Heterogeneity, visco-elasticity and the universality class of earthquake occurrence

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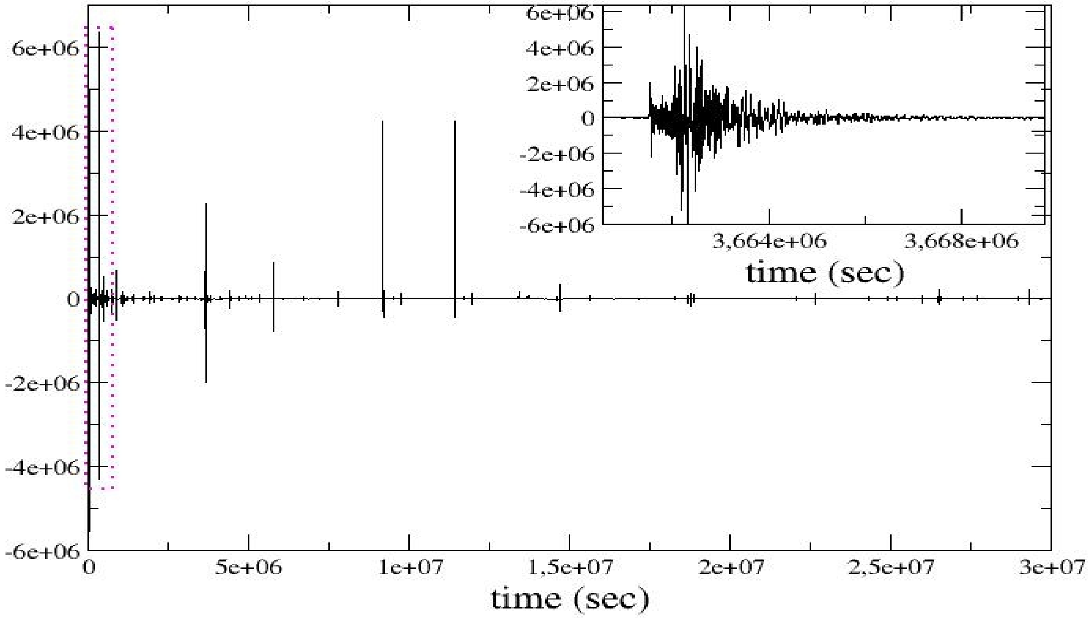
Seismic Glossary

Earthquake: the shaking of the surface of the Earth, resulting from the sudden release of energy in the Earth's upper part (the lithosphere) that creates seismic waves.

The ground accceleration caused by the 2016 Accumoli eartqhauke



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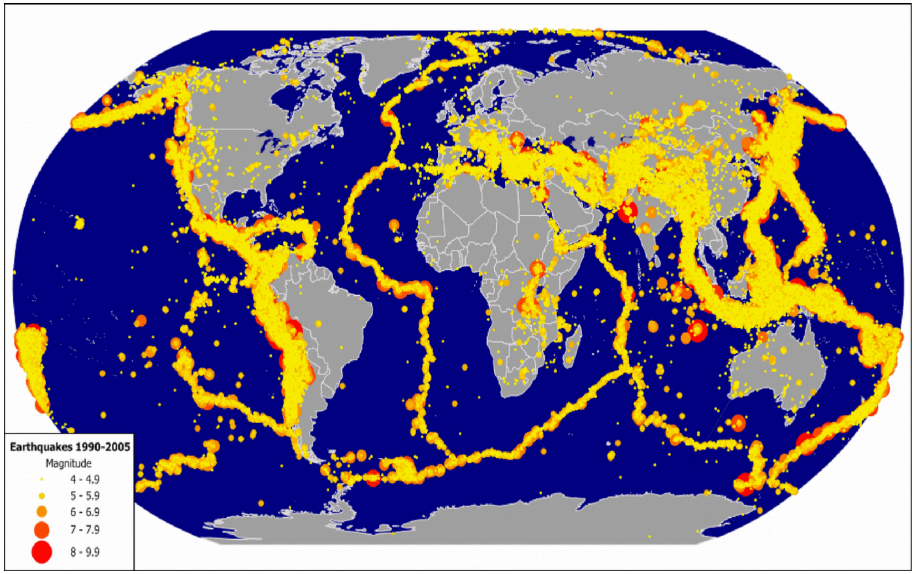
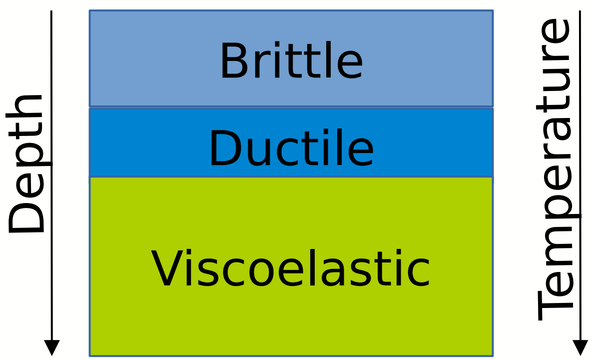
Earthquakes mostly occur on preexisting faults



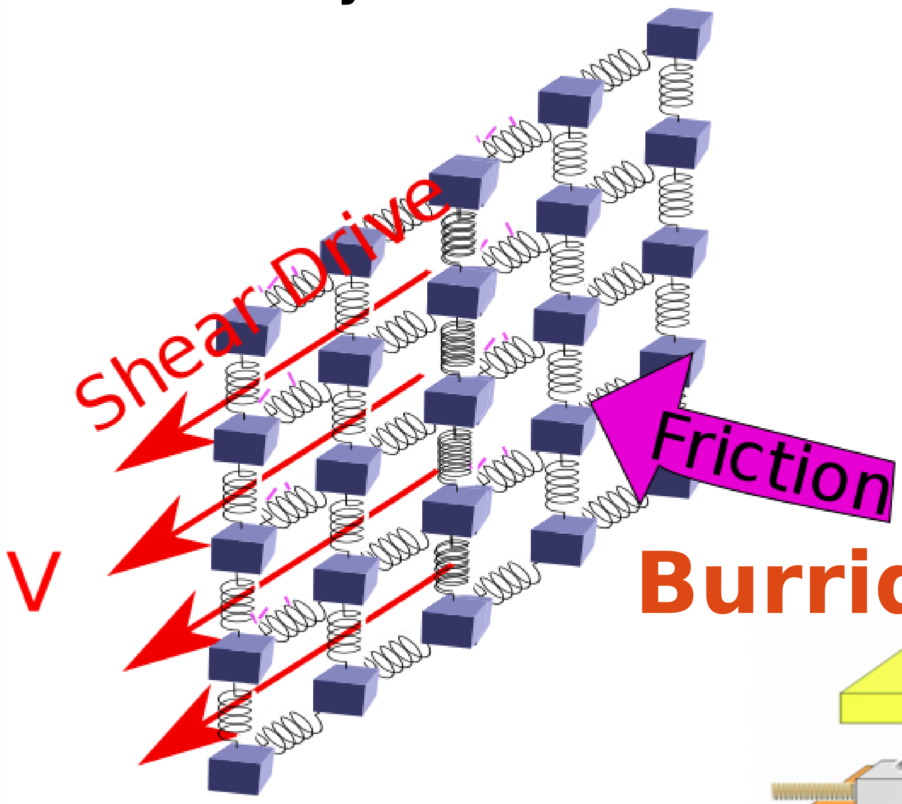
Global earthquake epicenters in the years [1990,2005]. Colored dots indicate epicentral coordinates with magnitude ranges expressed by the color code.



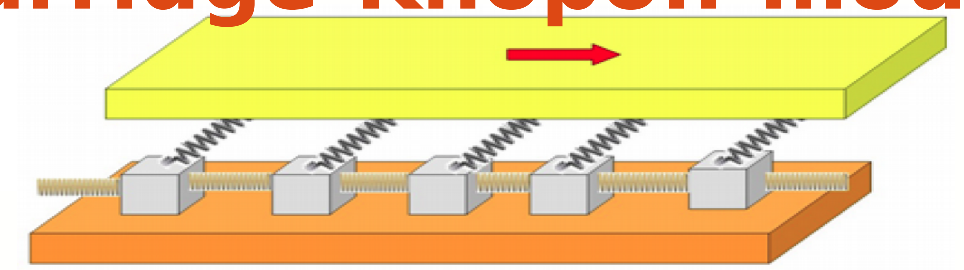
Earthquake occur in the upper layer of the Crust which exhibits a brittle-elastic behavior

Minimal description:

Elastic interface pushed by a normal pressure on a rough surface and driven by shear the tectonic drive at the velocity V



Burridge-Knopoff model



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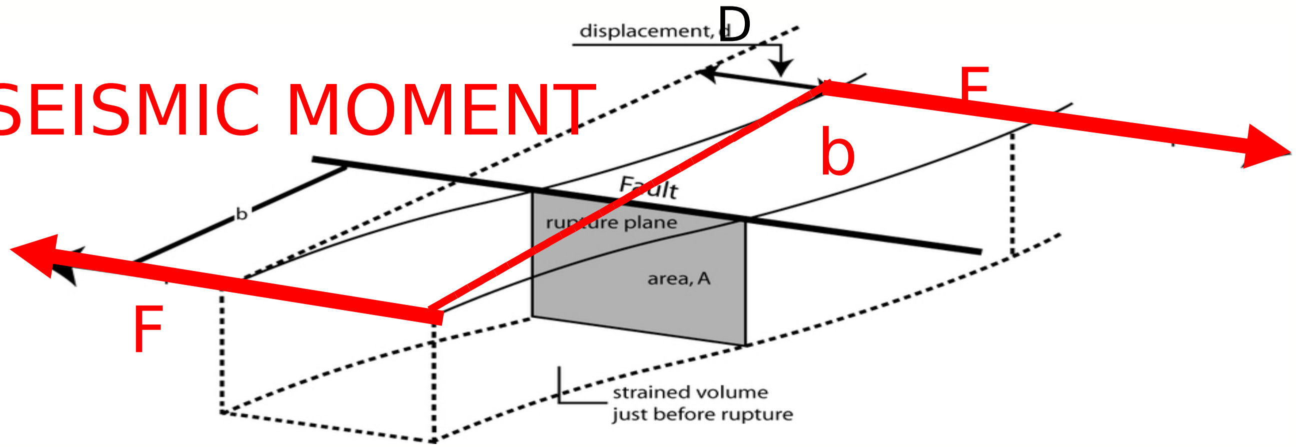
Seismic Glossary



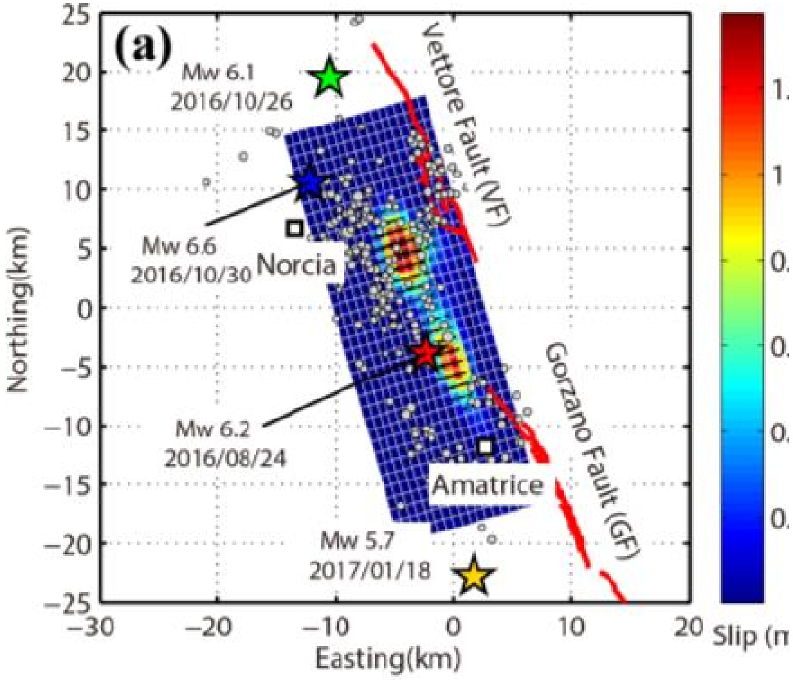
The seismic moment is a measure of the size of an earthquake based on the slipped area A, the average slip D, and the force that was required to overcome the friction sticking the rocks

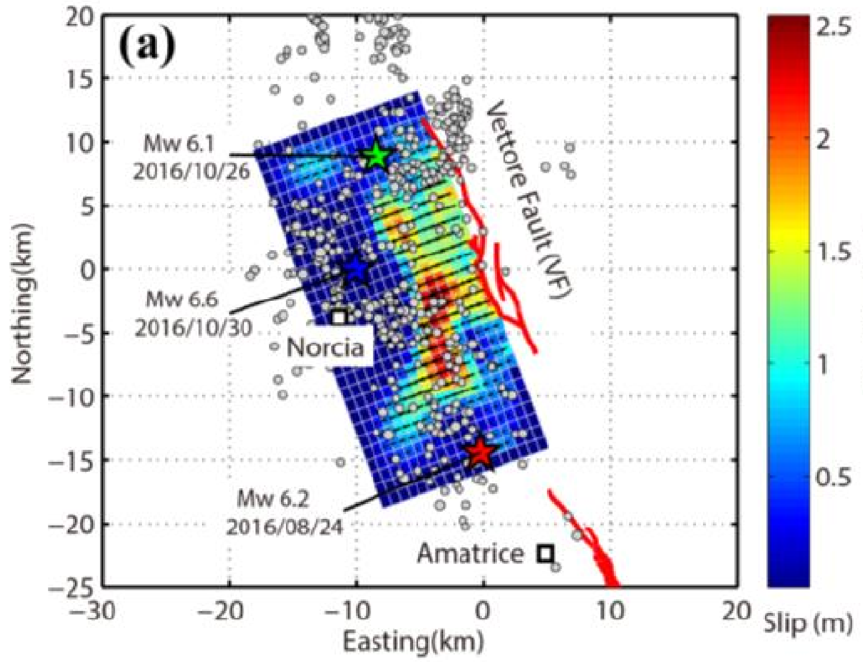
$$M_0 = \mu AD$$

μ Lamè constant (shear modulus)

Slip history

Each individual earthquake presents its own slip history





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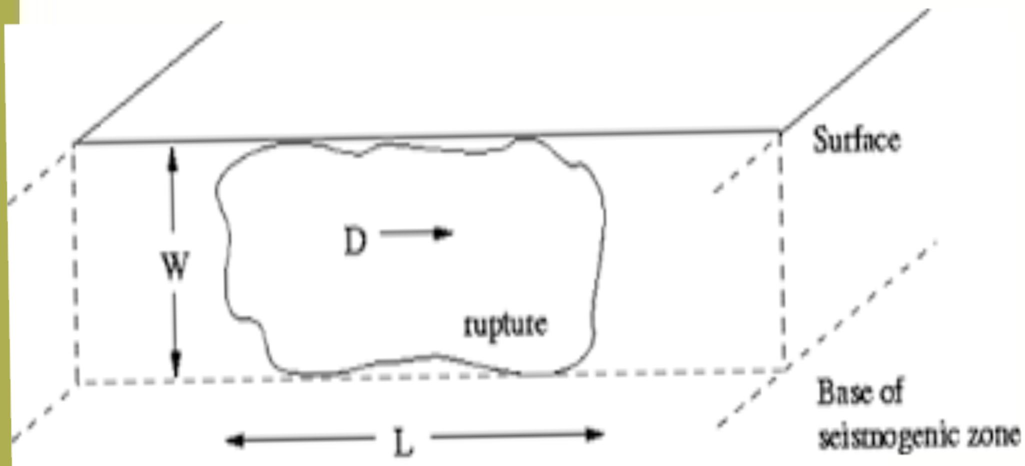
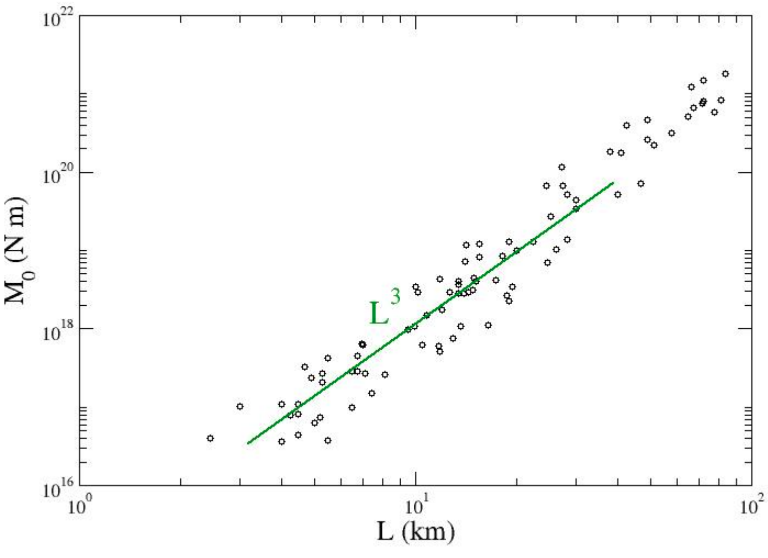
SCALING LAWS IN SEISMIC OCCURRENCE

In the geophysical community scaling laws are related to the standard definition of scale invariance: only one length scale in the process L

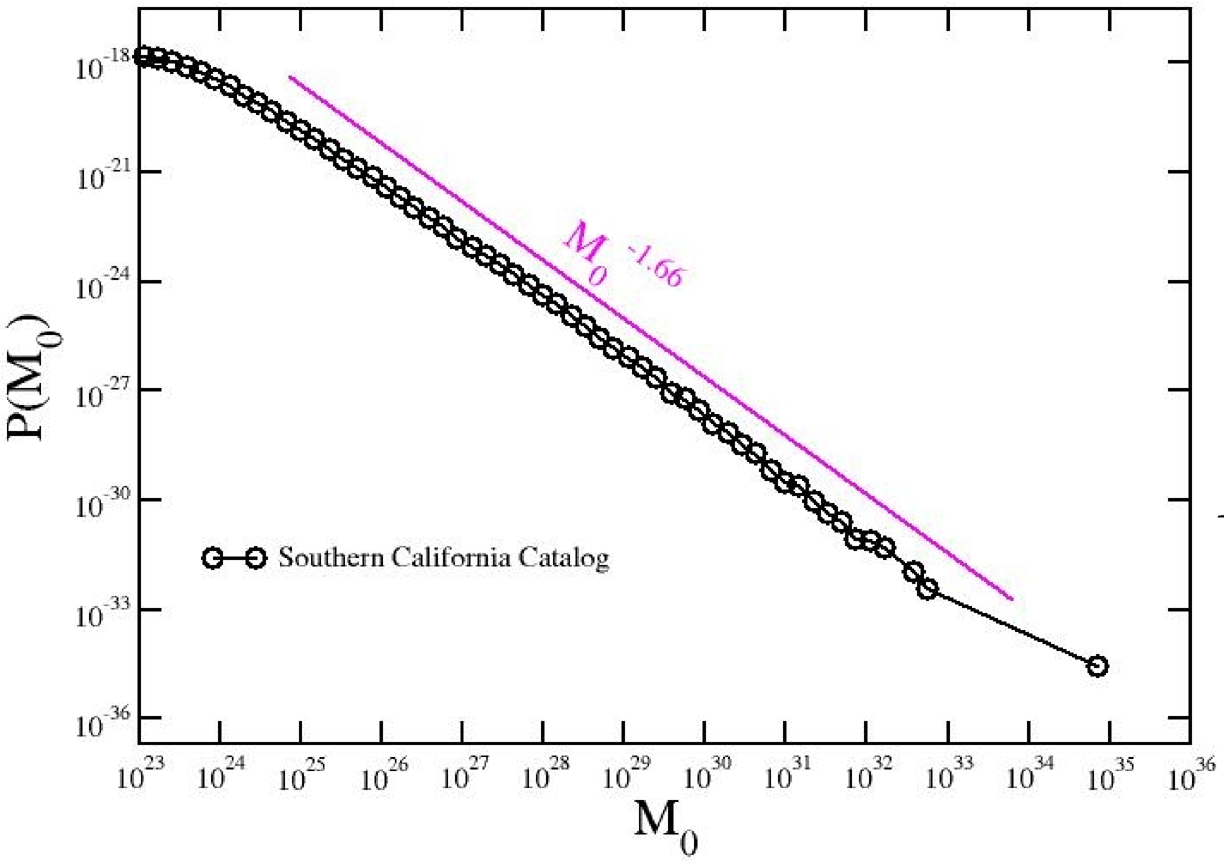


$$\begin{cases} W \sim L \\ D \sim L \\ A \sim L^2 \\ M_0 \sim L^3 \end{cases} \qquad M_0 = \mu A D$$



SCALING invariance between small and large earthquakes

Power law behavior of size distribution as at a critical point: Diverging correlation length



$$M_0 = \mu A D$$

$$P\left(M_0\right) \propto M_0^{-B}$$

$$B = 1 + \frac{2}{3} b \approx 1.7$$

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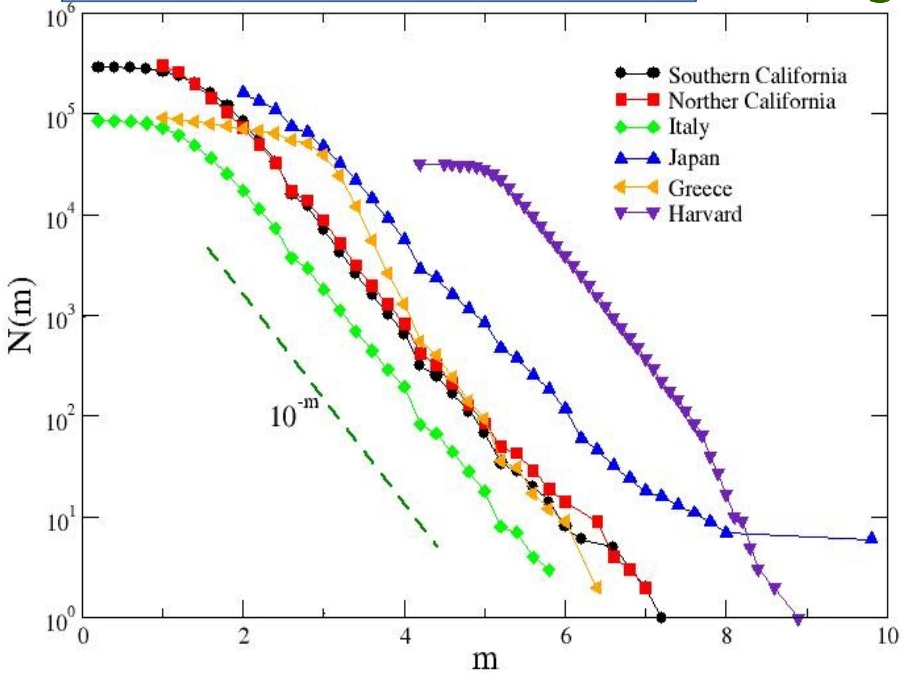
INSTRUMENTAL CATALOGS: GUTENBERG-RICHTER law

$$N(m) \propto 10^{-bm}$$

Number of earthquakes with magnitude in the range(m,m+δm)



b~1 quite universal

$$m = \frac{2}{3}\log_{10}(M_0) - 10.7$$

$$N(M_0) \propto M_0^{-B}$$

$$B = 1 + \frac{2}{3}b \approx 1.7$$

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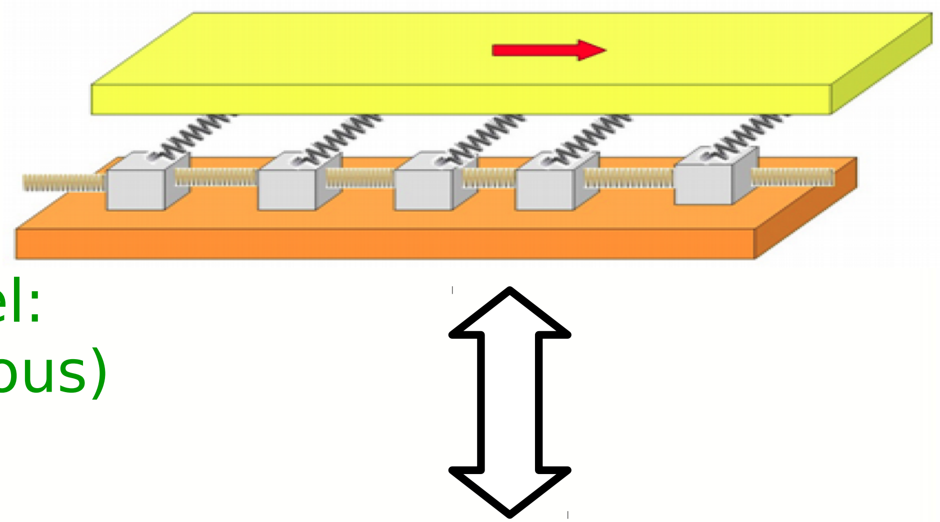
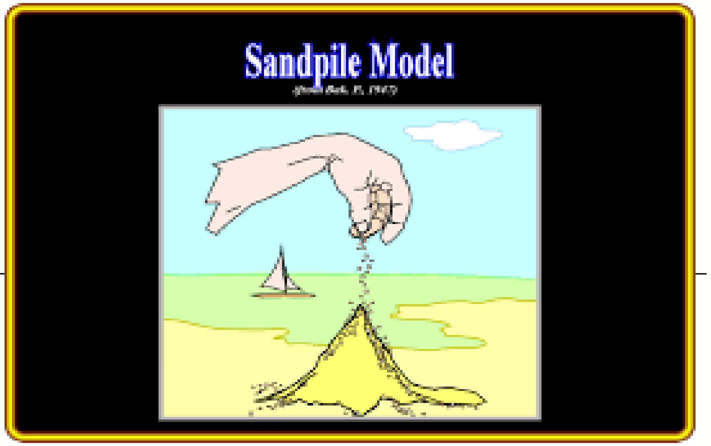
This supports the idea that the Earth Crust is in a Critical state

Self-Organized Criticality
(Bak,Tang,Wiesenfeld 1989)
(Olami,Feder,Christensen, 1992)



The Burridge-Knopoff model
In the limit of infinite
time scale separation
maps on the sand-pile model:
fast avalanches (instantaneous)
slow drive velocity V

What is Self-Organized Criticality?



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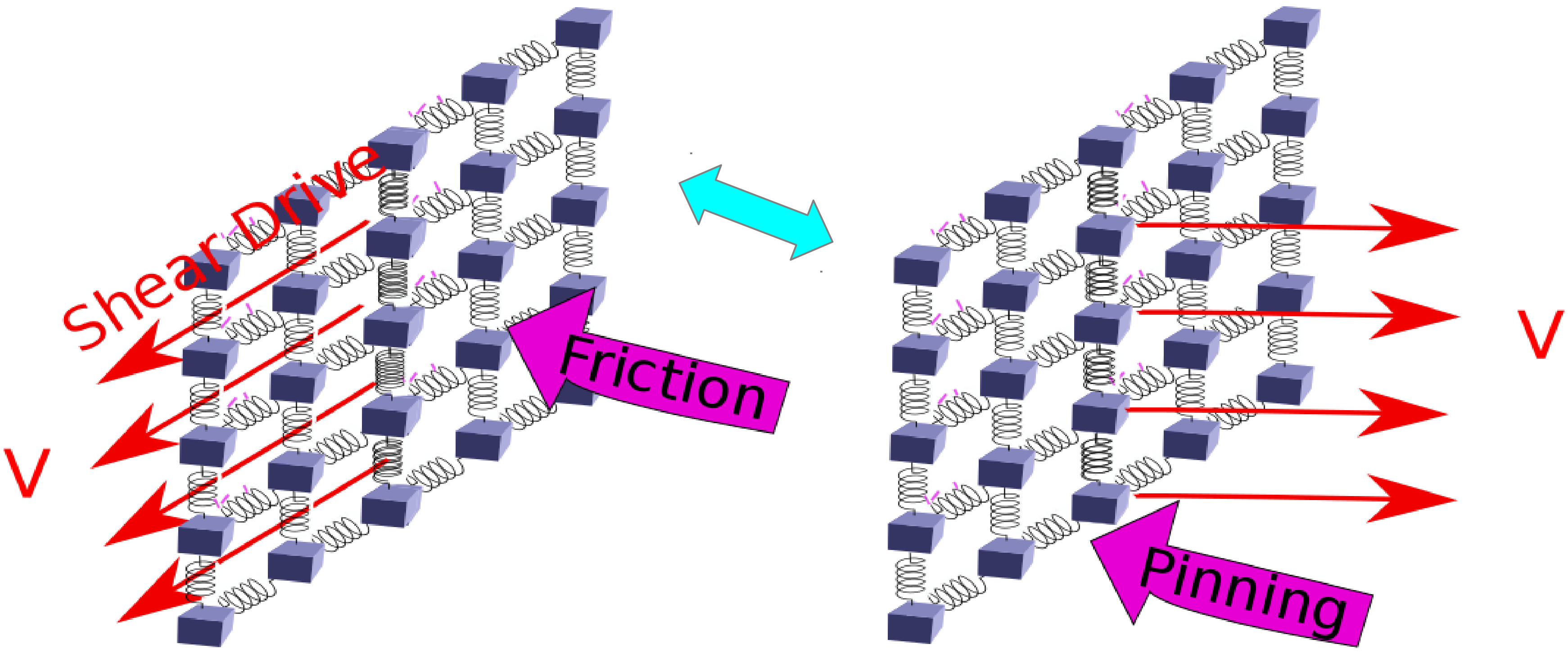
The Map on elastic interface depinning

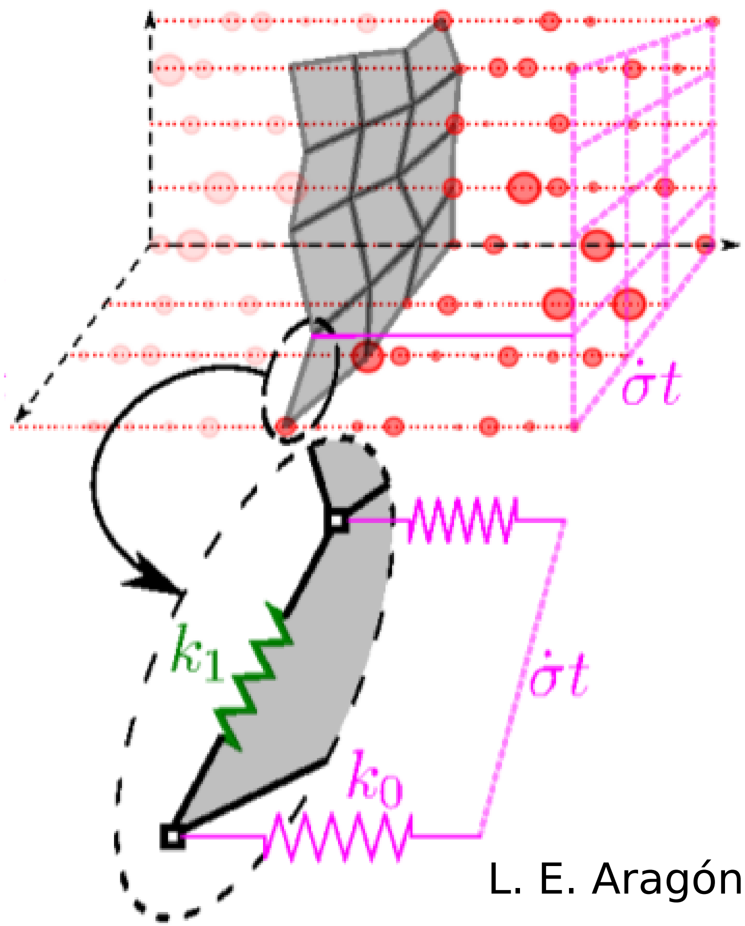


Friction force ⟷ Pinning force

Drive parallel to the interface ⟷ Drive perpendicular to the interface

The Map on elastic interface depinning

quenched Edwards-Wilkinson (qEW) model



Red dots represent pinning centers

heterogeneous in space and in depth

L. E. Aragón, E. A. Jagla, and A. Rosso, Phys. Rev. E (2012)

The Map on elastic interface depinning

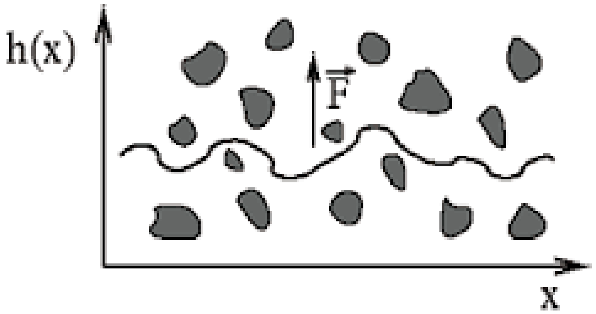
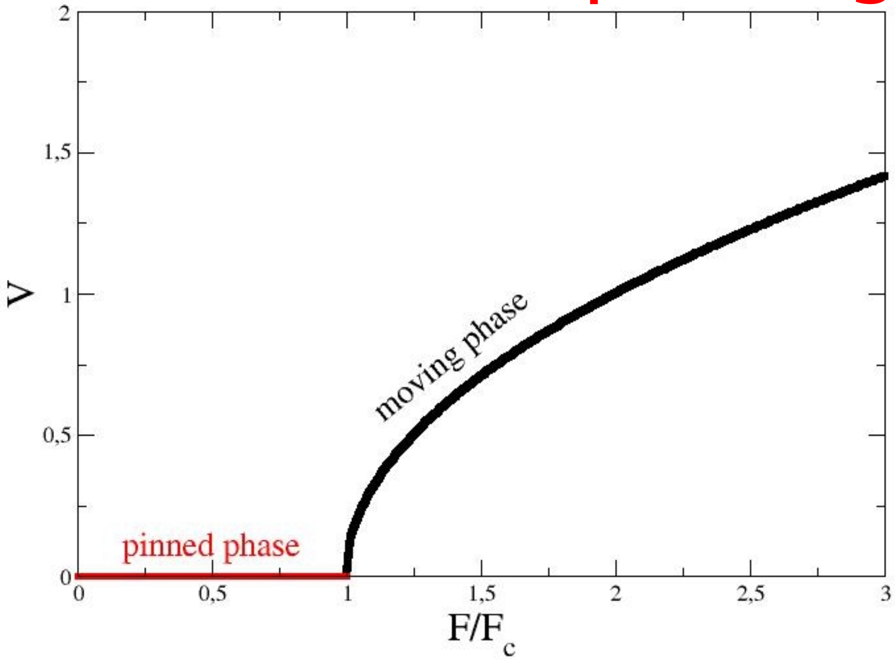


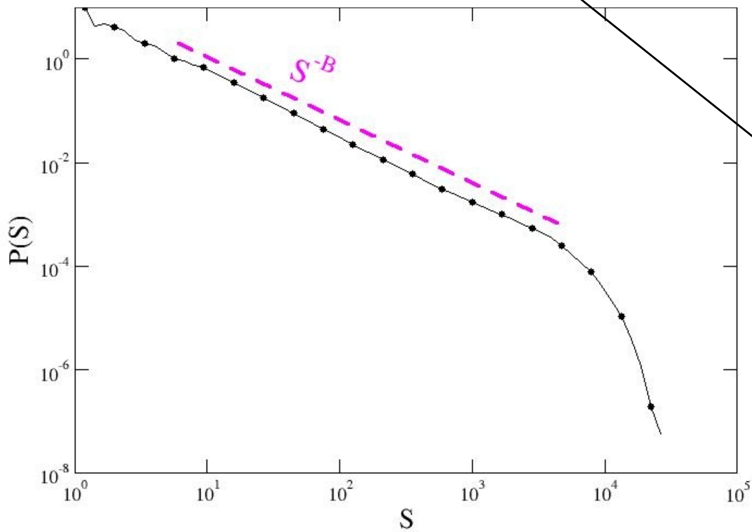
Figure 4. Schematic representation of a driven interface in a disordered media.

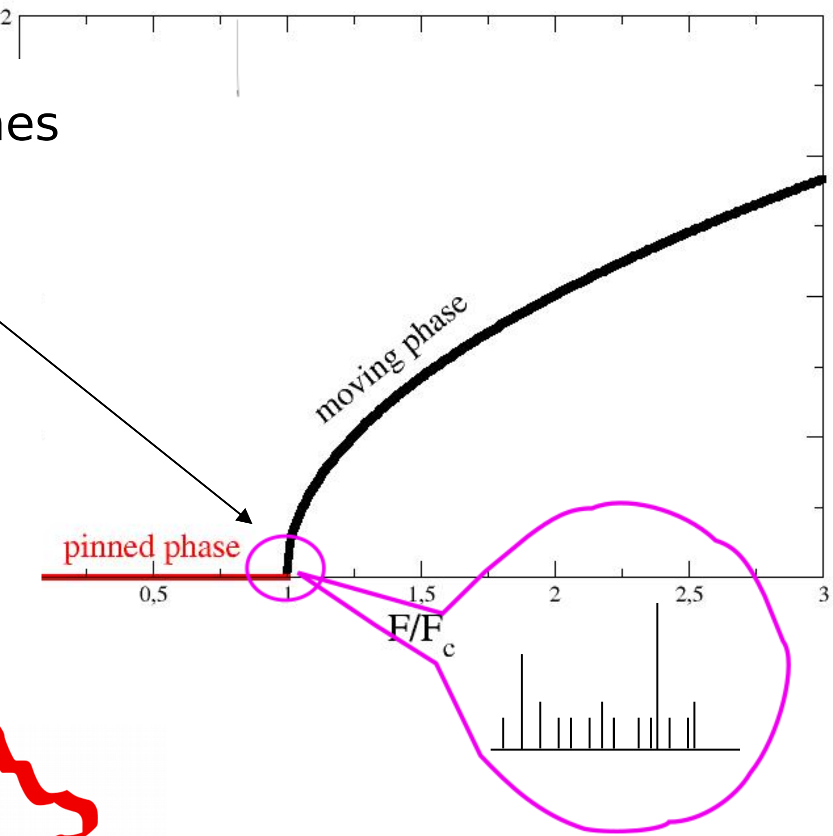


Dynamical Phase Transition: Pinned Phase – Moving phase

The depinning transition

Intermittent behavior: avalanches

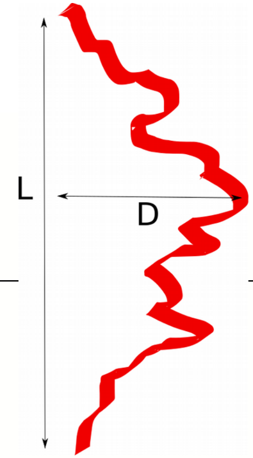




$$P(M_0) \propto M_0^{-B}$$

B=2-2/(D+ξ)

$M_0 \sim L^{D+\xi}$



ζ is the usual roughening exponent **D** ~ L^{ξ}

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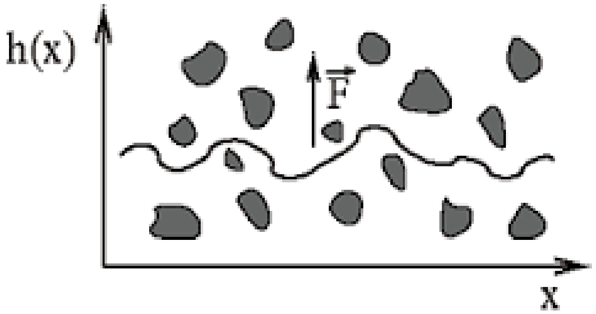
The Map on elastic interface depinning



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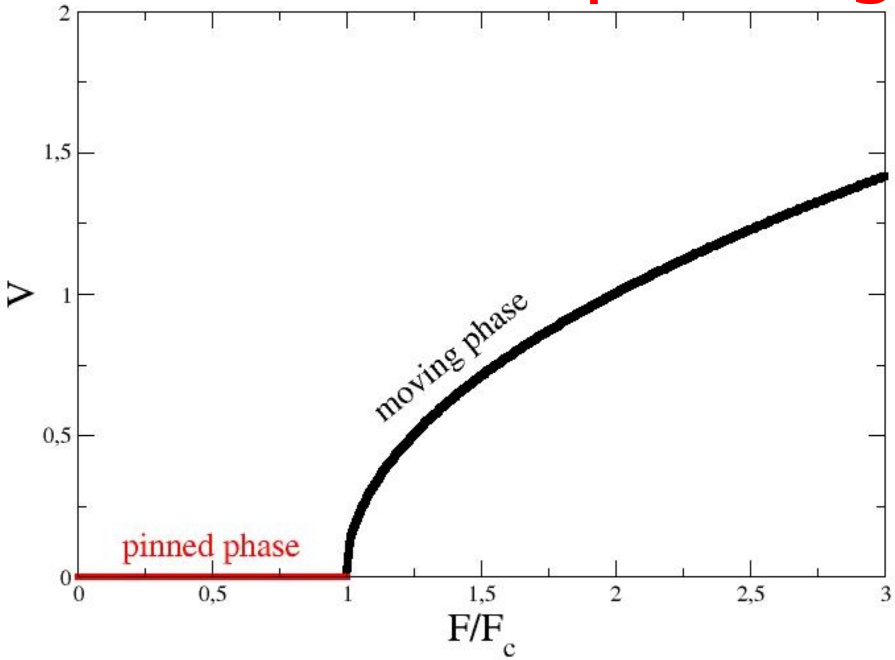

Non uniform force $F=K\,(V_0 t - x(t))$, when $\mathbf{V_0 \sim 0}$ $\mathbf{F \sim F_c}$

Always close to a critical point

$B=2-2/(D+\xi)$

$\mathbf{M_0 \sim L^{D+\xi}}$

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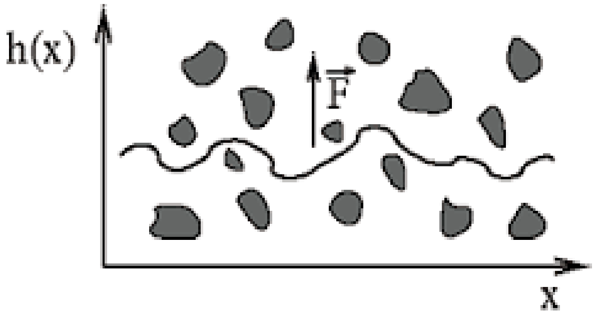
The Map on elastic interface depinning



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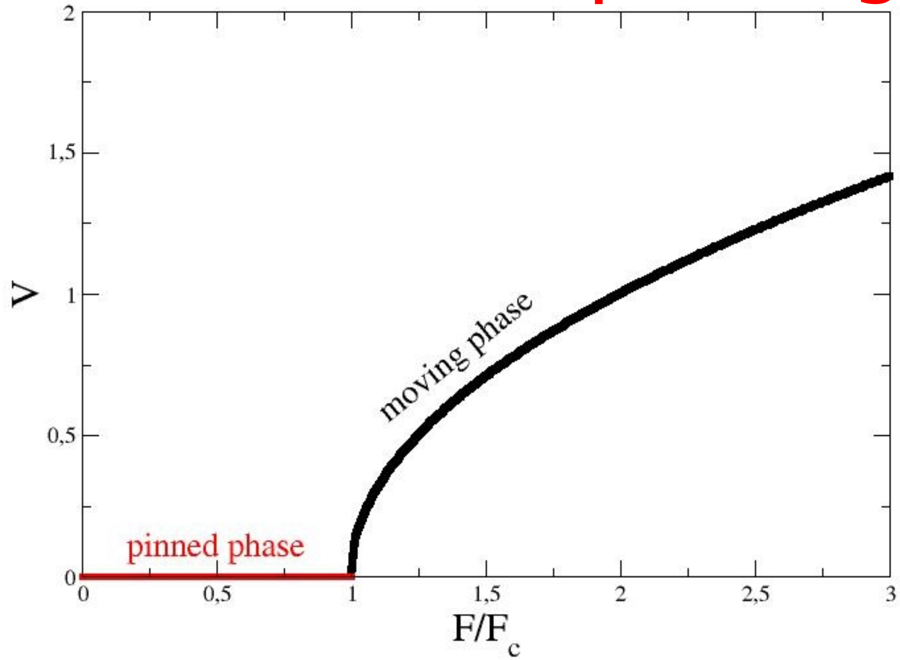

Non uniform force $F=K\,(V_0 t - x(t))$, when $\mathbf{V_0 \sim 0}$ $\mathbf{F \sim F_c}$

Always close to a critical point

$B=2-2/(D+\xi)$

$\mathbf{M_0 \sim L^{D+\xi}}$

$\xi=0.75$

$B=1.27 < 1.7$

$\mathbf{M_0 \sim L^{2.75} < L^3}$

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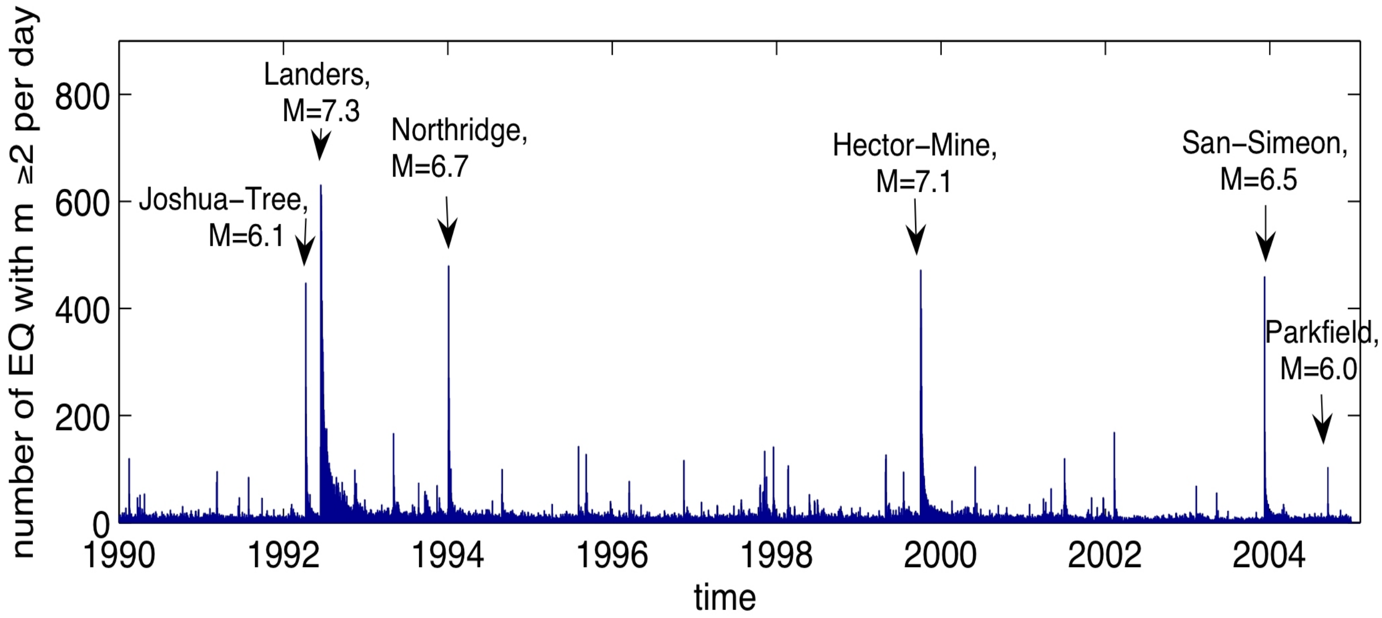
Different exponents of those of earthquake occurrence!!

Temporal Clustering



The majority of events in seismic catalogs are aftershocks!

Aftershocks: earthquakes that follow the largest shock.

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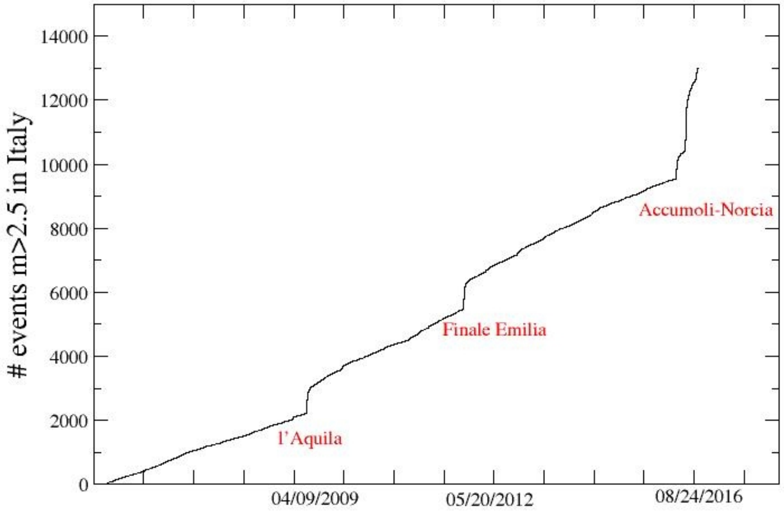
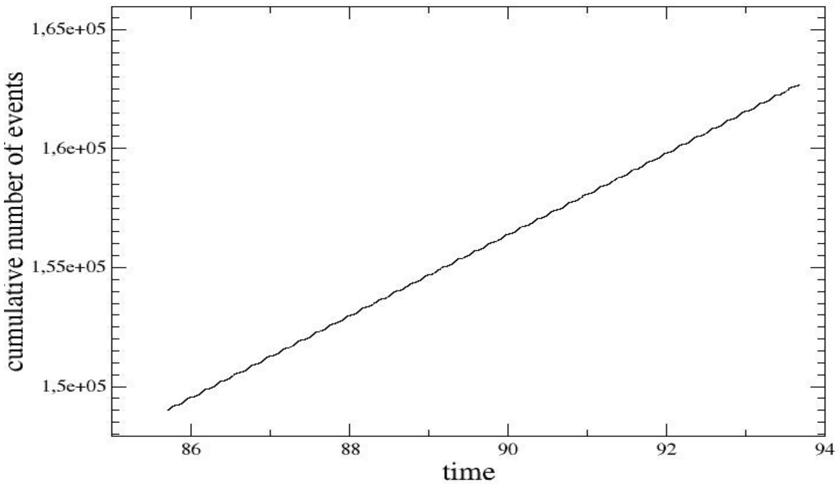
Temporal Clustering



Strong temporal clustering due to aftershocks

N0 temporal clustering (NO aftershocks) in the qEW model



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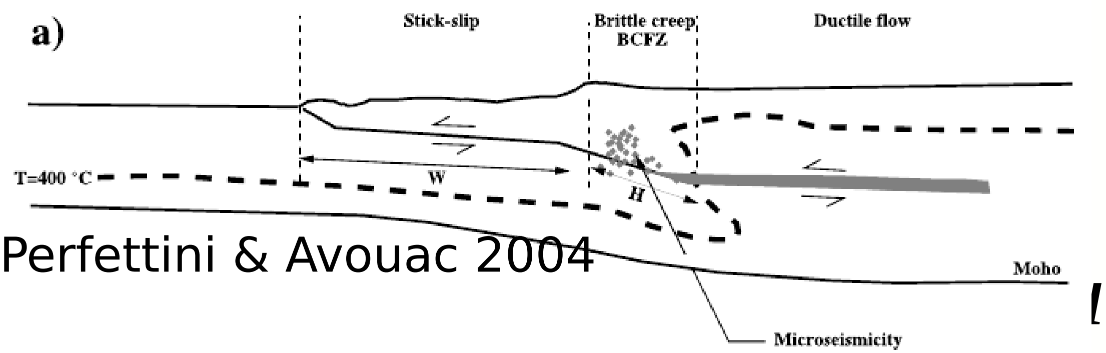
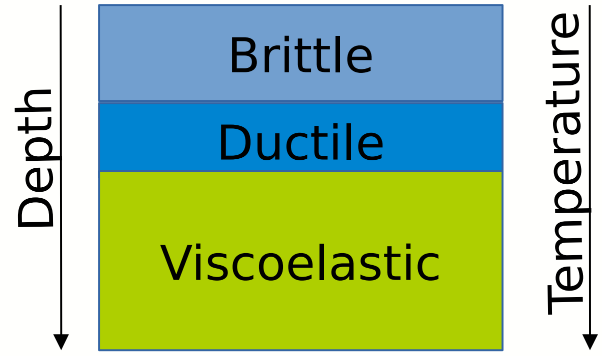
The origin of aftershocks

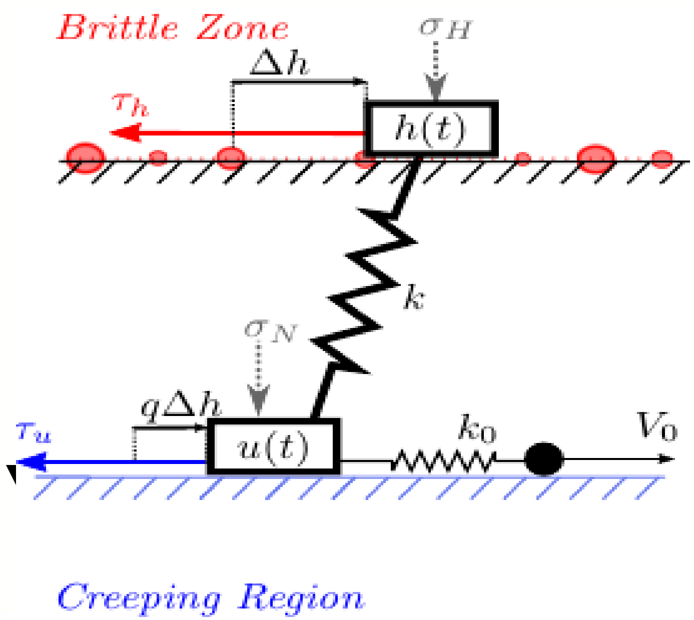
Coupling with the ductile layer



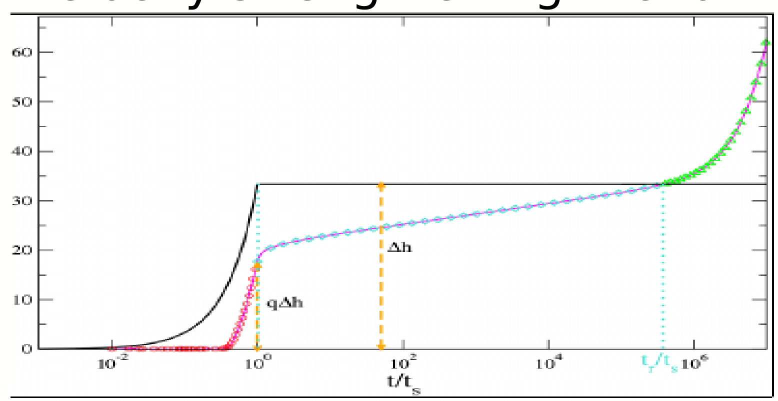
Perfettini & Avouac 2004



Two block model (Lippiello et al. 2018)



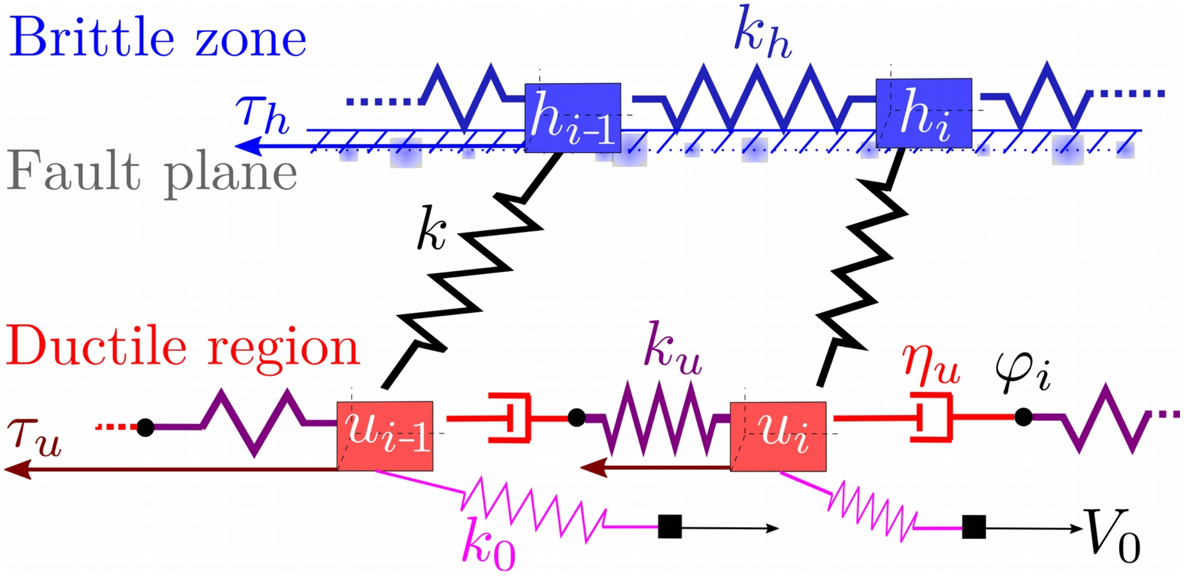
The slip of h(t) induces the coseismic Slip of the u(t) which subsequent relaxes logarithmically because of velocity strengthening friction



$$\dot{u} \propto \frac{1}{t}$$

The 2 Layer qEW model

Generalization of the two block model



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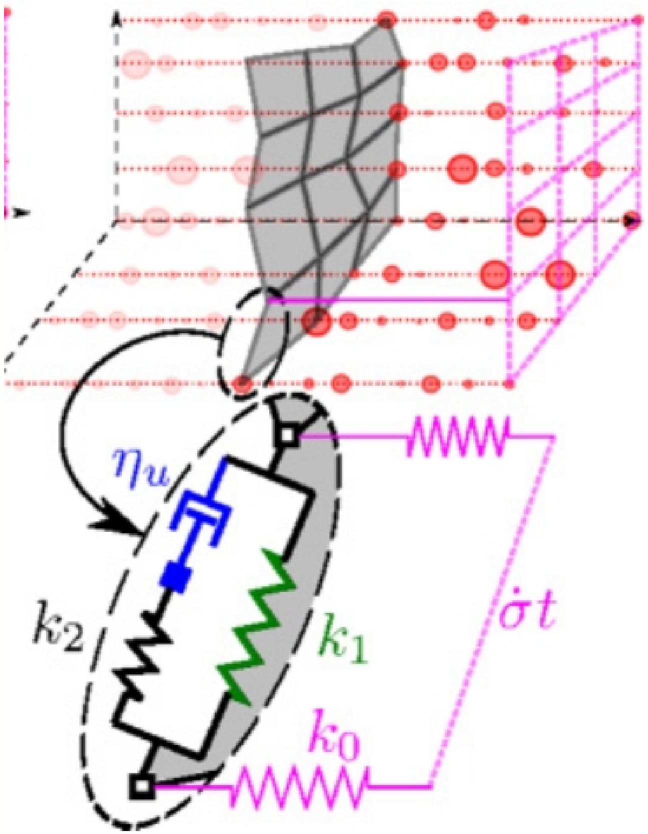


The Viscoelastic qEW model

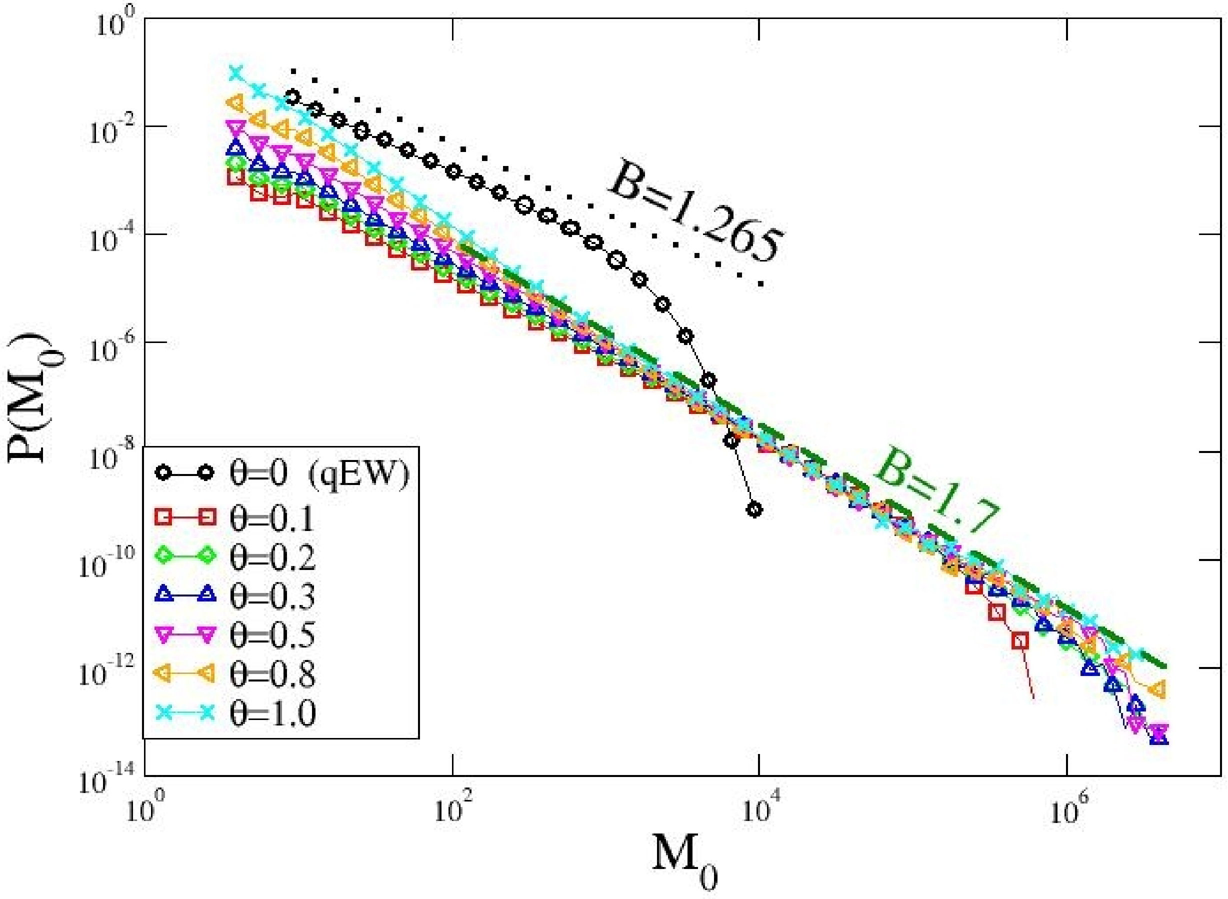
All the dynamics can be described in terms of the local stress value

$$F_i = (1-\theta) F_i^{(fast)} + \theta \, F_i^{(slow)}(t)$$

<u>Only one parameter θ</u>

For $\theta=0$ we have the qEW model

Size distribution in the 2LqEW model



The B=1.7 in Indepedent of θ

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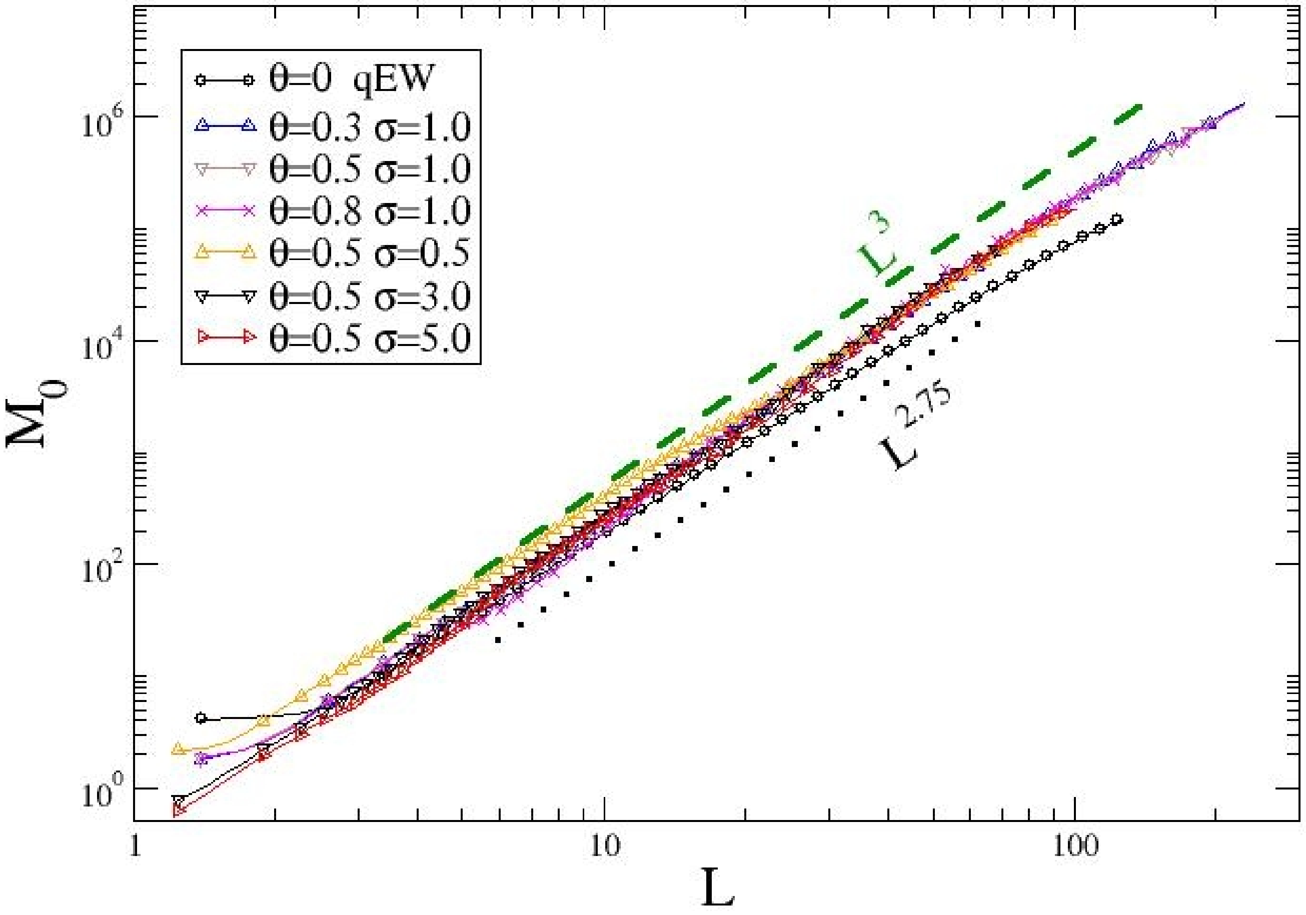
Scaling in the 2LqEW model



Indepedent of θ

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All relevant scaling laws in seismic occurrence
Are recovered at quantitative level

$$P(M_0) \propto M_0^{-1+2/3b}$$

Gutenberg-Richter law

$$N(t) \propto \frac{1}{(t+c)^p}$$

Omori-Utsu law

$$N(M_0) \propto M_0^{2/3\alpha}$$

Productivity law

$$N(r) \propto \frac{1}{(r+d)^\nu}$$

Space Clustering law

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CONCLUSIONS

We have introduced the
viscous quenched EW model
with same scaling behavior of earthquake occurrence.

From theoretical point of view:
A new universality class

From earthquake point of view:
A new tool to investigate open problems in seismic occurrence

REFERENCES

Statistical physics approach to earthquake occurrence and forecasting
L de Arcangelis, C Godano, JR Grasso, E Lippiello
Physics Reports 628, 1 (2016)

(for the 2-block model)
Fault heterogeneity and the connection between aftershocks and afterslip
E. Lippiello , G. Petrillo , F. Landes , A. Rosso
BSSA, 2018

The influence of the brittle-ductile transition zone on aftershock and foreshock occurrence
E. Lippiello , G. Petrillo , F. Landes , A. Rosso
Submitted