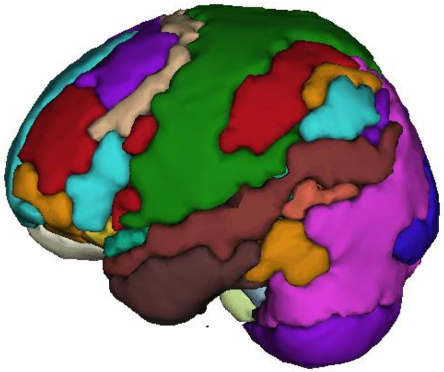


Network approach for bringing together brain structure and function

Sebastiano Stramaglia

Physics Dept. University of Bari & INFN

BCAM- Basque Center Applied Math Bilbao

Capri 31 agosto 2015
Complex Collective Dynamics: Brains and beyond

http://lanl.arxiv.org/abs/1410.7959

Sci. Rep. 2015

Work done with:

Paolo Bonifazi (Tel Aviv)

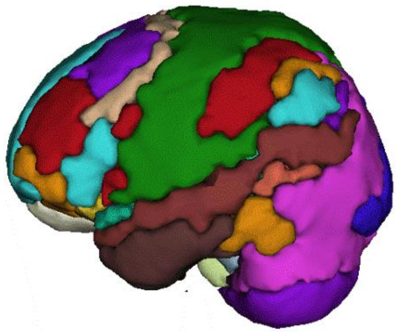
Ibai Diez (Bilbao)

Iñaki Escudero(Bilbao)

Beatriz Mateos (Bilbao)

Miguel A. Muñoz (Granada)

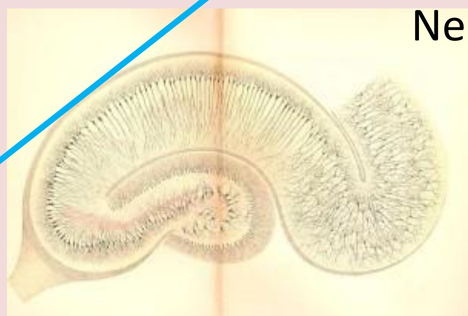
Jesus M Cortes (Bilbao)



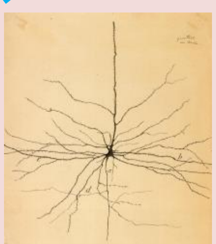
STRUCTURE

space

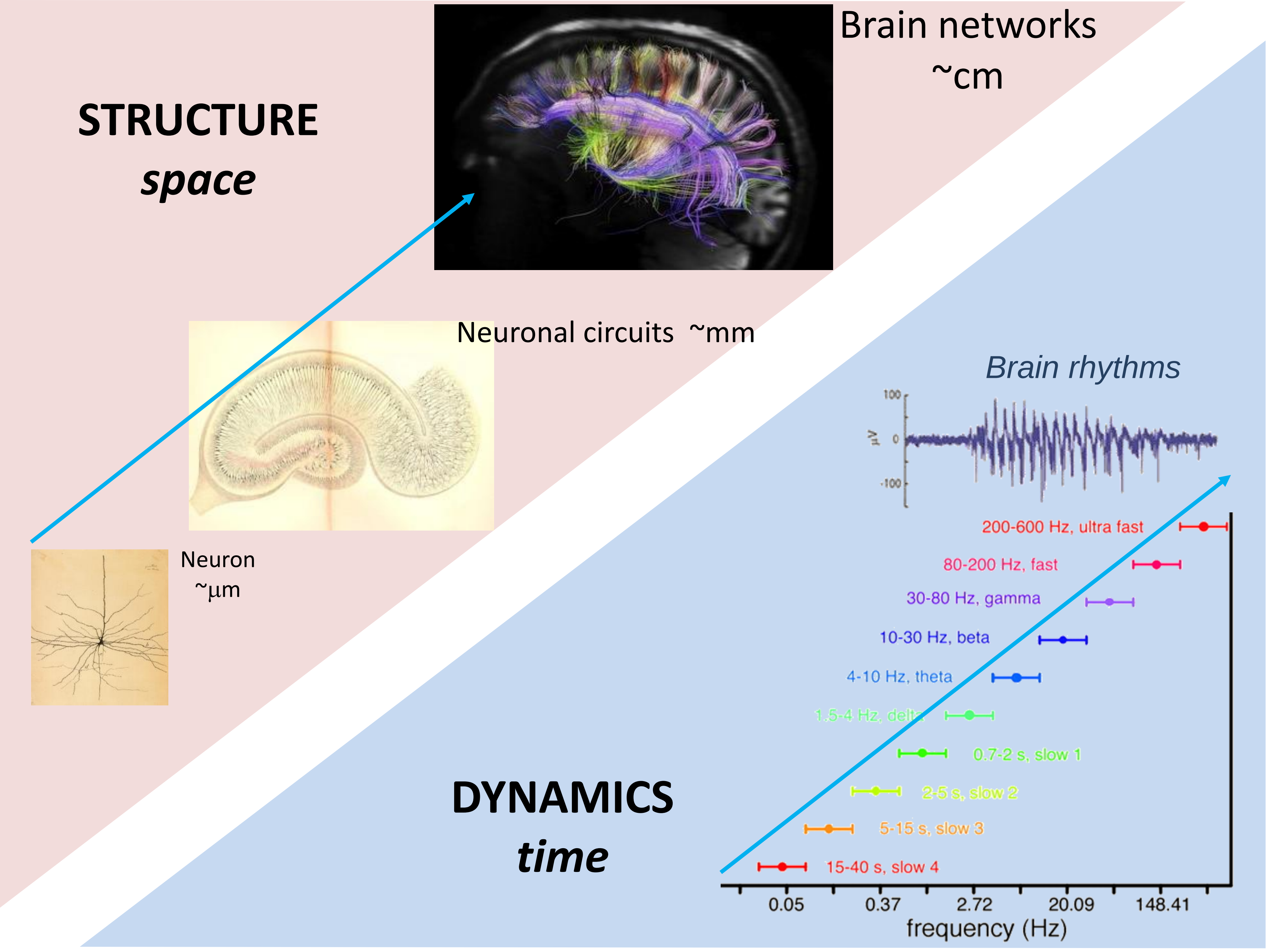
Brain networks
~cm



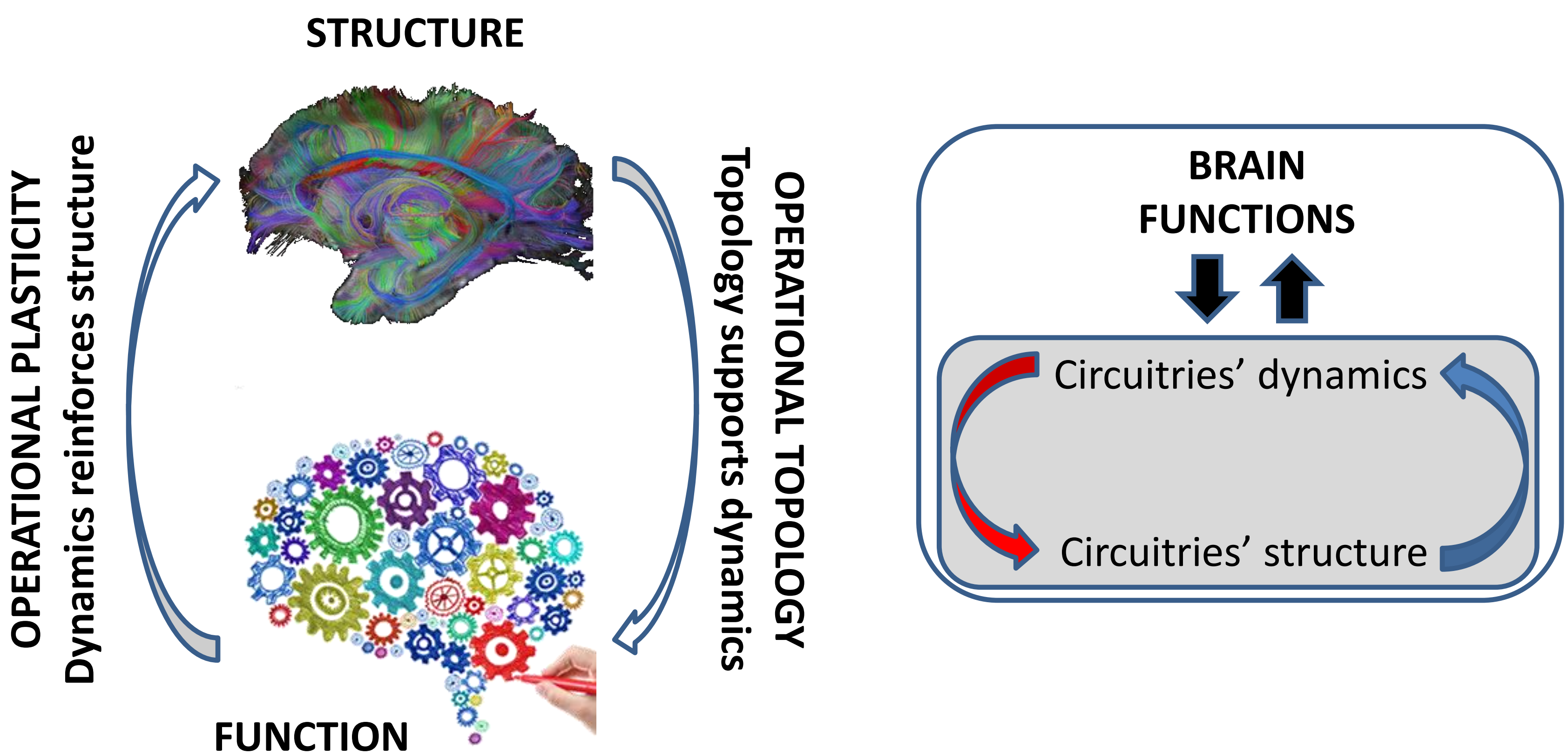
Neuronal circuits ~mm



Neuron
~μm


STRUCTURE
space
Brain networks
~cm
Neuronal circuits ~mm
Neuron
~µm
Brain rhythms
100
µV
0
-100
200-600 Hz, ultra fast
80-200 Hz, fast
30-80 Hz, gamma
10-30 Hz, beta
4-10 Hz, theta
1.5-4 Hz, delta
0.7-2 s, slow 1
2-5 s, slow 2
5-15 s, slow 3
15-40 s, slow 4
0.05
0.37
2.72
20.09
148.41
frequency (Hz)
DYNAMICS
time

<u>The operational brain</u>: the structural-functional cycle



REVIEW SUMMARY

Structural and Functional Brain Networks: From Connections to Cognition

Hae-Jeong Park[1]* and Karl Friston[2]

Background: The human brain presents a puzzling and challenging paradox: Despite a fixed anatomy, characterized by its connectivity, its functional repertoire is vast, enabling action, perception, and cognition. This contrasts with organs like the heart that have a dynamic anatomy but just one function. The resolution of this paradox may reside in the brain's network architecture, which organizes local interactions to cope with diverse environmental demands—ensuring adaptability, robustness, resilience to damage, efficient message passing, and diverse functionality from a fixed structure. This review asks how recent advances in understanding brain networks elucidate the brain's many-to-one (degenerate) function-structure relationships. In other words, how does diverse function arise from an apparently static neuronal architecture? We conclude that the emergence of dynamic functional connectivity, from static structural connections, calls for formal (computational) approaches to neuronal information processing that may resolve the dialectic between structure and function.

Science 2013

The conjecture of the brain at criticality

REVIEW ARTICLES | INSIGHT
PUBLISHED ONLINE: 1 OCTOBER 2010 | DOI: 10.1038/NPHYS1803
nature physics

Emergent complex neural dynamics

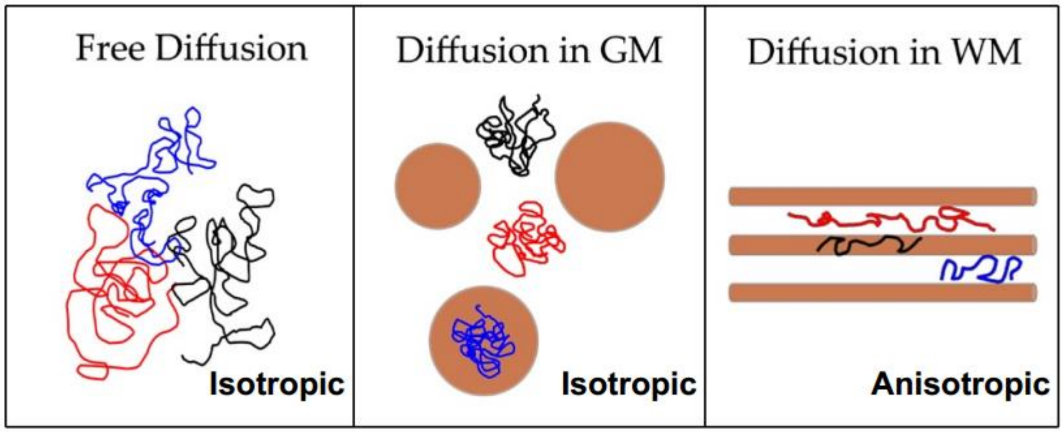
Dante R. Chialvo[1,2]*

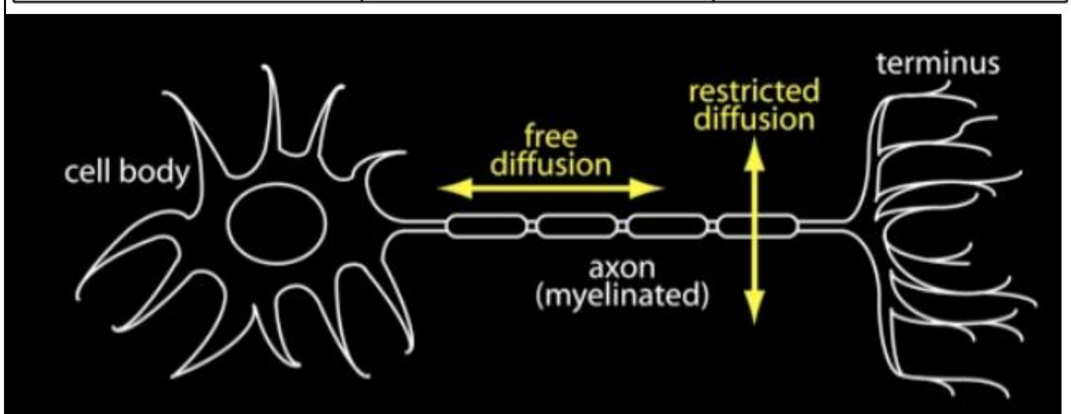
A large repertoire of spatiotemporal activity patterns in the brain is the basis for adaptive behaviour. Understanding the mechanism by which the brain's hundred billion neurons and hundred trillion synapses manage to produce such a range of cortical configurations in a flexible manner remains a fundamental problem in neuroscience. One plausible solution is the involvement of universal mechanisms of emergent complex phenomena evident in dynamical systems poised near a critical point of a second-order phase transition. We review recent theoretical and empirical results supporting the notion that the brain is naturally poised near criticality, as well as its implications for better understanding of the brain.

Chialvo D.R. and Bak P. (1999)
Bak P and Chialvo D.R. (2001)
Eguíluz V.M., Chialvo D.R., Cecchi G., Baliki M, and Apkarian AV. (2004)
Chialvo, D. R. (2004)
D. Fraiman, P. Balenzuela, J. Foss and D. R. Chialvo (2004)
D. R. Chialvo (2010)

Macroscale structural networks: Connectome from Diffusion Tensor Imaging

- It measures the magnitude and orientation of water molecules diffusion within brain tissues





$$< x^2 >= 2nDt$$

mean squared displacement

Diffusion coefficient

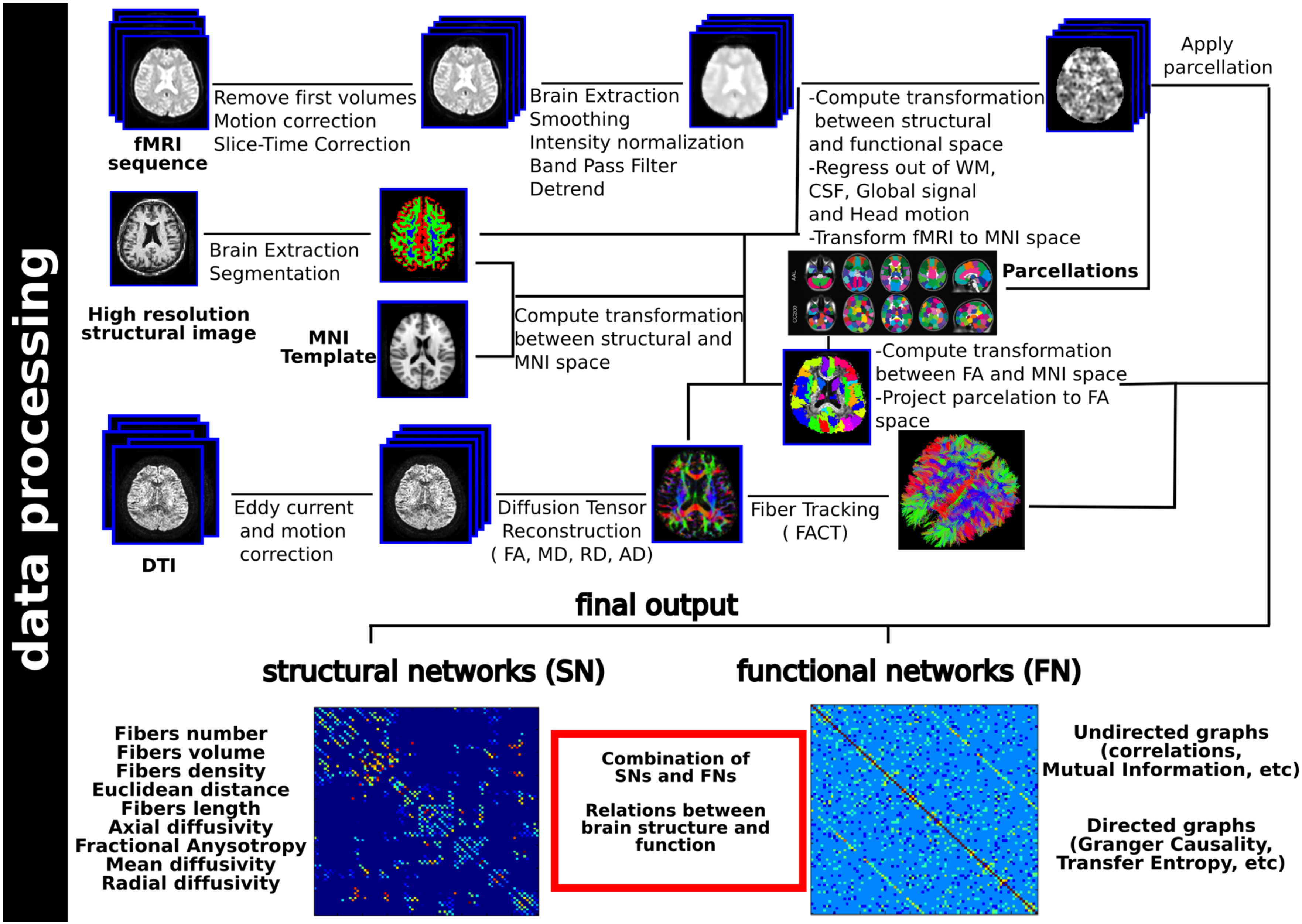
time

$D \sim 2.4\ \mu m^2/ms$
$t \sim 50ms$ ➡ $x = \sqrt{6Dt} \sim 27\mu m$

$$\mathbf{D} = \begin{bmatrix} D_{xx} & D_{xy} & D_{xz} \\ D_{xy} & D_{yy} & D_{yz} \\ D_{xz} & D_{yz} & D_{zz} \end{bmatrix}$$

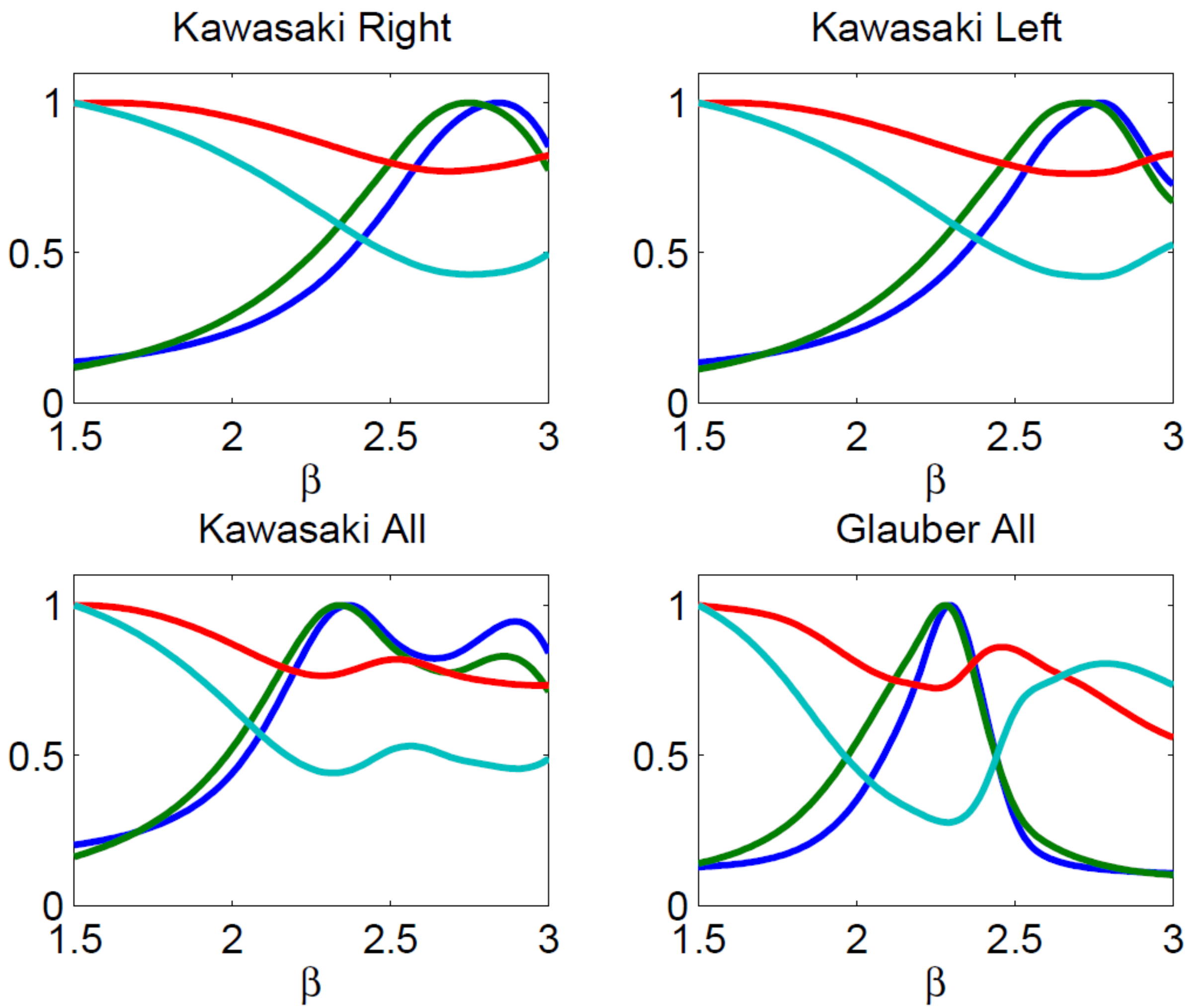
Functional Connectivity

- Statistical dependency between neuronal units (also distant ones)
- Correlation between BOLD time series

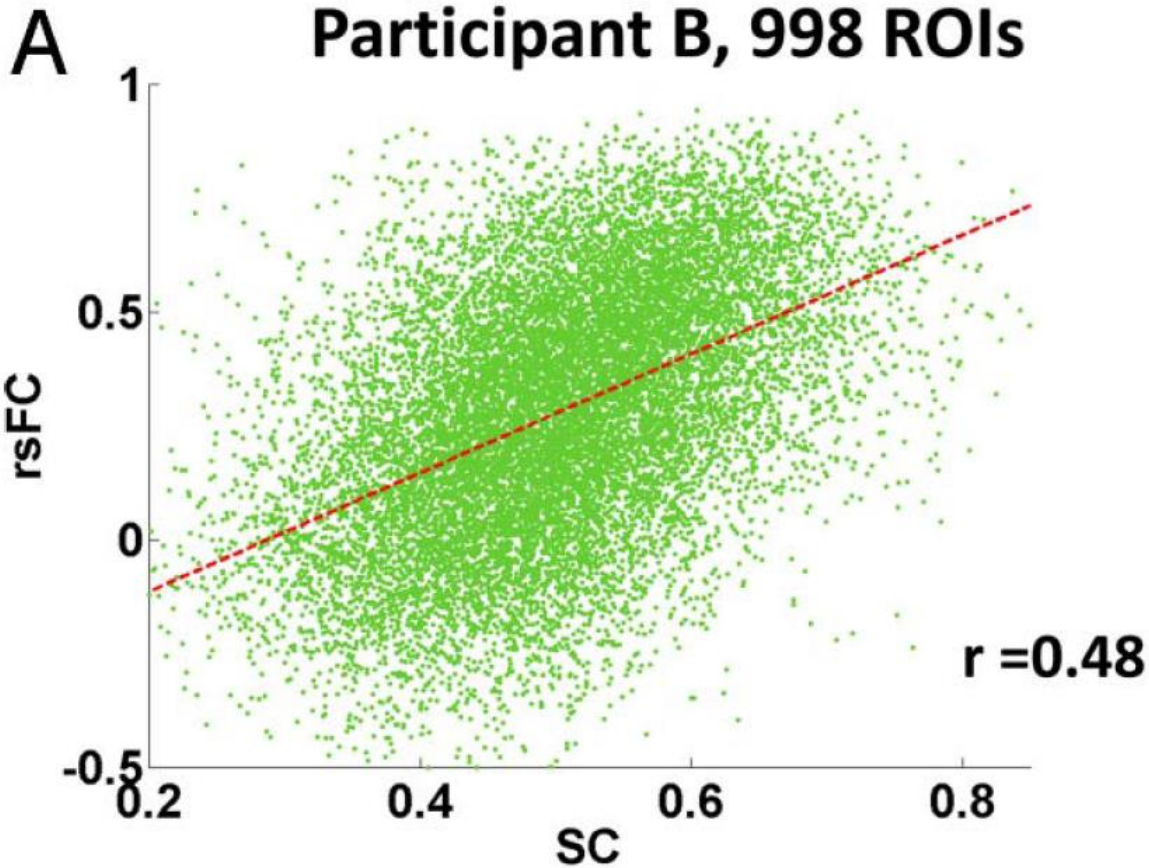


Dynamical systems on the connectome: Chialvo, Sporns, Deco, Jirsa, Marinazzo, SS …

Link-wise comparison Ising model

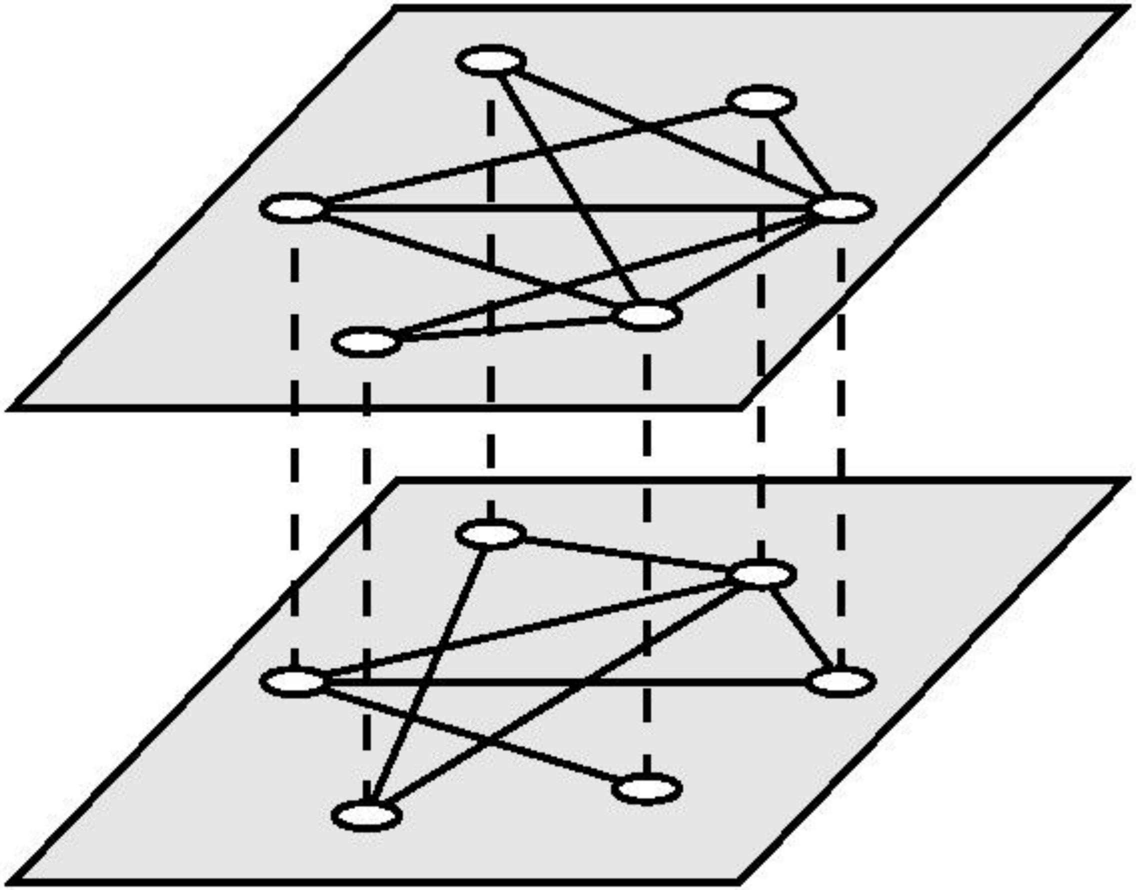


Pairwise link-to-link comparison



From Honey,…Sporns, PNAS 2009

Multilayer networks



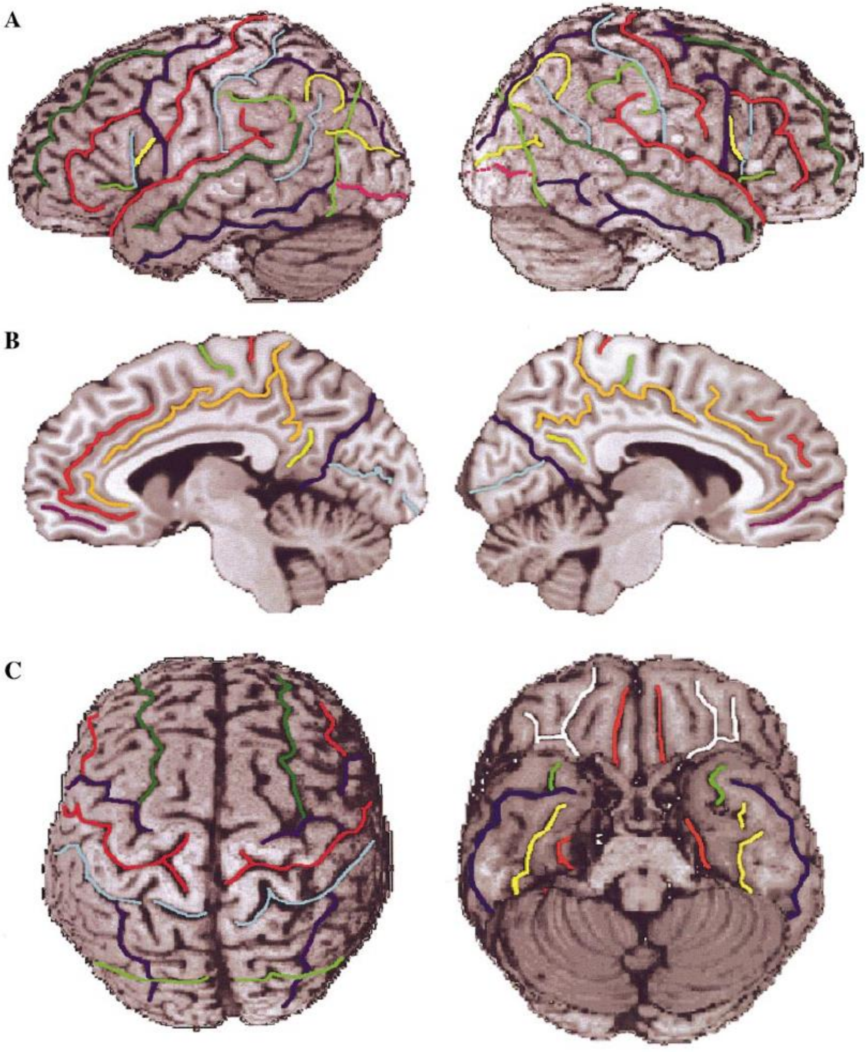
S **Boccaletti**, et al. **Physics Reports** 544 (1), 1-122, 2014

Decomposing the brain in modules

- Important to reduce the variability of anatomical and functional patterns in the class of healthy subjects
- Paradigm signal vs noise -> patient vs healthy
- Parcellations based on anatomy or function, separately, are well known (AAL, RBN, …)
- The question we pose here: is there a decomposition accounting for both structure and function?
- Ans: YES
- What is the most suitable resolution of the modular decomposition to describe the common structure-function modular skeleton?
- Ans: Cross-modularity

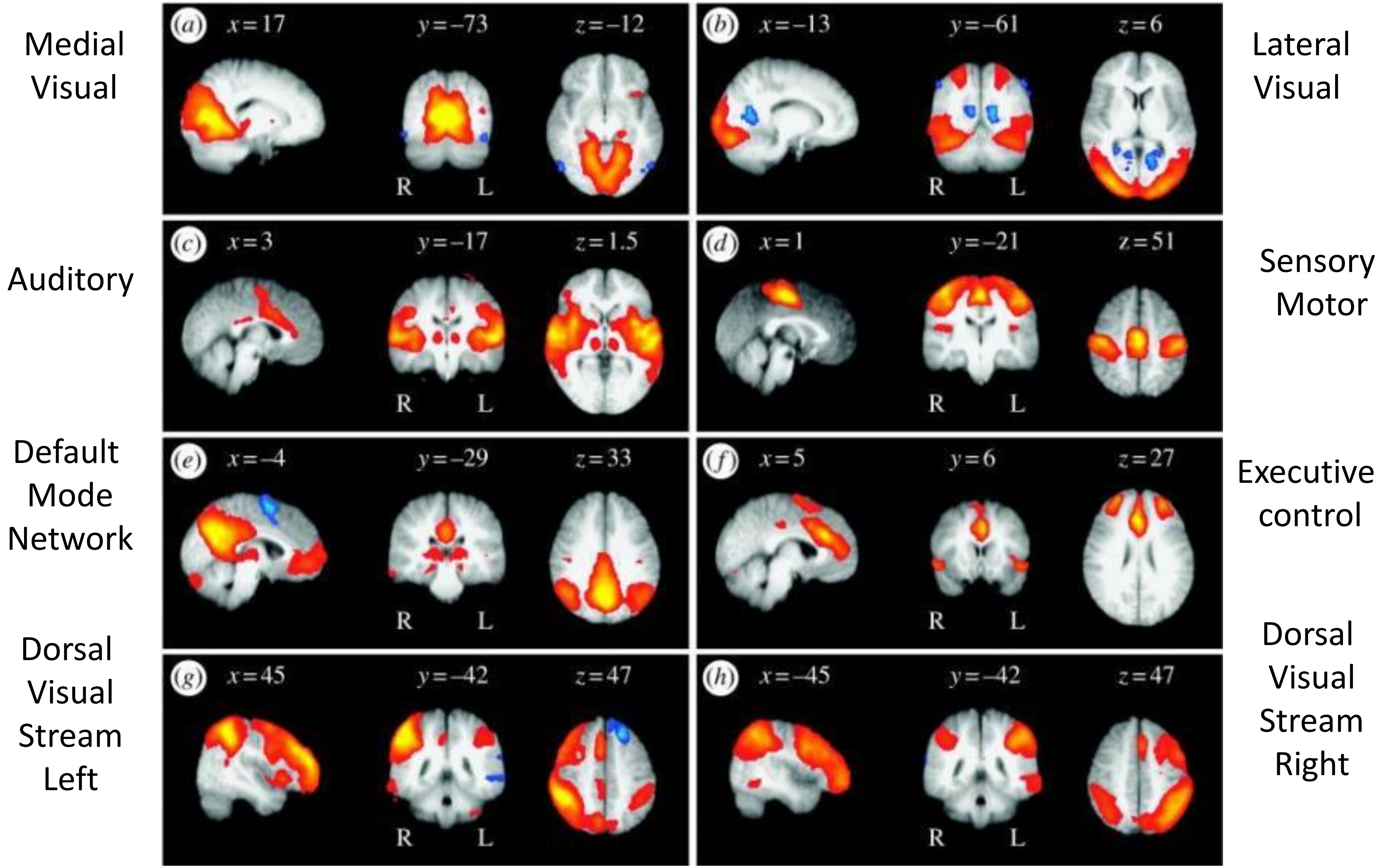
Automated Anatomical Labeling parcellation of the brain: 90 anatomical areas

N. Tzourio-Mazoyer, B. Landeau,D. Papathanassiou, F. Crivello, O. Etard, N. Delcroix, Bernard Mazoyer and M. Joliot, NeuroImage 2002



RESTING BRAIN NETWORKS

- Distributed sets of brain regions whose spontaneous activity exhibits a large degree of temporal coherence (Biswal et al., 1995)
- Identified by Independent Component Analysis (ICA)
- a high degree of reproducibility of RSNs both across healthy subjects and across datasets acquired on the same subject.
- RSNs correspond to regions that are known to share and support cognitive functions
- Alterations in resting state networks have been reported in several brain pathologies and diseases



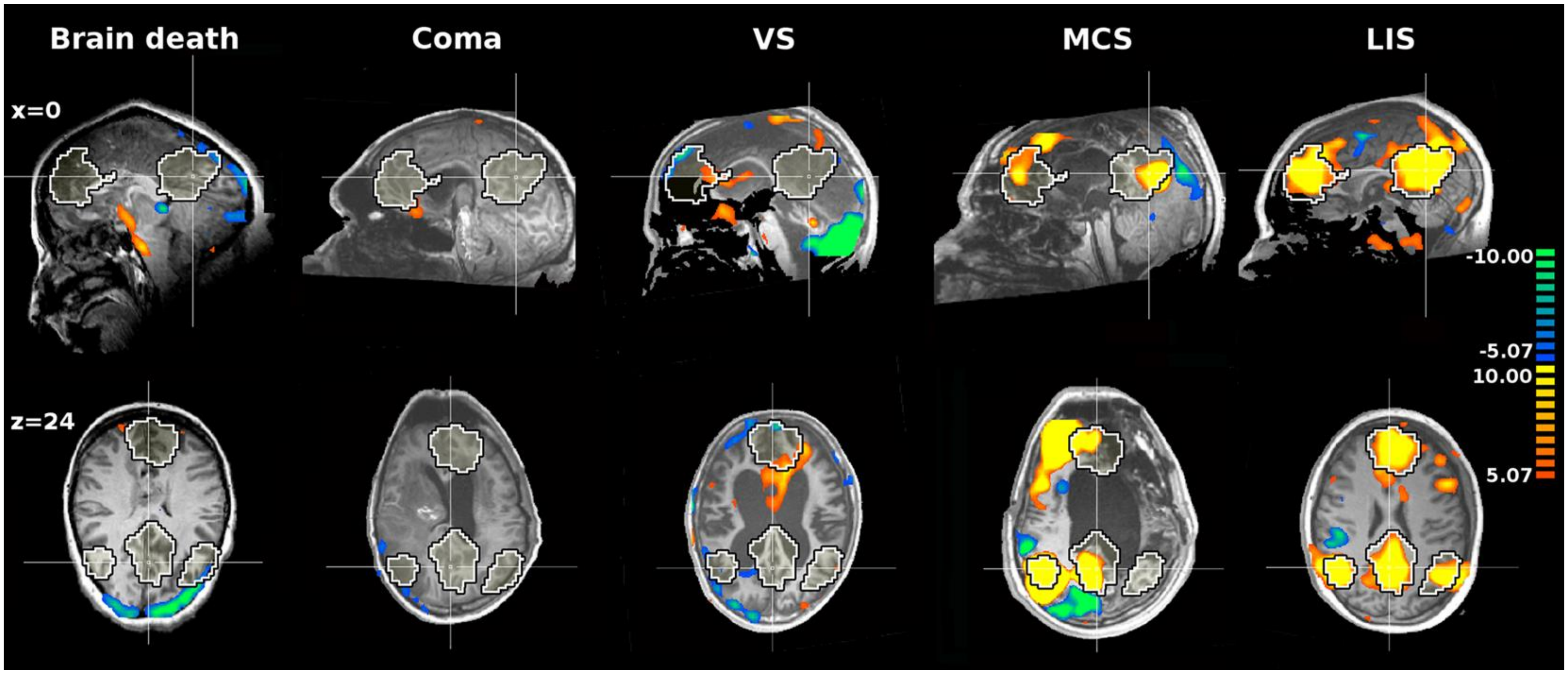
COGNITIVE CORRELATES OF THE RSNs

Traumatic Brain Injury patients

Vegetative State

Minimally Conscious State

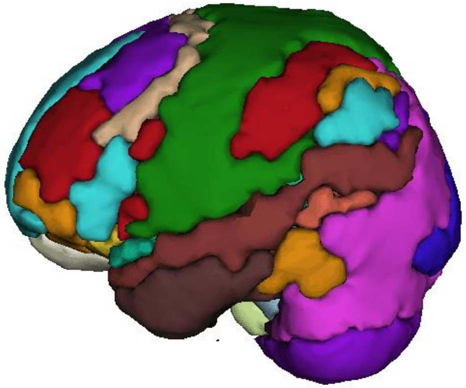
Locked-In Syndrome



no aware no awake	partial aware (arousal) no awake	aware no awake	aware awake (can't move)

(Noirhomme et al 2010)

Relation between structural and functional networks

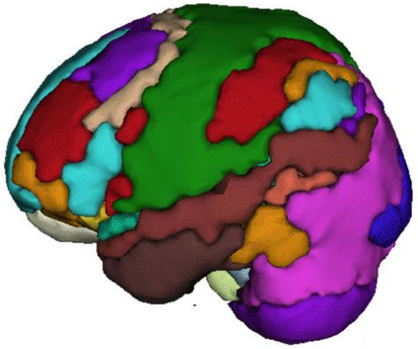


Our data set

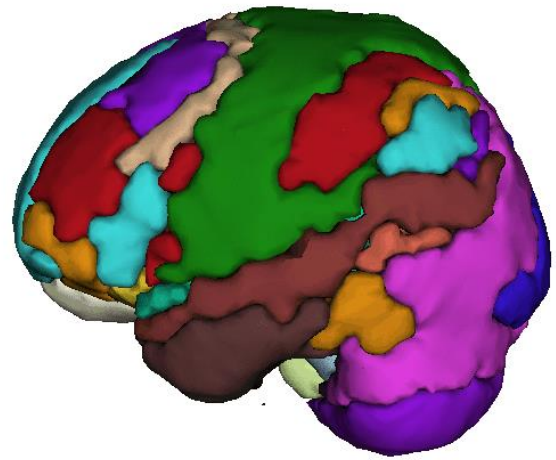
Structural Connectivity and Functional Connectivity (resting conditions) from the same subject (Bilbao Cruces Hospital)

12 Healthy human subjects, age 33.5 ± 8.7

Resolution: 2514 ROIs



Our approach: comparison at the moduli level



Contrast functional and structural networks by exploiting thier hierarchical modular organization

(Skudalski et al 2008, Betzel et al 2013, Kolchinsky et al 2014)

Cosine distance between ROIs

- For each ROI, the feature vector is the connectivity to all the 2514 ROIs.
- For each pair of ROIs, the cosine distance is defined as one minus the cosine between the two feature vectors

Agglomerative Hierarchical Clustering

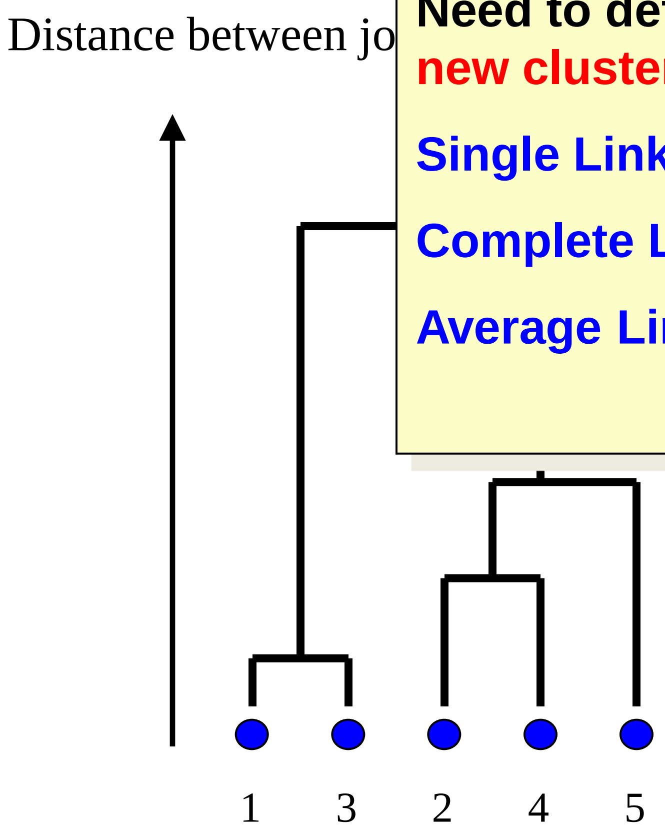
Need to define the distance between the new cluster and the other clusters.

Single Linkage: **distance between closest pair.**

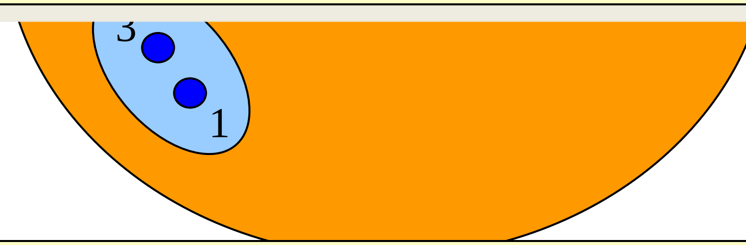
Complete Linkage: **distance between farthest pair.**

Average Linkage: **average distance between all pairs**

or distance between cluster centers



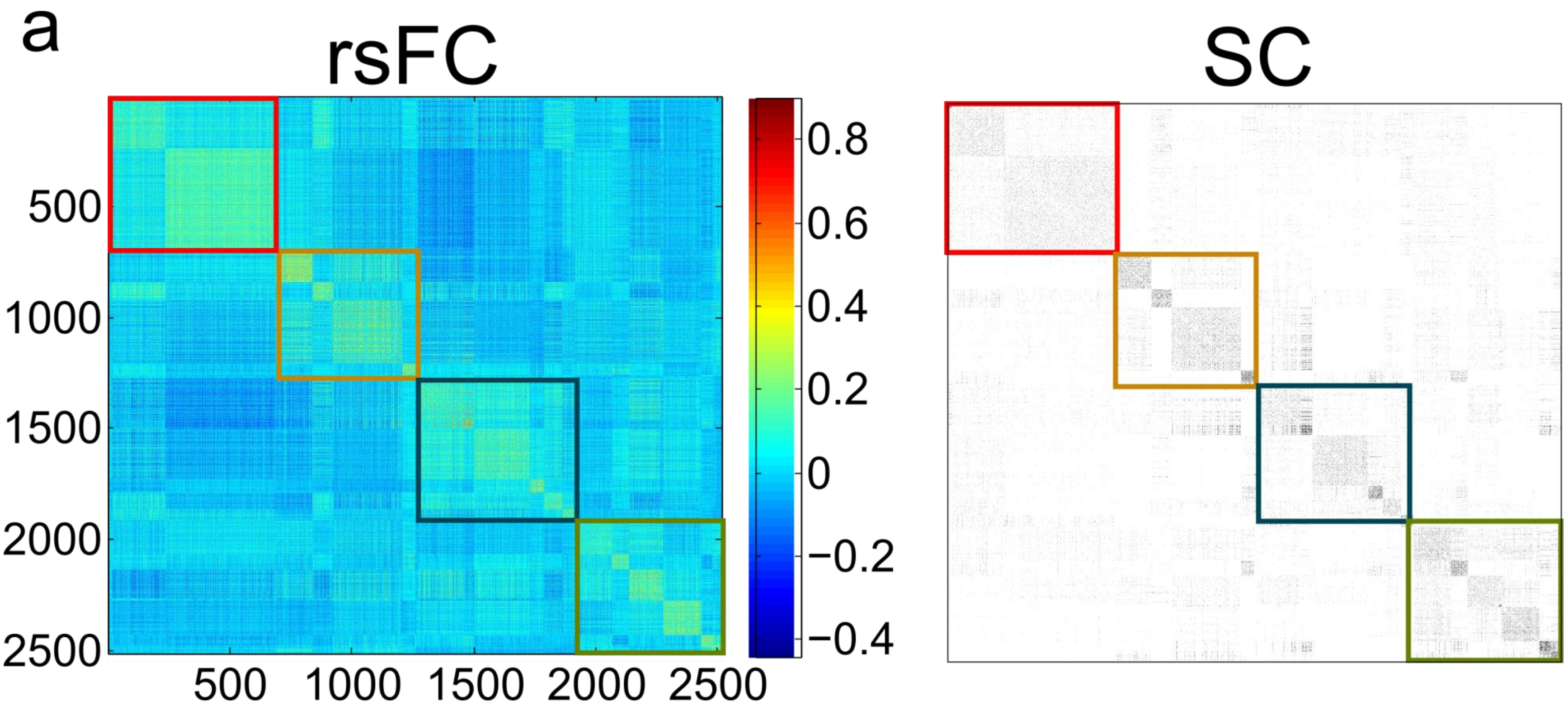
Dendrogram

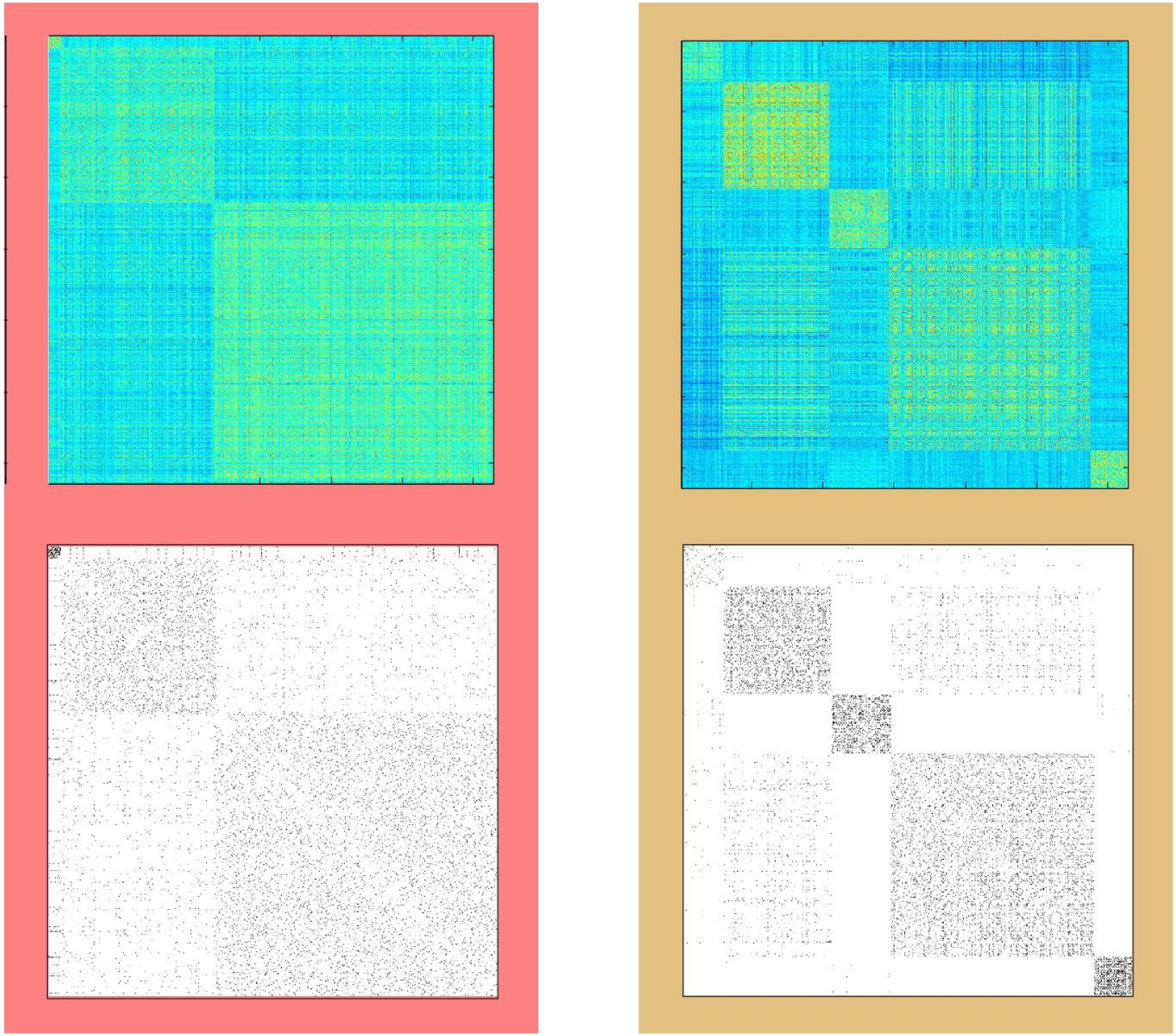


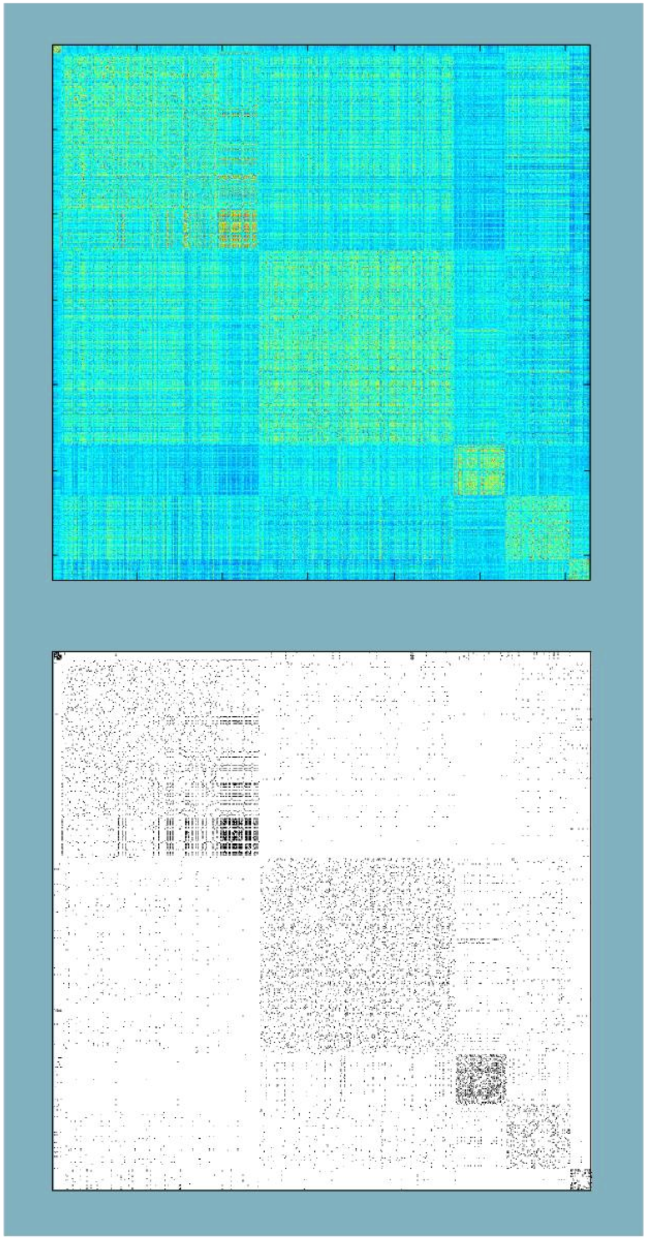
The dendrogram induces a linear ordering of the data points

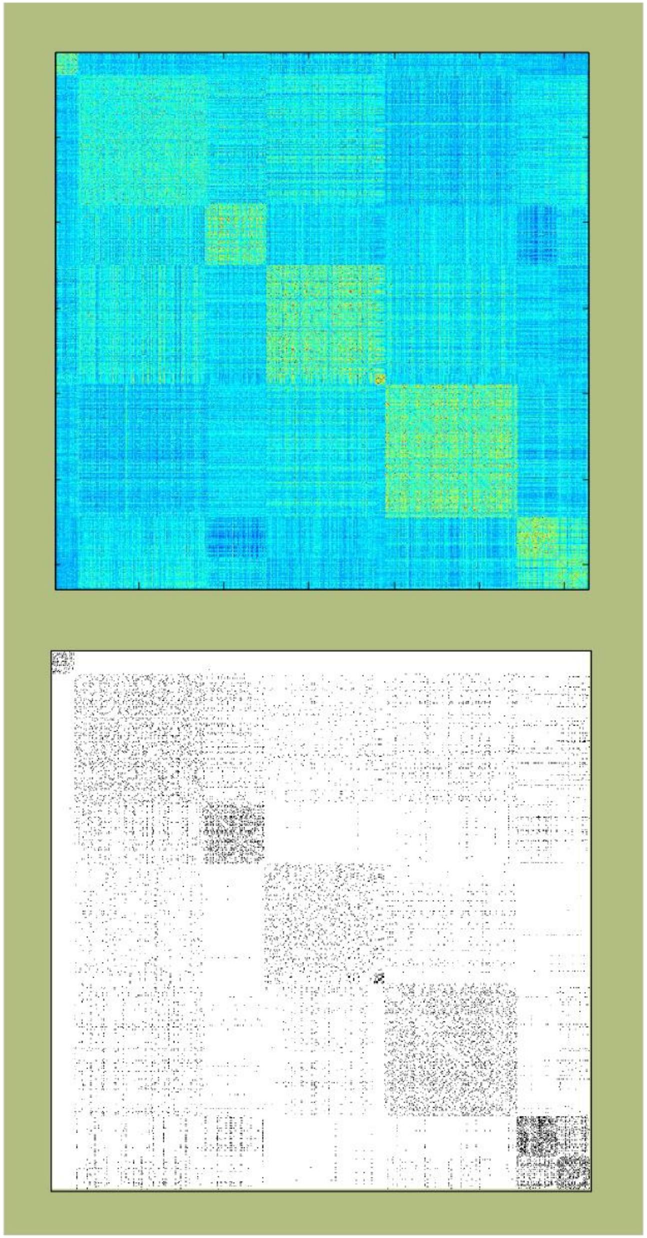
Comparison at the moduli level

Clustering of rsFC -> ordering for both rsFC and SC



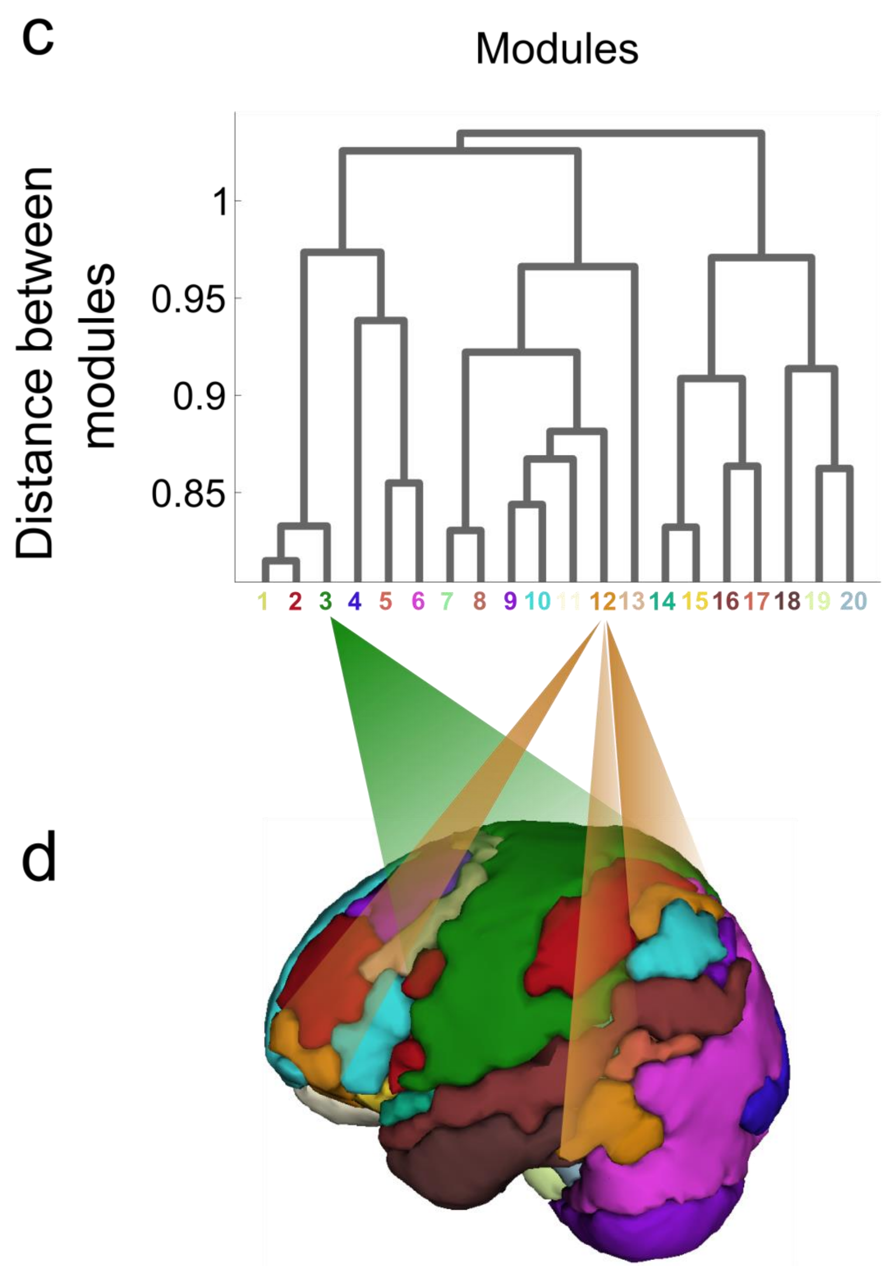






Hierarchical Clustering provides a tree of modules

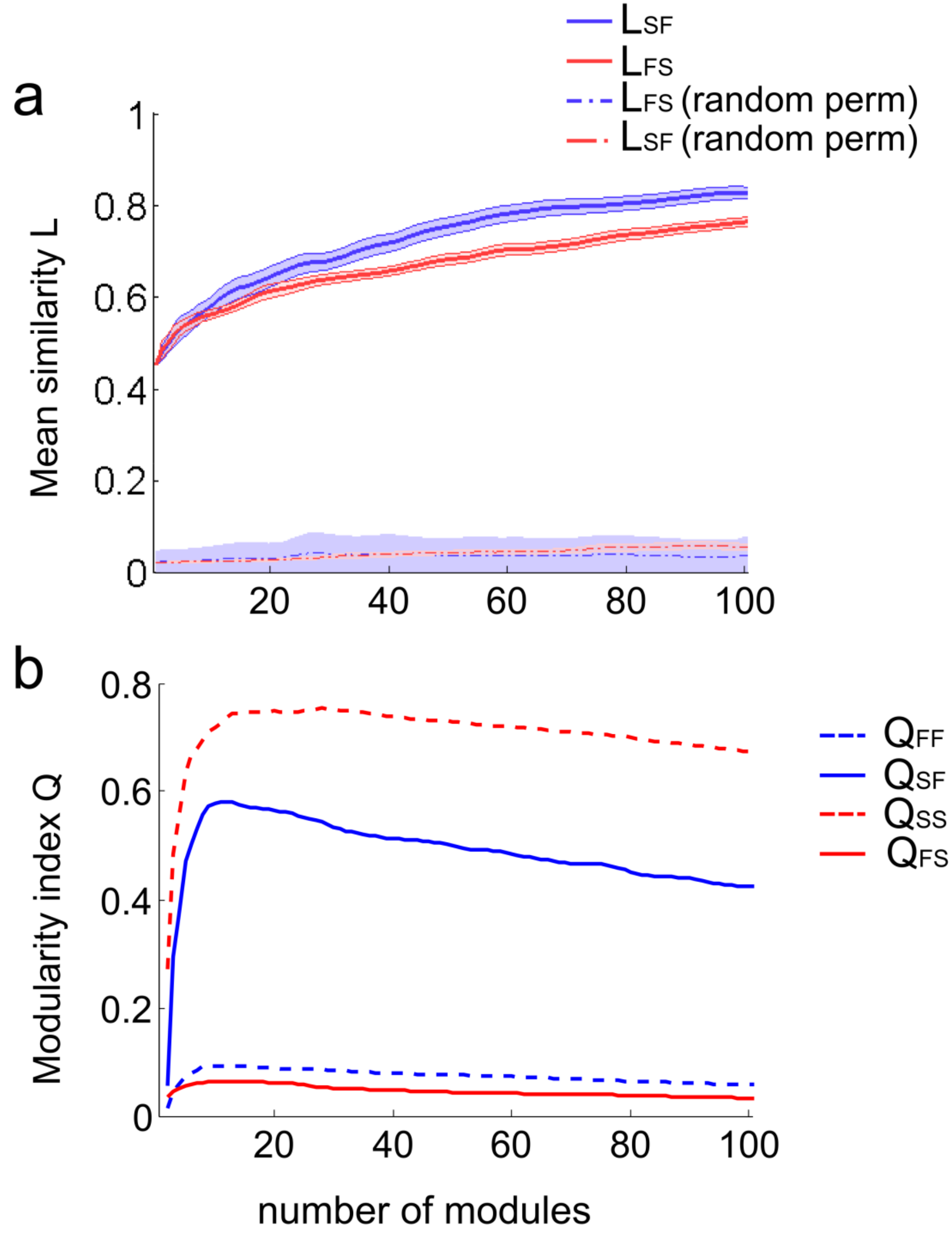
How to choose the optimal resolution of clustering?



Similarity Sorensen index L

$$\frac{2|a \cap b|}{|a| + |b|}$$

Modularity Q

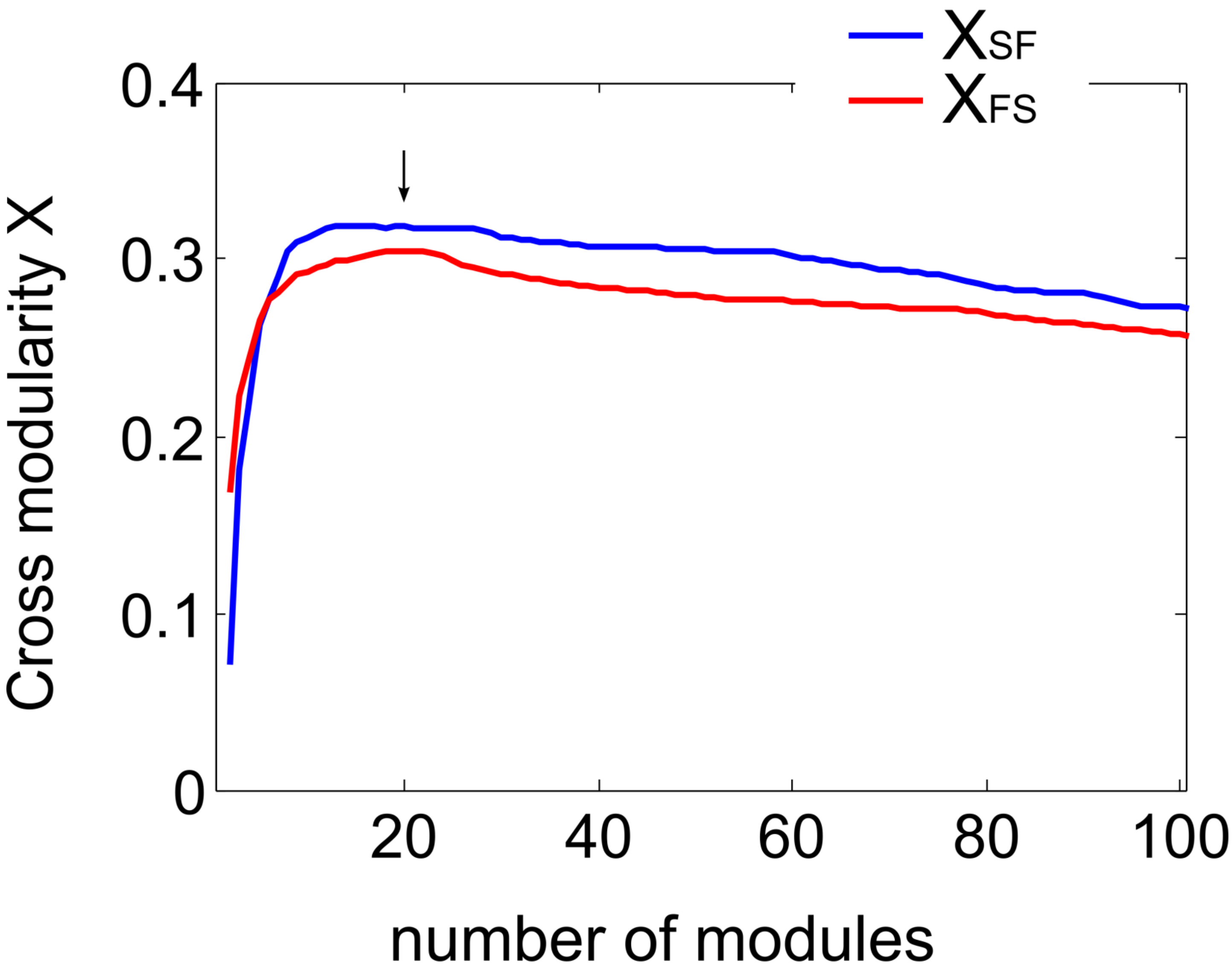


Cross Modularity X

A, B two networks with the same nodes

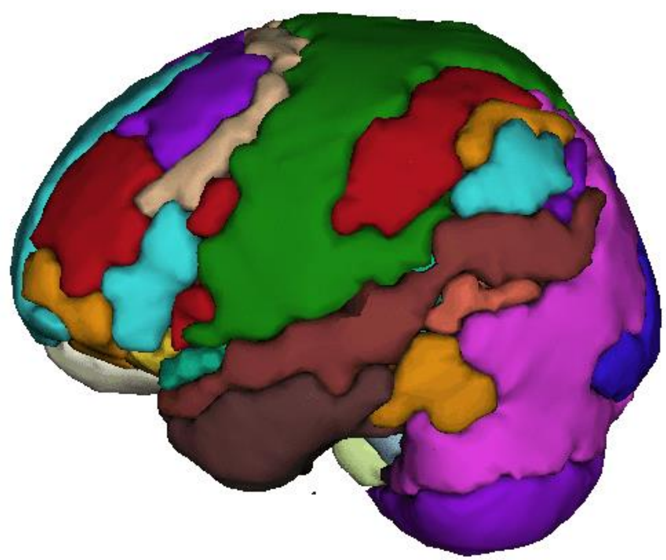
Π a partition of nodes

$$X[\Pi] = \left(Q_A L_{AB} Q_B\right)^{\frac{1}{3}}$$



XSF
XFS
0.4
0.3
0.2
0.1
0
Cross modularity X
20
40
60
80
100
number of modules

Optimal partition 20 modules

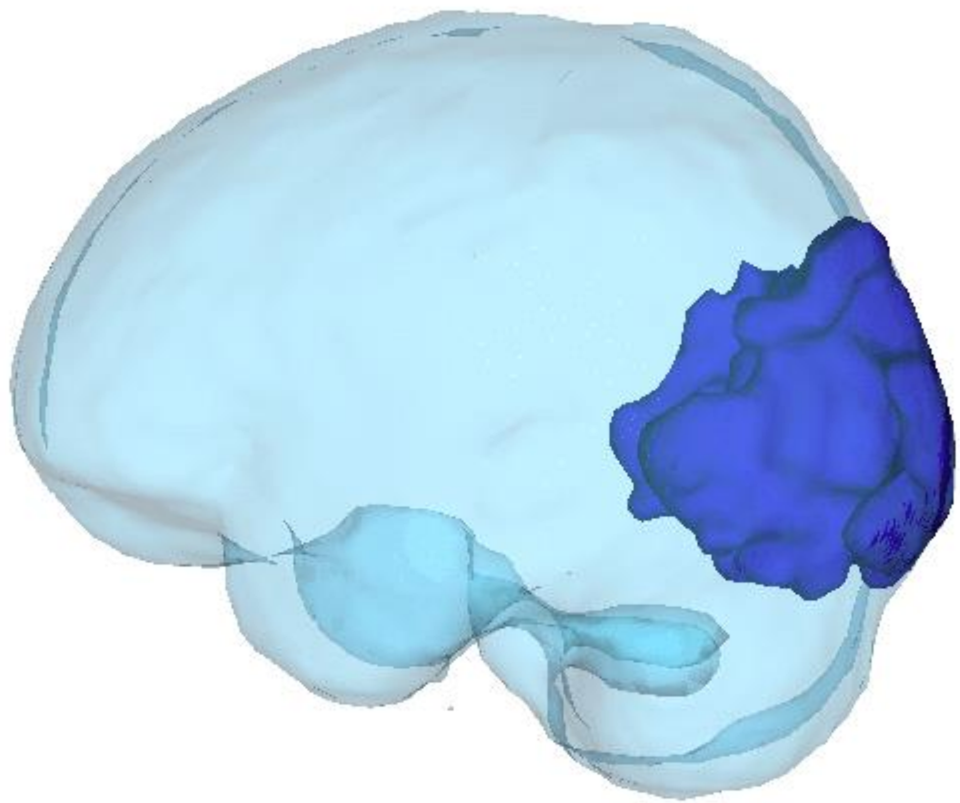


All the modules are characterized anatomically (and have cognitive correlates)

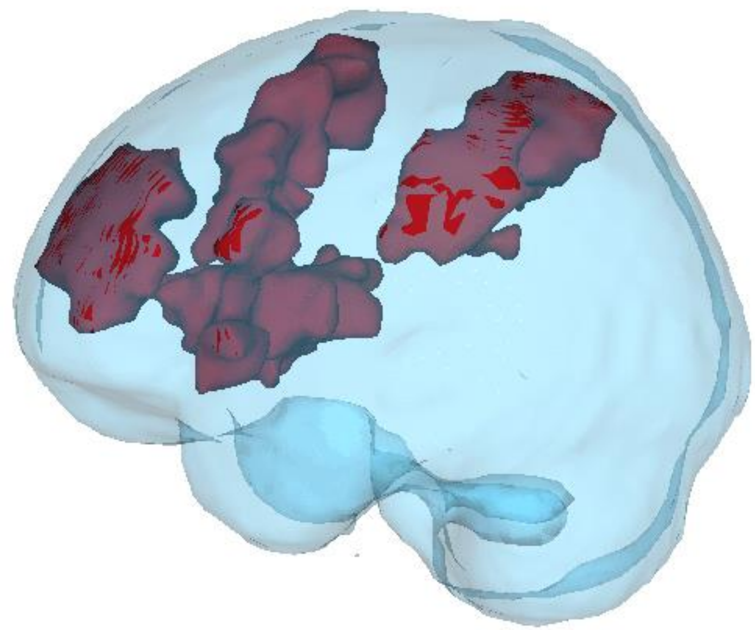
Table S1: Anatomical description of the 20 modules defined after hierarchical agglomerative clustering (HAC) of rsFC. In the first column, we also provide the module volume and links to the 3D movies are given in the third column.

Module number (volume size)	Anatomical description	Link to 3D representation
module 1 (7.26 cm^3)	**Posterior cingulate:** posterior area of the cingulate gyrus or callosal convolution. Located above the corpus callosum, it goes from the frontal lobe back to the temporal uncus and up to the splenium. It belongs to the Default Mode Network.	Movie S1
module 2 (104.36 cm^3)	**Putamen:** a round structure located at the base of the telencephalon. It is also one of the basal ganglia structures. **Anterior cingulate:** anterior frontal region of the cingulate gyrus, initiated above the rostrum of the corpus callosum. **Rostral pars of the middle frontal gyrus:** anterior inferior end of the middle frontal gyrus. **Superior parietal gyrus:** parietal gyrus located posterior to the postcentral gyrus. **Supramarginal gyrus**: region in the parietal lobe encircling the posterior extreme of the Sylvian fissure.	Movie S2

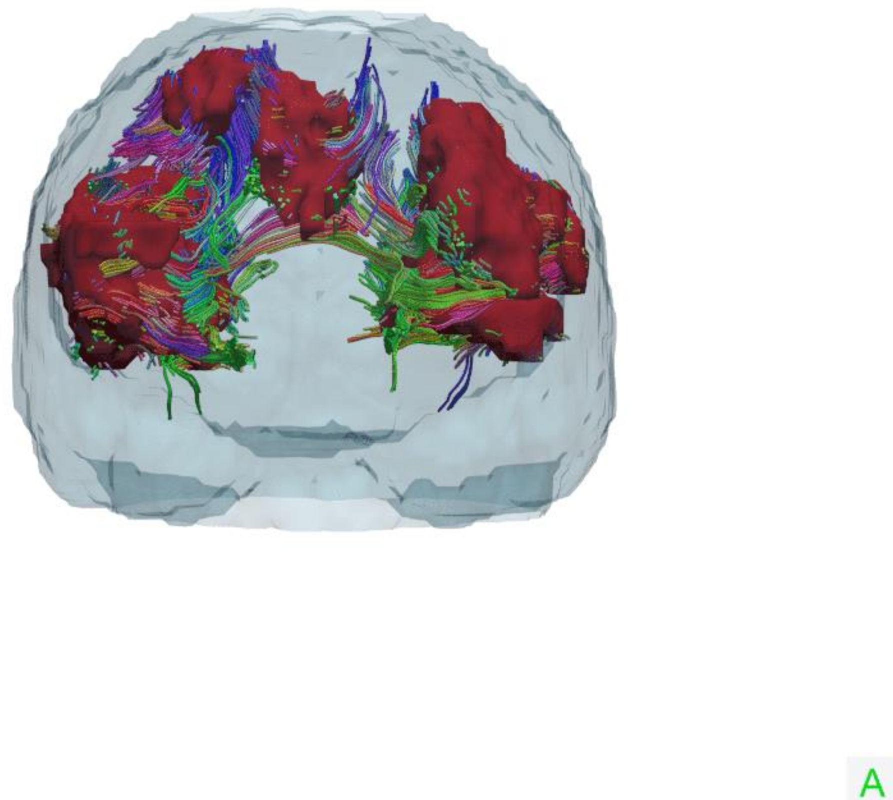
Some modules are compact



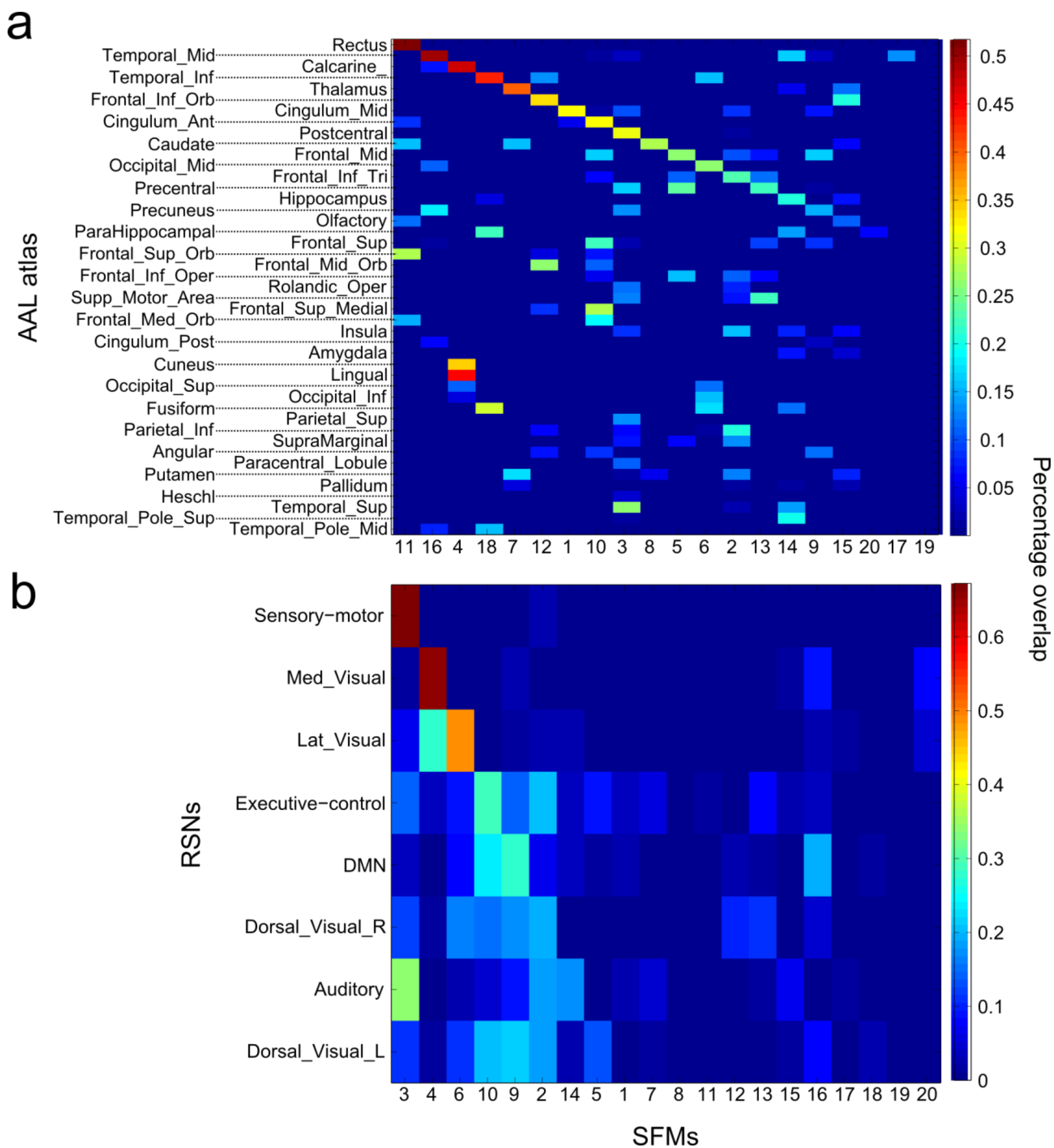
Some are made of anatomically distinct components



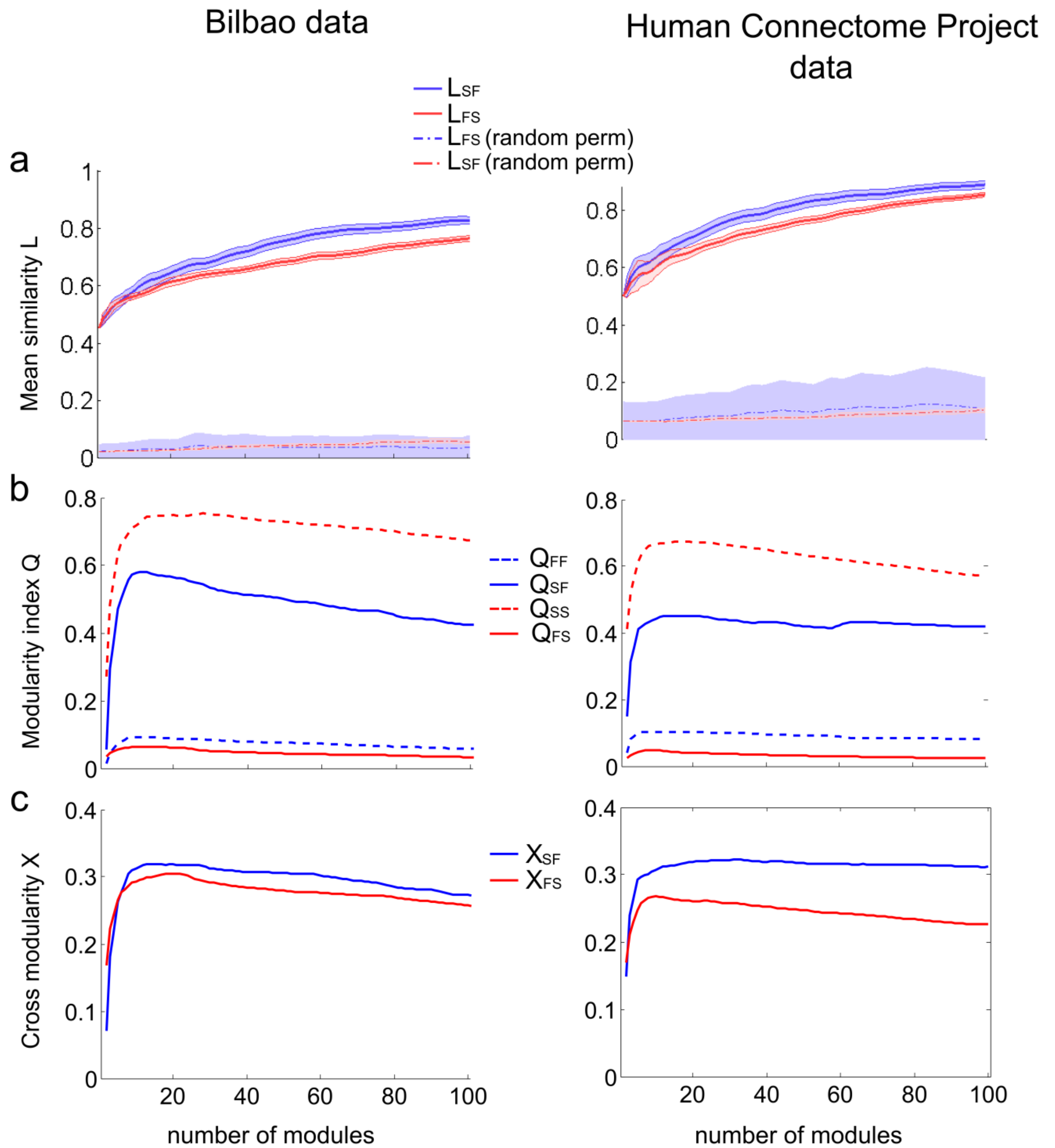
The wiring among these components is evident after plotting fibers



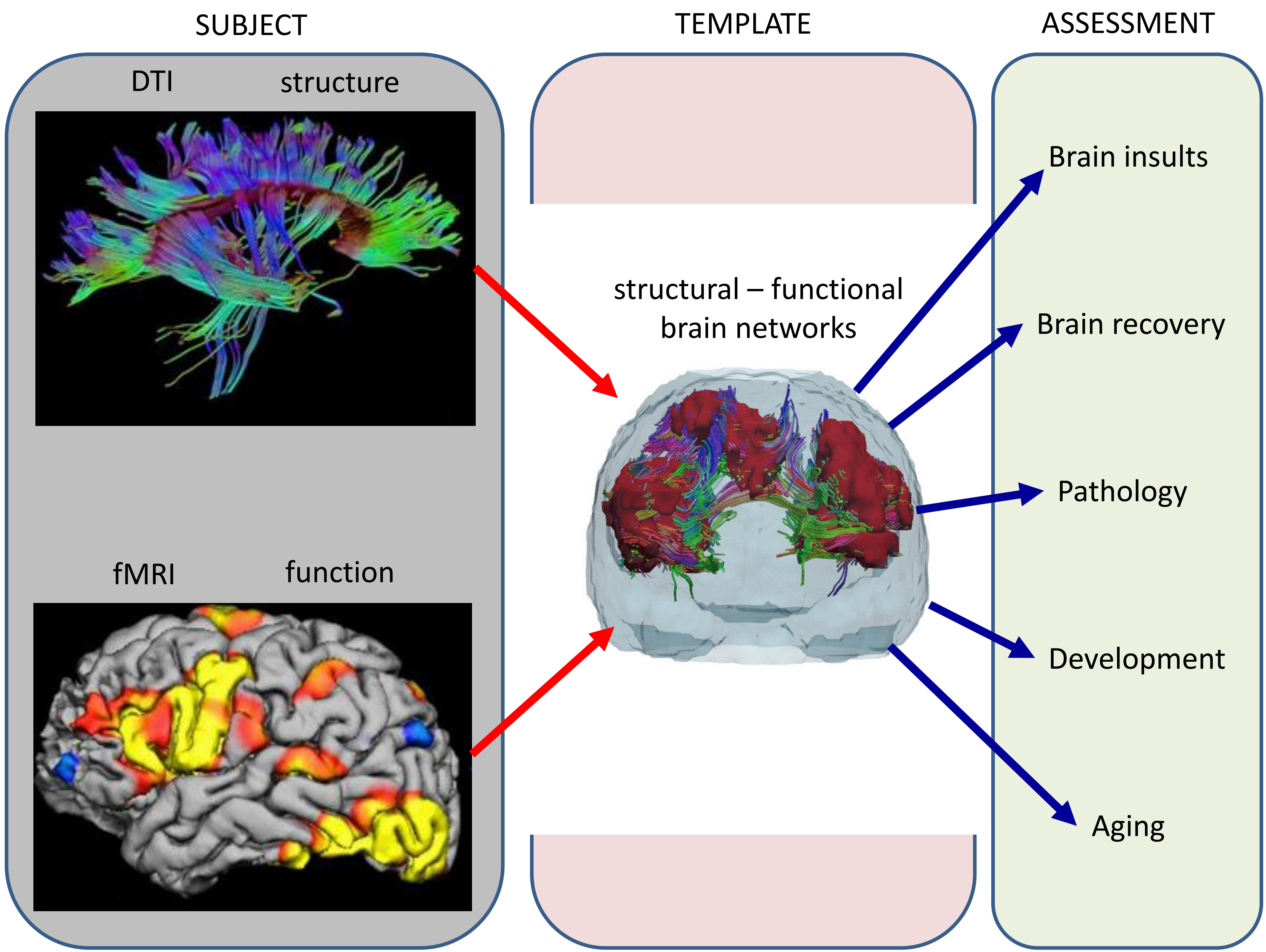
Overlap with AAL and RBN modules



Robustness



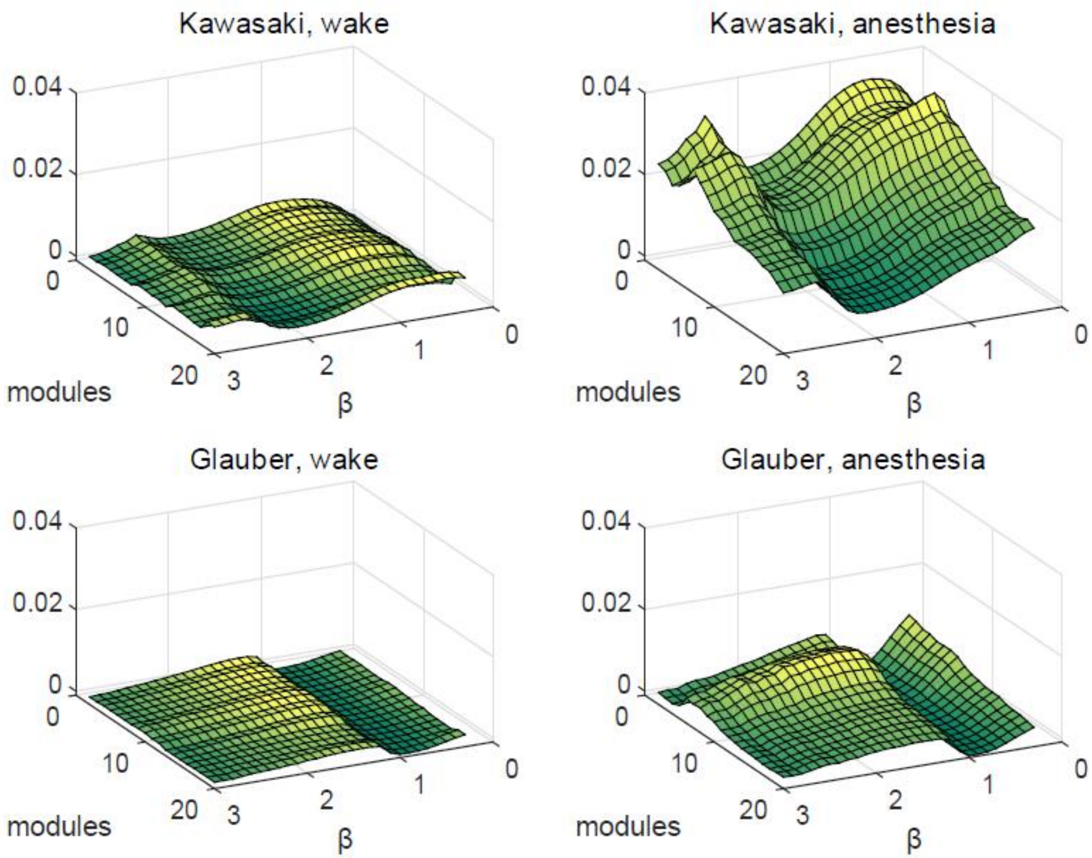
Bilbao data
Human Connectome Project data
a
b
c
LSF
LFS
LFS (random perm)
LSF (random perm)
Mean similarity L
QFF
QSF
QSS
QFS
Modularity index Q
XSF
XFS
Cross modularity X
number of modules
number of modules


SUBJECT
TEMPLATE
ASSESSMENT
DTI
structure
fMRI
function
structural – functional
brain networks
Brain insults
Brain recovery
Pathology
Development
Aging

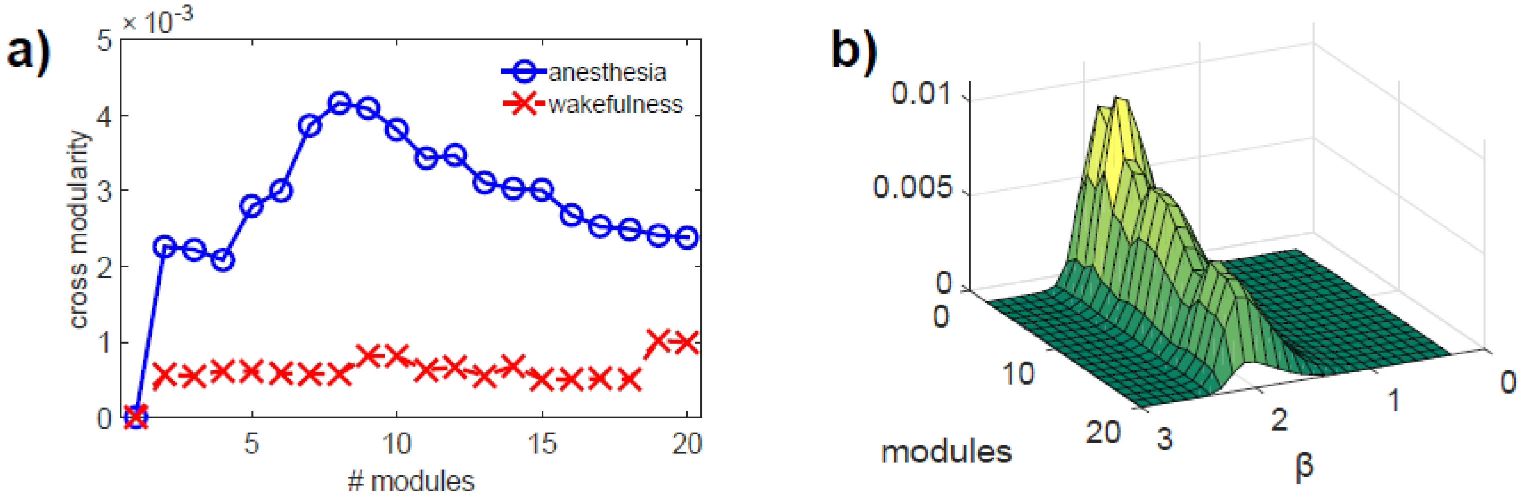
Usefulness of cross-modularity: Real data

- 14 healthy subjects in wakefulness and propofol anesthesia
- 116 ROIs resolution

CM empirical-model functional correlations



CM structural-empirical fc



Conclusions

Our results show that when trying to correlate brain structure with function, a clear structure-function matching emerges when applying a hierarchical modular approach.

This new large-scale brain division will have an impact to study brain disorders , as anomalies in this partition might reflect pathologies with both a functional and anatomical character.

www.nitr.org/projects/biocruc_hcatlas

To download the hierarchical partition, the brain networks and the code for cross-modularity