Parallels between Earthquakes, Financial crashes and epileptic seizures

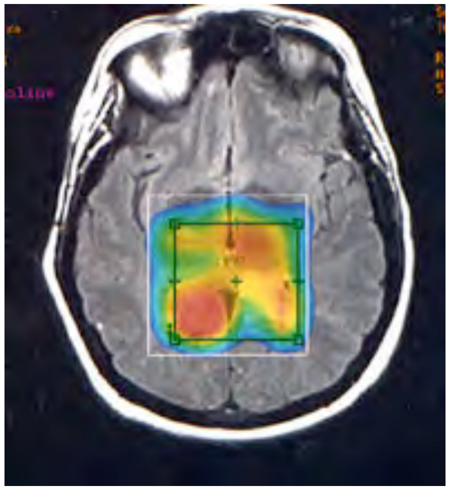
Didier SORNETTE

[1]Department of Management, Technology and Economics,ETH Zurich, Switzerland

[2]Department of Physics, ETH Zurich, Switzerland

[3]Department of Earth Sciences ETH Zurich, Switzerland

[3]Institute of Geophysics and Planetary Physics and Department of Earth and Planetary Sciences, UCLA, California.



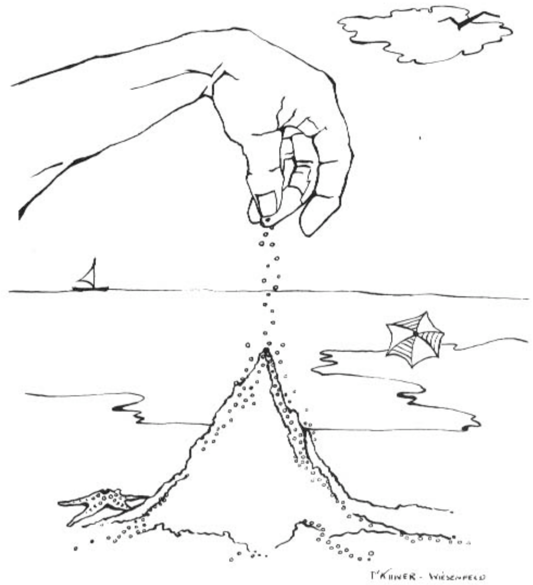
http://www.newscientist.com/channel/fundamentals/mg18725171.300

The World's 10 Biggest Ideas, New Scientist 17 September 2005

Excerpts: Certain questions define the way we see the world. How did the universe begin? What is matter made of? What shaped our planet? How did the amazing diversity of life arise? We take many of the answers for granted, but maybe we shouldn't.

1 The big bang
2 Evolution
3 Quantum mechanics
4 The theory of everything
5 Risk
6 Chaos
7 Relativity
8 Climate change
9 Plate tectonics
10 Science

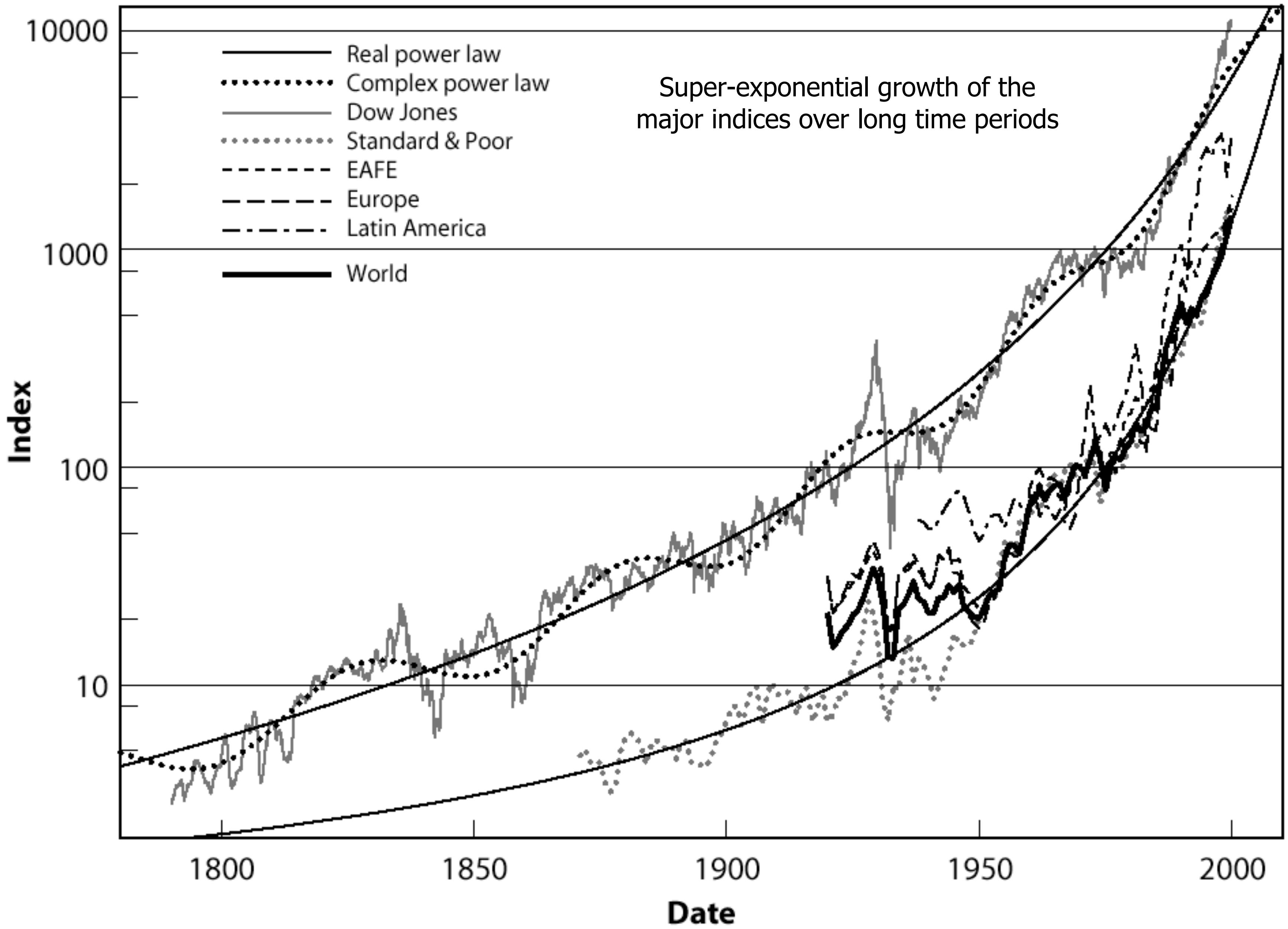
• Self-organization?
Extreme events are just part of the tail of power law distribution due to "self-organized criticality"? (endogenous)



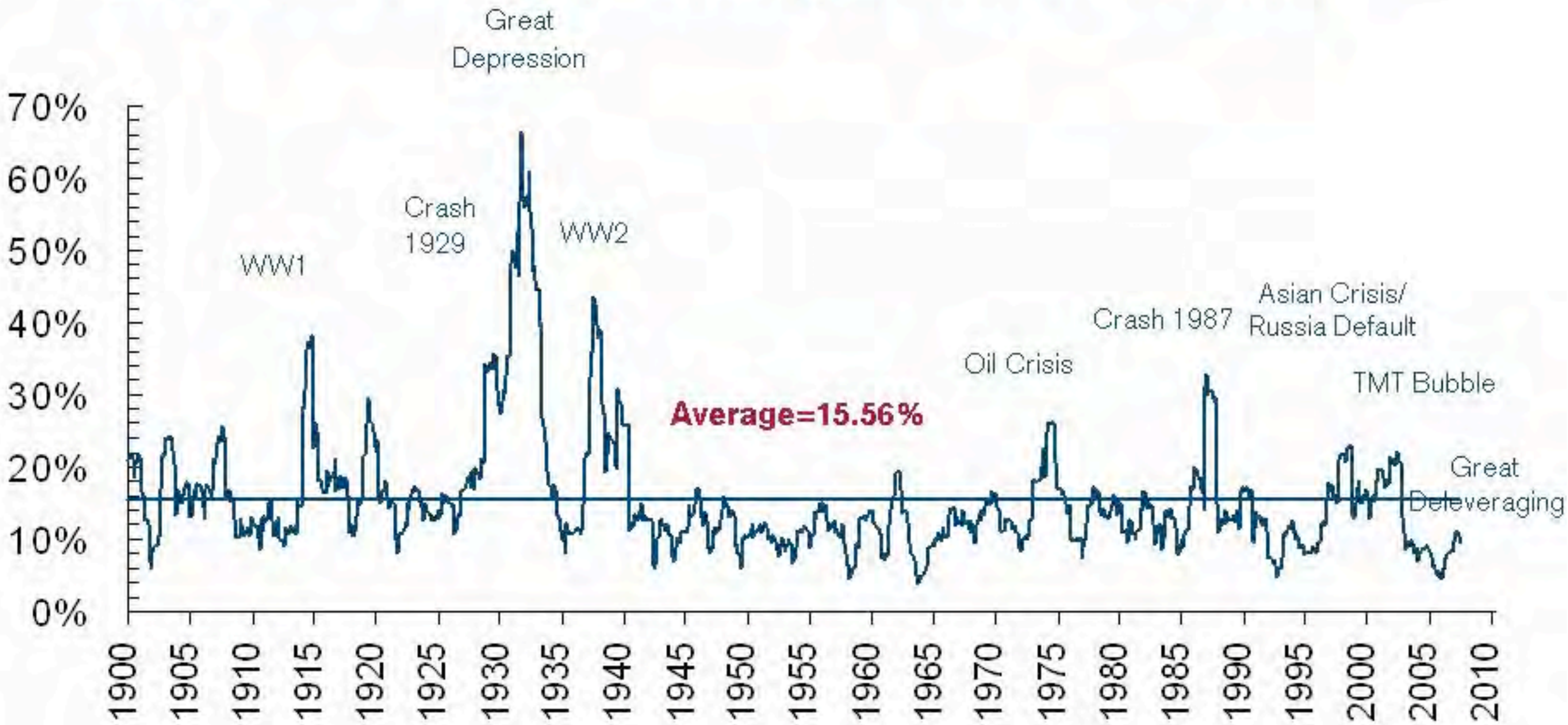
Artwork by Elaine Wiesenfeld
(from Bak, How Nature Works)

•"Catastrophism": extreme events require extreme causes that lie outside the system (exogenous)

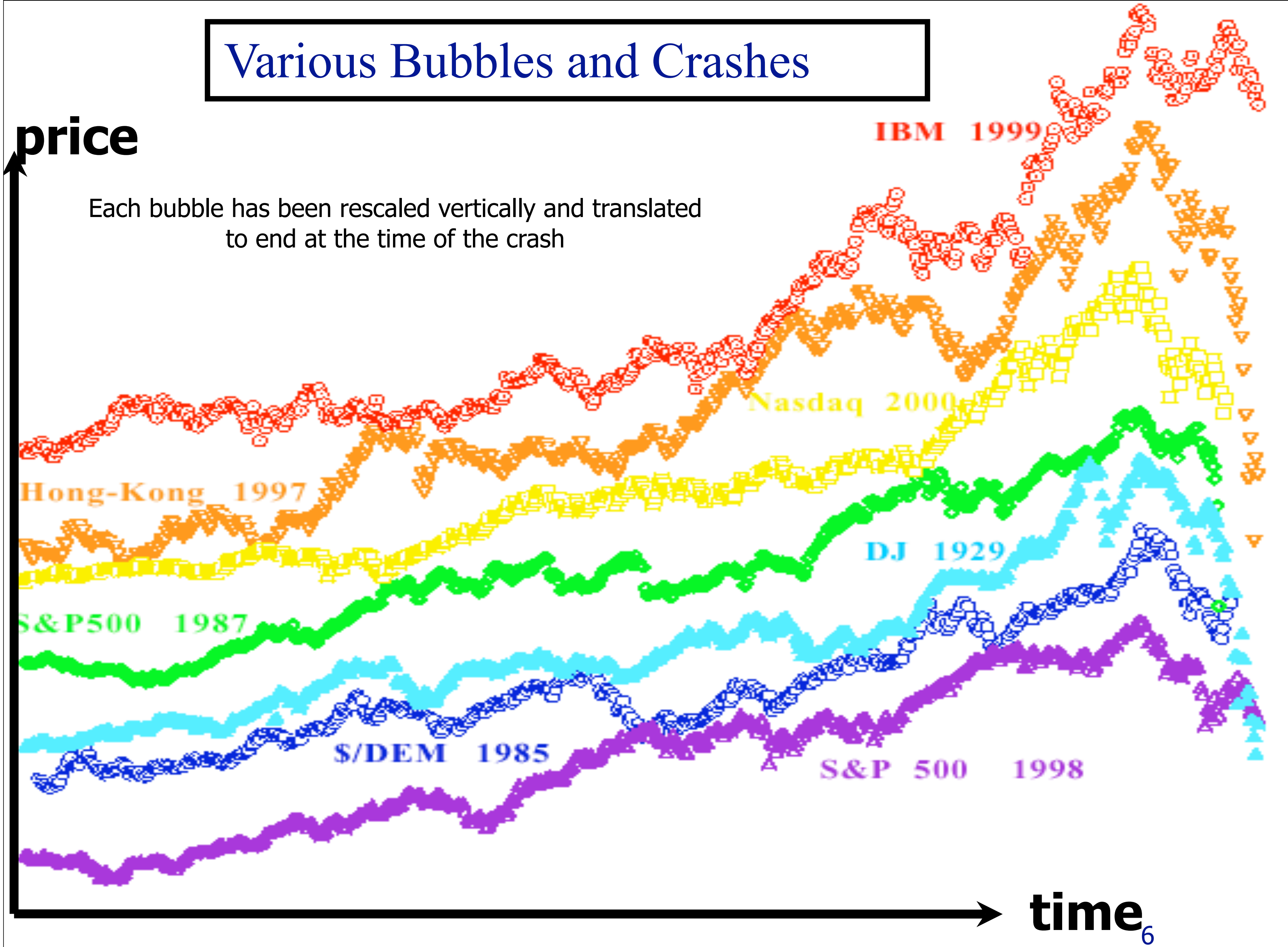
•A mixture? How would it work?

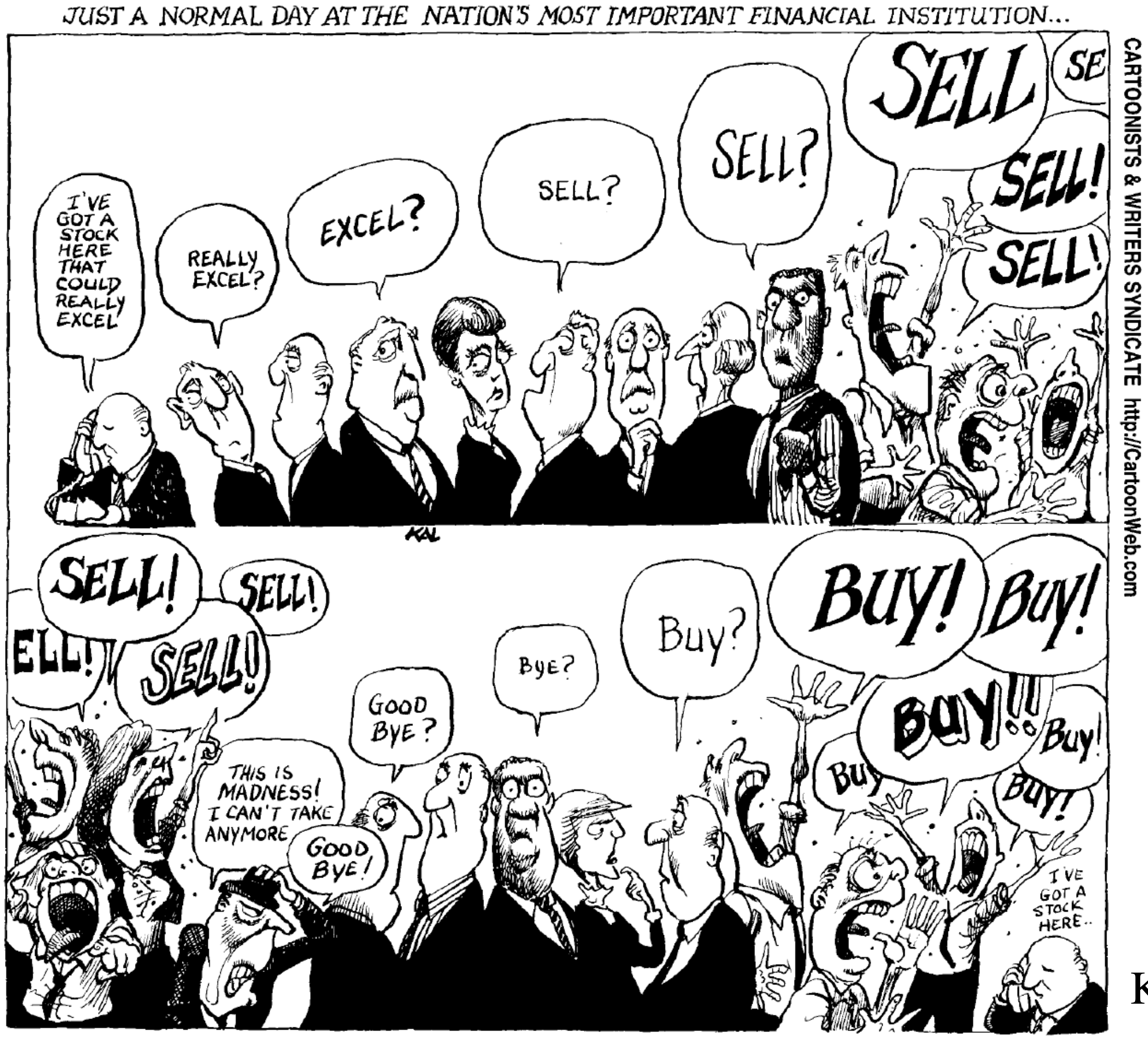

Super-exponential growth of the
major indices over long time periods
Real power law
Complex power law
Dow Jones
Standard & Poor
EAFE
Europe
Latin America
World
10000
1000
100
10
Index
1800
1850
1900
1950
2000
Date

Long term volatility of monthly Dow-Jones Returns



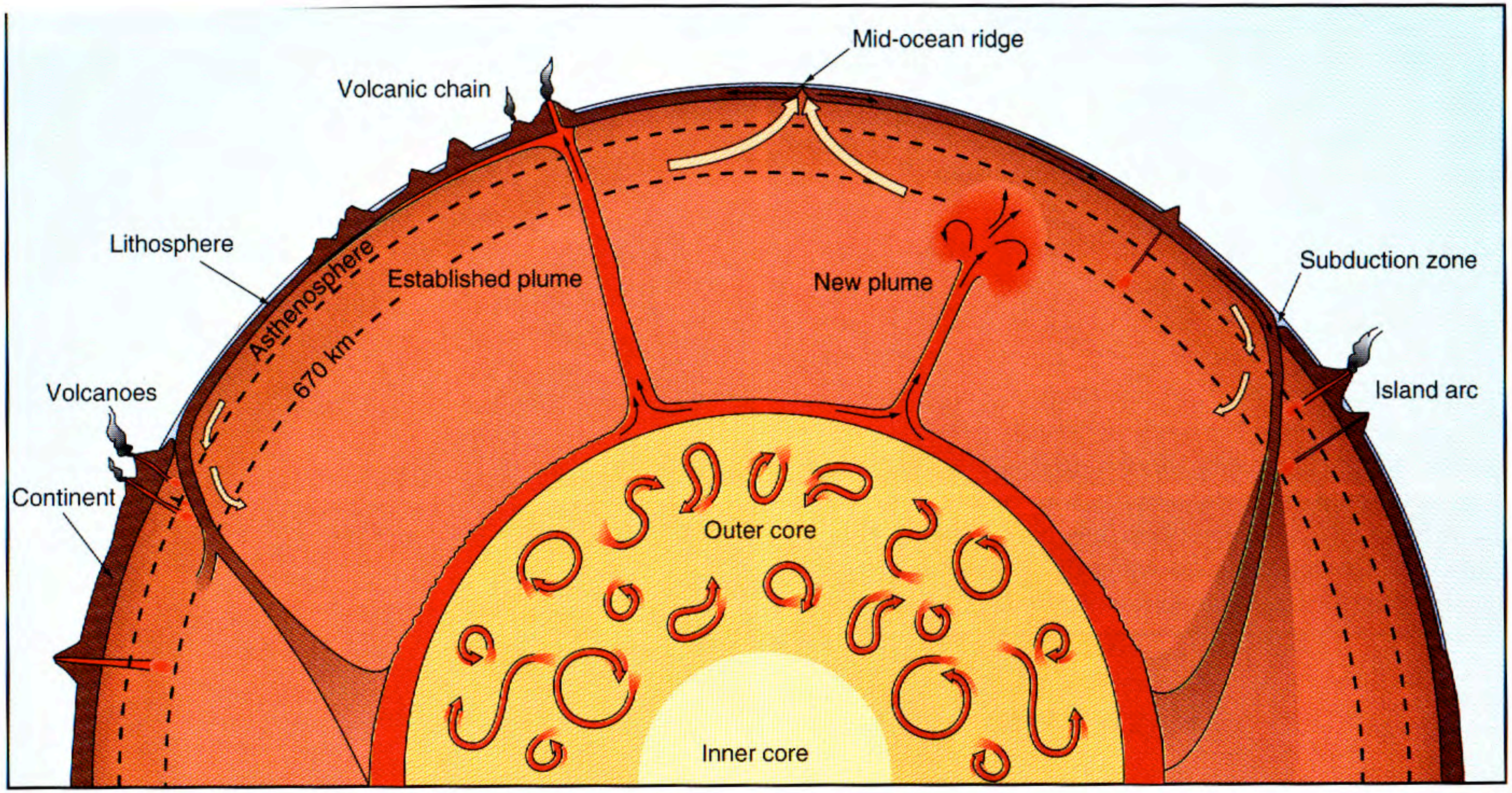
Various Bubbles and Crashes

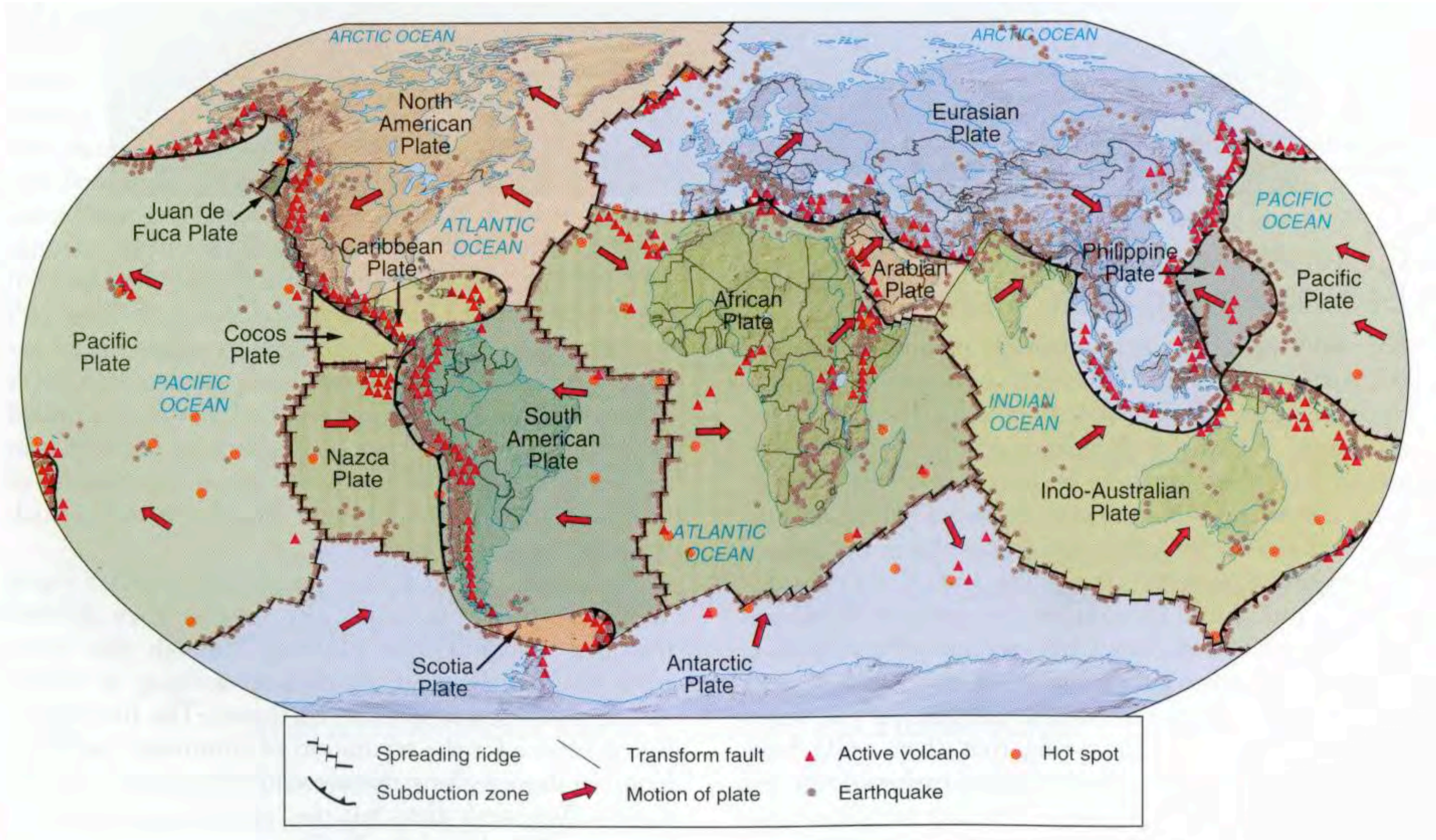



JUST A NORMAL DAY AT THE NATION'S MOST IMPORTANT FINANCIAL INSTITUTION...
I'VE GOT A STOCK HERE THAT COULD REALLY EXCEL
REALLY EXCEL?
EXCEL?
SELL?
SELL?
SELL
SE
SELL!
SELL!
KAL
SELL!
SELL!
ELL!
SELL!
THIS IS MADNESS! I CAN'T TAKE ANYMORE
GOOD BYE!
GOOD BYE?
BYE?
Buy?
BUY!
Buy!
BUY!!
Buy!
Buy
BUY!
I'VE GOT A STOCK HERE..
CARTOONISTS & WRITERS SYNDICATE http://CartoonWeb.com

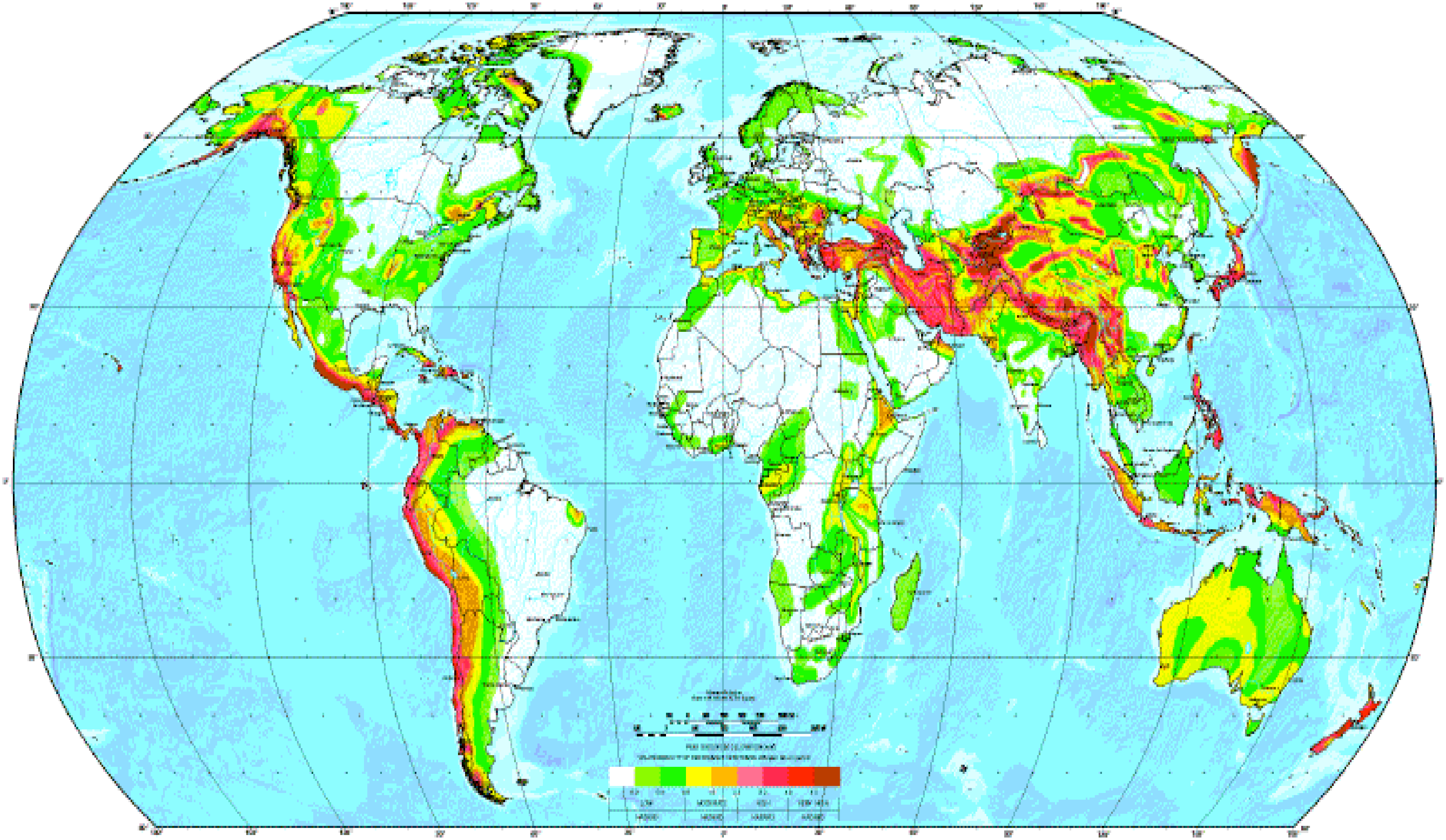
Kal

Convecting system




ARCTIC OCEAN
ARCTIC OCEAN
North American Plate
Eurasian Plate
PACIFIC OCEAN
Juan de Fuca Plate
ATLANTIC OCEAN
Caribbean Plate
Arabian Plate
Philippine Plate
African Plate
Pacific Plate
Cocos Plate
Pacific Plate
PACIFIC OCEAN
INDIAN OCEAN
South American Plate
Nazca Plate
Indo-Australian Plate
ATLANTIC OCEAN
Scotia Plate
Antarctic Plate
Spreading ridge
Subduction zone
Transform fault
Motion of plate
Active volcano
Earthquake
Hot spot

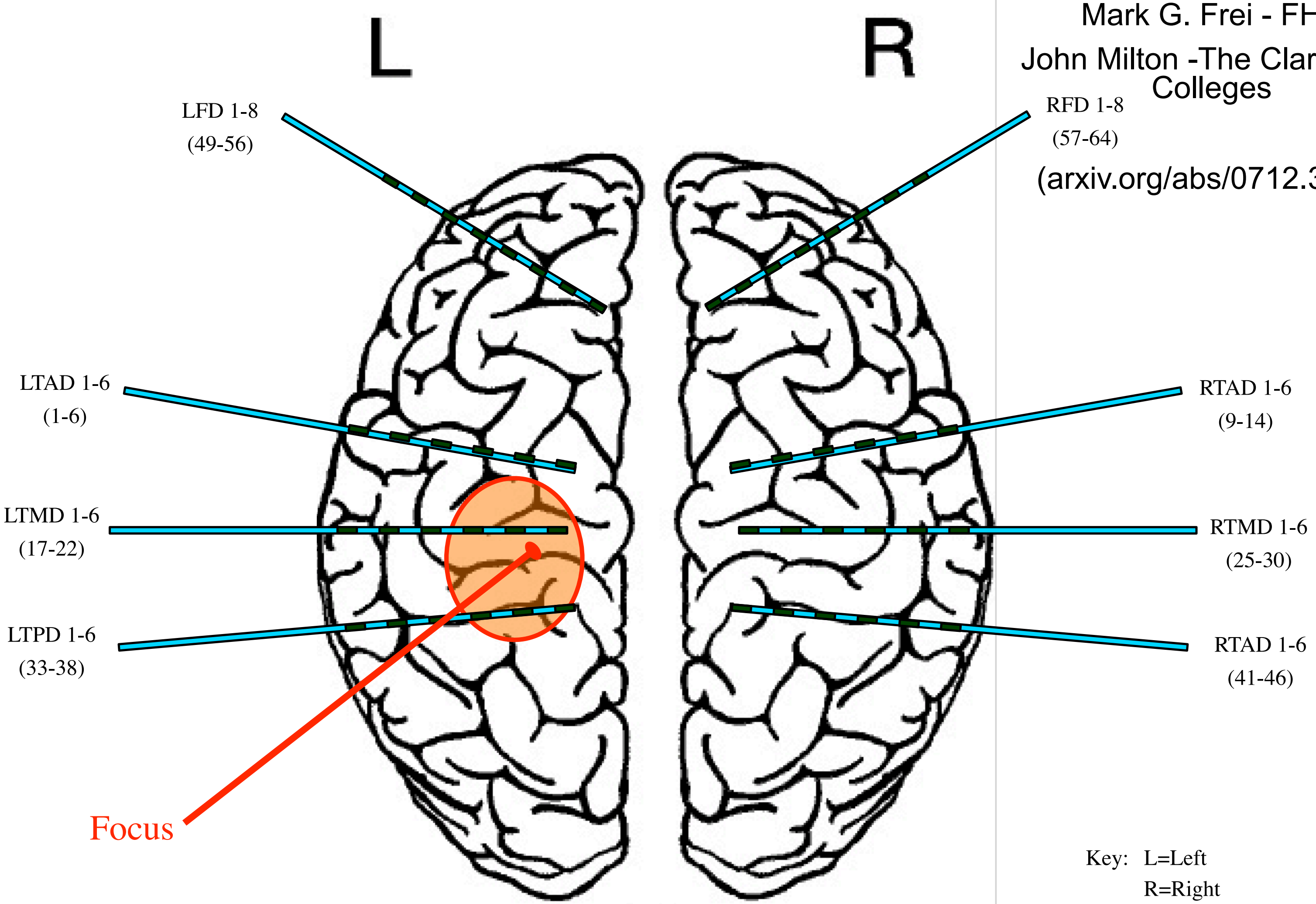
GLOBAL SEISMIC HAZARD MAP

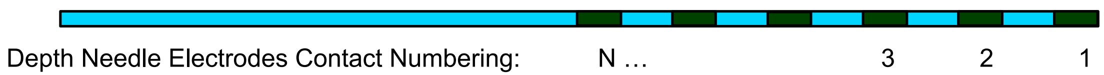


Epileptic Seizures – Quakes of the Brain?

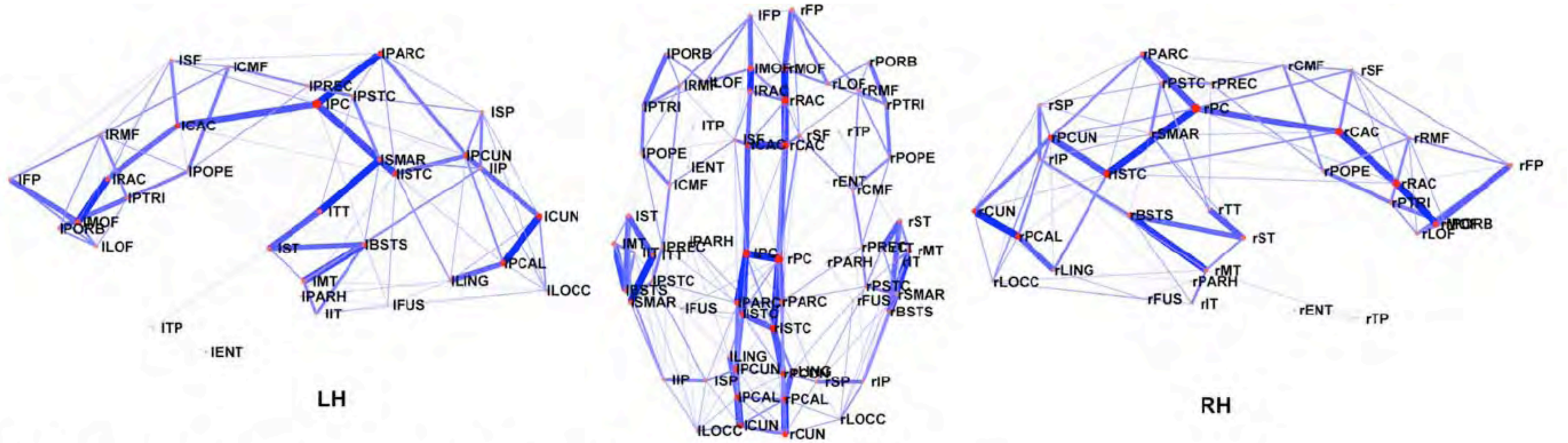
with Ivan Osorio – KUMC & FHS
Mark G. Frei - FHS
John Milton -The Claremont Colleges

(arxiv.org/abs/0712.3929)

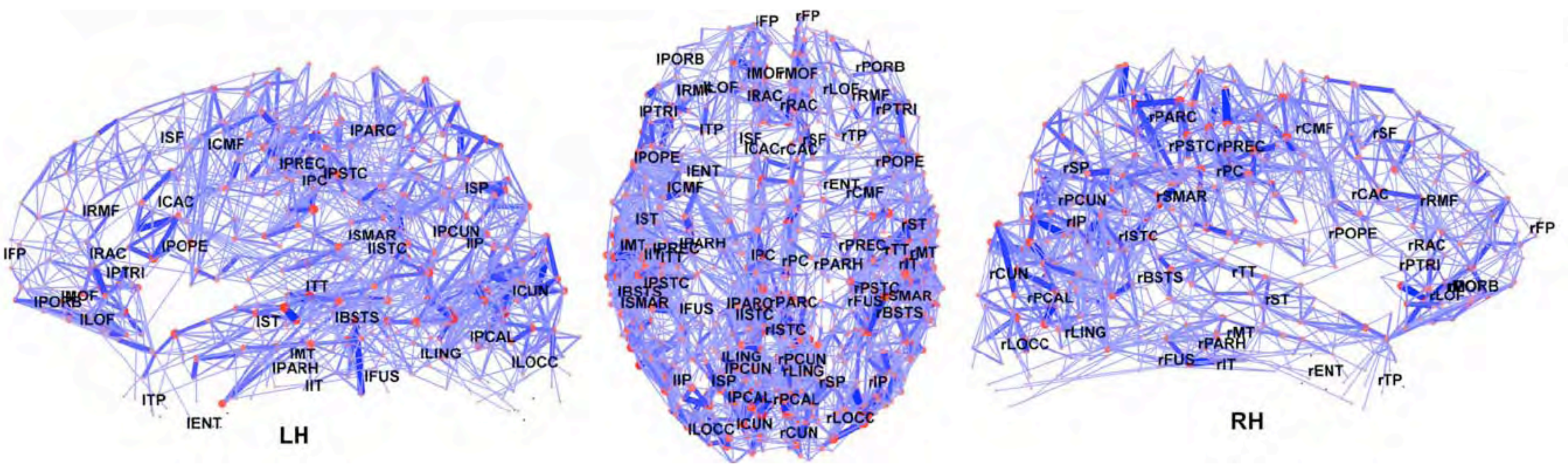




Key: L=Left
R=Right
A=Anterior
M=Mesial
P=Posterior
D=Depth
T=Temporal



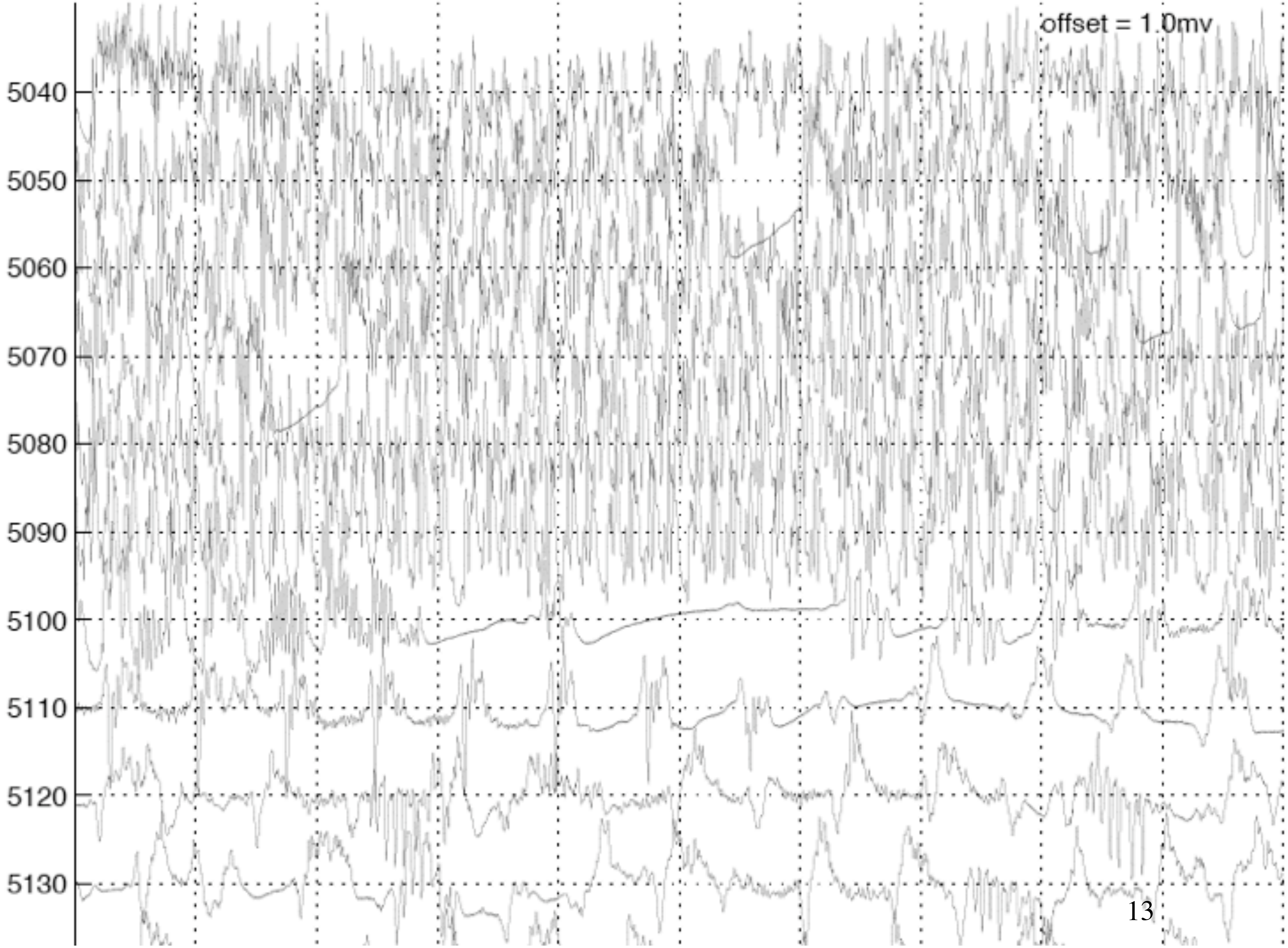
Average Regional Connection Matrix, Network Layout, and Connectivity Backbone

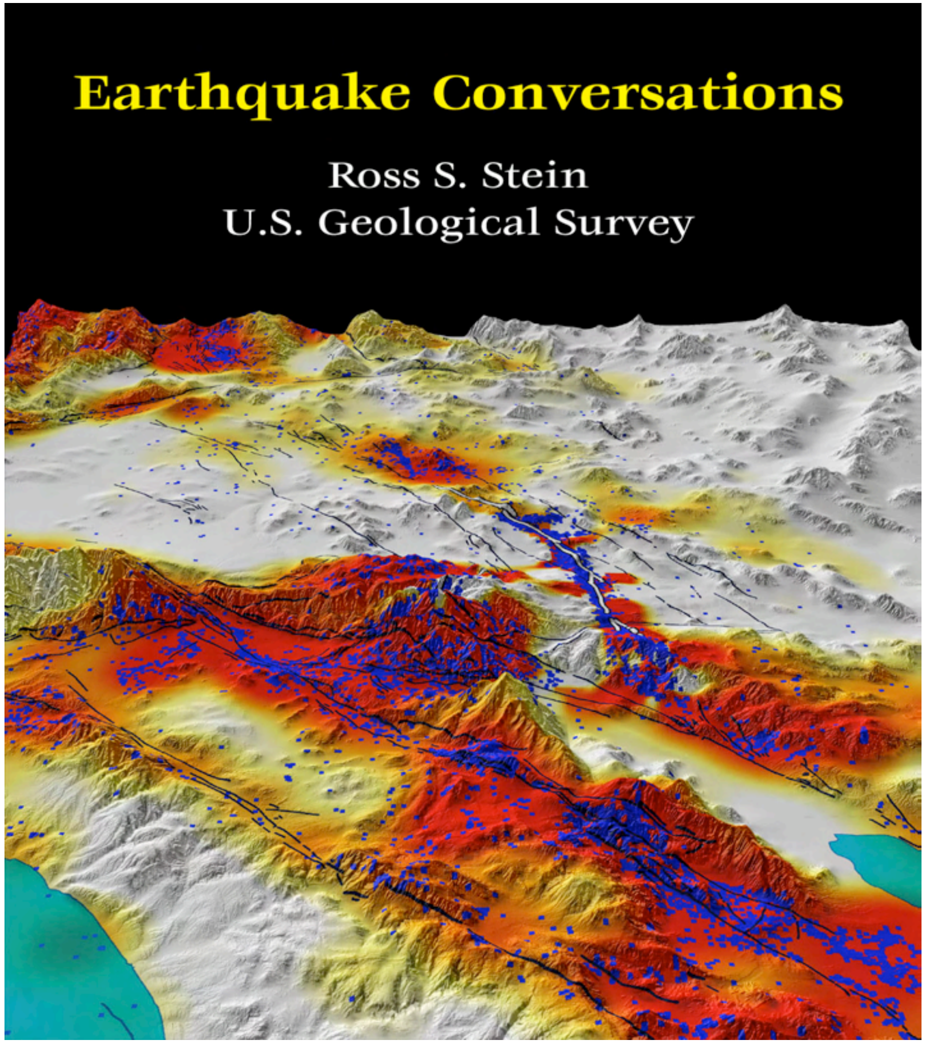


. High-Resolution Connection Matrix, Network Layout and Connectivity Backbone

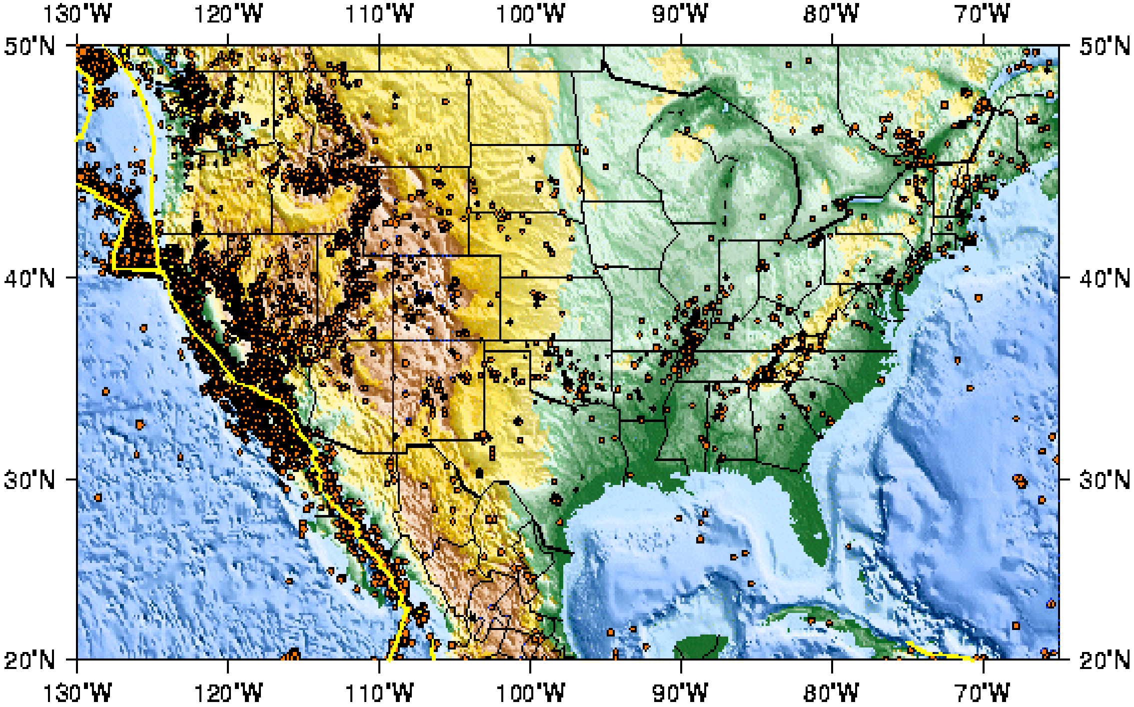
P. Hagmann et al. (2008)

Bursts and Seizures





Epidemic processes by word-of-mouth, sentiment, convention...

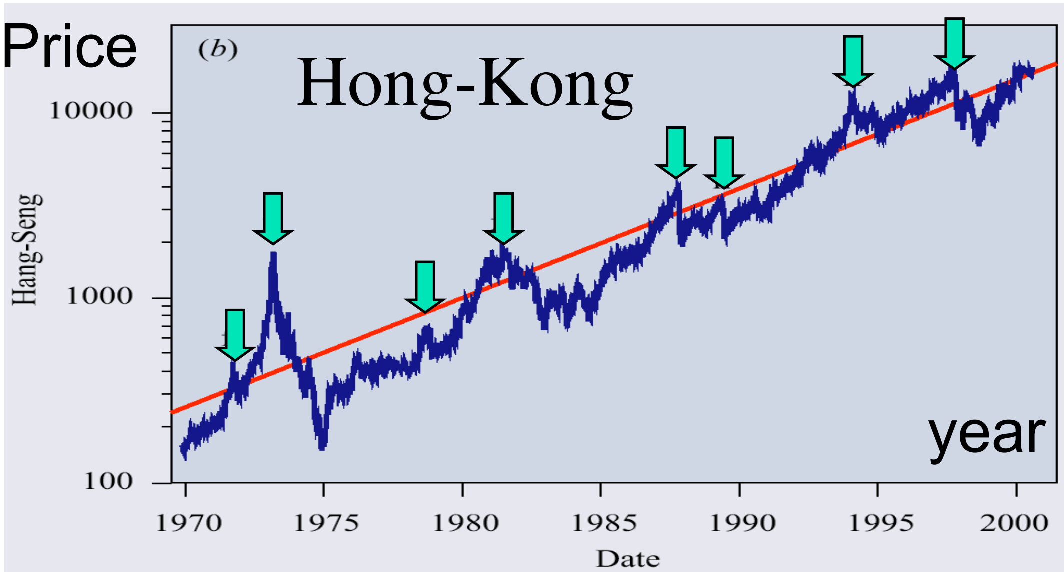

130°W
120°W
110°W
100°W
90°W
80°W
70°W
50°N
40°N
30°N
20°N

Statistical laws of seismicity

- Gutenberg-Richter law: $\sim 1/E^{1+\beta}$ (with $\beta \approx 2/3$)
- Omori law $\sim 1/t^p$ (with $p \approx 1$ for large earthquakes)
- Productivity law $\sim E^a$ (with $a \approx 2/3$)
- PDF of fault lengths $\sim 1/L^2$
- Fractal/multifractal structure of fault networks $\zeta(q)$, $f(\alpha)$
- PDF of seismic stress sources $\sim 1/s^{2+\delta}$ (with $\delta \geq 0$)
- Distribution of inter-earthquake times
- Distribution of seismic rates

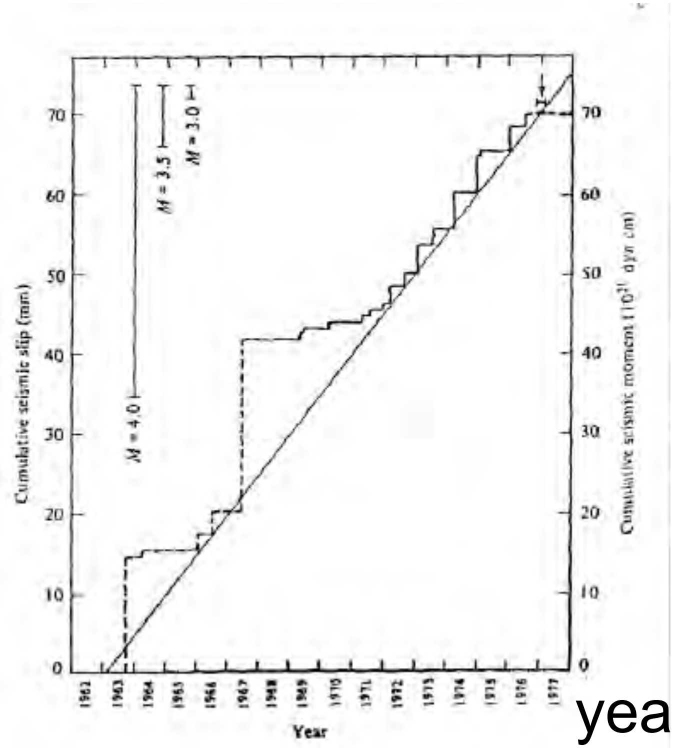
Stylized facts of financial markets

- Heavy-tail pdf of returns
- Omori law and Long-memory of volatility
- Price impact function — Price ~ V^β with β=0.2-0.6
- Pareto distribution of wealth
- Multifractal structure of returns
- PDF of news' sizes?
- Distribution of inter-shock times
- Distribution of limit order sizes
- "Leverage" effect



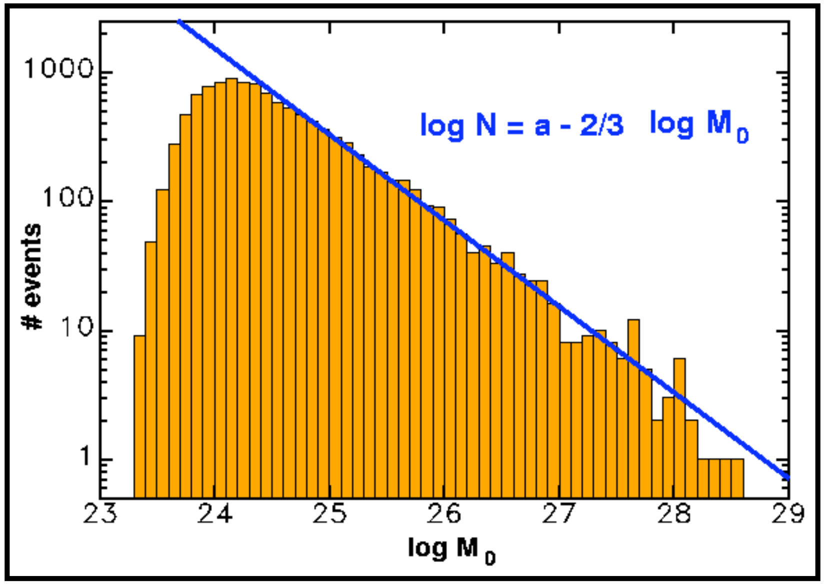
Red line is 13.8% per year: but The market is never following the average growth; it is either super-exponentially accelerating or crashing

Cumulative Slip

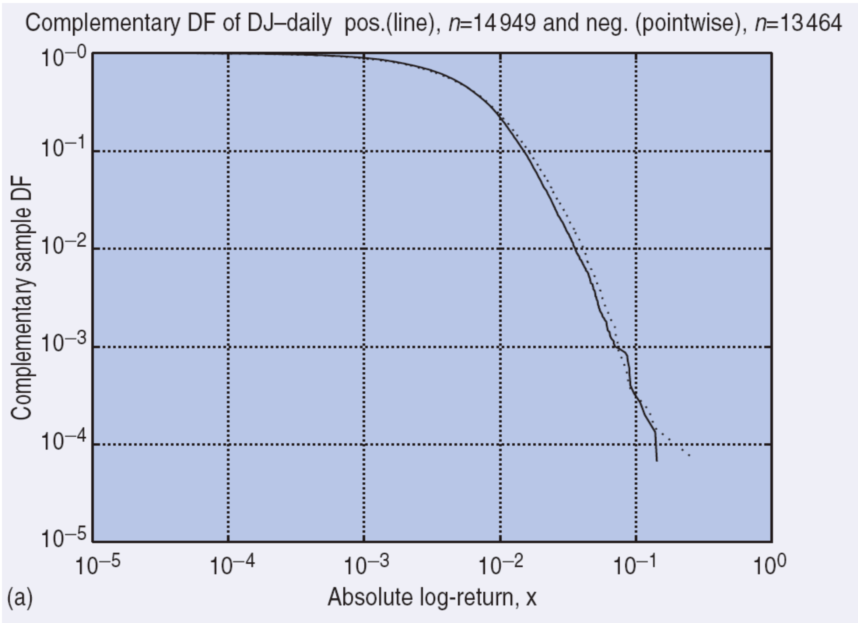


year

Cumulative moment and seismic slip in a zone of the Calaveras fault (1962-77)

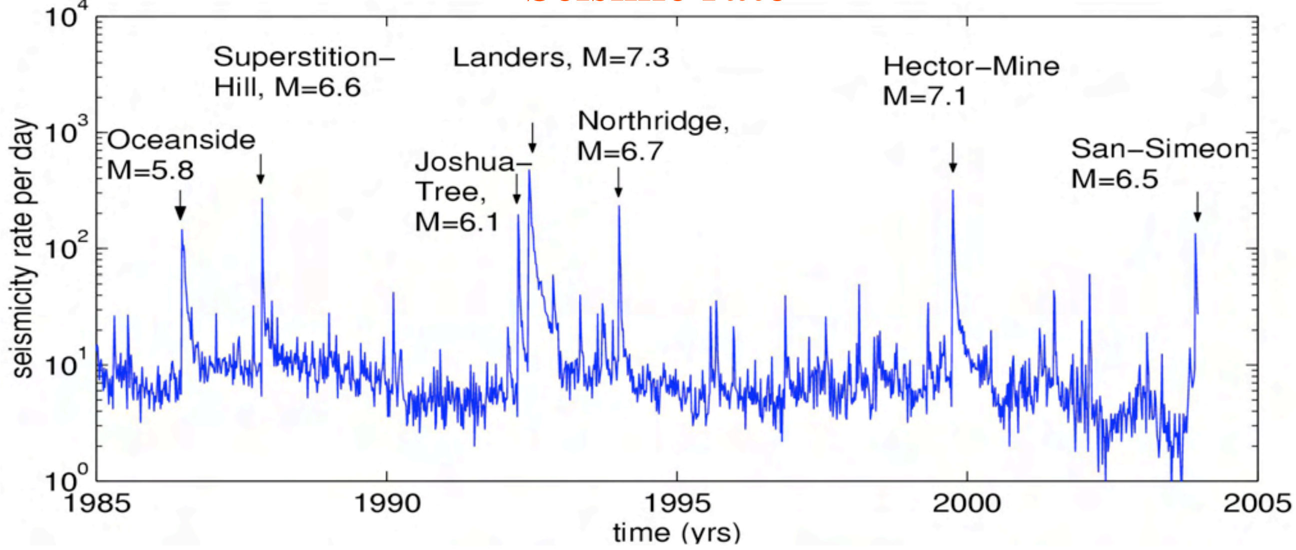


Heavy tails in pdf of earthquakes b=2/3

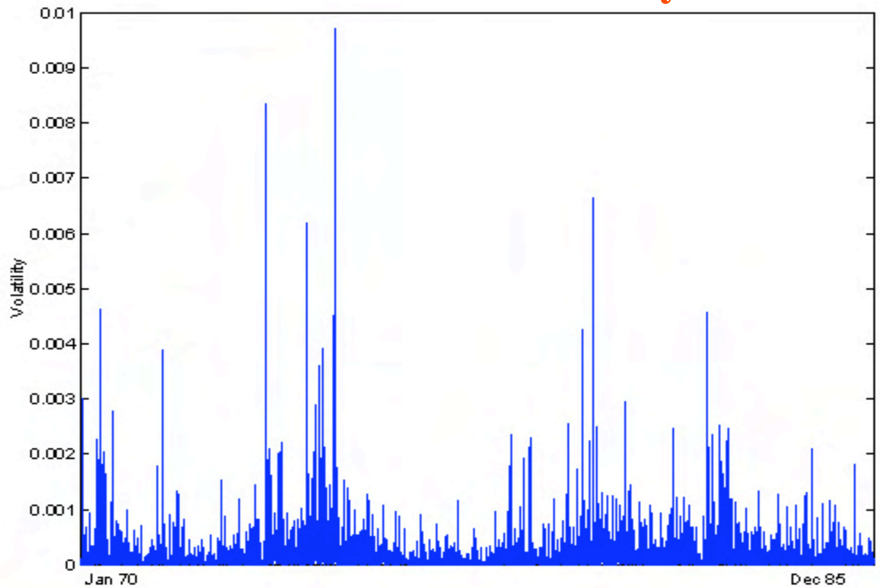


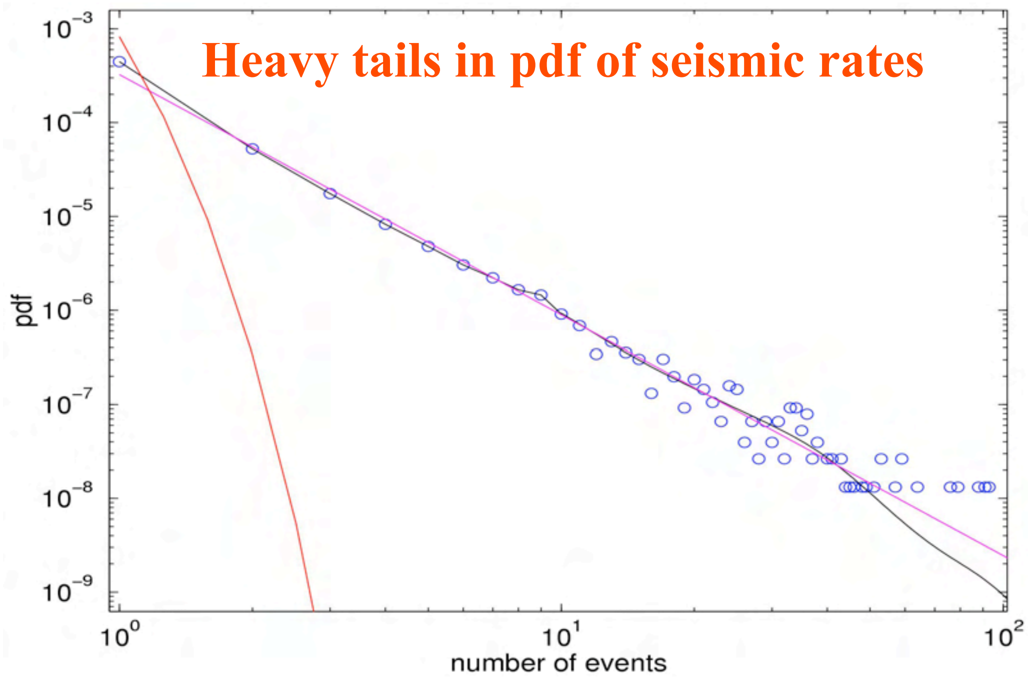
Heavy-tails of price changes b=3

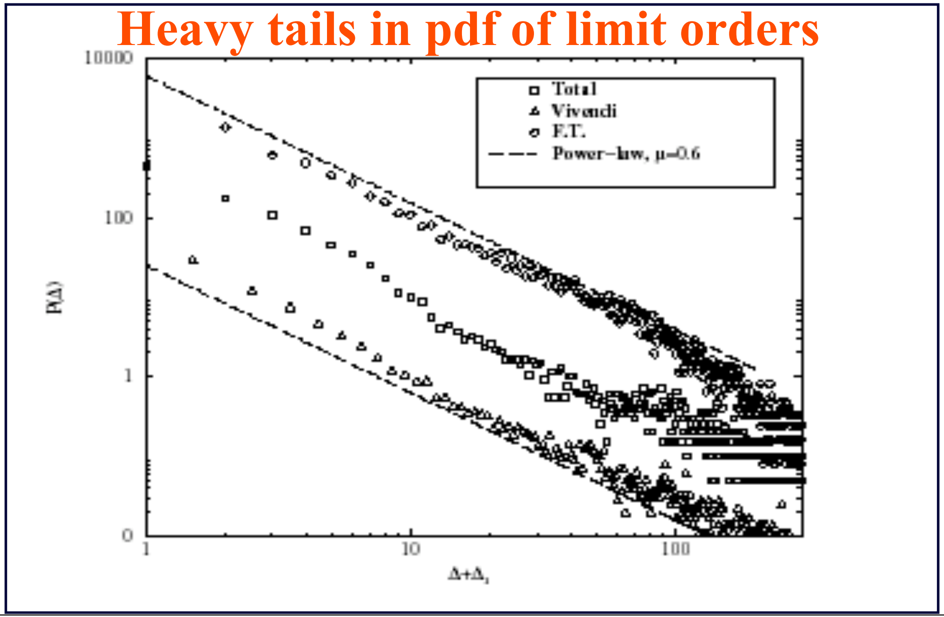
Seismic rate



Financial Volatility

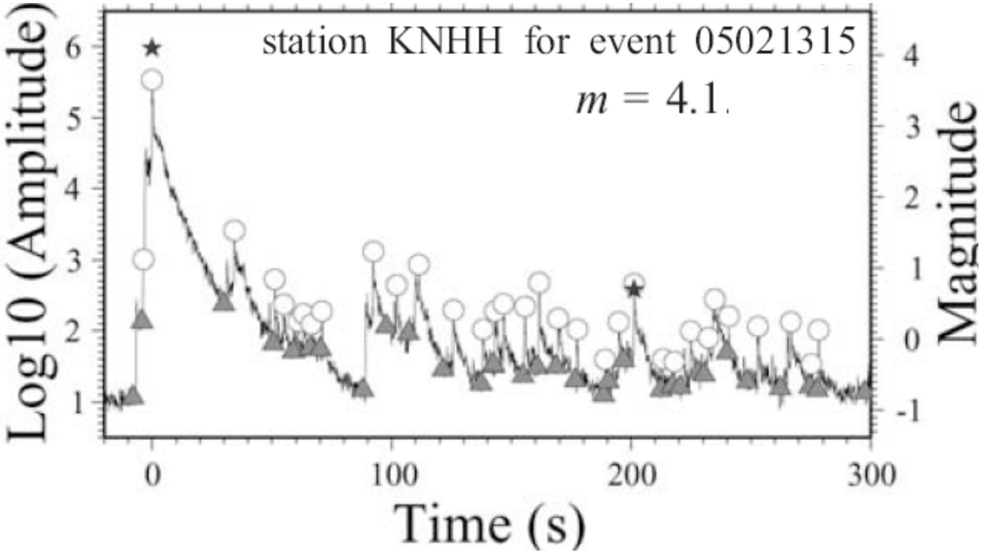


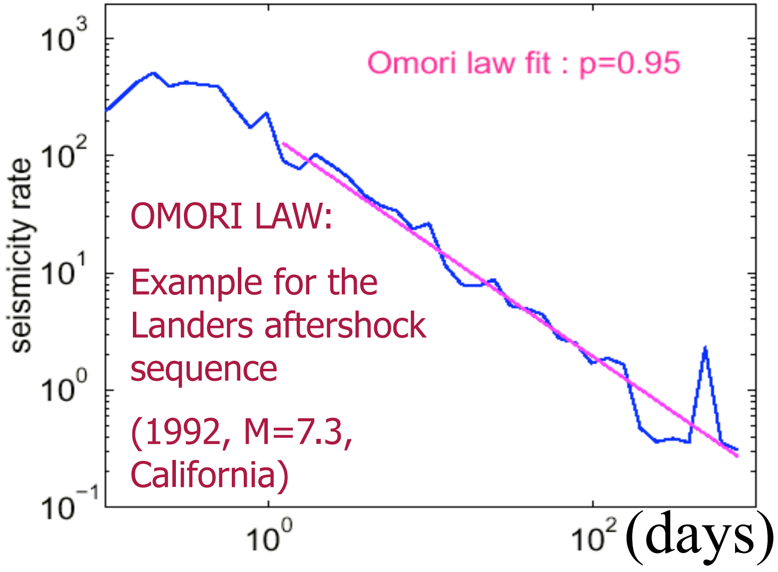

Heavy tails in pdf of seismic rates
pdf
number of events
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8
10^-9
10^0
10^1
10^2

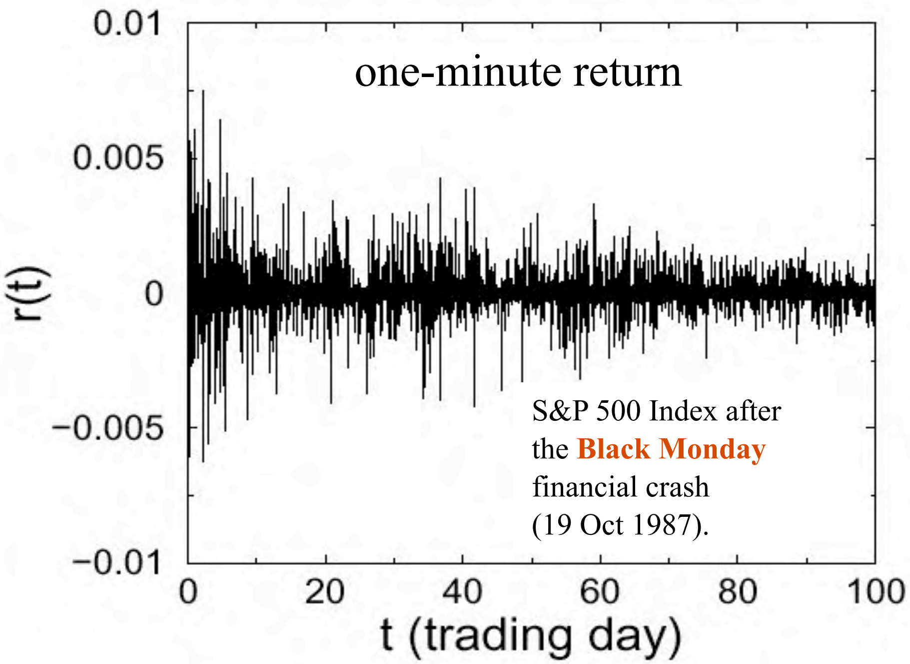

Heavy tails in pdf of limit orders
Total
Vivendi
F.T.
Power-law, μ=0.6
P(Δ)
Δ+Δi
10000
100
1
0
1
10
100

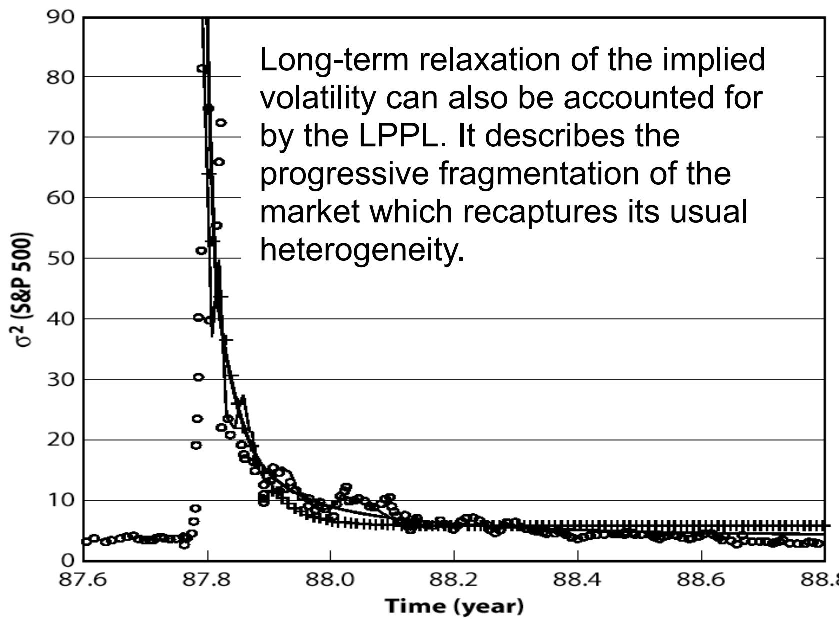
Peng et al.

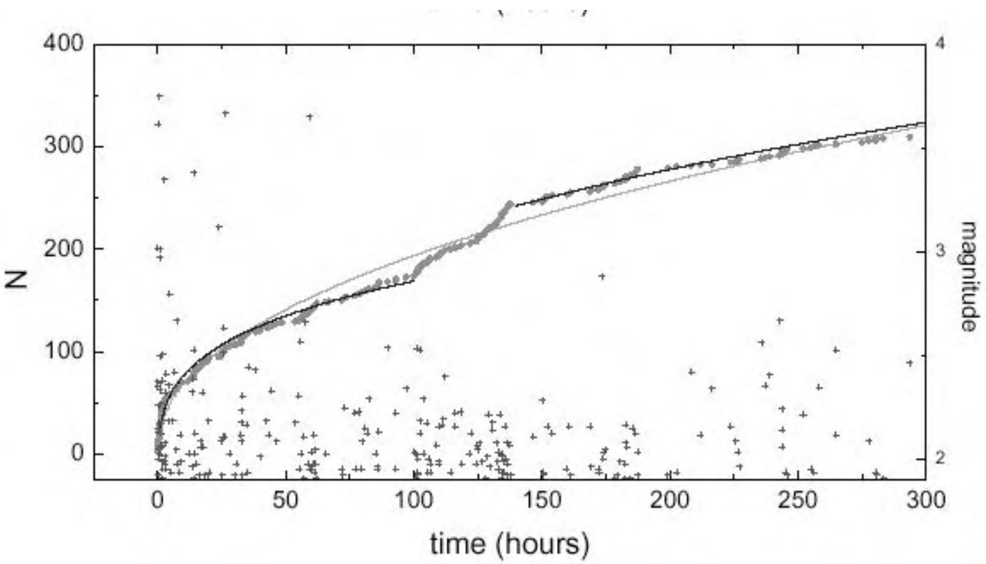
JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 112, B03306, doi:10.1029/2006JB004386, 2007







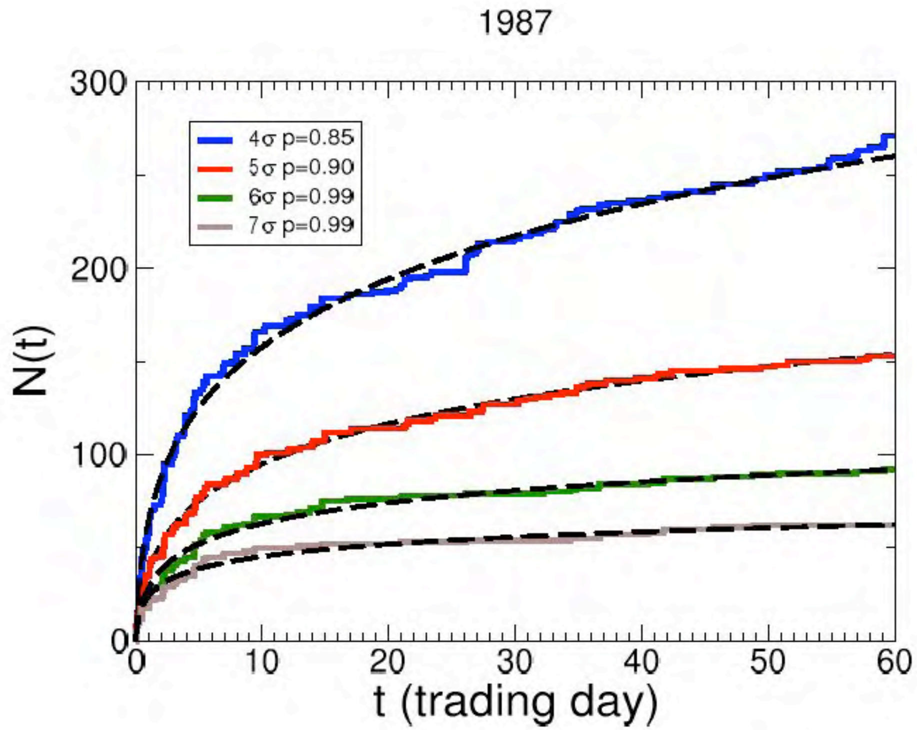




Cumulative number of aftershocks in the earthquake occurring in eastern Pyrenees on February 18, 1996 (from Moreno *et al*., J. of Geophys. Res., **106 B4**, 6609-6619 (2001))

$$n(t) \propto t^{-p}; \qquad N(t) = \int_0^t n(s)ds$$

N(t)=K[(t+τ)$^{1-p}$- τ^{1-p}]/(1-p)



Oct. 1987 crash: Cumulative number of S&P500 index returns exceeding a given threshold **nσ**

†Lillo and Mantegna, PRE **68**, 016119 (2003)

Critical earthquakes? Critical crashes?

Sornette and Sammis [1995]

RENORMALIZATION GROUP THEORY OF EARTHQUAKES

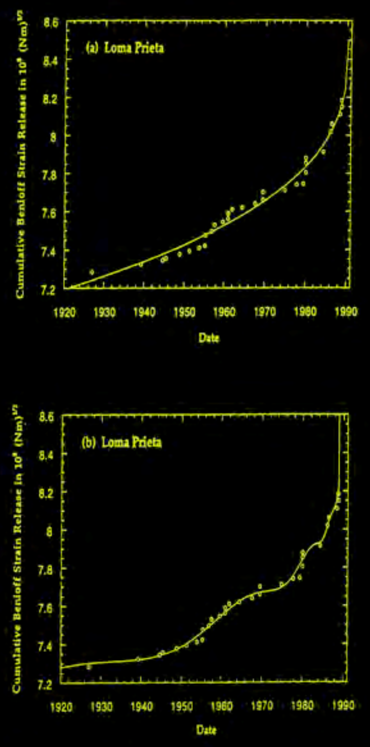
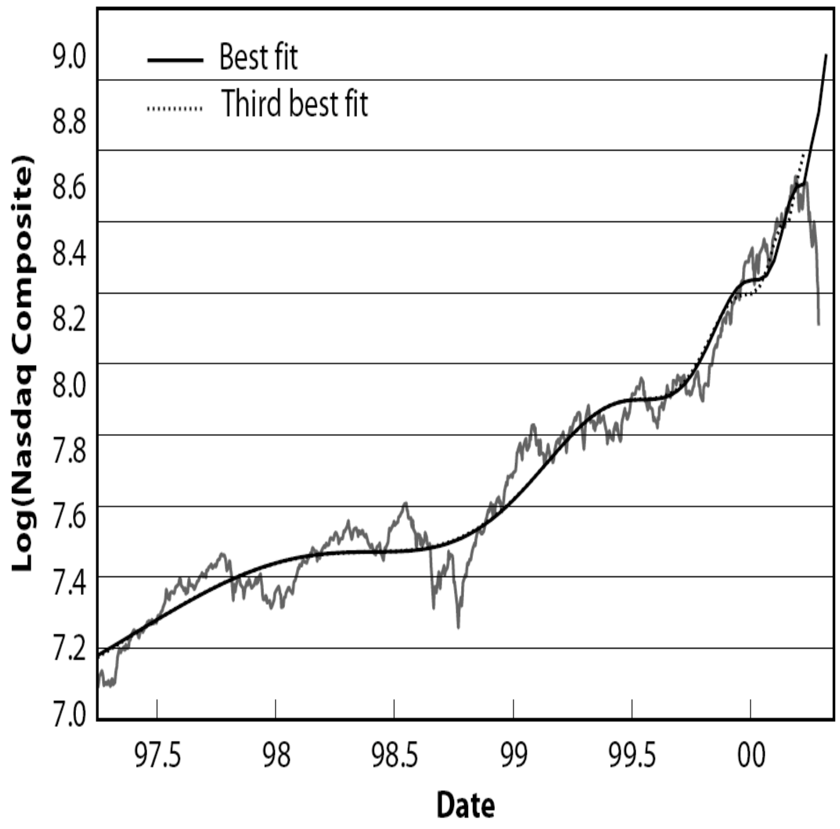
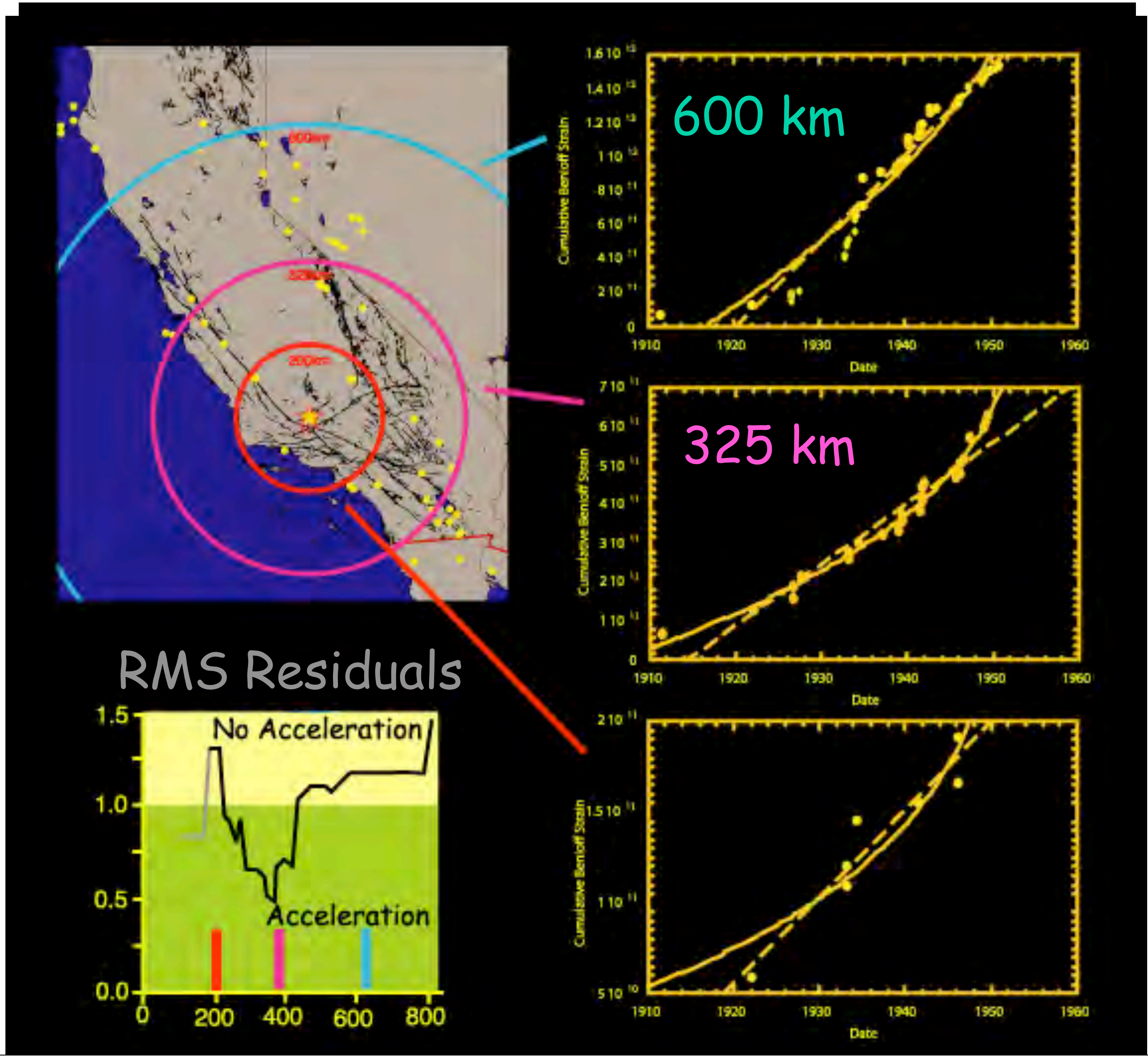


Fig. 1. — Cumulative Benioff strain released by magnitude 5 and greater earthquakes in the San Francisco Bay area prior to the 1989 Loma Prieta eaerthquake (from Ref. [32]). In (a), the data have been fit to the powerlaw equation (2) as in Bufe and Varnes [32]. In (b), the data have been fit to equation (8) which includes the first order correction to scaling. Parameters of both fits are given in Table I.

THE NASDAQ CRASH OF APRIL 2000



Selecting a critical region: 1952 Kern County Earthquake



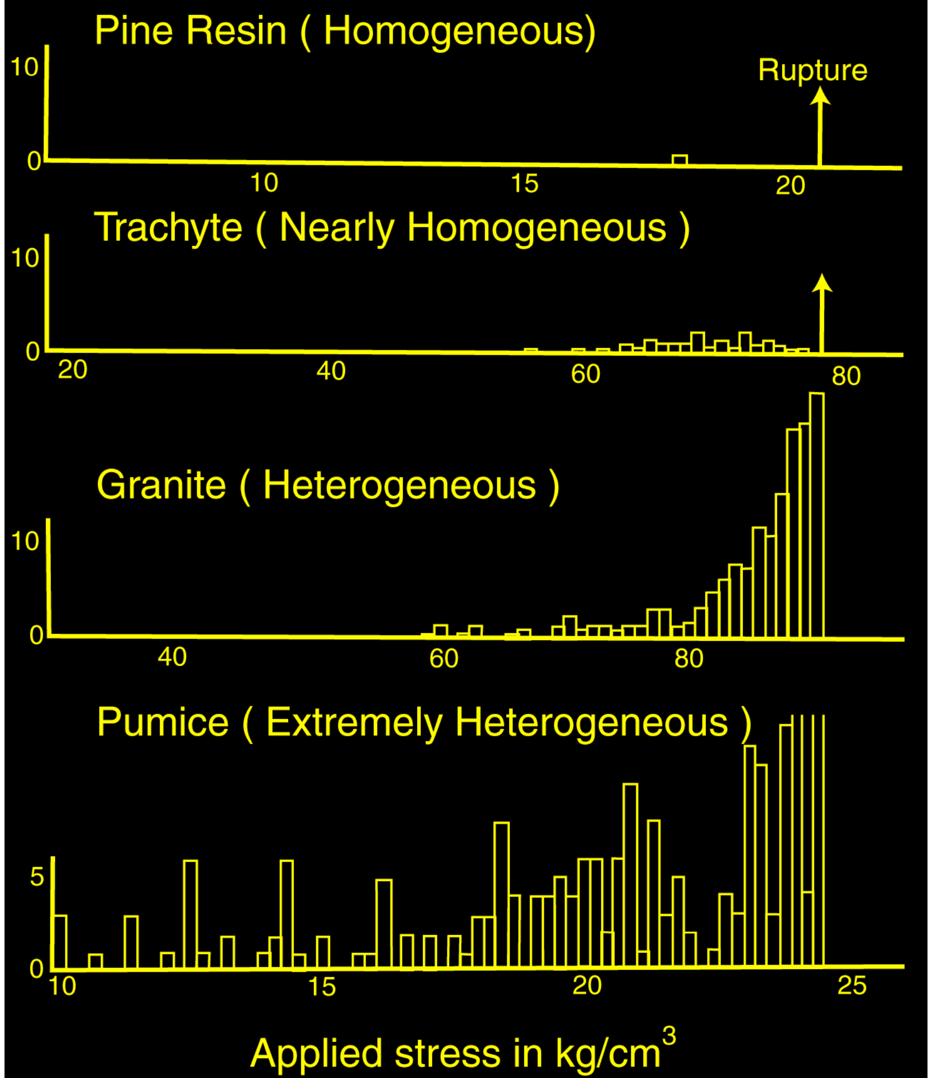


Fig. 4. Frequency of elastic shocks under increasing stresses in materials with different heterogeneity. From Mogi [1962]

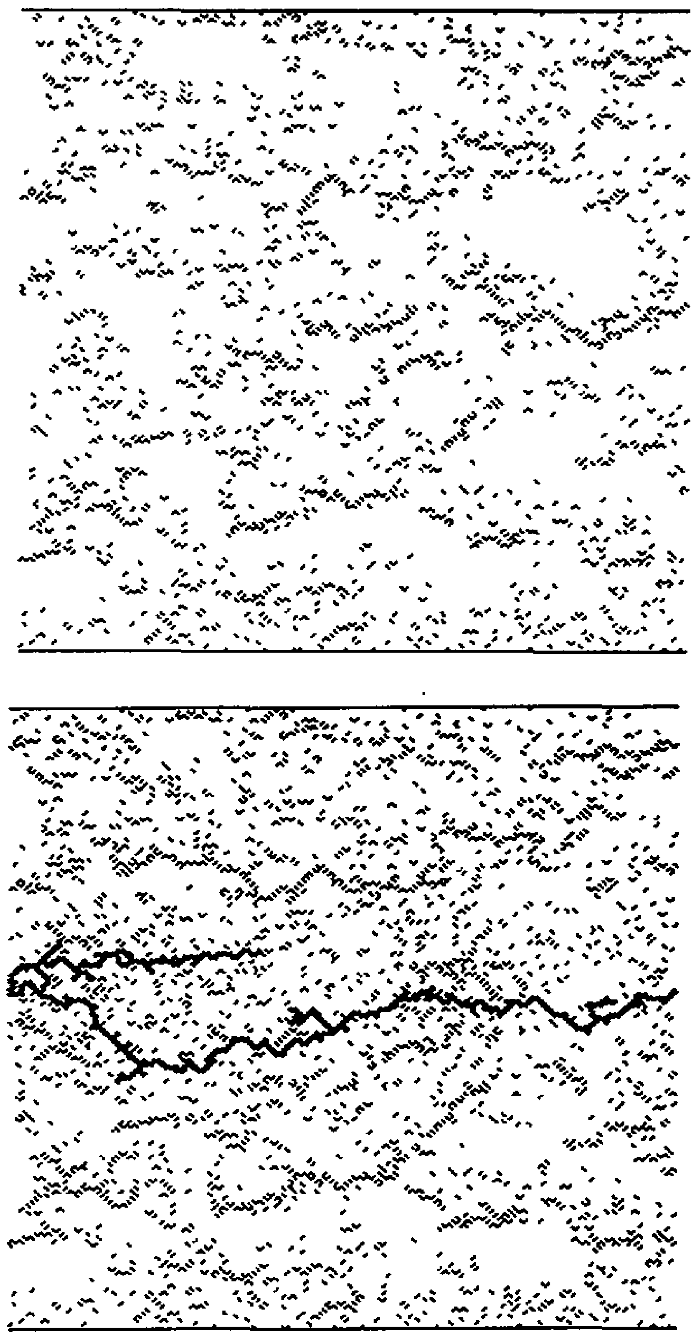
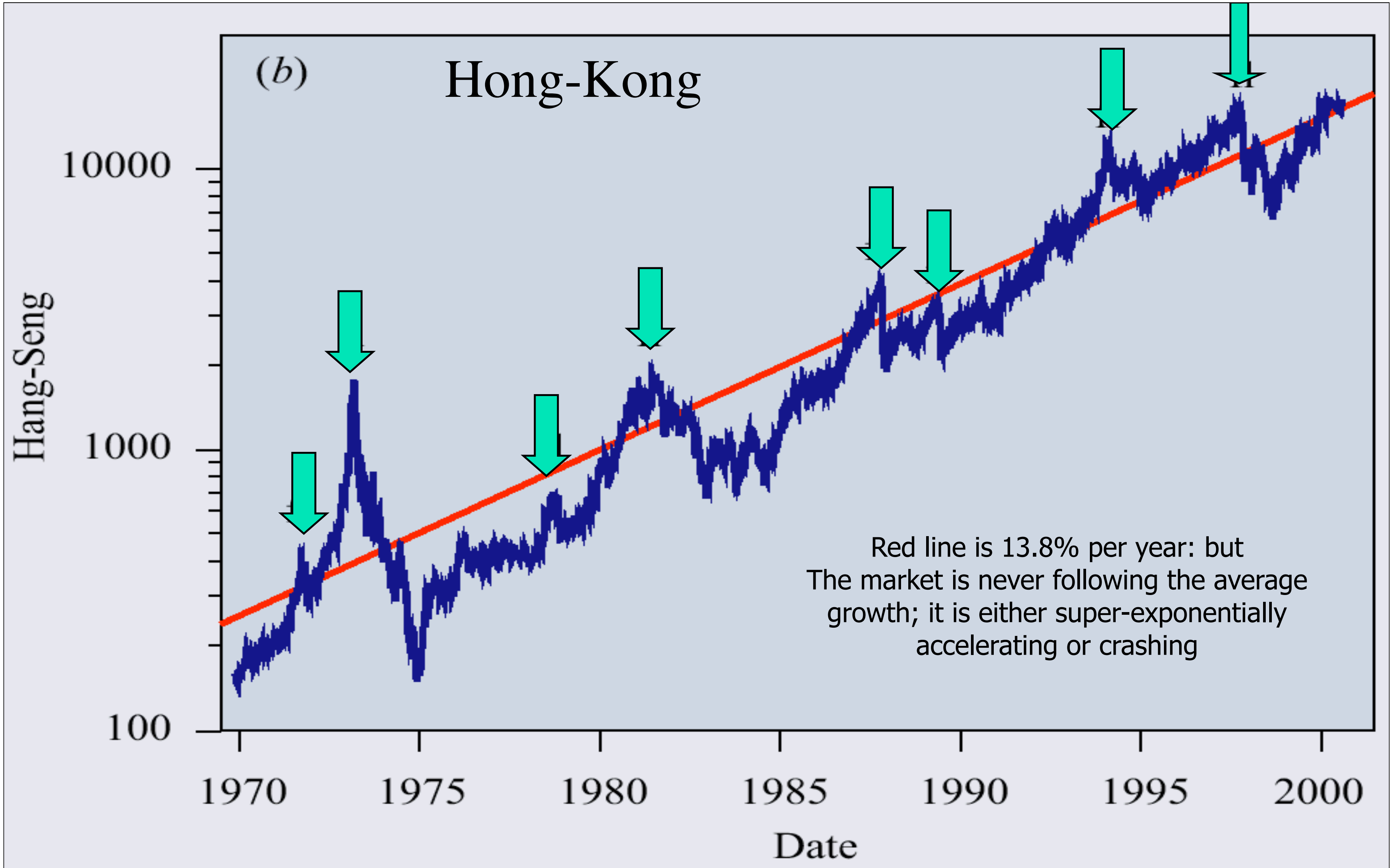


Figure 1: Ariane 5 composite high pressure tanks

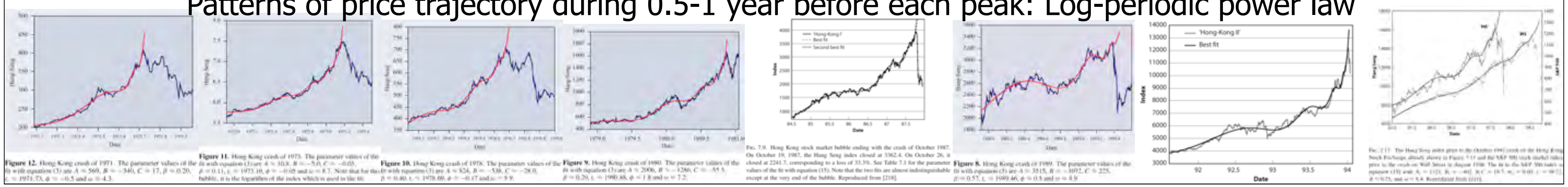
Our prediction system is now used in the industrial phase as the standard testing procedure.

EADS LAUNCH VEHICLES

J.-C. Anifrani, C. Le Floc'h, D. Sornette and B. Souillard
"Universal Log-periodic correction to renormalization group scaling for rupture stress prediction from acoustic emissions", J.Phys.I France 5, n°6, 631-638 (1995)



Patterns of price trajectory during 0.5-1 year before each peak: Log-periodic power law



What is the cause of the crash?

✓ Proximate causes: many possibilities

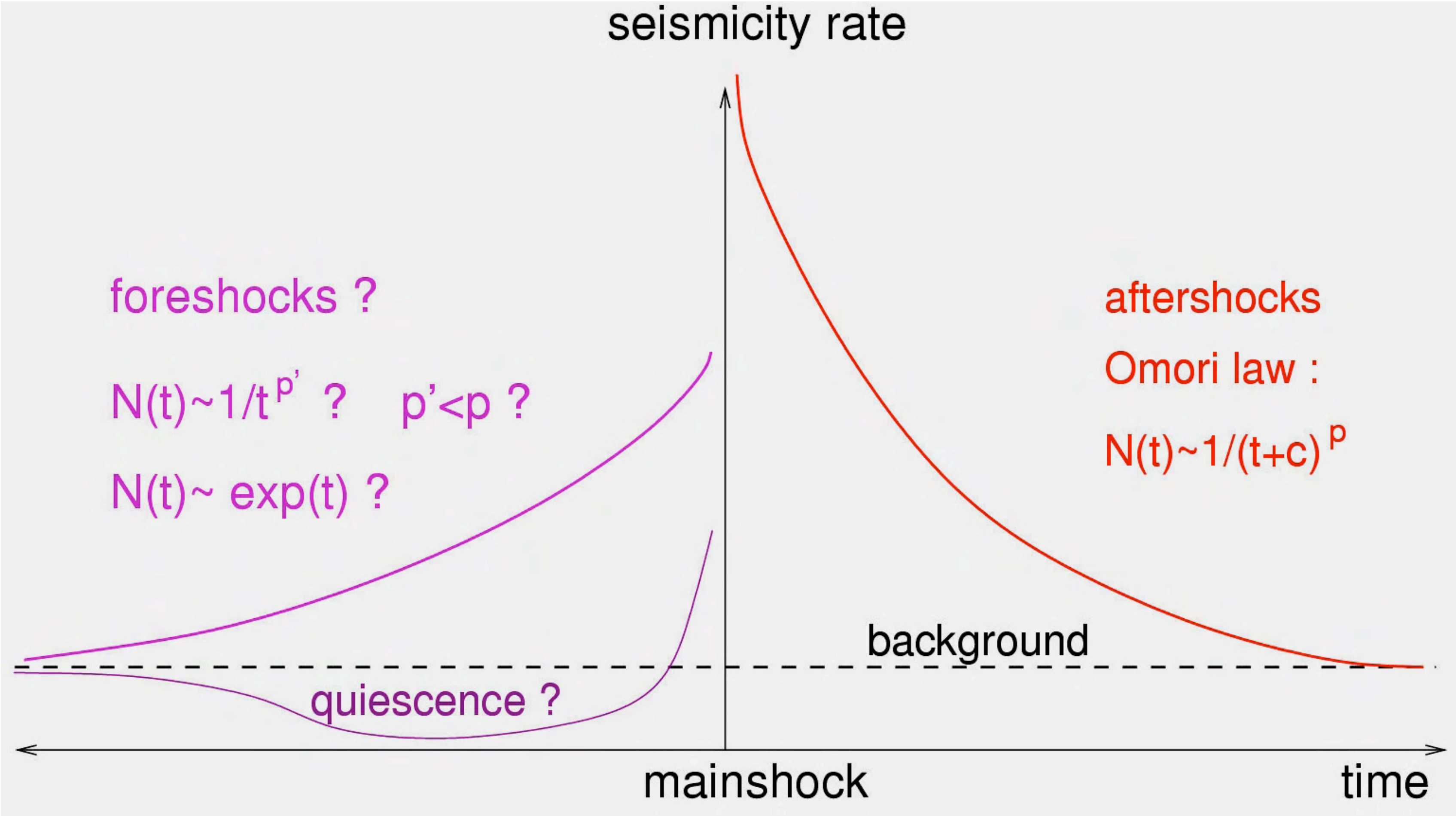
✓ Fundamental cause: maturation towards an instability

An instability is characterized by

- large or diverging susceptibility to external perturbations or influences
- exponential growth of random perturbations leading to a change of regime, or selection of a new attractor of the dynamics.

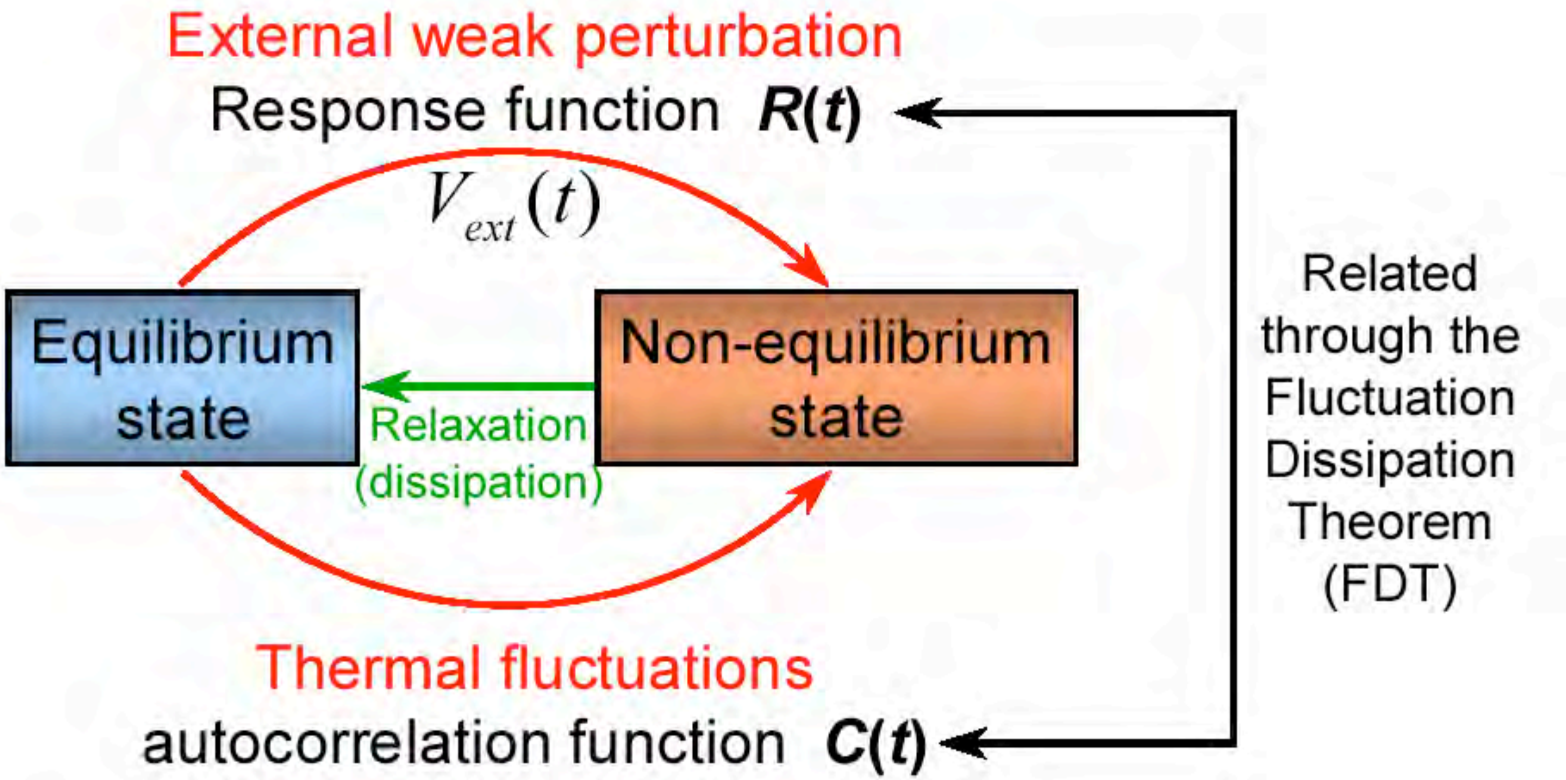
Endogenous versus Exogenous responses

Financial volatility

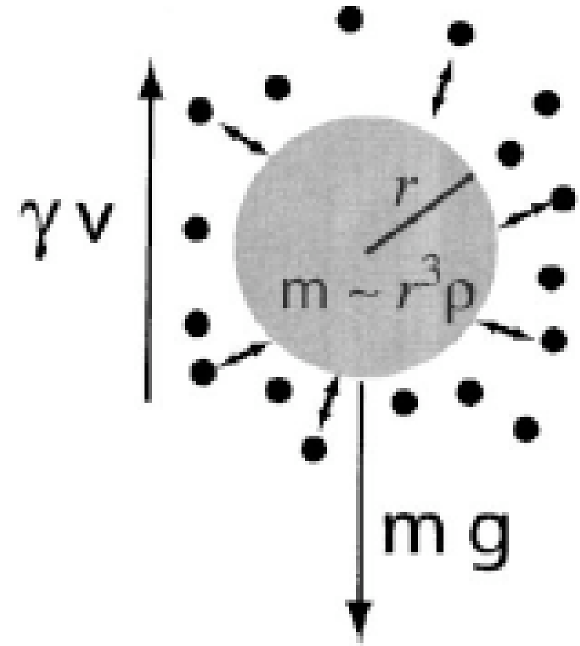


Guidelines from Physics: perturb and study the response

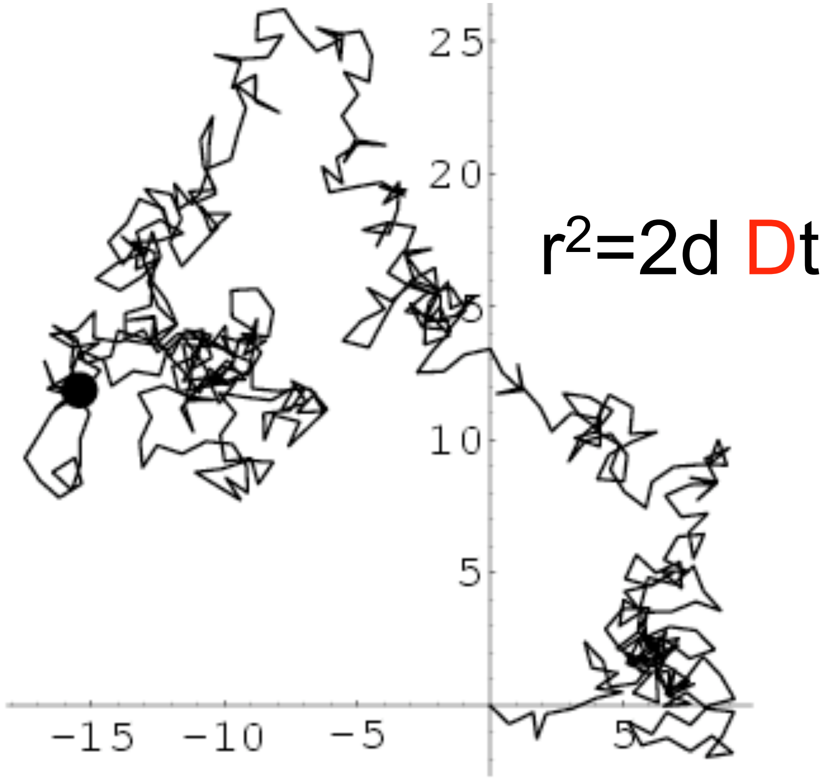
Linear Response Theory



EXO:Drag resistance under an external force



ENDO: Random walk



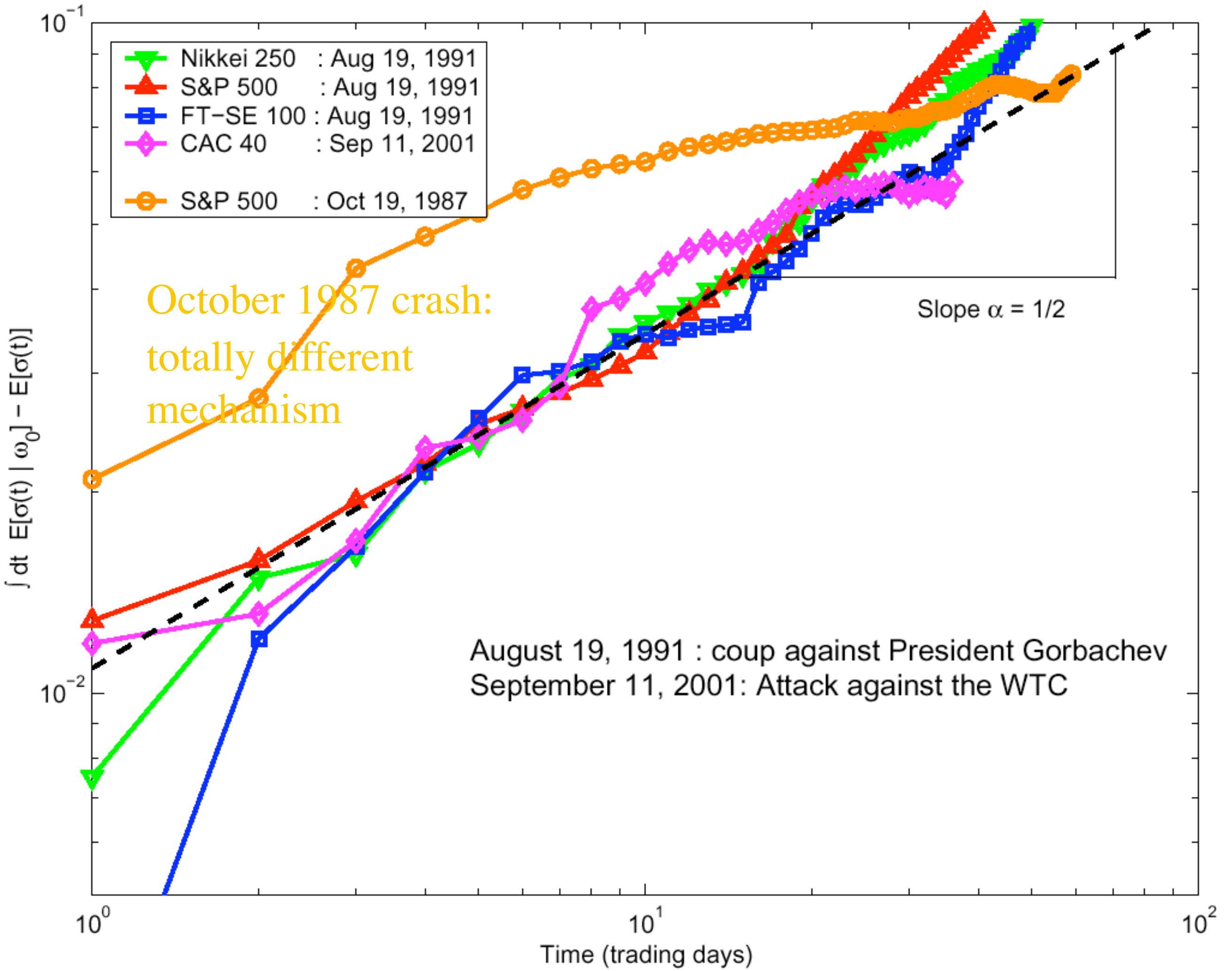
$$D = k_B T / \gamma$$

(Einstein, 1905)

Linear response to an external shock

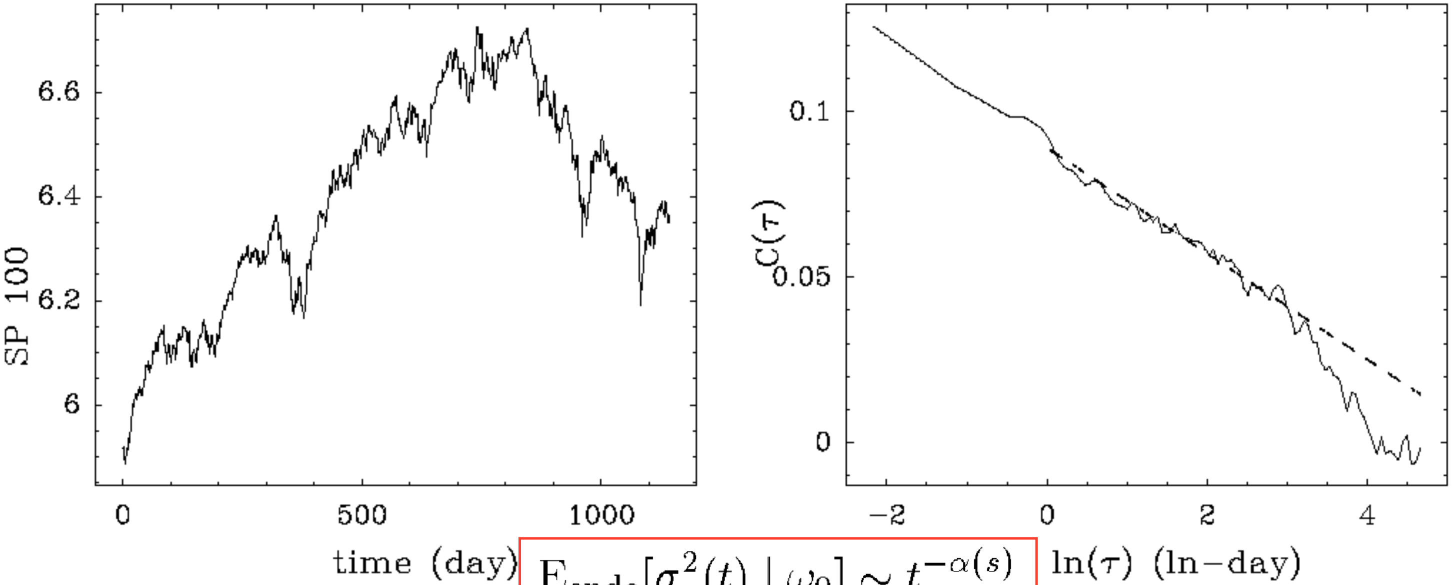
(Multifractal Random Walk model)

$$\mathrm{E}_{\mathrm{exo}}[\sigma^2(t) \mid \omega_0] - \overline{\sigma^2(t)} \propto e^{2K_0 t^{-1/2}} - 1 \approx \frac{2K_0}{\sqrt{t}}$$

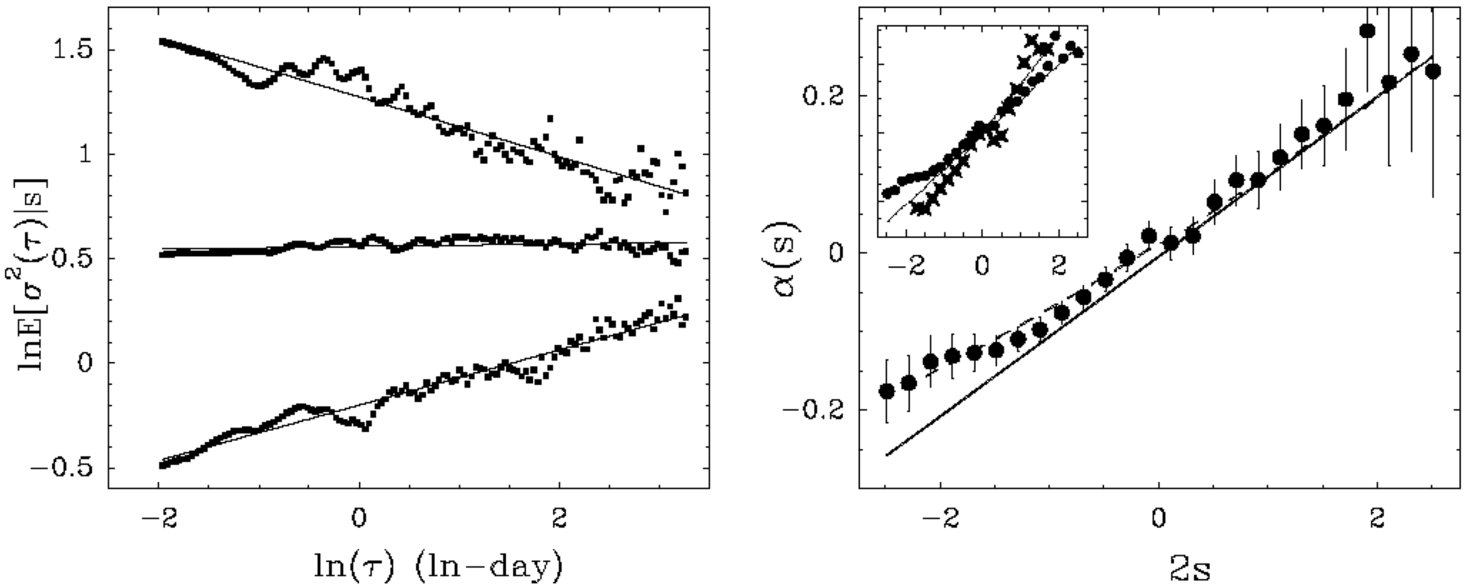


D. Sornette, Y. Malevergne and J.F. Muzy. Risk 16 (2), 67-71 (2003)

Endogenous shocks and Multifractal Random Walk model

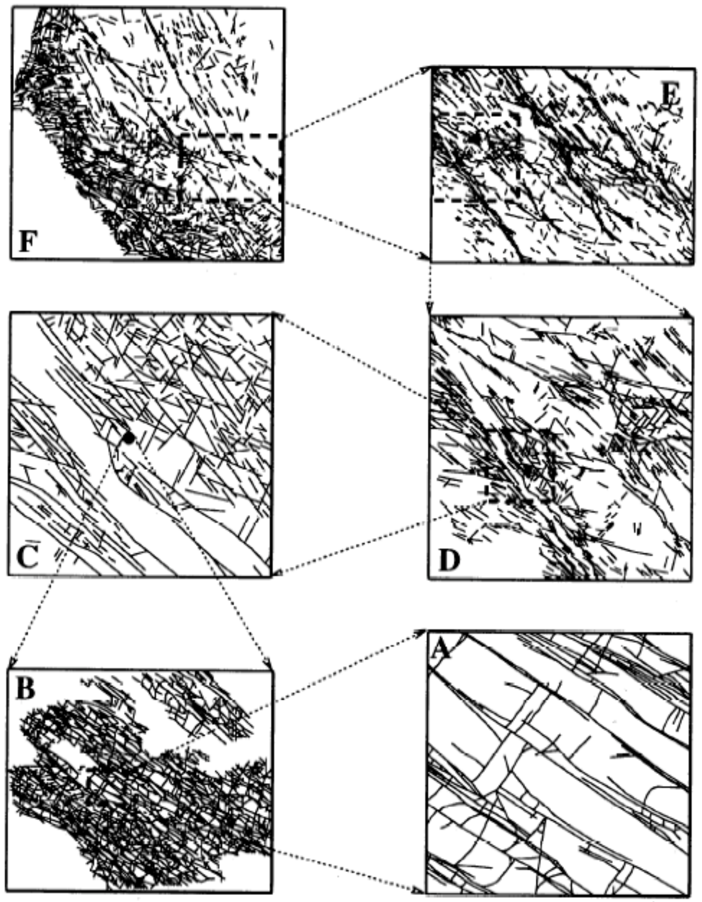


$$\mathrm{E}_{\mathrm{endo}}[\sigma^2(t) \mid \omega_0] \sim t^{-\alpha(s)}$$

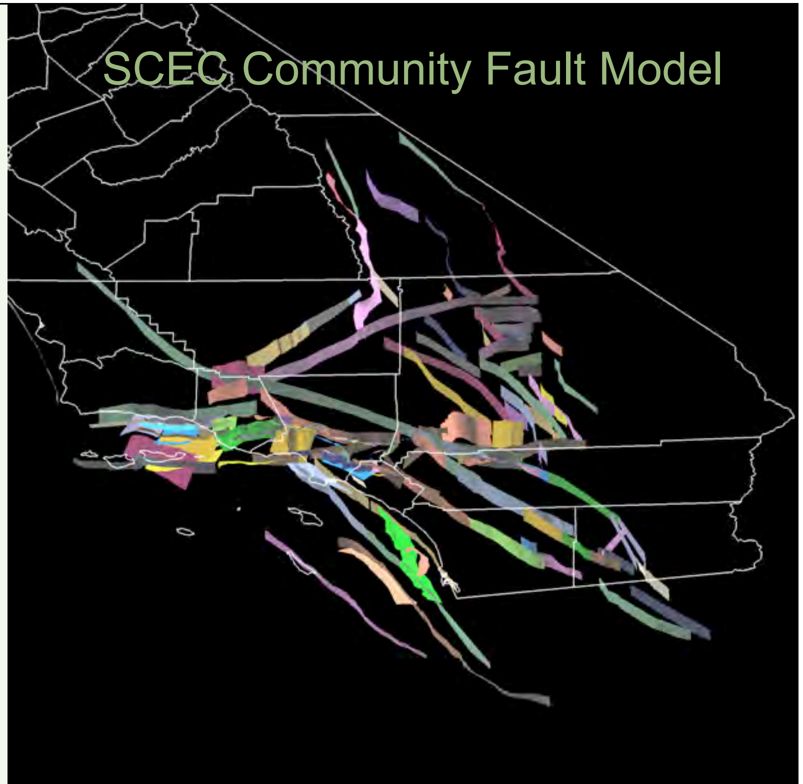


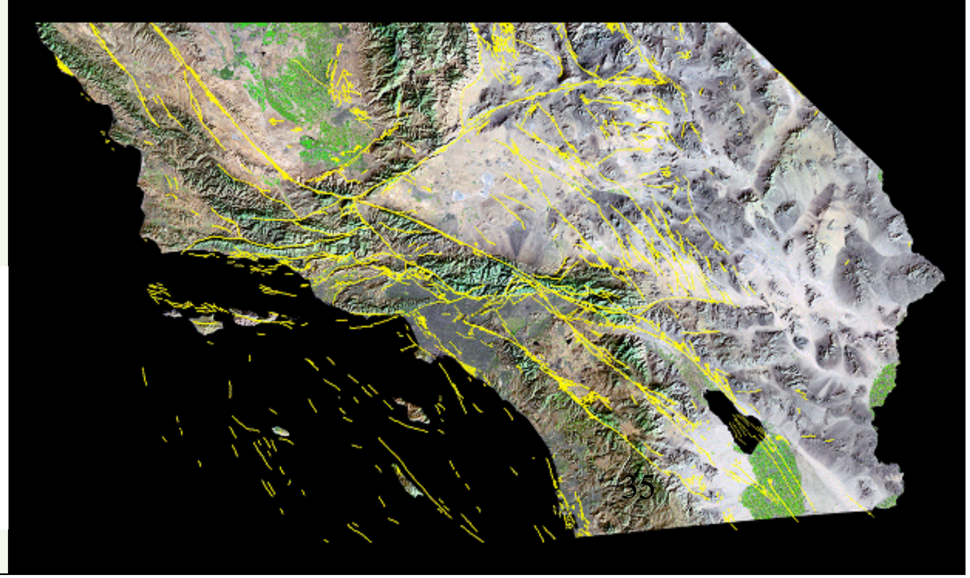
Hierarchical geometry of faulting

Ouillon, Castaing, Sornette (JGR 1996)

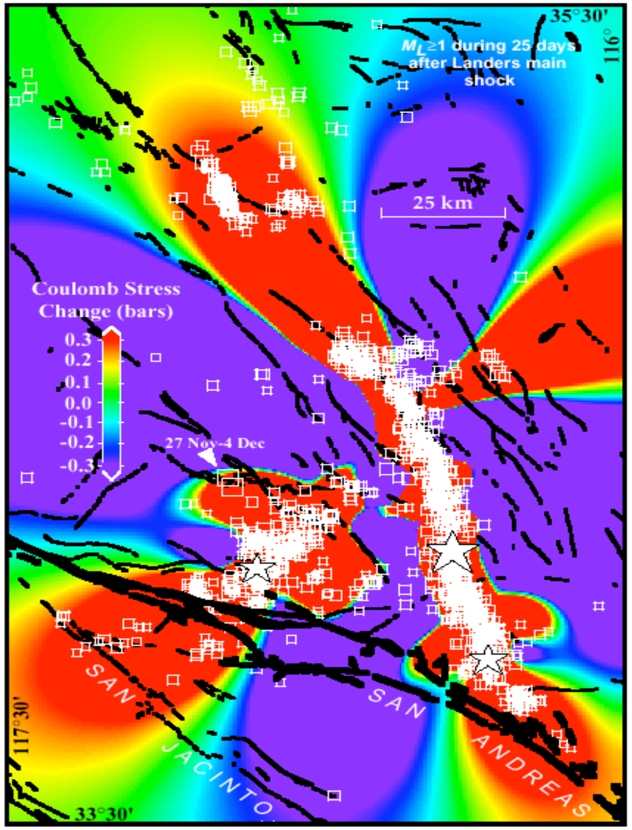


Map A: linear size=10 m, orig. scale=1:1
Map B: linear size=60 m, orig. scale=1:220
Map C: linear size=11 km, orig. scale=1:62,500
Map D: linear size=45 km, orig. scale=1:125,000
Map E: linear size=150 km, orig. scale=1:250,000
Map F: linear size=400 km, orig. scale=1:1,000,000





Taking account of history and boundary conditions



$$\lambda(\vec{r},t) = \lambda_0' \exp\left(\frac{\sigma(\vec{r},t)}{kT}V\right)$$

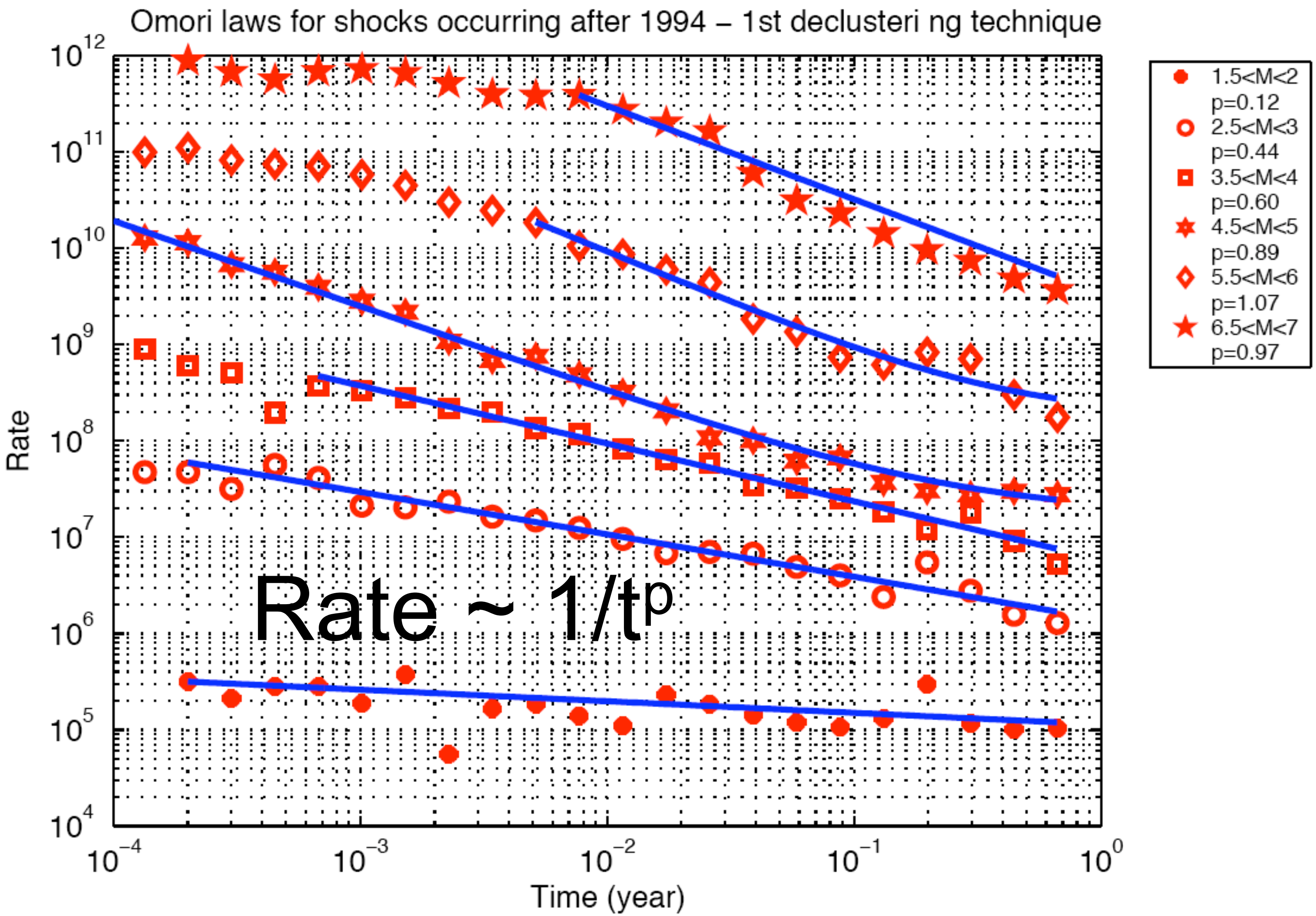
$$\Sigma(\vec{r},t) = \Sigma_{\text{far field}}(\vec{r},t) + \int_{-\infty}^{t} \int dN[d\vec{r}\,' \times d\tau]\Delta\sigma(\vec{r}\,',\tau)g(\vec{r}-\vec{r}\,',t-\tau)$$

local stress

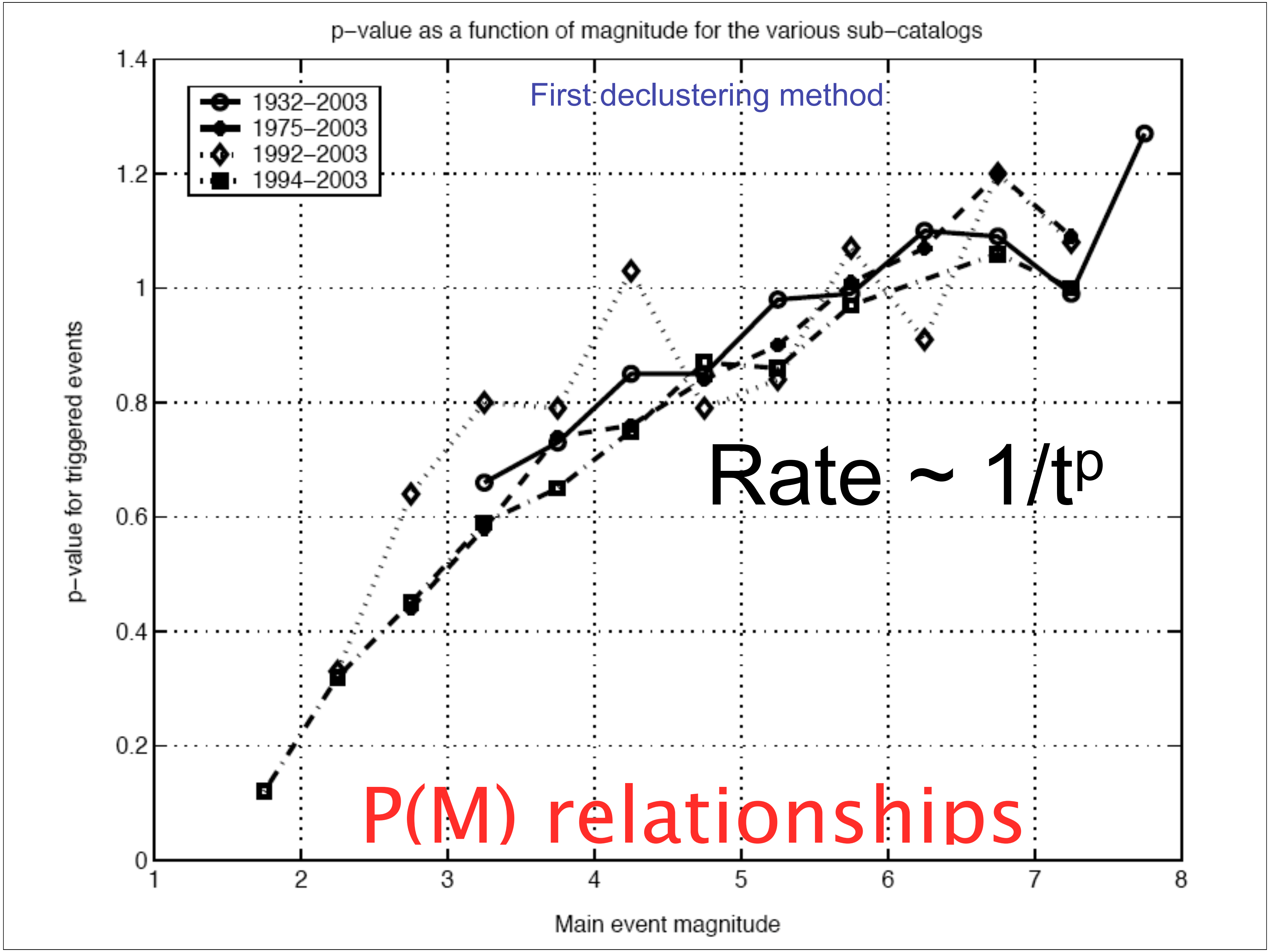
tectonic loading

Stress fluctuations induced by all past events in the system

D. Sornette and G. Ouillon, Multifractal Scaling of Thermally-Activated Rupture Processes, Phys. Rev. Lett. 94, 038501 (2005)
G. Ouillon and D. Sornette, Magnitude-Dependent Omori Law: Theory and Empirical Study, J. Geophys. Res., 110, B04306, doi:10.1029/2004JB003311 (2005).



D. Sornette and G. Ouillon, Multifractal Scaling of Thermally-Activated Rupture Processes, Phys. Rev. Lett. 94, 038501 (2005)

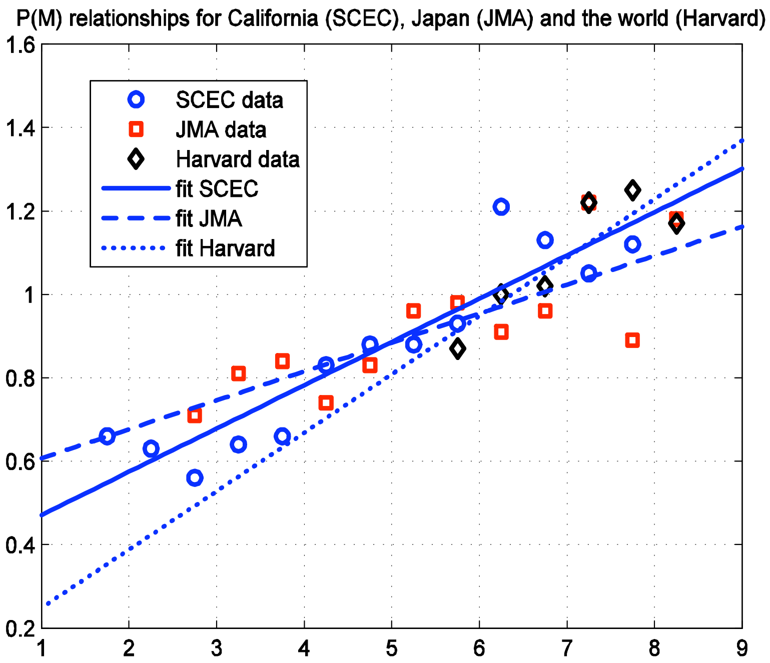

p–value as a function of magnitude for the various sub–catalogs
First declustering method
1932–2003
1975–2003
1992–2003
1994–2003
Rate ~ 1/t^p
P(M) relationships
p–value for triggered events
Main event magnitude
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1
2
3
4
5
6
7
8

p(M) = aM + b

We processed three catalogs, that we pre-processed to check for their completude and its evolution with time.
We then computed stacked aftershocks time series, sorting them within intervals of 0.5 magnitude amplitudes.

We clearly observed a linear dependence of *p* with magnitude M.

Statistical tests have been performed using a bootstrap strategy, and we were able to show that all slopes were significantly different from 0, and that all linear relationships were significantly different from each other.



Ribeiro et al, 2006

For Southern California (SCEC catalog):

$$p(M) = 0.10M + 0.37$$

For Japan (JMA catalog):

$$p(M) = 0.07M + 0.54$$

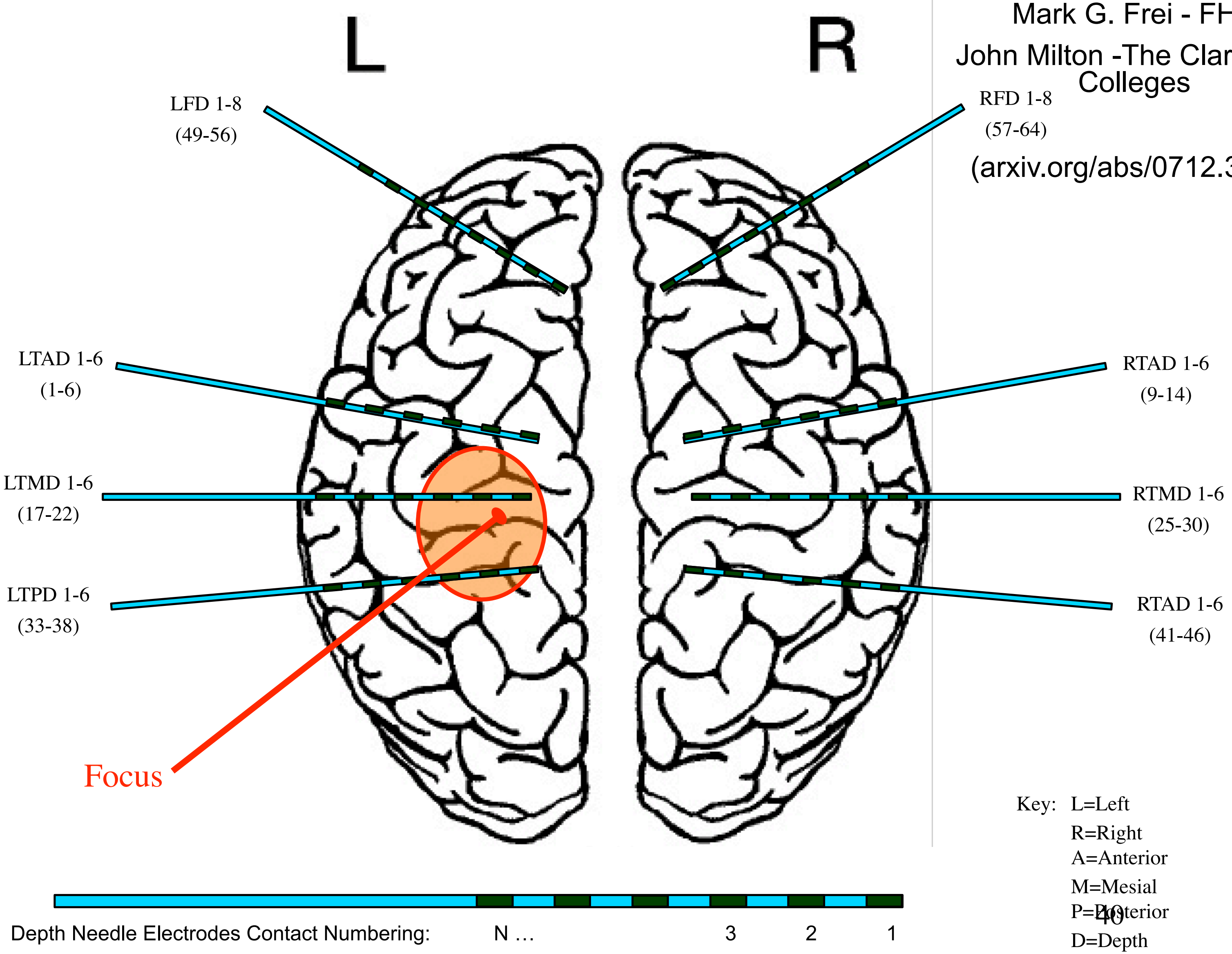
For the World (Harvard catalog):

$$p(M) = 0.14M + 0.11$$

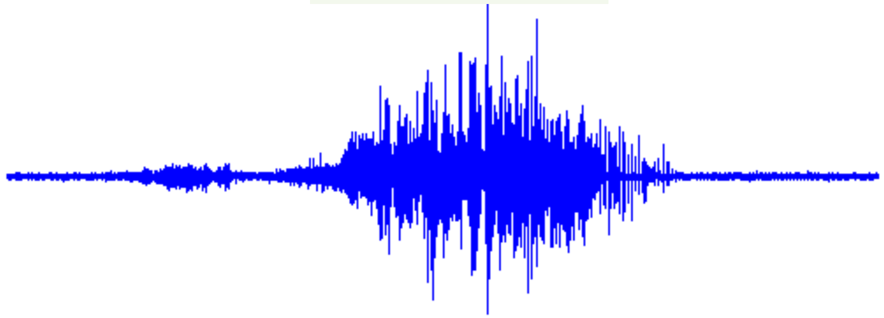
Epileptic Seizures – Quakes of the Brain?

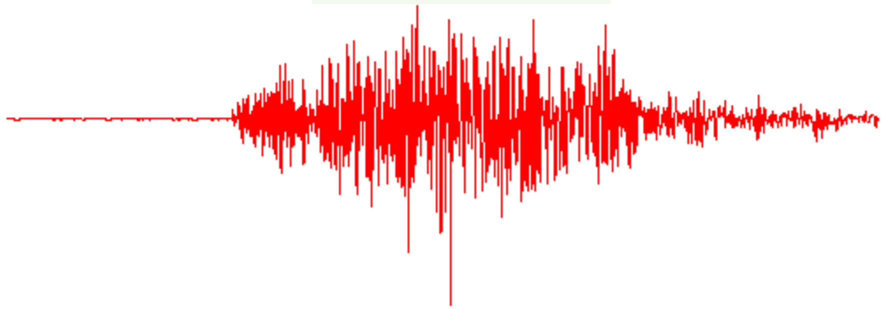
with Ivan Osorio – KUMC & FHS
Mark G. Frei - FHS
John Milton -The Claremont Colleges

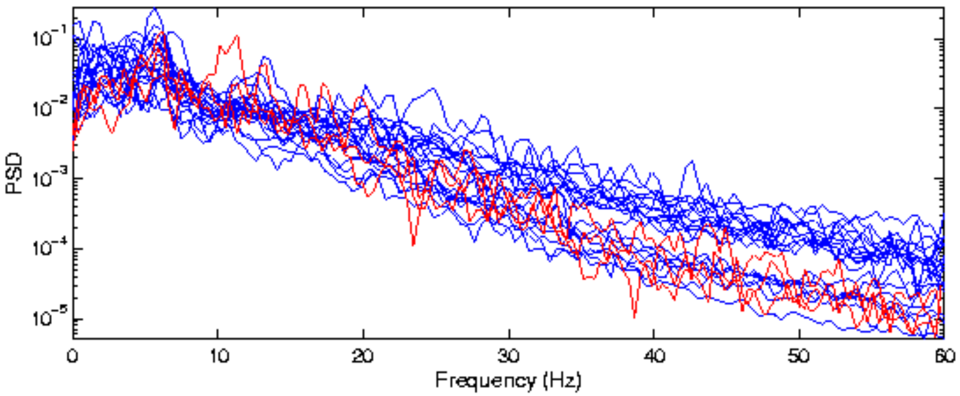
(arxiv.org/abs/0712.3929)

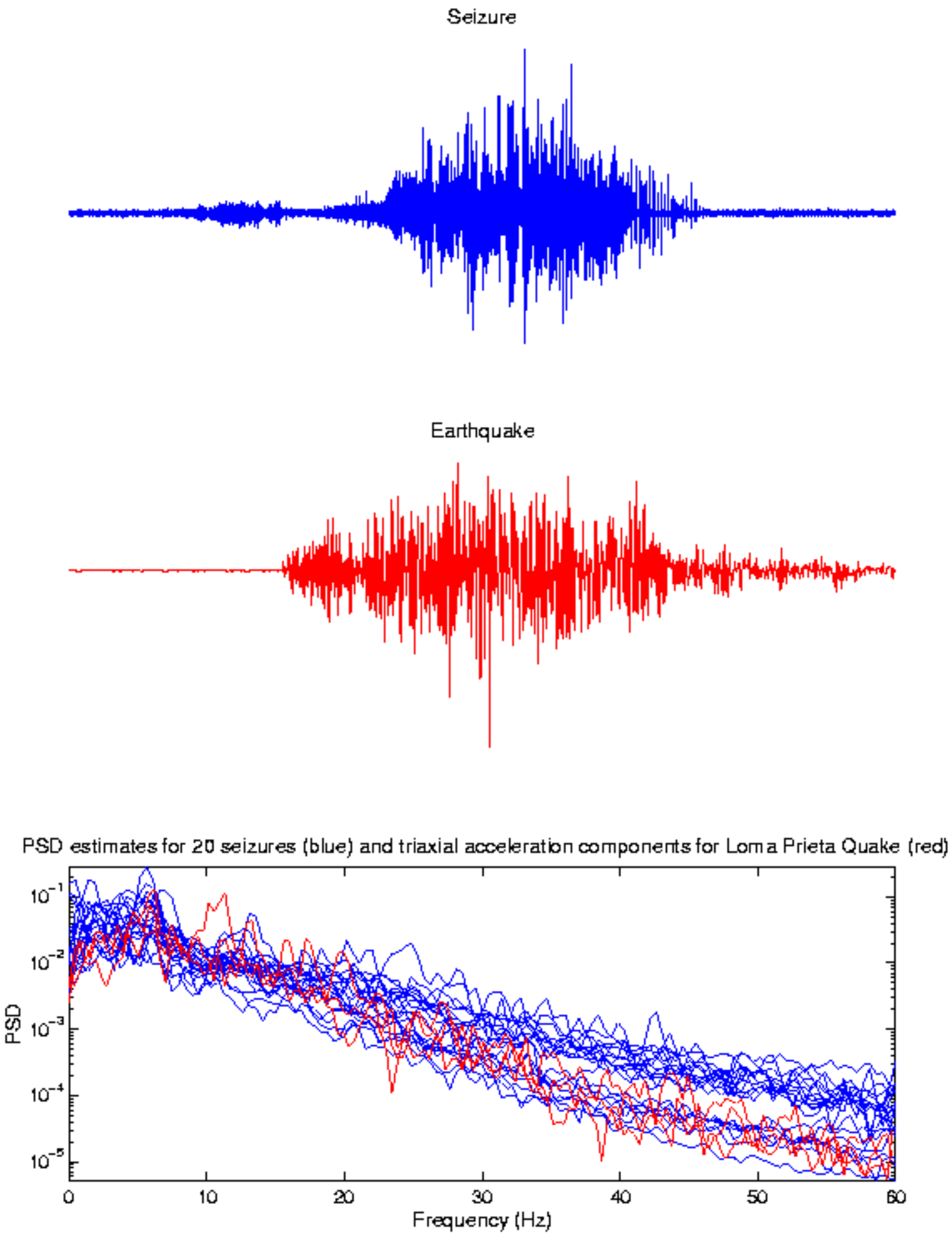


Key: L=Left
R=Right
A=Anterior
M=Mesial
P=Posterior
D=Depth
T=Temporal

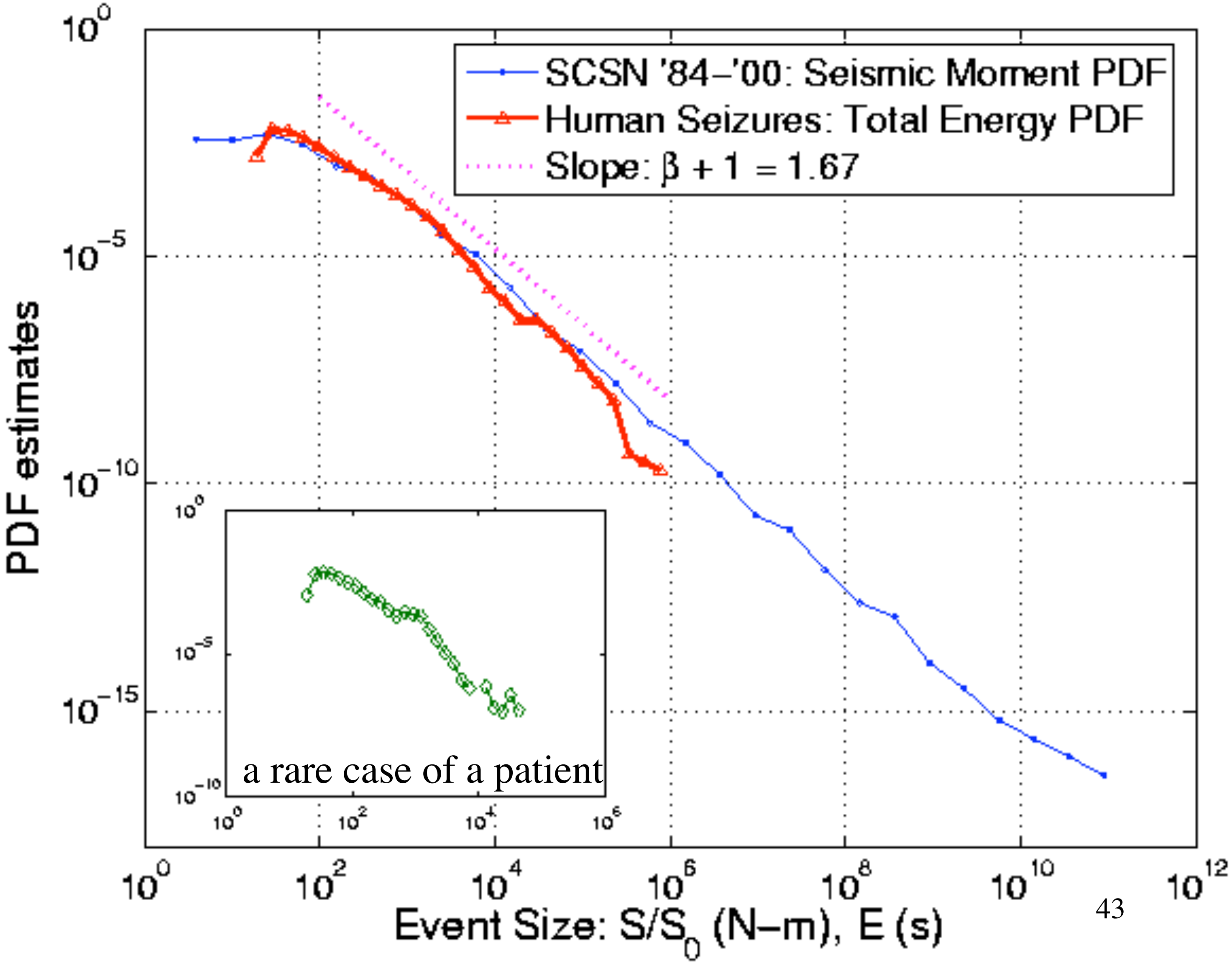




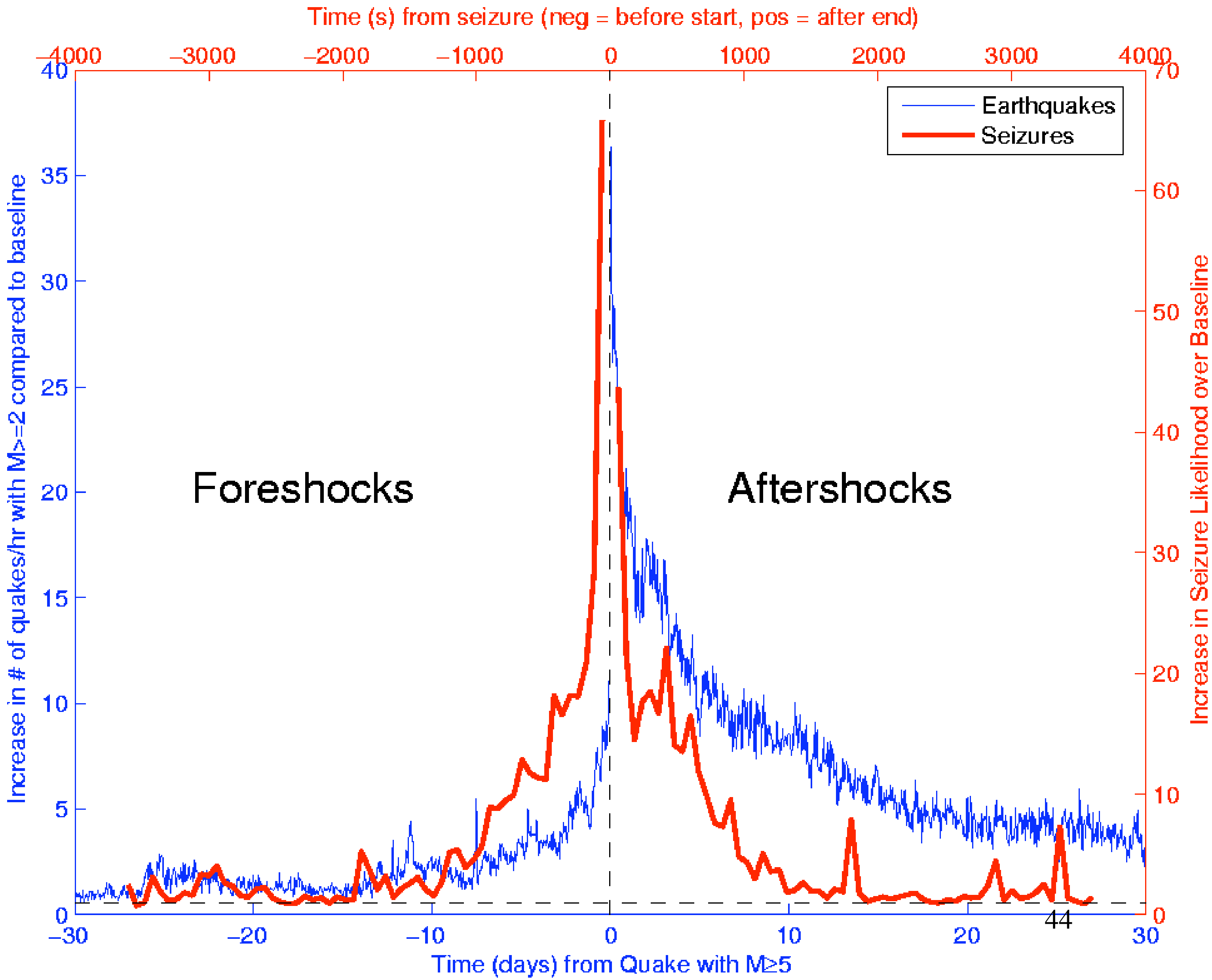

PSD
10^-1
10^-2
10^-3
10^-4
10^-5
0
10
20
30
40
50
60
Frequency (Hz)

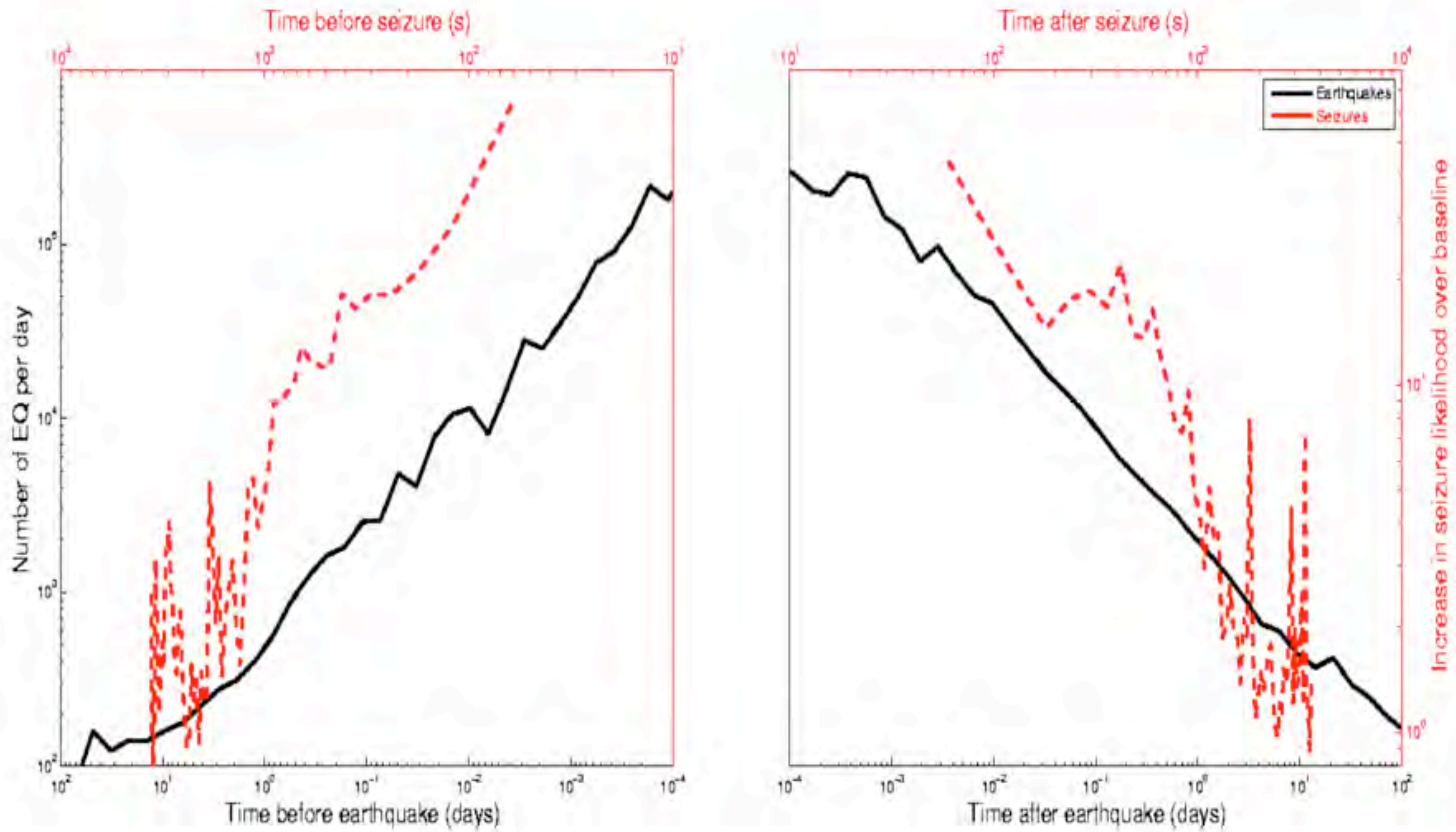

Seizure
Earthquake
PSD estimates for 20 seizures (blue) and triaxial acceleration components for Loma Prieta Quake (red)
PSD
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
0
10
20
30
40
50
60
Frequency (Hz)

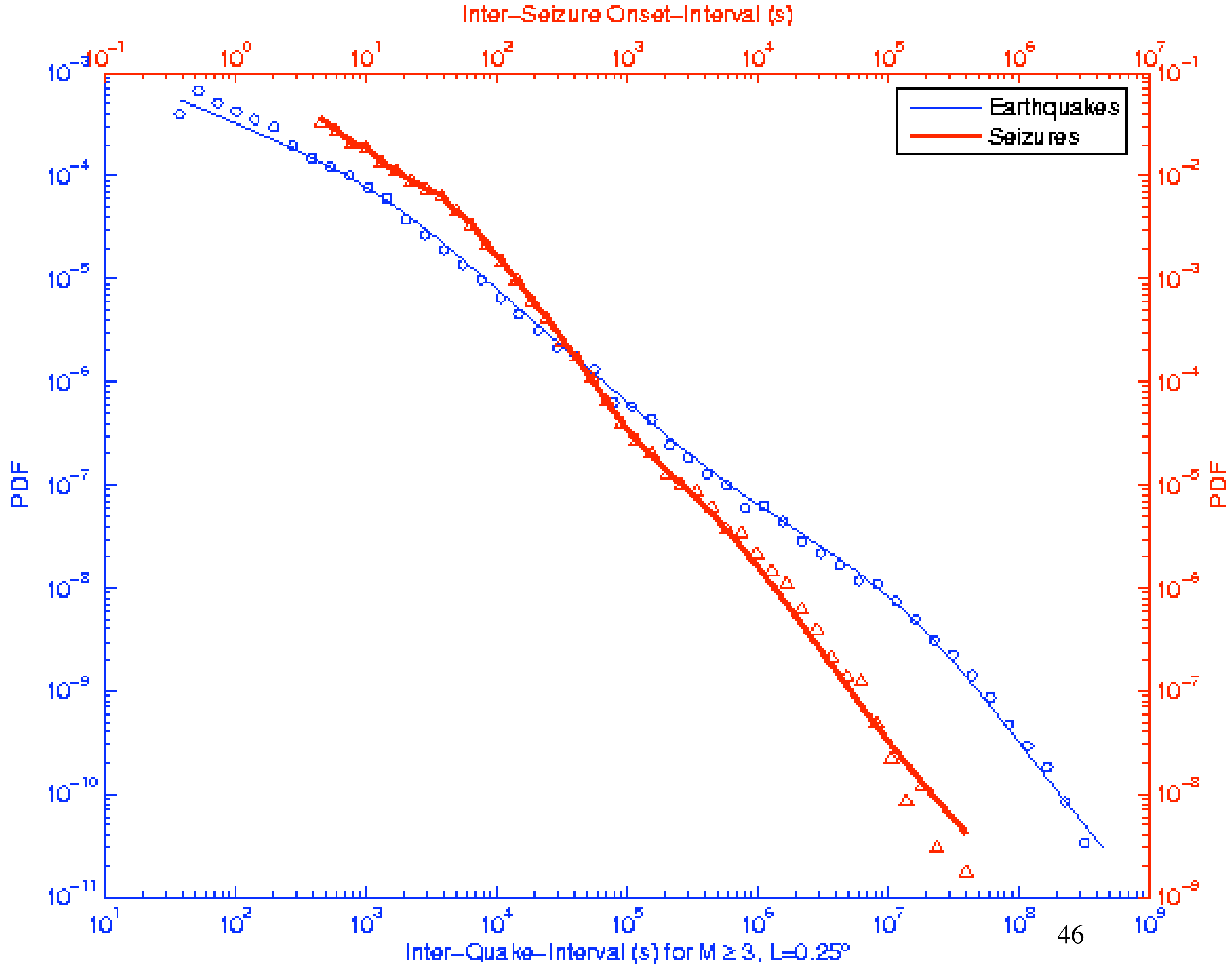
Gutenberg-Richter distribution of sizes



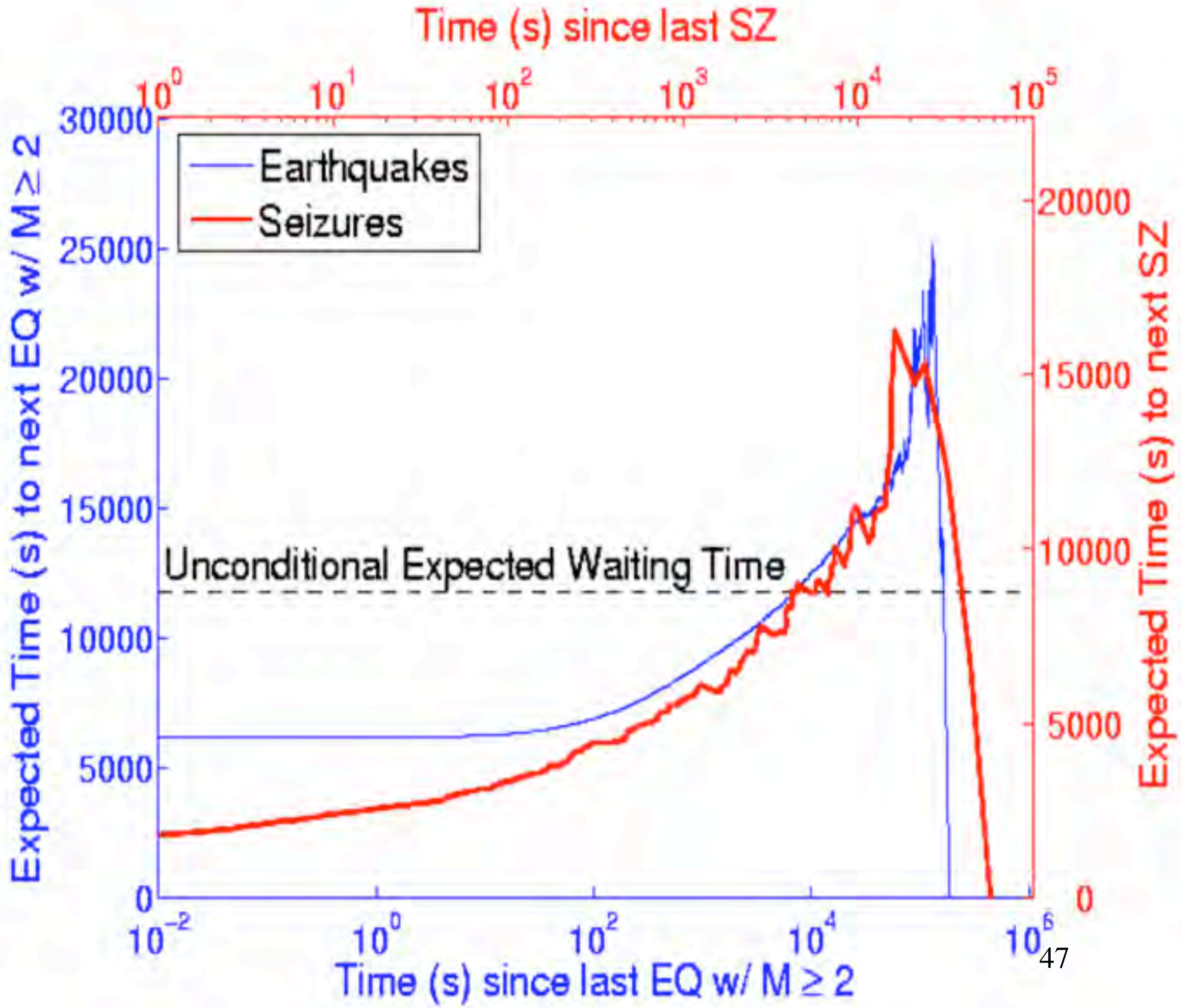
Omori law: Direct and Inverse



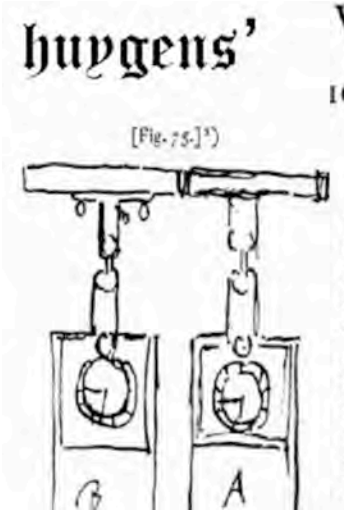

Time before seizure (s)
Time after seizure (s)
Earthquakes
Seizures
Number of EQ per day
Increase in seizure likelihood over baseline
Time before earthquake (days)
Time after earthquake (days)


Inter–Seizure Onset–Interval (s)
Earthquakes
Seizures
PDF
PDF
Inter–Quake–Interval (s) for M ≥ 3, L=0.25°

The longer it has been since the last event,
the longer it will be since the next one! (Sornette&Knopoff, 1997)



SYNCHRONISATION AND COLLECTIVE EFFECTS IN EXTENDED STOCHASTIC SYSTEMS



22 febr. 1665.

Diebus 4 aut 5 horologiorum duorum novorum in quibus catenulæ [Fig. 75], miram concordiam obſervaveram, ita ut ne minimo quidem exceſſu alterum ab altero ſuperaretur. ſed conſonarent ſemper reciprocationes utriuſque perpendiculi. unde cum parvo ſpatio inter ſe horologia diſtarent, ſympathiæ quandam ³) quaſi alterum ab altero afficeretur ſuſpicari cœpi. ut experimentum caperem turbavi alterius penduli reditus ne ſimul incederent ſed quadrante horæ poſt vel ſemihora rurſus concordare inveni.

Fireflies

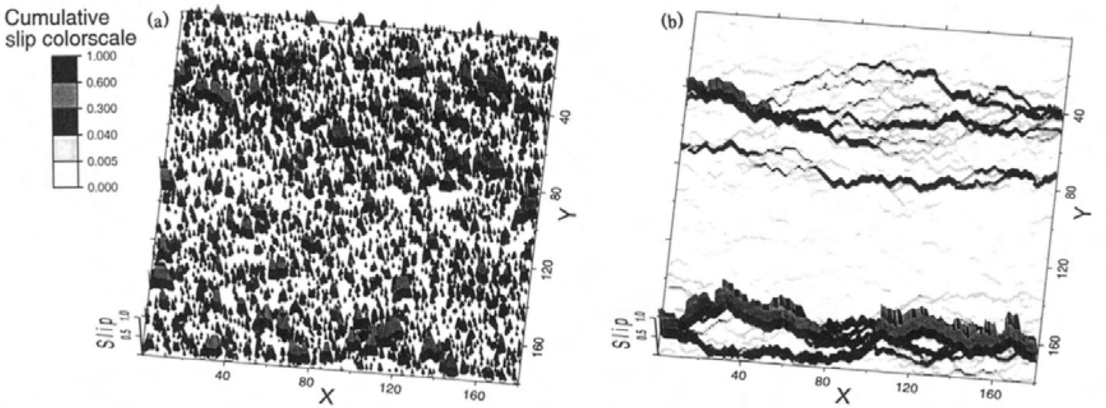
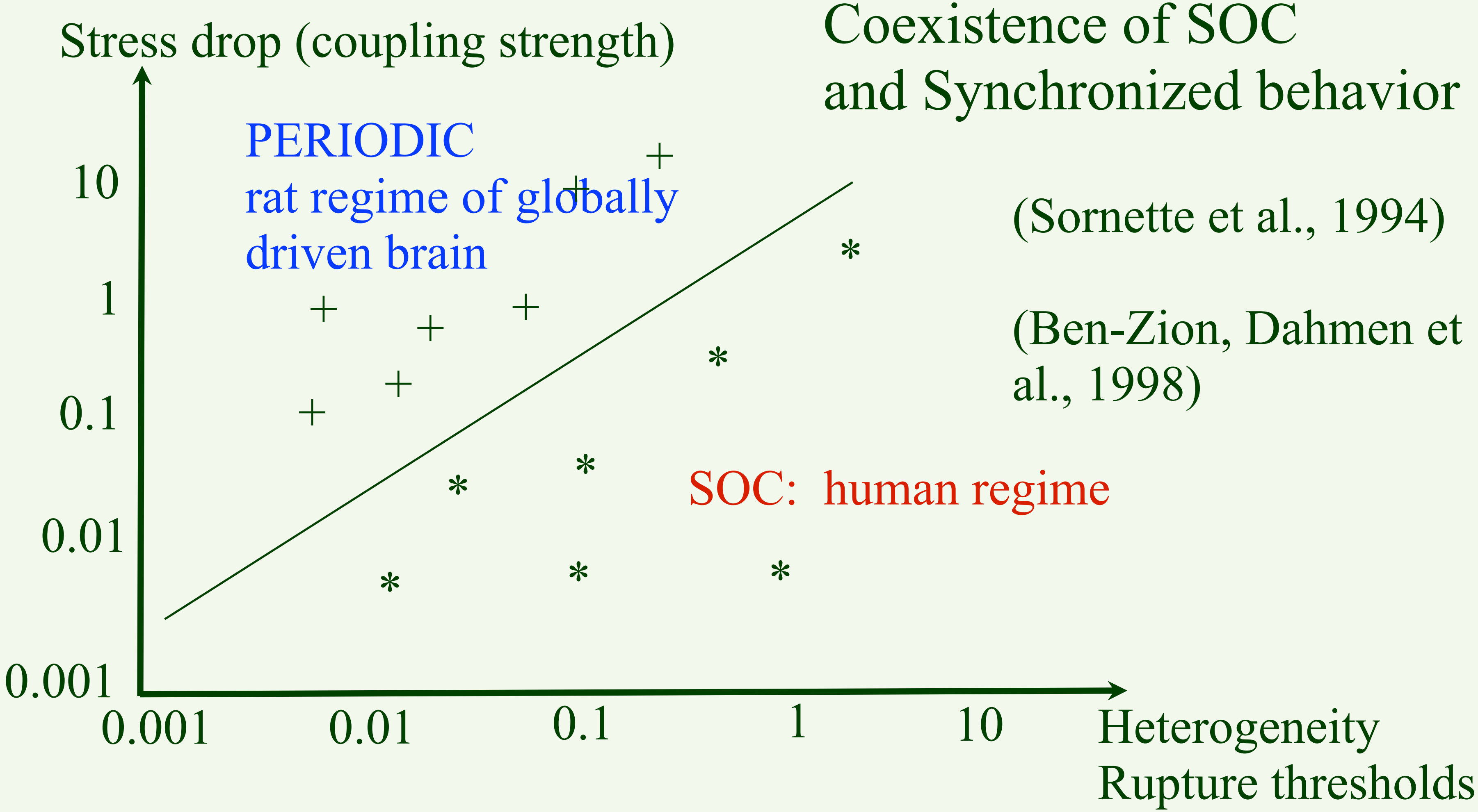


FIG. 1. Evolution of the cumulative earthquake slip, represented along the vertical axis in the white to black color code shown above the picture, at two different times: (a) early time and (b) long time, in a system of size $L=90$ by $L=90$, where $\Delta\sigma=1.9$ and $\beta=0.1$.

Miltenberger et al. (1993)



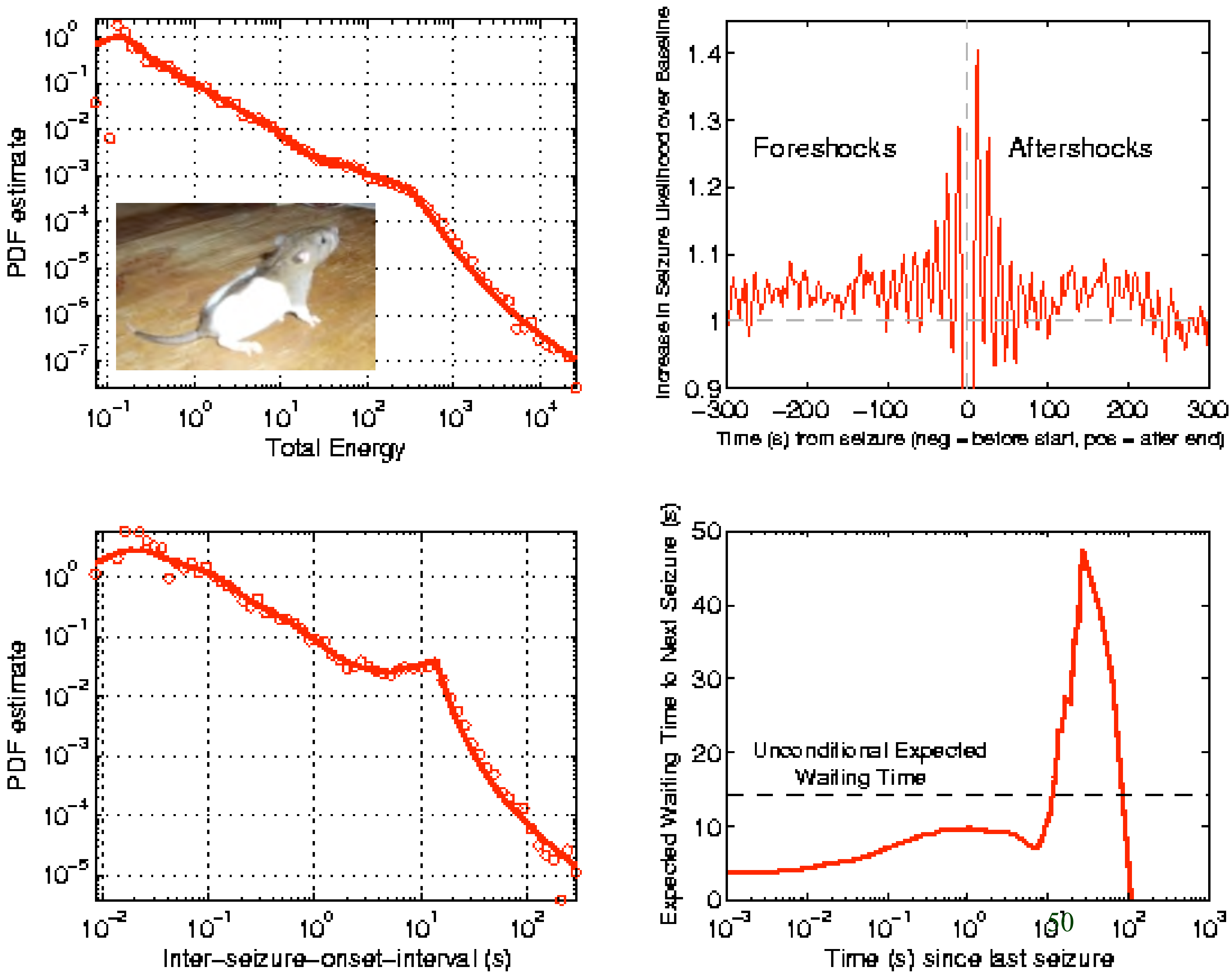
Coexistence of SOC and Synchronized behavior

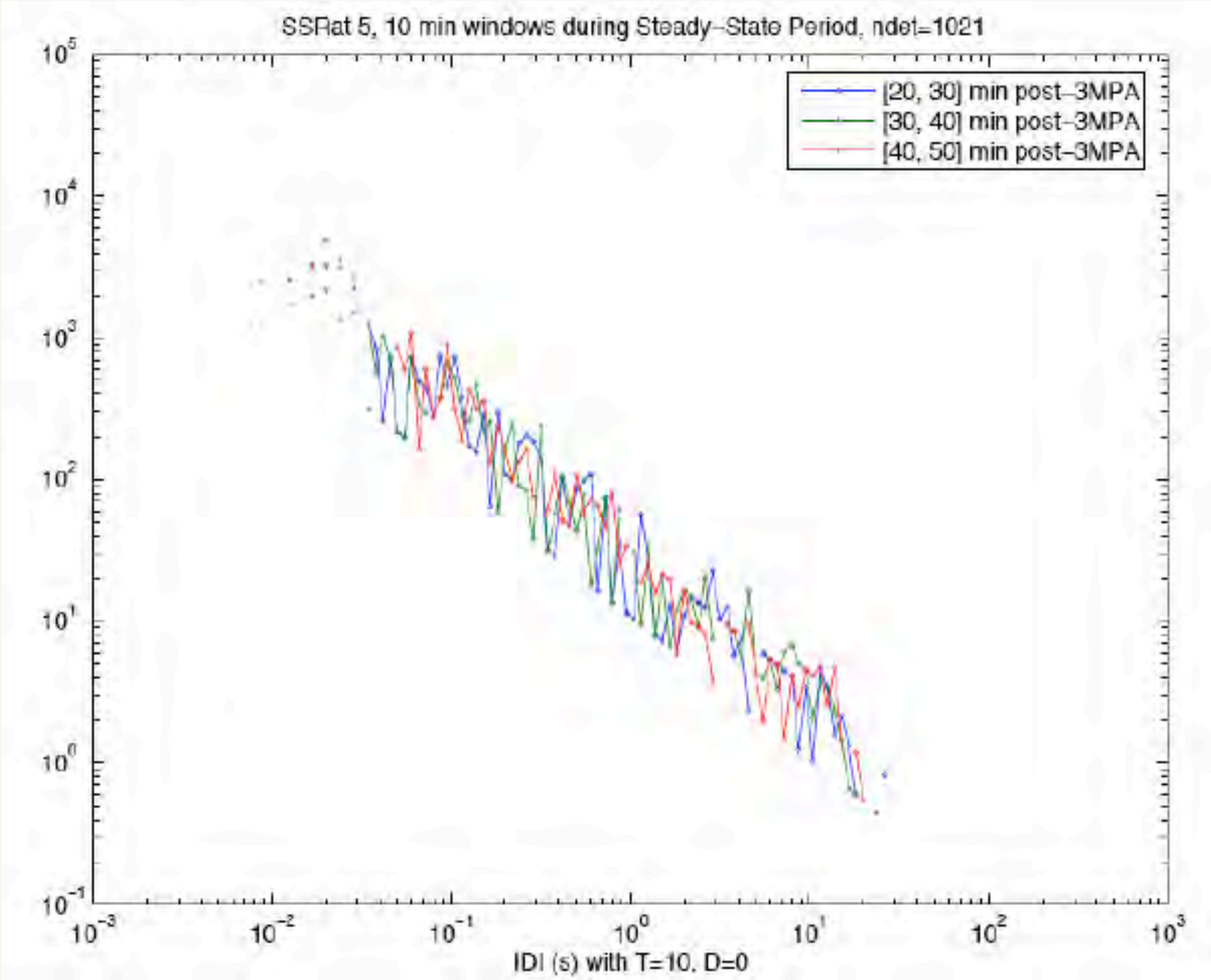
(Sornette et al., 1994)

(Ben-Zion, Dahmen et al., 1998)

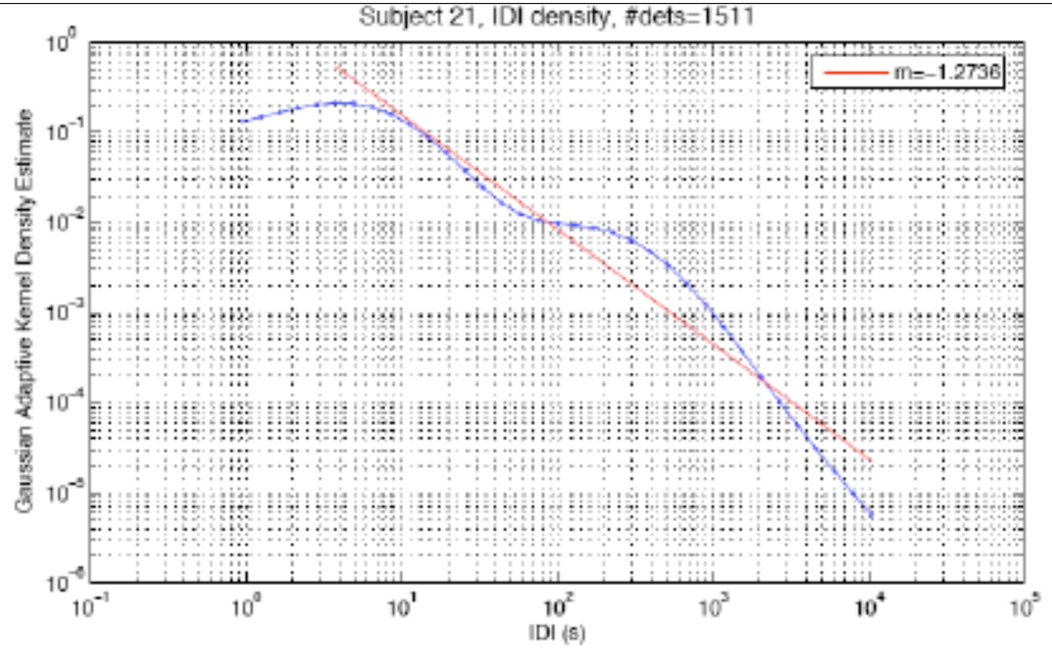
"Phase diagram" for the model in the space (heterogeneity, stress drop). Crosses (+) correspond to systems which exhibit a periodic time evolution. Stars * corresponds to systems that are self-organized critical, with a Gutenberg-Richter earthquake size distribution and fault localization whose geometry is well-described by the geometry of random directed polymers.

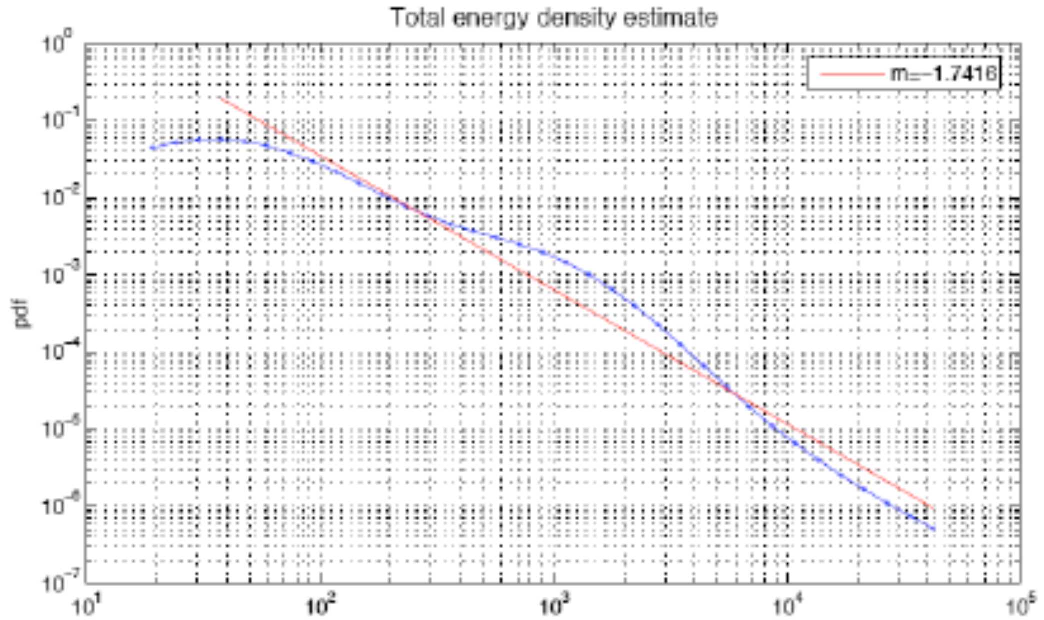
19 rats treated intravenously (2) with the convulsant 3-mercapto-proprionic acid (3-MPA)





Distribution of inter-seizure time intervals for rat 5, demonstrating a pure power law, which is characteristic of the SOC state. This scale-free distribution should be contrasted with the pdf's obtained for the other rats, which are marked by a strong shoulder associated with a characteristic time scale, which reveals the periodic regime.



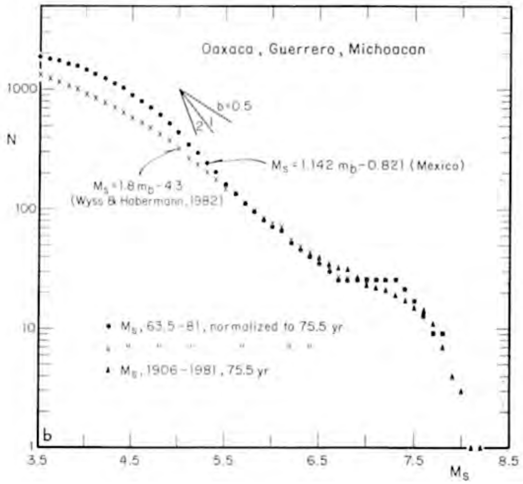


The pdf's of the seizure energies and of the inter-seizure waiting times for subject 21.

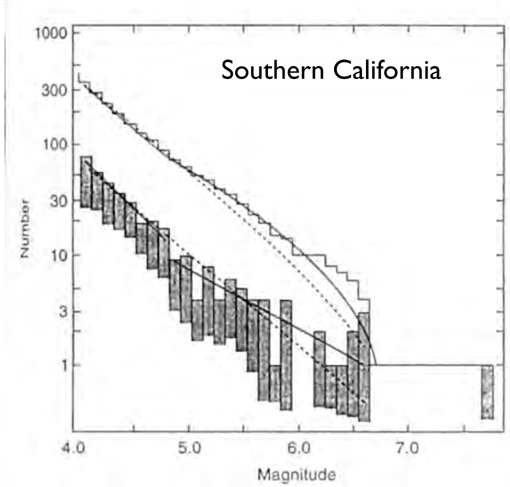
Note the shoulder in each distribution, demonstrating the presence of a characteristic size and time scale, qualifying the periodic regime.

Complex magnitude distributions

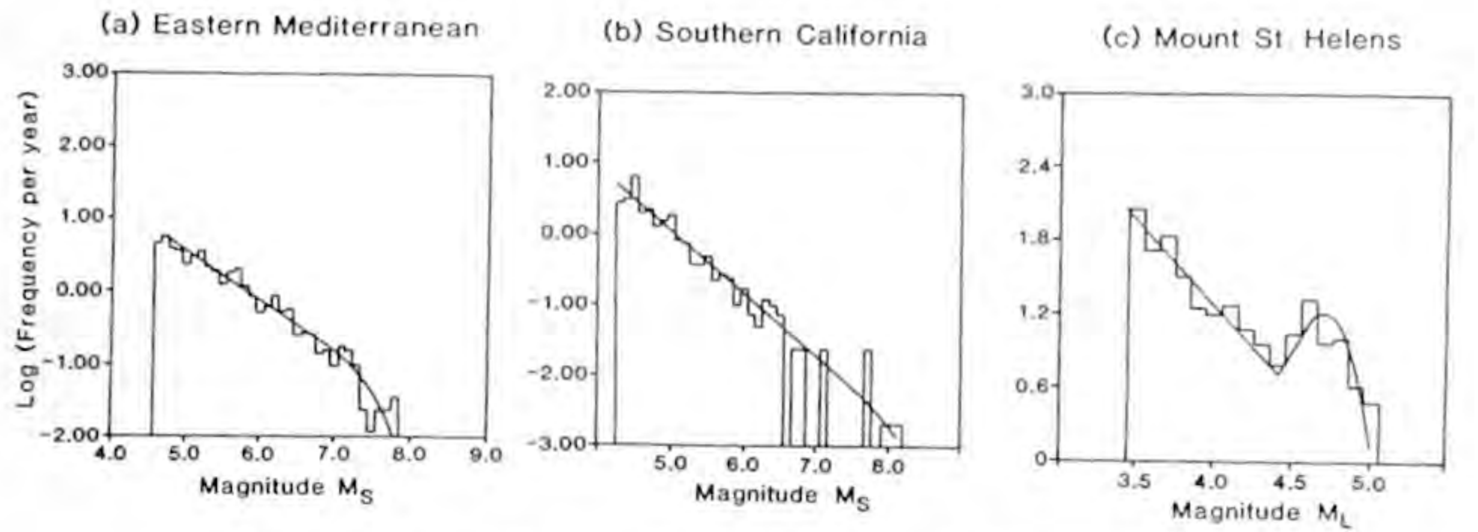
Characteristic earthquakes?



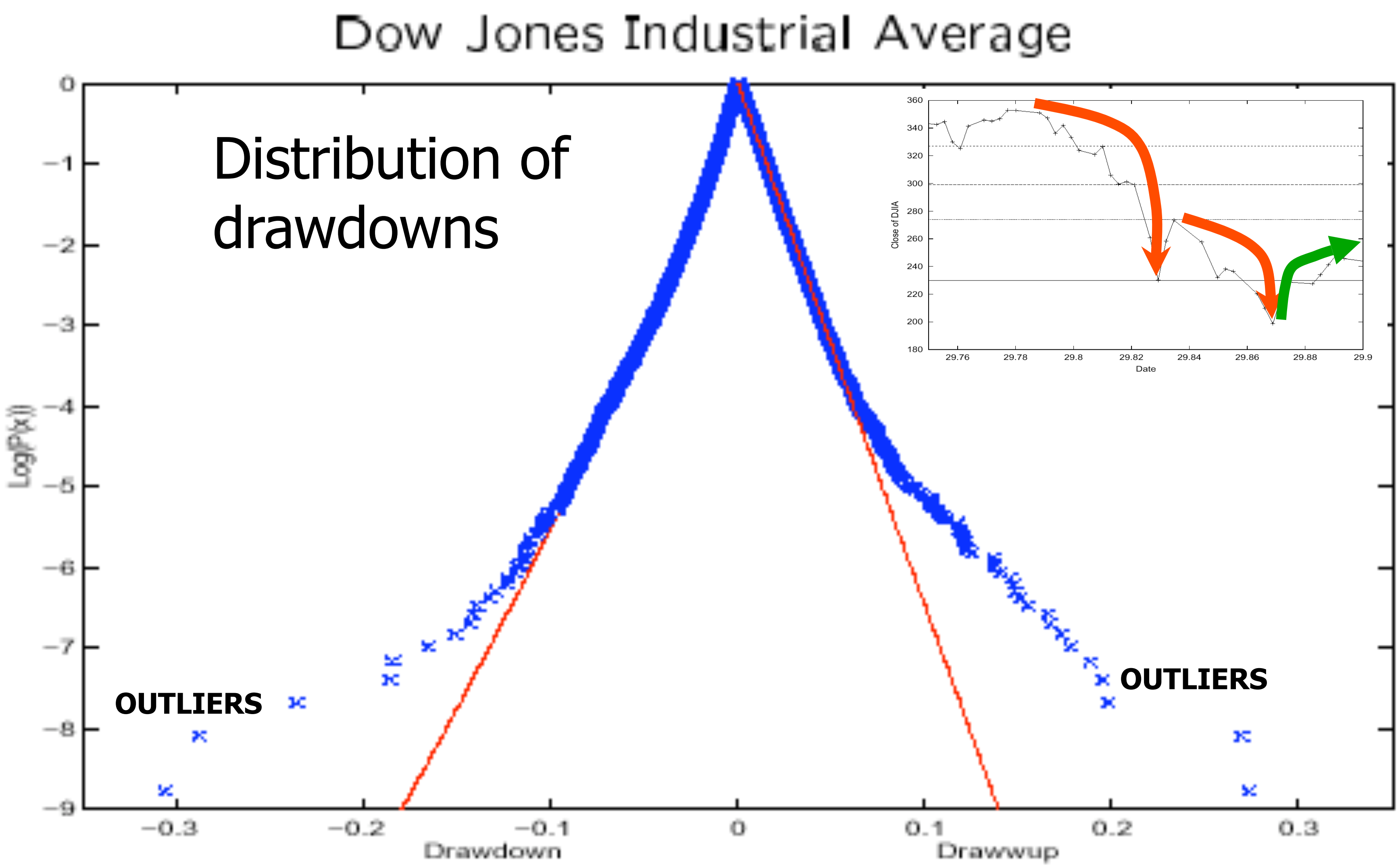
Singh, et. al., 1983, BSSA 73, 1779-1796



Knopoff, 2000, PNAS 97, 11880-11884



Main, 1995, BSSA 85, 1299-1308

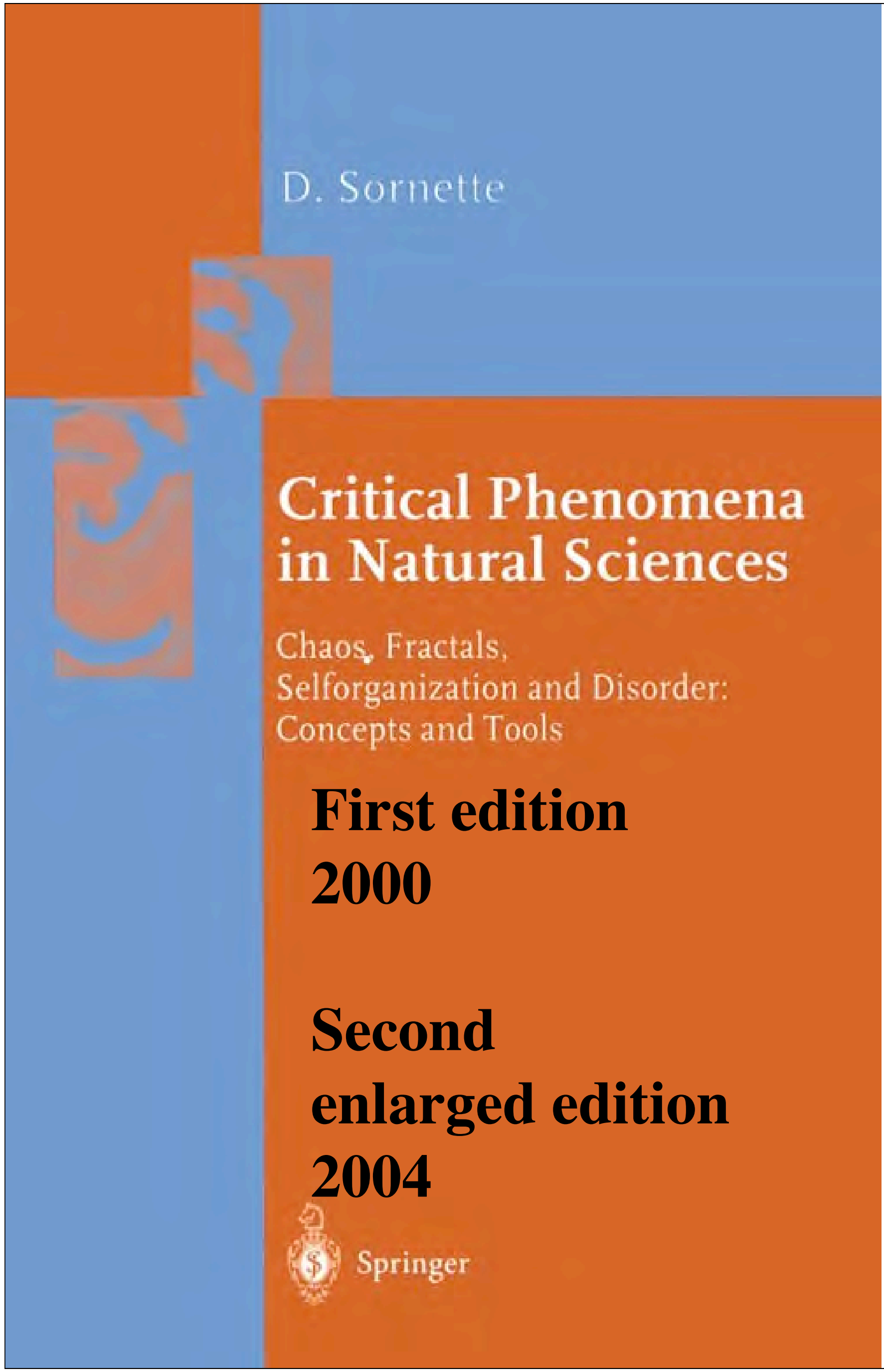


A. Johansen and D. Sornette, Stock market crashes are outliers,
European Physical Journal B 1, 141-143 (1998)

A. Johansen and D. Sornette, Large Stock Market Price Drawdowns Are Outliers,
Journal of Risk 4(2), 69-110, Winter 2001/02

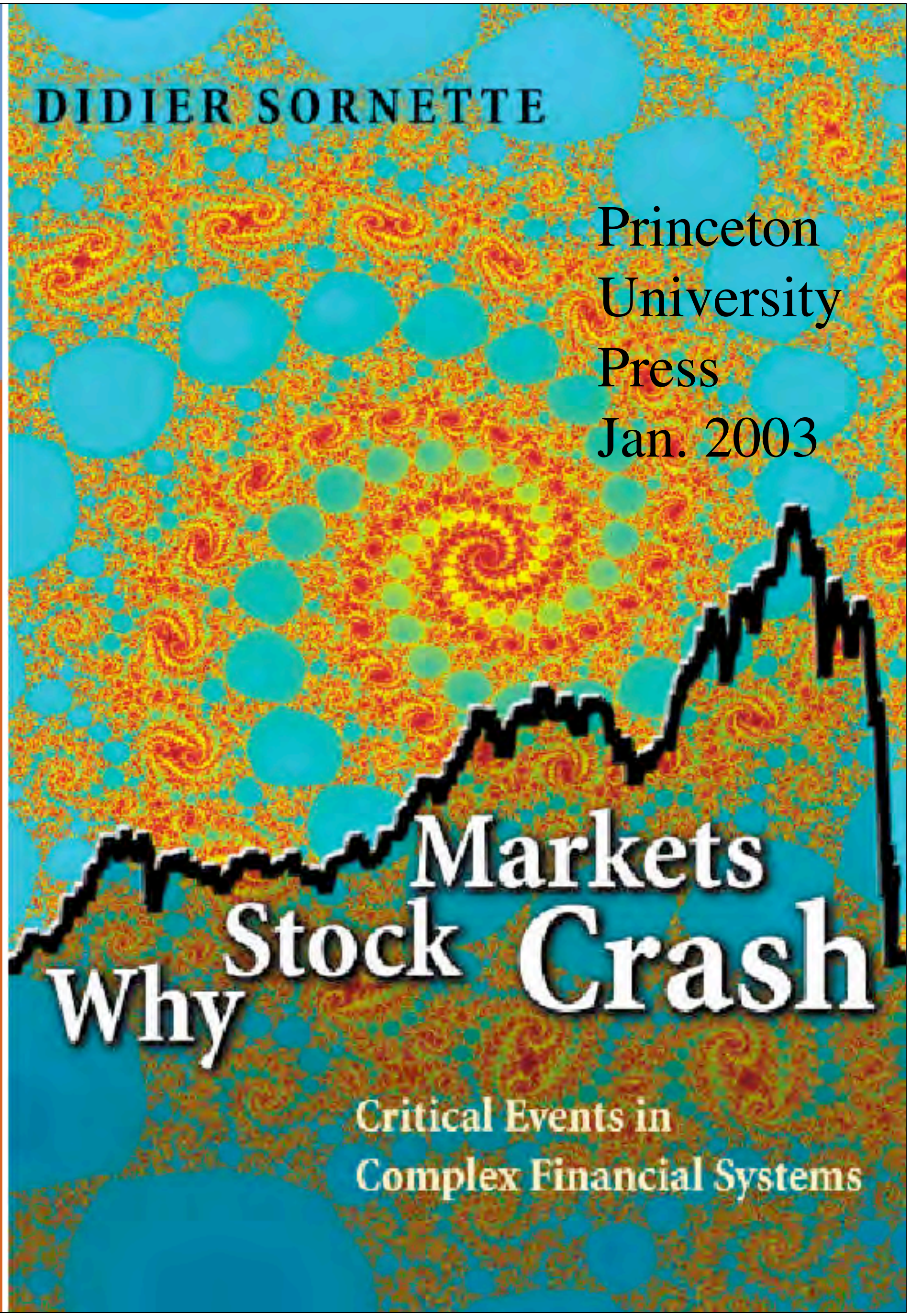
SUMMARY

- Earthquakes, financial crashes, epileptic seizures
- Parallels: pdf of sizes, inter-event times, Omori laws for foreshocks and aftershocks, criticality, ...
- Endogenous vs exogenous response to shocks (financial volatility and earthquakes): Rate ~ $1/t^p$ with p(m)
- Foreshocks and aftershocks of Seizures
- Universal scenario: coupled heterogeneous threshold oscillators of relaxation
- Systematic classification and prediction of new phenomena
- Implication for predictability

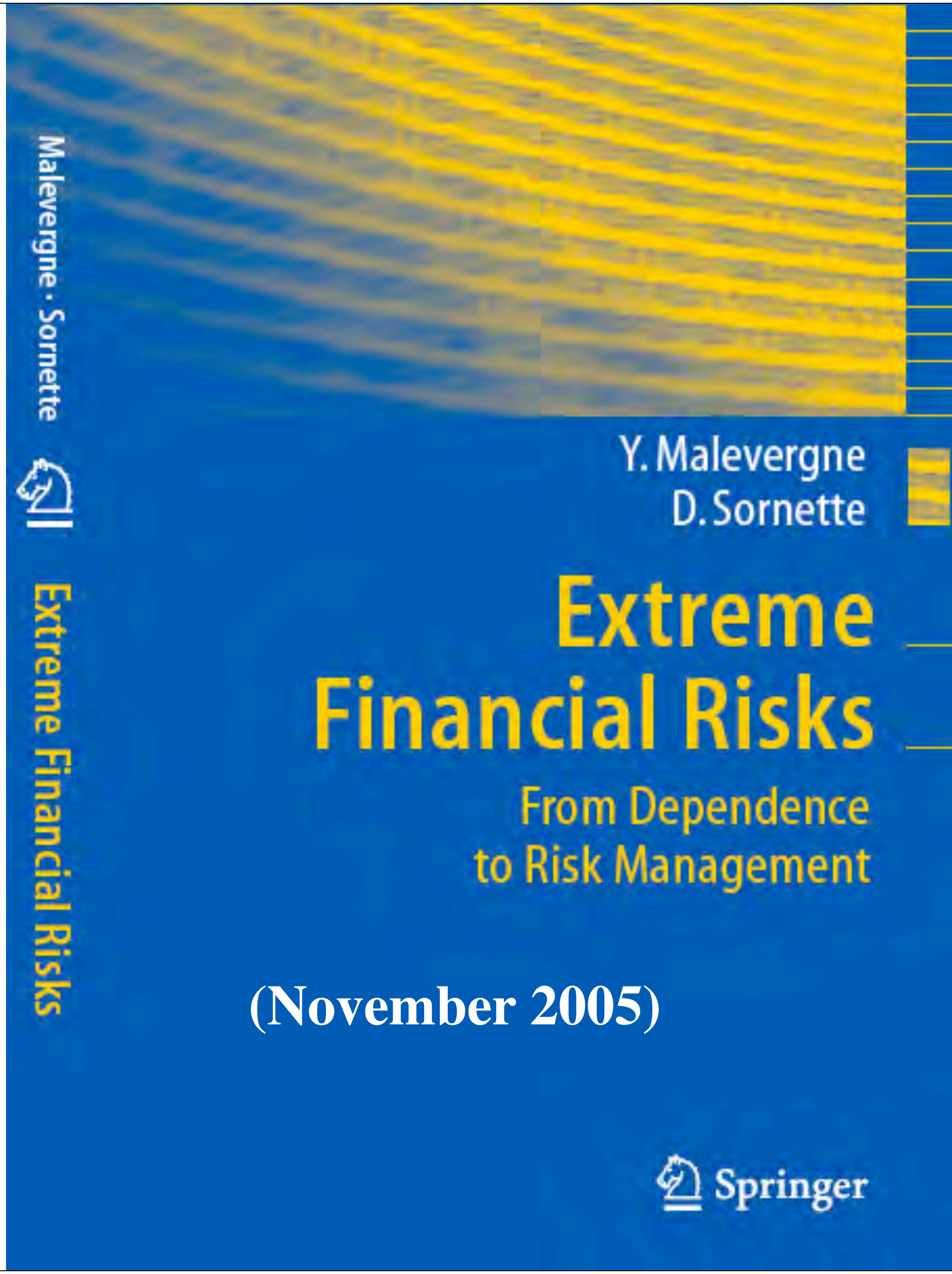


First edition 2000

Second enlarged edition 2004



Princeton University Press Jan. 2003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