Inertial effects in crackling noise: magnetic materials and granular matter

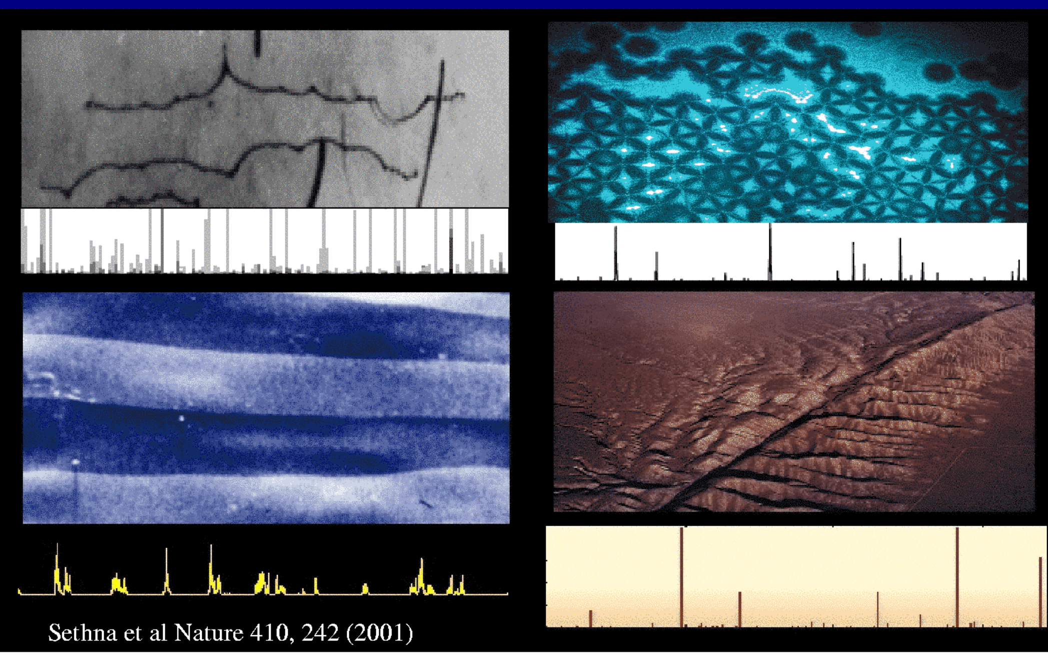
Stefano Zapperi
INFM, CNR
Roma

Magnetic materials:
Claudio Castellano
Francesca Colaiori
Gianfranco Durin

Granular media:
Andrea Baldassarri
Fergal Dalton
Alberto Petri
Giorgio Pontuale
Luciano Pietronero

Crackling noise:

from atomic to tectonic



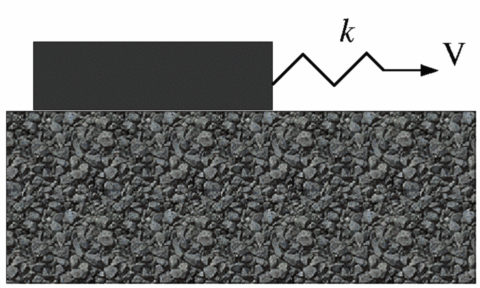
outline & motivation

Crackling noise:
broad (power law)
amplitude distributions,
$1/f^a$ power spectra,
avalanches.

Questions:
can we explain the phenomenology?
is there universality?
can we walk across different
scales and phenomena?

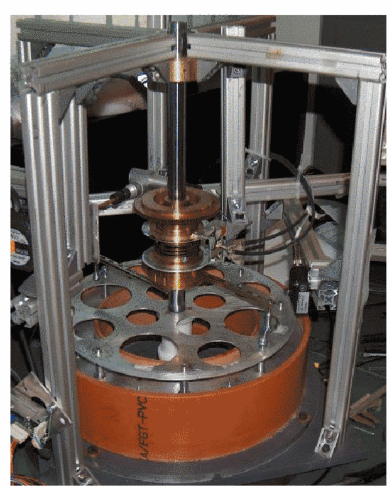
Outline:
Stick-slip in granular friction
Analogy with magnetic Barkhausen noise
combined analysis of experiments and models

Granular friction

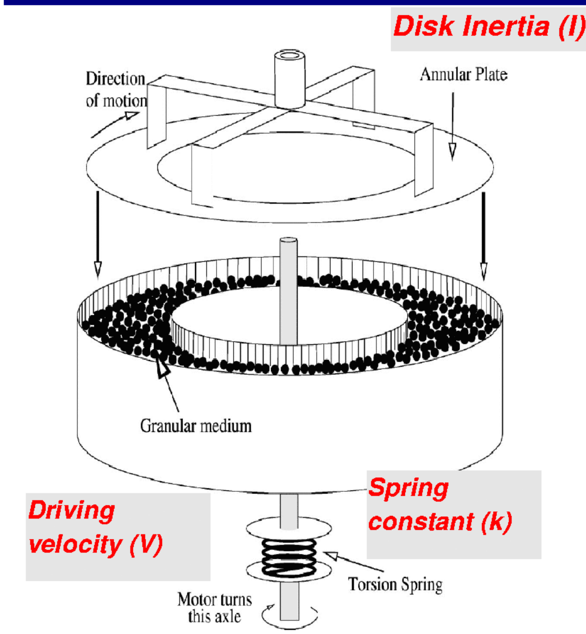


- Macroscopic contacts
- Dilatancy
- Strong internal stress fluctuations

Relevant for earth sciences
(see previous talks in this program)



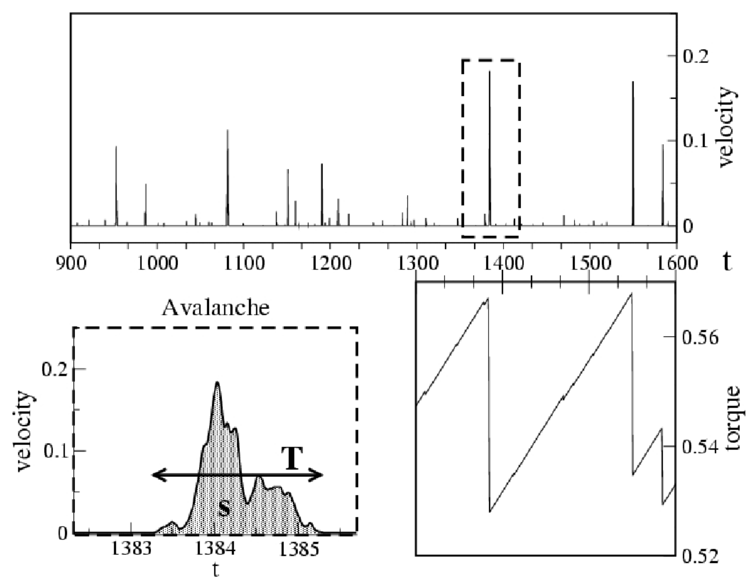
Sheared granular medium

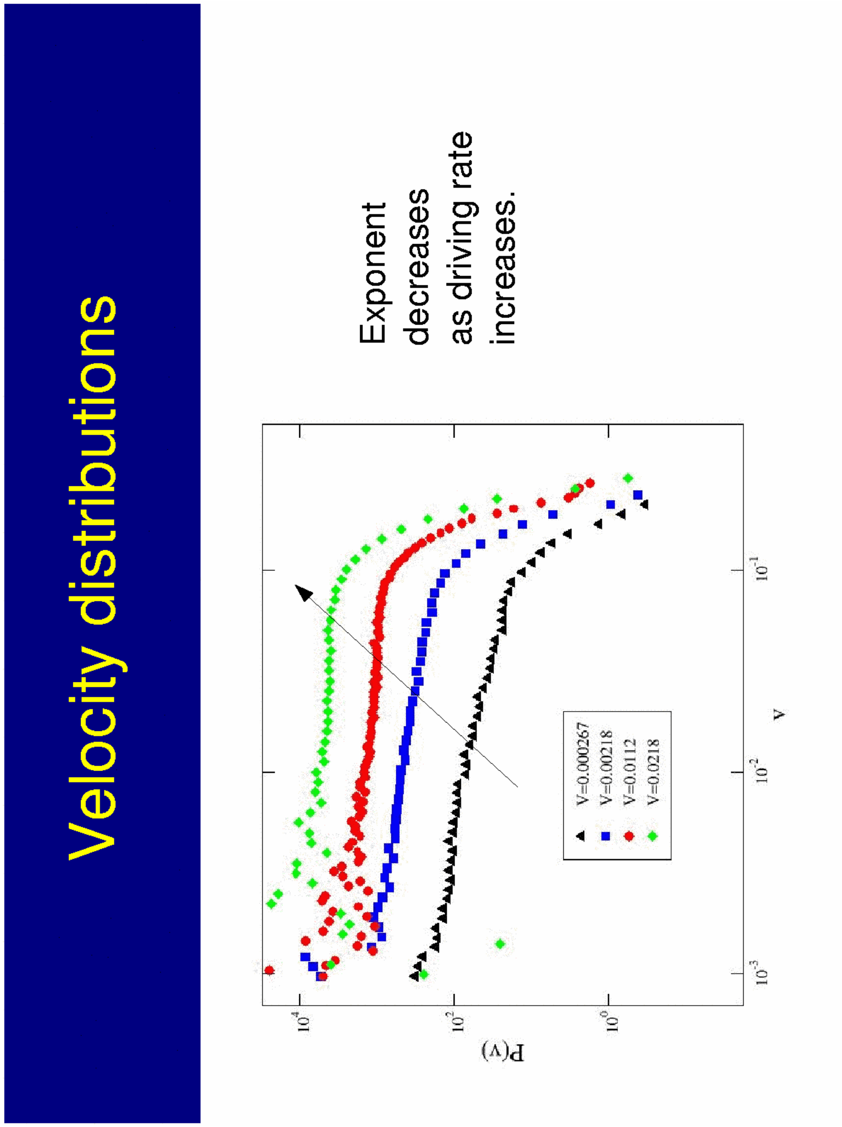


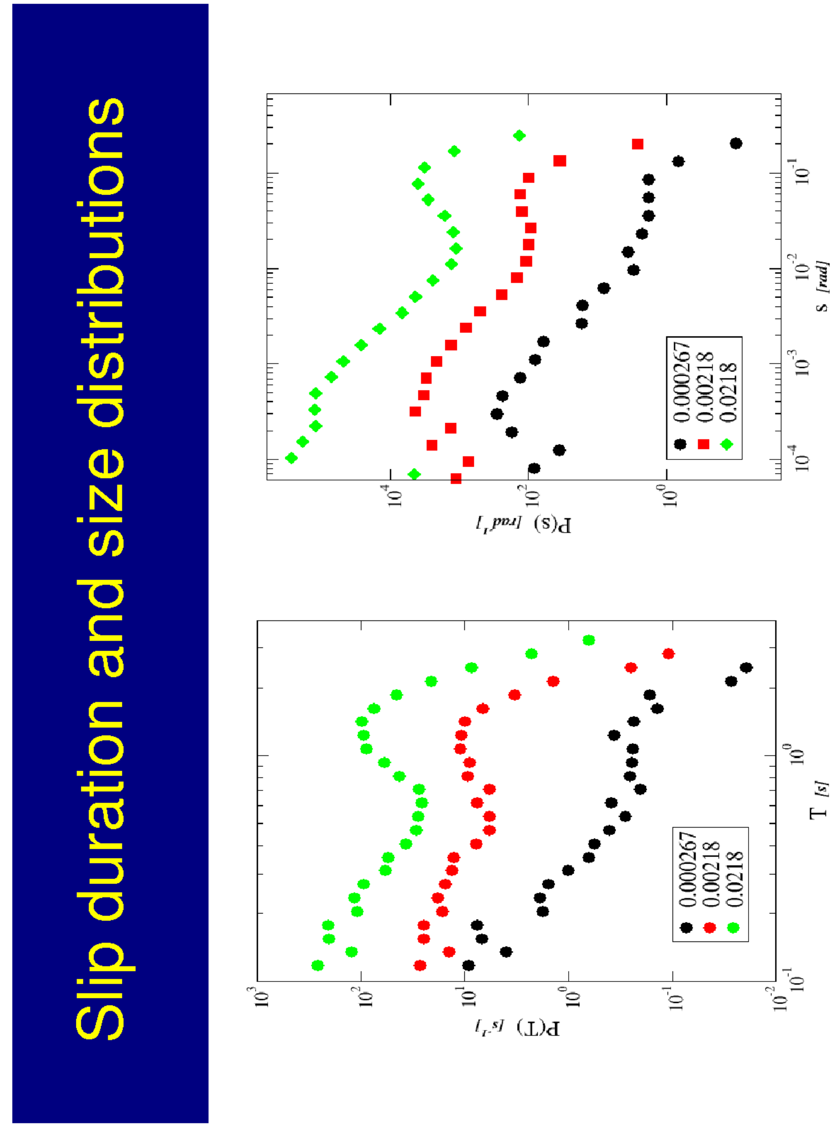
- Annular shear cell, Couette geometry, driven by overhead plate *via* a torsion spring
- 2mm glass beads
- Max. humidity ~ 40%
- Temperature 18-23°C
- Free dilation of the bed

control parameters: $I \ V \ k$

Stick-slip and velocity fluctuations




Velocity distributions
Exponent decreases as driving rate increases.
V=0.000267
V=0.00218
V=0.0112
V=0.0218
P(v)
v


Slip duration and size distributions
0.000267
0.00218
0.0218
P(S) [rad⁻¹]
S [rad]
P(T) [s⁻¹]
T [s]

Equation of motion

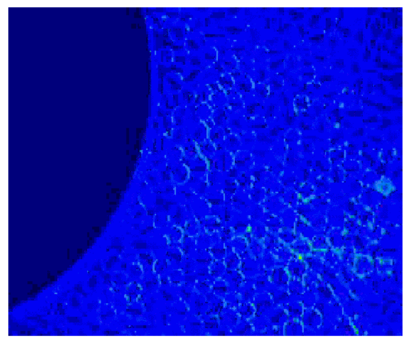
$$I\ddot{\theta}=k(Vt-\theta)-F(\theta,\dot{\theta},...)$$

Disk inertia

Torsion spring stiffness

Spring elongation

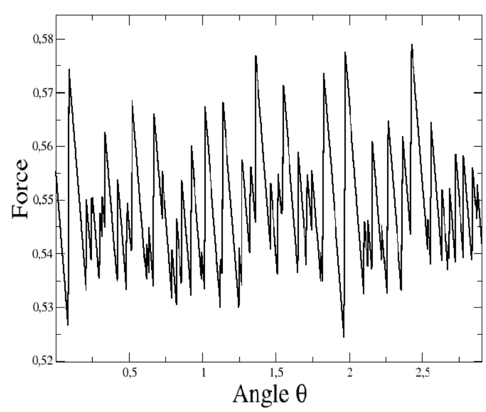
Friction force

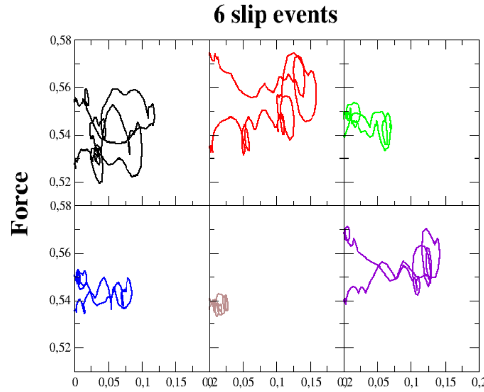


http://www.phy.duke.edu/~dhowell/research.html

Question: how to model the friction force?

Friction forces



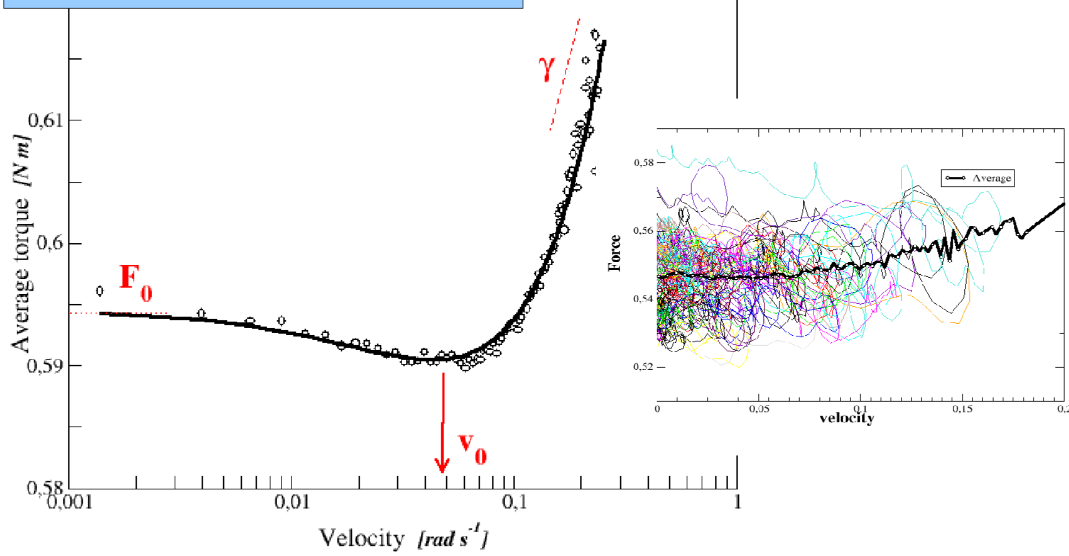


Hypothesis:
- Average viscous force
- Slip dependent random force

$$F(\theta,\dot{\theta})=\bar{F}(\dot{\theta})+F_f(\theta)$$

Viscous force

$$\bar{F}(v) = F_0 + \gamma(v - v_0 \log(1 + v/v_0))$$



Random forces

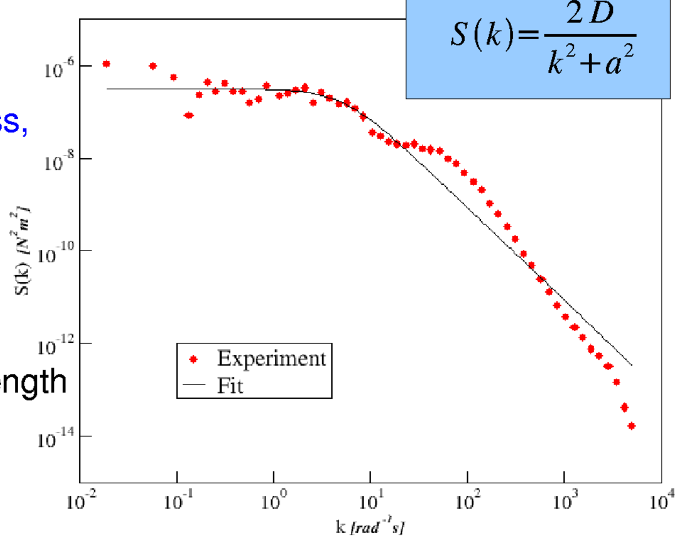
The random frictional term is modeled by a confined Brownian process,

$$\frac{d F_f}{d \theta} = \eta(\theta) - a F_f$$

a inverse correlation length

$D = \langle \eta^2 \rangle$ noise variance

$$S(k) = \frac{2D}{k^2 + a^2}$$



The model

$$I\ddot{\theta}=k(Vt-\theta)-F_0+\gamma(\dot{\theta}-v_0\log(1+\dot{\theta}/v_0))+F_f(\theta)$$

$$\frac{dF_f}{d\theta}=\eta(\theta)-aF_f \qquad \langle\eta(\theta)\eta(\theta')\rangle=D\delta(\theta-\theta')$$

No disorder limit:

$D = 0 \;\; a = 0$

$V < v0$: periodic stick-slip

$T^* \sim (I/k)^{1/2}$

$V > v0$: steady sliding

Overdamped limit:

$\gamma V >> I \quad V >> v_0$

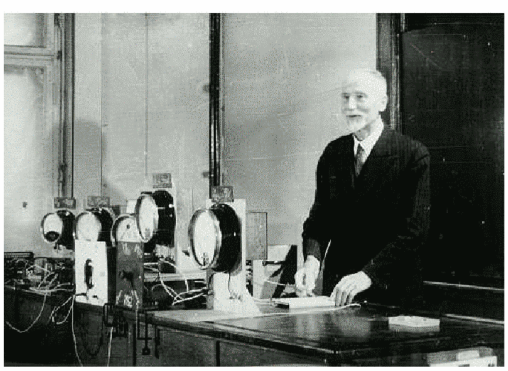
disorder dominated dynamics

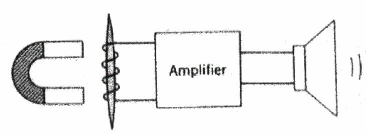
power law scaling

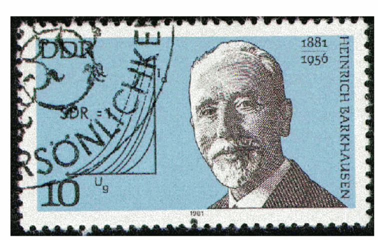
Domain wall model!

Intermezzo

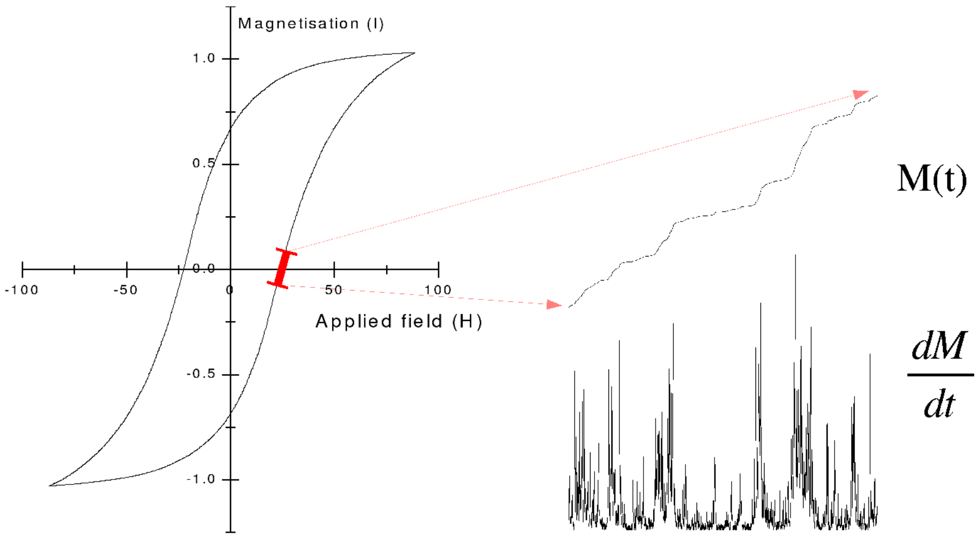
the Barkhausen effect



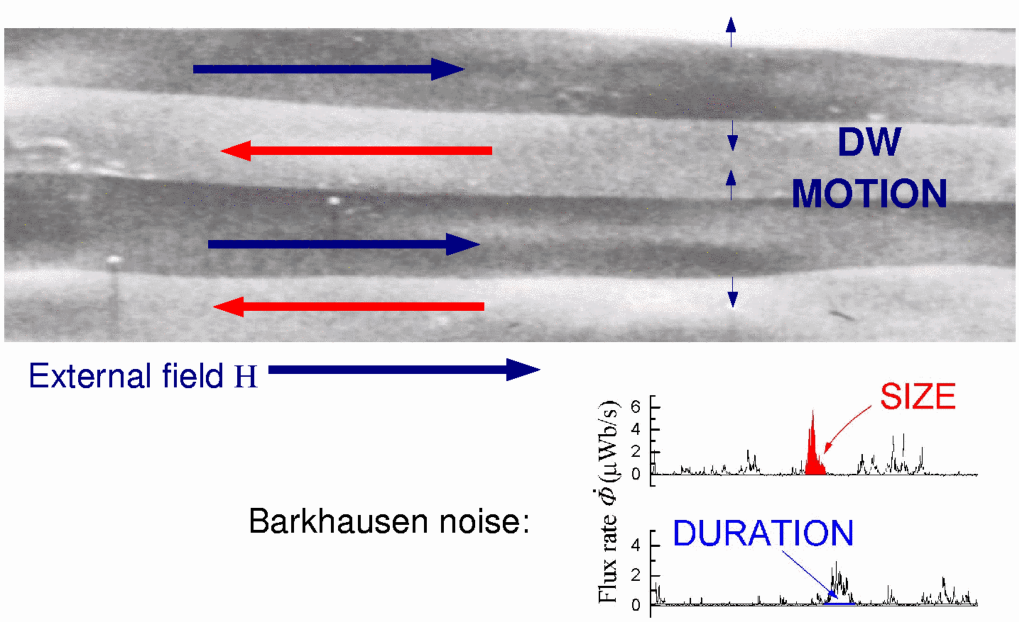




The Barkhausen effect



Domain wall motion



Domain wall model (ABBM)

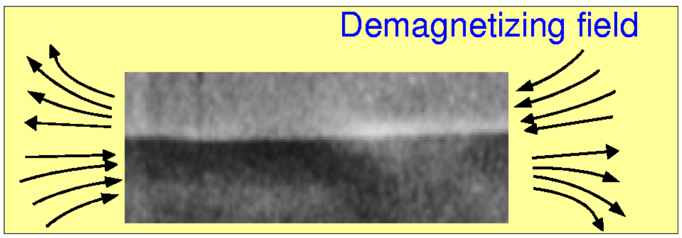
$$\Gamma \frac{dx}{dt} = ct - kx - H_{pin}(x)$$

B Alessandro, C Beatrice, G Bertotti, A Montorsi
Journal of Applied Physics 68, 2901 (1990).

Damping – eddy currents

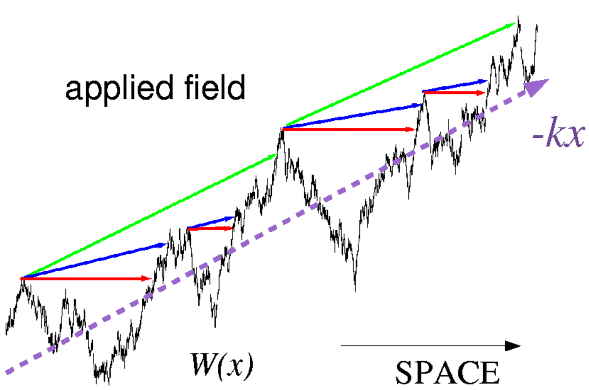
Applied field – constant rate

Pinning field – Brownian correlations



$$\frac{dH_{pin}}{dx} = \eta(x)$$

Avalanches in the ABBM model



Exact results:

velocities

$$P(v) = v^{c-1} \exp(-kv)/N$$

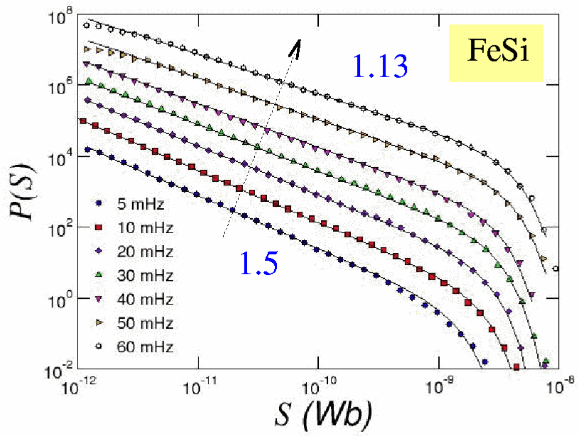
sizes

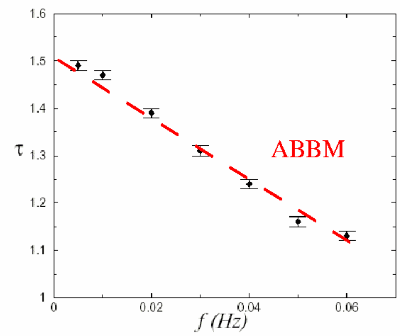
$$P(s) = s^{-3/2+c/2} f(sk^2)$$

durations

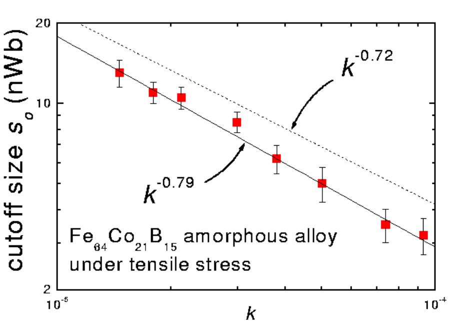
$$P(T) = T^{-2+c} g(Tk)$$

Field rate dependence





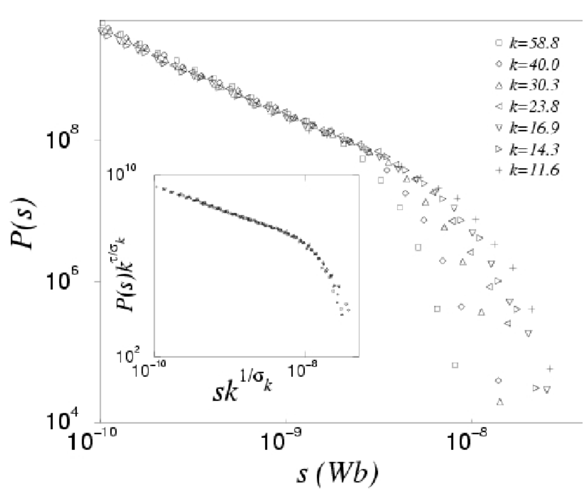
Effect of the demagnetizing field



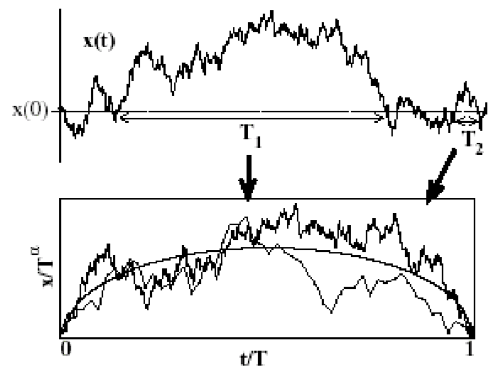
cutoff to the power law increases as k decreases but not as $1/k^2$

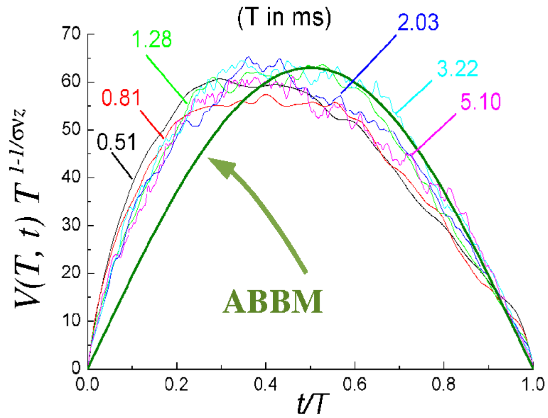
The exponent can be understood considering DW fluctuations

Durin & Zapperi Phys. Rev. Lett. 84, 4705 (2000).



Average pulse shape

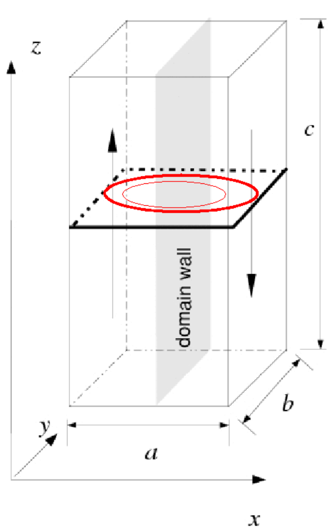




Theoretical shape is symmetric
also true for RFIM, DW depinning...

Experiments are asymmetric!

Eddy current damping



Damping comes from eddy currents:

$$\partial_t H_e - \sigma \mu \nabla^2 H_e = 0$$

$$\partial_x H_e^{\leftarrow} - \partial_x H_e^{\rightarrow} = 2 \sigma I_s v(t)$$

In the quasistatic approximation we get:

$$\Gamma v\, dx = H_{eff}\, dx$$

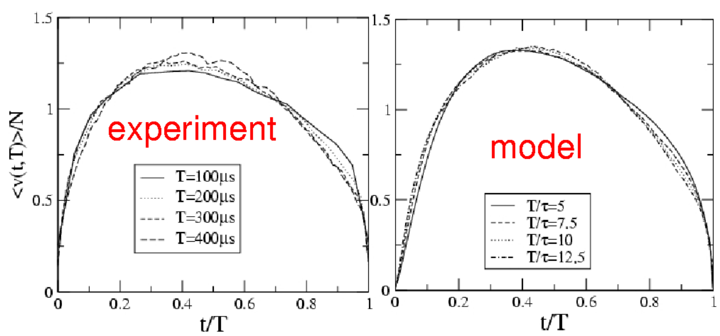
Energy dissipated by eddy currents — Work done by the field

S. Zapperi et al. Nature Physics **1,** 46 (2005)

Beyond the quasi-static approximation: non-local damping

$$\Gamma v(t) \rightarrow \int_0^t dt' f(t-t') v(t')$$

$$f(t) = -\frac{32 I_s^2}{\mu \sigma \pi^2} \theta_2 [e^{-4\pi^2 t/(a^2 \mu \sigma)}] \sum_n \frac{e^{-t/\tau_n}}{(2n+1)^2}$$

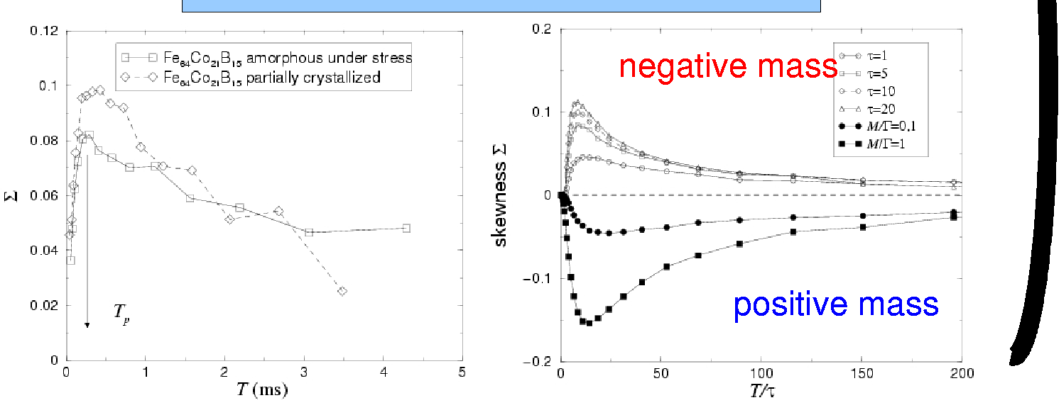


Negative domain wall mass

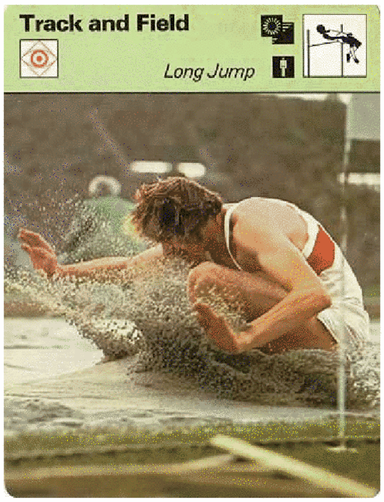
In Fourier space: $f(\omega) v(\omega) = (\Gamma + i\omega M(\omega)) v(\omega)$

the effective mass M is negative at all frequencies:

$$M(\omega=0) = -8 I_s^2 b^3 \mu \sigma / \pi^5 \approx 7 \cdot 10^{-5} Kg/m^2$$



back to....
Granular friction



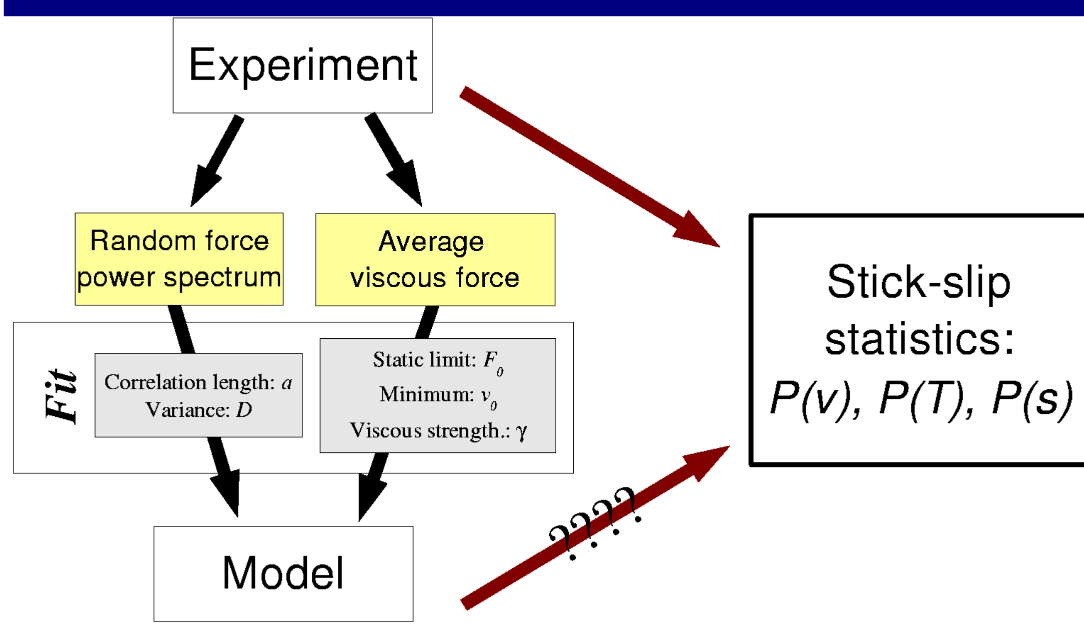
$$I\ddot{\theta}=k(Vt-\theta)-F(\theta,\dot{\theta})$$

$$F=F_0+\gamma(\dot{\theta}-v_0\log(1+\dot{\theta}/v_0))+F_f(\theta)$$

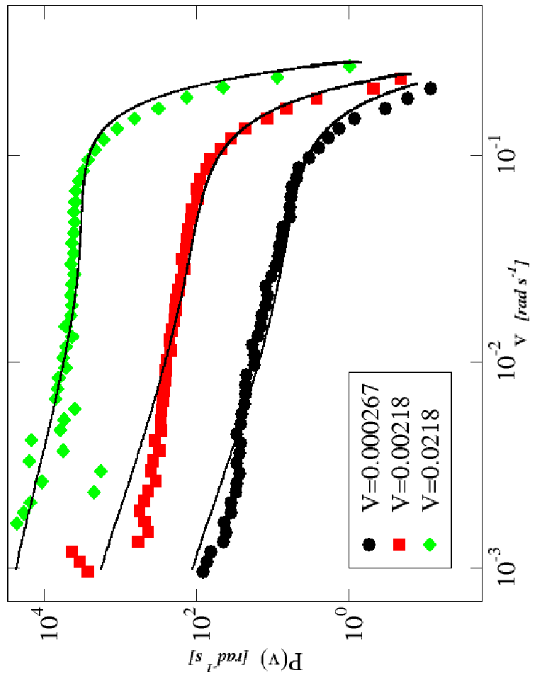
$$\frac{dF_f}{d\theta}=\eta(\theta)-aF_f$$

$$\langle\eta(\theta)\eta(\theta')\rangle=D\delta(\theta-\theta')$$

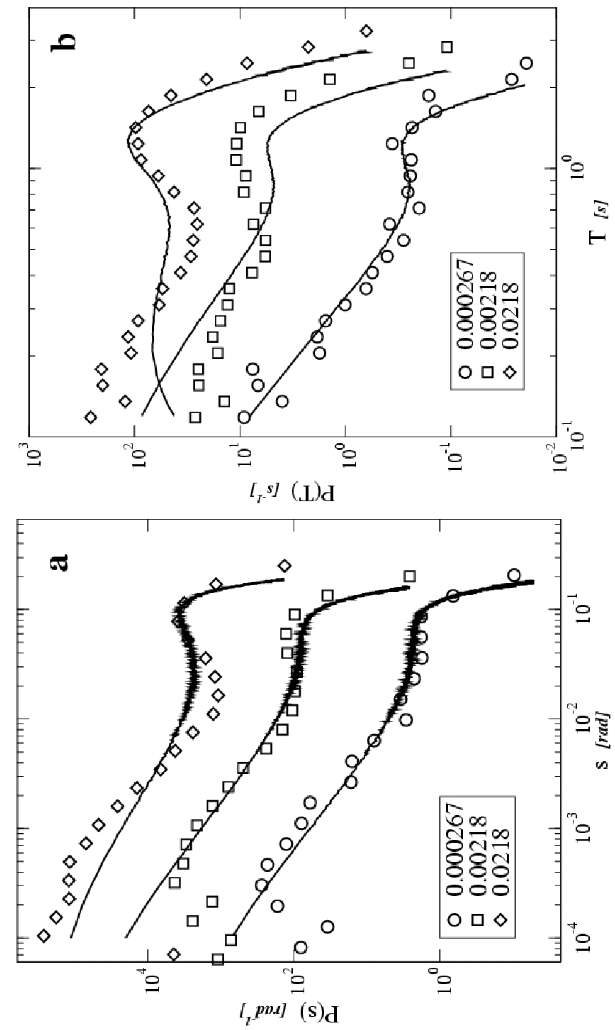
Comparison
Experiments & Model



Simulations: velocity distributions

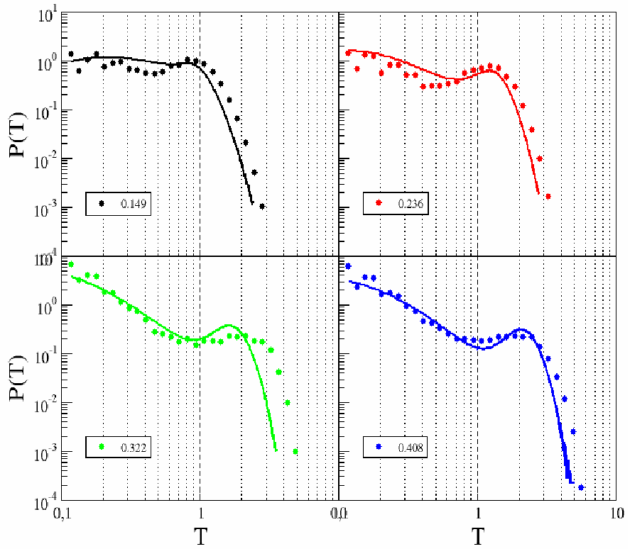


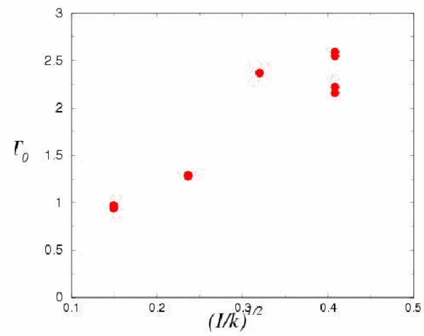
Simulation results: avalanches



Effect of spring and inertia

Several values of $\sqrt{I/k}$



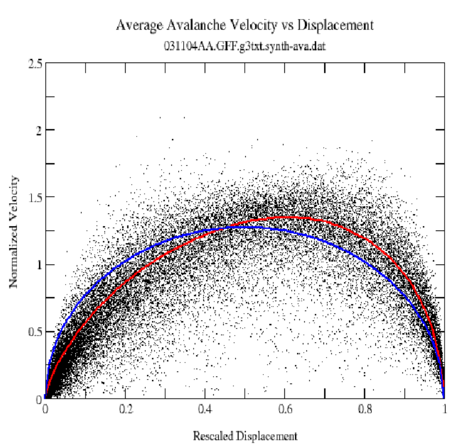


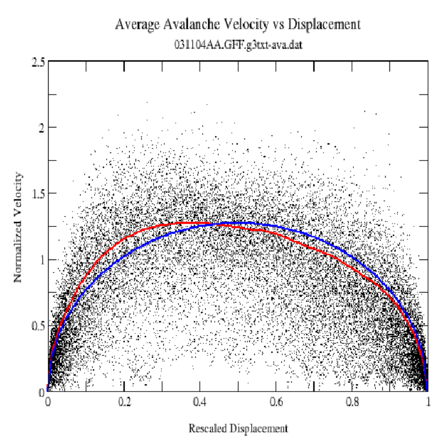
Granular pulse shapes

(...in progress...)

Model:
positive mass

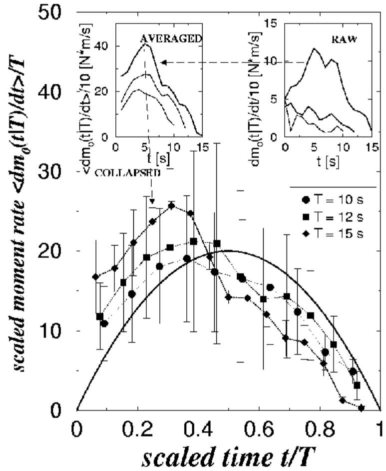
Experiments:
negative mass?



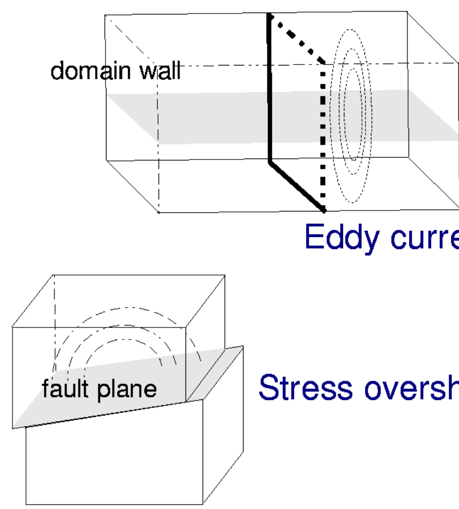


....and Earthquakes?

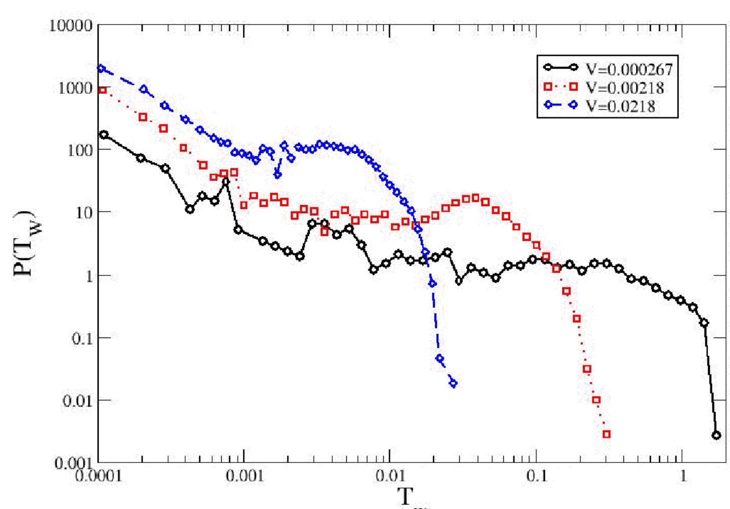
asymmetric shape maybe due to similar mechanism?



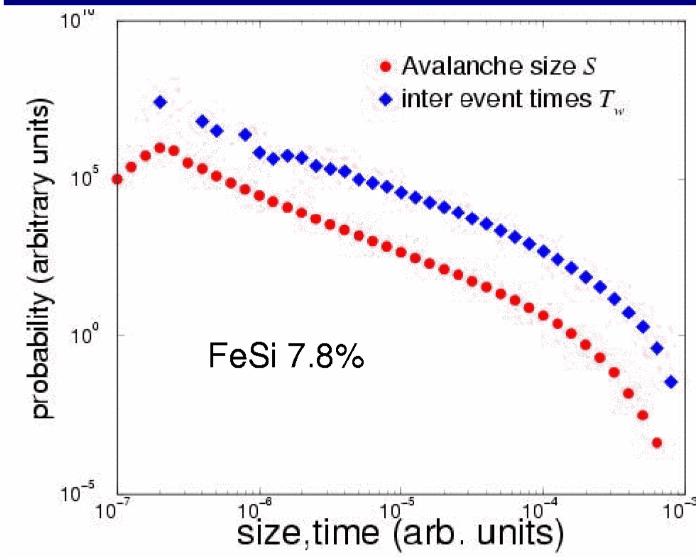
cond-mat/0509226



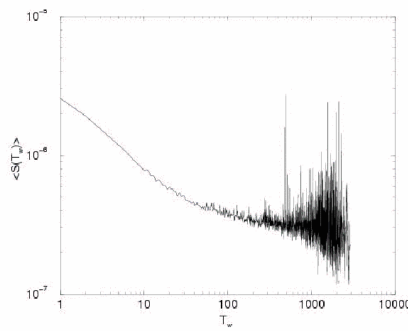
Inter-event time distribution for granular friction



Inter-event time distribution for Barkhausen noise



hypothesis: $S \propto T_w$



Domain walls and Granular media

$$I\ddot{\theta} = K(Vt-\theta) - F_0 - \gamma(\dot{\theta} - v_0 \log(1+\dot{\theta}/v_0)) - \delta F(\theta)$$

slip	$\theta \to x$	domain wall jump
shear rate	$KV \to c$	magnetic field rate
spring constant	$K \to k$	demagnetizing factor
frictional damping	$\gamma \to \Gamma$	eddy current dissipation
random forces	$\delta F \to W$	pinning forces
inertia	$I \to -M$	eddy current mass

$$M\ddot{x} = ct - kx - \Gamma\dot{x} - W(x)$$