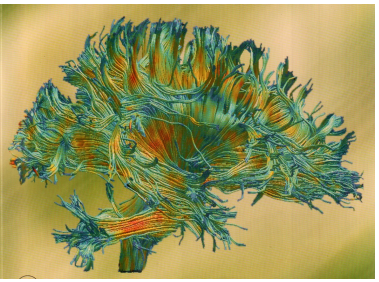
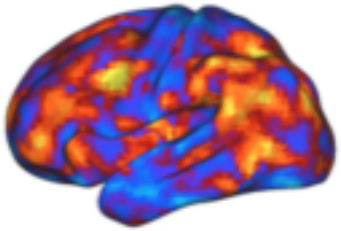




What kind of noise is "brain noise"?

The physics of the brain "dolce far niente"

Some insights from critical phenomena

Dante R. Chialvo

dchialvo@ucla.edu

Papers: www.chialvo.net

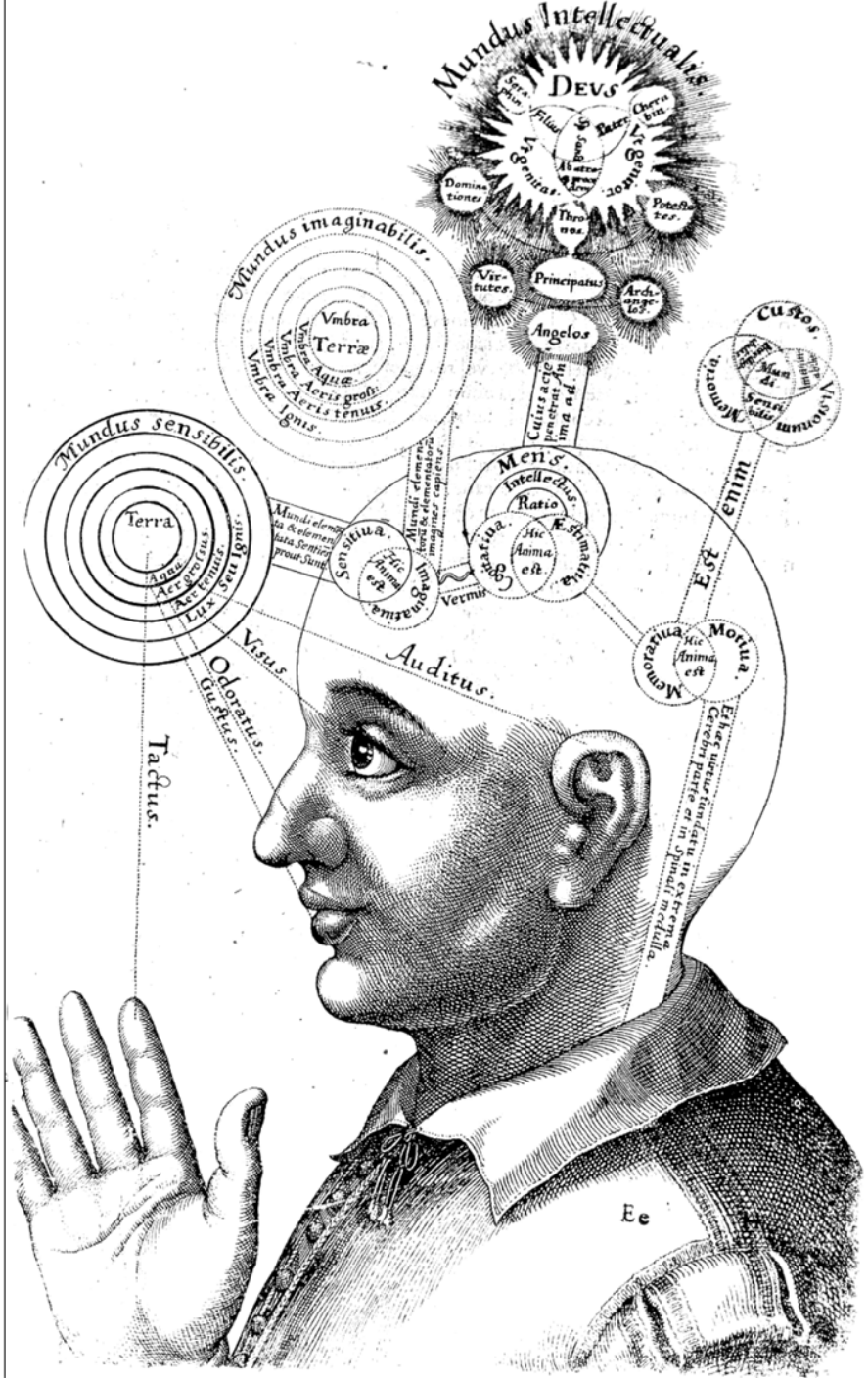
Perugia NIPS July 8, 2013

CONICET

Emc³ Lab

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

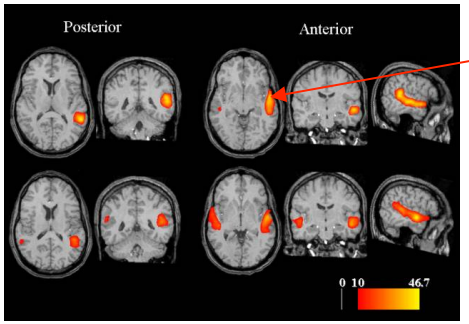
In the past brain states were unaccesible and wild speculations were limited to outside of your head

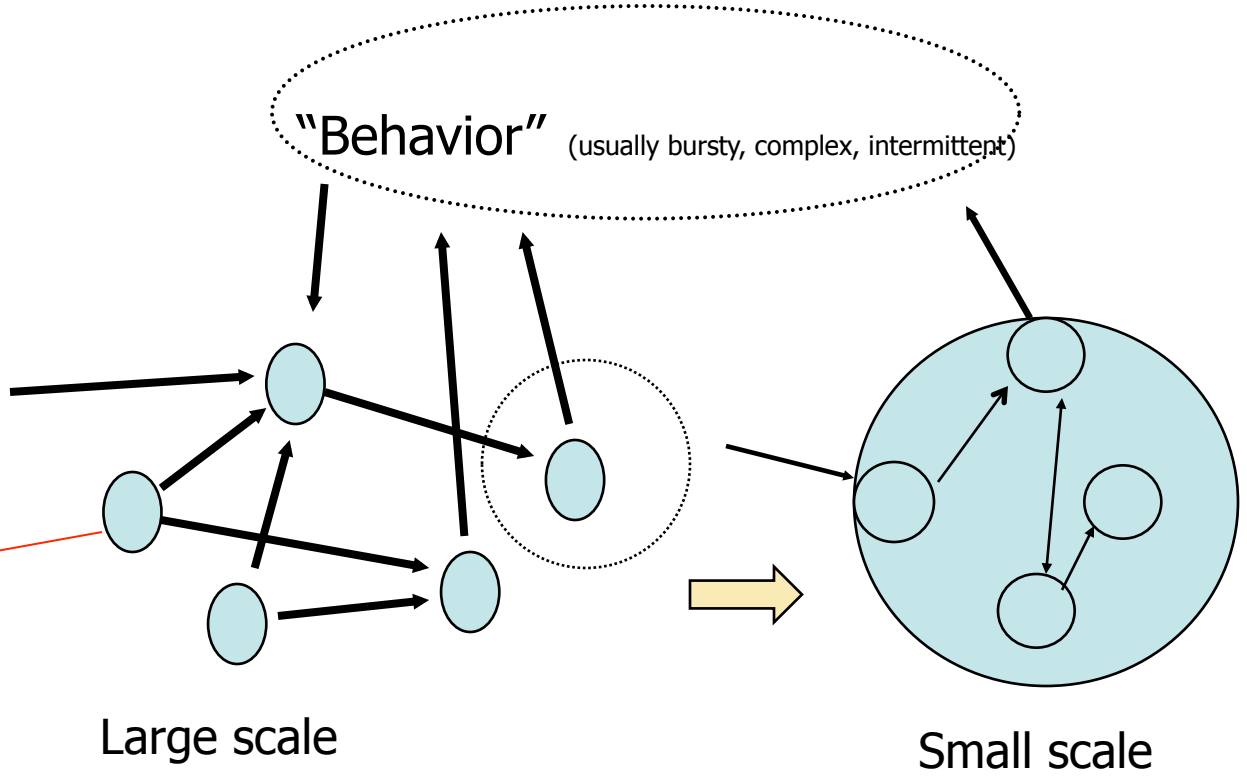


Brains are networks producing behavior ...

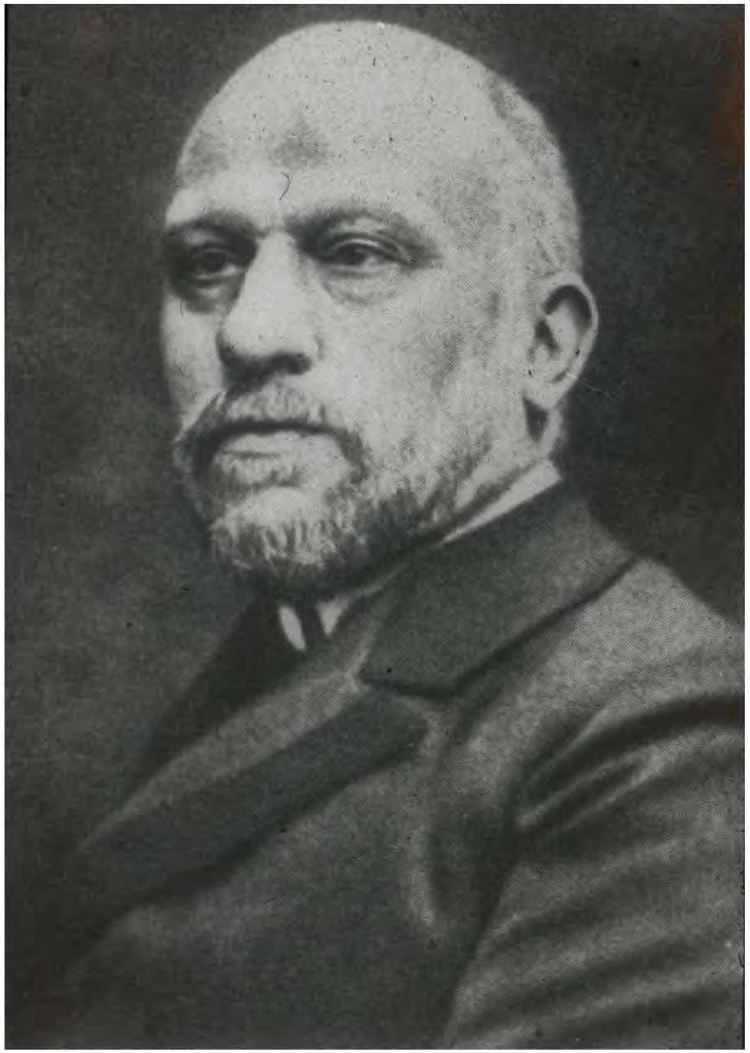
at various scales…

Nowadays we can see these **states**…



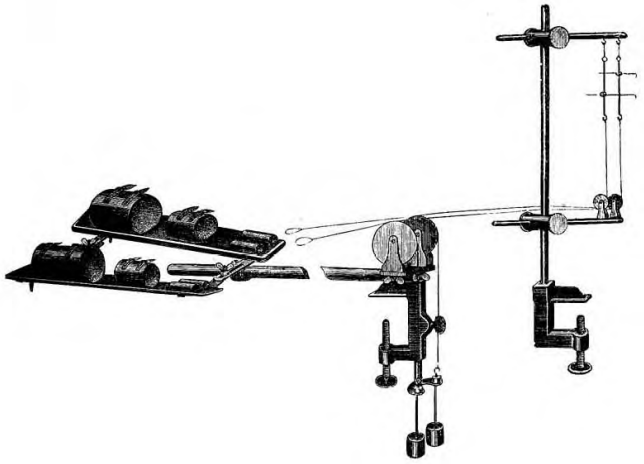


The first connection between blood flow and mental activity

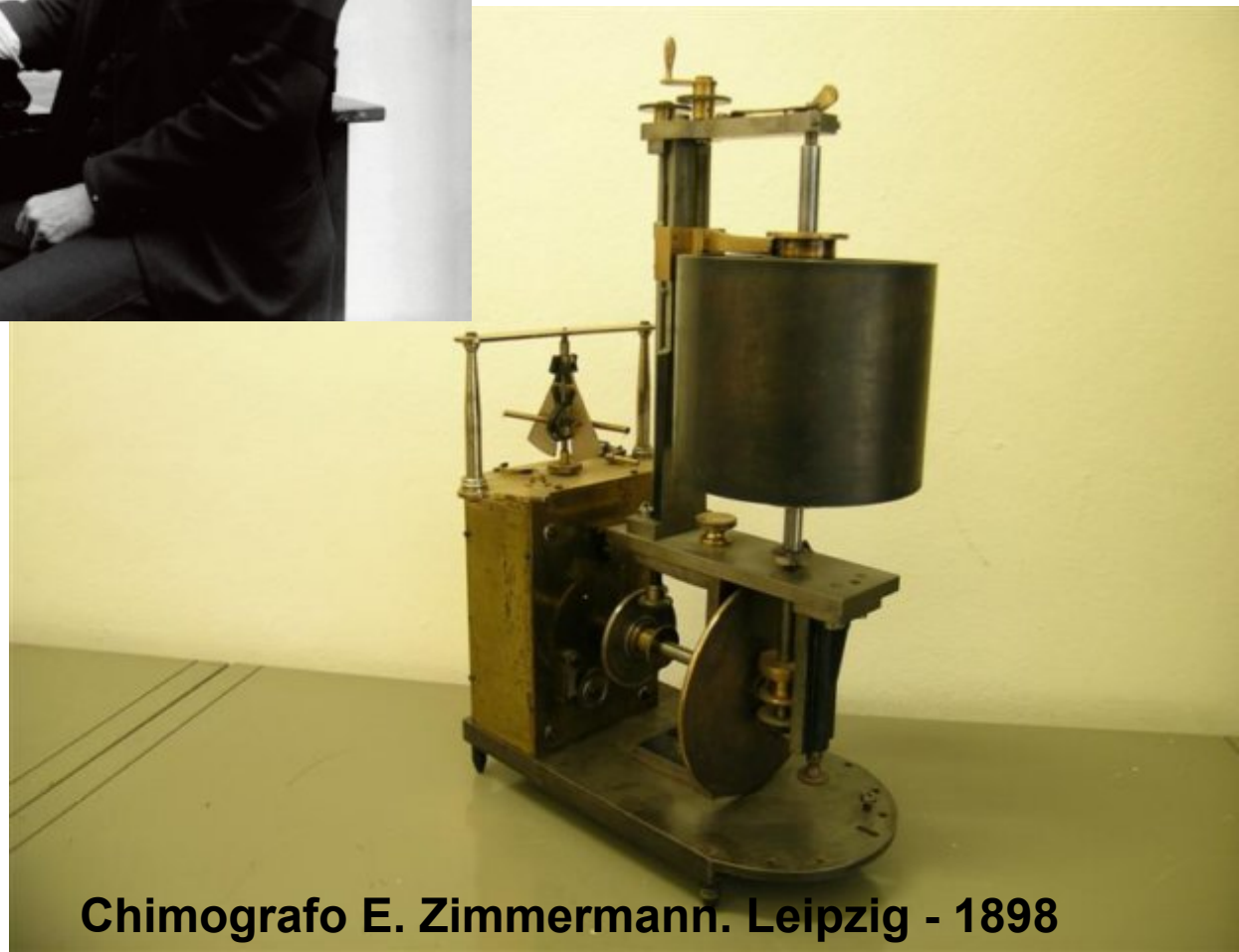


Angelo Mosso
30 May 1846 - 24 November 1910

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



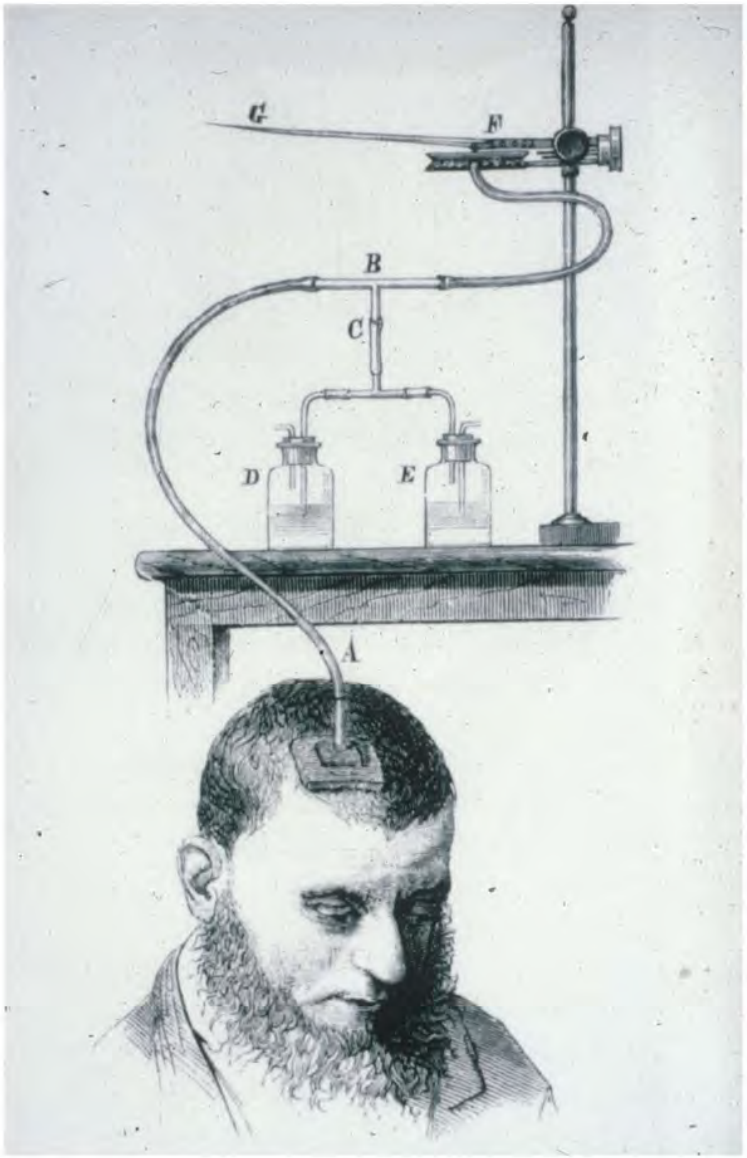
Inventor del primer ergografo para medir la fuerza muscular



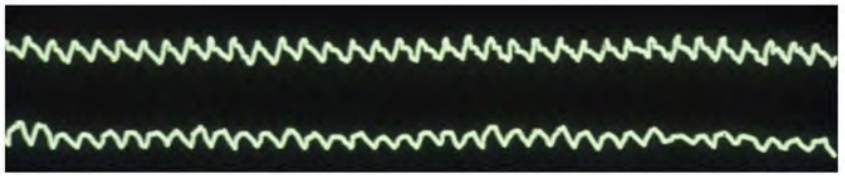
Chimografo E. Zimmermann. Leipzig - 1898

Monday noon, September 23, 1878

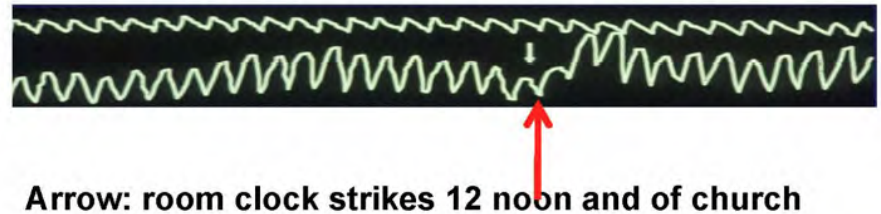
1878 Experiment with Bertino



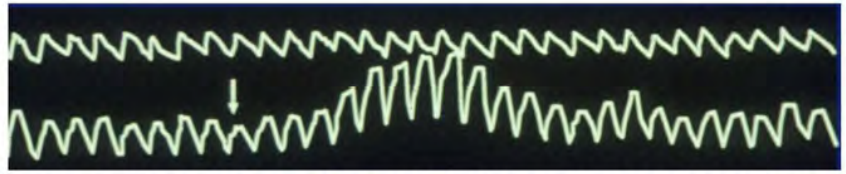
From: Angelo Mosso (1881)



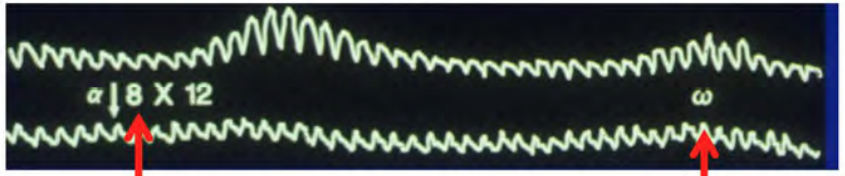
Resting quietly



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



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



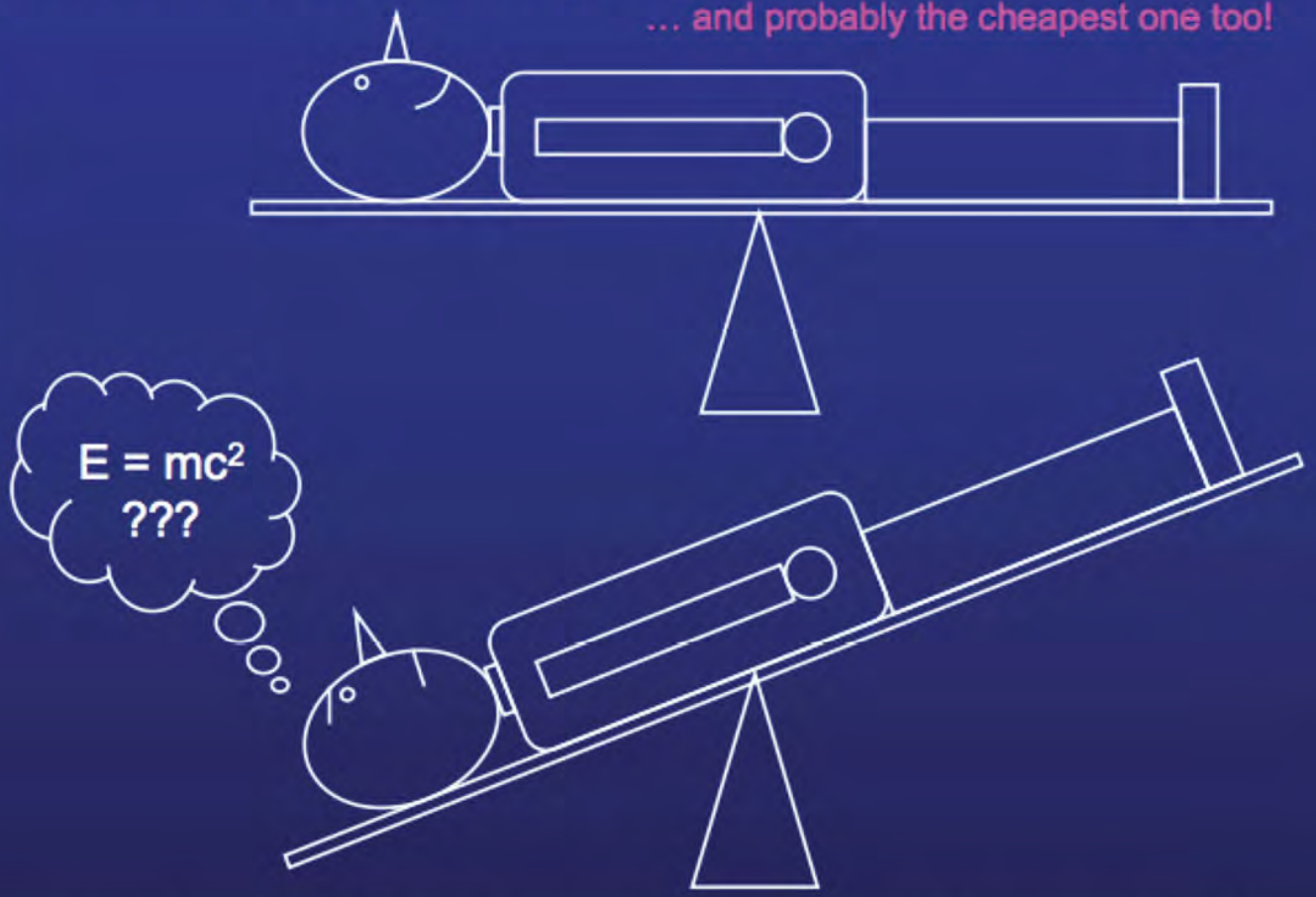
"What is 8 x 12?"

ω: response

The First "Brain Imaging Experiment"

… and probably the cheapest one too!

Angelo Mosso
Italian physiologist
(1846-1910)



"[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."

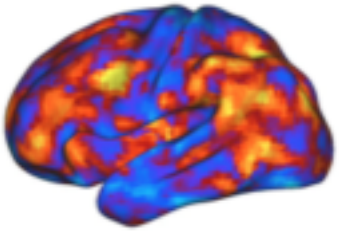
-- William James, *Principles of Psychology* (1890)

Italian physiologist Angelo Mosso is buried in a very simple tomb in one of the Meritorious people arches inside the Monumental Cemetery of Turin (3rd extension, Arch 56).

The Italian inscription reads as follows:

"AD ANGELO MOSSO / FISIOLOGO INSIGNE / CON MOLTEPLICE OPERA INFATICATA / ILLUSTRATORE DELLE MODERNE SCIENZE / QUI TORINO SERBA PERPETUO ONORE

/ 31 MAGGIO 1846 – 24 NOVEMBRE 1910/



We know better now

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*
- *When "does something" a few places increase 1 - 2 % that number*

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

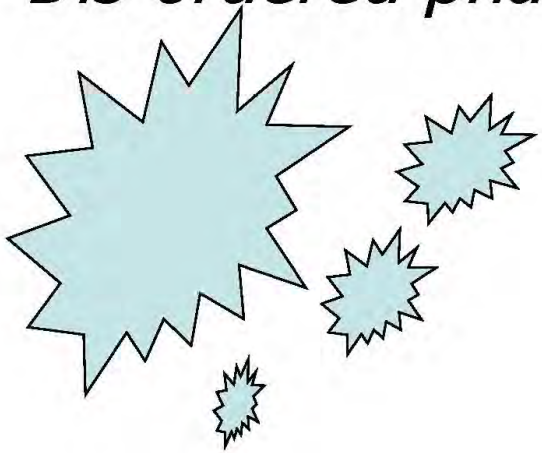
Answer: critical dynamics

What is this business (without any rigor) of criticality about?

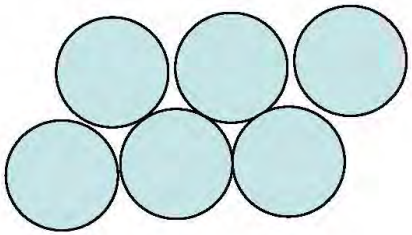
(in 5 minutes)

Crisis??? What means being "critical"

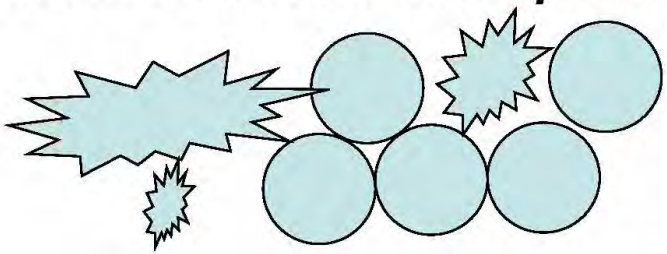
Dis-ordered phase



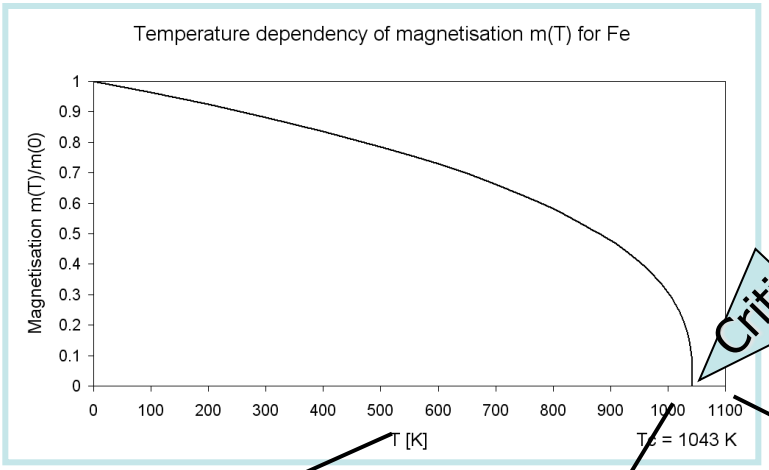
Ordered phase



Critical= In between two phases



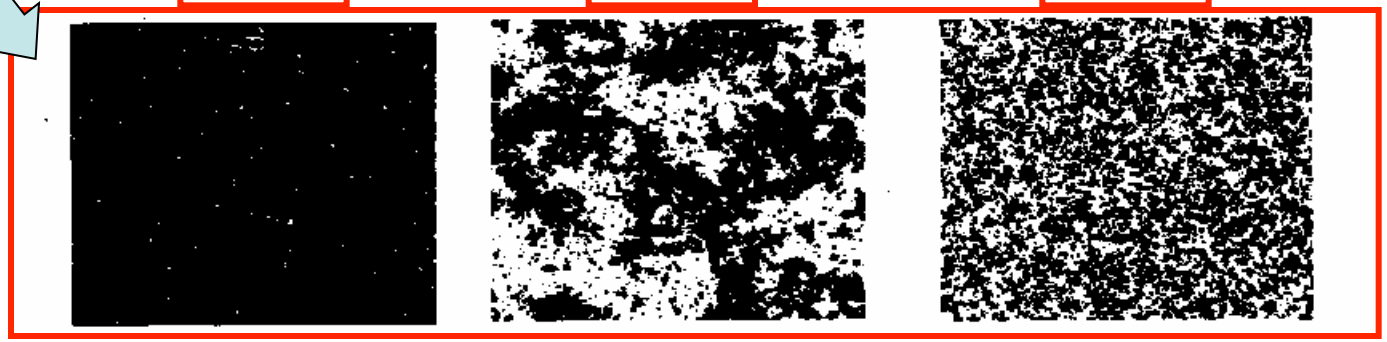
What is special about being critical?
Recall Ferromagnetic-paramagnetic Phase-Transition



Critical Temperature

Snapshots of spins states in a model system (Ising)

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



SubCritical Critical SuperCritical

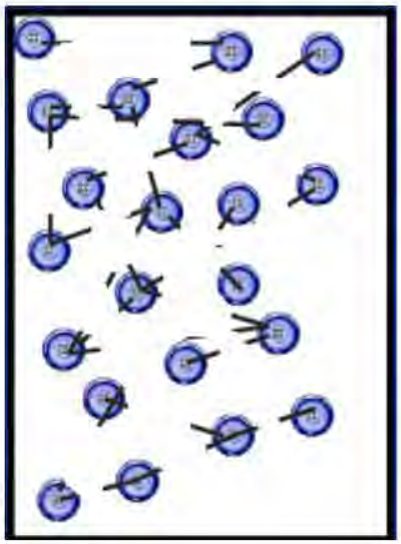
Only at Tc

*Large fluctuations and long range (power law) correlations

*Divergence of correlation length

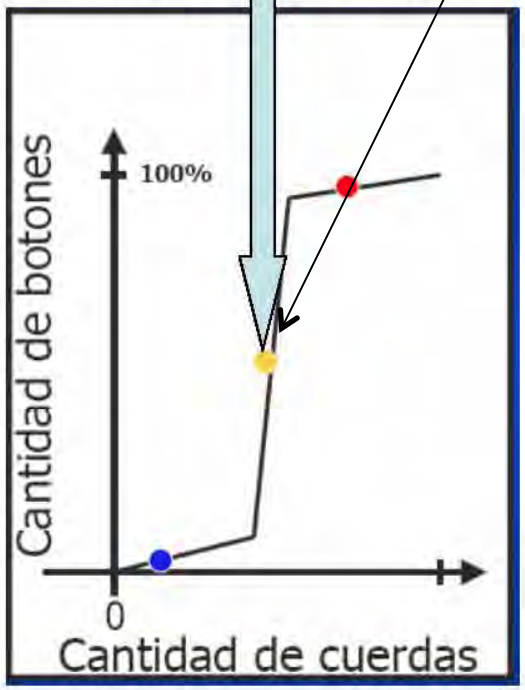
*Highest susceptibility (highest variability)

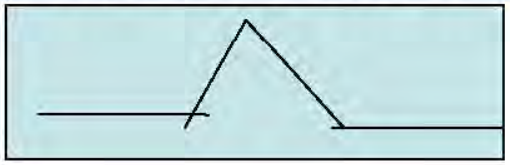
highest variability always at the transition



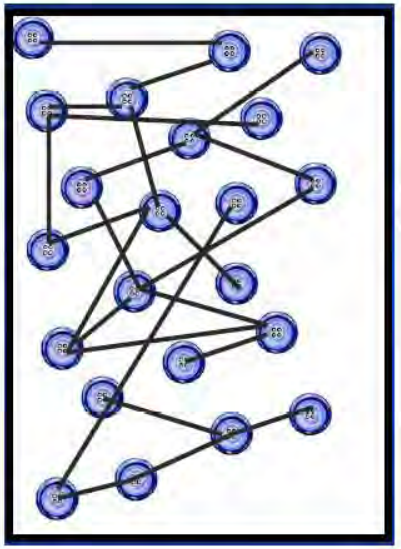
Fase
desconectada

Cantidad de
cuerdas critica





Variabilidad
es máxima en
la transición



Fase
conectada

Criticality & Brain

- *1941: Warren 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: Chialvo et al. → Ising like dynamics → networks with scale free topology = brains.*
- *2008: Expert et al. -> Correlation Function @ resting state is critical.*
- *2010: Chialvo et al. → Correlations diverge in fMRI -> Criticality.*
- *2011: Tagliazucchi et al. → order/control parameter show that the brain is not critical .. (all the time…)*
- *2012: Haimovici et al. → writing critical brain models*

If criticality is the solution …
what is the problem?

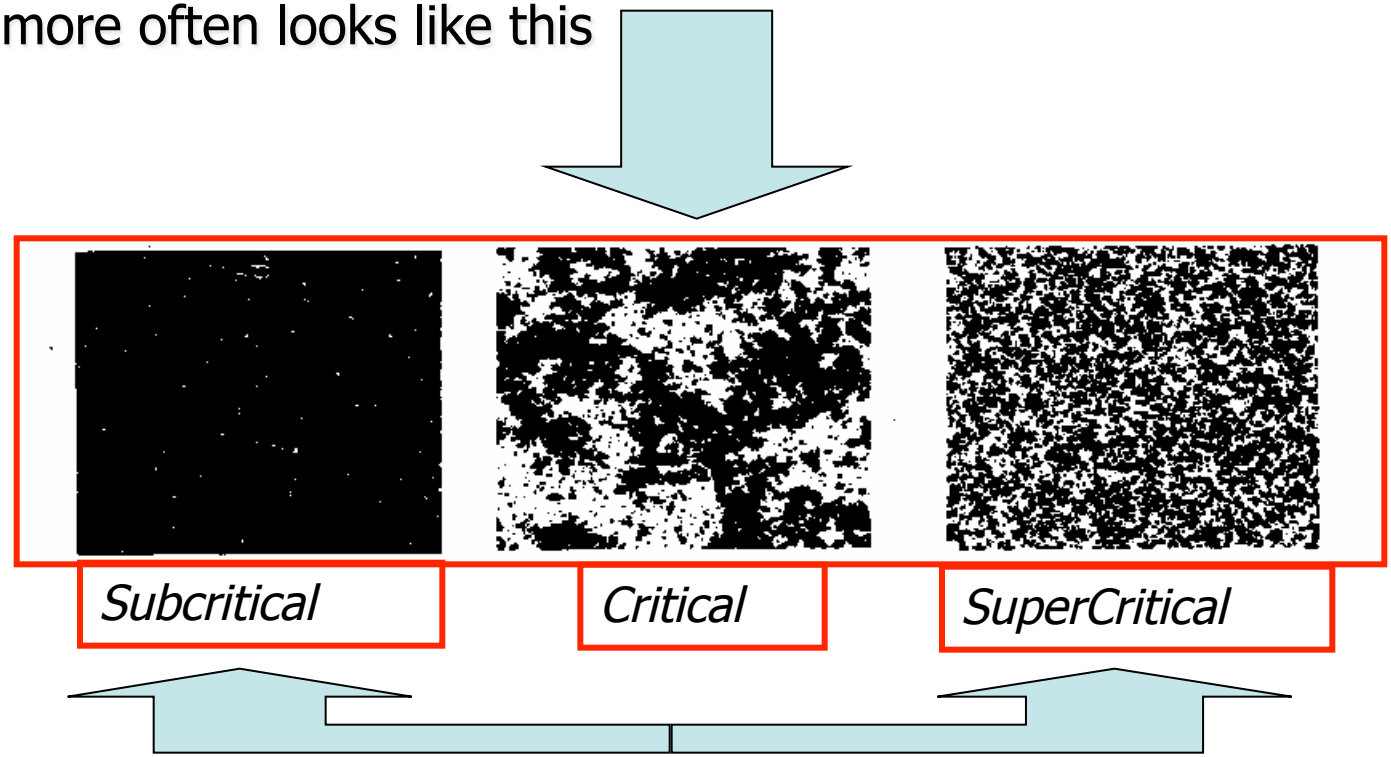
Because always there is a solution…

Which is related to the question:

Why do we need a brain at all?

Four Fs (of evolution): fighting, fleeing, feeding, and reproduction

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



Not like that!

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 only necessary to navigate in a complex, critical world .

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

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.

Collectives: A few conflictive demands ...

As a collective the brain have a few conflictive demands:

"Integrated" AND "segregated" dilema (Edelman,Sporns,Tononi, etc).

„The brain has to be integrated AND segregated"

This "dilema" is probably not unique of brains but generic of complex systems.

Q: how different is this conflict from being spontaneously posed at a phase transition in between order and disorder?

...thus the problem is to understand how the brain manage to produce a range of cortical configurations (some to segregate some to integrate) 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.

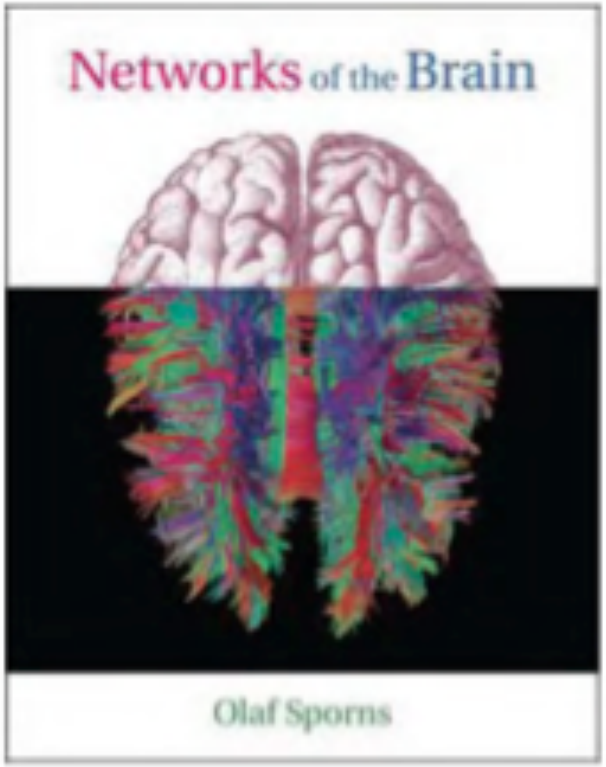
The critical brain conjecture

The world at large is critical, then an evolved brain in such conditions must be critical

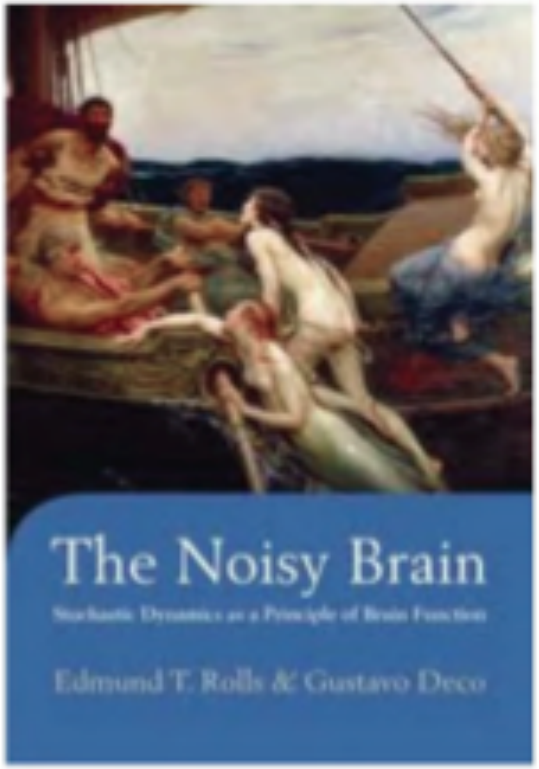
Flexible adaptive behavior is produced by fast brain "reconfigurations" which can only be possible if the brain operates near a critical point

Neither a subcritical (too ordered) or a supercritical (too disordered) brain are compatible with "health".

THE ALTERNATIVE: SWITCHES and/or EQUILIBRIUM MODELS



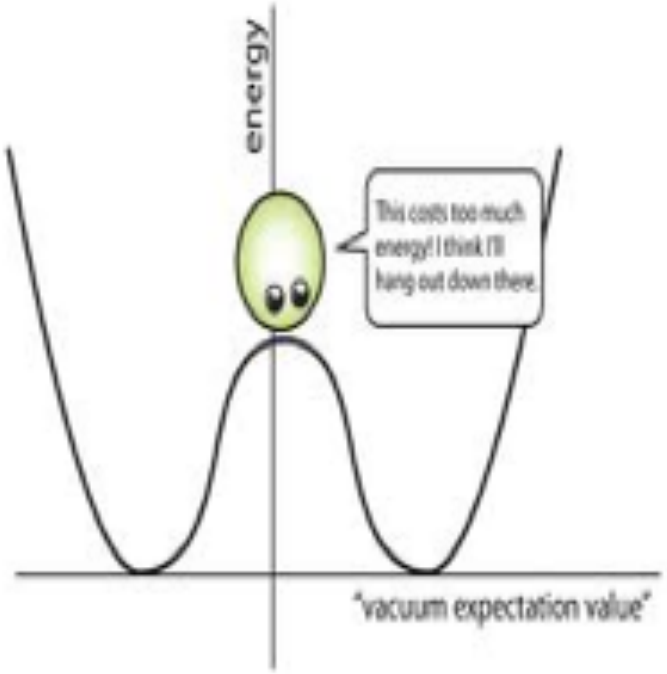
If the brain is a network…
Where is the router?



If noise allows for transitions…
Who control the noise?

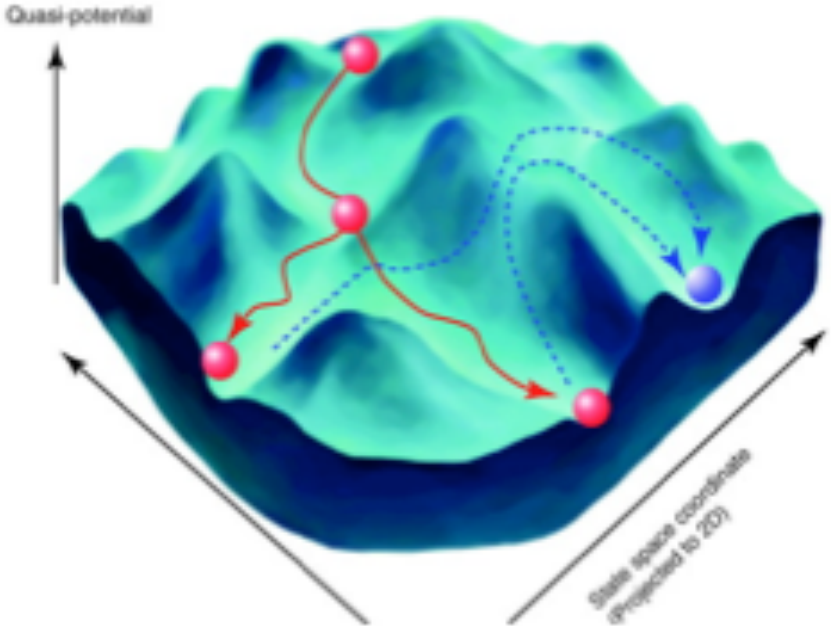
Two opposed views

Attractor (stable) networks, deep sinks



Circuits

Critical always shallow sinks



Rivers beds

If we are right, and the brain is critical: What should we observe?

I) At small scales[2]:

- "Neuronal avalanches" as an homeostatic state of neocortical circuits. ("cortical-quakes").

II) At large scales[1,4]:

- Cortical Long range correlations in space and time (Ising like scale-free networks),
- divergence of correlation length,
- "zero magnetization",
- large-scale avalanches
- generic properties of a 2nd order phase transition

III) At behavioral level[3]:

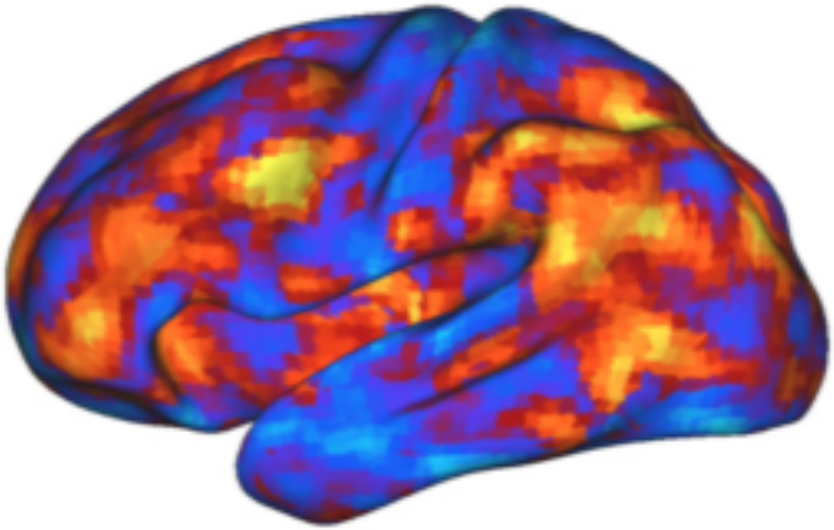
- Adaptive behavior should be "bursty" and apparently unstable, (always at the "edge of failing", "raising the bar effect")

[1] Chialvo DR. Physica A, (2004); Eguiluz et al., Phys. Rev. Letters (2005); Chialvo (2005, 2006); Chialvo et al (2008); Fraiman et al., (2008), Baliki et al., J. Neuroscience (2008);

[2] Beggs & Plenz, J. Neuroscience (2003). Plenz & Chialvo, arxiv.org/abs/0912.5369.

[3] Anteneodo & Chialvo, Chaos (2009). [4] Tagliazucchi et al (2011-2012).

1) divergence of correlation length.

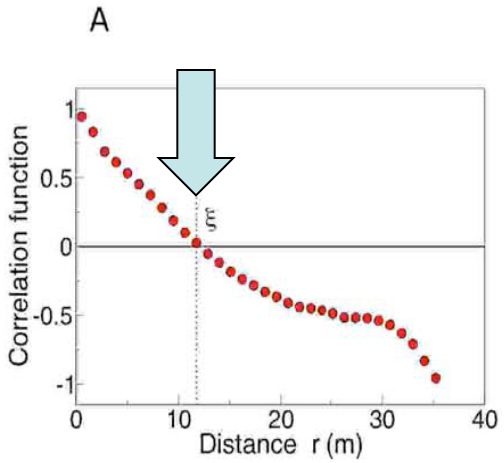


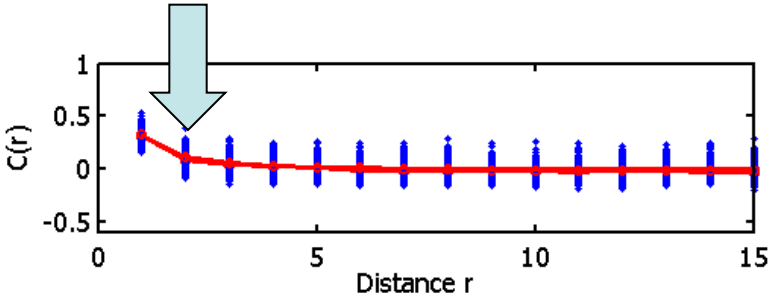
300000 starlings in the spring (real time.)

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

Both are self-organized spatiotemporal patterns lacking a characteristic scale

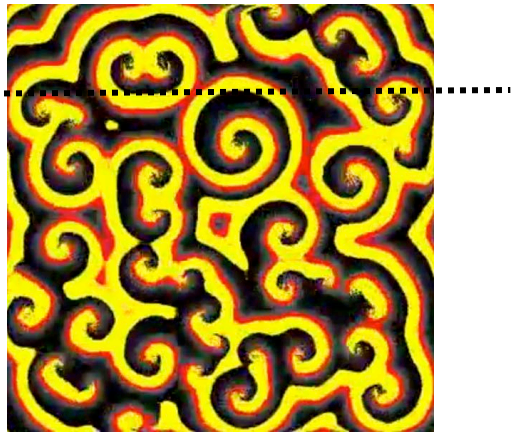
Example of a system with finite correlation ξ length (independent of system's size)

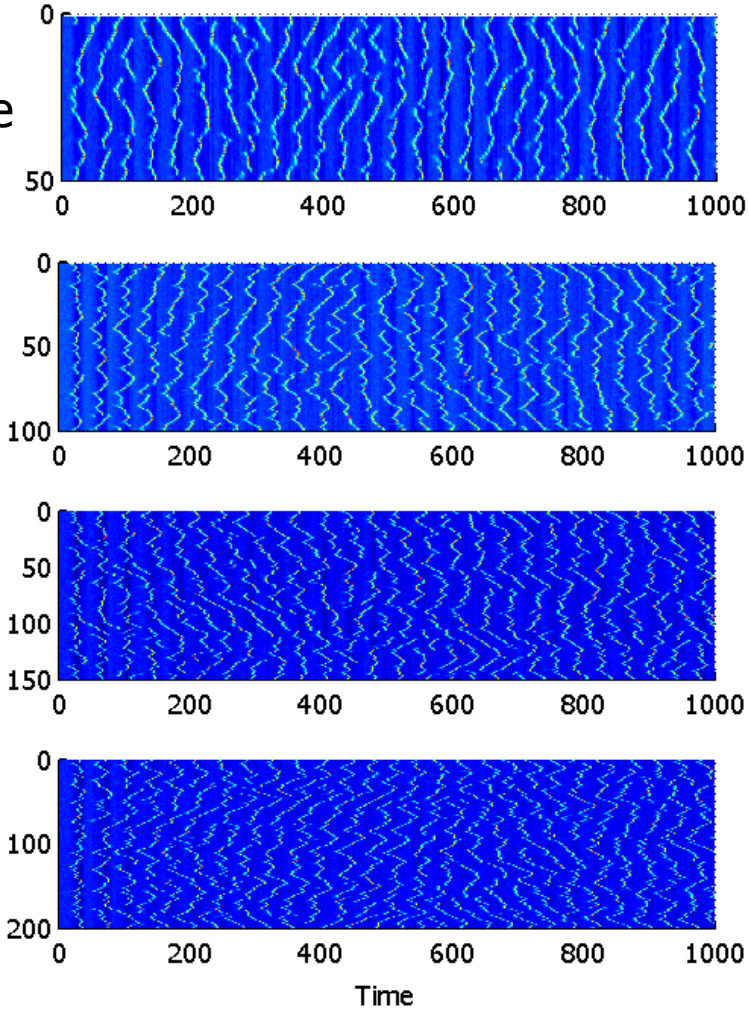




System Size increases

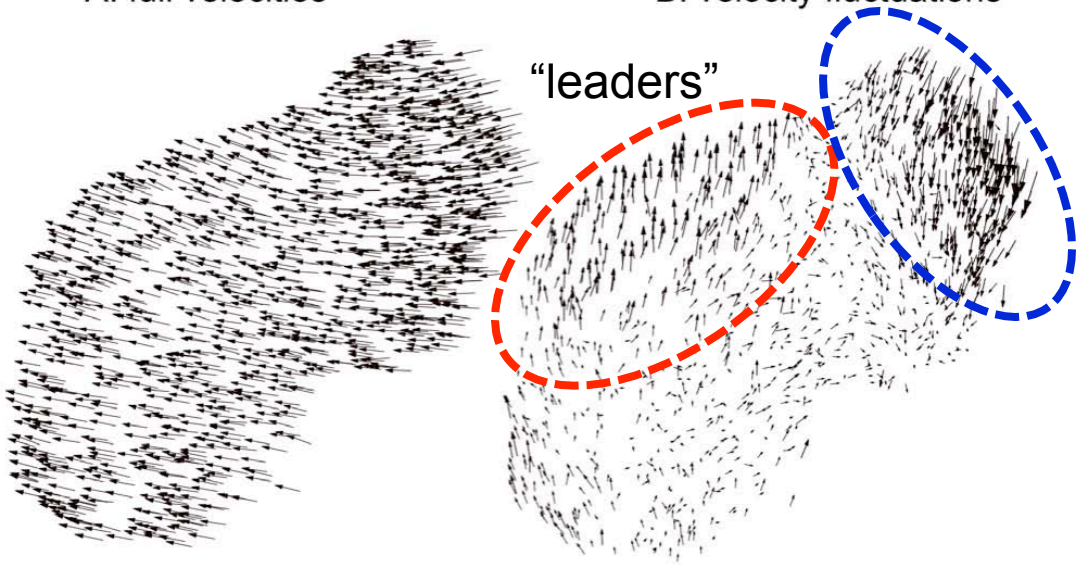
Compute the correlation length ξ for increasing system's size: It is a constant





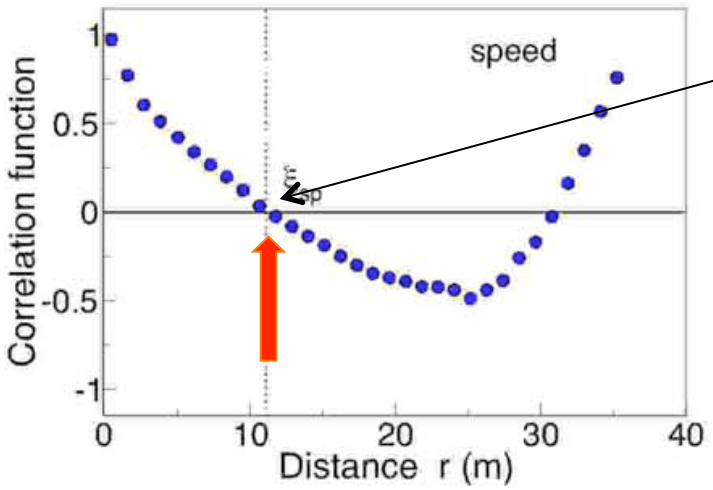
A: full velocities

B: velocity fluctuations

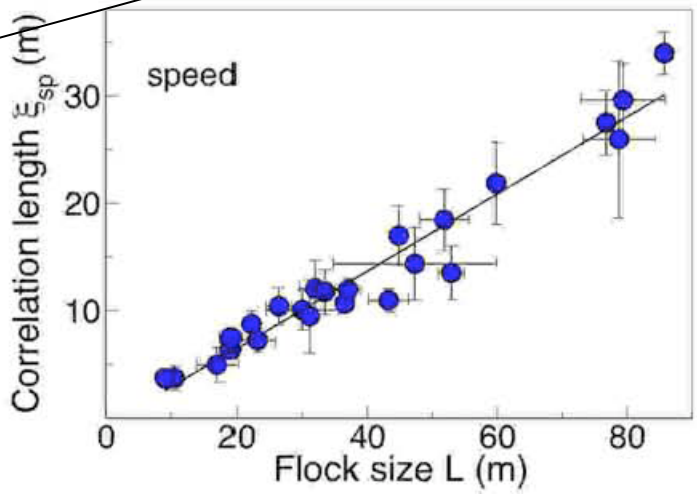


10 meters

Correlation function of one flock



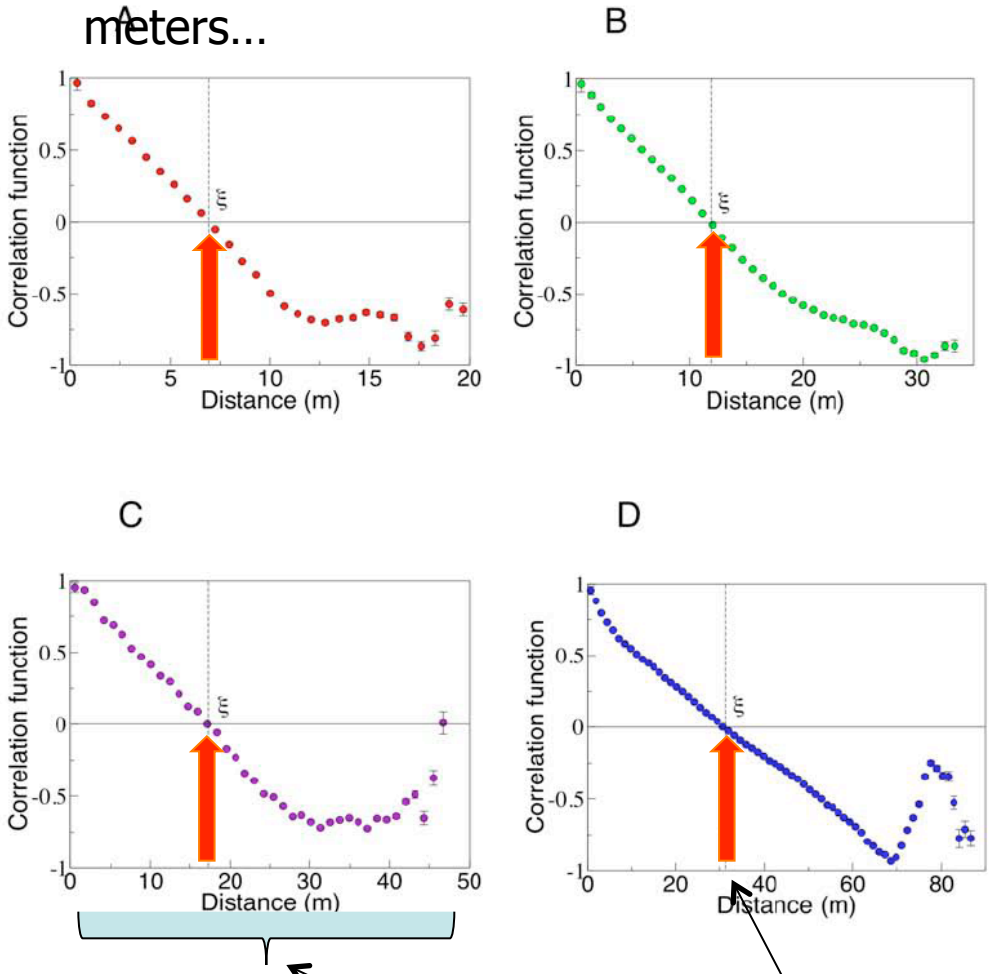
Correlation length of many flocks

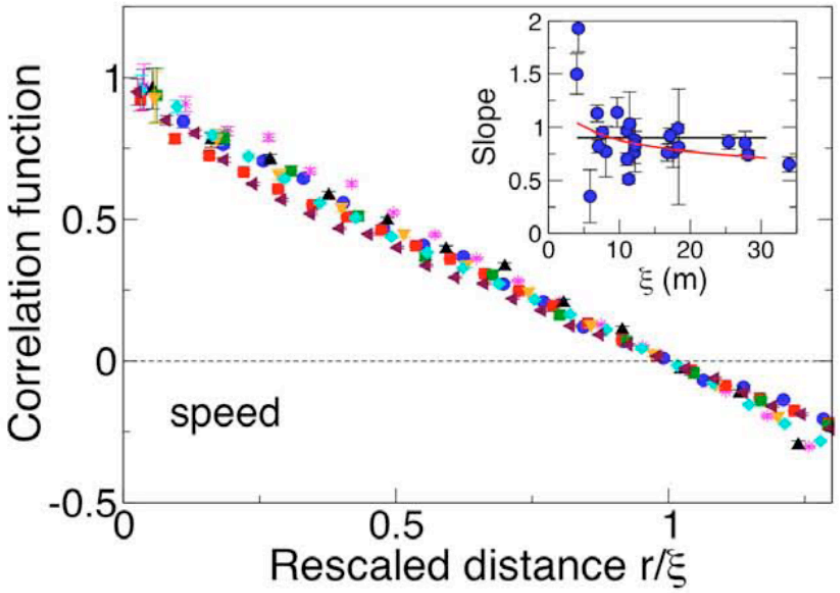


From Cavagna et al, Scale-free correlations in bird flocks, arXiv:0911.4393, (2010); Also in PNAS (2010)

All flocks, big and small obeys the same laws*

In English: The speed fluctuations of two birds 1 meter apart, flying in a flock of 10 meters are as correlated as two birds separated 10 meters on a flock of 100 meters…

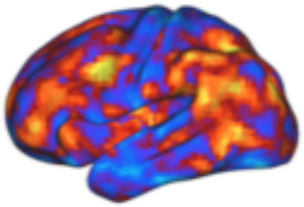




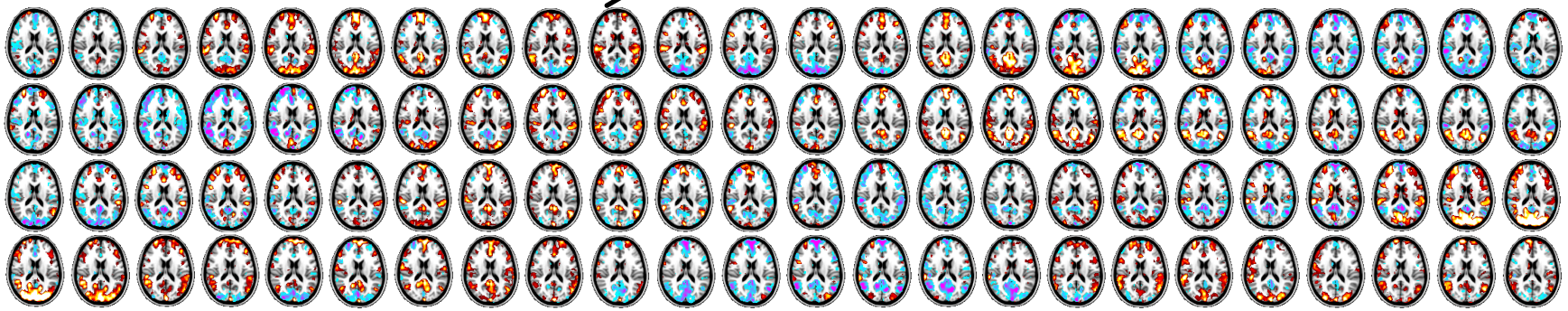
Rescaling the distance axis by its correlation length gives a unique correlation function

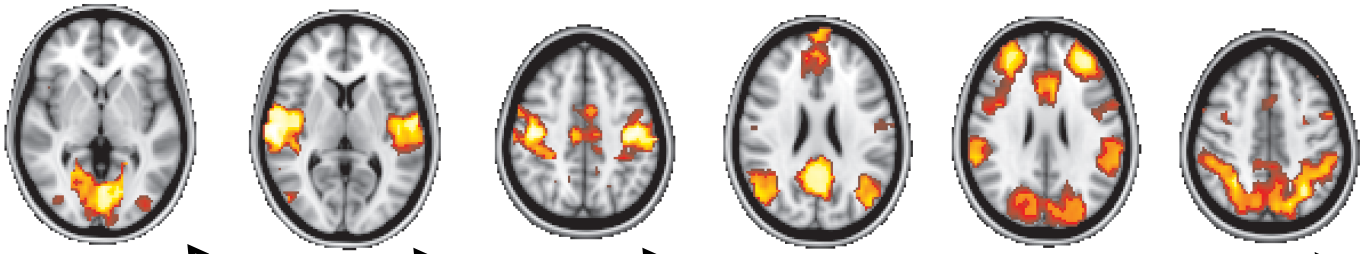
*From Cavagna et al, Scale-free correlations in bird flocks, arXiv:0911.4393, (2010) ; Also in PNAS (2010)

Where are the birds in your head?



Time (one image every 2.5 sec.)





Correlation patterns derived from the data above

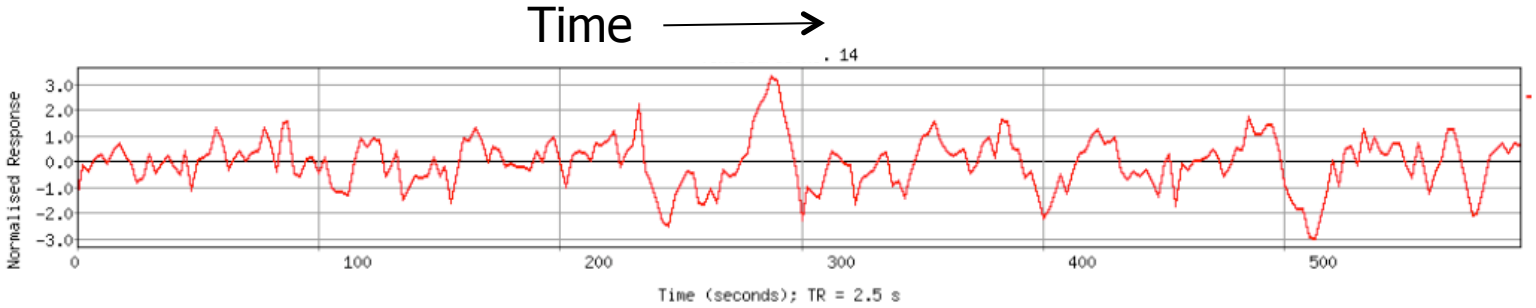
Chialvo DR. Emergent complex neural dynamics: the brain at the edge. Nature Phys, (2010)

Networks of "brain at rest":
Appropriate mathematical analysis of the temporal activity of brain fMRI signals **at rest** uncovers **6 to 10 distinct interacting "networks"**.

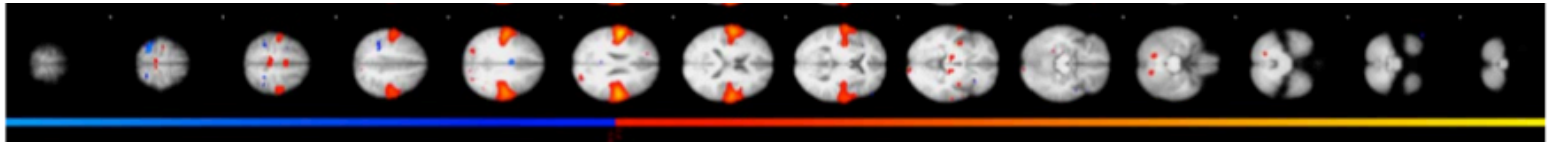
Think about these networks as
•orchestras (networks)
•playing different symphonies (fMRI signals)
•at various parks (brain regions) of a city.

Here one symphony (here one corresponding to the sensory motor network):

One piece of "music" (ie., one IC)



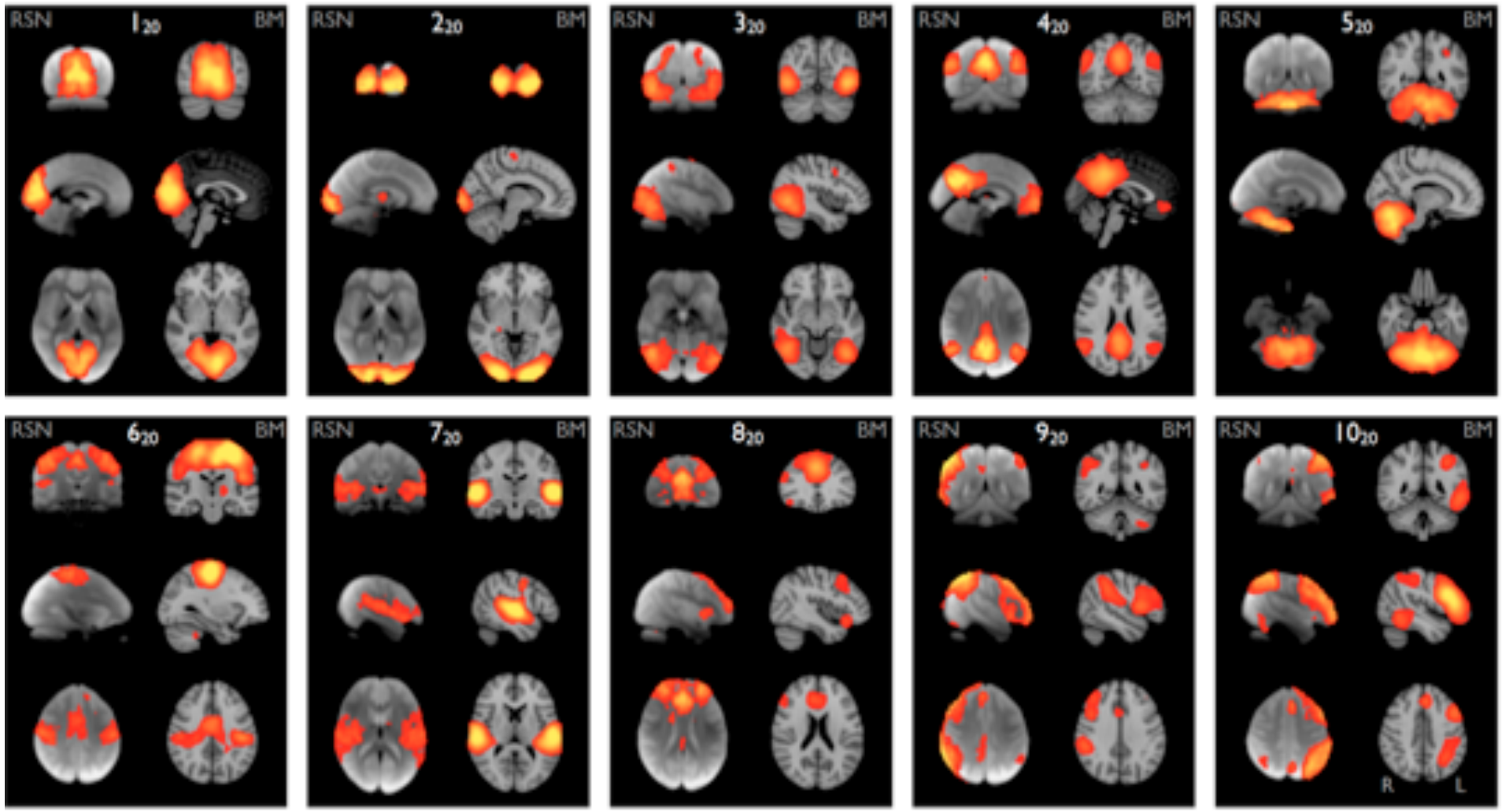
Four "bands" playing it (i.e., the IC location)



Top (of head)

Bottom

The "top 10 bands"

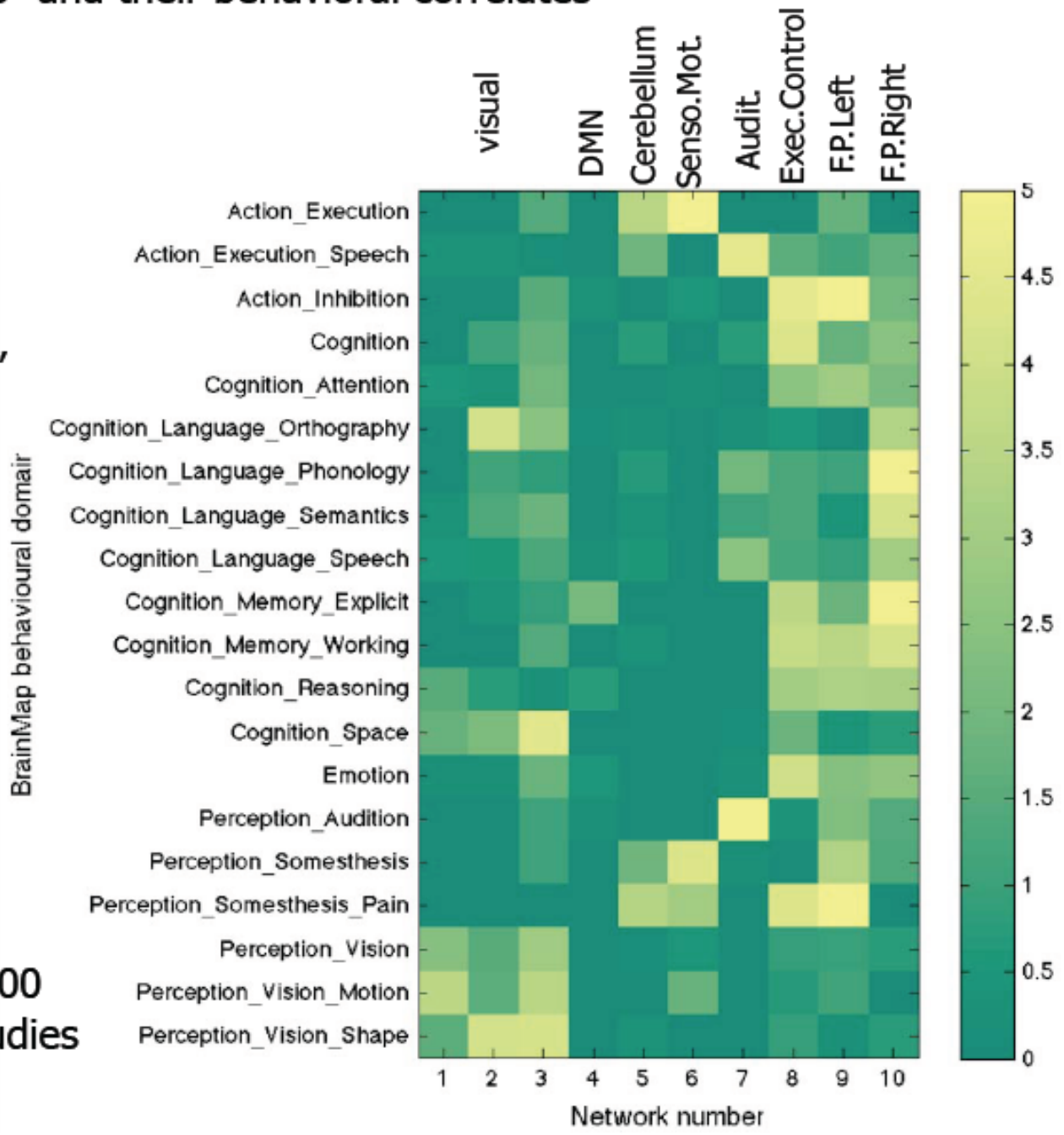


*From Smith et al., The brain's functional architecture, PNAS, 106(31) 2009.

The top 10 "bands" and their behavioral correlates

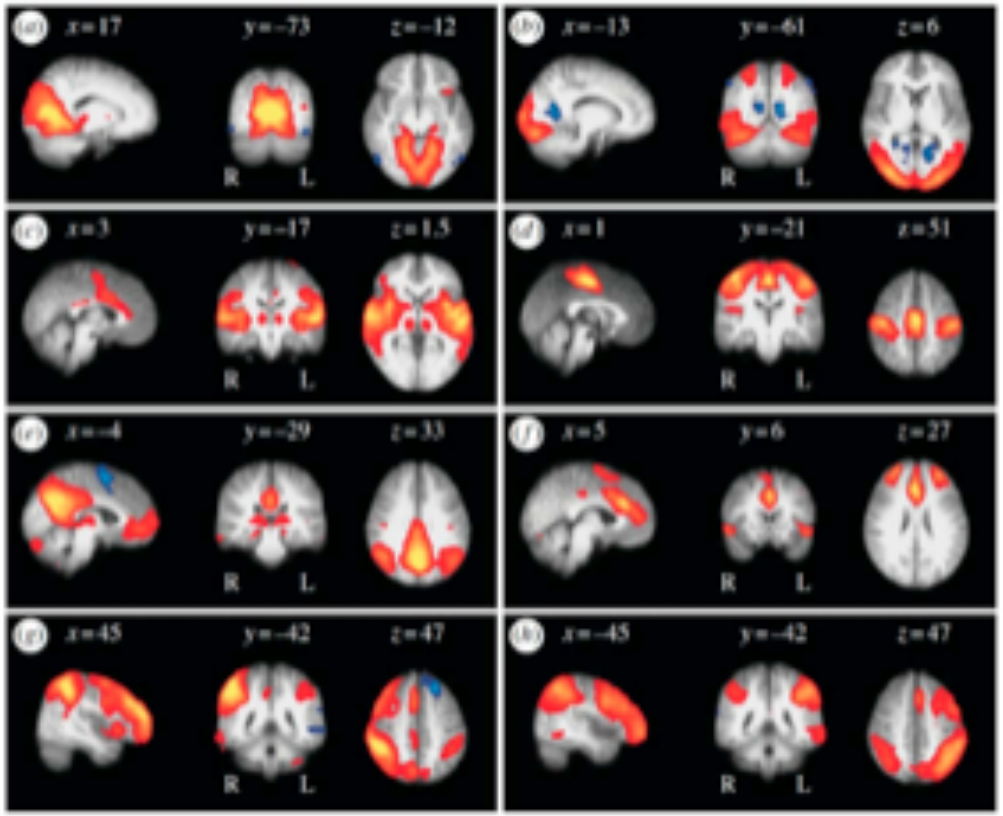
Think about this as the "brainome"

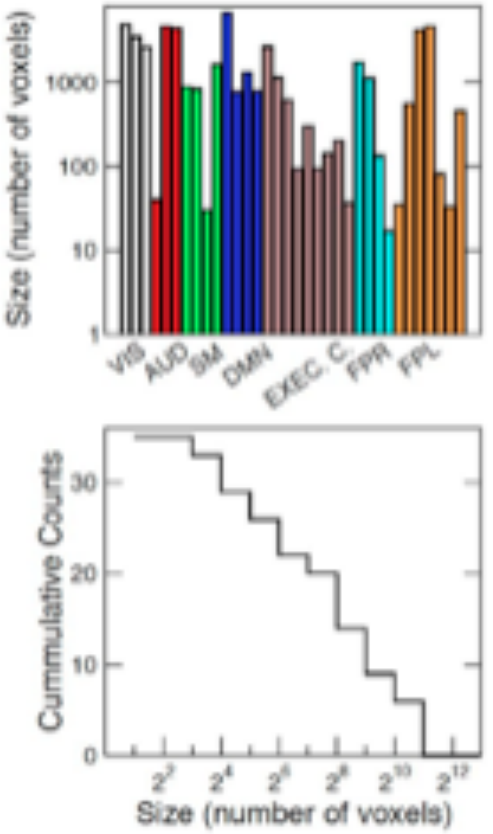
from more than 30000 subjects, > 1600 studies



Using Principal Components select the eight most relevant

split into 35 clusters

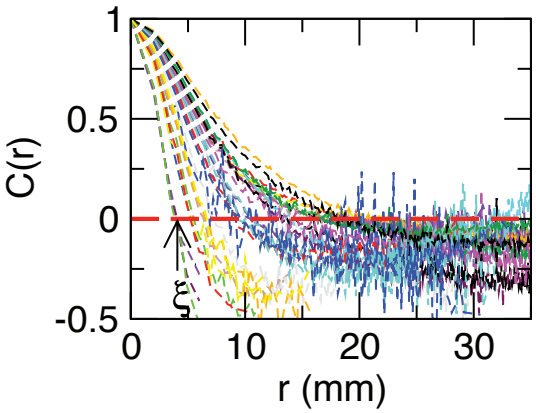




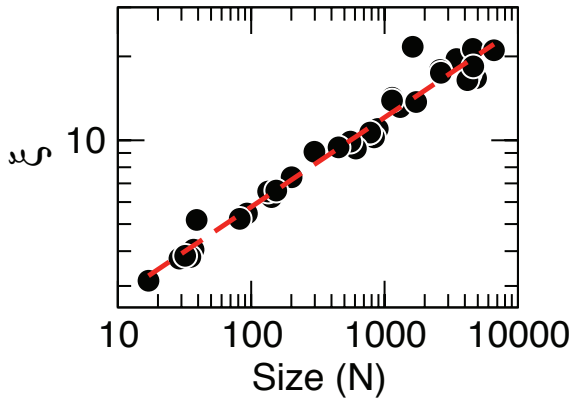
Eight PICA-estimated resting patterns estimated from a group of subjects.

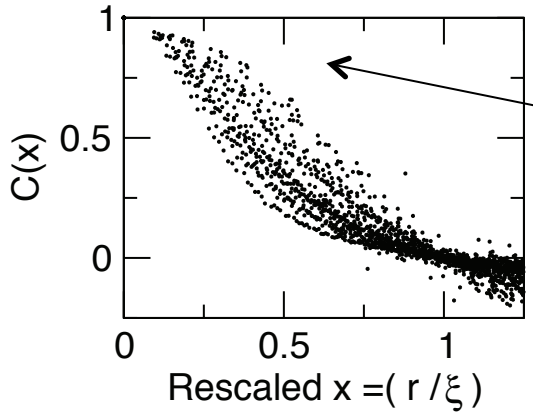
Left panels shows the sagital, coronal and axial views for each map. Right panels depict the size of each of 35 clusters (a.k.a “blobs”) analyzed (top) and its distribution.

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



Correlation length





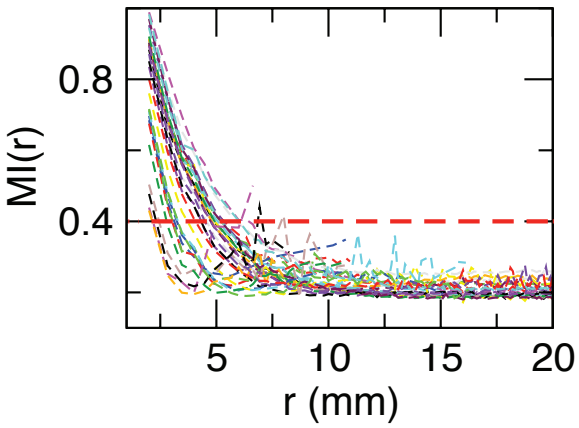
Correlation length diverges with cluster size

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

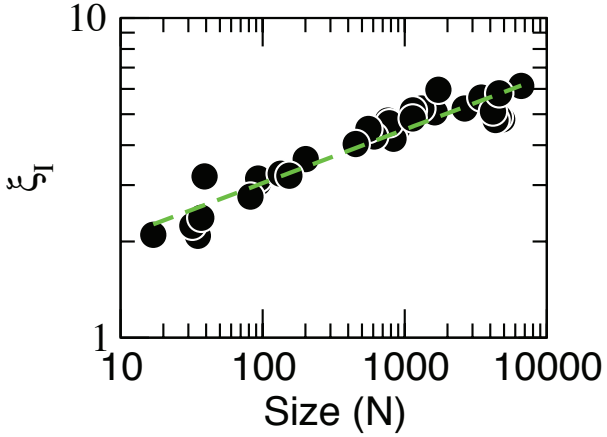
Chialvo DR & Fraiman D. Optimal information-sharing in brain resting state network.



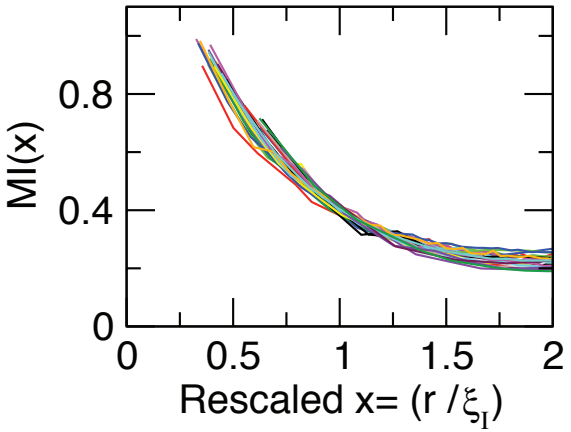
Doing the same for Mutual Information

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

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



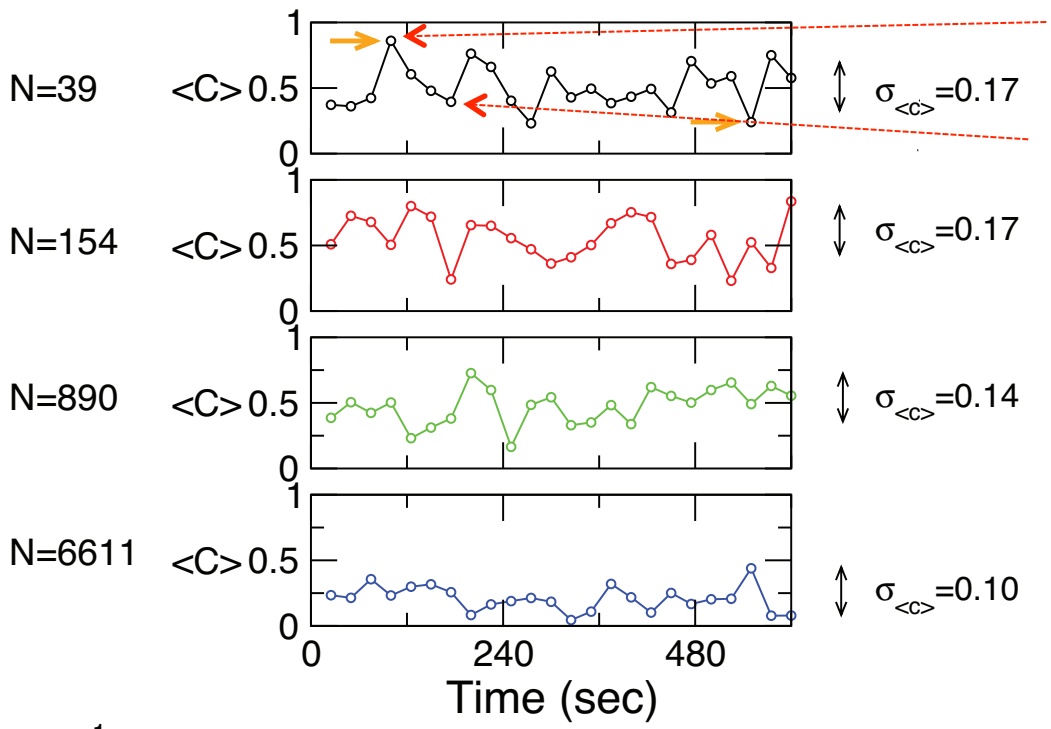
Mutual information diverges with cluster size.



Rescaled mutual information

Chialvo DR & Fraiman D. Optimal information-sharing in brain resting state network.

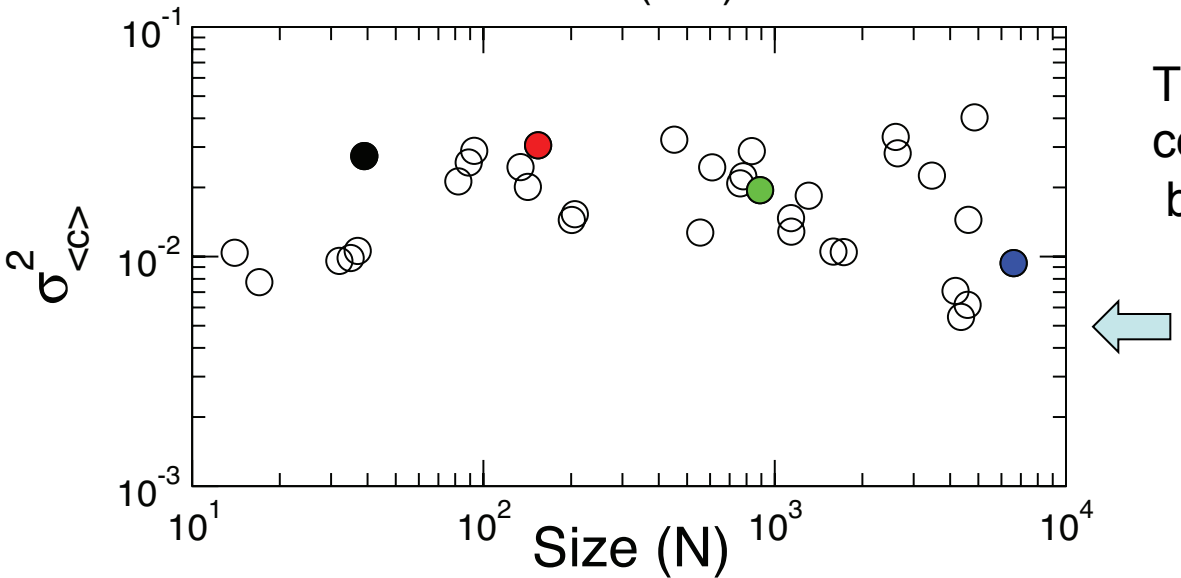
What is the origin of the anomalous scaling of the variance of the mean activity



Spikes of high correlation

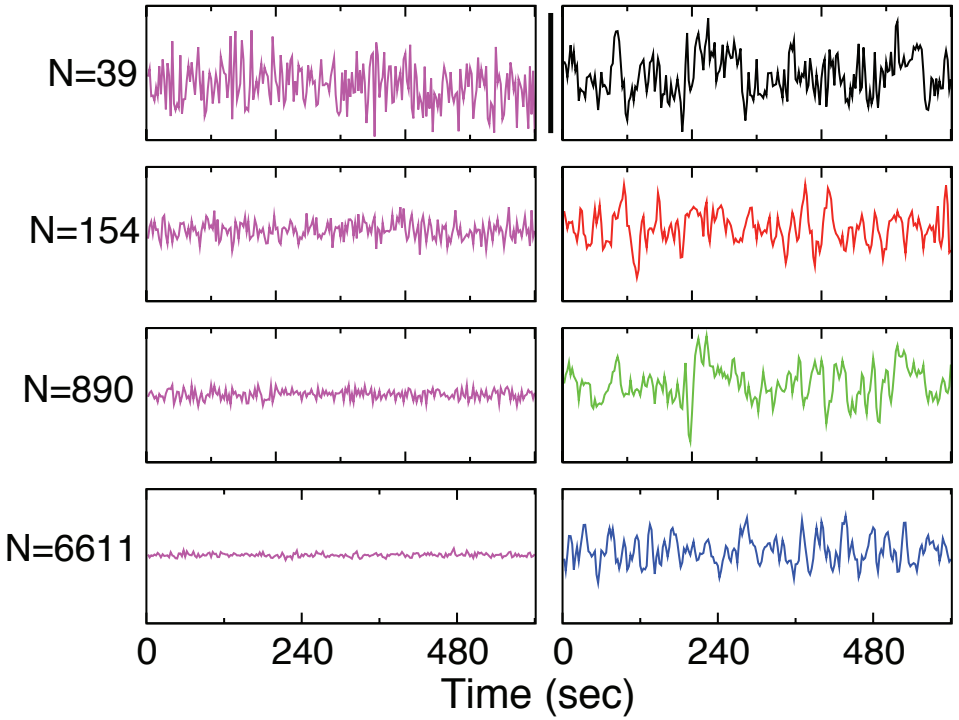
Spikes of low correlation

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



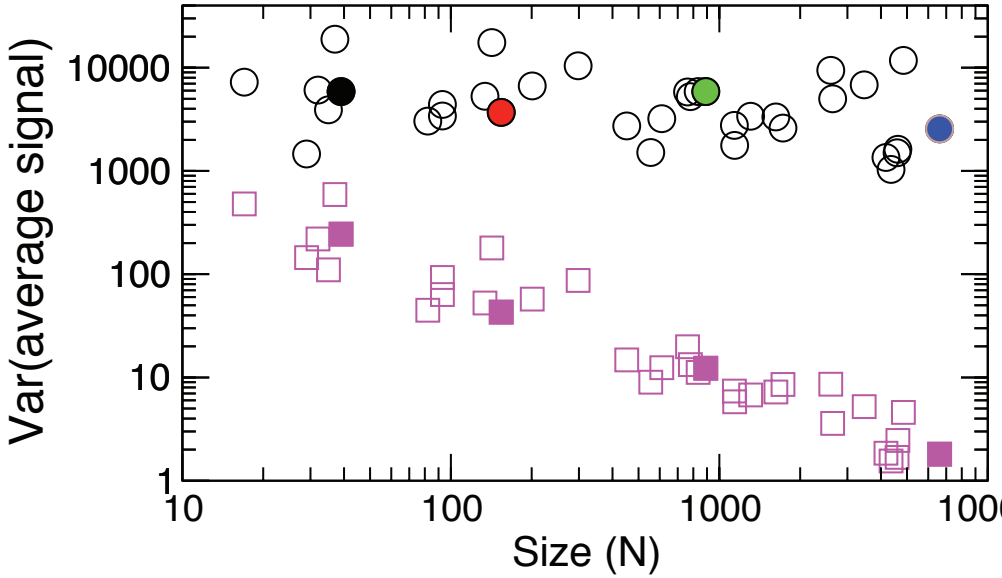
The variance of the correlations computed for the thirty five blobs is **independent** of size

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



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

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

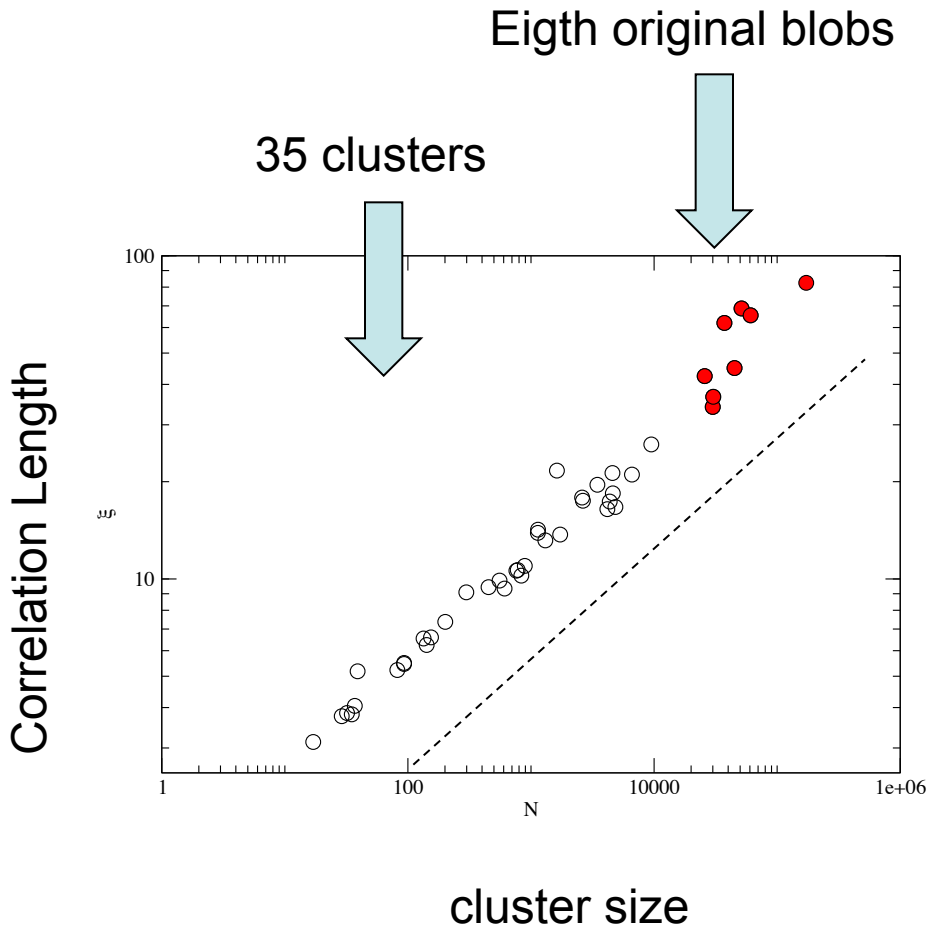


variance of the fluctuations computed for the thirty five blobs

variance of the fluctuations computed for randomized data

Chialvo DR & Fraiman D. Optimal information-sharing in brain resting state network.

Another control: the original unpartitioned blobs (the eight brain systems)



Chialvo DR & Fraiman D. Optimal information-sharing in brain resting state network.

2) All at once: renormalization

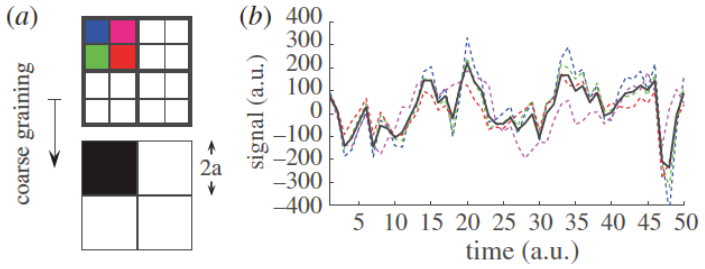
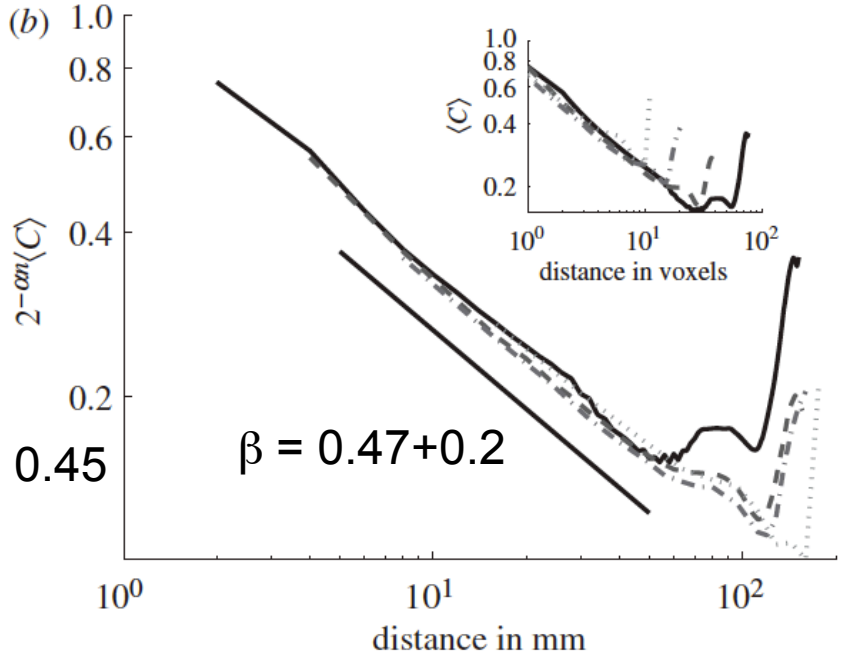


Figure 6. (*a*) Example of coarse graining in two dimensions where there are four boxes $\mathcal{B}$ within a block-box $\mathcal{B}'$. (*b*) The four dashed-coloured signals from the four original boxes $\mathcal{B}$ are averaged to produce the solid-black coarse-grained signal of $\mathcal{B}'$.



α= 0.45

β = 0.47+0.2

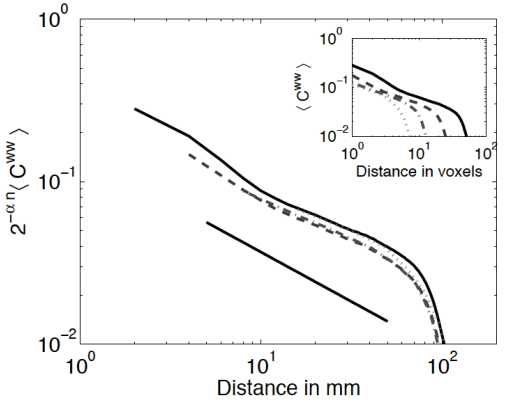
JOURNAL OF THE ROYAL SOCIETY Interface
J. R. Soc. Interface (2010) **00**, 1–8
doi:10.1098/rsif.2010.0416
Published online 00 Month 0000

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

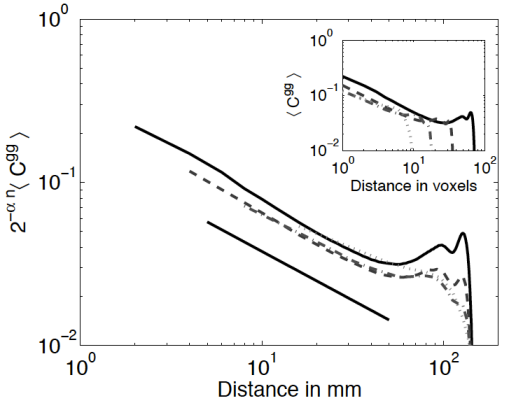
Paul Expert[1,2], Renaud Lambiotte[1], Dante R. Chialvo[4], Kim Christensen[1,2], Henrik Jeldtoft Jensen[1,3,*], David J. Sharp[5] and Federico Turkheimer[5]

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

White matter



Grey matter

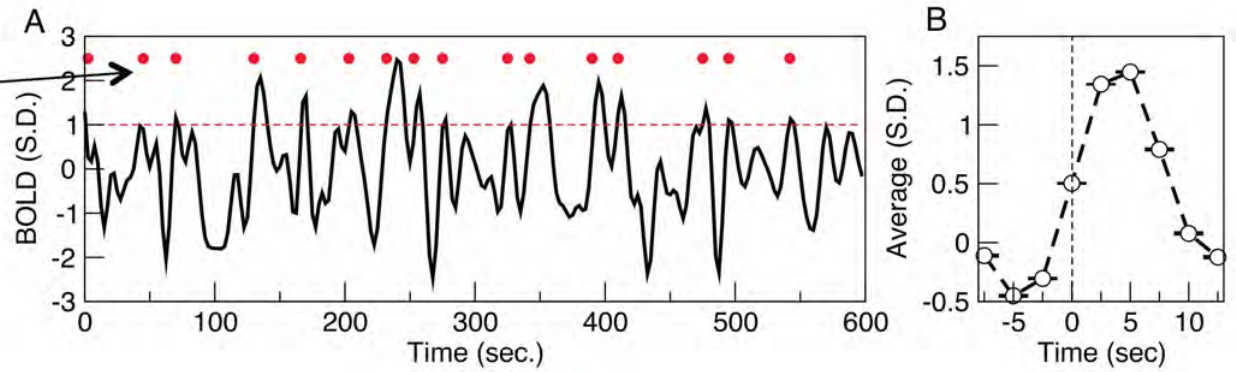


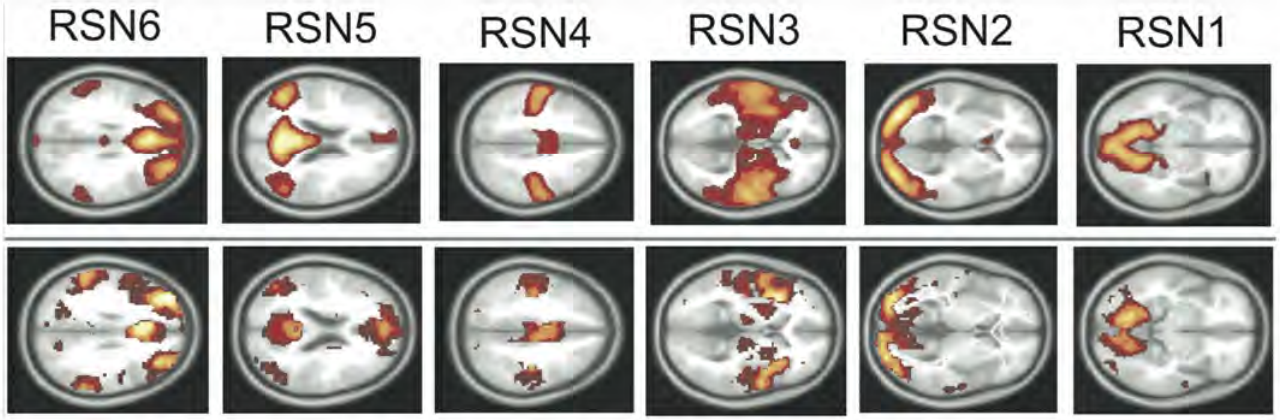
Brain' dynamics is relevant!

daaahhhh

Lets get the dynamics (thanks to Poincare)

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

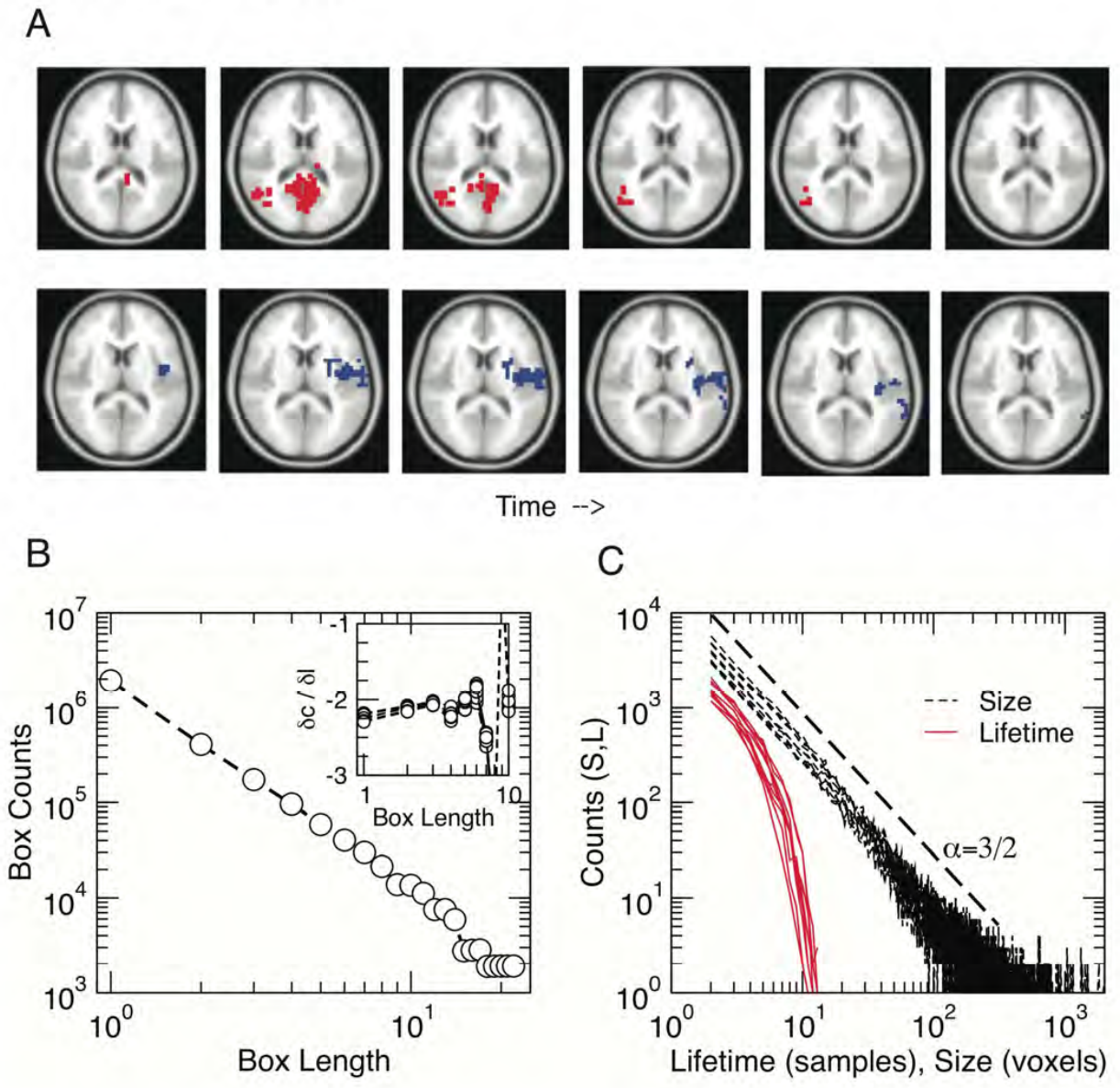




Moral: Despite the huge data reduction (> 95%) a few points holds more of the information.

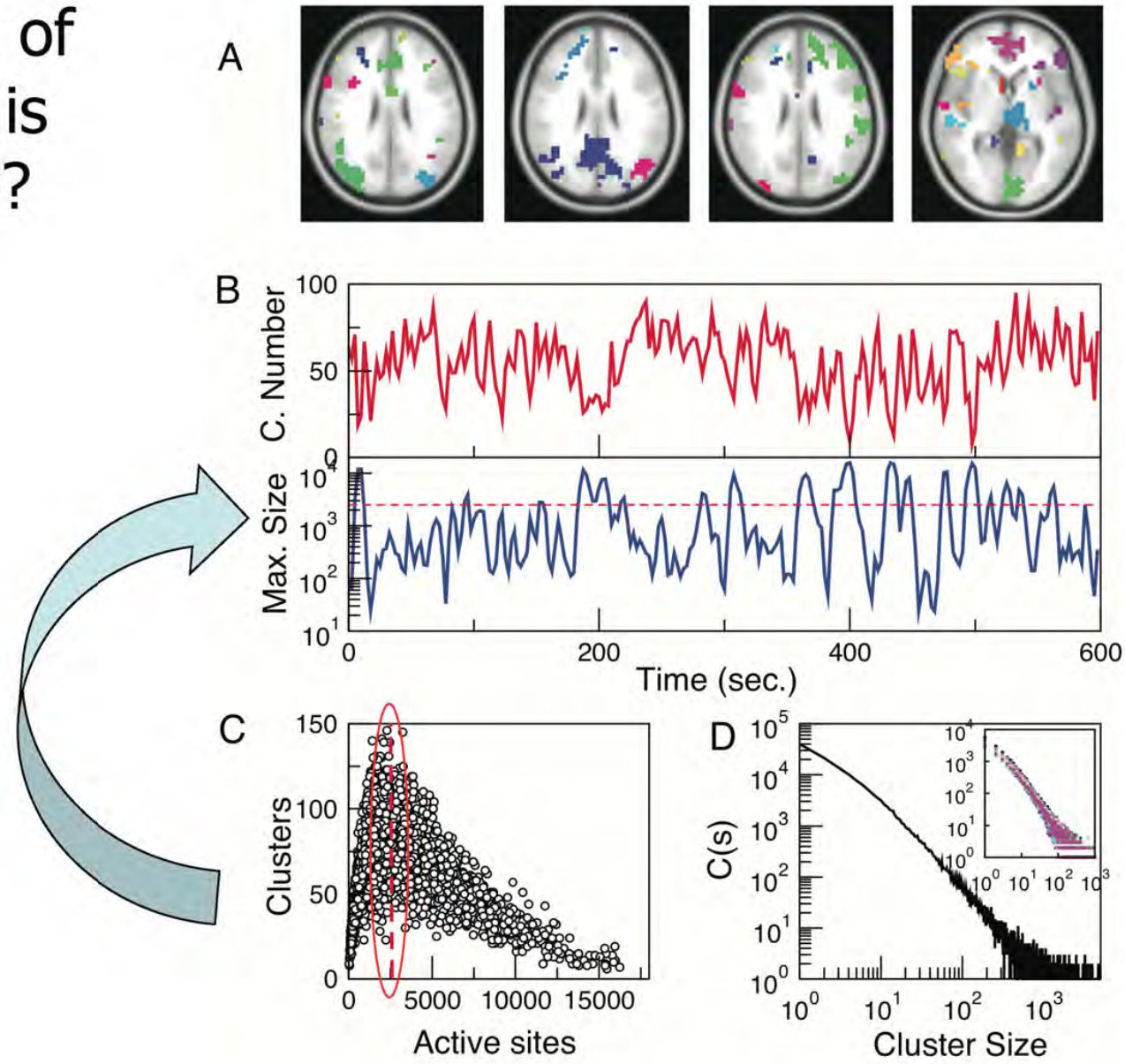
From Tagliazucchi et al (2011)

Earthquakes in your head

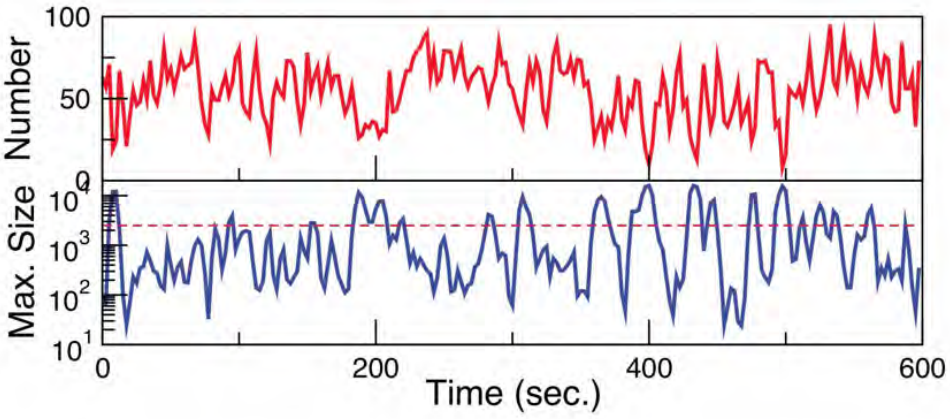


From Tagliazucchi et al (2011)

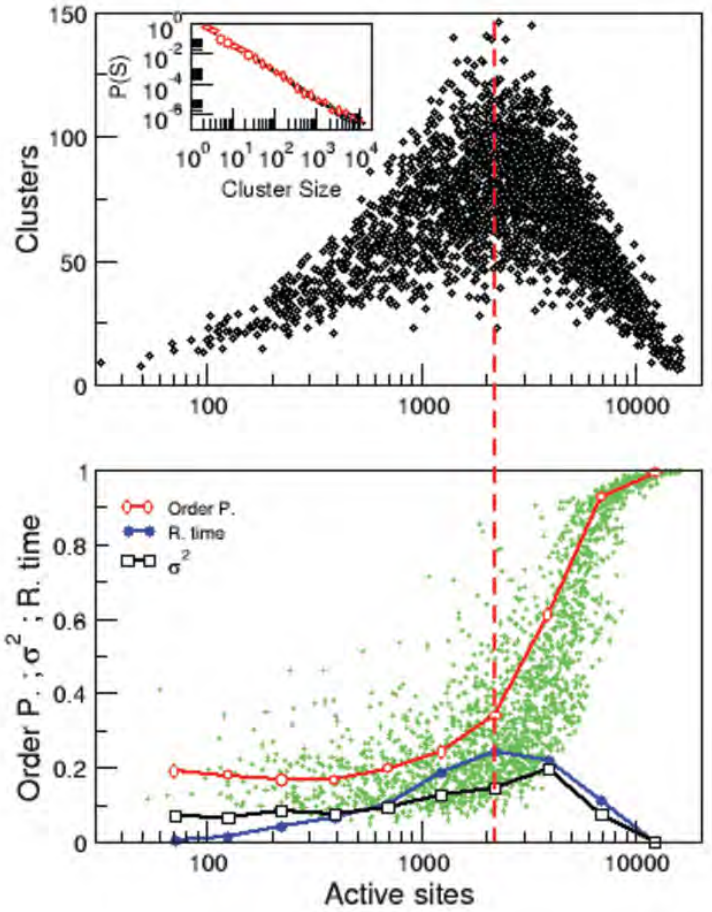
How much of your brain is active now?



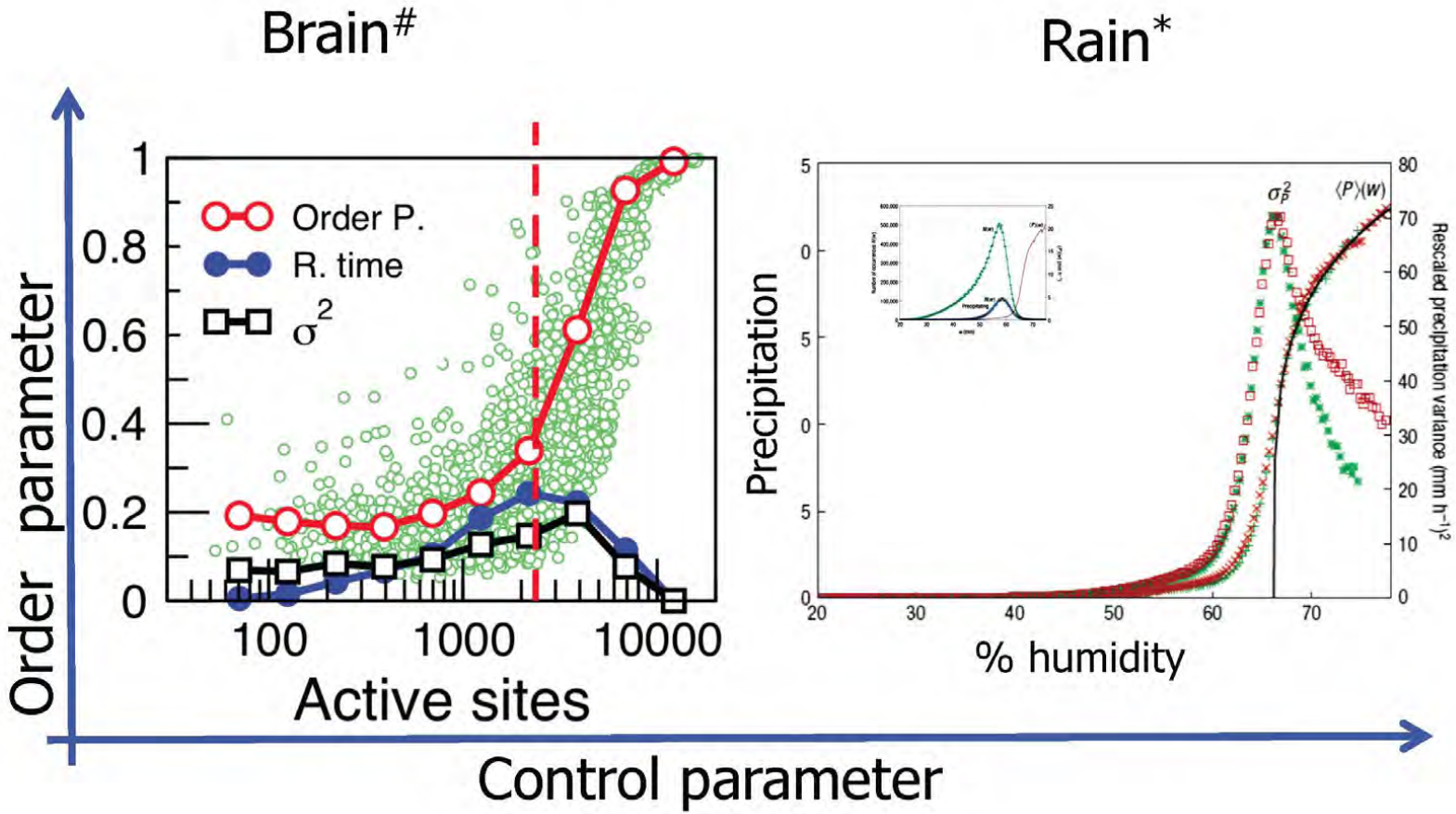
From Tagliazucchi et al (2011)



A phase transition



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

Physics

Physics **6**, 47 (2013)

Viewpoint

The Critical Brain

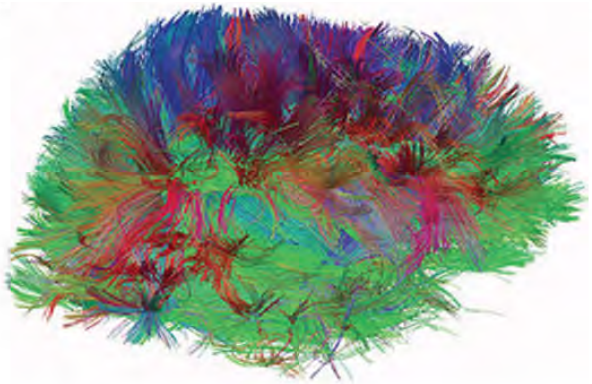
Dietmar Plenz

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

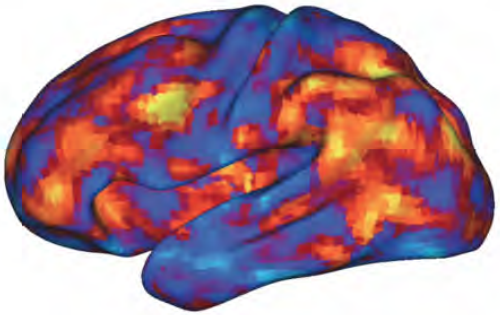
Published April 22, 2013

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**



+ ? =



+

=

Street map

- predictable
- simple to describe
- only short correlations

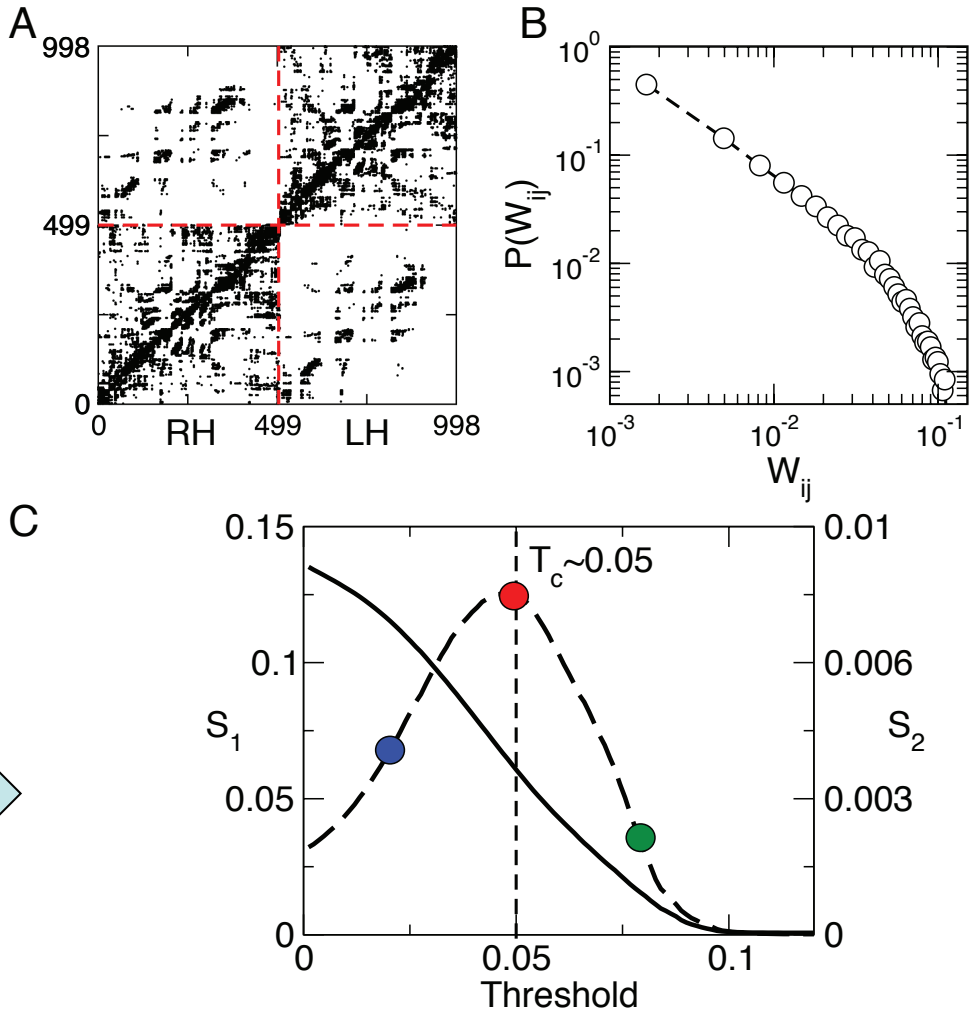
Traffic (…jam)

- unpredictable
- complex
- long range correlations

the connectome

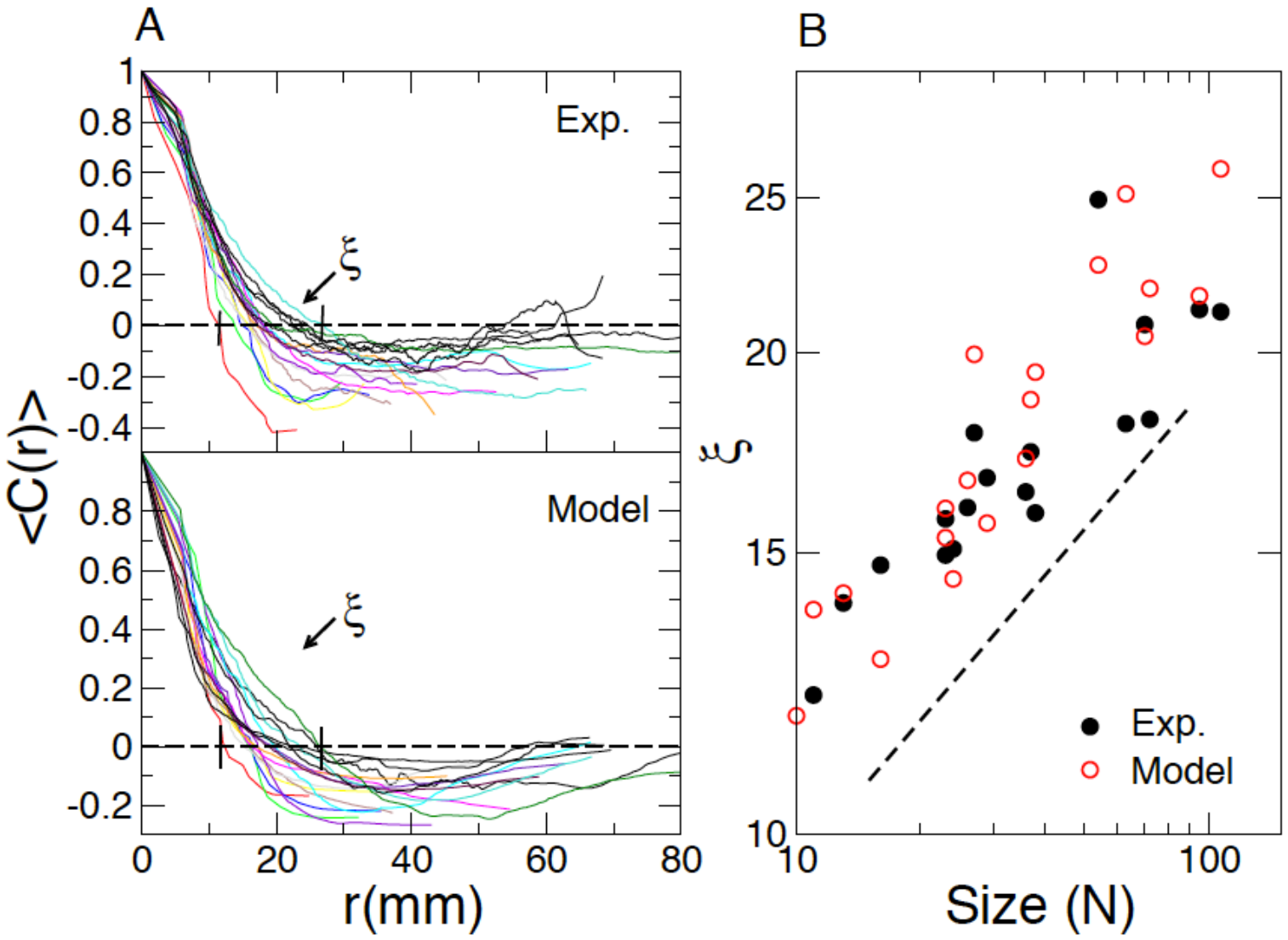
+ some dynamics

Phase transition



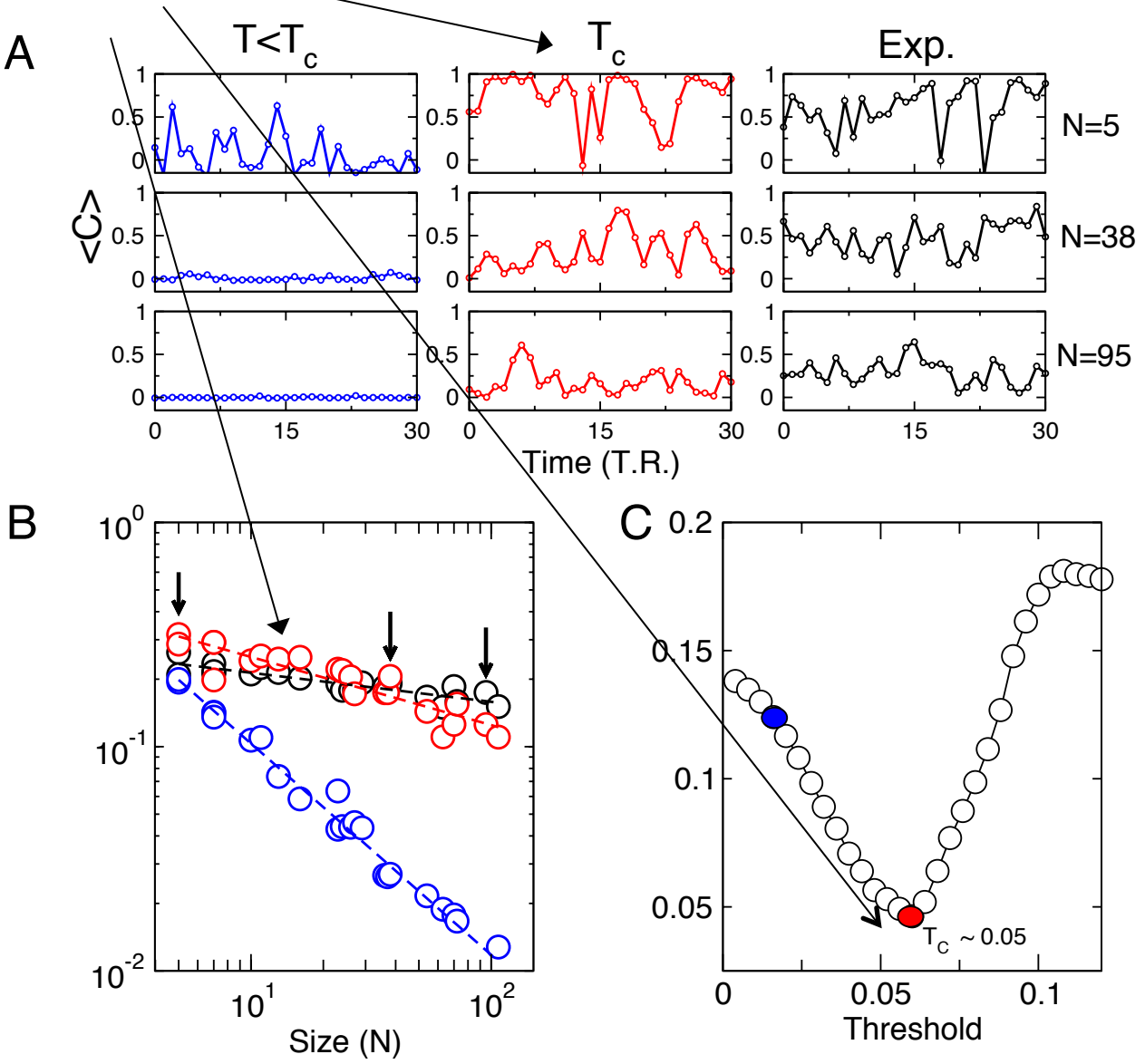
The experimental dynamics is replicated only at criticality

Divergence of correlations



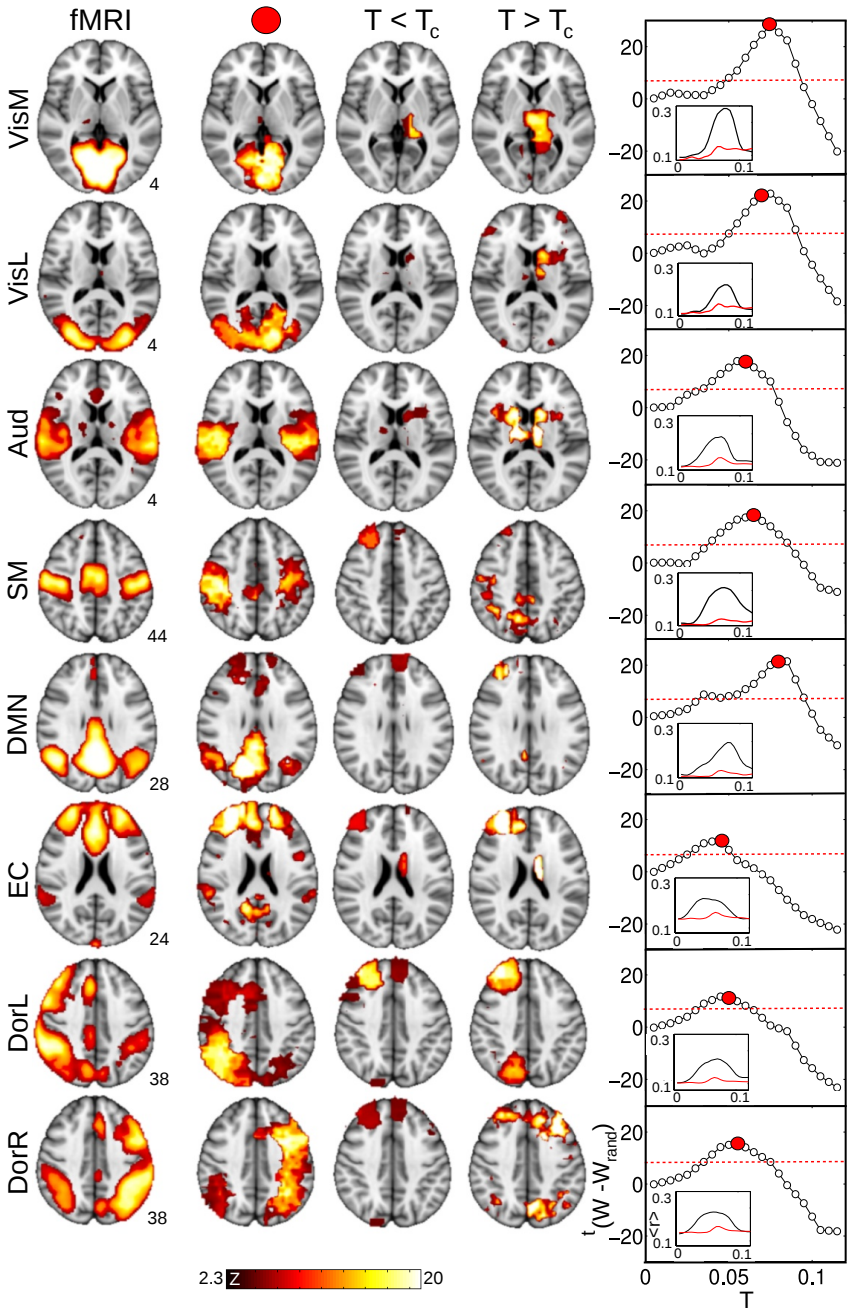
The experimental dynamics is replicated only at criticality

Anomalous scaling of short term correlations



The experimental dynamics is replicated only at criticality

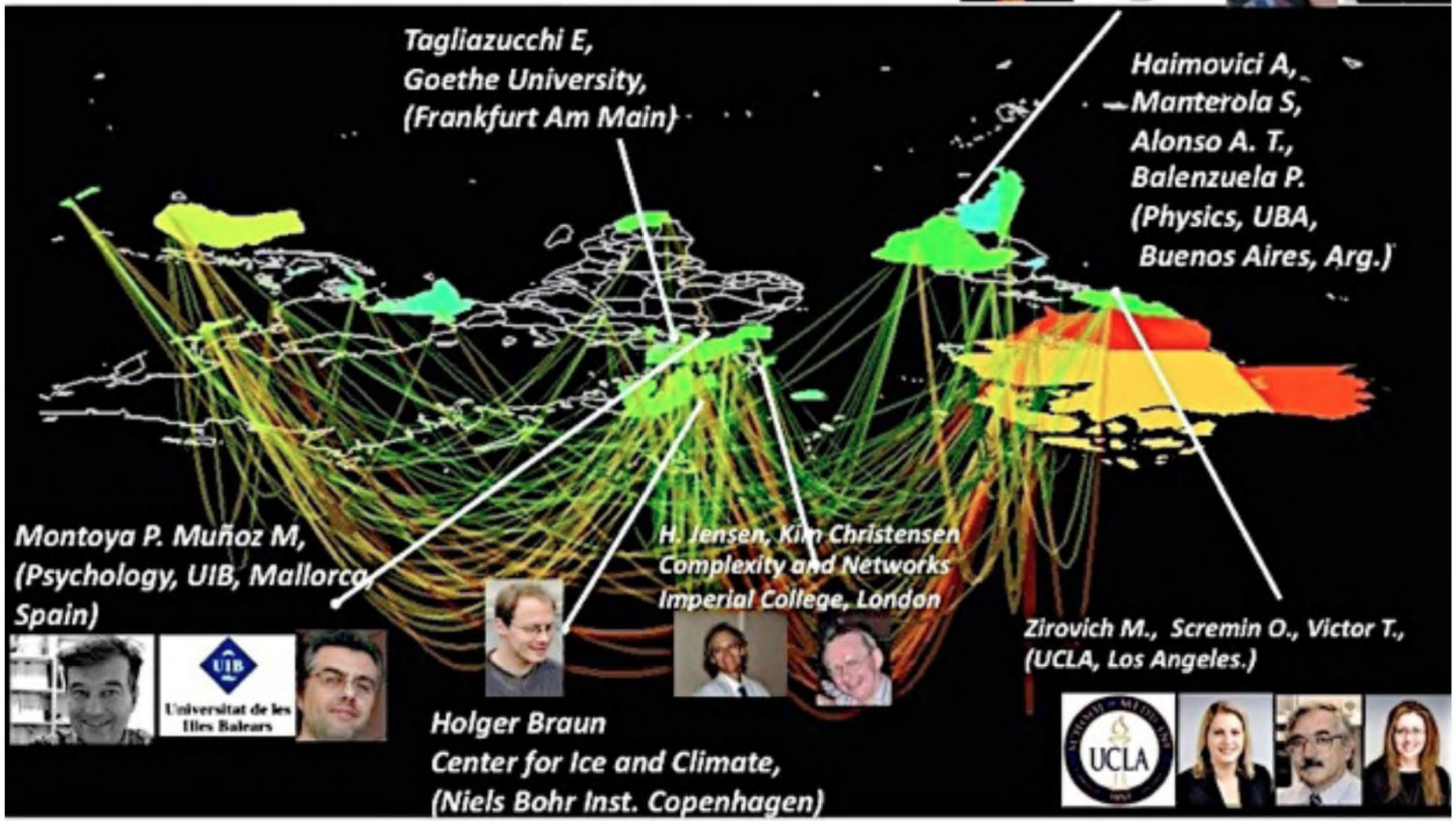
(resting state networks)



BlahBlahlogy

1) Functional correlations in cortical fMRI time series are scale-free (comparable with those seen near at a critical point in the Ising model).
2) Anomalous scaling/Correlation length diverges with size → implies criticality
3) phase transition identified. Jamming and scale-free avalanches seen at large scale at rest.
4) "Most of the time" near criticality…
5) A need for a "theory of fluctuating_control_parameter criticality", (sort of "foc" flex-organized criticality…)

Thanks


Tagliazucchi E,
Goethe University,
(Frankfurt Am Main)
Haimovici A,
Manterola S,
Alonso A. T.,
Balenzuela P.
(Physics, UBA,
Buenos Aires, Arg.)
Montoya P. Muñoz M,
(Psychology, UIB, Mallorca,
Spain)
H. Jensen, Kim Christensen
Complexity and Networks
Imperial College, London
Zirovich M., Scremin O., Victor T.,
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Center for Ice and Climate,
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