Should Physicists Analyse Heart Rate?

Zbigniew R. Struzik

 no!

Physics is one of the oldest academic disciplines, perhaps the oldest through its inclusion of astronomy. Over the last two millennia, physics was a part of natural philosophy along with chemistry, biology, and certain branches of mathematics, but during the scientific revolution in the 17th century, the natural sciences emerged as unique research programs in their own right.

yes!

Physics intersects with many interdisciplinary areas of research, such as biophysics and quantum chemistry, and the boundaries of physics are not rigidly defined. New ideas in physics often explain the fundamental mechanisms of other sciences while opening new avenues of research in areas such as mathematics and philosophy.

maybe?

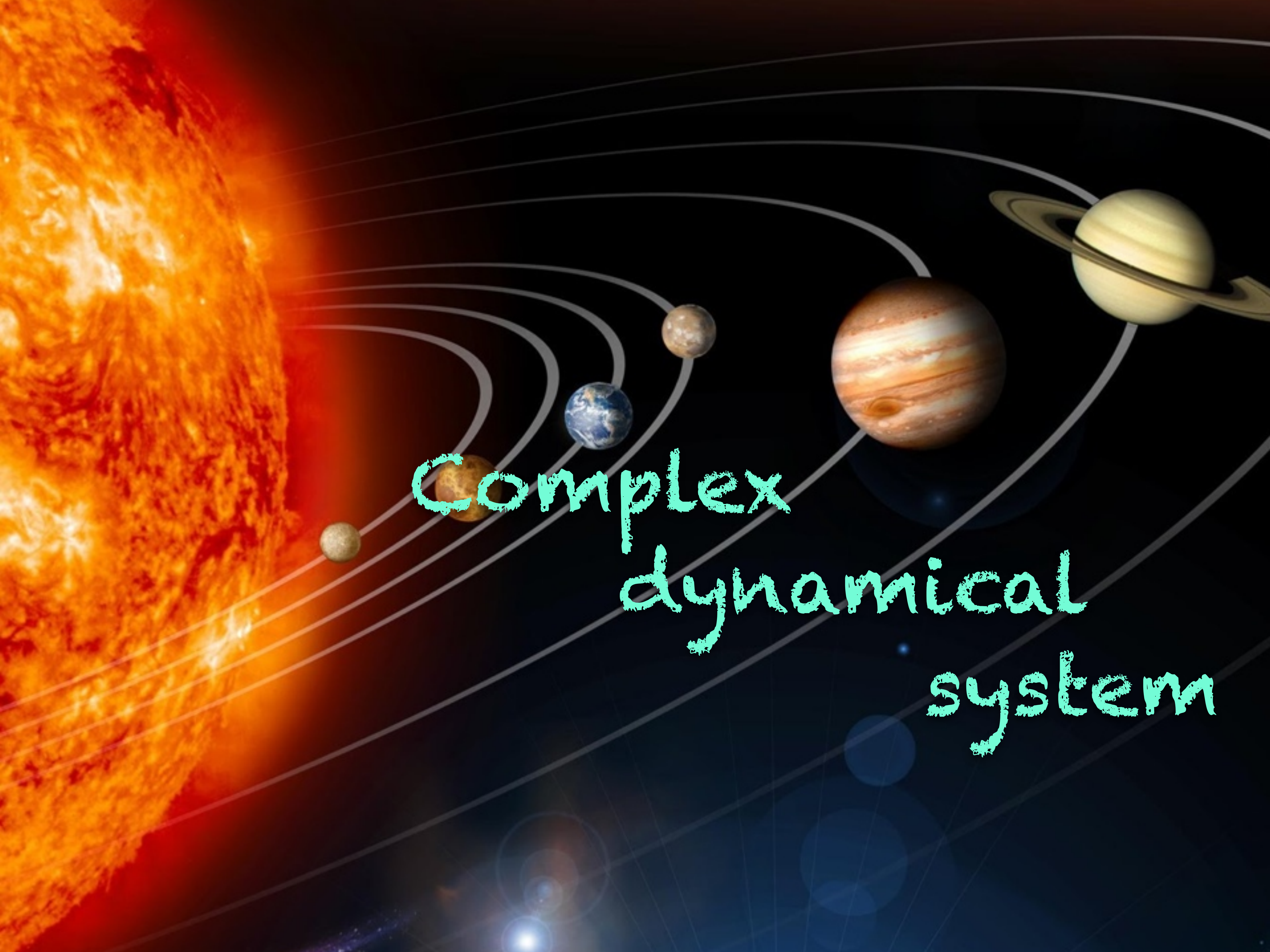
life

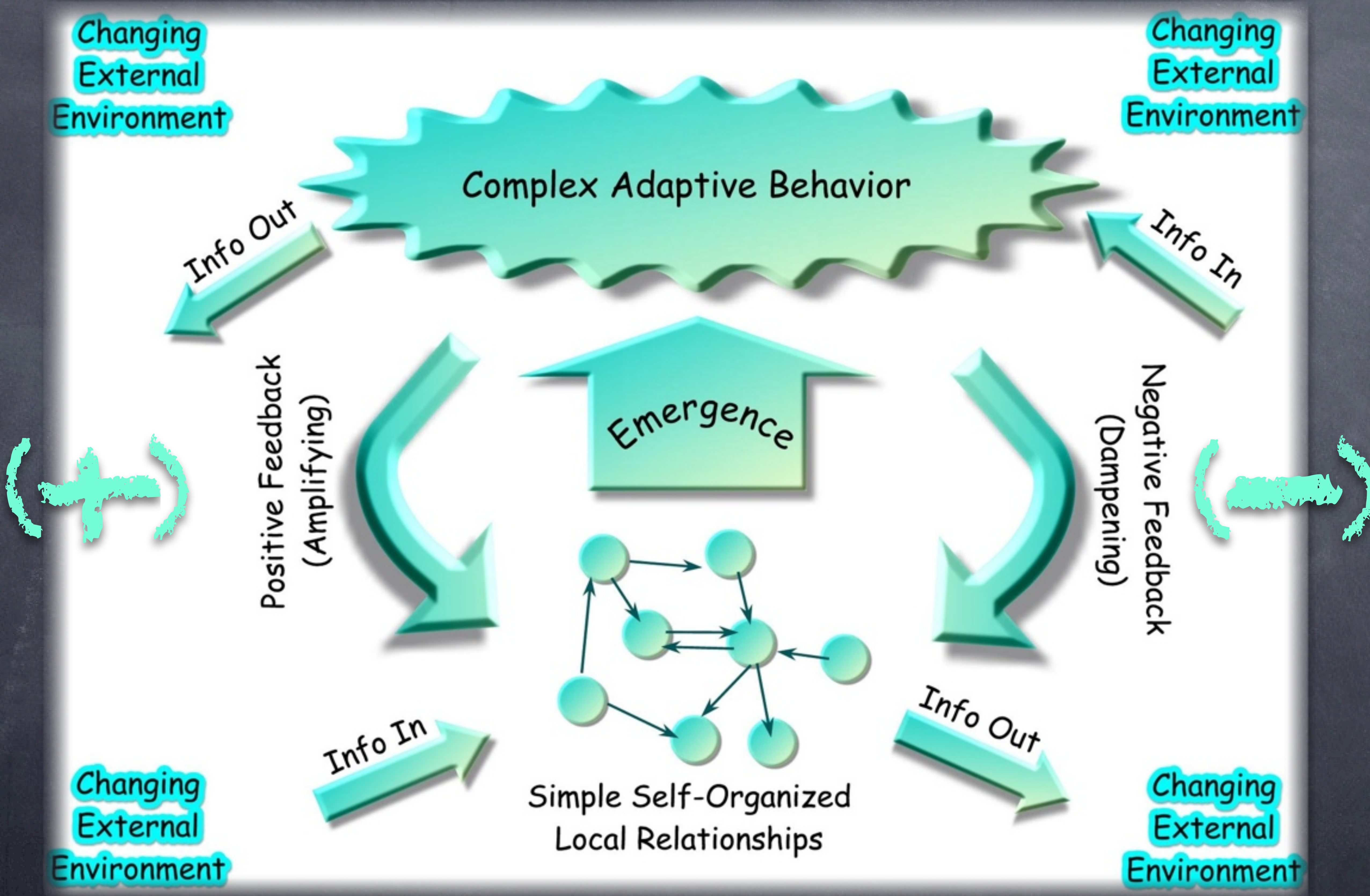
=

complex

adaptive

system


Complex
dynamical
system

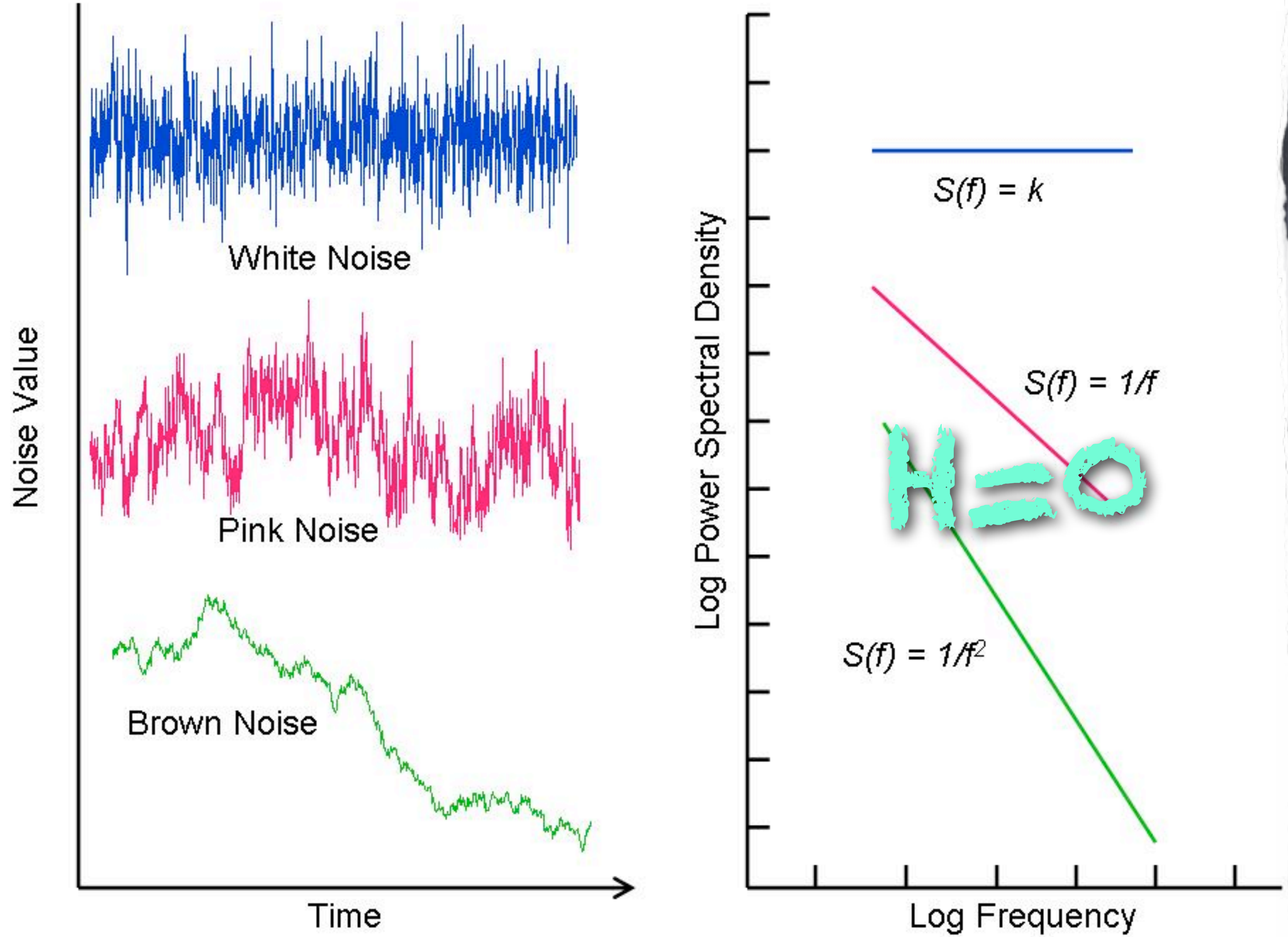

Changing External Environment
Changing External Environment
Complex Adaptive Behavior
Info Out
Info In
Positive Feedback (Amplifying)
+
Emergence
Negative Feedback (Dampening)
−
Info In
Info Out
Simple Self-Organized Local Relationships
Changing External Environment
Changing External Environment

cross-level
interactions
remain
under-explored

For decades, physicists have hoped that the emergent, collective phenomena of life could be captured using ideas from statistical mechanics. The stationary states of biological systems have a subtle structure, neither “frozen” into a well ordered crystal, nor chaotic and disordered like a gas. Further, these states are far from equilibrium, maintained by a constant flow of energy and material through the system. There is something special about the states corresponding to functional, living systems, but at the same time it cannot be that function depends on a fine tuning of parameters. Of the many ideas rooted in statistical physics that have been suggested to characterize these states, perhaps the most intriguing—and the most speculative—is the idea of self-organized criticality

Thierry Mora &·William Bialek
J Stat Phys (2011) 144:268–302


pink noise ;-)

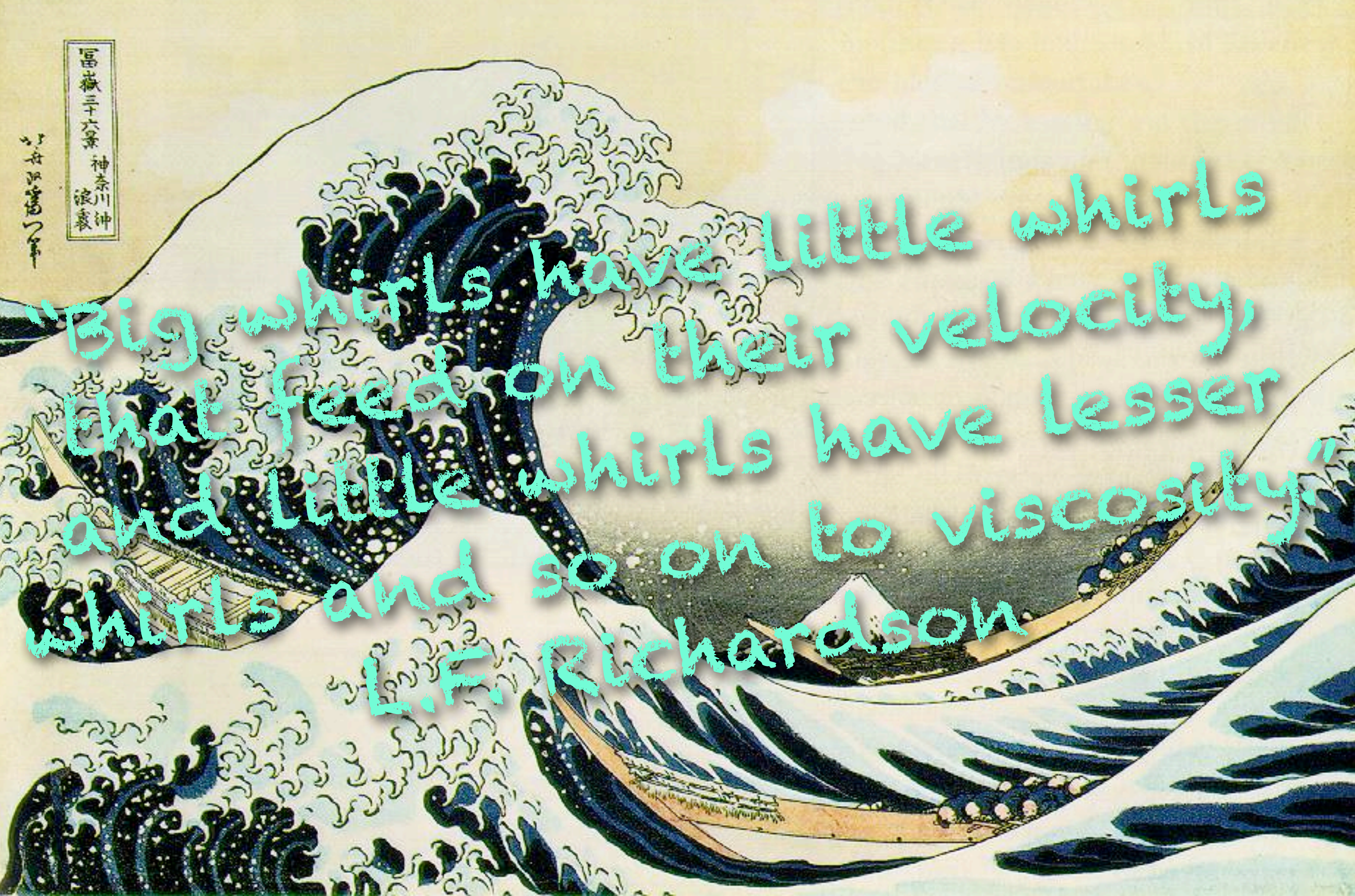


Toshimitsu Musha, Yohei Kobayashi

1/f noise

$\Downarrow$

scale invariant fluctuations



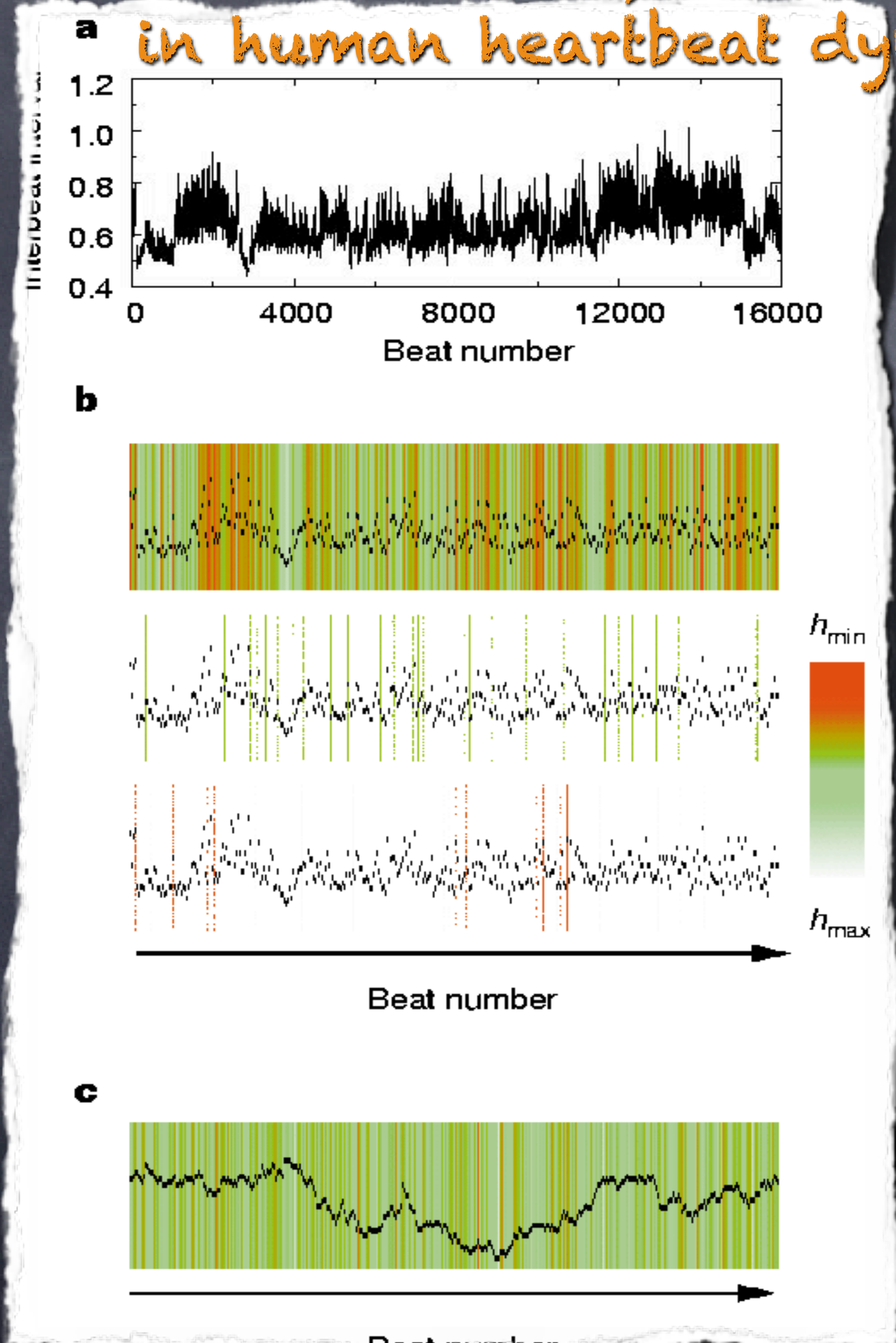
The Great Wave off Kanagawa, Katsushika Hokusai

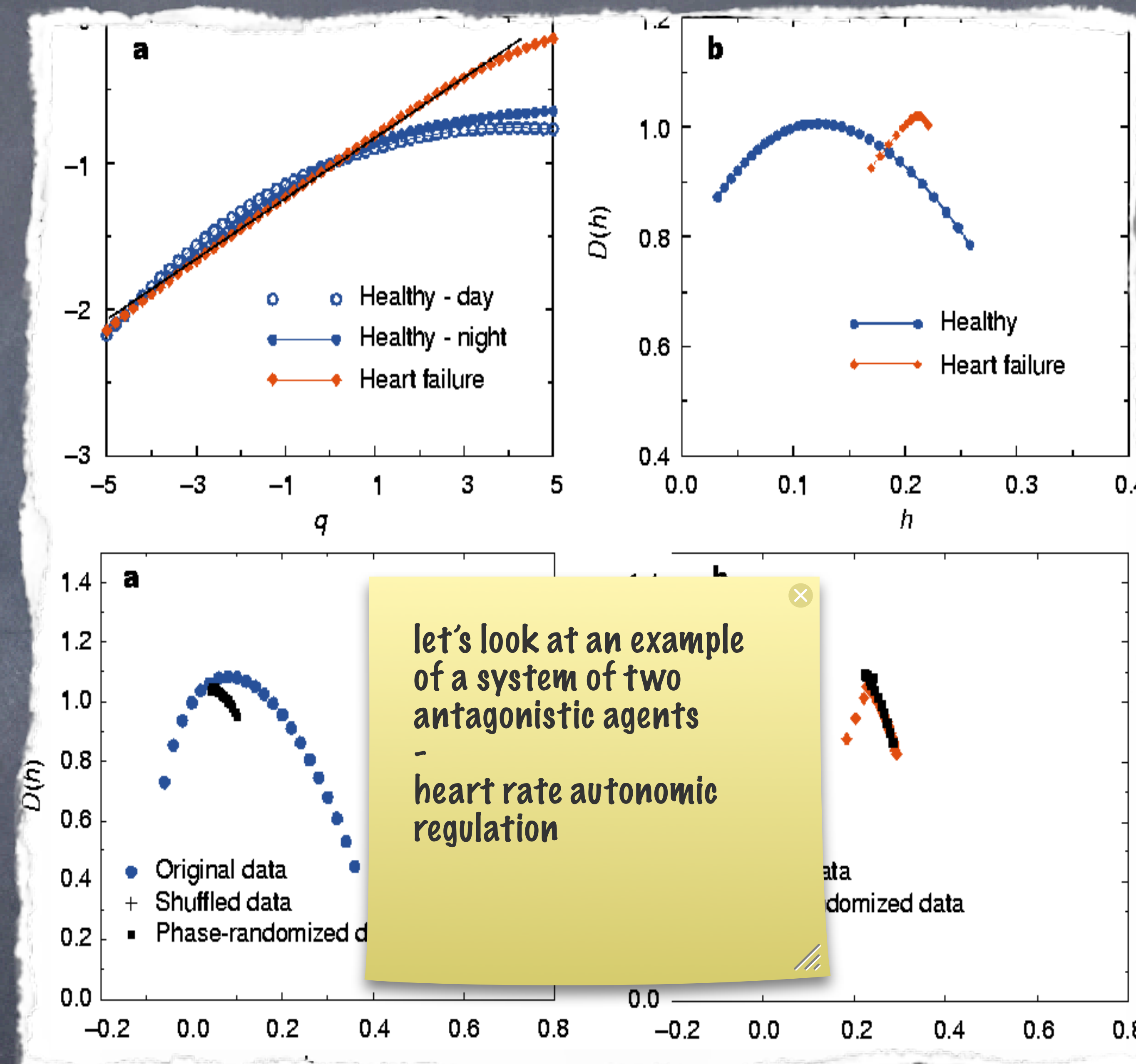
Multiplicative (energy) cascade

$\Downarrow$

multifractals

P.Ch. Ivanov, L.A.N. Amaral, A.L. Goldberger, S. Havlin, M.G. Rosenblum, Z.R. Struzik, H.E. Stanley, Multifractality in human heartbeat dynamics, Nature 399, pp461, 1999.





let's look at an example
of a system of two
antagonistic agents
-
heart rate autonomic
regulation

Multiplicative cascade

$\Downarrow$

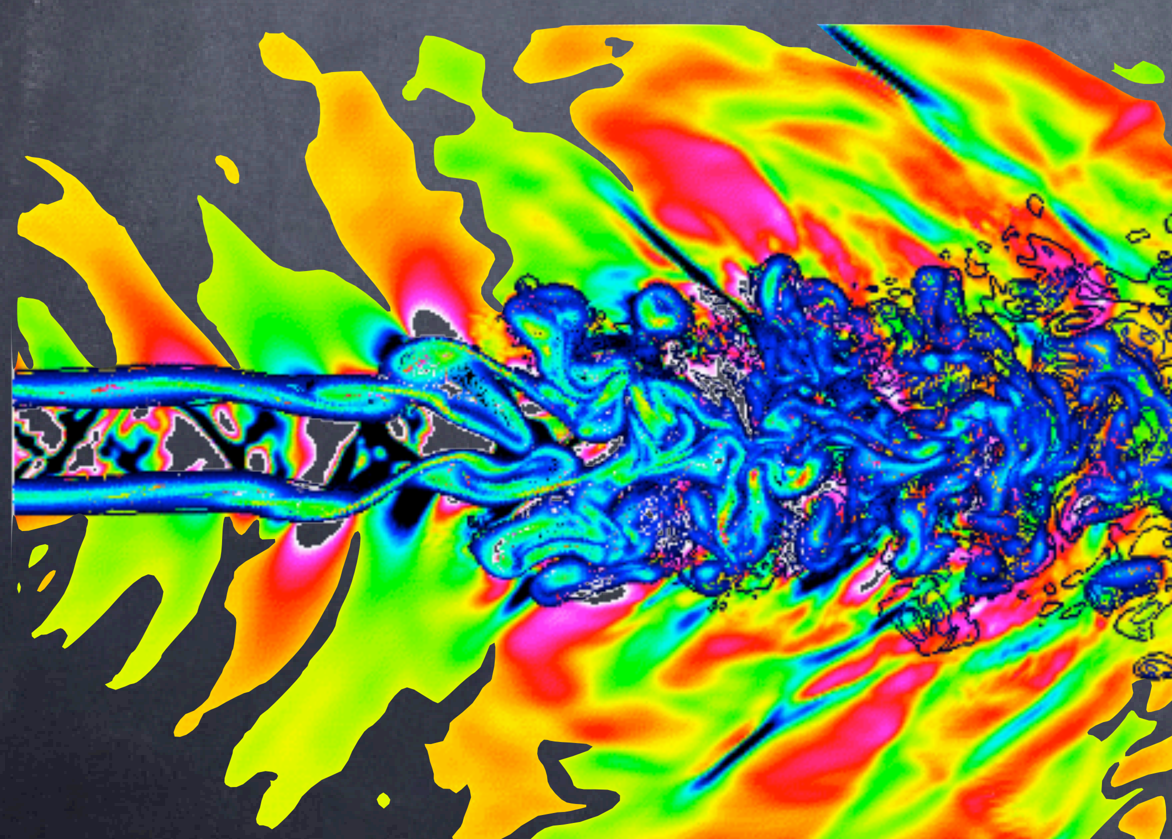
heavy tail pdf

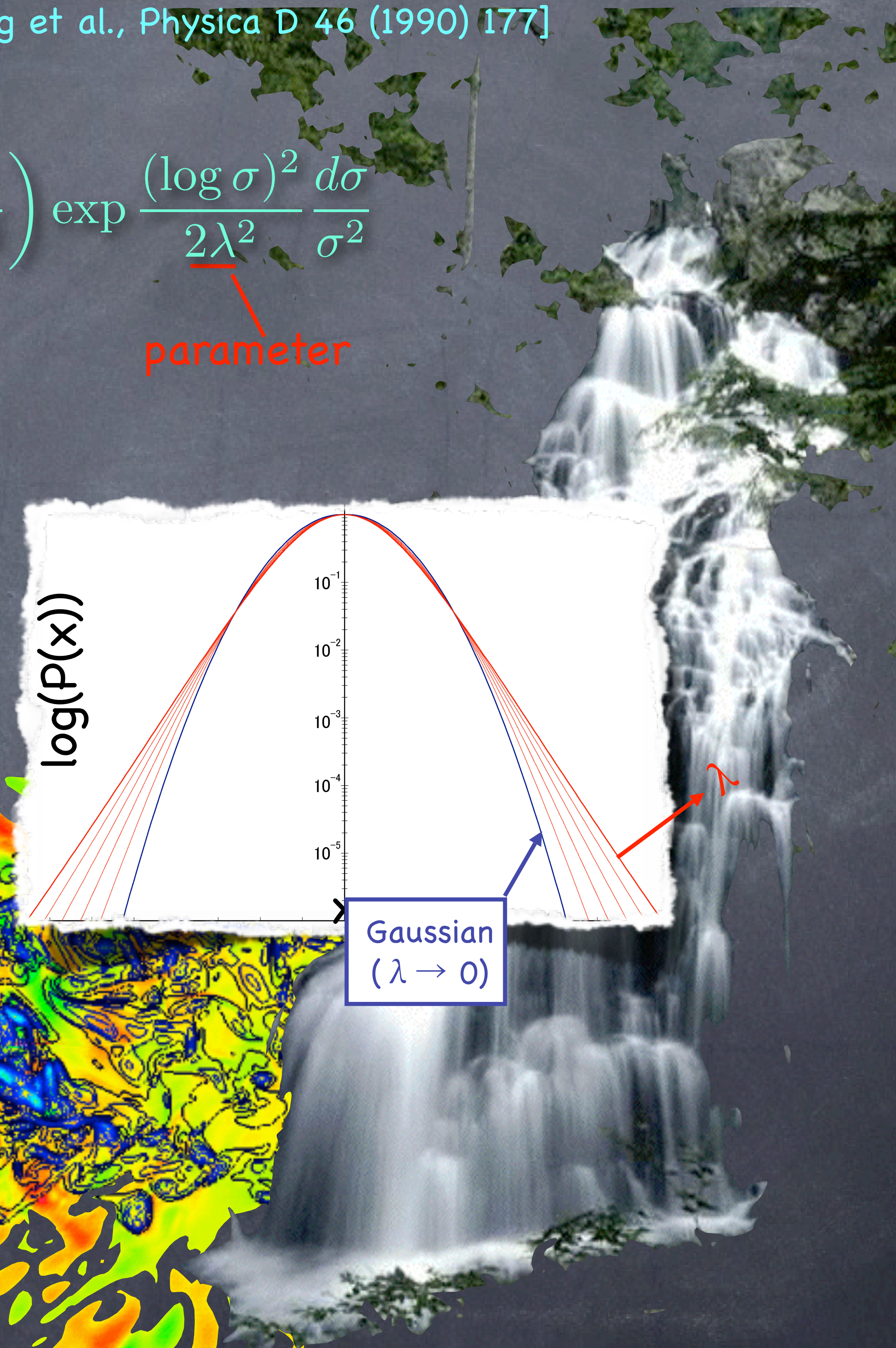
PDF based on Castaing's equation (log-normal cascade)

[Castaing et al., Physica D 46 (1990) 177]

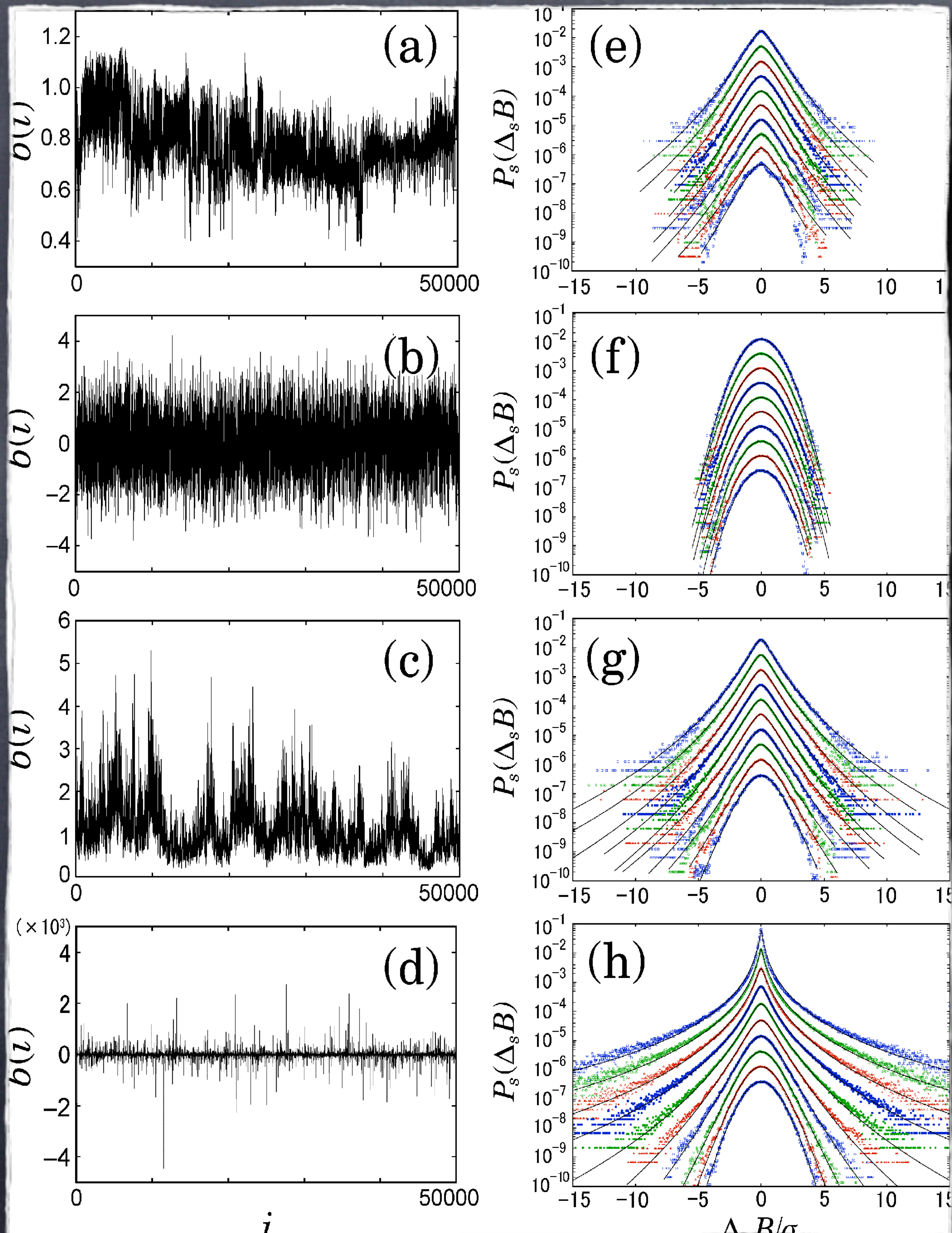
$$P(x) = \frac{1}{2\pi\lambda}\int_0^\infty \exp\left(-\frac{x^2}{2\sigma^2}\right)\exp\frac{(\log\sigma)^2}{2\underline{\lambda}^2}\frac{d\sigma}{\sigma^2}$$

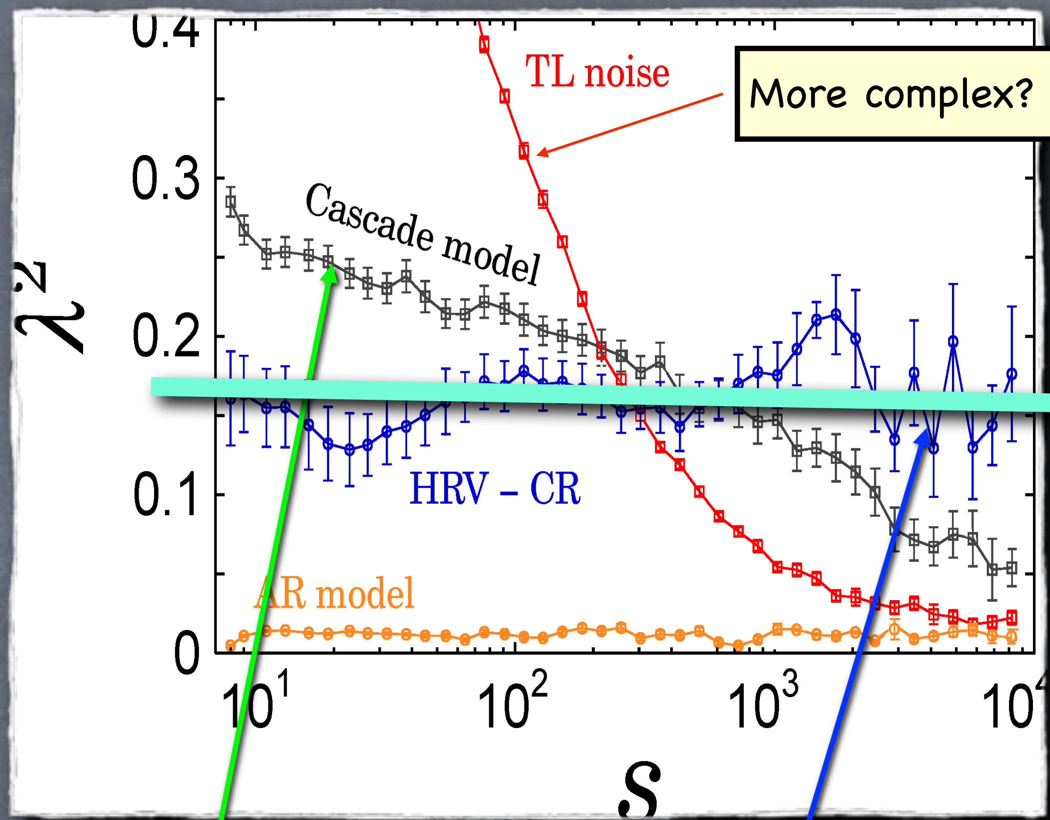
parameter





Is non-Gaussianity of the PDF sufficient to characterise complexity?





cascade ~ log(s)

CLT violation?

Central Limit Theorem (IID)
s^(0.5) convergence speed -
Berry-Esseen theorem
W.Feller book Vol. 2.

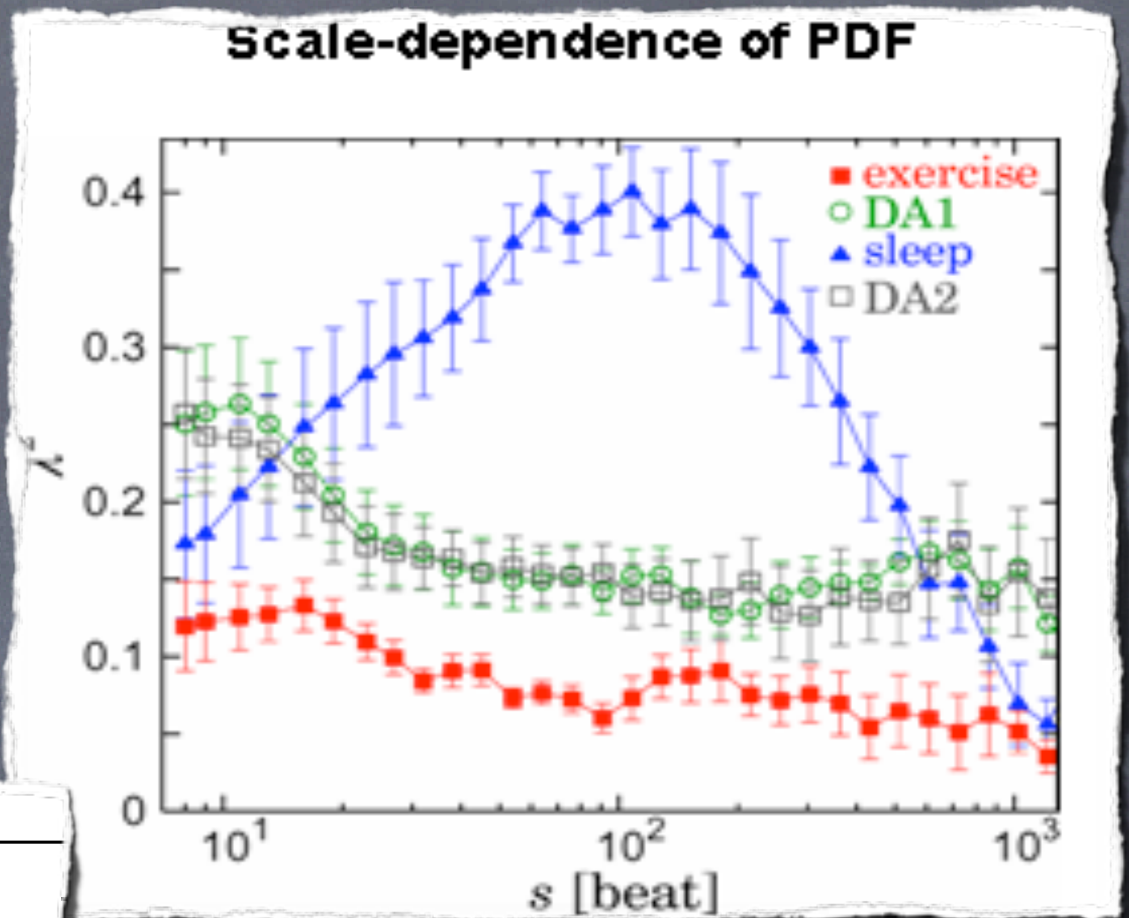
Multiplicative cascade

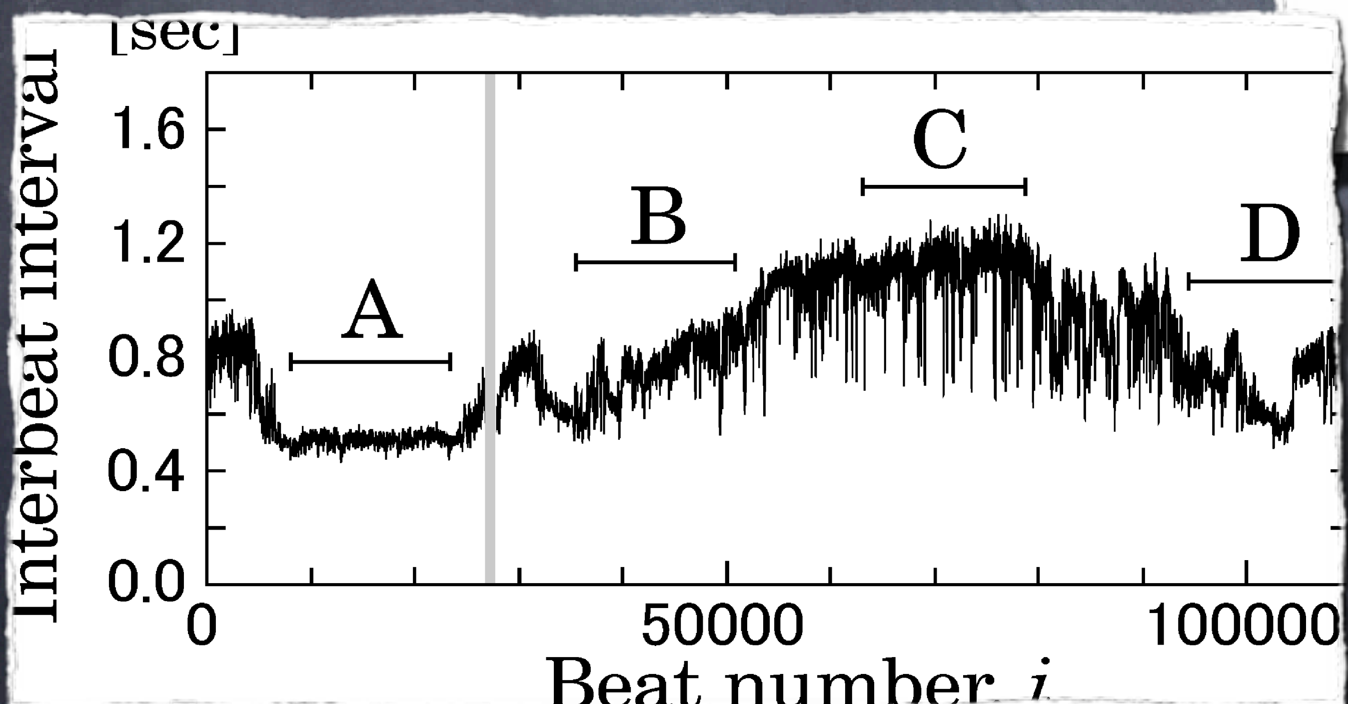
$\Downarrow$

scale invariant correlations

Phase transition in healthy human HRV - K. Kiyono et al, PRL 95, 2005.

- heartbeat intervals measured for 24 hours (13:00--)
- seven healthy subjects (mean age 25.3)
- three physiological states:
  - normal daily activity
  - experimental exercise
  - controlled sleep





also confirmed in a model
K. Kotani et al, PRE, 2005

Two point magnitude correlation function (Arneodo et al, PRL 1998)

Let's define local scalewise energy:

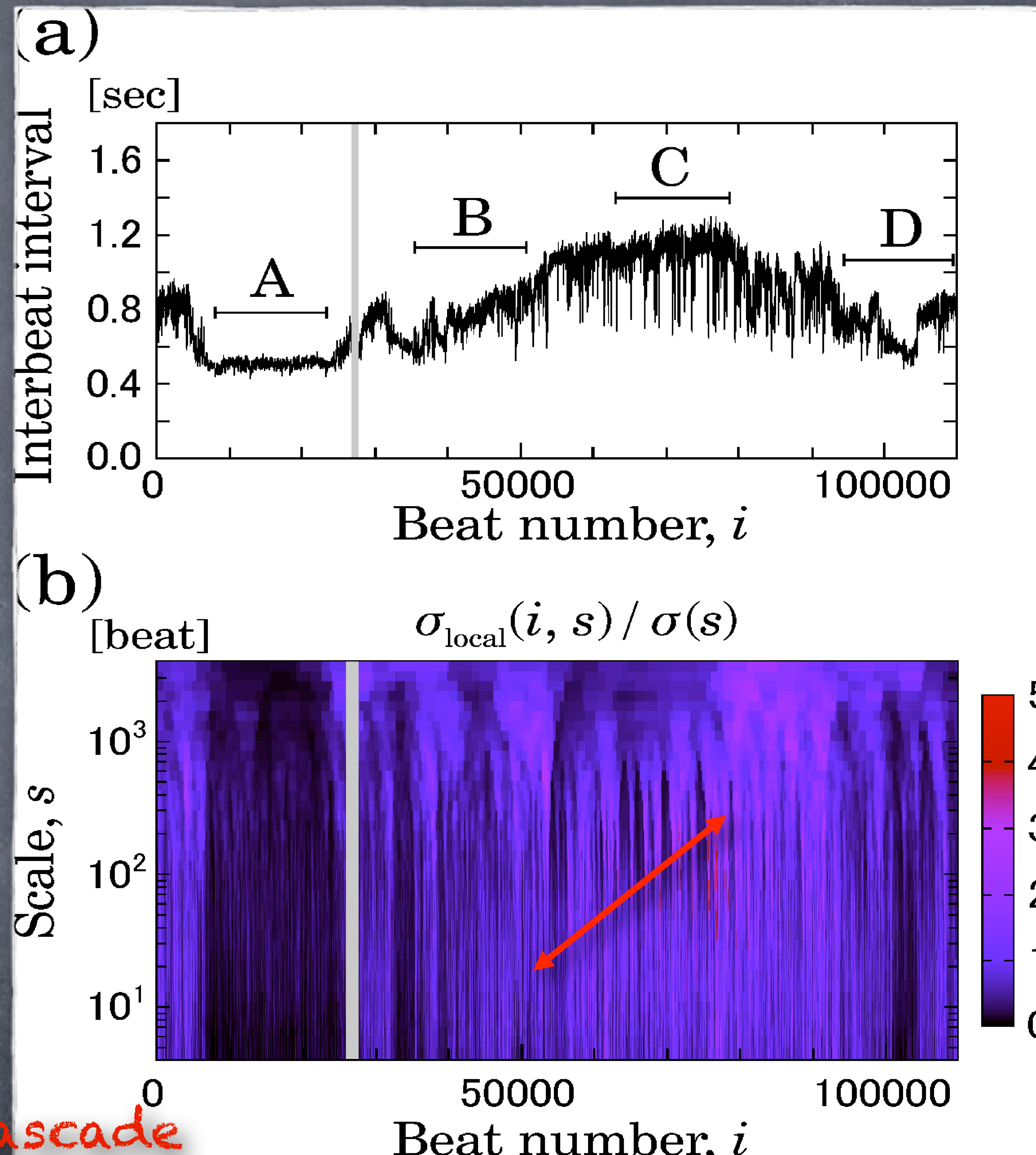
$$\sigma_s^2(i) = \frac{1}{s} \sum_{j=1+s(i-1)}^{si} \Delta_s B(j)^2$$

and its magnitude:

$$\bar{\omega}_s(i) = \frac{1}{2} \log \sigma_s^2(i)$$

The magnitude correlation function:

$$C(\tau, s_1, s_2) =$$
$$= \langle (\bar{\omega}_{s_1}(i) - \langle \bar{\omega}_{s_1} \rangle)(\bar{\omega}_{s_2}(i+\tau) - \langle \bar{\omega}_{s_2} \rangle) \rangle$$

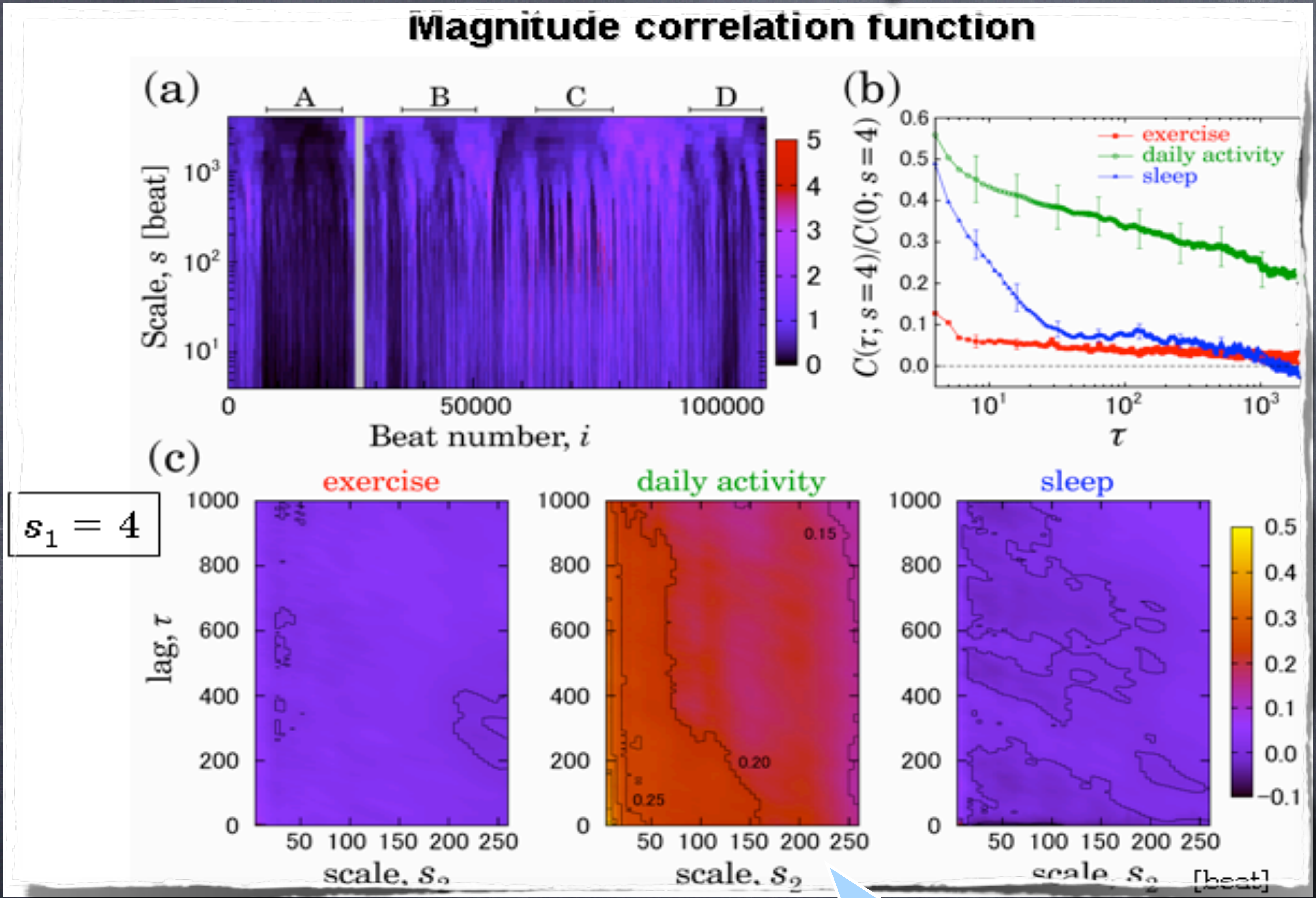


C is invariant for a multiplicative cascade

"one-scale" magnitude correlation: $s_1 = s_2$

"two-scale" magnitude correlation: $s_1 > s_2$

Phase transition scenario in healthy human HRV confirmed with two-point magnitude correlation function - K. Kiyono et al, PRL 95, 2005.



not scale invariant!

(Healthy) heart rate is multifractal, but not a cascade!

1/f noise

$\Downarrow$

criticality

Let the fingers do the walking

parasympathetic - (faster dynamics)

sympathetic (slower dynamics)

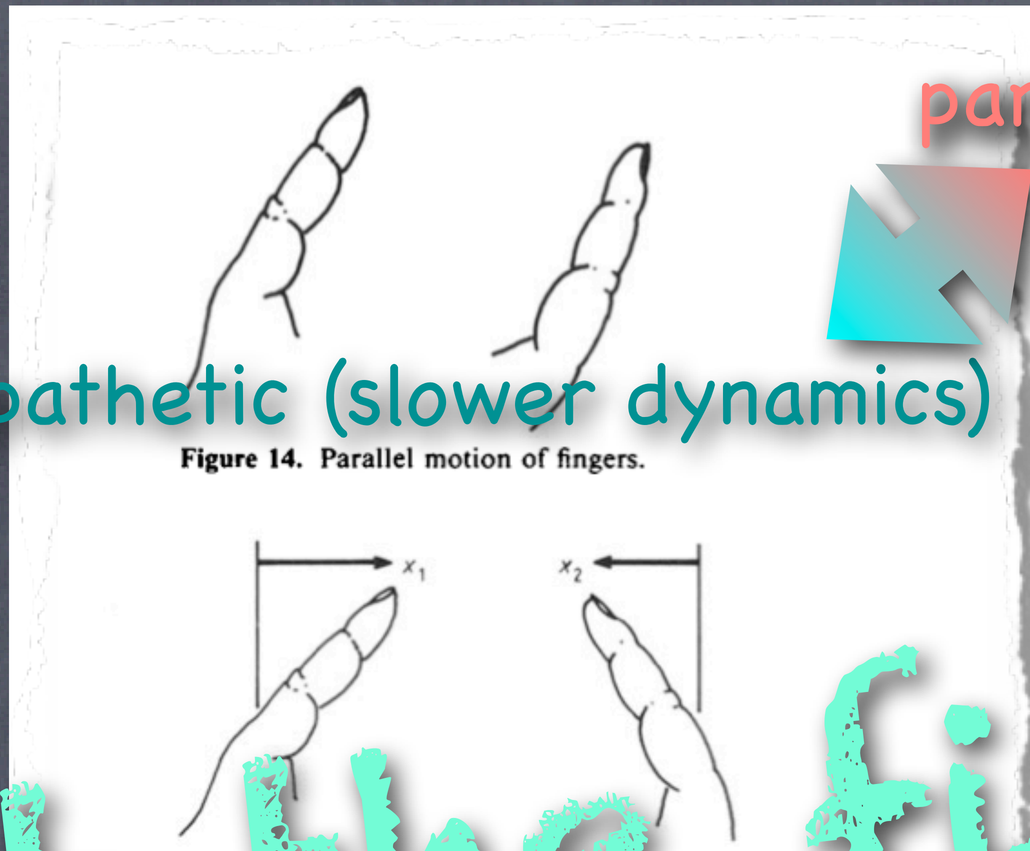
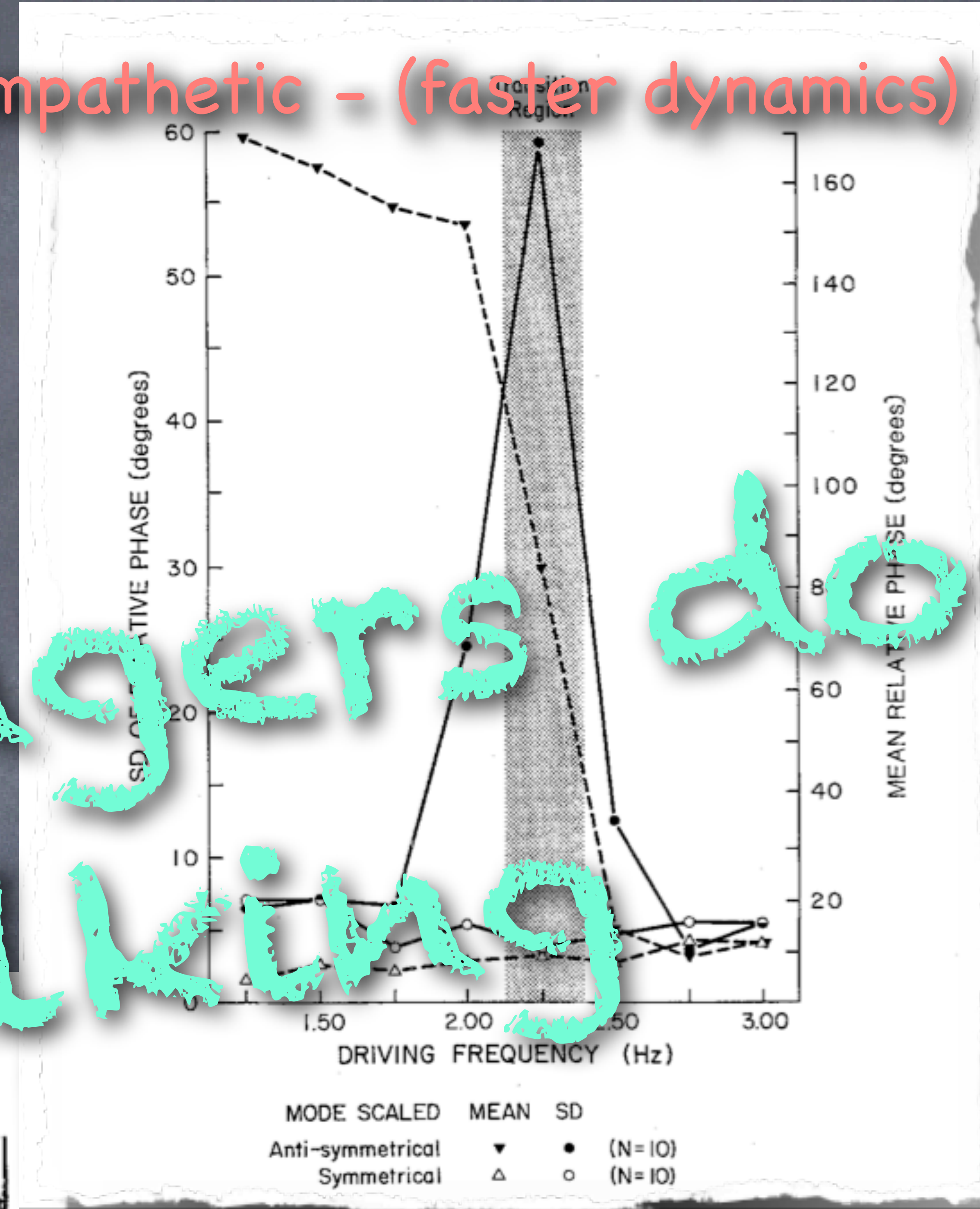


Figure 14. Parallel motion of fingers.

Figure ... motion of fingers.

Haken, Biol. Cyb. '85



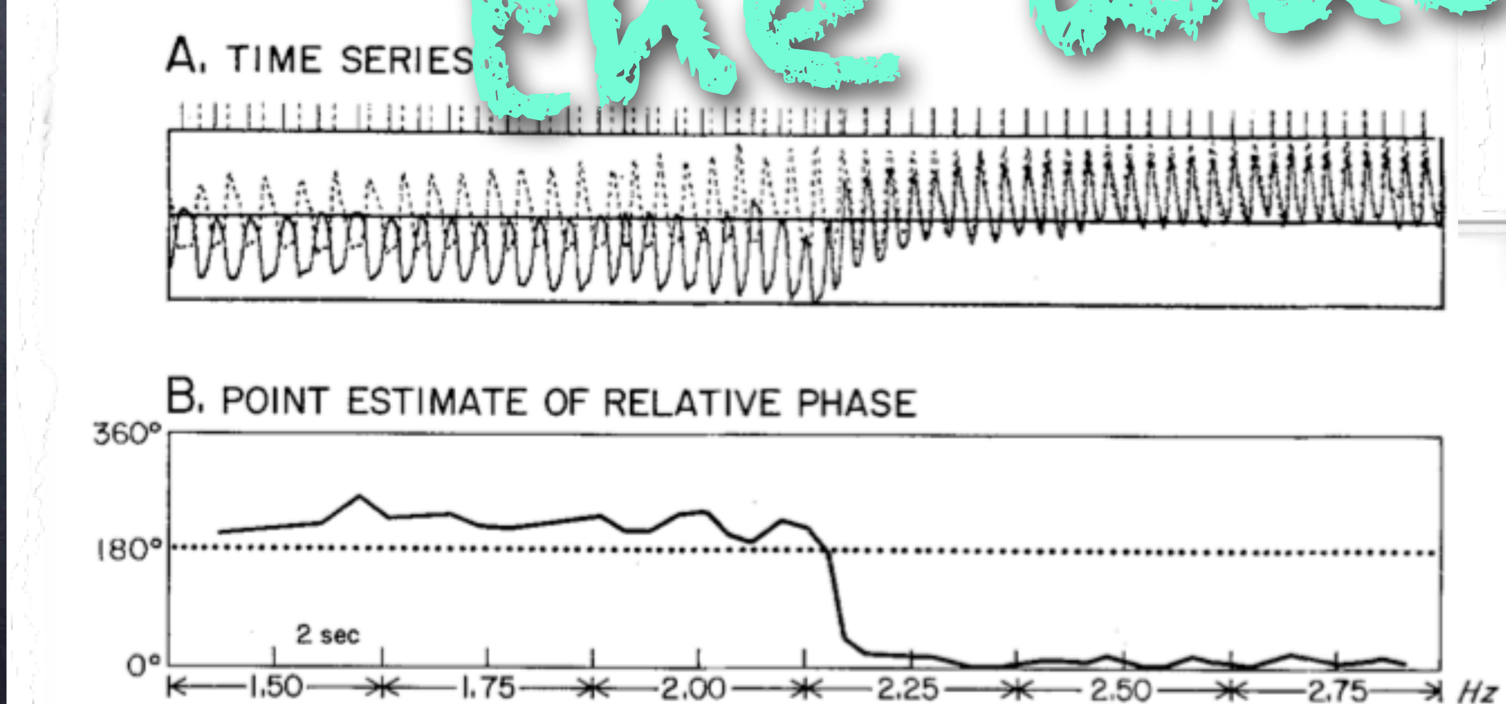


Fig. 1. **A** Time series showing position over time of left *(dashed line)* and right *(solid line)* index fingers as the control parameter, *F*, is systematically scaled. **B** The corresponding point estimate of relative phase, i.e., the phase of one finger's oscillatory peak relative to the other (see text for details)

the damped anharmonic oscillator

Haken, R 75

The beauty of physics is that we can describe incomprehensibly complex phenomena with very simple models:
soft modes/hard excitations, oscillatory behaviour caused by underdamping, accompany critical slowing down...

$$m \ddot{q} + \gamma \dot{q} = - \alpha q - \beta q^{3}$$

- coordinate q may stand for the coordinate of a particle, for its velocity, for the size of the charge, for the magnetization, for the electric field strength, etc.
- denote its mass by m, its damping constant by γ, the linear "restoring" force by $-\alpha q$, and we introduce the nonlinear restoring force $-\beta q$

soft modes

hard excitations

symmetry breaking

instability

critical slowing down

critical fluctuations (+ correlations)

slowing down of the dynamics occurs on approaching the (Hopf, pitchfork) bifurcation

the potential V characterises 'local' and 'global' stability

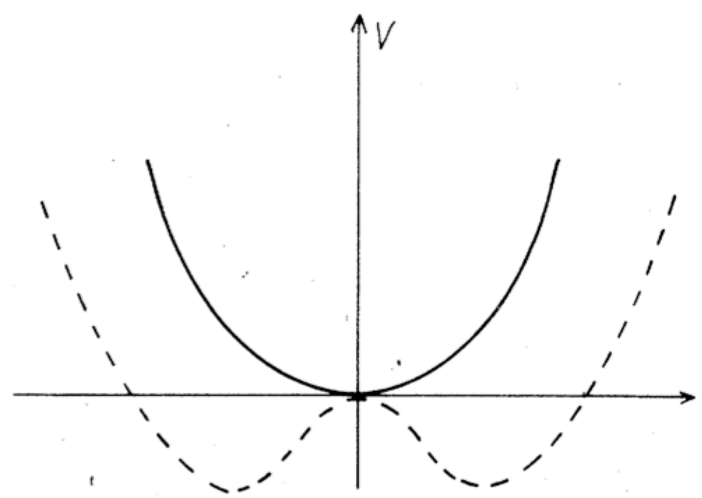


FIG. 1. The potential V (2.4) as a function of q for $\beta > 0$. Solid curve, $\alpha > 0$; dashed curve, $\alpha < 0$.

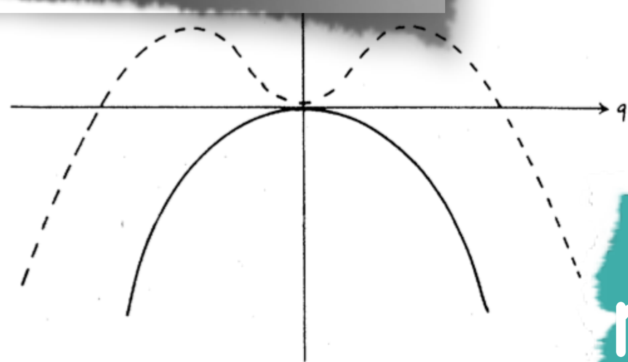
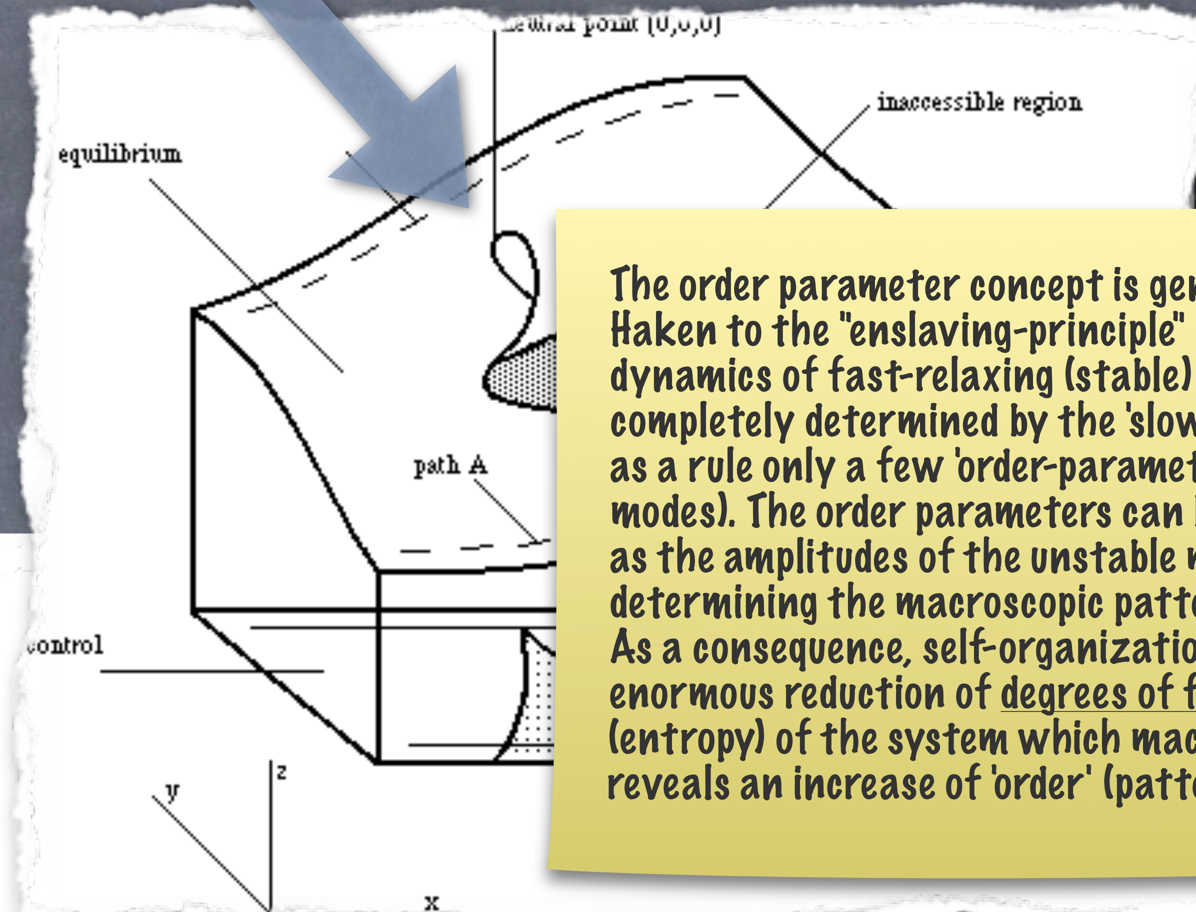


FIG. 2. The potential V (2.4) as a function of q fo[r] $\beta < 0$. Solid curve, $\alpha < 0$; dashed curve, $\alpha > 0$.



The order parameter concept is genera
Haken to the "enslaving-principle" say
dynamics of fast-relaxing (stable) mo
completely determined by the 'slow' d
as a rule only a few 'order-parameters
modes). The order parameters can be i
as the amplitudes of the unstable mod
determining the macroscopic pattern
As a consequence, self-organization w
enormous reduction of degrees of free
(entropy) of the system which macros
reveals an increase of 'order' (pattern

$$m\,\ddot{q} + \gamma\,\dot{q} = -\,\alpha q - \beta q^3$$

this is a generic paradigm

...hence, the field of 'synergetics' was born

...furthermore, the paradigm has a direct thermodynamical interpretation

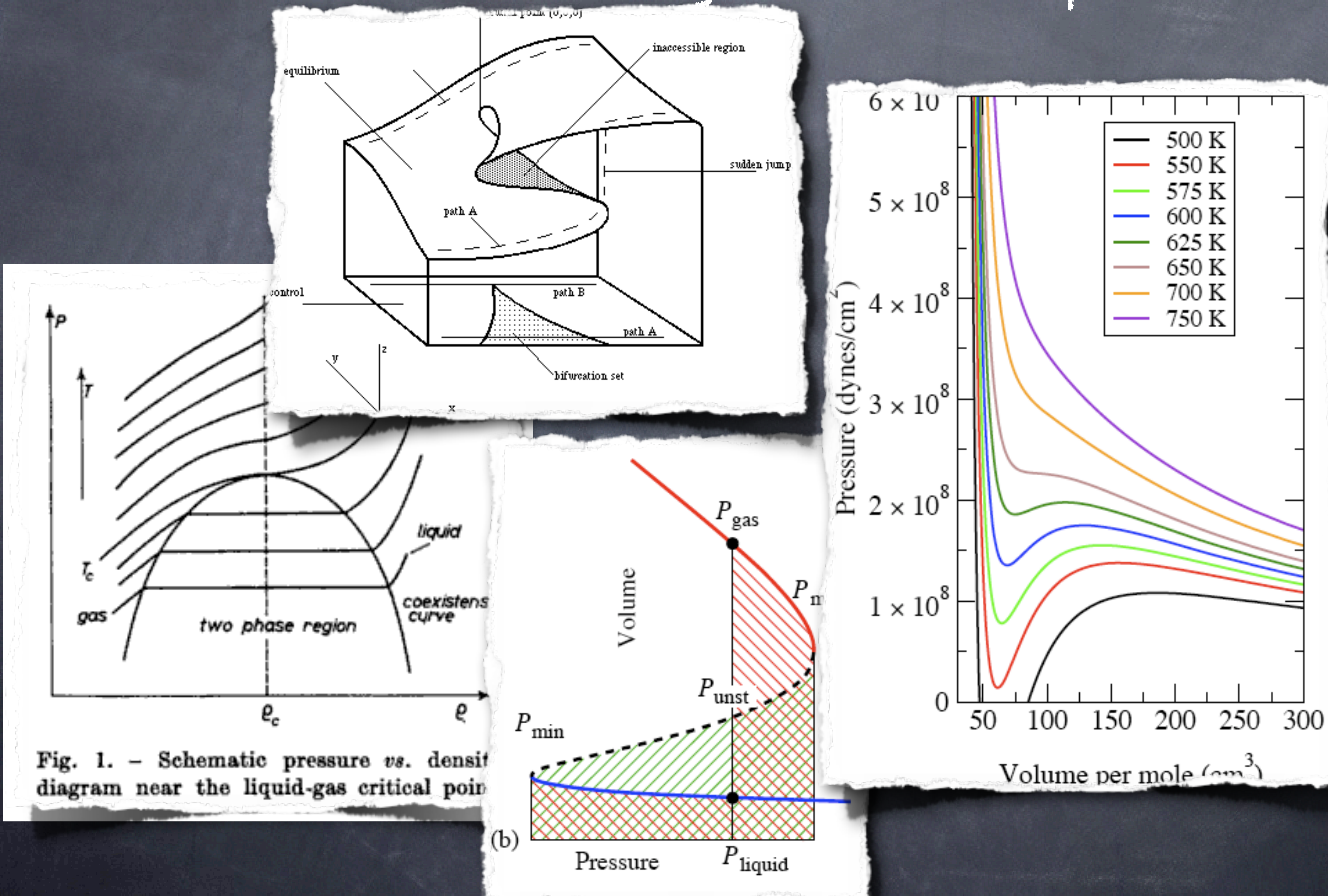
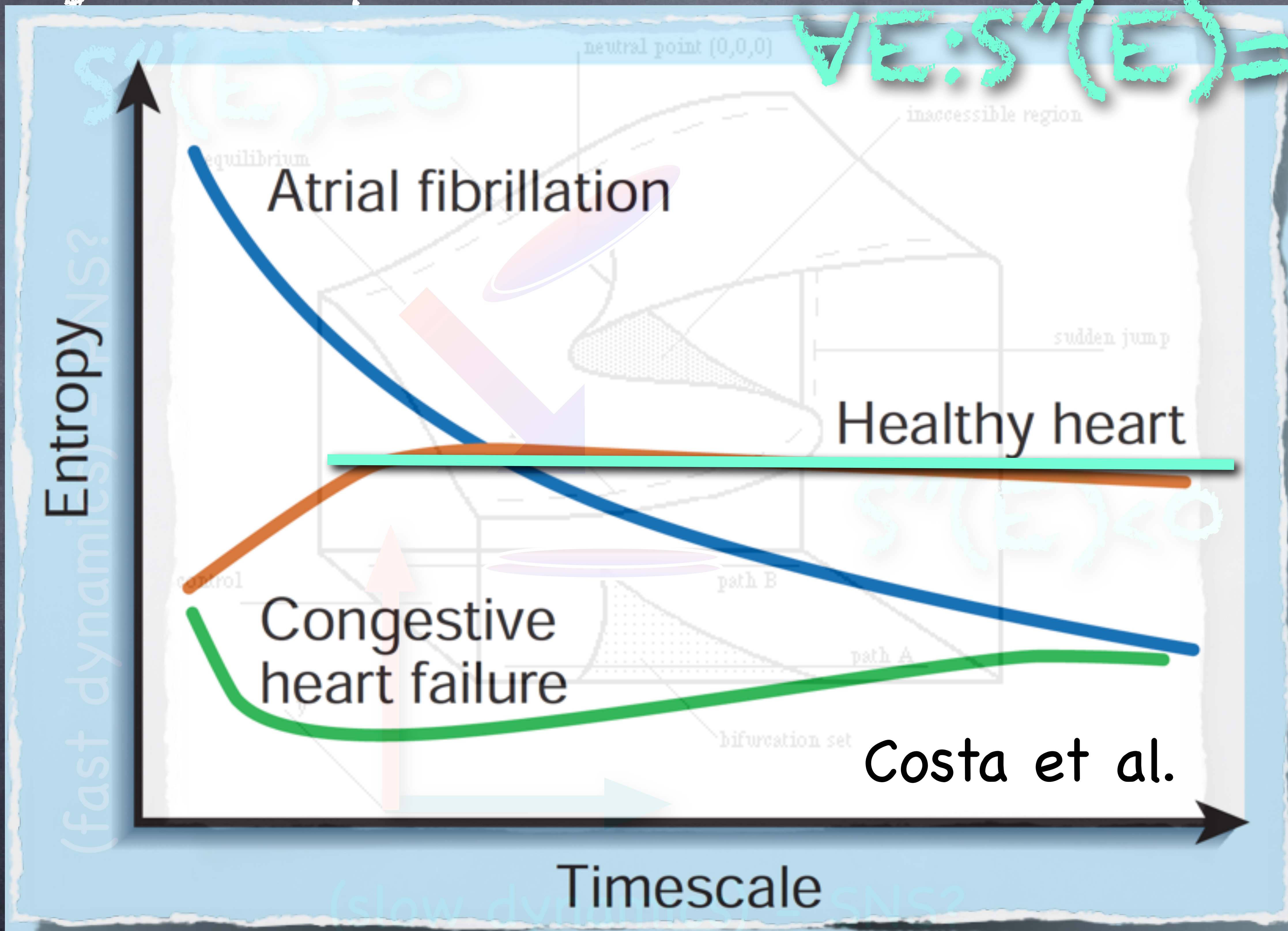


Fig. 1. – Schematic pressure *vs.* densit[y] diagram near the liquid-gas critical poin[t]

(Healthy) heart rate shows critical dynamics healthy heart operates in the self-organised critical regime

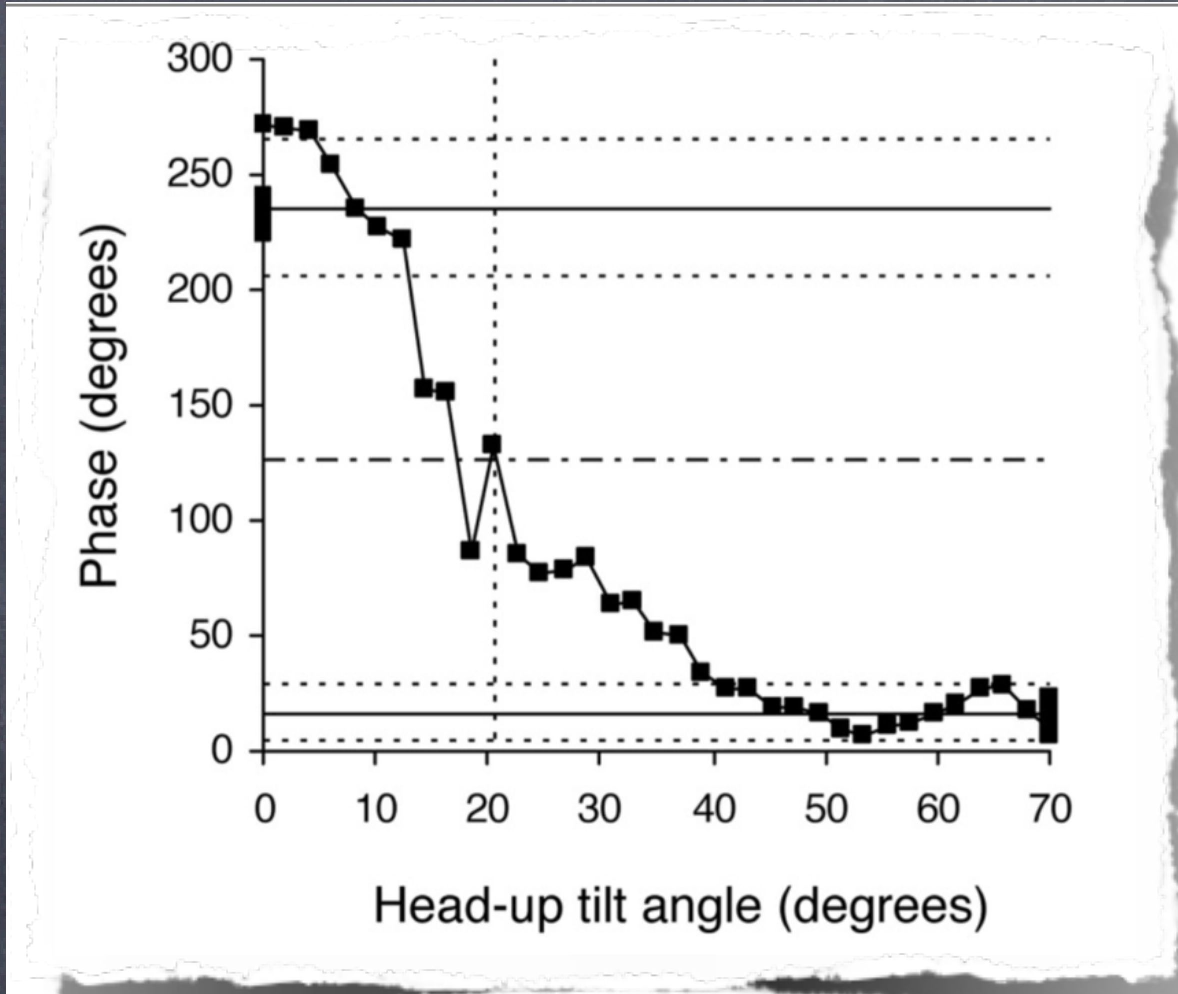
$\forall E: S''(E)=0$

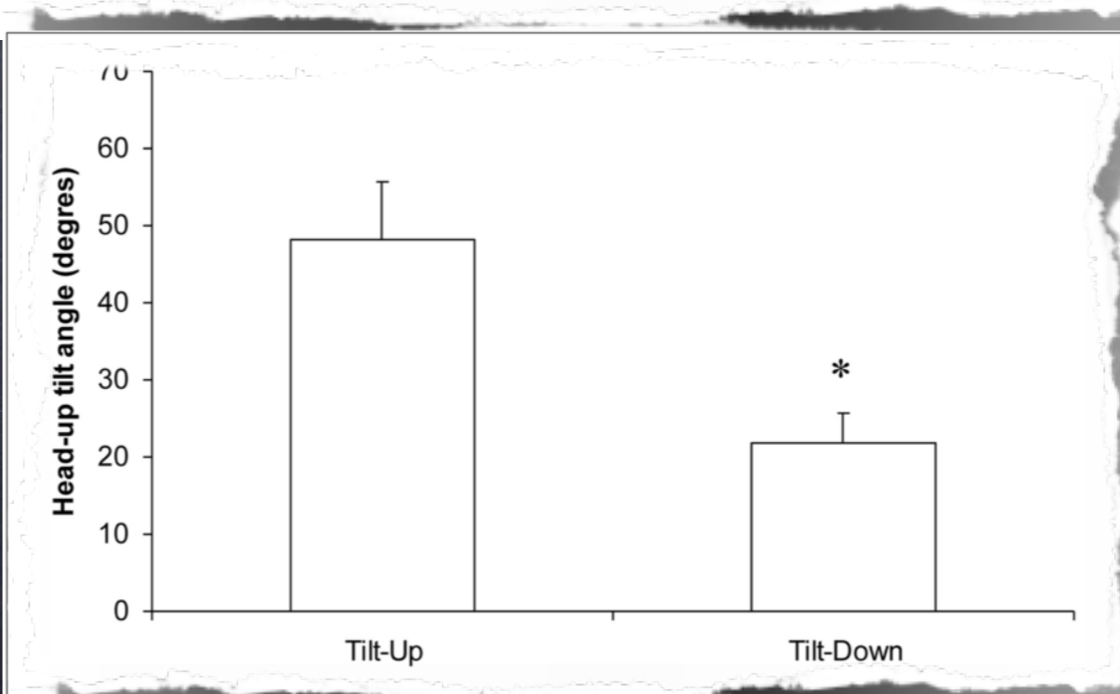


Entropy ~ Energy

$\Downarrow$

subextensive $\rightarrow 0$





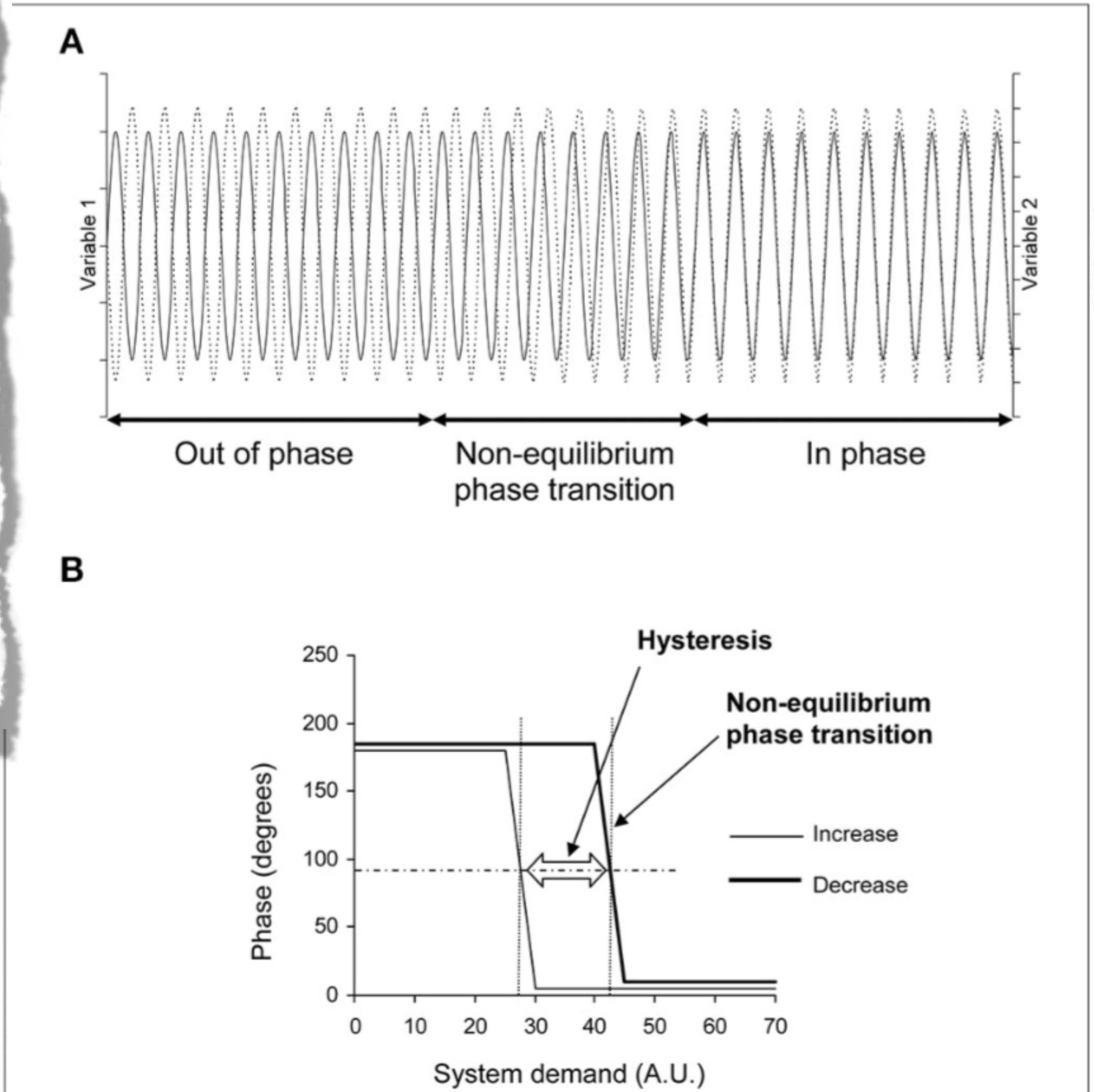
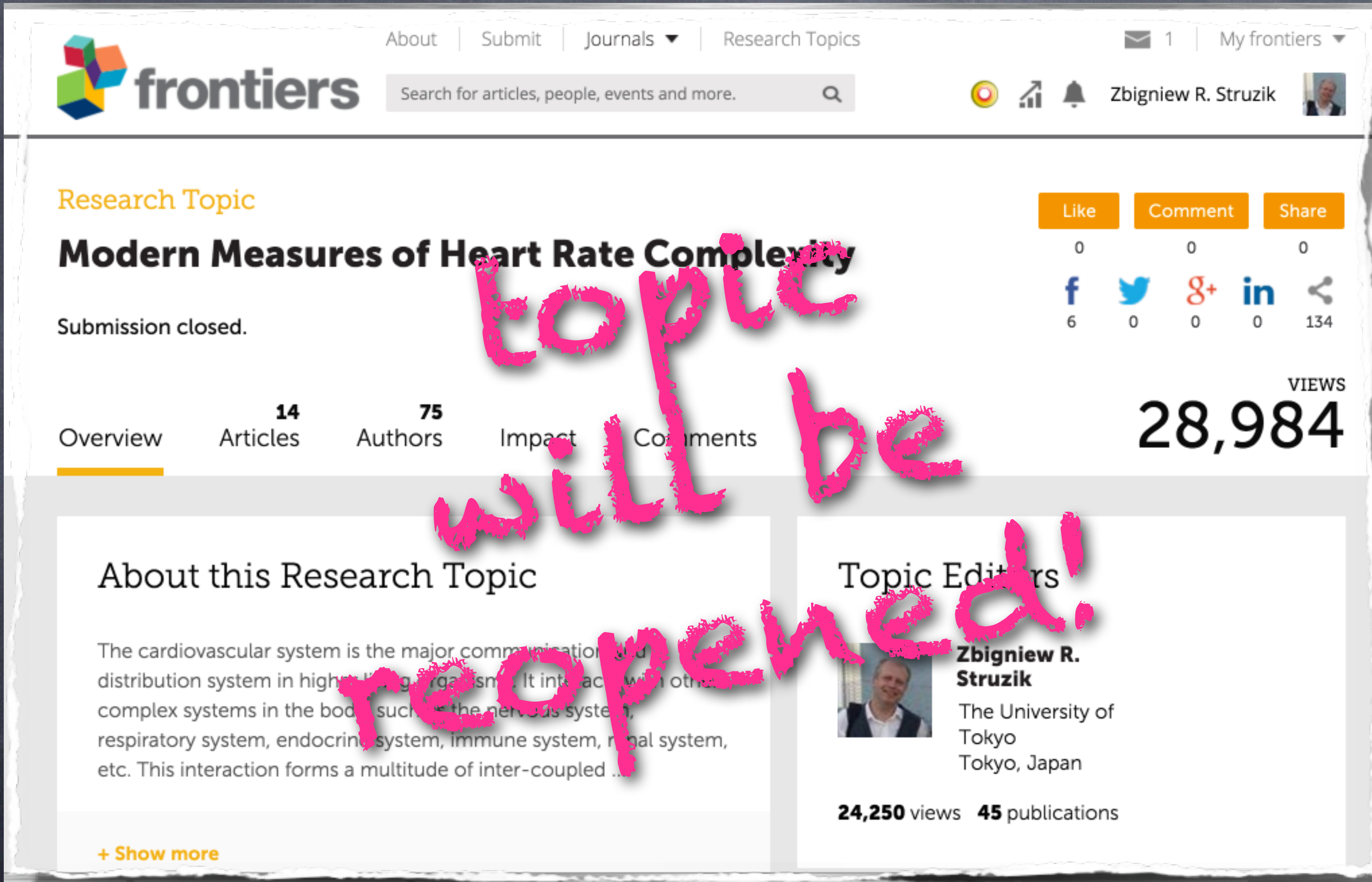


FIGURE 1 | Theoretical evolution of two variables related to two effectors of a self-organized system during demand increase and decrease on the system. (A) Oscillations of these variables in the time domain (x-axis) during demand increase on the system (for example). They are

cross spectral analysis between the RR-interval and Total Peripheral Resistances time series maybe?

yes!

Modern Measures of Heartrate Complexity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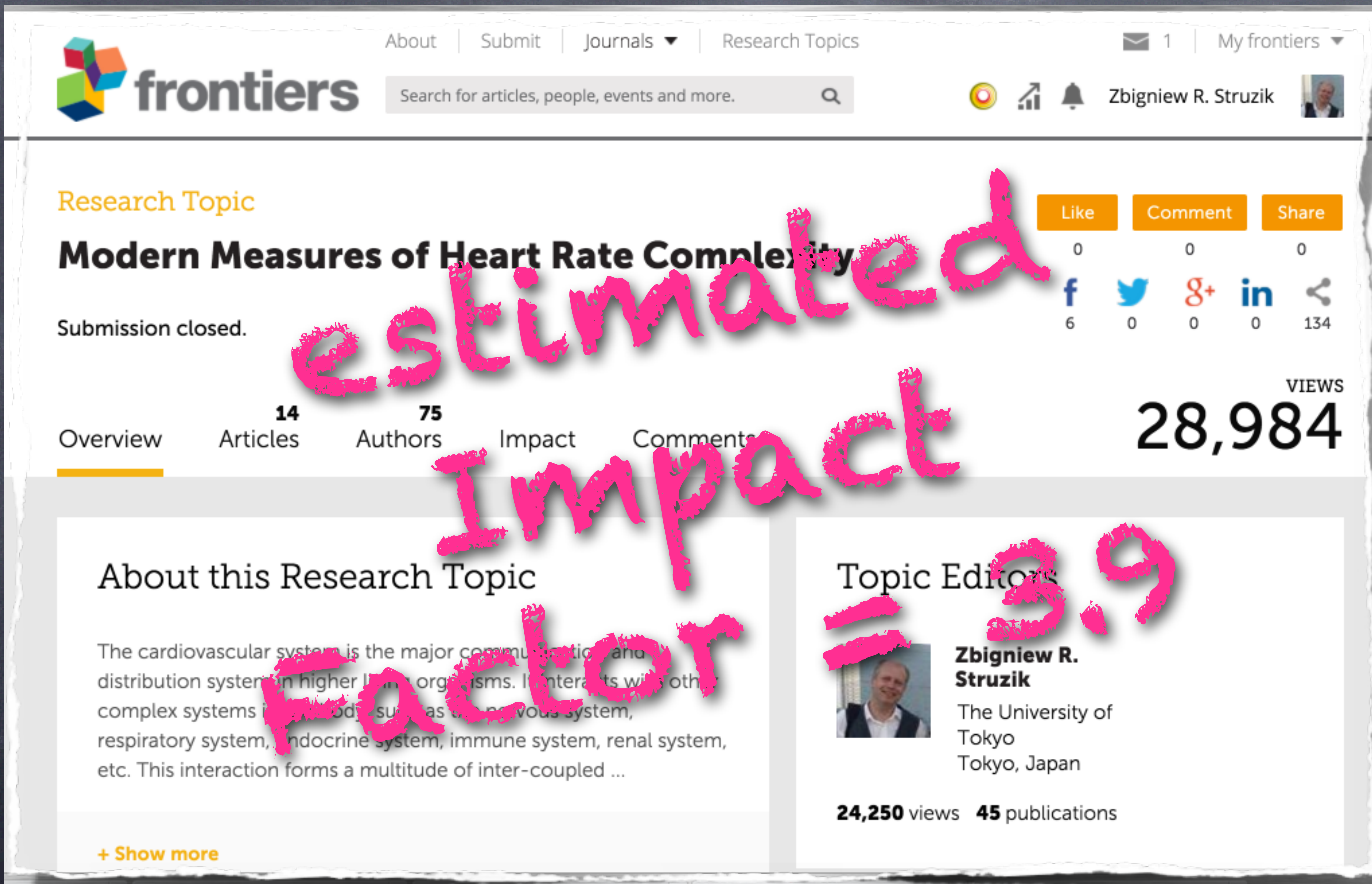
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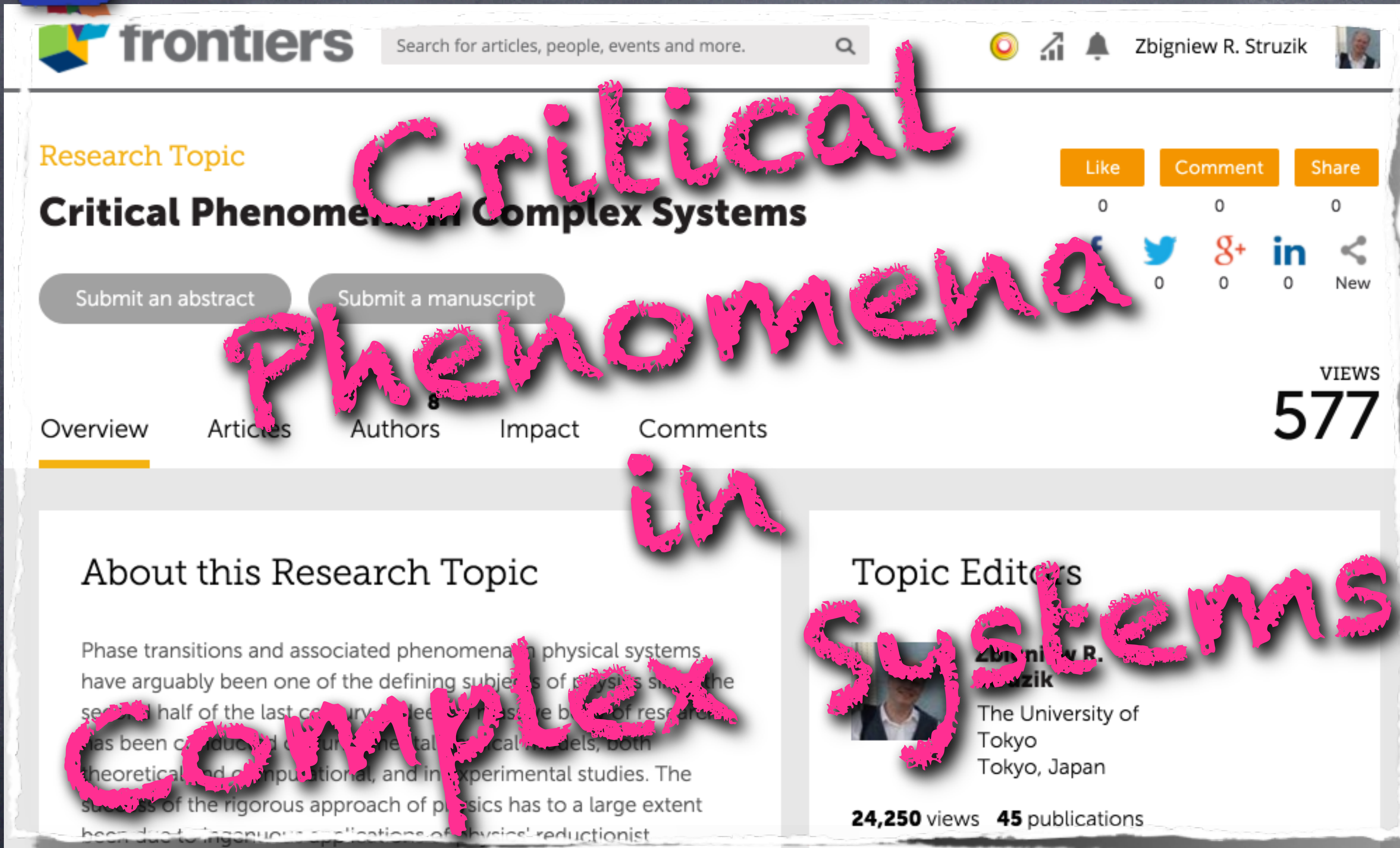
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✓critical opalescence
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