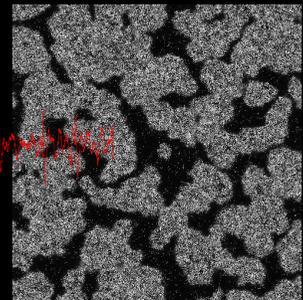
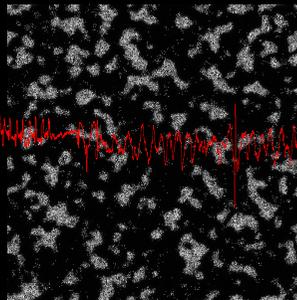
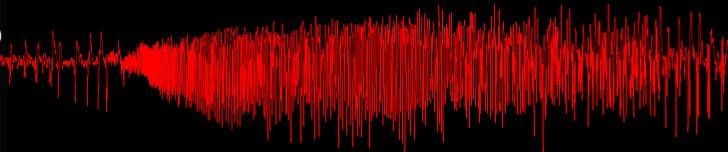


# Seizures and chimeras in epileptic brain networks

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for Complex Systems



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Dept. of Epileptology  
Neurophysics Group

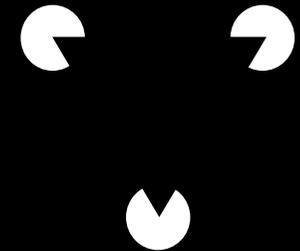


Helmholtz-Institute  
for Radiation- and  
Nuclear Physics

# Synchronization Phenomena in the Human Brain

## ***Physiologic synchronization:***

movement, cognition, attention, learning, memory, emotions, motivation, language, reasoning, planning, personality, consciousness, ...



## ***Pathophysiologic synchronization:***

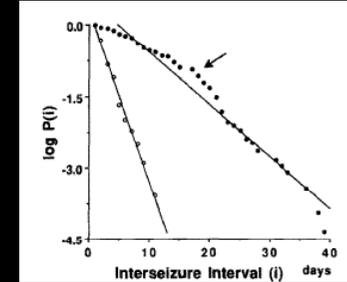
Parkinson's disease, schizophrenia, ataxia, **epilepsy**, ...



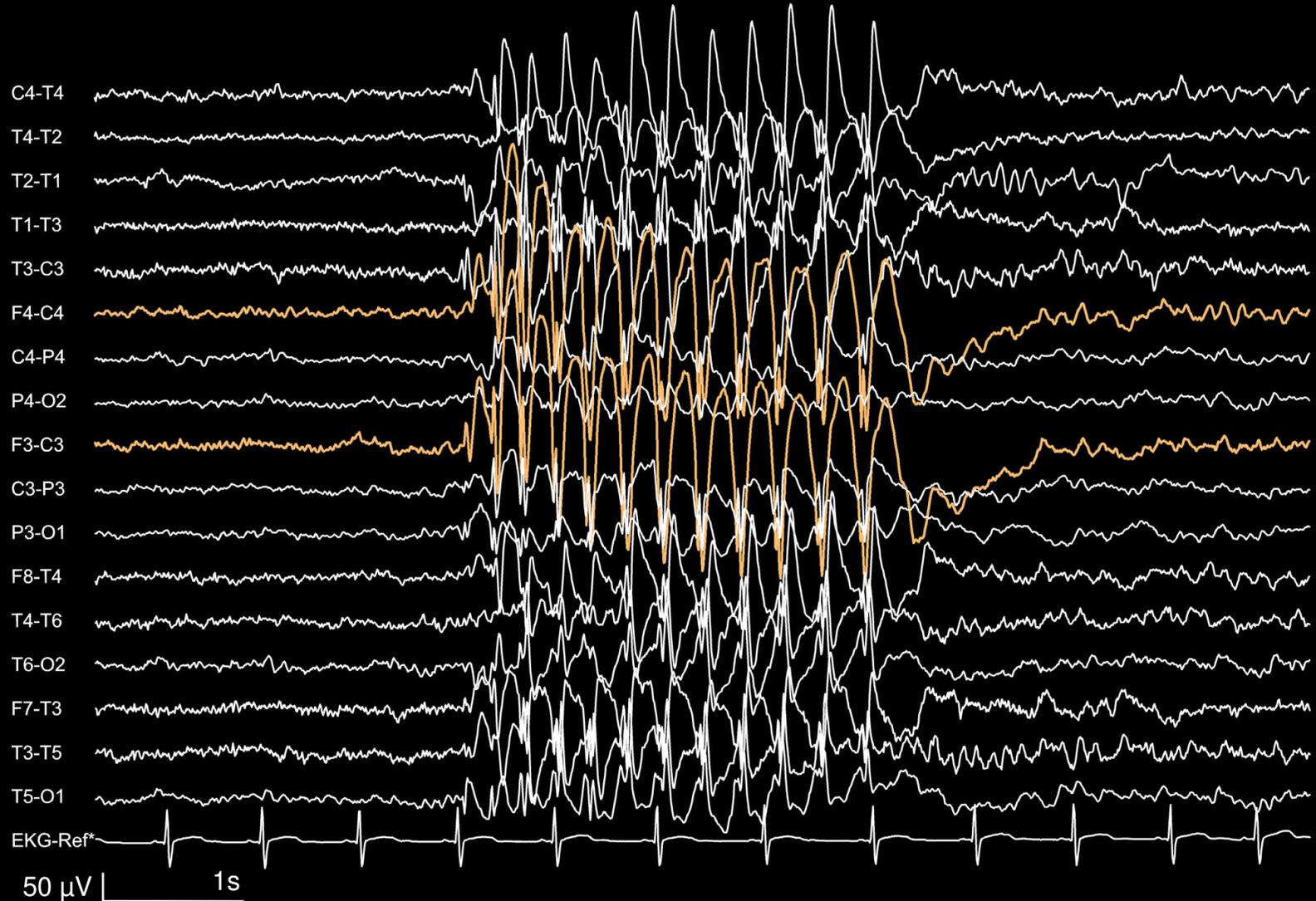
*how to differentiate between physiologic and pathophysiologic synchronization?*

# Extreme Event Epileptic Seizure

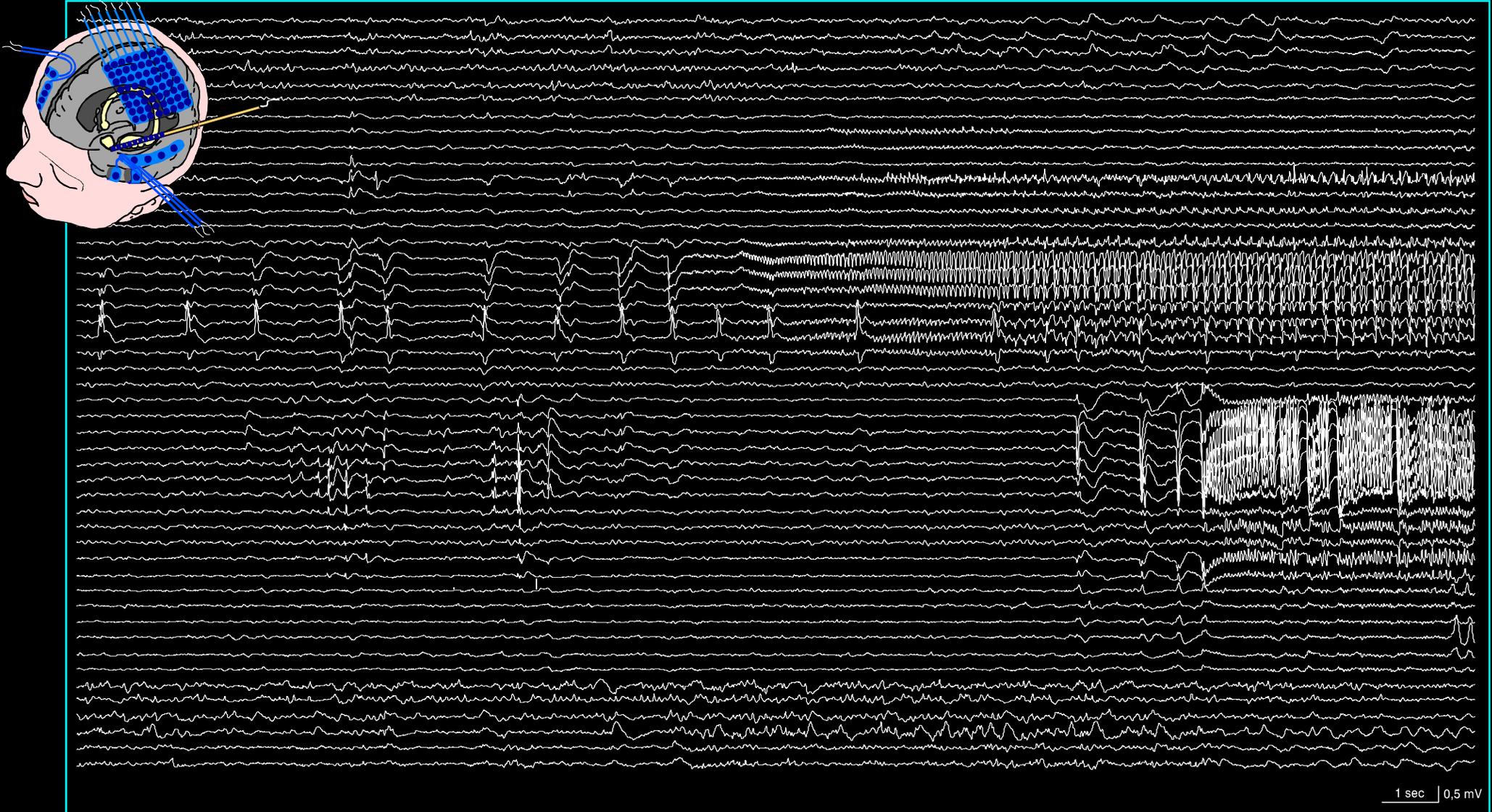
- frequency: ~ 3 szrs/mon (max.: several 100 szrs/day)
- inter-seizure-intervals mostly Poissonian distributed
- (apparently) non-predictable (exception: reflex epilepsies)
- duration: 1 – 2 min (exception: status epilepticus > 5 min)
- during the seizure: impaired mental functions, altered consciousness, loss of consciousness, involuntary movements, ...
- after the seizure: neurologic dysfunctions, depression, ...
- main seizure types:
  - generalized seizure (apparently instantaneous)
  - focal seizure (with/without generalization)



# Epilepsy: Primary Generalized Seizure



# Epilepsy: Focal Seizure with spreading

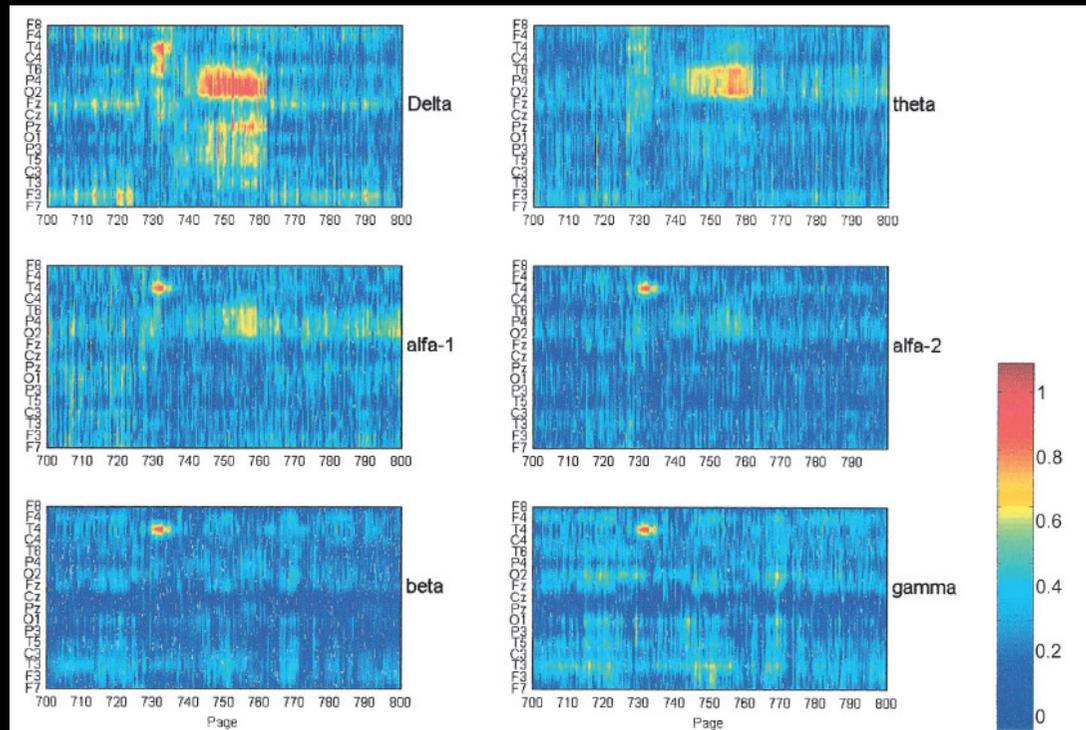


# Seizure is Synchrony

*traditional view:*

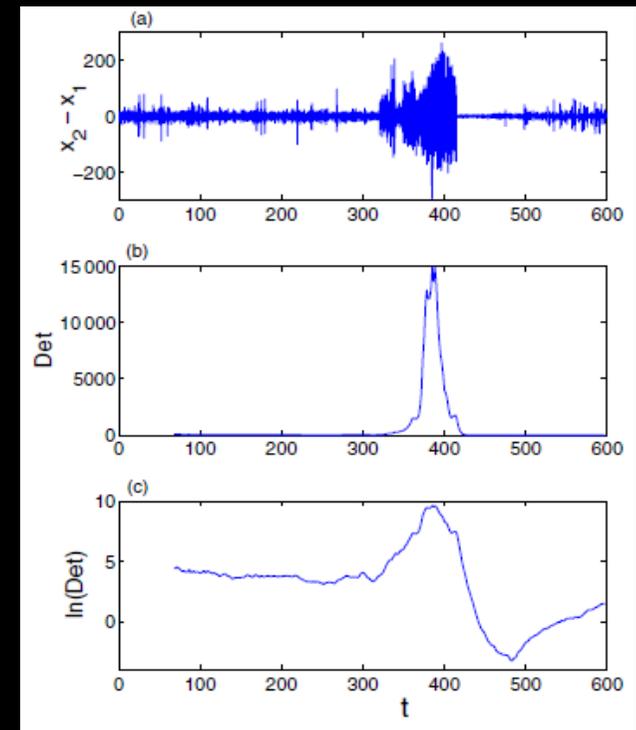
seizure = excess synchronized electrical activity in the brain

nearest neighbor phase  
synchronization (human szr.)



MJ van Putten, *J Clin Neurophysiol* 20, 320, 2003

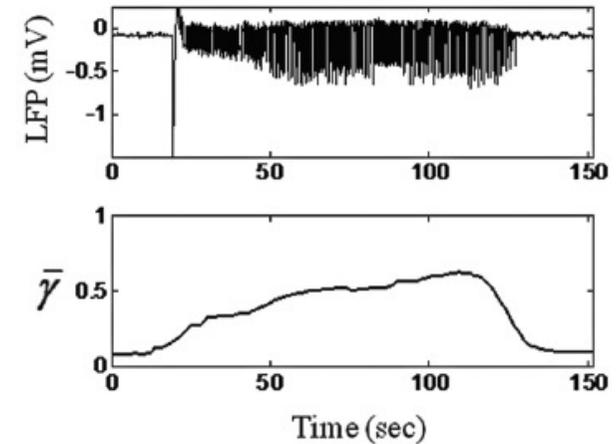
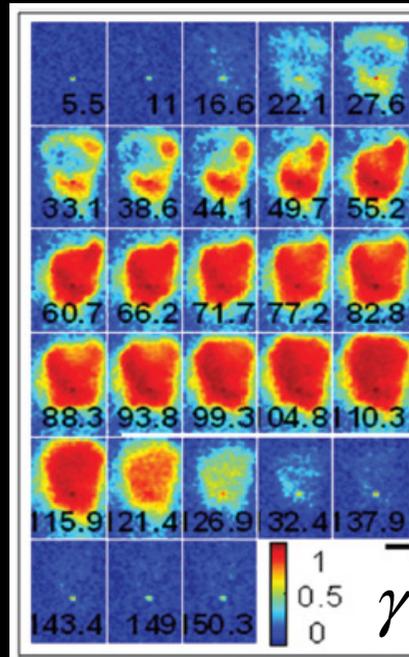
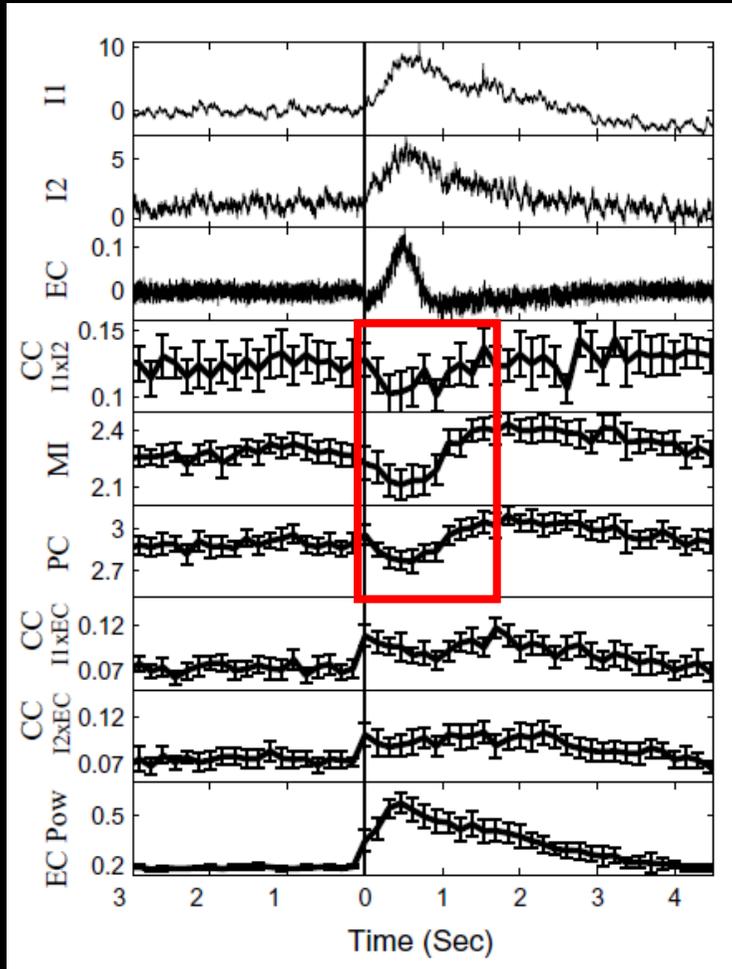
phase synchronization  
time matrix (human szr.)



YC Lai et al., *PRL* 98, 108102, 2007

# Seizure is Synchrony ----- Or not?

decreased or increased sync during induced seizures in rats

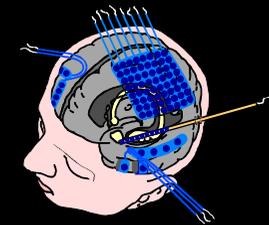
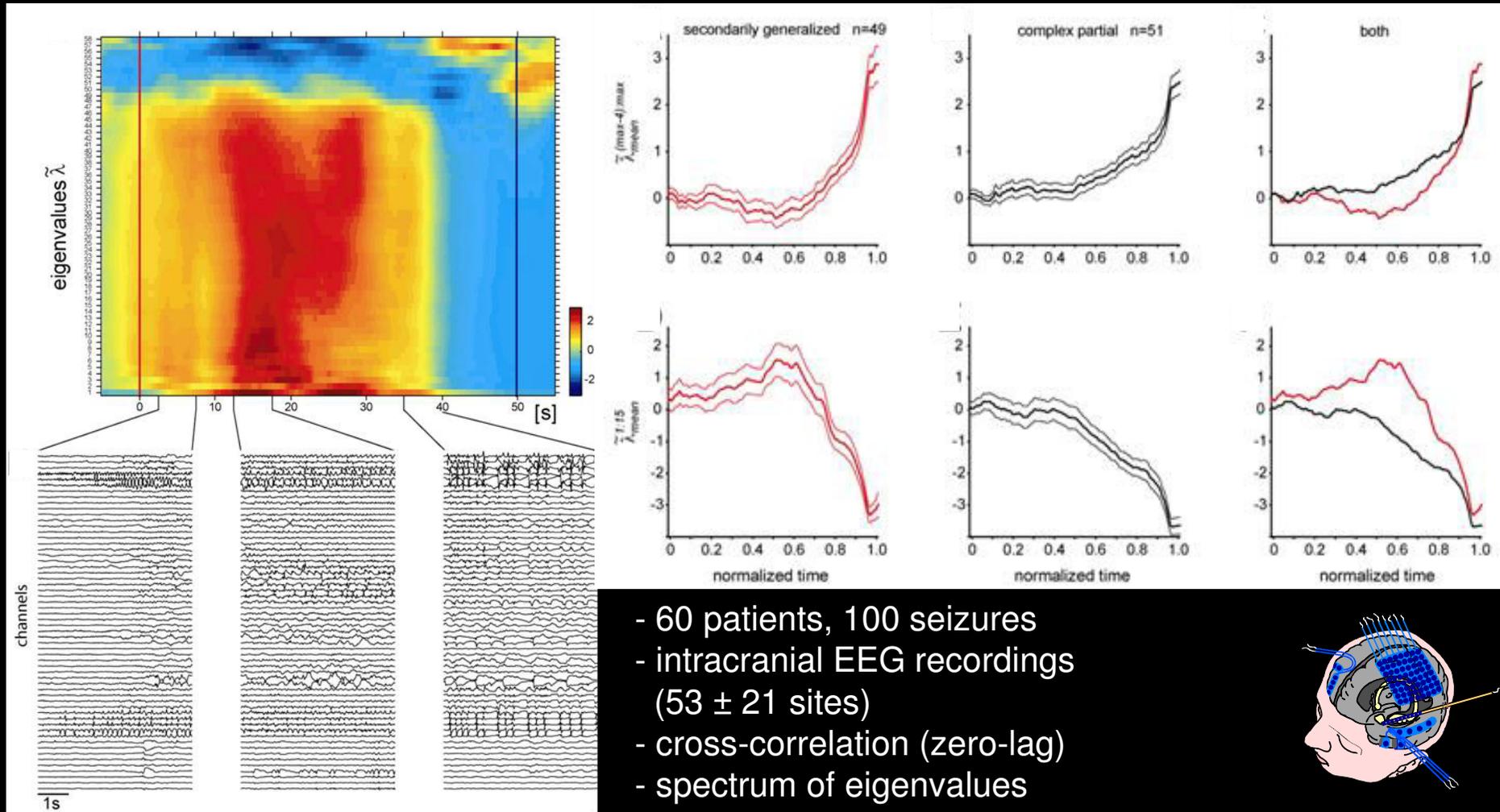


D Takeshita and S Bahar, *Chaos* 21, 047506, 2011

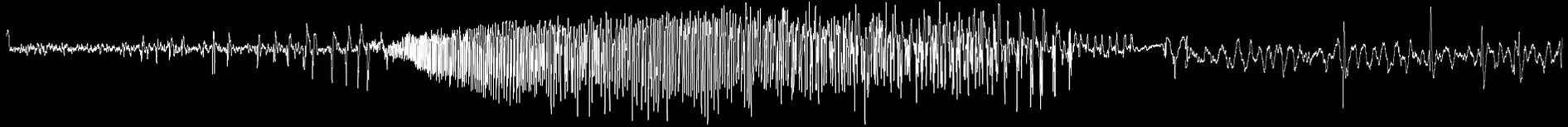
TI Netoff and SJ Schiff, *J Neurosci* 22, 7297, 2002

# Epileptic Networks during Seizures

*network sync: a mechanism for seizure termination?*



# Seizures and Synchrony



from an *incoherent* to a *coherent* and back to an *incoherent* pattern

focal seizures:

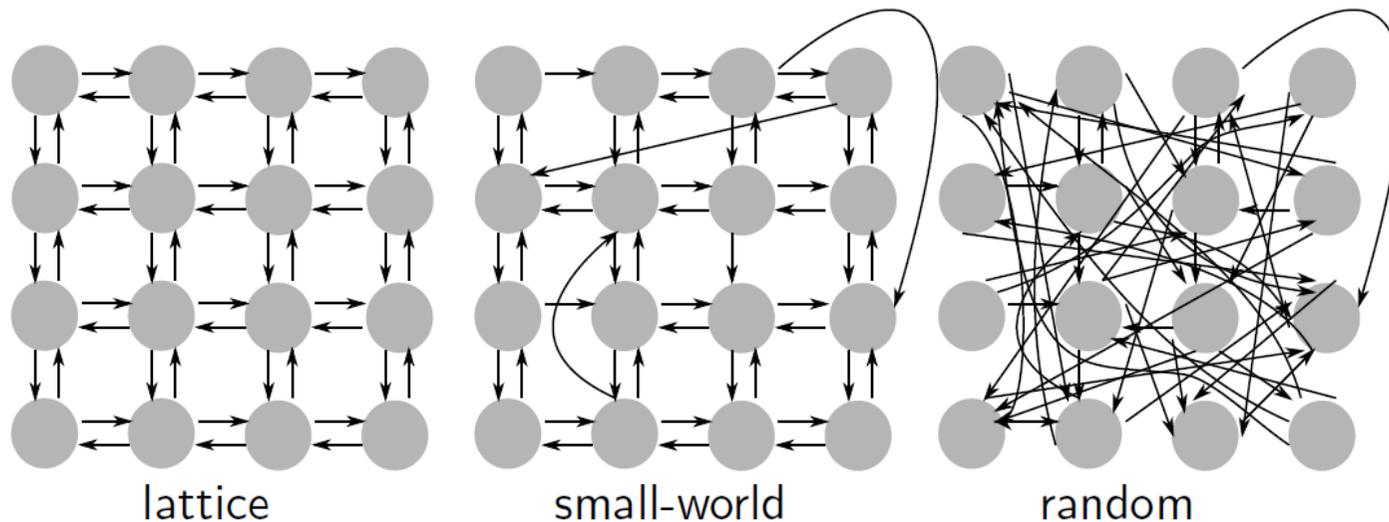
- locally synchronized neural dynamics embedded in asynchrony
- macroscopically: partial synchrony
- interplay between synchronization and de-synchronization
- complex connection topology (structure and function)

**... are focal seizures chimera states?**



# Small-world Network of Pulse-Coupled Oscillators

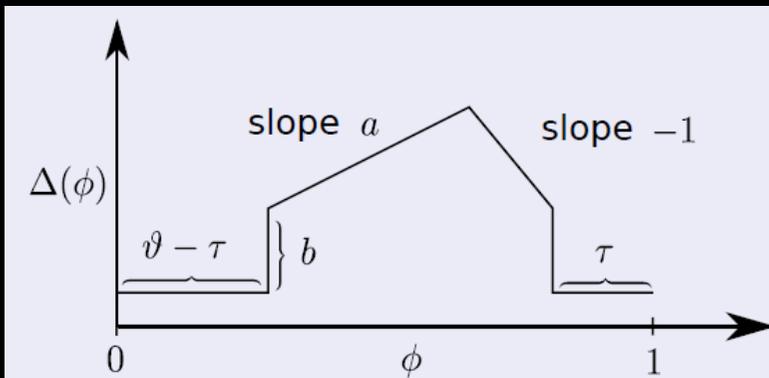
- $N \times N$  oscillators
- connect each oscillator to its  $m$  nearest neighbors
- cyclic boundary conditions (torus)
- replace fraction  $p$  of connections by connections between randomly chosen oscillators



# Small-world Network of Pulse-Coupled Oscillators

## *pulse-coupled phase oscillators (IF neurons)*

- intrinsic dynamics:  $\dot{\phi}_n = 1, \phi_n \in (0, 1]$
- oscillator  $n$  fires ( $\phi_n(t_f) = 1$ )
  - ▶ excite all oscillators  $n'$  connected to  $n$   
 $\phi_j(t_f^+) = R(\phi_{n'}(t_f)) = \Delta(\phi_{n'}(t_f)) + \phi_{n'}(t_f)$
  - ▶ reset oscillator  $n$ :  $\phi_n(t_f^+) = 0$



integrate-and-fire oscillators

$\tau$  time delay

$\vartheta$  refractory period

$b$  coupling strength

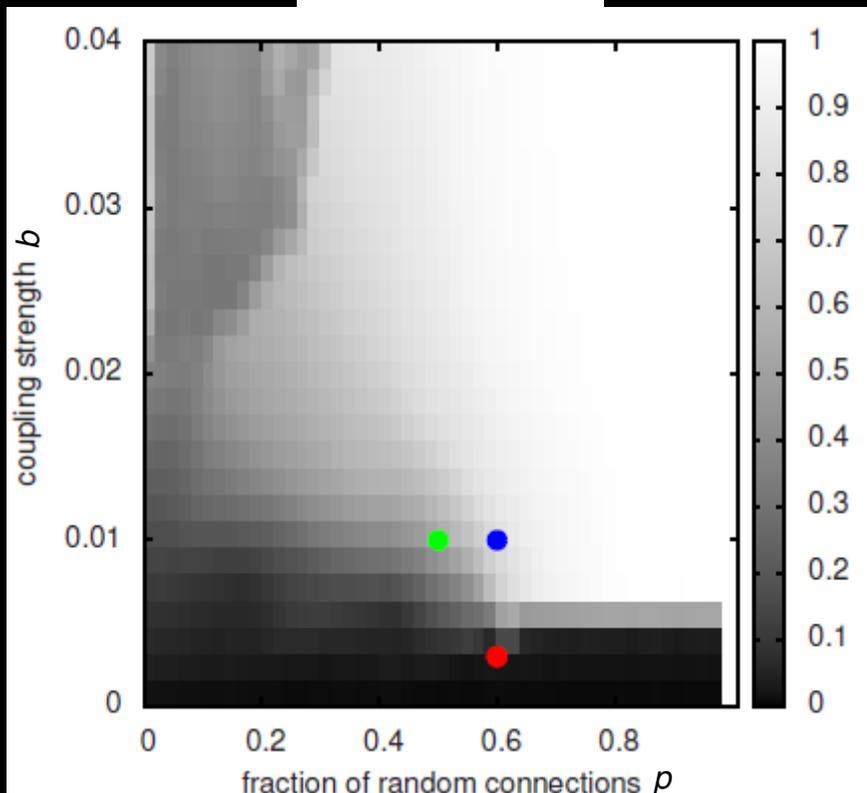
$$a = b/2$$

measuring synchrony with Kuramoto's order parameter:  $r(t) = 1/|N| \left| \sum_{n \in N} e^{2\pi i \phi_n(t)} \right|$

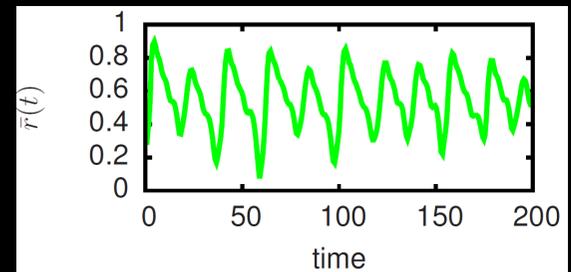
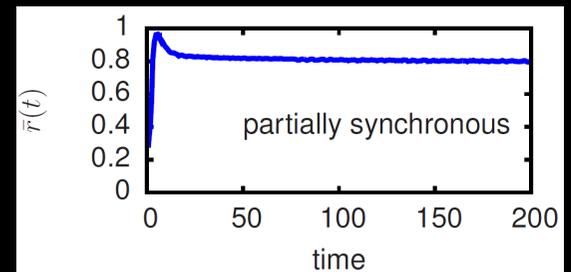
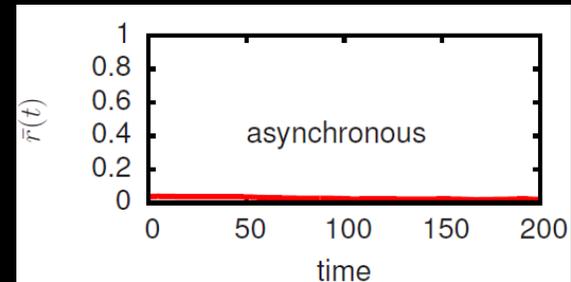
# Small-world Network of Pulse-Coupled Oscillators

$$r(t) = 1/N \left| \sum_n e^{2\pi i \phi_n(t)} \right|, \quad \bar{r}(t) \text{ local maxima of } r(t)$$

mean of  $\bar{r}$



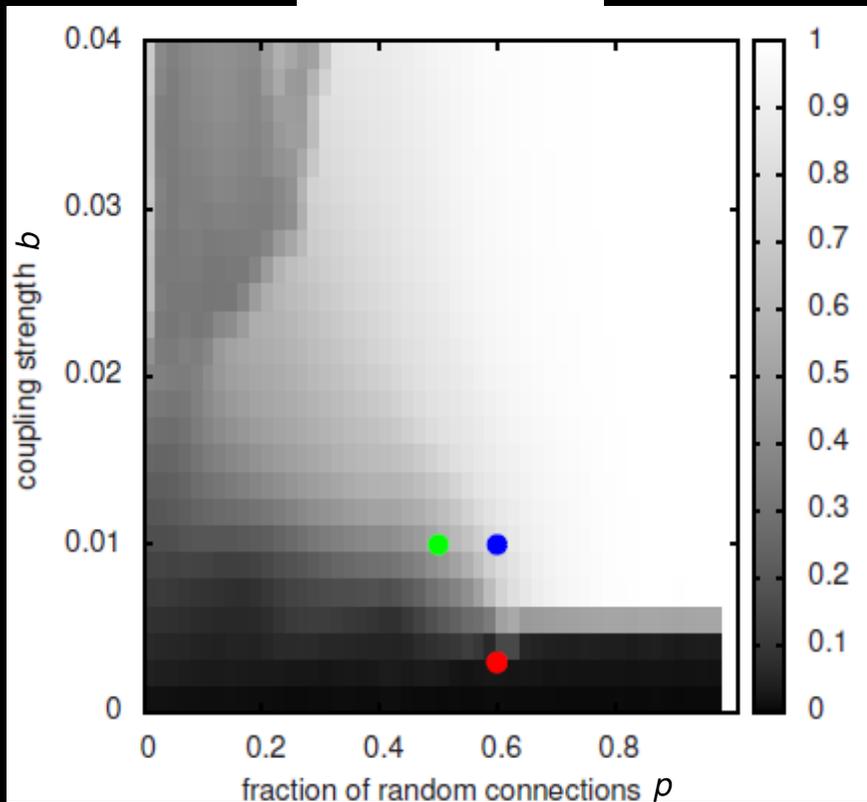
$N = 500 \times 500, m = 50, \tau = 0.01, \vartheta = 0.05;$



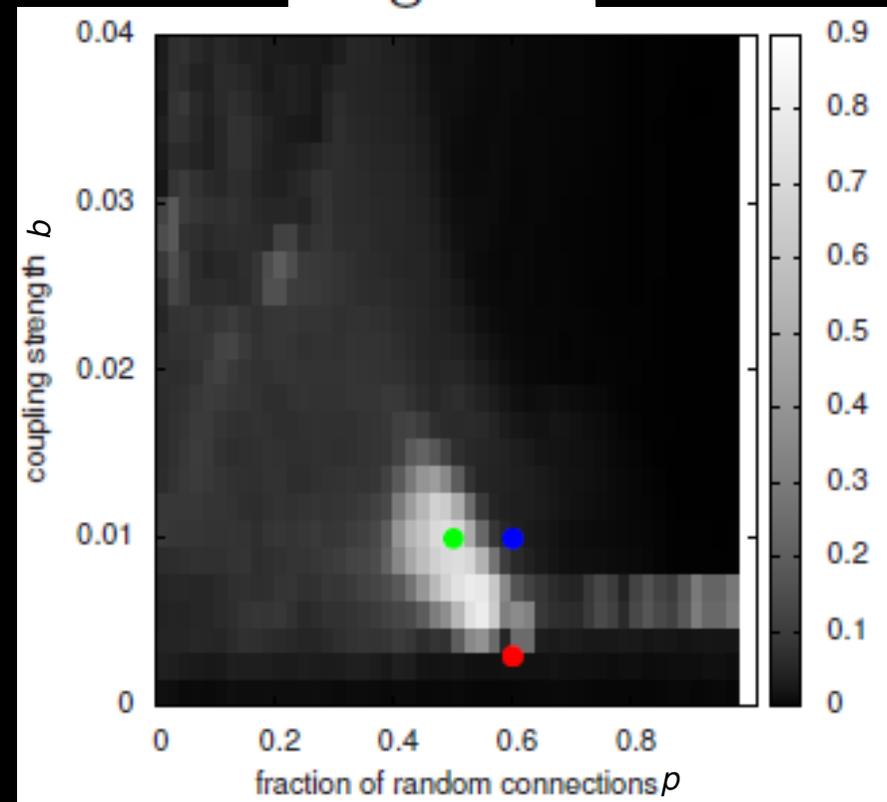
# Small-world Network of Pulse-Coupled Oscillators

$$r(t) = 1/N \left| \sum_n e^{2\pi i \phi_n(t)} \right|, \quad \bar{r}(t) \text{ local maxima of } r(t)$$

mean of  $\bar{r}$



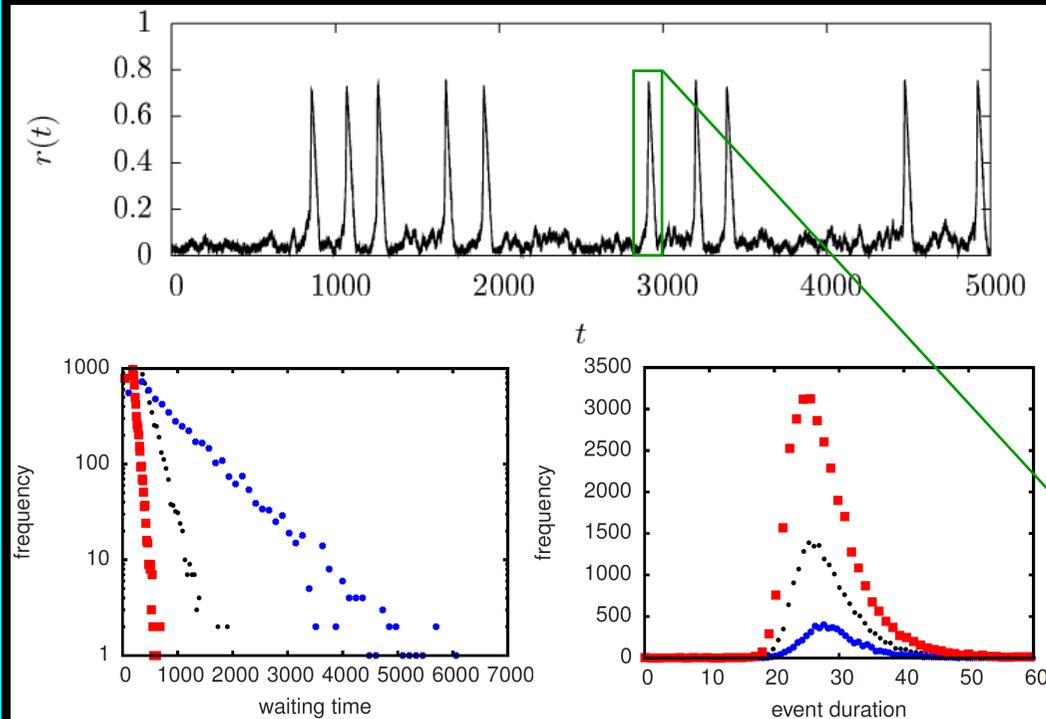
range of  $\bar{r}$



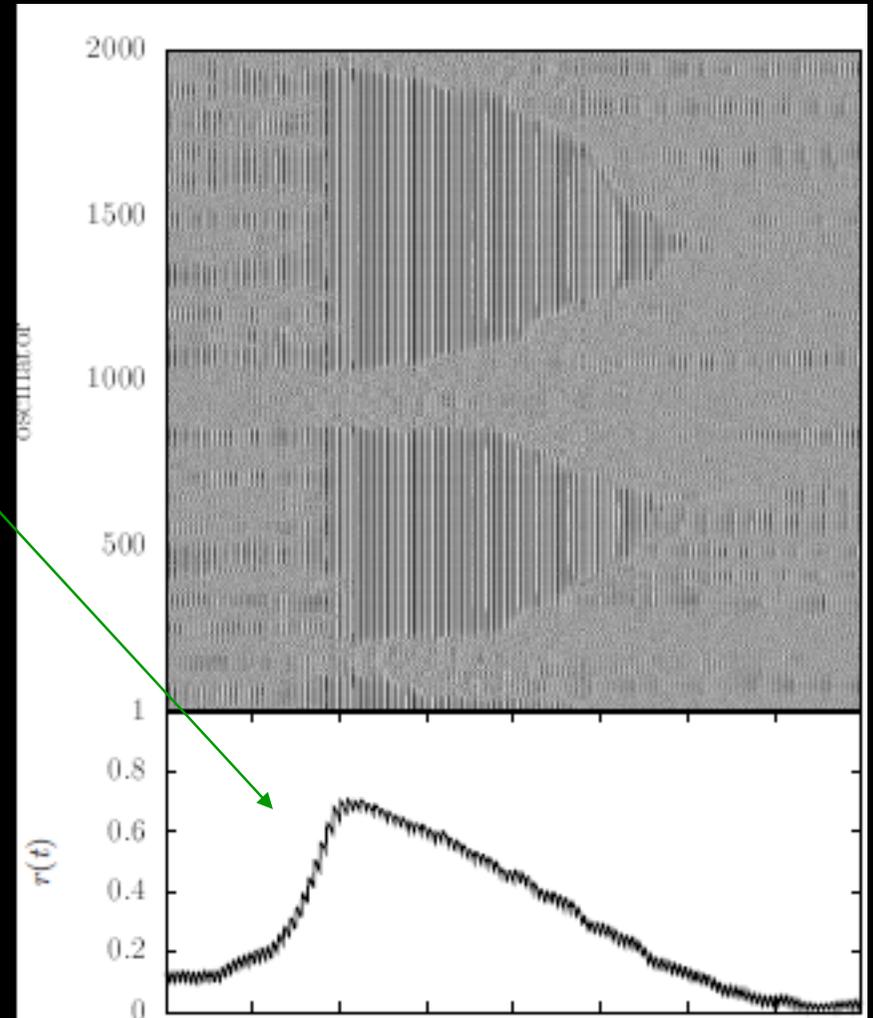
$N = 500 \times 500, m = 50, \tau = 0.01, \vartheta = 0.05;$

# Self-Initiation and -Termination of Sz-like Events

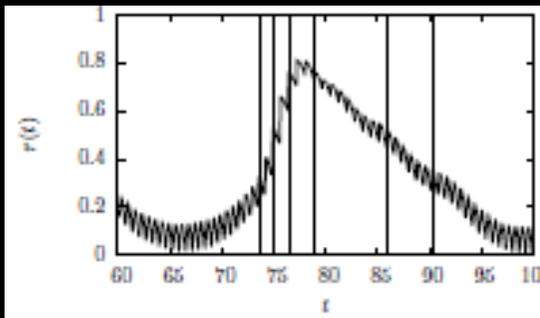
$N = 500 \times 500$ ,  $p = 0.5$ ,  $m = 50$ ,  $\tau = 0.01$ ,  $b = 0.01$ , various  $\nu$



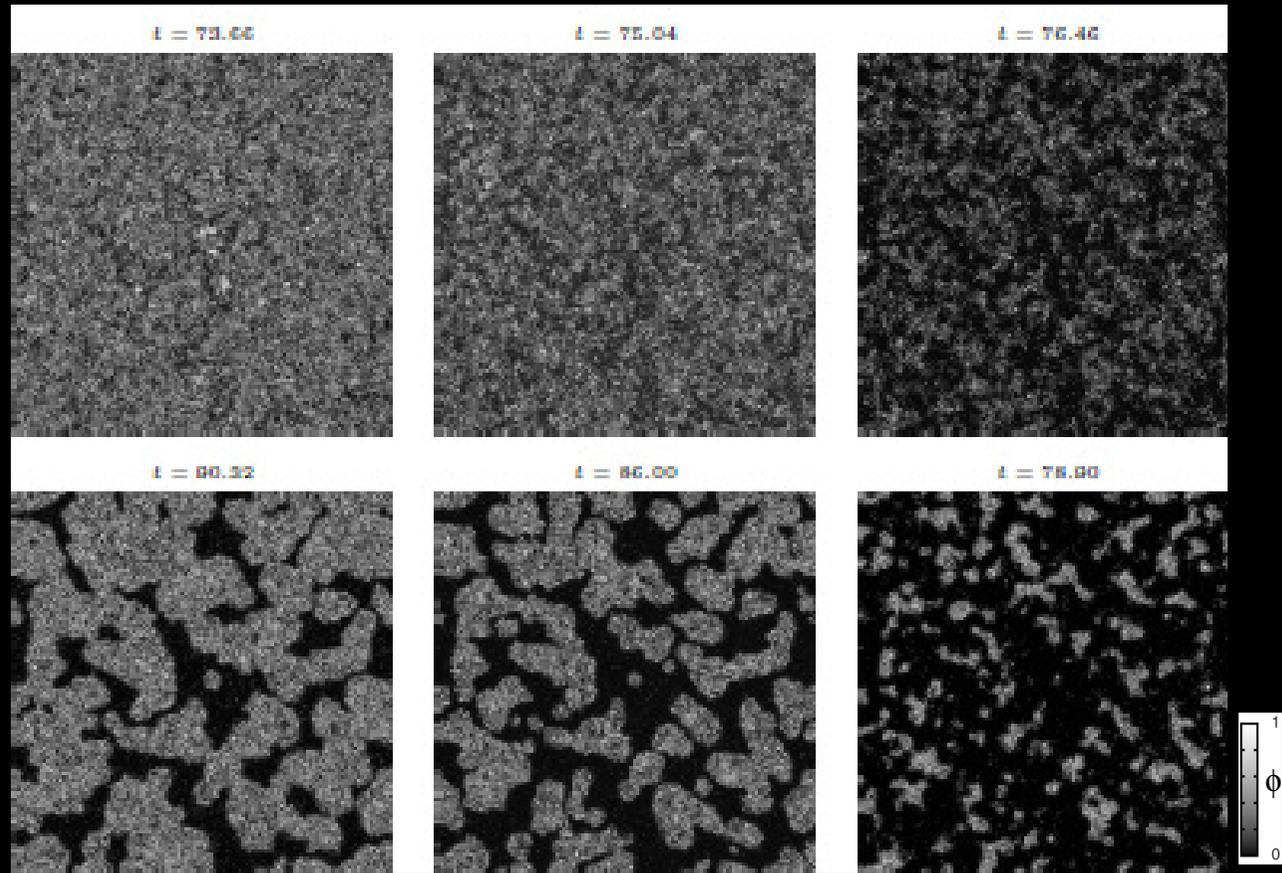
- small-amplitude oscillations with average phase velocity of oscillators
- non-converging macroscopic behavior, network-generated rhythms



# Self-Initiation and -Termination of Sz-like Events

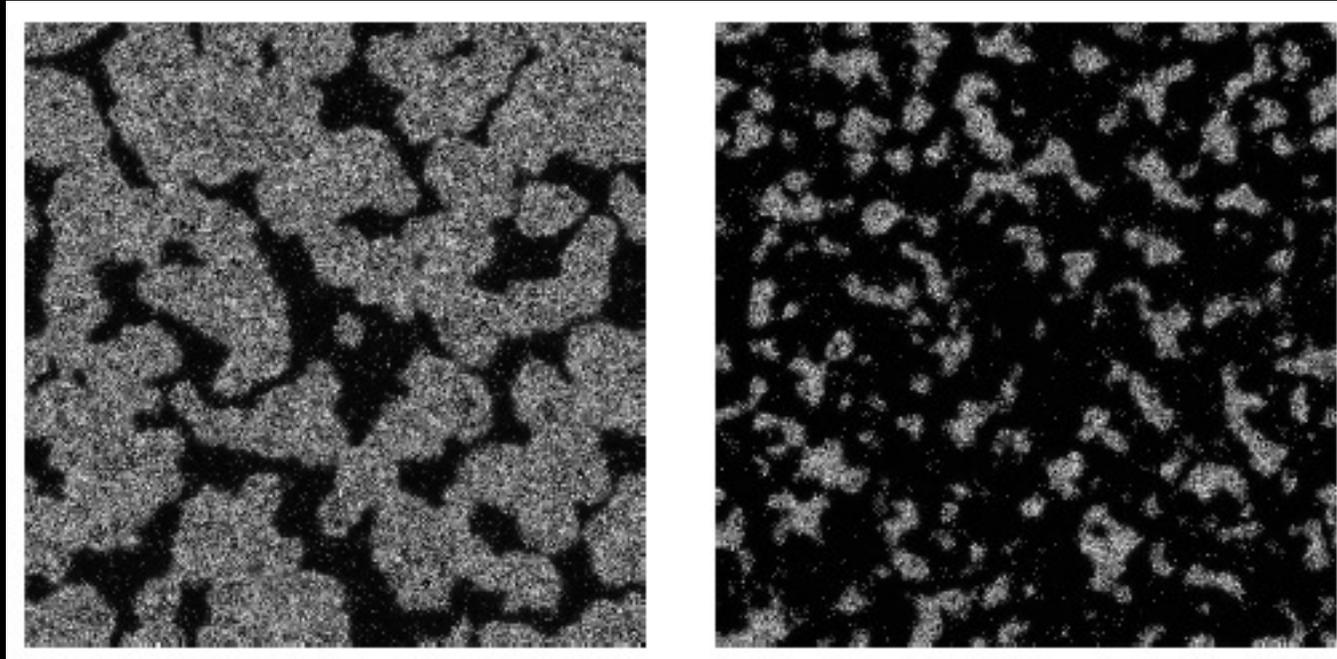


$N = 500 \times 500$ ,  $m = 50$ ,  $\tau = 0.01$ ,  $b = 0.01$ ,  $v = 0.05$



- comparable values of  $r(t)$  during ascending and descending part of event
- distributed asynchronous regions during ascending part
- connected asynchronous regions during descending part

# Self-Initiation and -Termination of Sz-like Events



mechanisms:

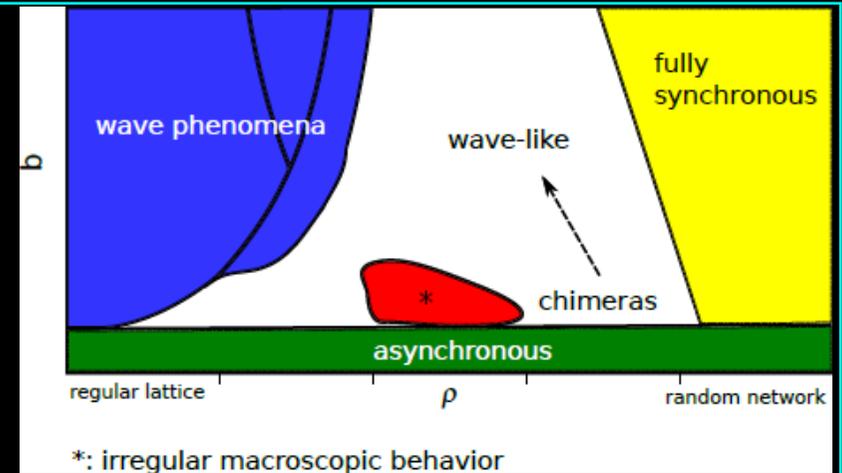
- stability of asynchronous regions
- stability of synchronous regions
- growing of asynchronous regions
- shrinking of asynchronous regions

long-range connections

short-range connections

# Self-Initiation and -Termination of Sz-like Events

- *no inhibition*
- *no pacemaker*
- *rhythm is network phenomenon*



- irregular macroscopic dynamics and sz-like events due to self-organized generation of chimera states
- cumulative size of asynchronous regions determined by control parameters
- event initiation via long-range connections
- even termination via short-range connections
- importance of complex coupling topology

# Summary

## ***Observations (seizures in humans and animals)***

- locally synchronized neural dynamics embedded in an asynchronous environment (chimera state?)
- complex connection topology

## ***Model (small-world networks of pulse-coupled oscillators)***

- self-generated and -terminated sz-like events due to chimeras
- importance of complex coupling topology

## ***Outlook***

- new therapeutic possibilities through modification of (functional) epileptic network