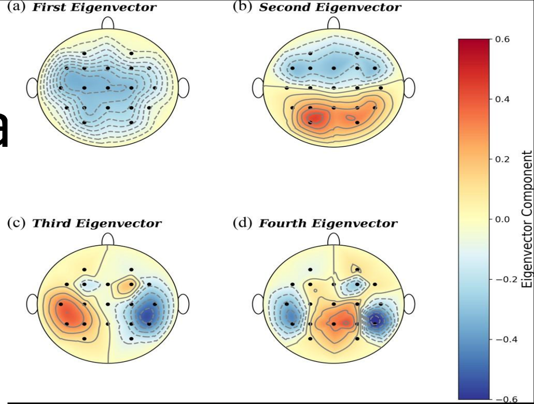
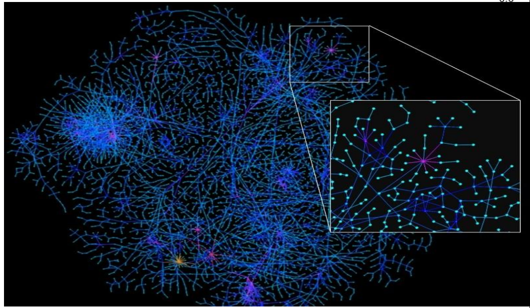
Phase Transitions, Scale Invariance and Critica in Self Organized Systems



Alejandro Frank

ECN, C3, ICN



Symmetry and conservation Laws

Translation (all times and/or positions are equivalent)---- Energy and momentum conservation

All directions equivalent : Rotation ---- angular momentum conservation

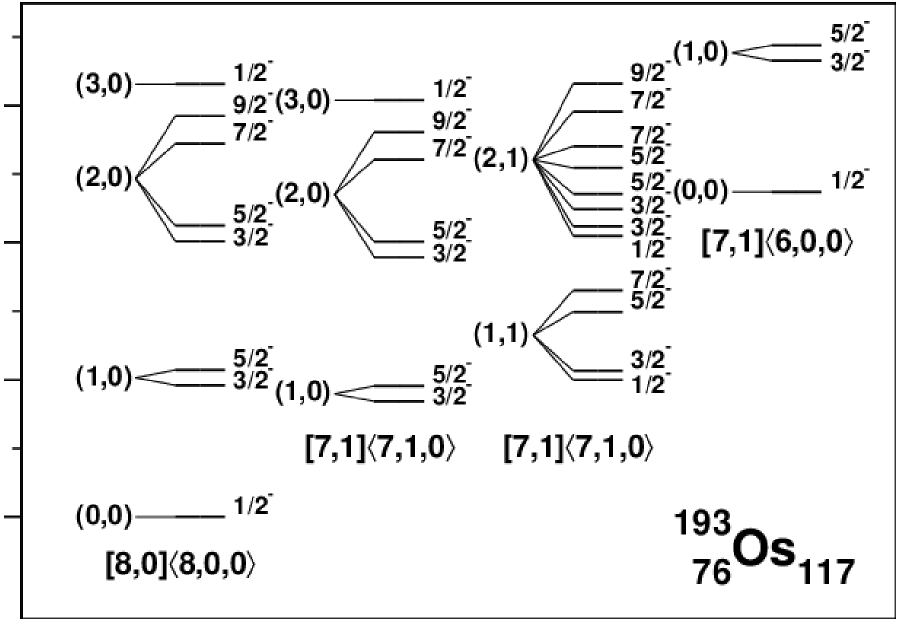
“Internal symmetries” quantum numbers: spin, isospin, up, down, strange,..

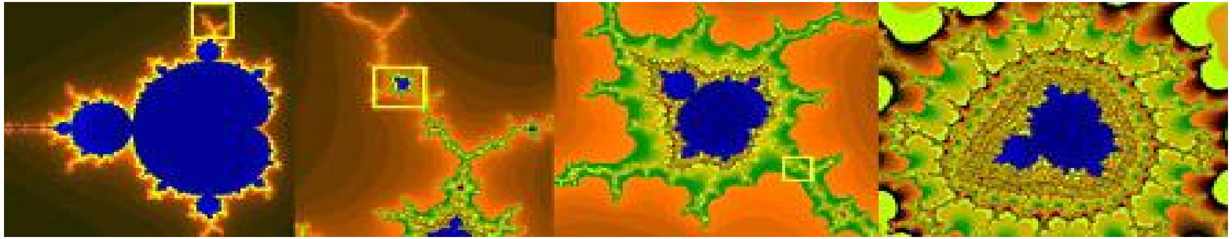
Gauge Symmetries in Field Theory……

Symmetries in Nuclear Physics

Elliot´s SU(3)
Isospin Symmetry
IBM1 and IBM2
IBFM
Nuclear Susy
Electron-Vibron Model
Algebraic Scattering Theory
F-Spin Symmetry
Symmetry Adapted Polyatomic Molecules
E(5), X(5)

- ……..





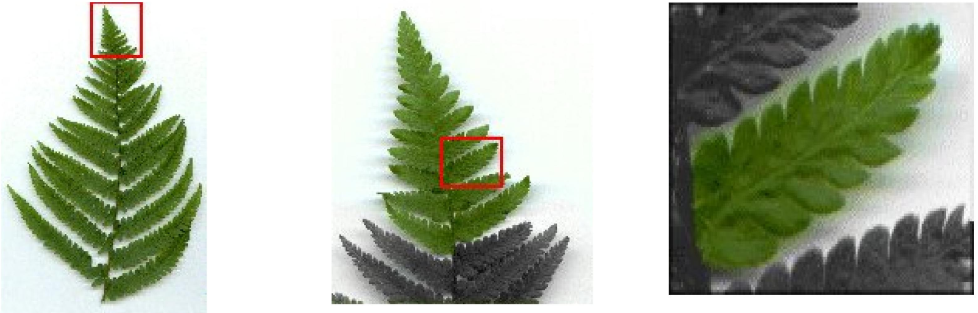
Scale
Invariance
Symmetry

Similarity and Scale
Invariance

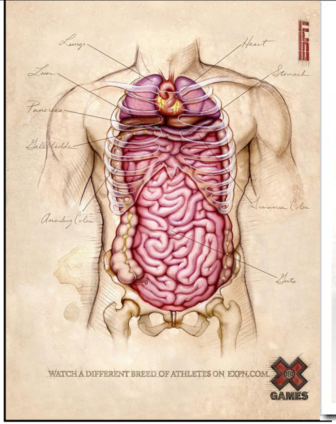
What abour Biology?

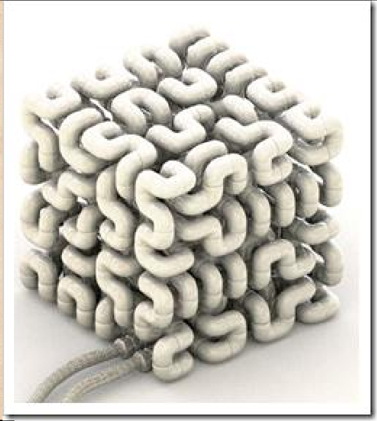
brócoli

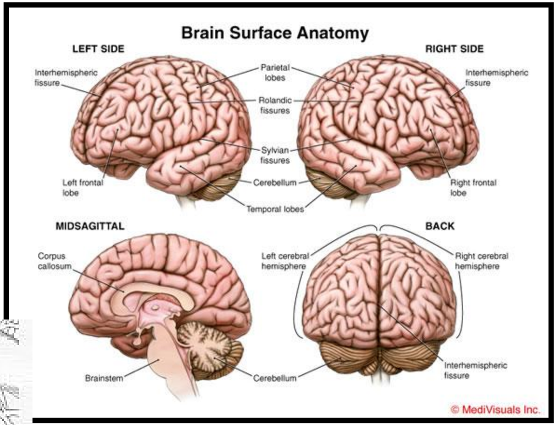
living systems : self similarity,fractality



Fractal Structure of organs:
<u>An OPtimization strategy of nature</u>







Fractality Self similarity in units and subunits.

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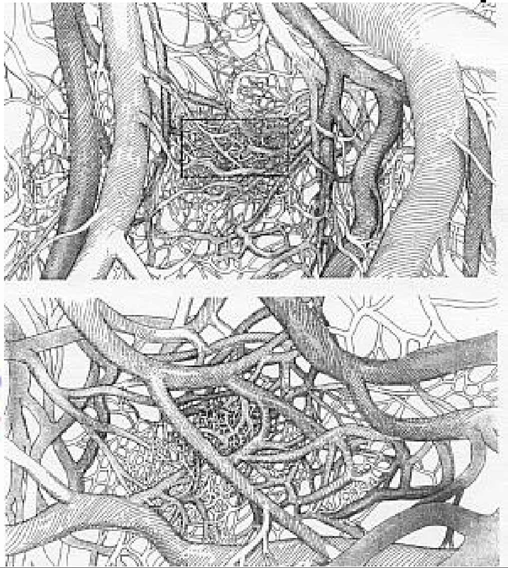
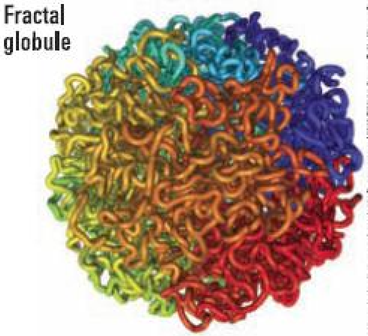
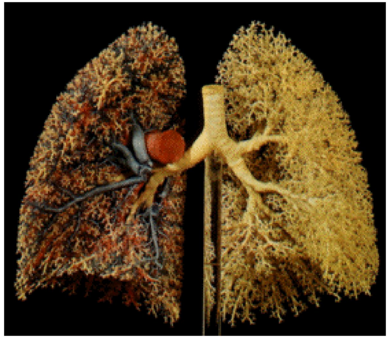
Cardiovascular and nervous systems



DNA

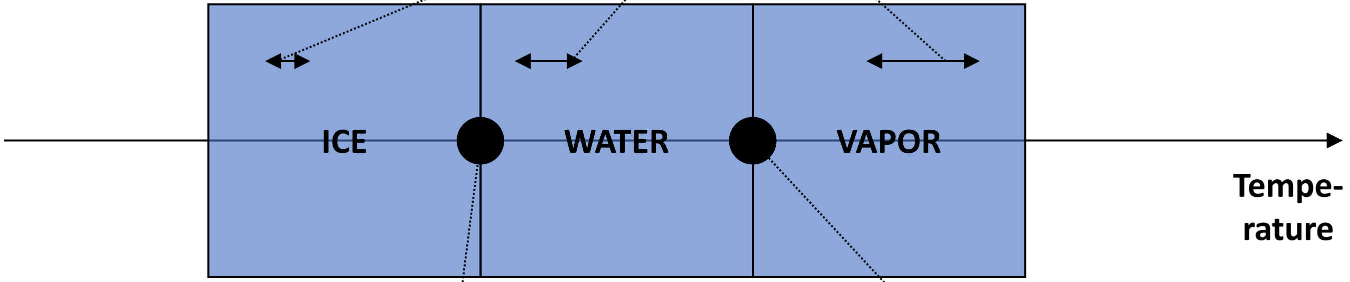




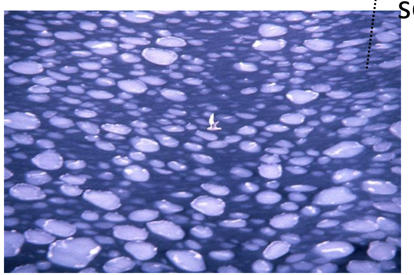
Adult lungs gas exchange Area:

From Physics: Phase transitions and critical points

A single scale defines the molecular interactions in each pase.



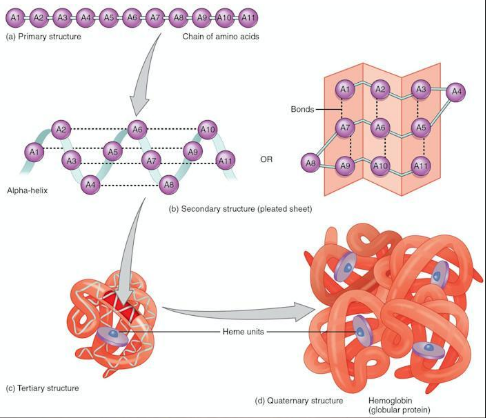
Critical point: ice-water :all scales



Critical mixing of wáter and vapor : all scales appear.

What about function? Phase transitions in biological systems.

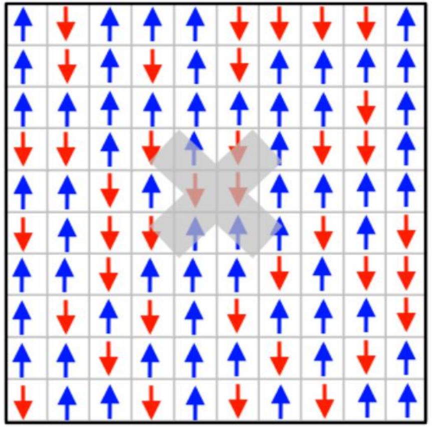
- It has been proposed that some biological systems might lie near critical points.
- Examples include neural networks in the salamander retina, bird flocks, gene expression networks in Drosophila and protein folding.
- **Biological organisms share two key properties of phase transitions: the change of macroscopic behavior and the**



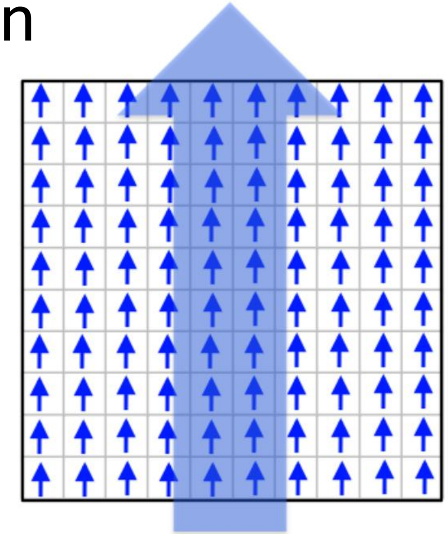
How to define criticality in time series

Ising model and criticality

Simple model for magnetization



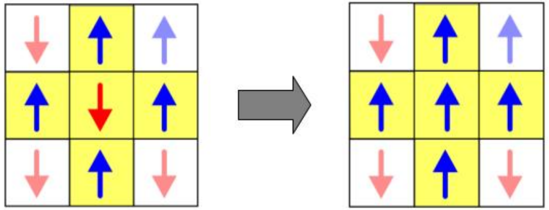
Not magnetized



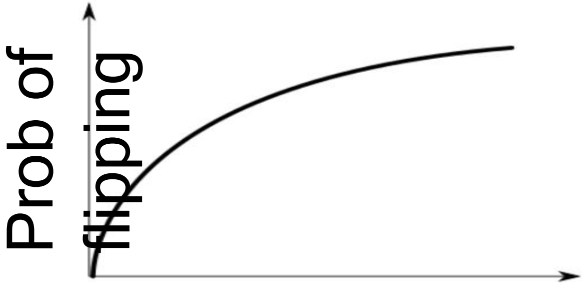
Magnetized

Two competing dynamics:

1. Local interactions define spin alignements

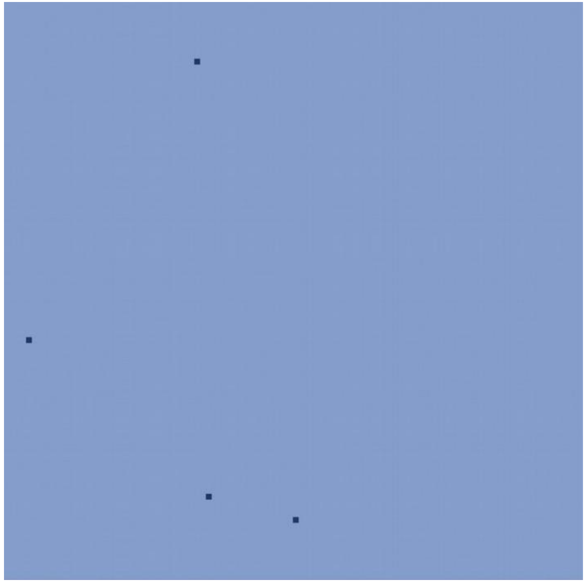


2. Random spin flipping defined by temperature with Boltzmann distribution



Criticality: Ising Model Space reference frame

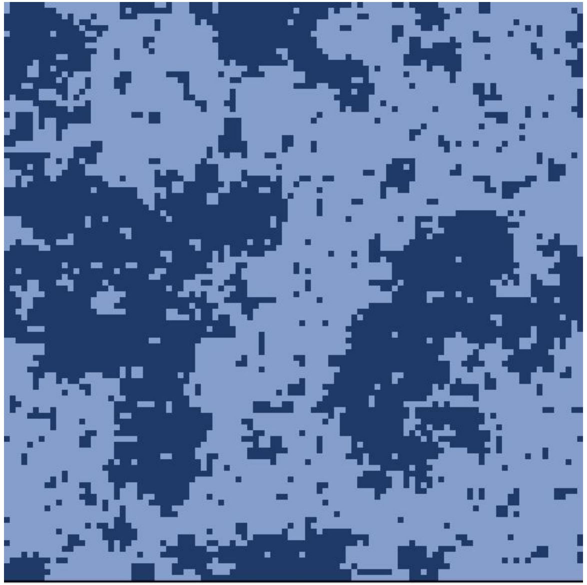
T < Tc



Order

Uniformity

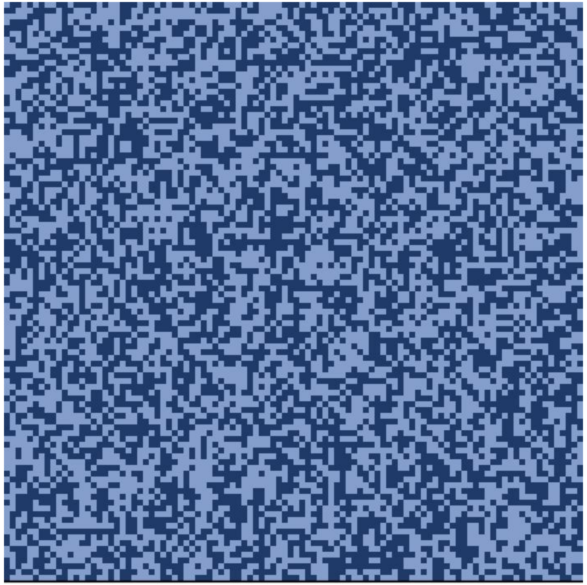
T = Tc



Criticalty

Fractality, scale invariance

T > Tc

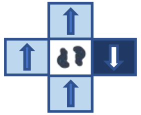


Disorder

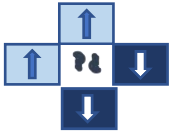
Random fluctuations

THE ISING MODEL

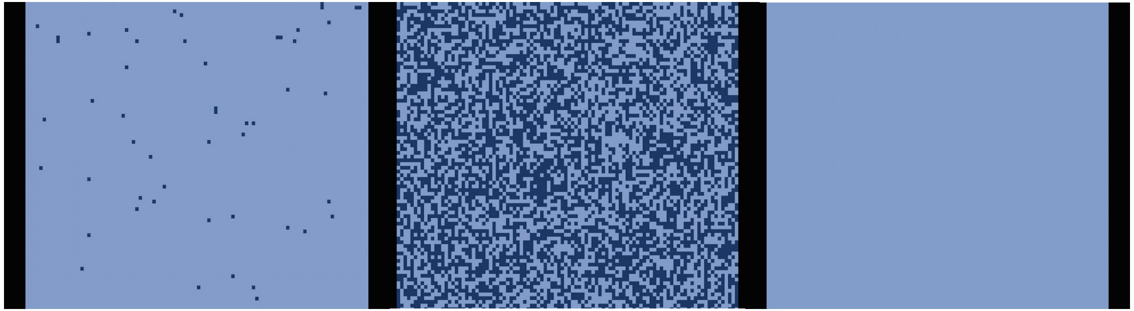
LESS FAMILIAR : THE DYNAMICS CAN BE STUDIED VIA PERTURBATION METROPOLIS-MONTECARLO METHODS

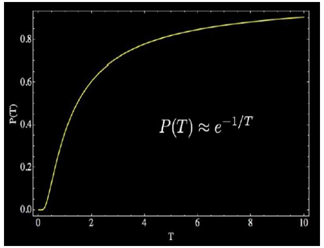


Balance



subcritical **criticality.** **supercritical**

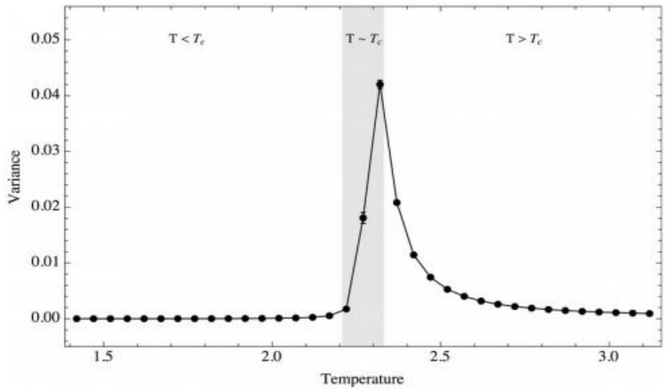




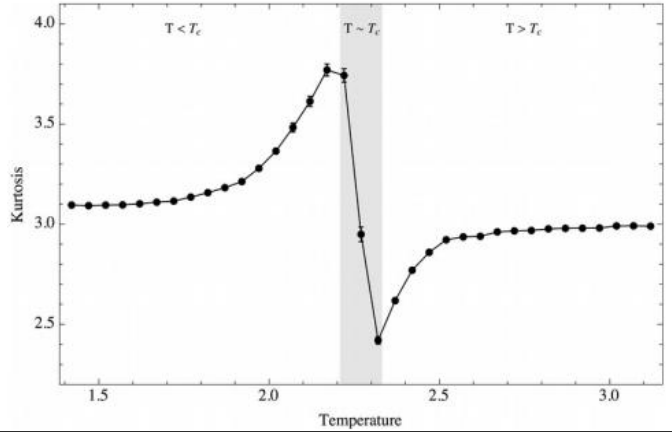
Morales et al. (2015) *PLoS ONE* **10**:e0130751.

Total magnetization as a function of temperature: Ising Model

Behavior at criticality

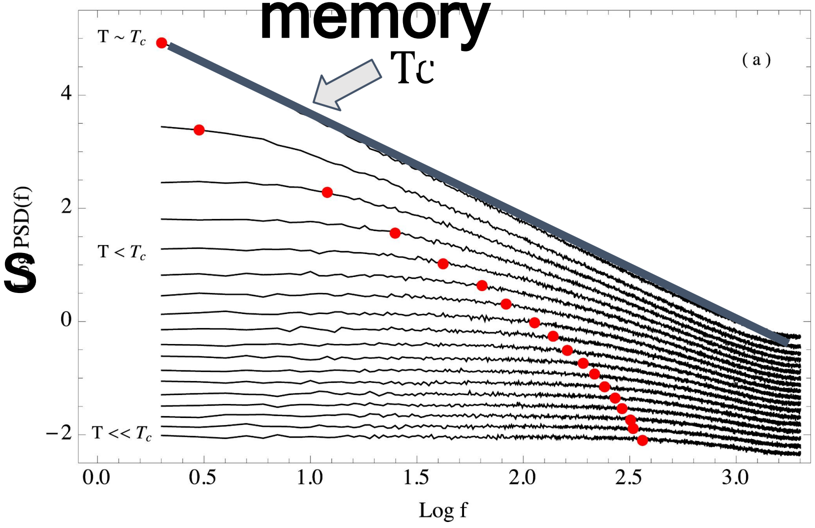


variance



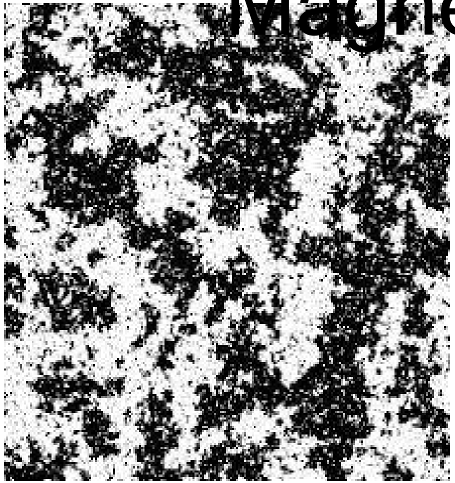
kurtosis

Power spectra autocorrelation & memory



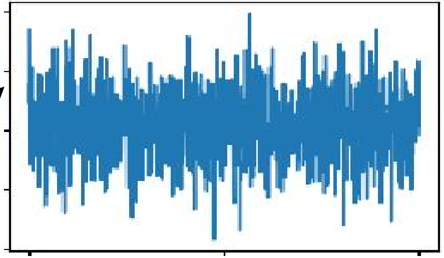
Complexity Approach: Time series and criticality

Compute total Magnetizati

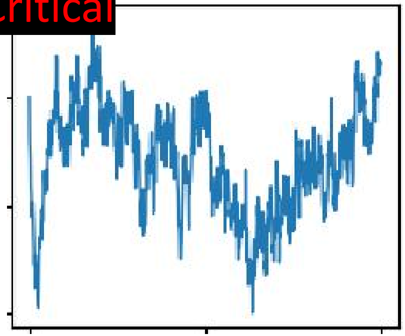


Ising Model

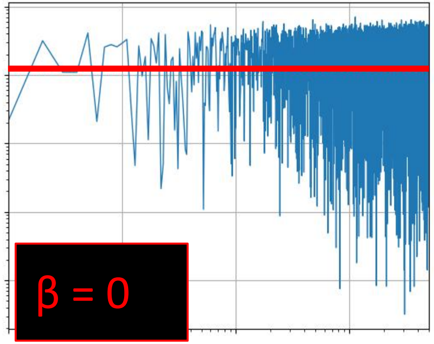
subcrítical



Crítical



Power Spectra



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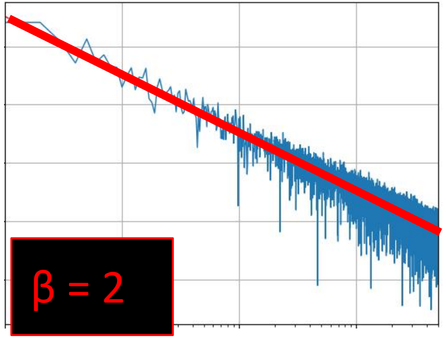
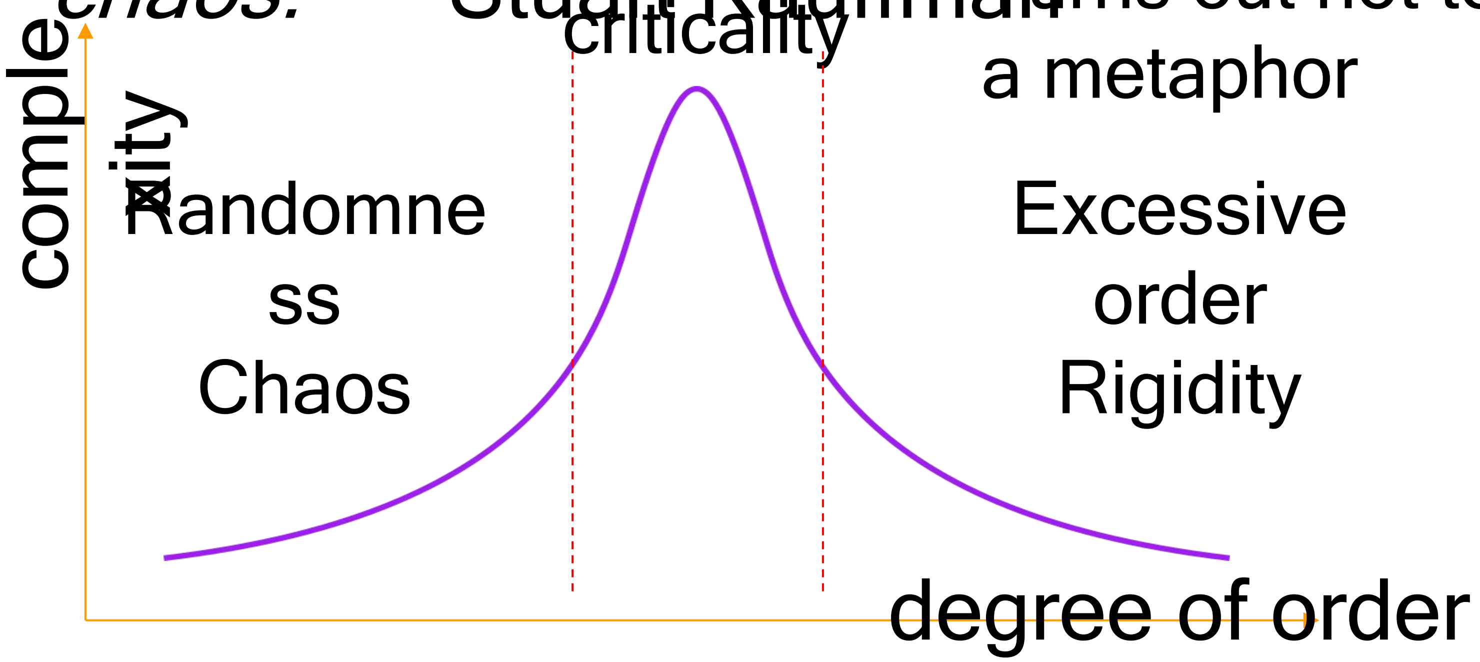


Complexity: at the border between order and chaos

“Living systems exist at the border of chaos.” –Stuart Kauffman

Turns out not to be a metaphor



Main Hypothesis, Living Organisms: evolution and criticality

- Organisms and their organs develop under constantly changing environments.

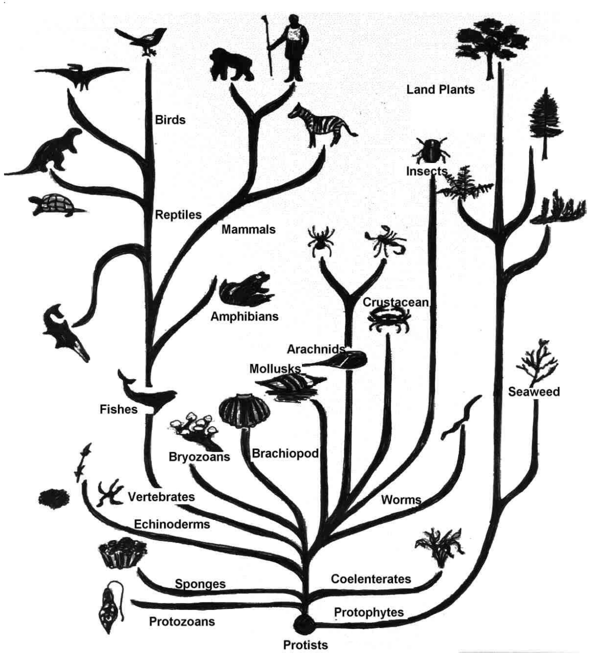
- Two **antagonistic** requirements:

- **Robustness: phenotypes should be robust as they evolve.**

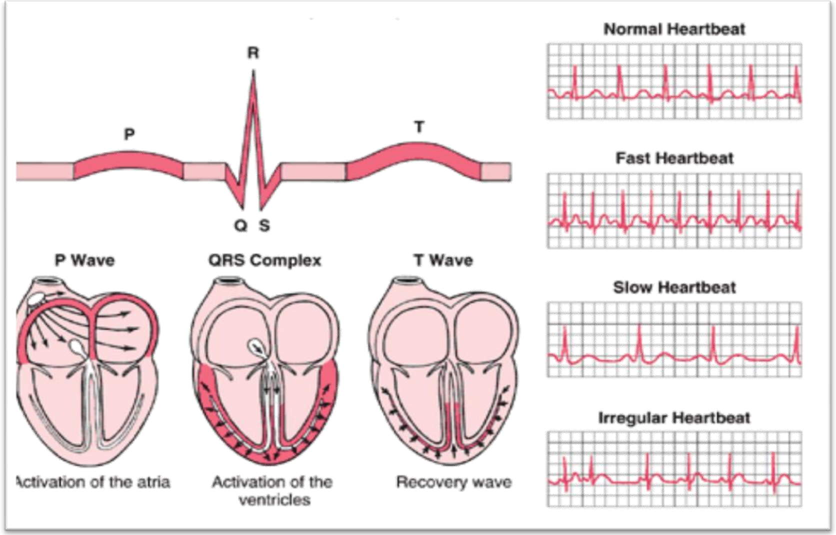
- **Adaptability:Individuals must adapt to changes**

- **Criticality : optimal equilibrium (alostasis).**

- **Darwinian selection leads to criticality**



A one dimensional example: Heartbeats ECG



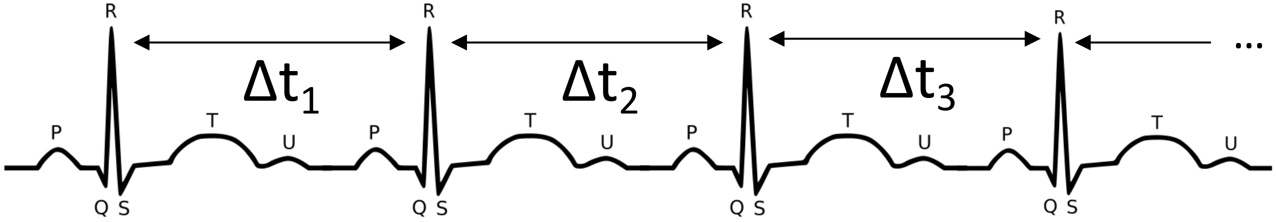
Serie de tiempo

Intervalos RR

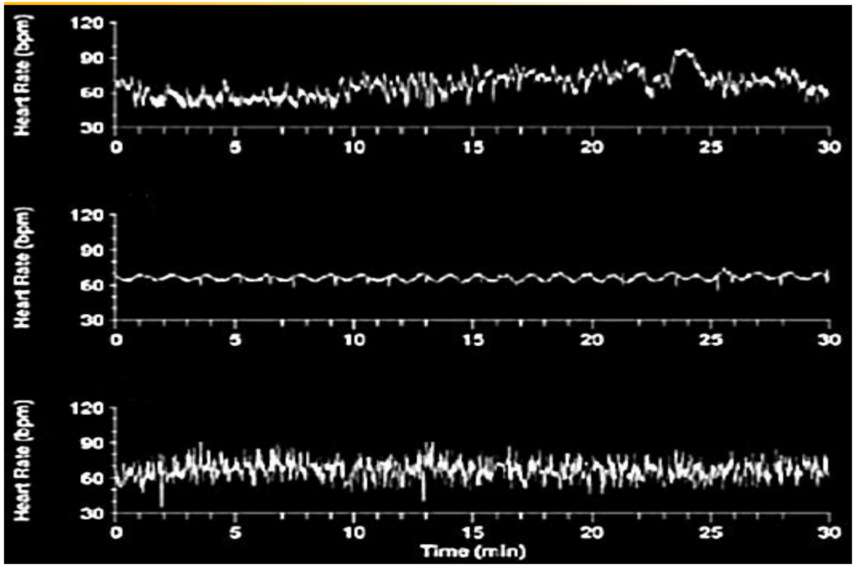
$\Delta t_1, \Delta t_2, \Delta t_3, \ldots \Delta t_n$

Fluctuaciones

$$\frac{\Delta t_i - \overline{\Delta t}}{\overline{\Delta t}}$$



CARDÍAC VARIABILITY



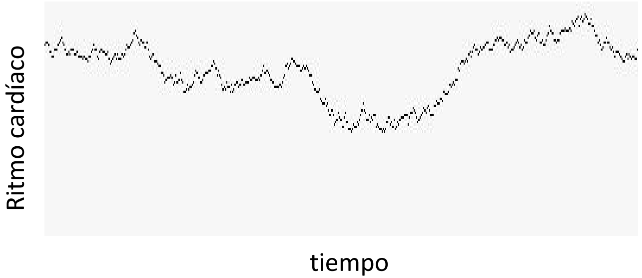
healthy heart

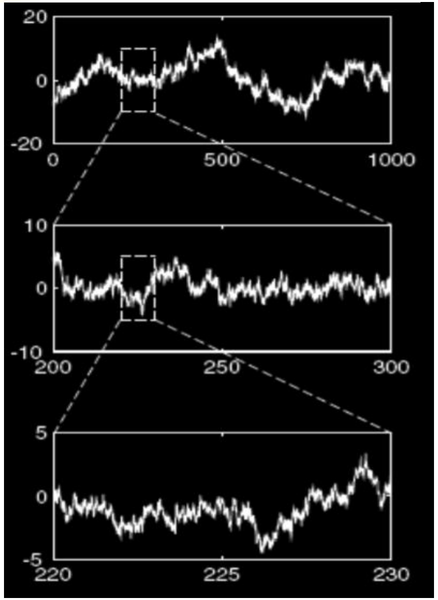
cardiac insufficiency

ventricular fibrilation

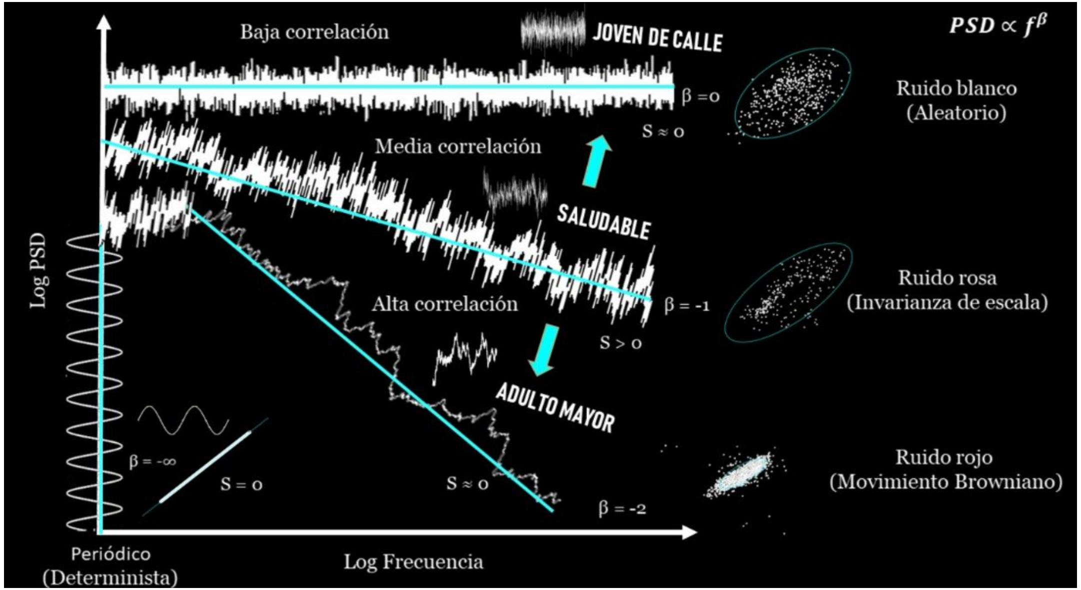
Goldberger et al. (2002) *PNAS* **99**:2466

Scale invariance at criticality.



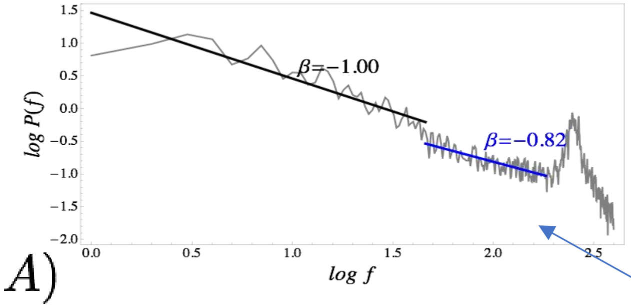


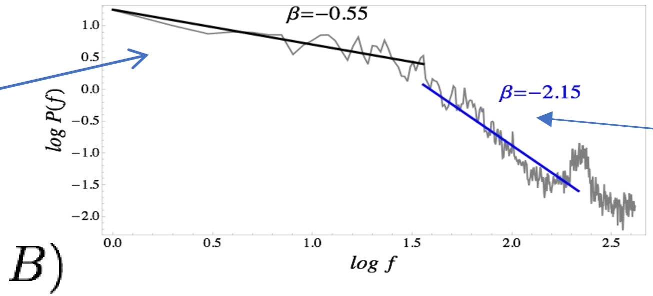
POWER SPECTRA



Power Spectra of R-R intervals

Change of slopes





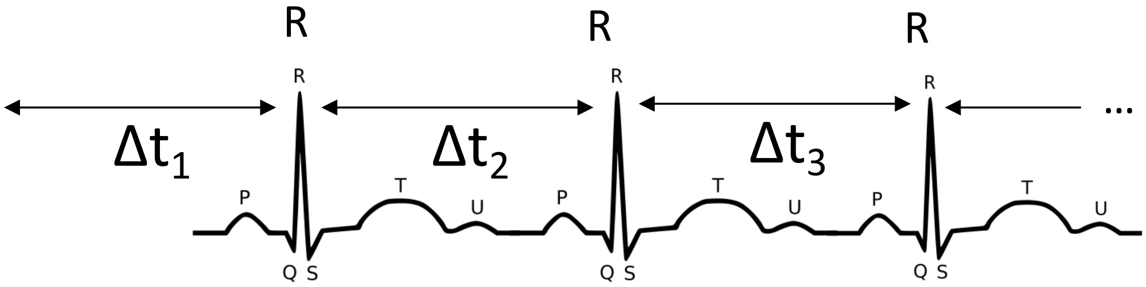
Correlation loss at low frequencies (longer times)

Collaboration Hospital of Nutrition and Cardiology: Prof. Dr. Bruno Estañol:

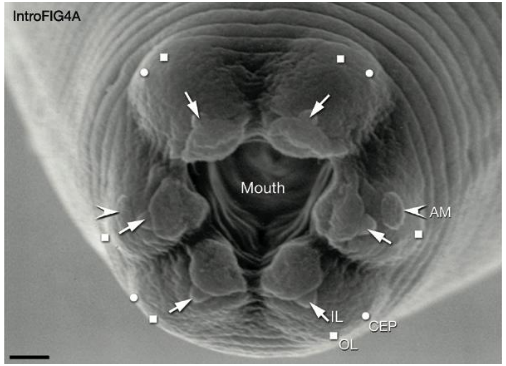
Detection of Pre-diabetes and Diabetes, Metabolic Syndrome, for early warnings: IBI and Blood Pressure. Coronary Obstruction, Intensive Therapy, Epilepsy.

A) young (21-34 years old),

B) older (68-84 years old). Physionet.

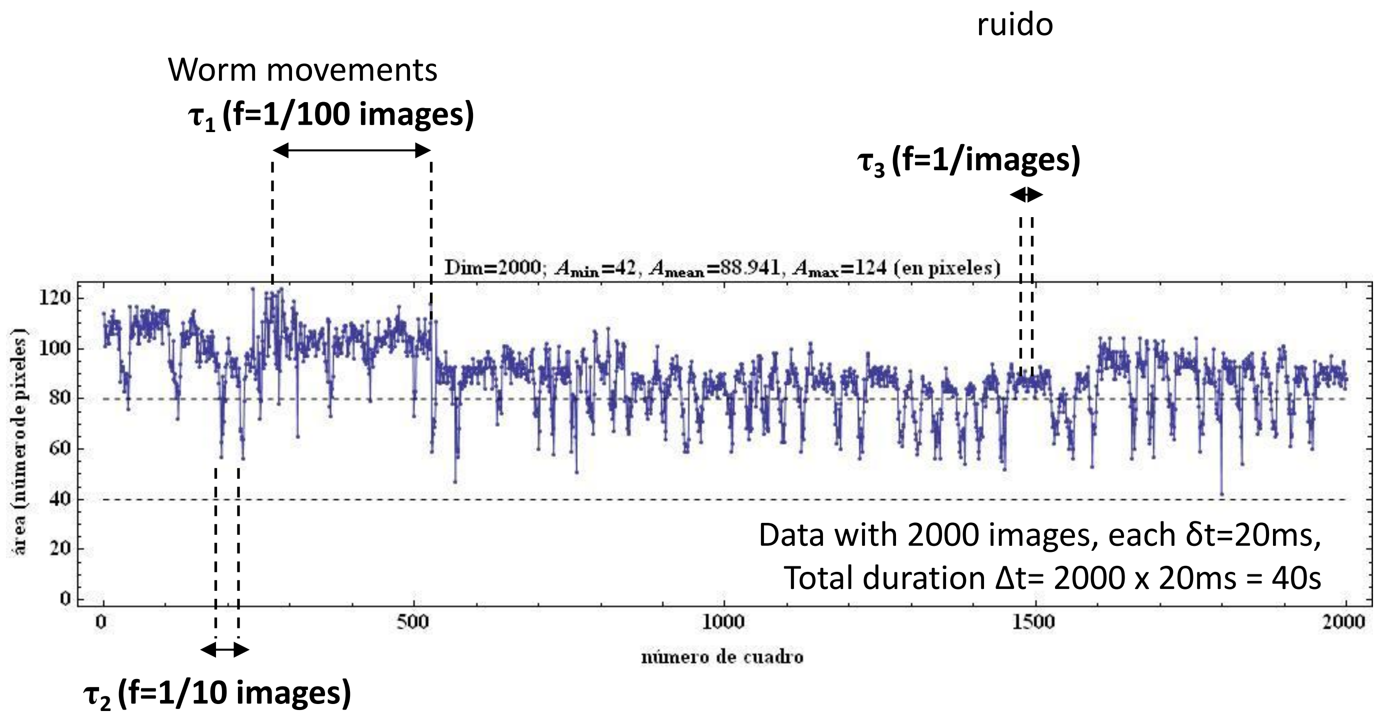


A simple model: C Elegans



Pharynx oscillations display perfect scale invariance for young healthy worms

High speed camera . Area measurements

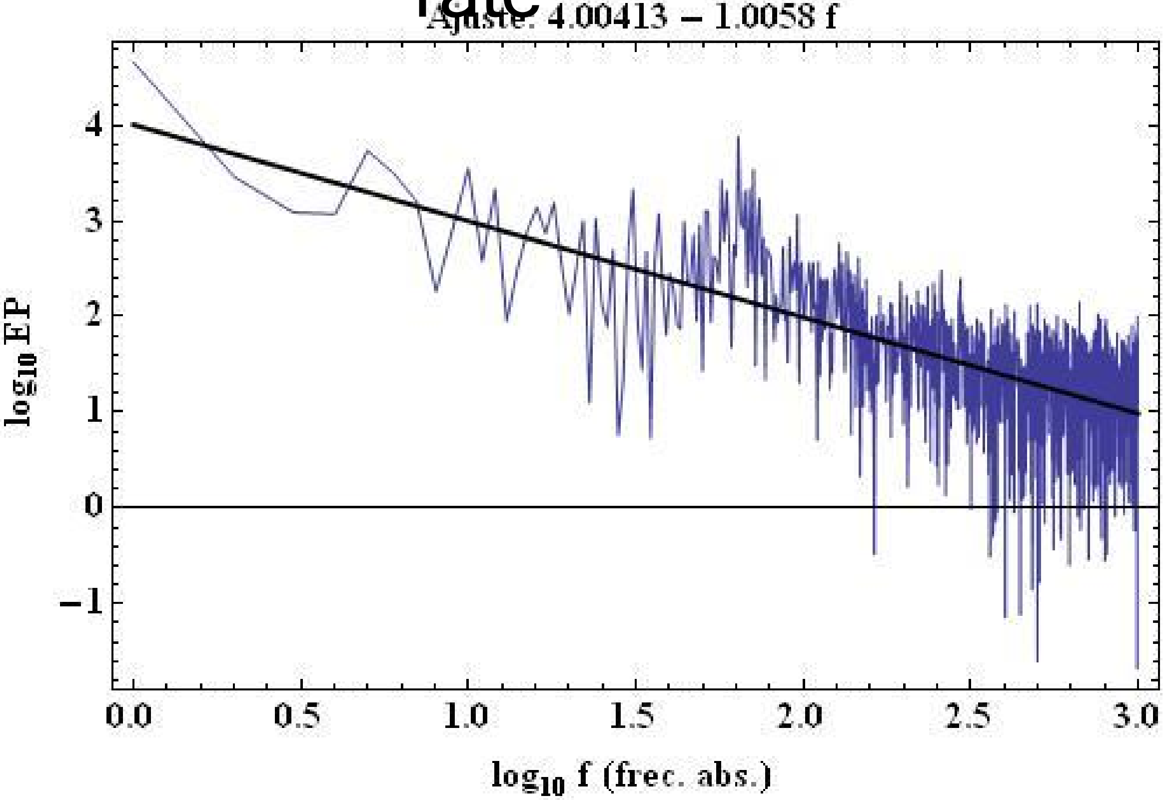


C-elegans

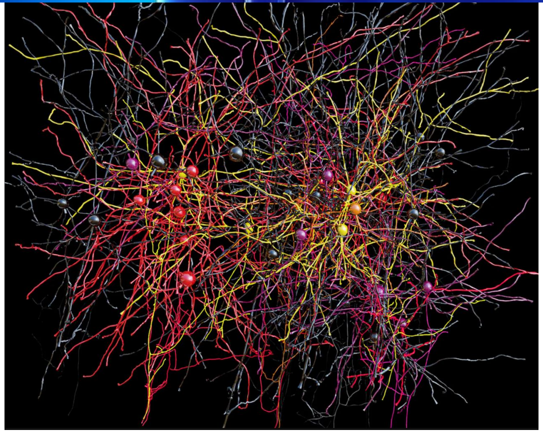
Pharynx oscillation rate

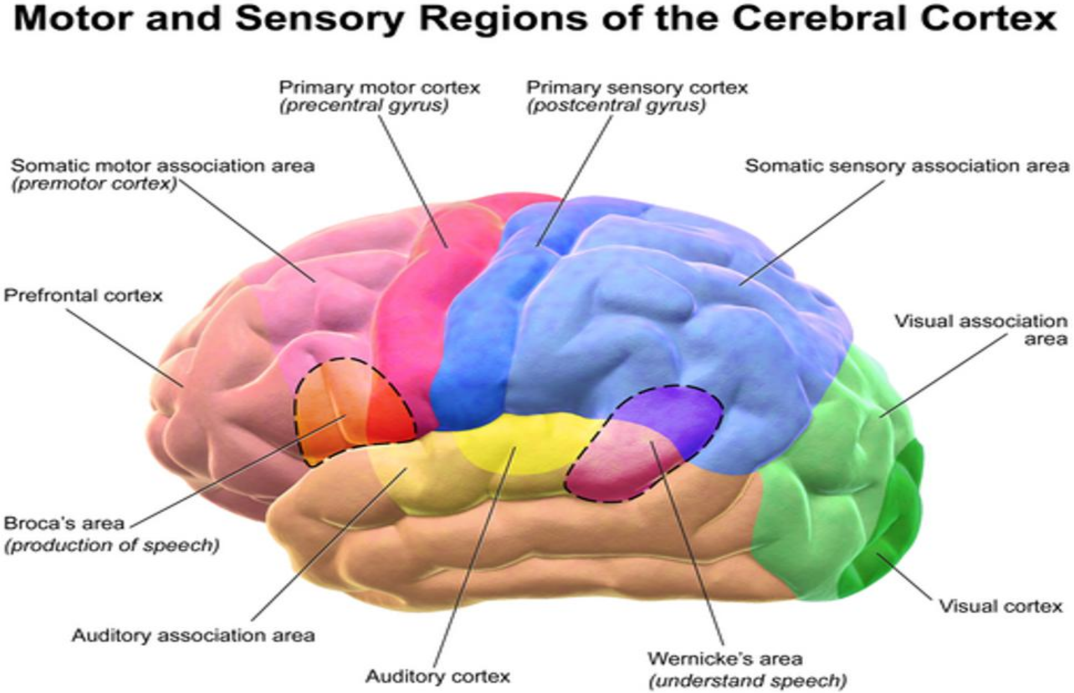
Young C-elegans

Older become irregular



Organic growth of brain networks produces areas of functional specialization

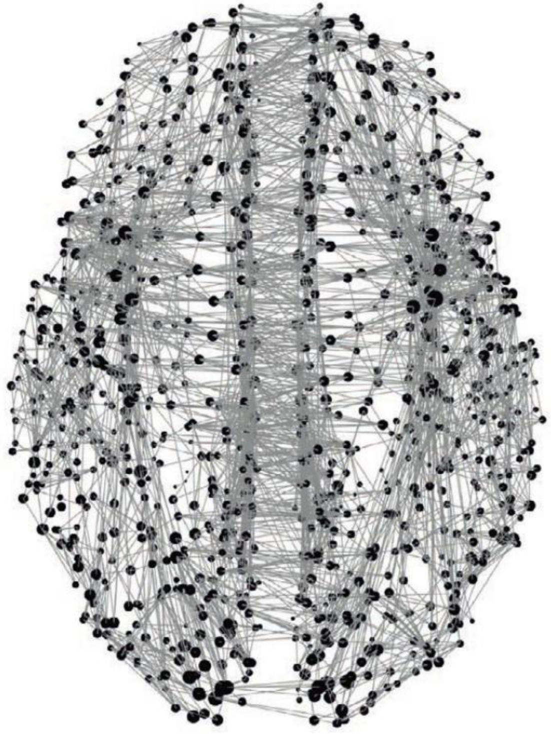




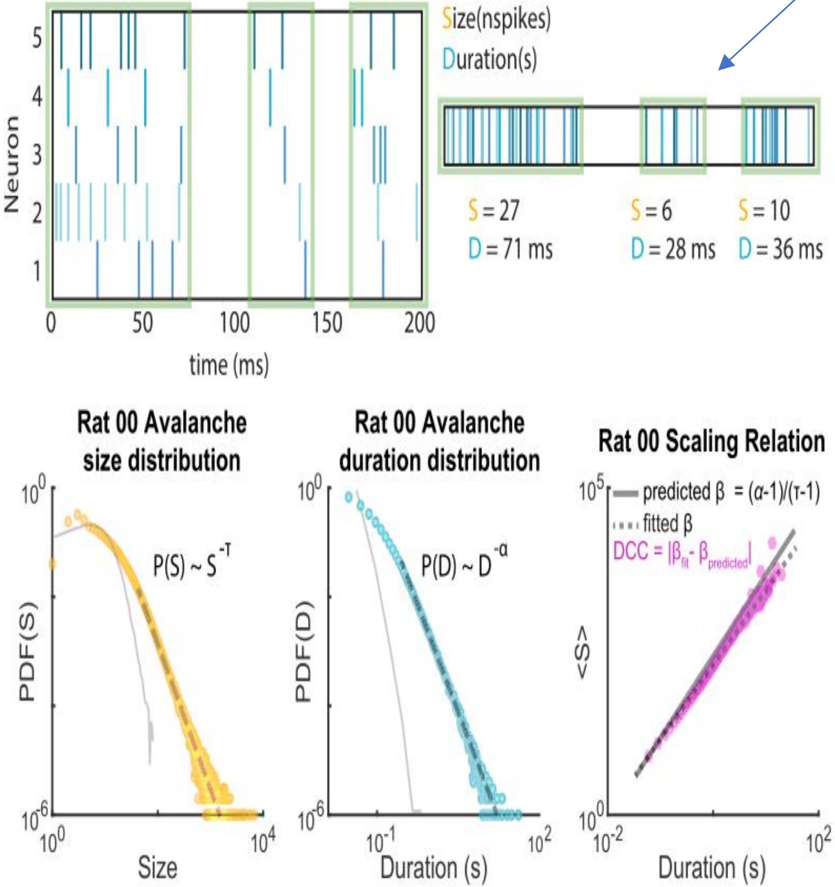
Brain Criticality ?

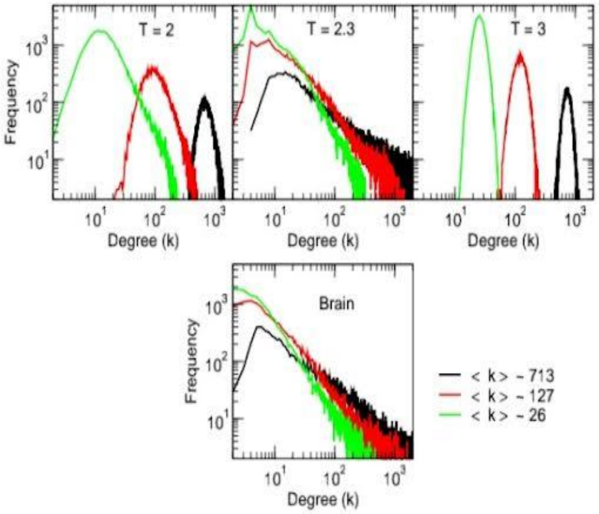
There is evidence that brain behavior is critical.
Scale invariance helps explain the emergence of complex structures

Optimizes information processing (transmission, storage)
Produces diversity and functional flexibility
Provides functional robustness in the face of serious alterations (injuries)



Evidence through Experiments with rats (invasive) AND Models





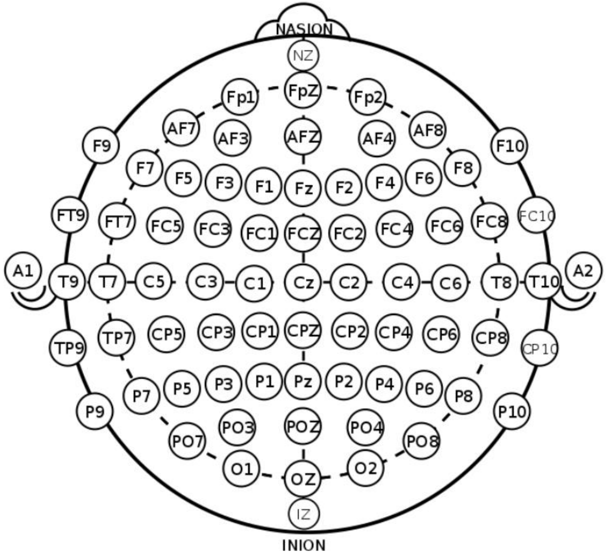
Ising

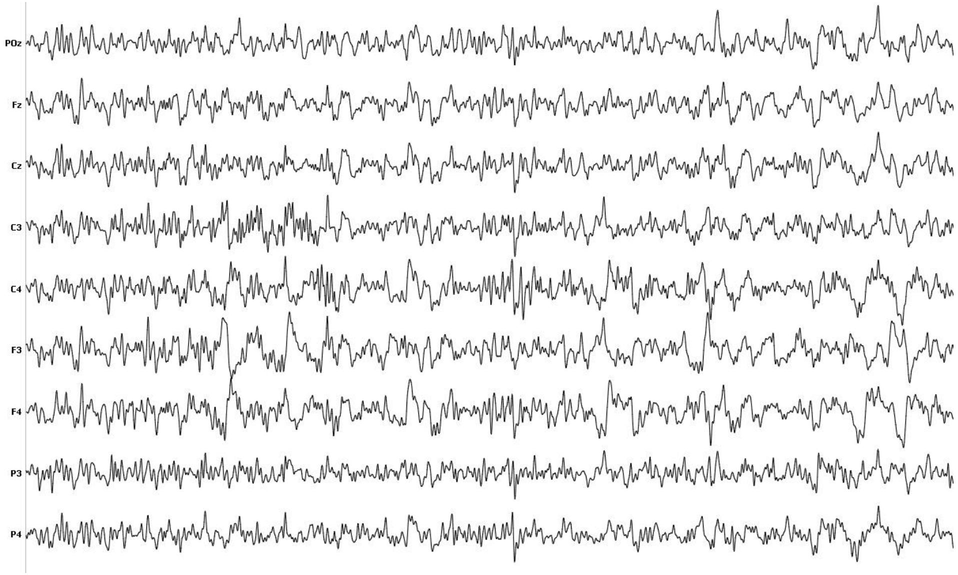
Brain

At criticality, brain and Ising networks are indistinguishable from each other. The graphs show a comparison of the link density distributions computed from correlation networks extracted from brain data (bottom panel) and from numerical simulations of the Ising model (top three panels) at three temperatures: critical ($T = 2.3$), sub ($T = 2$) and supercritical ($T = 3$). Top three panels depict the degree distribution for the Ising networks at $T = 2$, $T = 2.3$ and $T = 3$ for three representative values of $\langle k \rangle \approx 26$, 127, and 713. Bottom panel: Degree distribution for correlated brain network for the same three values of $\langle k \rangle$. Figure redrawn from Fraiman et al [42].

Multicriticality (multisignal criticality)

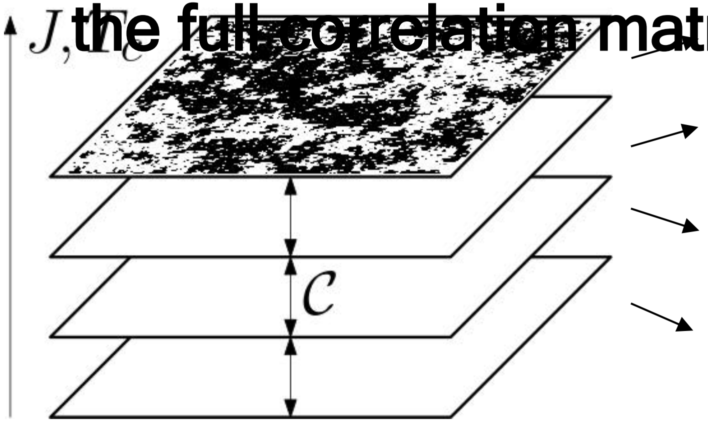
How to define and study criticality in a multiple signal system?

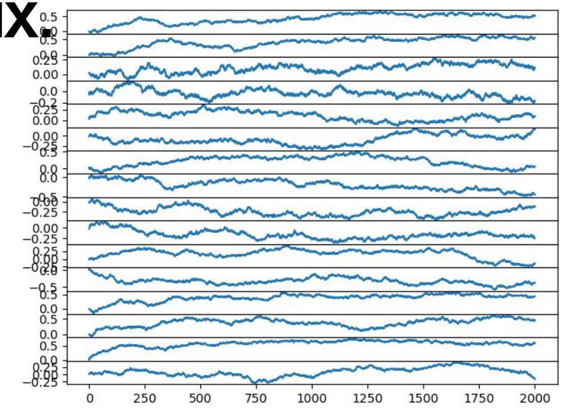


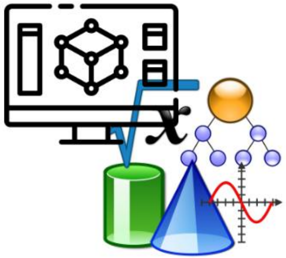


Ising multilayer model

Multilayer Ising model, each layer havs a different coupling strength, vertically coupled to its nearest neighbors. We evaluate each layer’s magnetization time series and compute the full correlation matrix.







PCA

PHYSICAL REVIEW E 103, 042111 (2021)

Criticality in a multisignal system using principal component analysis

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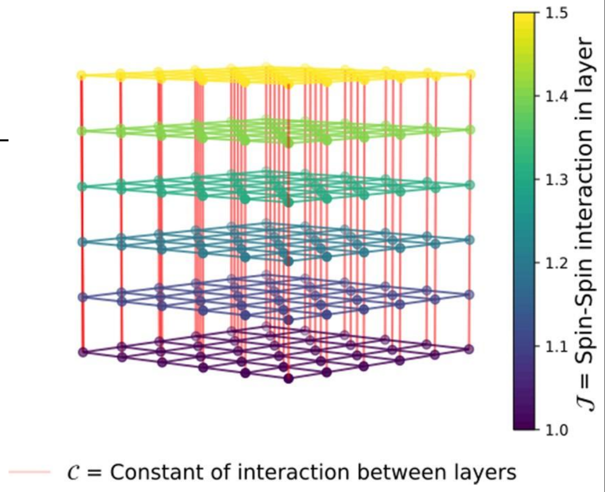
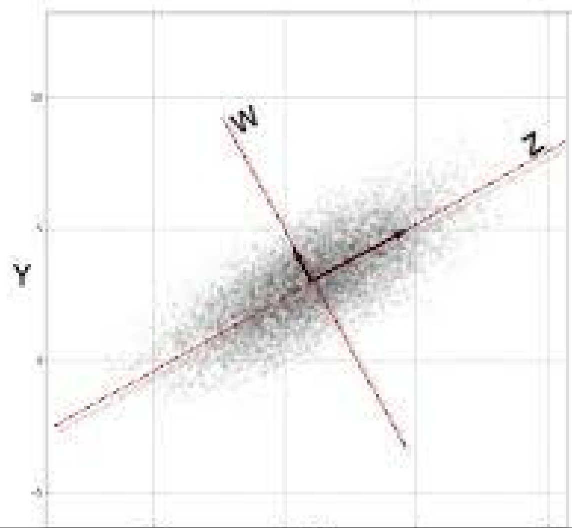
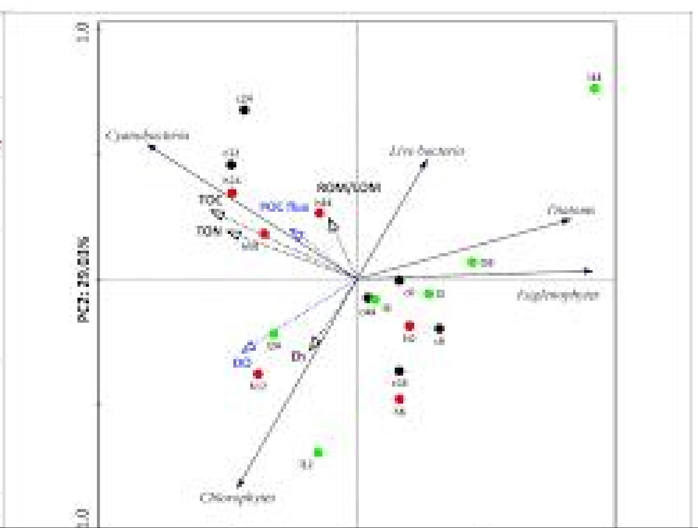
(accepted 11 March 2021; published 6 April 2021)



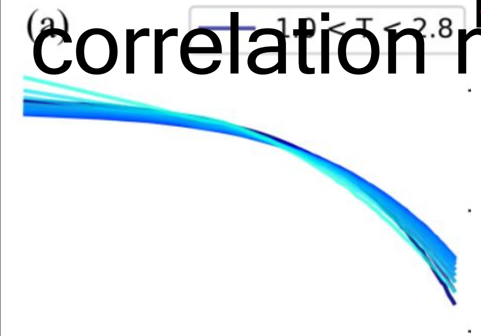




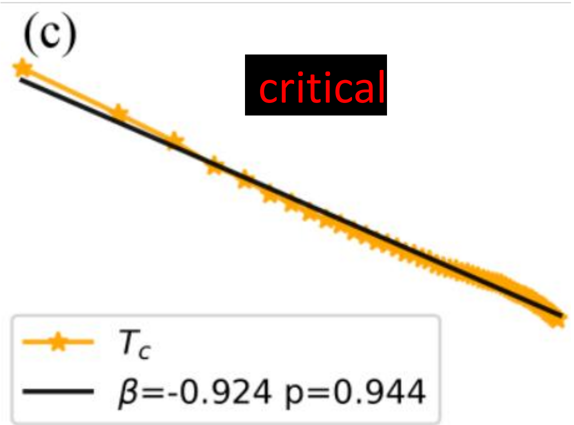
Multilayer Ising Model

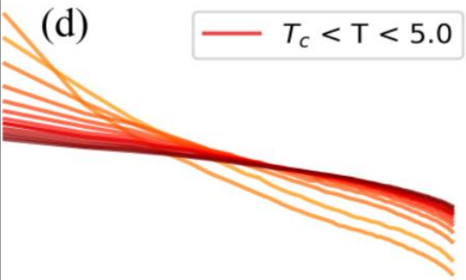
Using PCA we calculate the ordered eigenvalues and eigenfunctions of the correlation matrix.

sub-crítical



critical

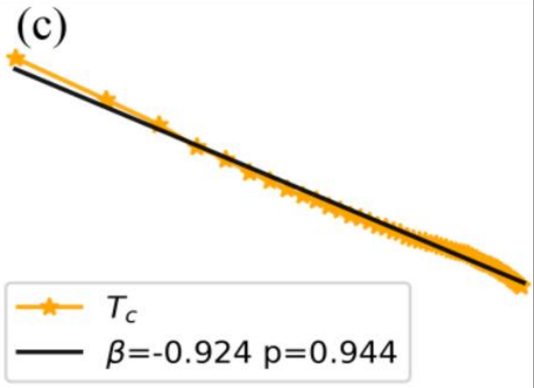




supercritical

We find a power law for the ordered eigenvalues precisely (and only) at ality

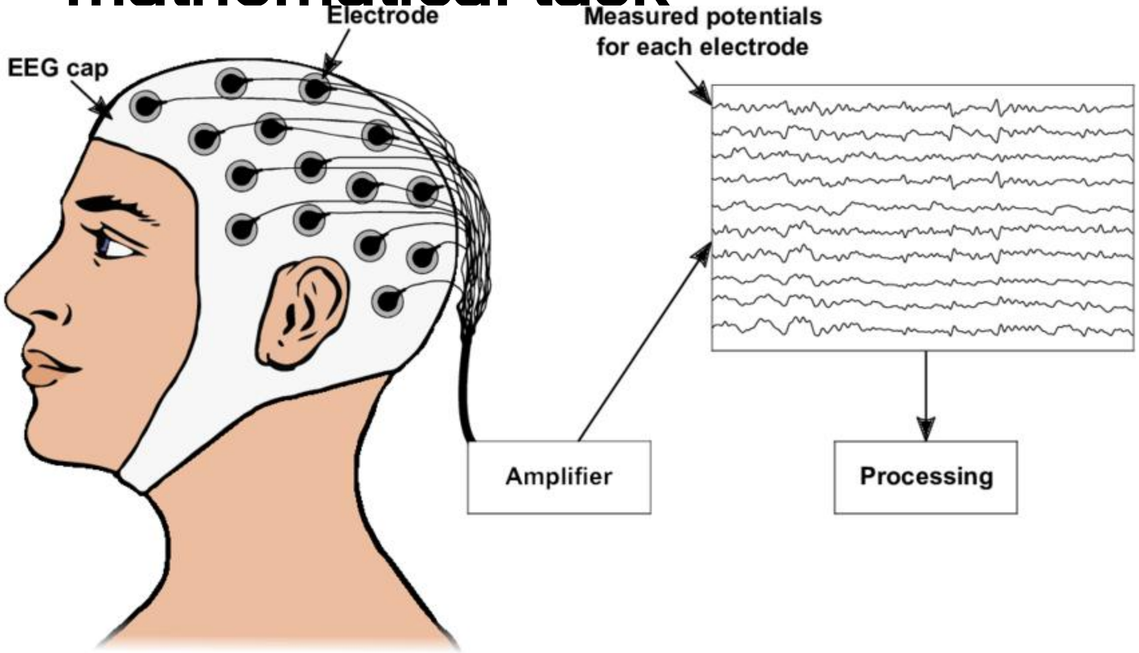
What is the meaning of this result?

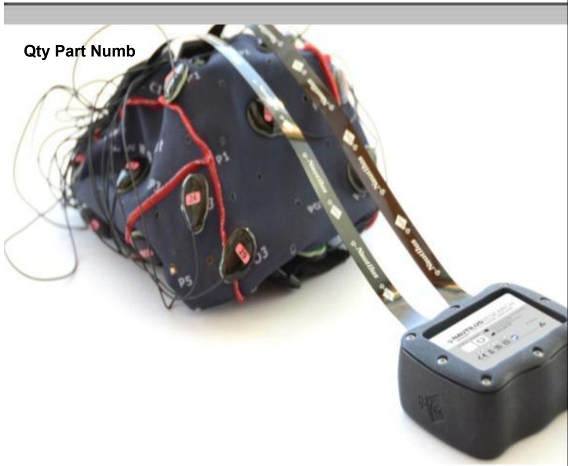


- Our result implies scale invariance of the correlation matrix.
  We postulate the following conjectures:
- 1): Given a complex system where n different signals are simultaneously measured, the system is in a critical state if the associated correlation matrix is scale invariant.
- 2): A (symmetric) matrix is scale invariant if its

Brain criticality

We tested our methodology by taking eeg's of young people **at rest** or **carrying out a mathematical task**



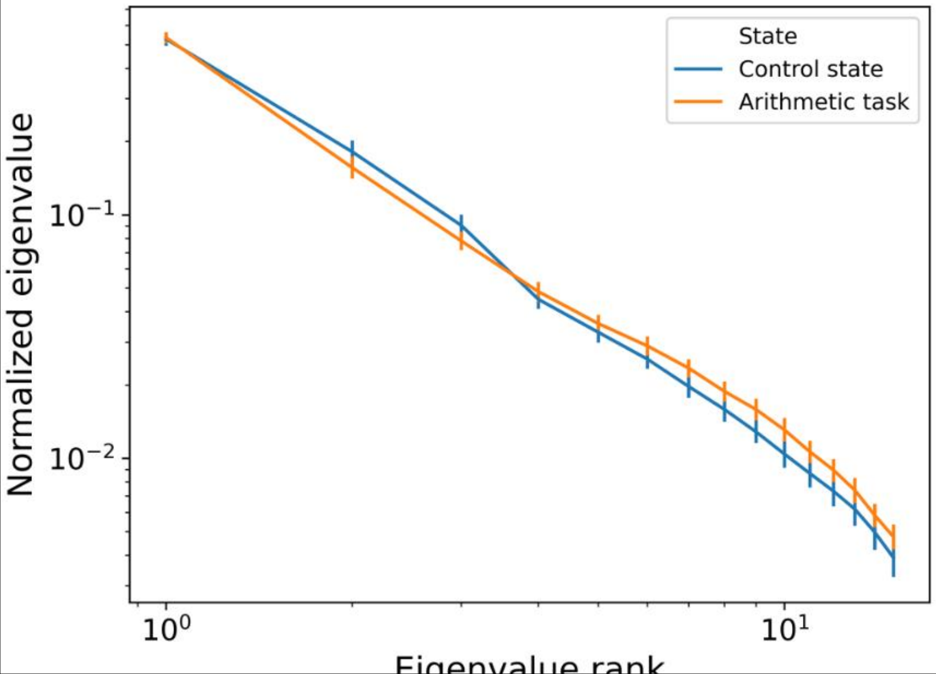


Criticality of the brain

We find almost exact power laws in both cases,

ishable by this

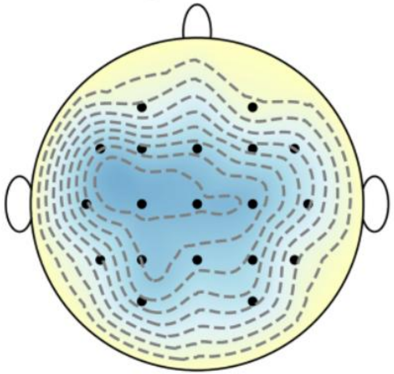
n.



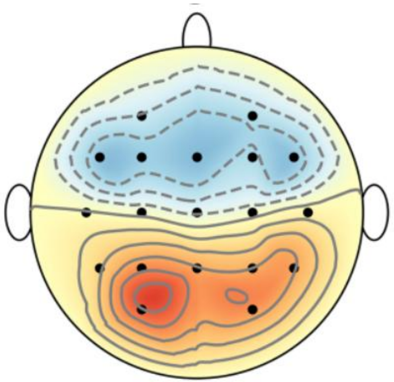
Power laws in eigenvalues of brain eeg´s

The brain’s principal (normal) modes display symmetric modes

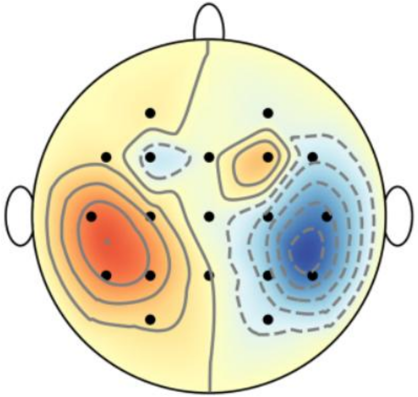
Mode 1: Average



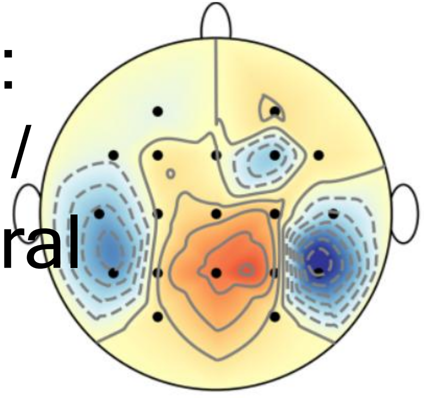
Mode 2: back/forth



Mode 3: left/right



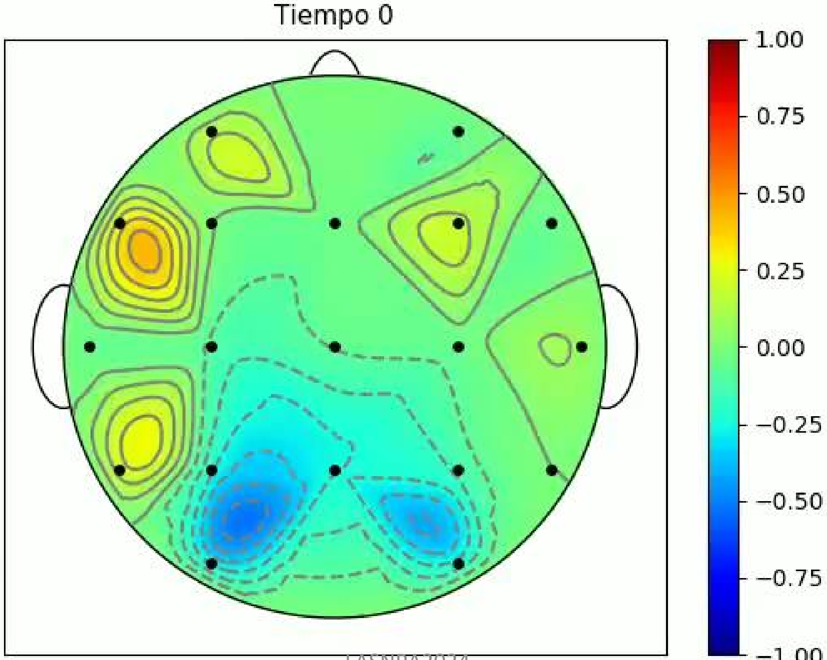
Mode 4: Central / peripheral



The critical brain: Time dependent modes

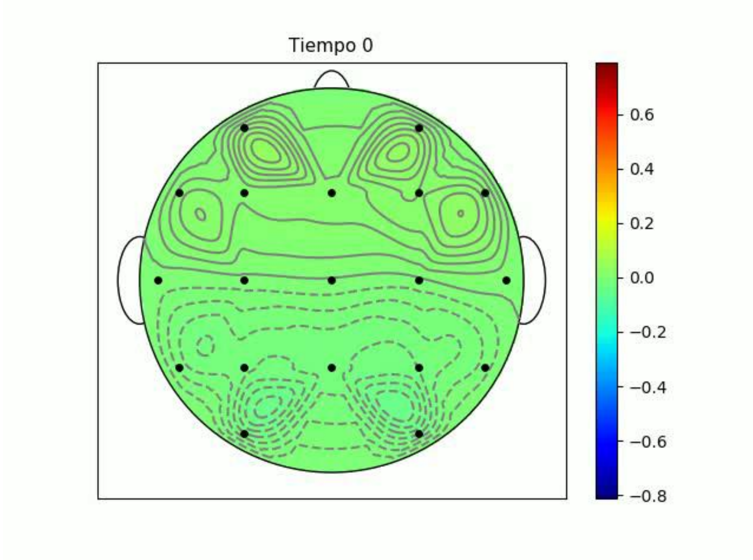
Full EEG of resting brain:

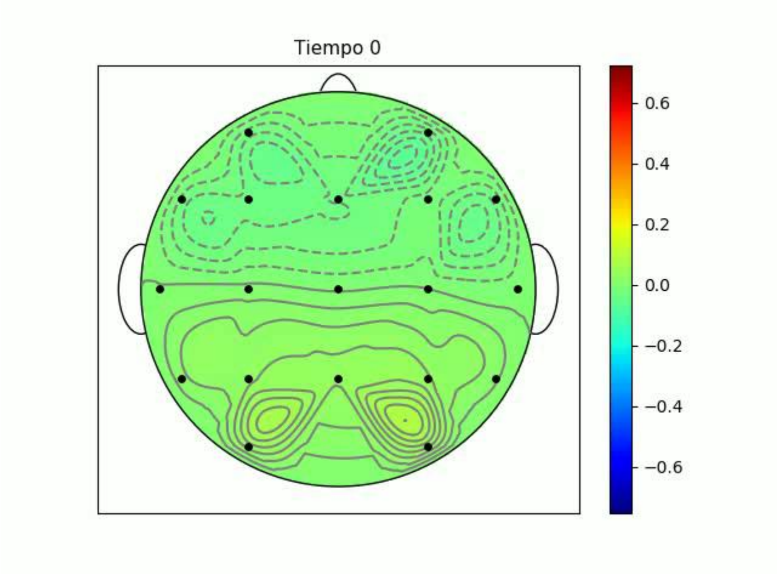
-



Subject no.10 at rest and with task
Front-Back Mode

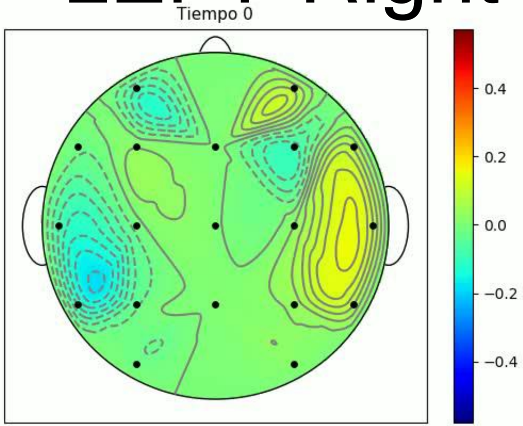
pc2

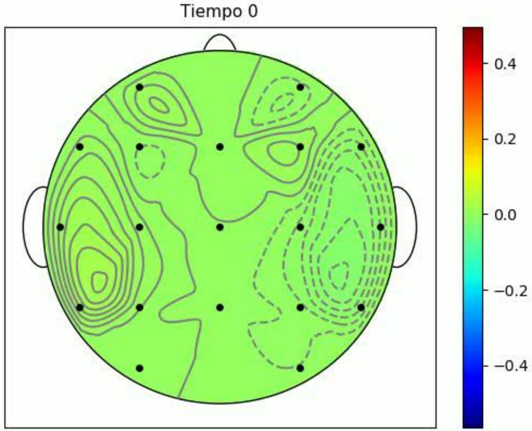




Subject no.10 at rest and with task LEFT-Right MODE

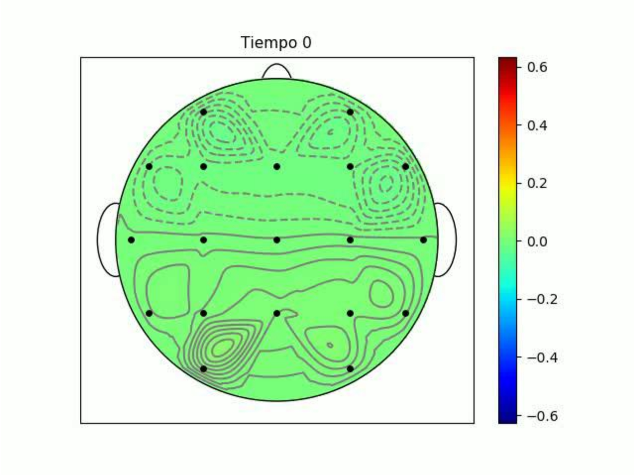
pc3

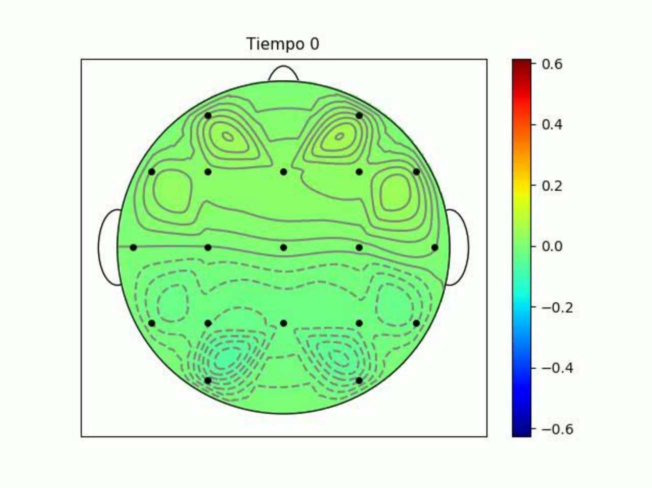




THESE MODES ARE SEEN IN ALL OUR SUBJECT Subject no.12 at rest and with task

pt2

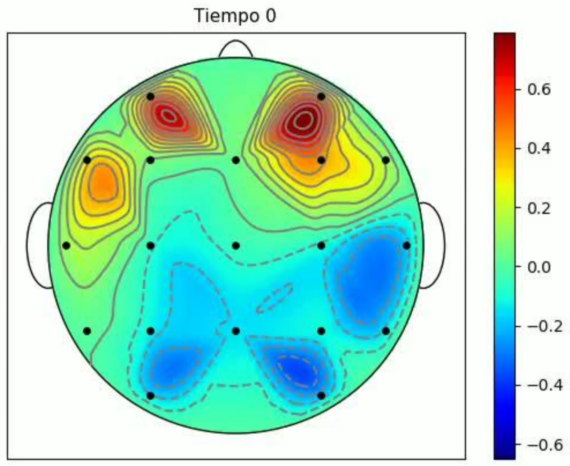


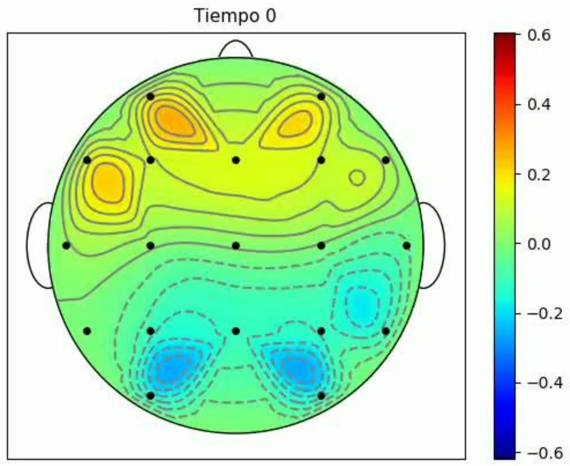


Behavior is almost identical between different people.

Critical Brain. SUBJECT 15 , REST AND WITH TASK

- SECOND PRINCIPAL COMPONENT **PC2**





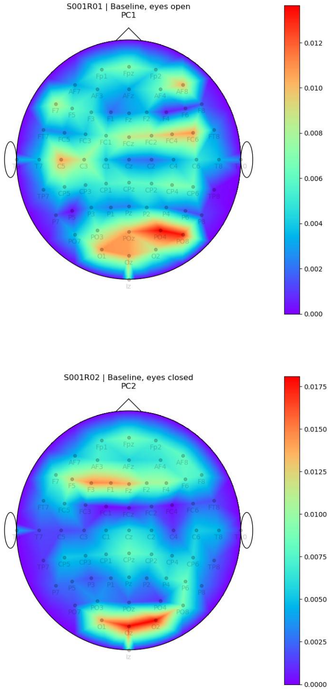
Multicriticality in the brain

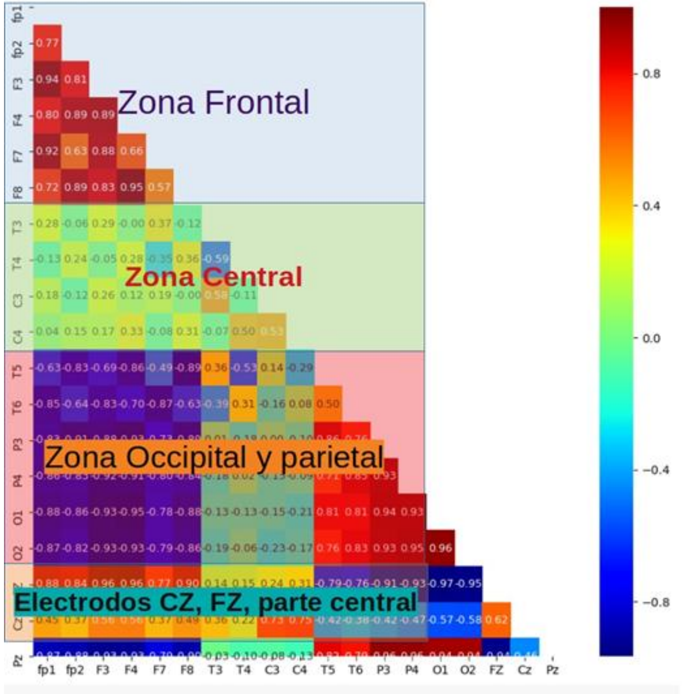
PHYSICAL REVIEW E **103**, 042111 (2021)

Criticality in a multisignal system using principal component analysis

Miguel Sánchez-Islas ,Juan Claudio Toledo-Roy, and Alejandro Frank

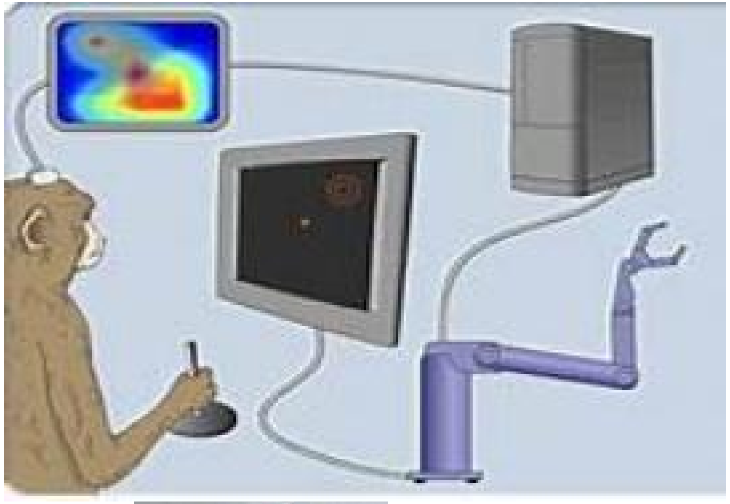
Lower modes PC4, PC5 can distinguish brain activity





Machine learning algorithm recognizes ~100% of cognitive task in these modes

Brain Modes, Correlation Matrix



EEG´s, NMR, Laser Opto-measureme

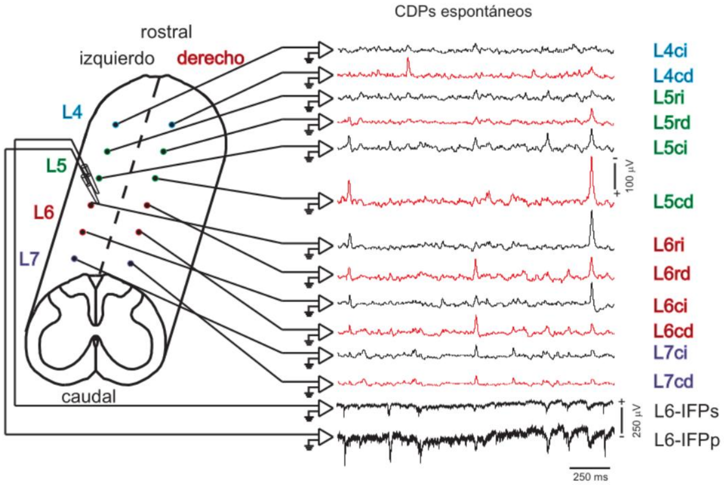
Prof. Ranulfo Romo

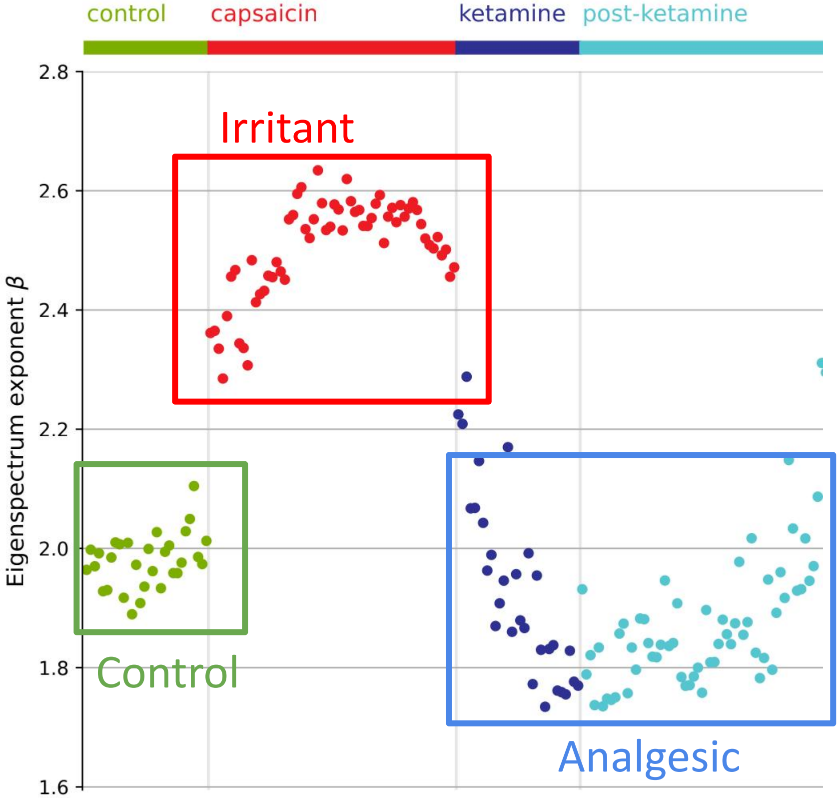
Neurophysiology Laboratory, Unam, Research on monkey connectome learning modifications

Other nervous system experiments

Neurophysiology Lab,
CINVESTAV
Prof, P

domín,



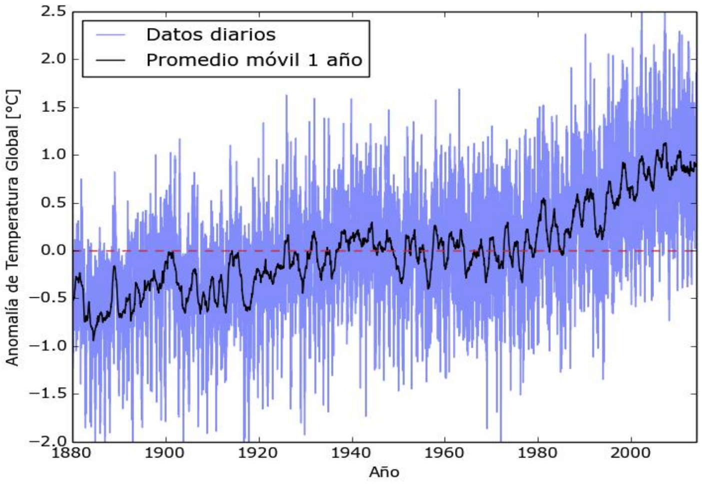


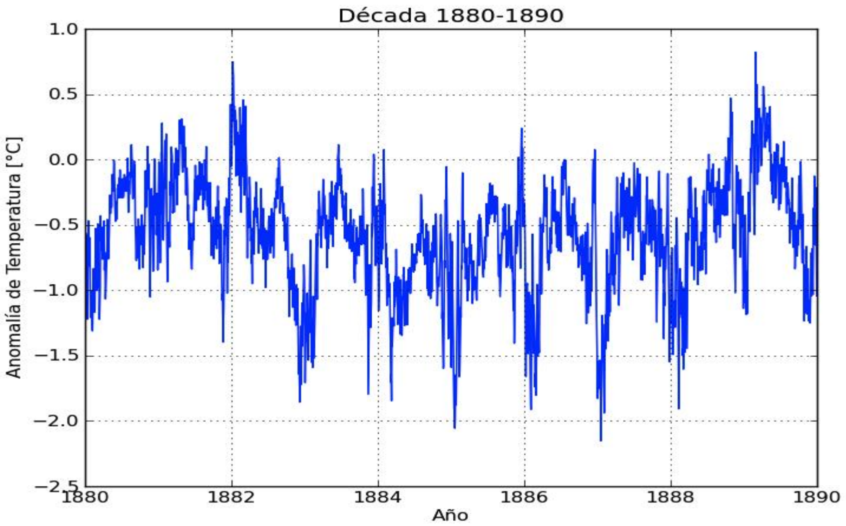
Other signals

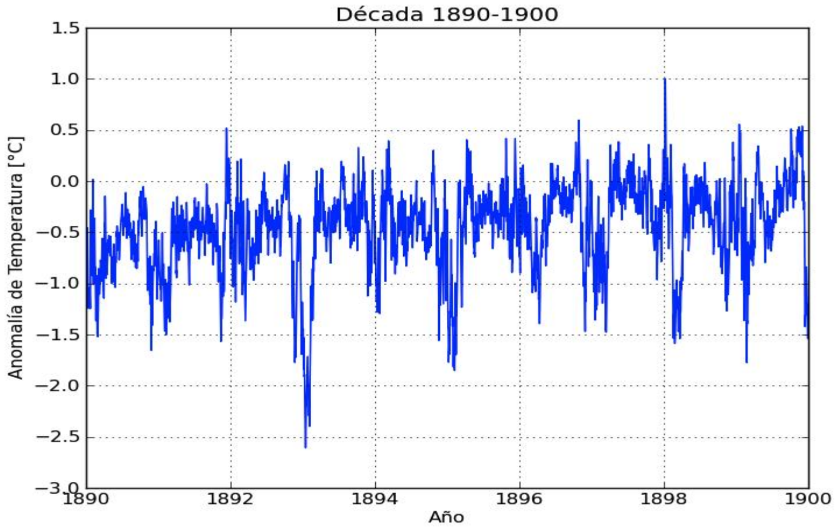
LASNPA2024

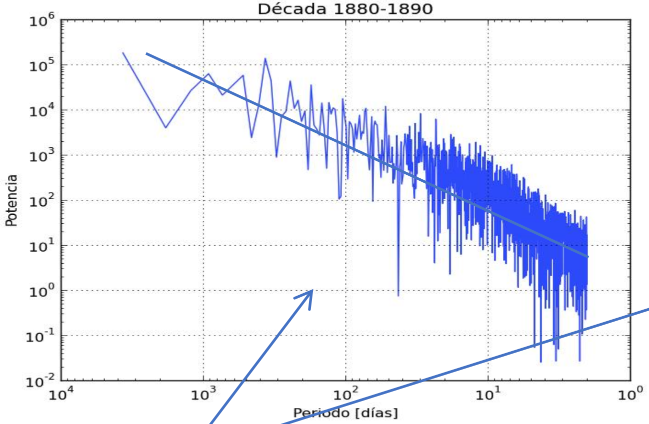
Earth´s average temperature: 1880-2010

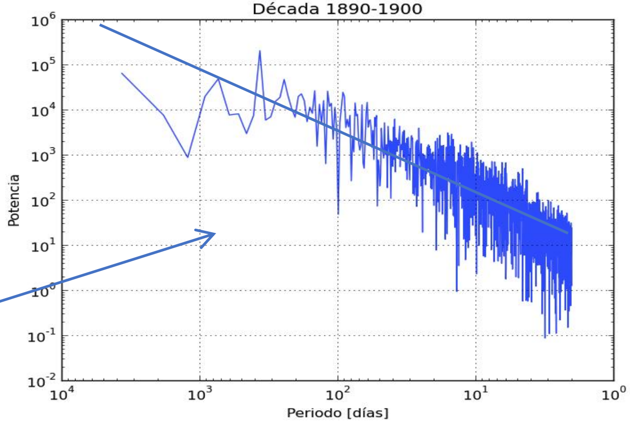
Fluctuation Analysis by decad





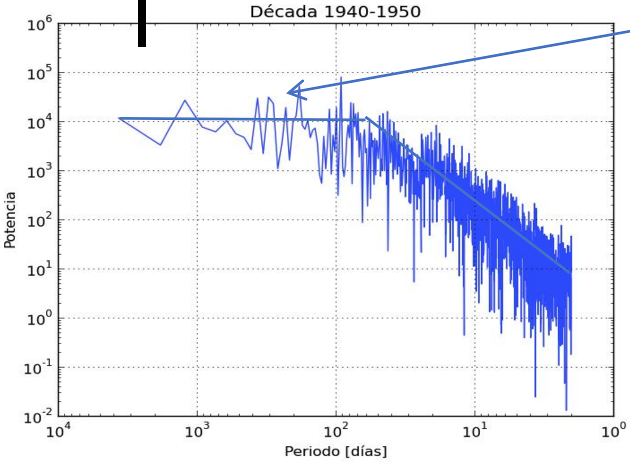


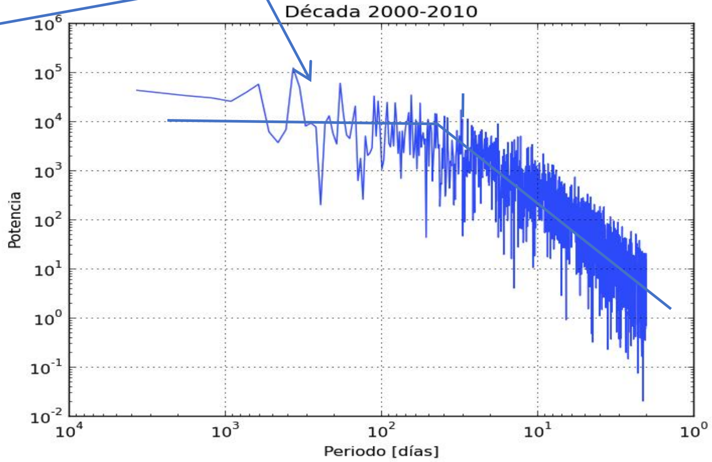




Critica
l

Loss of



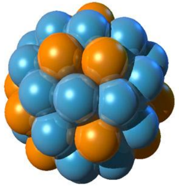


Microscopic systems versus self organized systems (a pond))

Elementary

Dominant Scale

Fundamental Symmetries: The system remains isolated from other scales



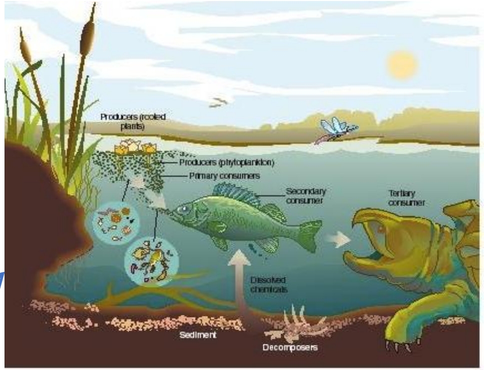
Symmetries= conserved quantities

Complex

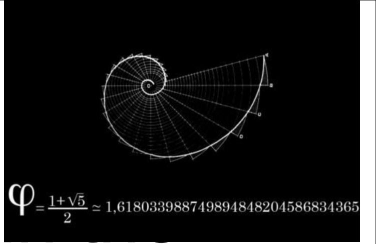
Multiple scales

Self similarity, scale invariance. Cascading communication among different scales

Criticality=. Evolutionary equilibrium



Conclusions:



1.Symmetry ideas have had few applications
biological domain,
particularly beyond the static fractal nature.of some living organisms.
2.Self organized biological systems are characterized by and evolve towards critical points and dynamical self similarity.
3.Evolution leads to self similar (or scale invariant) behavior, which signals homeostatic dynamical equilibrium in living organisms. Optimization of

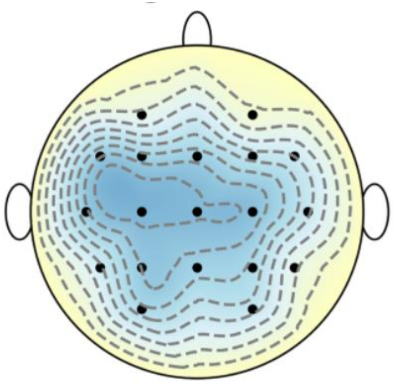
SUMMARY

Criticality in biological systems refers to the delicate balance and interplay of various components within living organisms that allows for optimal functioning and adaptability.
The concept of criticality suggests that biological systems operate at a point where they are neither too ordered (rigid) nor too disordered (chaotic), but rather at a state of dynamic equilibrium that enables efficient information processing and response to external stimuli.

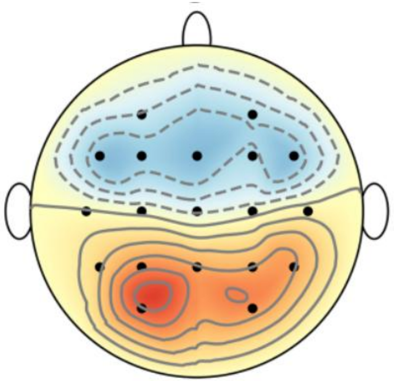
Studying criticality in physical or biological systems with many variables, such as EEGs of the brain, can provide valuable insights into the underlying principles of brain function, cognitive processes, and the mechanisms that govern complex behaviors. By investigating the dynamics of neural activity at criticality, researchers aim to uncover the fundamental principles that govern brain dynamics and contribute to our understanding of brain health, cognition, and neurological disorders.

THANK YOU!

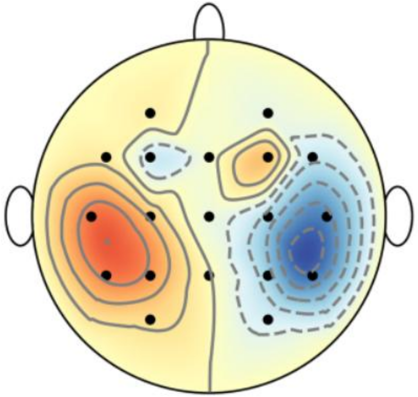
Mod
e 1:
Aver
age



Mode
2:
back/fo
rth



Mode
3:
left/rig
ht



Mode 4:
Central /
peripheral