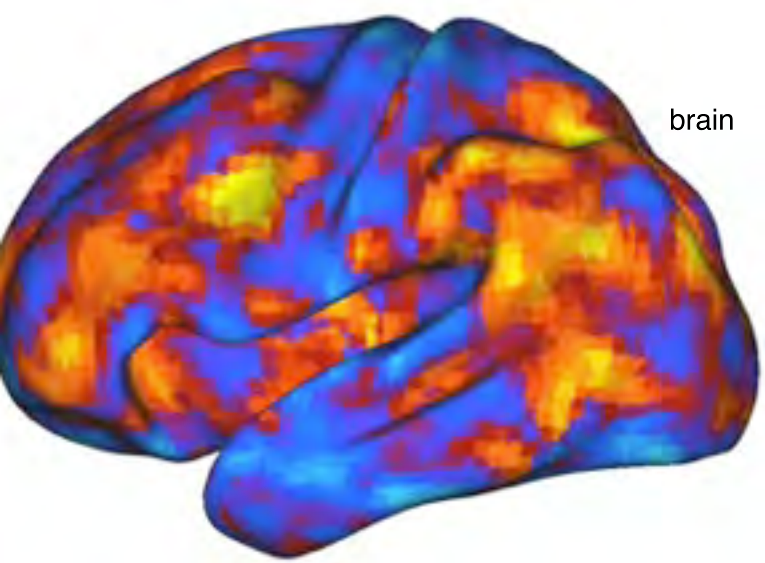
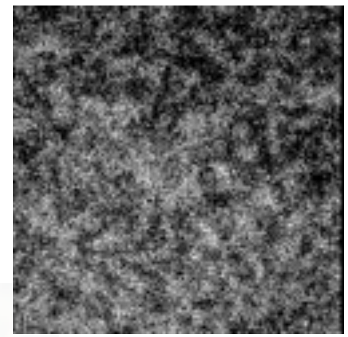

"The laws of physics are simple but nature is complex"

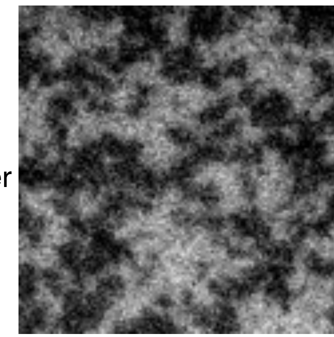


brain

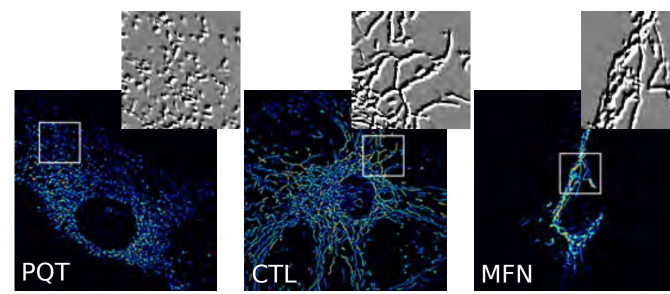
protein



lipid bilayer



mitochondria

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ESCUELA DE CIENCIA Y TECNOLOGÍA

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Curso de Complejidad
in Biologia y Medicina
FaMAF, UNC.
(Agosto-Setiembre, 2005)

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# Outline

Today -Why life is always found near criticality? (a 10 minutes manifesto for the non-cognoscenti on “Not too rigid, neither very flexible”)

-We apply these ideas to:

Today
- Brains (results on critical brain dynamics)

Perhaps
- Proteins (finite size scaling analysis on NMR data from the PDB database). (with Y.T. Tang,Physical Review Letters 118, 088102, 2017)

Perhaps
- Mitochondria (critical fusion-fision balance of the mitochondrial network). (with N&E Zamponi et al, Nature Sci. Reports 8, 363, 2018)

-Summary & questions

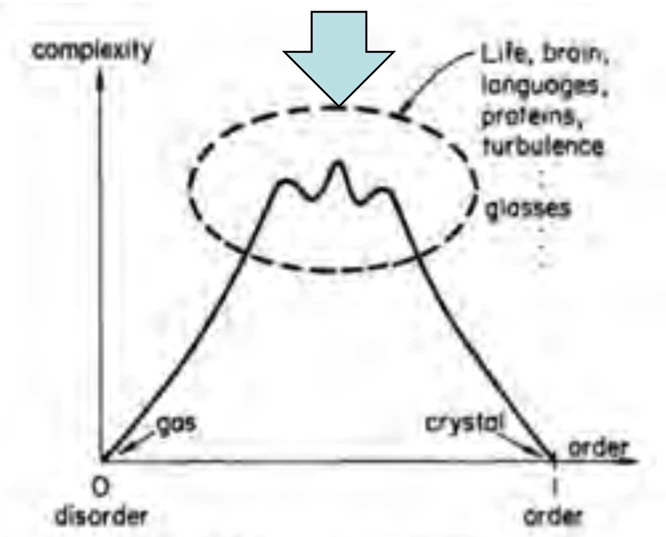
# "In god we trust. All others, bring data" (W. Edwards Deming)

- *"Emergent complex neural dynamics"* Chialvo DR, Nature Physics 6 (10), 744-750 (2010)
- *"Learning from mistakes"* DR Chialvo, P Bak. Neuroscience 90 (4), 1137-1148 (1997).
- *"What kind of noise is brain noise?"* Fraiman & Chialvo, Frontiers in Phys., (2011).
- *"Criticality in large-scale brain fMRI dynamics…"* Frontiers in Phys. (2012).
- "*Brain organization into resting state networks emerges from the connectome at criticality"* Haimovici et al., Physical Review Letters, 110 (17), 178101 (2013).
- *"Large-scale signatures of unconsciousness are consistent with a departure from critical dynamics".* Journal of The Royal Society Interface, 13 (114), 20151027 (2016).
- *"Critical Fluctuations in the Native State of Proteins"* Tang QY et al., Physical Review Letters 118 (8), 088102 (2017).
- "*Mitochondrial network complexity emerges from fission/fusion dynamics"* Zamponi N. et al, Scientific Reports 8 (1), 363 (2018).
- "*La mente es crítica"* J. Marro & D. Chialvo. Univ. of Granada Editora, (2017).
- "Universal and nonuniversal neural dynamics on small world connectomes: A finite size scaling analysis" Zarepour M et al, Physical Review. E, (2019, in press)

*The results we describe are not anecdotal, they were already generalized to other systems, scales and setups by a number of authors.

| 80's | 90's | nowadays |
|---|---|---|
| Intuition | Theory (Including Self-Organized Criticality) | Experiments |

*critical*




H. Frauenfelder NYAS 1987

K. Christensen, D. Chialvo, Per Bak & Z.Olami. Brookhaven National Lab. (Feb. 1992).

Physicals, social and biological systems are shown to be "complex" because they operate near criticality.

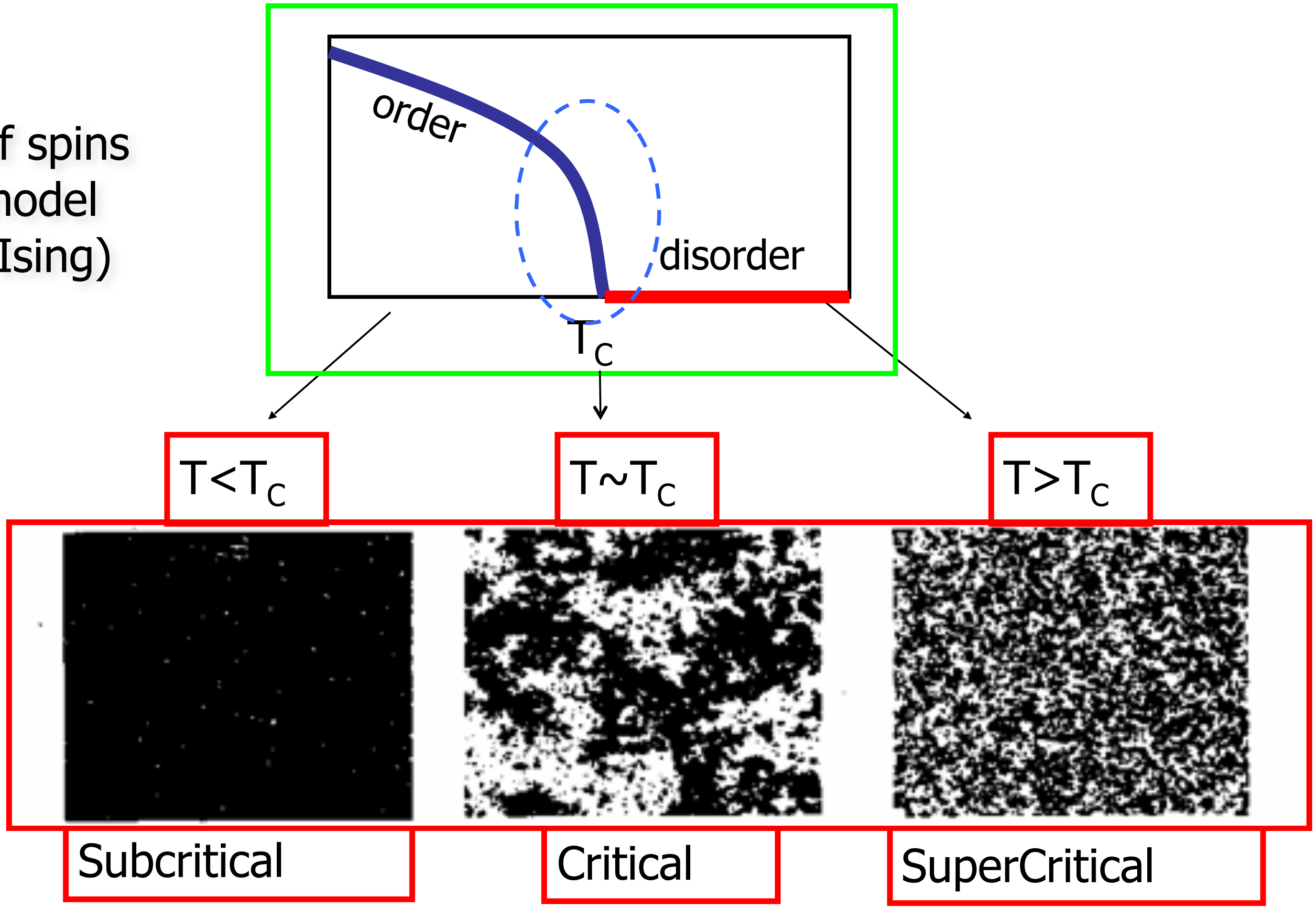
*"A Fundamental Theory to Model the Mind"* by Jennifer Ouellette in Quanta Magazine and Scientific American April, 2014.

*"Criticality and phase transitions in biology"* by Philip Ball in New Scientist, 2014.

*"La mente es crítica"* by J. Marro & D. Chialvo. Granada Editora, 2017

# Ferromagnetic-paramagnetic Phase-Transition

Snapshots of spins states in a model system (2D Ising)




Snapshots of spins states in the Ising model.

Long range correlations emerges at the phase transition

Critical (for non - physicists)

# What means to be “Critical” (in 5 sec) Example traffic

“solid”

+

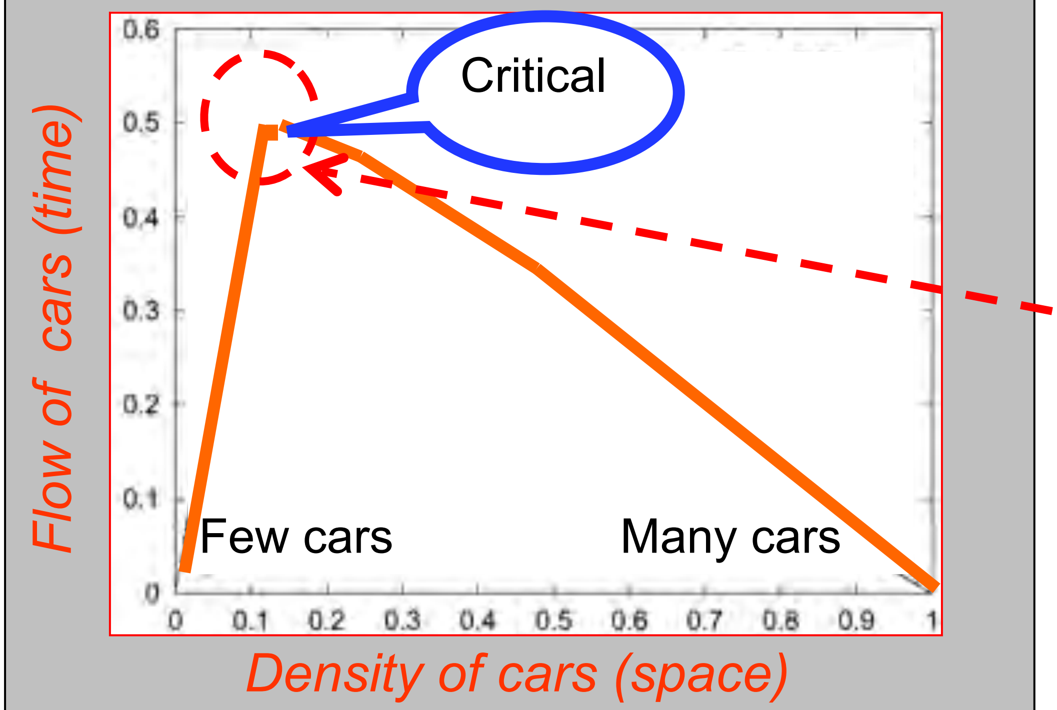
=

“gas”

Structure (the network of streets) + Individual Non-linear Dynamics (drivers) = “phases”

# What means to be "Critical" -qualitatively speaking-

*Traffic jams as a critical process*

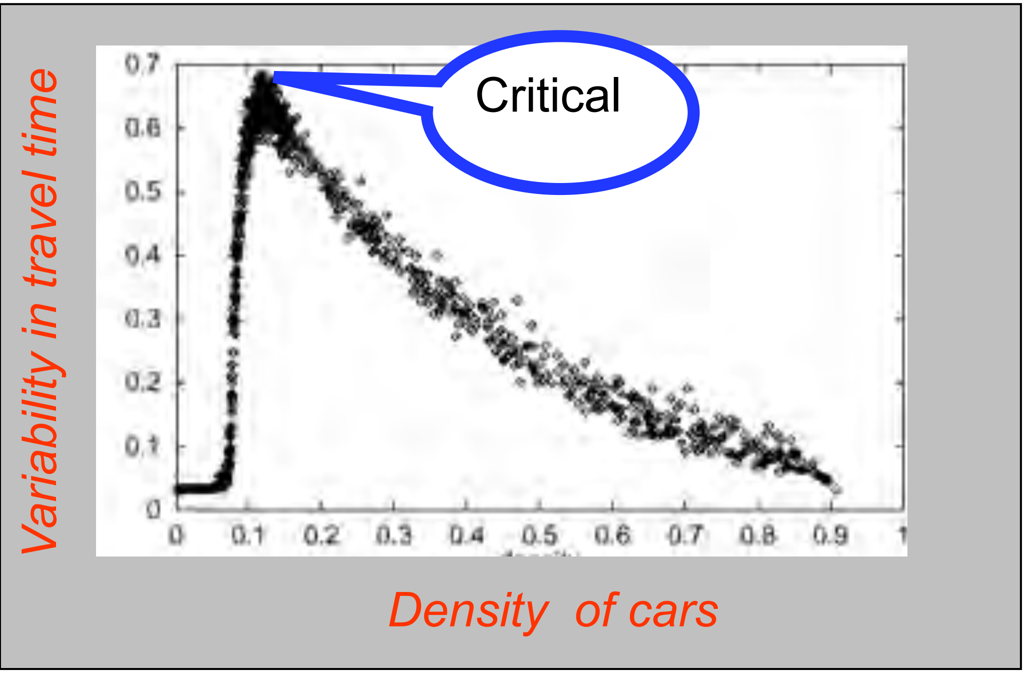



*Number of vehicles passing through a point (flow) as a function of the density of vehicles*

- *Two phases* — *- Free flow*, *-Jamming*
- *For the traffic engineer the maximum "efficiency" is at the transition*

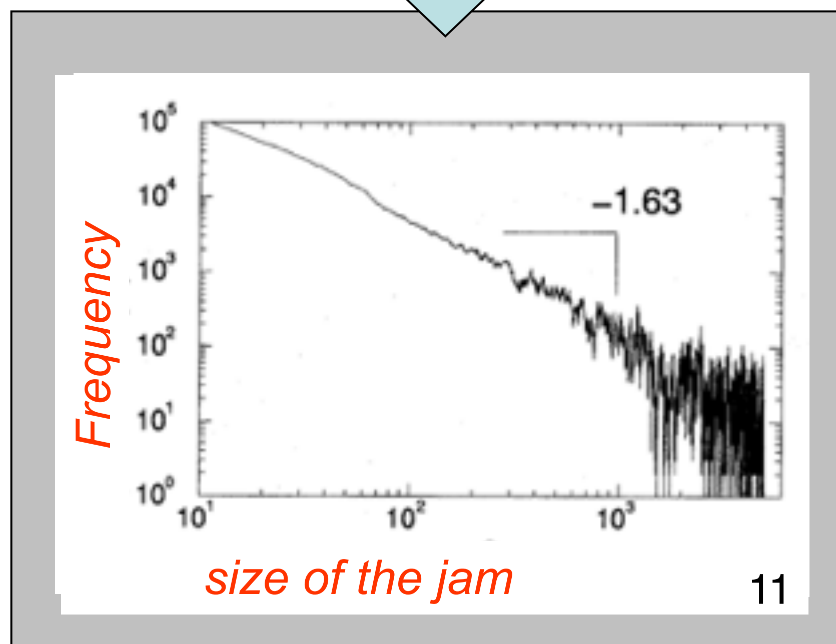
  *at the Critical point*

- *For the driver the Critical density is the worst case scenario!*




- *At criticality the travel time' variability is maximum*

- *Jams of all sizes*




- Higher efficiency and unpredictability both at criticality (counterintuitive, and important for management…)

Summing up, near criticality:

- The variability of the order parameter peaks at criticality (i.e, “susceptibility”) increasing with size as $N^{\text{some exponent}}$
- Clusters (jams) of all sizes (i.e, long range spatial correlations observed as power law distributions of clusters).
- The action of a single driver at any point in the system can have repercussion very far away both in time and space. (long range correlation and contingency)
- Despite that *interactions* are **short-range**, *correlations* can be **unlimited**, as large as the system itself.

These properties are *universal* (they don’t depend on the details of the system (cars, etc)

# Brains

If criticality is the solution …
what is the problem?


The brain can not work like a electrical circuit, because a circuit is something rigid (will need another brain to change the connections)

Synaptic interactions are fix (at the time scale of interest and very weak!!

Scale free clustering (weak ordering) without synchronization!

# Remember: brain pairwise correlations are always weak

## Strong ordering emerging of weak pairwise correlations

Vol 440|20 April 2006|doi:10.1038/nature04701 nature

ARTICLES

# Weak pairwise correlations imply strongly correlated network states in a neural population

Elad Schneidman[1,2,3], Michael J. Berry II[2], Ronen Segev[2] & William Bialek[1,3]

Biological networks have so many possible states that exhaustive sampling is impossible. Successful analysis thus depends on simplifying hypotheses, but experiments on many systems hint that complicated, higher-order interactions among large groups of elements have an important role. Here we show, in the vertebrate retina, that weak correlations between pairs of neurons coexist with strongly collective behaviour in the responses of ten or more neurons. We find that this collective behaviour is described quantitatively by models that capture the observed pairwise correlations but assume no higher-order interactions. These maximum entropy models are equivalent to Ising models, and predict that larger networks are completely dominated by correlation effects. This suggests that the neural code has associative or error-correcting properties, and we provide preliminary evidence for such behaviour. As a first test for the generality of these ideas, we show that similar results are obtained from networks of cultured cortical neurons.

…The (yet) unsolved problem: how the brain manage to produce a huge range of cortical configurations in a flexible manner …

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.**

# These notions are already ancient (2003-2005)

## Scale-Free Brain Functional Networks

Victor M. Eguíluz,[1] Dante R. Chialvo,[2] Guillermo A. Cecchi,[3] Marwan Baliki,[2] and A. Vania Apkarian[2]
[1]*Instituto Mediterráneo de Estudios Avanzados, IMEDEA (CSIC-UIB), E07122 Palma de Mallorca, Spain*
[2]*Department of Physiology, Northwestern University, Chicago, Illinois, 60611, USA*
[3]*IBM T.J. Watson Research Center, 1101 Kitchawan Rd., Yorktown Heights, New York 10598, USA*
(Received 13 January 2004; published 6 January 2005)

Functional magnetic resonance imaging is used to extract *functional networks* connecting correlated human brain sites. Analysis of the resulting networks in different tasks shows that (a) the distribution of functional connections, and the probability of finding a link versus distance are both scale-free, (b) the characteristic path length is small and comparable with those of equivalent random networks, and (c) the clustering coefficient is orders of magnitude larger than those of equivalent random networks. All these properties, typical of scale-free small-world networks, reflect important functional information about brain states.

DOI: 10.1103/PhysRevLett.94.018102 PACS numbers: 87.18.Sn, 87.19.La, 89.75.Da, 89.75.Hc

ELSEVIER Review TRENDS in Cognitive Sciences Vol.8 No.9 September 2004
Full text provided by www.sciencedirect.com
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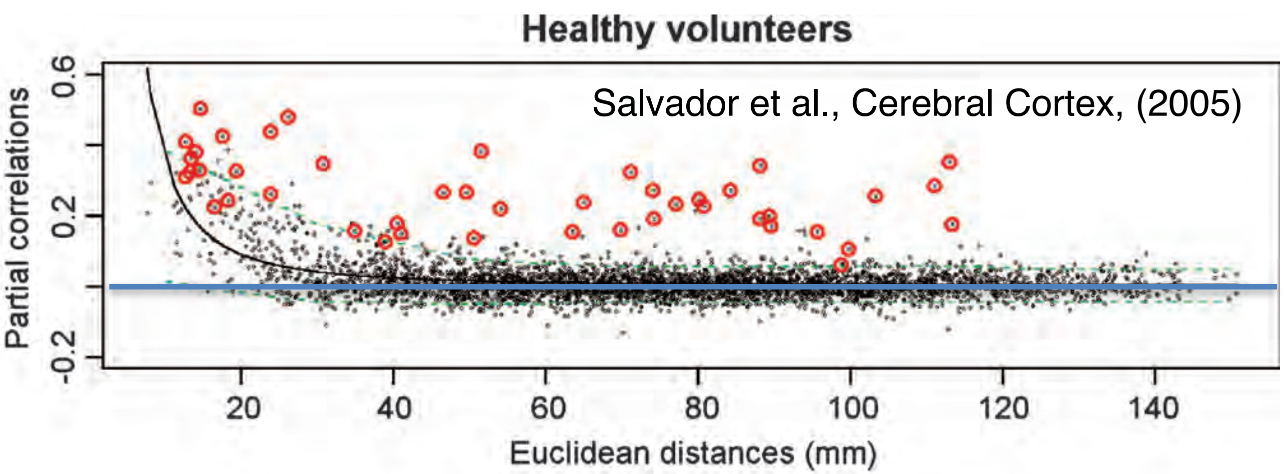
## Organization, development and function of complex brain networks

Olaf Sporns[1], Dante R. Chialvo[2], Marcus Kaiser[3] and Claus C. Hilgetag[3]

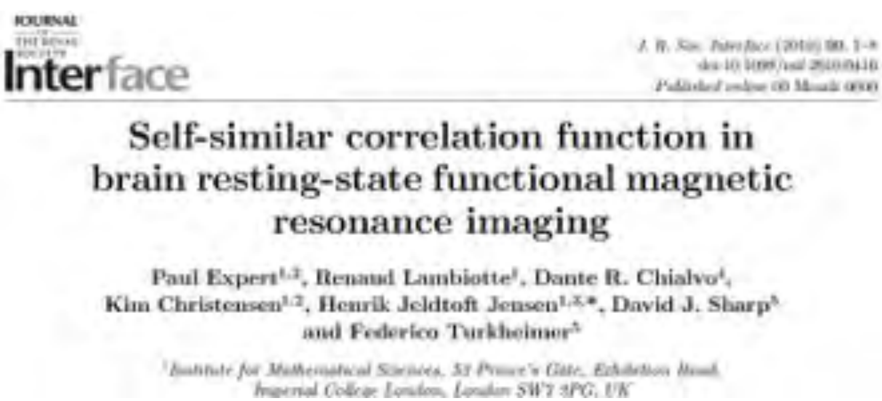
# Brain' average two-point correlation functions computed from Functional Magnetic Resonance Images during rest (no task)




Most of C pairs are weak

Expert et al., J. Royal Soc. (2010)

C decays with distance as a power law

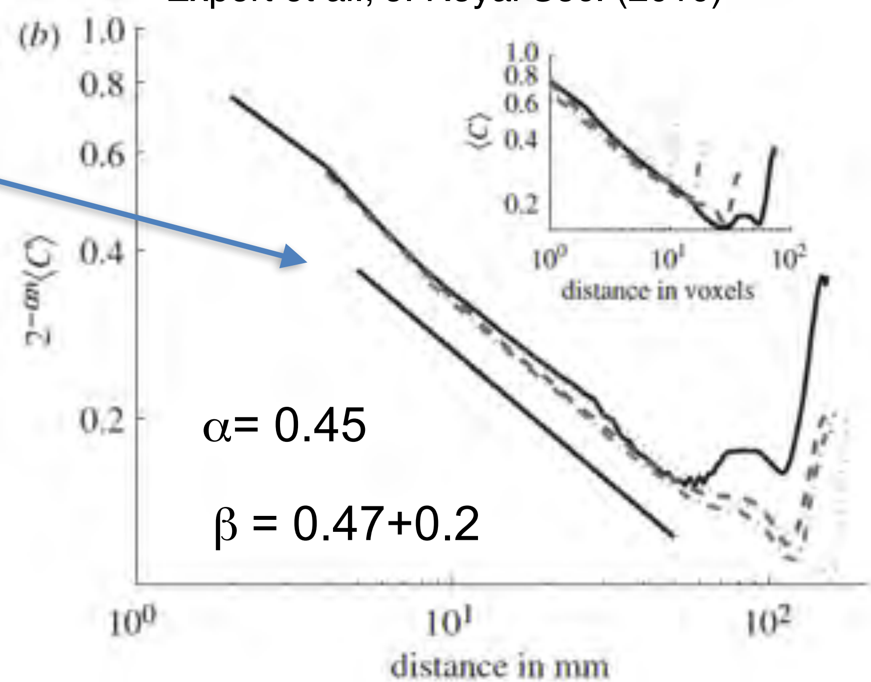


Interface

**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[1,2,3,*], David J. Sharp[5] and Federico Turkheimer[5]

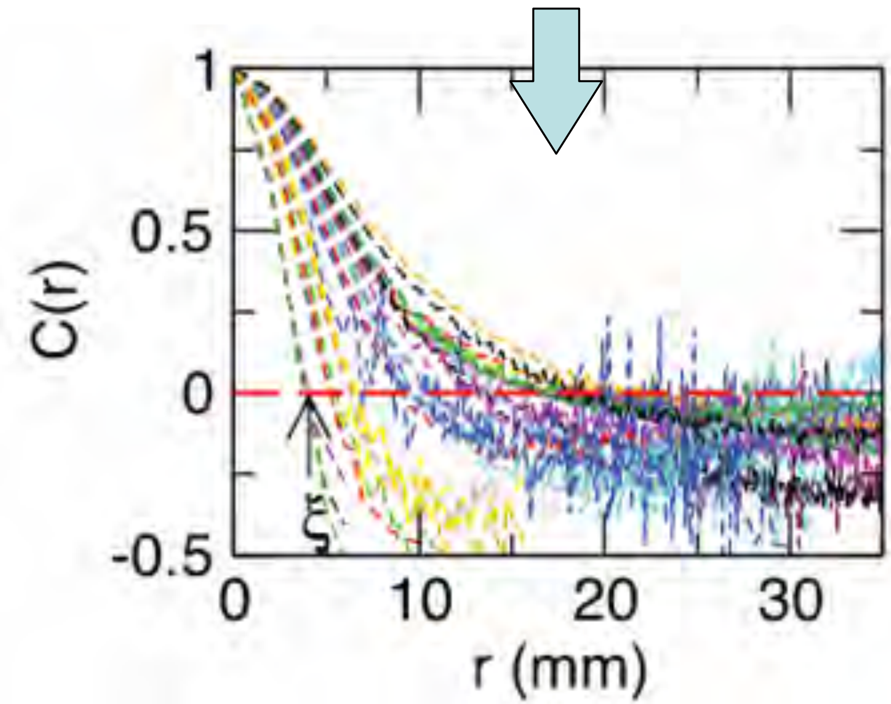
[1]Institute for Mathematical Sciences, 53 Prince's Gate, Exhibition Road, Imperial College London, London SW7 2PG, UK

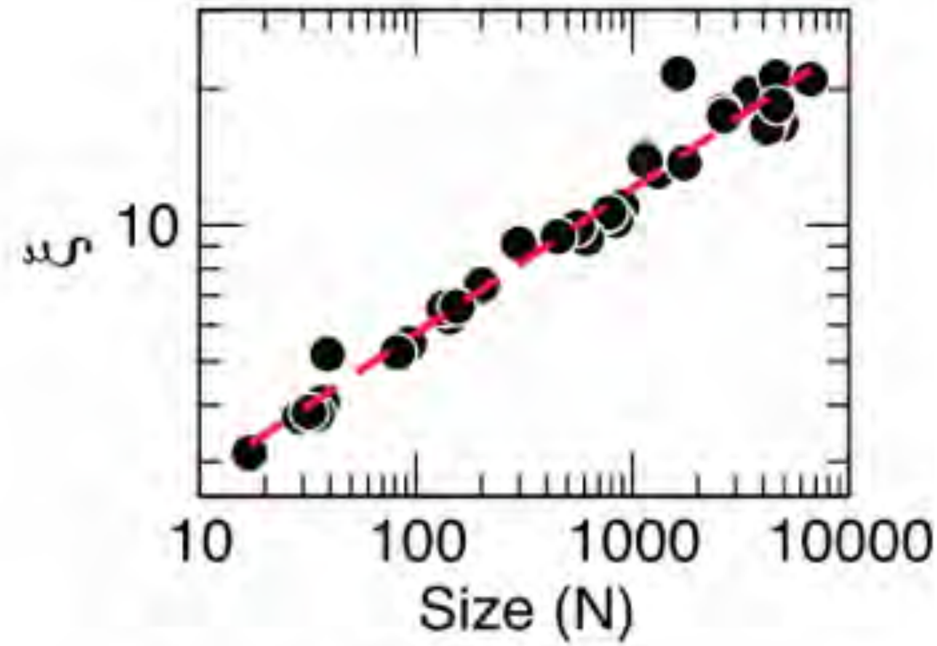


What truly matters is the correlation length

Choose many ROIs.
Compute the average connected correlation function
for each ROI & plot it as a function of distance

Correlation length increases
with ROI size



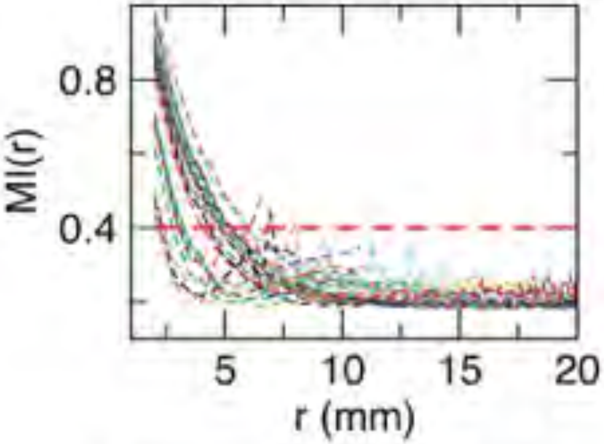

The bottom line: Big, intermediate and small regions all behaves in the same way

For example: Two places 4 mm apart on a blob of 20 voxels are as correlated as those 40 mm apart on a blob of 4000 voxels



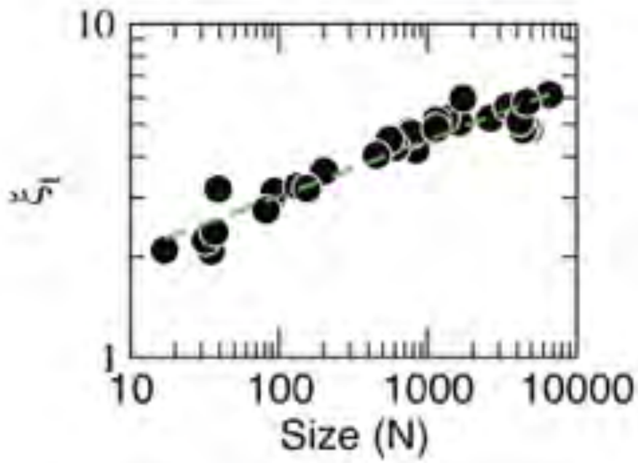
Chialvo DR & Fraiman D. (2010)

# You could do the same for Mutual Information

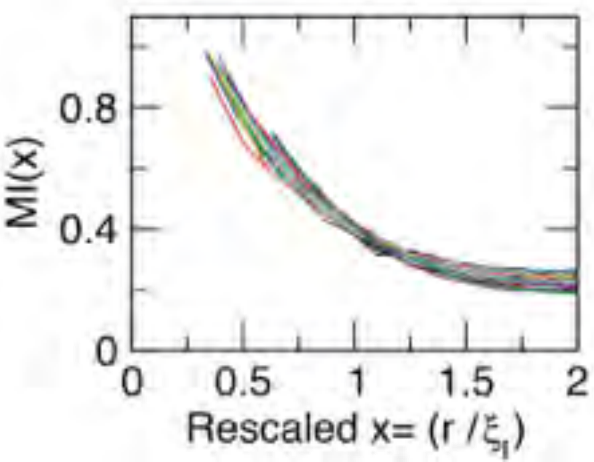



MI(X;Y) = H(X) - H(X I Y)

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




Mutual information increases with cluster size.



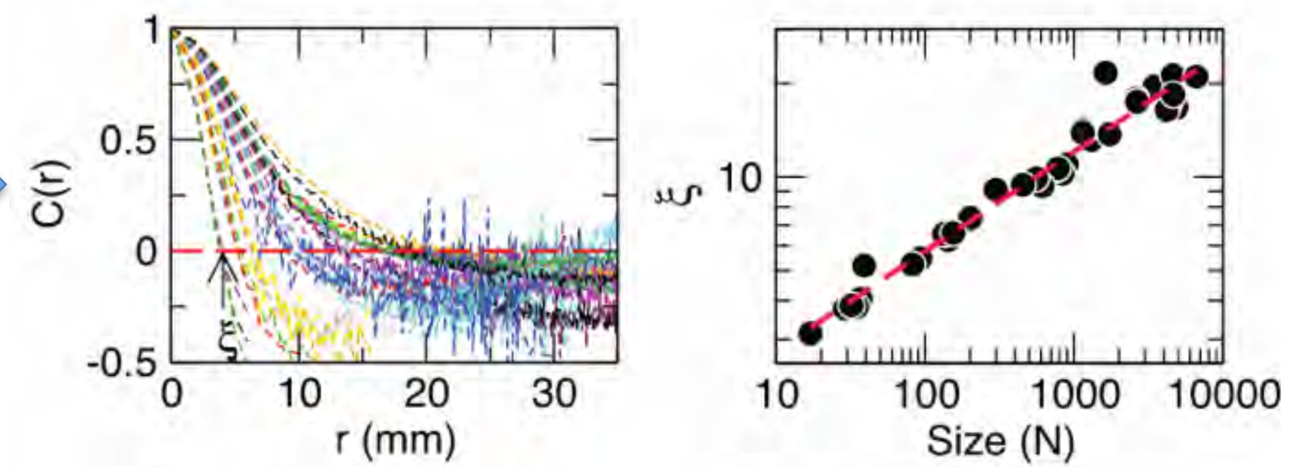

Rescaled mutual information

Chialvo DR & Fraiman D. (2010)

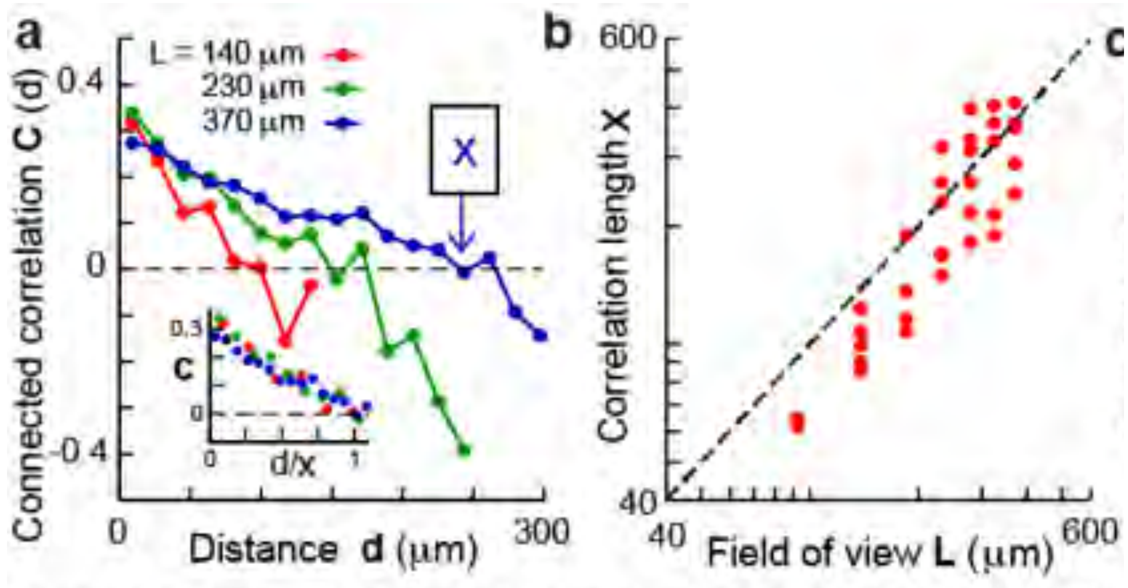
correlation length: at criticality, it increases with system size

Data from human fMRI

(Fraiman & Chialvo, 2011)



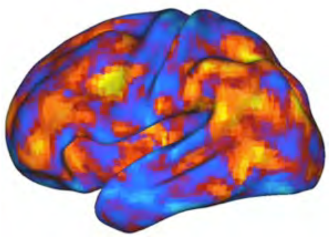

Data from optogenetic 2P recording in behaving mice AI cortex
Plenz & Chialvo, 2017

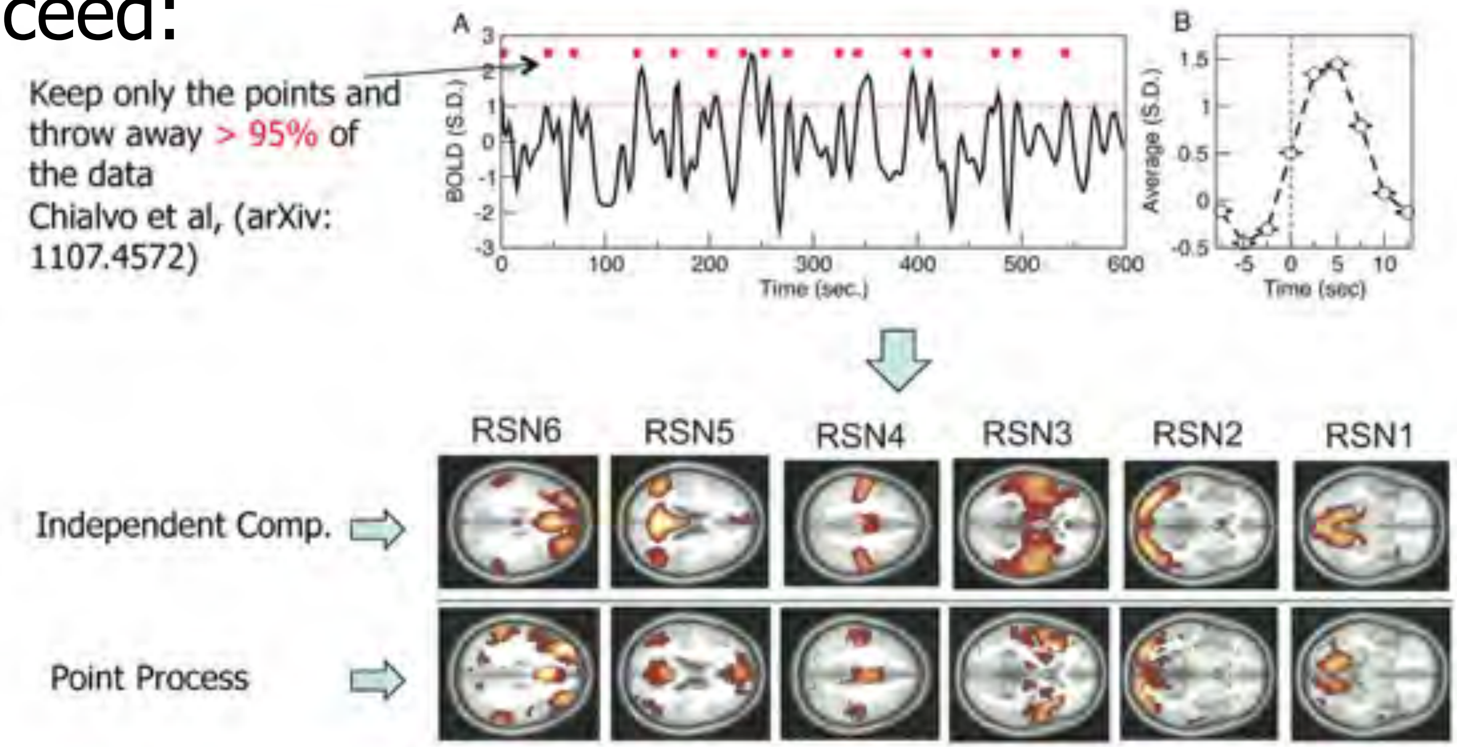


# Brain "meteorology" (searching for order in very large scale, fMRI)

**First**, get the instantaneous dynamics (peaks)

how we proceed:



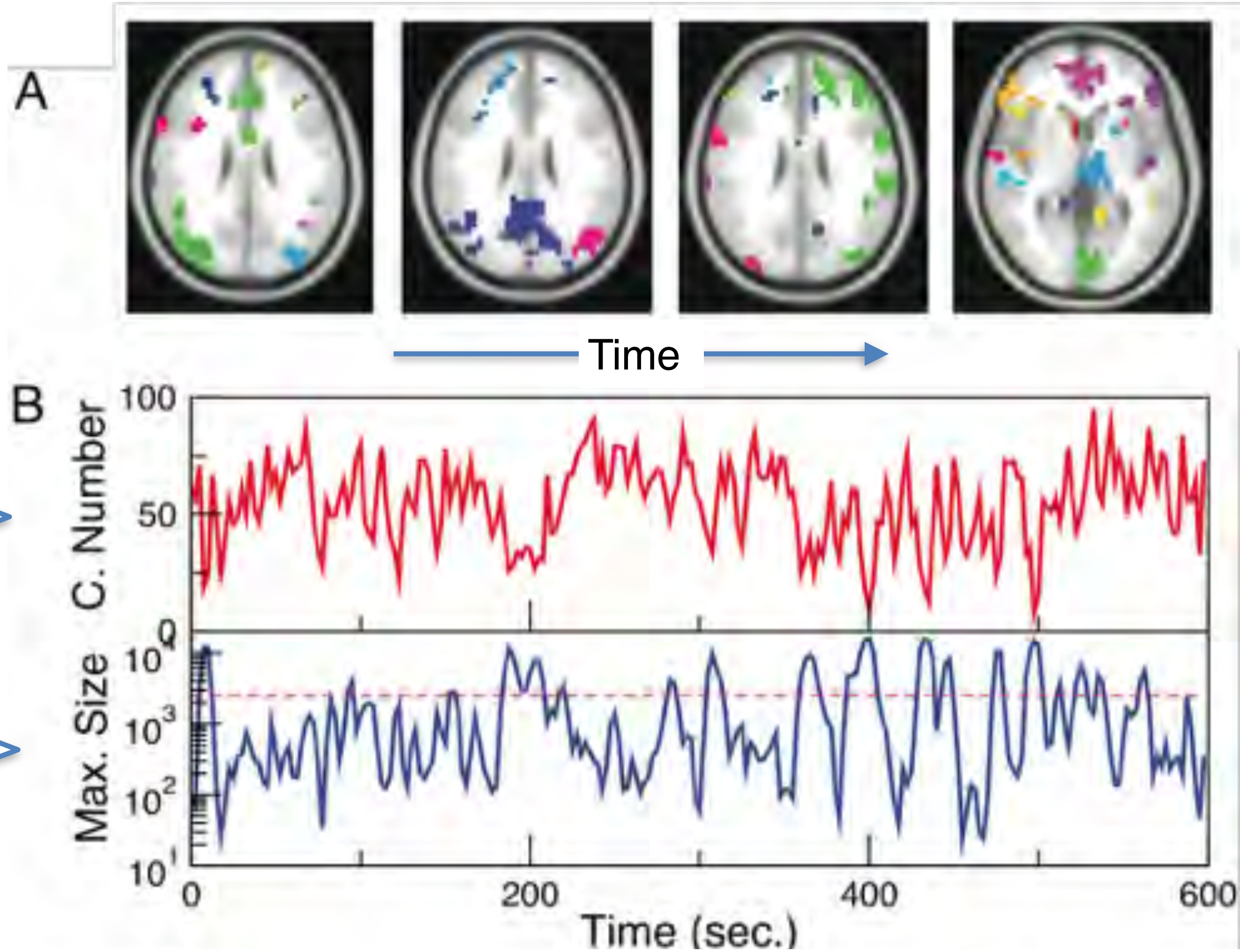



Moral: large scale dynamics is preserved despite a huge data reduction (95%) most of the information is in the peaks.

# Brain "meteorology"

**Second**, identify clusters of activity (like clouds in the sky)

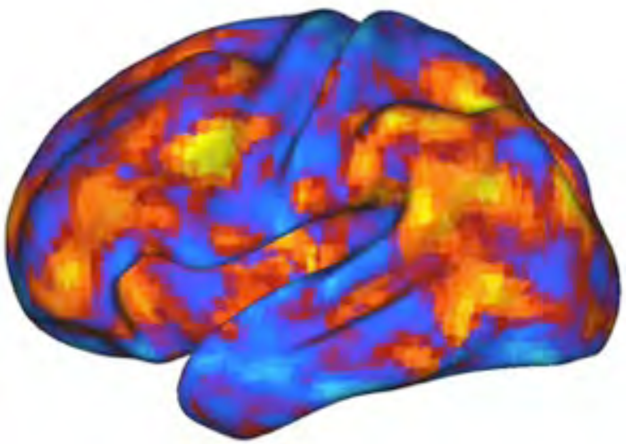
pixels in green belong to one cluster, blue to another, etc

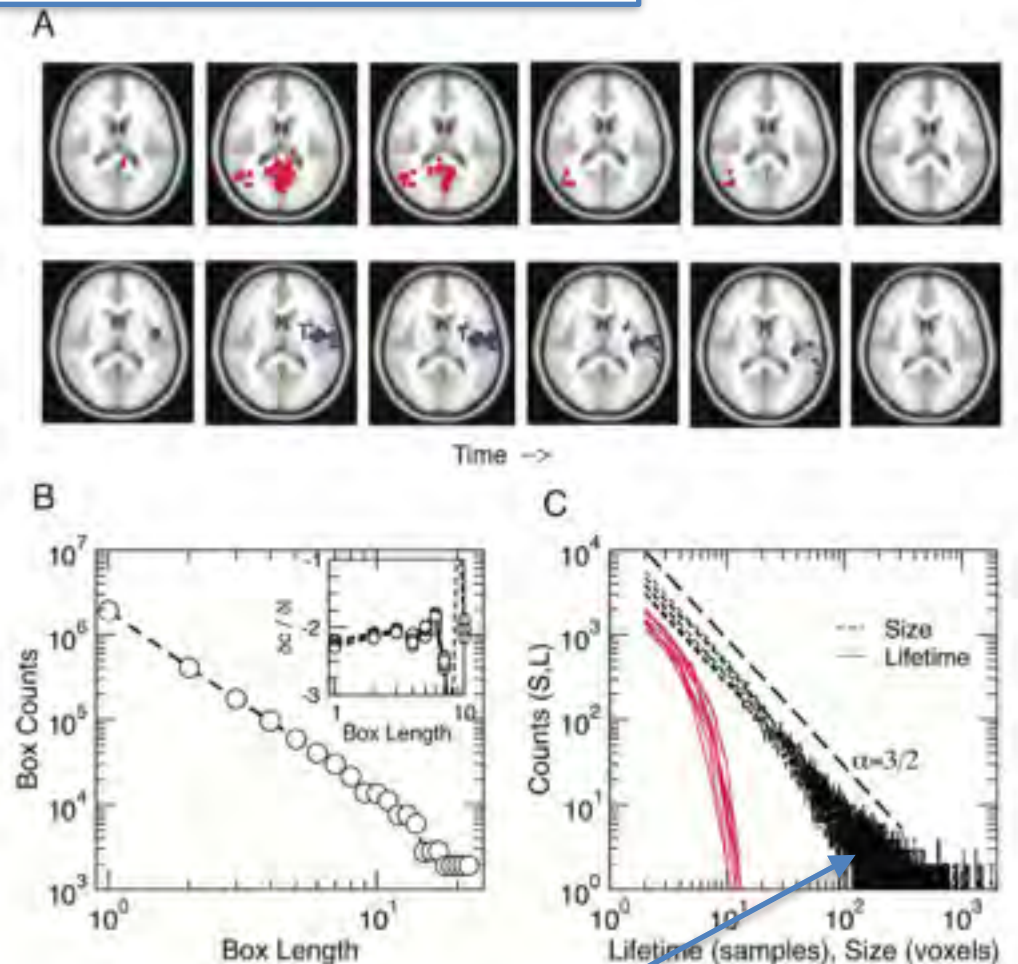



Number of clouds

Size of the largest cloud (sort of "order" parameter)

**Third**, identify spatiotemporal correlations (avalanches)






Fractal Dimension

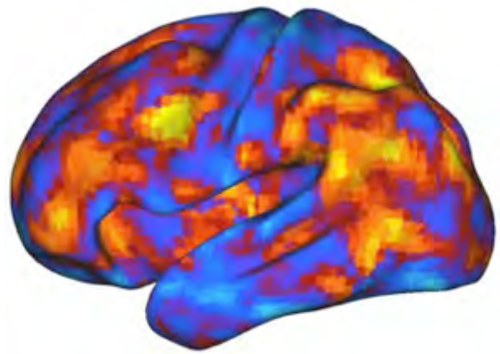
Lifetime PDF

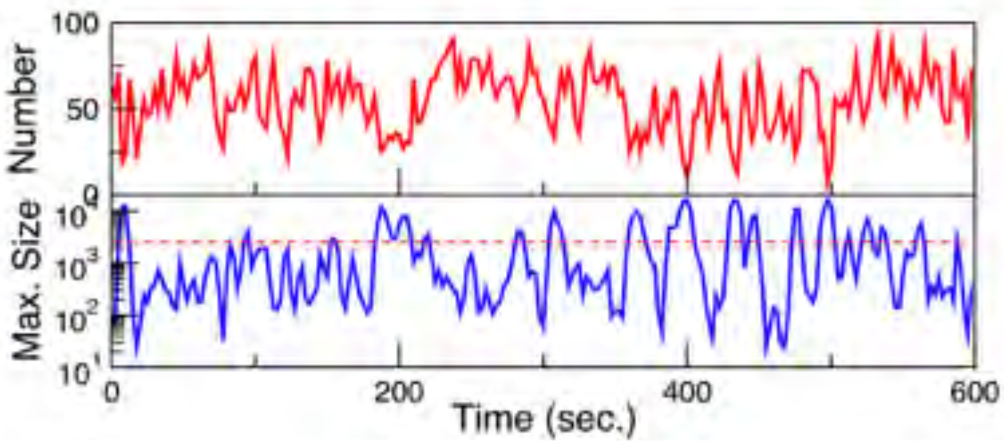
Size PDF

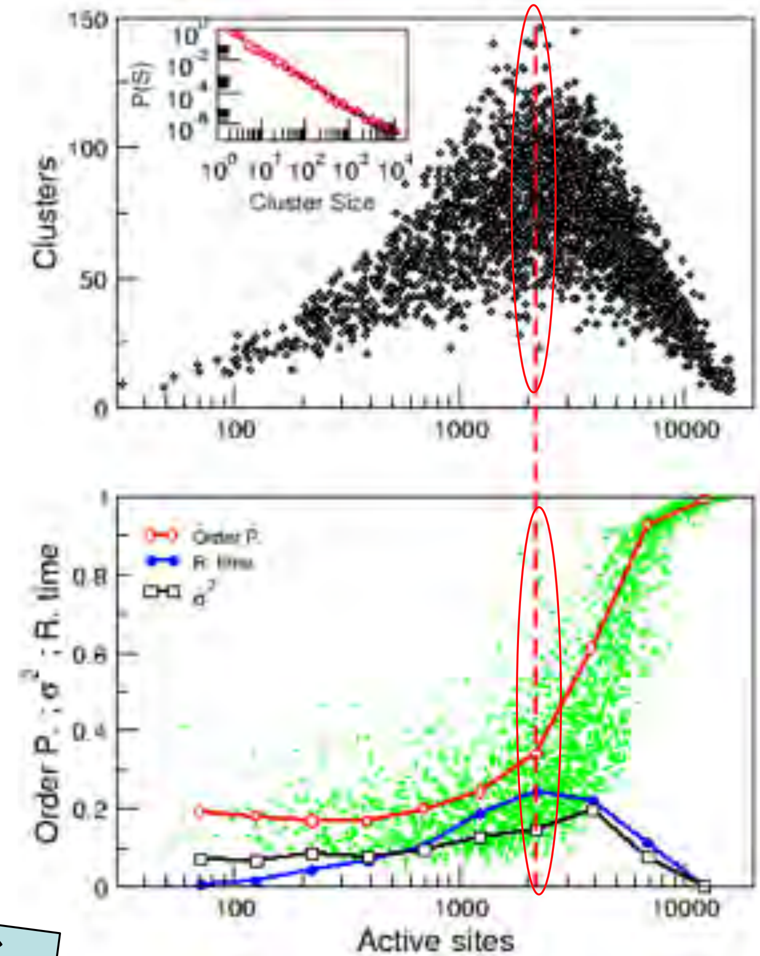
Avalanches of activity are scale free

From Tagliazucchi et al, Frontiers in Physiol. 2012.

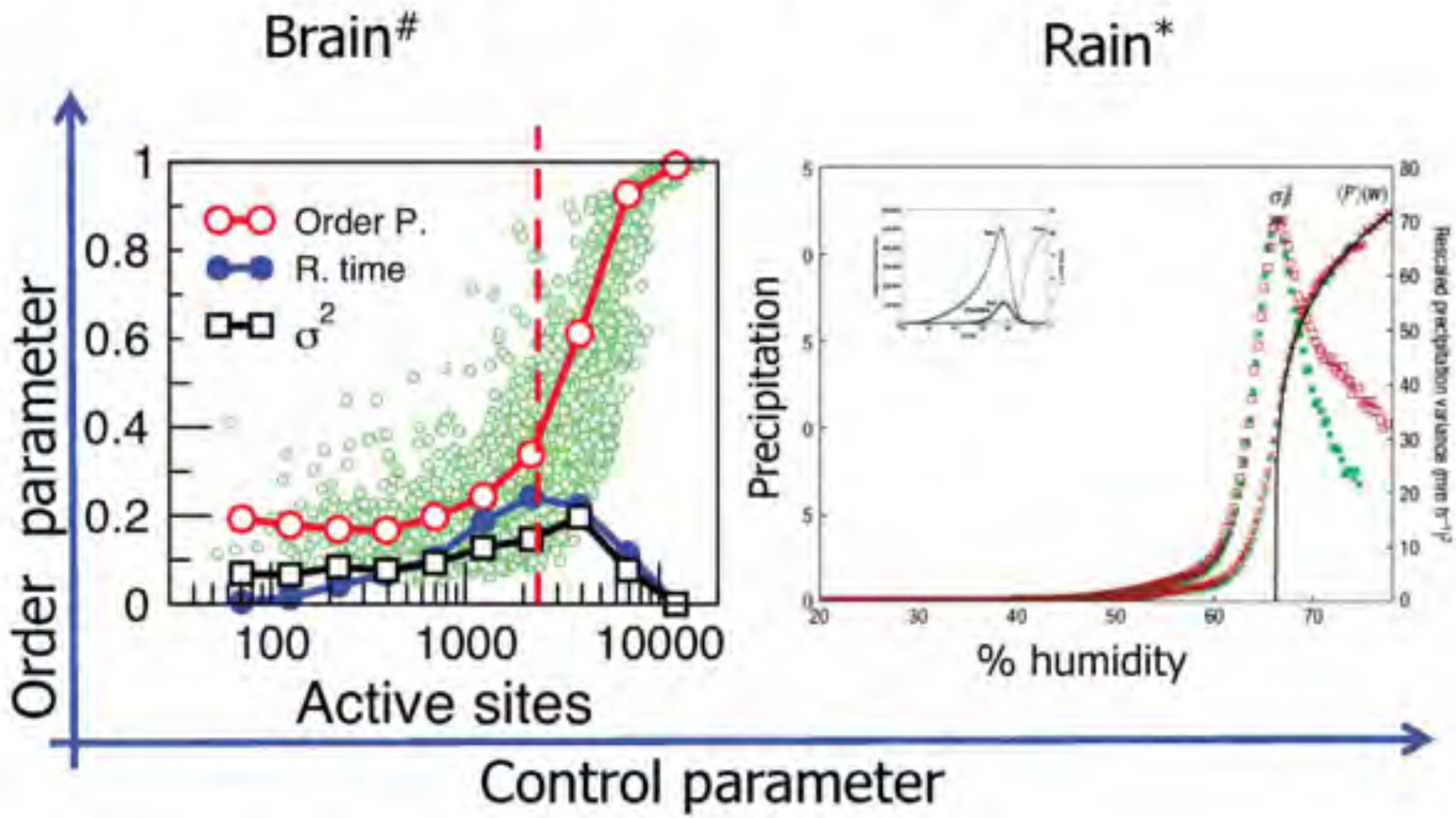
# **Fourth**, check for "control" versus "order" parameter






Spontaneous fluctuations of brain activity evolve as in a continuous phase transition, being most of the time at a regime with the largest variance




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

# Tagliazucchi et al, Frontiers (2012).

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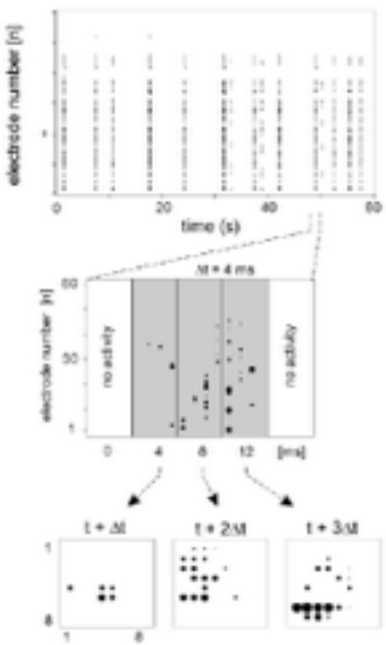
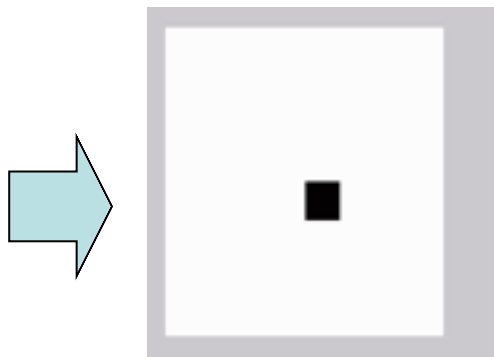
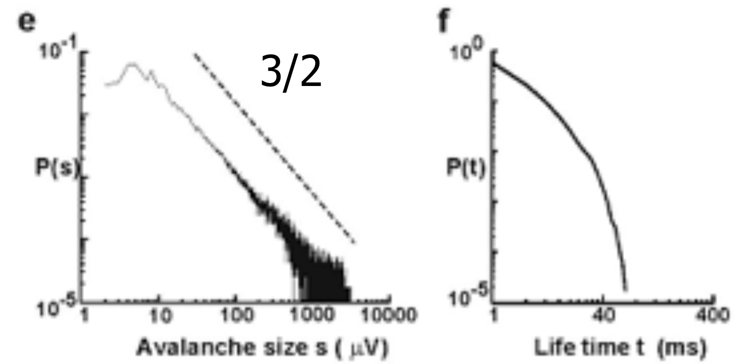
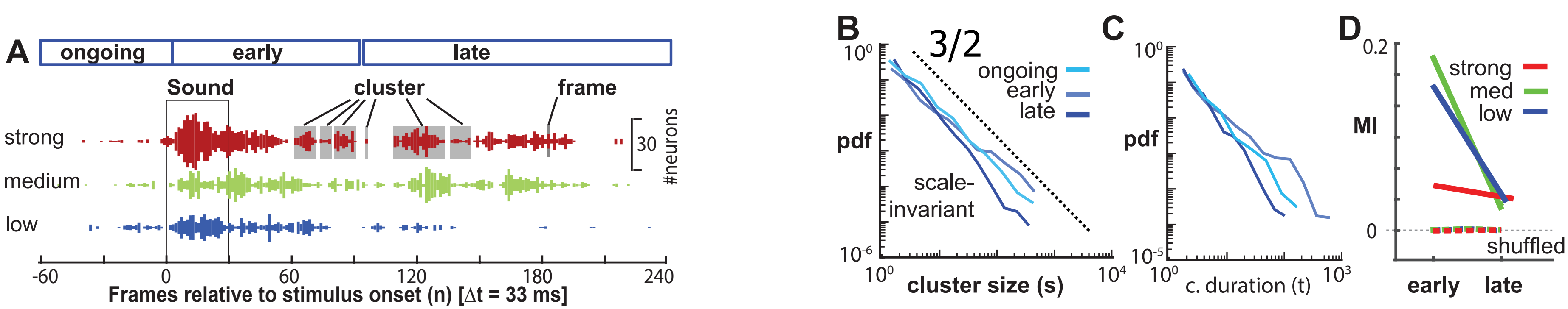
# Identical avalanches were described in vivo & in vitro preps.



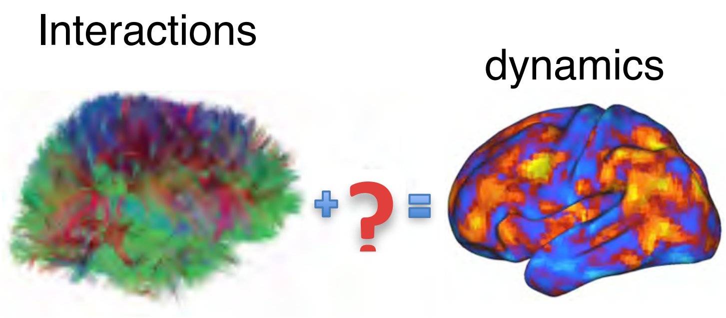


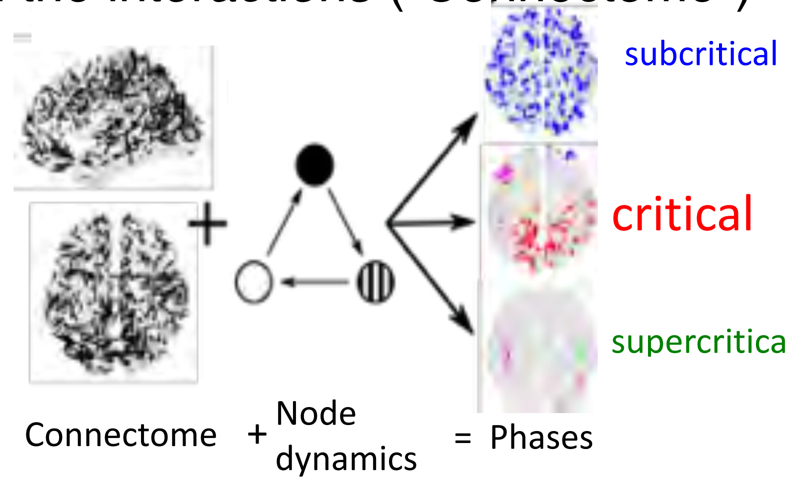

cultured rat cerebral cortex (Beggs & Plenz, 2003)

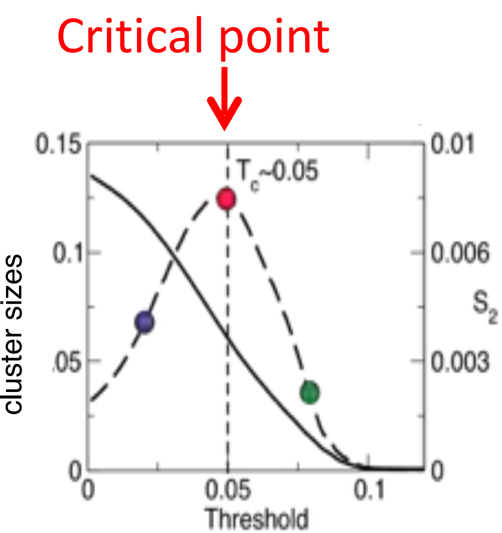


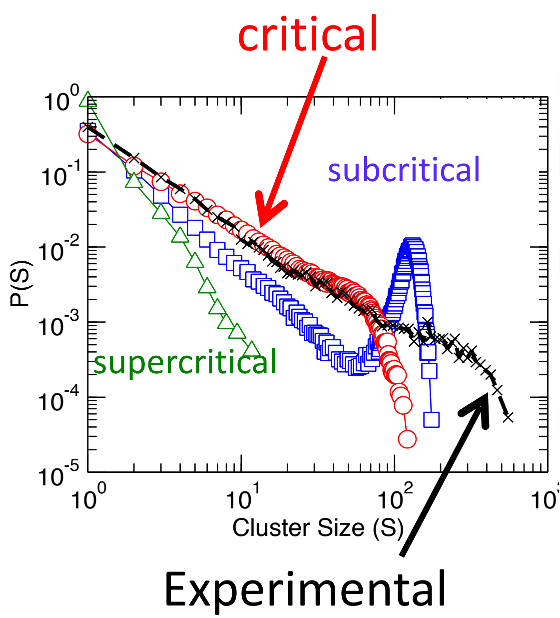

Optogenetic 2P recording in behaving mice AI cortex (Plenz & Chialvo, 2018) two words about modeling

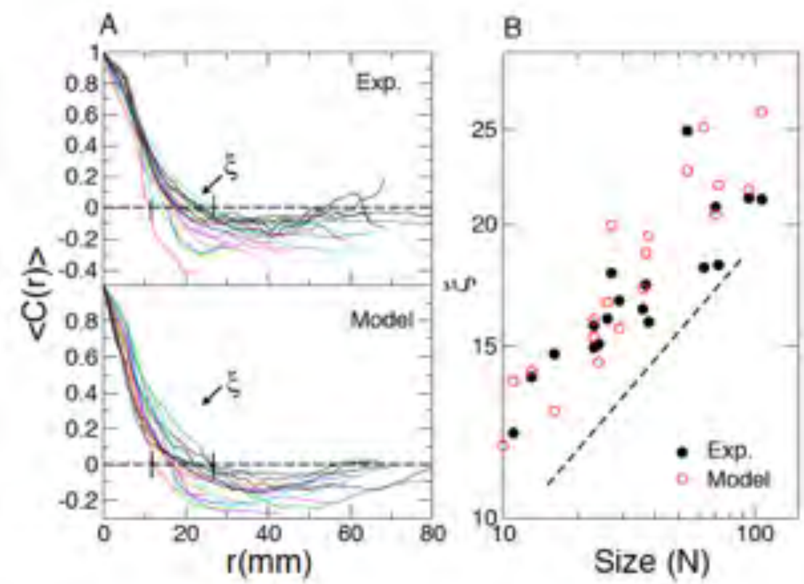
# one parameter toy model
## Getting the experimental *correlations* from the *interactions* (“Connectome")



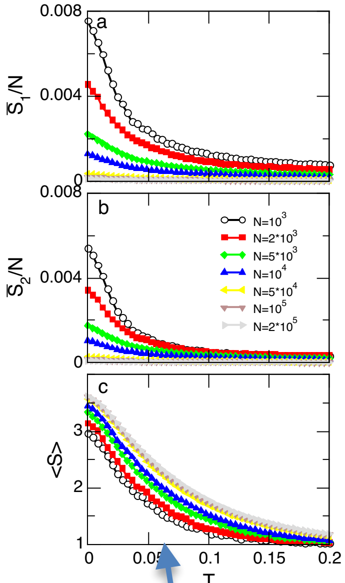

From Haimovici et al, Phys. Rev. Letters 2013.

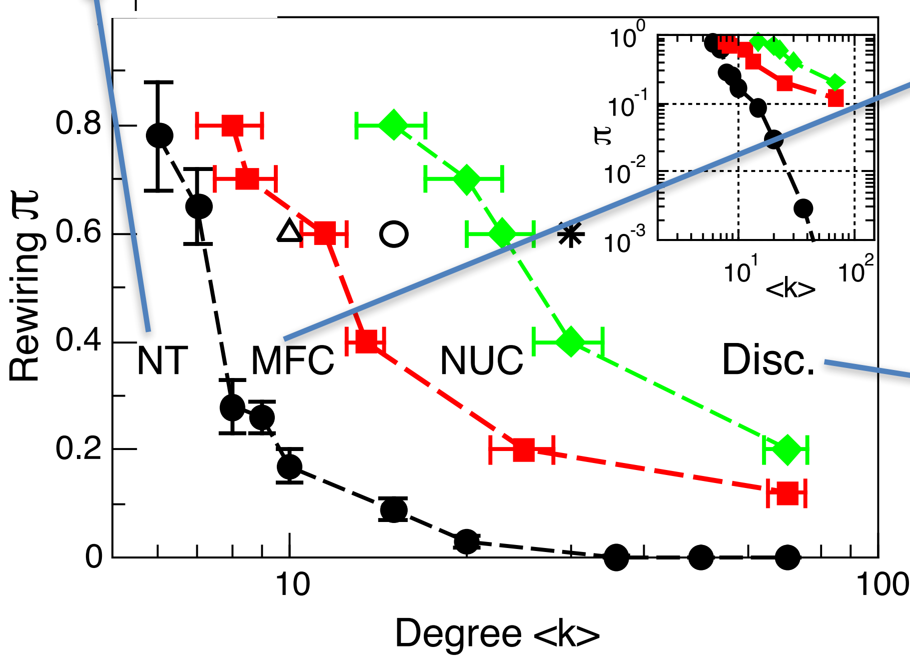
# How the topology of interactions shapes brain dynamics?

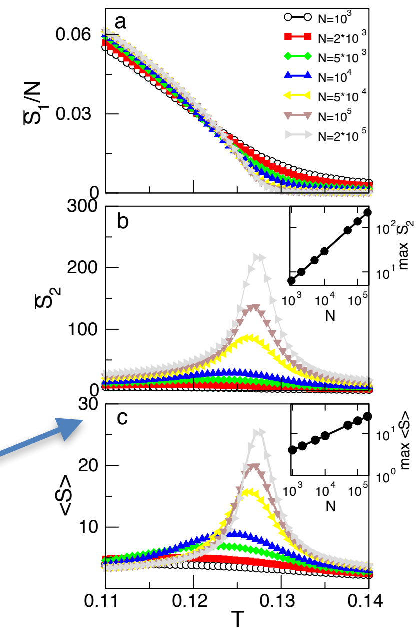
**Universal and non-universal neural dynamics on small world connectomes: a finite size scaling analysis**

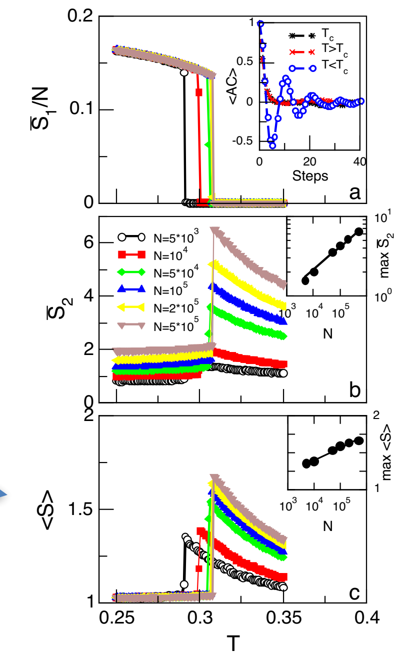
Mahdi Zarepour,[1] Juan I. Perotti,[2] Orlando V. Billoni,[2] Dante R. Chialvo,[3] and Sergio A. Cannas[2]

[1]*Instituto de Física Enrique Gaviola (IFEG-CONICET)*
*Ciudad Universitaria, 5000 Córdoba, Argentina*



# Summary

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

- ✓ 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)
- ✓ Scale invariance in the clusters size distribution
- ✓ Scale invariance in avalanches sizes distribution

2- A model based on the brain connectivity replicates the observations ONLY at criticality, implying that "connectivity" is not enough to understand the dynamics.

3- it seems that a degree of disorder is needed in the interactions

4- more theory is needed

Thanks to all collaborators