Stochastic synchronization of dynamics on the human connectome

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February 10, 2020

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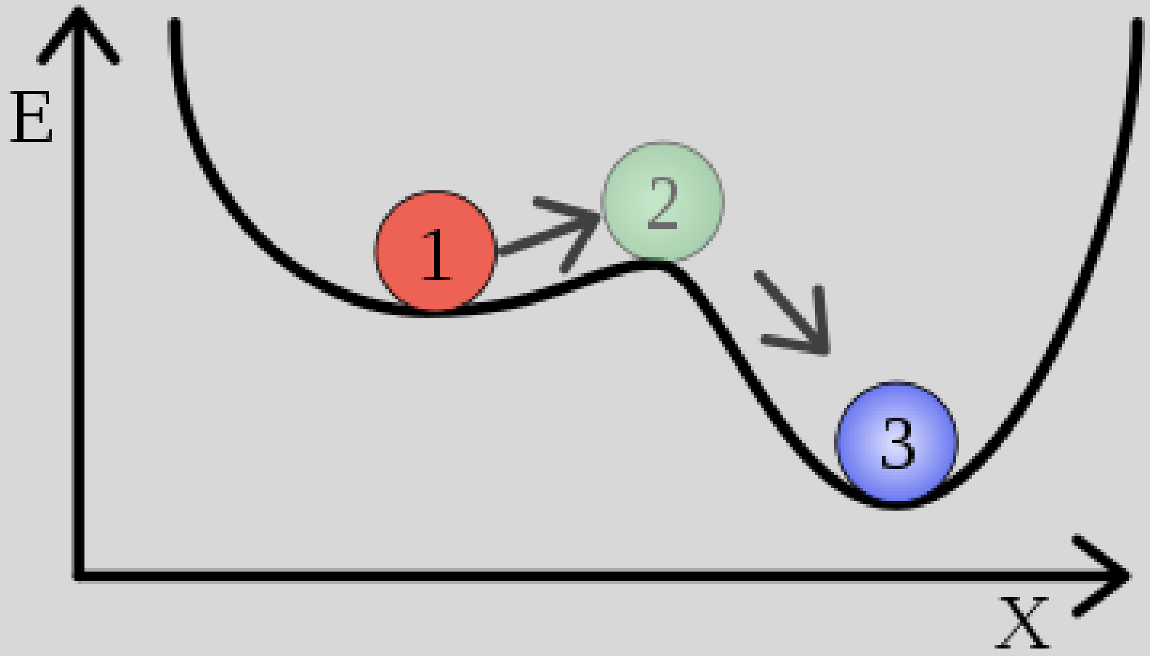
دینامیک های همگامی تصادفی بر روی کانکتوم مغز انسان

OUTLINE

Metastability	Coherent	Coupling	Synchronization
شبه پایداری	همدوسی	جفت شدگی	همگامی

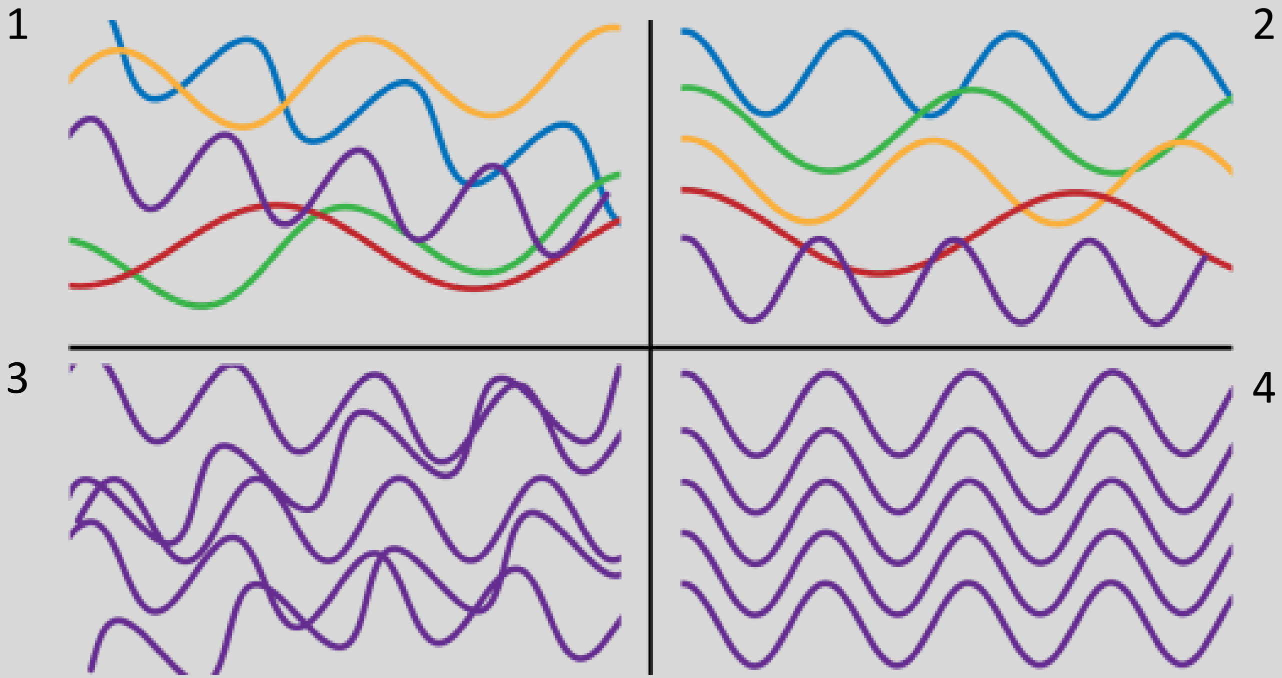
Metastability

شبه پایداری



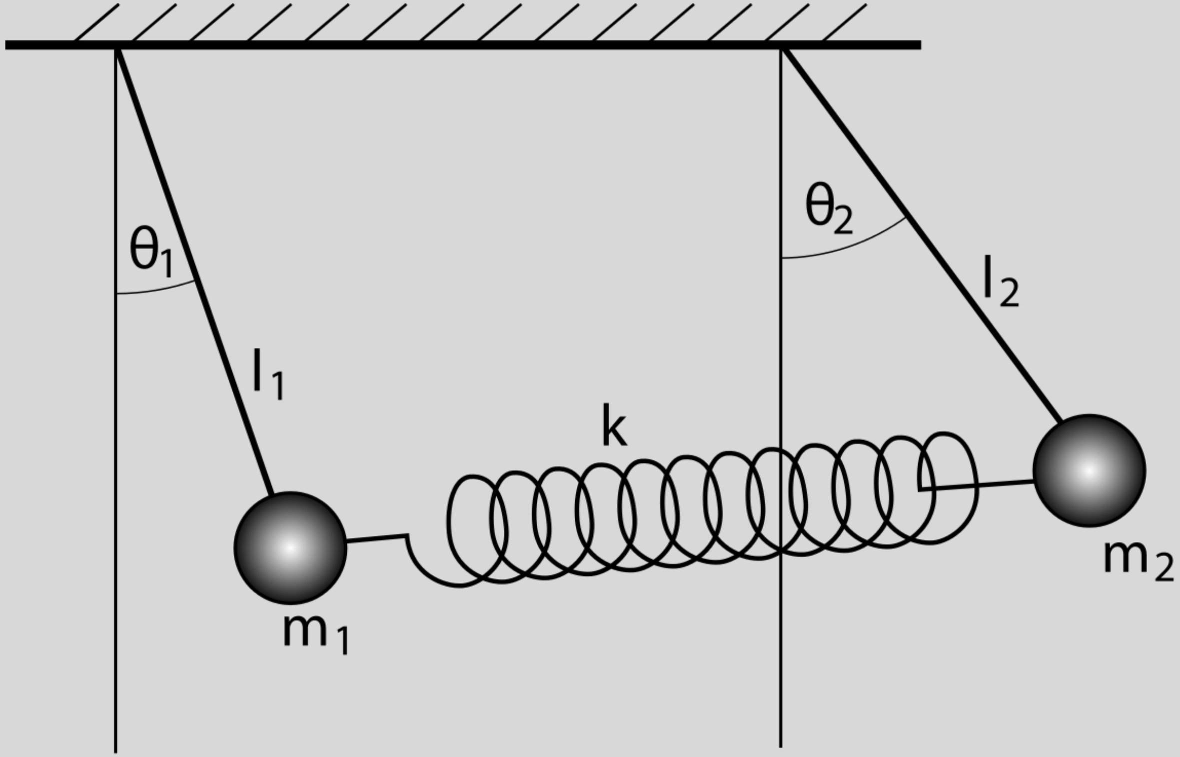
Coherent

همدوسی



Coupling

جفت شدگی

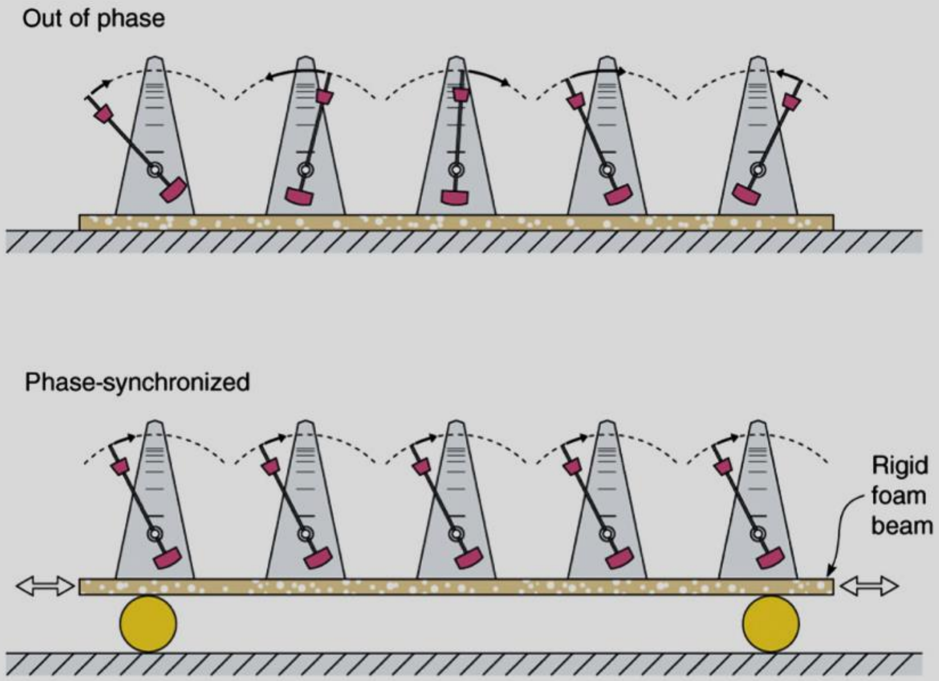


Synchronization

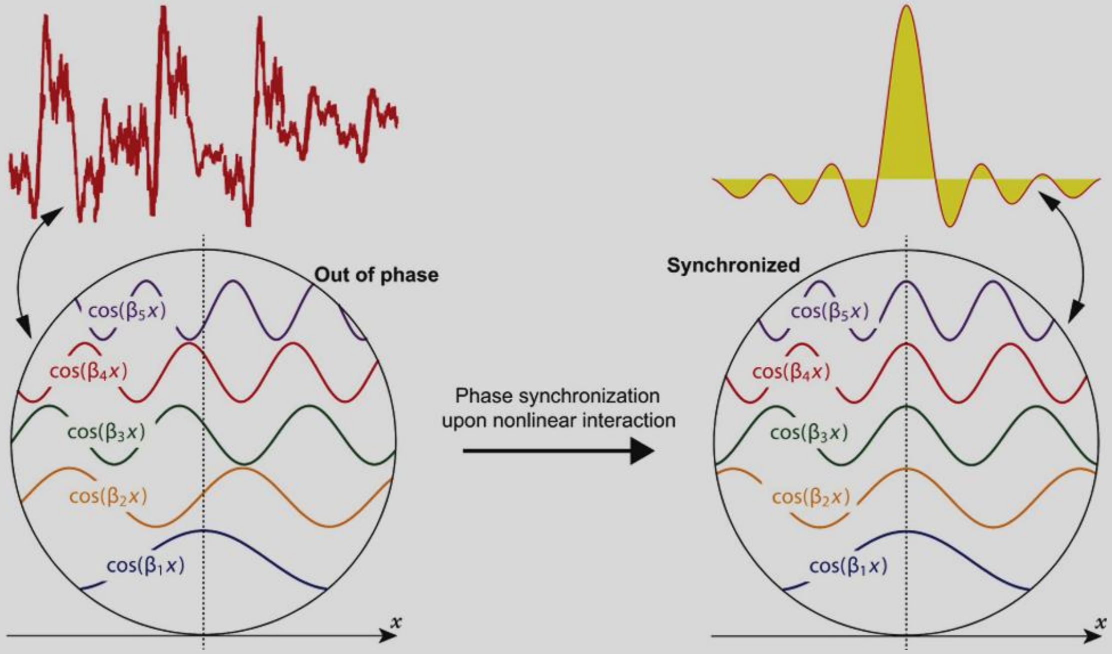
همگامی

Synchronization is a collective mechanism by which oscillatory networks achieve their functions.

Network's topological

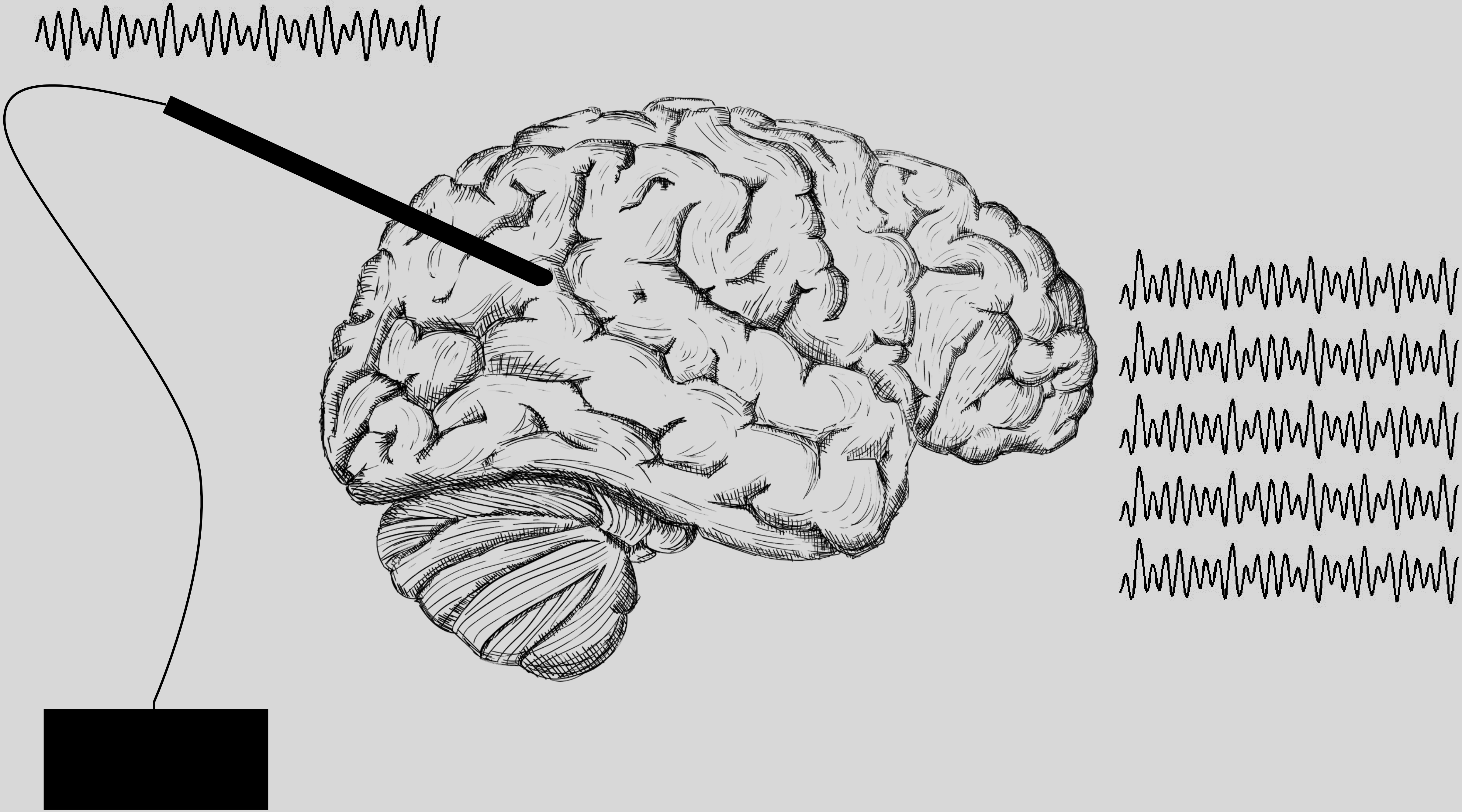


Dynamical properties



Photosensitive epilepsy (PSE)

صرع حساس به نور



Here, we aim to systematically address this problem using a large-scale model of the human brain network (i.e., the human connectome).

The results show that the model can produce complex synchronization patterns transitioning between incoherent and coherent states.

Network synchronization crucially depends on several factors such as

$$\sum_{k=1}^{N} A_{jk} \sin(\theta_k - \theta_j)$$

$$\omega_j^0$$

1-network architecture
2-intrinsic frequency of the oscillators
3-strength of the interaction between oscillators $\longrightarrow c$
4-external inputs.

$$\sigma dW_j(t)$$

connectivity matrix A where element Ajk describes the strength of the connection from oscillator k to j

natural frequency of oscillation ω0j

noise represented by the Wiener process dWj

$$d\theta_j(t) = \left[\omega_j^0 + c\sum_{k=1}^{N} A_{jk}\sin(\theta_k - \theta_j)\right] dt + \sigma dW_j(t)$$

coupling strength c that scales the connection strengths between oscillators

noise strength σ that scales the noise amplitude

all nodes in the network are perturbed by independent Gaussian noise realizations with the same standard deviation σ.

frequency limits ωmin = 0.01 Hz and ωmax = 0.1 Hz are set to match the frequency bandwidth of fMRI

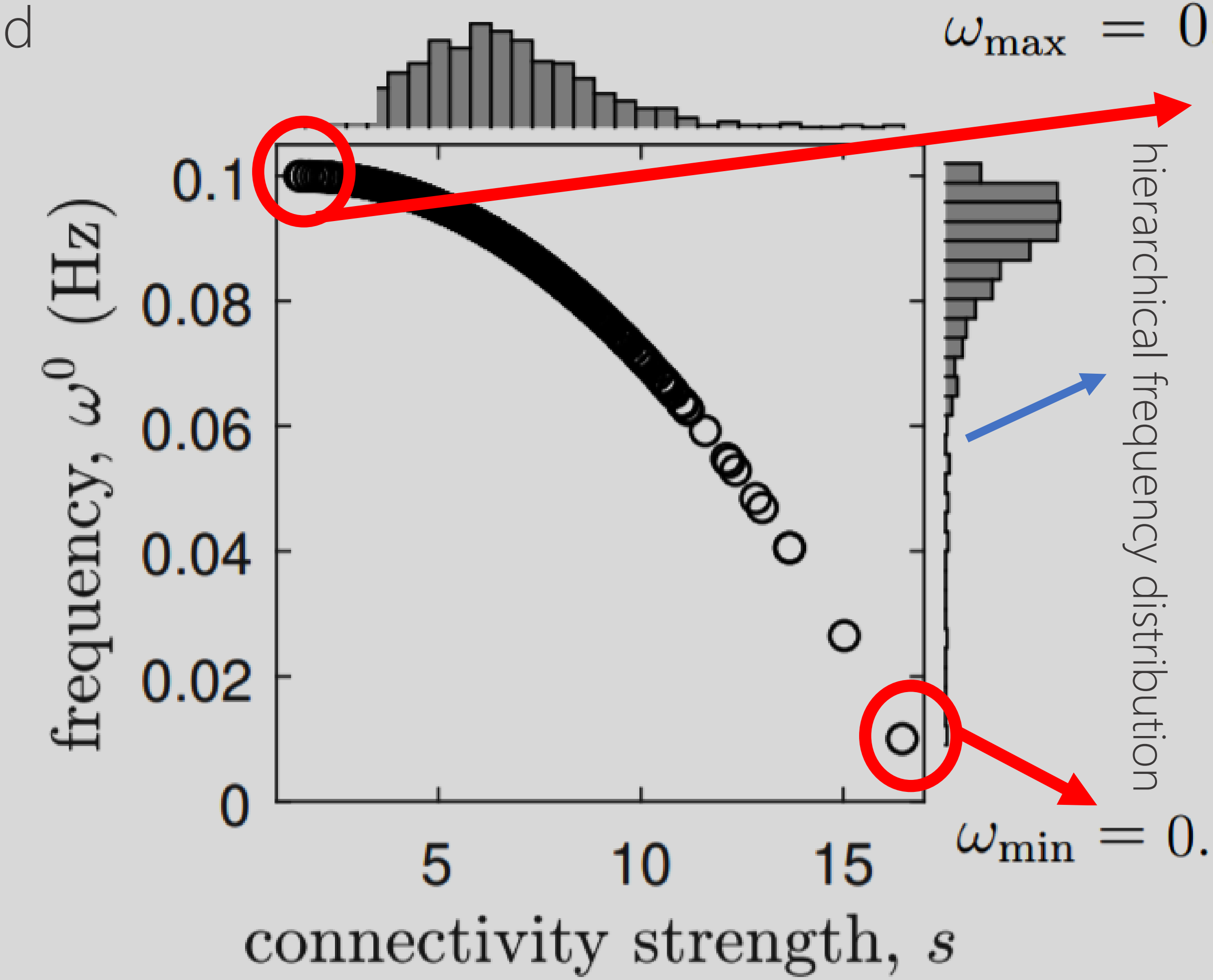
sj is the node’ s connectivity strength given by

$$s_j = \sum_k A_{jk}$$

$$\omega_j^0 = \omega_{\max} - (\omega_{\max} - \omega_{\min}) \left(\frac{s_j - s_{\min}}{s_{\max} - s_{\min}} \right)^2$$

smin is the minimum of all node strengths, and smax is the maximum of all node strengths

$\omega_{\max} = 0.1$ Hz



$\omega_{\min} = 0.01$ Hz

نشان میدهد که هرچه قدرت اتصال بیشتر باشد برای یک نود یا یک ناحیه از مغز که در نظرگرفته ایم، فرکانس ذاتی اون آهسته تر است.

پس یعنی هاب ها فرکانس های کمتر و نود های حاشیه ای فرکانس های بیشتری دارند.

For the connectivity matrix A, we use a human structural connectome derived from healthy participants.

It is a weighted and symmetric matrix

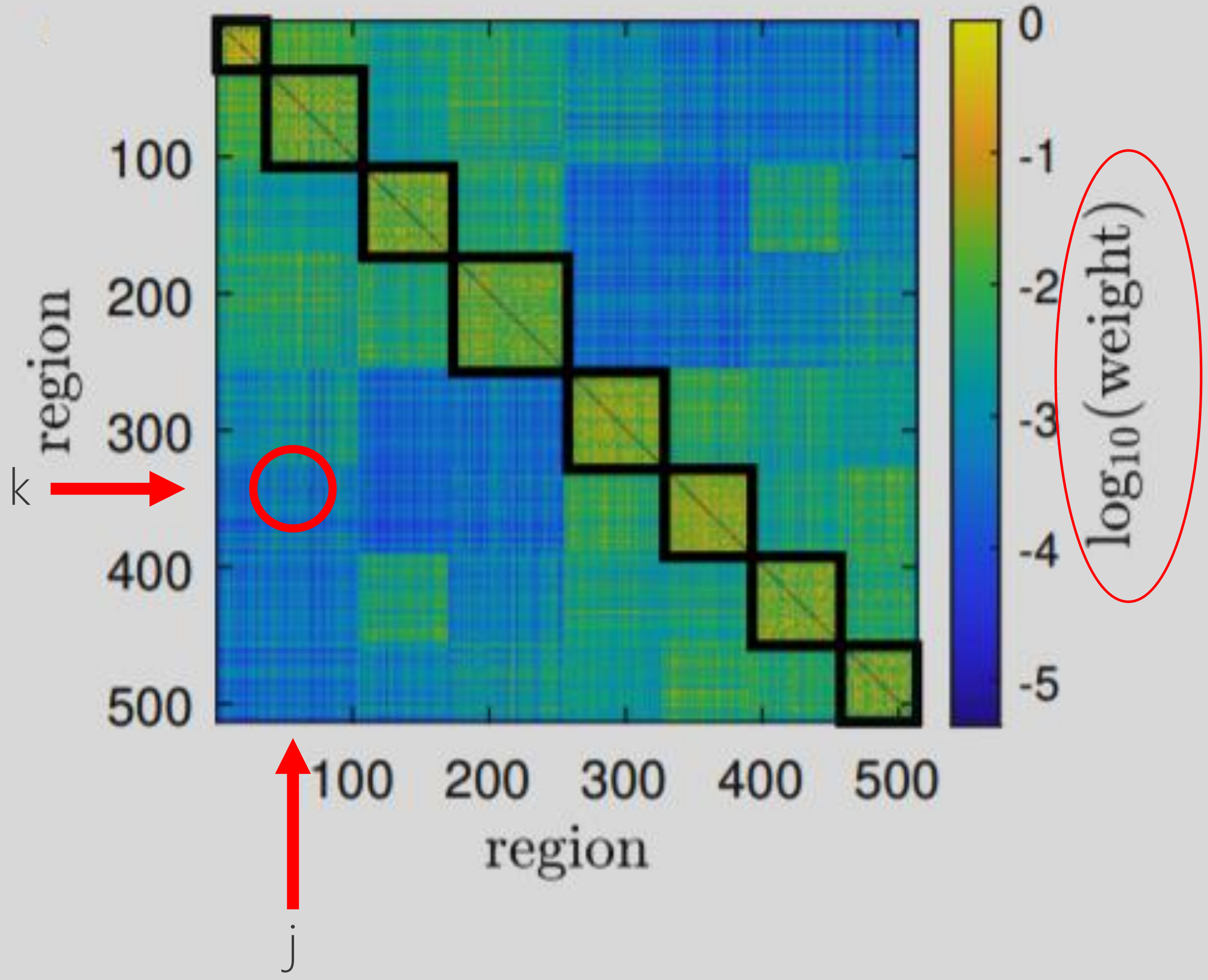
each row or column representing a brain region that aggregates populations of neurons

each connection Ajk is related to the number of fibers reconstructed between region j and k

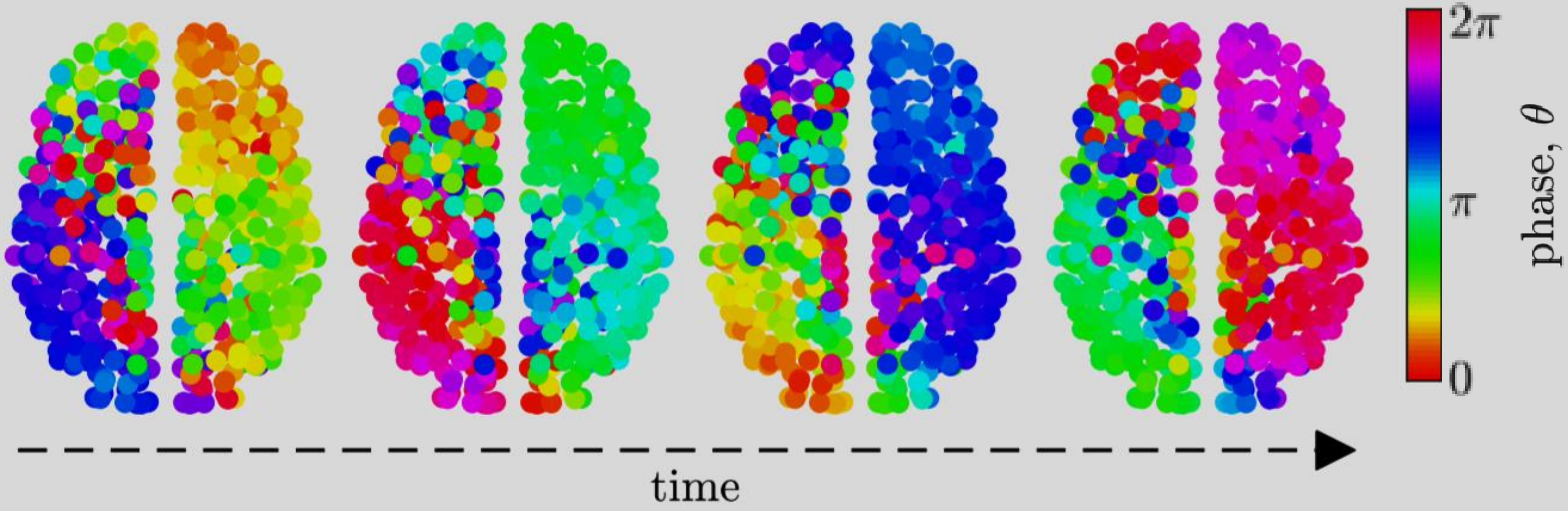
It has several features such as

a hierarchical-modular organization

and a spatial embedding characterized by an exponentially decaying edge weight-fiber length relationship



The above two model ingredients provide the structure and dynamics of the human brain, which when combined allows oscillations on the connectome to emerge and evolve through mutual interactions without the need for any external input.



coherence R synchronization S metastability M coupling strength c

coherence R captures the phase alignment of all oscillators in the network at each instance in time, with its value varying between 0 (fully incoherent state) and 1 (fully coherent state)

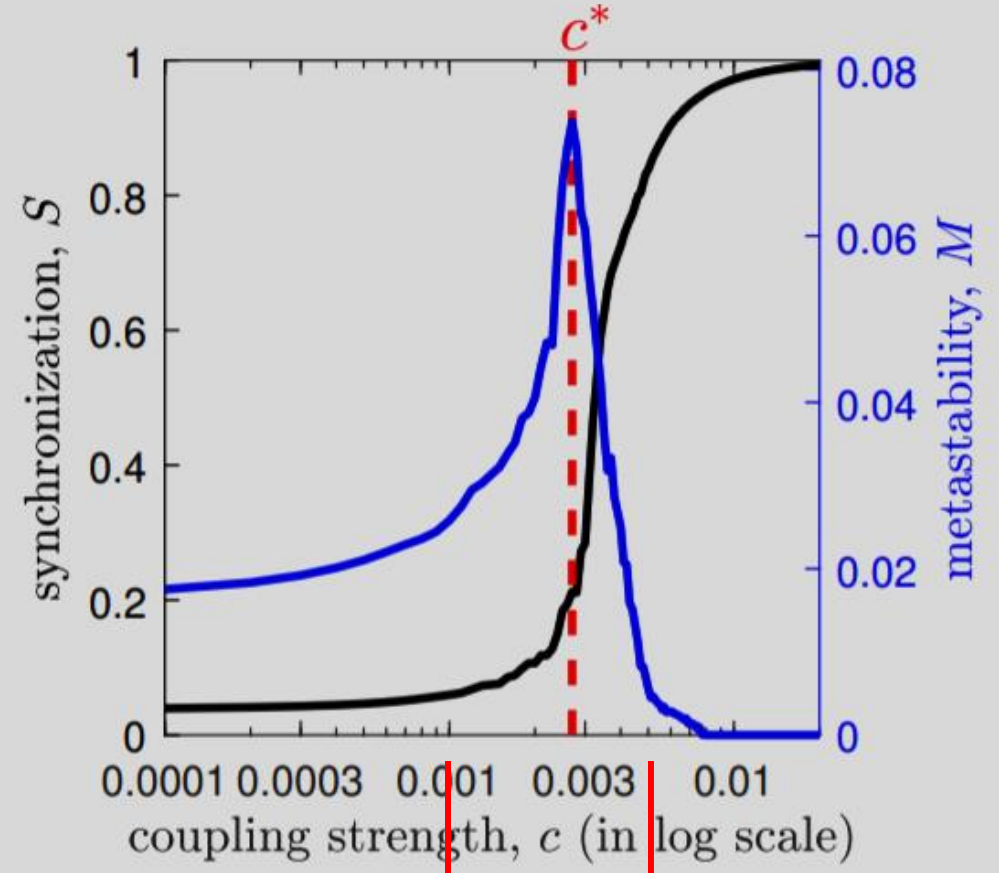
Synchronization S and metastability M are summary statistics at steady state capturing the mean and variability of R, respectively

$$\sigma = 0$$

$$d\theta_j(t) = \left[\omega_j^0 + c\sum_{k=1}^{N} A_{jk}\sin(\theta_k - \theta_j)\right] dt + \sigma dW_j(t)$$

Our results reveal that nodes in the network organize into diverse states of collective dynamics by just tuning c

$$c = c^* = 0.0027$$



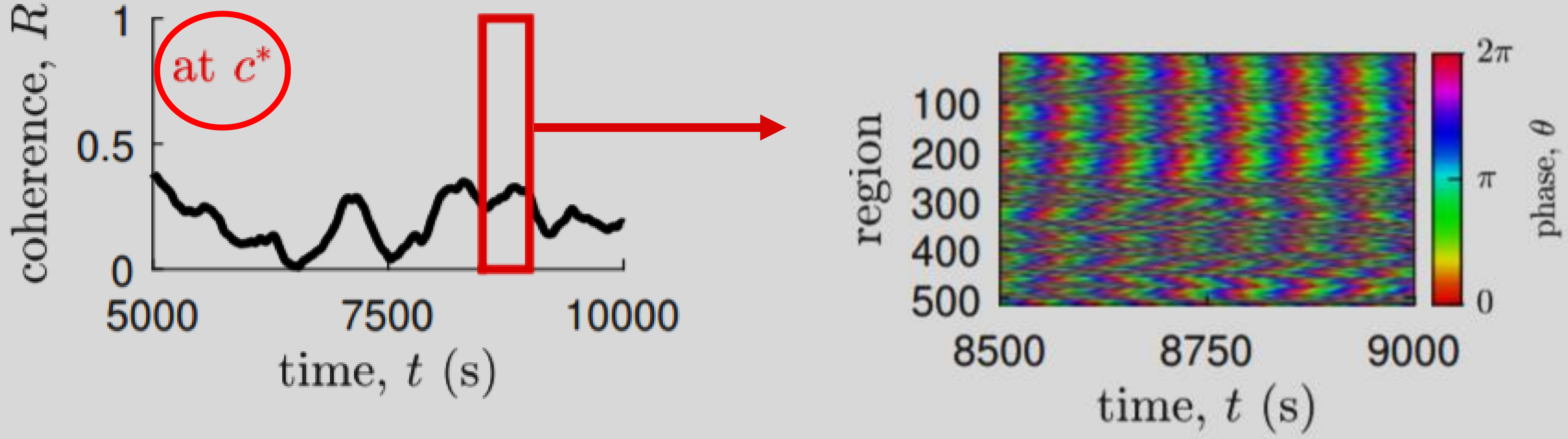
weak coupling

$c \leq 0.001$

stronger coupling

$c \geq 0.006$

This critical coupling strength places the network in a flexible regime that spontaneously accesses both states of order and disorder.



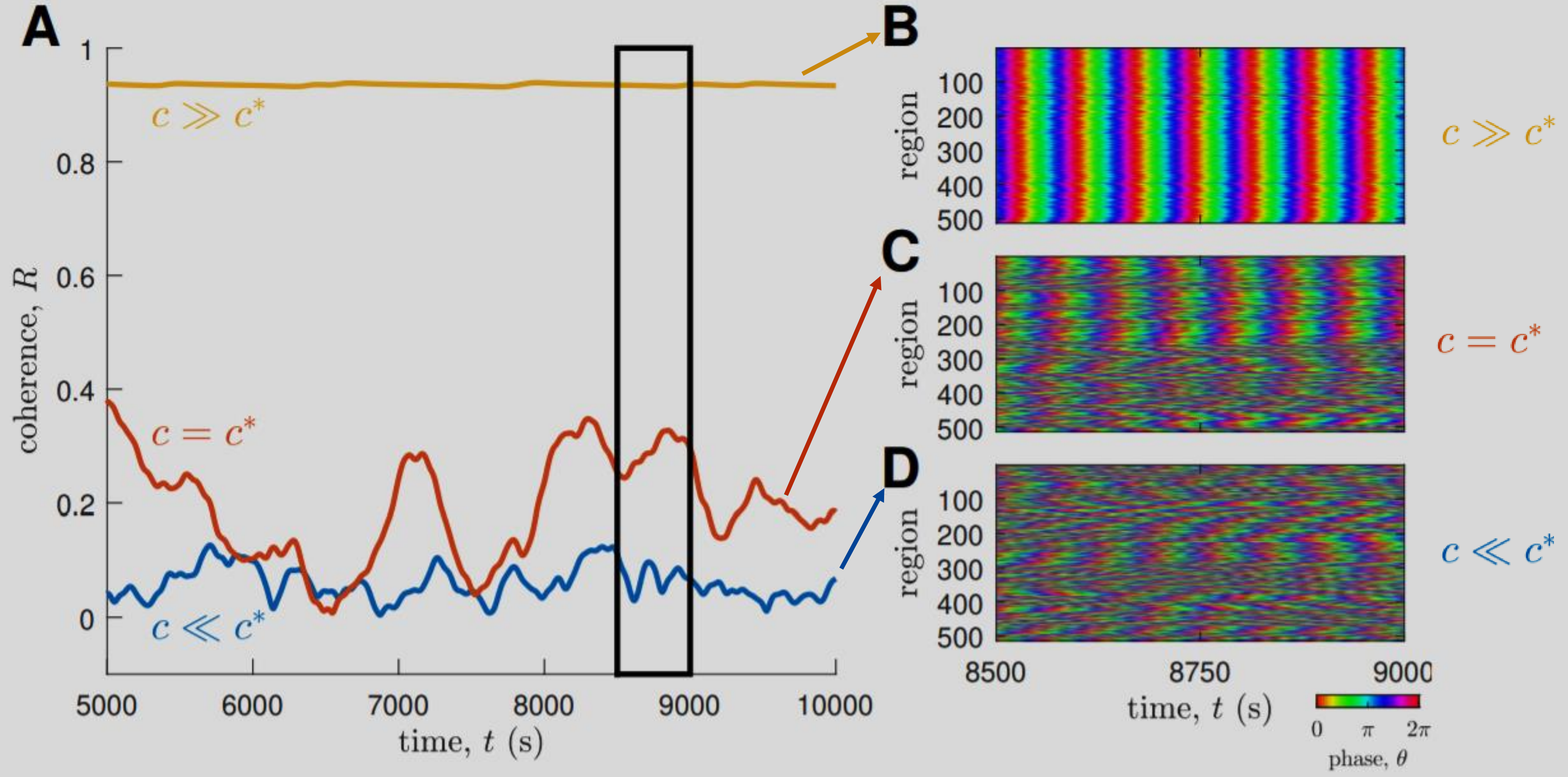
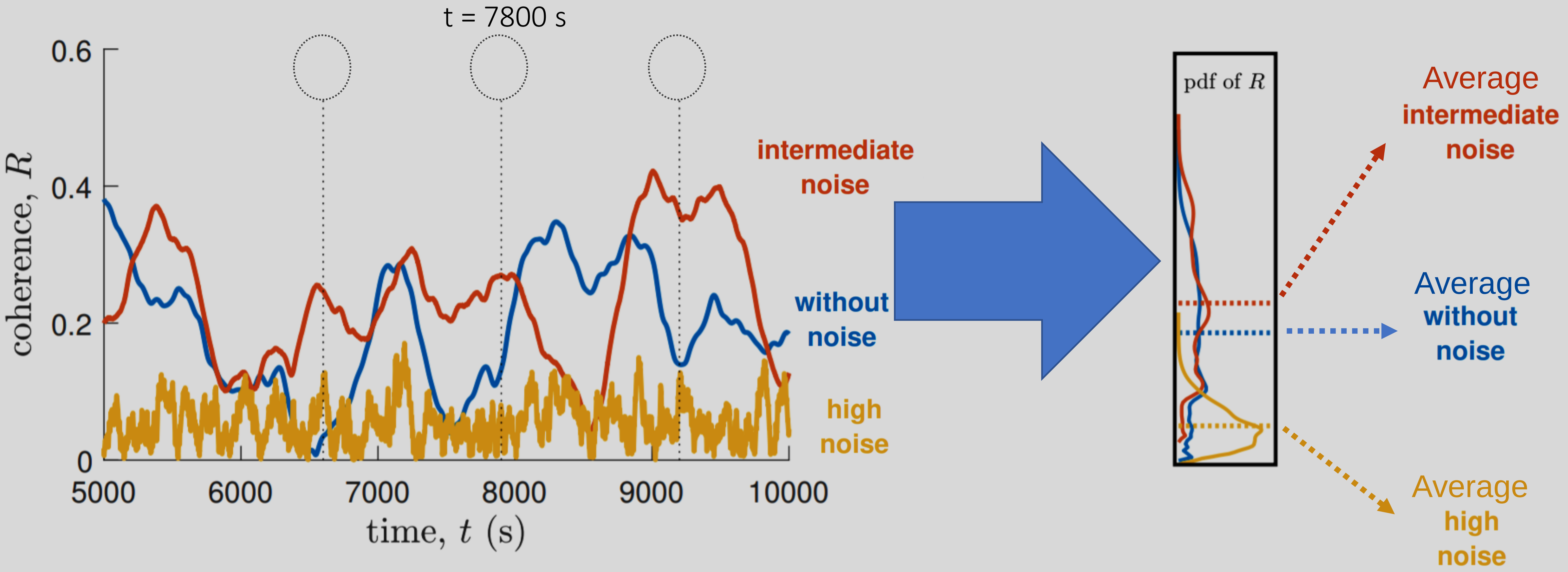


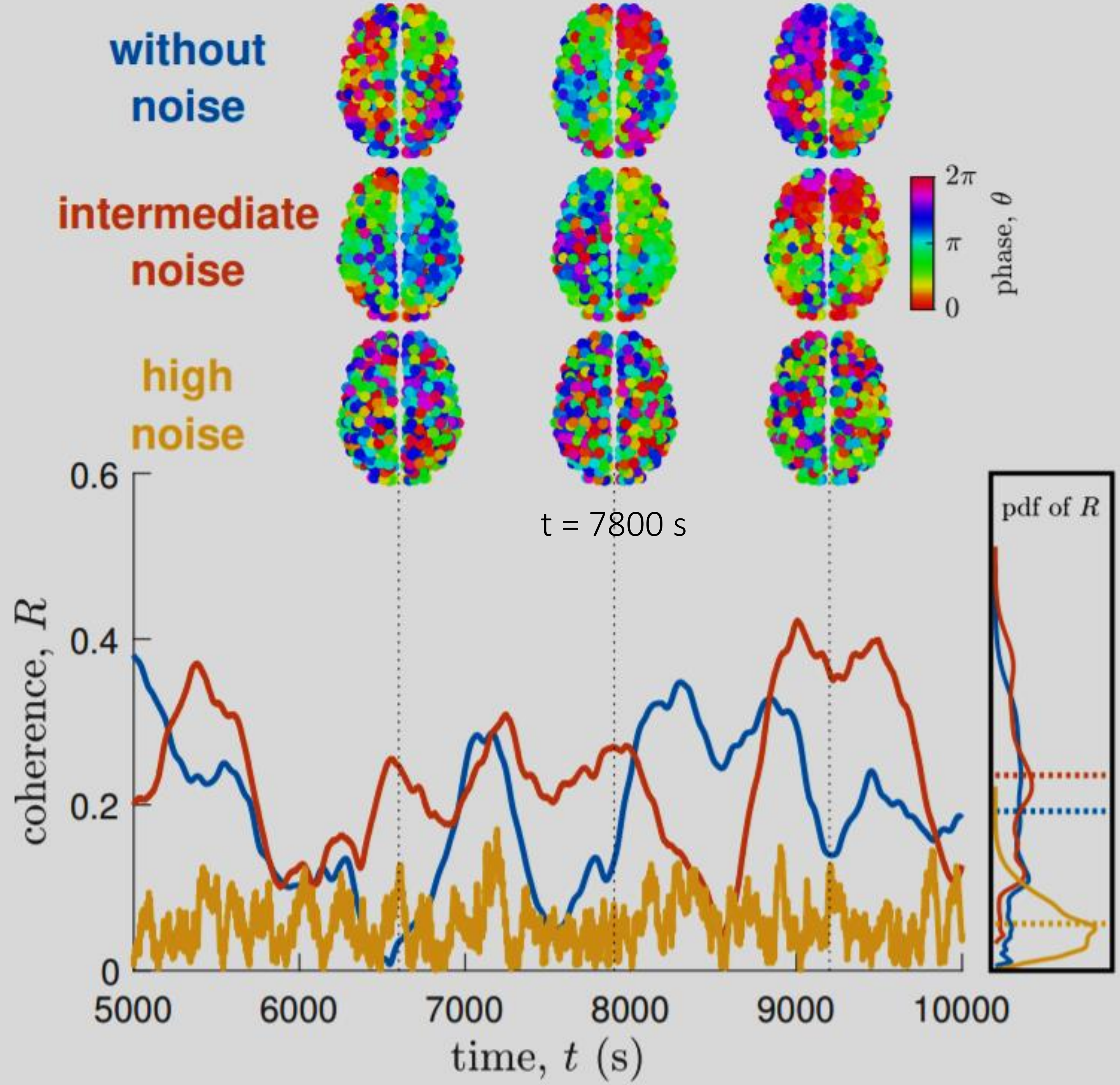
Figure S1: Network coherence and spatiotemporal dynamics for various coupling strengths. **(A)** Time evolution of network coherence R for $c \gg c^*$ (yellow), $c = c^*$ (red), and $c \ll c^*$ (blue). **(B)** Local phase dynamics for $c \gg c^*$. **(C)** Same as panel B but for $c = c^*$. **(D)** Same as panel B but for $c \ll c^*$. For panels B, C, and D, the dynamics shown are within the time window highlighted by the black solid box in panel A.

Emergence of stochastic synchronization

we analyze the network's behavior for three noise strengths:

- the original case without noise (σ = 0)
- intermediate noise (σ = 0.008)
- high noise (σ = 0.2)





without noise
intermediate noise
high noise
2π
π
0
phase, θ
t = 7800 s
pdf of R
coherence, R
0.6
0.4
0.2
0
5000
6000
7000
8000
9000
10000
time, t (s)

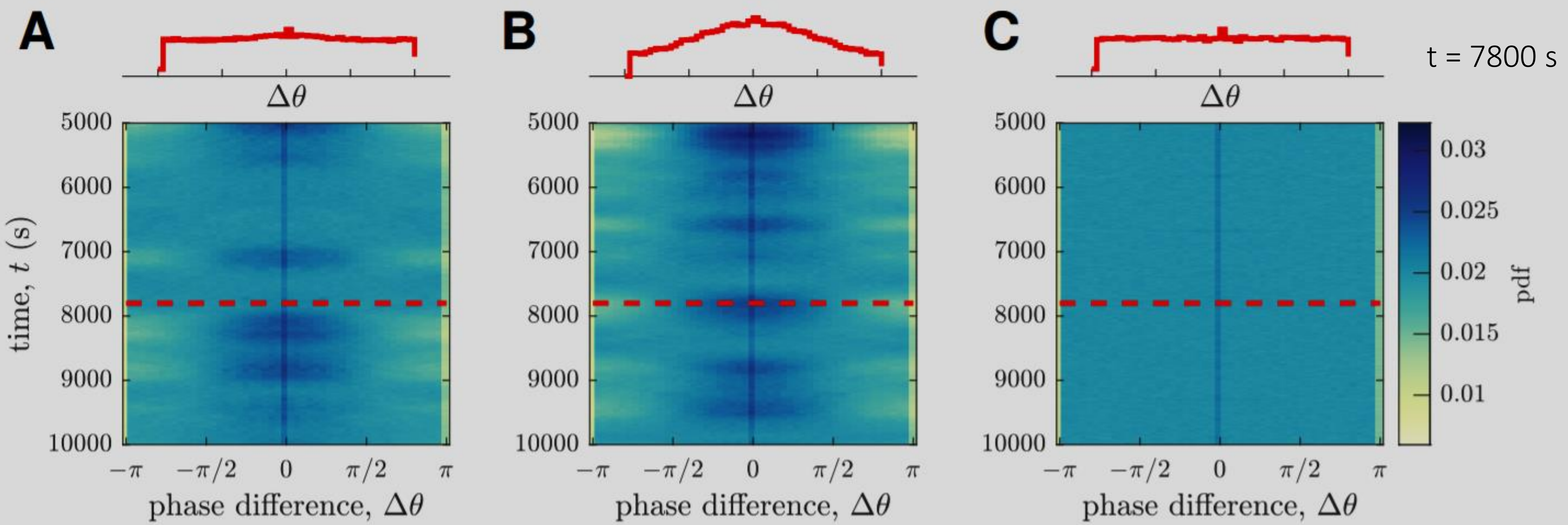
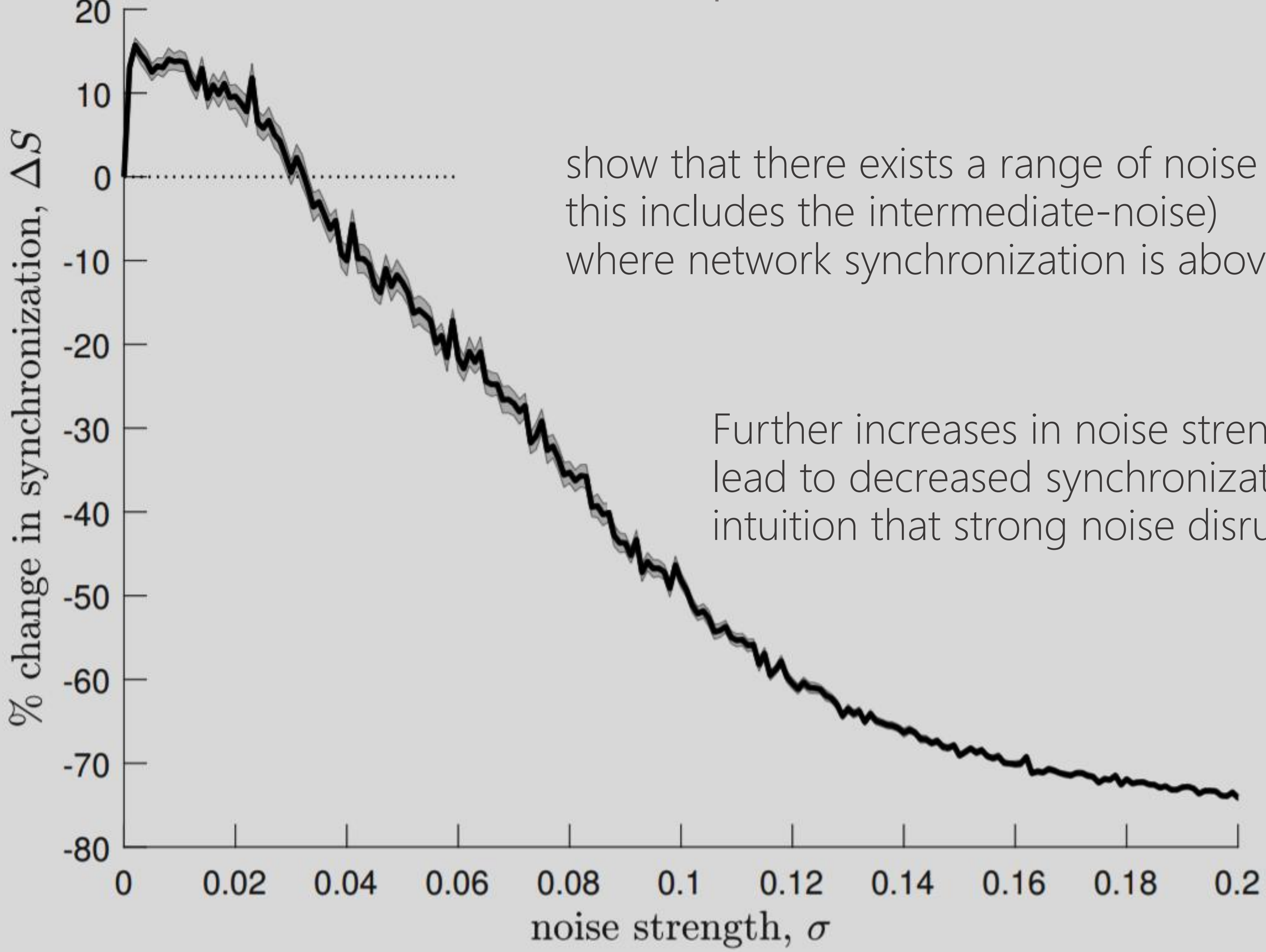


Figure S2: Time evolution of the distribution of phase differences for various noise strengths. **(A)** Pdf of phase difference $\Delta\theta$ for dynamics without noise. **(B)** Same as panel A but with intermediate noise. **(C)** Same as panel A but with high noise. The pdf at $t = 7800$ s highlighted by the red dashed line is shown above the panels.

The solid line represents an ensemble average of 50 noise realizations

the shaded area represents the standard error of the mean.



show that there exists a range of noise strengths ($0 < \sigma < 0.033$; this includes the intermediate-noise) where network synchronization is above the baseline ($\Delta S > 0$)

Further increases in noise strength (this includes the high-noise) lead to decreased synchronization (i.e., $\Delta S < 0$), in line with the intuition that strong noise disrupts synchrony.

the phenomenon only exists when the network is placed around the critical coupling strength c ∗

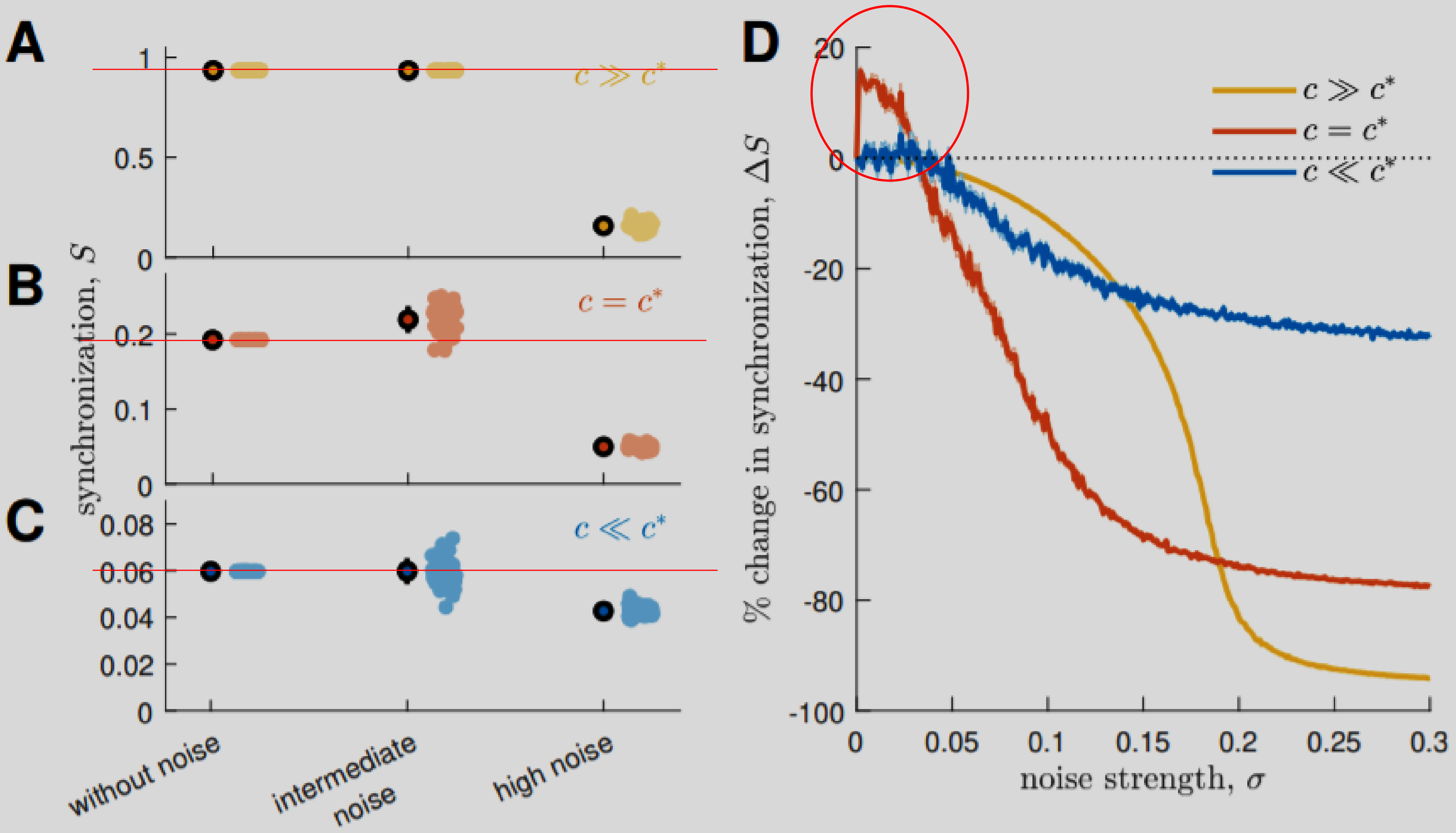
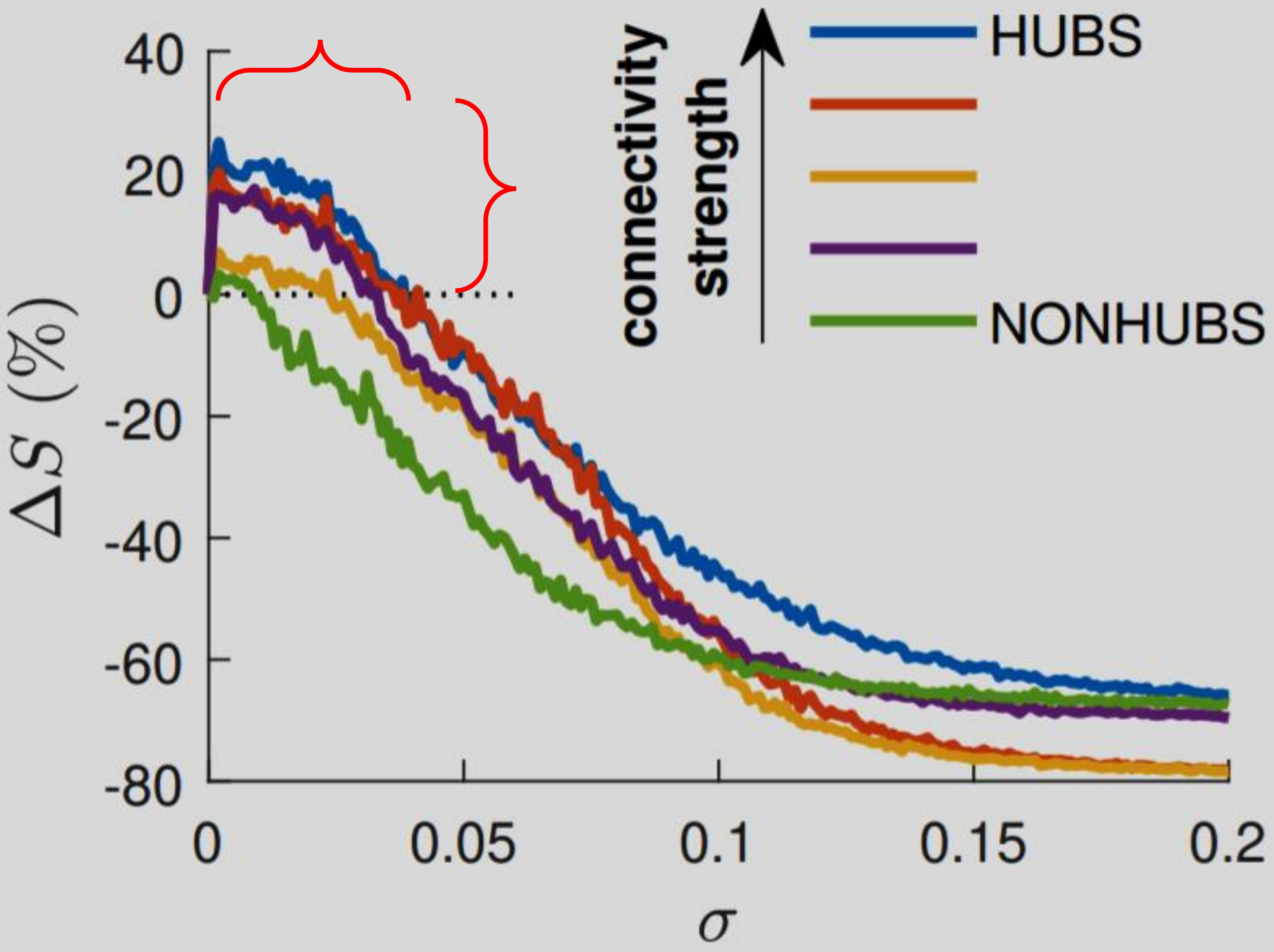


Figure S3: Synchronization for various coupling and noise strengths. **(A)** Synchronization S for $c \gg c^*$. **(B)** S for $c = c^*$. **(C)** S for $c \ll c^*$. For panels A, B, and C, the cloud of points represent 50 noise realizations, the thick markers represent ensemble averages of all noise realizations, and the vertical lines represent standard deviations. **(D)** Percent change of network synchronization ΔS vs noise strength σ (yellow: $c \gg c^*$; red: $c = c^*$; yellow: $c \ll c^*$). The solid lines represent ensemble averages of 50 noise realizations and the shaded areas represent the standard errors of the means.



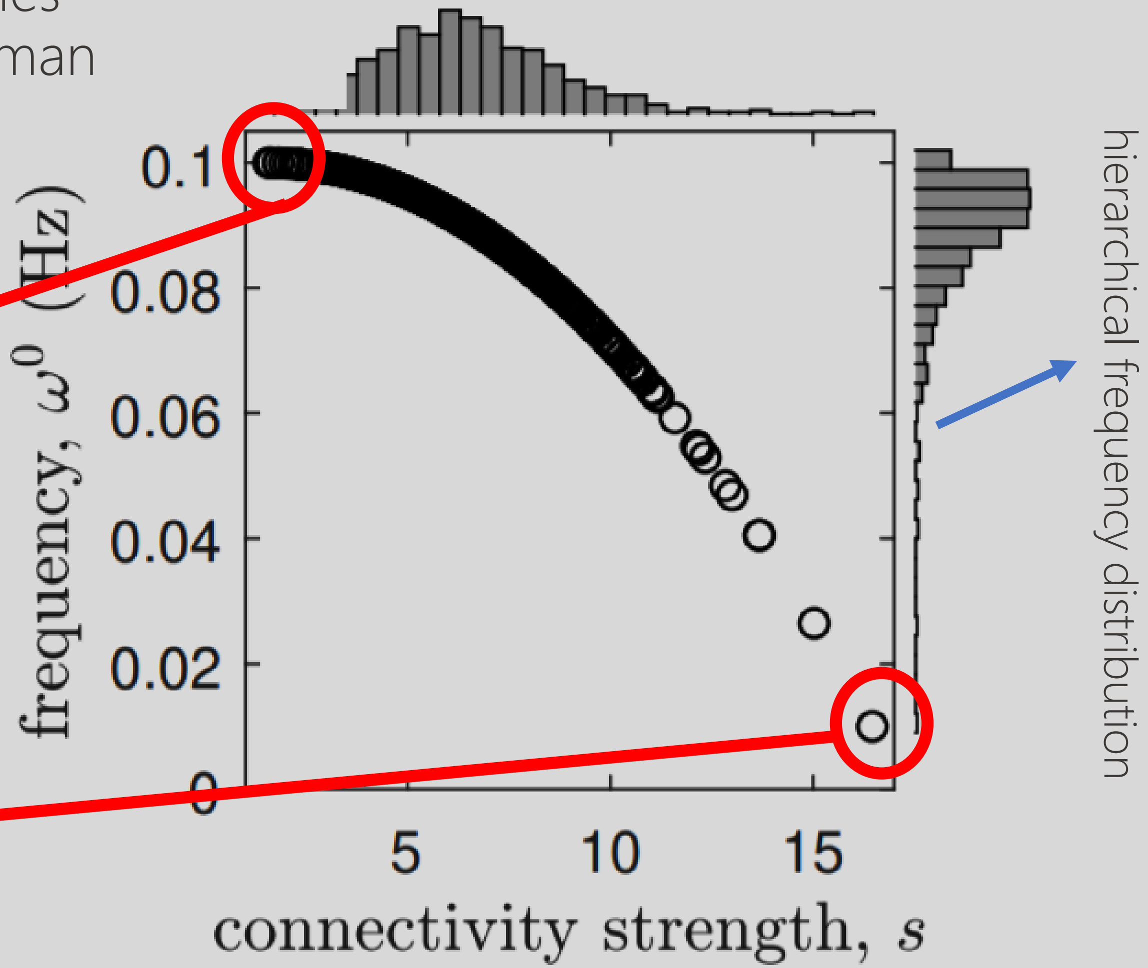
40
20
0
-20
-40
-60
-80
0
0.05
0.1
0.15
0.2
ΔS (%)
σ
connectivity strength
HUBS
NONHUBS

Drivers of stochastic synchronization

we conjecture that the paradoxical phenomenon could be due to the intrinsic node frequencies and/or the rich network topology of the human connectome.

$$\omega_{\max} = 0.1 \ \text{Hz}$$

$$\omega_{\min} = 0.01 \ \text{Hz}$$

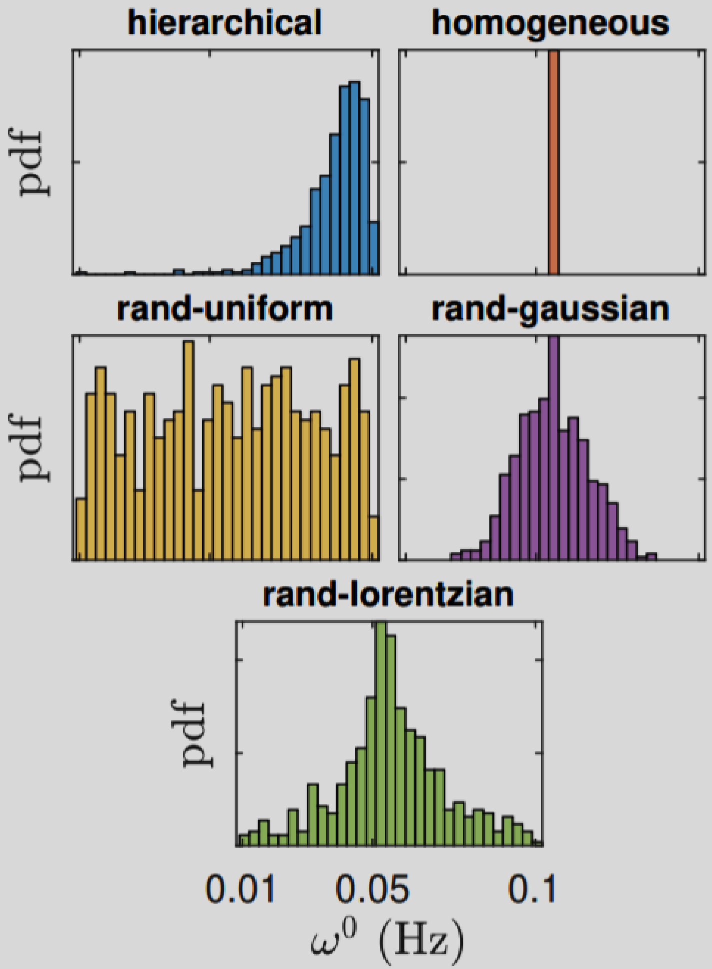


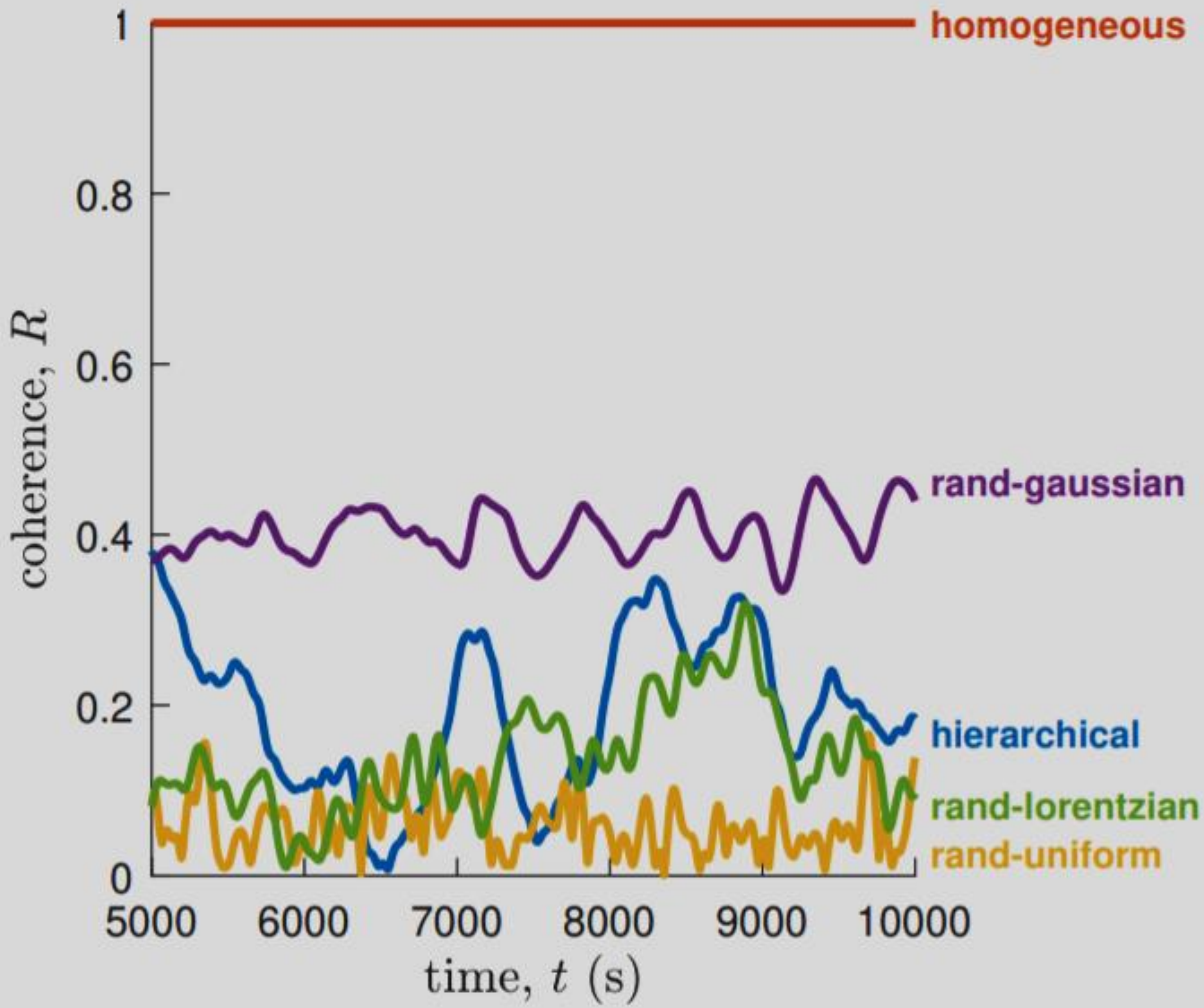
(i) Dirac-delta (homogeneous)

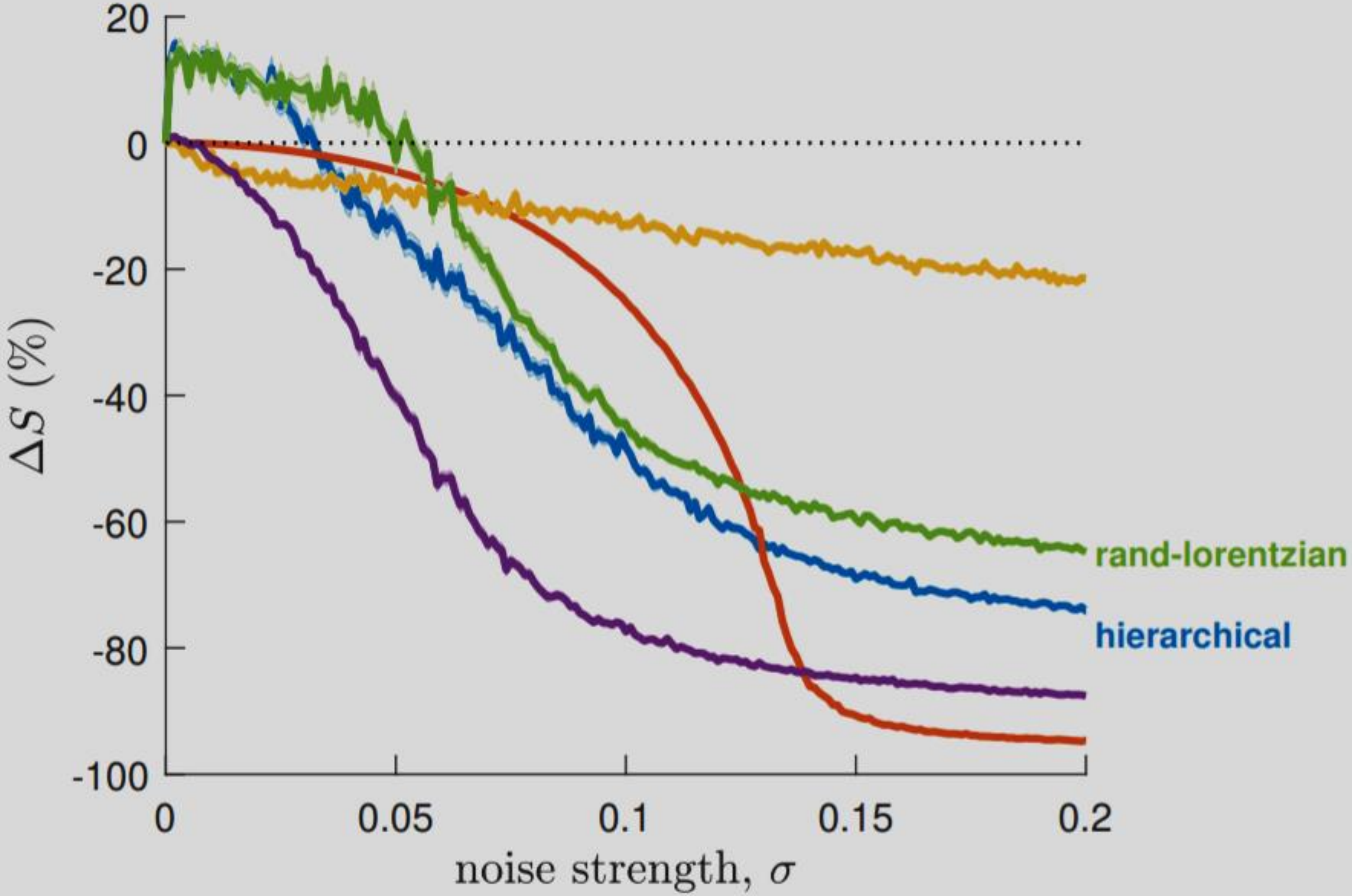
(ii) random uniform

(iii) random Gaussian

(iv) random Lorentzian







20
0
-20
-40
-60
-80
-100
ΔS (%)
0
0.05
0.1
0.15
0.2
noise strength, σ
rand-lorentzian
hierarchical

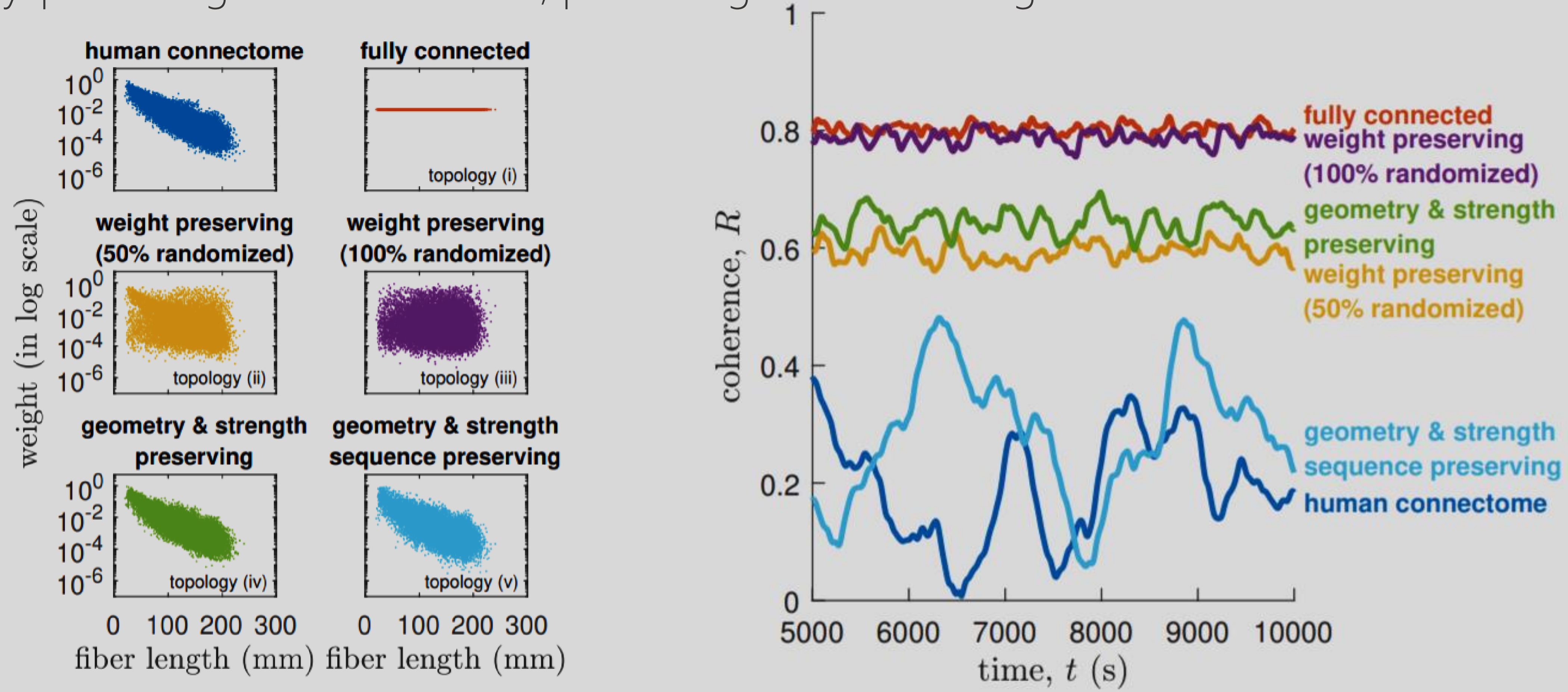
(i) fully connected network

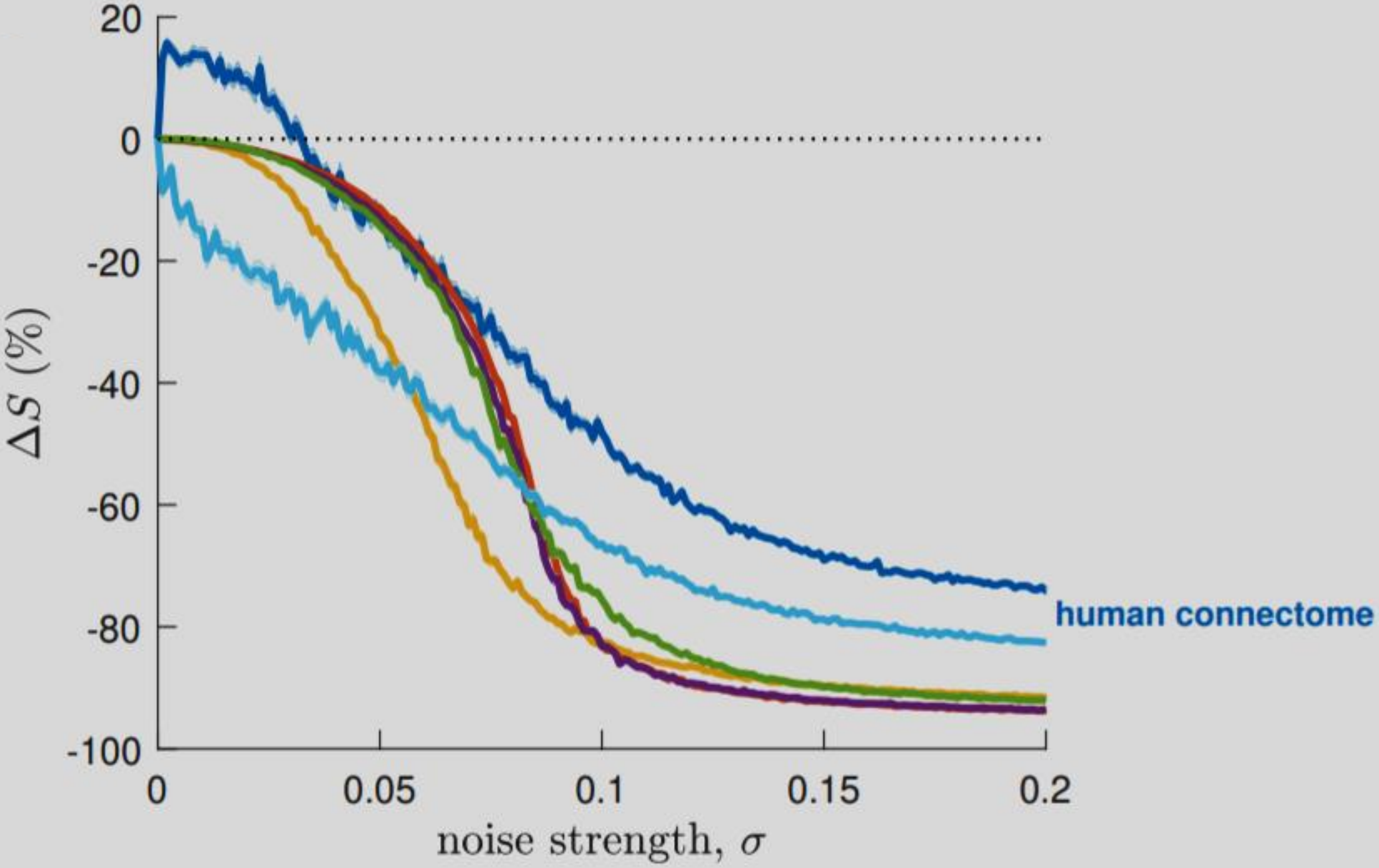
(ii) weight-preserving random network, randomizing 50% of the connections

(iii) weight-preserving random network, randomizing 100% of the connections

(iv) geometry-preserving random network, preserving the node strengths

(v) geometry-preserving random network, preserving the nodestrength sequence.




20
0
-20
-40
-60
-80
-100
ΔS (%)
0
0.05
0.1
0.15
0.2
noise strength, σ
human connectome

SeizureFirstAid

What to do in the event of a seizure

1 **STAY** with the person and start timing the seizure. Remain ***calm*** and check for medical ID.

2 Keep the person **SAFE.** Move or guide away from ***harmful objects***.

3 Turn the person onto their **SIDE** if they are not awake and aware. ***Don't block airway***, put something small and soft under the head, loosen tight clothes around neck.

4 Do **NOT** put ***anything*** in their mouth. Don't give water, pills or food until the person is awake.

5 Do **NOT** ***restrain.***

6 **STAY** with them until they are awake and alert after the seizure. ***Most seizures end in a few minutes.***

Call 911:

- ☒ Seizure lasts longer than 5 minutes
- ☒ Repeated seizures
- ☒ Difficulty breathing
- ☒ Seizure occurs in water
- ☒ Person is injured, pregnant, or sick
- ☒ Person does not return to their usual state
- ☒ First time seizure

This publication is made possible with funding from the Centers for Disease Control and Prevention (CDC) under cooperative grant agreement number 1NU58DP006256-02-00. Its contents are solely the responsibility of the Epilepsy Foundation and do not necessarily represent the views of the CDC.

EFA440/PAB0918

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PURPLE DAY
FOR EPILEPSY
March 26/Farvardin 7