A critical brain in a critical world

What kind of brain we need to survive?

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Questions I am concerned with:

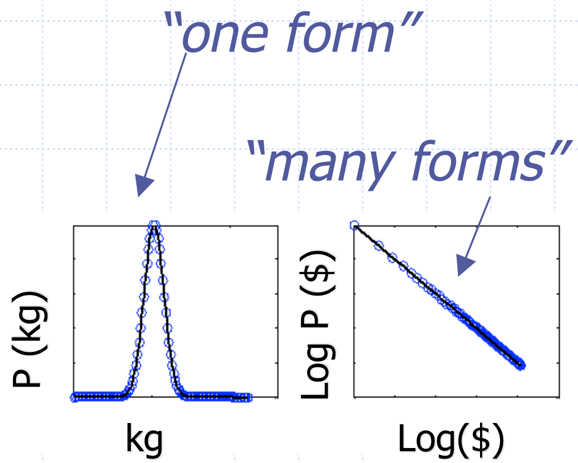
How to describe understand and manipulate complexity in nature without a new explanation for each manifestation...

Universality

The statistics we learnt describe uniformity (gaussians, exponentials)

Nature is NON HOMOGENEOUS!!!,

Example: distribution of weigth versus distribution of income $



Complexity = nonuniformity

The laws of physics are simple, how is that the world is complex

How to generate complexity out of simple laws

Reading:

- *Articles:*
  - *»Eguiluz V, Chialvo DR, Cecchi G, Baliki M, AV Apkarian. Scale-free brain functional networks. Phys. Rev. Letters 92, 018102 (2005).*
  - *»Chialvo DR. Critical brain networks. Physica A, 340,4,756-765 (2004).*
  - *»Beggs J. & Plenz D, Neuronal Avalanches in Neocortical Circuits J. of Neuroscience, 3 23(35):11167 (2003).*
  - *»Chialvo DR. The brain near the edge. www.arxiv.org (2006)*
  - *»Chialvo DR. Are our senses critical? Nature Physics (2006).*
- *Review:*
  - *»Sporns O, Chialvo DR, Kaiser M, and Hilgetag CC. Organization, Development and Function of Complex Brain Networks. Trends in Cognitive Sciences, 8 (9): 387-433 (2004).*
- *Books :*
  - *»How Nature Works. (Per Bak)*
  - *»Things that think. (Chialvo, 2007)*

Roadmap:

We discuss theoretical results from the physics of critical phenomena showing that nature -by far- is spontaneously posed at the border of an instability, a critical phase transition between order and disorder.

Fact: The most important consequence of that state is that energy in the world is released (dissipated) both in space and time in a highly non-uniform fashion. Bursts, flooding, intermittent draughts, quakes, avalanches, period of abundance, etc are all examples of observables distributed as power laws, with -more than expected- extreme events.

Conjecture: If we accept that view, then it follows that, to survive under those world conditions, a brain would evolve to be also critical.

Fact: Several aspects of brain dynamics are critical.

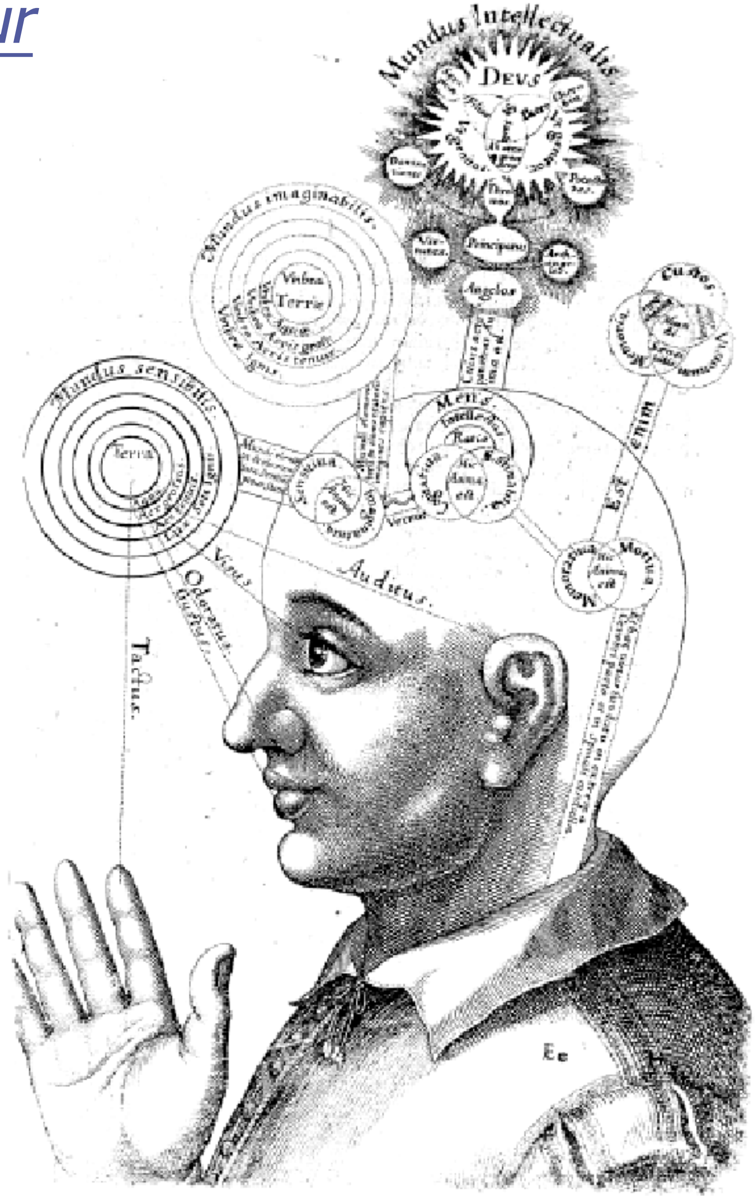
Collective phenomena

– Almost all interesting macroscopic phenomena, from gravity to fotosintesis, from supeconductivity to muscle contraction are product of an underlying collective phenomena

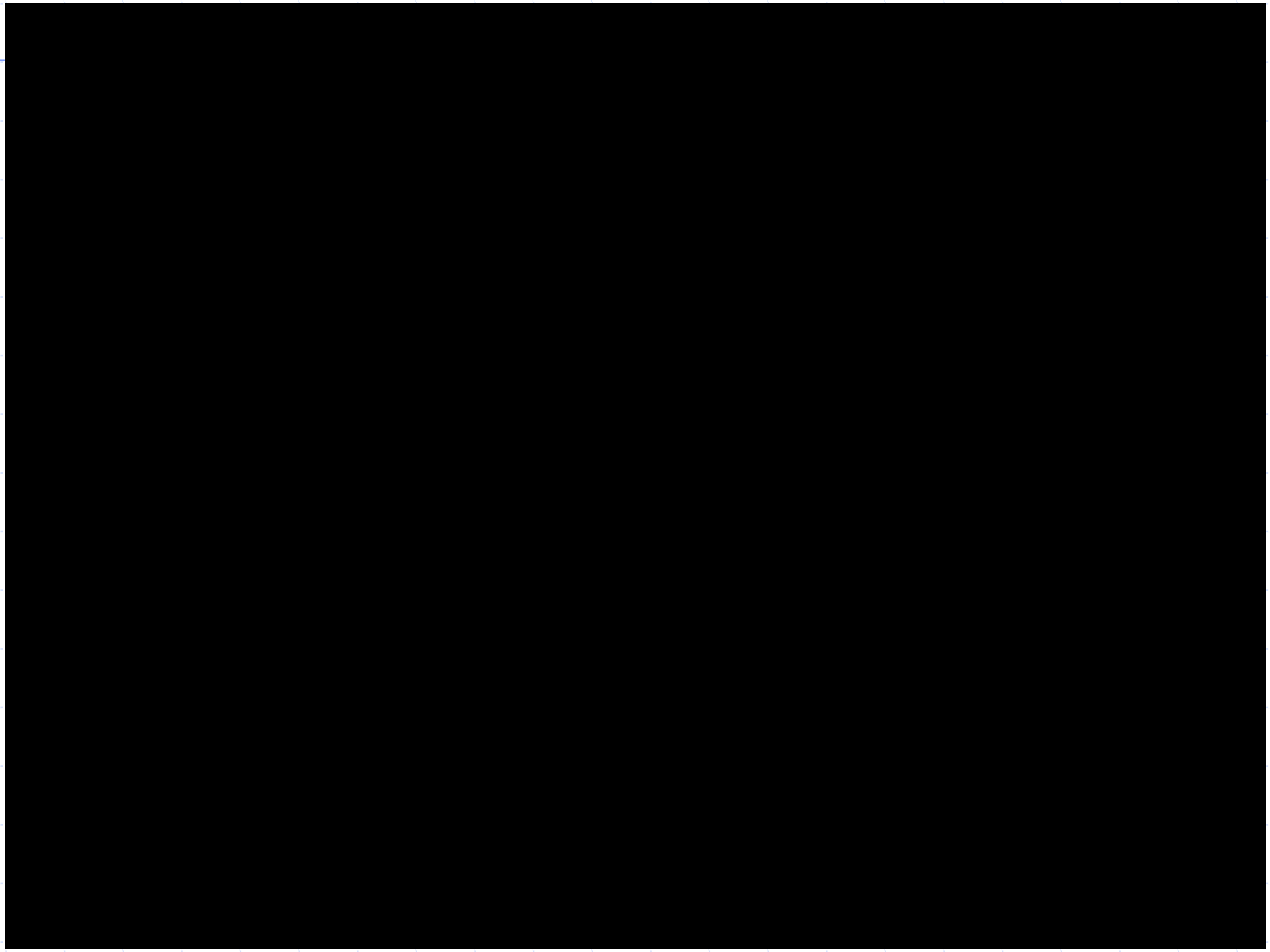
–Science is often seen as explaining a phenomena at one level from fundamental laws at another level

–Biology and neuroscience are not exception, thus we need to explain behavior (what we see) in terms of the underlying collective (what often is partially hidden to us)

We must find which collective phenomena are able to generate relevant behaviour



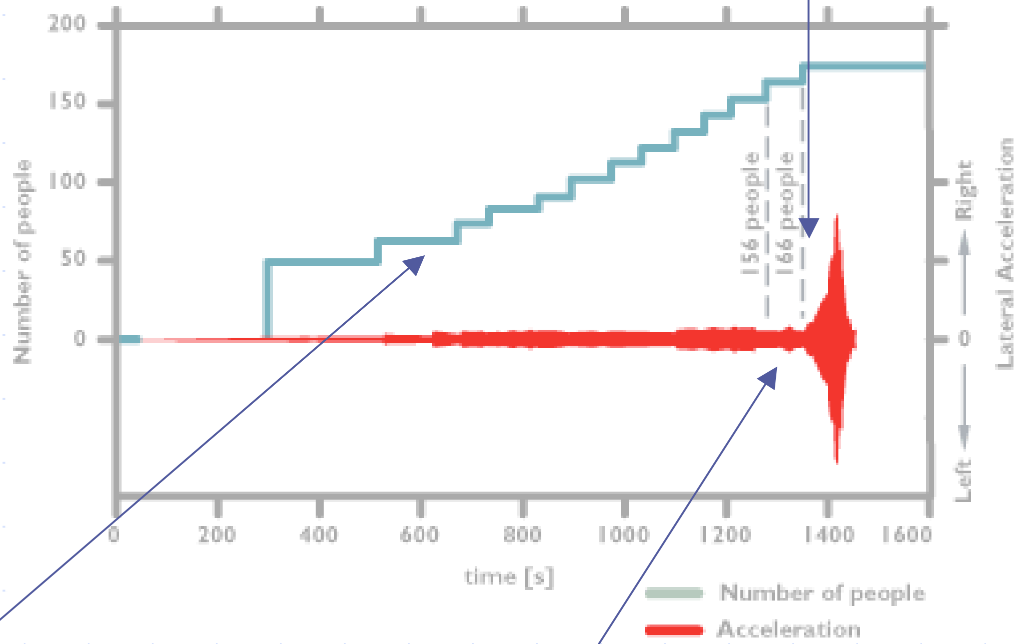
*Example 1: Macroscopic phenomena emerging out of the interaction of **many** degrees of freedom*



Example: London Milleniun Bridge (Opening Day)

*Interaction of **166 nonlinear** degrees of freedom ...*

166 walkers = Critical point



Number of people *Lateral acelleration of the bridge*

The mechanism

- Each individual -in complete isolation and minding his/her own business- tilts to the right or to the left (with some fraction of a sec. delay) to stay comfortably vertical.
- Doing so, each individual adds 80 or more kilos opposite to any initial displacement.
- For a large enough N a collective oscillation appears with people tilting out of phase with the bridge.

It is a macroscopic phenomena
with
an underlying, nonlinear, collective mechanism.

Good news

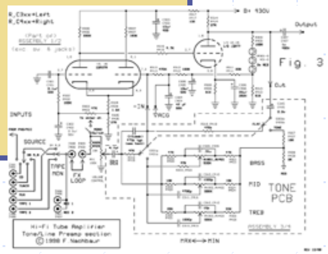
- There are useful tools to analyze and understand the mechanisms of this kind of collective phenomena arising in high dimentional nonlinear dissipative dynamical systems
- These are the “Newtons laws” for complex systems and as in more classical mechanics, they are universal up to some degree.
- Next some hints about of where and how these principles apply.

Complex or complicated?

Complicated systems

Many linear pieces + supervisor + blue print = "whole"

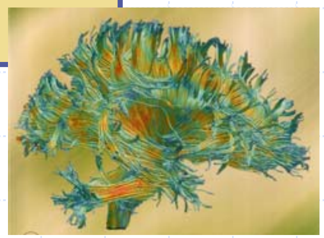
Example: a TV set.



Complex systems

Many non linear pieces + coupling (interaction) + energy = emergent properties

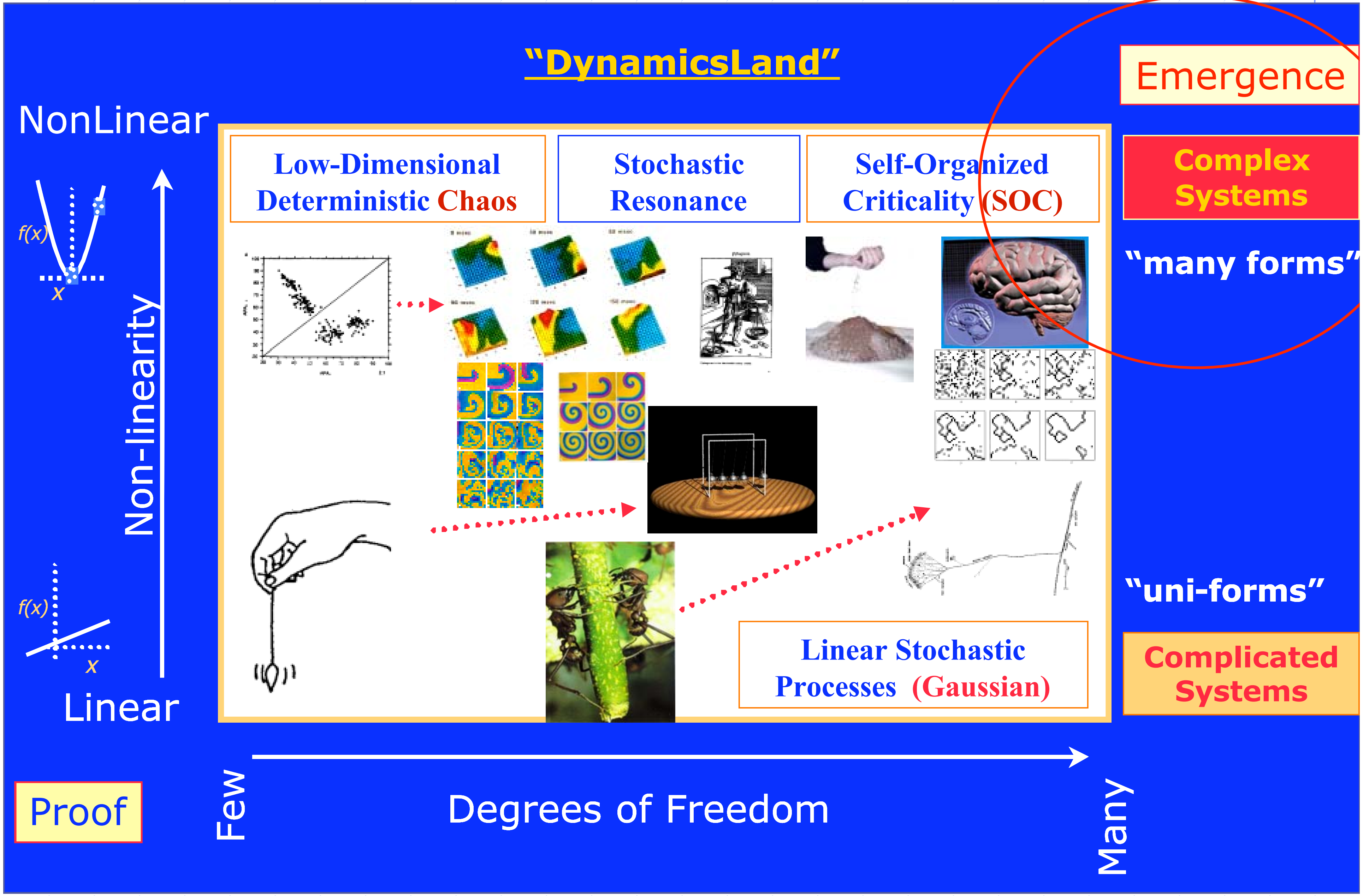
Example: nature, societies, brains.



¨Complexity for free¨

- o Complex systems SELForganize!!!
- o Linear systems can not SELForganize

Complicated vs. Complex



What kind of dynamics we see in the upper right corner?

Short answer:

power-law correlated in space time

(scale free)

Example 1:

Game of life

Self-organized criticality in the 'Game of Life'

Per Bak, Kan Chen & Michael Creutz

Department of Physics, Brookhaven National Laboratory, Upton, New York 11973, USA

Bak, Per, Kan Chen, and Michael Creutz, "Self-organized criticality in the 'Game of Life'," *Nature*, vol. 342, December 14, 1989, pp. 780- 782

Self-organized criticality in the 'Game of Life'

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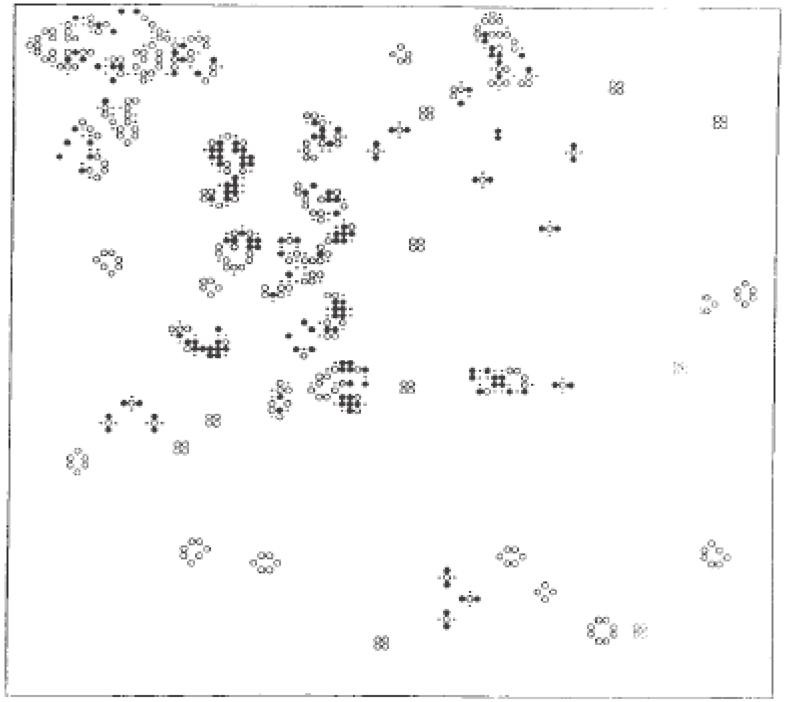
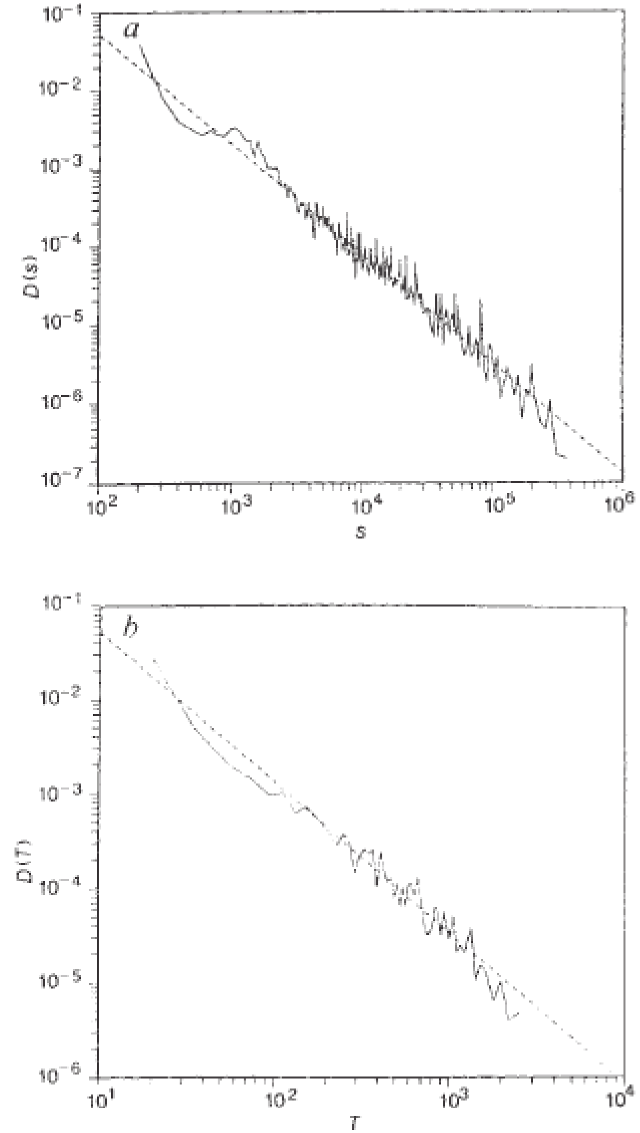


FIG. 2 Configuration of a 100×100 system responding to a perturbation Live passive sites are open circles, dying active sites are filled circles; the dots indicate sites where birth will take place at the next time step. Note configurations of still life (clusters of open circles), cyclic life with period 2 and propagating gliders.



IG. 1 a, Log–log plot of distribution of cluster size for a 100×100 system. . Distribution of the duration for evolution of clusters. The deviation from ower-law behaviour for large clusters is a finite-size effect.

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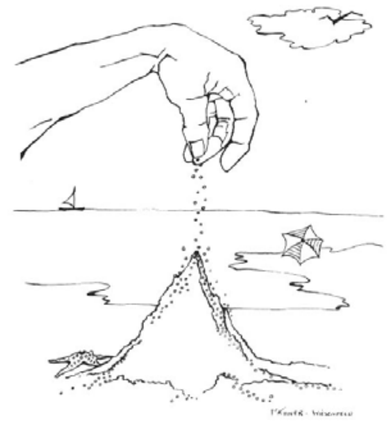
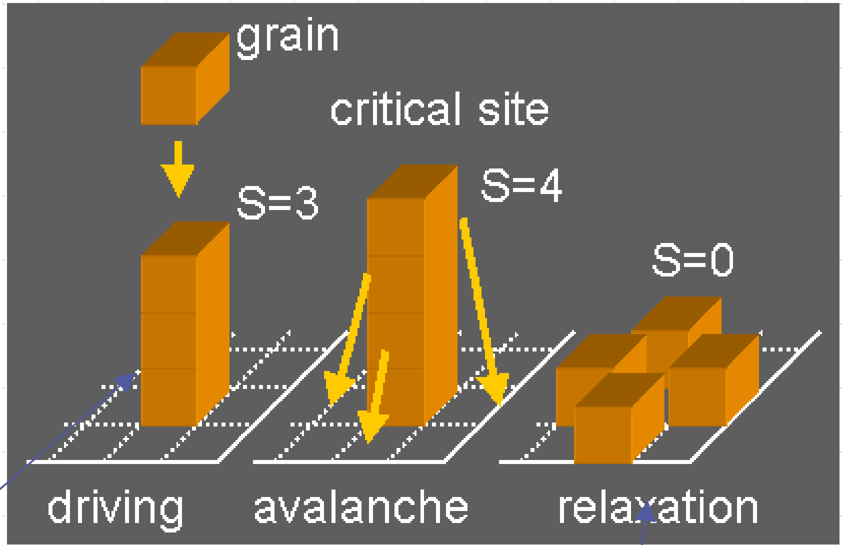


Example 2:

Avalanches in a sand pile:

Bak, Per, Chao Tang, and Kurt Wiesenfeld, "Self-Organized Criticality: An Explanation of 1/f Noise, " *Physical Review Letters*, vol. 59, no. 4, July 27, 1987, pp. 381-384.

Toy model of real sand piles



1) Add one grain

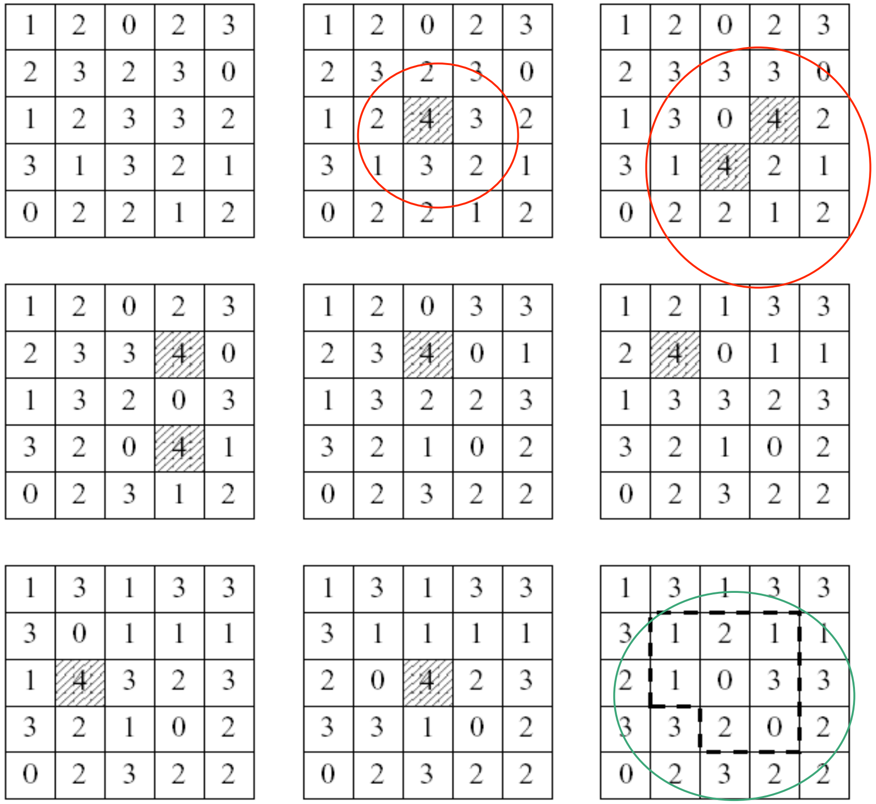
2) Check if any site heigth > 4 if so -> relax

3) Go back to 1

That is all

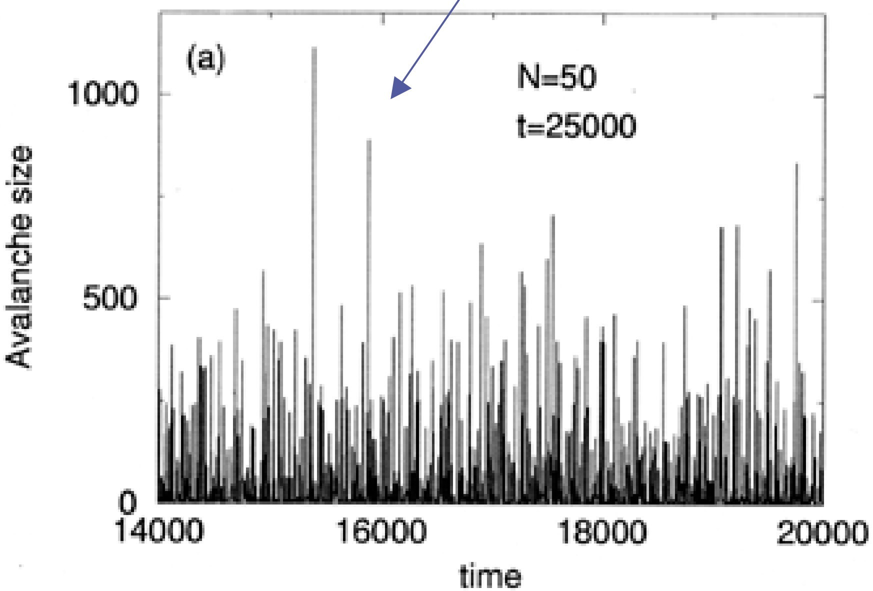
Toy model of real sand piles
One avalanche

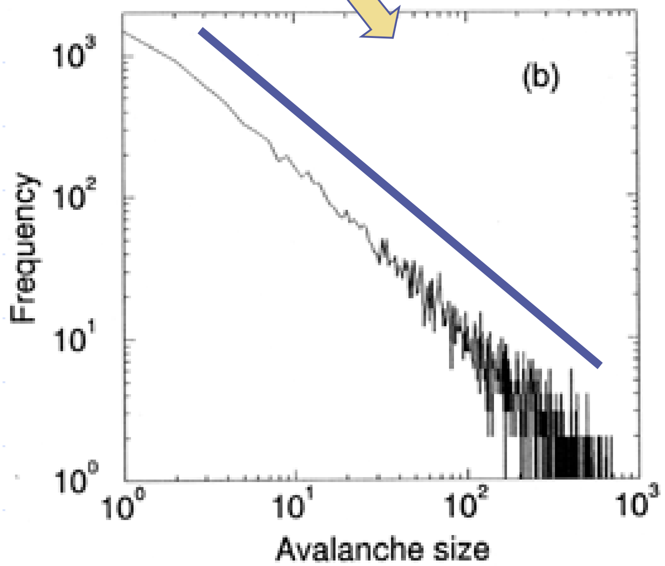
Illustration of one avalanche



The system reachs spontaneously a state with avalanches of all sizes

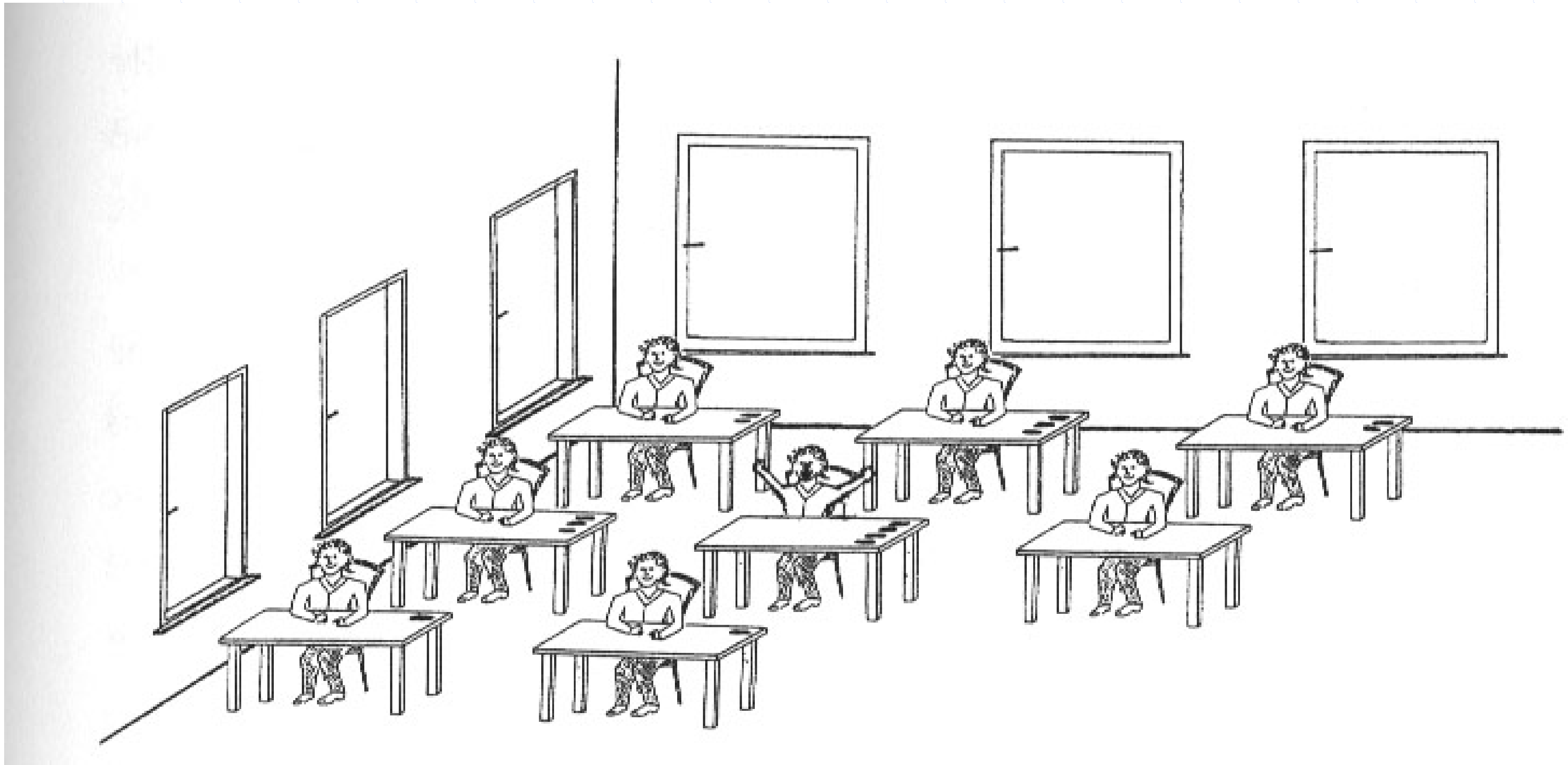
Highly non-uniform fluctuations





- Avalanches are a deterministic emergent complex phenomena, high dimensional
- This (critical) state is the most unstable yet the most robust, because the system always returns to it.
- Only crucial elements are *large N* of *nonlinear interacting* elements, and driving energy

Sand pile model (bureaucrat version)



1) Your paperwork safelly lands at one desk
2) Bureacrat check his/her work load. If he/she has > 4 pass one to each nearest colleague (or tru the window)
3) Go back to 1

That is all

What kind of dynamics we see in the upper right corner?

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(scale free)

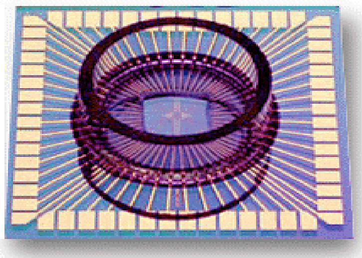
Example 3:

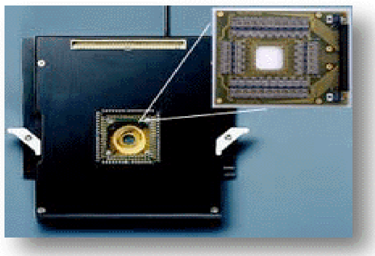
Avalanches in rat cortex:

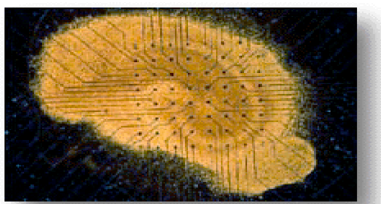
Beggs J. & Plenz D, Neuronal Avalanches in Neocortical Circuits J. of Neuroscience, 3 23(35):11167 (2003).

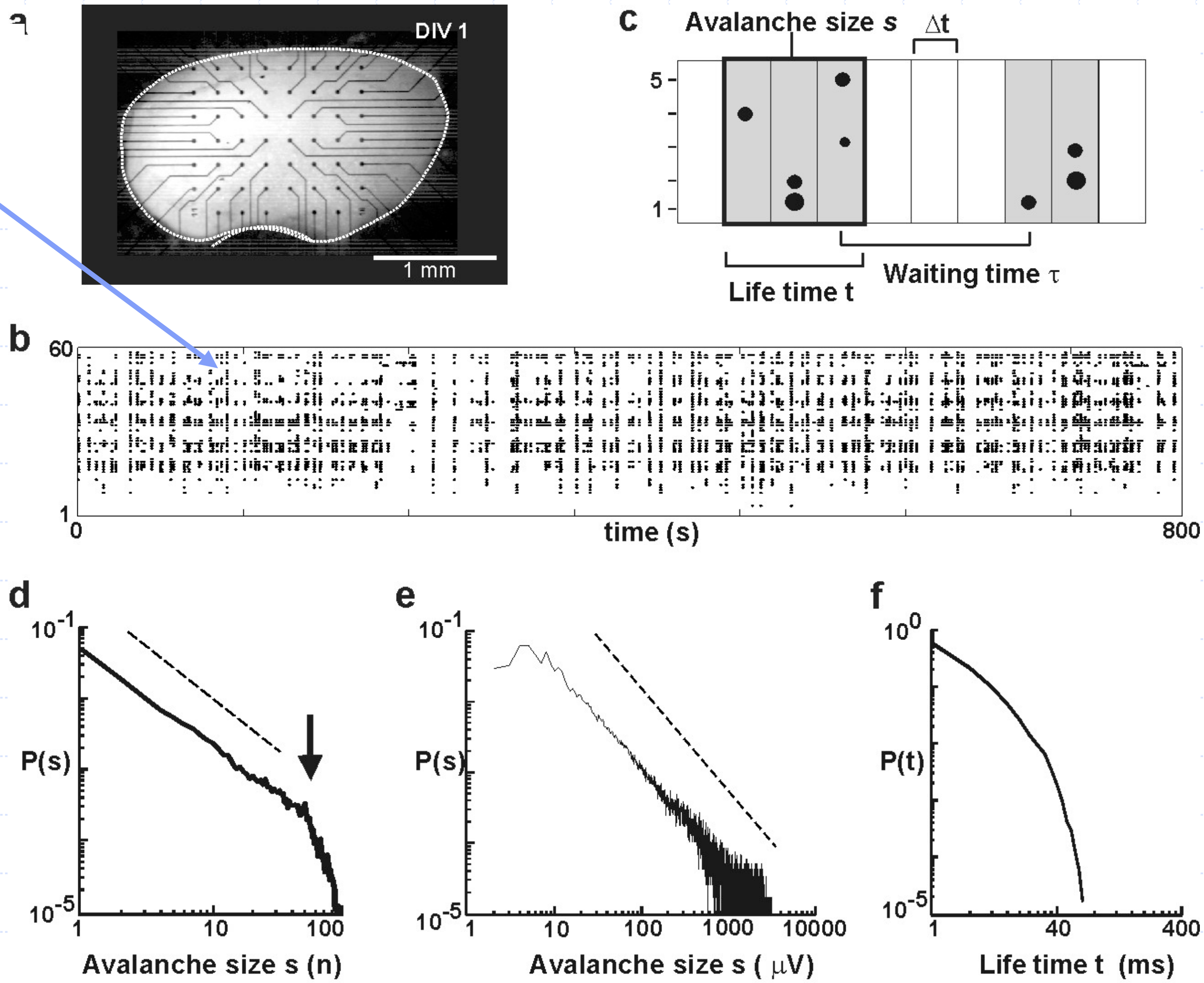
Avalanches in rat cortex

"Neuronal avalanches"









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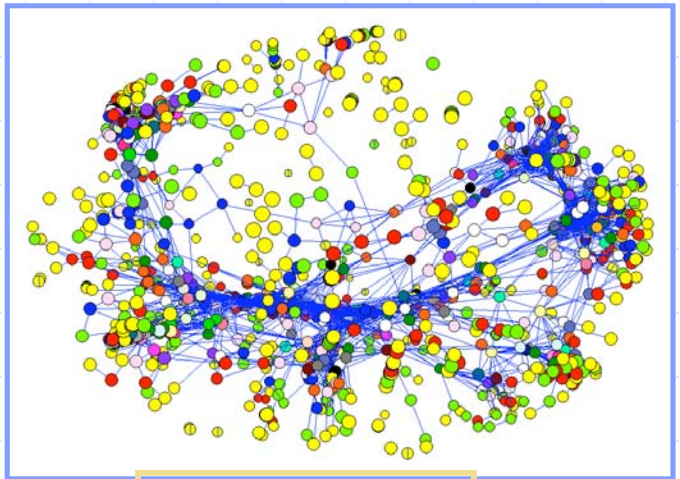
Example 4:

Scale free bran functional networks:

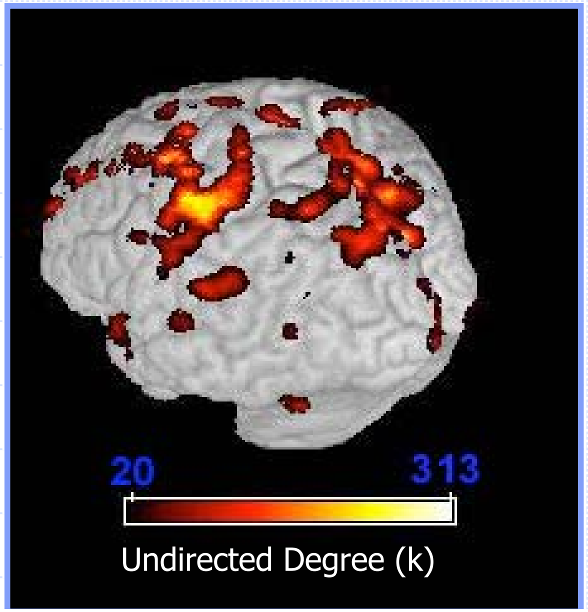
Eguiluz V, Chialvo DR, Cecchi G, Baliki M, AV Apkarian. Scale-free brain functional networks. Phys. Rev. Letters 92, 018102 (2005).

My brain's network

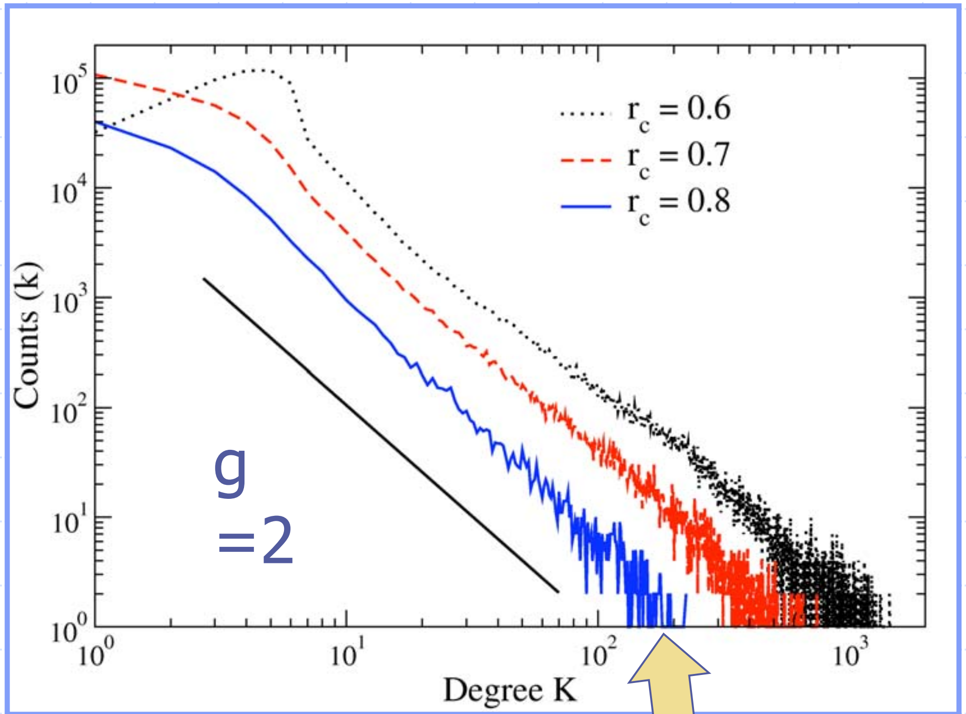
Topology



Topography

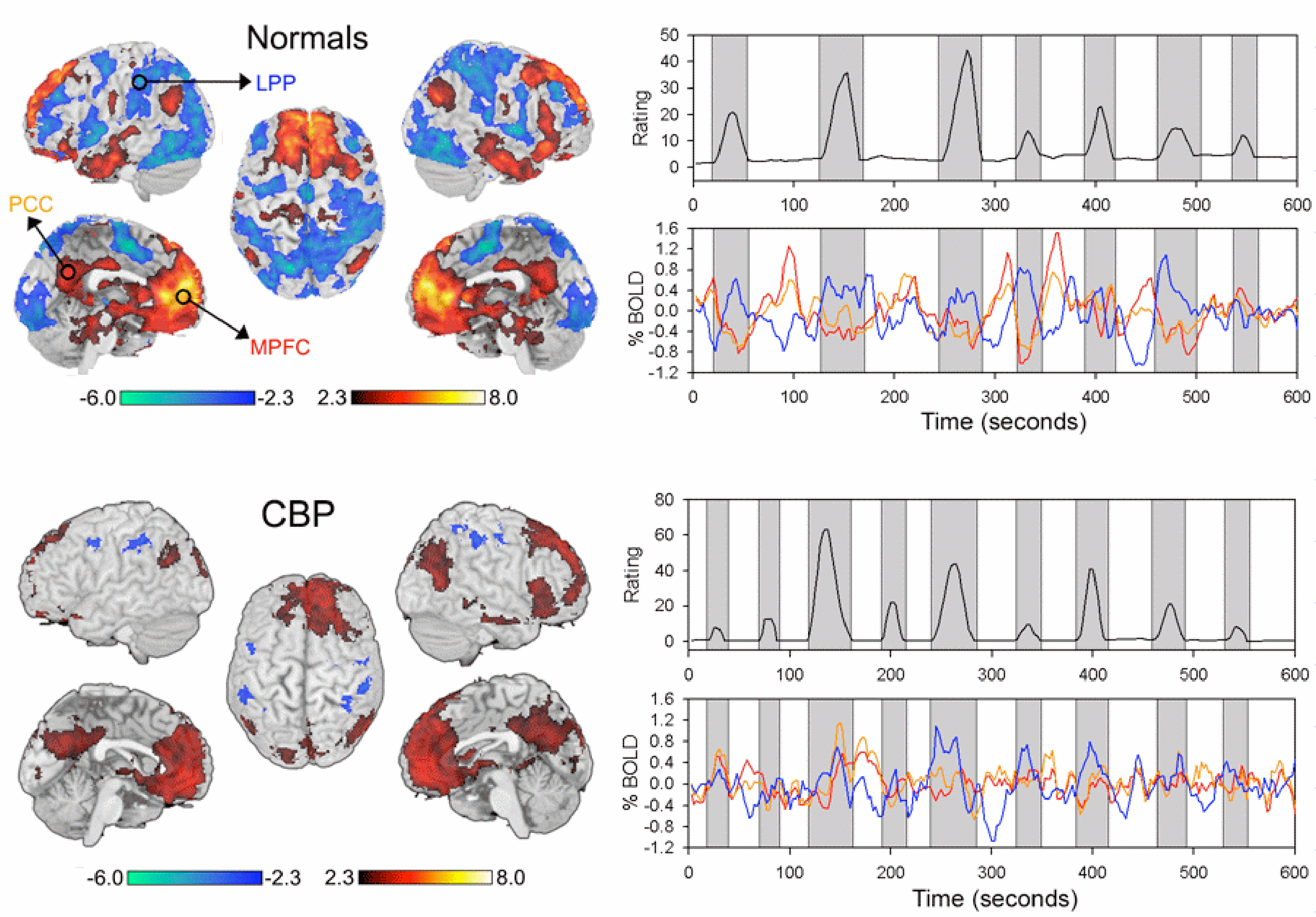


Scale free distribution of functional connections



Few but very well connected brain sites

In the critical state each positively correlated clique should have a negatively correlated contrapart



Healthy Volunteers

Chronic Pain Patients

Chialvo et al, Submitted(2006)

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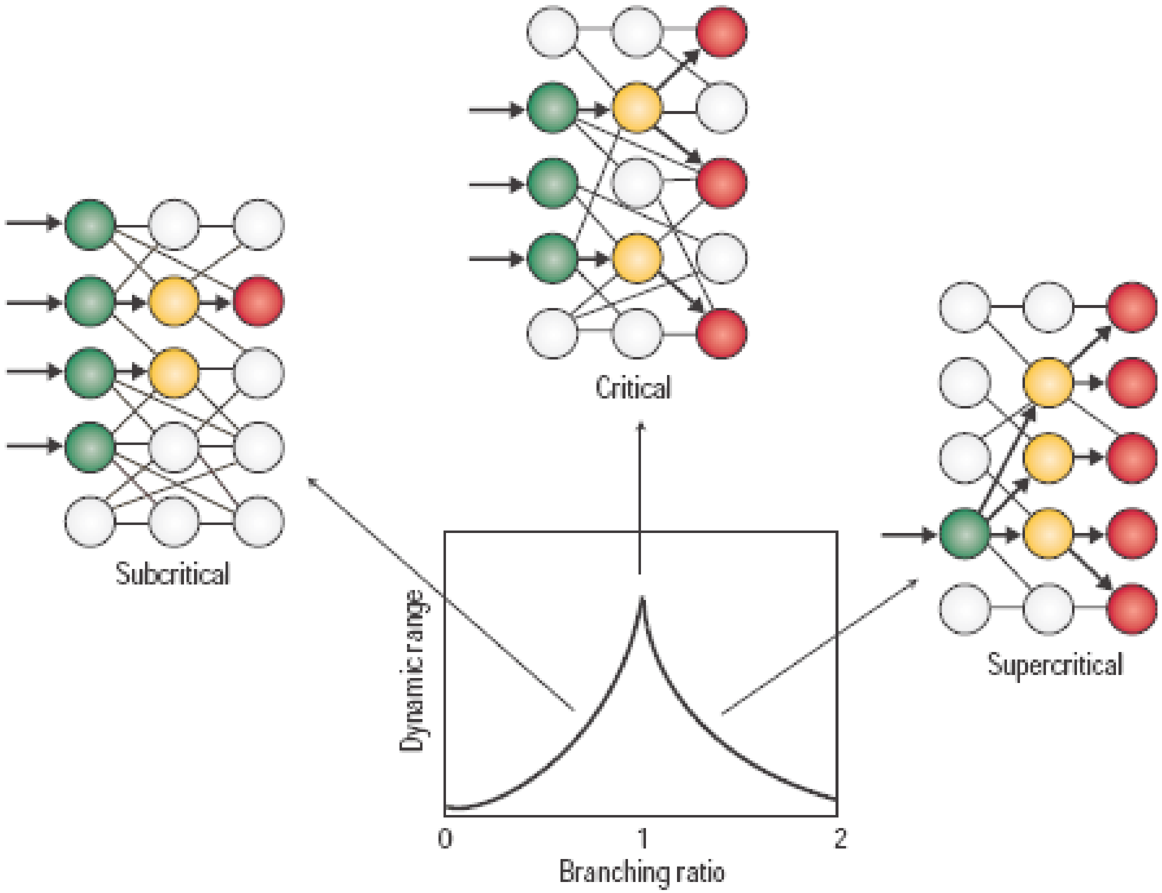
Example 5:

The physics of psyco physics:

Copelli et al, Nature Physics

Sensory systems optimize dynamic range at criticality

A neuronal mechanism to account for Weber-Fechner-Stevens law

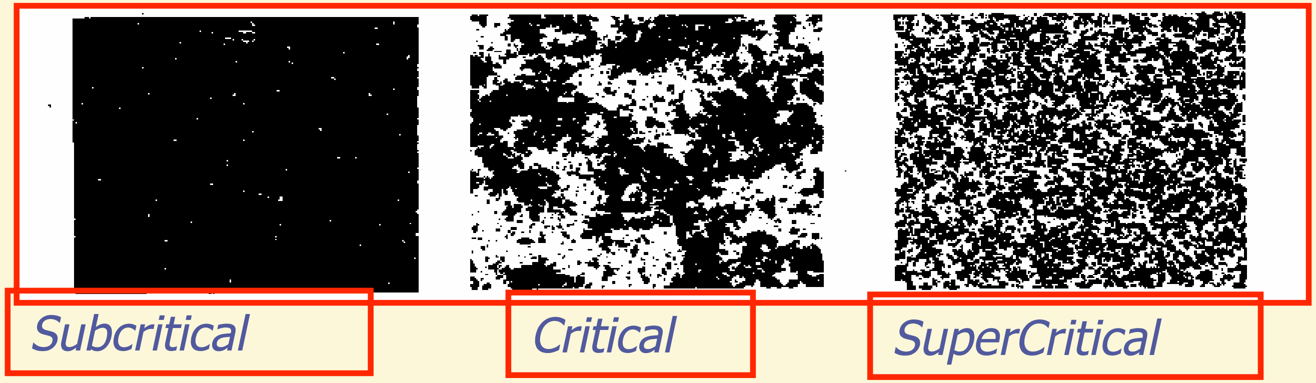


Chialvo, Nature Physics (2006)

Why do we need a brain?

Why do we need a brain at all?

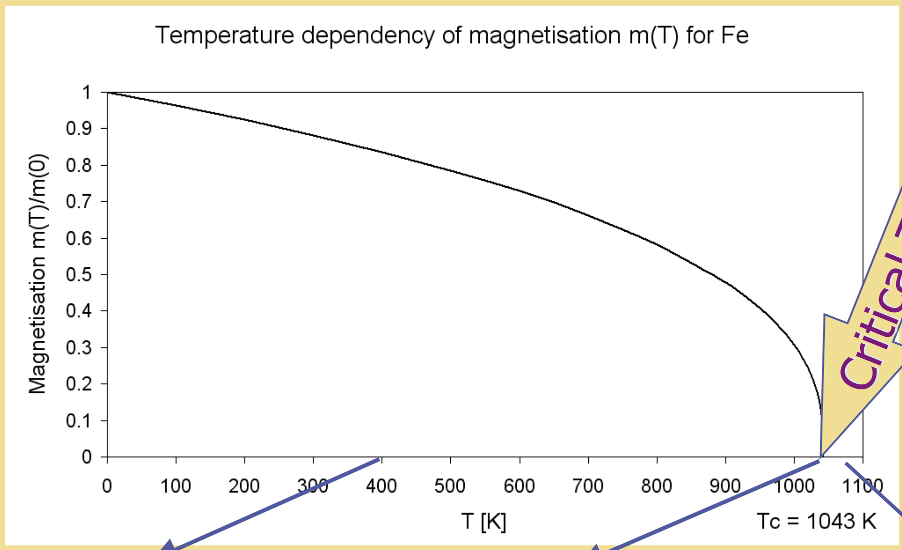
Because the world around us - in which brains have to survive- more often looks like this



not like that!

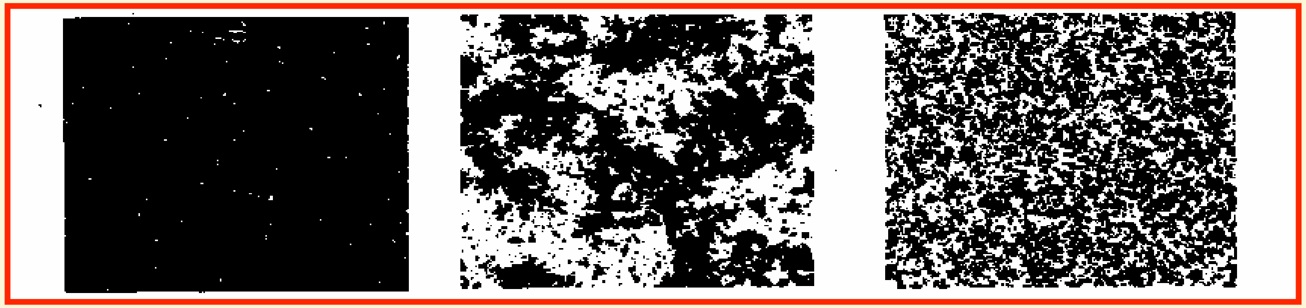
What is special about being critical?
Recall Ferromagnetic-paramagnetic Phase-Transition

Critical Temperature



Snapshots of spins states in a model system (Ising)

$T<T_C$ | $T\sim T_C$ | $T>T_C$



SubCritical | Critical | SuperCritical

Long Range Correlations Only at the Critical state!

Ok, even if the physical world is plenty of critical stuff but... Why the brain should be Critical?

Why do we need a brain at all?

•In a sub-critical world everything would be simple and uniform - there would be nothing to learn.

•In a supercritical world, everything would be changing all the time - it would be impossible to learn.

The brain is necessary to navigate in a complex, critical world .

A brain not only have to remember, but also to forget and adapt.

•In a sub-critical brain memories would be frozen.

•In a supercritical brain, patterns change all the time so no long term memory would be possible.

To be highly susceptible, the brain itself has to be in the in-between critical state.

Blah-Blah-logy

Driven large interacting nonlinear systems such as nature societes brains, economies and so on, can spontaneously reach and stay at a highly fluctuating state with extreme, power law correlated events similar to critical phenomena at a continuous phase transition.

A simple theory, with a large number of nonlinear interacting elements can explain most of the statistical properties of such critical state

Experiments in real and modeled sand piles by Bak and colleagues, by God in quakes and rainfalls , by Plenz in neurons and many other over the last 10 years, lead credibility to the widespread application of these ideas.

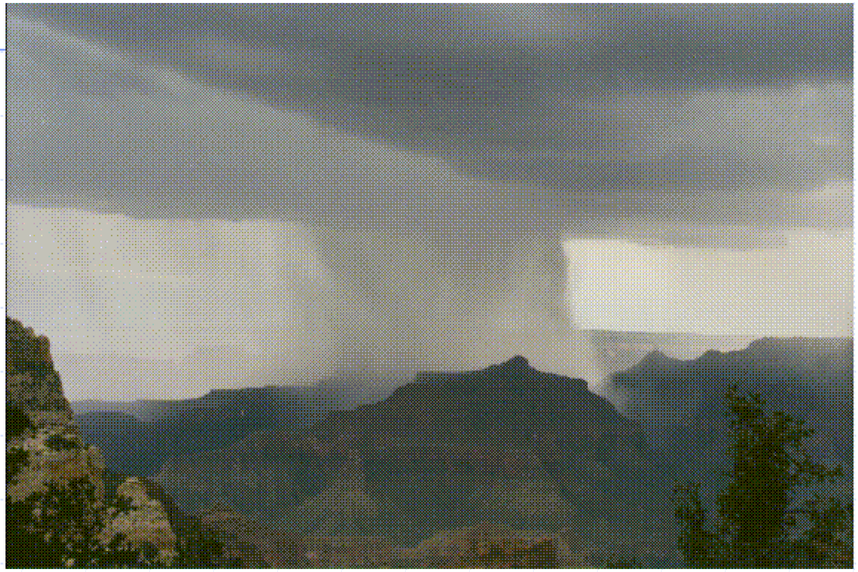
Brains are critical

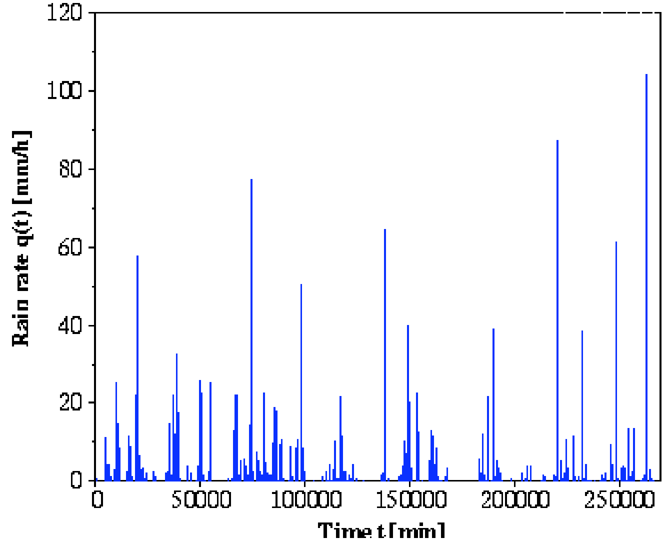
"Per, for me the brain is critical"…

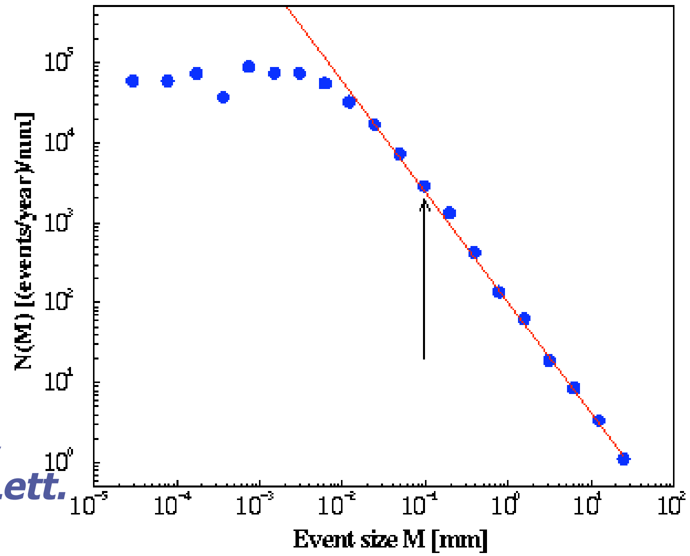
"Yes, for me too Dante!"

DRC & Per Bak (Brookhaven N. Lab. 1991)

Aplicaciones:
Lluvia como “terremotos en el cielo”*

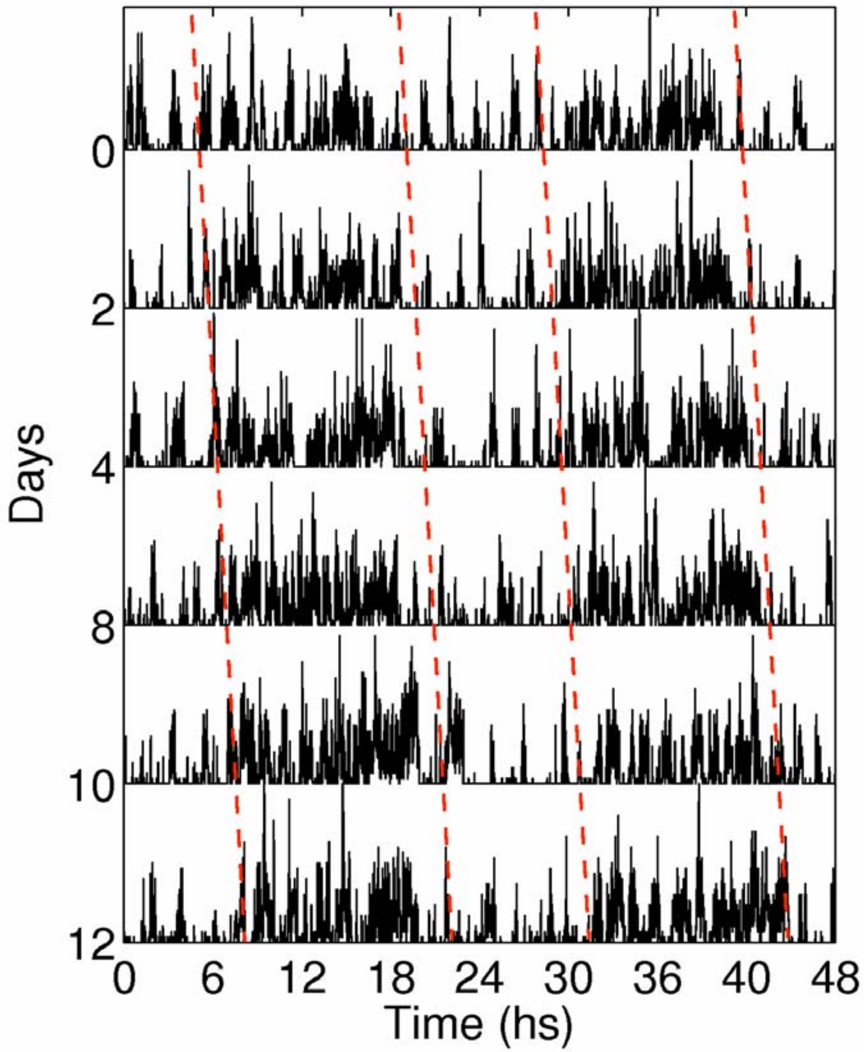






- La dinamica de la lluvia es equivalent a la ley de Gutenberg-Richter de los terremotos y a la distribucion scale-free de avalanchas en pilas de arena.

***Figuras de www.cmth.ph.ic.ac.uk/kim O. Peters, C. Hertlein, and K. Christensen, *A complexity view of rainfall, Phys. Rev. Lett.* 88, 018701, 1-4 (2002).**


Days
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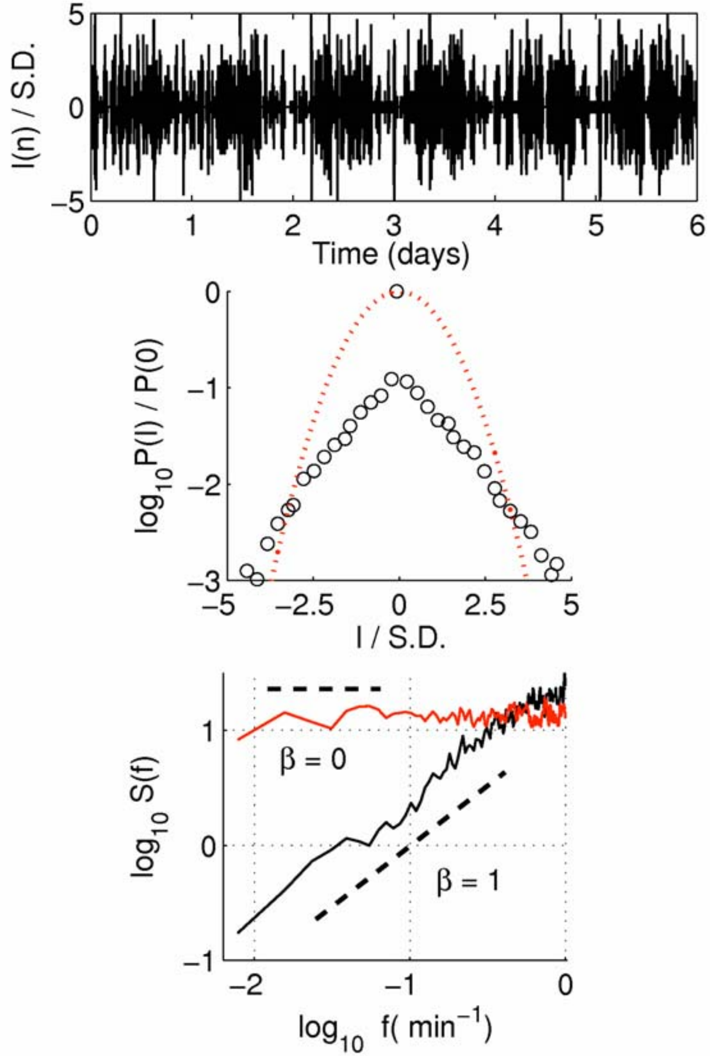
48
Time (hs)


I(n) / S.D.
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6
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log10P(I) / P(0)
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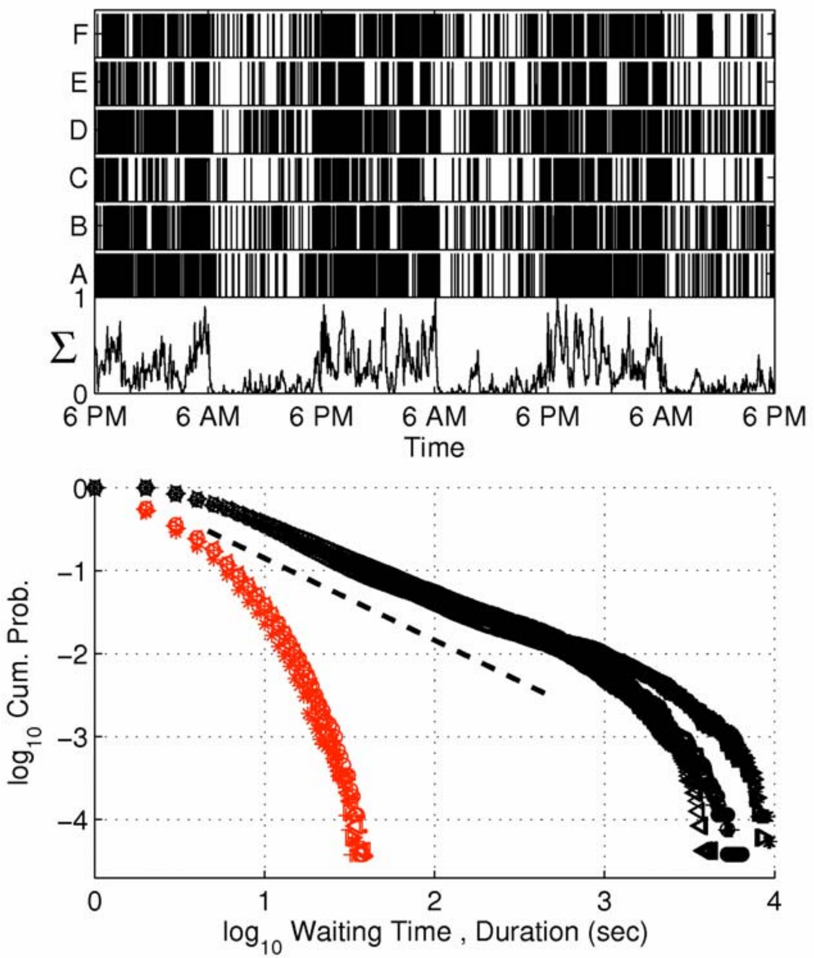
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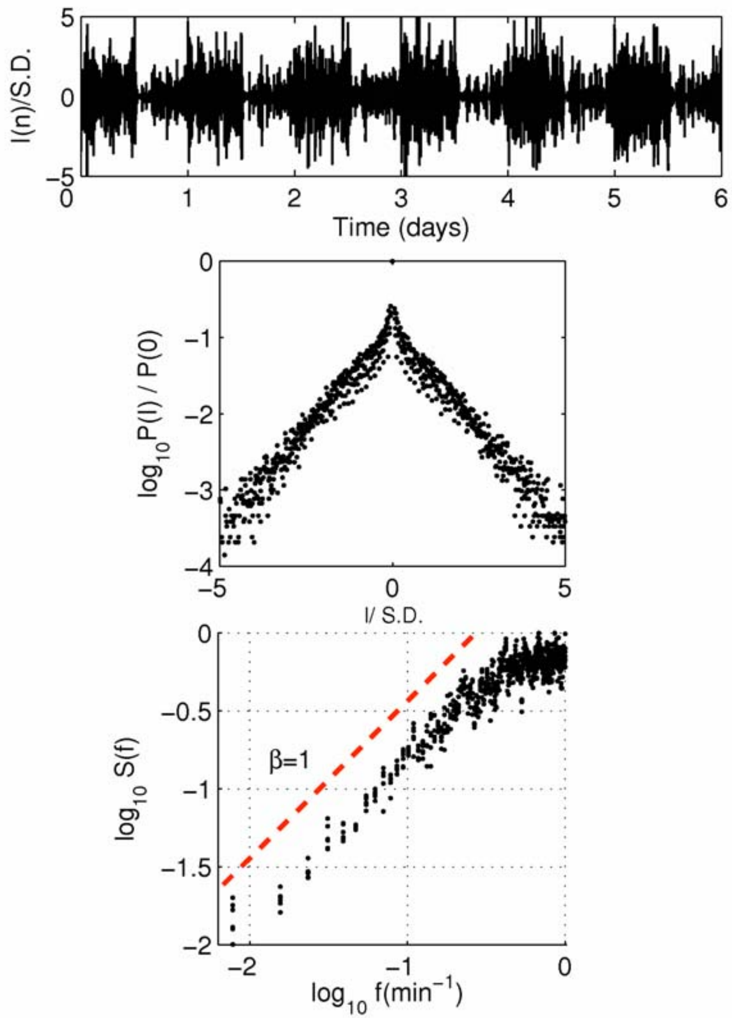
log10 Waiting Time , Duration (sec)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Time (days)
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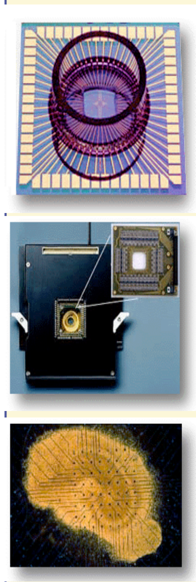
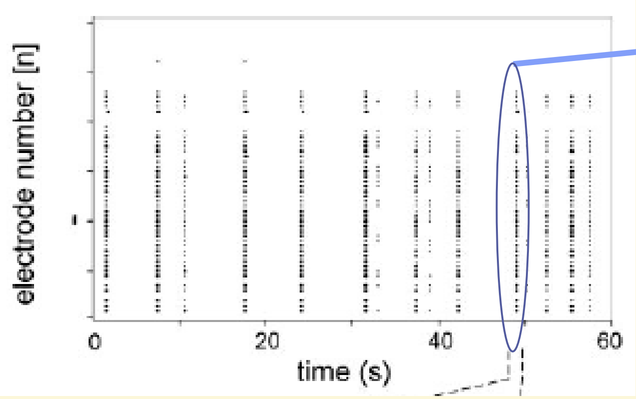
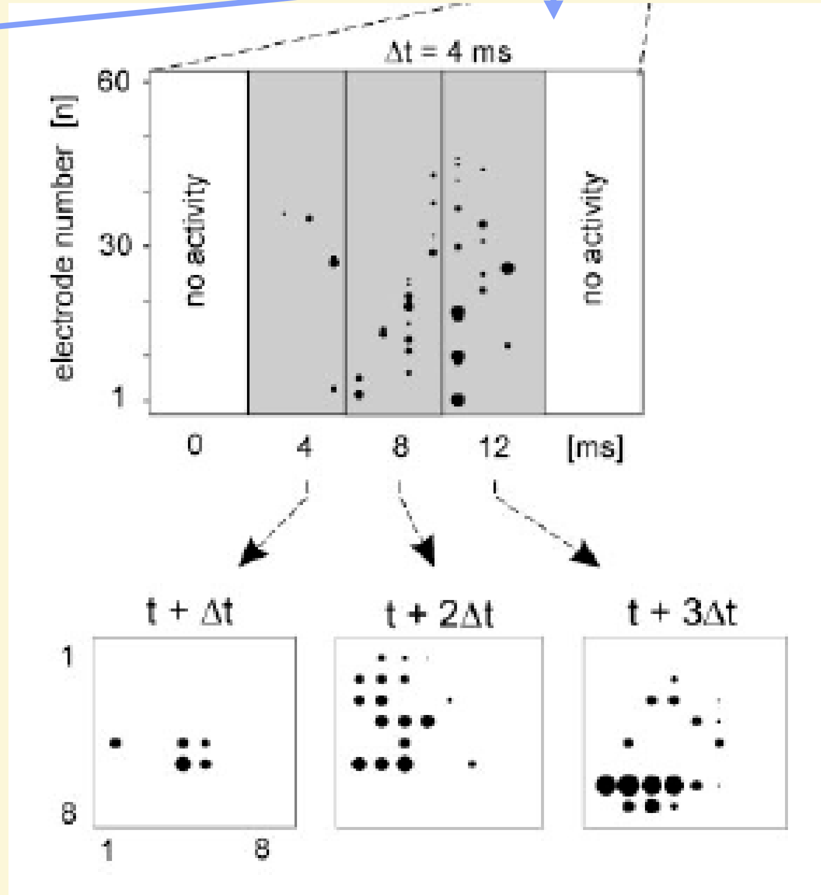
−4
log10 P(I) / P(0)
−5
0
5
I/ S.D.
0
−0.5
−1
−1.5
−2
log10 S(f)
β=1
−2
−1
0
log10 f(min−1)

Aplicaciones: Neuronal avalanches



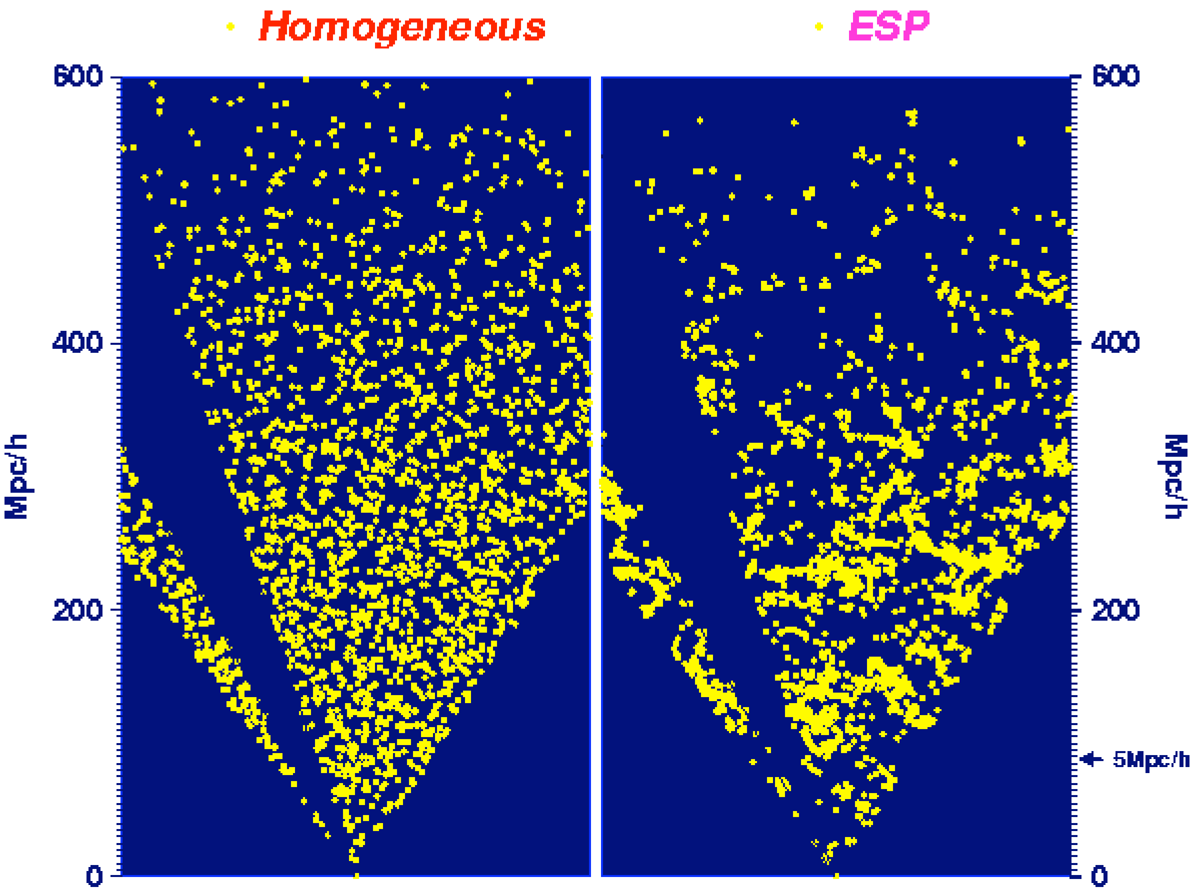


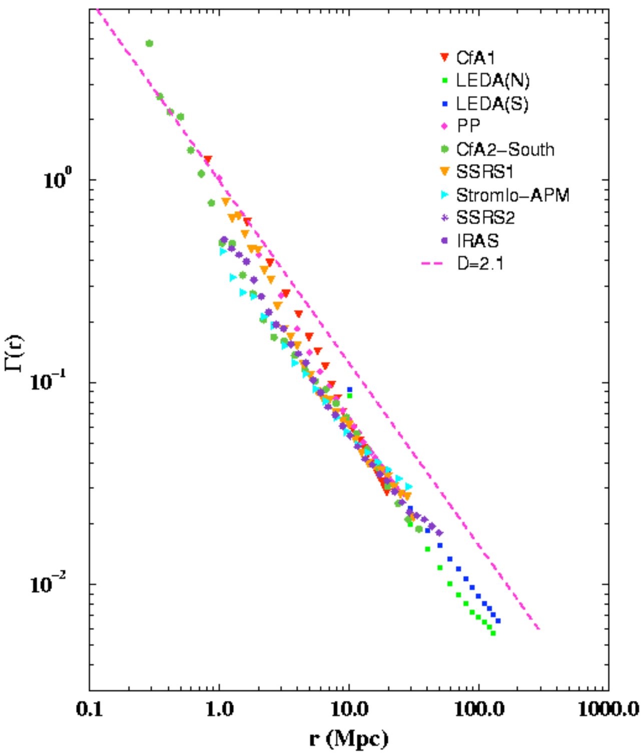


"Neuronal avalanches"

From Beggs & Plenz J. Neurosci., 2003 • 23(35):11167

El universo es fractal ...complejo





Full correlation for the various available redshift catalogues in the range of distances 0.1 -100 Mpc/h .