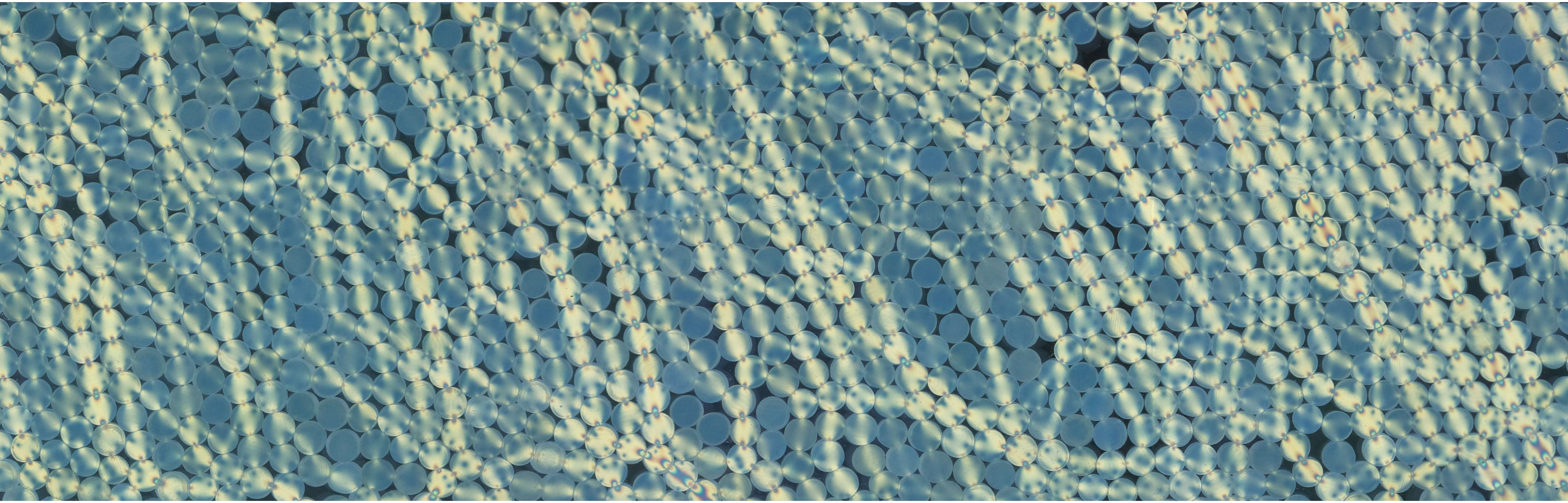
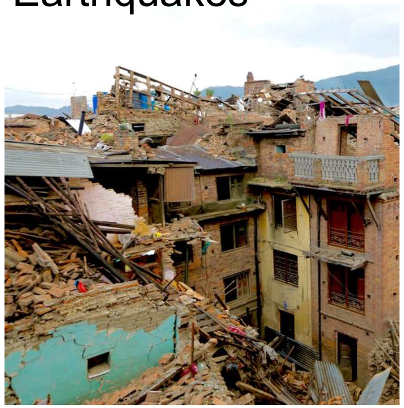


The *LabQuakes* project: from a granular fault to earthquake statistics

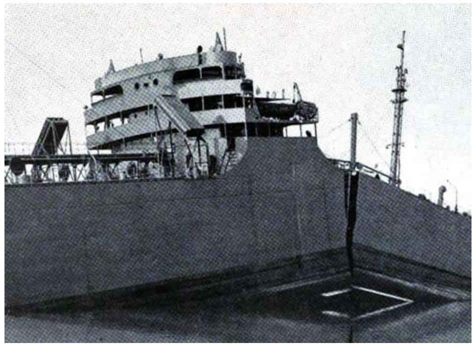
Osvanny Ramos

Avalanche 2022, Debrecen, Hungary, 30/08/22

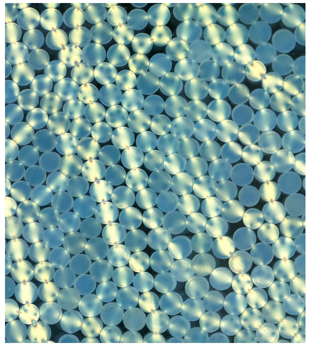
Scale-invariant avalanches



Earthquakes

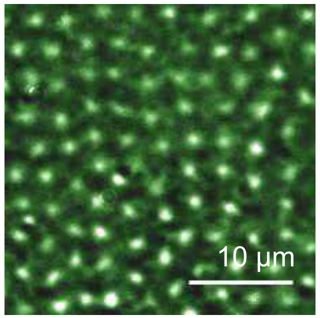


Subcritical fracture

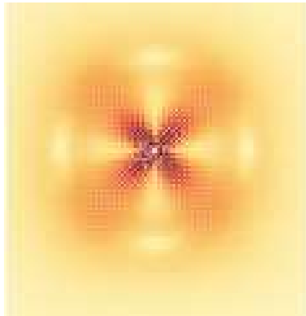


Granular shear

Stock markets



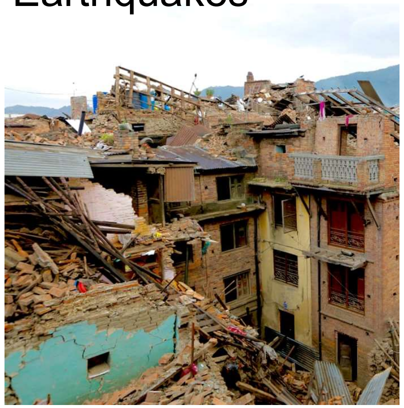
Superconducting vortices



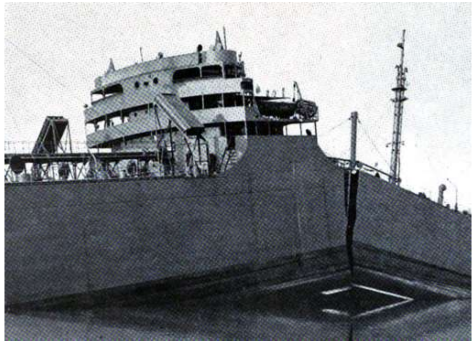
Amorphous solids

Scale-invariant avalanches

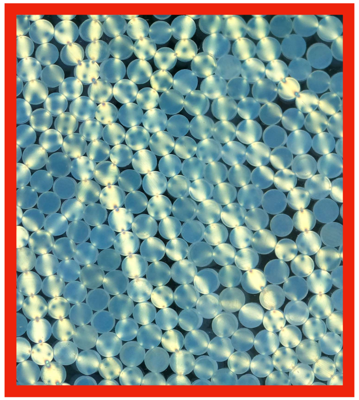
Earthquakes



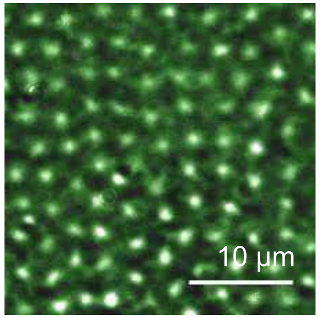
Subcritical fracture



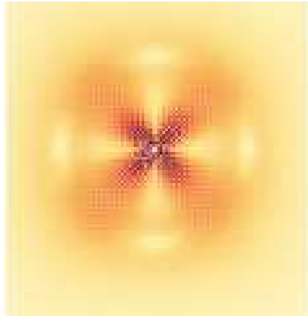
Granular shear



Stock markets

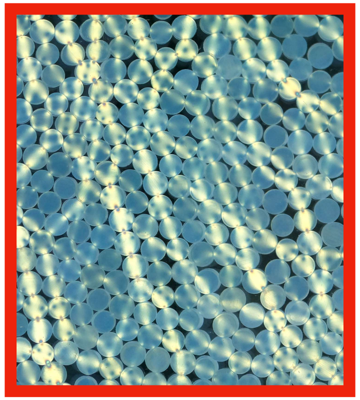


Superconducting vortices

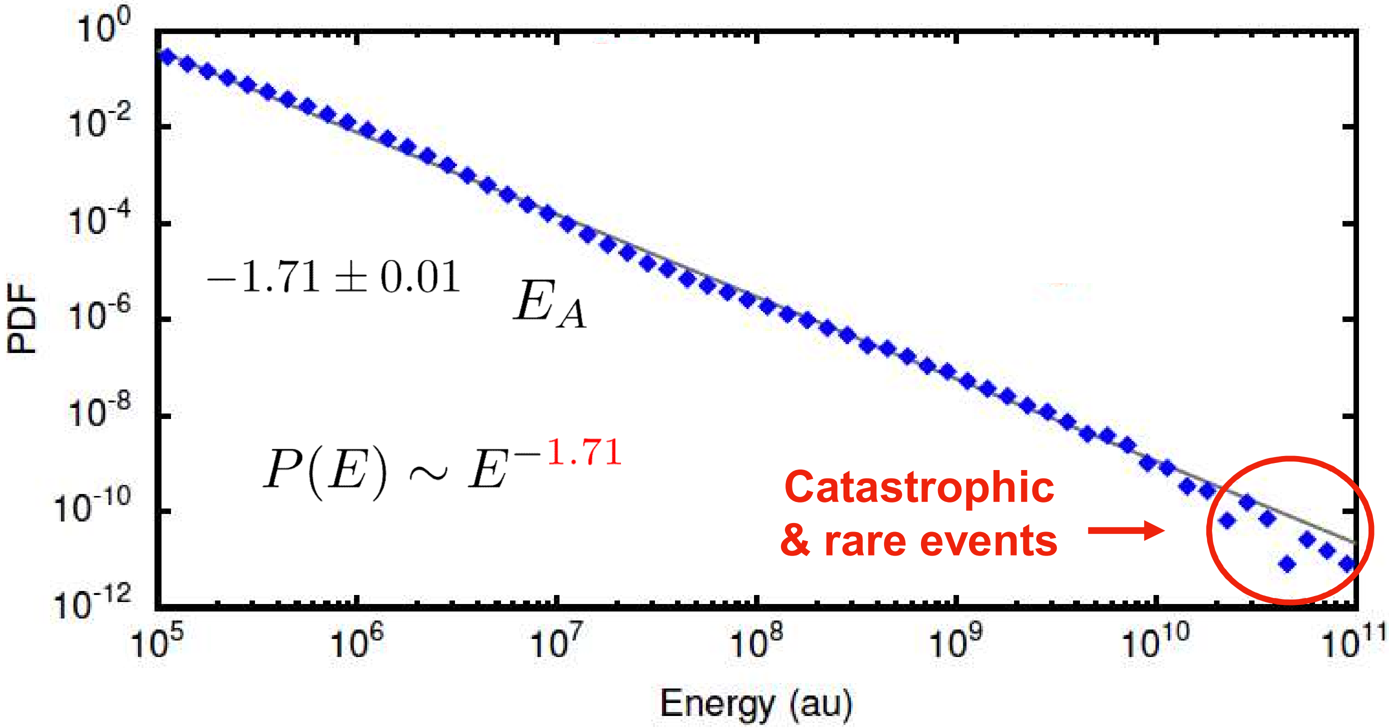


Amorphous solids

Granular shear



Energy distribution:



Some open questions in scale-invariant avalanches

Physics of scale-invariant avalanches

Phase transitions
Critical dynamics

Predictability
Inherently impossible?
Memory effects
Prediction of catastrophic events?

Scale-invariance
Origin?
Robustness?
Common features:
Clustering, memory?

?

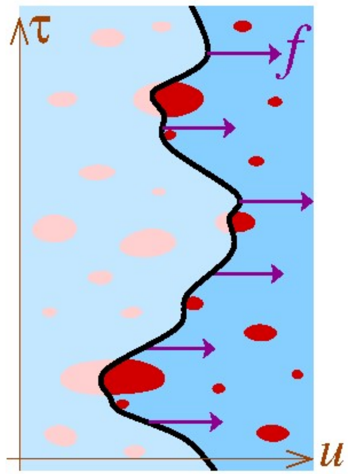
Critical properties
Universality classes?
Experiments: Not-robust exponent values & exponent values larger than 3/2
Diverging correlation lengths?

Elastic line in a disordered landscape

PHYSICAL REVIEW E **79**, 051106 (2009)

Size distributions of shocks and static avalanches from the functional renormalization group

Pierre Le Doussal and Kay Jörg Wiese
Laboratoire de Physique Théorique de l'Ecole Normale Supérieure, CNRS, 24 rue Lhomond, 75231 Paris Cedex, France
(Received 20 January 2009; published 7 May 2009)

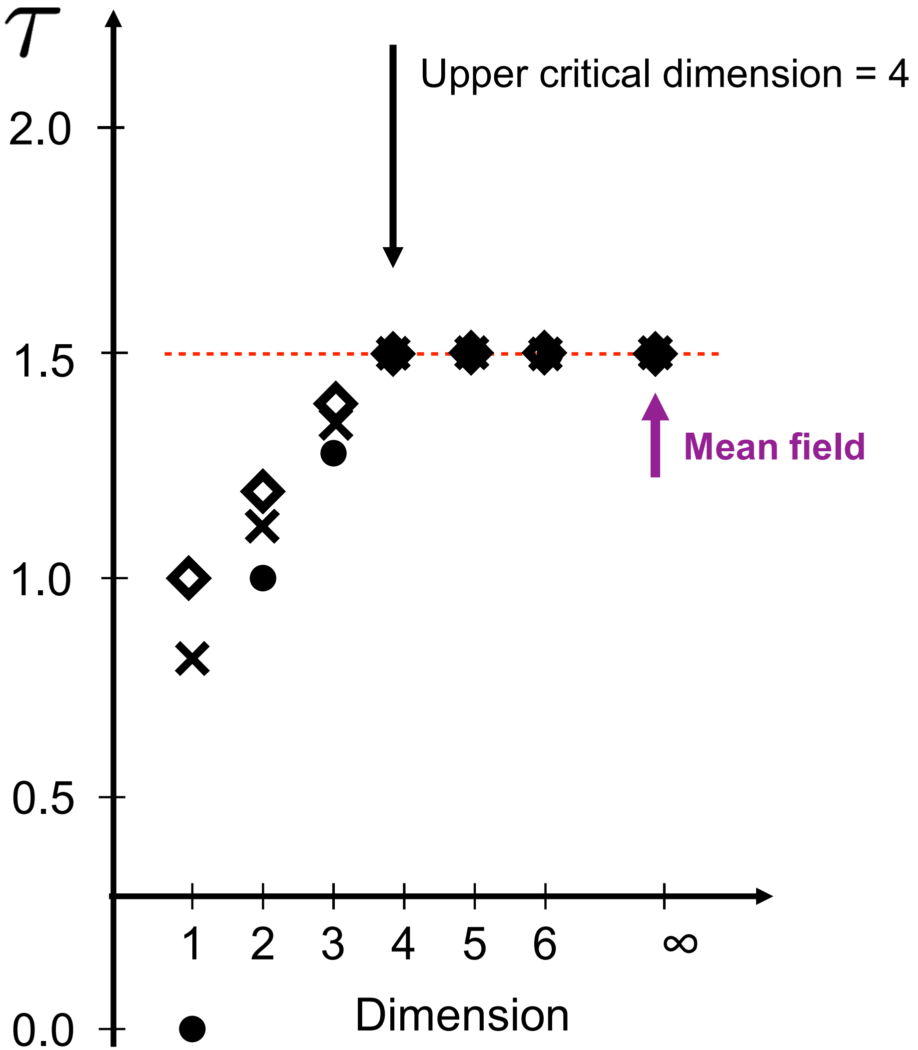


Interfaces pinned by quenched disorder are often used to model jerky self-organized critical motion. We study static avalanches, or shocks, defined here as jumps between distinct global minima upon changing an external field. We show how the full statistics of these jumps is encoded in the functional-renormalization-group fixed-point functions. This allows us to obtain the size distribution $P(S)$ of static avalanches in an expansion in the internal dimension d of the interface. Near and above $d=4$ this yields the mean-field distribution $P(S)\sim S^{-3/2}e^{-S/4S_m}$, where S_m is a large-scale cutoff, in some cases calculable. Resumming all one-loop contributions, we find $P(S)\sim S^{-\tau}\exp(C(S/S_m)^{1/2}-\frac{B}{4}(S/S_m)^{\delta})$, where B, C, δ, and τ are obtained to first order in $\epsilon=4-d$. Our result is consistent to $O(\epsilon)$ with the relation $\tau=\tau_\zeta:=2-\frac{2}{d+\zeta}$, where ζ is the static roughness exponent, often conjectured to hold at depinning. Our calculation applies to all static universality classes, including random-bond, random-field, and random-periodic disorders. Extended to long-range elastic systems, it yields a different size distribution for the case of contact-line elasticity, with an exponent compatible with $\tau=2-\frac{1}{d+\zeta}$ to $O(\epsilon=2-d)$. We discuss consequences for avalanches at depinning and for sandpile models, relations to Burgers turbulence and the possibility that the relation $\tau=\tau_\zeta$ be violated to higher loop order. Finally, we show that the avalanche-size distribution on a hyperplane of codimension one is in mean field (valid close to and above $d=4$) given by $P(S)\sim K_{1/3}(S)/S$, where K is the Bessel-K function, thus $\tau_{\text{hyper plane}}=\frac{4}{3}$.

DOI: 10.1103/PhysRevE.79.051106 PACS number(s): 05.40.−a, 05.10.Cc

Exponent values in avalanche size distributions

$$P(s) \sim s^{-\tau}$$



Renormalization group in elastic lines

● RP ✕ RB ◇ RF Le Doussal & Wiese, PRE 2009

Avalanches in branching processes

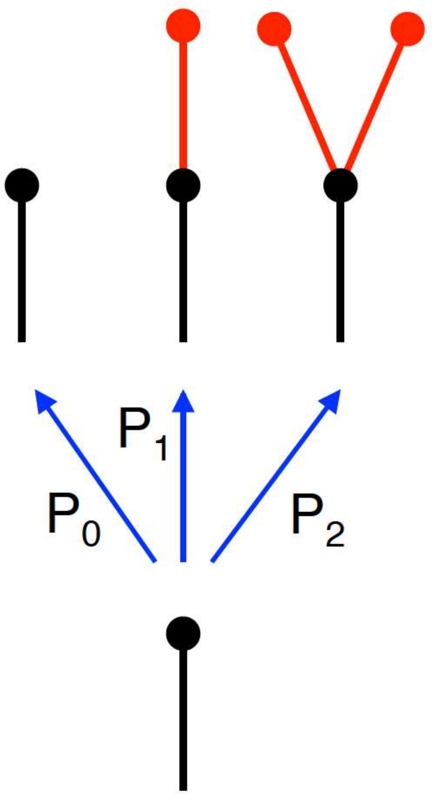


Figure 26: Branching process with $n_{max} = 2$.

$$\sum_{0}^{n_{max}} nP_n = 1 + G$$

$$\sum_{0}^{n_{max}} P_n = 1$$

$$\downarrow \; G = 0$$

$$P(s) \sim s^{-3/2} exp(-s/\lambda)$$

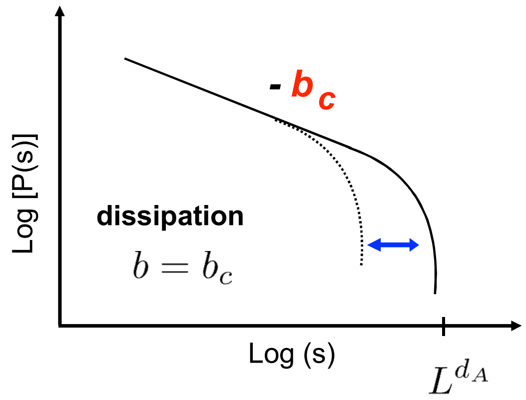
$$\uparrow \; \lambda \sim L$$

dissipation

$$\downarrow \; G < 0$$

$$P(s) \sim s^{-3/2} exp(-s/\lambda)$$

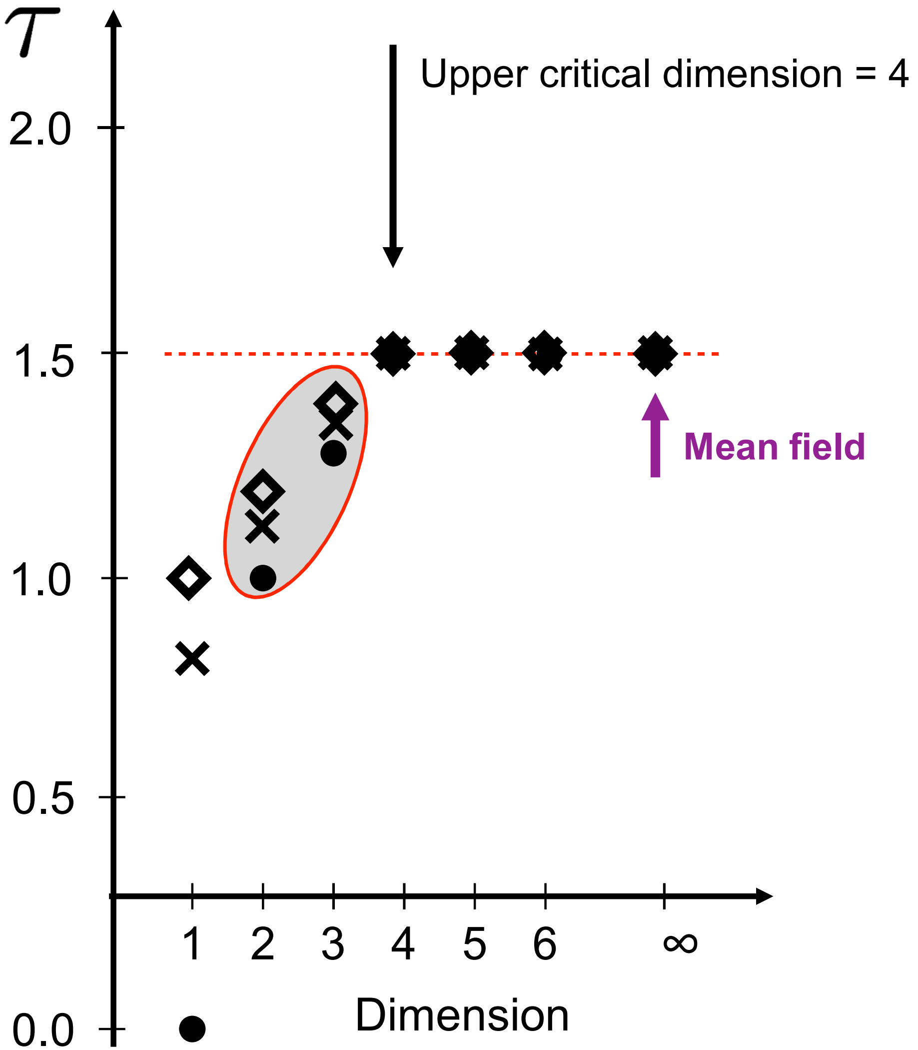
$$\uparrow \; \lambda < L$$



Preben Alstrøm. Mean-field exponents for self-organized critical phenomena. Phys. Rev. A, 38:4905–4906, 1988.

Exponent values in avalanche size distributions

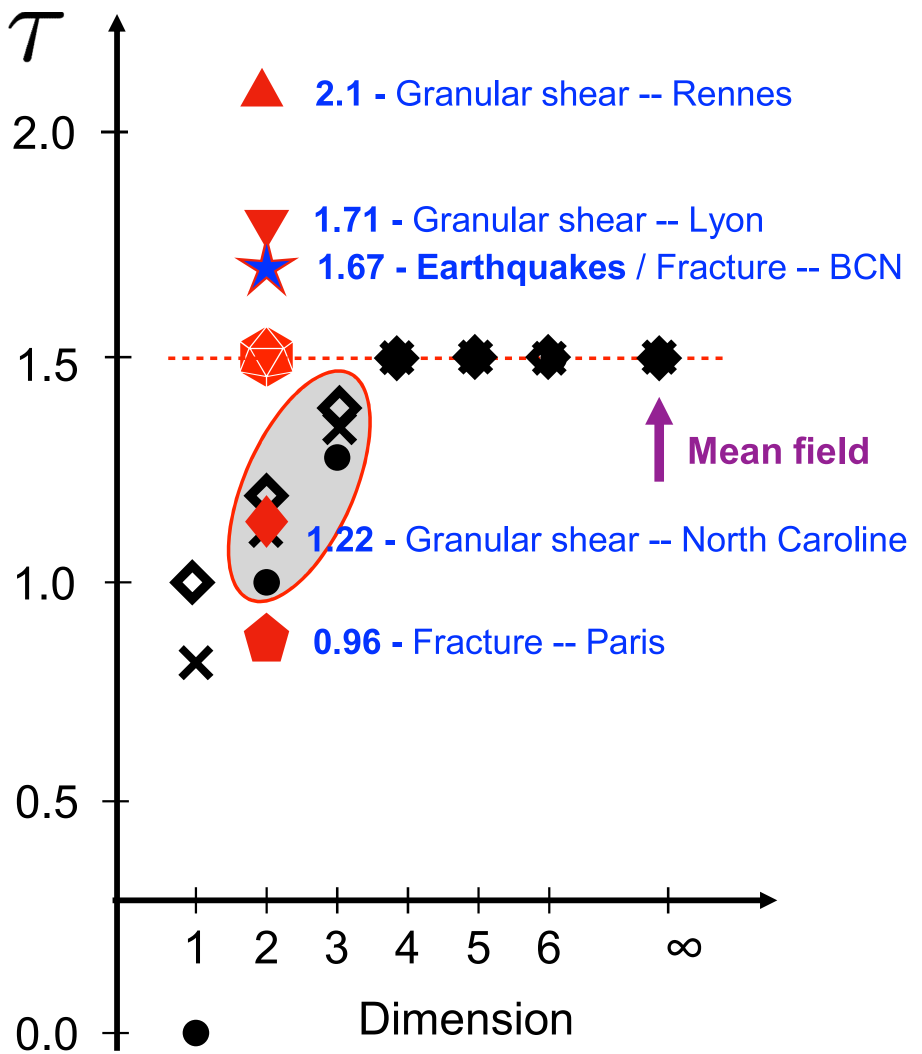
$$P(s) \sim s^{-\tau}$$



Renormalization group in elastic lines

● RP ✕ RB ◇ RF Le Doussal & Wiese, PRE 2009

Exponent values in avalanche size distributions $P(s) \sim s^{-\tau}$



Avalanche size

Which is the "right" variable to measure ?

Which is the "right" variable to measure ?

O. Ramos, HDR (2015)

67 *Which is the "right" variable to measure?* Let us consider a power law $P(s) = \frac{1}{N} s^{-b}$, where N is a normalization constant. The variable s can be written as $s = s_l^{D_A}$ (the most common case is $E \sim A^2$, where E and A are the energy and the amplitude respectively).

$$P(s)ds = P(s_l)ds_l \qquad (21)$$

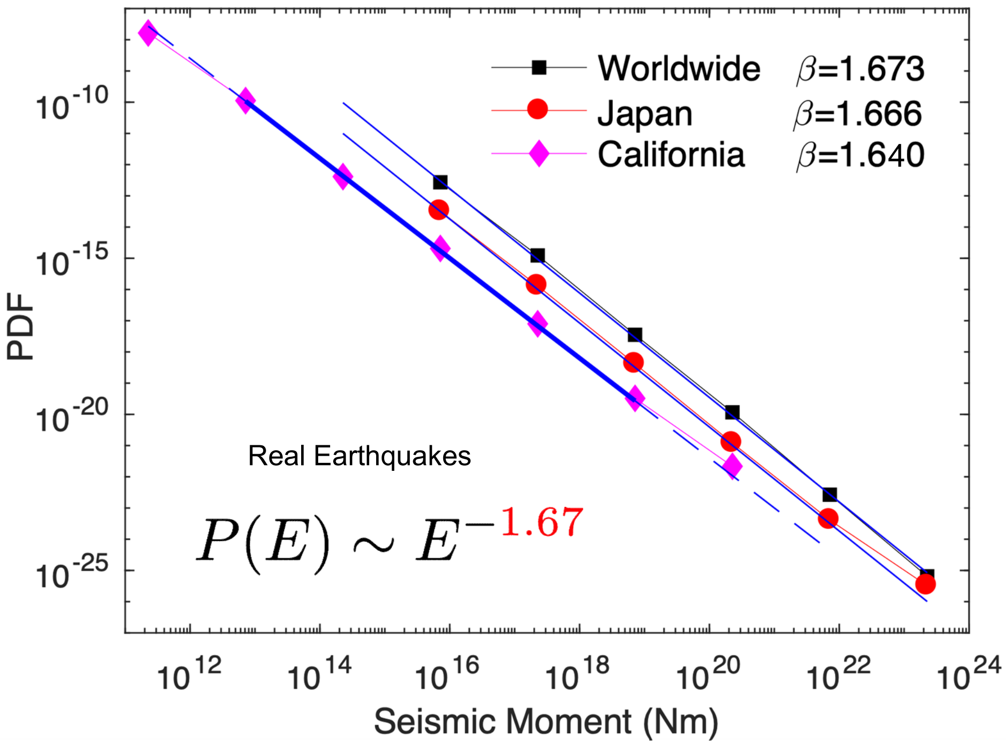
$$\frac{1}{N} s_l^{-bD_A} D_A s_l^{D_A - 1} ds_l = P(s_l)ds_l \qquad (22)$$

$$P(s_l) = \frac{D_A}{N} s_l^{-\beta} \qquad (23)$$

$$\textit{with} \quad \beta = (b-1)D_A + 1 \qquad (24)$$

As a result, we have two power laws, with two different exponents, describing the same process. In the case of critical phenomena, the standard manner to define the size of an event is by measuring its volume [Stauffer and Aharony, 2003] (in a n-dimensional space). Therefore, in order to analyze the critical properties of a given process, the variable to choose is the one proportional to the volume. In the case of earthquakes, we introduced the energy and the amplitude: $P(E) \sim E^{-5/3}$, $P(A) \sim A^{-2}$; and it is the energy the one proportional to the area of the two-dimensional event. Notice that the relation between the two is given by $E \sim A^{D_A}$ with $D_A = (2-1)/(5/3-1) = 3/2$ (instead of the common $E \sim A^2$).

Which is the "right" variable to measure: ***the volume of the avalanche***



Seismic Moment

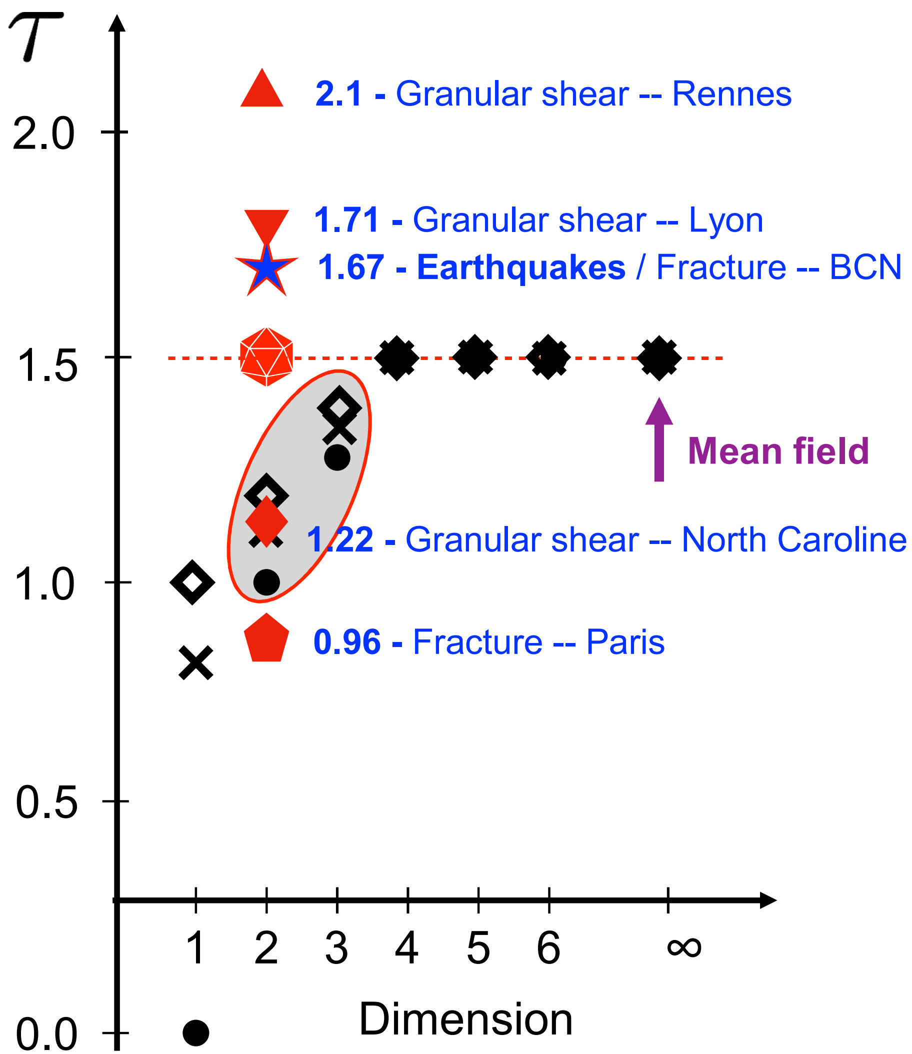
$$E = M_0 = \mu A D$$

Shear modulus of the rocks

Area of the rupture along the geological fault

Average slip

Exponent values in avalanche size distributions $P(s) \sim s^{-\tau}$



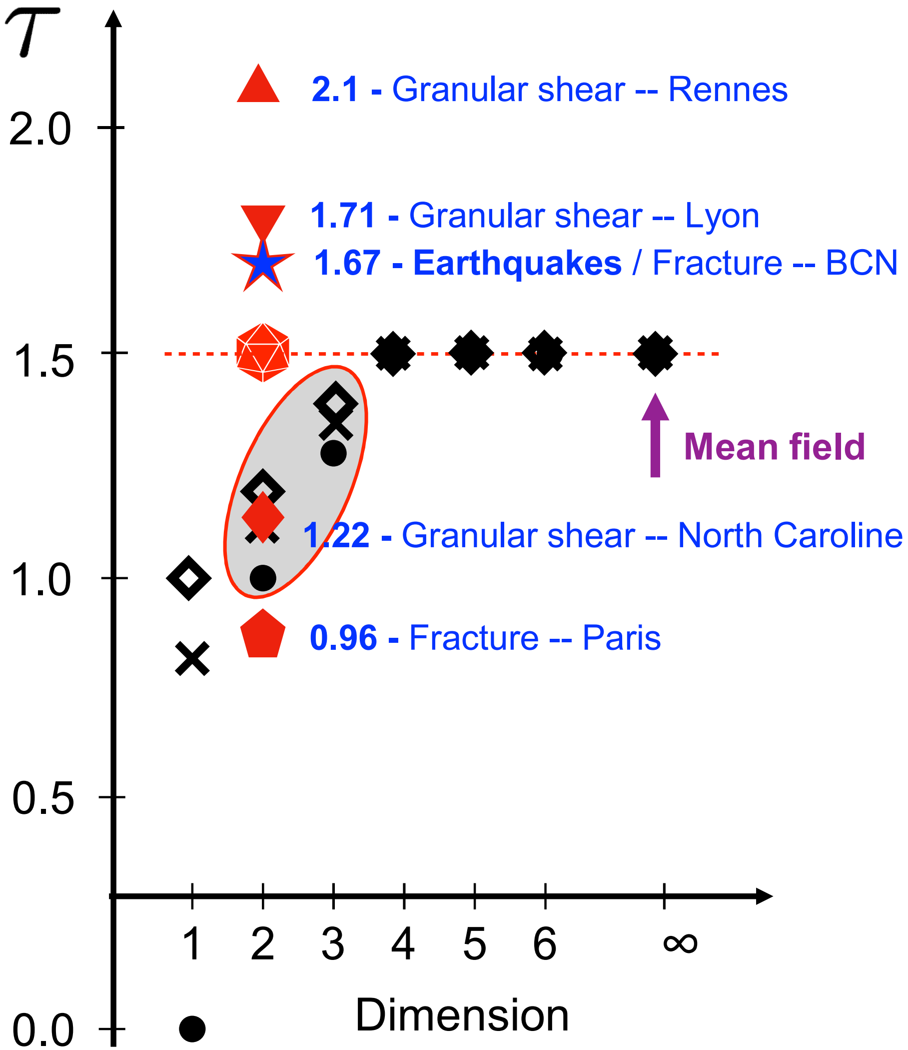
Avalanche size distributions

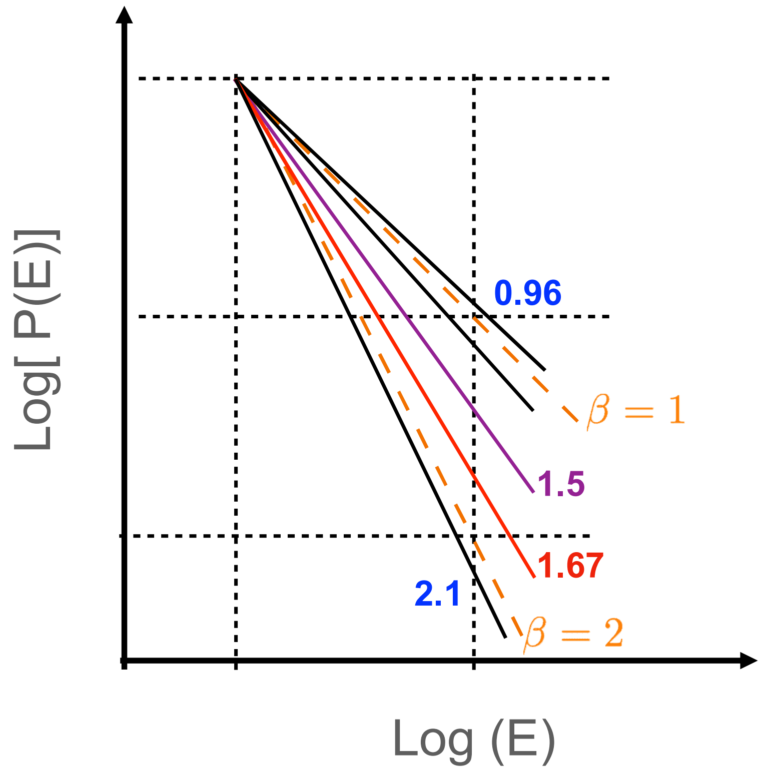
Getting familiar with exponent values

Exponent values in avalanche size distributions

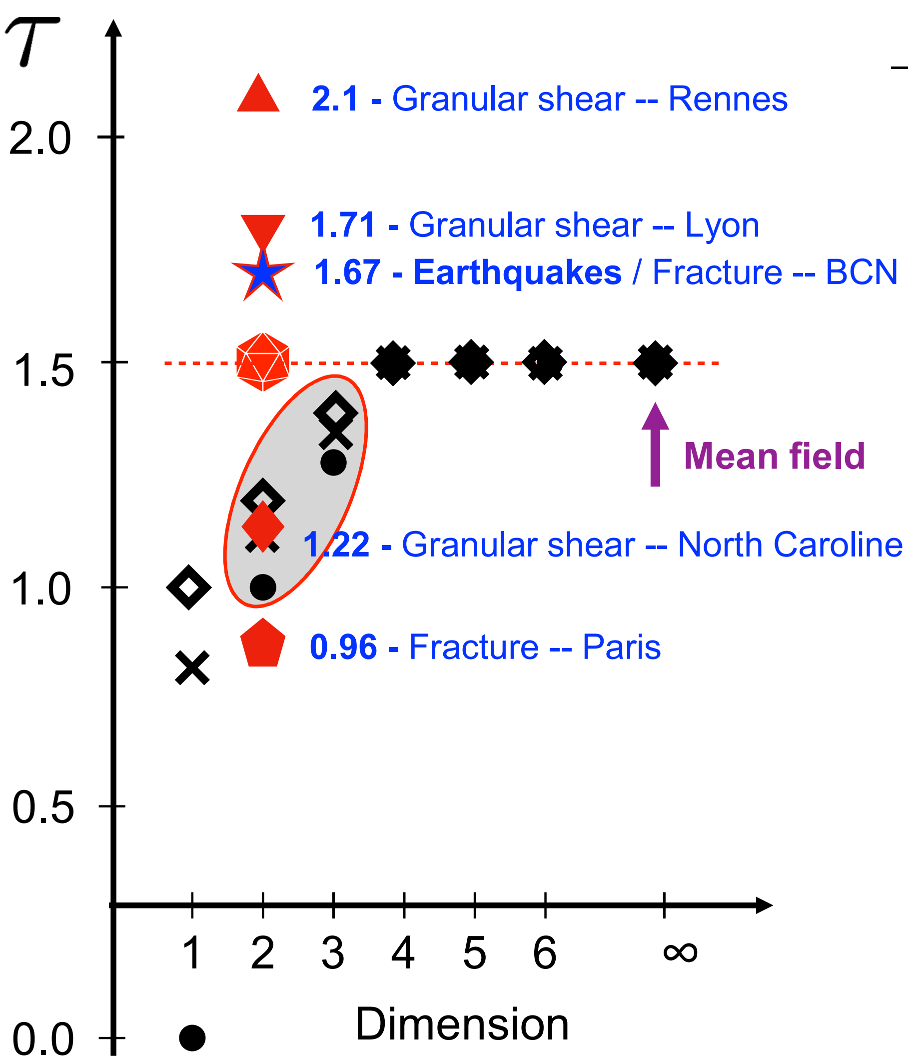
$$P(s) \sim s^{-\tau}$$

$$P(E) \sim E^{-\beta}$$





Exponent values in avalanche size distributions



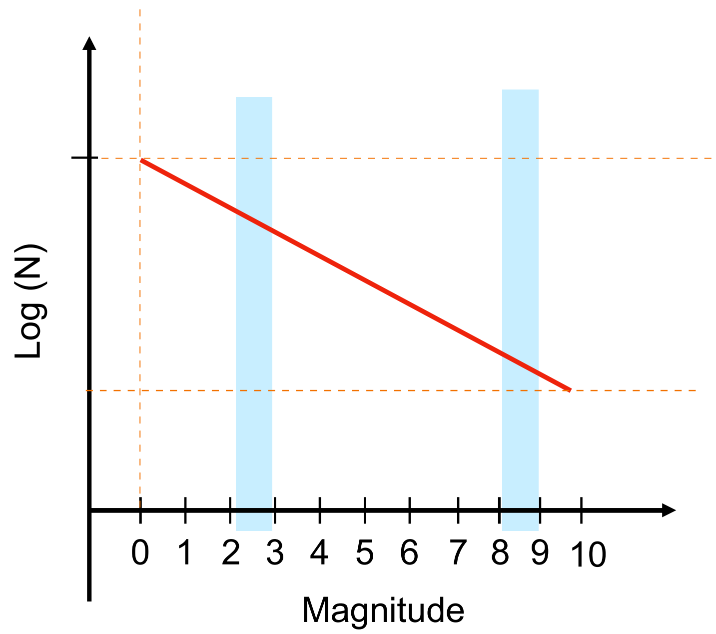
b	$R_{\frac{M2+}{M8+}}$
1.0	10^6

$$P(s) \sim s^{-\tau}$$

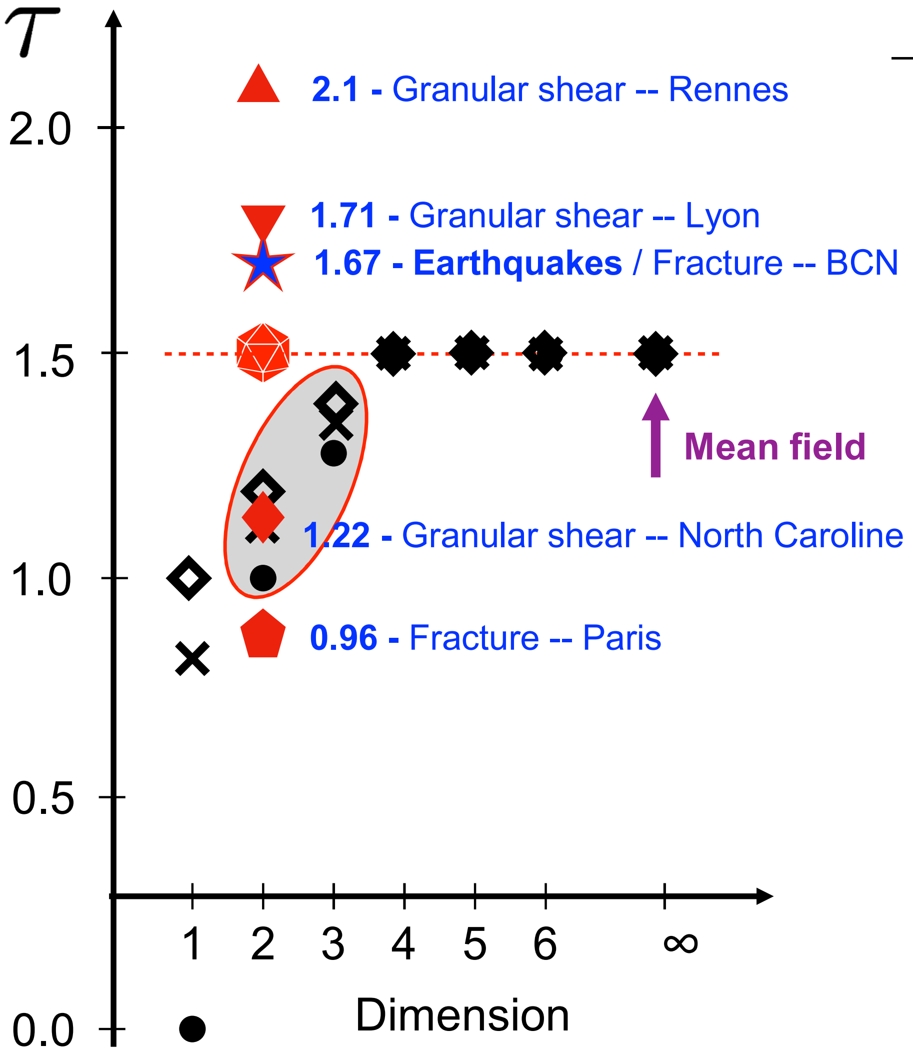
$$P(E) \sim E^{-\beta}$$

$$b = 3/2(\beta - 1)$$

$$Log_{10}(N) \sim -b \; Magnitude$$



Exponent values in avalanche size distributions



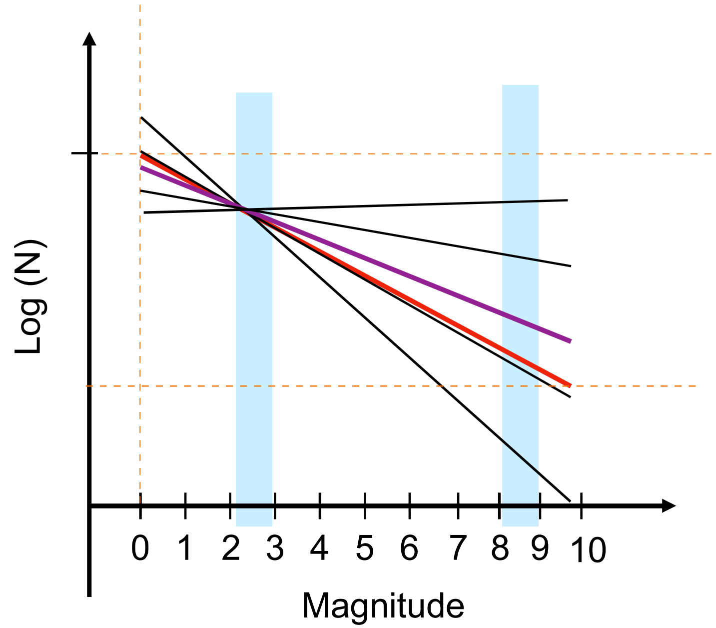
b	$R_{\frac{M2+}{M8+}}$
1.65	8×10^9
1.06	2×10^6
1.0	10^6
0.75	3×10^4
0.33	10^2
−0.06	0.4

$$P(s) \sim s^{-\tau}$$

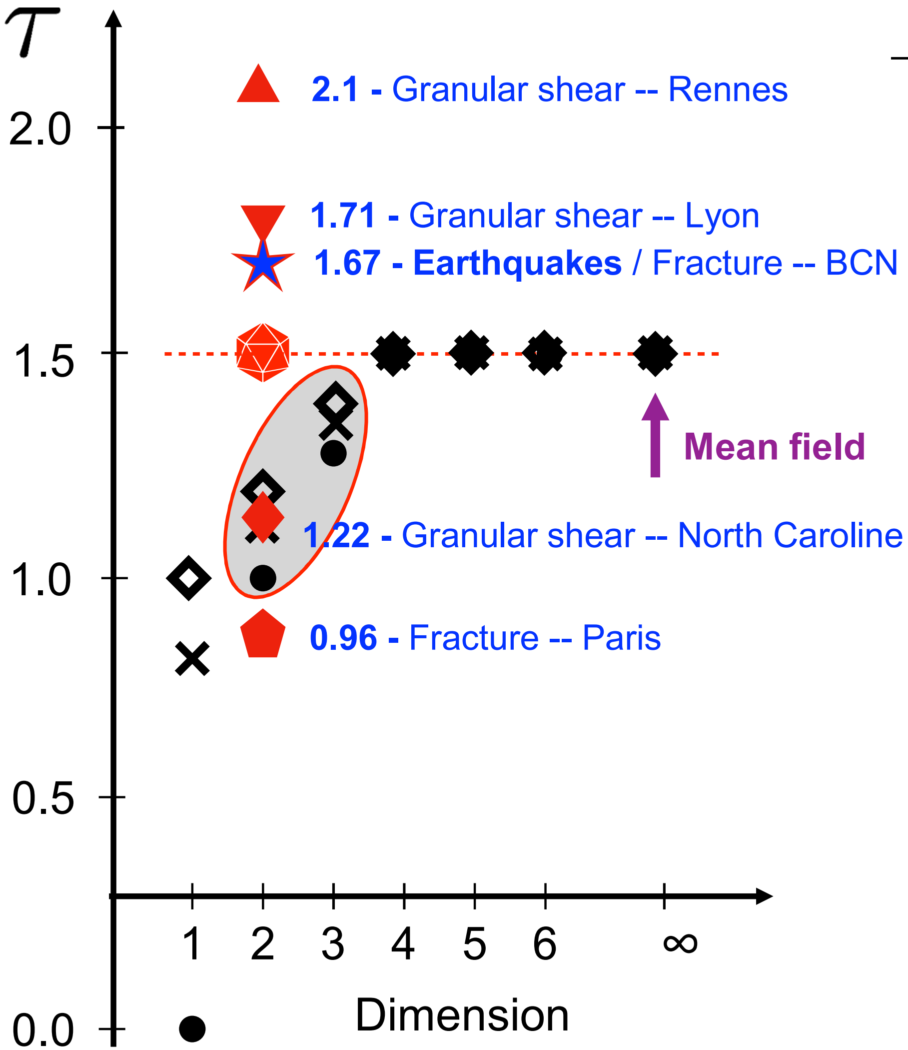
$$P(E) \sim E^{-\beta}$$

$$b = 3/2(\beta - 1)$$

$$Log_{10}(N) \sim -b \ Magnitude$$



Exponent values in avalanche size distributions



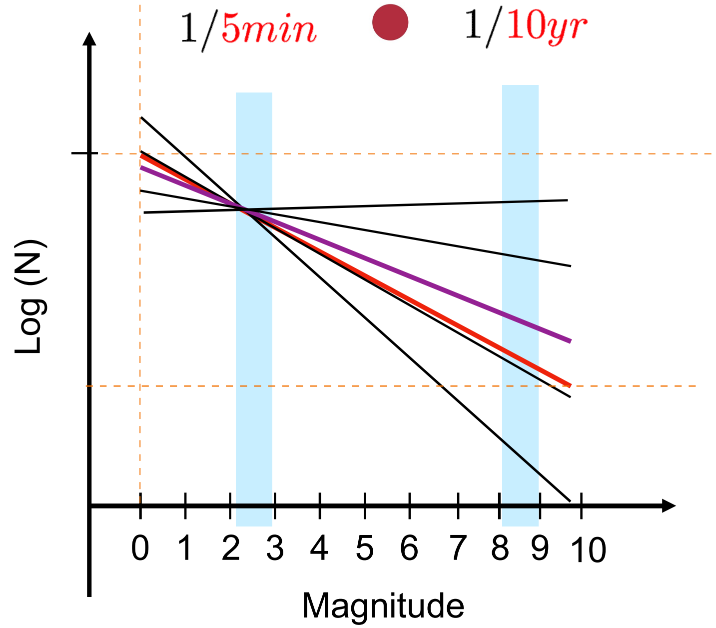
b	$R_{\frac{M2+}{M8+}}$	●
1.65	8×10^9	$1/80000yr$
1.06	2×10^6	$1/20yr$
1.0	10^6	$1/10yr$
0.75	3×10^4	$1/3months$
0.33	10^2	$1/9hours$
-0.06	0.4	$1/2min$

$$P(s) \sim s^{-\tau}$$

$$P(E) \sim E^{-\beta}$$

$$b = 3/2(\beta - 1)$$

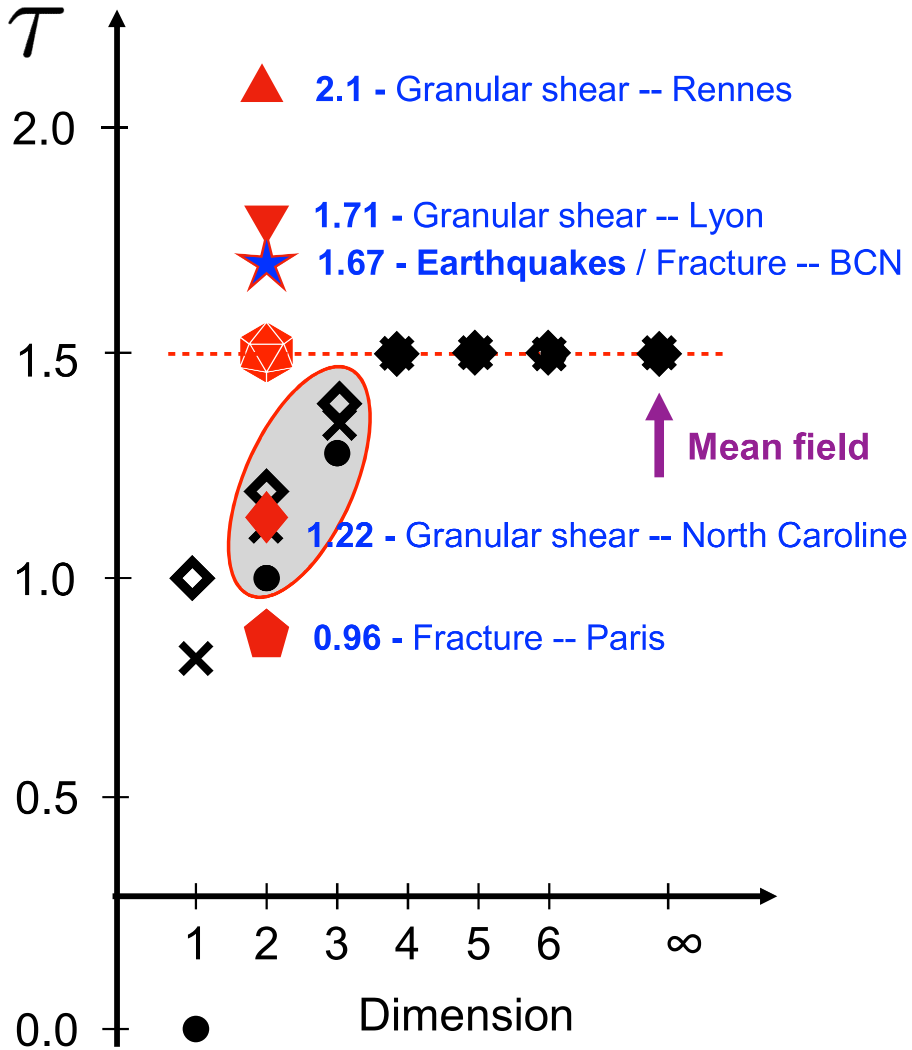
$$Log_{10}(N) \sim -b \; Magnitude$$



Exponent values

What to compare with ?

Exponent values in avalanche size distributions $P(s) \sim s^{-\tau}$



In seismology, these models have been fairly successful in reproducing the Gutenberg and Richter (1944) statistics of earthquakes. This empirical law states that the frequency of earthquakes of (energy) magnitude

$$M_e = \tfrac{2}{3}\log(E) - 2.9, \tag{11}$$

where E is the energy release, in a given region obeys the power-law relation $\log P(m \geq m_0) \simeq -bm_0 + \text{const}$, where $b \simeq 0.88$, or equivalently

$$p(E) \sim E^{-\tau}, \quad \text{with} \quad \tau = 1 + \tfrac{2}{3}b \approx 1.5.$$

For accuracy, we ought to say that there exist several earthquake magnitude scales besides that of Eq. (11). They roughly coincide at not too large values; in fact, M_e is not the initial Richter scale. More importantly, the value of the exponent $b \in [0.8, 1.5]$ depends on the considered earthquake catalog and notably on the considered region. For sandpilelike

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 94, NO. B11, PAGES 15,635–15,637, NOVEMBER 10, 1989

Earthquakes as a Self-Organized Critical Phenomenon

PER BAK AND CHAO TANG

Brookhaven National Laboratory, Upton, New York

The Gutenberg-Richter power law distribution for energy released at earthquakes can be understood as a consequence of the earth crust being in a self-organized critical state. A simple cellular automaton stick-slip type model yields $D(E) \approx E^{-\tau}$ with $\tau \approx 1.0$ and $\tau \approx 1.35$ in two and three dimensions, respectively. The size of earthquakes is unpredictable since the evolution of an earthquake depends crucially on minor details of the crust.

INTRODUCTION

The distribution of energy released during earthquakes has been found to obey the famous Gutenberg-Richter law [*Gutenberg and Richter*, 1956]. The law is based on the empirical observation that the number N of earthquakes of size greater than m is given by the relation

$$\log_{10} N = a - bm \tag{1}$$

The precise values of a and b depend on the location, but generally b is in the interval $0.8 < b < 1.5$. The energy released during the earthquake is believed to increase exponentially with the size of the earthquake,

$$\log_{10} E = c - dm \tag{2}$$

so the Gutenberg-Richter law is essentially a power law connecting the frequency distribution function with the energy release E (or other physical quantities such as the "seismic moment")

$$dN/dE \propto m^{-1-b/d} = m^{-\tau} \tag{3}$$

with $1.25 < \tau < 1.5$.

Despite the universality of the Gutenberg-Richter relation, model must necessarily be grossly simplified. The immediate goal is not to produce an accurate model but to point out a general mechanism leading to the power law distribution of earthquakes. In the following section an effort will be made to connect the concept of self-organized criticality to earthquakes.

SELF-ORGANIZED CRITICALITY AND MODEL CALCULATIONS

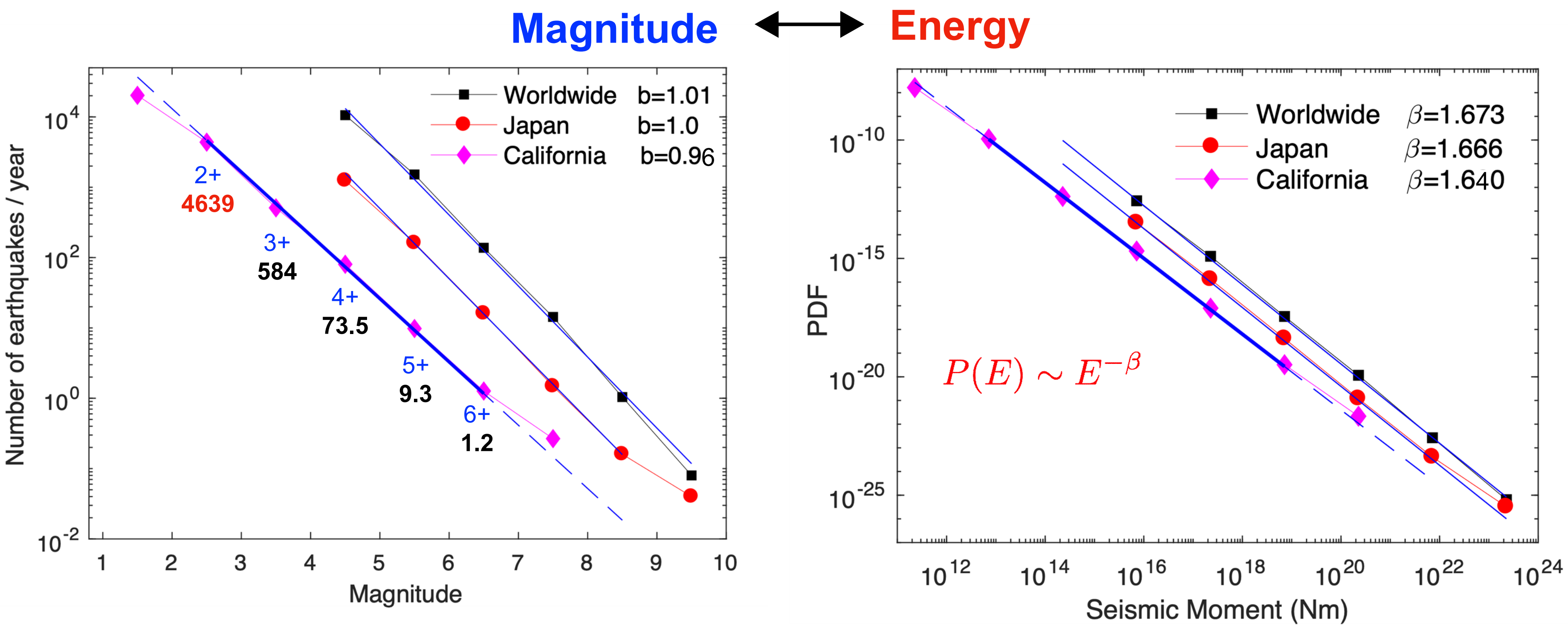
It is generally assumed that the dynamics of earthquakes is due to a stick-slip mechanism involving sliding of the crust of the earth along faults [*Stuart and Mavko*, 1979; *Sieh*, 1978; *Choi and Huberman*, 1984]. When slip occurs at some location, the strain energy at that position is released, and the stress propagates to the near environment. While this picture is rather well established, no connection between stick-slip models and the actual spatial and temporal correlations has been demonstrated. It has been suggested that the stick-slip picture can be modeled as a branching process [*Kagan and Knopoff*, 1987]. The observed power law behavior is then rather remarkable since one would naively expect some exponential distribution, e.g., $D(E) \approx e^{-E/E_0}$, where E_0 is roughly the energy released at a single slip.

Size distributions of earthquakes

U.S. Geological Survey (USGS)
http://earthquake.usgs.gov/earthquakes/search/
1990-01-01 00:00:00 to **2019**-12-31 23:59:59
(**30 years period**)

3/2 (**Magnitude** + 6.07) = Log (**Seismic Moment**)

$$b = 3/2(\beta - 1)$$



We can do rely on recent earthquake data !

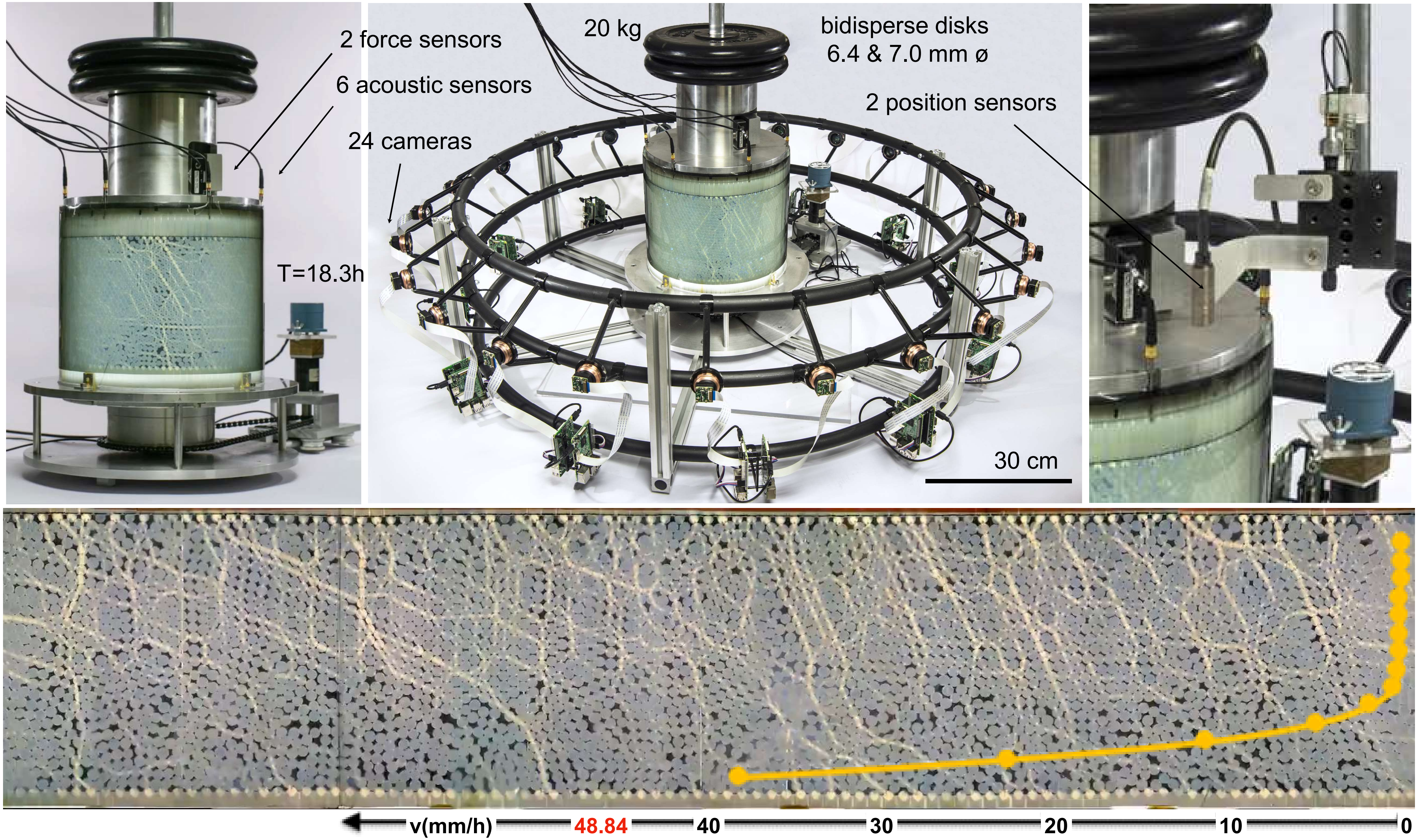
Get updated.

U.S. Geological Survey (USGS)
http://earthquake.usgs.gov/earthquakes/search/

Southern California Earthquake Data Center
https://scedc.caltech.edu/data/QTMcatalog.html

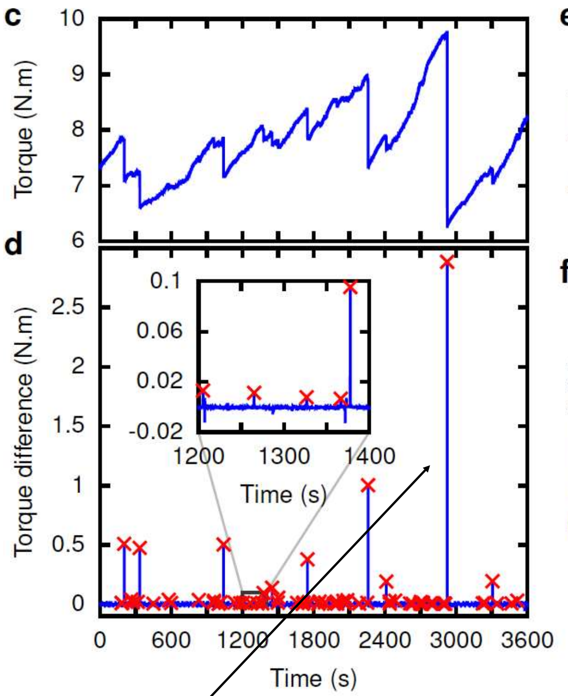
High Sensitivity Seismograph Network Japan
https://www.hinet.bosai.go.jp

Our experiment

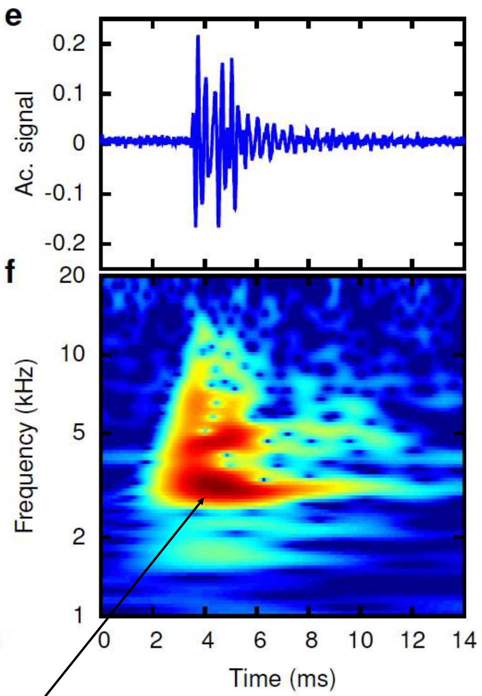

2 force sensors
6 acoustic sensors
24 cameras
T=18.3h
20 kg
bidisperse disks
6.4 & 7.0 mm ø
2 position sensors
30 cm
v(mm/h)
48.84
40
30
20
10
0

Measurements

Torque Γ(t)



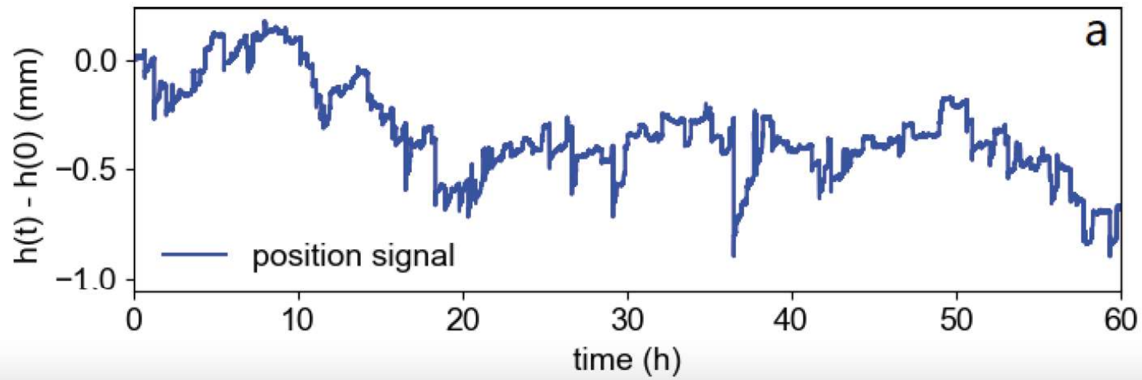
Acoustics



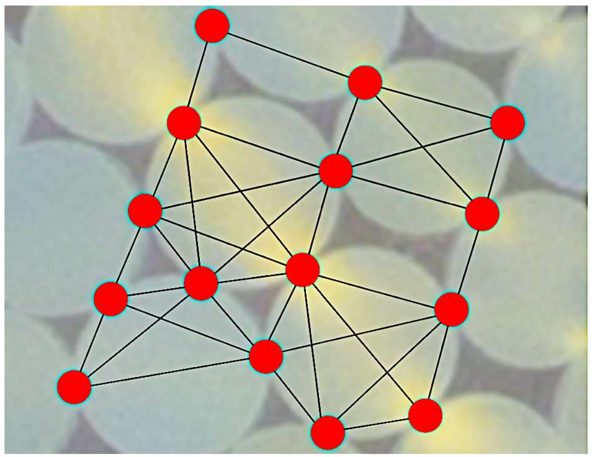
$$E_\mathrm{m} \sim ({\Gamma_i}^2 - {\Gamma_f}^2)$$

$$E_A$$

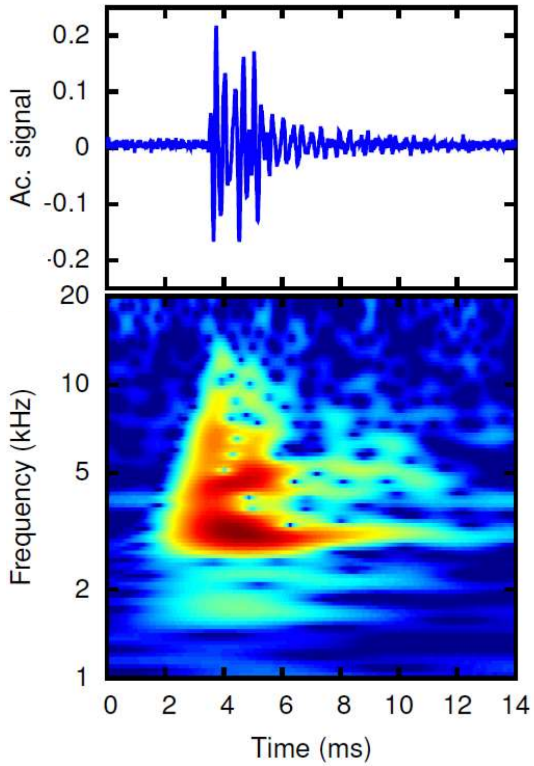
Position h(t)



Granular structure

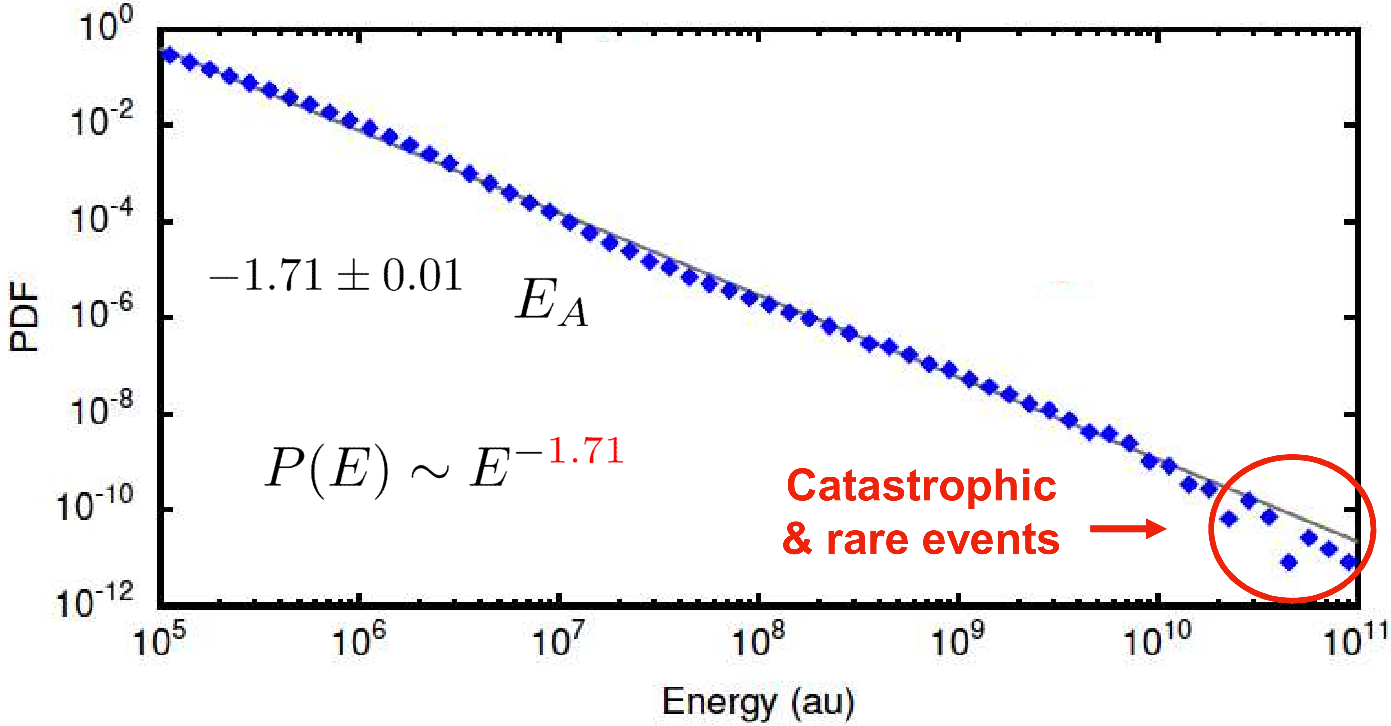


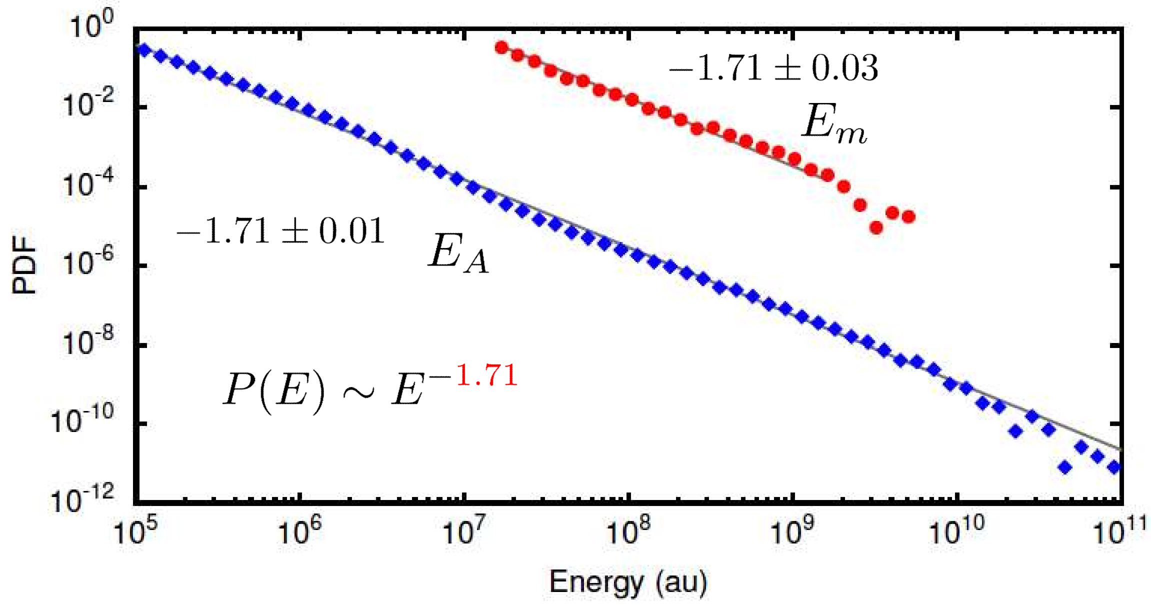
Quantitative analogies with earthquake statistics

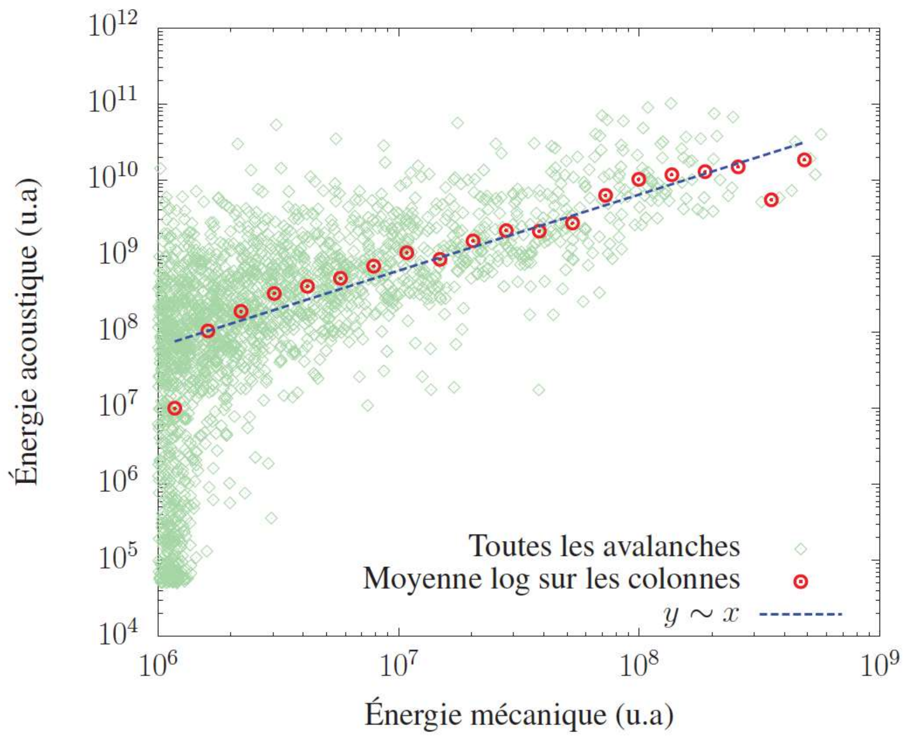


Scale-invariant avalanches

Energy distribution:

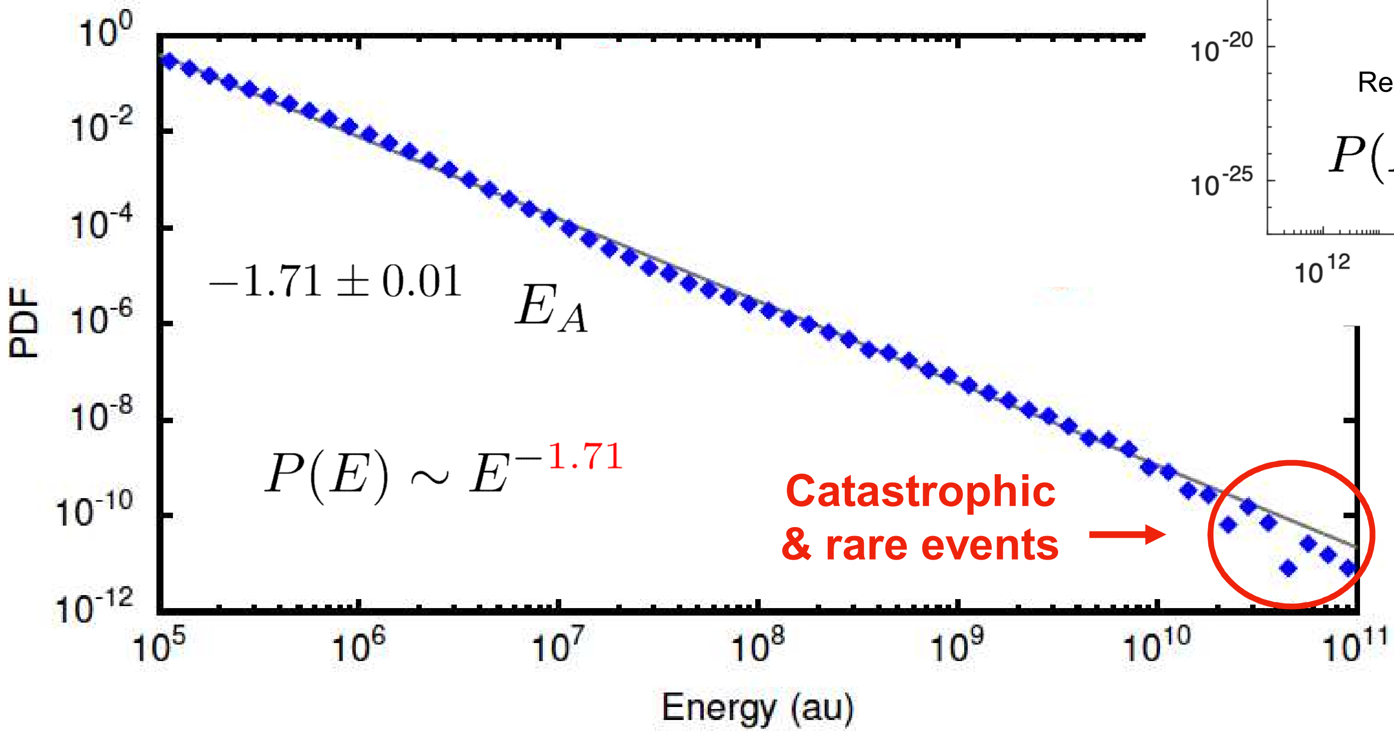



-1.71 ± 0.03
E_m
-1.71 ± 0.01
E_A
$P(E) \sim E^{-1.71}$
PDF
Energy (au)

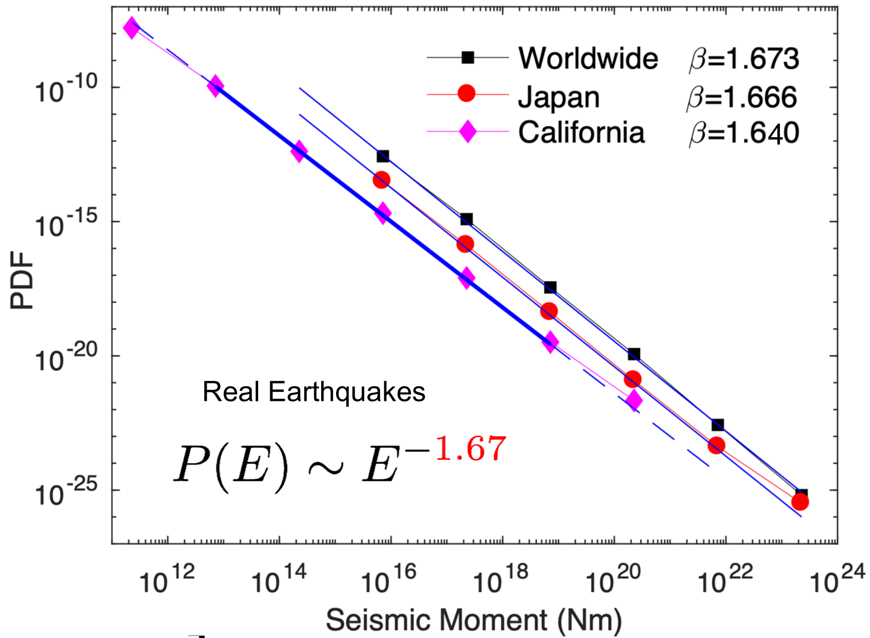

Énergie acoustique (u.a)
Toutes les avalanches
Moyenne log sur les colonnes
$y \sim x$
Énergie mécanique (u.a)

Quantitative analogies with earthquake statistics

Energy distribution:



Real Earthquakes

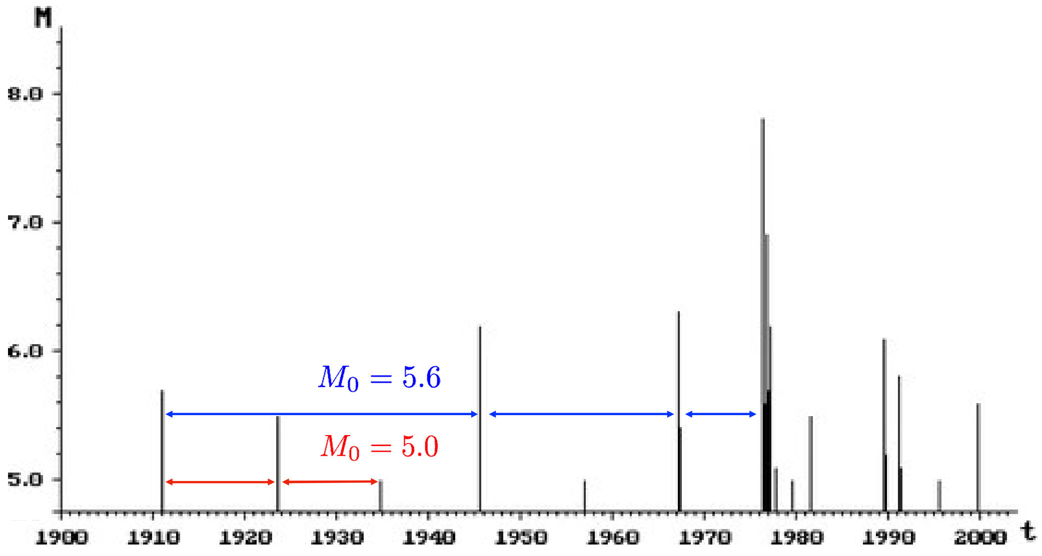


Quantitative analogies with earthquake statistics

Inter-event time distribution:

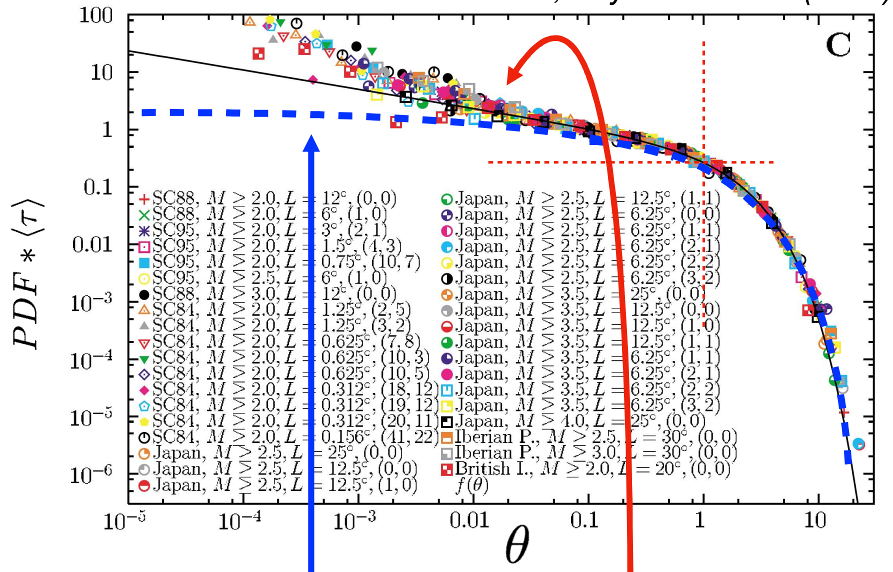
$$f(\theta) \sim \theta^{-0.3} \exp(-\theta/1.5)$$

$$\theta = \tau_{M \geqslant M_0} / \langle \tau \rangle_{M \geqslant M_0}$$



Zhang et at, (2013)

Real Earthquakes *A. Corral, Phys. Rev. Lett. (2004)*



Exponential distribution
=
Poisson process
=
No memory

Memory of past events !

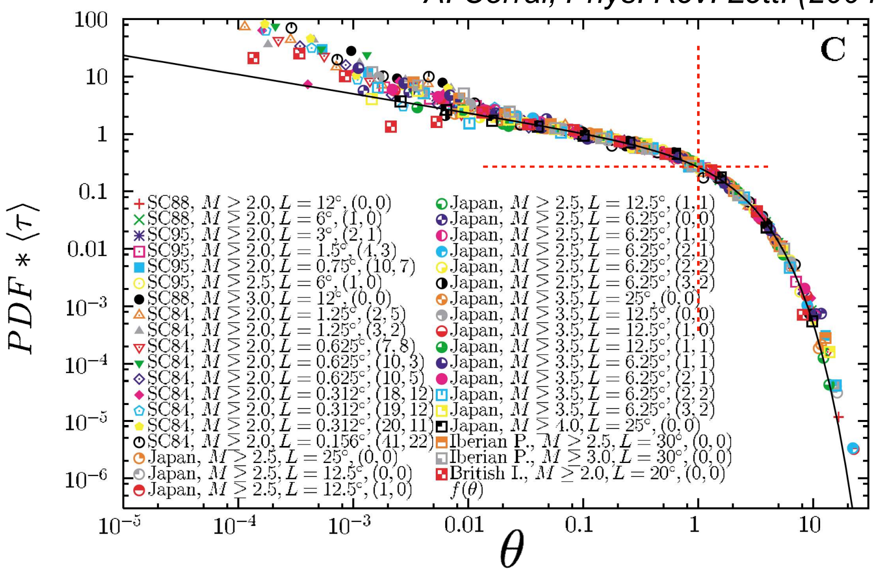
Quantitative analogies with earthquake statistics

Inter-event time distribution:

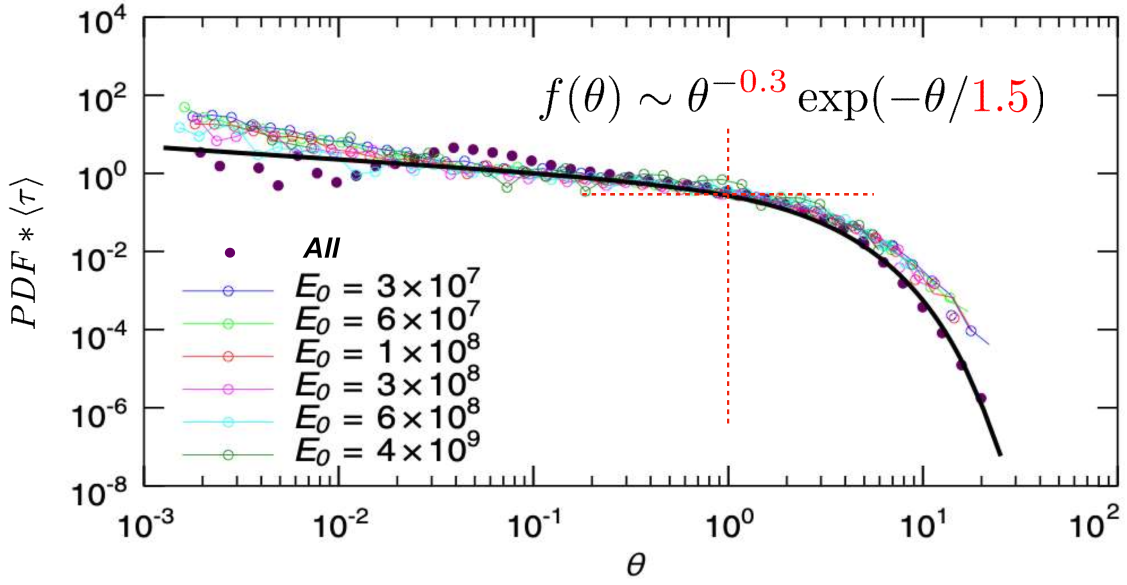
$$f(\theta) \sim \theta^{-0.3} \exp(-\theta/1.5)$$

$$\theta = \tau_{M \geqslant M_0} / \langle \tau \rangle_{M \geqslant M_0}$$

Real Earthquakes *A. Corral, Phys. Rev. Lett. (2004)*



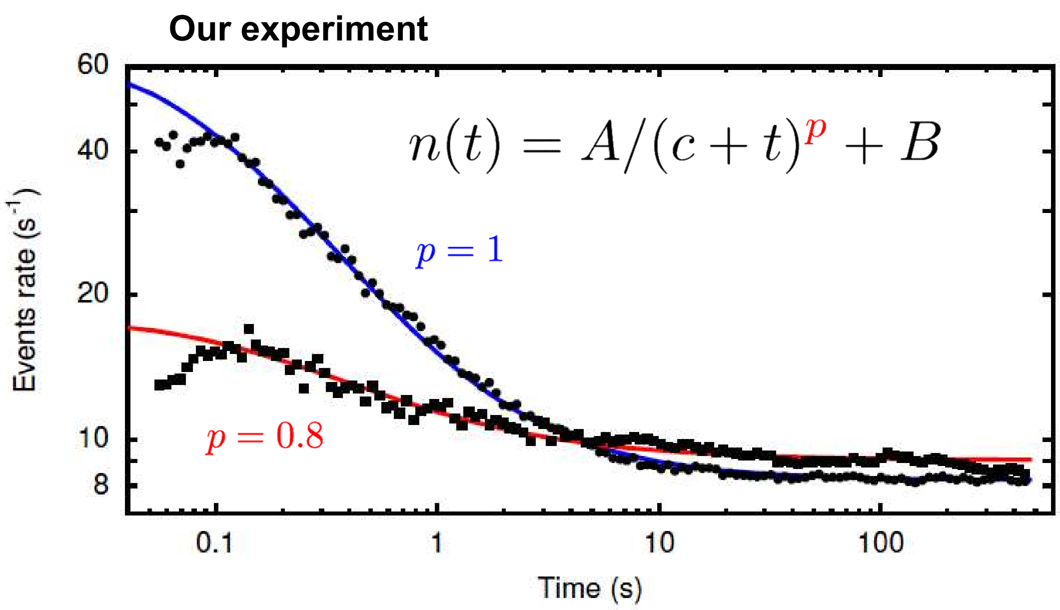
Our experiment



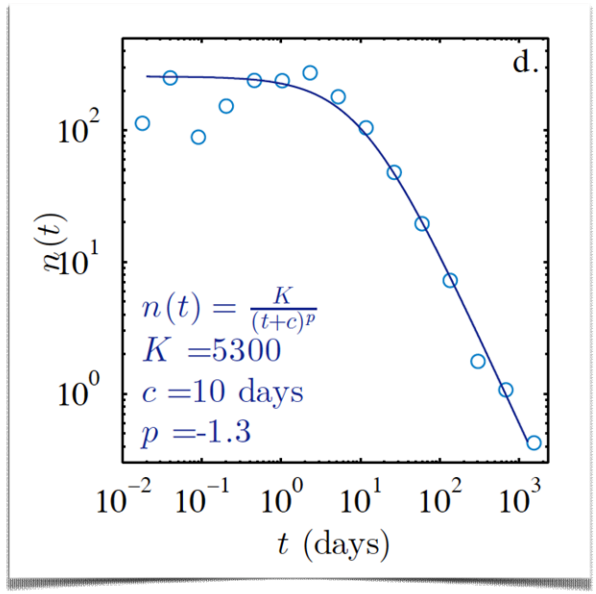
Quantitative analogies with earthquake statistics

Omori's law:

Our experiment

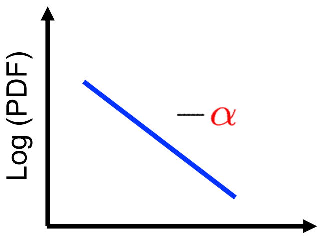


Real Earthquakes



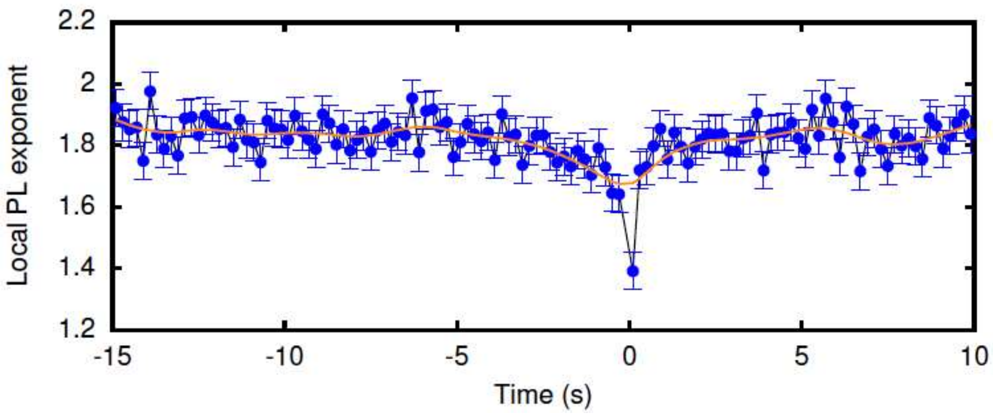
Landers (1992)
M=7.3

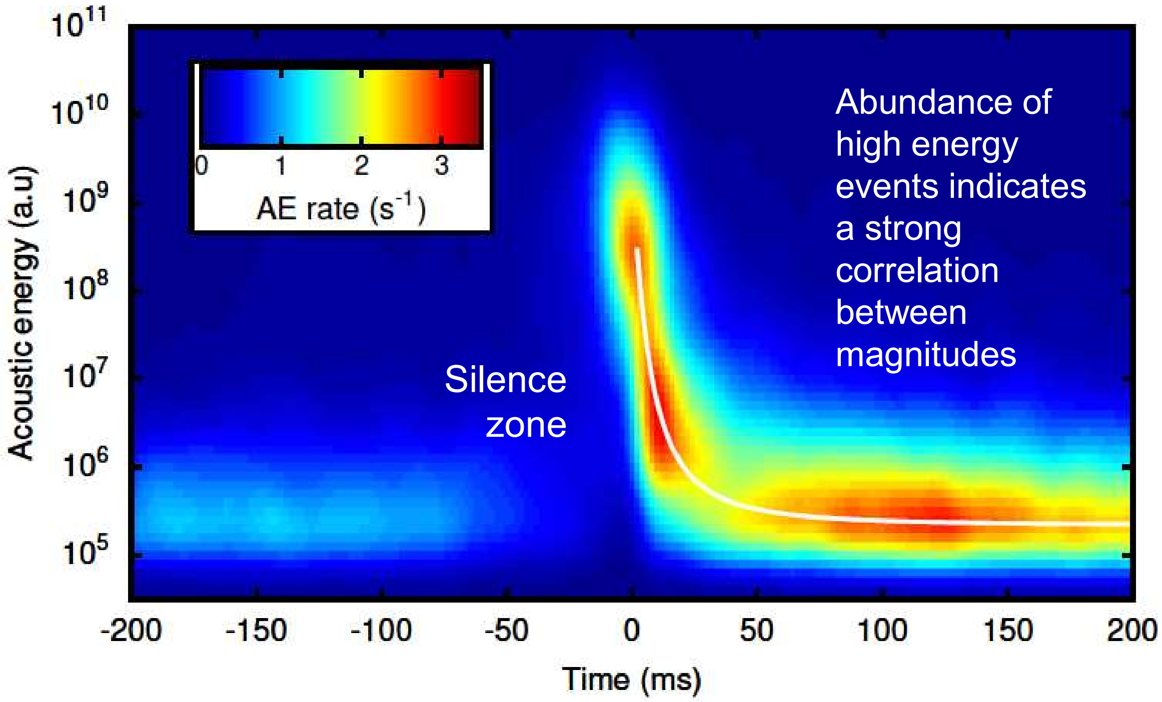
Qualitative analogies with earthquake statistics



$$P(E) \sim E^{-\alpha}$$

Variations before *Large* events





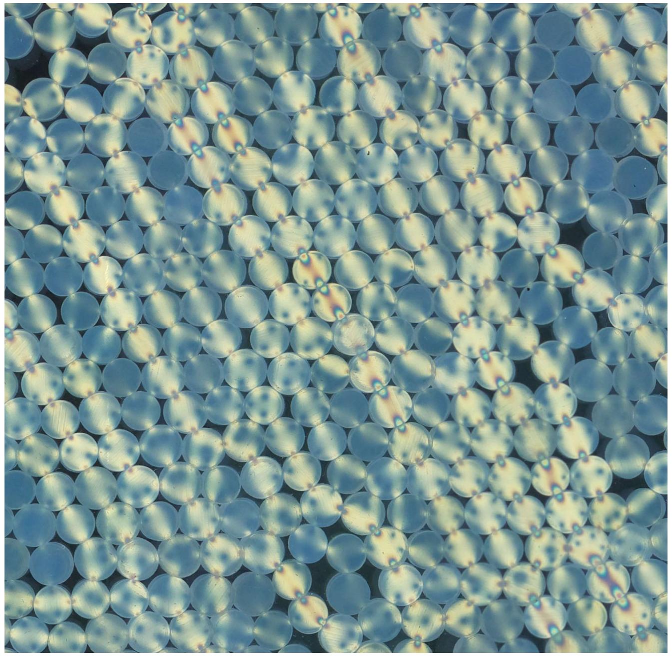
- Lherminier et al, *Continuously Sheared Granular Matter Reproduces in Detail Seismicity Laws*, **Phys. Rev. Lett** (2019)

Highlighted in

Physics, Suggestion, CNRS, physicsworld, Science

Why is this analog experience (*to earthquakes*) relevant?

- Quantitative similarities strongly suggest a common physics



We are currently trying to understand its dynamics:

- Parameter dependences (robustness) & origin of the dynamics
- Memory effets
- Possibilities of predicting large events
- Separating common ("universal") features of the dynamics vs. specific ones to earthquakes or to our granular fault.

- A relevant difference: $R = 17.35$ quakes/s

A **48h experiment** brings a similar number of events as **150 years of seismicity** with magnitude ≥2 in California (very suitable for *Artificial Intelligence* analysis).

Some open questions in scale-invariant avalanches

Physics of scale-invariant avalanches

Phase transitions
Critical dynamics

Predictability
Inherently impossible?
Memory effects
Prediction of catastrophic events?

Scale-invariance
Origin?
Robustness?
Common features:
Clustering, memory?

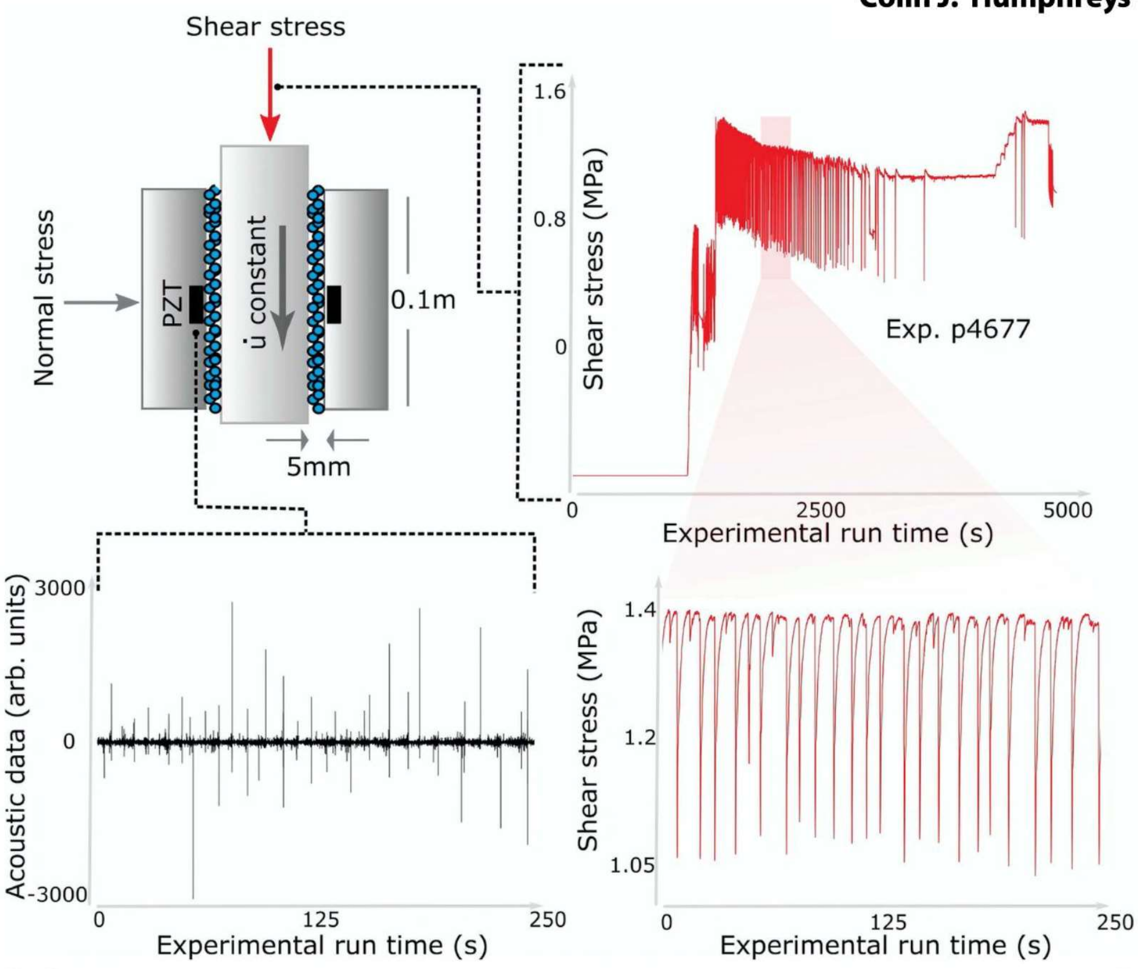
?

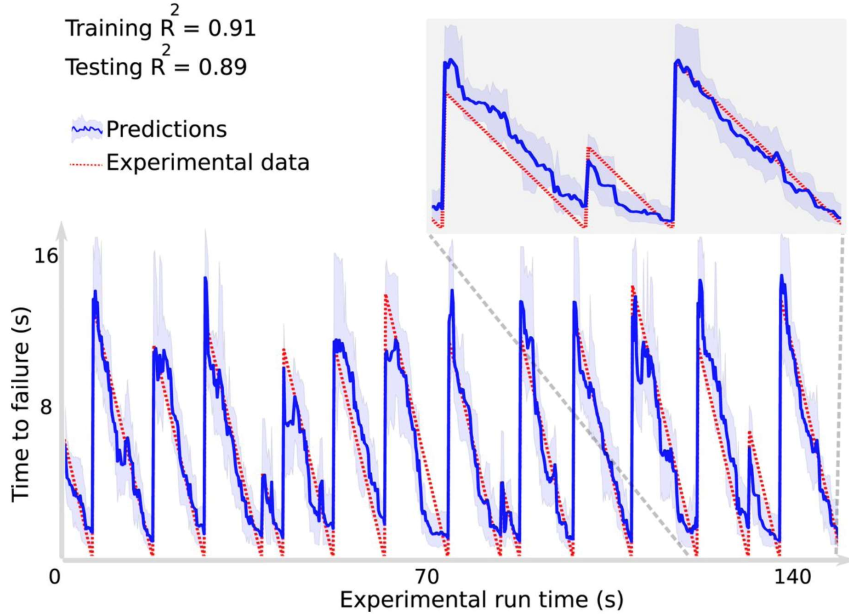
Critical properties
Universality classes?
Experiments: Not-robust exponent values & exponent values larger than 3/2
Diverging correlation lengths?

Machine Learning Predicts Laboratory Earthquakes

Bertrand Rouet-Leduc[1,2], Claudia Hulbert[1], Nicholas Lubbers[1,3], Kipton Barros[1], Colin J. Humphreys[2], and Paul A. Johnson[4]

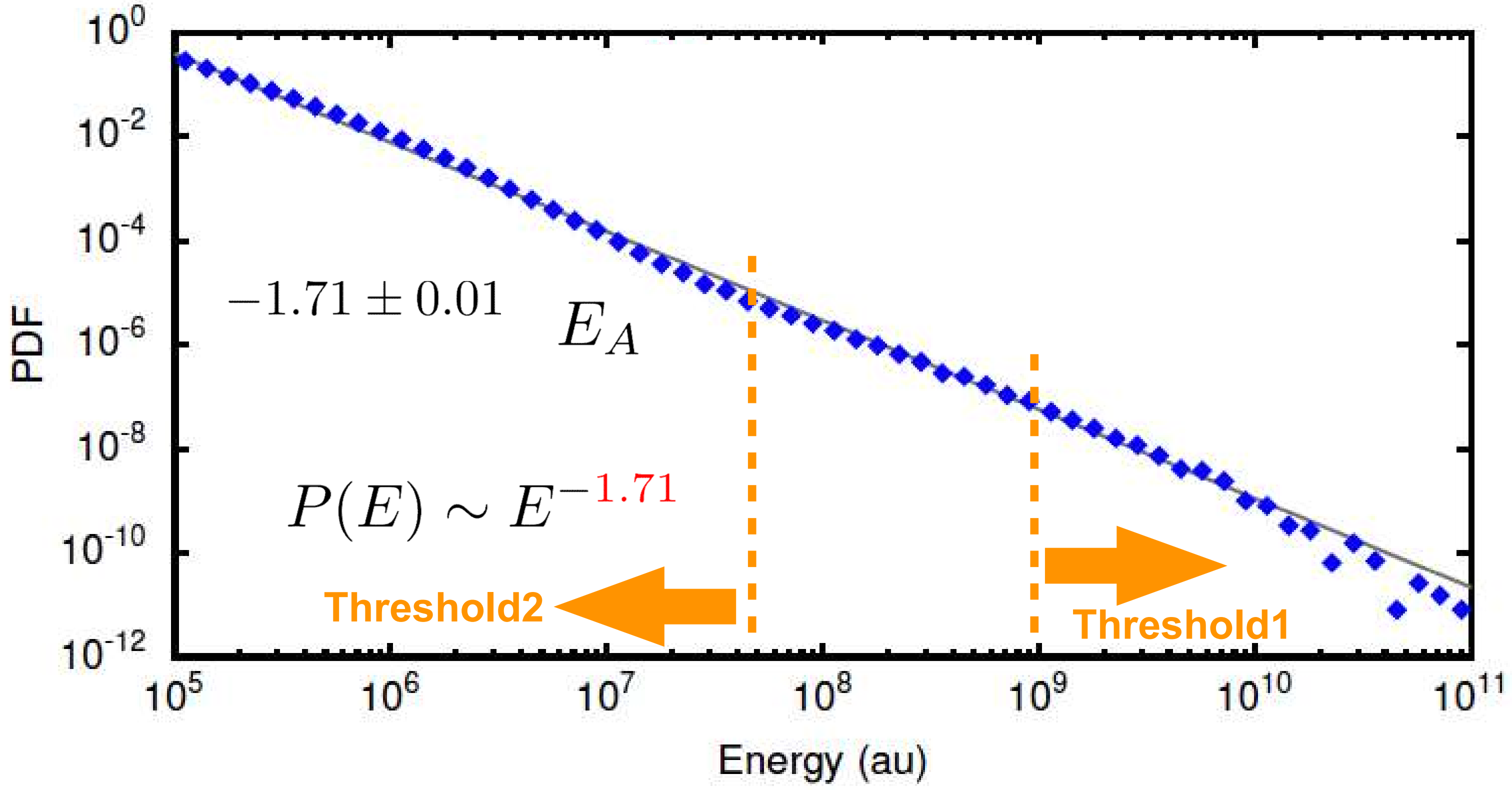
JGR, 2017





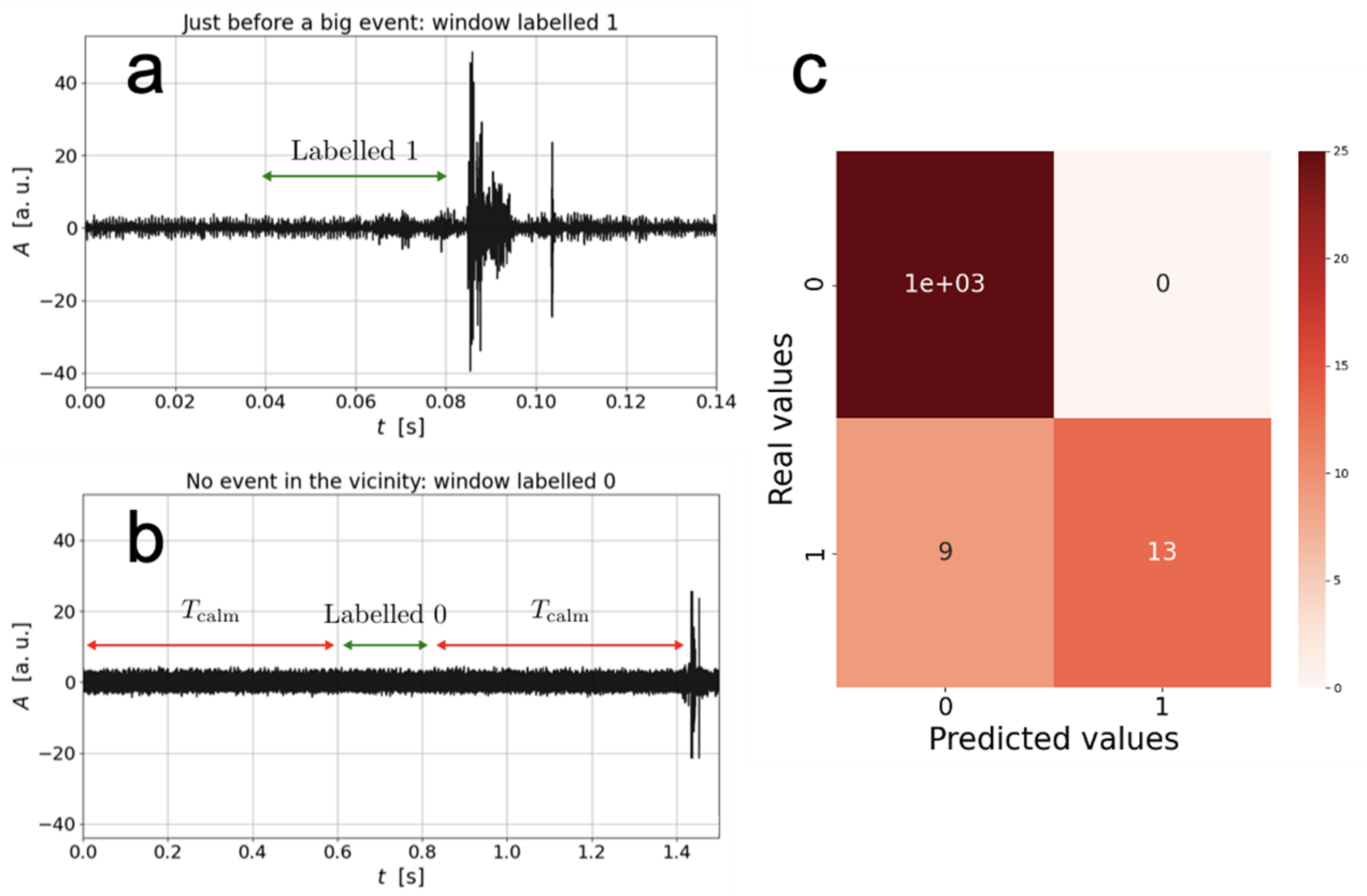
focusing on predictability:

Machine Learning analysis of LabQuakes time series



focusing on predictability:

Machine Learning analysis of LabQuakes time series



Take-away messages

- Different exponent values can reflect a very different physics

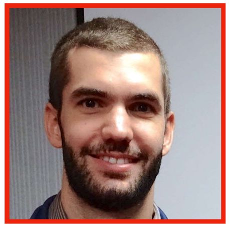
- We can rely on recent earthquake data, and it is an excellent tool to test and better understand our methods and actual data. Get updated !

- We are working on generating reliable and high quality data with controlled experiments, and so far the results look quite promising.

THANK YOU!

People


M. Stojanova


S. Lherminier


R. Planet


V. Levy dit Vehel


L. Combe


O. Cochet-Escartin


G. Simon


L. Vanel


K. J. Måløy


S. Deschanel


T. Hatano


S. Durand

Fundings

cnrs dépasser les frontières

cnrs MITI MISSION INTERDISCIPLINAIRE POUR LES INITIATIVES TRANSVERSES ET INTERDISCIPLINAIRES

iLM INSTITUT LUMIÈRE MATIÈRE

AXA | AXA Research Fund Through Research, Protection

LABEX LIO UNIVERSITÉ DE LYON

LABEX IMUST UNIVERSITÉ DE LYON

Adding **dissipation** to avalanche models

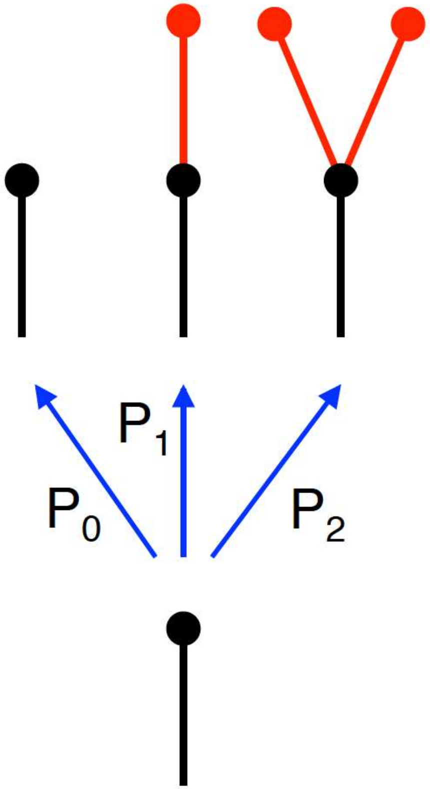


Figure 26: Branching process with $n_{max} = 2$.

$$\sum_{0}^{n_{max}} n P_n = 1 + G$$

$$\sum_{0}^{n_{max}} P_n = 1$$

$$G = 0$$

$$P(s) \sim s^{-3/2} exp(-s/\lambda)$$

$$\lambda \sim L$$

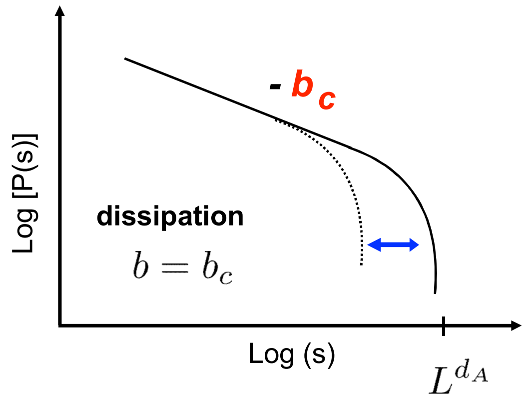
Preben Alstrøm. Mean-field exponents for self-organized critical phenomena. Phys. Rev. A, 38:4905–4906, 1988.

dissipation

$$G < 0$$

$$P(s) \sim s^{-3/2} exp(-s/\lambda)$$

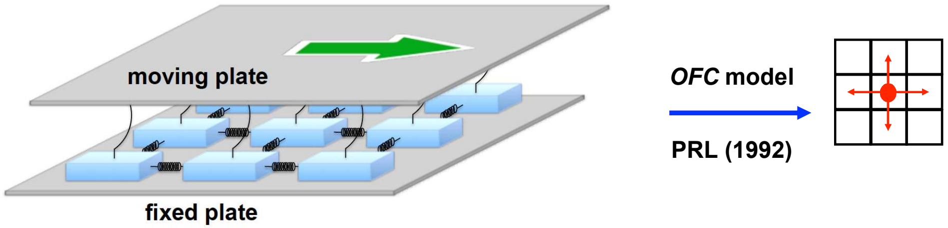
$$\lambda < L$$



$$\xi \sim \lambda$$

$$\xi \sim s_{max}^{1/d_A}$$

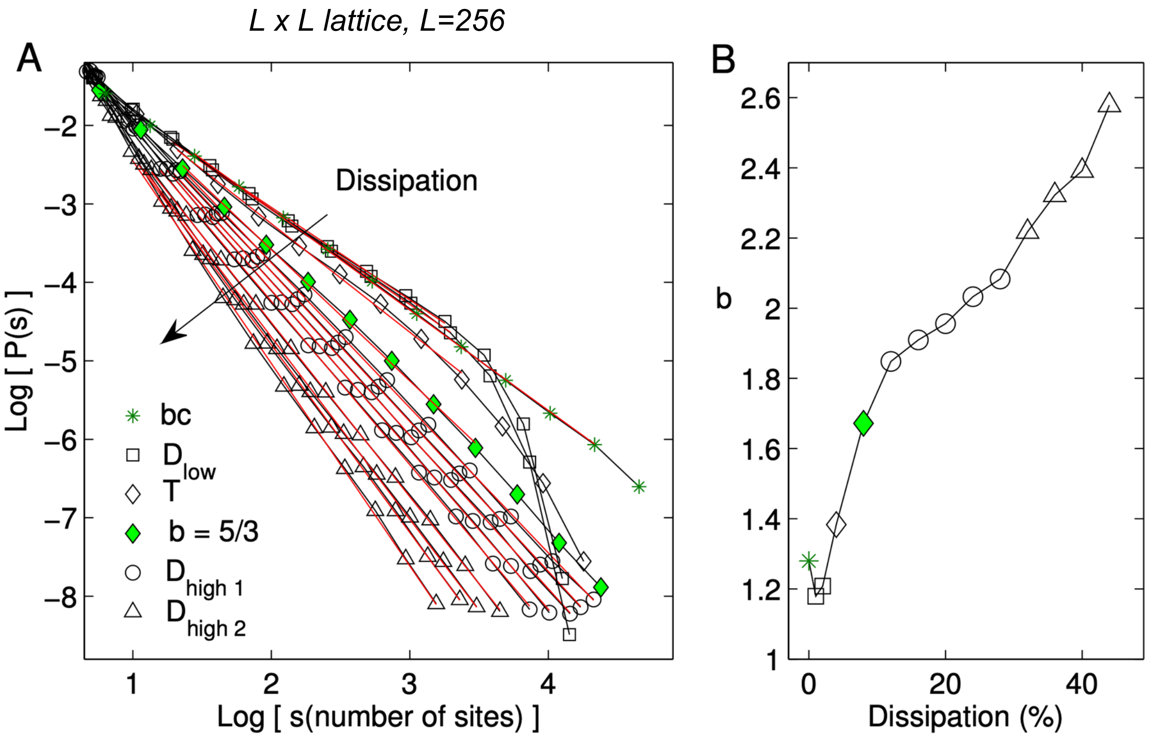
OFC model: changing the exponent value with dissipation

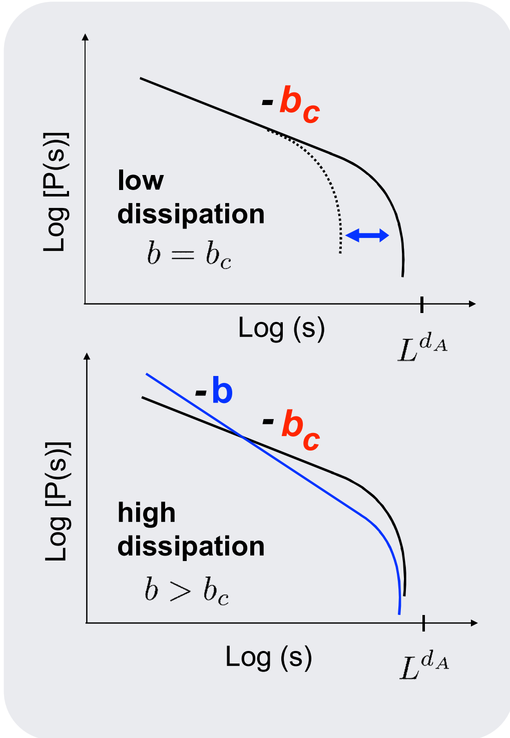


Force: $f(x,y) = f(x,y) + \delta f$

Friction thresholds: $Th(x,y) \longrightarrow$ Gaussian

Dissipation





Subcritical Statistics in Rupture of Fibrous Materials: Experiments and Model

Stéphane Santucci, Loïc Vanel, and Sergio Ciliberto
Laboratoire de physique, CNRS UMR 5672, Ecole Normale Supérieure de Lyon, 46 allée d'Italie, 69364 Lyon Cedex 07, France
(Received 20 May 2004; published 26 August 2004)

We study experimentally the slow growth of a single crack in a fibrous material and observe stepwise growth dynamics. We model the material as a lattice where the crack is pinned by elastic traps and grows due to thermally activated stress fluctuations. In agreement with experimental data we find that the distribution of step sizes follows subcritical point statistics with a power law (exponent 3/2) and a stress-dependent exponential cutoff diverging at the critical rupture threshold.

DOI: 10.1103/PhysRevLett.93.095505 PACS numbers: 62.20.Mk, 46.50.+a, 81.40.Np

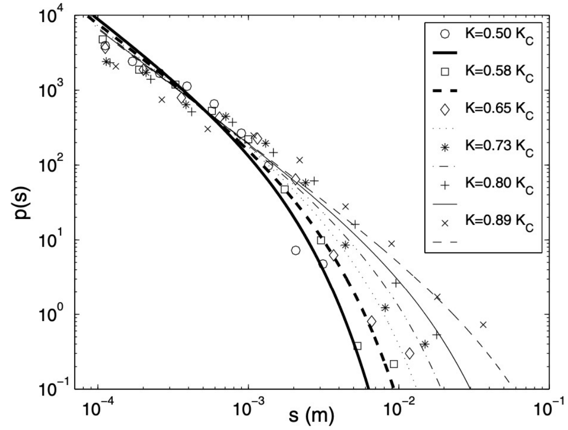


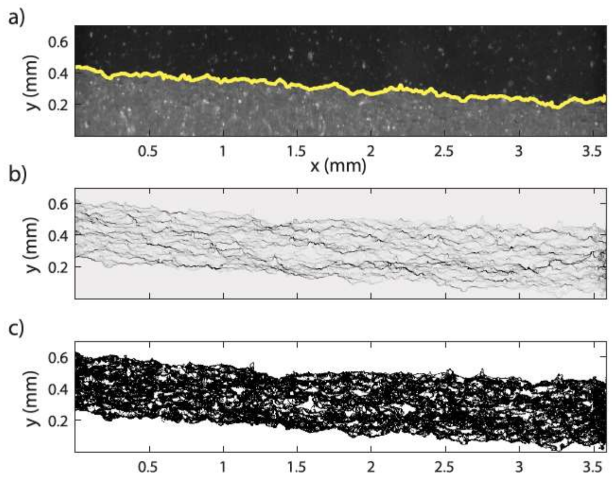
FIG. 2. Probability distribution of step sizes for various values of stress intensity factor. Choosing $\lambda = 50\ \mu$m, the different curves are the best fits of Eq. (3) giving an average value $V = 5 \pm 1$ Å^3.

Local Waiting Time Fluctuations along a Randomly Pinned Crack Front

Knut Jørgen Måløy,[1] Stéphane Santucci,[1] Jean Schmittbuhl,[2] and Renaud Toussaint[2]
[1]*Fysisk Institutt, Universitetet i Oslo, P.O. Boks 1048 Blindern, N-0316 Oslo 3, Norway*
[2]*Institut de Physique du Globe de Strasbourg, UMR 7516, 5 rue René Descartes, F-67084 Strasbourg Cedex, France*
(Received 26 August 2005; published 30 January 2006)

The propagation of an interfacial crack along a heterogeneous weak plane of a transparent Plexiglas block is followed using a high resolution fast camera. We show that the fracture front dynamics is governed by local and irregular avalanches with very large size and velocity fluctuations. We characterize the intermittent dynamics observed, i.e., the local pinnings and depinnings of the crack front by measuring the local waiting time fluctuations along the crack front during its propagation. The deduced local front line velocity distribution exhibits a power law behavior, $P(v) \propto v^{-\eta}$ with $\eta = 2.55 \pm 0.15$, for velocities v larger than the average front speed $\langle v \rangle$. The burst size distribution is also a power law, $P(S) \propto S^{-\gamma}$ with $\gamma = 1.7 \pm 0.1$. Above a characteristic length scale of disorder $L_d \sim 15$ μm, the avalanche clusters become anisotropic providing an estimate of the roughness exponent of the crack front line, $H = 0.66$.

DOI: 10.1103/PhysRevLett.96.045501 PACS numbers: 62.20.Mk, 05.45.Df, 61.43.−j, 81.40.Np



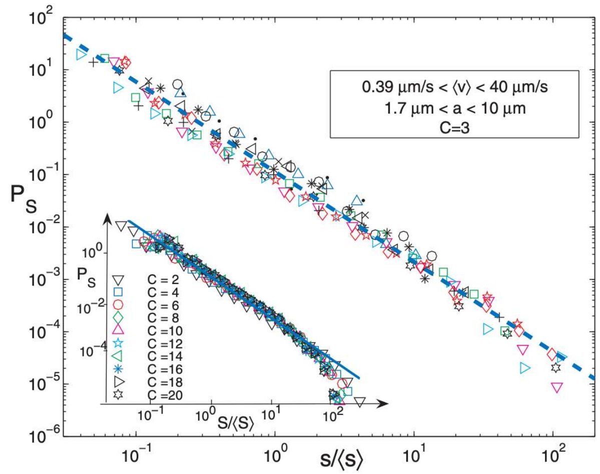


FIG. 3 (color). Burst size S distribution $P(S/\langle S \rangle)$, normalized by the average burst size $\langle S \rangle$, for different experimental conditions (the various symbols correspond to those on Fig. 2). The bursts detected for each experiment correspond to clusters of velocities 3 times larger than the average crack front speed. A fit on all the data (dashed line) gives a slope equal to 1.71. Inset: Normalized bursts size distribution $P(S/\langle S \rangle)$ averaged over all the different experimental conditions, for a wide range of different threshold levels C. A fit to all the data, cutting the largest clusters at which a cutoff appears due to the lack of statistics (solid line), gives a slope equal to 1.67.

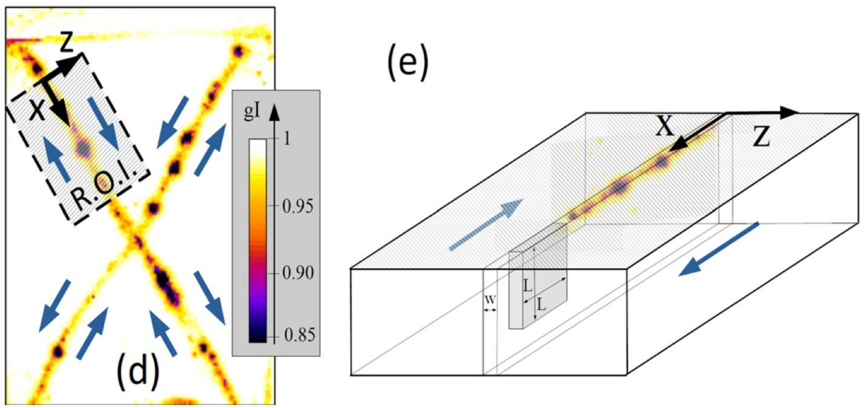
communications
earth & environment

ARTICLE

https://doi.org/10.1038/s43247-021-00147-1 OPEN

Micro-slips in an experimental granular shear band replicate the spatiotemporal characteristics of natural earthquakes

David Houdoux[1], Axelle Amon[1], David Marsan[2], Jérôme Weiss[3] & Jérôme Crassous[1✉]



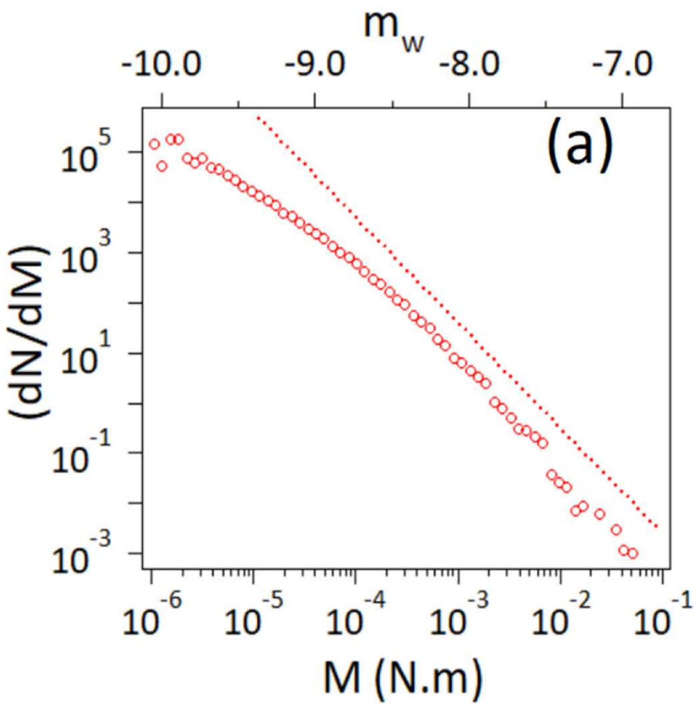


Fig. 3 Scaling law of events. a Probability density dN/dM of events of moment M. Dotted line is a power-law ~$M^{-2.1}$.

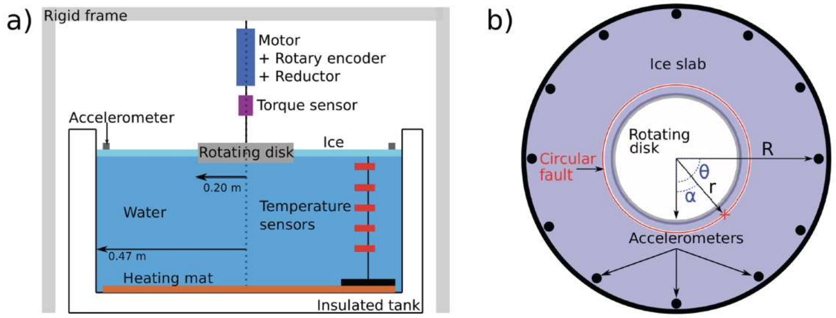
JGR Solid Earth

Micro-Seismic Monitoring of a Shear Fault Within a Floating Ice Plate

Cédric Lachaud[1,2], David Marsan[1], Maurine Montagnat[2], Jérôme Weiss[3], Ludovic Moreau[3], and Florent Gimbert[2]

[1]Université Savoie Mont-Blanc, CNRS, IRD, IFSTTAR, ISTerre, Chambéry, France, [2]Université Grenoble Alpes, CNRS, IRD, G-INP, IGE, Grenoble, France, [3]Université Grenoble Alpes, CNRS, IRD, IFSTTAR, ISTerre, Grenoble, France

Abstract The deformation of a circular fault in a thin floating ice plate imposed by a slow rotational displacement is investigated. Temporal changes in shear strength, as a proxy for the resistance of the fault as a whole, are monitored by the torque required to impose a constant displacement rate. Micro-seismic monitoring is used to study the relationship between fault average resistance (torque) and micro-ruptures. The size distribution of ruptures follows a power-law scaling characterized by an unusually high exponent ($b \simeq 3$), characteristic of a deformation driven by small ruptures. In strong contrast to the typical brittle dynamics of crustal faults, an 'apparently aseismic' deformation regime is observed in which small undetected seismic ruptures, below the detection level of the monitoring system, control the slip budget. Most ($\simeq$ 71%) of the detected ruptures are organized in bursts with highly similar waveforms, suggesting that these ruptures are only a passive by-product of apparently aseismic slip events. The seismic signature of this deformation regime has strong similarities with crustal faulting in settings characterized by high temperature and with non-volcanic tremors.



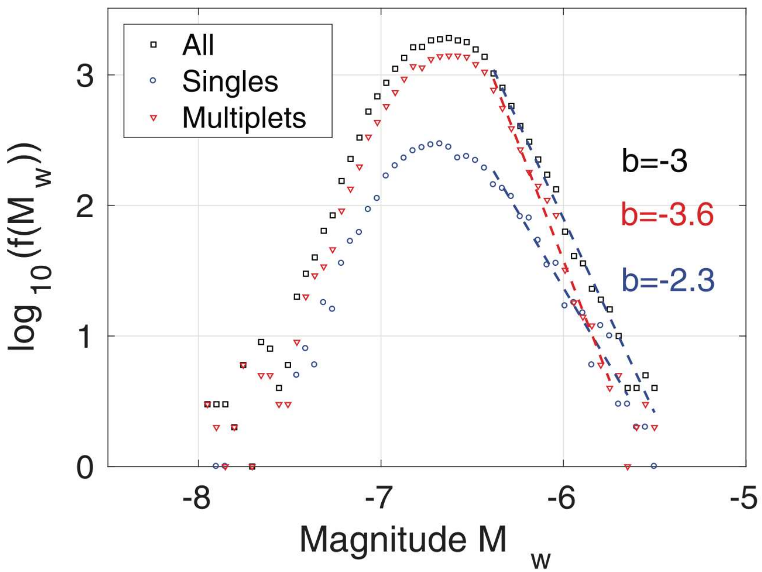


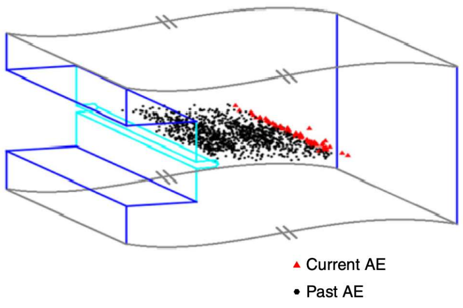
Figure 7. Probability density function of the relative magnitude, M_w, (symbols) and the best linear fits (dashed lines) taking into account all the ruptures (black), ruptures not included in a multiplet only (blue) and ruptures in a multiplet only (red).

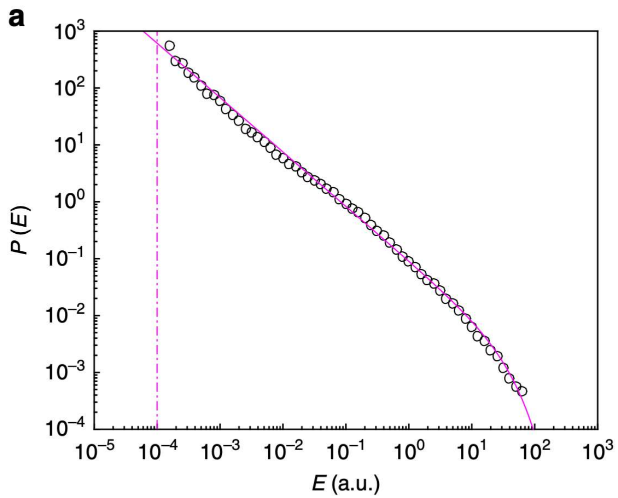
ARTICLE

DOI: 10.1038/s41467-018-03559-4 OPEN

Aftershock sequences and seismic-like organization of acoustic events produced by a single propagating crack

Jonathan Barés[1,2], Alizée Dubois[1], Lamine Hattali[1,3], Davy Dalmas[4] & Daniel Bonamy[1]





The Gutenberg–Richter law and self-similarity. We now turn to the global statistical characterization of the AE time series. In all the experiments, the probability density function, $P(E)$, decays as a power-law over nearly five decades up to an upper corner energy (Fig. 2a). It is well-fitted by:

$$P(E) \propto E^{-\beta} \exp(-E/E_0), \tag{1}$$

with $E \geq E_{\min}$. The lower cutoff, $E_{\min} = 10^{-4}$, is the same in all our experiments. It is set by the sensitivity of the acquisition system. Conversely, the exponent β and the upper corner energy E_0 depend on both crack speed (slightly) and material microstructure (more importantly). We will return at the end of this section to the analysis of these dependencies. Equation 1 is reminiscent of the Gutenberg–Richter law. Note, however, that the energy distributions observed in seismology often take the form of a pure power-law. Then, earthquake sizes are more commonly quantified by their magnitude, which is linearly related to the logarithm of the energy[28]: $\log_{10}E = 1.5M + 11.8$. The energy distribution takes the classical Gutenberg–Richter frequency–magnitude relation: $\log_{10}N(M) = a - bM$, where $N(M)$ is the number of earthquakes per year with magnitude larger than M and a and b are constants. The b-value relates to the exponent β involved in Eq. 1 via: $\beta = b/1.5 + 1$.

Fig. 2 The Gutenberg–Richter law and time–energy self-similarity. a Distribution of AE energy in one of the experiments (microstructure length-scale: d = 583 μm, crack speed: "v 1⁄4 2:7 μms1). Solid magenta line is a gamma function P(E) ∝ E−βexp(−E/E0) for E ≥ Emin = 10−4 (vertical magenta dashed line), with fitted parameters β = 0.96 ± 0.02 and E0 = 38 ± 9.

PHYSICAL REVIEW E **99**, 052902 (2019)

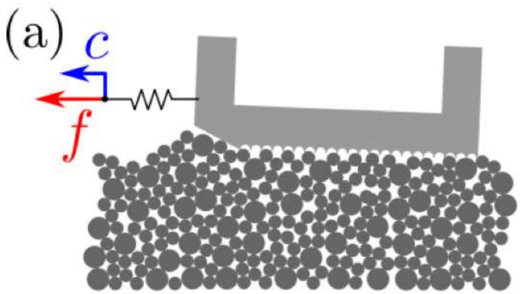
Seismicity in sheared granular matter

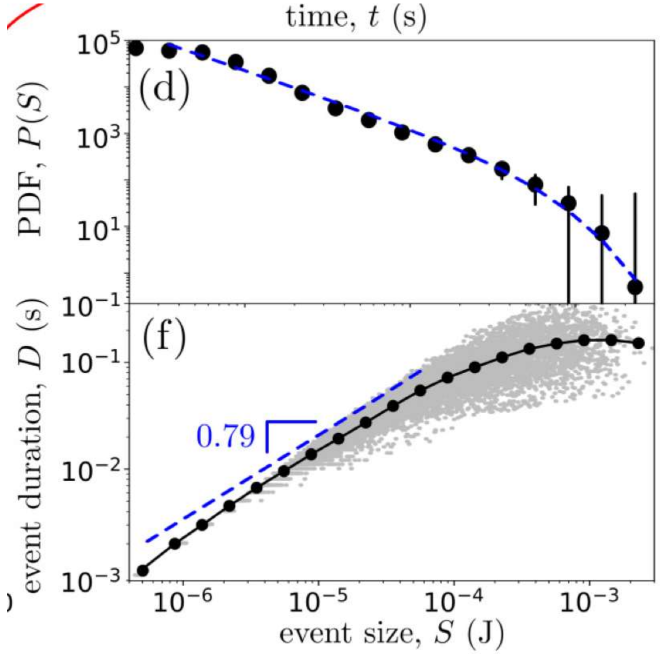
Aghil Abed Zadeh,[1,*] Jonathan Barés,[2] Joshua E. S. Socolar,[1] and Robert P. Behringer[1,†]
[1]*Department of Physics & Center for Non-linear and Complex Systems, Duke University, Durham, North Carolina 27708, USA*
[2]*Laboratoire de Mécanique et Génie Civil, Université de Montpellier, CNRS, Montpellier, France*

(Received 13 November 2018; revised manuscript received 11 April 2019; published 20 May 2019)

We report on experiments investigating the dynamics of a slider that is pulled by a spring across a granular medium consisting of a vertical layer of photoelastic disks. The motion proceeds through a sequence of discrete events, analogous to seismic shocks, in which elastic energy stored in the spring is rapidly released. We measure the statistics of several properties of the individual events: the energy loss in the spring, the duration of the movement, and the temporal profile of the slider motion. We also study certain conditional probabilities and the statistics of mainshock-aftershock sequences. At low driving rates, we observe crackling with Omori-Utsu, Båth, and waiting time laws similar to those observed in seismic dynamics. At higher driving rates, where the sequence of events shows strong periodicity, we observe scaling laws and asymmetrical event shapes that are clearly distinguishable from those in the crackling regime.

DOI: 10.1103/PhysRevE.99.052902





III. CRACKLING DYNAMICS

When the slider is pulled very slowly, we observe crackling dynamics, as evidenced for $c = 0.1$ mm/s by the two decades of power-law decay in $P(S)$ shown in Fig. 1(d). The PDF is well fit by the Gutenberg-Richter form

$$P(S) \sim S^{-\beta} e^{-\frac{S}{S_{\max}}}, \quad (1)$$

with $\beta = 1.22 \pm 0.07$ and $S_{\max} = (6.1 \pm 0.7) \times 10^{-4}$ J.

Philip W. Anderson

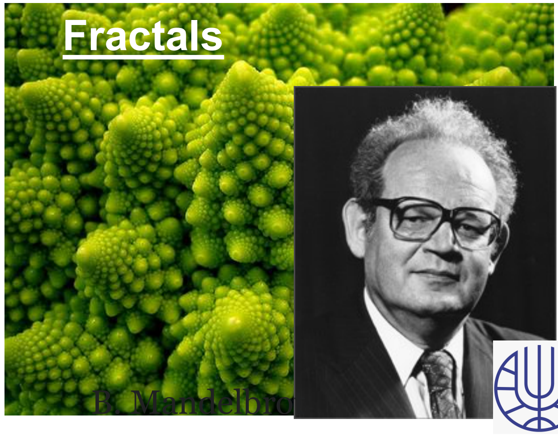
1977

More Is Different

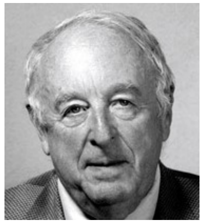
Science (04/08/1972)

"*The ability to reduce everything to simple fundamental laws does not imply the ability to start from those laws and reconstruct the universe.*"

Emergence of new properties resulting from the **interaction** of the elementary parts.



1993



D. Turcotte

J. Rundle

"Complexity" ⟶ **Earthquakes**

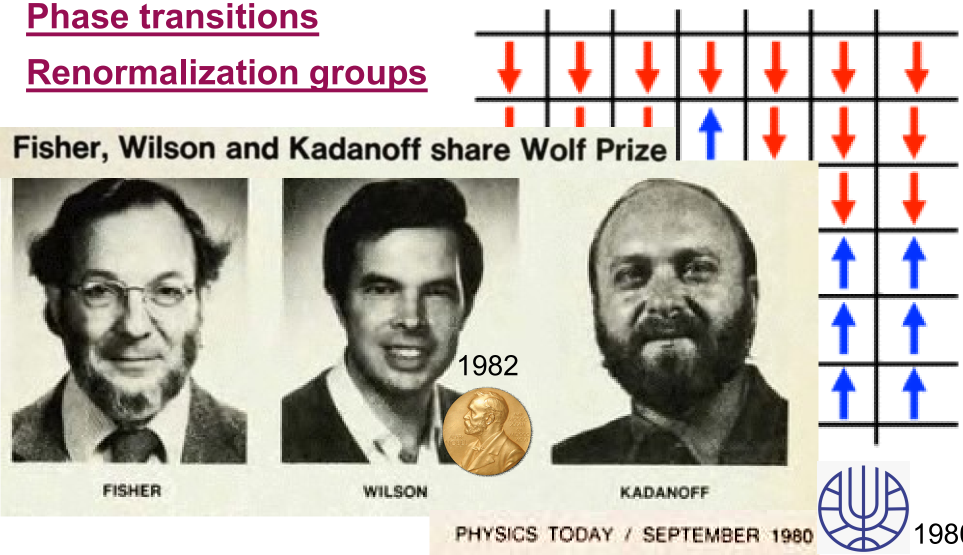
1985-90

Self-organized Criticality (SOC) 1988

as an attempt to explain *scale-invariance* in nature

Phase transitions

Renormalization groups



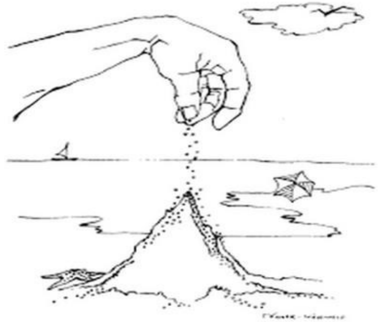
Fisher, Wilson and Kadanoff share Wolf Prize

FISHER WILSON KADANOFF

PHYSICS TODAY / SEPTEMBER 1980

1982

1980

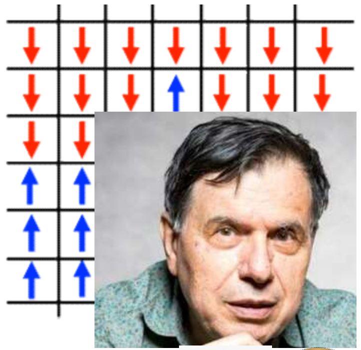


P. Bak

SOC & Earthquakes models (Bak, Sornette, Carlson, Langer, Shaw, Olami, Feder, Christensen, Main…—1989-92)

Friction & **Dissipation** affect (remove) the critical properties in SOC models

Spin Glasses



G. Parisi

2021

REVIEWS OF MODERN PHYSICS, VOLUME 82, JANUARY–MARCH 2010

Mean-field theory of hard sphere glasses and jamming

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Dipartimento di Fisica, INFM-CNR SMC, INFN, Università di Roma "La Sapienza," Piazzale Aldo Moro 2, 00185 Roma, Italy

Francesco Zamponi†

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It is worth noting that in experiments on granular systems and powders the role of friction is important (Dauchot *et al.*, 2005; Schröter *et al.*, 2005; Abate and Durian, 2006; Daniels and Behringer, 2006; Pica Ciamarra *et al.*, 2007; Shundyak *et al.*, 2007; Somfai *et al.*, 2007; Lechenault *et al.*, 2008), for instance, in determining the existence of loose packings (Onoda and Liniger, 1990; Jerkins *et al.*, 2008; Song *et al.*, 2008). Friction complicates a lot of the theoretical analyses of the packing problem since the system is intrinsically out of equilibrium and standard equilibrium statistical mechanics is, in principle, useless. Nevertheless, since the pioneering work of Edwards (Edwards and Oakeshott, 1989; Edwards, 1998), statistical mechanics ideas have been used to describe frictional systems, leading to remarkable results (Goldbart *et al.*, 2005). Comparison with experimental results is made difficult by the fact that in most experiments samples are polydisperse, often with a large range of particle sizes as in the case of many granulars.

For reasons of space, this paper is focused on our approach, that we will discuss in full detail; therefore, in the following we will consider mainly the statistical properties of a system of frictionless spheres, since our method is based on equilibrium statistical mechanics. We will not discuss in detail neither the geometrical properties (unless needed to compare numerical data with our results) of amorphous packings nor how their properties are influenced by the presence of friction.

Physics of disordered systems
using **hard & frictionless spheres**

Spatial frustration
(Jamming)

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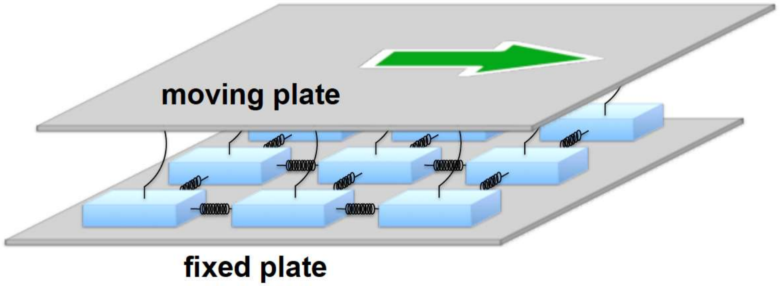
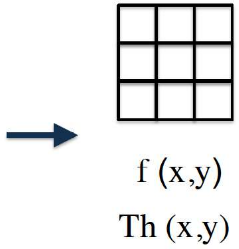
Physics of **actual granular**
(disordered) **systems**,

friction plays an essential role
(Jamming)

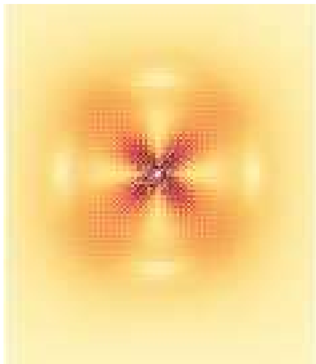
Models of Avalanches

- cellular automata

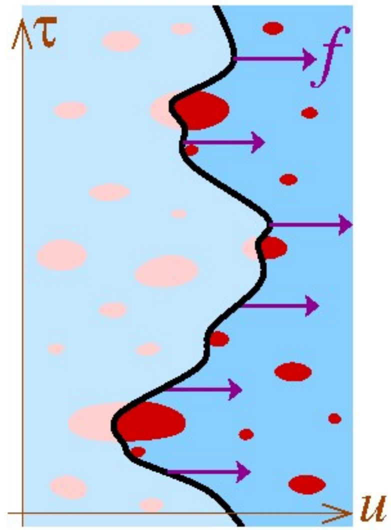




- Mesoscopic approaches (elastoplastic models)



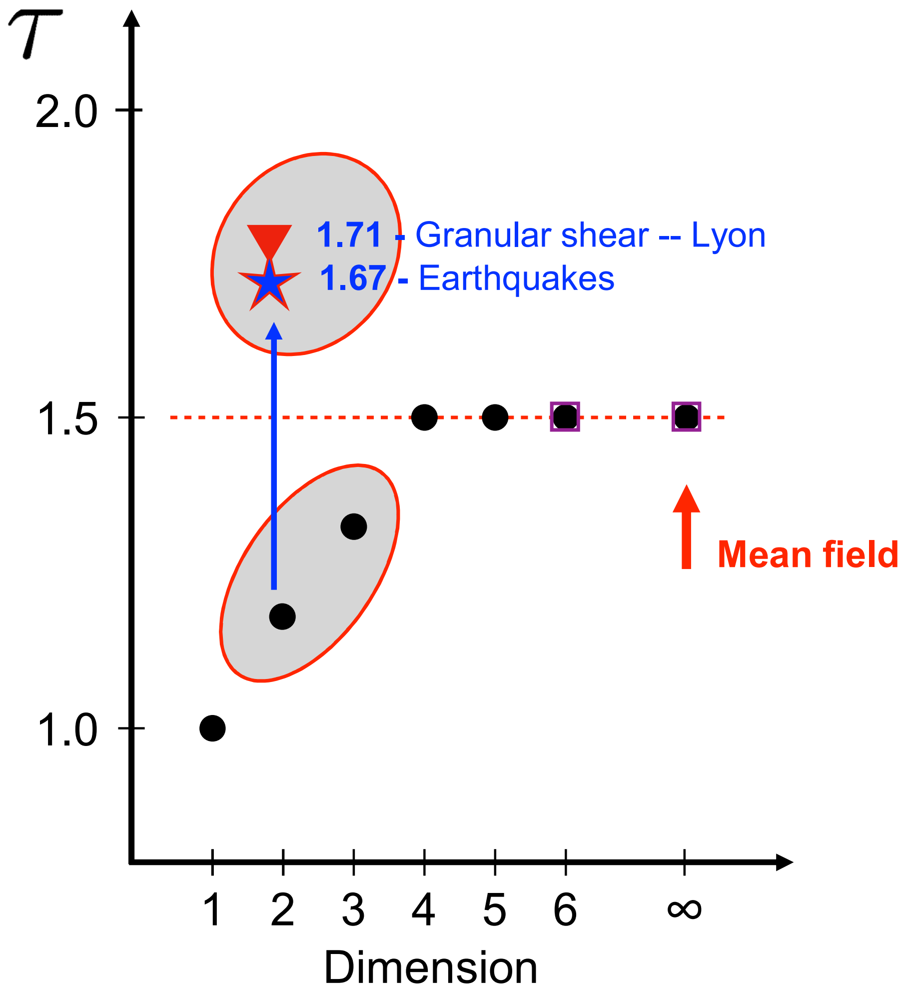
- Elastic line is a disordered landscape (**renormalization groups)**



Exponent values in avalanche size distributions

$$P(s) \sim s^{-\tau}$$

● Renormalization group in elastic lines



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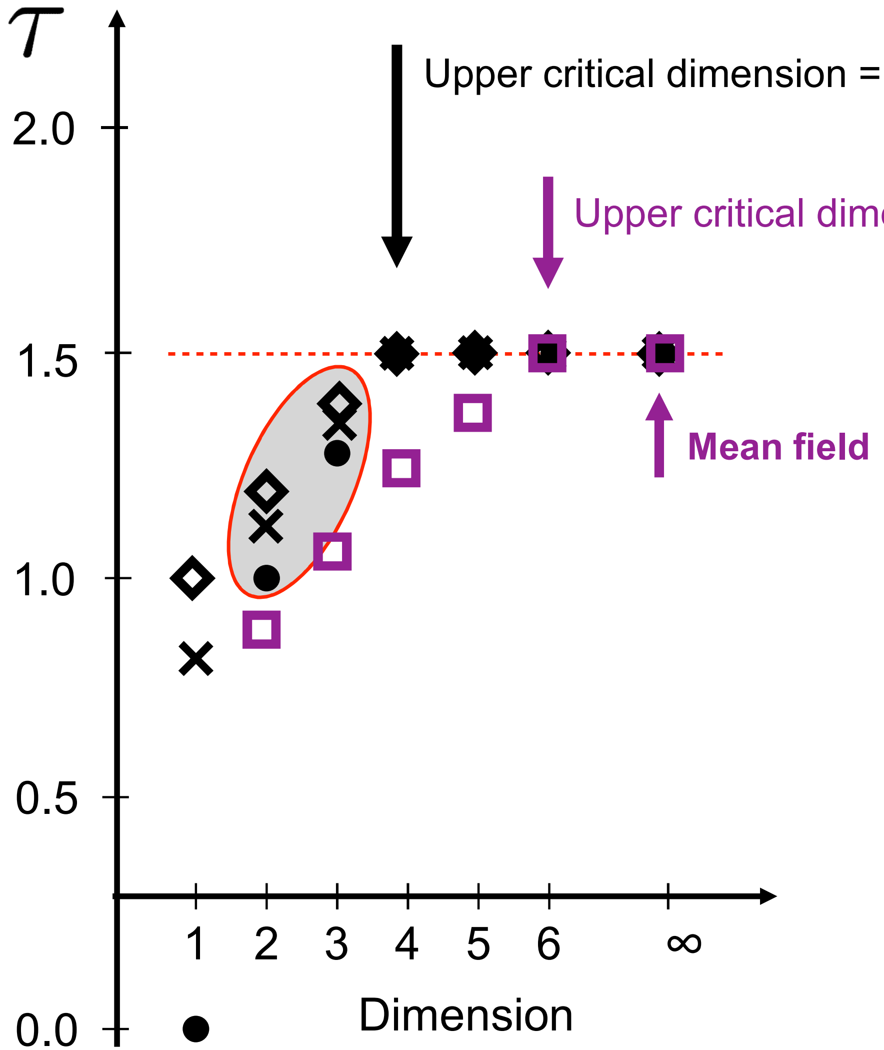

Renormalization group in elastic lines

● RP ✕ RB ◇ RF Le Doussal & Wiese, PRE 2009

□ Percolation