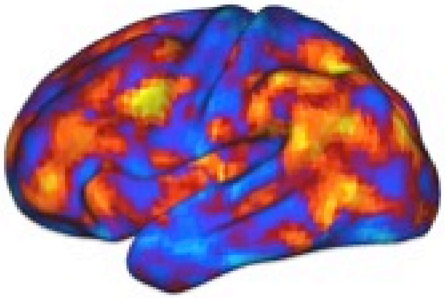
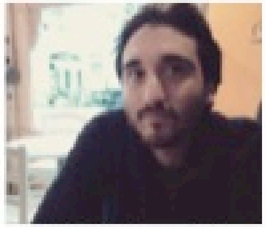


The brain at the edge

Enzo Tagliazucchi



Ariel Haimovici

Dante R. Chialvo
dchialvo@ucla.edu
Papers: www.chialvo.net

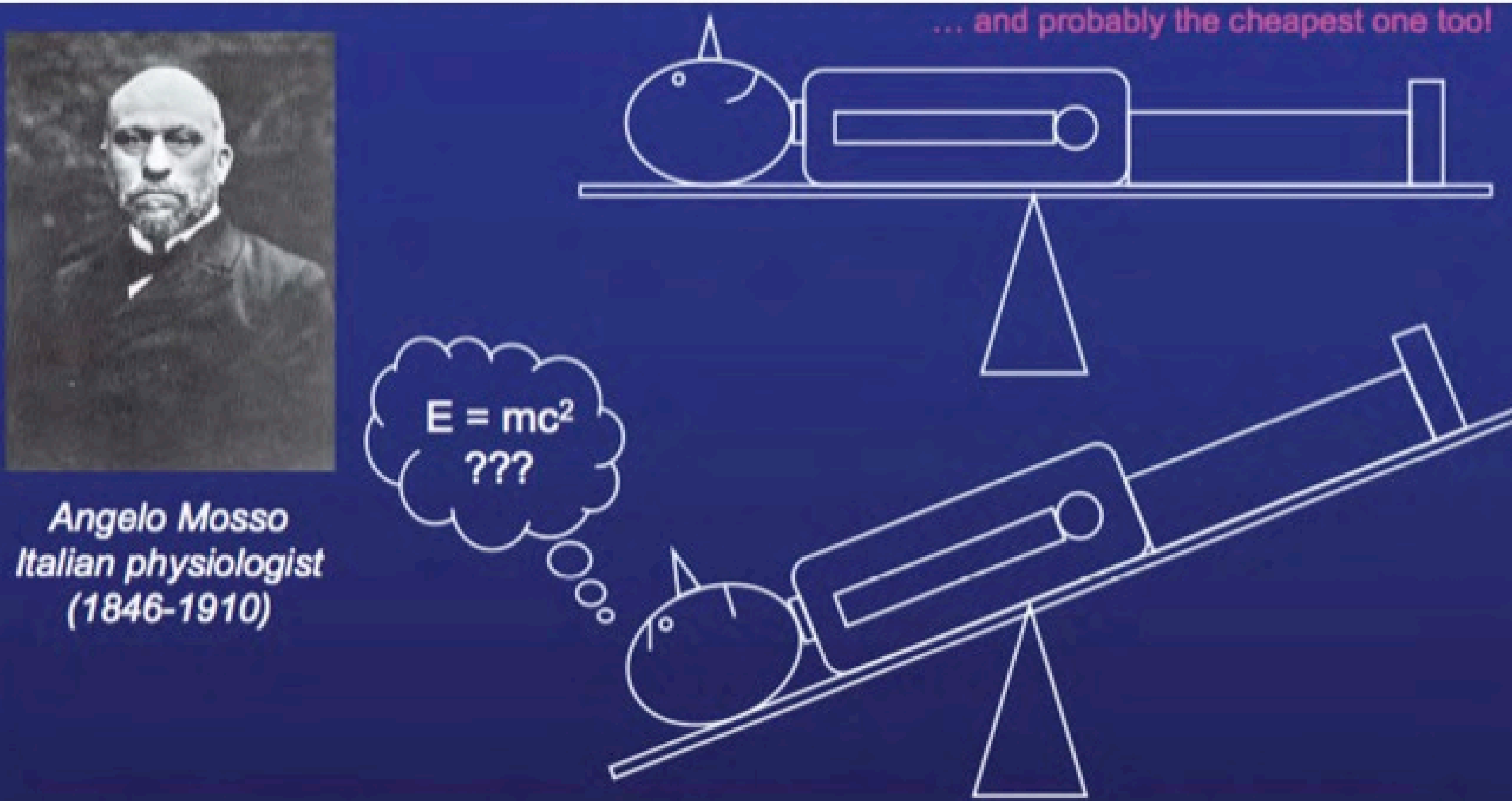
Dresden June 18, 2014

CONICET

Emc^3 Lab

Estudios **M**ultidisciplinarios en **C**iencias del **C**erebro y sistemas **C**omplejos

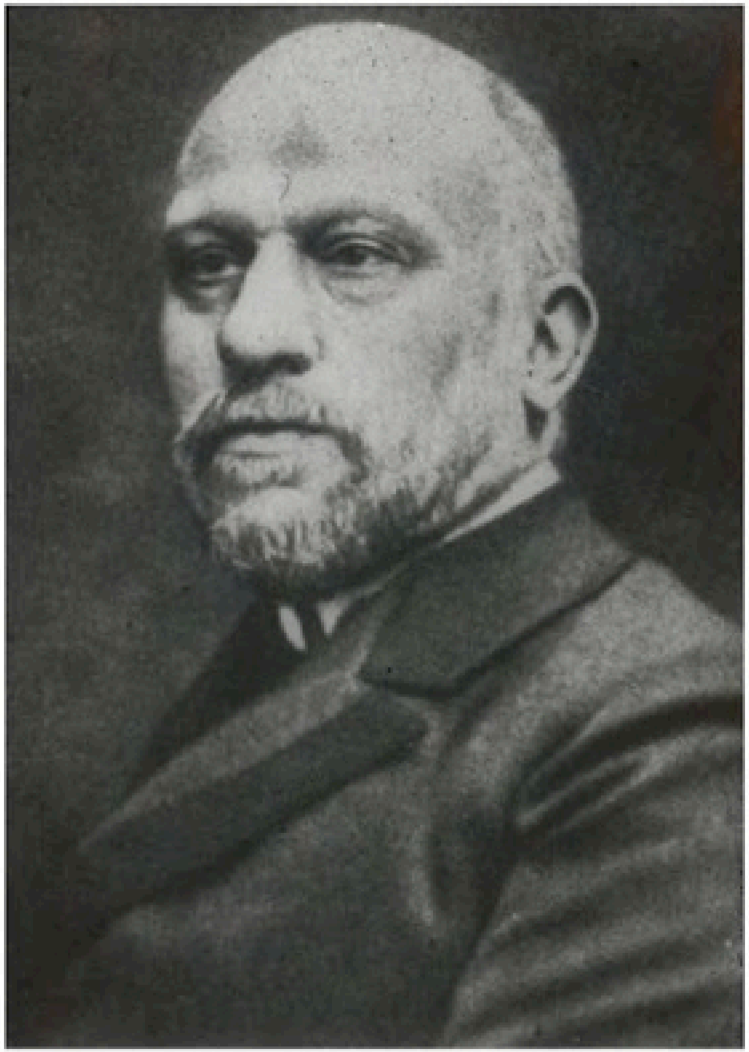
The first brain critical experiment (~1880)



"[In Mosso's experiments] the subject to be observed lay on a delicately balanced table which could tip downward either at the head or at the foot if the weight of either end were increased. The moment emotional or intellectual activity began in the subject, down went the balance at the head-end, in consequence of the redistribution of blood in his system."

– William James, *Principles of Psychology* (1890)

The first connection between blood flow and mental activity



Angelo Mosso
30 May 1846 - 24 November 1910

Veber den Kreislauf des Blutes in Menschlichen Gehirn (Concerning the circulation of the blood in the human brain)
Verlag von Viet & Company: Leipzig, 1881

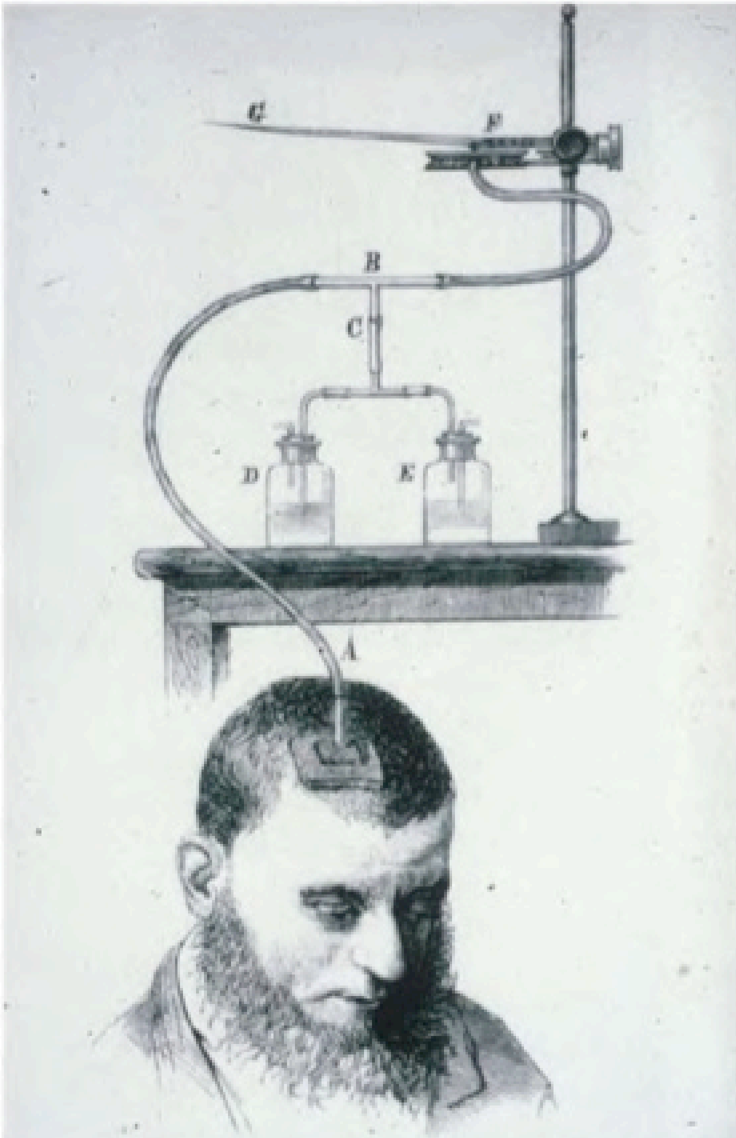
Inventor of the first device to measure muscle force


Angelo Mosso
e il suo ergografo
(archivio ASTUT)

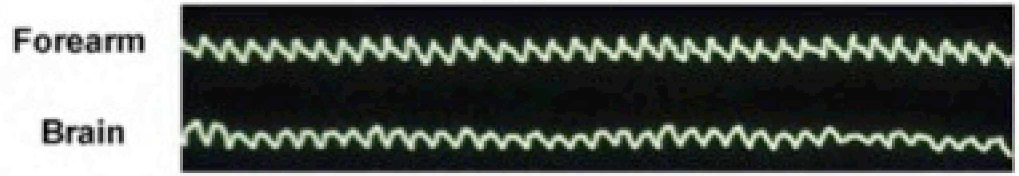

Chimografo E. Zimmermann. Leipzig - 1898

Monday noon, September 23, 1878

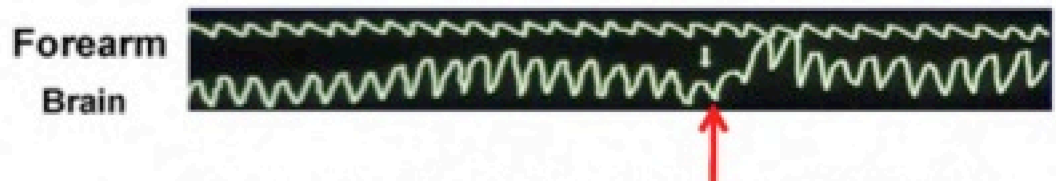
1878 Experiment with Bertino



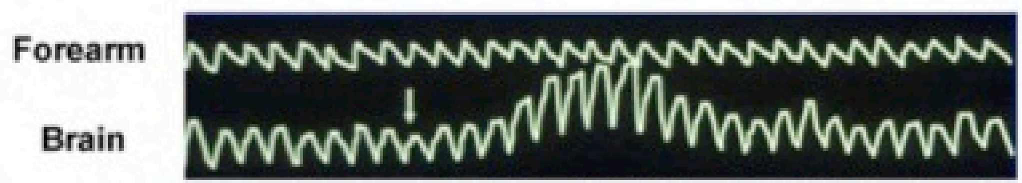
From: Angelo Mosso (1881)



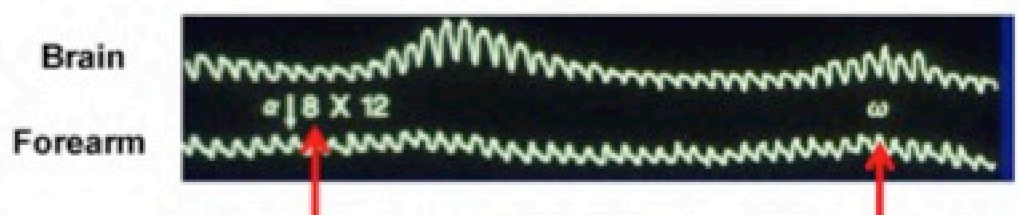
Resting quietly



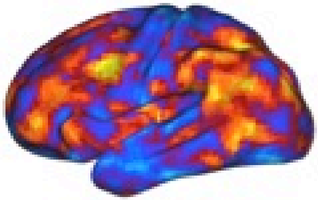
Arrow: room clock strikes 12 noon and of church bells heard



Arrow: Mosso asked Bertino if the Ave Maria should have been said



"What is 8 x 12?" ω: response



Now we know better why Mosso was unsuccessful in his critical experiment…

- *The brain exhibits large spontaneous activity ("brain noise")*
- *This activity evolves on the (so-called) Resting State Networks (RSN)*
- *Even "not doing anything" the brain uses 30% of the body energy* ~ 30 Watts
- *When "does something" a few places increase 1 - 2 % that number*

What is the origin and mechanism of that "noise"?

Answer: critical dynamics

Two recent reviews

(download from www.chialvo.net/Publications)

nature physics

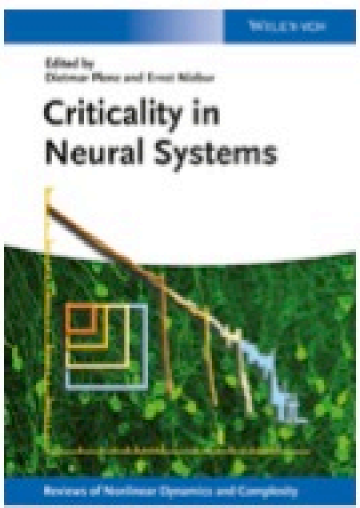
REVIEW ARTICLE

PUBLISHED ONLINE: XX MONTH XXXX | DOI: 10.1038/NPHYS1803

Emergent complex neural dynamics

Dante R. Chialvo[1,2]*

A large repertoire of spatiotemporal activity patterns in the brain is the basis for adaptive behaviour. Understanding the mechanism by which the brain's hundred billion neurons and hundred trillion synapses manage to produce such a range of cortical configurations in a flexible manner remains a fundamental problem in neuroscience. One plausible solution is the involvement of universal mechanisms of emergent complex phenomena evident in dynamical systems poised near a critical point of a second-order phase transition. We review recent theoretical and empirical results supporting the notion that the brain is naturally poised near criticality, as well as its implications for better understanding of the brain.



Critical Brain Dynamics at Large Scale

Dante R. Chialvo

Some general properties expected near the critical point of a continuous phase transition:

- Long range correlations in space and time.
- Correlation length scales with system size
- Anomalous scaling of the variance of the fluctuations
- Variance of the order parameter peaks at the critical point (susceptibility)
- Scaling in the clusters size distribution
- Scaling of avalanches sizes

- Long range correlations in space and time.

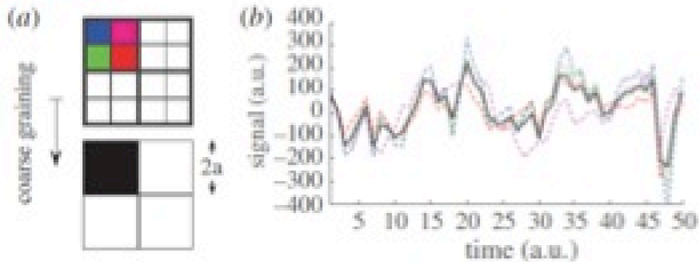
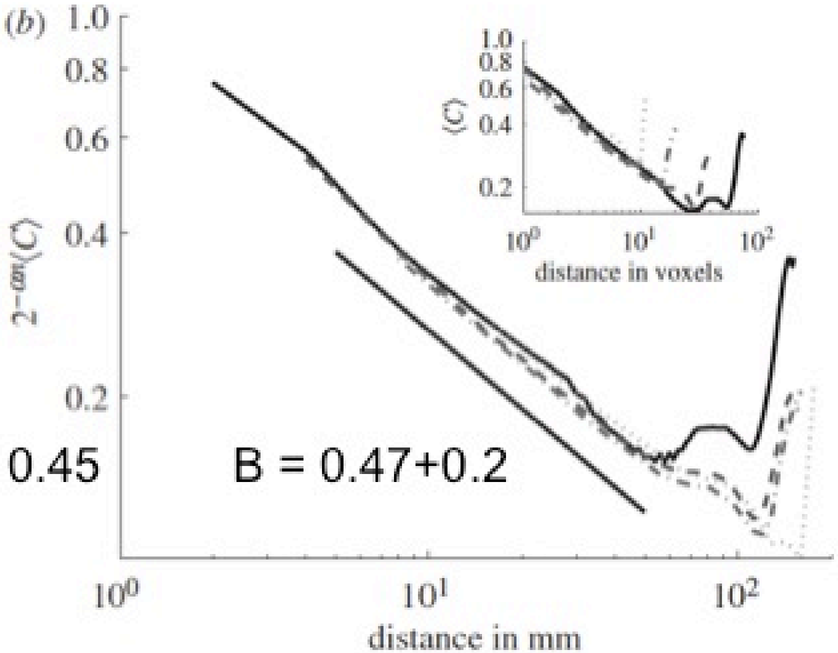


Figure 6. (*a*) Example of coarse graining in two dimensions where there are four boxes *B* within a block-box *B*'. (*b*) The four dashed-coloured signals from the four original boxes *B* are averaged to produce the solid-black coarse-grained signal of *B*'.



α= 0.45 B = 0.47+0.2

JOURNAL OF THE ROYAL SOCIETY Interface

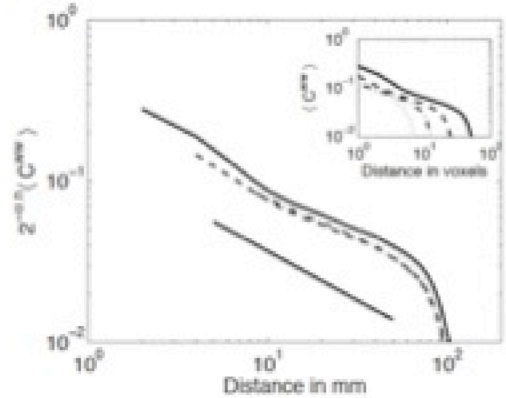
J. R. Soc. Interface (2010) 00, 1–8
doi:10.1098/rsif.2010.0416
Published online 00 Month 0000

Self-similar correlation function in brain resting-state functional magnetic resonance imaging

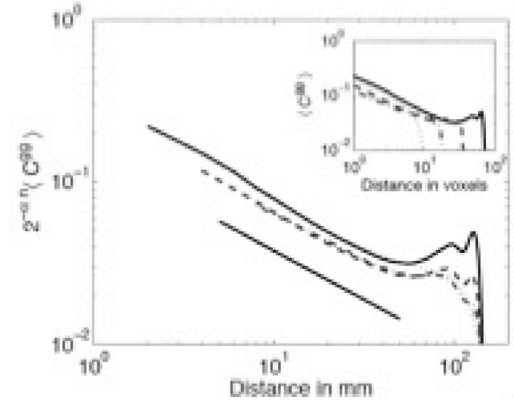
Paul Expert[1,2], Renaud Lambiotte[1], Dante R. Chialvo[4], Kim Christensen[1,2], Henrik Jeldtoft Jensen[1,3,*], David J. Sharp[5] and Federico Turkheimer[5]

[1]Institute for Mathematical Sciences, 53 Prince's Gate, Exhibition Road, Imperial College London, London SW7 2PG, UK

White matter



Grey matter



Some general properties expected near the critical point of a continuous phase transition:

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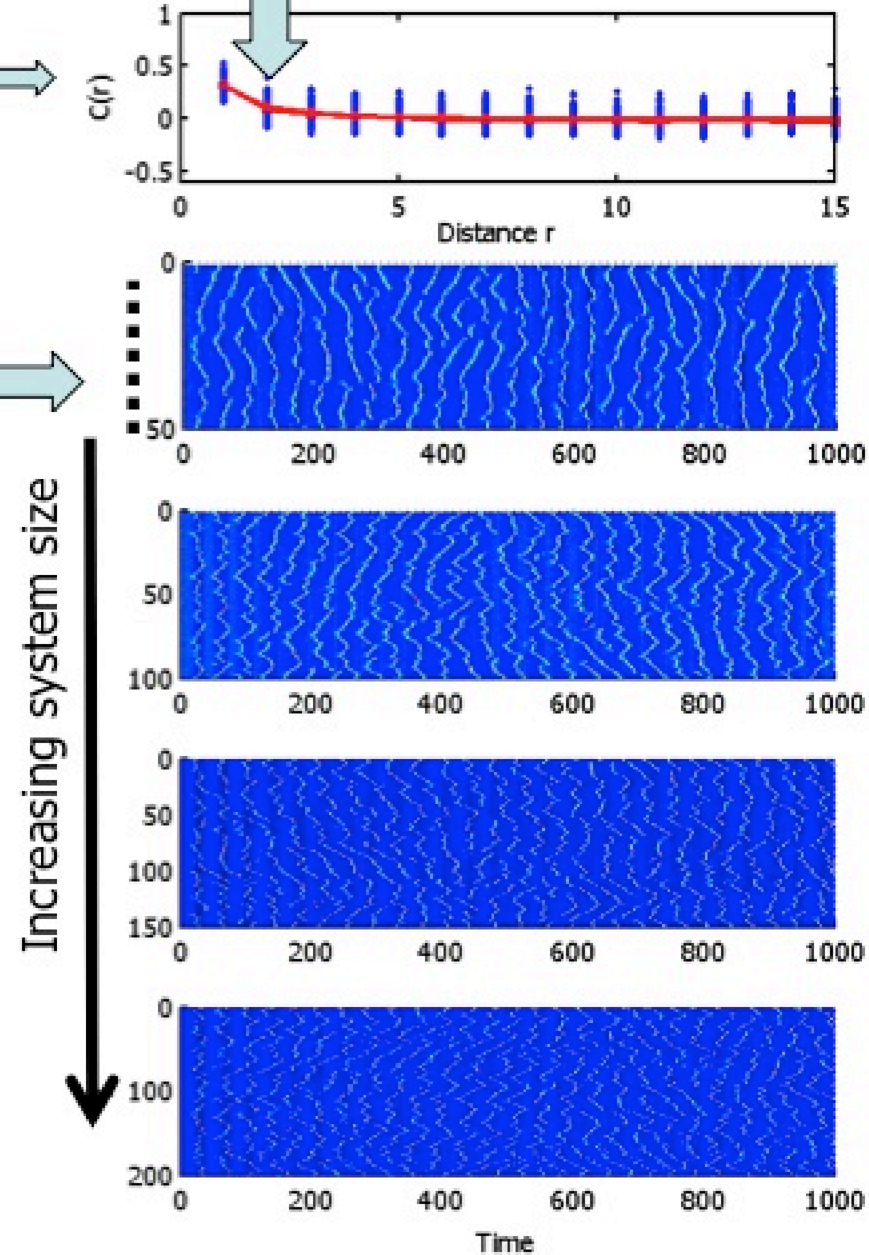
- Scaling of avalanches sizes

Simple example of a apparently complex dynamic with finite correlation length

1- Estimate the (average) two point correlation function of all pairs (as a function of Euclidean distance between the pair)

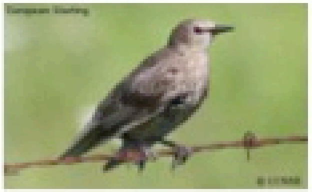
2- Repeat for increasing system's size



In this example the correlation length is a constant: is the trivial "wave length"

one
bird

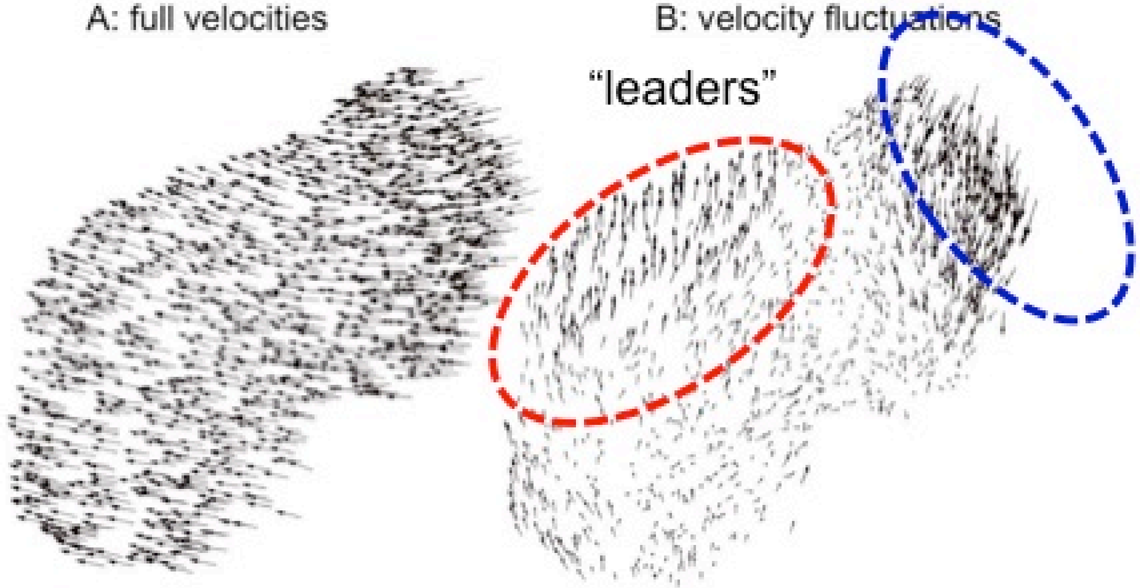
two
birds



Too
many
birds

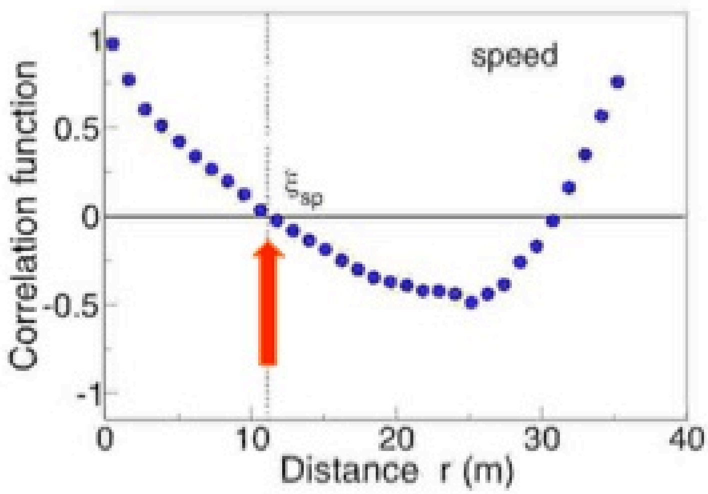
300000 starlings in the spring (real time.)

Example of a complex dynamic with non-finite correlation length

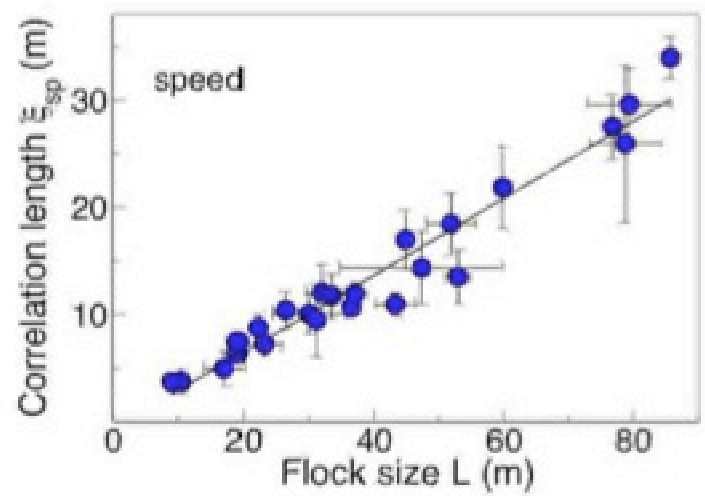


10 meters

Correlation function of one flock

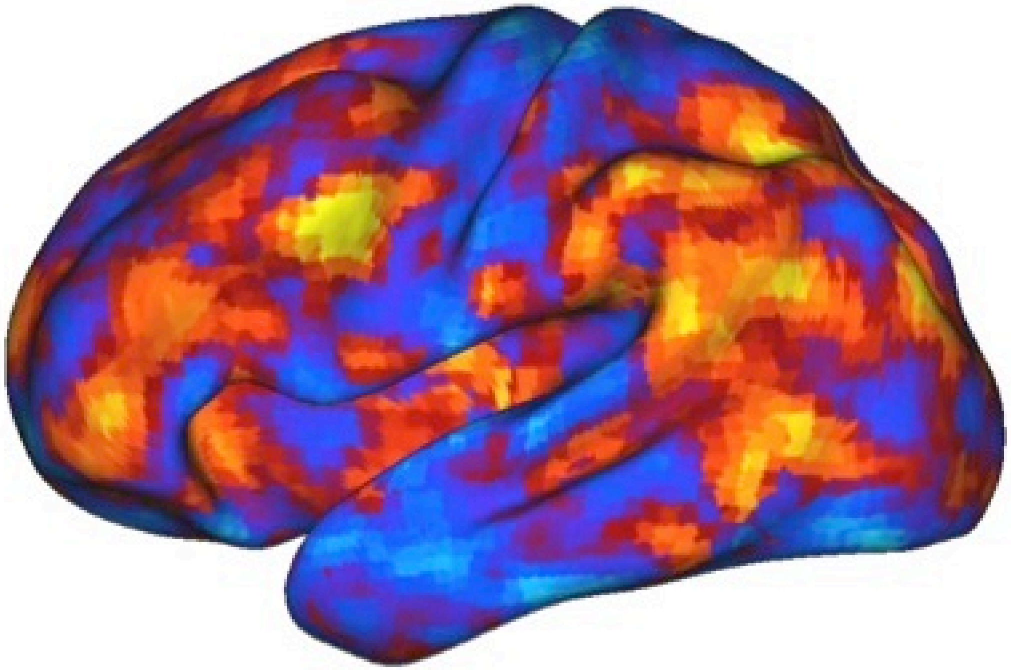


Correlation length of many flocks

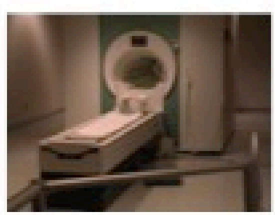


From Andrea Cavagna et al, Scale-free correlations in bird flocks, arXiv:0911.4393, (2010); Also in PNAS (2010)

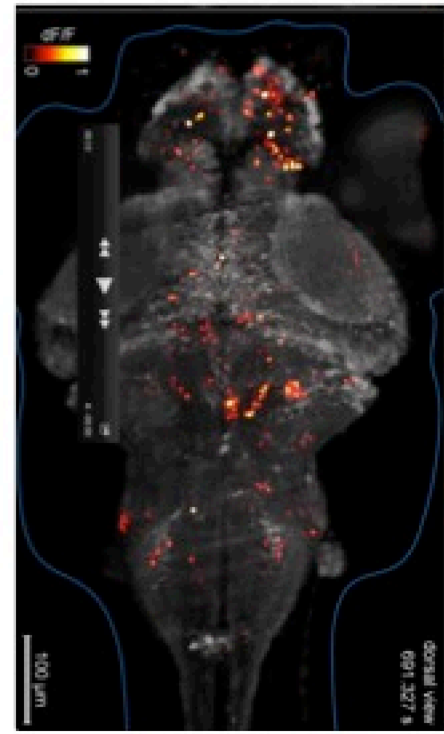
Example of another complex dynamics



fMRI data from a healthy subject during resting state, shown about 13 times faster than real time (BOLD signal with the mean substracted).



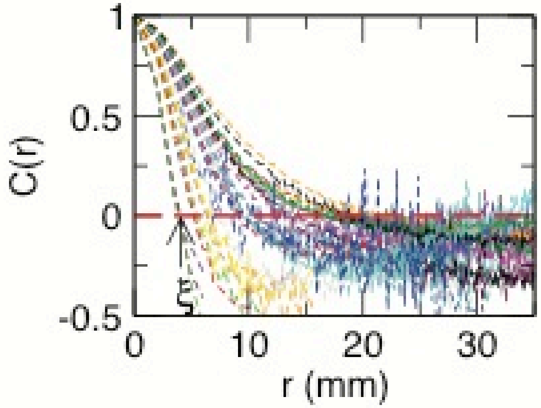
Head



Tail

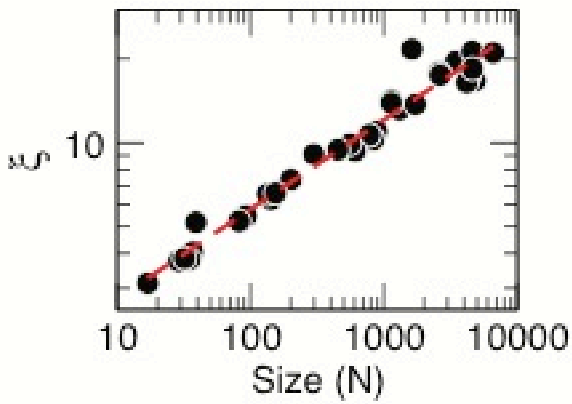
Whole-brain functional imaging at cellular resolution using light-sheet microscopy.
Misha B Ahrens et al , Nature Methods. (2013)

Compute the average two point correlation for blobs, plot as a function of distance



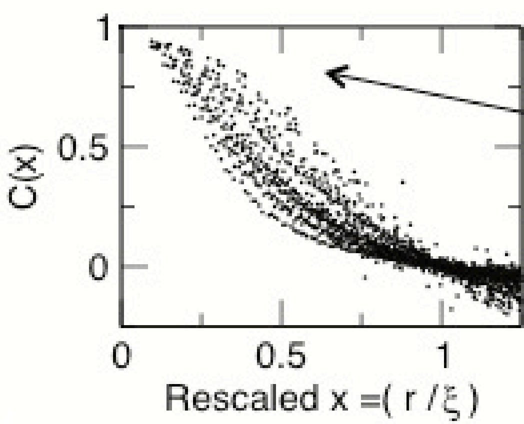
Correlation length diverges with cluster size

Correlation length



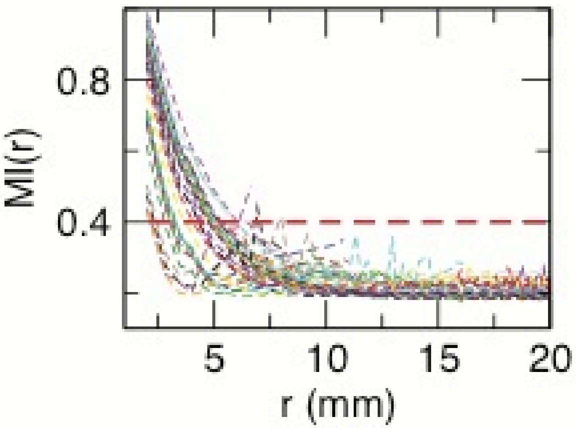
Big, intermediate and small “blobs” behaves all in the same way

The bottom line: Two places 4 mm appart on a blob of 20 voxels are as correlated as those 40 mm appart on a blob of 4000 voxels



Rescaled C(x) is not very good and worst for less spherical blobs, as expected

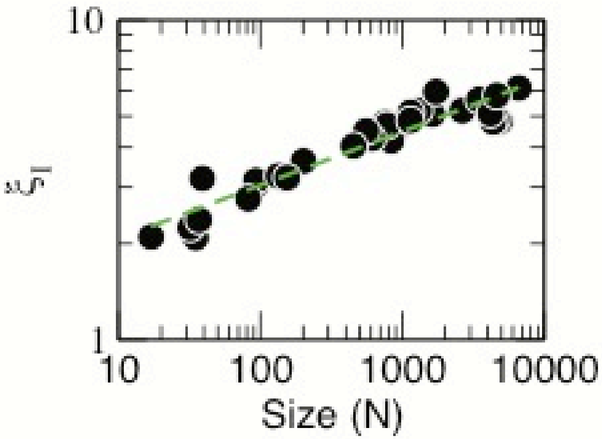
Fraiman D. & Chialvo DR. What kind of noise is brain noise. Frontiers in Fractal Physiology. (2012)



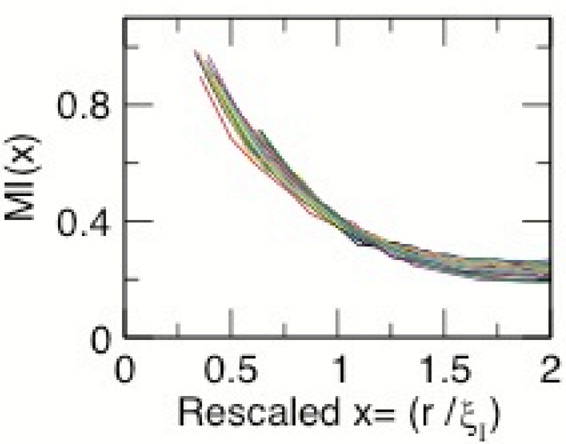
Doing the same for Mutual Information

$$MI(X;Y) = H(X) - H(X \mid Y)$$

Mutual information MI(r) as a function of distance r averaged over all time series of each of the thirty five blobs.



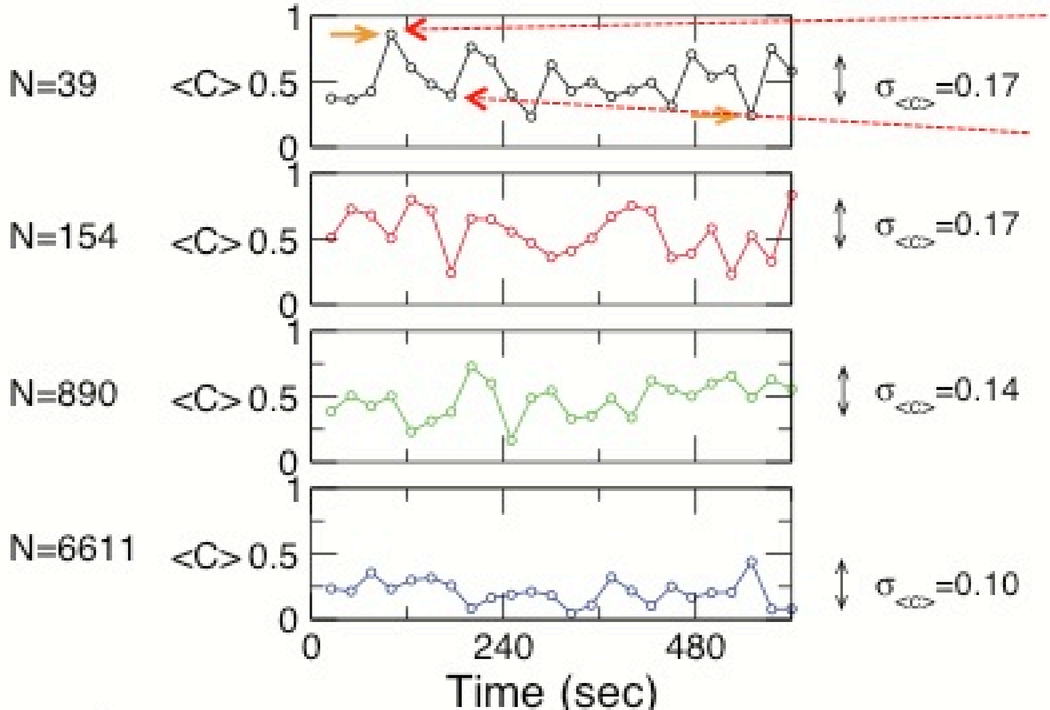
Mutual information diverges with cluster size.



Rescaled mutual information

Fraiman D. & Chialvo DR. What kind of noise is brain noise. Frontiers in Fractal Physiology. (2012)

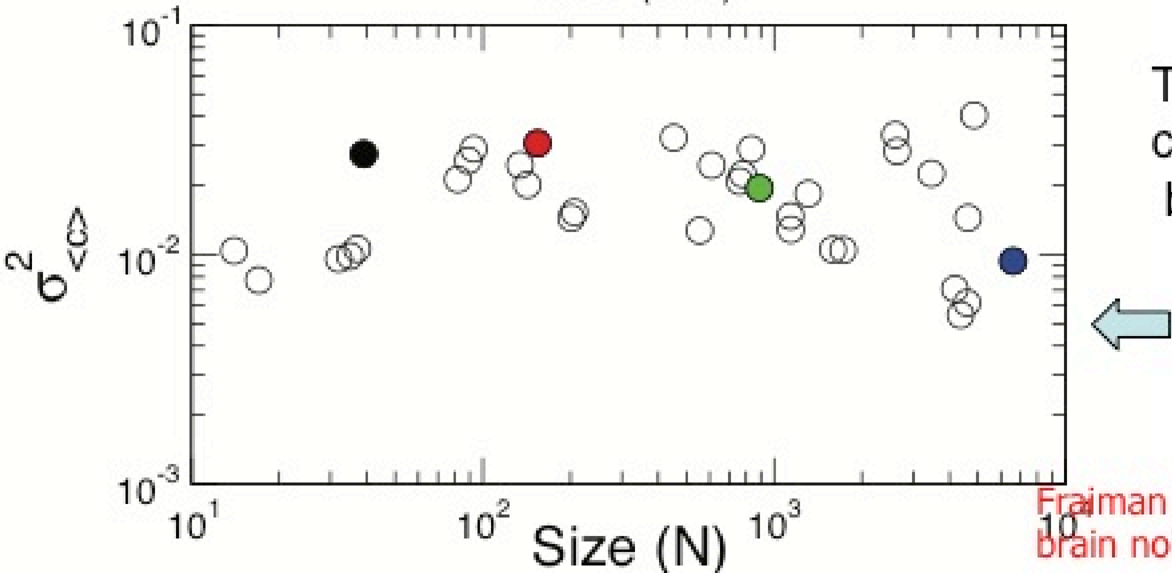
Transient bursts in the correlation at all sizes



Spikes of high correlation

Spikes of low correlation

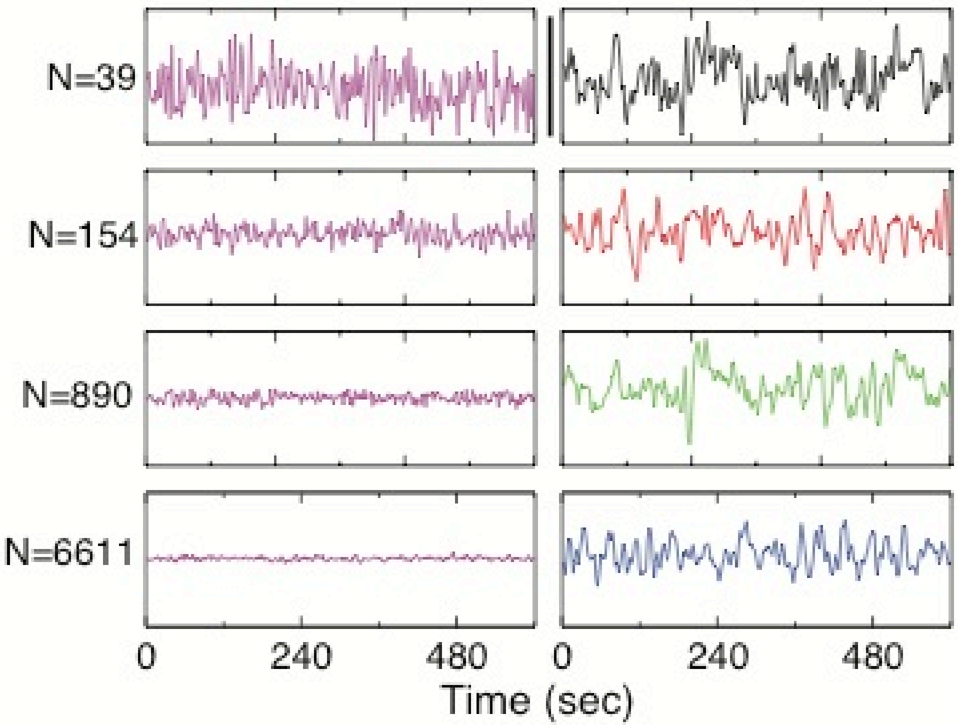
The variance of the correlations is **independent** of the blob size



The variance of the correlations computed for the thirty five blobs is **independent** of size

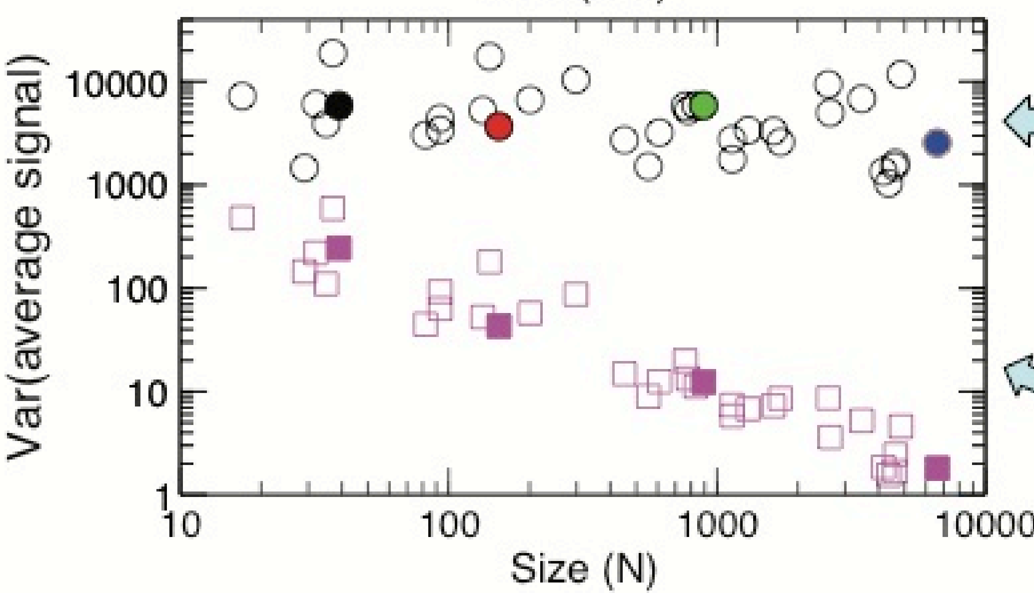
Fraiman D. & Chialvo DR. What kind of noise is brain noise. Frontiers in Fractal Physiology. (2012)

Anomalous scaling of the variance of the mean "brain activity"



The variance of the temporal fluctuations is **independent** of the blob size.

Moral:
Brain numerical models, by construction, WONT scale like that!!



○ variance of the fluctuations computed for the thirty five blobs

□ variance of the fluctuations computed for randomized data

Fraiman D. & Chialvo DR. What kind of noise is brain noise. Frontiers in Fractal Physiology. (2012)

Some general properties expected near the critical point of a continuous phase transition:

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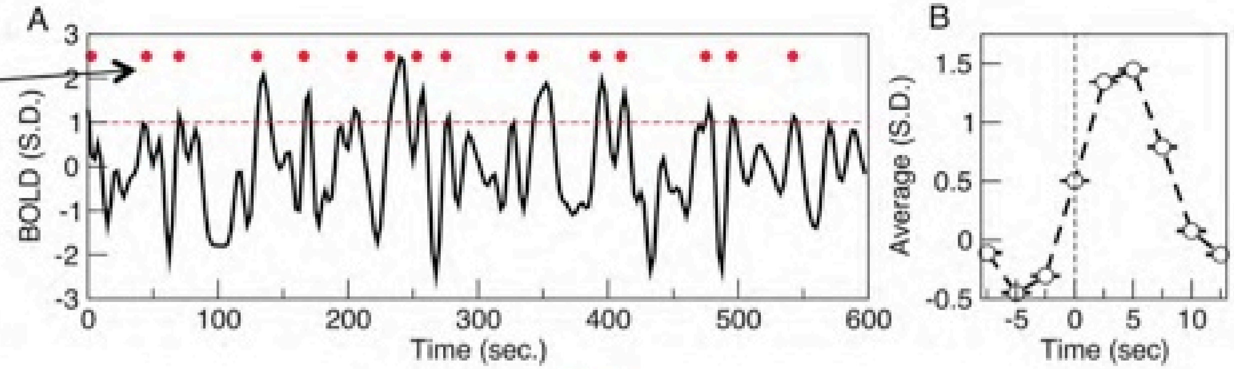
- Scaling in the clusters size distribution
- Scaling of avalanches sizes

We need to resample the dynamics

Let call Poincare

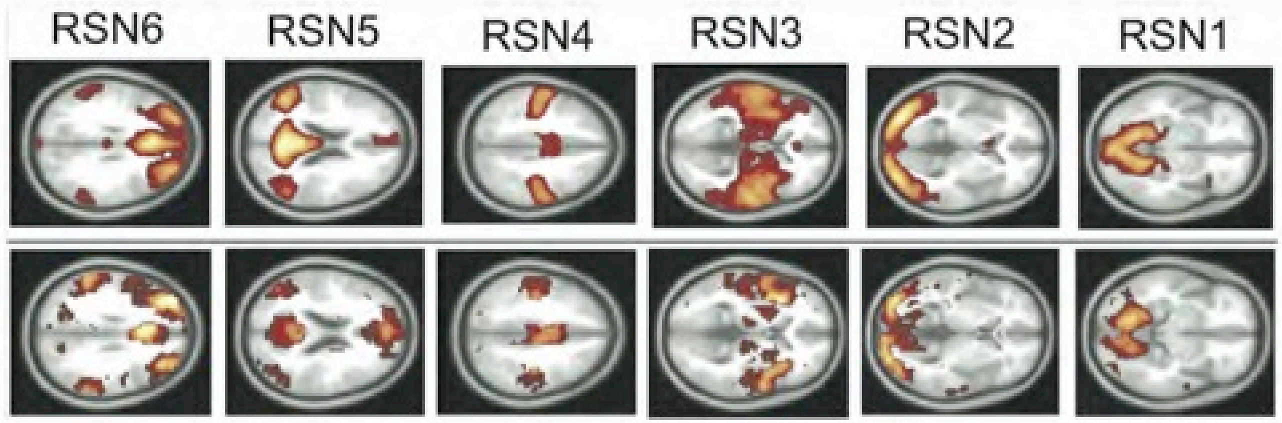
(Compresing and resampling thanks to Poincare)

Keep only the points and throw away > 95% of the data
Chialvo et al, (arXiv: 1107.4572)



Independent Comp.

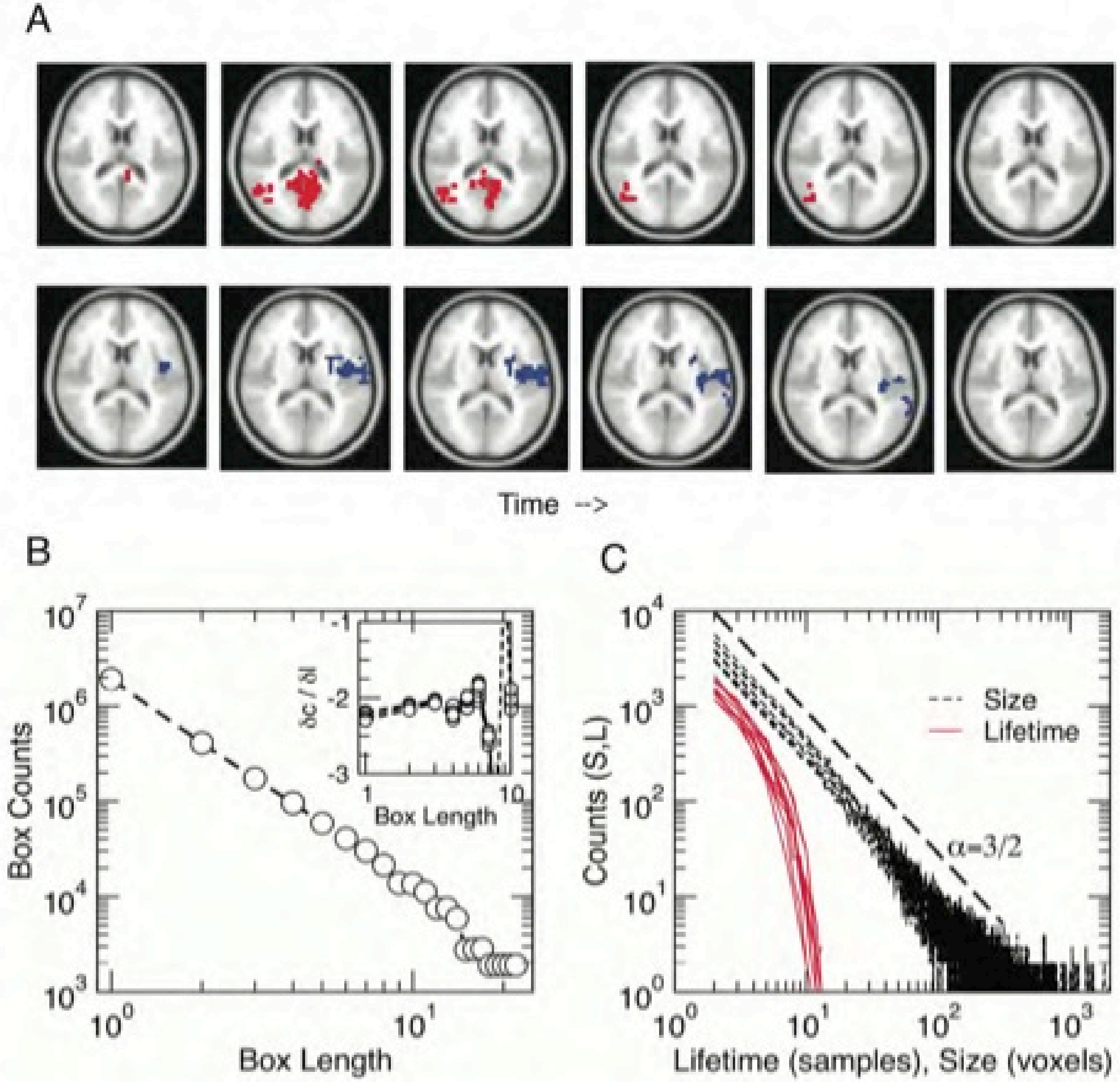
Point Process



Moral: Despite the huge data reduction (> 95%) a few points holds more of the information.

From Tagliazucchi et al (2011)

Earthquakes in your head



From Tagliazucchi et al (2011)

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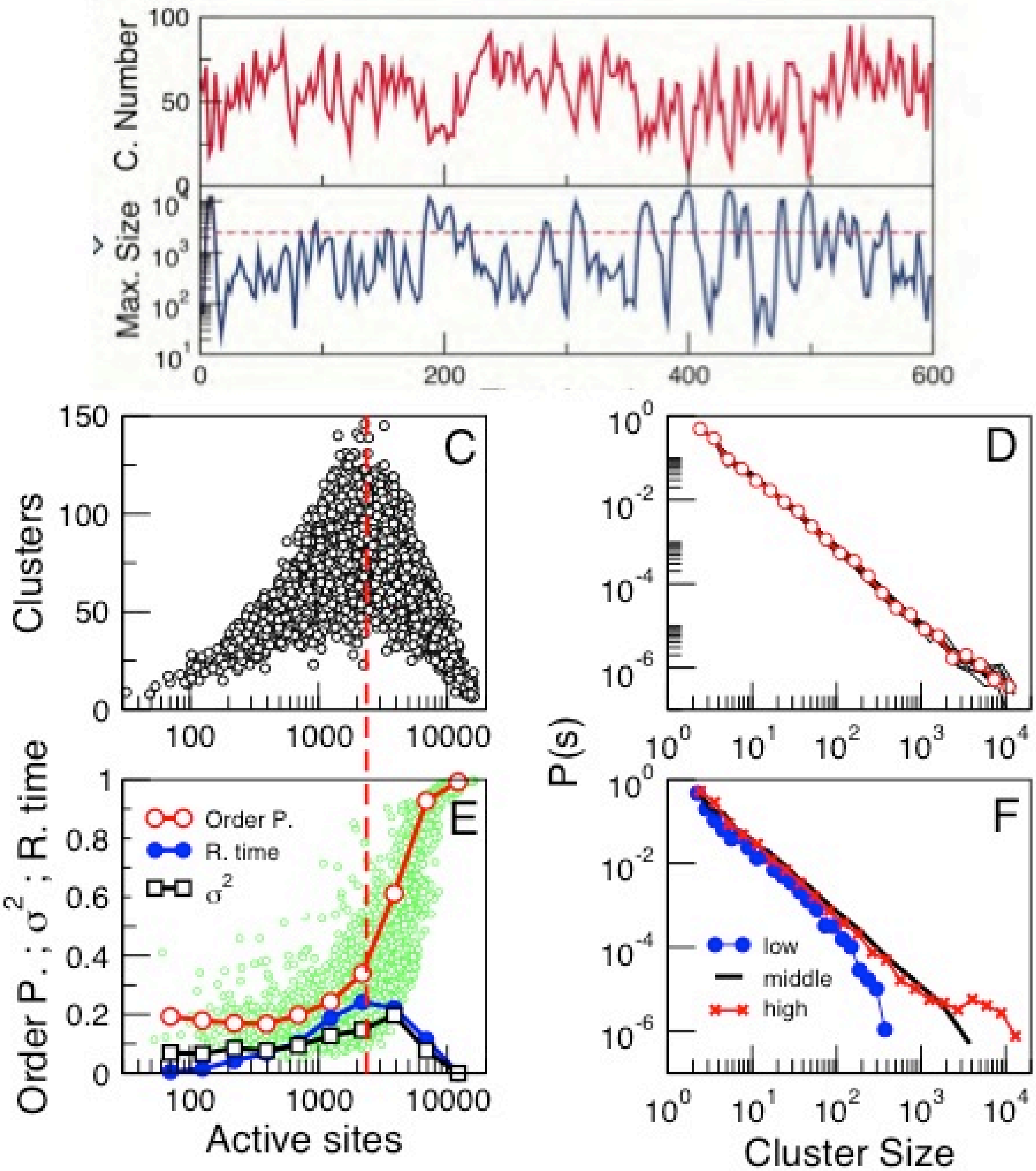
C. Number
Max. Size
C
D
E
F
Clusters
Order P. ; σ²; R. time
Order P.
R. time
σ²
Active sites
P(s)
low
middle
high
Cluster Size

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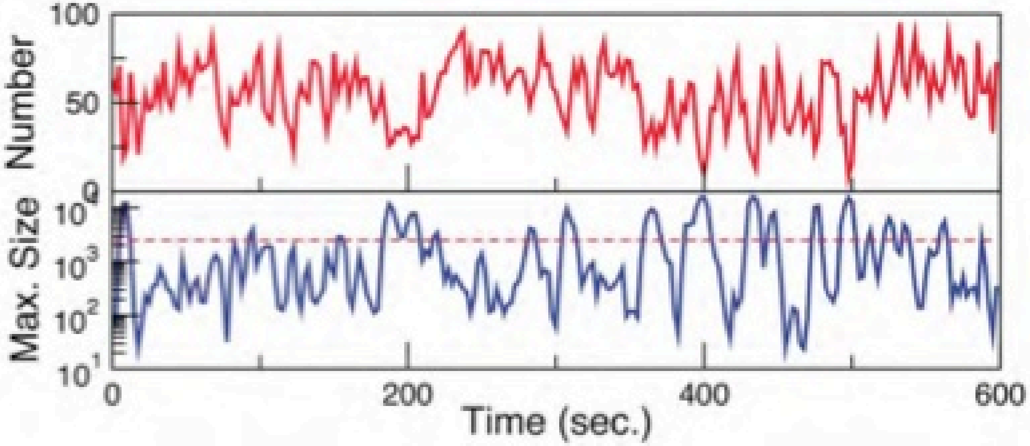
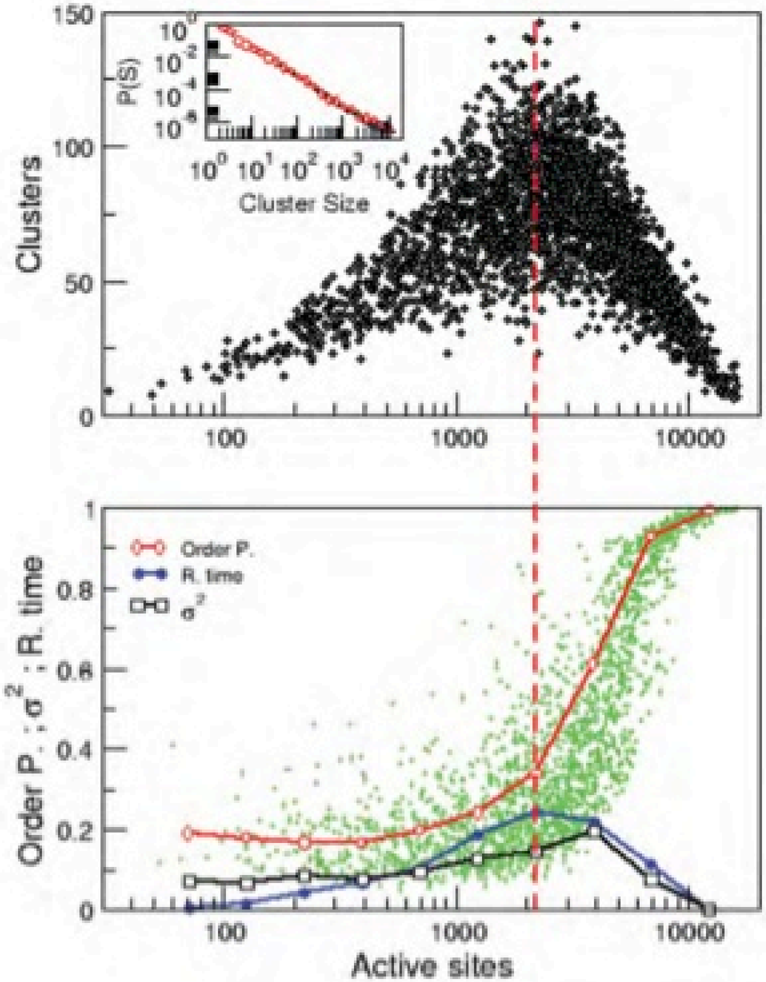
- ✓ Scaling of avalanches sizes
- ✓ Scaling in the clusters size distribution
- Variance of the order parameter peaks at the critical point (susceptibility)

Largest variance



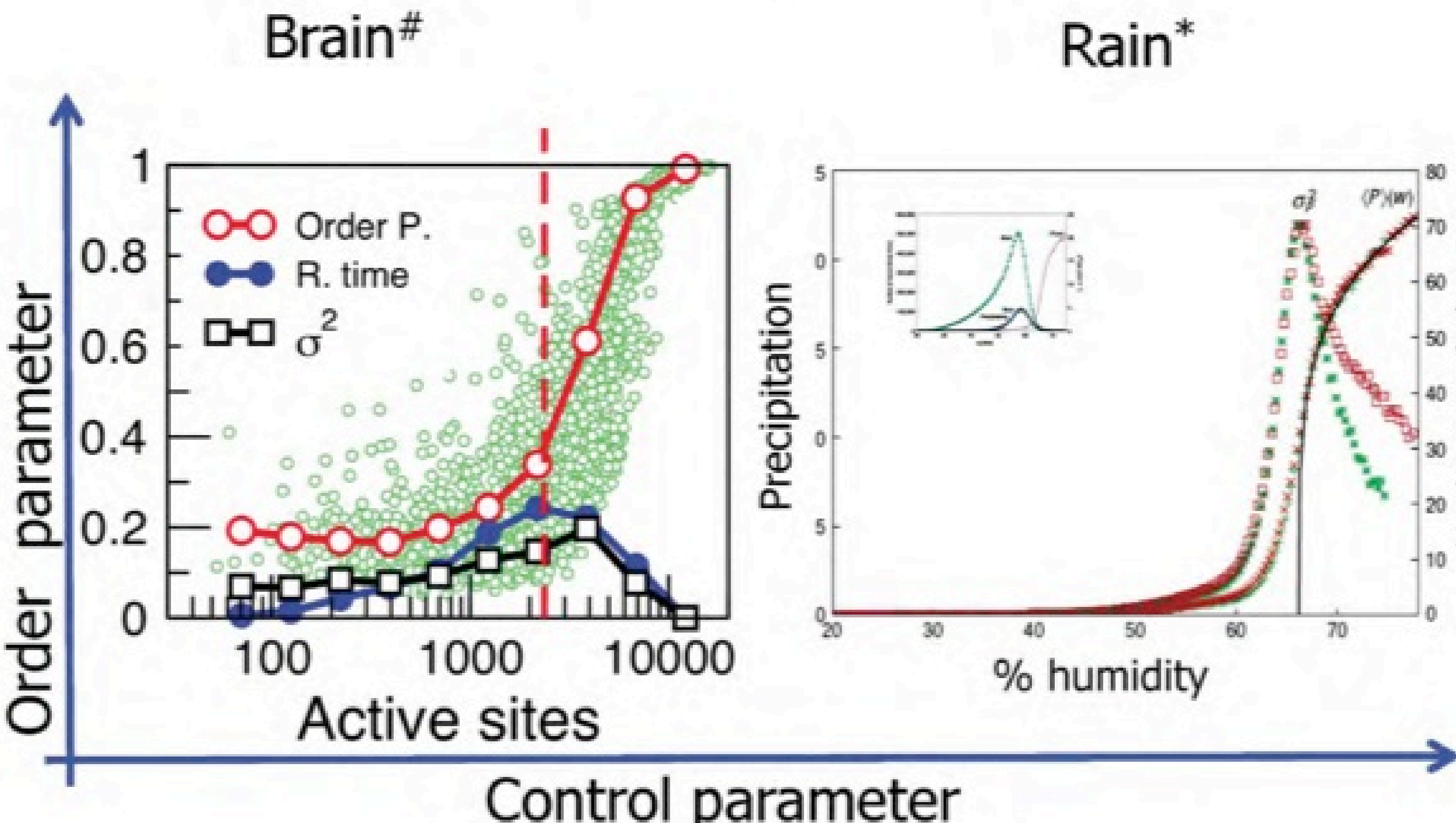
A phase transition



Some general properties expected near the critical point of a continuous phase transition that are seen in fMRI brain data:

- ✓ Long range correlations in space and time.
- ✓ Correlation length scales with system size
- ✓ Anomalous scaling of the variance of the fluctuations
- ✓ Scaling of avalanches sizes
- ✓ Scaling in the clusters size distribution
- ✓ Variance of the order parameter peaks at the critical point (susceptibility)

The end of Brain SOC?



*Peters & Neelin, Nature Phys. (2006).

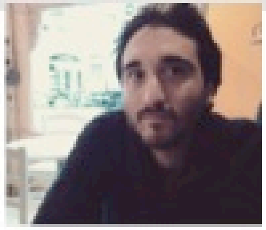
Tagliazucchi et al, Frontiers (2012).

30

Lets do some modeling

Modeling the connectome

Brain Organization into Resting State Networks Emerges at Criticality on a Model of the Human Connectome
Ariel Haimovici, Enzo Tagliazucchi, Pablo Balenzuela, and Dante R. Chialvo
Phys. Rev. Lett. **110**, 178101 (2013) – Published April 22, 2013



Ariel Haimovici

Physics

Physics **6**, 47 (2013)

Viewpoint

The Critical Brain

Dietmar Plenz
Section on Critical Brain Dynamics, National Institute of Mental Health, NIH, Bethesda, MD 20892, USA

Published April 22, 2013

A model describing the brain as a system close to a phase transition can capture the global dynamics of brain activity observed in fMRI experiments.

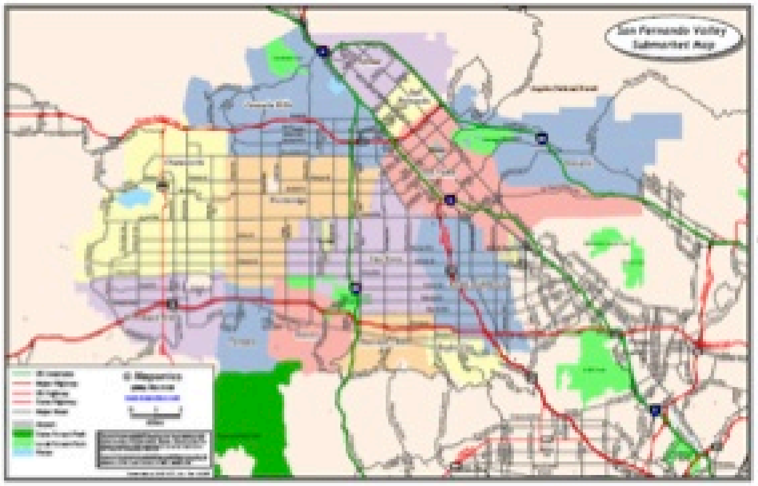
Subject Areas: **Biological Physics**

Mapping the brain: MegaProjects ($$$)

1. *Human Connectome Project, USA.*
2. *BRAIN (Brain Research through Advancing Innovative Neurotechnologies), USA.*
3. *Human Brain Project, Europe.*
4. *Brainnetome Project, China.*

---These projects all focus on determining "connections"…(brain as a "circuit")
--- Our work shows that connections are insufficient to understand the brain

A related problem to help our thinking traffic



+

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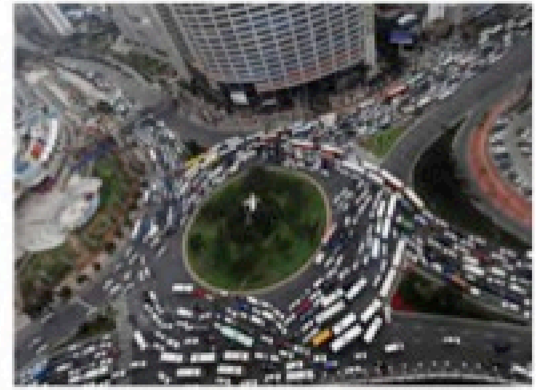
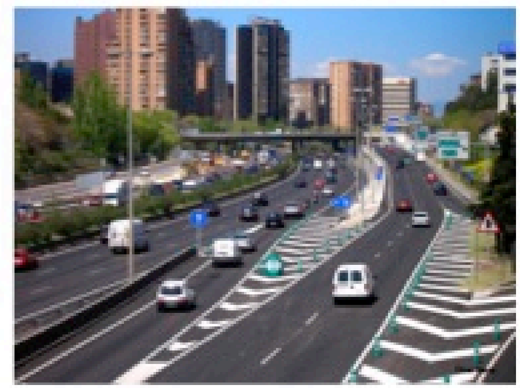


solid



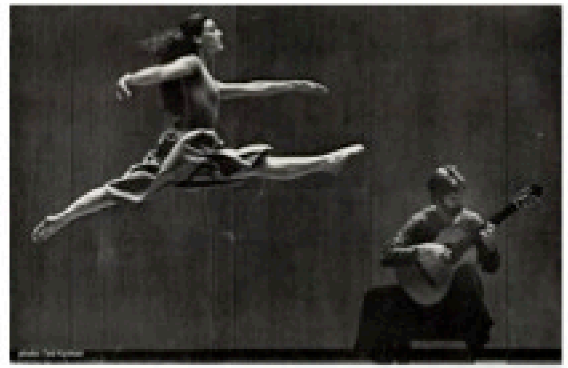
gas

structure + Individual Non-linear dynamics = "phases"

"Streetome"

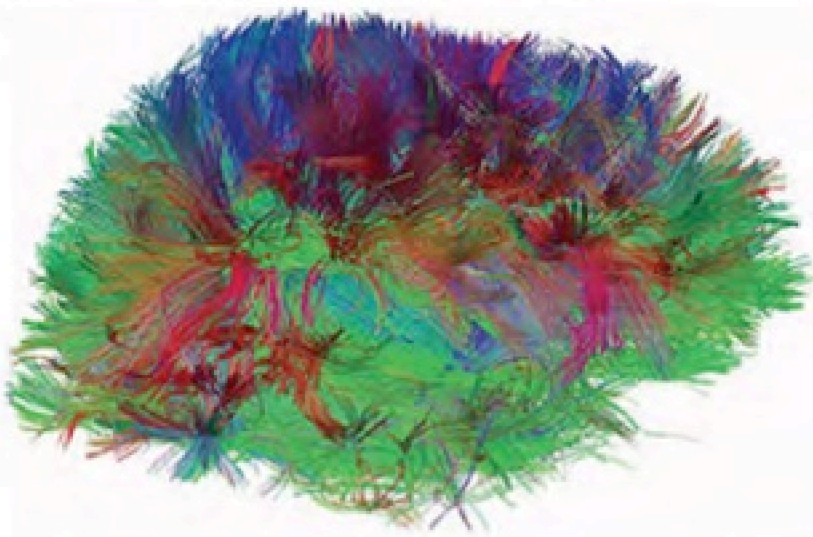
The problem:

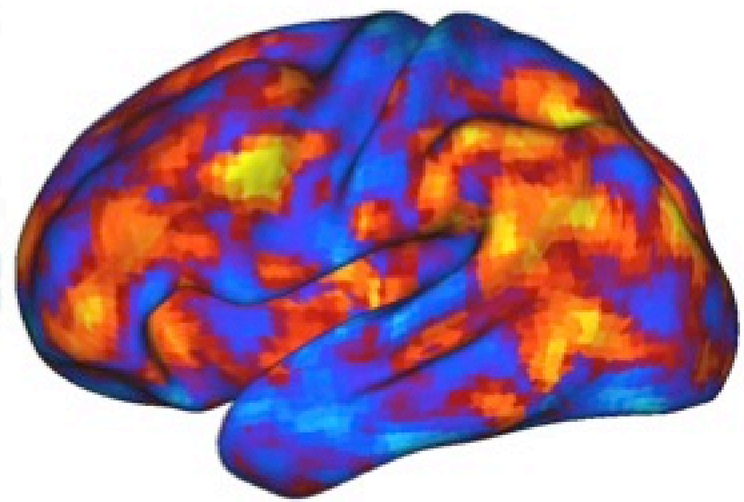
Behaviors



long term

short term

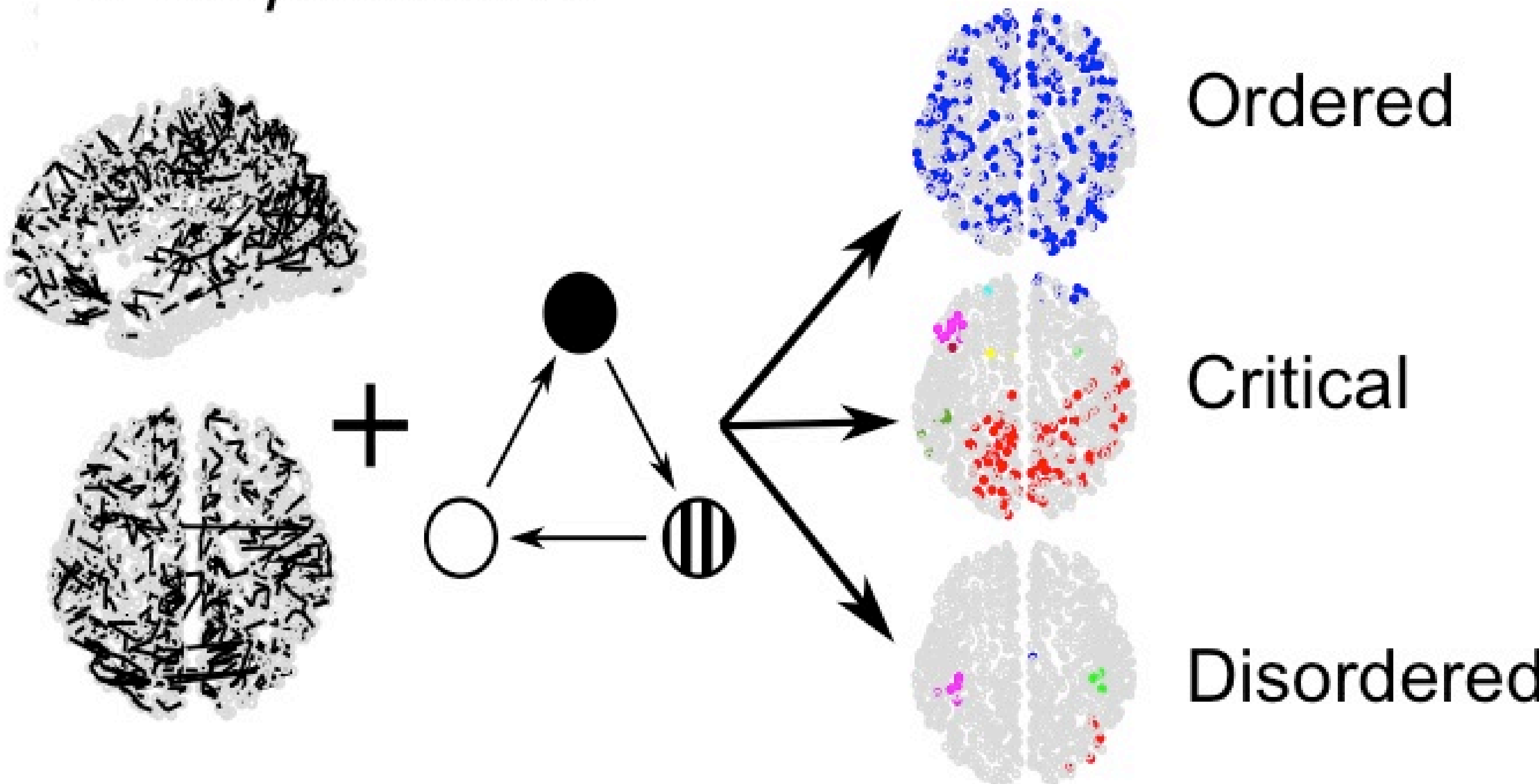




Connectome

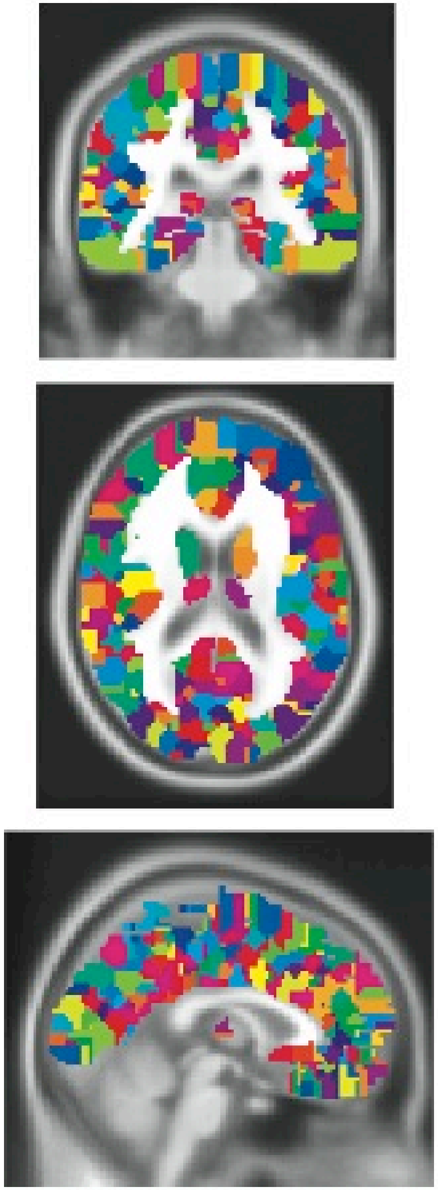
Collective dynamics

The solution:
A simple model

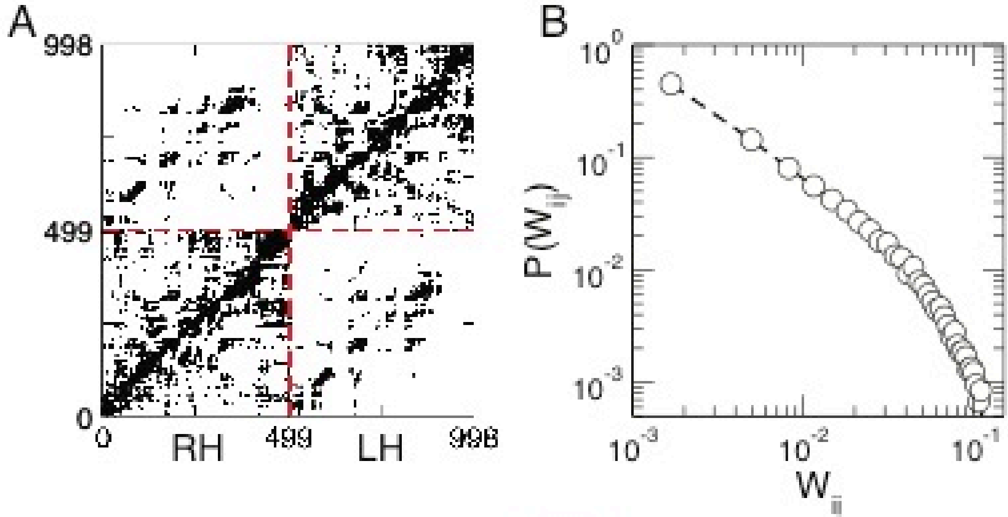


Structure + Individual Non-linear dinamics = phases

The structure: the human connectome



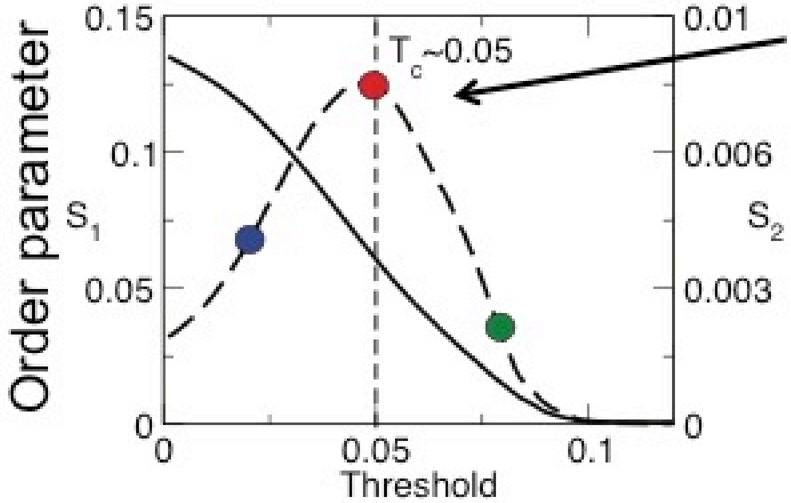
x=0, y=-36, z=18



Plus some "simple" dynamics actually (if universality applies almost any nonlinear one should give the same result…

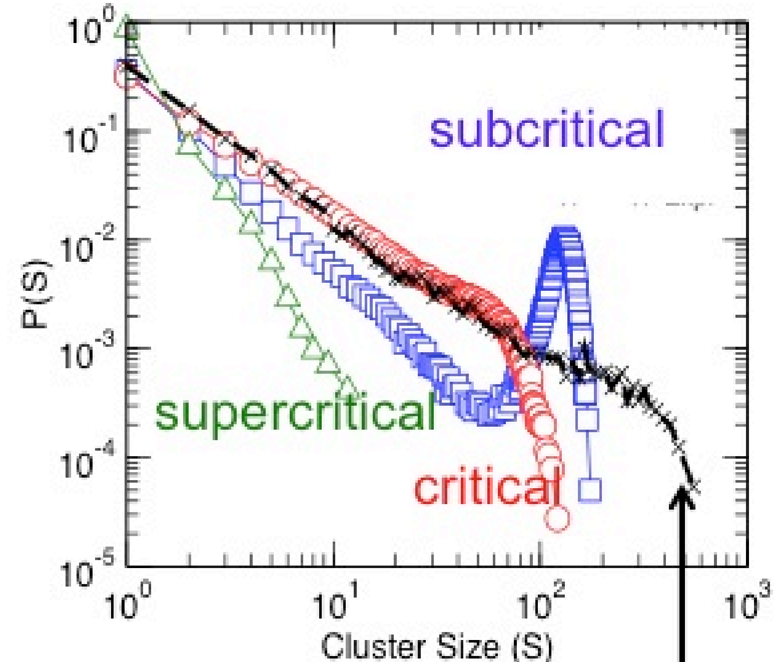
-Haimovici A, et al. Brain organization into resting state networks emerges from the connectome at criticality. PRL (2013).

The model's collective dynamic exhibit different phases



Phase transition

Control parameter

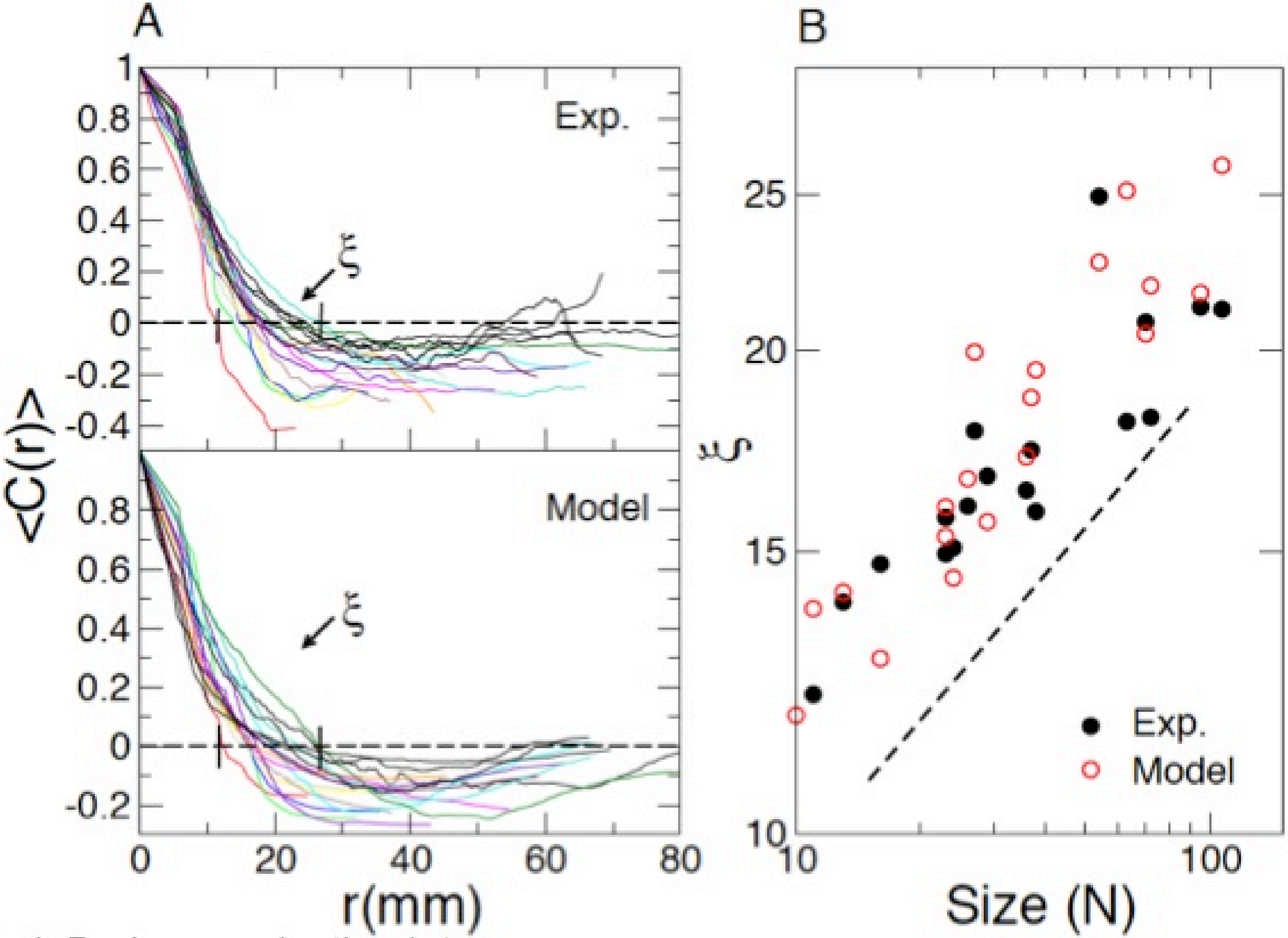


Experimental

-Haimovici A, et al. Brain organization into resting state networks emerges from the connectome at criticality. PRL (2013).

The experimental dynamics is replicated only at criticality

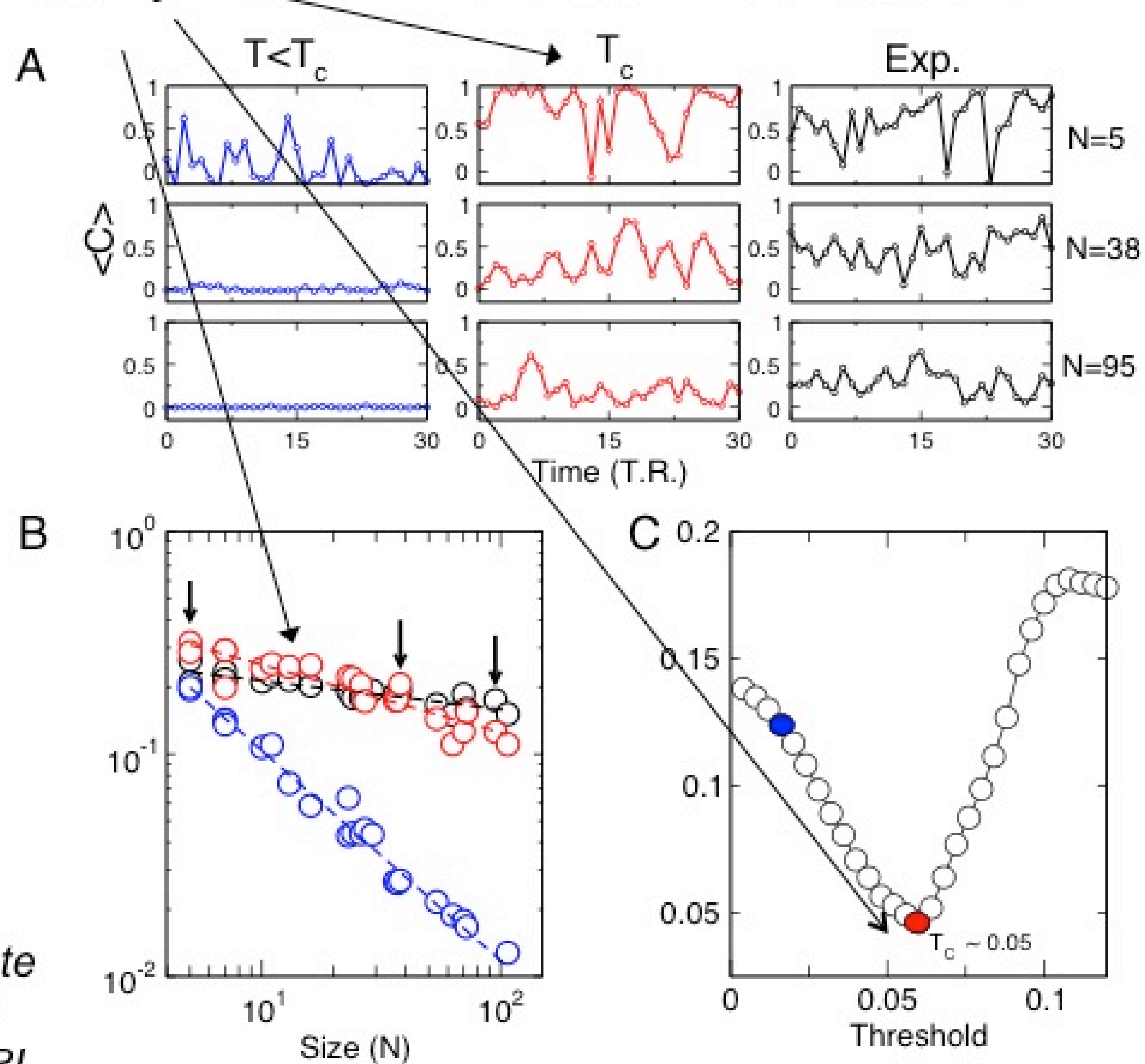
Divergence of correlations



-Haimovici A, et al. Brain organization into resting state networks emerges from the connectome at criticality. PRL (2013).

The experimental dynamics is replicated only at criticality

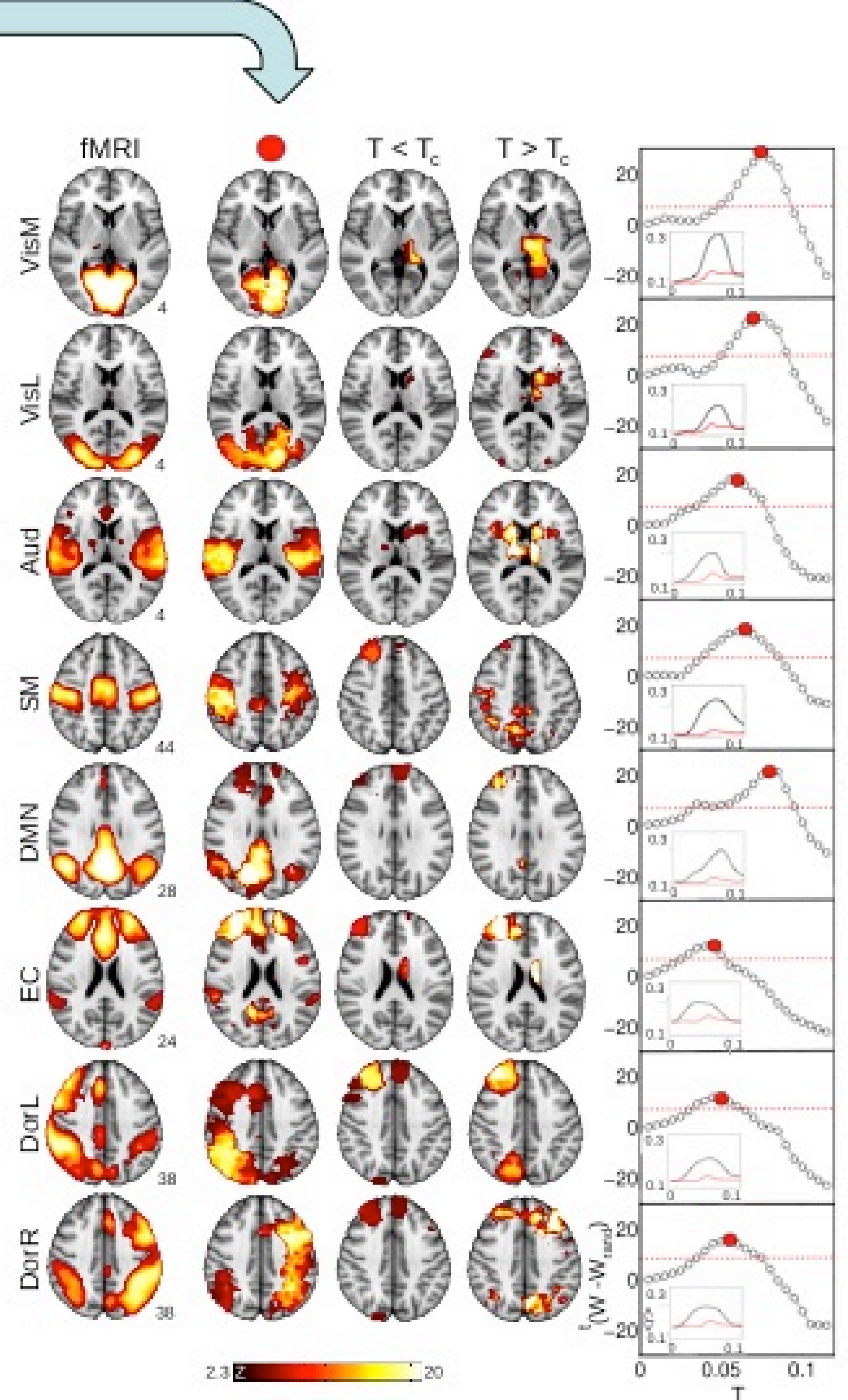
Anomalous scaling of short term correlations



-Haimovici A, et al. Brain organization into resting state networks emerges from the connectome at criticality. PRL (2013).

The experimental dynamics is replicated only at criticality

(resting state networks)



-Haimovici A, et al. Brain organization into resting state networks emerges from the connectome at criticality. PRL (2013).

Summary

1- Some general properties expected near the critical point of a continuous phase transition are seen in fMRI brain data:

- ✓ Long range correlations in space and time.
- ✓ Correlation length scales with system size
- ✓ Anomalous scaling of the variance of the fluctuations
- ✓ Variance of the order parameter peaks at the critical point (susceptibility)
- ✓ Scaling in the clusters size distribution
- ✓ Scaling of avalanches sizes

2- A model based on the brain connectivity replicates the observations ONLY at criticality

3- Despite 1 & 2 no theory is at hand to formally explain how the brain does it…