Connectivity and synchronization: comparison of neural observations and experiments with toy networks

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Two views on brain organization

Functional specialisation:

What regions respond to a particular experimental input?

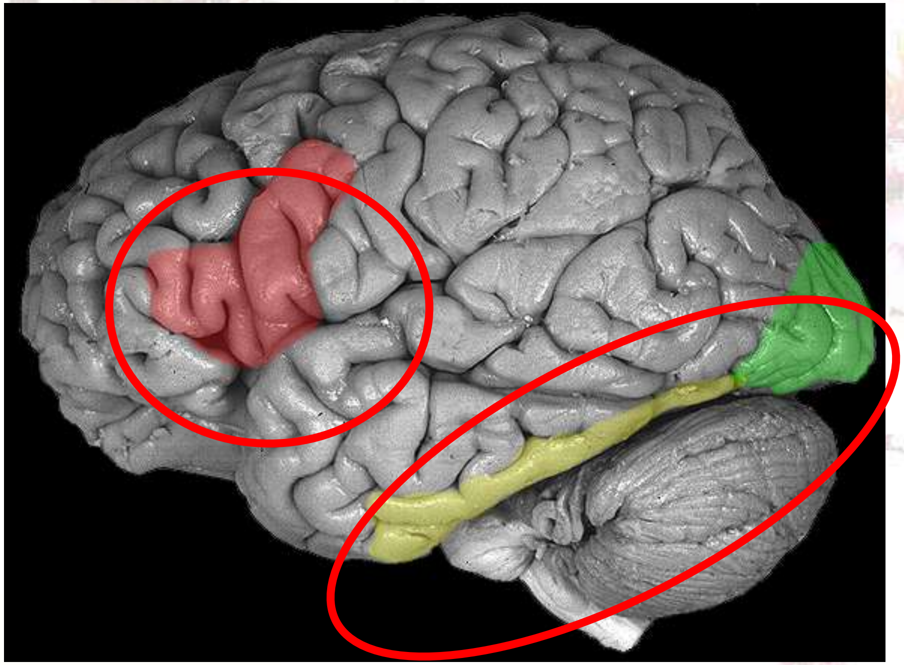


Image source: Sporns 2007, SPM Course

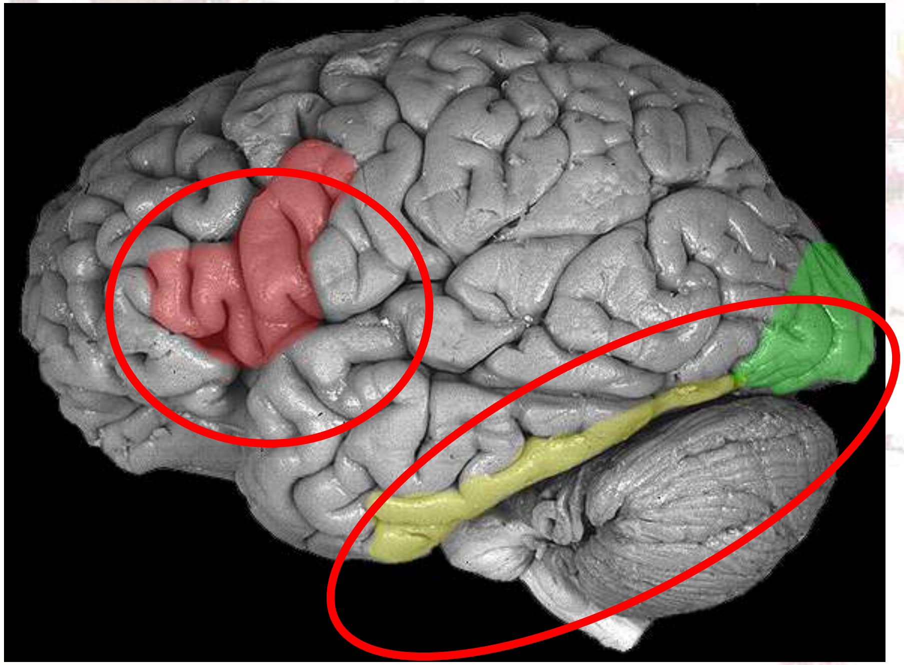
Two views on brain organization

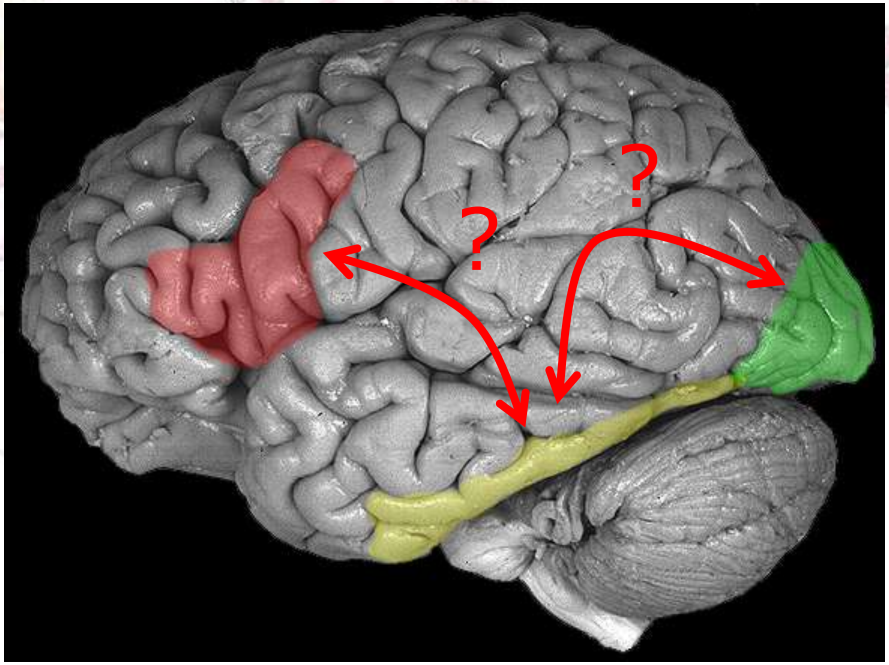
Functional specialisation:

What regions respond to a particular experimental input?

Functional integration:

How do regions influence each other? How does cognition <u>emerge</u> from interacting regions?





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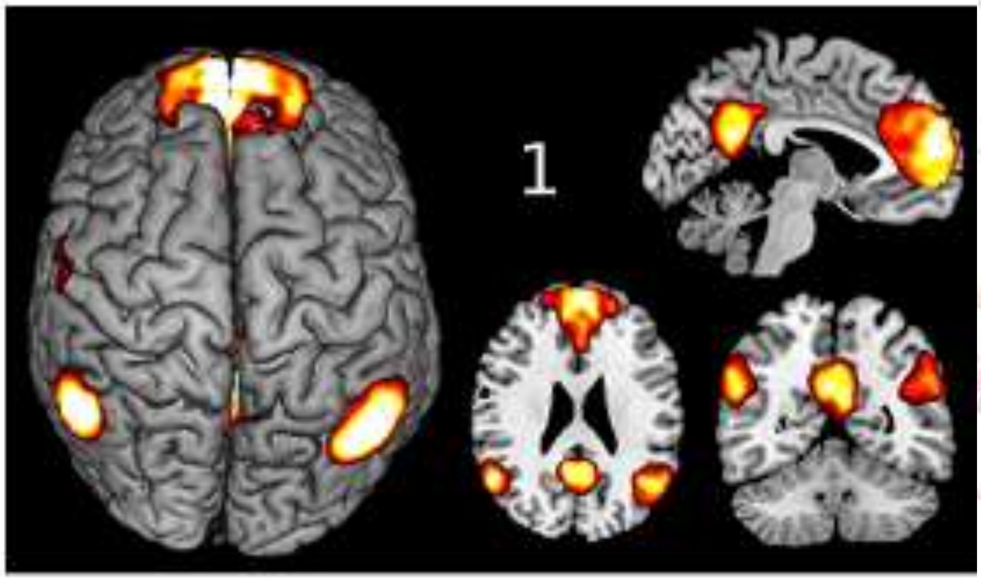
Topography to topology



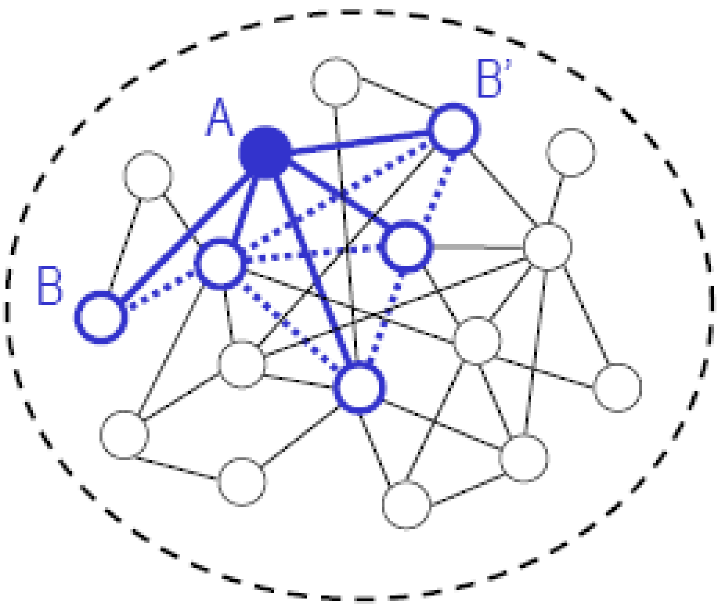


Image source: Eileen Kraemer, 2005; Rosazza & Minati, 2011; © Authors and Springer Verlag

Networks are everywhere

Network	*Nodes*	*Edges*
Internet	*routers*	*wires*
brain	*neurons*	*synapses*
WWW	*pages*	*hyperlinks*
Hollywood	*actors*	*movies*
gene regulation	*proteins*	*binding sites*
ecology web	*species*	*competition*

Image source: Eileen Kraemer, 2005

Properties of self-organized networks

Small-world-ness:

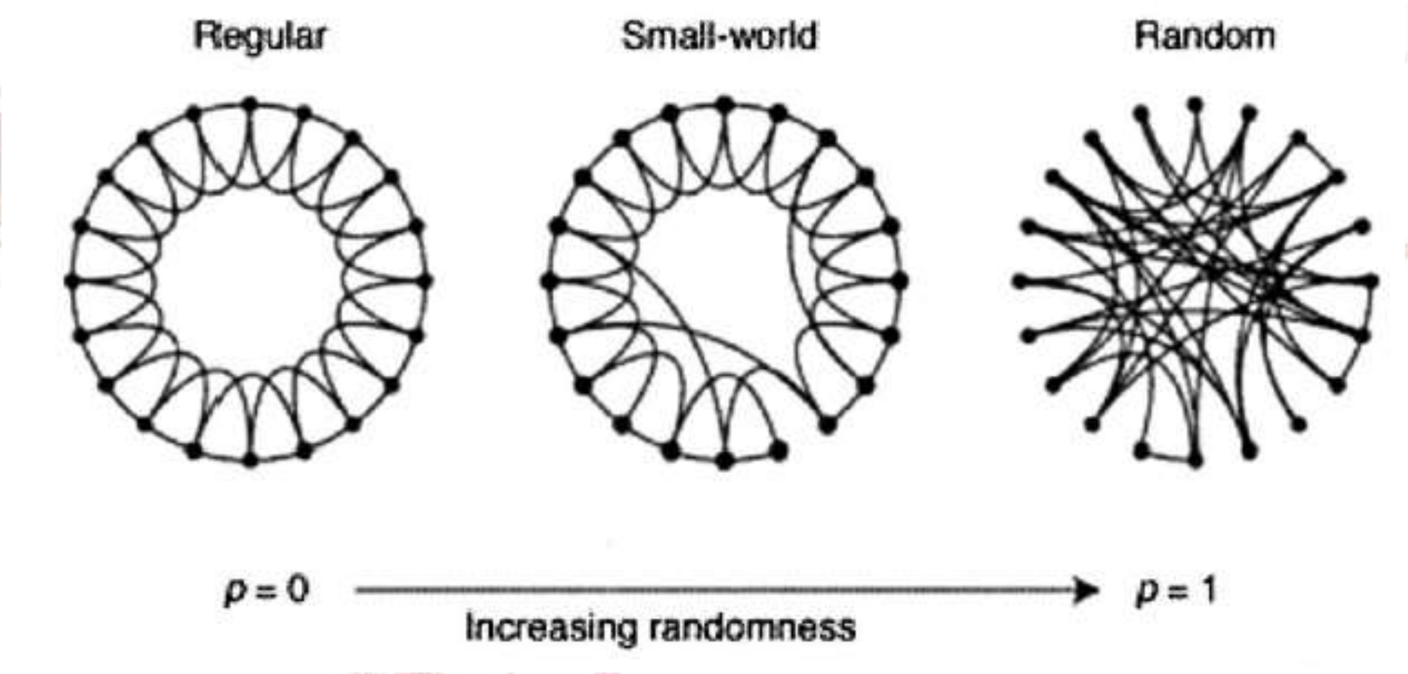


Image source: Jean Vaucher, 2005

Properties of self-organized networks

Scale-free-ness:

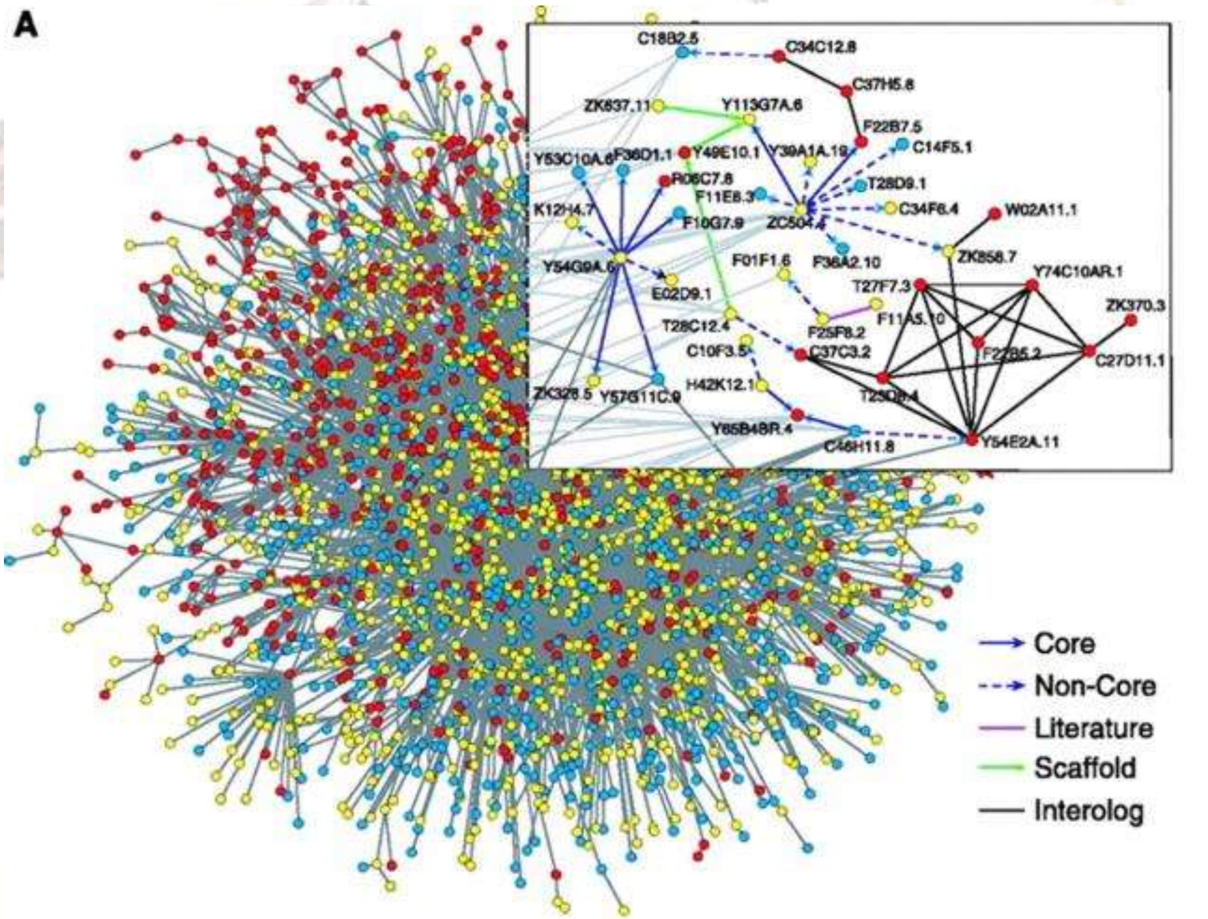
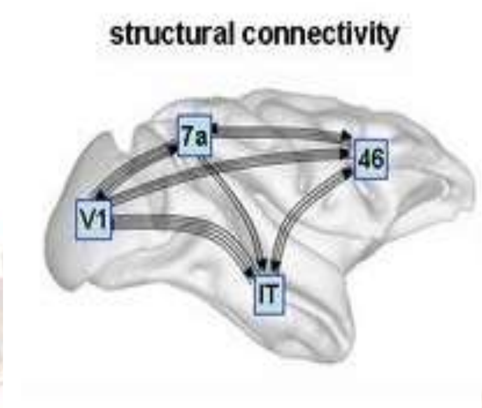


Image source: not known

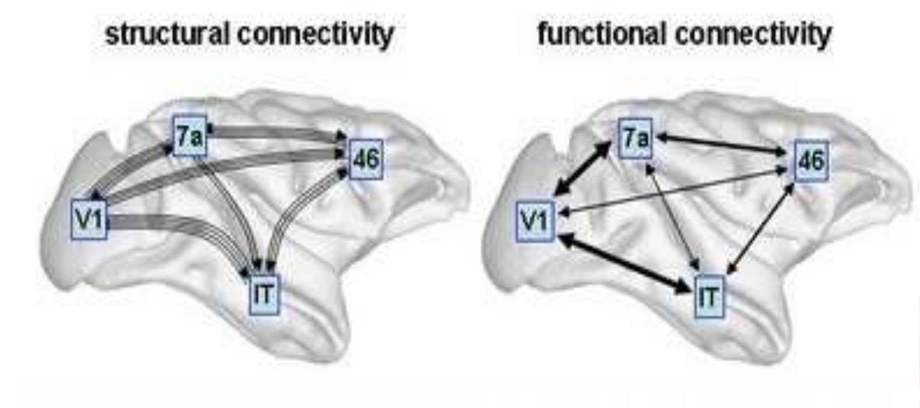
Three aspects of brain connectivity



- anatomical/structural connectivity
  = presence of axonal connections

Image source: Sporns 2007, SPM Course

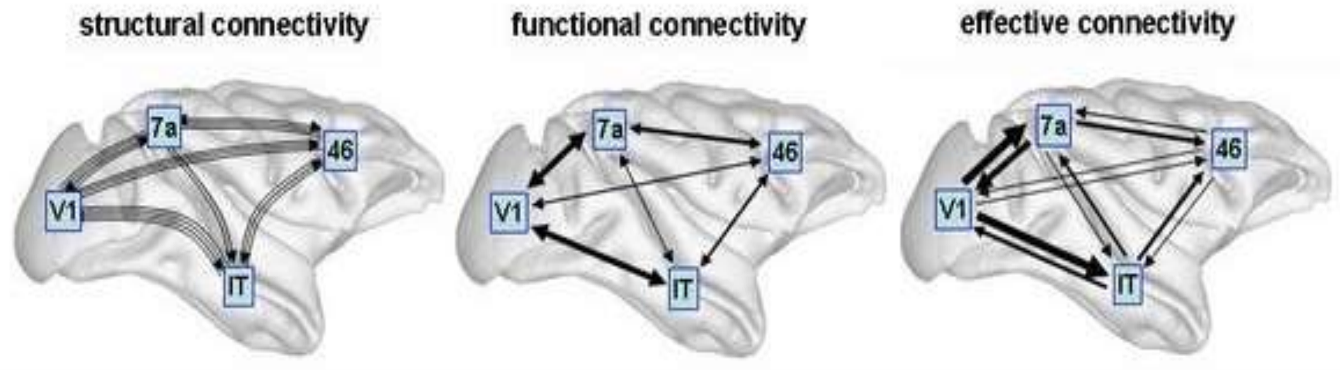
Three aspects of brain connectivity



- anatomical/structural connectivity
  = presence of axonal connections
- functional connectivity
  = statistical dependencies between regional time series

Image source: Sporns 2007, SPM Course

Three aspects of brain connectivity



- anatomical/structural connectivity
  = presence of axonal connections
- functional connectivity
  = statistical dependencies between regional time series
- effective connectivity
  = causal (directed) influences between neurons or neuronal populations

Image source: Sporns 2007, SPM Course

Brain connectivity and dynamics

Structural connectivity (i.e. physical links)

↓ Dynamics

Functional connectivity (i.e. synchronization)

Brain connectivity and dynamics

Structural connectivity (i.e. physical links)

Dynamics

Plasticity

Functional connectivity (i.e. synchronization)

Multiple scales

- *Microscale* (10^2-10^3 neurons)
  - Cortical (groups of) columns/microcircuits
  - Receptive field tiling, "building blocks" for larger circuits
- *Mesoscale* (10^5-10^7 neurons)
  - Gyral/sub-gyral circuits
  - Multi-sensory integration, associative functions
- *Macroscale* (10^9-10^{11} neurons)
  - Large-scale multi-gyral/bihemispheric circuits
  - Higher cognitive functions, consciousness

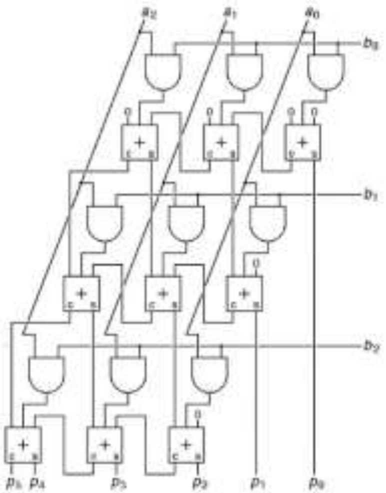
Topological and dynamical properties

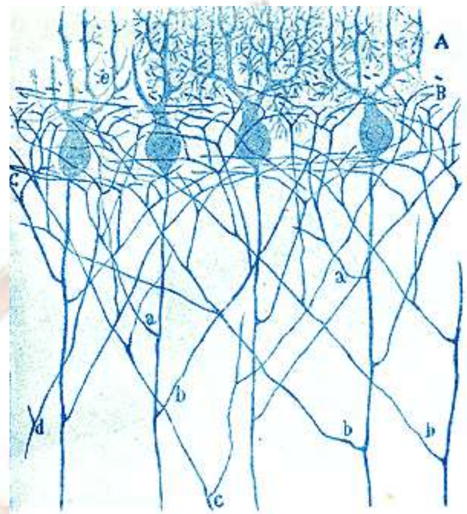
- *Topology*
  - Modularity
  - Scale-free-ness
  - Small-world-ness

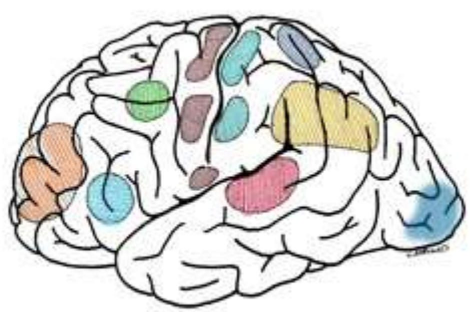
- *Dynamics*
  - Non-linearity
  - Possible chaoticity
  - Criticality

The brain is totally unlike a digital computer

Design vs. Emergence







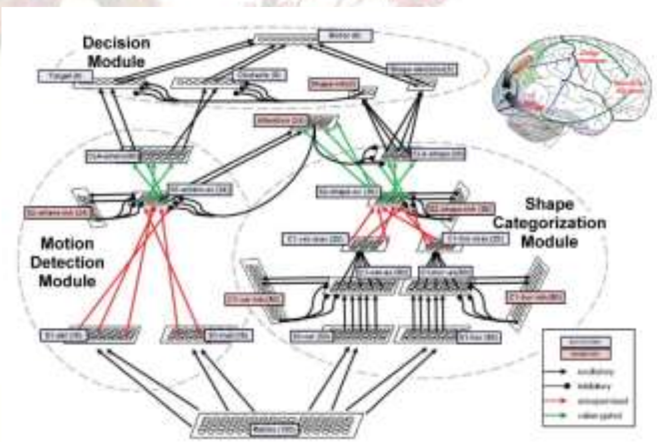
J. Von Neumann
1903-1957

A. Turing
1912-1954

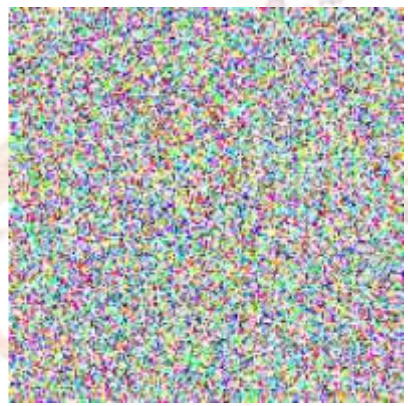
Image credit: Wikipedia, others

Is there anything *physically* unique about it?

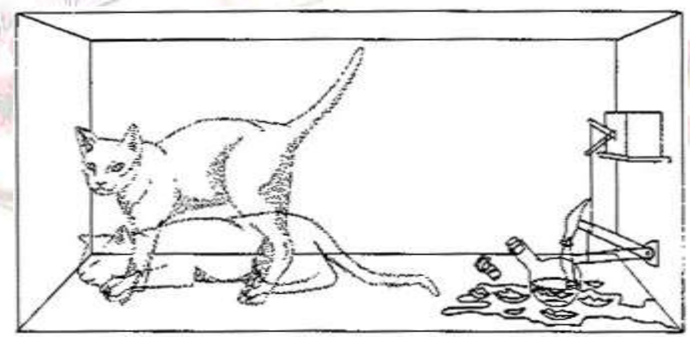
Cartesian determinism



Stochastic



Quantum



Seemingly, everywhere one looks, there is a paradox...

Image credit: Wikipedia, DARPA, others

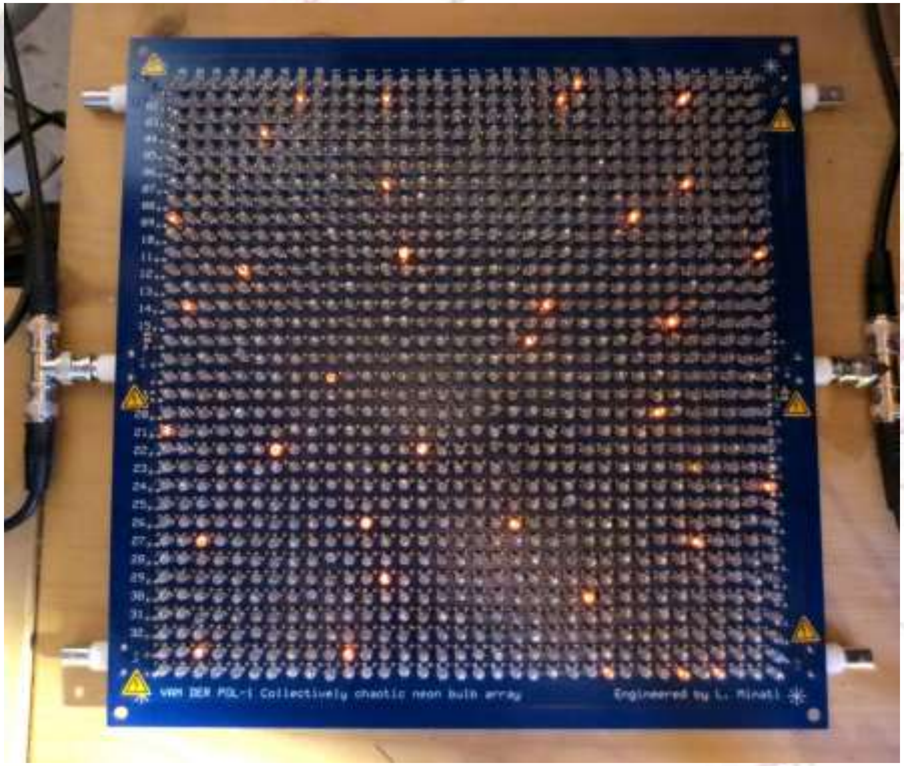
Centrality and universality of emergence

Whole (collective behavior) >> Sum of parts (elemental dynamics)

Image credit: Wikipedia, others

Why compare to other *physical* systems?

e.g. non-linear electronics



Numerical simulation

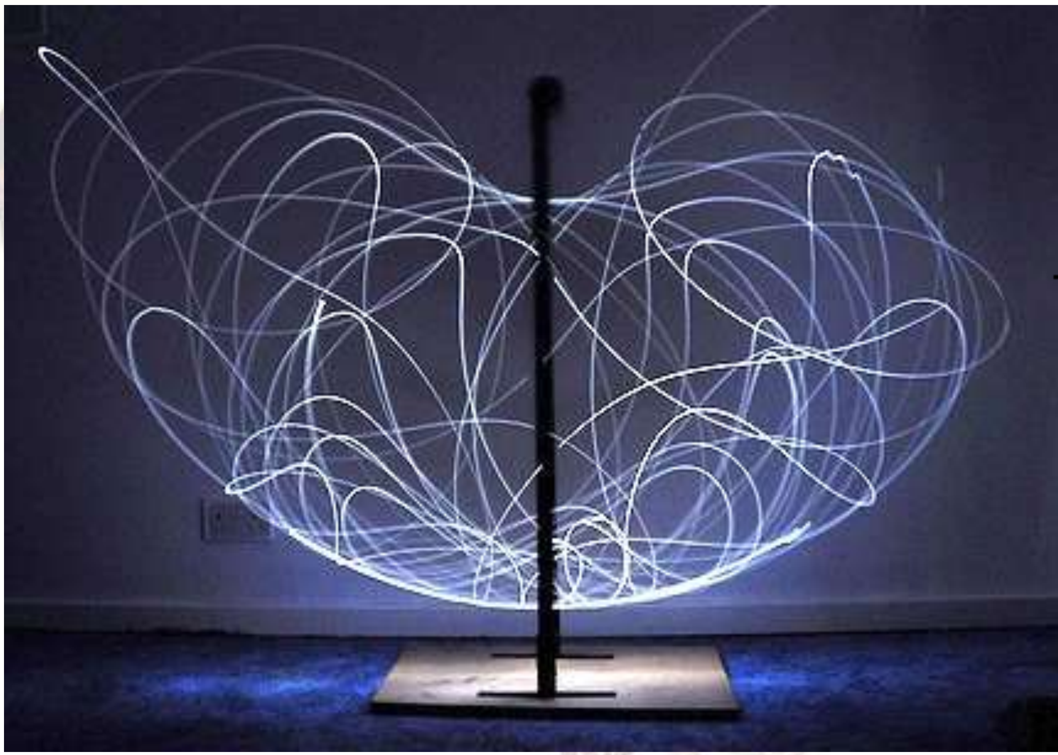
Why compare to other *physical* systems?

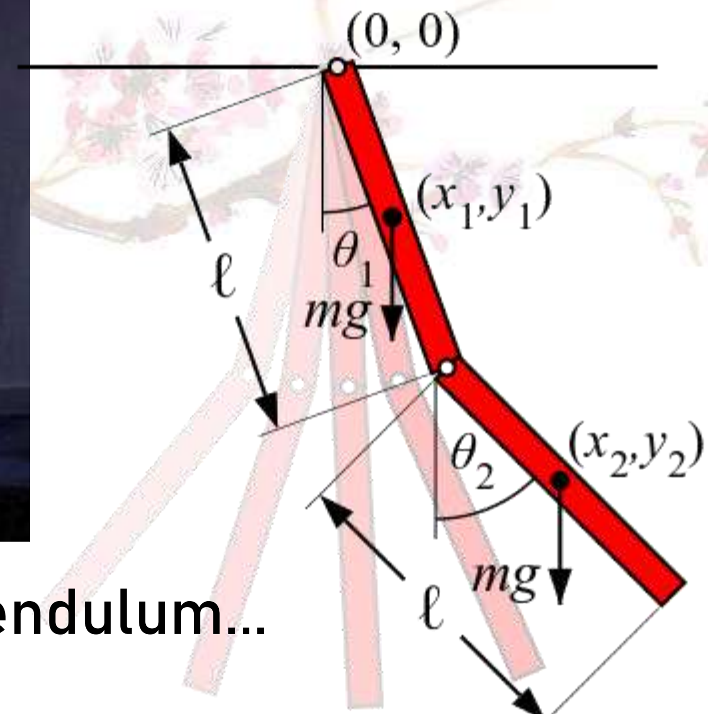
In non-linear physical systems the emergence of global properties often fundamentally influenced by "nuances" such as:

- Parametric mismatches between constituent elements,
- Electrothermal noise in the oscillatory variables,
- Noise in the dynamical parameters,
- Non-ideal behaviours such as presence of "parasitic" elements,
- Lack of discretization and so on.

Not at all trivial to capture numerically!

Why would chaotic networks be interesting?





A classic example: the double-rod pendulum…

Why would chaotic networks be interesting?

Rapid divergence… but it is not the main point…

$$x(t) = f^t(x_0)$$

$$x(t) + \delta x(t) = f^t(x_0 + \delta x_0)$$

$$\| \delta x(t) \| \approx e^{\lambda t} \| \delta x_0 \|$$

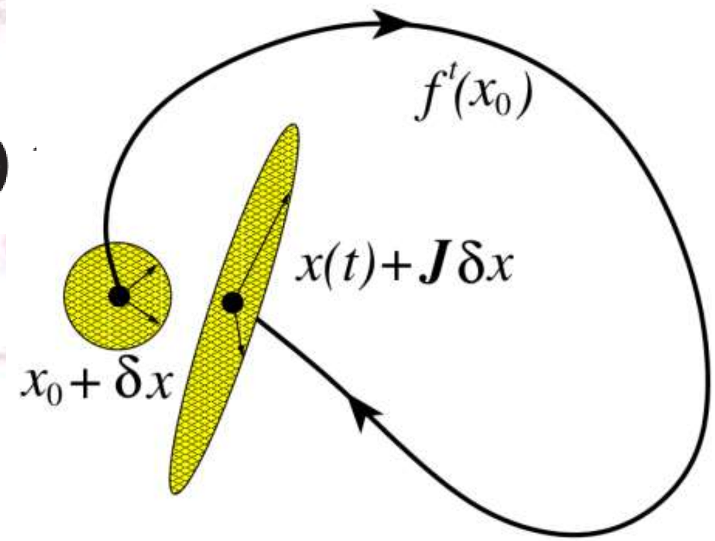
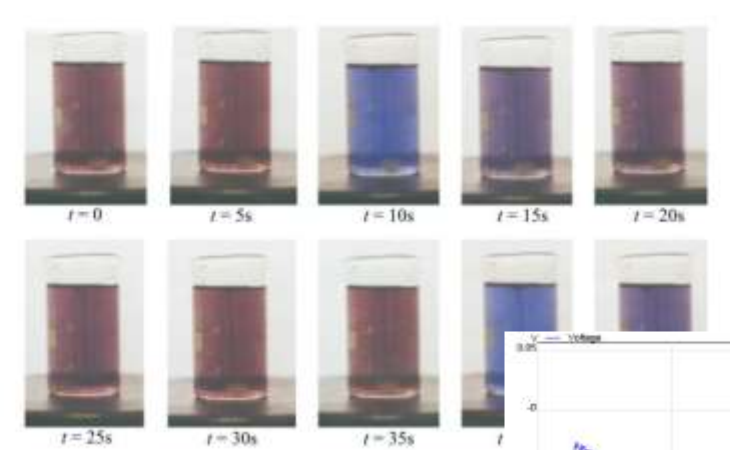


Image credit: Chaosbook.org

Why would chaotic networks be interesting?

Self-organization: paradigmatic case of the Belousov-Zhabotinsky reaction



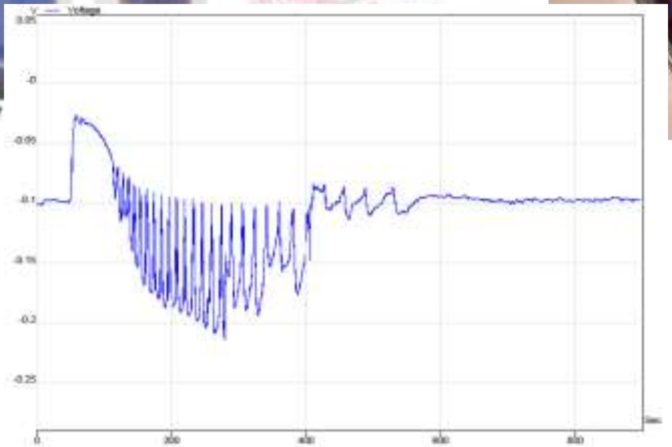
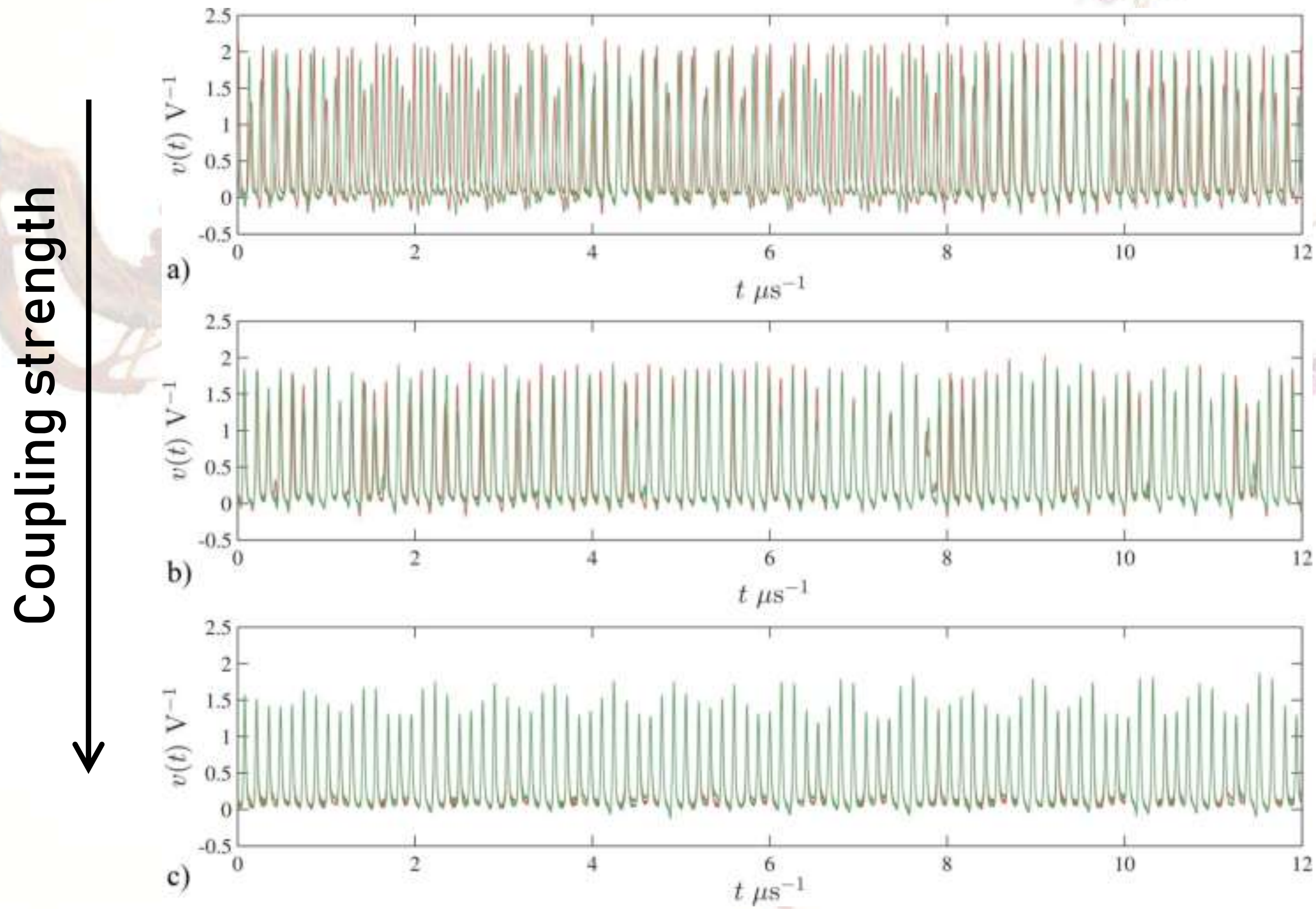
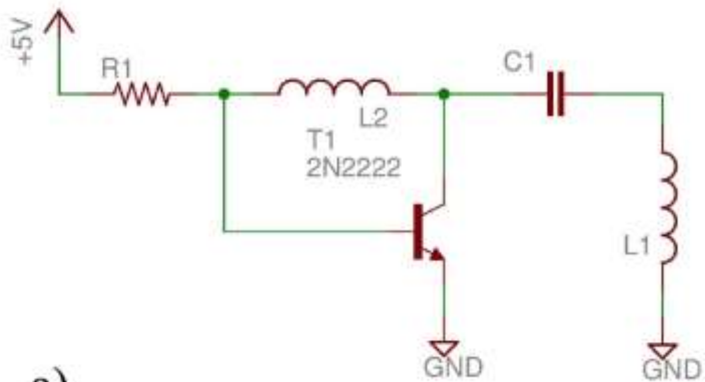


Image credit: Wikipedia, others

Chaos synchronization

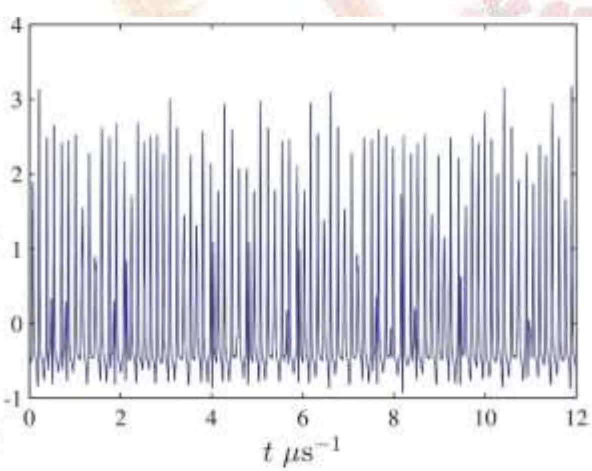


Complexity in simple transistor circuits

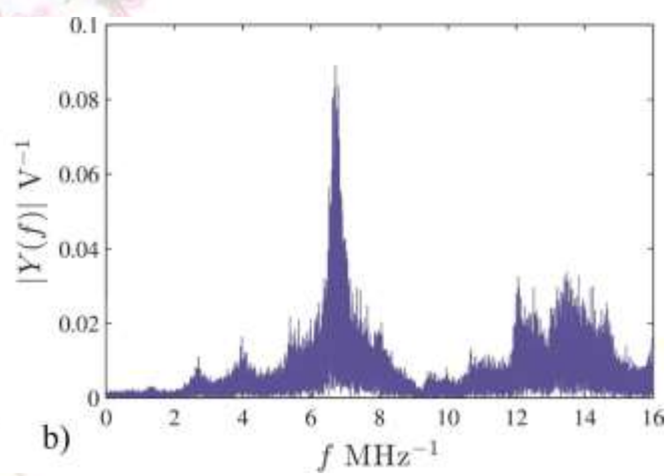


a)

b)



a)



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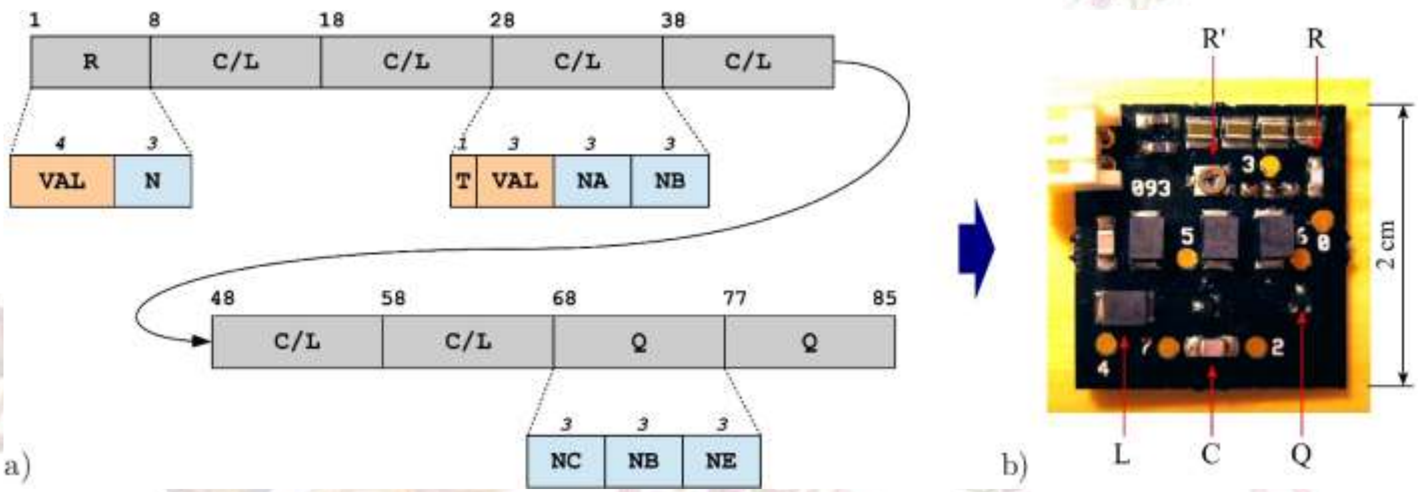
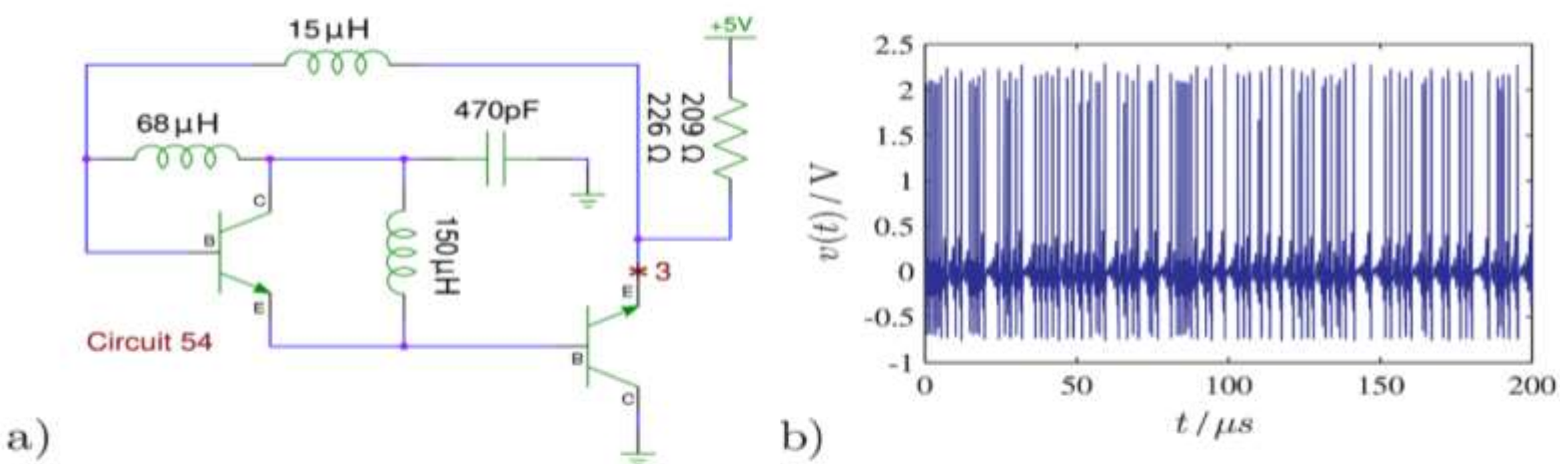
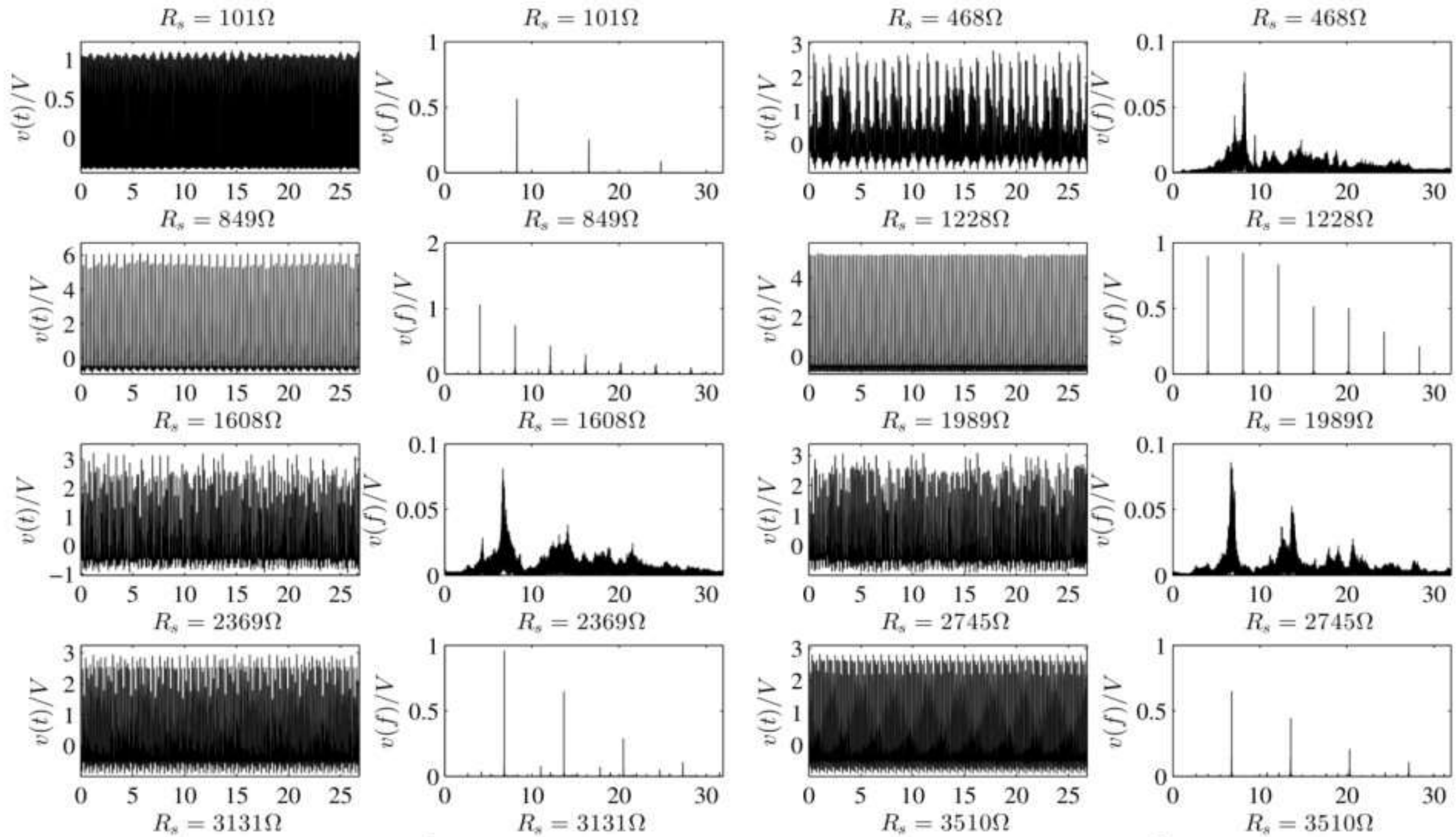
Complexity in simple transistor circuits

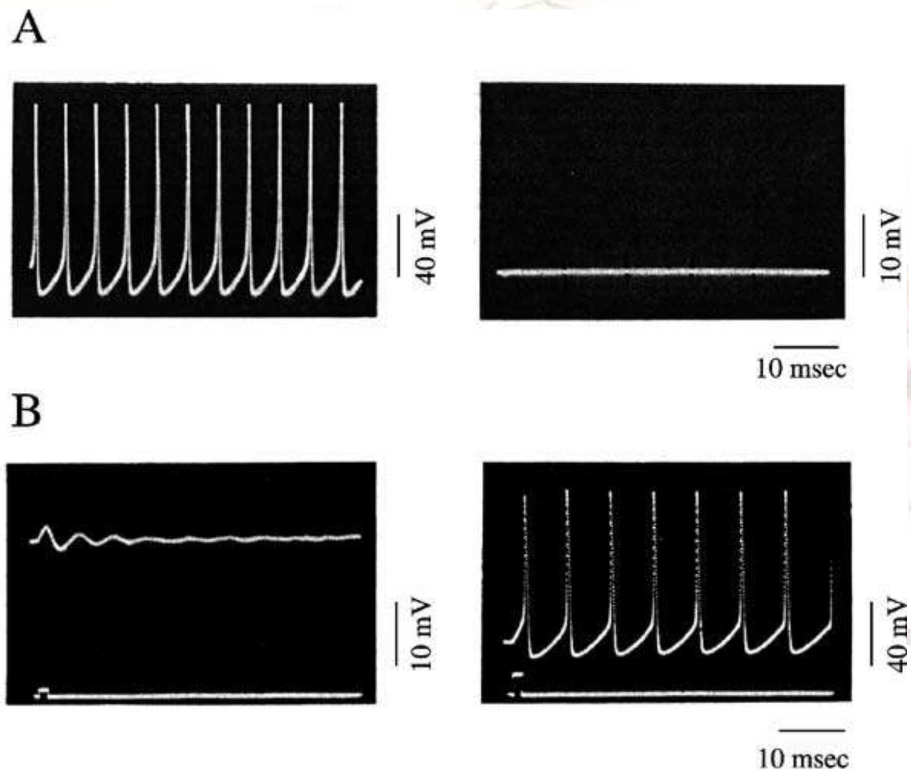


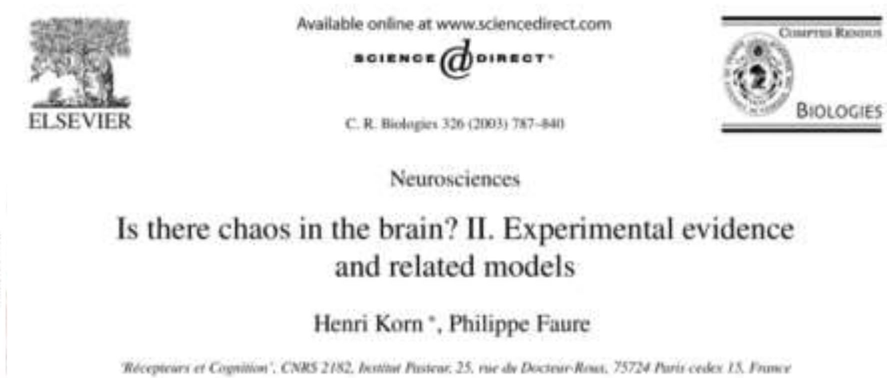


Complexity in simple transistor circuits



Complexity in simple transistor circuits

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Neurosciences

Is there chaos in the brain? II. Experimental evidence and related models

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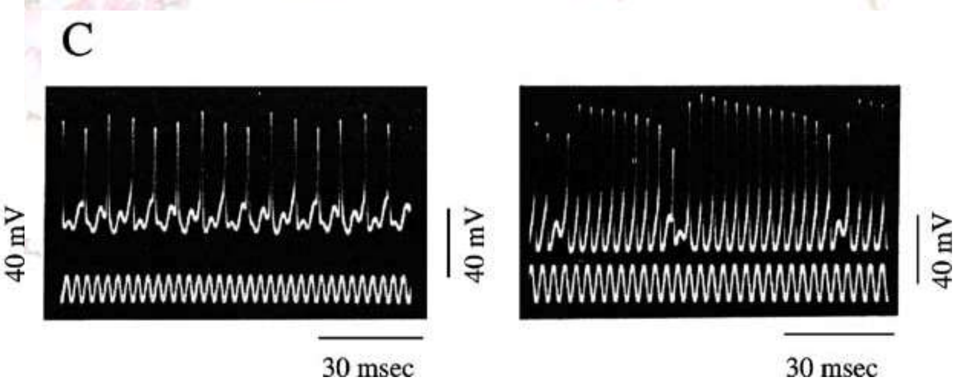


Emergence of community structure

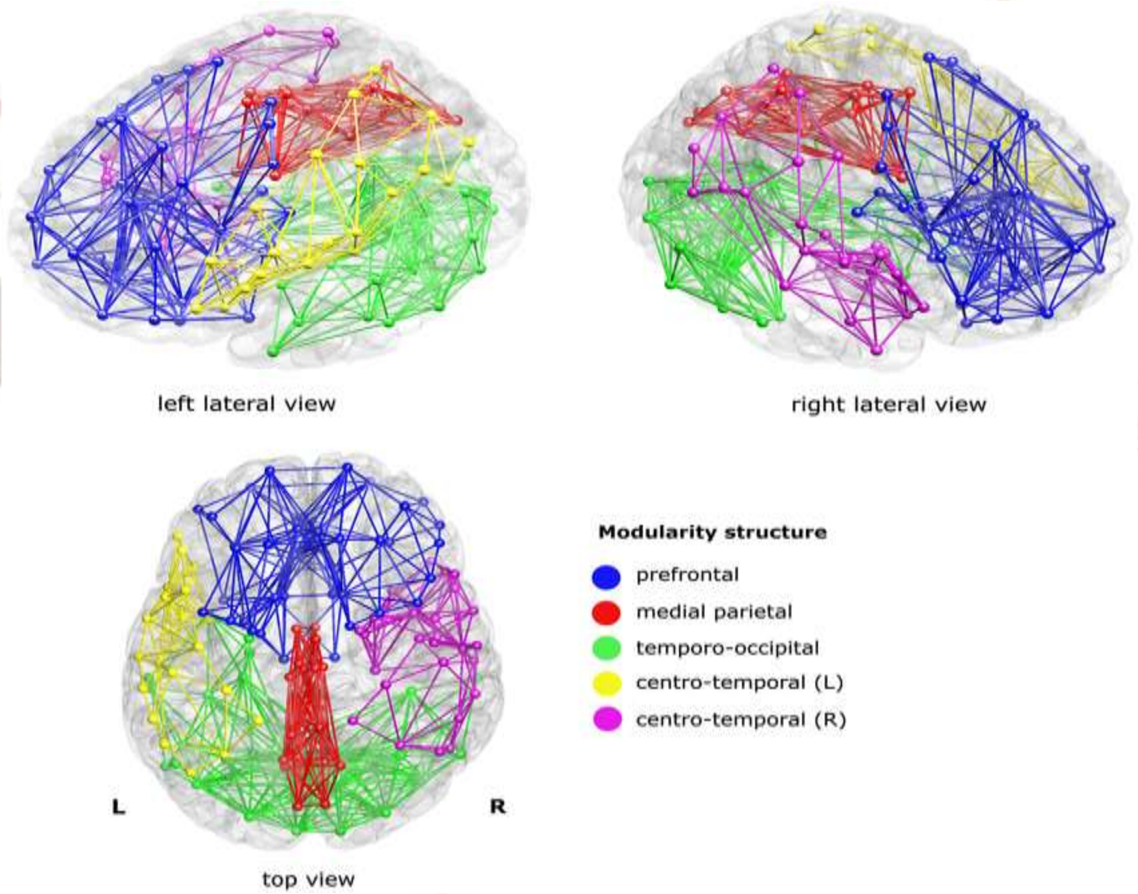
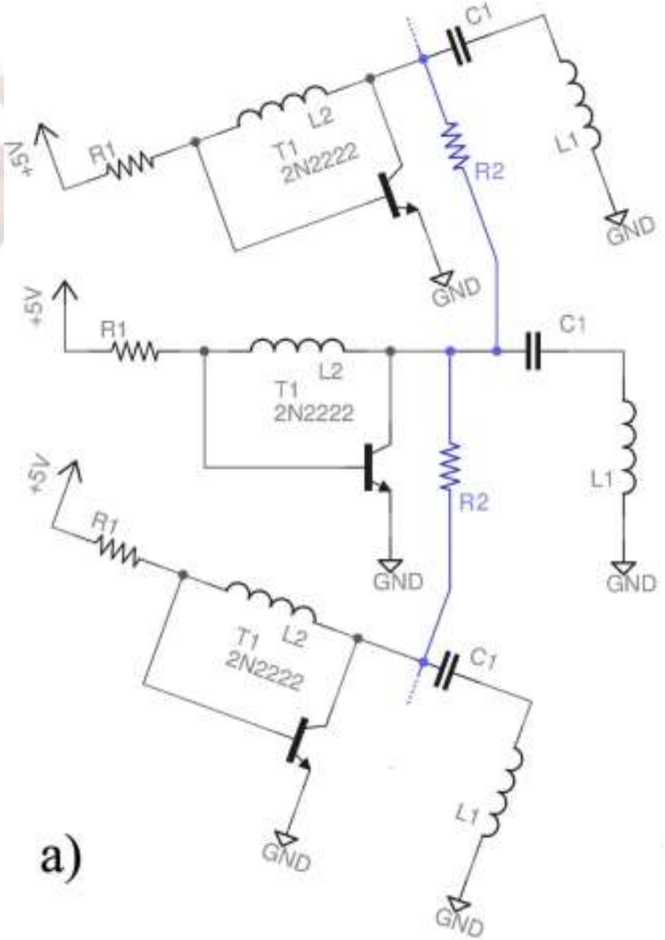


Image source: Besseling et al., © Elsevier

Emergence of community structure

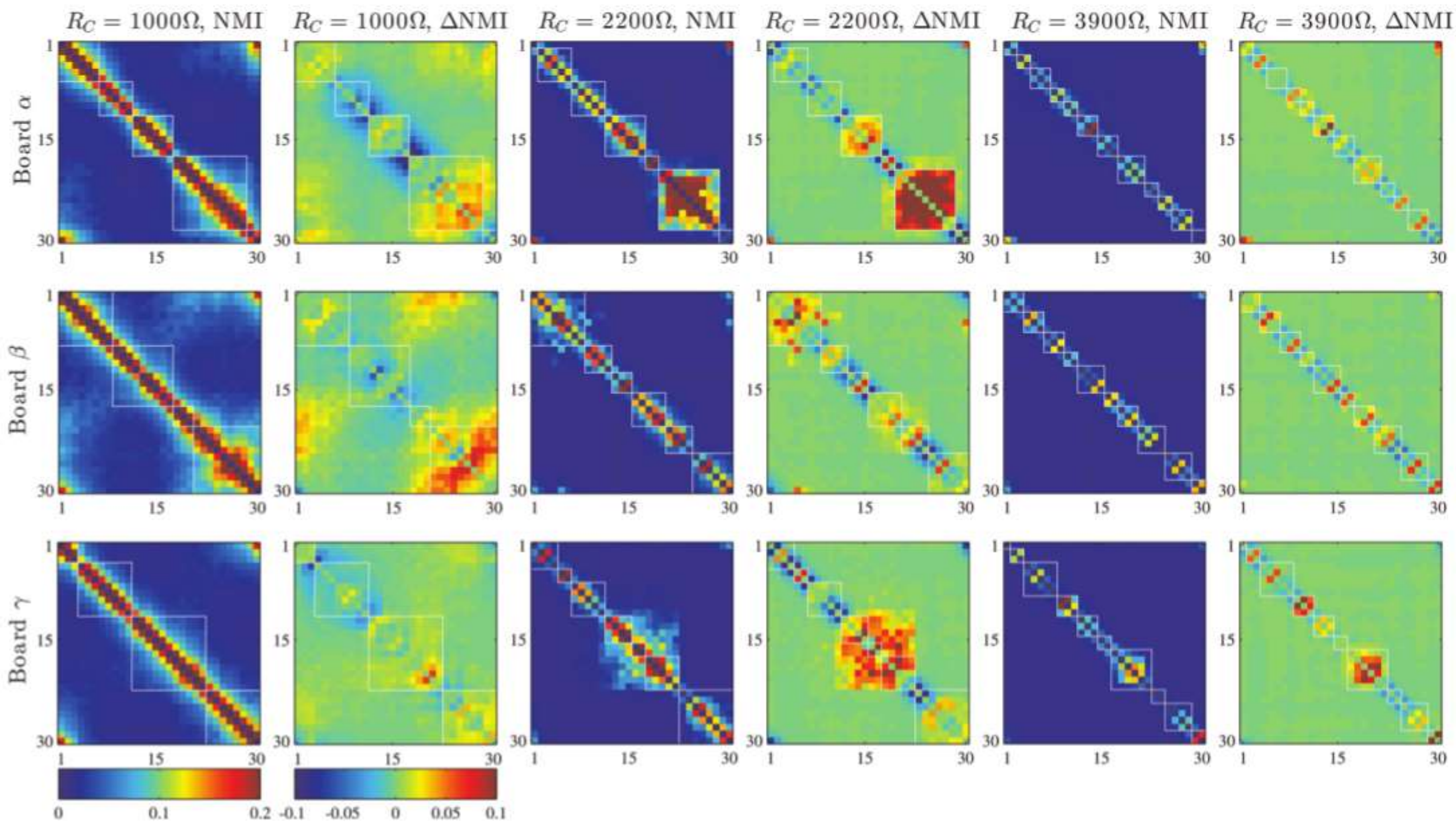
Ring structural connectivity
as elementary substrate



a)

b)

Emergence of community structure



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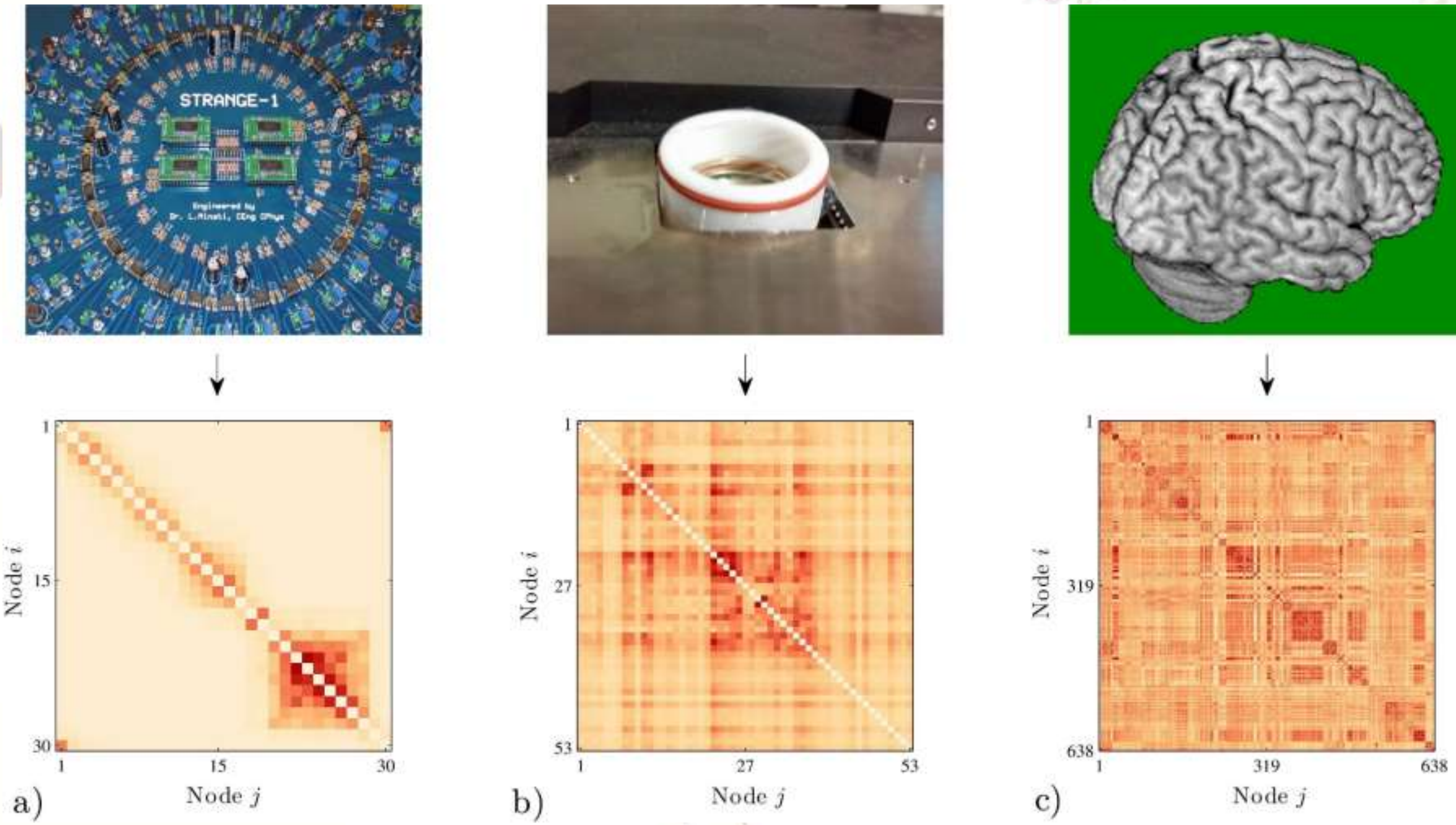
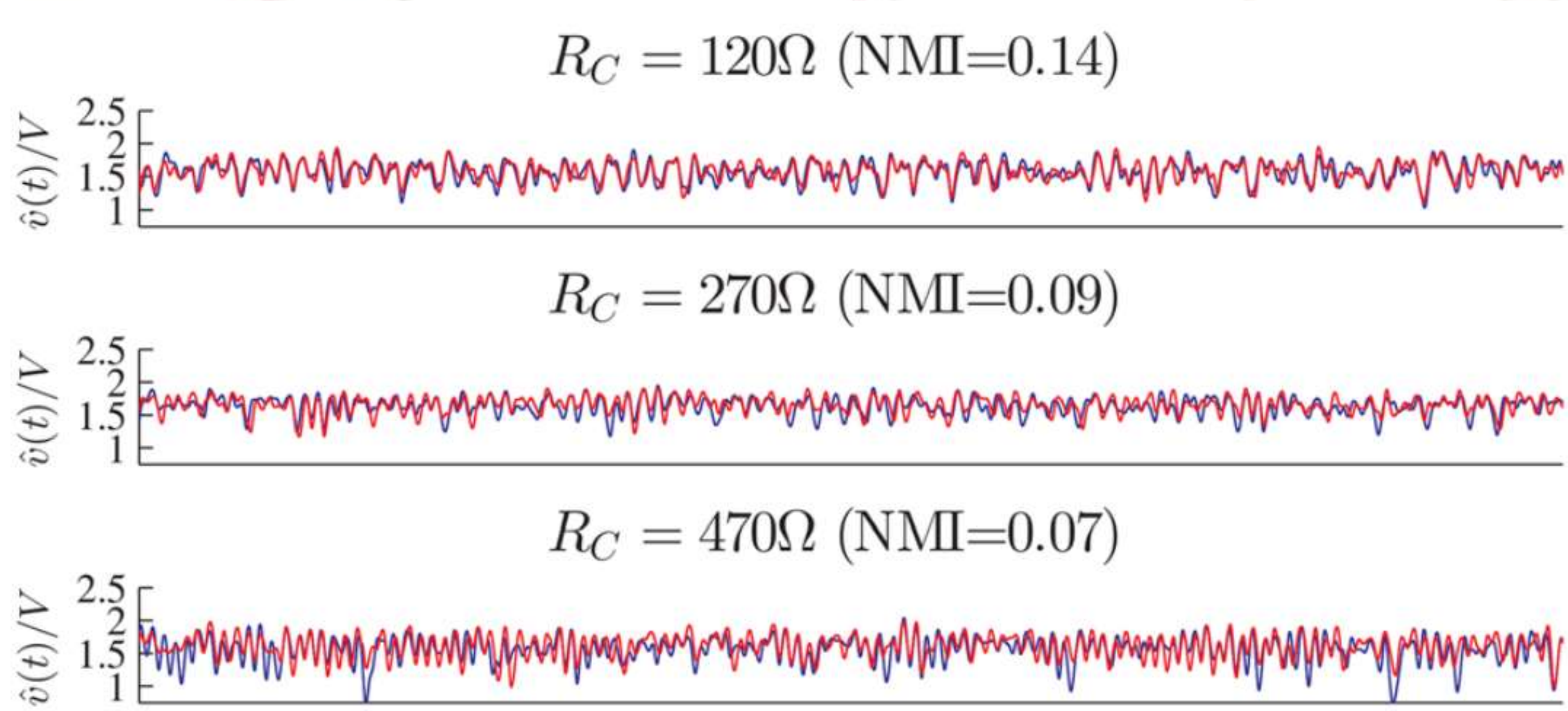
Emergence of community structure



Emergence of community structure

Amplitude fluctuations loosely resemble EEG...



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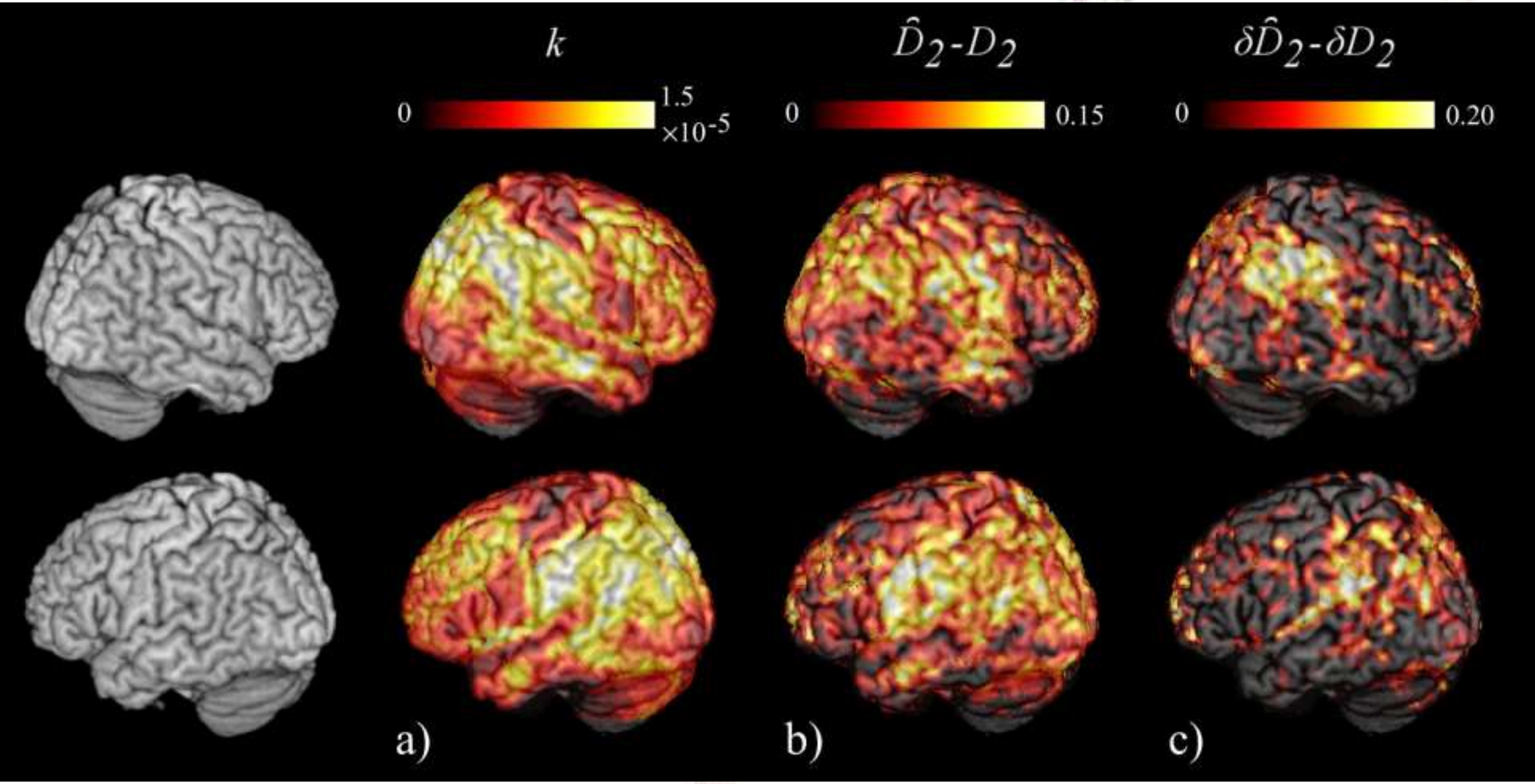
Dynamics within and outside hubs



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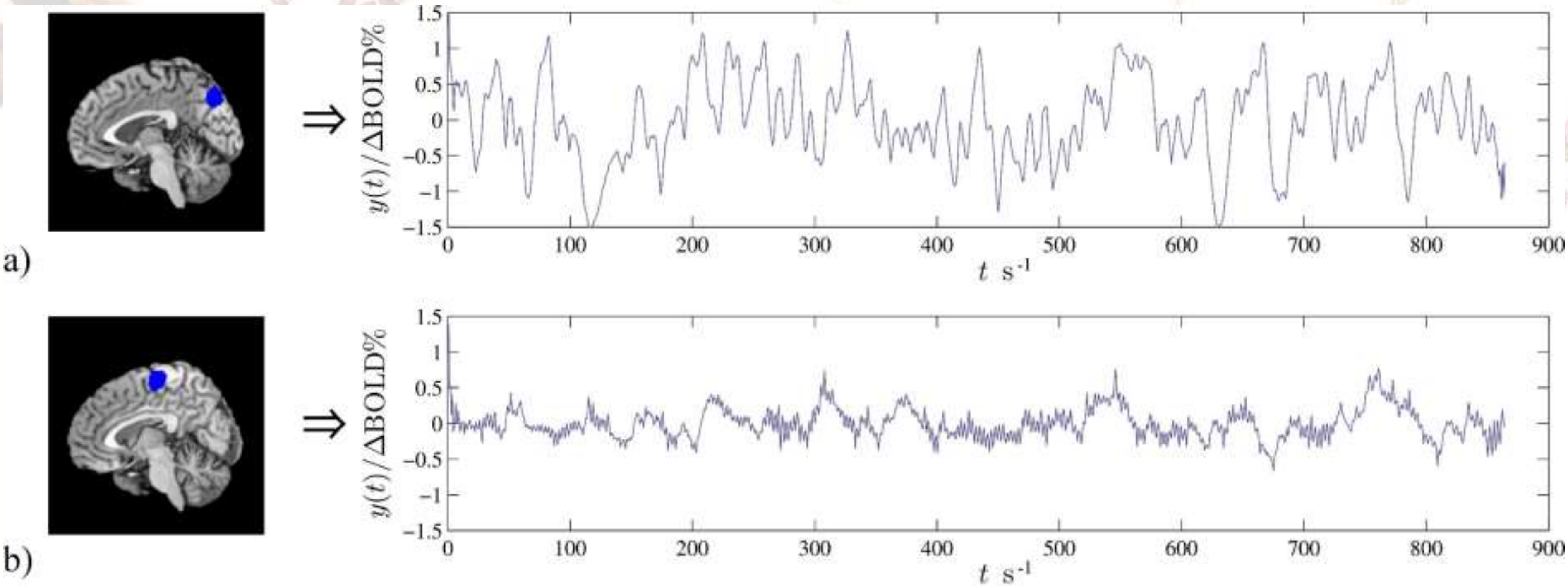
Dynamics within and outside hubs

Cortical hubs seem to yield deterministic, non-linear dynamics



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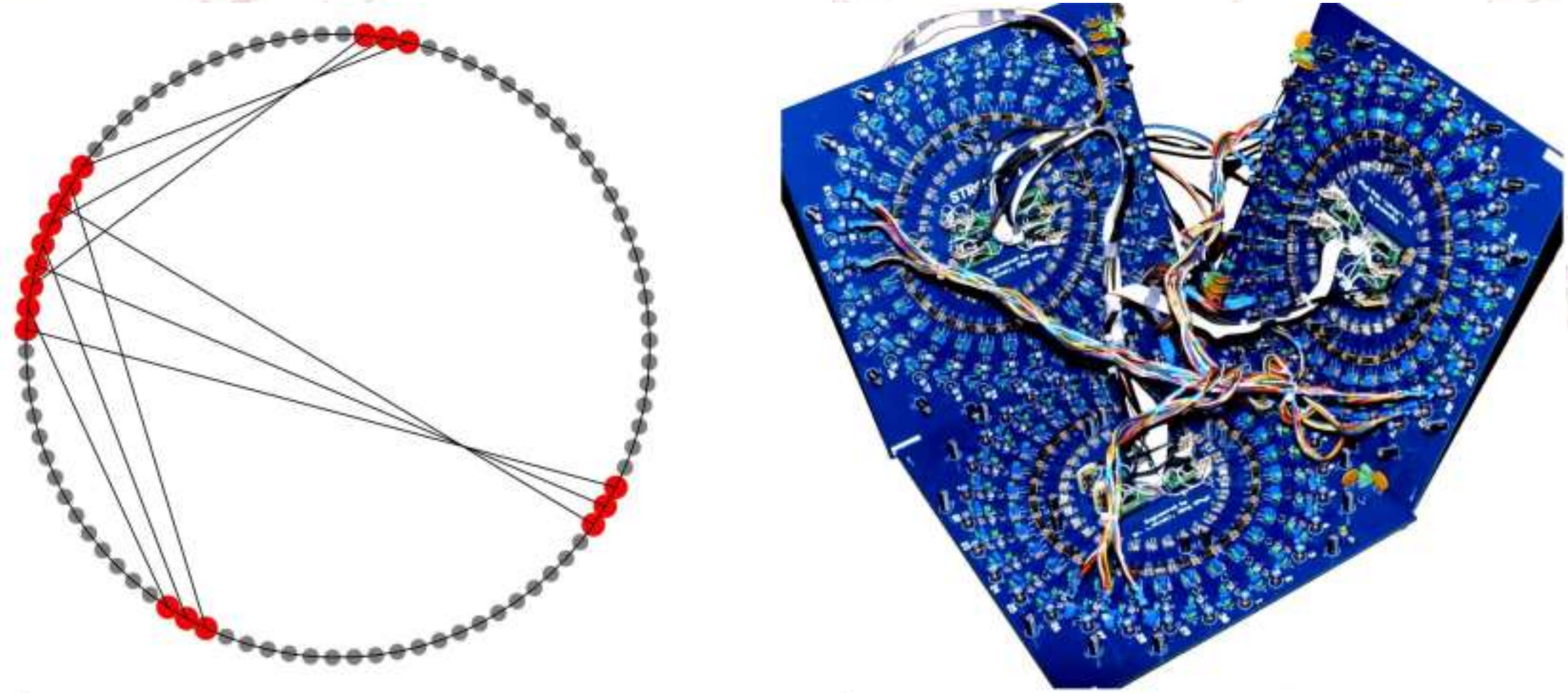
Dynamics within and outside hubs

A “toy model” of high-level brain connectivity



a) b)

Dynamics within and outside hubs

Selective emergence of slow, high-amplitude fluctuations in hubs

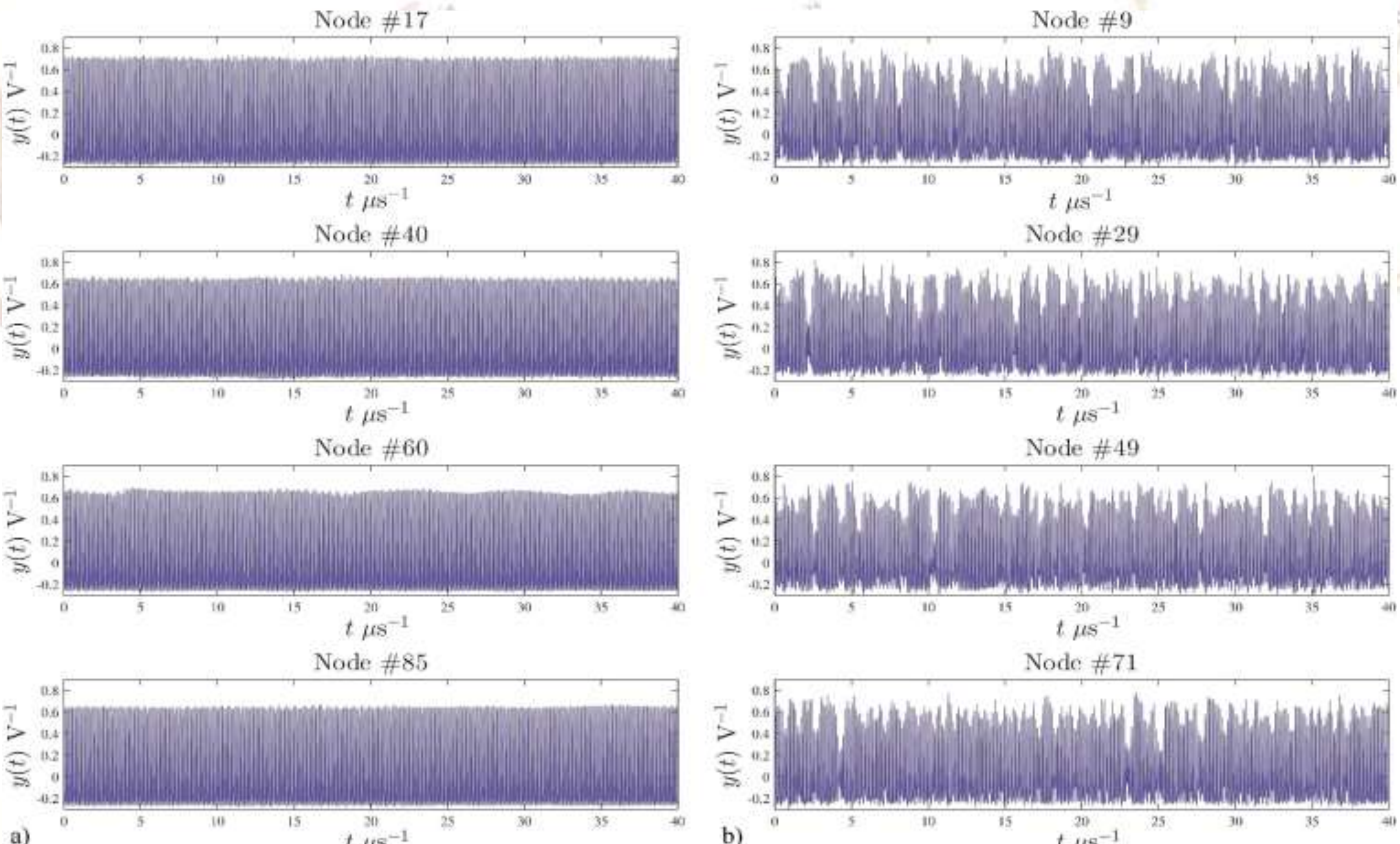


Image source: Minati et al., CHAOS 2015. © AIP

Conclusions

1) Relationship between brain connectivity and dynamics

2) Parallels between emergence in the brain and other physical systems

3) Phase transitions in neurons and chaotic oscillators

4) Brain modularity and cluster synchronization

5) Hubs and dynamics

Thank you for your attention

References:

1. Minati L. Experimental dynamical characterization of five autonomous chaotic oscillators with tunable series resistance. CHAOS. 2014; 24(3):033110
2. Minati L. Experimental synchronization of chaos in a large ring of mutually coupled single-transistor oscillators: phase, amplitude, and clustering effects. CHAOS. 2014; 24(4):043108
3. Minati L, Chiesa P, Tabarelli D, D'Incerti L, Jovicich J. Synchronization, non-linear dynamics and low-frequency fluctuations: analogy between spontaneous brain activity and networked single-transistor chaotic oscillators. CHAOS. 2015; 25(3):033107
4. Minati L. Atypical transistor-based chaotic oscillators: Design, realization, and diversity. CHAOS 2017; 27(7):073113

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