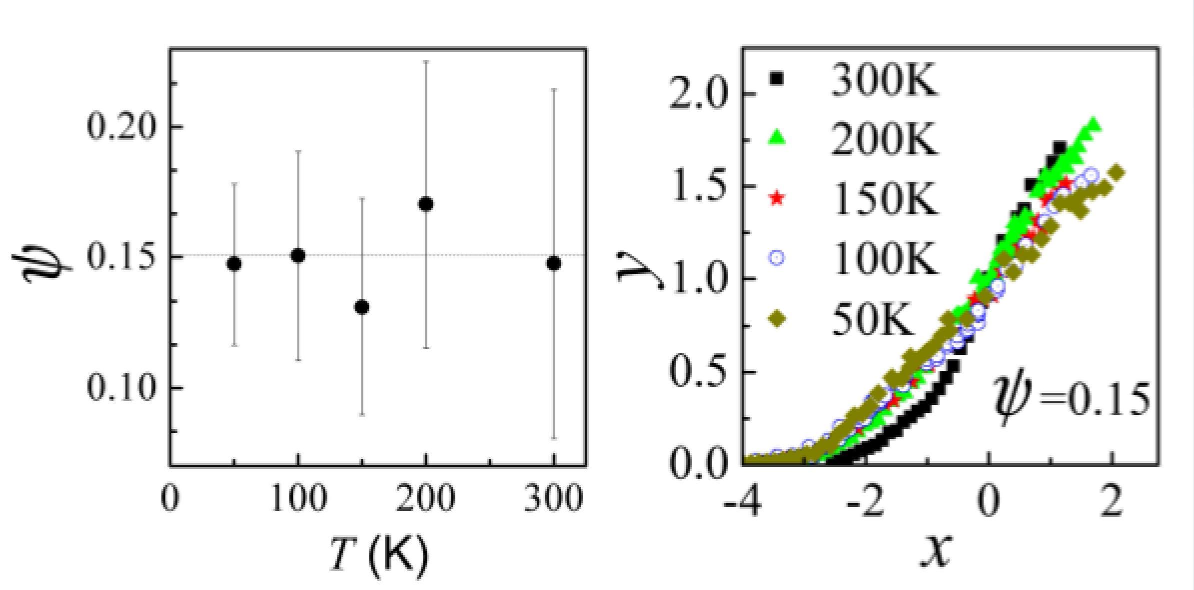
$$H = H_{dep} \Rightarrow v = v^0_{TAFF} \sim T^{\psi}$$

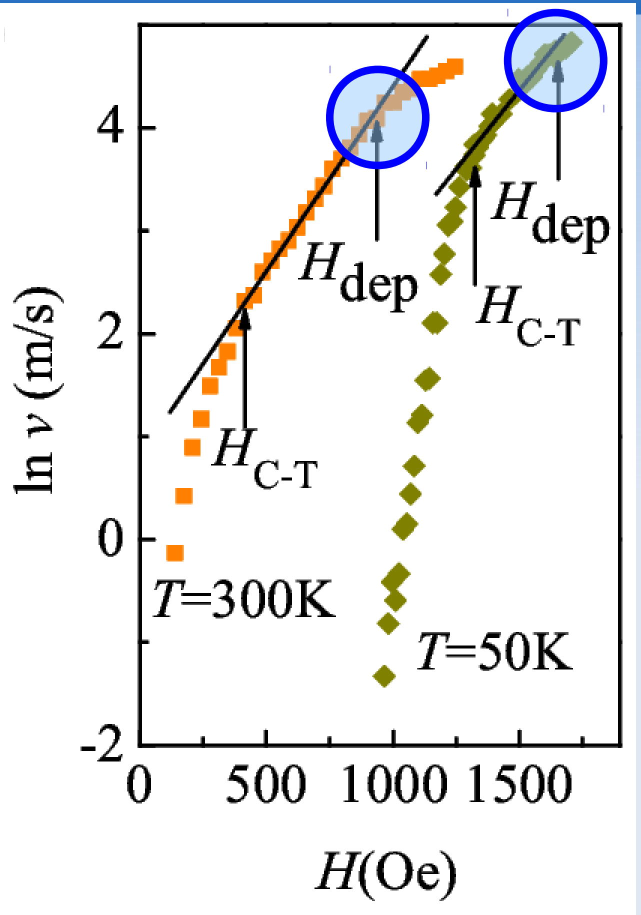
T (K)	300	200	150	100	50
M_s (erg/G.cm^3)	800(40)	1120(50)	1260(60)	1370(70)	1470(80)
m(m/s.Oe)	0.085(0.04)	0.083(0.05)	0.091(0.05)	0.089(0.06)	0.102(0.07)
$H_{C-T}(creep)$ (Oe)	480(20)	720(30)	870(40)	1080(40)	1170(40)
$H_{C-T}(TAFF)$ (Oe)	470(20)	730(30)	890(40)	1070(40)	1190(40)
$H_{dep}(TAFF)$ (Oe)	920(30)	1060(50)	1360(30)	1480(50)	1500(40)
$H_{dep}(depin.)$ (Oe)	900(40)	1190(40)	1335(50)	1360(50)	1470(50)
T_{dep} (K)	1880(110)	2500(150)	2700(160)	3200(190)	3500(210)

Depinning transition

Dynamical regimes

$$v_{dep}(H,T) = v^0_{dep}(T) G\left[\frac{H - H_{dep}}{H_{dep}}\left(\frac{T}{T_{dep}}\right)^{-\psi/\beta}\right]$$





$$v^0_{TAFF} \sim T^{\psi}$$

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

$$\psi = 0.15$$

Depinning transition

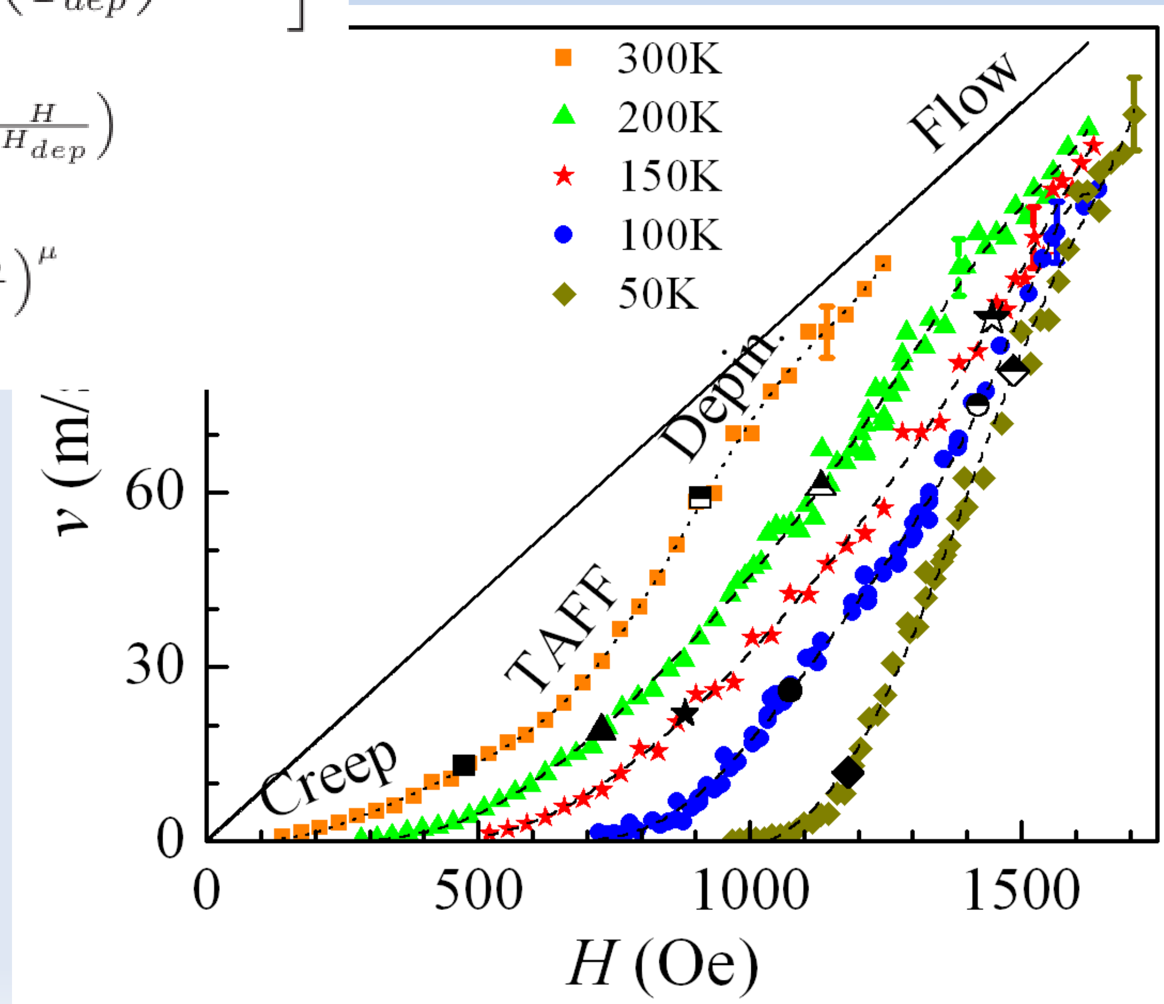
Dynamical regimes

$$v = mH$$

$$v_{dep}(H,T) = v^0_{dep}(T)G\left[\frac{H - H_{dep}}{H_{dep}}\left(\frac{T}{T_{dep}}\right)^{-\psi/\beta}\right]$$

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

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



H_{dep}, T_{dep} and *m* are temperature dependent parameters
$\rightarrow$ relevance of scaling variables

$$\frac{T}{T_{dep}} \approx 0.05$$

Depinning transition

Partial conclusions

- We have shown that when $F = F_c \Rightarrow V \sim T^{\psi}$

  with a thermal rounding exponent $\psi = 0.15$

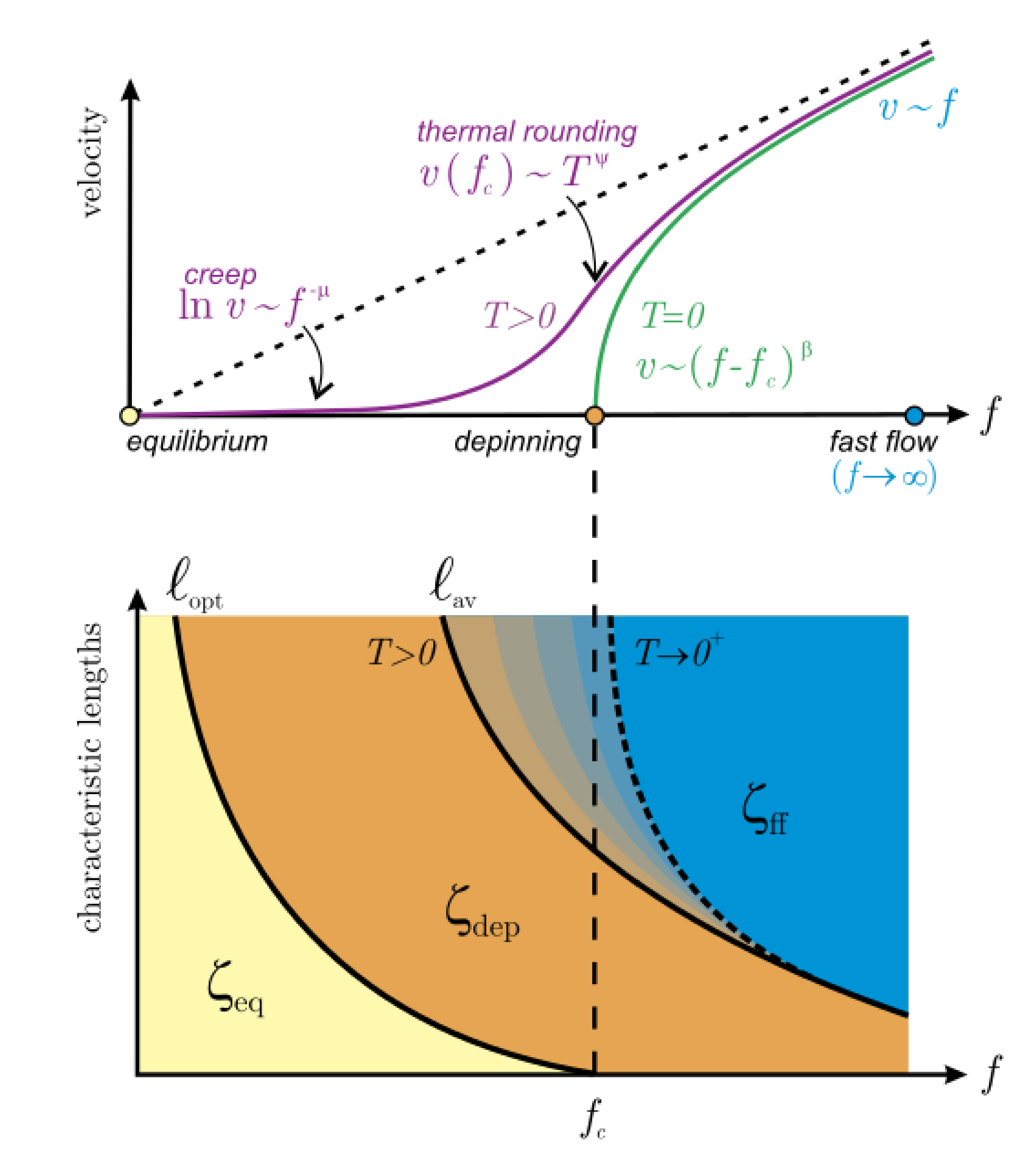
- We have shown, using proper scaling functions, that depinning in Pt/Co/Pt can be well described by EW-RM exponents

$$\beta = 0.25 \quad \psi = 0.15 \quad \mu = 0.25 \quad \zeta = 1.25$$

Many questions!!!
- Why EW-RM exponents? Is there a cut-off?
- What is the origin of the thermal rounding exponent?
- What about the geometrical properties?
- How does de TAFF come into play?
- More on temperature effects: current induced DW motion and Joule heat

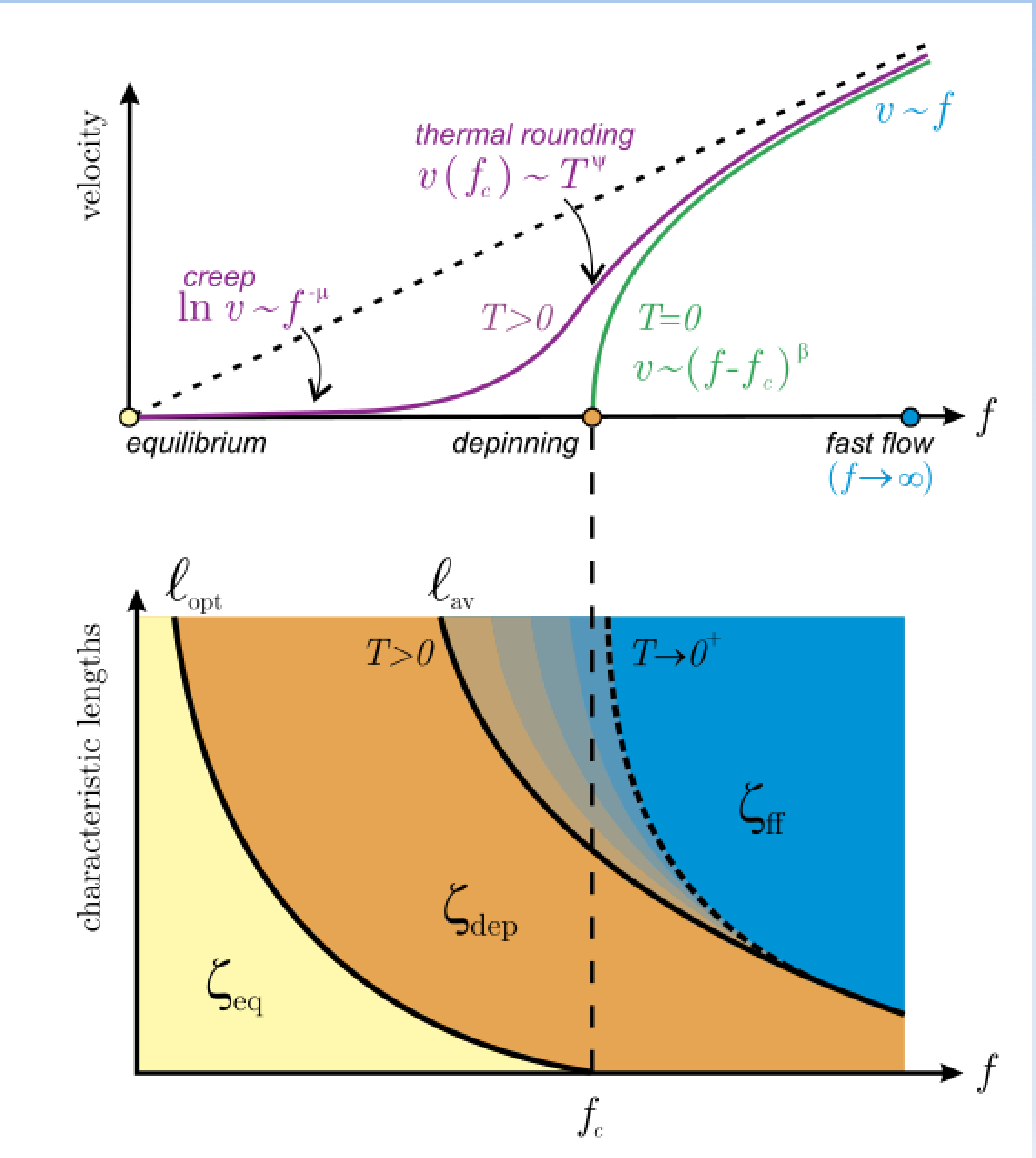
Depinning transition

Dynamical regimes



Depinning transition

Dynamical regimes



THANKS!