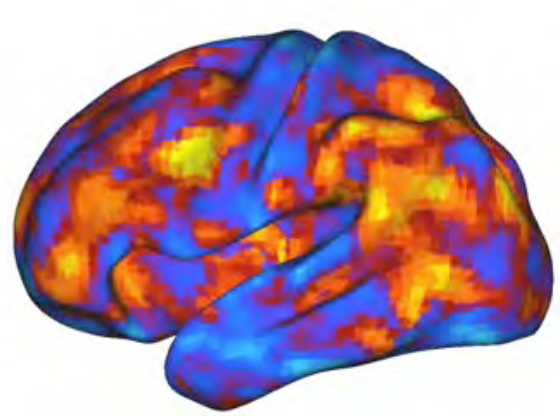
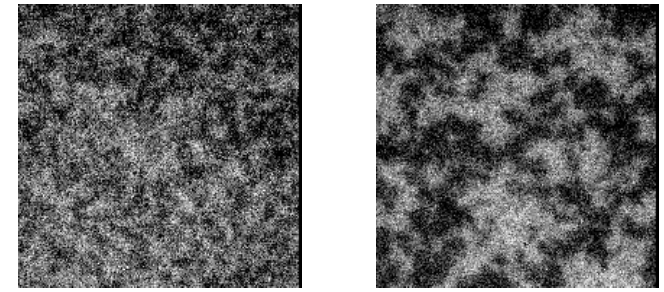
Complexity, criticality and all that jazz

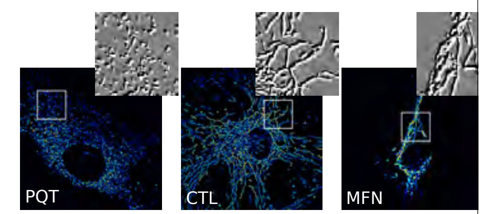


brain



lipid bilayer

protein



mitochondria

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"The laws of physics are simple but nature is comp

CONICET
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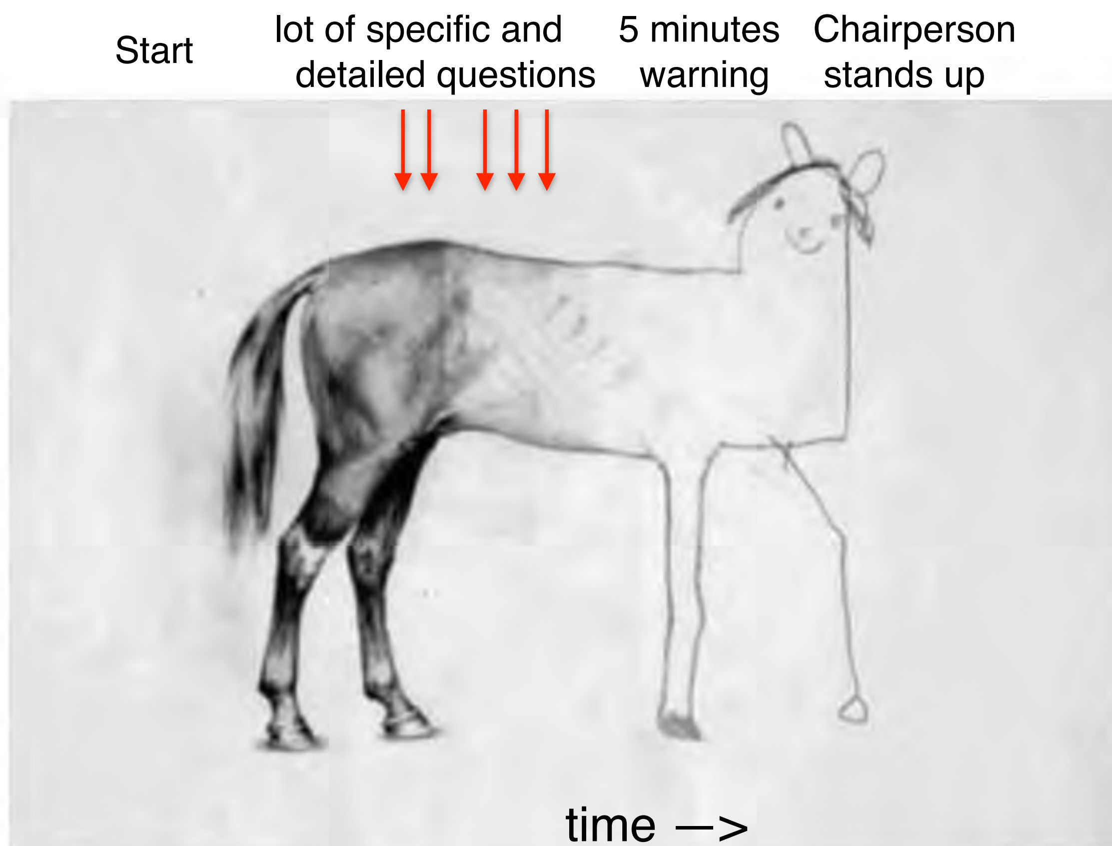
ESCUELA DE CIENCIA Y TECNOLOGÍA

"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. Editora Univ. of Granada, Spain (2018).

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

Disclaimer: How a typical “outsider talk” goes



Outline

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

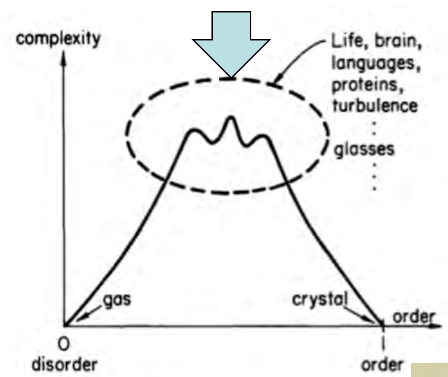
-We apply these ideas to:

Today
- Brains (results on critical brain dynamics)
- Proteins (finite size scaling analysis on NMR data from the PDB database) 15 min. (with Y.T. Tang,Physical Review Letters 118, 088102, 2017)
- Mitochondria (critical fusion-fision balance of the mitochondrial network) 15 min. (with N&E Zamponi et al, Nature Sci. Reports 8, 363, 2018)

-Summary & questions

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).

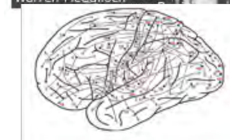
Physicals, social and biological systems are shown to be complex because the operate near criticality.

"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. Univ. of Granada Eds. (Spain), 2018

Criticality & Brain



- 1941: W. McCulloch “Strychnine Avalanches” J. Neuroph. 1941.
- 1957: A. Turing → “An idea presented to such a mind will on average give rise to less than one idea in reply.”
- 1994: Per Bak → “the world is critical = the brain is critical”…
- 1997: Bak & Chialvo →“learning with extremal dynamics is critical”.

- .

- 2003: Beggs & Plenz →“Neuronal avalanches”

- 2003: Eguiluz et al. →“fMRI Brain functional networks are scale free
- 2004: DRC et al. → Brain Ising-like dynamics.
- 2008: Expert et al. -> Correlation function is critical.
- 2010: Fraiman & DRC → Correlations diverge in fMRI -> Criticality.
- 2011: Tagliazucchi et al. → order/control parameters
- 2012: Haimovici et al. → critical brain models
- Most recents studies on how is affected by anaesthesia, psychedelics drugs, -> conscious brain is critical

dont worry I wont talk about all of these

Choose a system you know exhibits all these properties at once:

1- large number of degrees of freedom, with (mostly) short range interactions
2- long(est) correlated states (everyone ‘feels’ everyone else)
3- large fluctuations
4-highest susceptibility (very sensitive to even extremely minute “perturbations”)
5- very large dynamic range (very sensitive, but yet *no saturation* for extremely large perturbations)
6- largest (distributed) memory storage (no limits)
7- longest memory (in time) (no limits)
8- shows contingency (dependence on “unique” long-gone past events)
9- largest (respect to size) number of internal states (a.k.a “configurations”)
10- insensitive (up to a degree) to its *detailed* structure
11- scale free
12- …and more

Answer:
any system able to go near a second order phase transition ("relatively large distributed nonlinear systems with short range interactions")

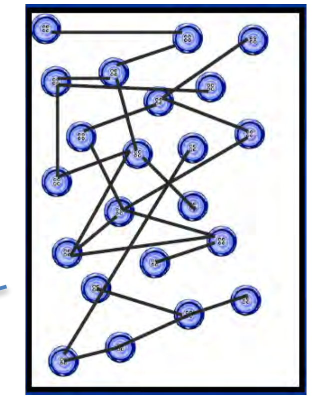
- A ferromagnet near Curie temperature
- Car traffic (approaching a jam) on a large city
- The earth atmosphere at large scale.
- large flocks of birds
- The inmune system
- The brain.
- Proteins at its native state.
- …

Part I: What means critical

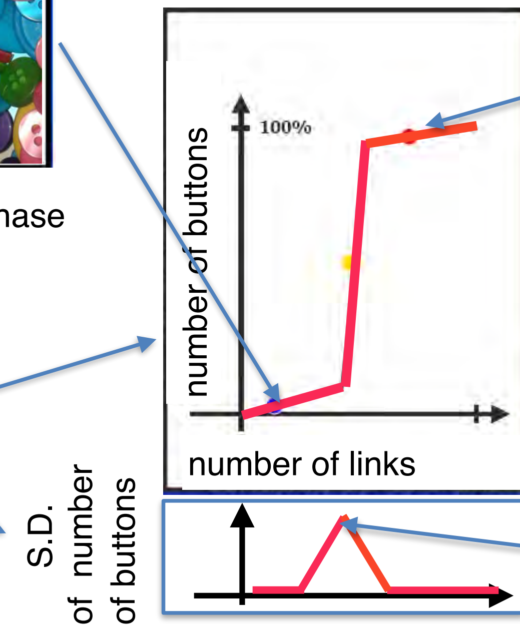
What means to be "Critical"? very simple example

disconnected phase

continuos phase transition



connected phase



do it many times and plot the average and the variance of the number of buttons

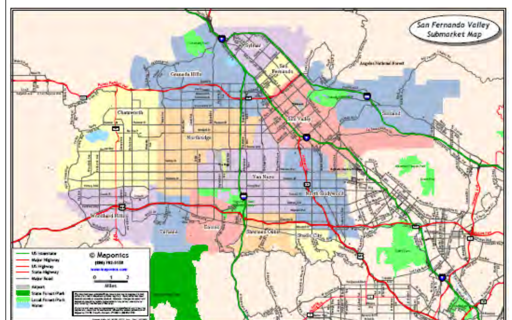
Moral: largest variability at the transition, largest cluster increases with N (system size)

largest cluster ~ N^{∂}

peak variability ~ N^{β}

What means to be “Critical” : another example, traffic

“solid”



+

=

“gas”

Structure
(the network of
streets)

+

Individual
Non-linear
Dynamics
(drivers)

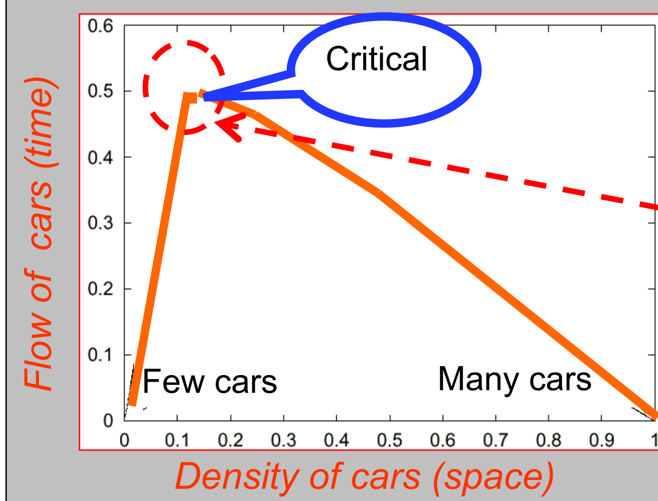
=

“phases”

El tráfico de un gran ciudad es un sistema complejo en donde para la misma estructura de calles, dependiendo del numero de autos y de los hábitos de los conductores podemos observar diferentes fases (tráfico fluido, congestionado, etc.)

What means to be "Critical" -qualitatively speaking-

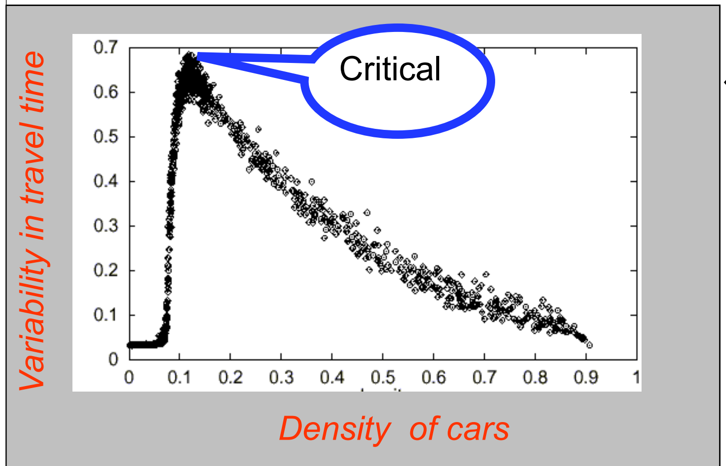
Traffic jams as a critical process



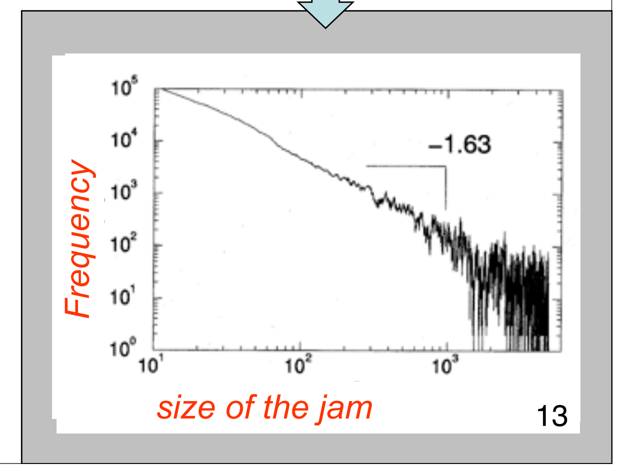
Number of vehicles passing through a point (flow) as a function of the density of vehicles

- *Two phases*
  - *Free flow*
  - *Jamming*
- *For the traffic engineer the maximum "efficiency" is at the Critical point*

■ *For the driver the Critical density is the worst case!*



- *At criticality the travel time' variability is maximum*
- *Jams of all sizes*



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

What means to be "Critical"? final example

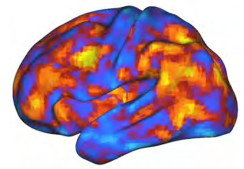
Interactions are short range & weak ; correlations are long range; Order?… depend of the day summing :

- The variability of the order parameter peaks at criticality (i.e, “susceptibility”) increasing with size as $N^{\text{some exponent}}$
- Clusters (jams/buttons_bunch) of all sizes (i.e, long range spatial correlations observed as power law distributions of clusters).
- The action of a single driver/link 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, buttons, etc)

Part II: Brain stuff

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 very weak , short range and fix (at the time scale of interest)!!

Scale free clustering (ordering) without synchronization!

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

Our proposal

nature physics

REVIEW ARTICLE

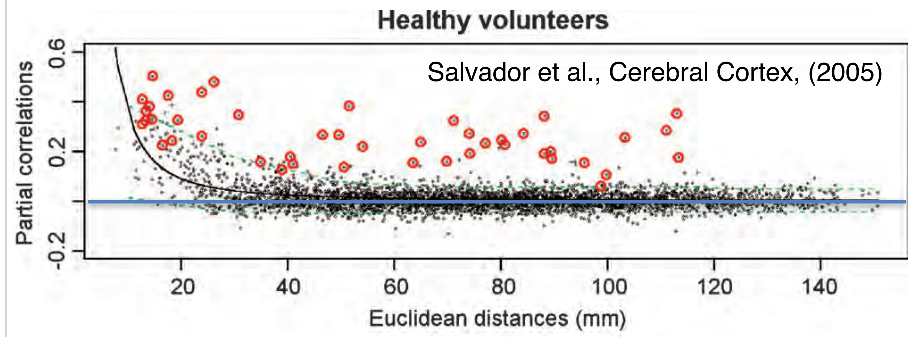
PUBLISHED ONLINE: XX MONTH XXXX | DOI: 10.1038/NPHYS1803

Emergent complex neural dynamics

Dante R. Chialvo[1,2]*

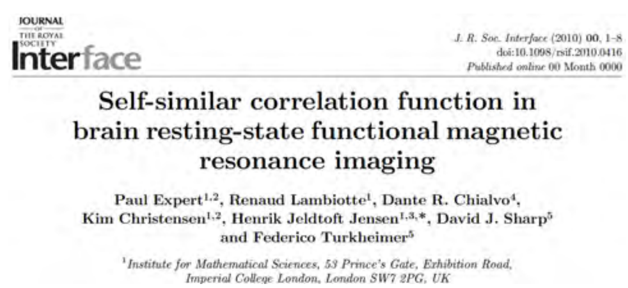
A large repertoire of spatiotemporal activity patterns in the brain is the basis for adaptive behaviour. Understanding the mechanism by which the brain's hundred billion neurons and hundred trillion synapses manage to produce such a range of cortical configurations in a flexible manner remains a fundamental 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.

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



Most of C(i,j) pairs are very *weak*

< C(i,j) > decay with distance as a power law



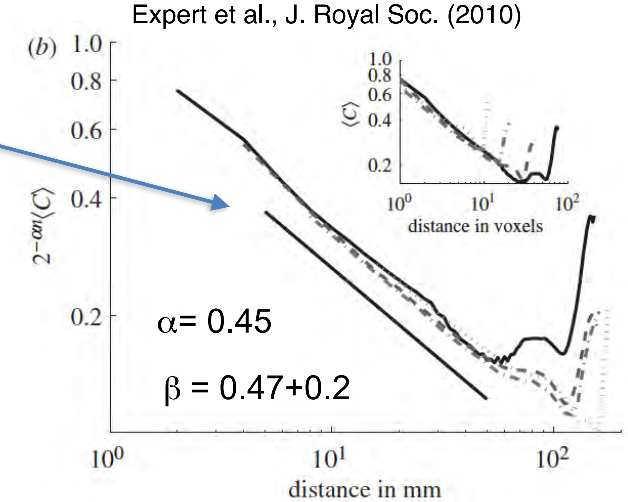
JOURNAL OF THE ROYAL SOCIETY Interface

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]

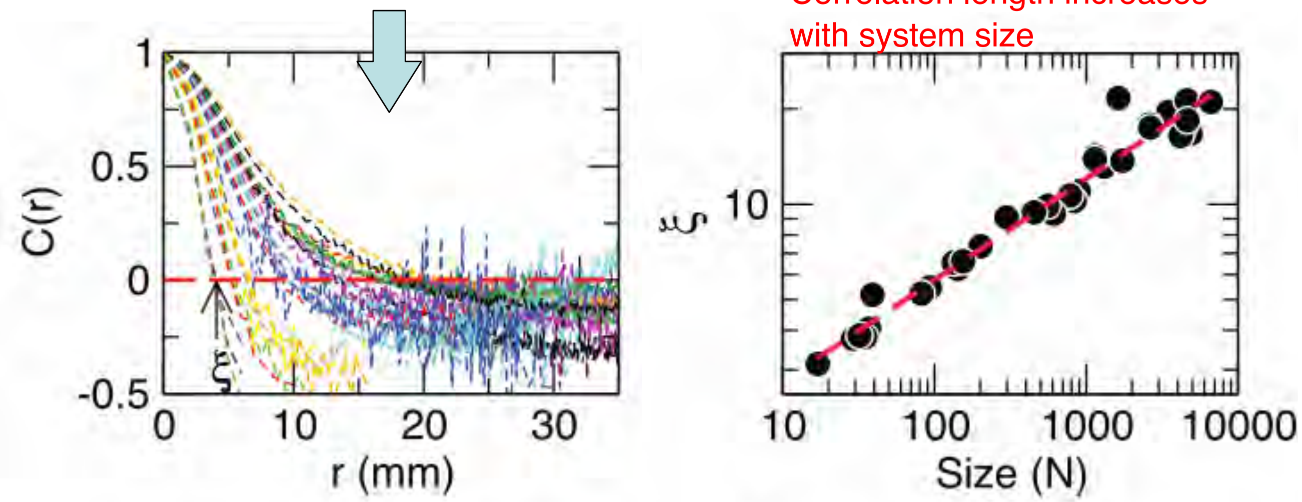
[1] *Institute for Mathematical Sciences, 53 Prince's Gate, Exhibition Road, Imperial College London, London SW7 2PG, UK*



What truly matters is to determine the correlation length

1- Record activity on many regions of interest far apart at various distances.
2- Compute the average connected correlation function (not any correlation) for each record & plot it as a function of mutual distance

Correlation length increases with system size

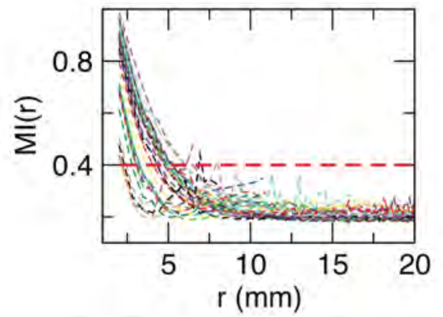


The bottom line: Big, intermediate and small regions behaves all in the same way

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

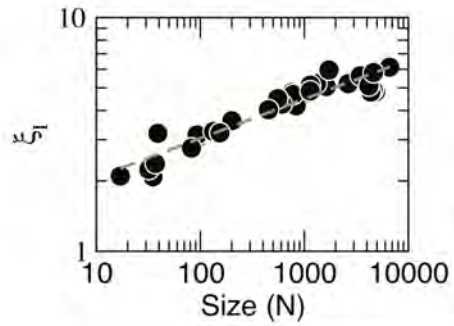
Chialvo DR & Fraiman D. (2010)

You could do the same for Mutual Information

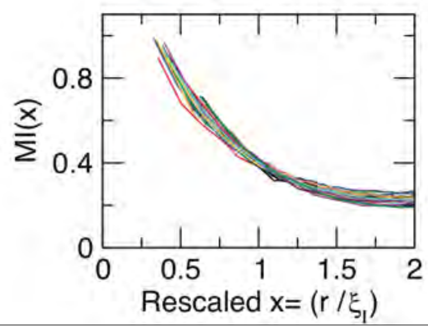


MI(X;Y) = H(X) - H(X I Y)

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



Mutual information increases with cluster size.



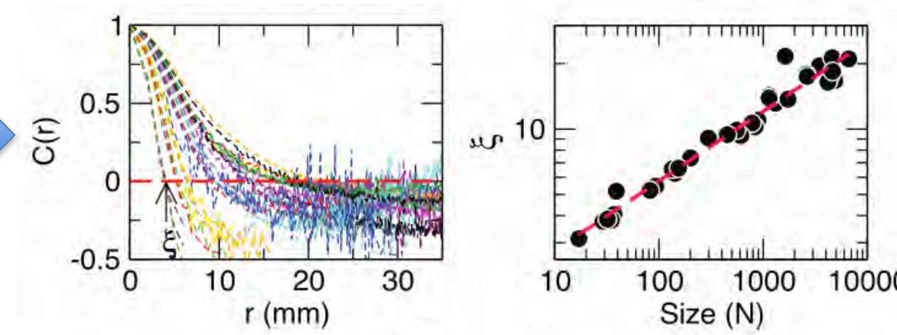
Rescaled mutual information

Chialvo DR & Fraiman D. (2010)

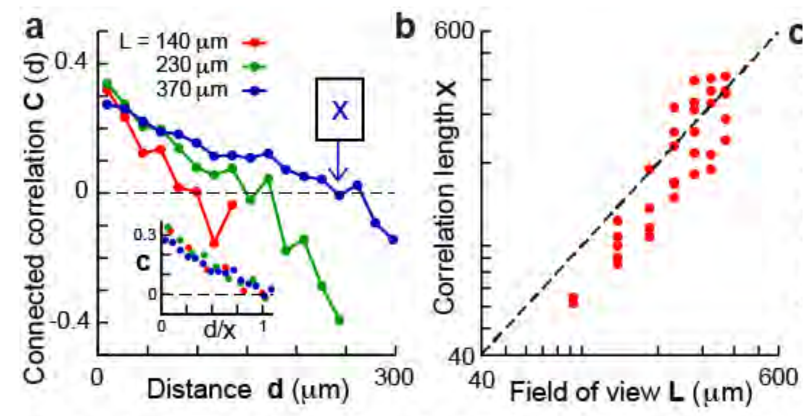
correlation length: at criticality increases with system size

Data from human fMRI

(Fraiman & Chialvo, 2011)



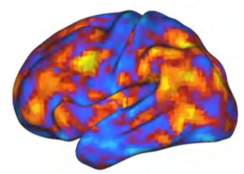
Data from optogenetic
2P recording in behaving
mice AI cortex
Plenz … & Chialvo, unpublished



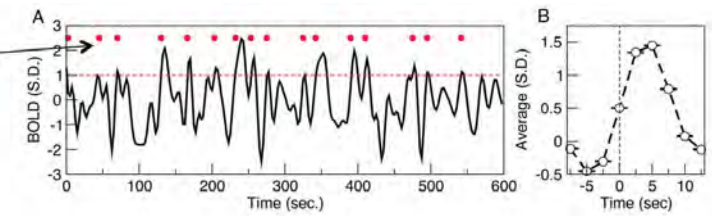
Brain "meteorology" (searching for order in very large scale, fMRI)

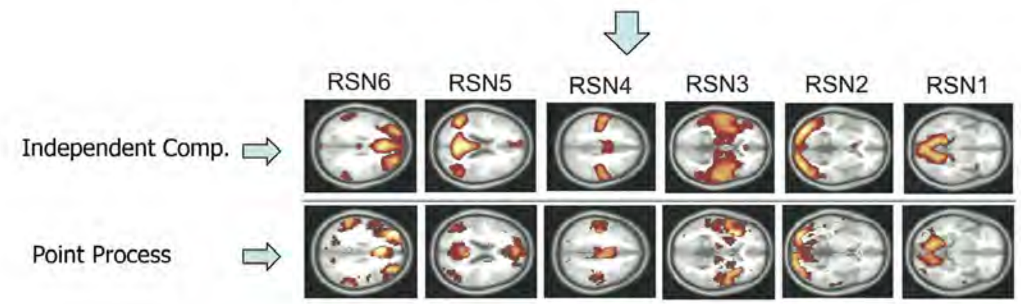
First, get the instantaneous dynamics (peaks)

how we proceed:



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



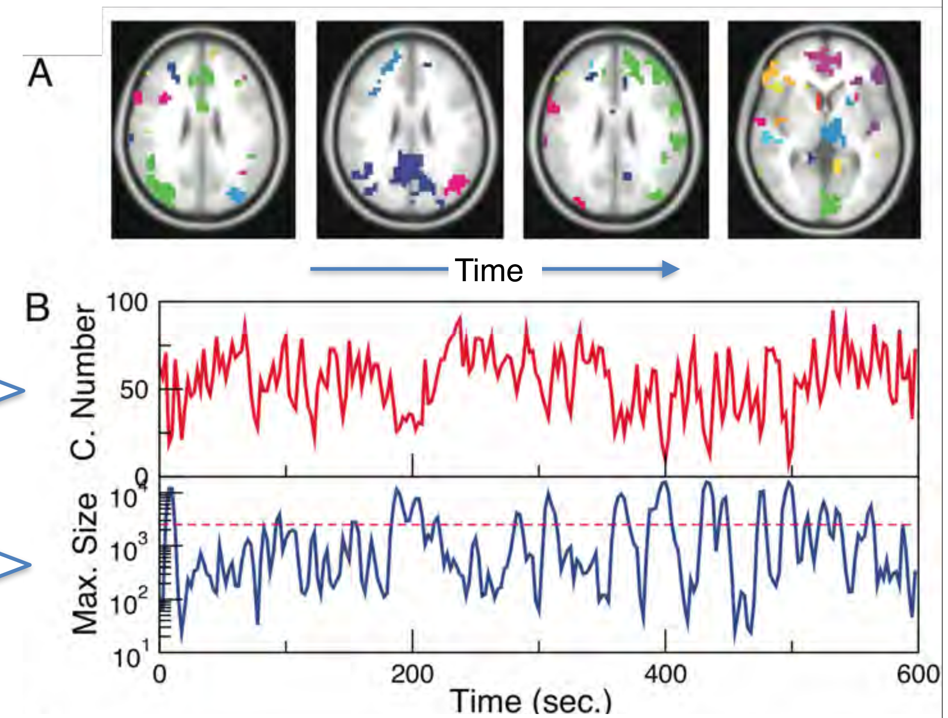


Moral: large scale dynamics is preserved despite a huge data reduction (95%) most of the information is in the peaks.

Brain "meteorology"

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

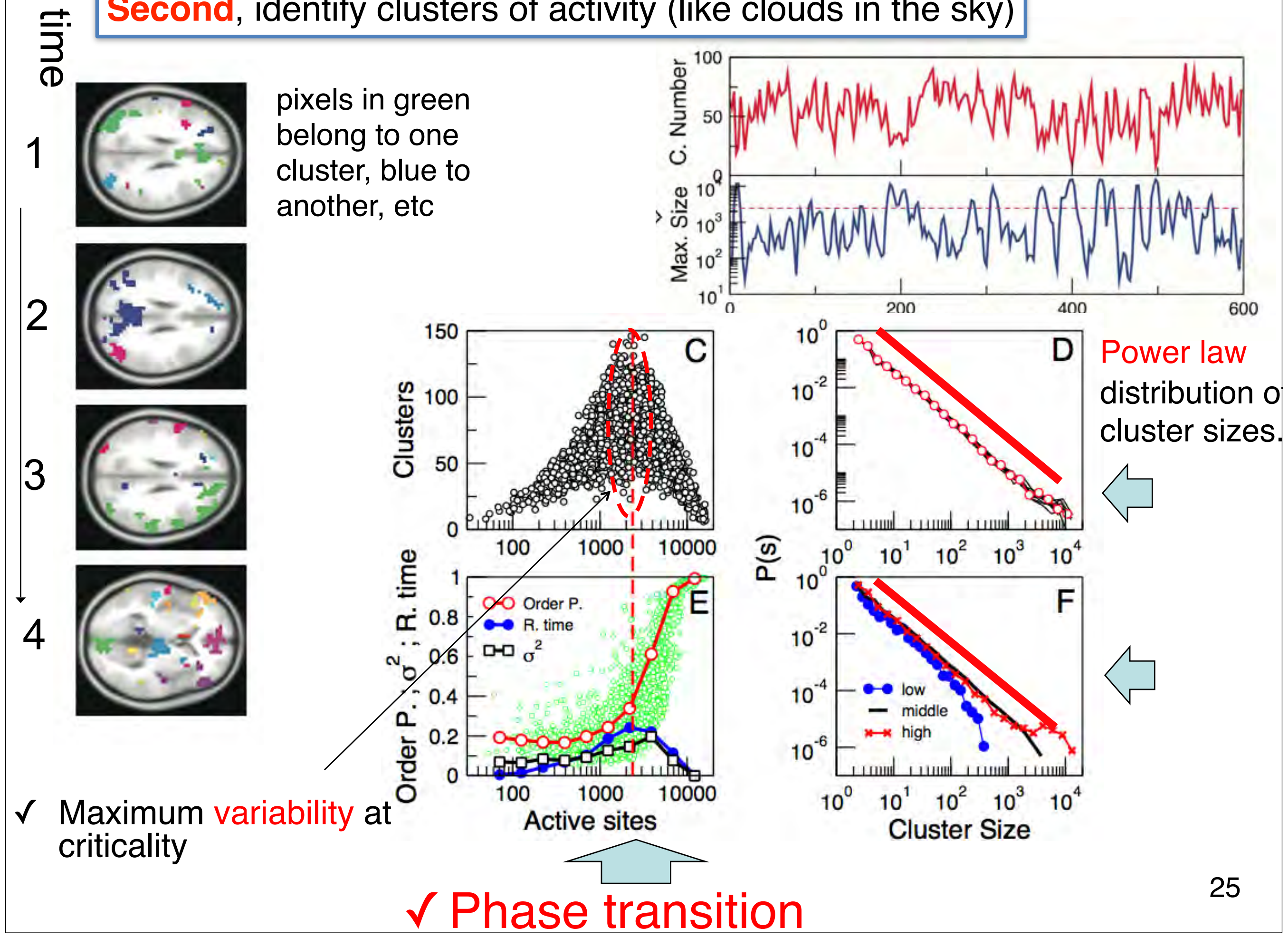
pixels in green belong to one cluster, blue to another, etc



Number of clouds

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

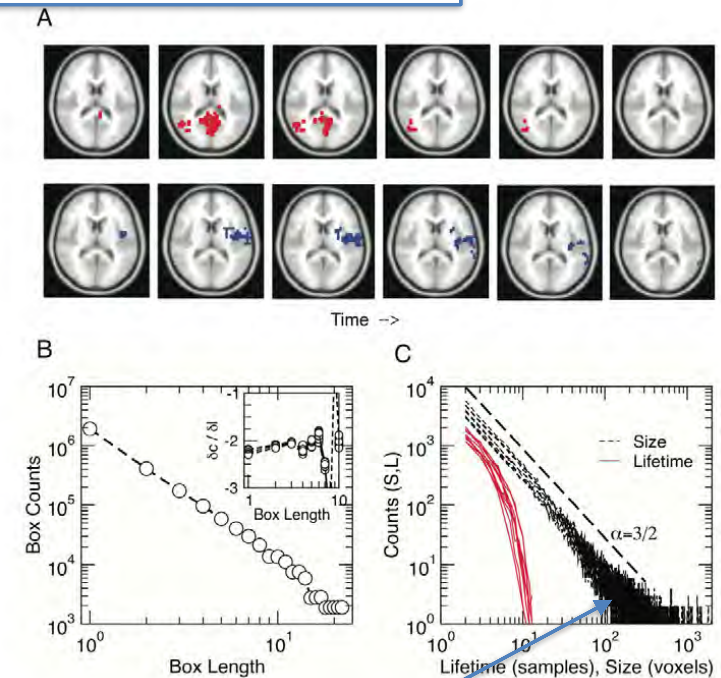
Second, identify clusters of activity (like clouds in the sky)

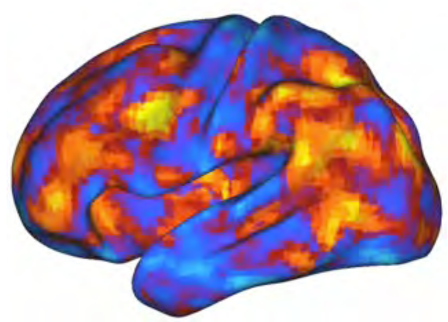


Third, identify spatiotemporal correlations (avalanches)

One avalanche

Another one





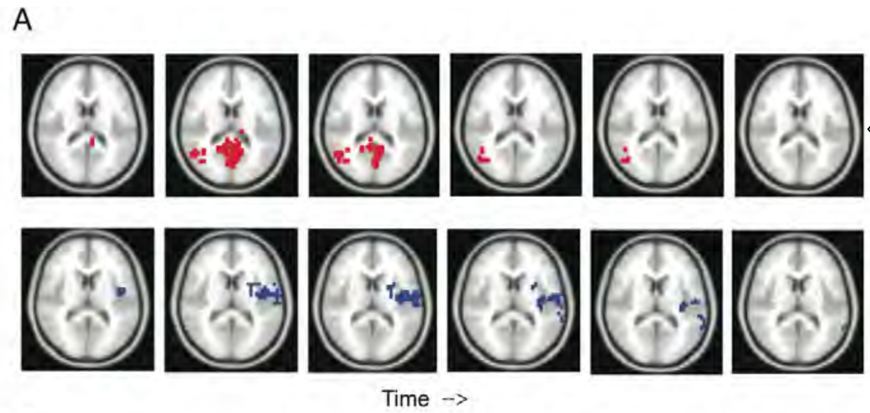
Fractal Dimension

Lifetime PDF

Size PDF

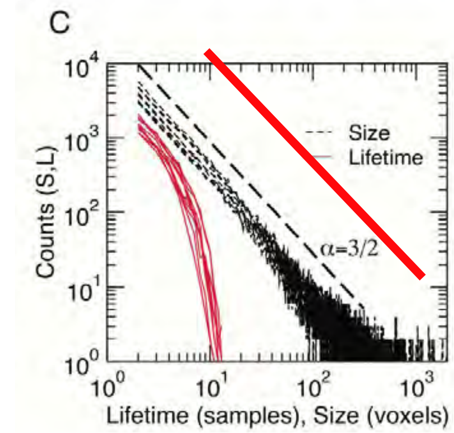
Avalanches of activity are scale free

From Tagliazucchi et al, Frontiers in Physiol. 2012.



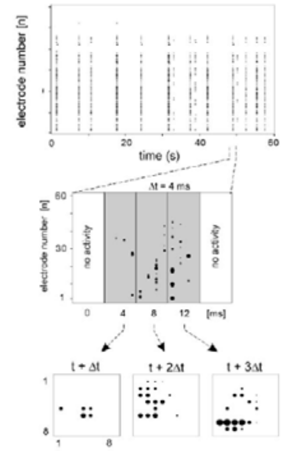
One avalanche

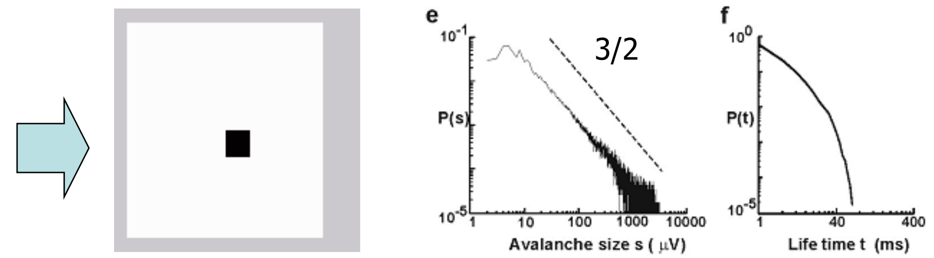
Another one



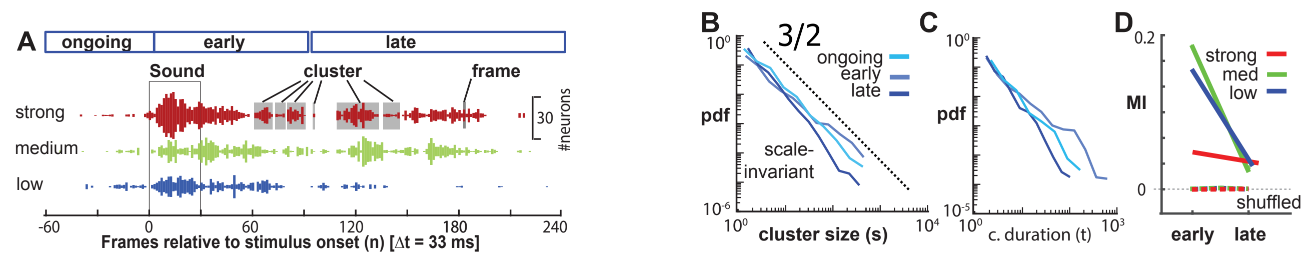
✓ Avalanches of activity of all sizes

Identical avalanches were described in vivo & in vitro preps.



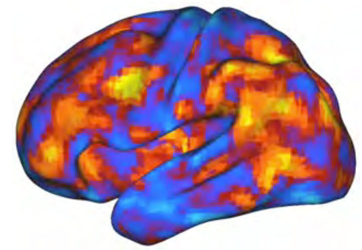


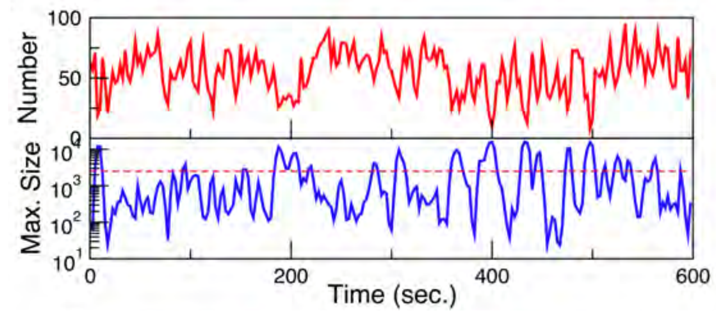
cultured rat cerebral cortex (Beggs & Plenz, 2003)

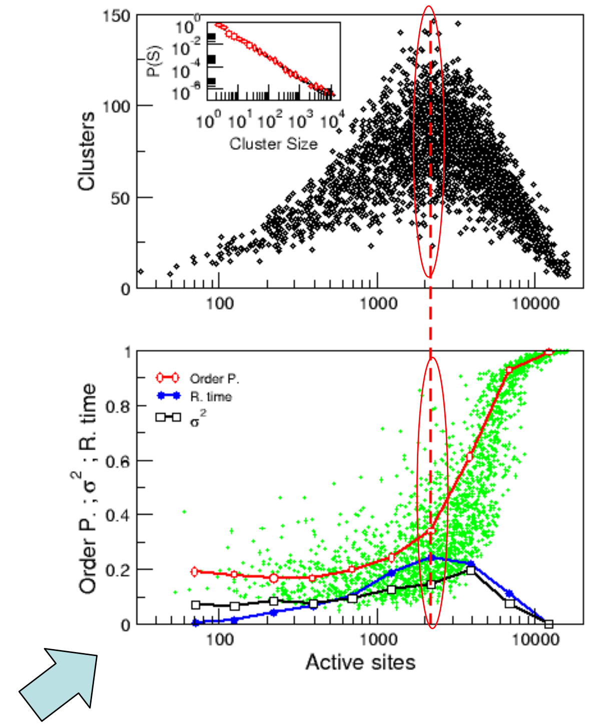


Optogenetic 2P recording in behaving mice AI cortex (Plenz et al, 2018)

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



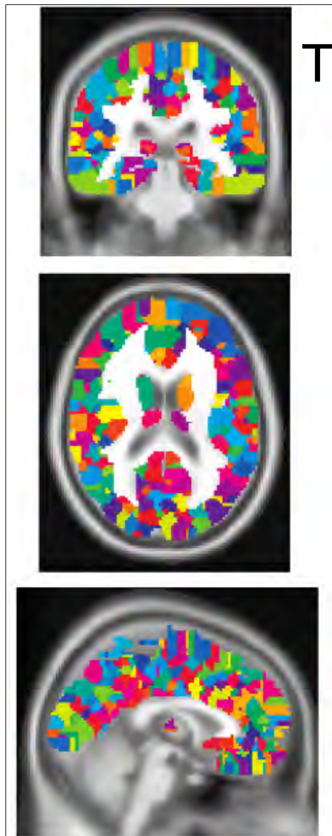


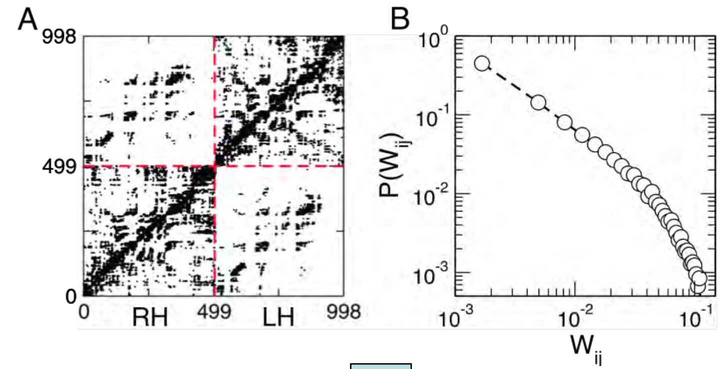


Spontaneous fluctuations of brain activity evolve as in a continuous phase transition, being most of the time at a regime with the largest variance

Part III: Models

The *interactions* from the human connectome

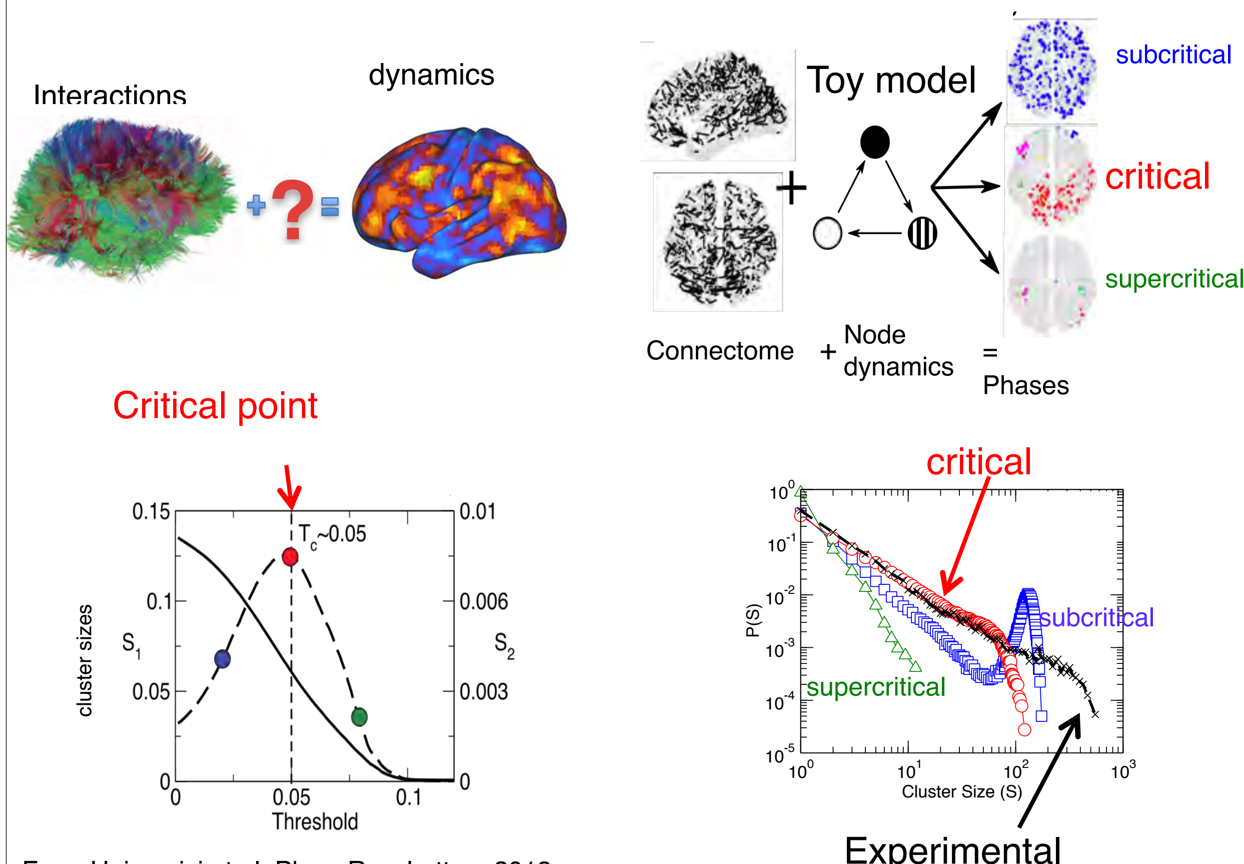




Plus some "simple" dynamics, actually (if universality applies) almost any nonlinear rule must give the exact same result…

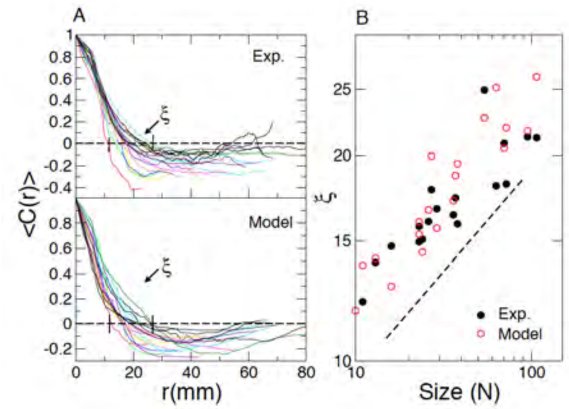
-Haimovici A, et al. "Brain organization into resting state networks emerges from the connectome at criticality". PRL (2013).

Getting the experimental *correlations* from the *interactions* ("Connectome")

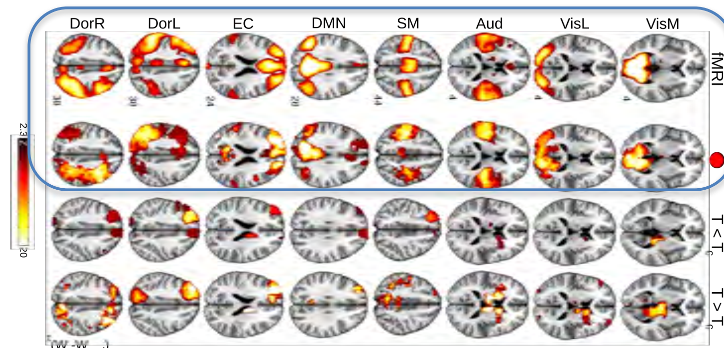


From Haimovici et al, Phys. Rev. Letters 2013.

Getting the same *correlations* from the known *interactions* ("Connectome")



Correlation length *increases* with cluster size exactly as seen in the real brain experiments



Experimental results (real brains).

critical

Sub critical

Super critical

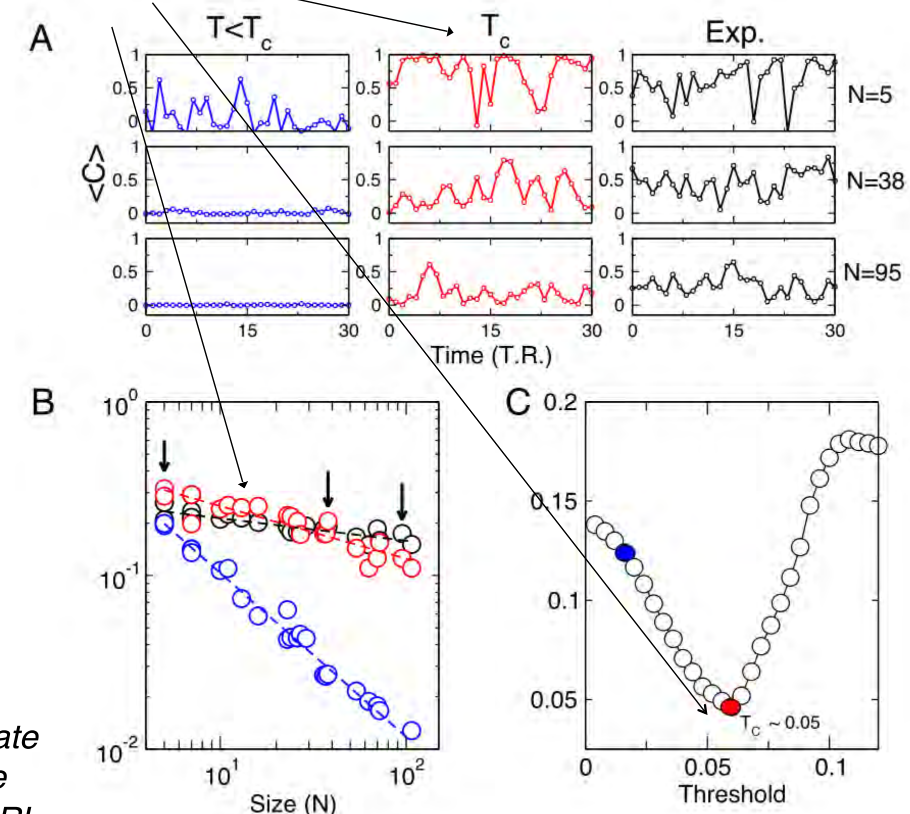
model

Only at *criticality* the model replicates the exp. data

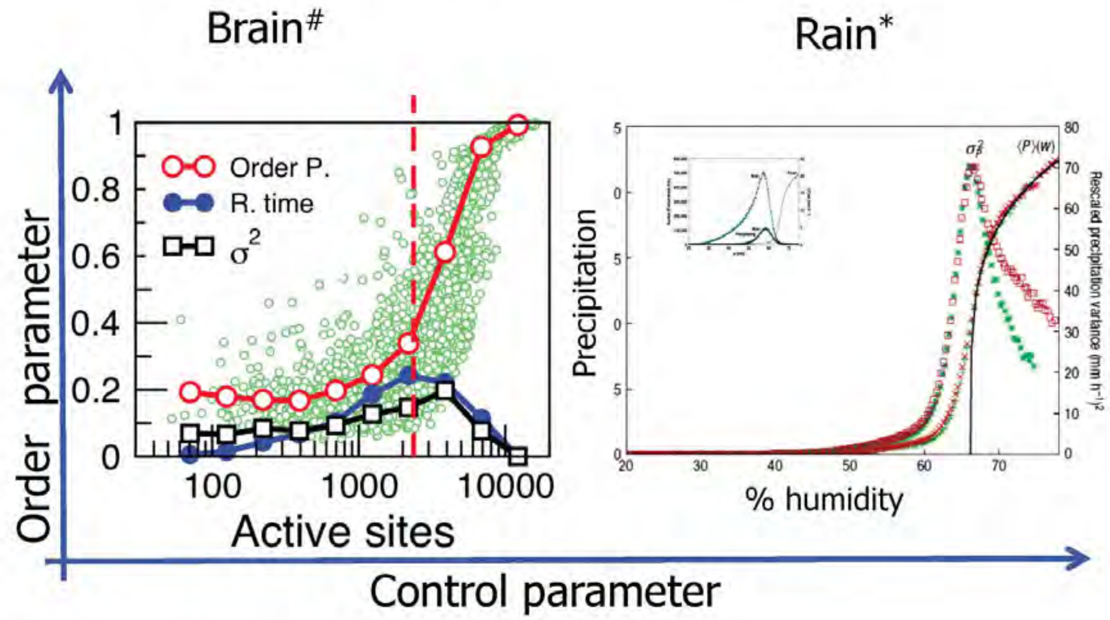
From Haimovici et al, Phys. Rev. Letters 2013.

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).



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

Tagliazucchi et al, Frontiers (2012).

Part IV: Summary

Summary

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

2- A model based on the brain connectivity replicates the observations ONLY at criticality, implying that “connectivity” is less relevant for understanding the dynamics.

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

Definitely , don't think about the brain as a CIRCUIT!

Part V: Implications for Neuromorphing

for “Neuro”morphing … almost none

for “Brain”morphing a few interesting ones

ask in the afternoon

The Danubio metaphor

The Danubio equivalent to the brain connectome

Thanks!

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