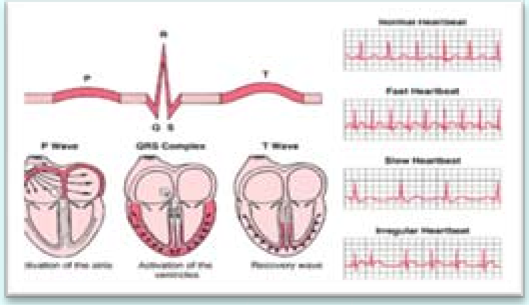
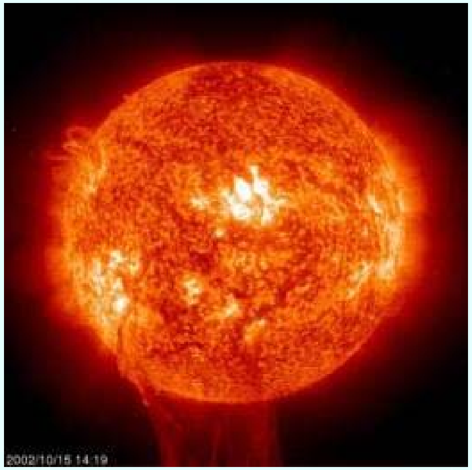
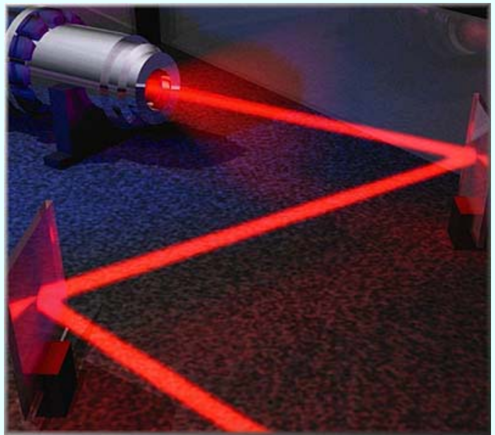
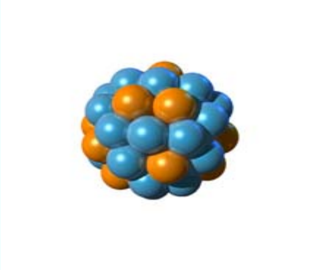
Time Series in Physics and biology: listening to Nature´s signals

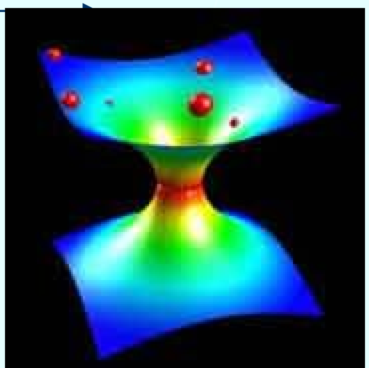
I. Morales, R. Fossion, E. Landa, A. Frank, ICN & C3, UNAM, México











Franco

Group Theory of IBM, IBFM, Supersymmetry, Vibron Model, Vibron-Electron Model, Symmetry Approach to Molecular Vibrations, Algebraic Scattering Theory, Eigen-potential Approach to Configuration Mixing, E(5), X(5),

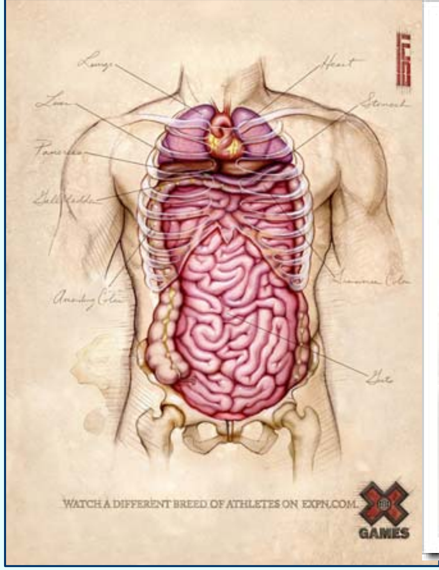
Random Hamiltonians

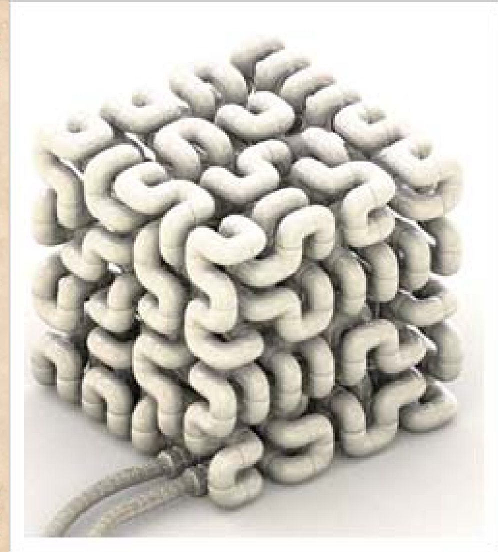
Chaos in Nuclei, Mass Calculations by Image Reconstruction

Chaos, Criticality, Complexity, Time Series, Early Warning Signals

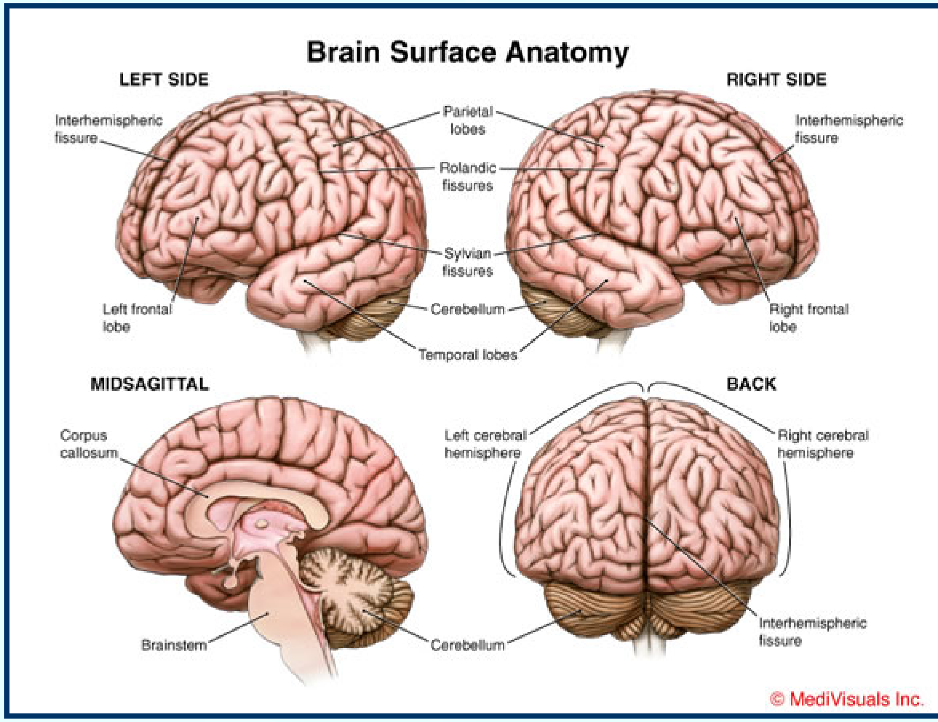
Motivation: Can we find pattern behind disorder?

Ruben Fossion

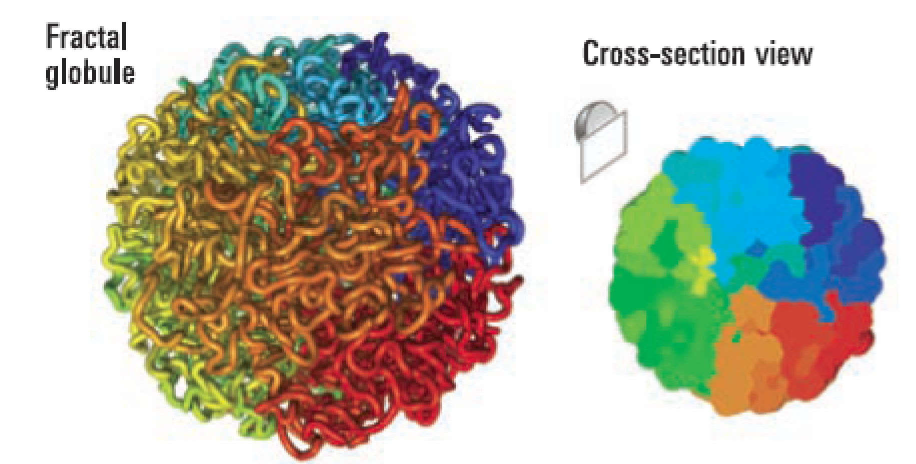




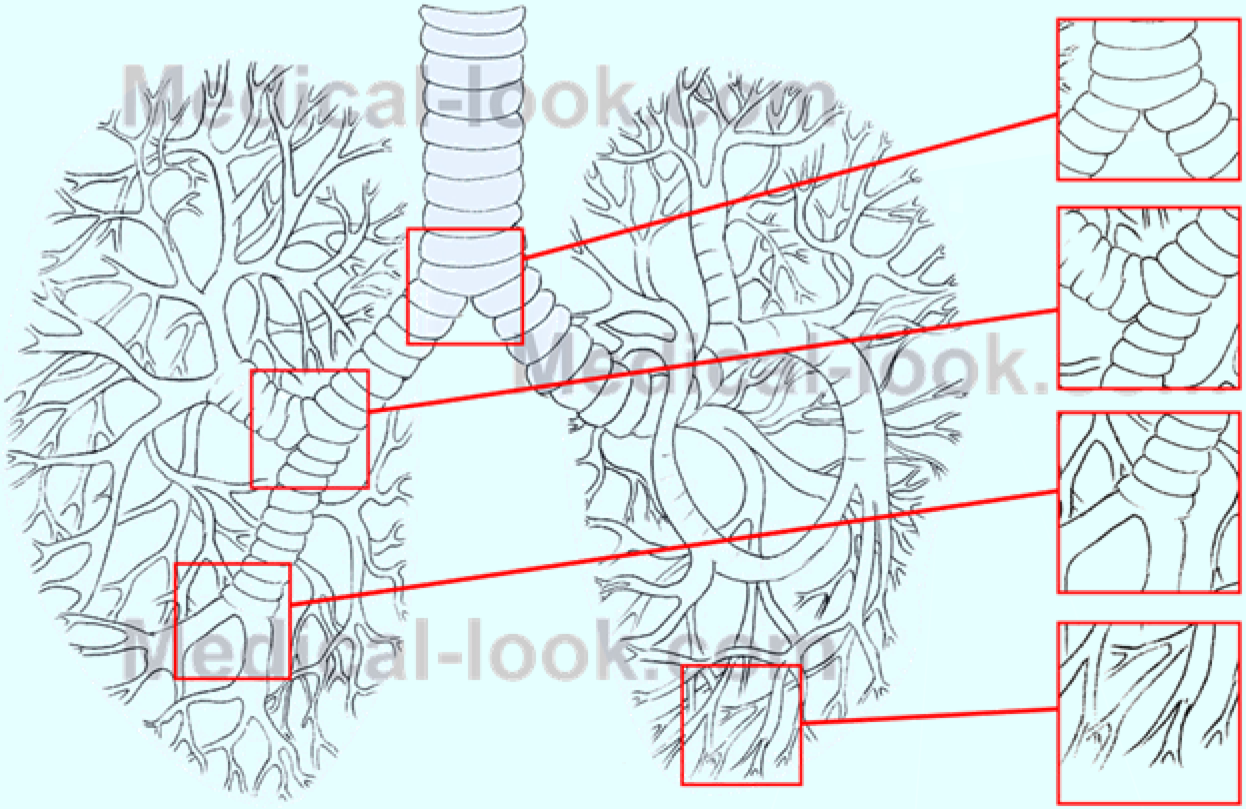
Fractal organization in human organs

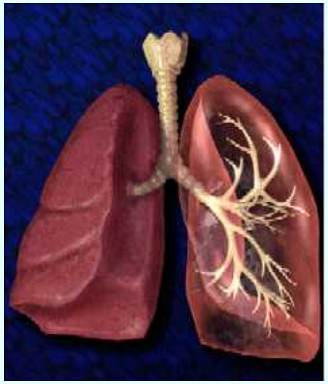


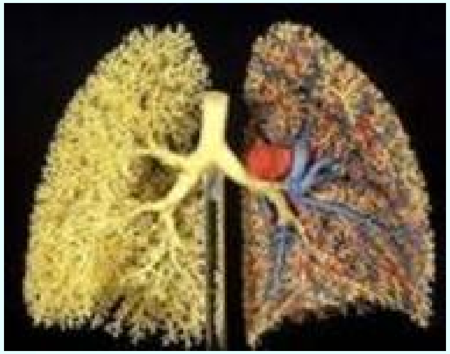
DNA

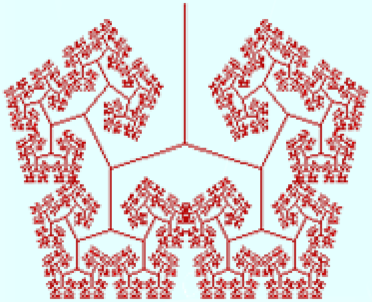


Bronquial tree









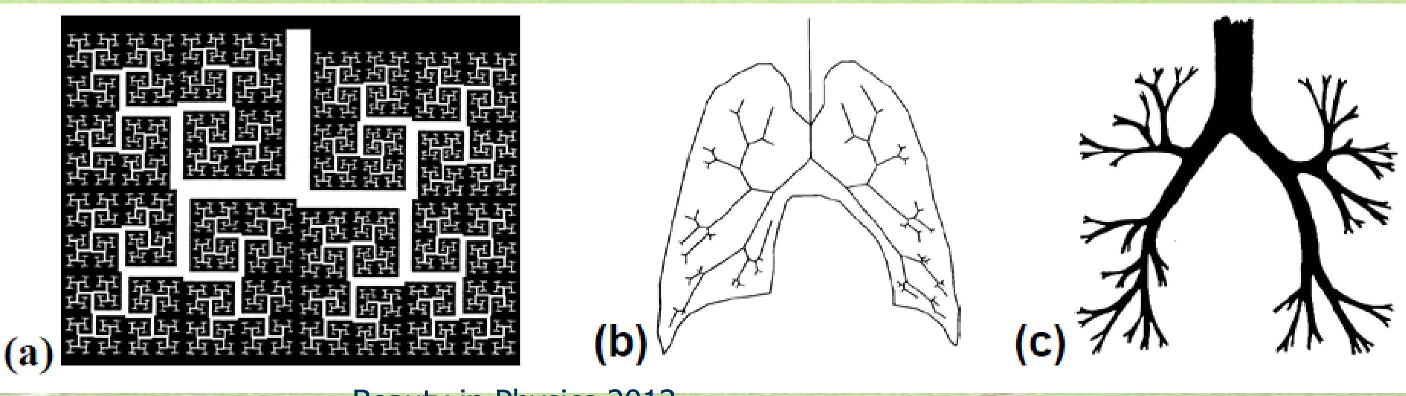
Fractal dimension δ~3 … Line approaching a volume

http://www.automatedtrader.net/glossary/List_of_fractals_by_Hausdorf

Biological Function of Fractals
Scaling Laws

Shape of leaves optimize the area for photosynthesis

Lungs maximize surface for gas. Surface can be as lkarge as a soccer field.



Blood Circulation

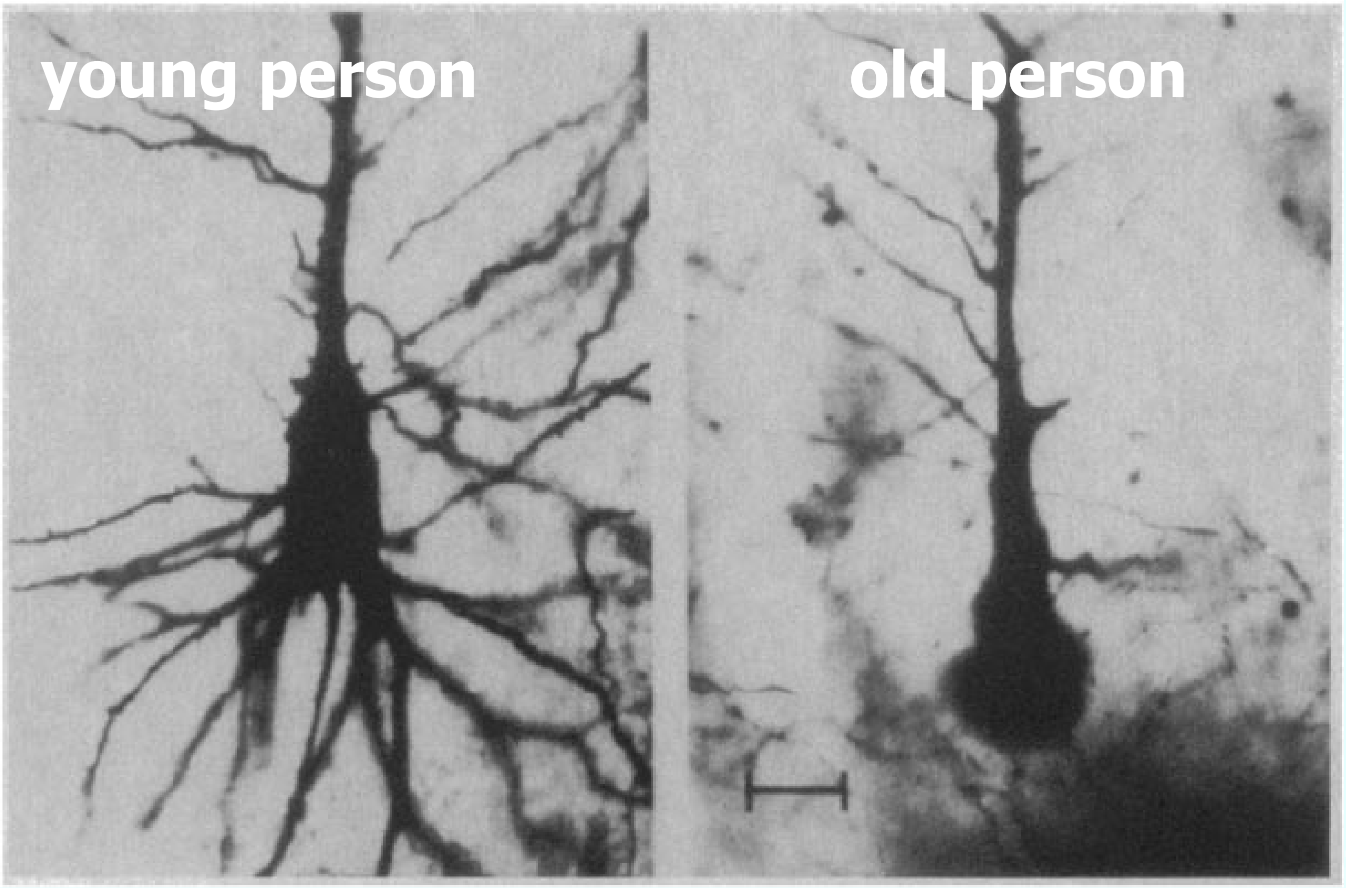
La auto-similitud como un c o de asemblaje

Fractal dimension
δ=2.7

Fractals in blood vessels
http://www.glimmerveen.nl/LE/Chaos.html

Korperwelten (Body Worlds)
Gunther von Hagens. *http://www.bodyworlds.com/en.html*

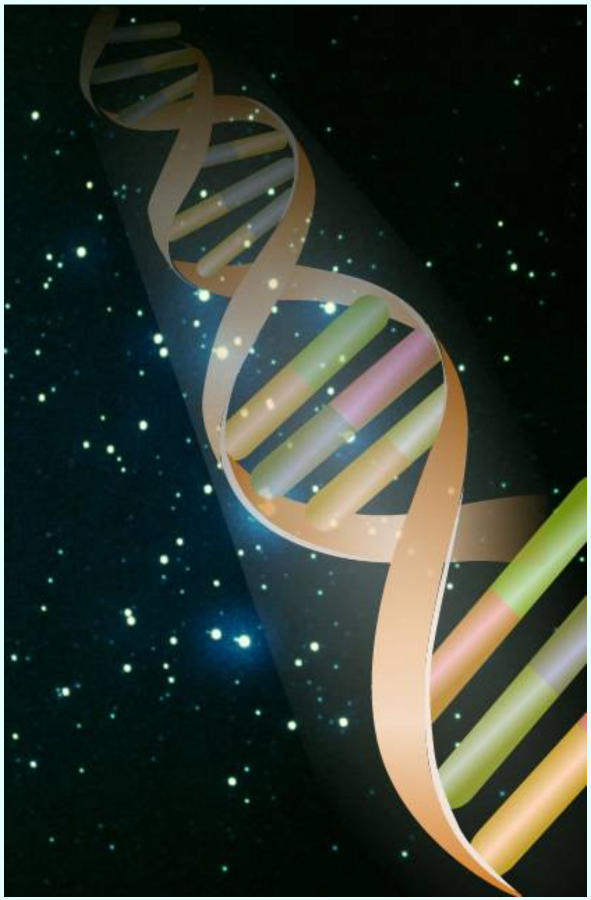
Loss of Fractality in Ageing Nervous System



Lipsitz & Goldberger, JAMA 267 (1992) 1806

Why Fractals? Self-similarity as an assembly code

100 000 genes



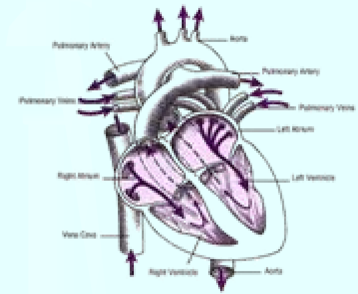
Repeated application of rules

DNA defines assembly rules

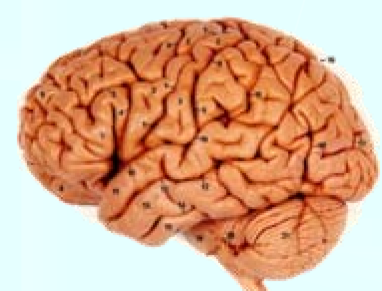
1) Economy
2) Stability aganst errors

Self-similar structures

1 000 000 blood vessels in the heart



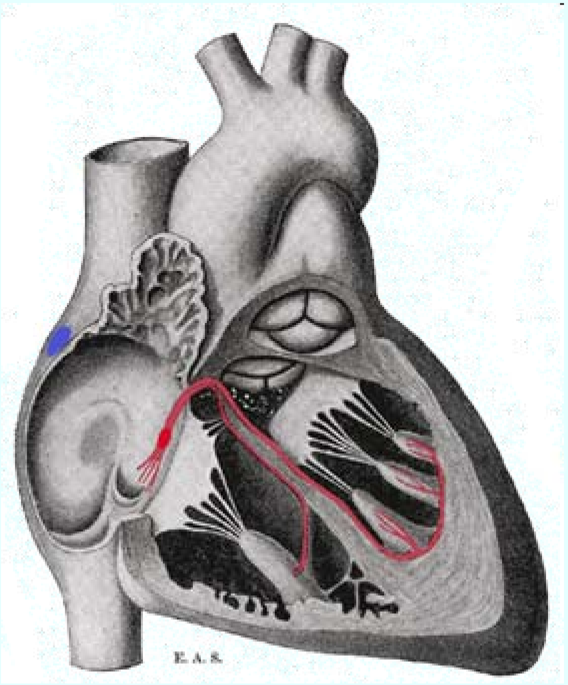
100 billion neurons in brain: networking

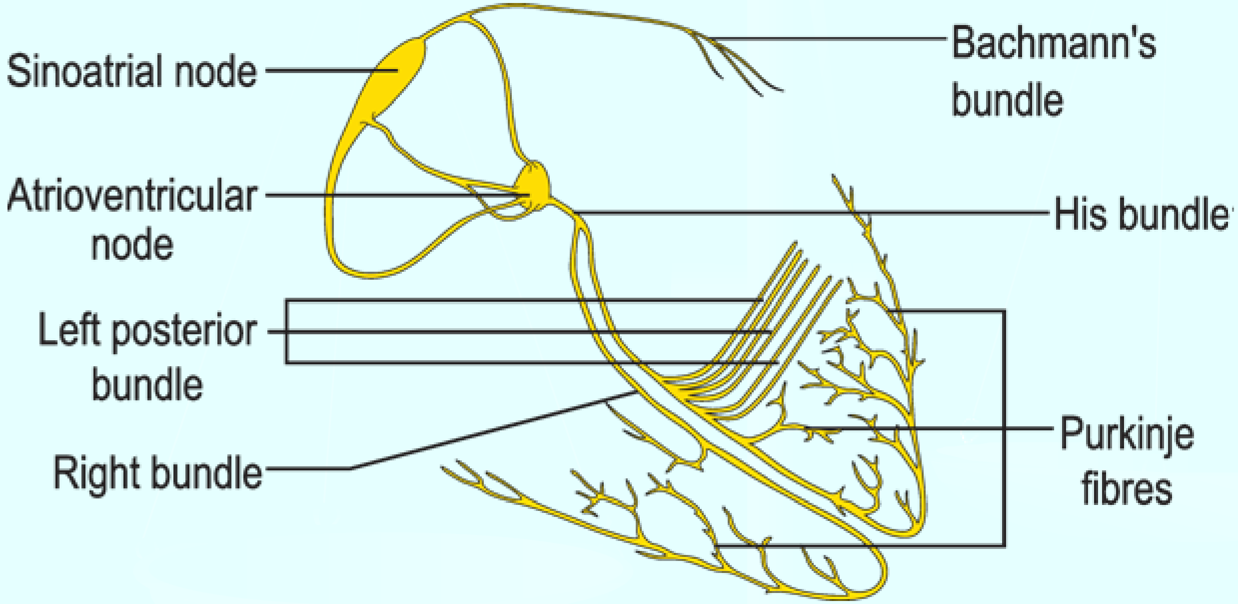


Larry S. Liebovitch
"Fractals and chaos simplified for the life sciences"

Redundancy and Health

Redundancy: repetitive structures at many scales

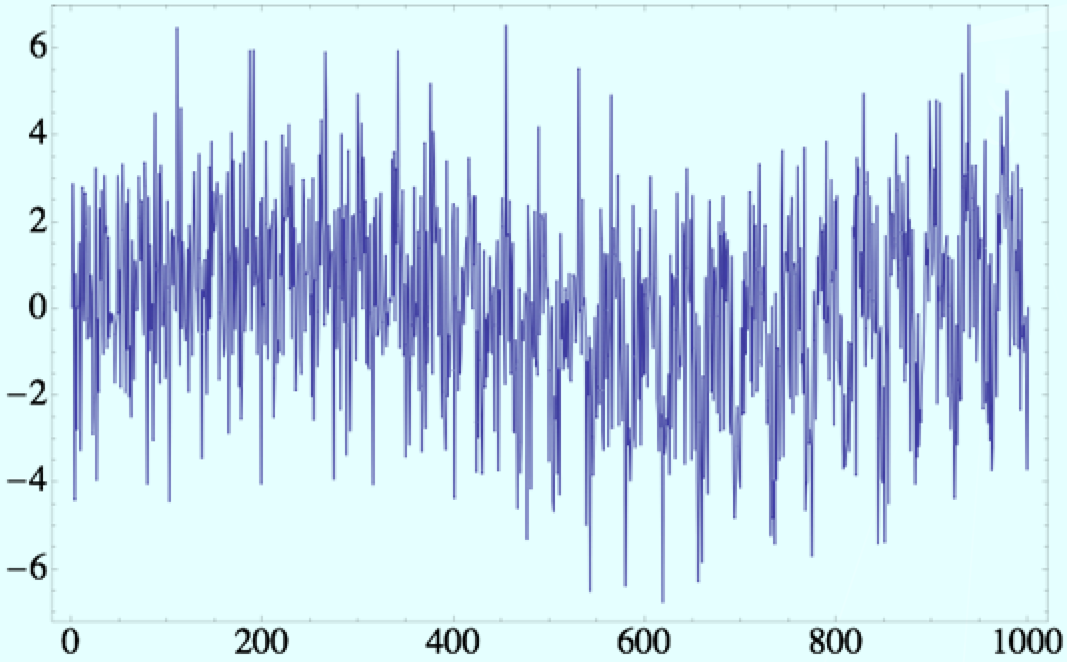




Goldberger et al., Sci. Am. 262 (1990) 42.
http://en.wikipedia.org/wiki/Bundle_of_His

How does this structure reflect itself in the time domain? Time Series

- Dynamic evolution of the system

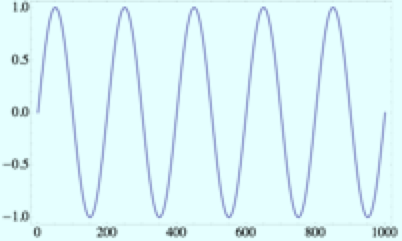


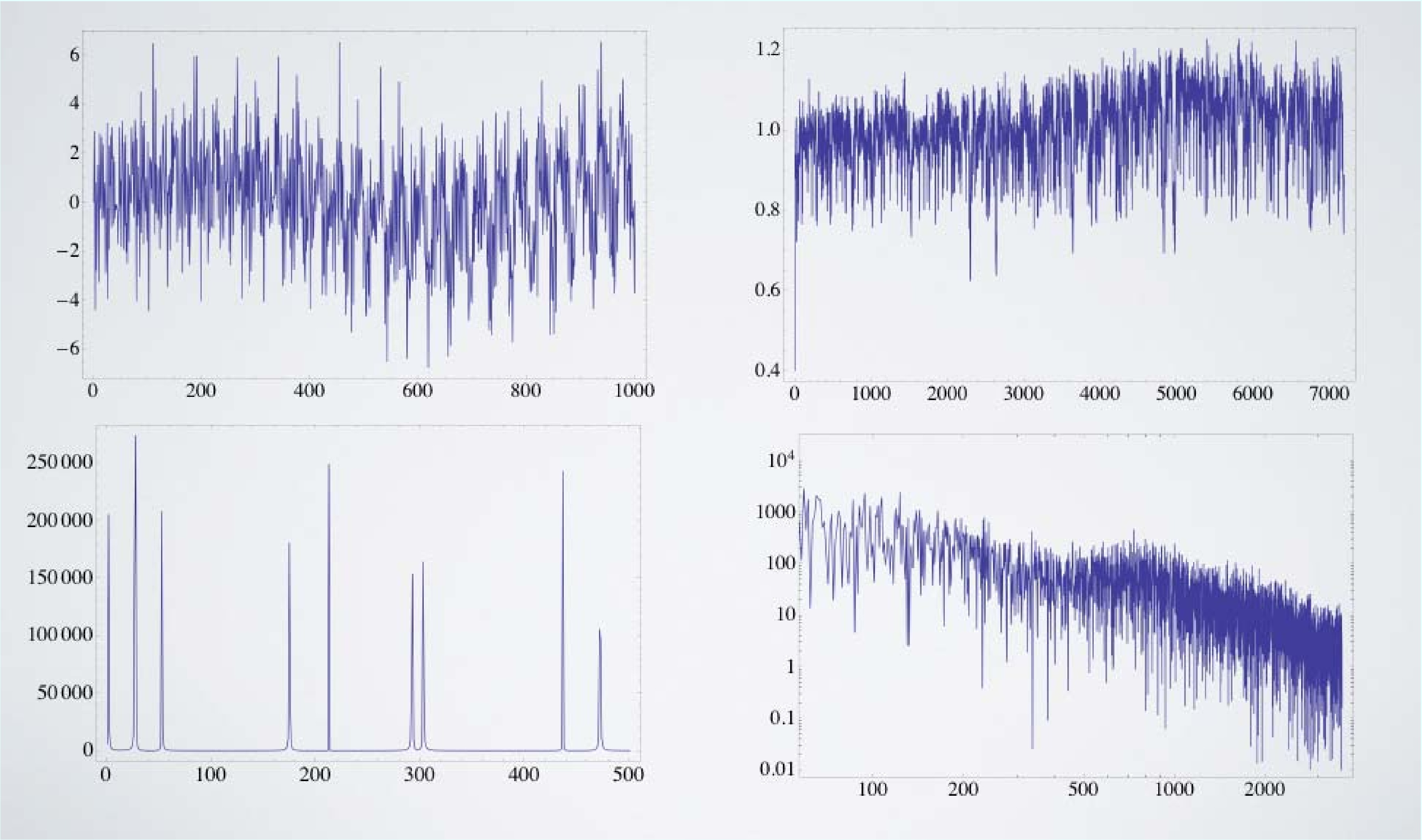
- For some systems is the only available information

-Correlated with the time-dependent state of the system

- Need to “listen” to the system in order to obtain information

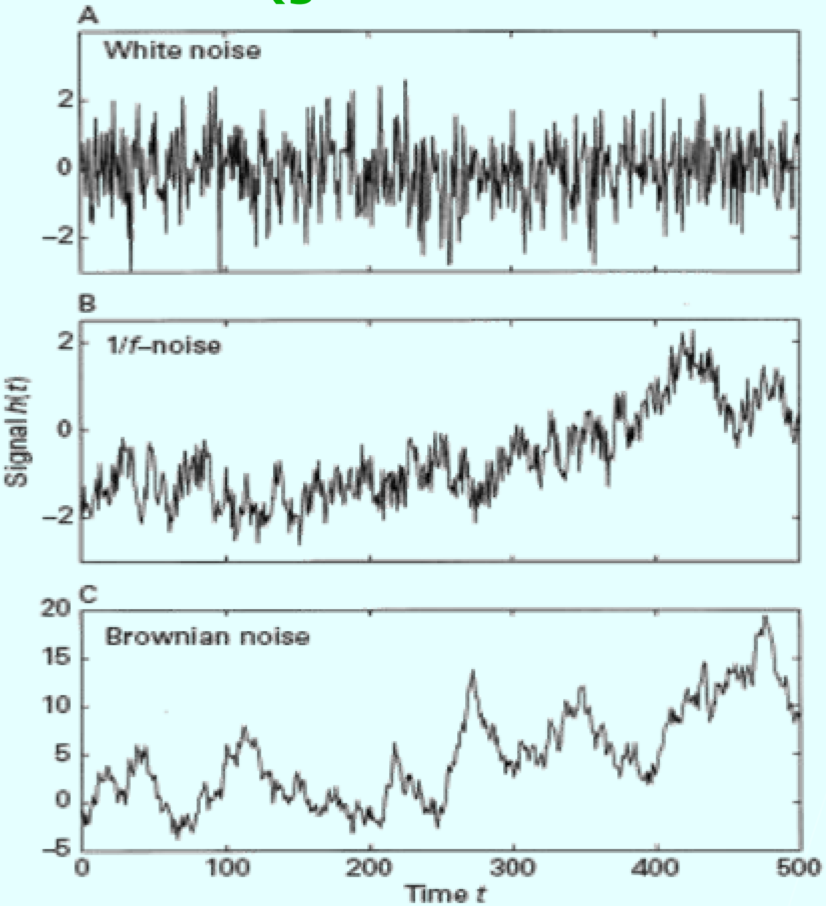
Fourier analysis



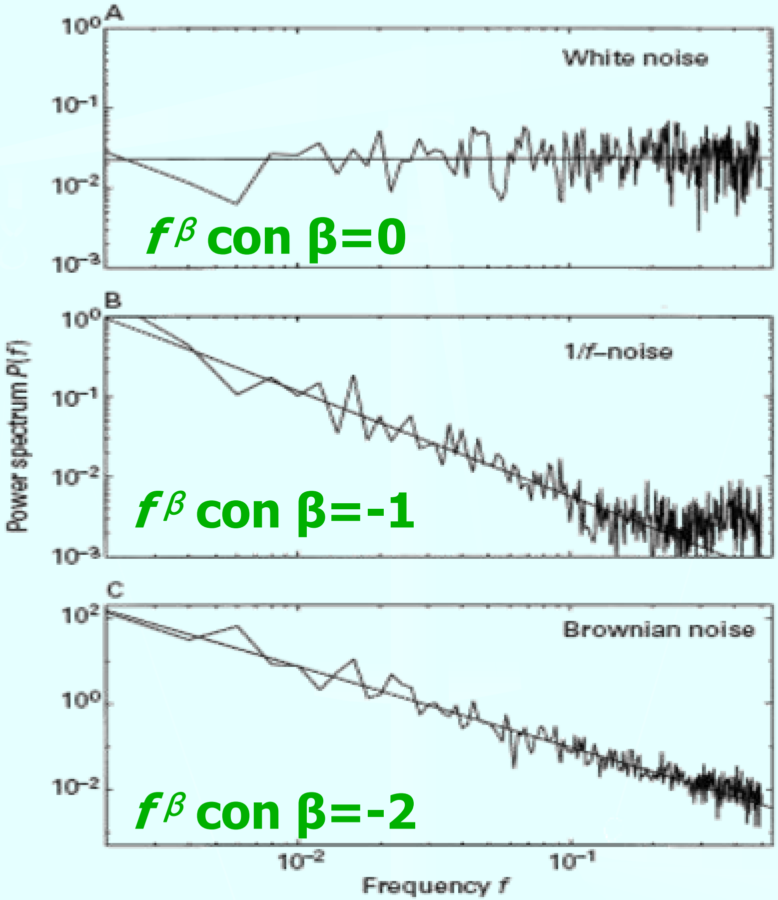


Spectral Analysis
of non-periodic correlated signals

Time Series(generic scale invariant noise)



Power Spectra



http://www.physionet.org/tutorials/fmnc/index.shtml

Gisiger, Biol. Rev. 76 (2001) 161.

Scale Invariance

- The auto-correlation function of a 1/f signal is scale independent, or: the auto-correlation function is a fractal.

$$F(\omega) = \int_{-\infty}^{\infty} f(t) e^{-j\omega t} dt$$

S = Power Spectrum

auto-correlation function

$$R_f(\tau) = \langle f(t) f(t+\tau) \rangle = \frac{1}{2\pi} \int_o^{\infty} S_f(\omega) e^{j\omega t} d\omega.$$

Special Case: $S_f(f) = 1/f$

$$R_f(\alpha\tau) = F^{-1}(1/f) = R_f(\tau)$$

MAIN RESULT: 1/f implies *autocorrelation* scale invariance

Time series analysis

The Royal Society

The empirical mode decomposition and the Hilbert spectrum for nonlinear and non-stationary time series analysis

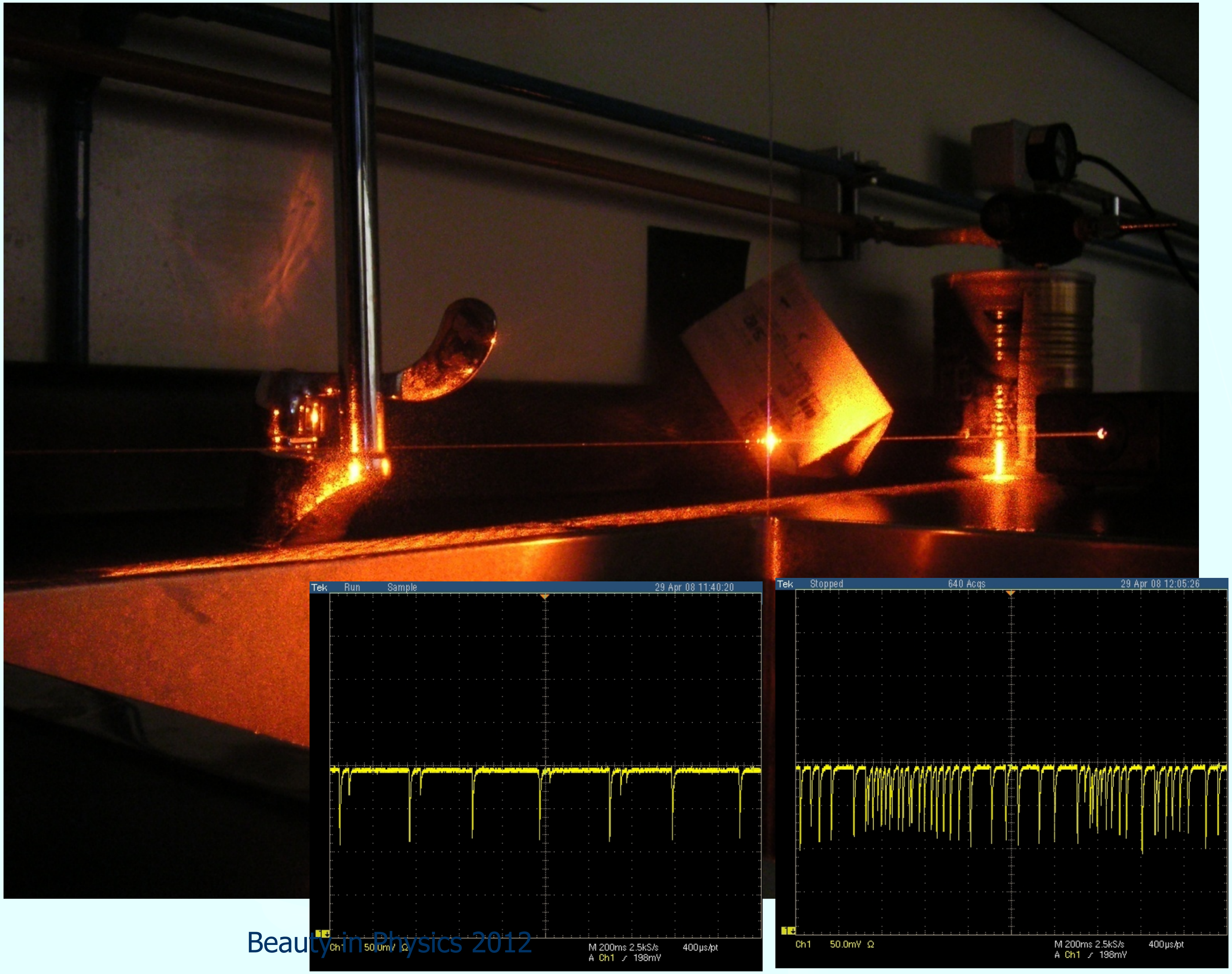
By Norden E. Huang[1], Zheng Shen[2], Steven R. Long[3], Manli C. Wu[4], Hsing H. Shih[5], Quanan Zheng[6], Nai-Chyuan Yen[7], Chi Chao Tung[8] and Henry H. Liu[9]

Experimental data is the link between natural phenomena and the mathematical models that we use to describe such phenomena.

Fourier → Empirical Mode Decomposition

Motivation: Dripping Faucet and phase transition

periodic – chaotic - continuous



Dripping Faucet

T.J.P. Penna y P.M.C. de Oliveira, PRE52 (1995) R2168.

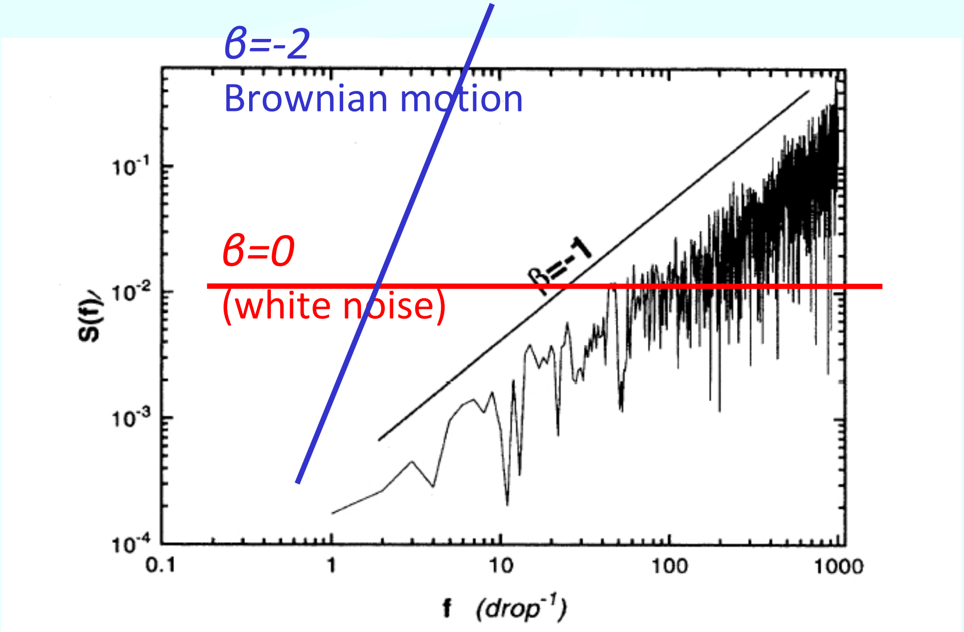
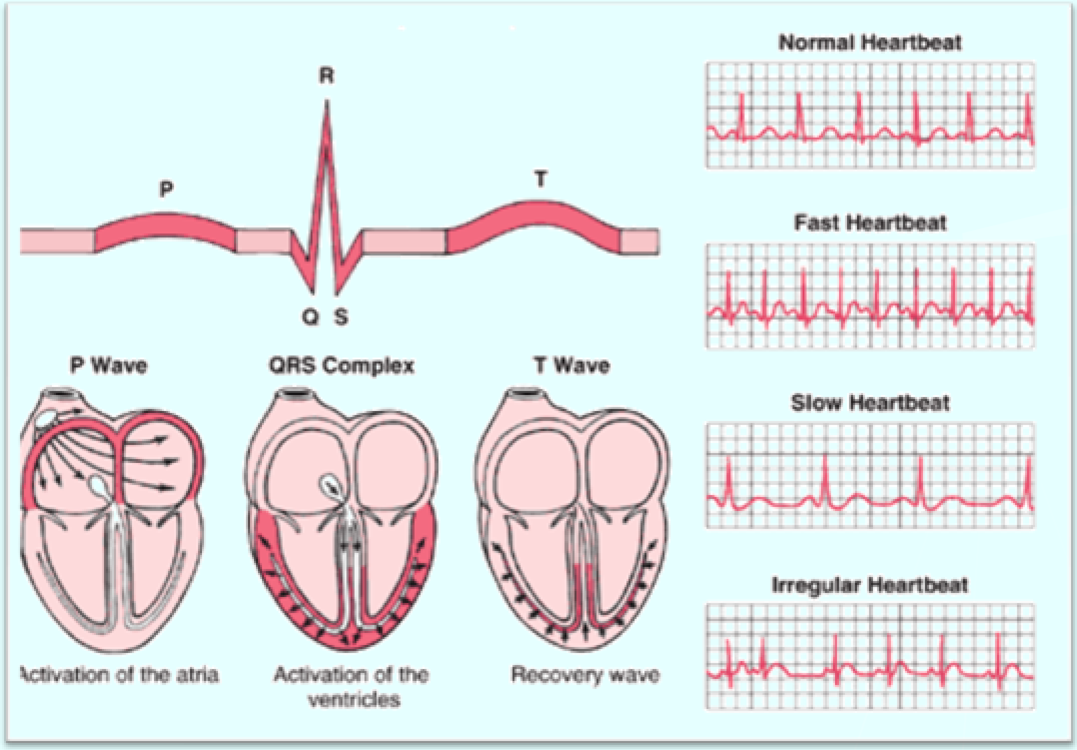


FIG. 4. Power spectra $S(f)$ for the interval increments for the time series presented in Fig. 1. A straight line corresponding to the $\beta=-1$ curve is presented for comparison.

Physiological Dynamics: Time Series
ECG: What can we find out about the heart?



Time Series

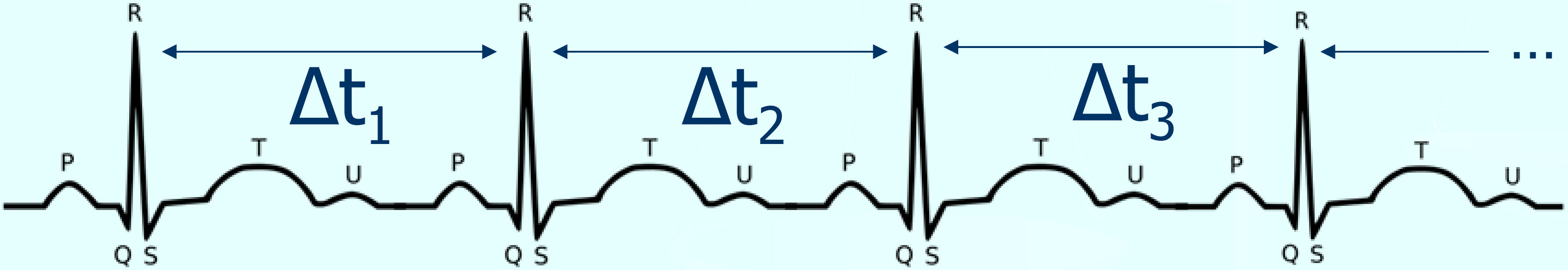
Intervals RR

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

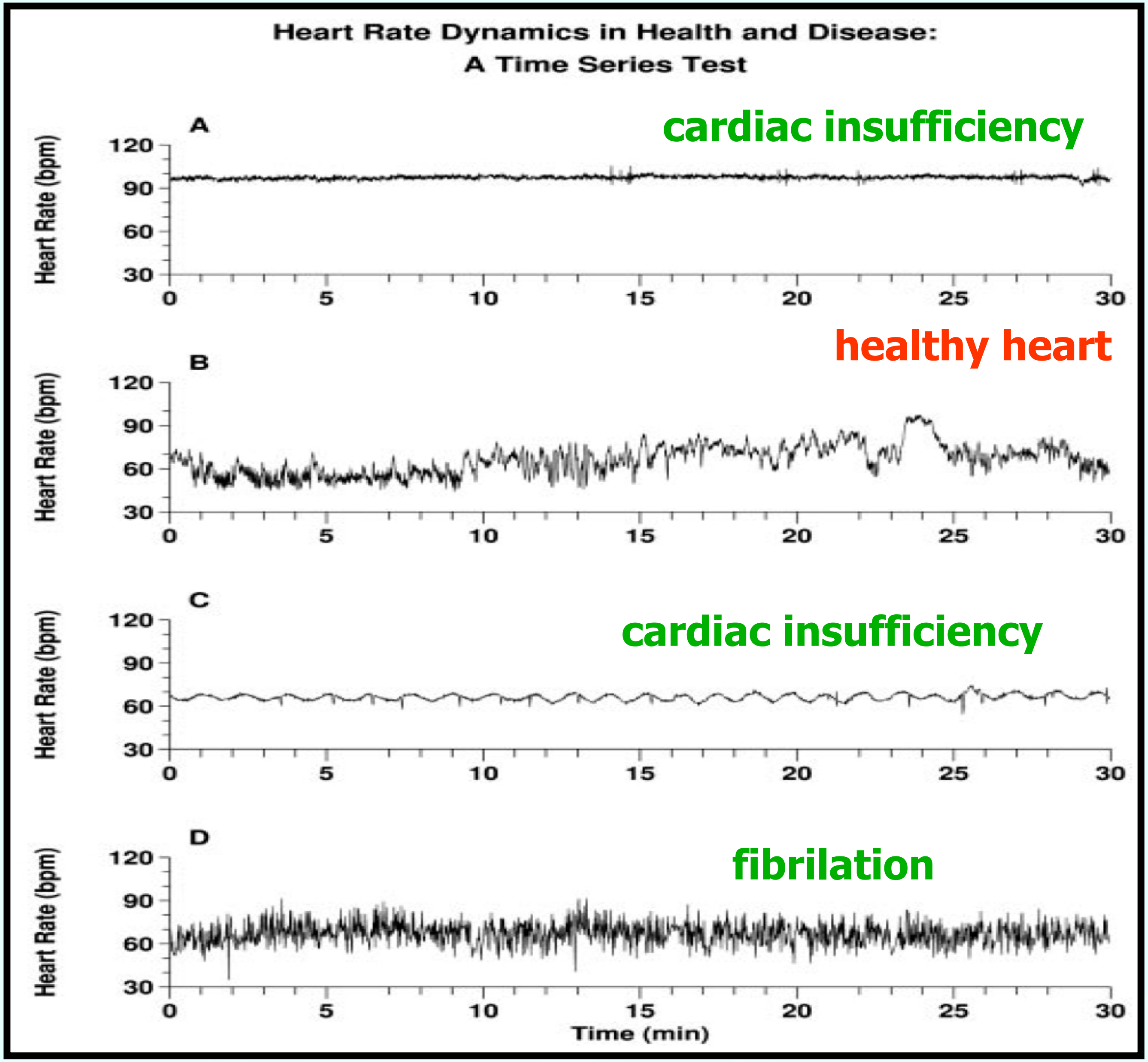
Fluctuations

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

$\overline{\Delta t}$



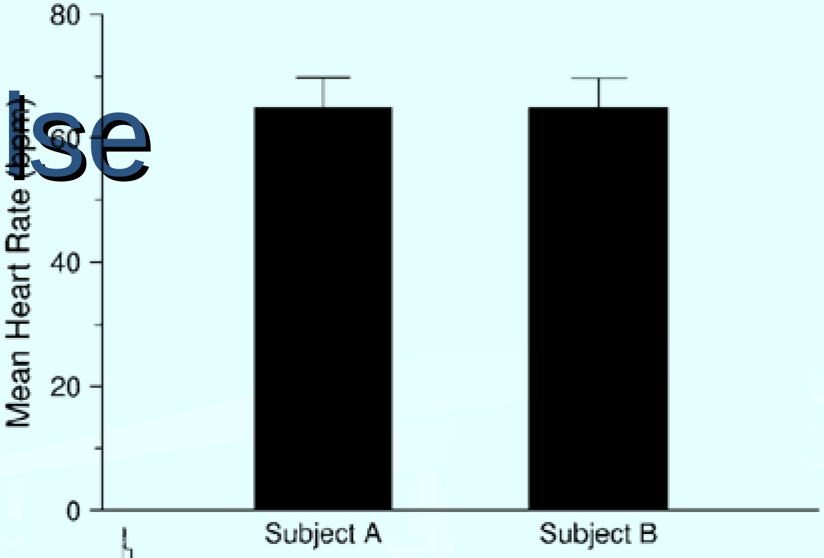
Heart-rate fluctuation time series

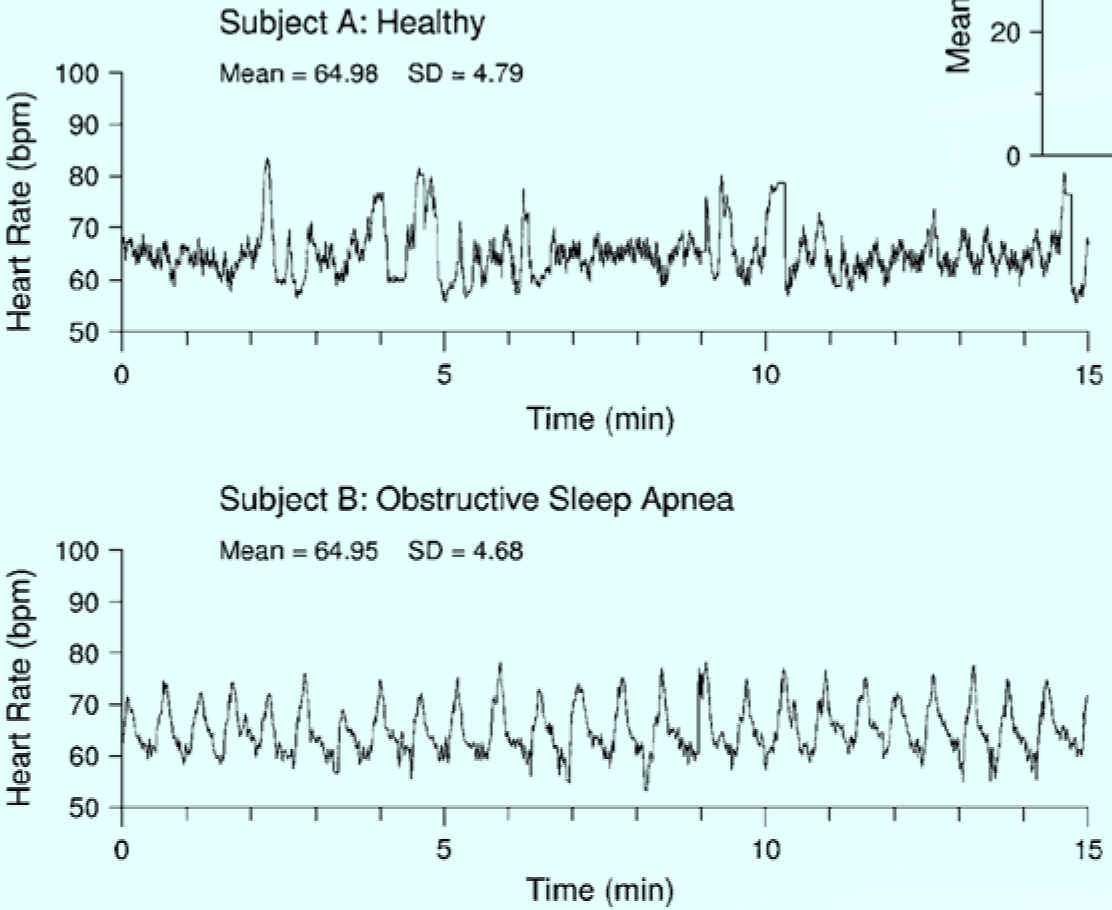


http://reylab.bidmc.harvard.edu/people/Ary.html

Goldberger et al., PNAS 99 (2002) 2466

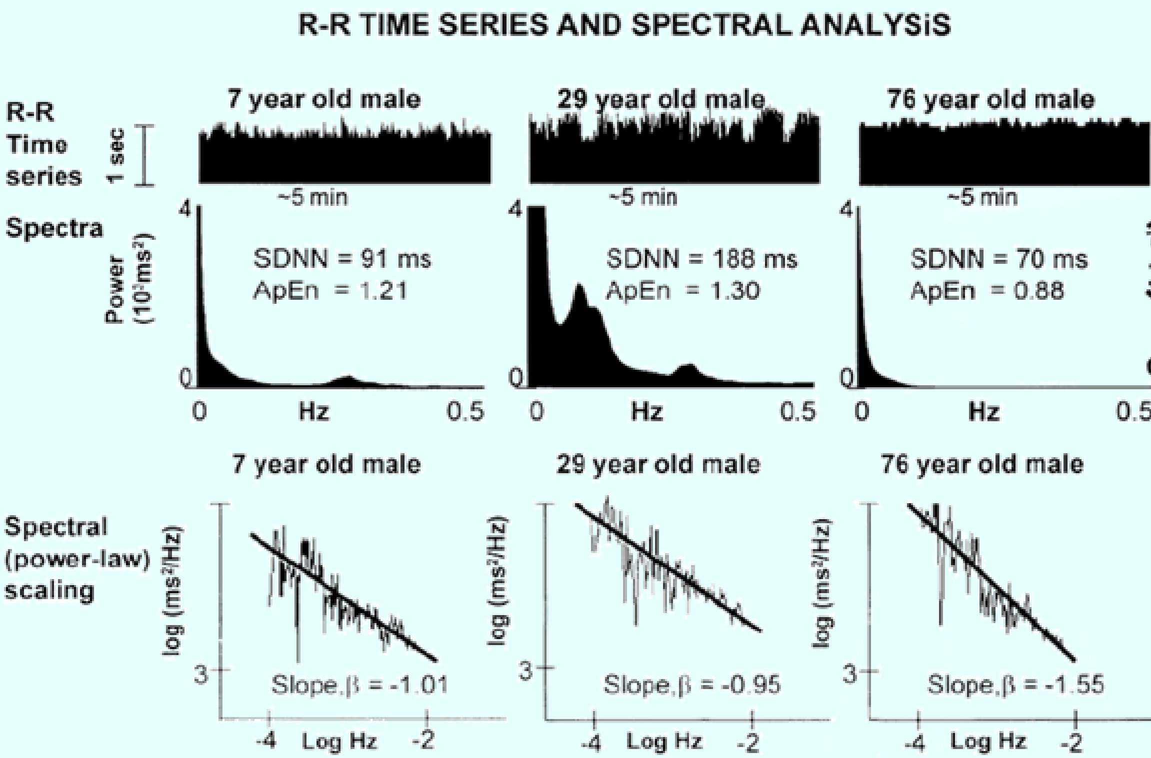
Measuring the pulse

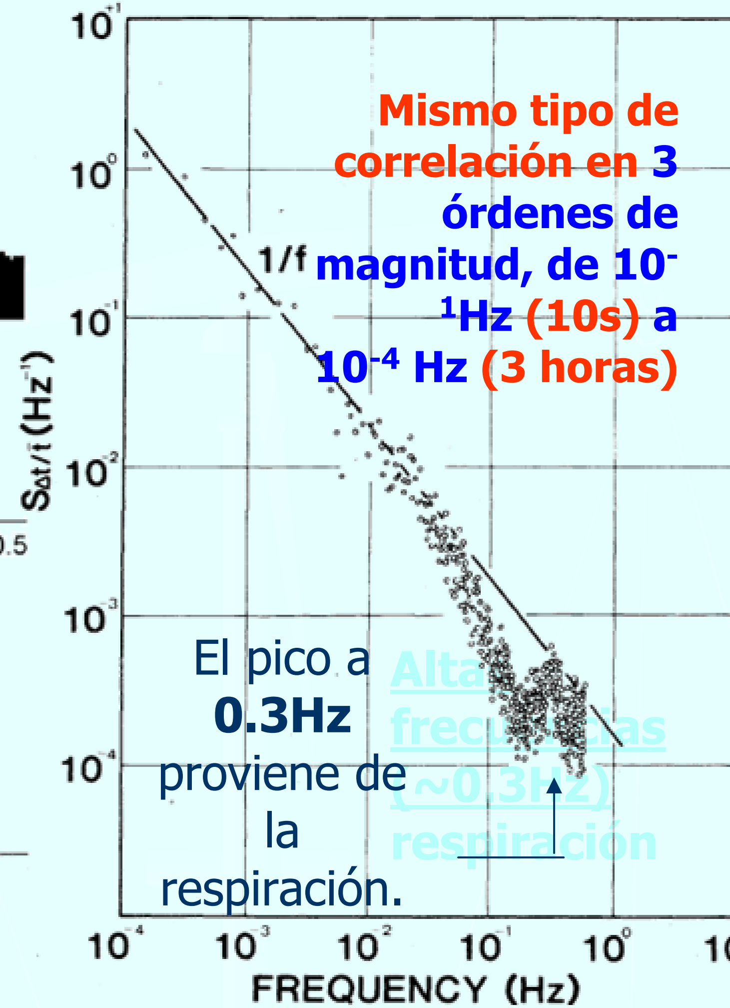




Goldberger, Proc. Am. Thor. Soc. 3 (2006) 467.

Illness and Treatment





Mismo tipo de correlación en 3 órdenes de magnitud, de 10^{-1}Hz (10s) a 10^{-4} Hz (3 horas)

El pico a **0.3Hz** proviene de la respiración.

"harmonious" mix of different time-scale frequencies

Pikkujämsä et al., Circulation 100 (1999) 393.

Exercise and criticality

Physical activity after 4 week control and six-week resistance training.

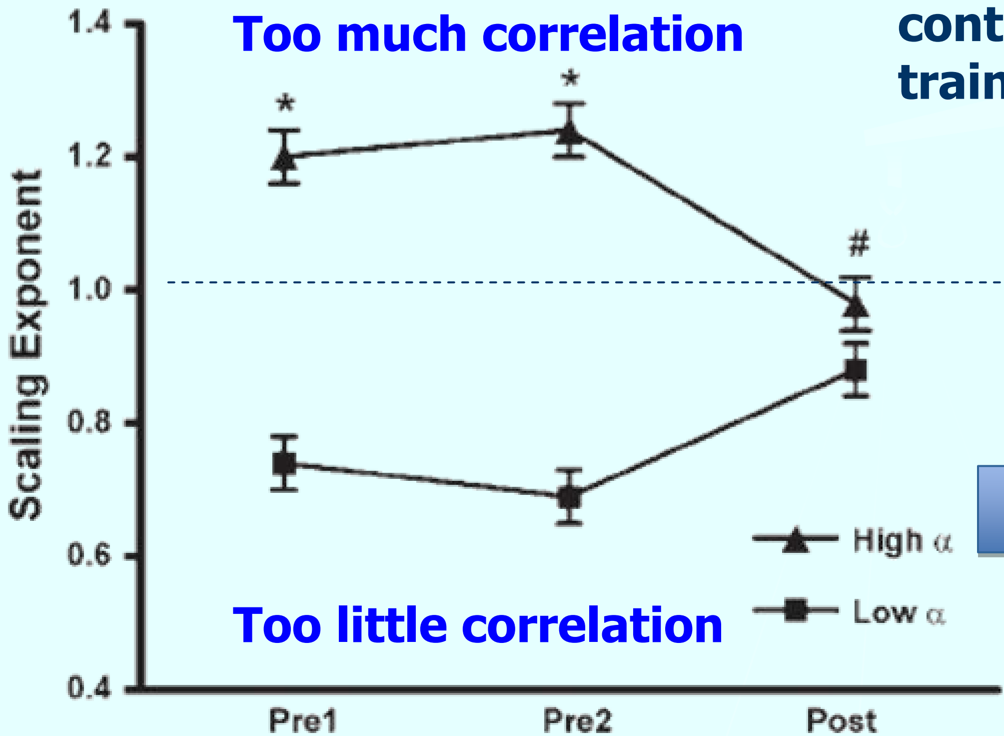


Fig. 1. Short-term scaling exponent (α_s) at baseline (Pre1), following a 4-wk time control period (Pre2) and following 6 wk of resistance training in men with low α_s and high α_s. *Significant group differences ($P < 0.05$). #Significant group × time interaction ($P < 0.05$).

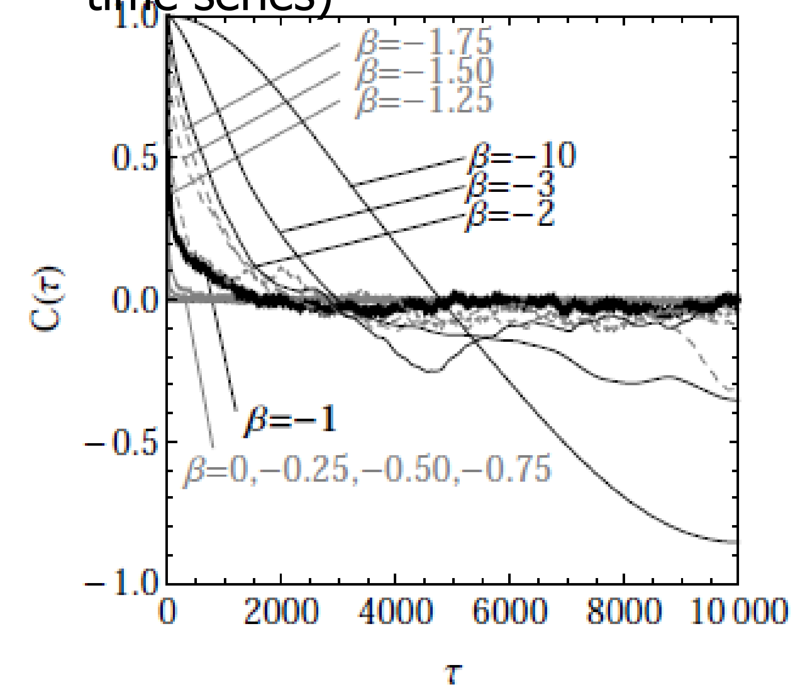
1/f Noise
Critical State

Can we detect obstructed hearts?

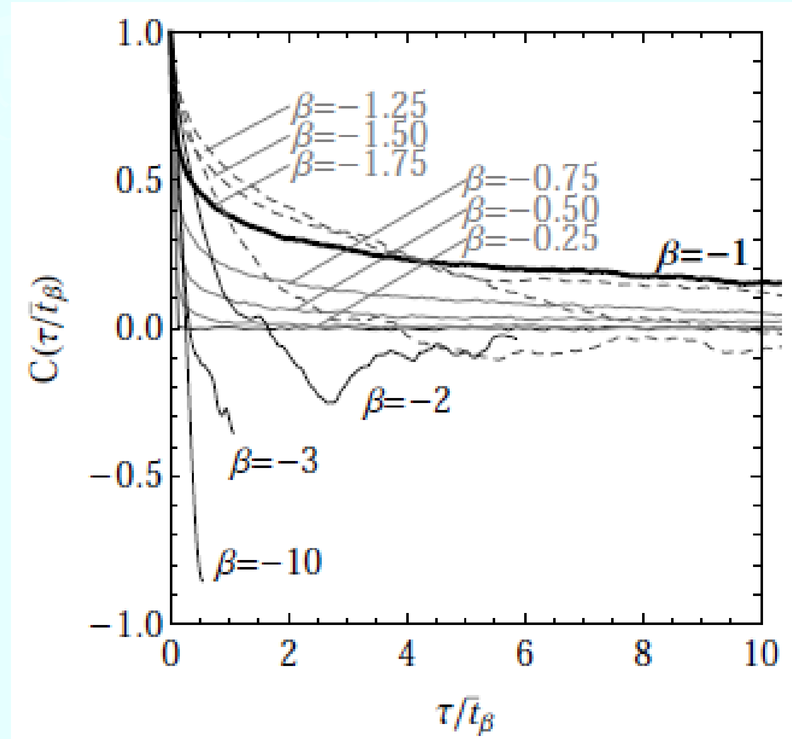
Heffernan,
J. Appl. Physiol. 105 (2008) 109

Why 1/f? Fractal time series
Correlation range (memory)

- Autocorrelation function (for linear and stationary time series)
- Mutual information function (also for non-linear and non-stationary time series)



(a) Tiempo absoluto τ



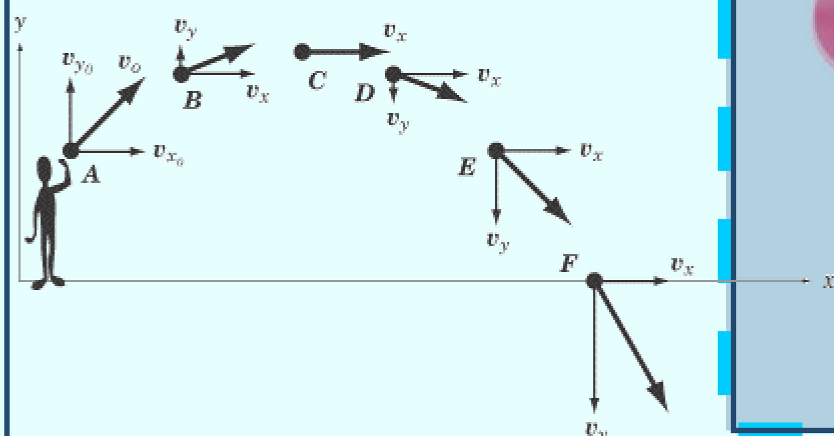
(b) Tiempo propio τ/ ⟨t⟩

R. Fossion et al., AIP Conf. Proc. 1323 (2010) 7

General Considerations: Order, Disorder and Criticality

Order determinism

En el espacio y el tiempo
p.ej. Trayectoria de proyectil



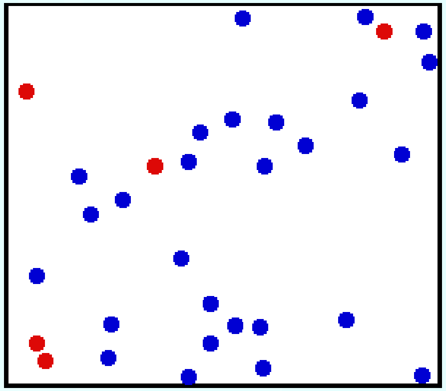
Precise predictions

Frontera

Complexity
Criticality

Disorder randomness

En el espacio y el tiempo
p.ej. Moléculas de un gas



statistics

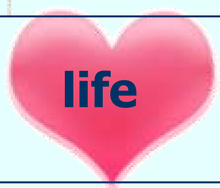
http://en.wikipedia.org/wiki/Kinetic_theory

TimeDomain

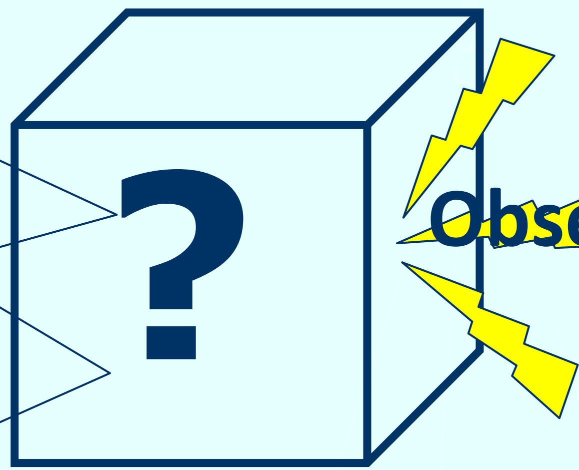
Black Box

mechanism

Order (regularity)
i.e. Cucu Clock



disorder (random)
i.e. radioactive decay



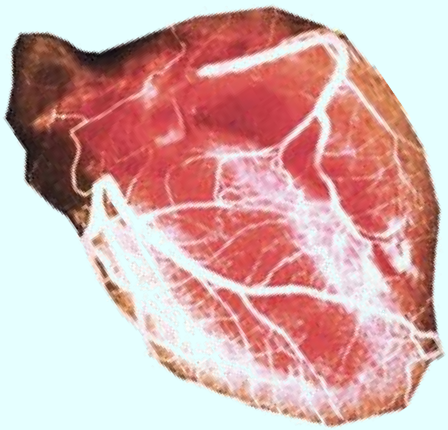
Observable

Random process

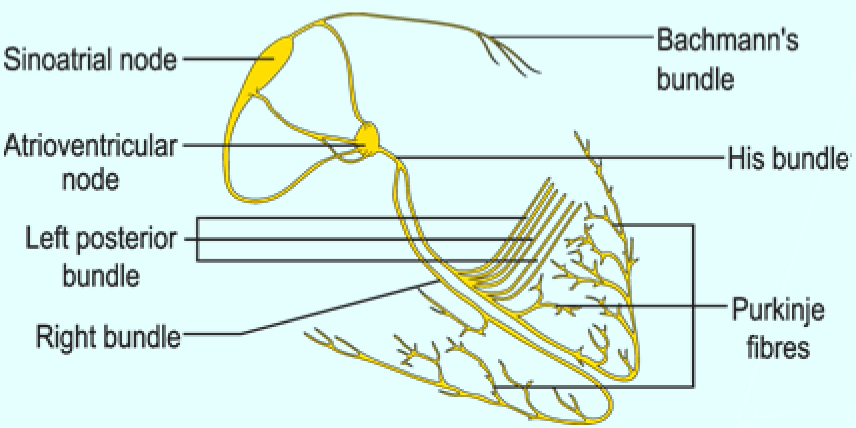
Criticality and Chao

Deterministic process

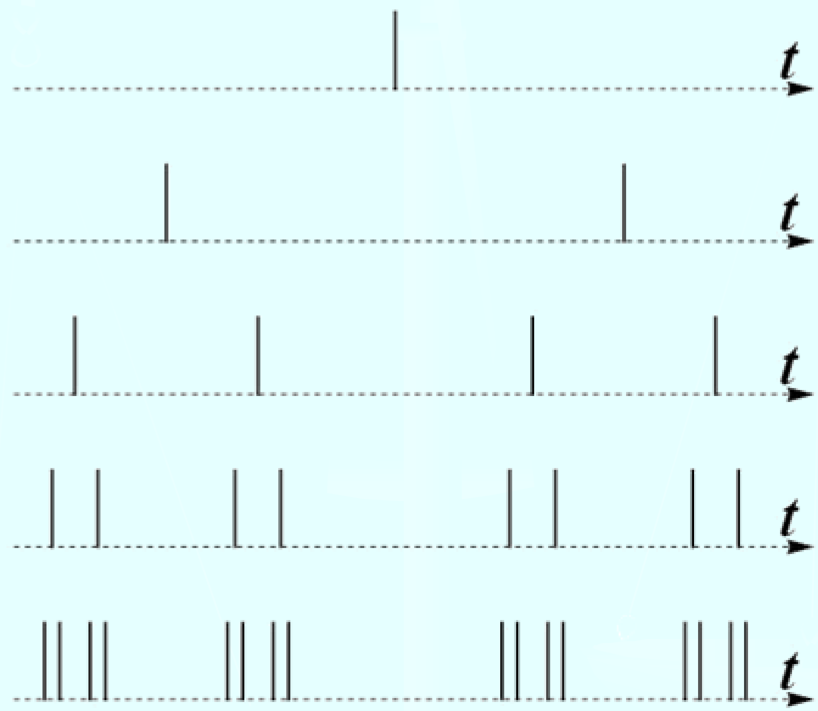
Can spacial fractality produce time domain fractality?



Fractal electrical network

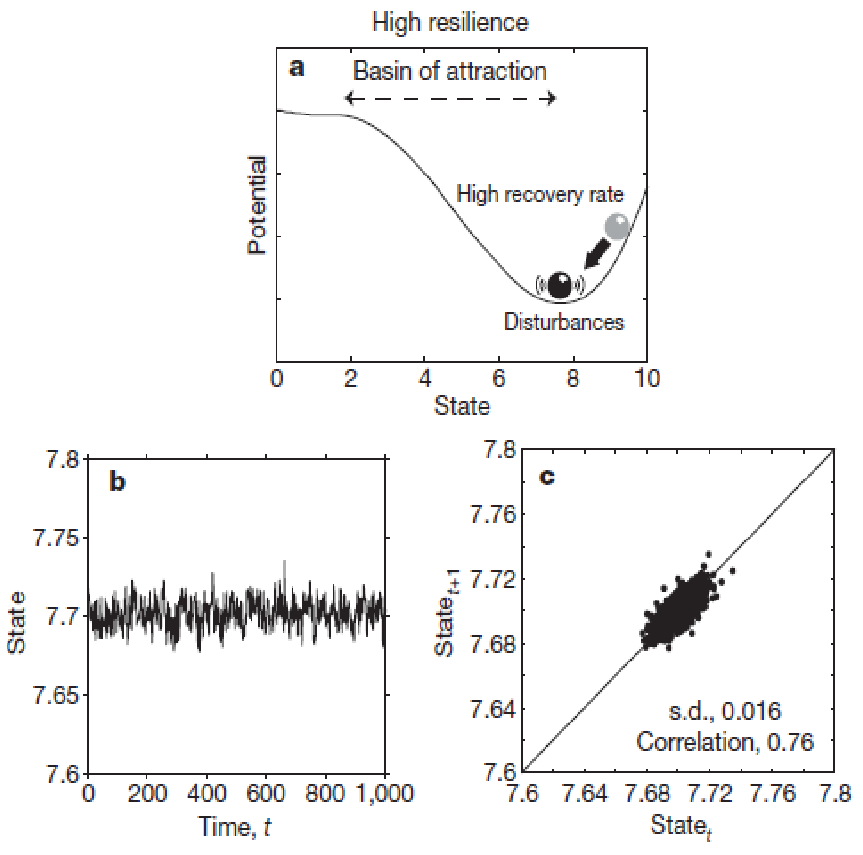


Electrical Pulse subdivides at bifurcations in a fractal way

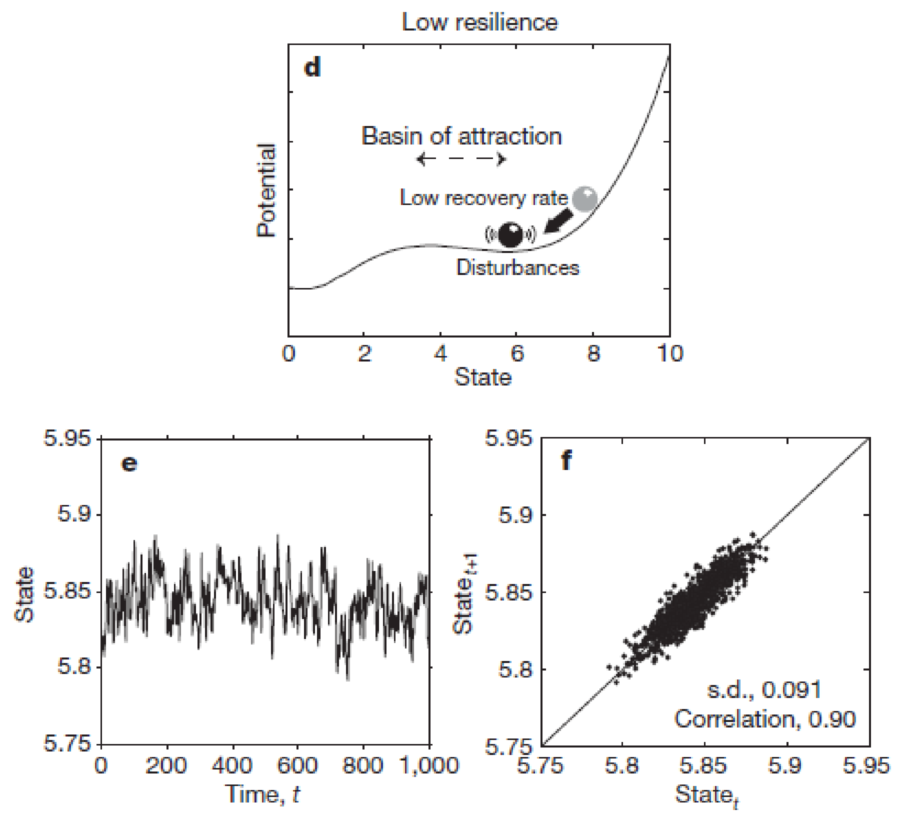


Dynamics: Phase transitions and time series.
Is the heart in a critical state? Optimal response.

Pure phase A
(far from critical point)



Critical point
(between phases A and B)

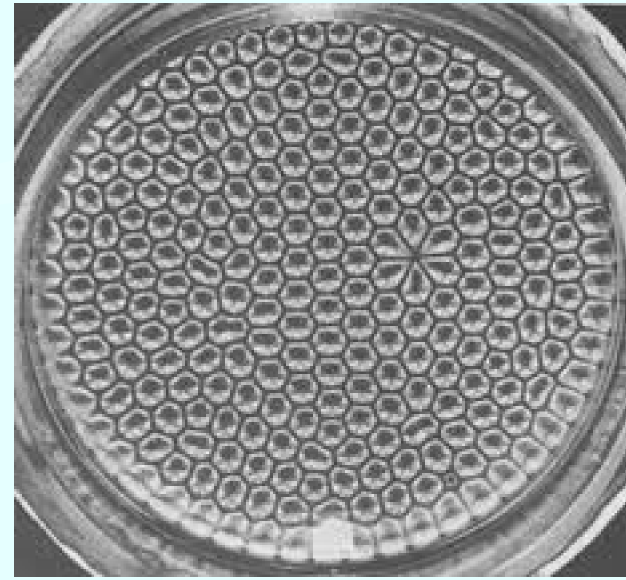


Early-warning signals for critical transitions
Marten Scheffer, Nature Vol 461, 3 September 2009

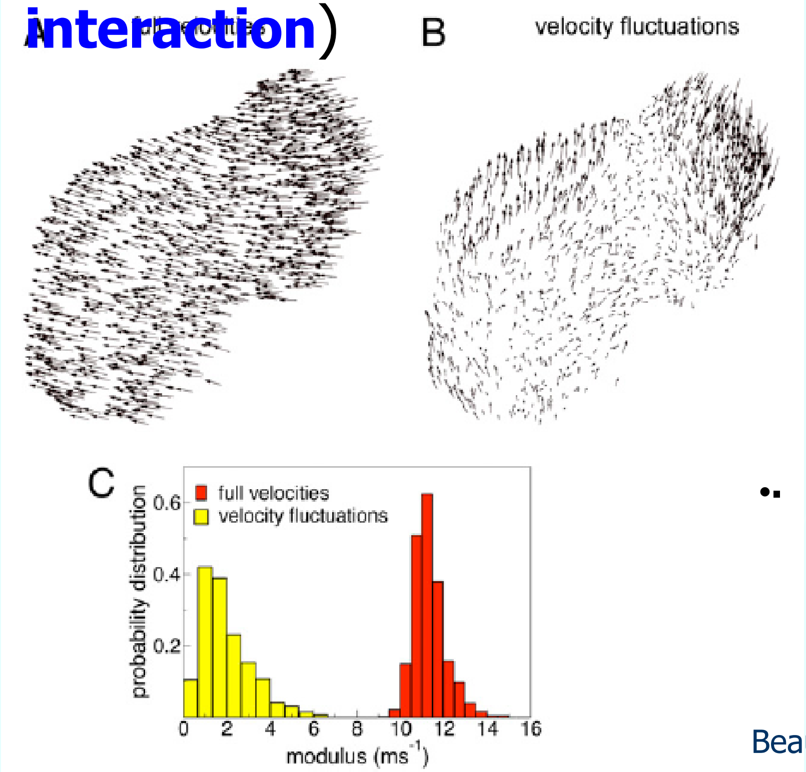
Long-range correlations: bubbles and stirling flocks

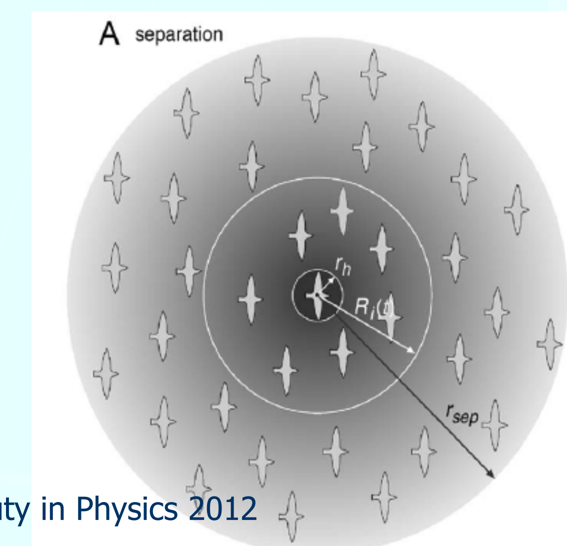
Bénard Cells in liquids.

How can **large flocks** of thousands of individual birds arise (**long-range correlations**) when birds only communicate with up to 7 of their **nearest neighbours** (**short-ranged bird-bird interaction**)



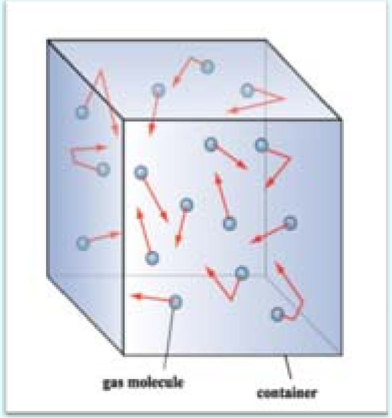
Bénard Cells





Self-organization

criticality in living systems



Critical region

"mean" between extremes

Dynamic system

Phase A

0% copying from neighbours

100% free will

"Ideal gas of random bird-particles"

Phase B

100% copying from neighbours

0% free will

"Flying brick (rigid object)"

X X X

Bird-bird Interaction

(copy from neighbours)

A practical endeavor: Early-warning signals

*"... Complex dynamical systems, ranging from **ecosystems** to **financial markets** and the **climate**, can have tipping points at which a sudden shift to a contrasting dynamical regime may occur.*
generic early-warning signals *may indicate for a wide class of systems if a critical threshold is approaching... "*

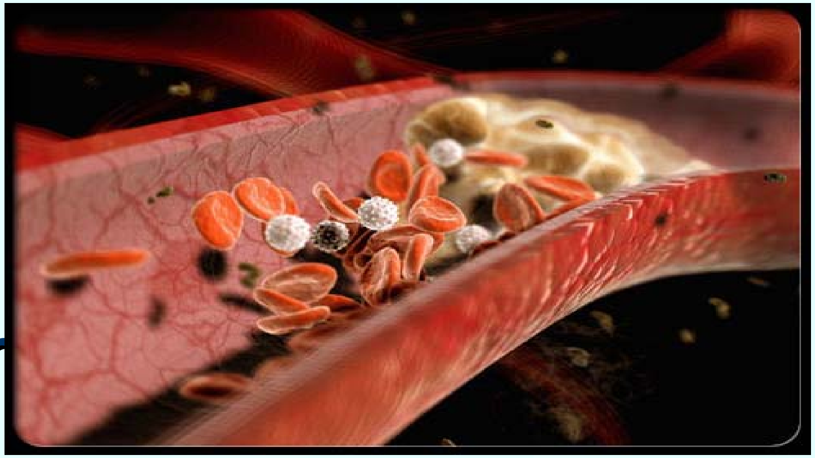
NATURE CLIMATE CHANGE | REVIEW
Early warning of climate tipping points
Timothy M. Lenton
Nature Climate Change 1, 201–209 (2011)1

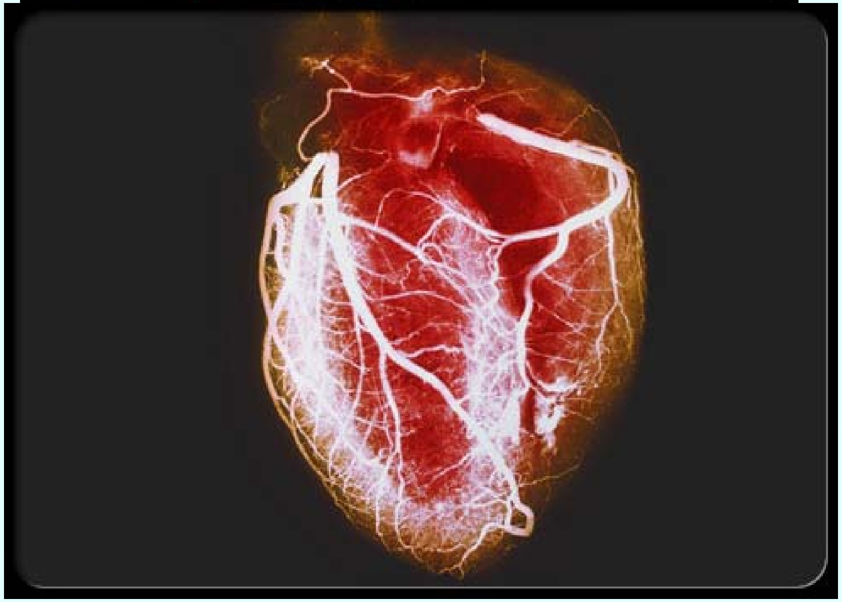
PLOS Computational Biology
Early Warning Signals for Critical Transitions: A Generalized Modeling Approach
Steven J. Lade*,

Early-warning signals

- **Critical slowing down**
- **Increase in autocorrelation strength**
- **Increased variance**
- **Increased fluctuation**
- **Flickering**

- **POWER LAWS: Increase in autocorrelation range (memory)**





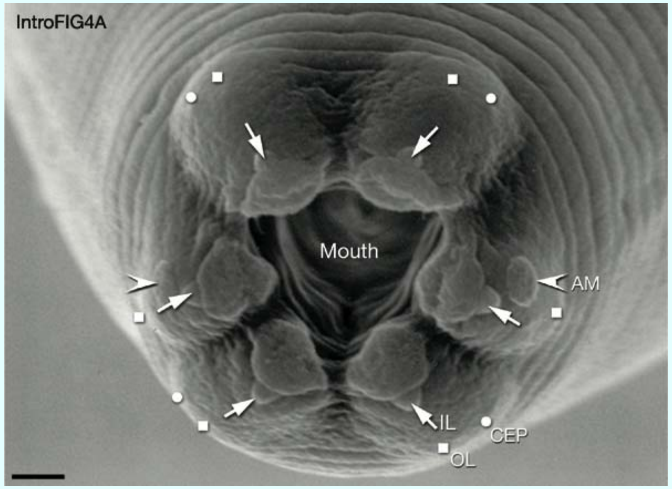
AN EXAMPLE:
Obstruction of the heart arteries: Early warning.

=>Transition to a high pressure regime of the heart.

Project with National Institutes of Cardiology and Geriatrics.
Fragility and Ageing: Marie Curie Project.

A simpler ageing model: Fragility in C Elegans

http://en.wikipedia.org/wiki/Caenorhabditis



http://shirleywho.wordpress.com/2008/09/21/departmental-retreats-academia-with-a-twist-of-karaoke/

http://www.wormatlas.org/ver1/handbook/anatomyintro/anatomyintro.htm

Time series of pharinx area of C elegans: pixel analysis

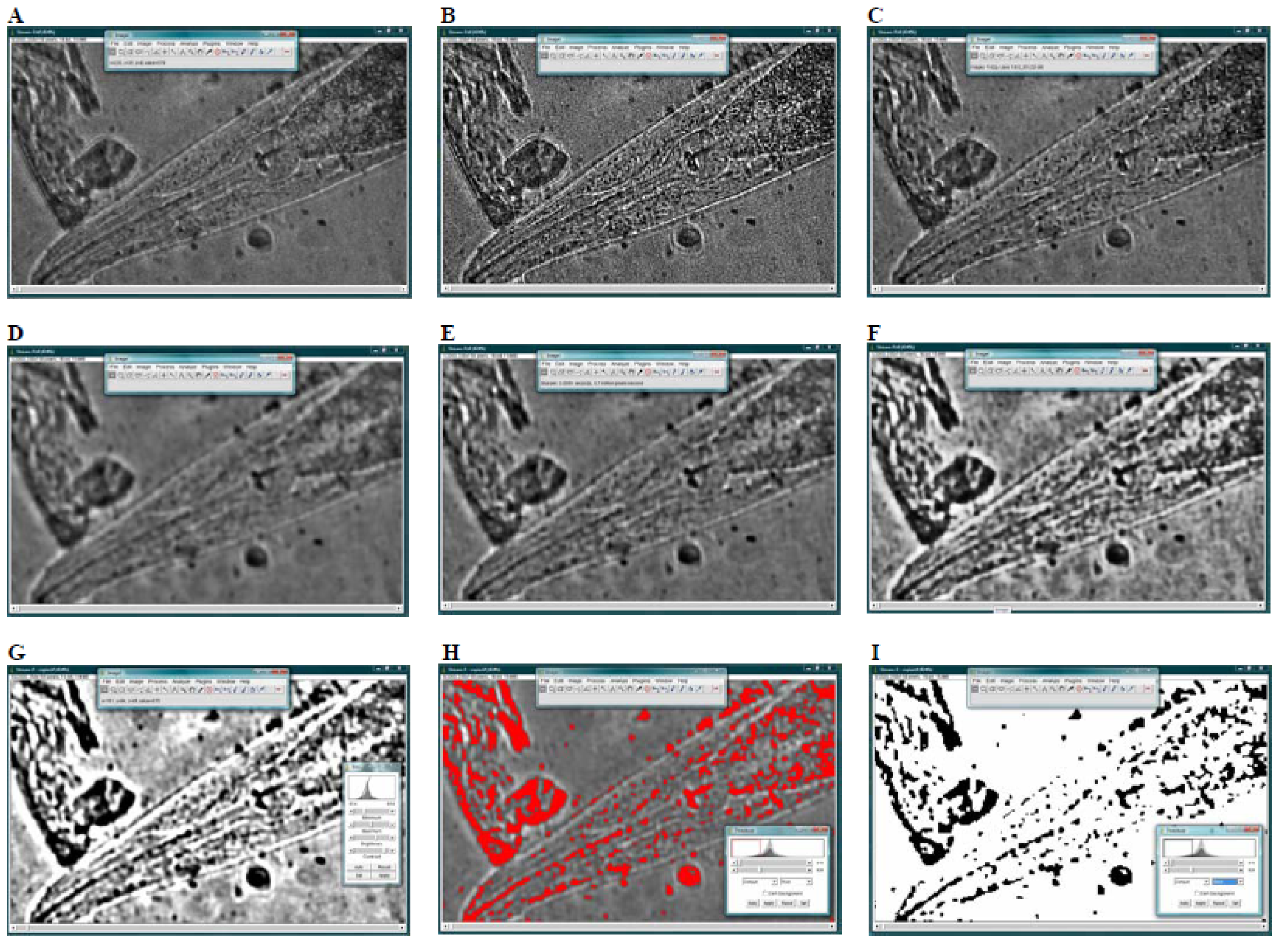


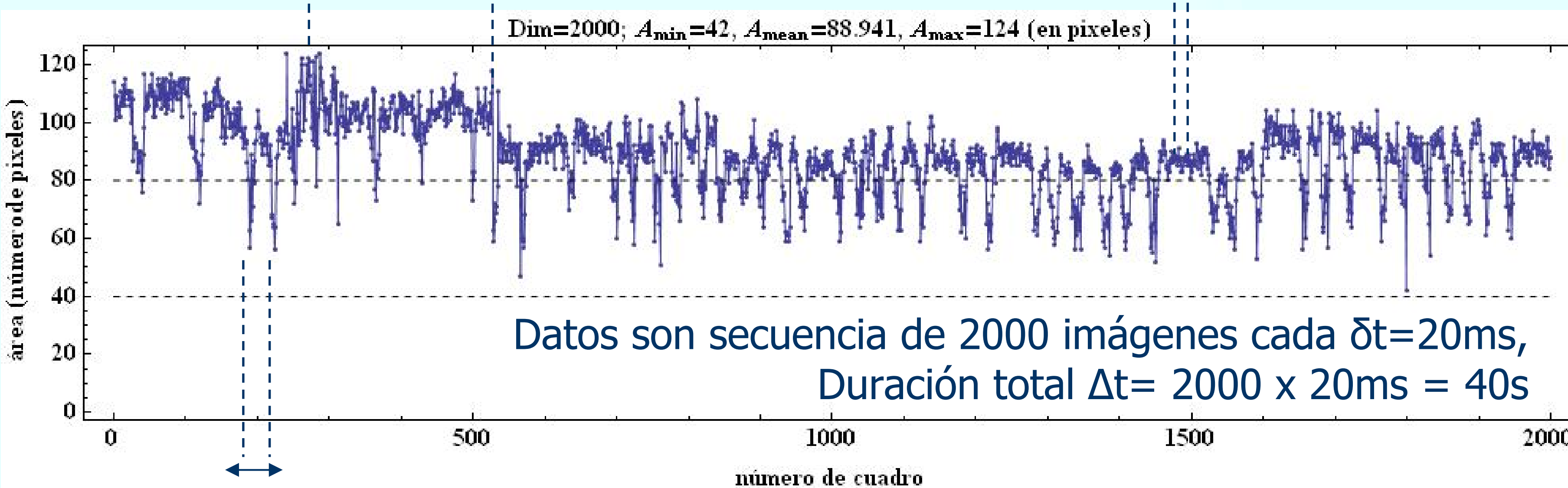
Figura ¿?. Método para la segmentación de las imágenes. **A)** imagen original. **B)** afilar la imagen. **C)** filtro de mediana . **D)** filtro pasobanda. **E)** afilar la imagen. **F)** realzar el contraste. **G)** modificar brillo y contraste. **H)** calibrar el umbral de las imágenes. **I)** segmentar la imagen.

Time Series
Correations in three different scales

Fluctuations on taping video?
Fluctuation in image analysis?

Worm movements
τ$_1$ (f=1/100 imágenes)

τ$_3$ (f=1/images)

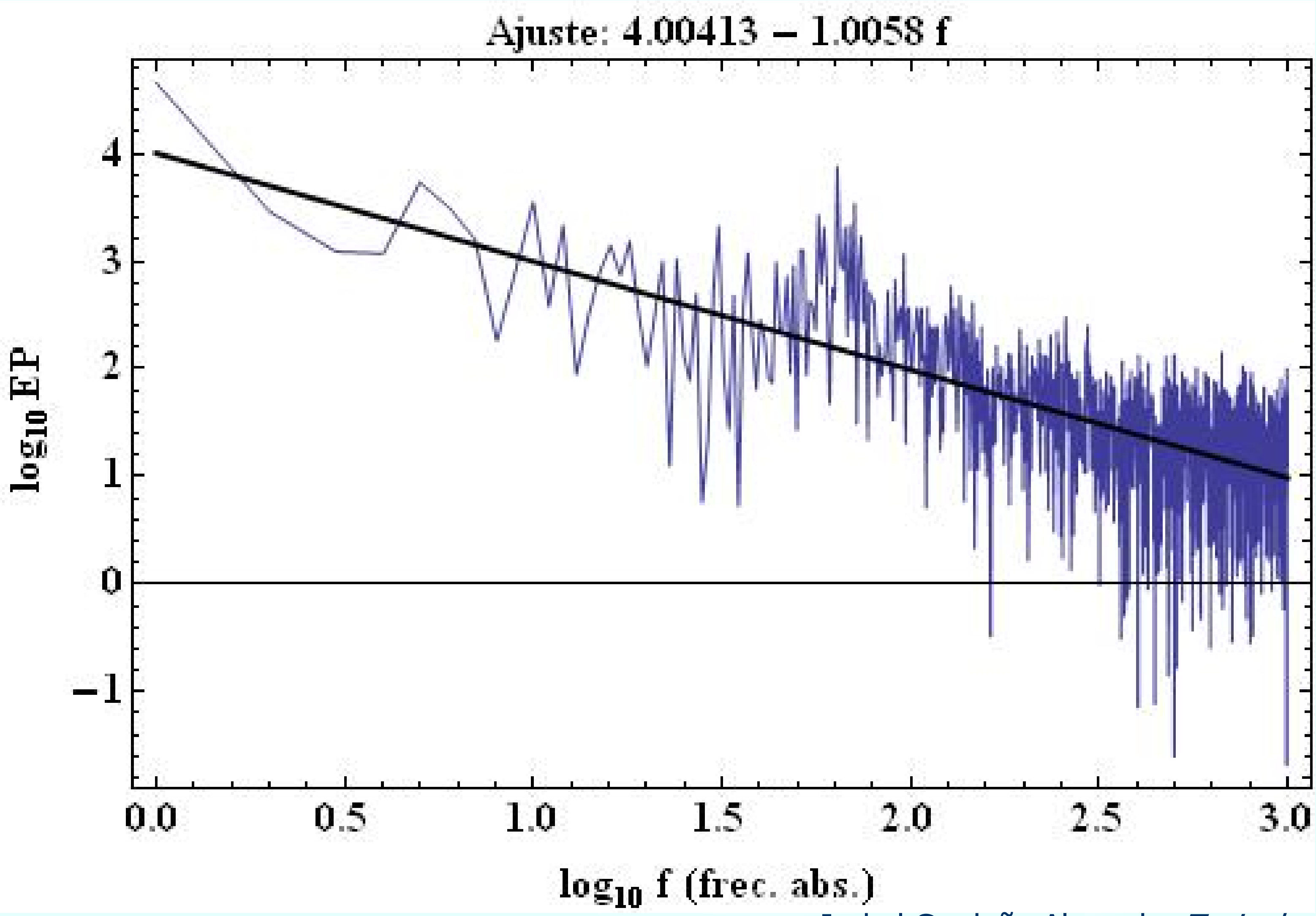


Datos son secuencia de 2000 imágenes cada δt=20ms,
Duración total Δt= 2000 x 20ms = 40s

τ$_2$ (f=1/10imágenes)
Pharinx
contractions

Ixchel Garduño Alvarado, R. Fossion, ***Tesis de licenciatura***

Slope of pharinx fluctuations



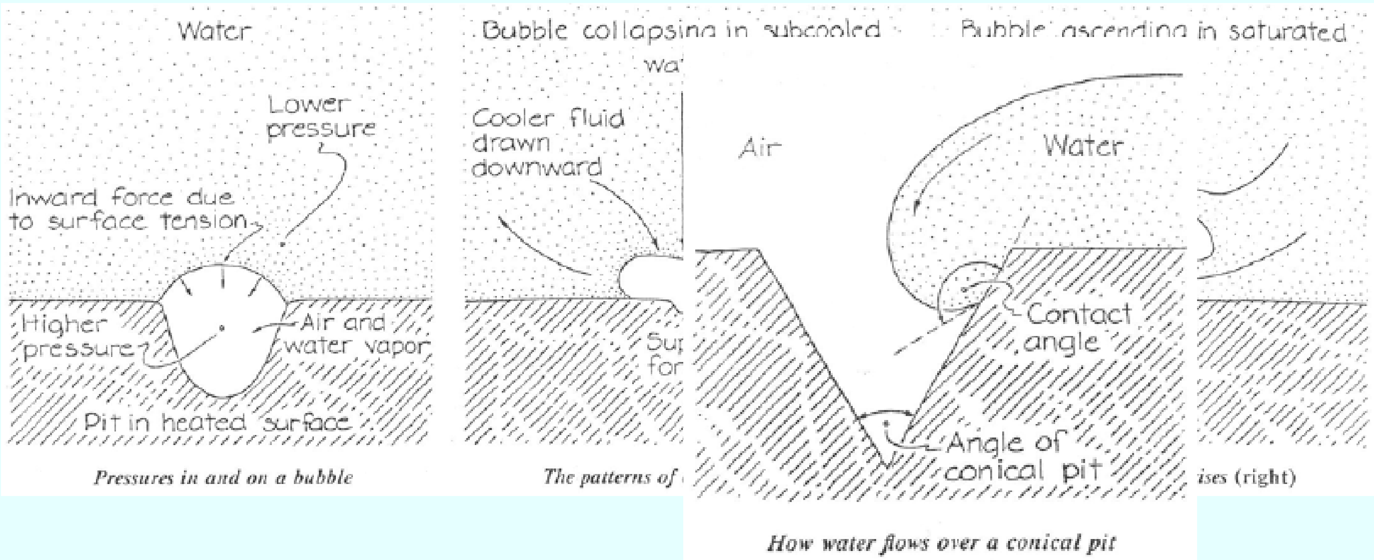
Ixchel Garduño Alvarado, *Tesis de licenciatura*

Criticality: phase transitions

The Boiling Song

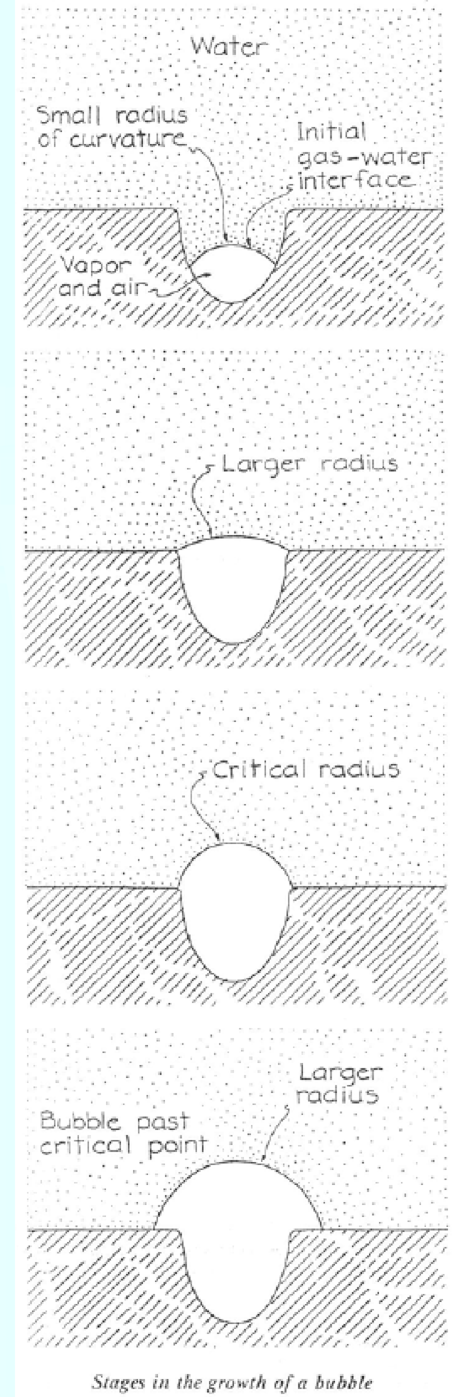
Can we verify whether 1/f behavior really signals criticality?

Bubbles that "sing"



Pressures in and on a bubble

How water flows over a conical pit



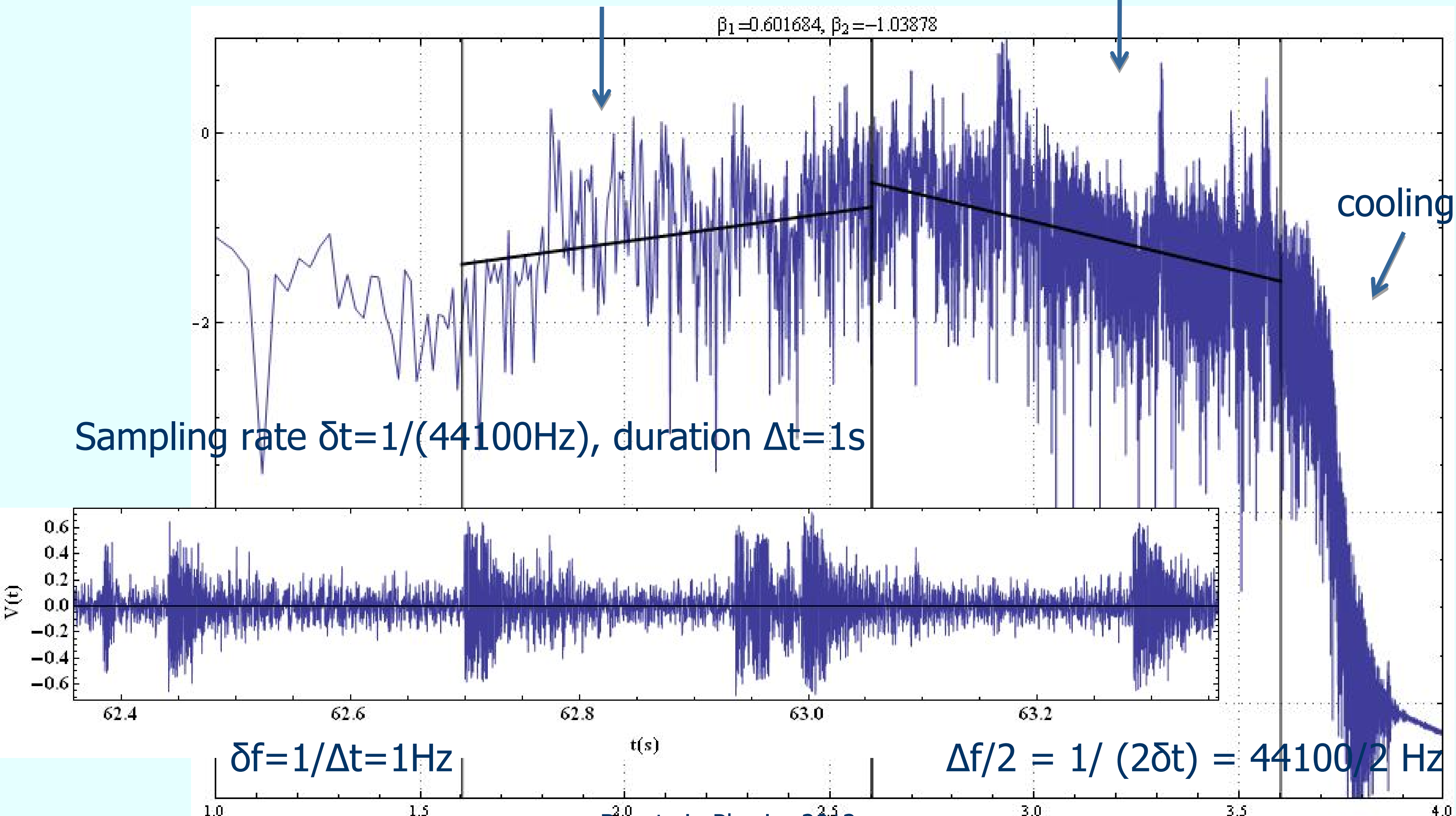
Stages in the growth of a bubble

J. Walker, *The amateur scientist: what happens when water boils is a lot more complicated than you might think,*
Sci. Am. 247(6) (1982) 162-171.

Water cooling immediately after boiling (1/f noise)

boiling

cooling

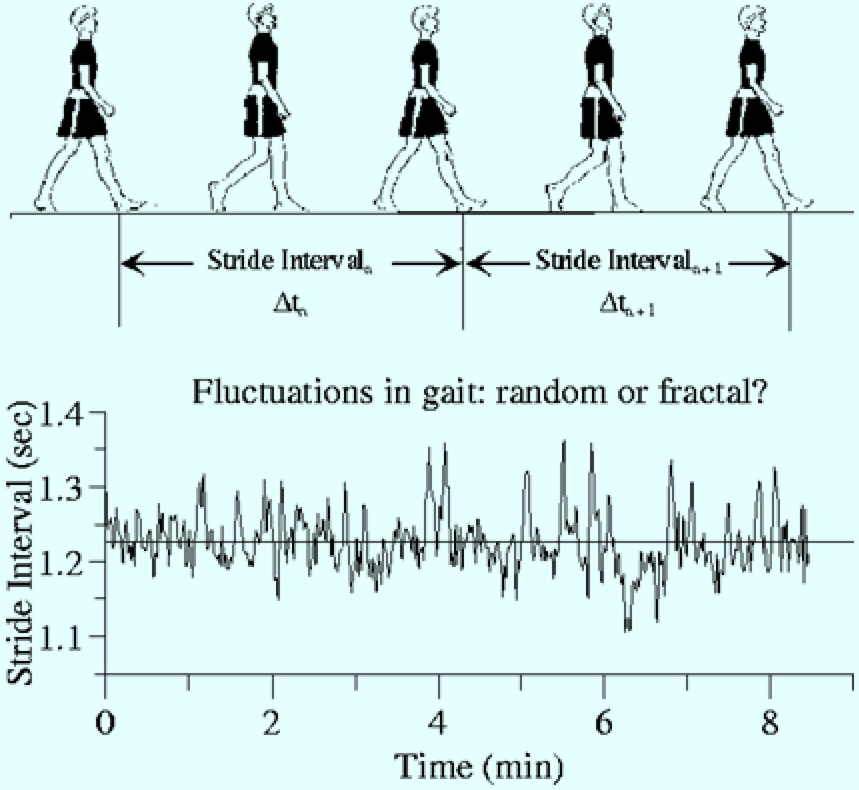


Sampling rate $\delta t=1/(44100\text{Hz})$, duration $\Delta t=1\text{s}$

$\delta f=1/\Delta t=1\text{Hz}$

$\Delta f/2 = 1/(2\delta t) = 44100/2$ Hz

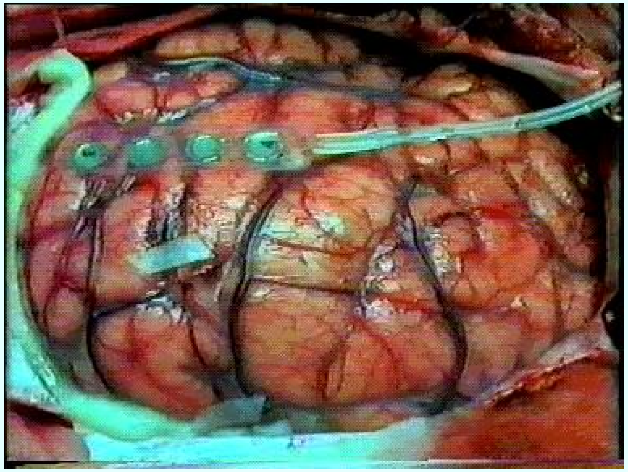
Other Rithms:Gait



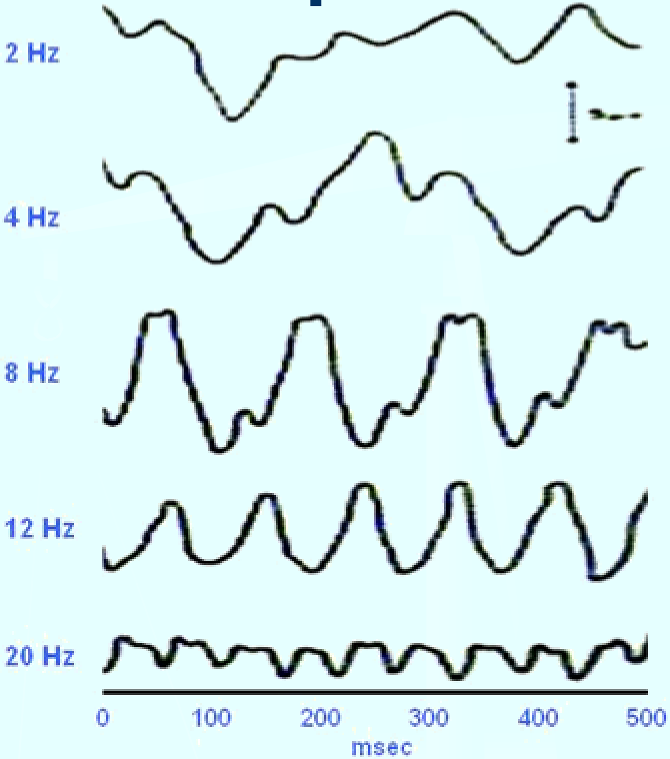
Goldberger et al., *Physionet*,
http://physionet.org/tutorials/fmnc/node11.html

Correlations change with age and fragility

Other Examples: Electro-encefalogram (EEG)

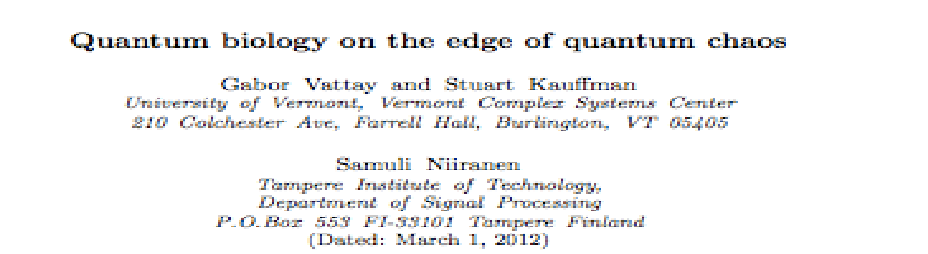


EEG at various frequencies



Can abnormal behavior be detected early?

Quantum Transitions:“Time Series” of excited nuclear states


Quantum biology on the edge of quantum chaos

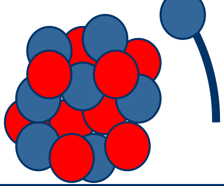
Gabor Vattay and Stuart Kauffman
University of Vermont, Vermont Complex Systems Center
210 Colchester Ave, Farrell Hall, Burlington, VT 05405

Samuli Niiranen
Tampere Institute of Technology,
Department of Signal Processing
P.O.Box 553 FI-33101 Tampere Finland
(Dated: March 1, 2012)

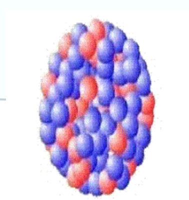
Dense spectrum:
statistical analysis

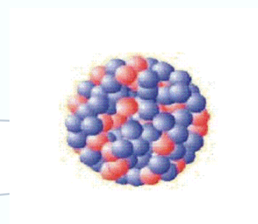
8 MeVNucleon separation energy

Nucleon individual excitations

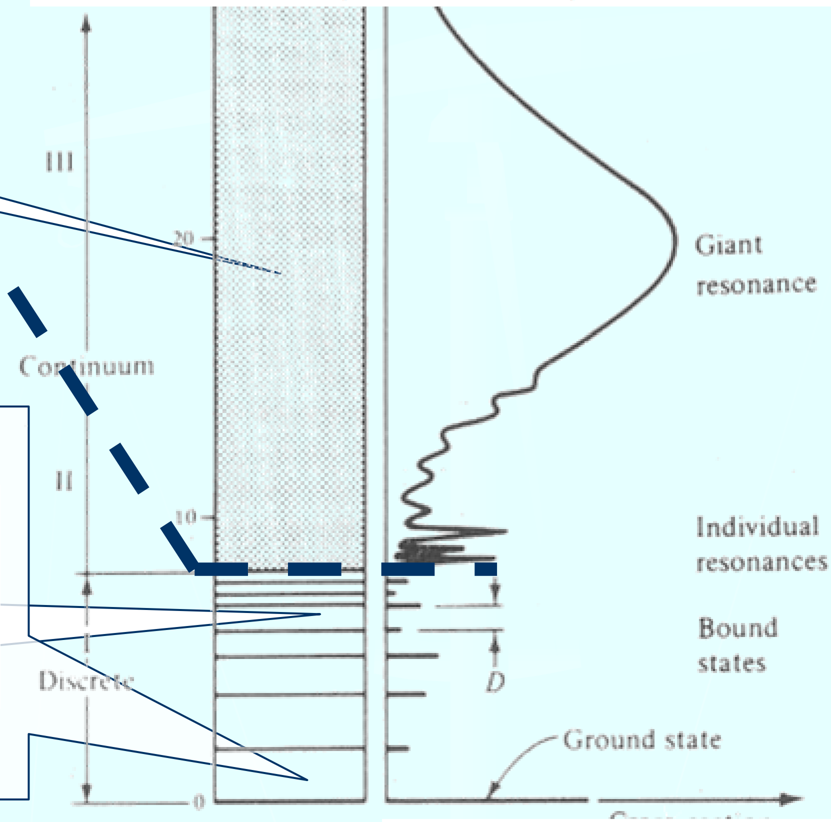


Collective excitations

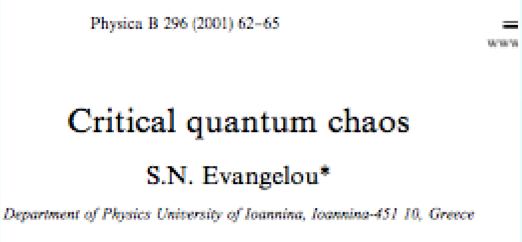




Rotations Vibrations



RMT gives 1/f behavior. Relaño et al.


Physica B 296 (2001) 62–65

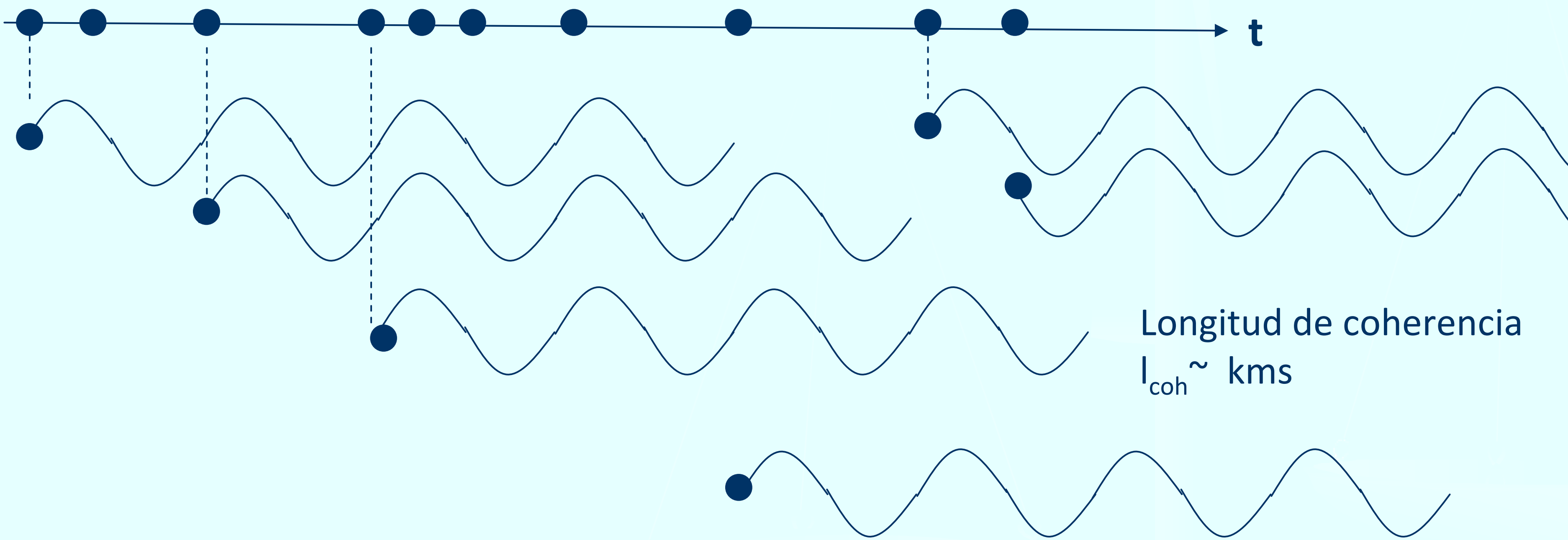
Critical quantum chaos

S.N. Evangelou*
Department of Physics University of Ioannina, Ioannina-451 10, Greece

The different "phases" of light

coherent light (lasers)

Propriedades:
-Intervalos interfotónicos aleatorios
-- Pero fotones viajan en fase.

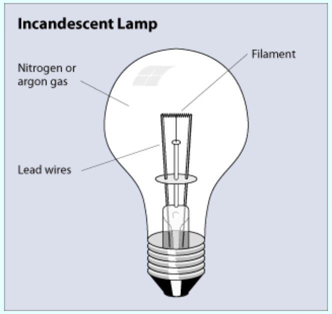


Longitud de coherencia
l_{coh}~ kms

Different Phases of Light

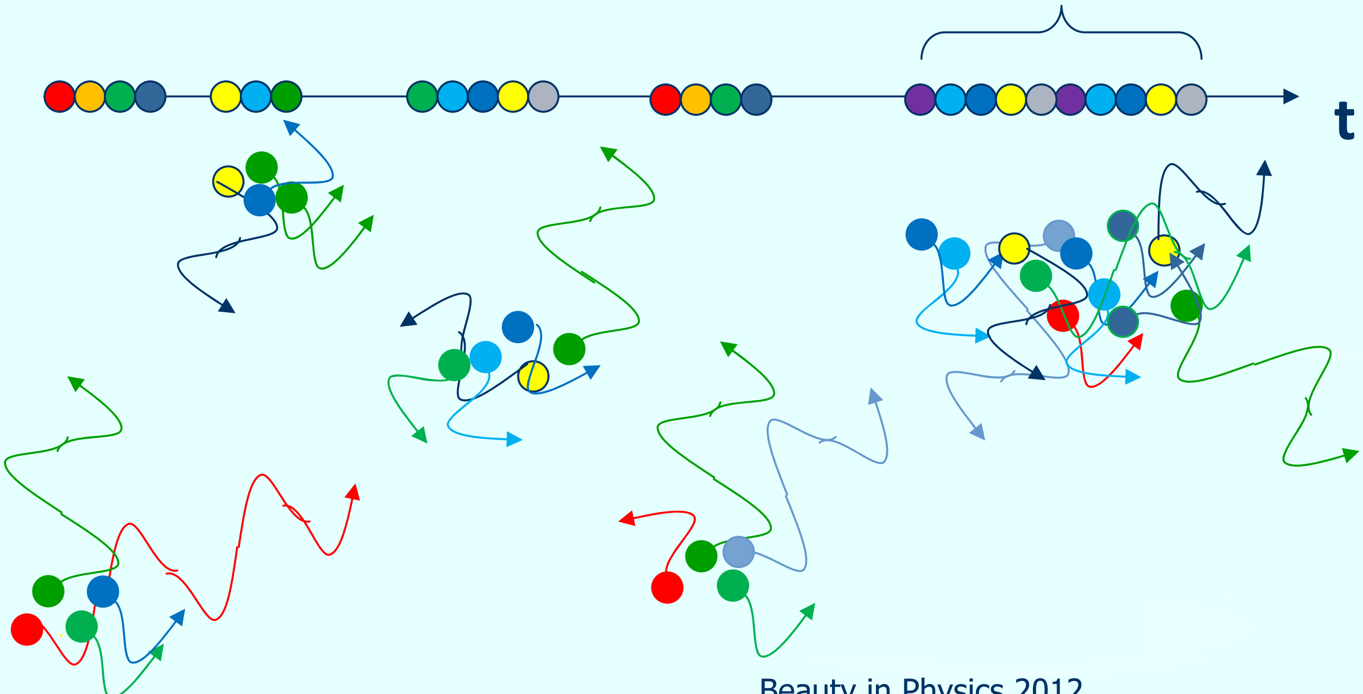
sol

lampara



Thermal light
"chaotic light"

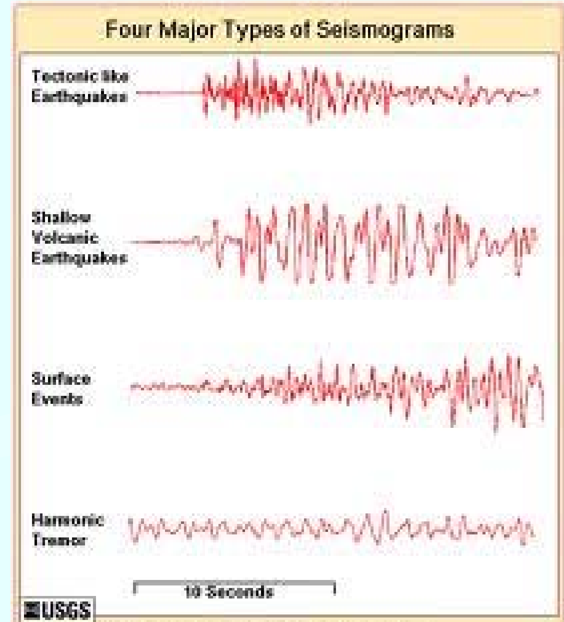
Coherence time
$\tau_{coh} = \lambda_{coh}/c \approx$ ns

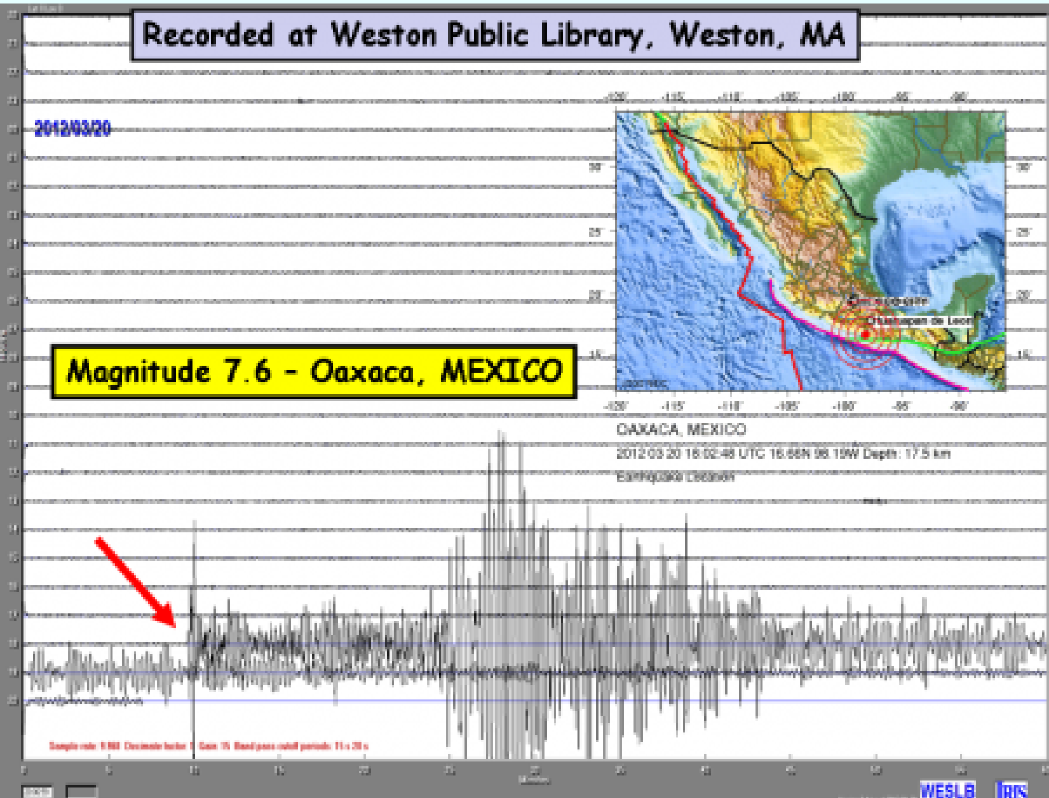


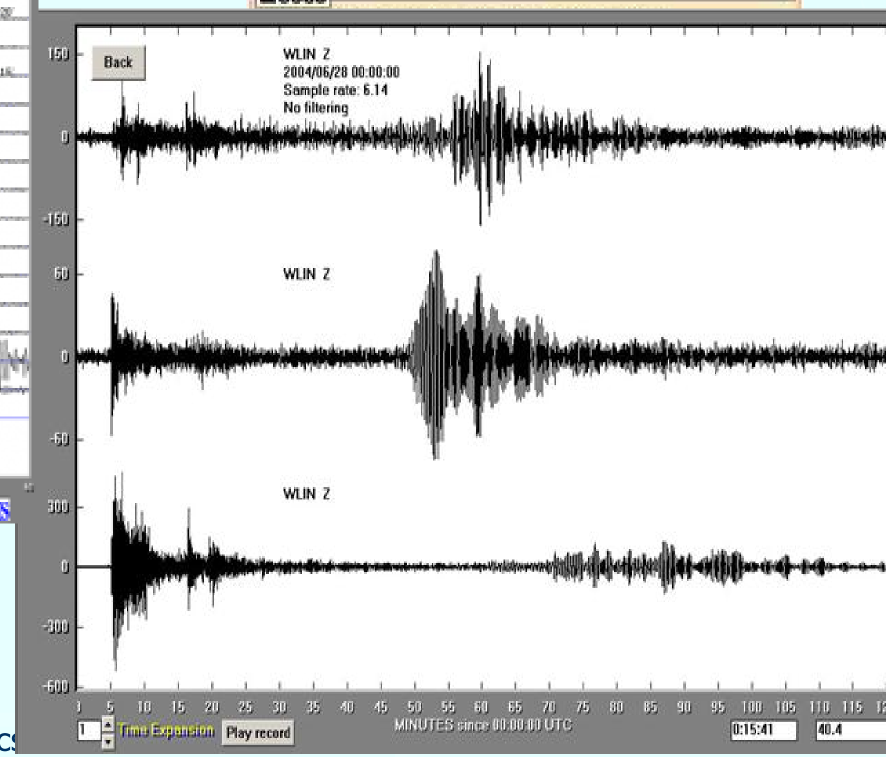
Properties:
- many frequencies
-Bunching/coherence

Also: **Quantum light: anticorrelations**

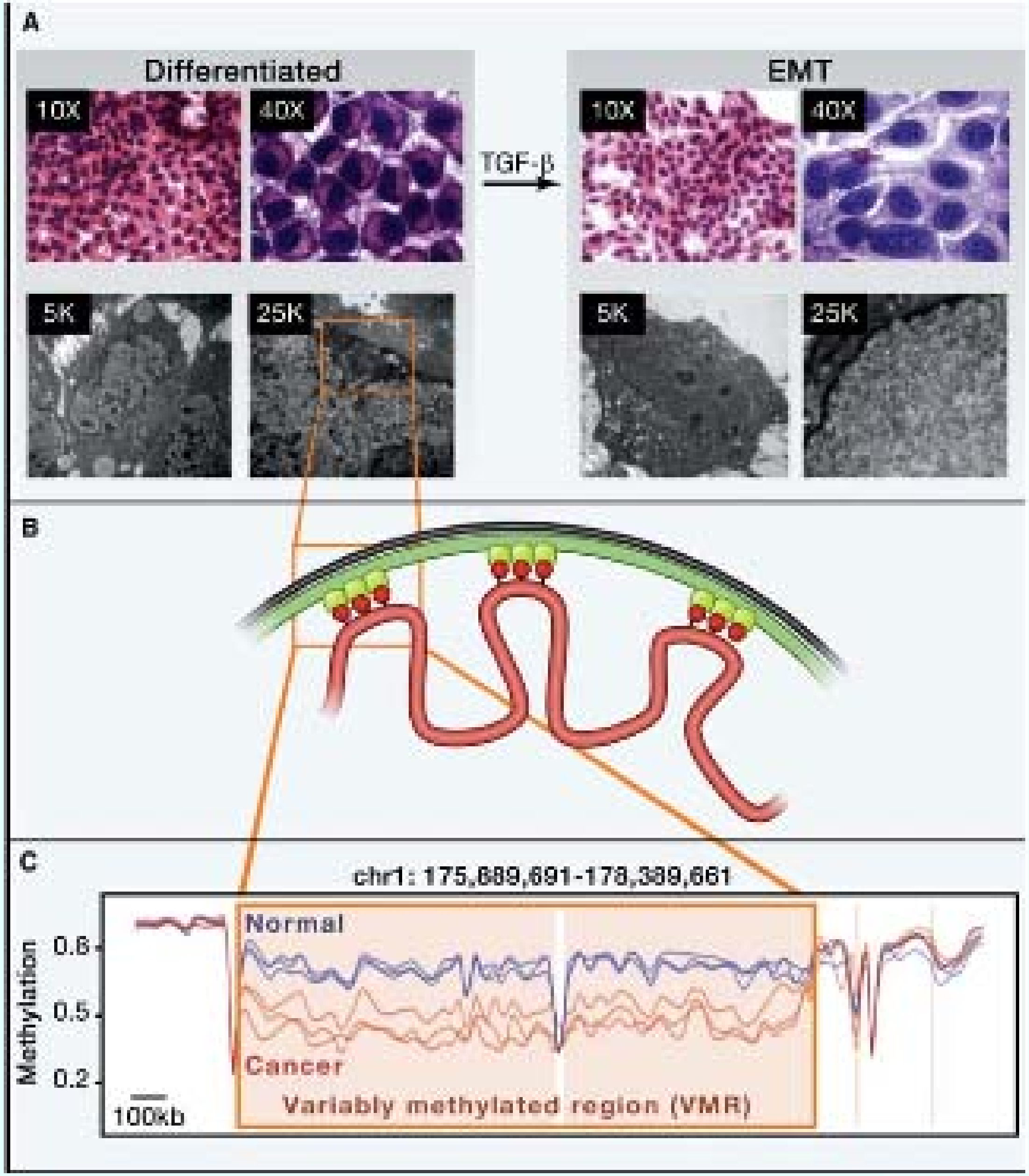
Earthquakes: early warning.







Epigenetic Sequences: Early Warning for Cancer?



What is the distribution of primes around its logarithmic trend?

- **Quantum-like Chaos in Prime Number Distribution and in Turbulent Fluid Flows**

- **A. M. Selvam**
- **Indian Institute of Tropical Meteorology Pune 411 008, India email: selvam@ip.eth.net website: http://www.geocities.com/amselvam**

- **1/f or Benford Distribution**

- **P_n = Log_(10) (1 + 1/n}**

Fourier: some problems

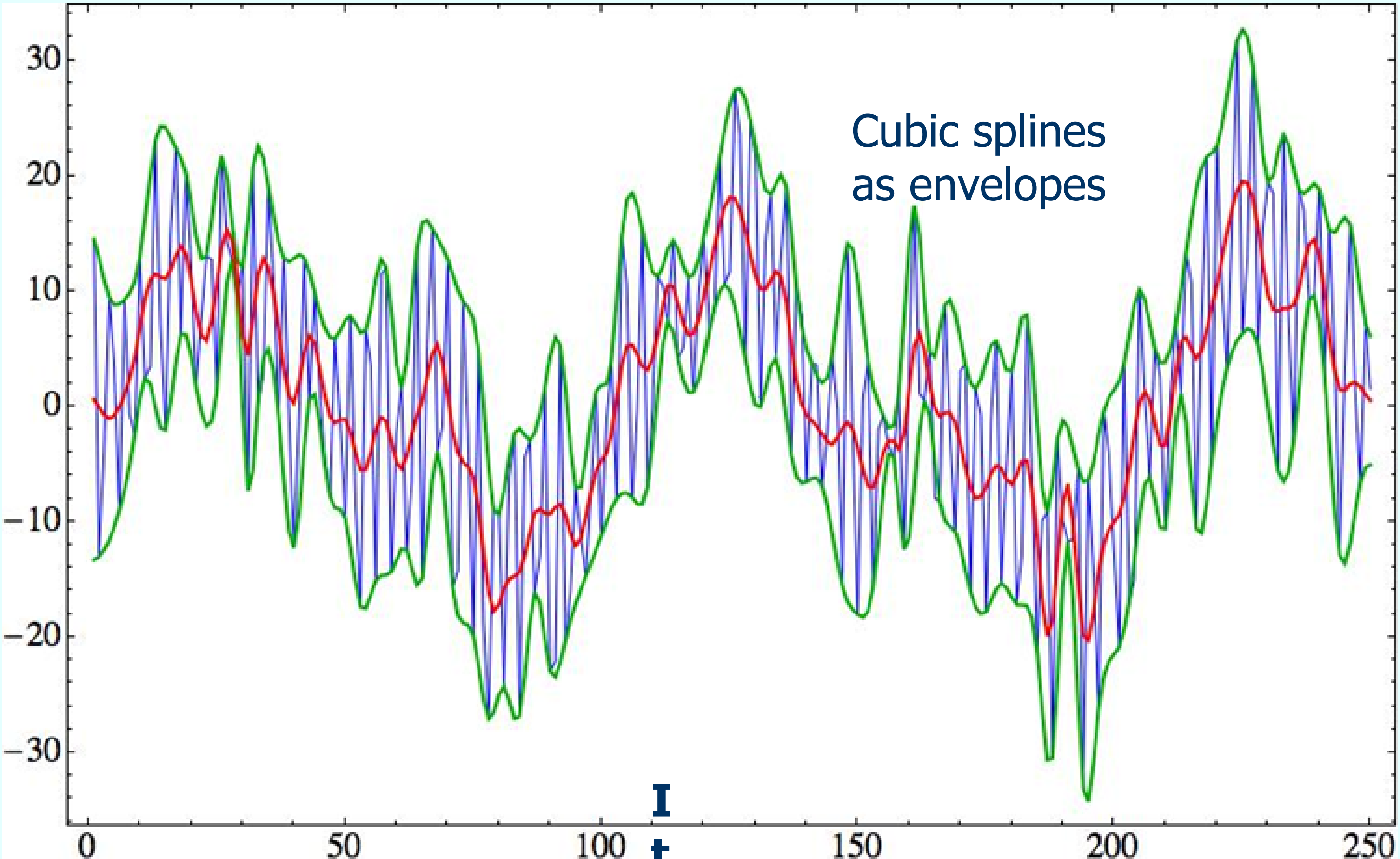
•Usually used to analyze energy-frequency distribution (very simple, very powerful)

•Physical systems can be approximated by linear systems, however most systems are NON-linear and NON-stationary (also data are finite, system always interact with detector devices)

•Many extra components are needed in order to simulate non-linear effects. The energy spreads to the neighboring frequencies.

•The Fourier decomposition has mathematical sense, but the physical sense is not clear

A new technique: Empirical Mode Decomposition (EMD): “normal” modes



$X(t)$

Ennvelopes

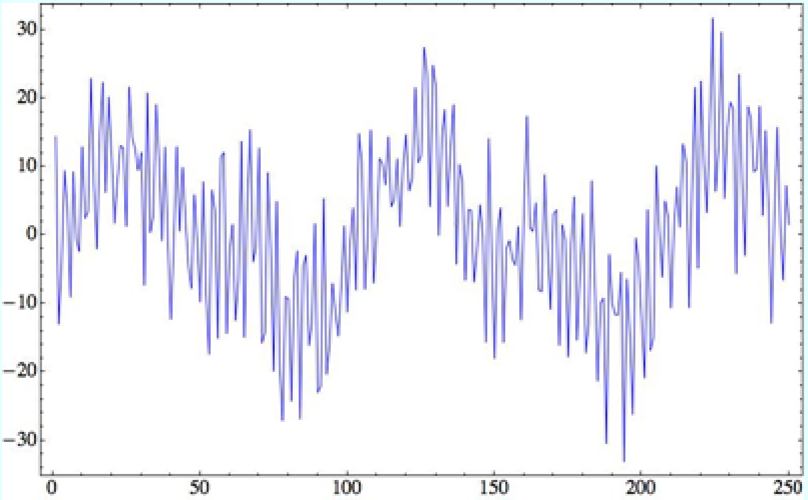
m_1

Iterat

$$X(t) - m_1 = h_1$$

Empirical Mode Decomposition (EMD)

•x(t) is composed of oscillations mounted on slower oscillations on different time scales which are defined by the distance between local extrema.

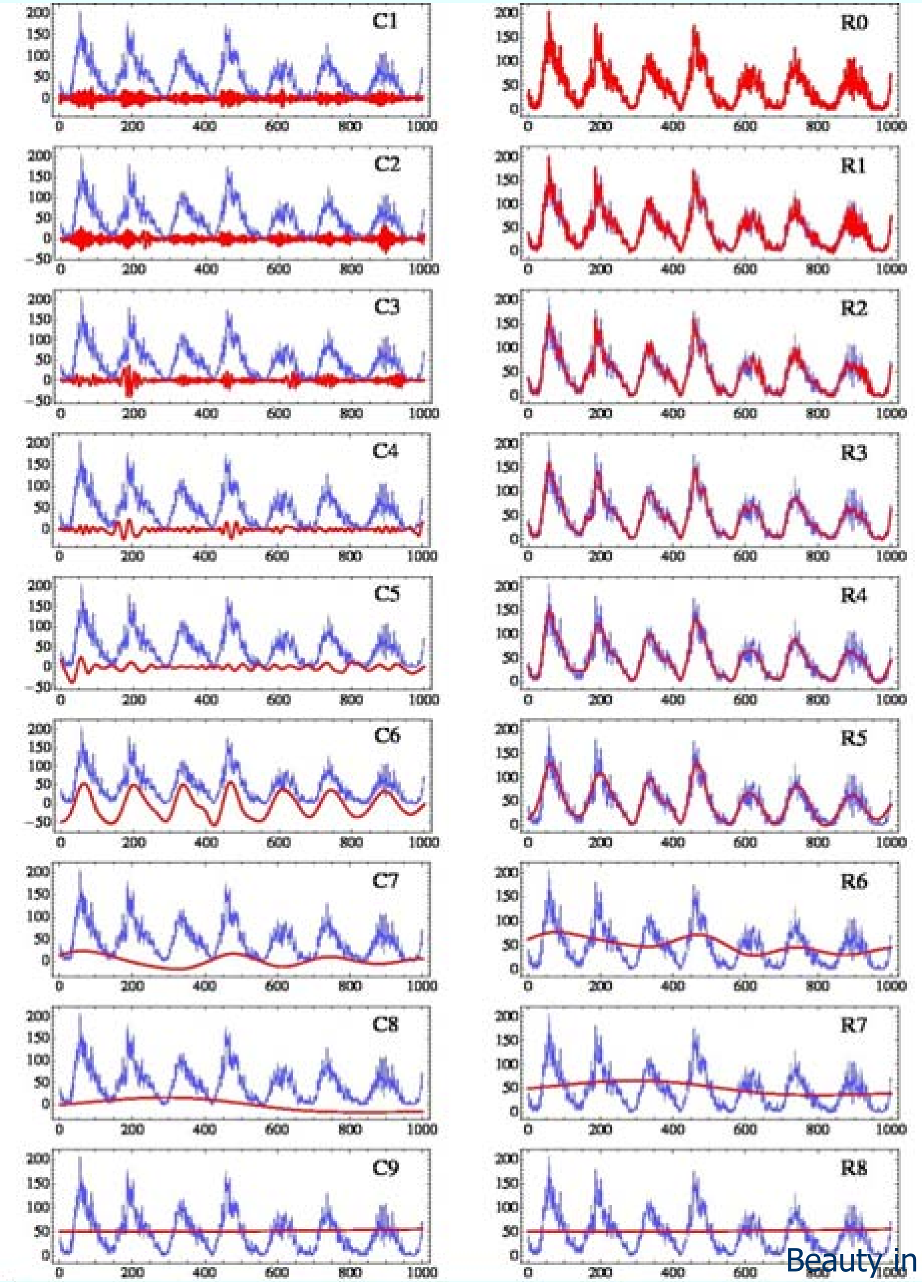


•These oscillations may directly represent physical coupled phenomena producing the dynamics of the whole system.

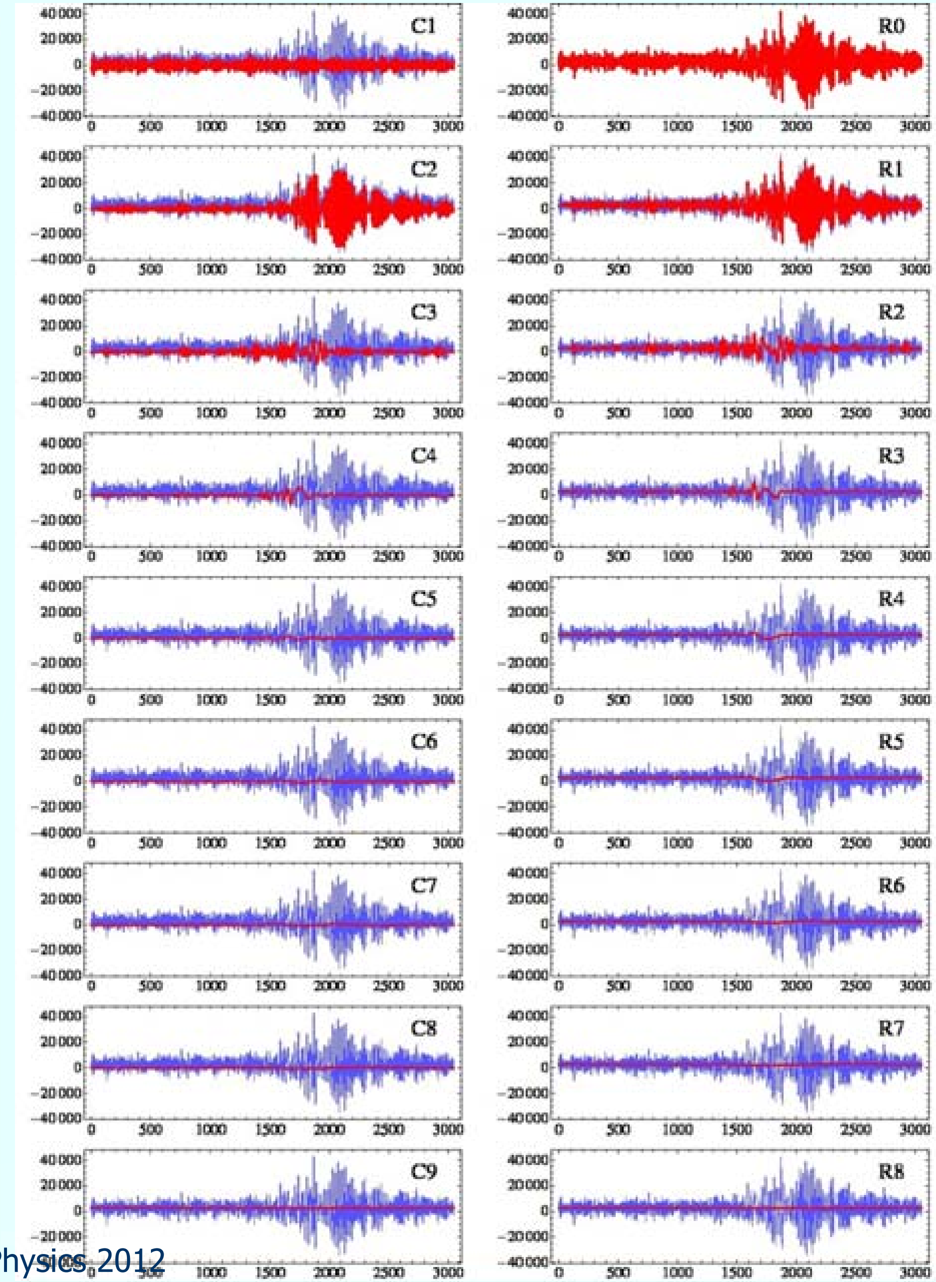
•E.g.

•Breathing mode in heart signals
•Seasonal, el niño, etc. in climate analysis

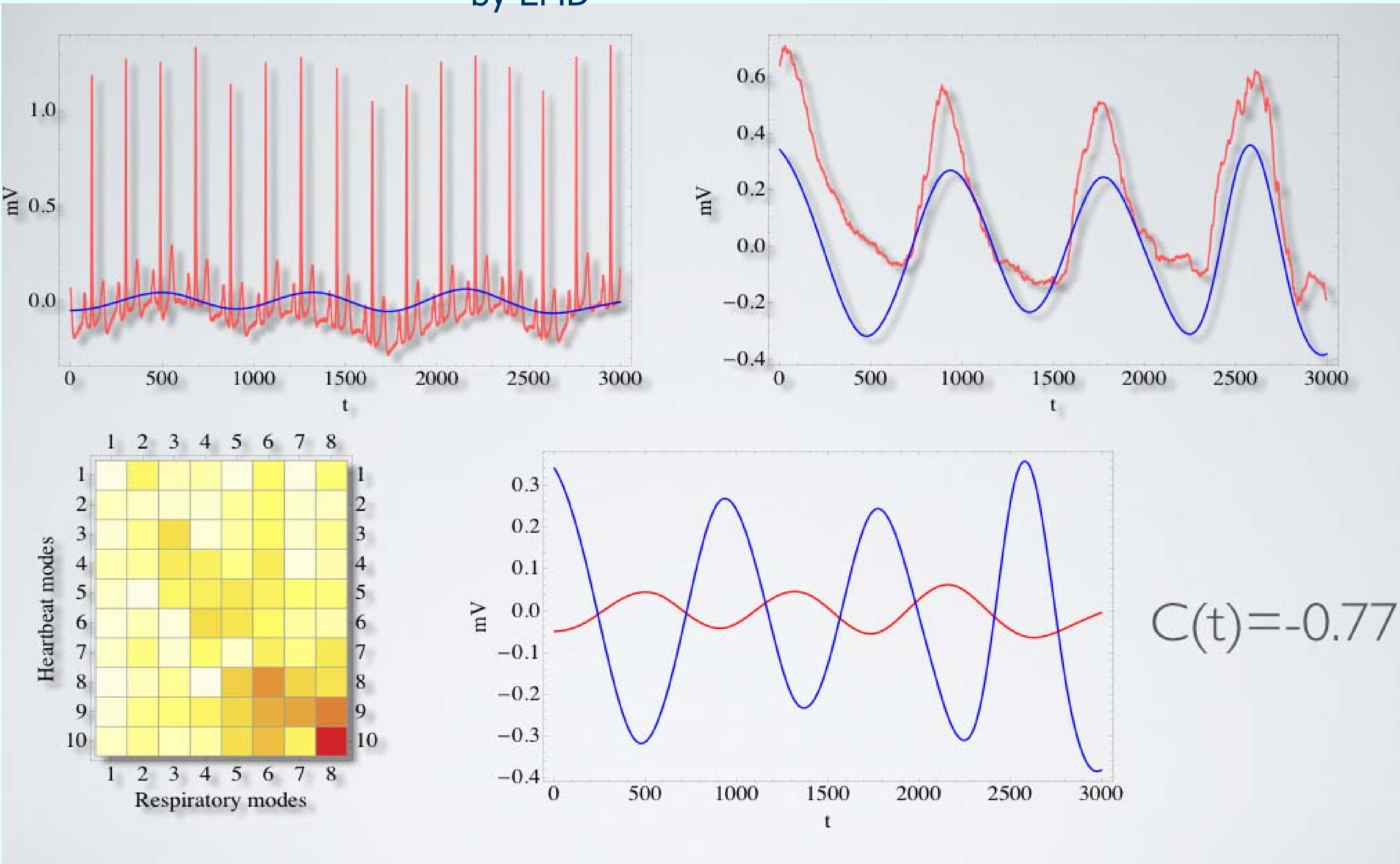
Sunspots



Kobe earthquake



Detecting the Breathing Mode by EMD



Application to Climate Change

Conclusions

- We can " listen" to physical and biological systems using mathematical methods, beyond Fourier analysis. These signals contain information about the system´s workings, fragility or robustness. It may be possible to detect early warning signals: "phase transitions", or critical behavior
- - There are generic traits for critical behavior in a large number of systems, including physical, biological and physiological, which may be treated within a single theoretical framework. Modelling can be implemented in a second stage. Multidisciplinary work.
- - Involuntary biological systems are on a "critical" regime, which often can be characterized by 1/f type signals. Deviations may be predictive of fragility and illness.
- Work in progress in several directions, in collaboration with experts in other fields.