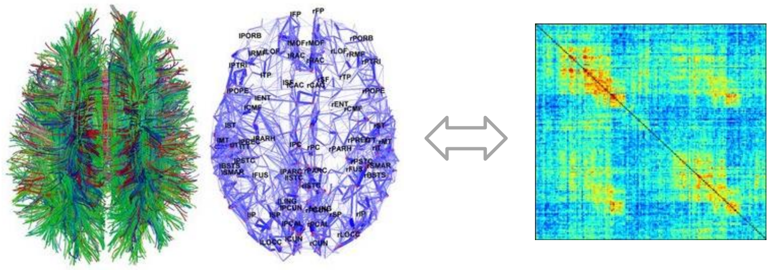
UNIVERSITY OF HELSINKI

IV INTERNATIONAL WORKSHOP
Complex Collective Dynamics: Brains and beyond
September 4, 2015

Human connectome

and

Propagation pathways of neuronal avalanches



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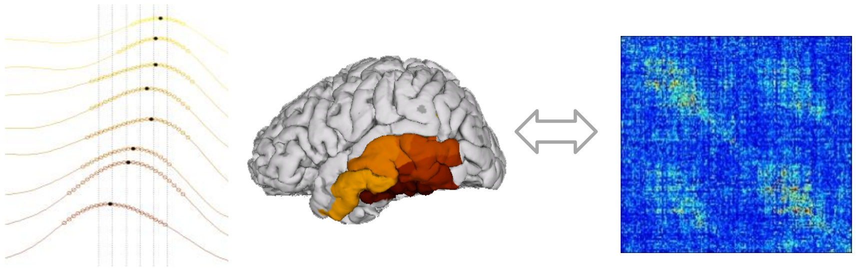

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Neuroscience Center, University of Helsinki

Outline

① Concept of criticality for the brain

② Critical dynamics in neuronal, behavioral and physiological data

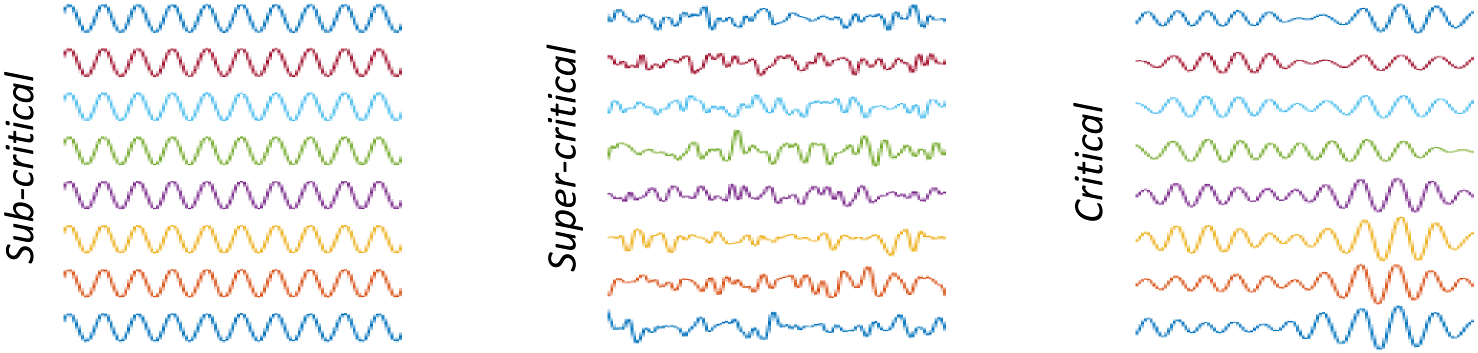
③ Critical dynamics and brain connectivity

Concept of criticality for the brain

Criticality concept for the brain

Per Bak, 1996, “How nature works”,

“If the brain in the **frozen subcritical state**, there will be only a local effect of changes <…>. If the brain is in a **chaotic disordered state** with neurons firing everywhere, it is not possible to communicate. Hence, the brain must operate at the **critical state** where the information is just barely able to propagate”.



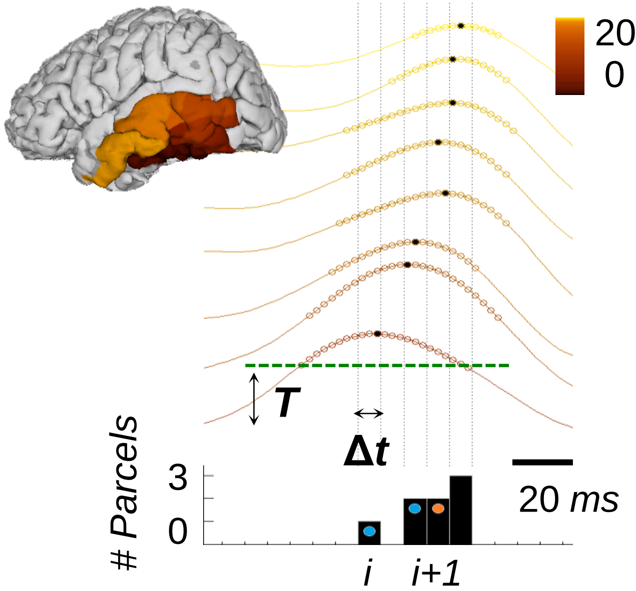
Recent modeling studies support this hypothesis,

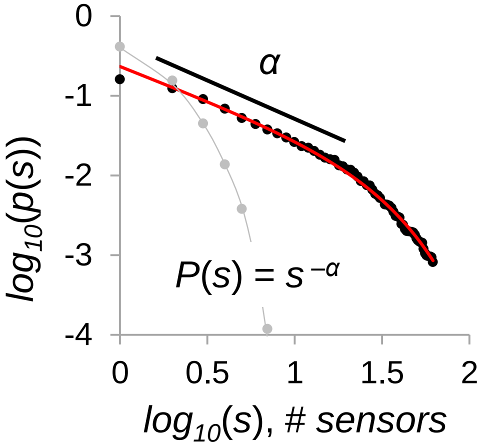
- **Number of metastable states is maximized at criticality** (Haldeman and Beggs, 2005)
- **Optimal dynamical range of excitable networks at criticality** (Kinouchi and Copelli, 2006)
- **Maximum dynamic range in cortical networks at criticality** (Shew et al., 2009)
- **Information capacity and transmission are maximized at balanced networks** (Shew et al., 2011)

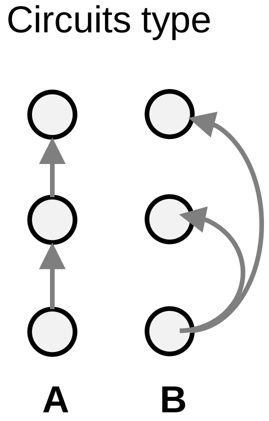
Chialvo, 2010, *Nat. Phys.*

Hallmarks of criticality in the brain

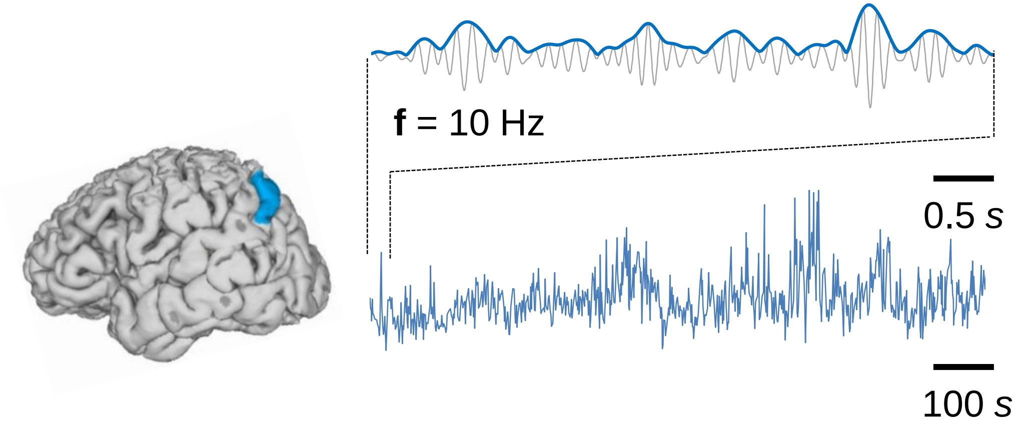
I. Power-law distribution of **avalanches sizes** / spatio-temporal dynamics, $10^{-3} – 10^{-1}$ s

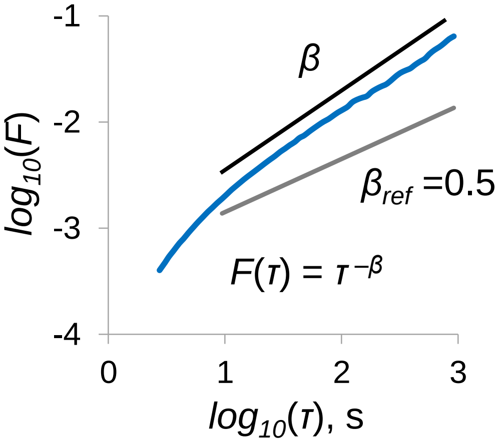






II. Power-law **long-range temporal correlations** (LRTCs) / temporal dynamics, $10^{1} – 10^{3}$ s



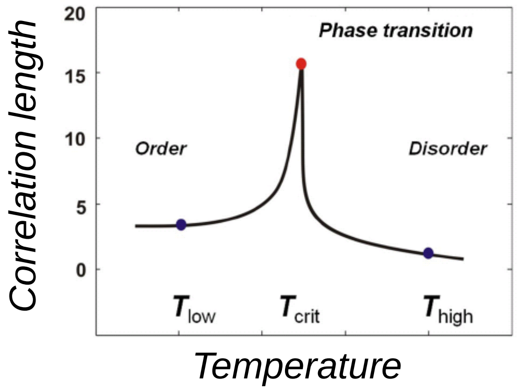


Evidence for criticality beyond power-laws

Presence of power-law suggest that system is critical but does not prove it (e.g., Beggs and Timme, 2012)

- the ability to tune the network from a subcritical regime through criticality to a supercritical regime.

Beggs & Timme, 2012, *Front. Physiol*.



- the existence of mathematical relationships between the exponents of the power laws for a system

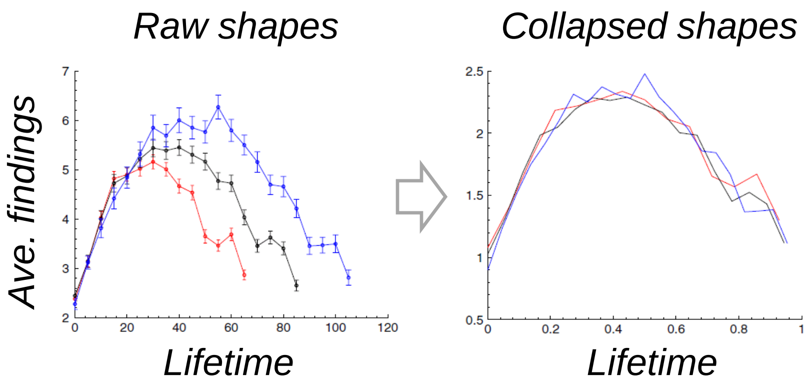
Stanley, 1999, *APS*

Magnet properties, $C_H \sim \varepsilon^{-\alpha}$; $M^2 \sim \varepsilon^{2\beta}$; $\chi_T \sim \varepsilon^{-\gamma}$

$$\boldsymbol{\alpha + 2\beta + \gamma = 2}$$

- the existence of a data collapse

Friedman et al., 2012, *Phys. Rev. Lett*.



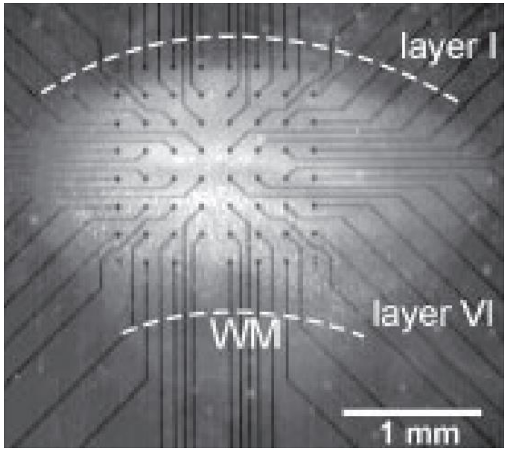
Story of neuronal avalanches

1. Superficial cortical layers

Originally neuronal avalanches have been observed for **superficial layers** only.

Beggs & Plenz, 2003, 2004, *J. Neurosci*.; Gireesh & Plenz, 2008, *PNAS*; Petermann et al., 2009, *PNAS*

(in tissue cultures, acute slices, anesthetized rats, awake rhesus monkeys)



> "All evidence so far suggests that it is not the brain that is critical, but it is its cortical core, the superficial layers".

Plenz, 2012, *APC*

2. "Homogeneous" neuronal networks

Originally neuronal avalanches have been observed at sub-millimeter scale where the structure of neuronal networks is **relatively homogeneous**.

Beggs & Plenz, 2003, 2004, *J. Neurosci*.; Gireesh & Plenz, 2008, *PNAS*; Petermann et al., 2009, *PNAS*

Modern story of neuronal avalanches

1. Superficial cortical layers & others

Invasive recordings *in vivo* [10^{-2} – 10^{2} mm, 10^{-4} – 10^{-2} s].

Hahn et al., 2010; Solovey et al., 2012; Priesmann et al., 2013; Zhigalov et al., 2015

Non-Invasive recordings *in vivo* [1 – 10^{2} mm, 10^{-3} – 1 s].

Allegrini et al., 2010; Tagliazucchi et al., 2012; Shriki et al., 2013; Palva et al., 2013

Importantly, the scaling exponents of avalanche size distribution differ between the studies.

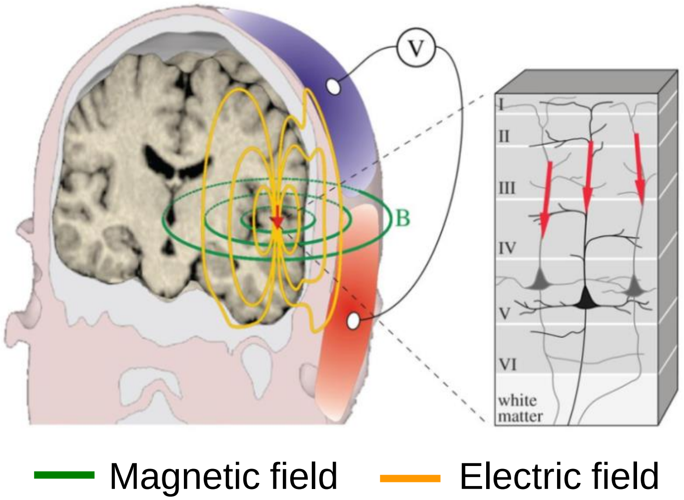
2. “Homogeneous” & “structured” neuronal networks

Recent studies emphasize the strong impact of topology of neuronal networks on critical dynamics.

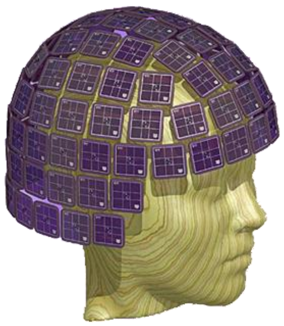
Moretti & Munoz, 2013, *Nat. Commun*; Ciuciu et al., 2014, *NeuroImage*; Hilgetag et al., 2014,*Tren. Cogn. Sci.*

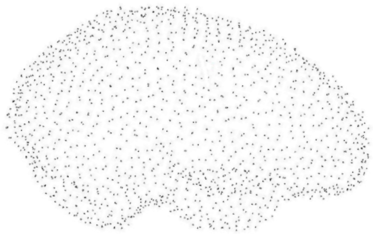
Critical dynamics in neuronal, behavioral and physiological data

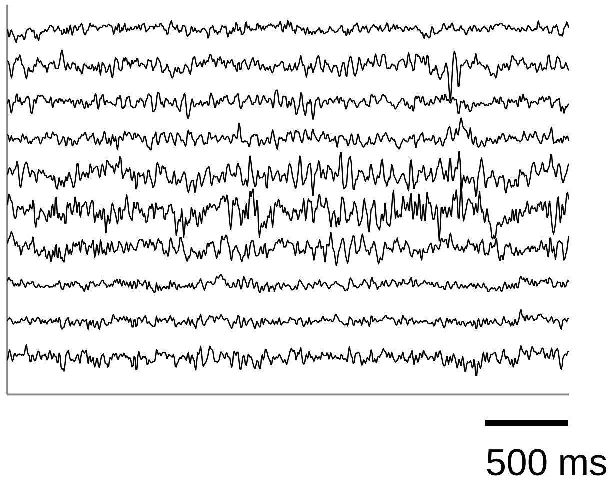
What can we measure with MEG?



Hari & Parkkonen, 2015, *Phil. Trans. Soc.*

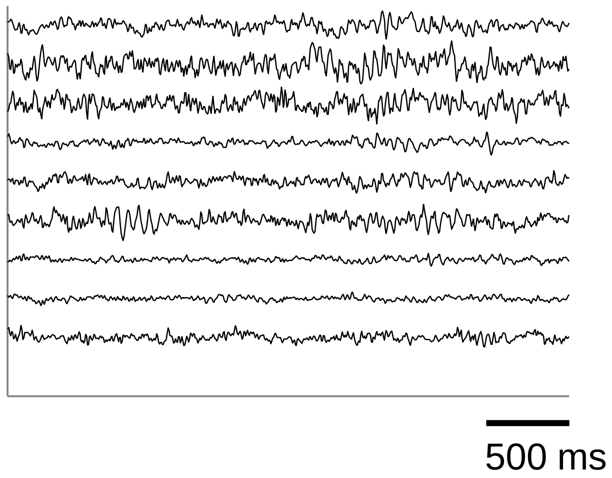


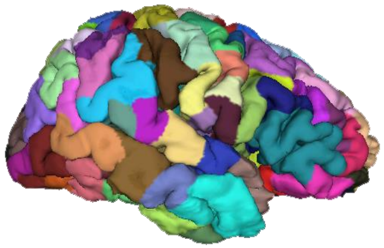


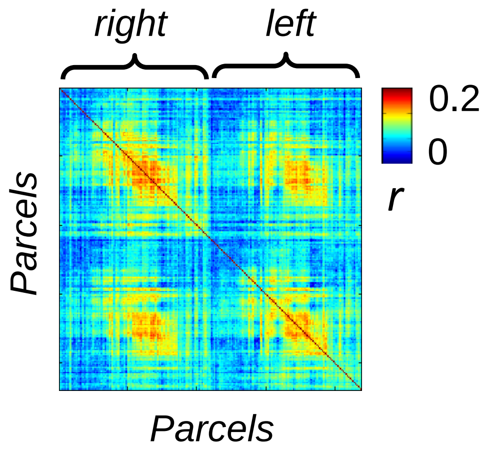


MEG source reconstruction

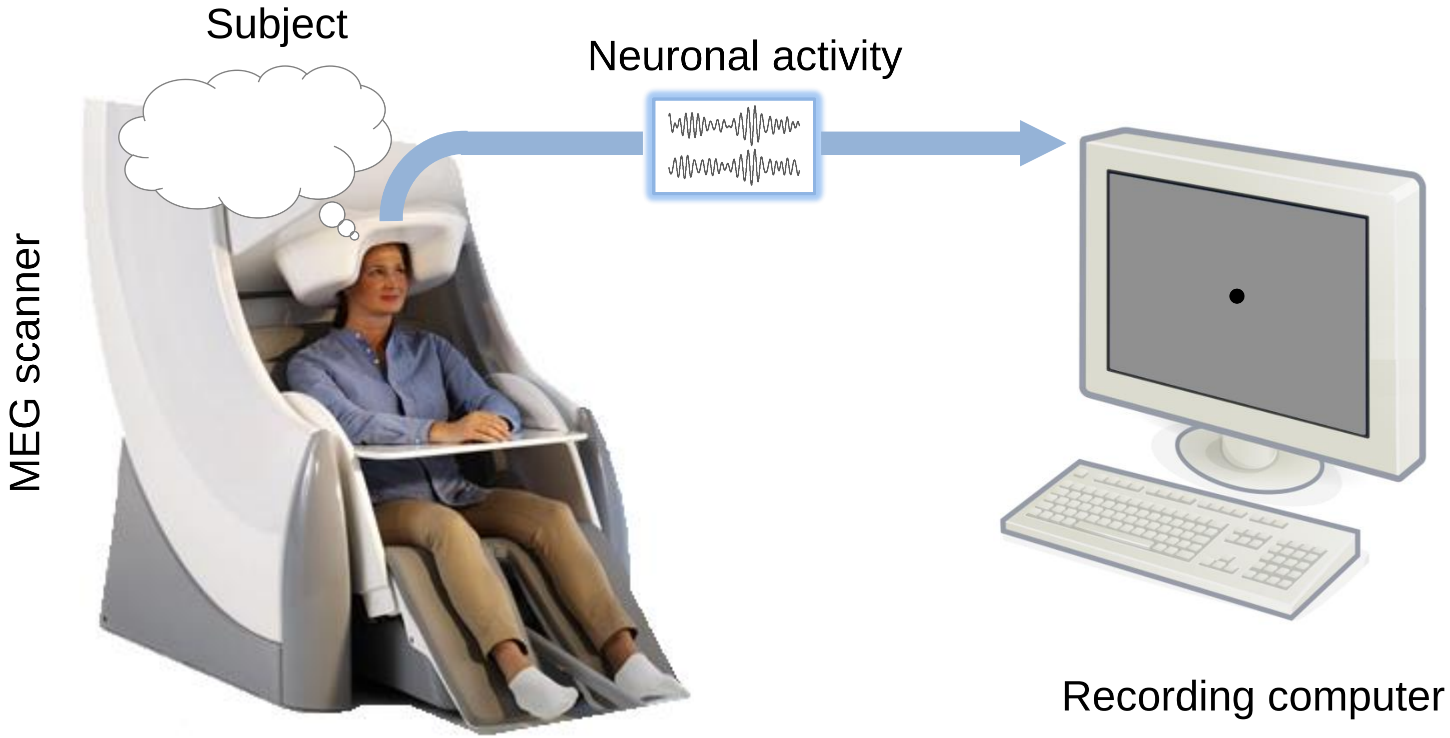
- BEM head model
- Distributed sources model, minimum norm estimator







Experiment type 1 / Resting state



Subject

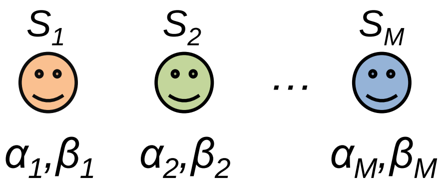
Neuronal activity

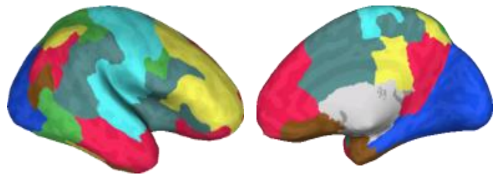
MEG scanner

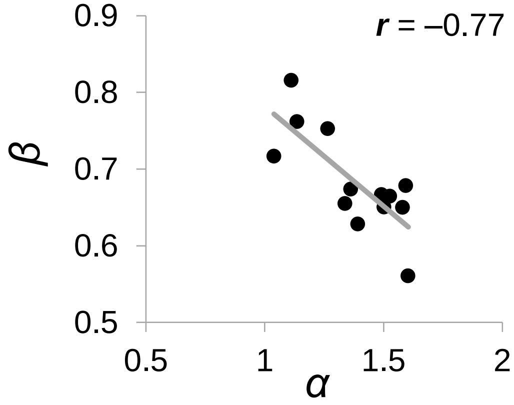
Recording computer

In the experiment subject is instructed to **focus** on the circle/cross on monitor screen without performing any mental task.

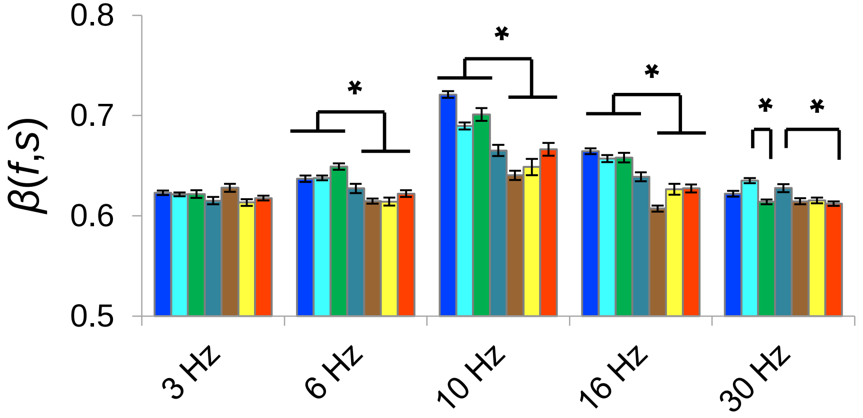
Relationship between neuronal avalanches and LRTCs

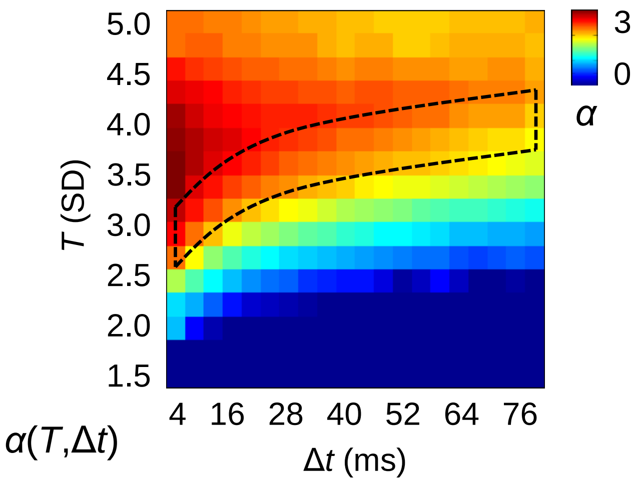


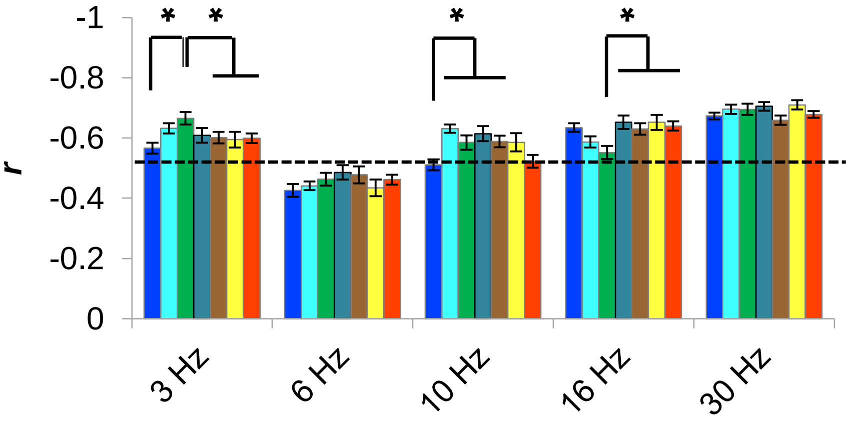




Palva et al., 2013, *PNAS*

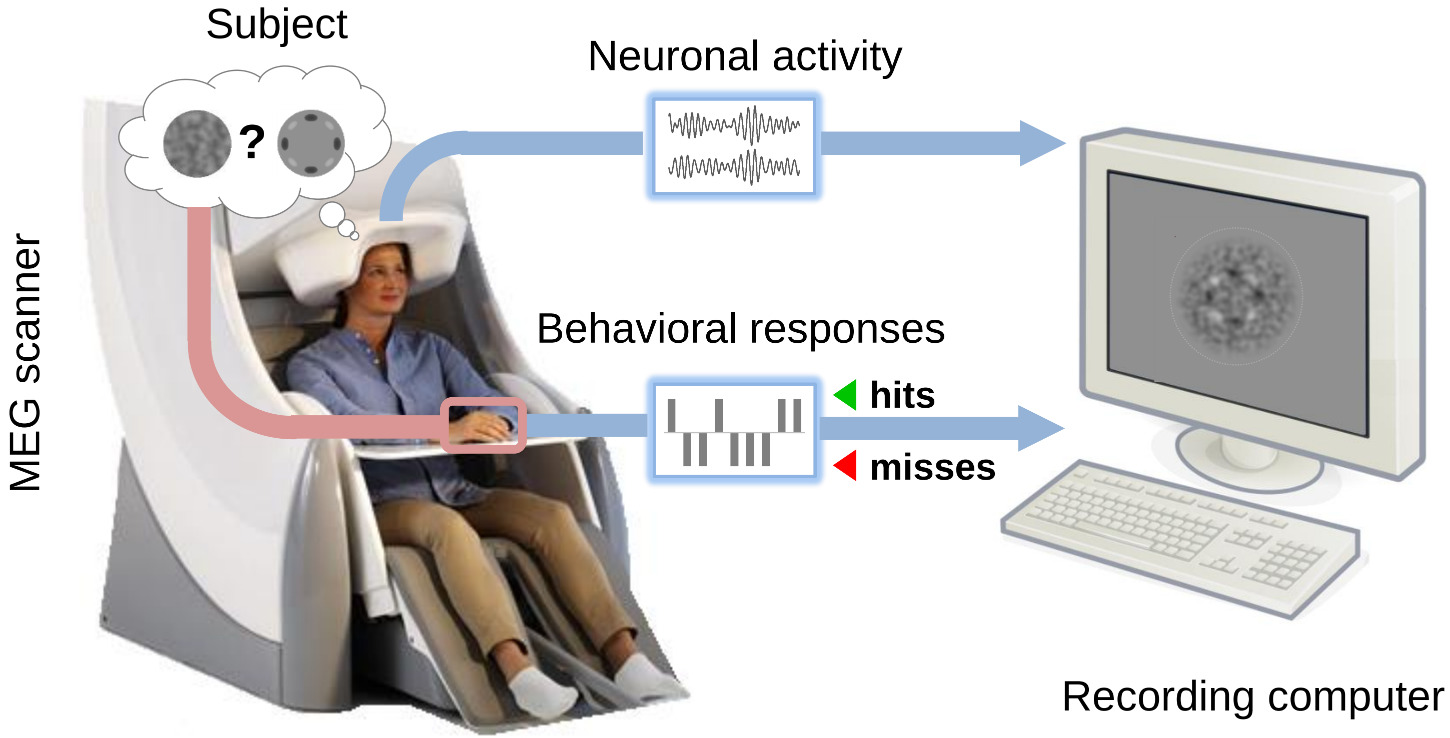






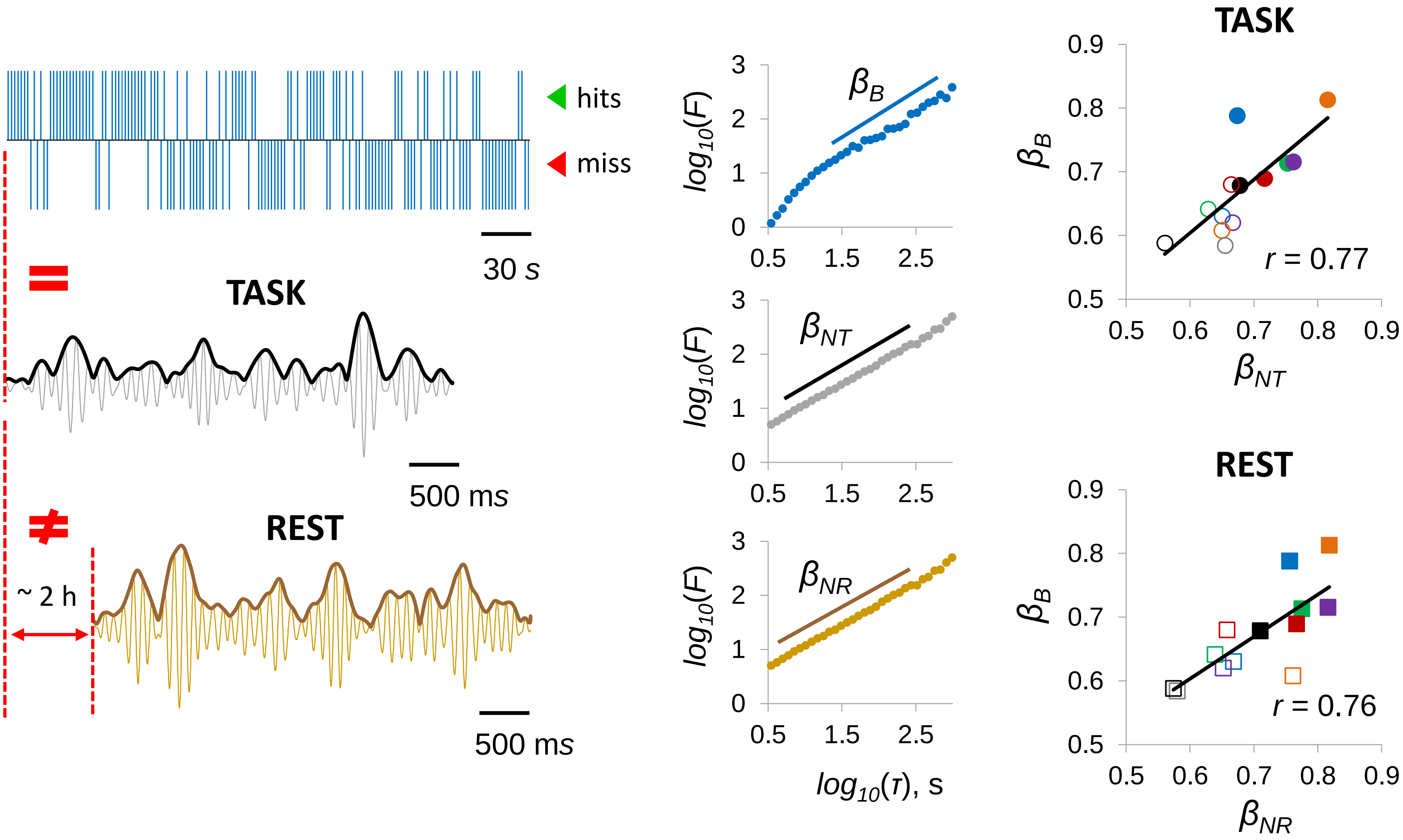
Zhigalov et al., 2015, *J. Neurosci.*

Experiment type 2, Behavioral task



In the experiment subject is instructed to **press the button** whenever he/she is able to detect a ”weak” visual stimulus. The stimuli are presented at random times.

Behavioral and neuronal criticality

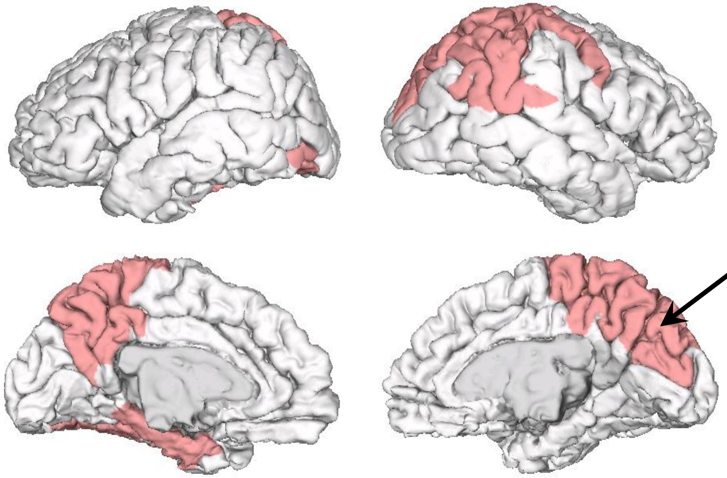


Palva et al., 2013, *PNAS*

Neuronal LRTCs in task and rest are correlated with LRTCs of behavioral performance.

Behavioral and neuronal criticality

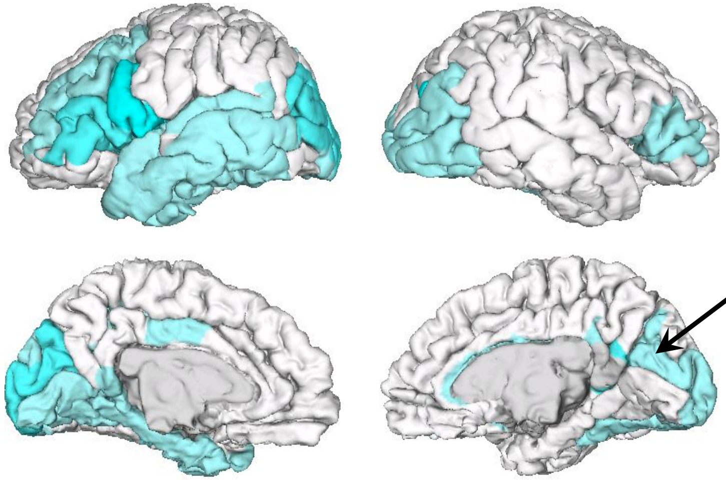
VISUAL TASK



f = 10 Hz

$r = corr\ (\beta_{BV,}\ \beta_{NR})$

AUDITORY TASK

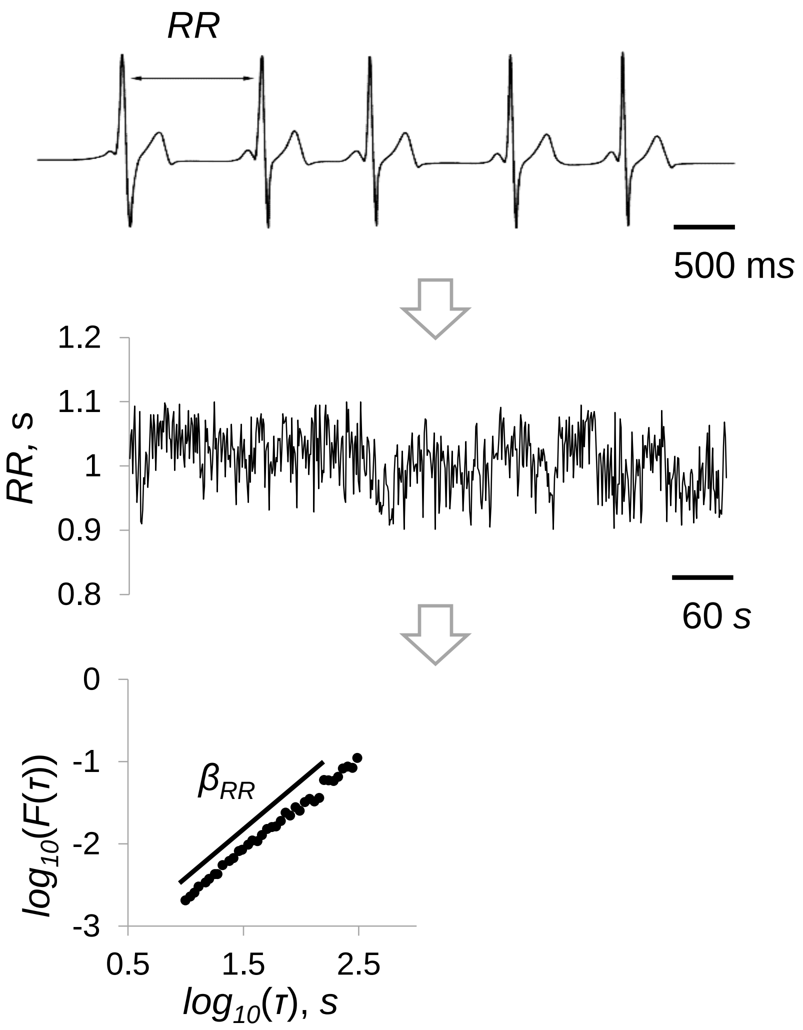


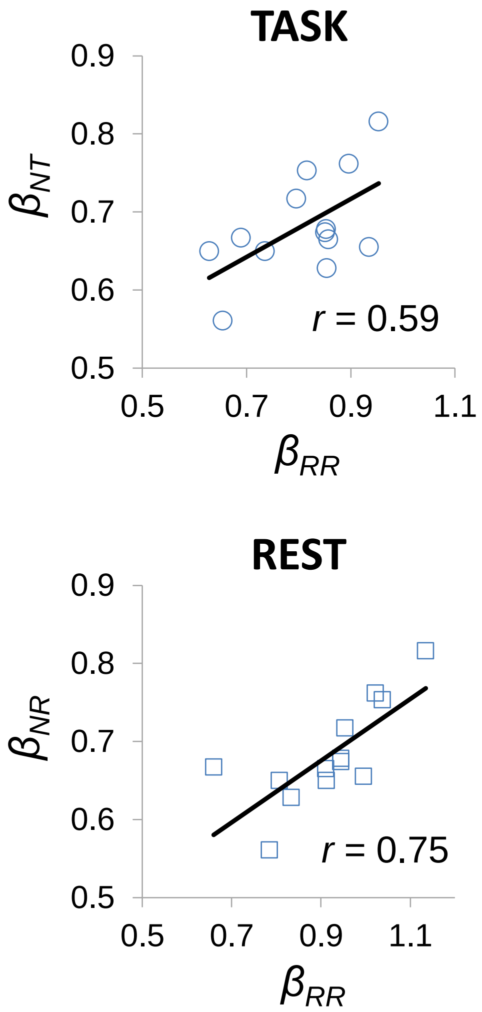
f = 10 Hz

$r = corr\ (\beta_{BA,}\ \beta_{NR})$

Palva et al., 2013, *PNAS*

Cardio and neuronal criticality





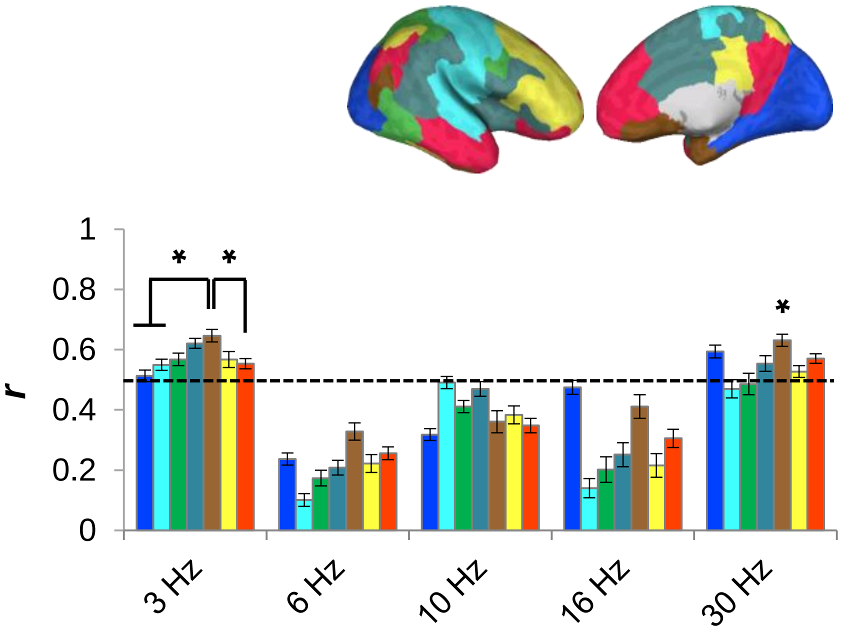
Ivanov et al., 1999, *Nature*

Palva et al., 2013*, PNAS;* Zhigalov et al., 2015, *J. Neurosci.*

Exponents of autonomous nervous system are correlated with those of central neural system.

Cardio and neuronal criticality

Functional specificity of correlations between the exponents of heart-rate variability and neuronal oscillations.



Zhigalov et al., 2015, *J. Neurosci.*

The strongest correlations have been observed in specific functional systems.

Conclusion on neuronal, behavioral and physiological criticality

- Critical dynamics are related at multiple levels neuronal, physiological and behavioral
- The dynamics are linked through specific projections/regions in the brain
- The dynamics can be manipulated by cognitive task, stimulation, drugs and so on
- Abnormalities in critical dynamics can be considered as indicator of some neurological disorders

Critical dynamics and connectivity

What is the human connectome?

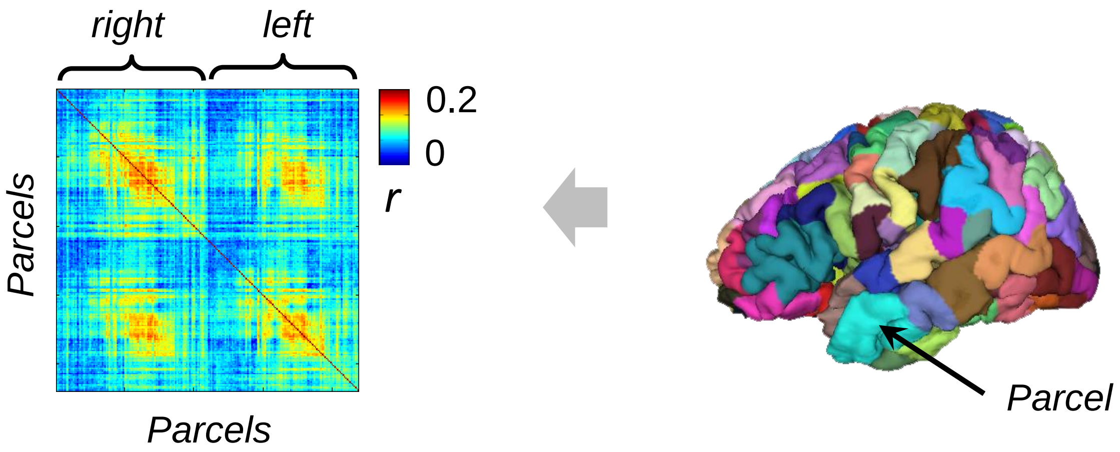
A connectome is a comprehensive map of neural connections in the brain.

Wikipedia

There are a few types of human connectomes have been introduced,

- **DTI connectome** / structural – characteristics of axonal fibers that link brain regions (length, density, etc.)
- **fMRI connectome** / functional – relationship between BOLD (blood oxygenation) signals of the brain regions
- **EEG/MEG connectome** / functional – relationship between neuronal fluctuations of the brain regions

Connectome is represented normally as an adjacency matrix.



The connectomes

○ Avalanche propagation connectome (APC) / **new**

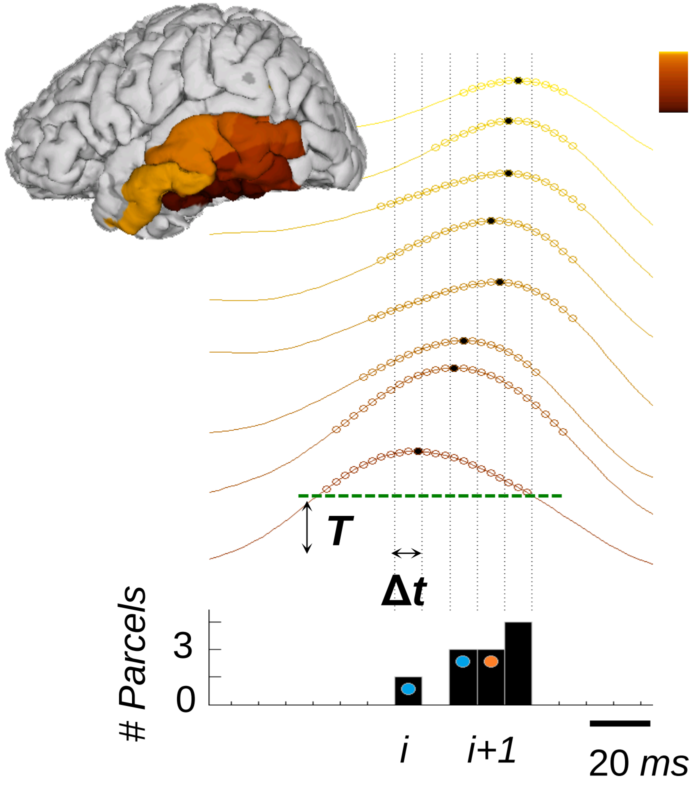
○ LRTCs scaling exponents connectome (SEC) / **new**

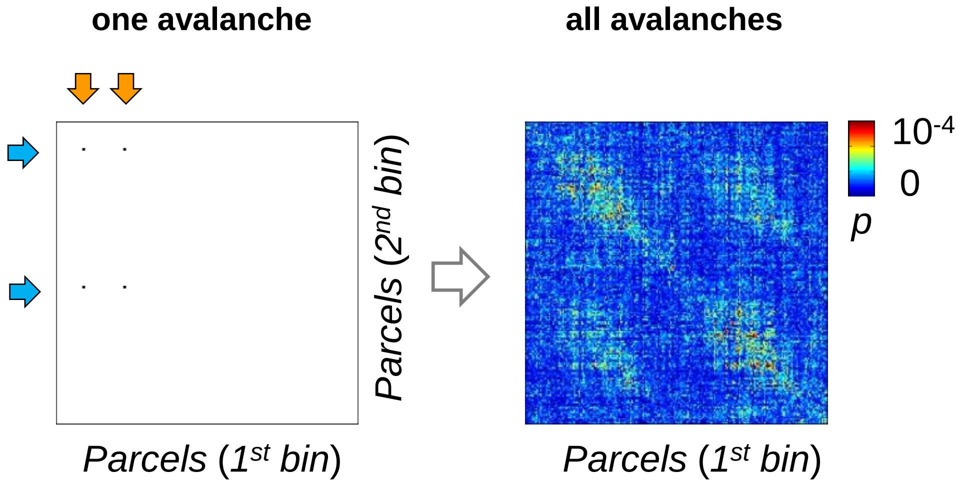
○ Amplitude-amplitude correlation connectome (AAC)

○ Phase-phase coupling connectome (PPC)

Avalanche propagation connectome (APC)

Broadband time series (1 – 40 Hz)



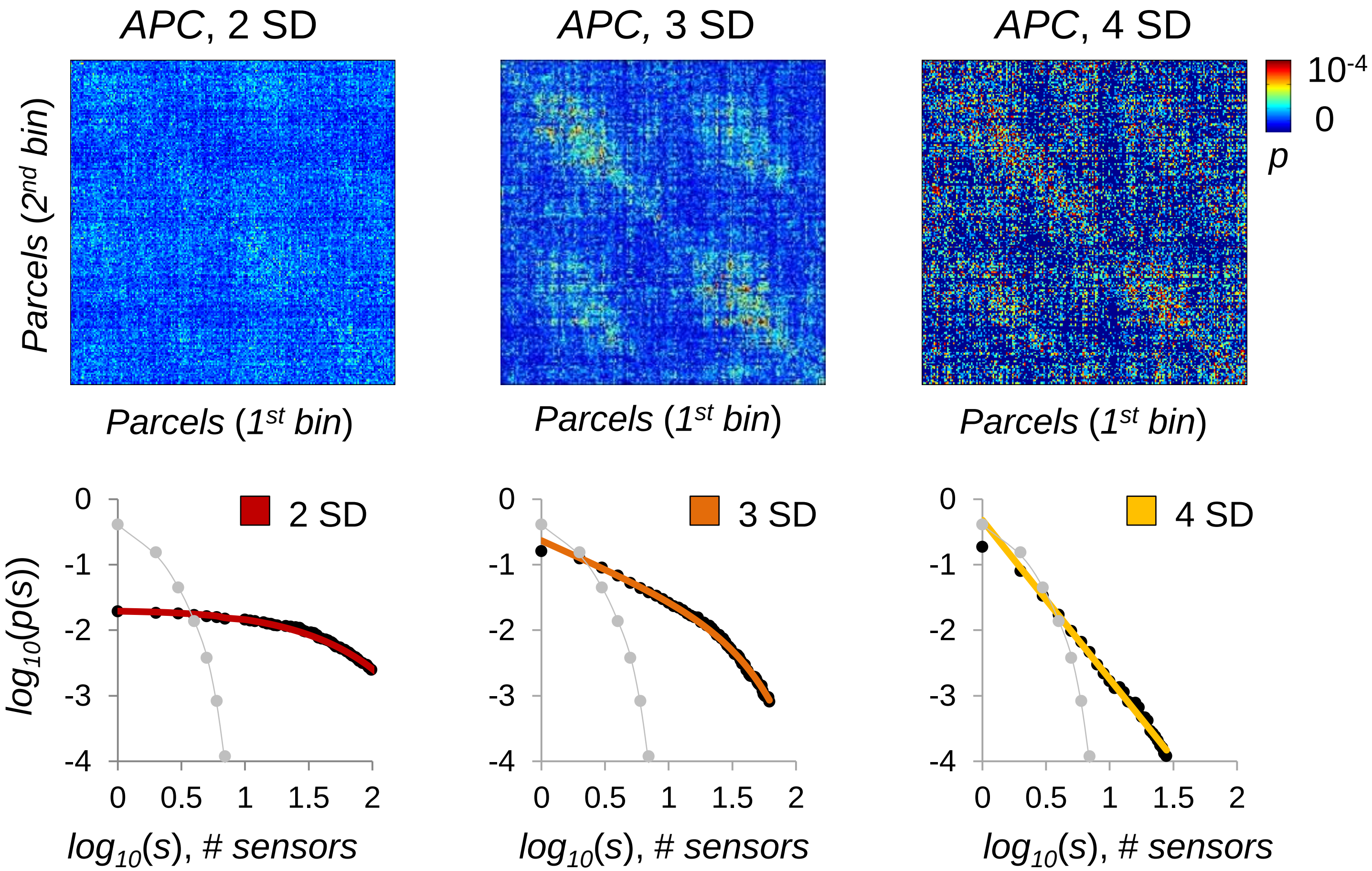


Parameters (for avalanche detection)

- ***T*** is threshold
- **Δ*t*** is time bin width

Zhigalov et al., (*submitted*)

Avalanche propagation connectome (APC)



Parameters (for avalanche detection)

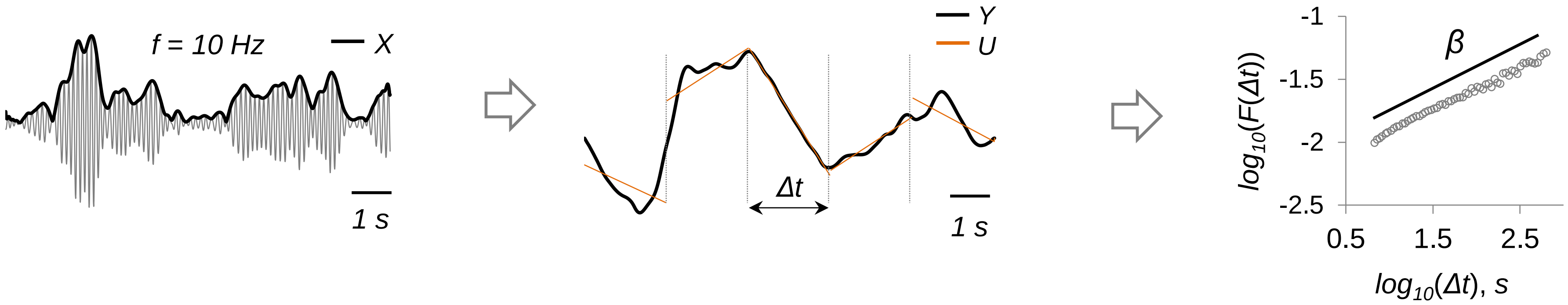
- ***T*** is variable, **2**, **3** and **4 SD**
- **Δ*t*** is fixed, **8 ms**

Propagation pathways of neuronal avalanches show different properties for different ”SNR”.

LRTCs scaling exponents connectome (SEC)

$$y(k) = \sum_{i=1}^{k} [X(i) - \langle X \rangle]$$

$$F(\Delta t) = \sqrt{\frac{1}{N} \sum_{k=1}^{N} [y(k) - u(k)]^2}$$



Parameters (for long-range temporal correlations, LRTCs)

- **f** is frequency of neuronal oscillations (3, …, 120 Hz)

Peng et al., 1995, *Chaos*

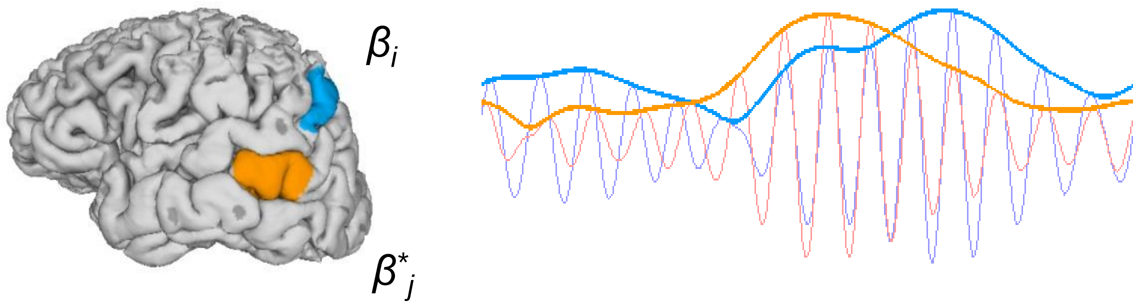
Note

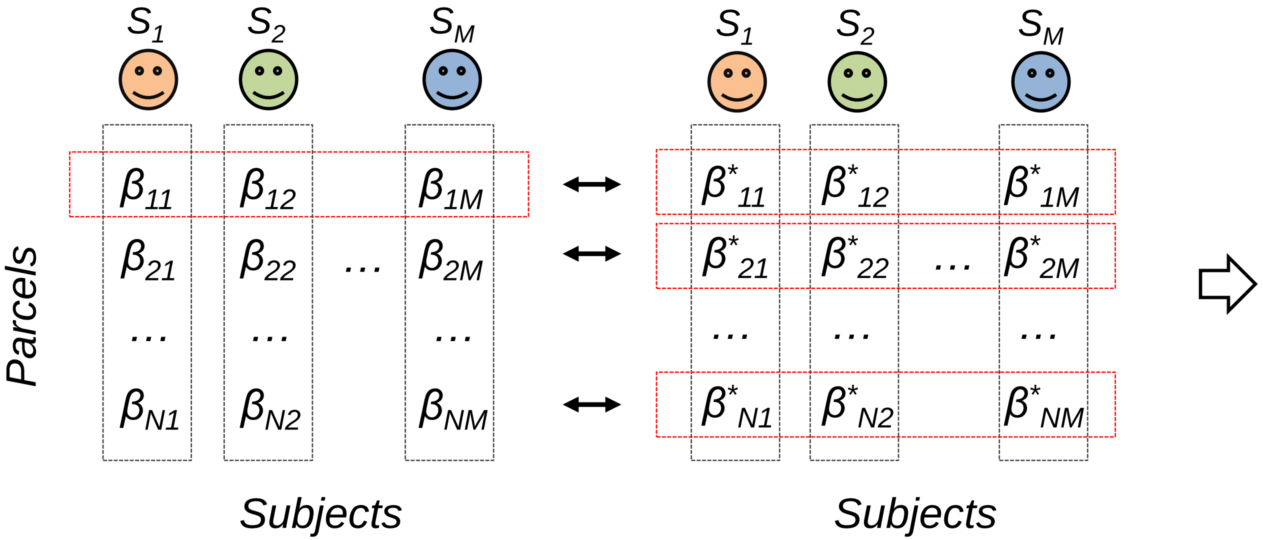
- Neuronal oscillations in the range of 0.1 – 70 Hz are functionally relevant for the brain and “unique”
- **High** frequencies are associated with local processing, while **low** frequencies with global processing

LRTCs scaling exponents connectome (SEC)

③

Narrowband time series

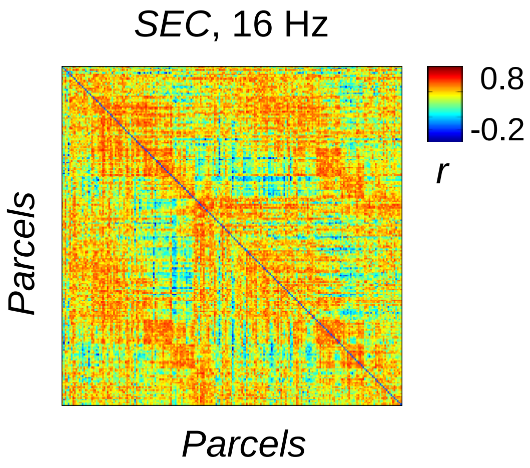




$$\begin{array}{ccccc} & S_1 & S_2 & & S_M \\ & \beta_{11} & \beta_{12} & & \beta_{1M} \\ \text{Parcels} & \beta_{21} & \beta_{22} & \dots & \beta_{2M} \\ & \dots & \dots & & \dots \\ & \beta_{N1} & \beta_{N2} & & \beta_{NM} \end{array} \begin{array}{c} \\ \leftrightarrow \\ \leftrightarrow \\ \\ \leftrightarrow \end{array} \begin{array}{cccc} S_1 & S_2 & & S_M \\ \beta^*_{11} & \beta^*_{12} & & \beta^*_{1M} \\ \beta^*_{21} & \beta^*_{22} & \dots & \beta^*_{2M} \\ \dots & \dots & & \dots \\ \beta^*_{N1} & \beta^*_{N2} & & \beta^*_{NM} \end{array} \Rightarrow$$

Subjects

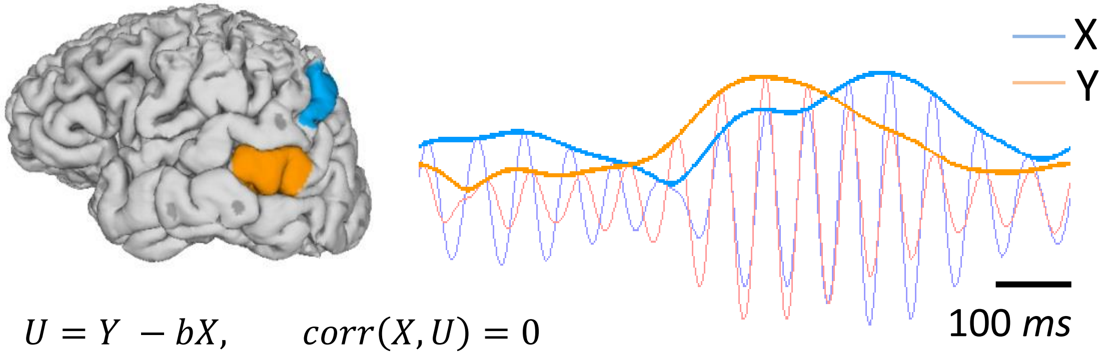
Subjects

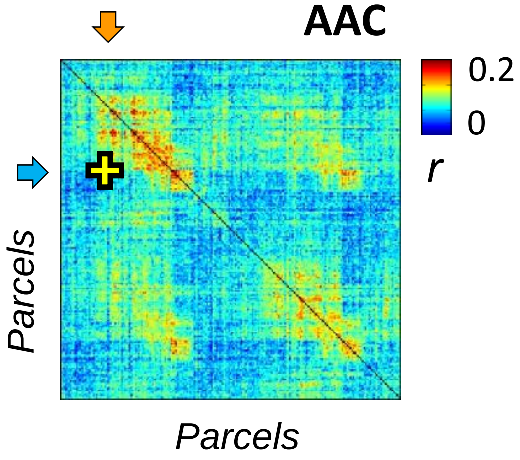


The relationship between LRTCs of the brain regions is similar across subjects.

Functional amplitude (AAC) and phase (PPC) connectomes

Narrowband time series

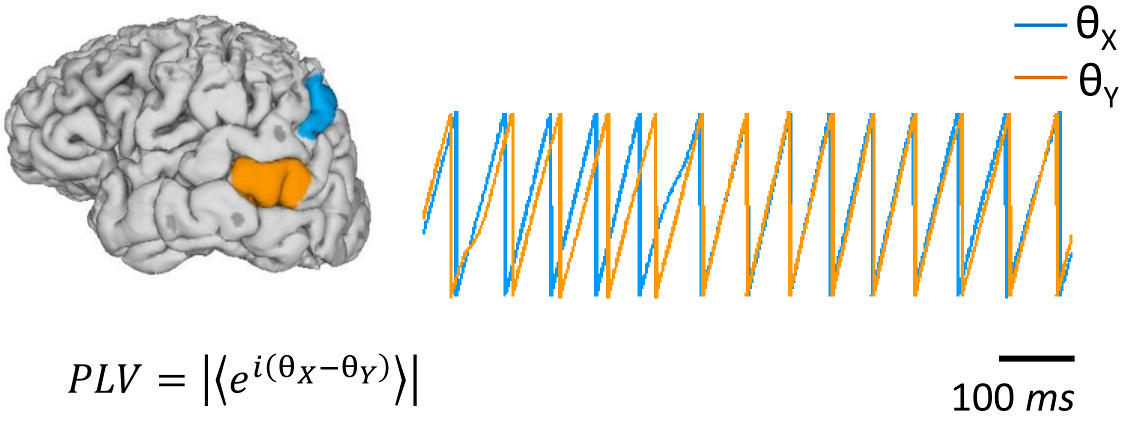


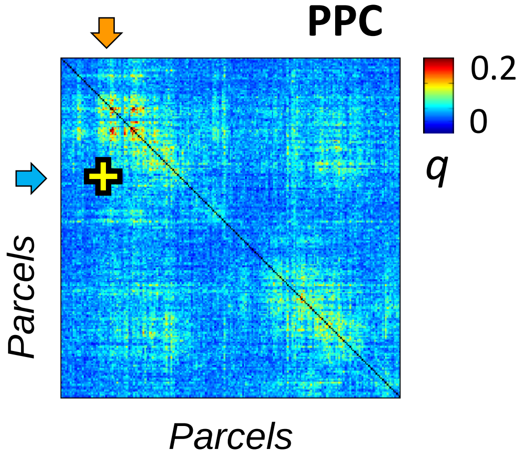


$$U = Y - bX, \qquad corr(X, U) = 0$$

$$r = corr(|X + iX|, |U + iU|)$$

Brookes et al., 2012, *NeuroImage*



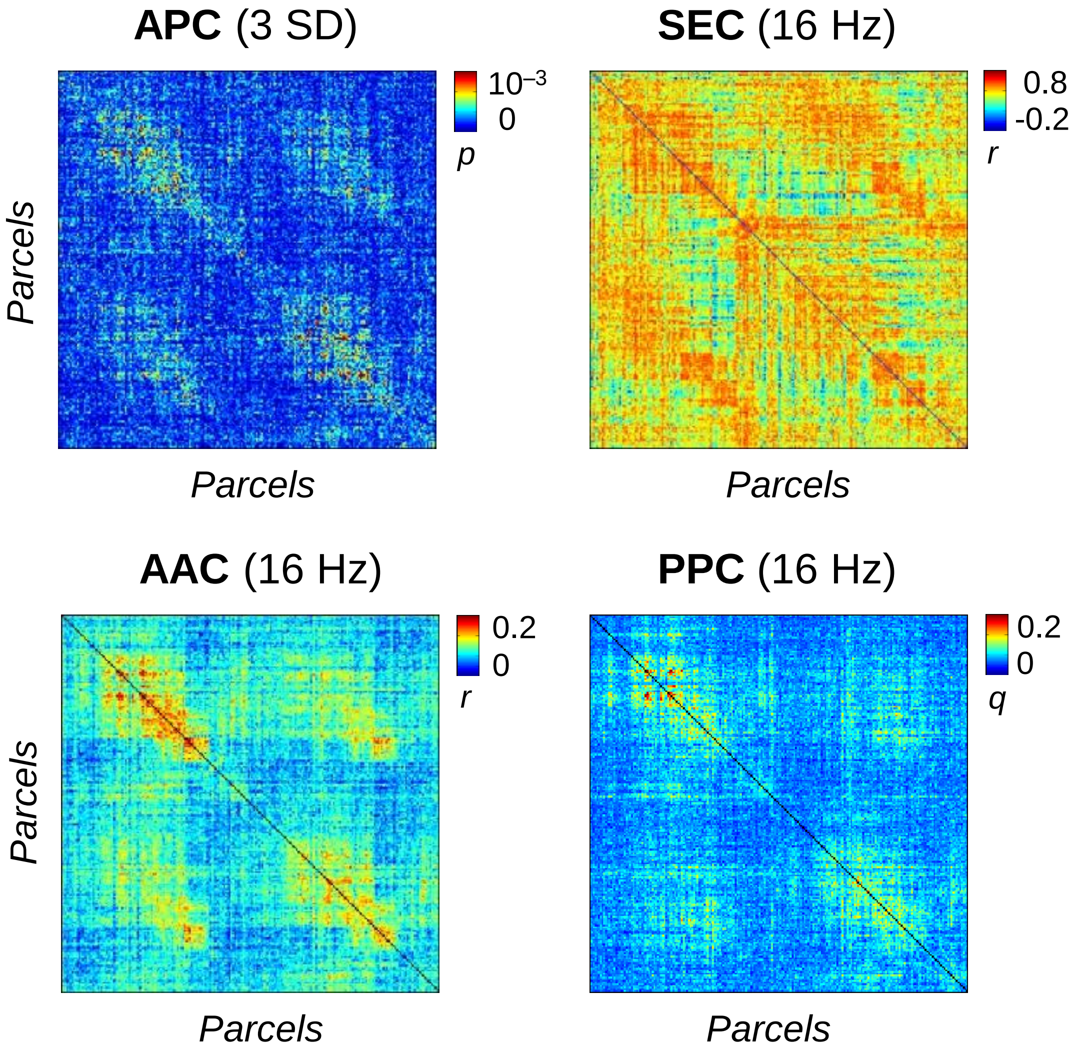


$$PLV = \left|\left\langle e^{i(\theta_X - \theta_Y)} \right\rangle\right|$$

$$q = im(PLV) = |\langle sin(\theta_X - \theta_Y) \rangle|$$

Palva & Palva, 2012, *TICS*

The connectomes

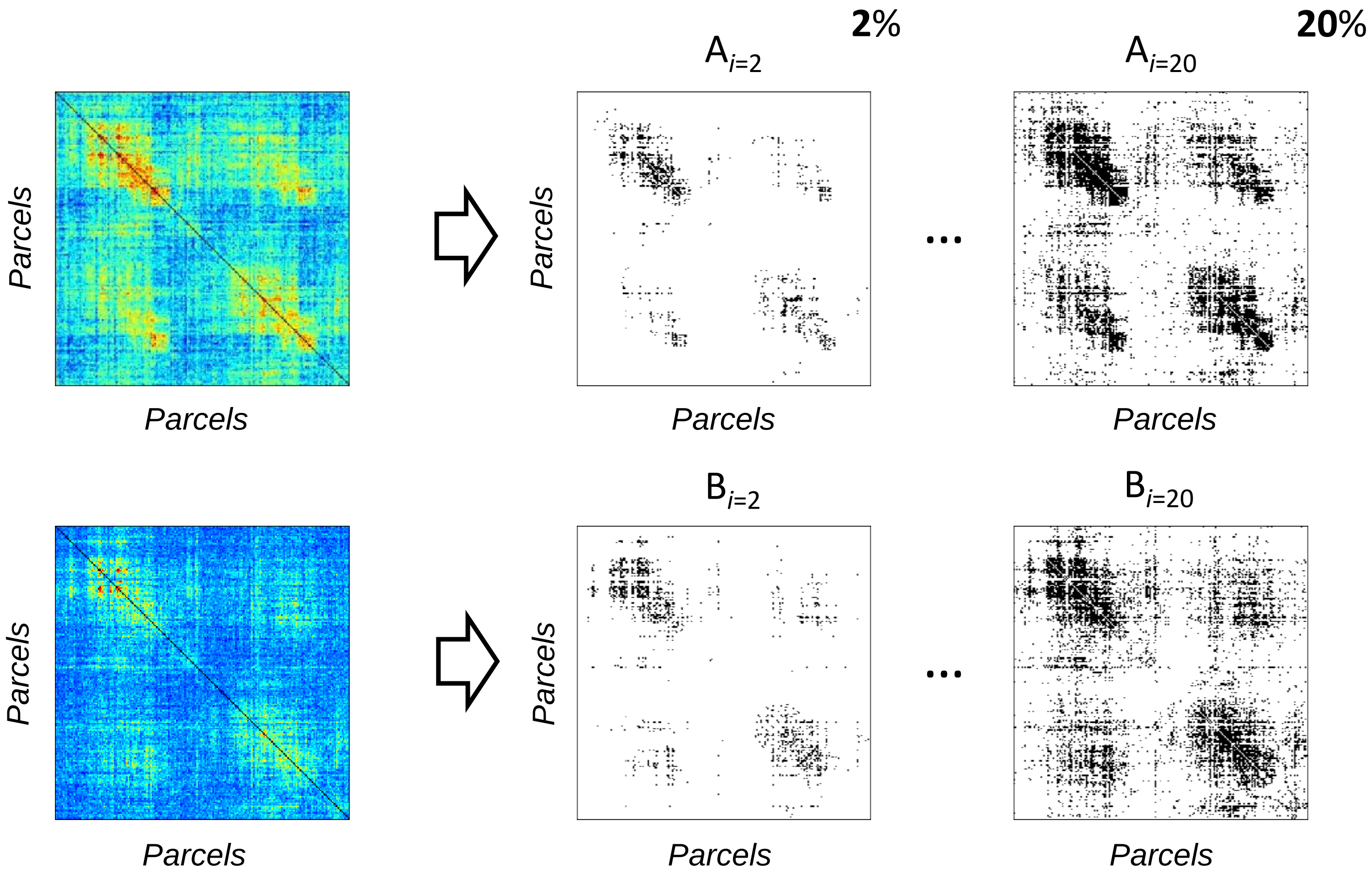


The connectomes show a similar structure.

Result I

Similarity between the connectomes

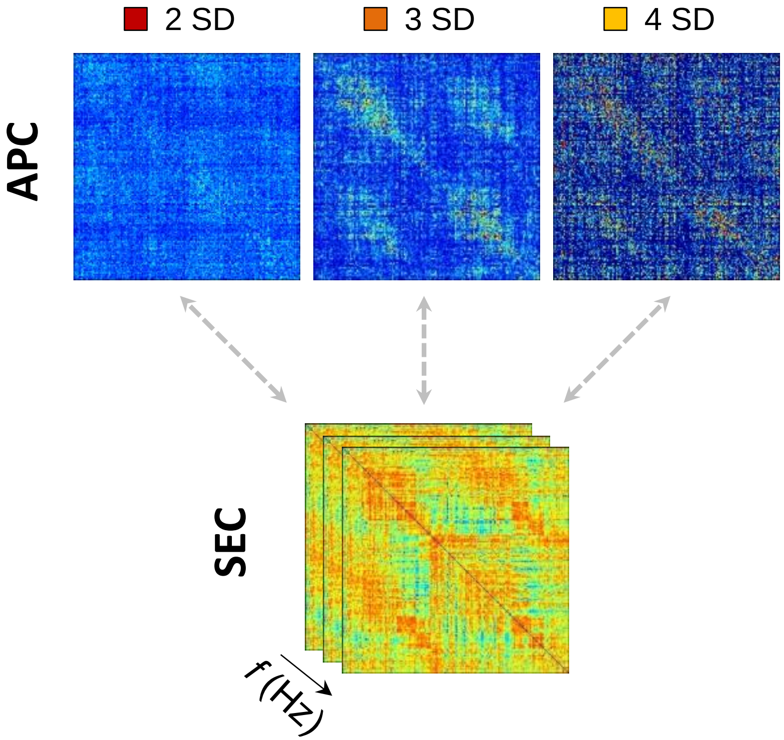
How do we assess similarity between the connectomes?

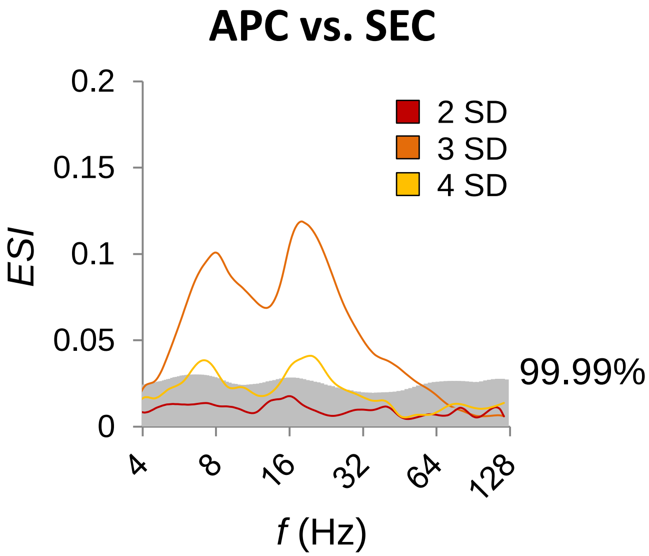


$$\mathrm{ESI} = \sum_{i} \frac{\sum A_i \cap B_i}{\sum A_i \cup B_i} / k$$

The method is less sensitive to outliers (large values) in comparison to correlation coefficient.

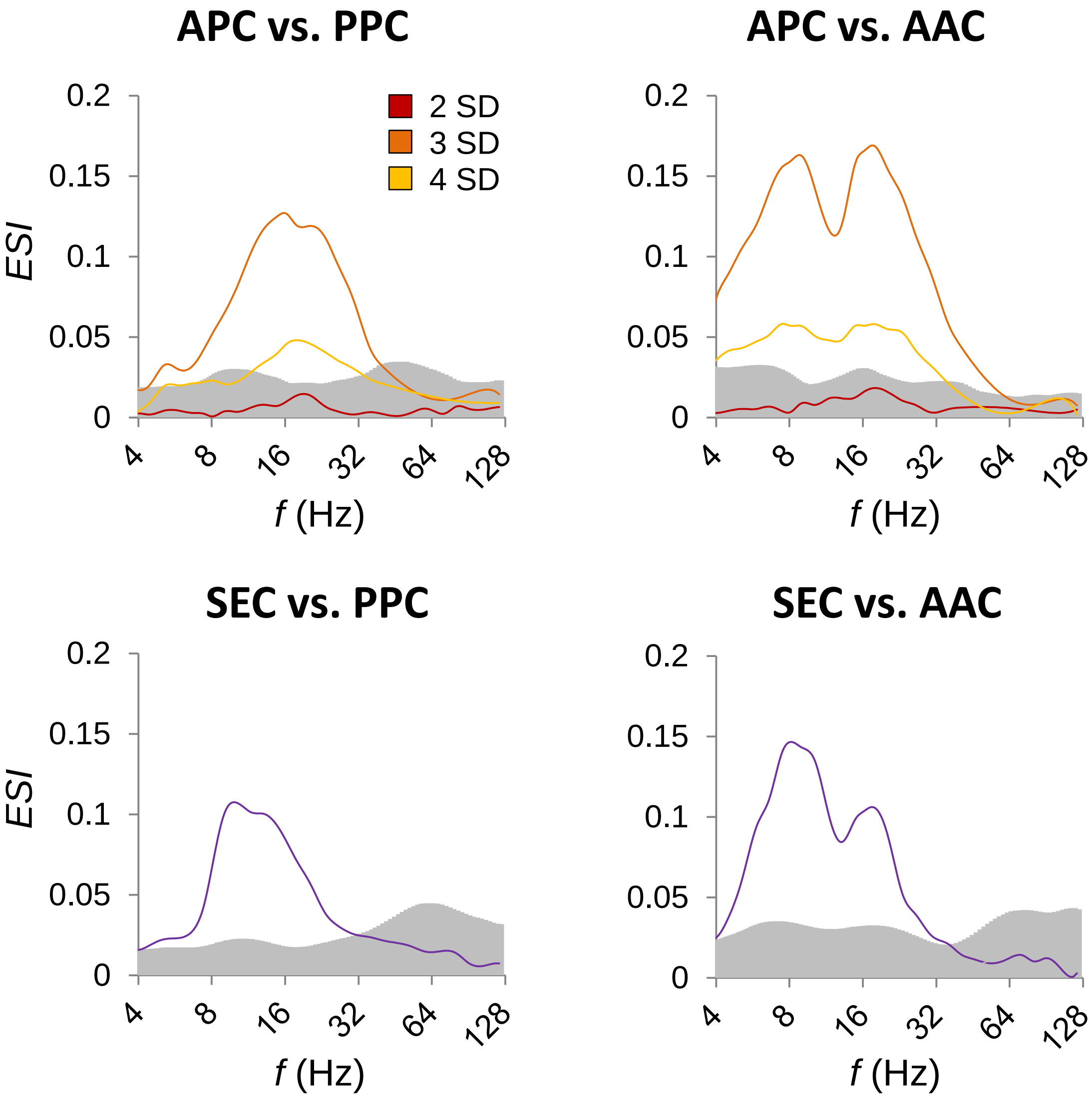
Results I / Similarity of the connectomes





The connectomes are highly similar at power-law regime.

Results I / Similarity of the connectomes



APC vs. PPC

APC vs. AAC

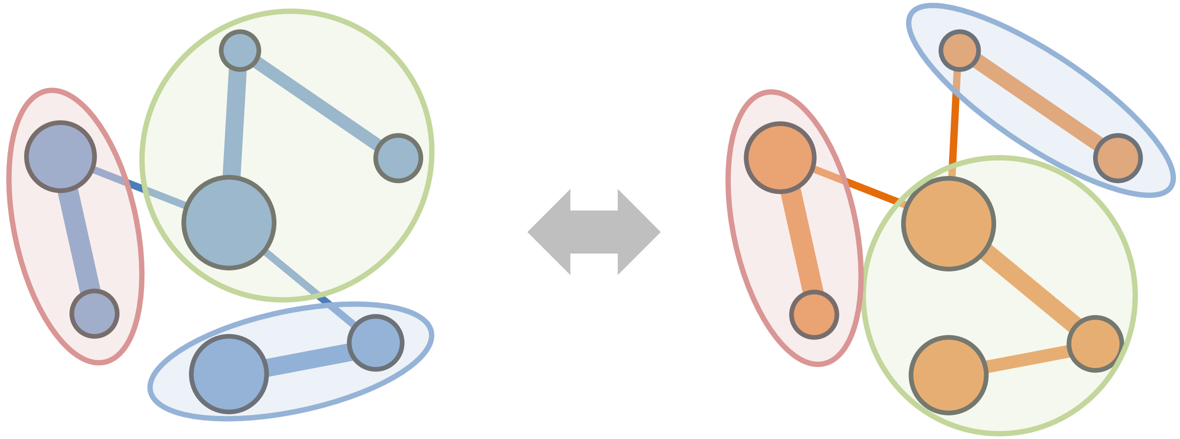
SEC vs. PPC

SEC vs. AAC

The connectomes similarity show strong spectral specificity.

from **Result I** to **Result II**

The similarity between the connectomes indicated that the connections are co-localized.



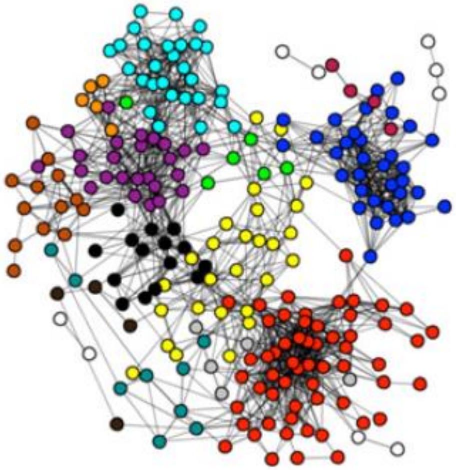
However, the similarity between connections doesn’t imply that these connections belong to the same modules or subgraphs.

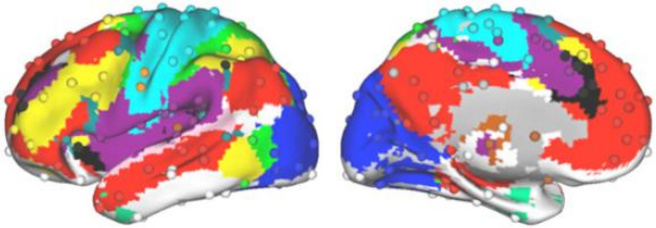
Result II

Similarity of the modular structure of the connectomes

Modular structure of the brain networks

The human brain shows hierarchical modular organization.



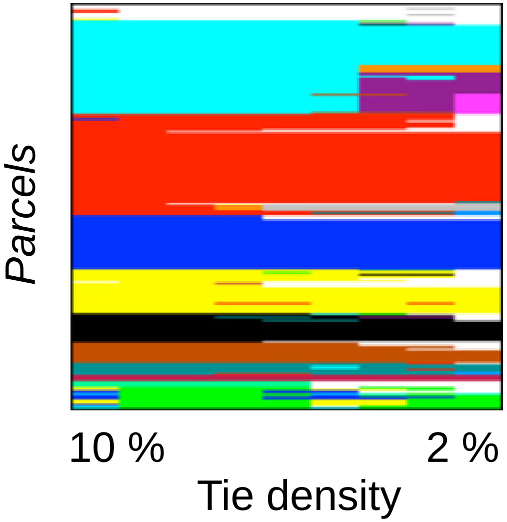


Balenzuela et al., 2010, *Front. Neuroinf.*

Meunier et al., 2010, *Front. Neurosci.*

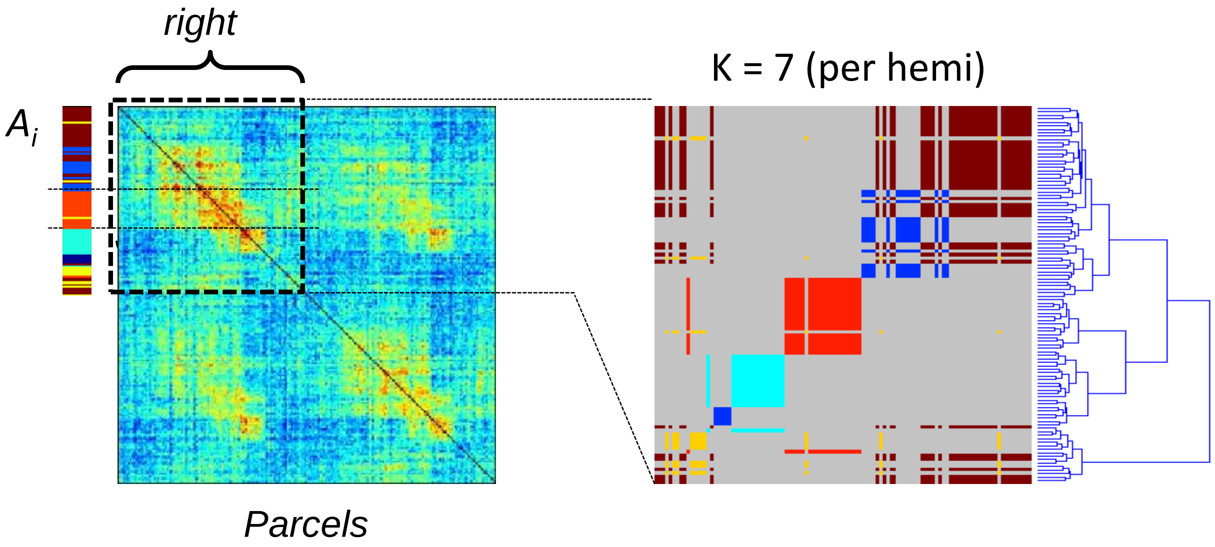
Gallos et al., 2012, *PNAS*

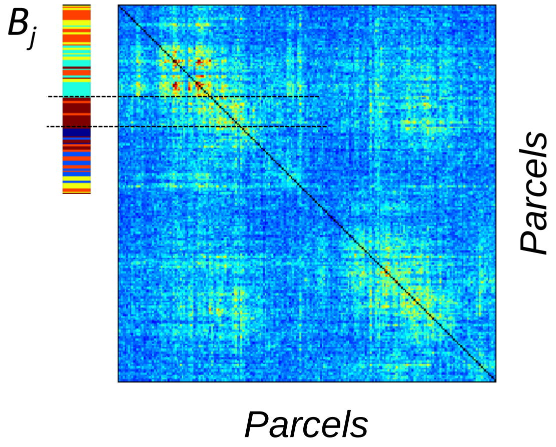
The modules are ”weakly” linked.



Power et al., 2011, *Neuron*

How do we assess similarity of modular structure of the connectomes?

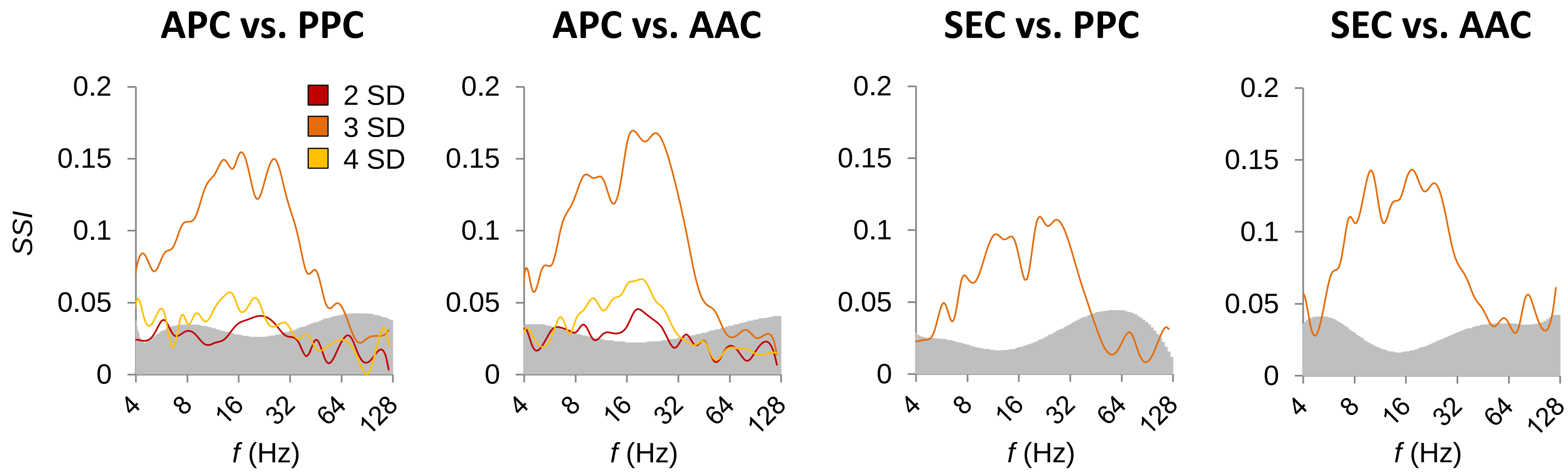


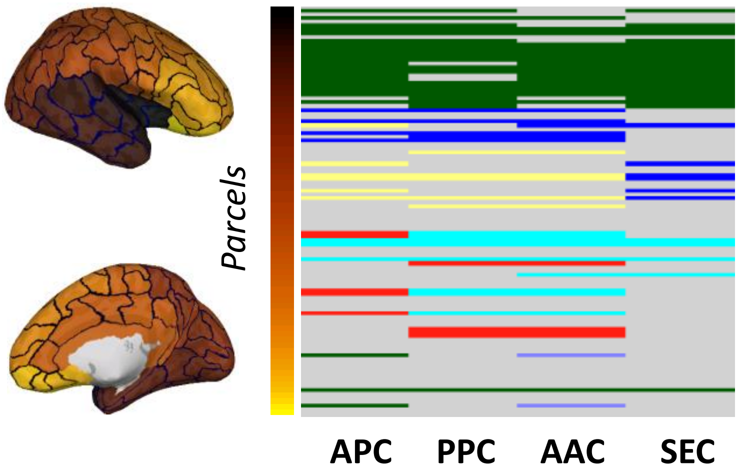


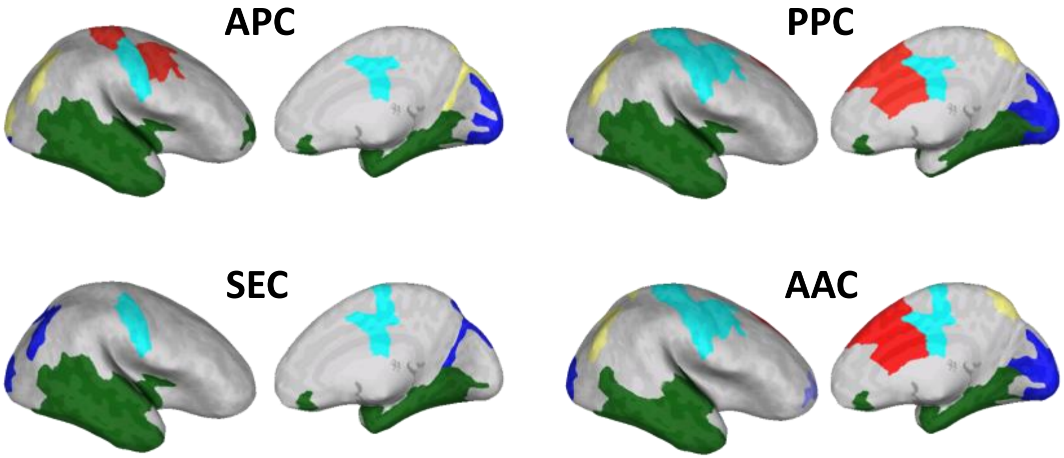
$$\mathrm{SSI} = \sum_{n} \frac{\sum A_i \cap B_j}{\sum A_i \cup B_j} / N$$

N $-$ *number of clusters*

Results II / Similarity of modular structure







The connectomes share near the same modular structure.

Zhigalov et al., (*submitted*)

Conclusion on criticality and connectivity

- Dynamics of neuronal avalanches and long-range temporal correlations are related in both spatial and temporal domains

- High amplitude events, *i.e*. neuronal avalanches, propagate along functional connections and can be operationally relevant for the brain

- Neuronal avalanches may provide an alternative communication mechanism which is different from amplitude- and phase-coupling

- Hierarchically organized and weakly coupled brain modules provides the dynamics-connectivity association

Thank you for your attention!