Investigating the structure/function relationship in the brain with the Ising model

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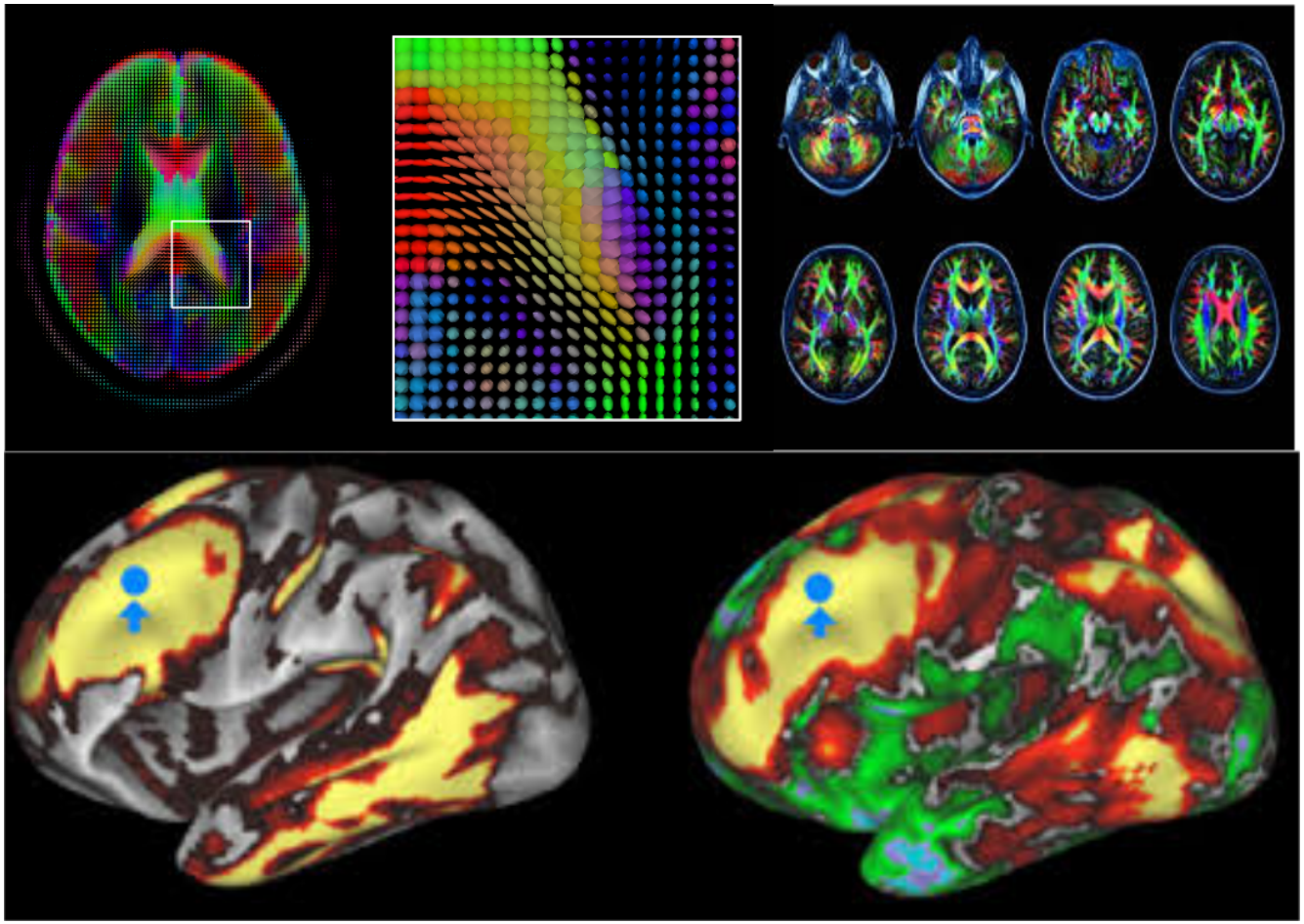
Structure, function and connectivity

Ursus Wehrli - Kunst aufräumen

- In the brain, structure shapes function
- What is the extent of this relationship?
- Graph theory provides a convenient picture
- How do we define nodes and links in the brain?

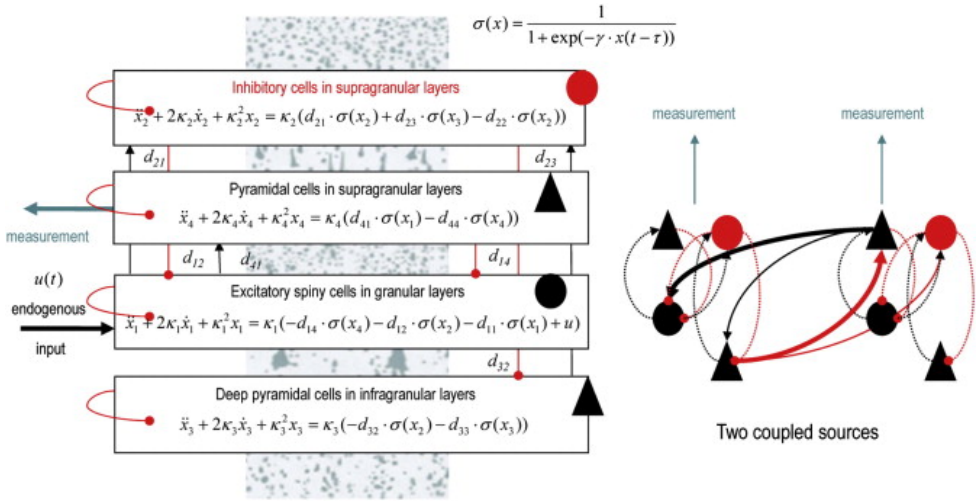
Structural and functional connectivity



Functional connectivity reflects statistical dependencies among time series recorded at different brain locations.

Exploring the relation between structure and function (dynamics)

Simulate a dynamical model on the connectome structure

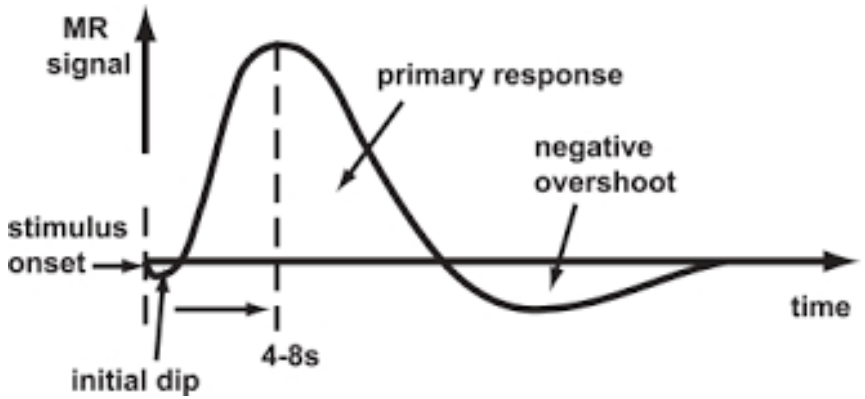


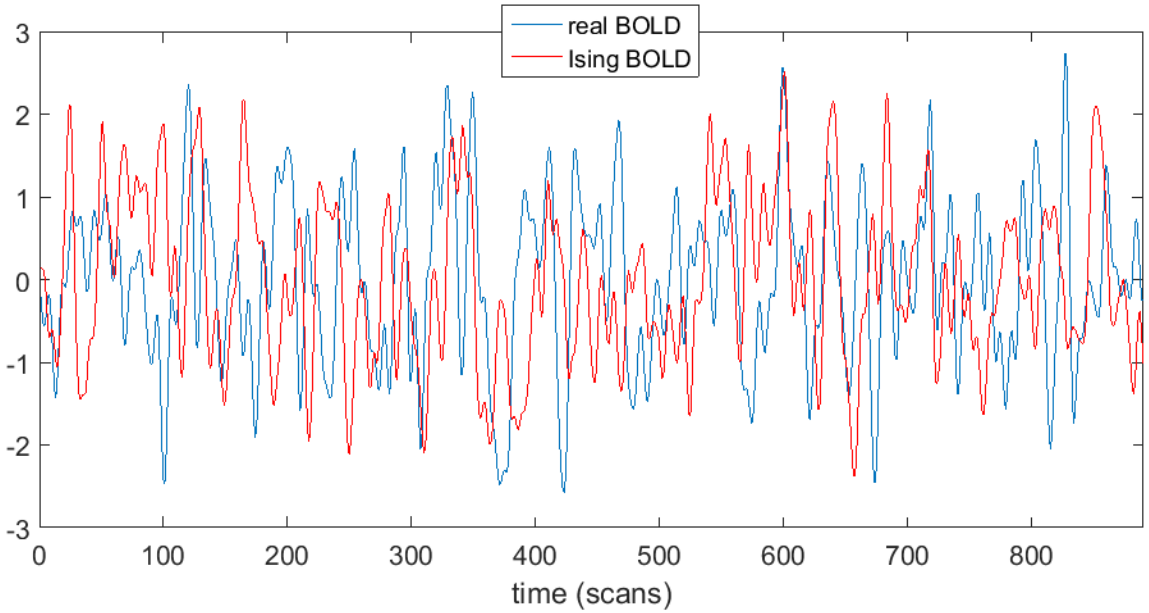
State-space model of a single source

Biologically detailed model, or a simplified one:
We consider the configurations $\{\sigma_i(t)\}_{i=1,\ldots,n}$ of an Ising system of n spins living on 116 nodes (anatomical brain areas)
Couplings $J_{ij} = \beta A_{ij}$.
β is the inverse temperature, A_{ij} the structural connections.

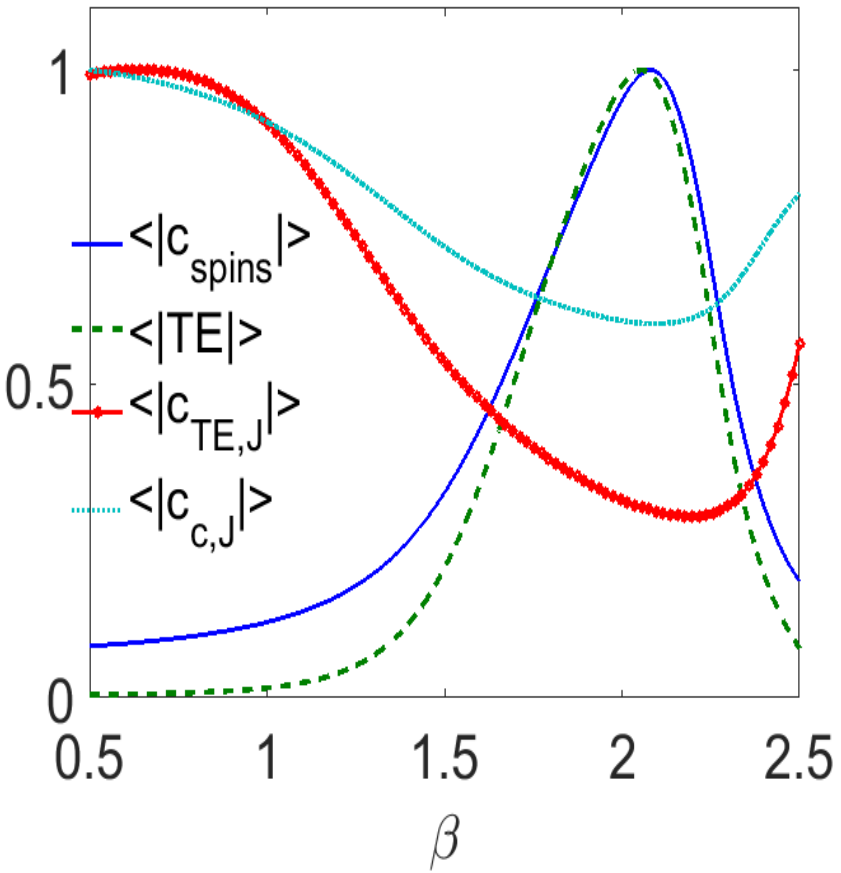
WTF? Simulating brain activity with binary series?

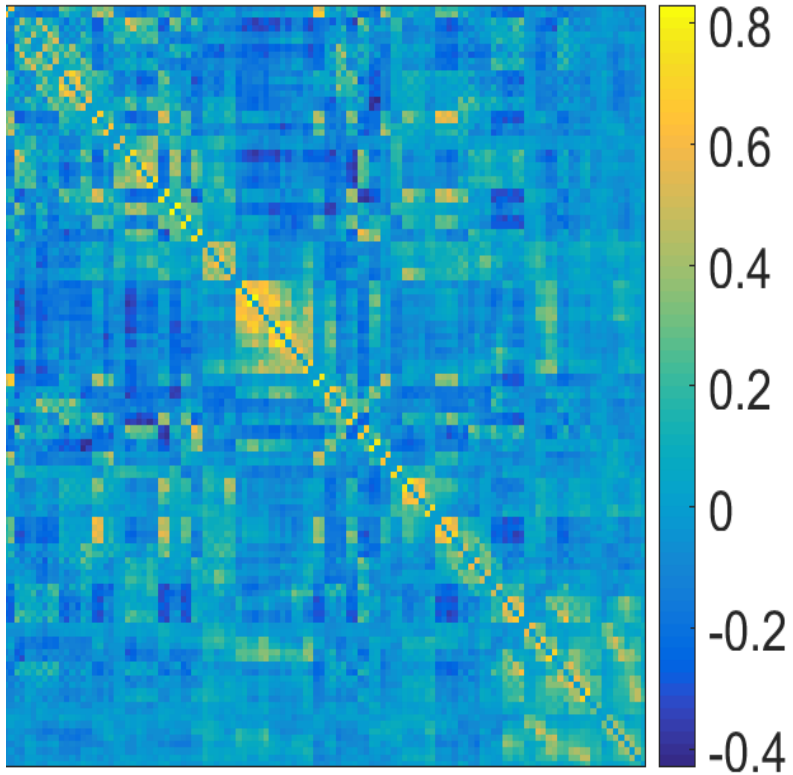
BOLD (fMRI) signal is neural signal convolved with the hemodynamic response function





Information transfer is maximized close to criticality, correlations structure-function are minimized

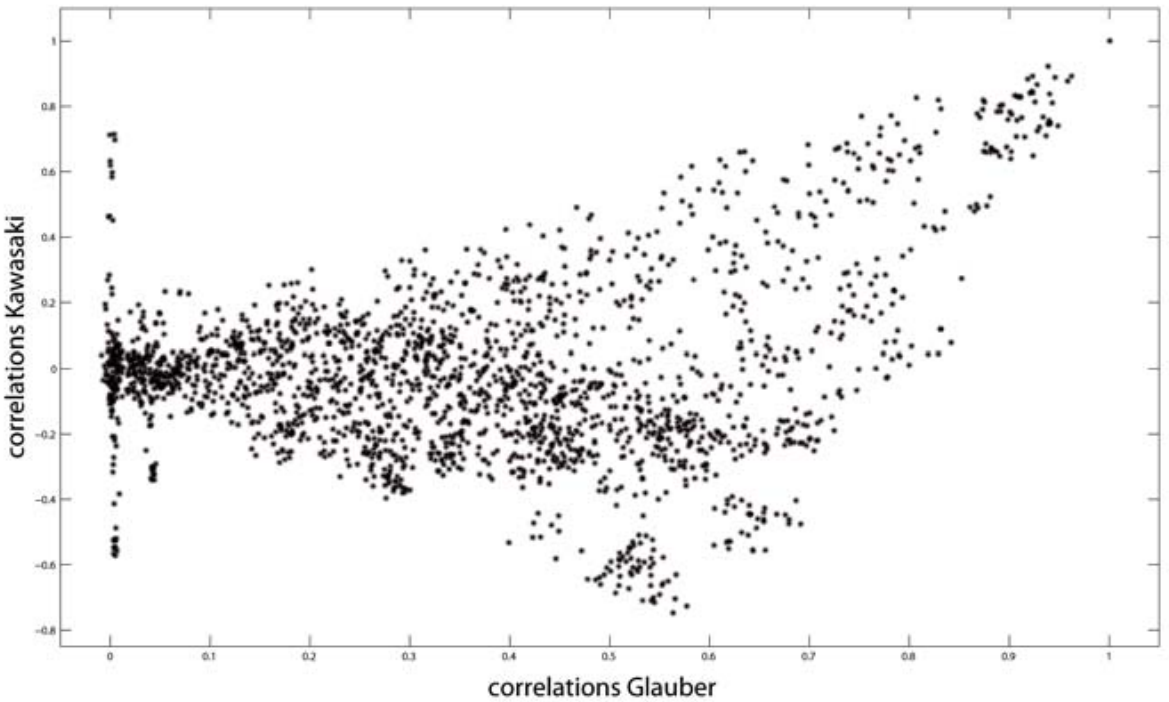




Empirical correlations assume also negative values

What happens if we preserve total magnetization?

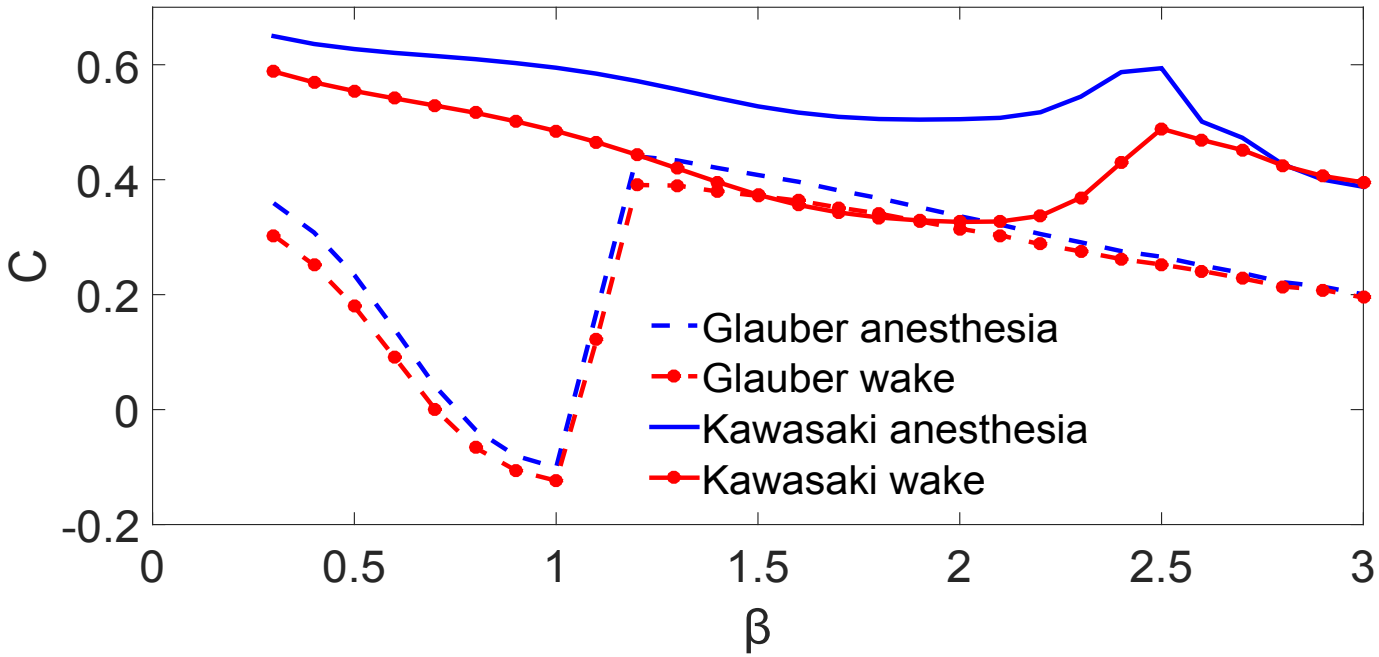
Kawasaki update rule (Kawasaki 1966)
At the critical point the spin correlations for the Kawasaki dynamics can be both positive and negative: negative correlations emerge due to the conservation constraint



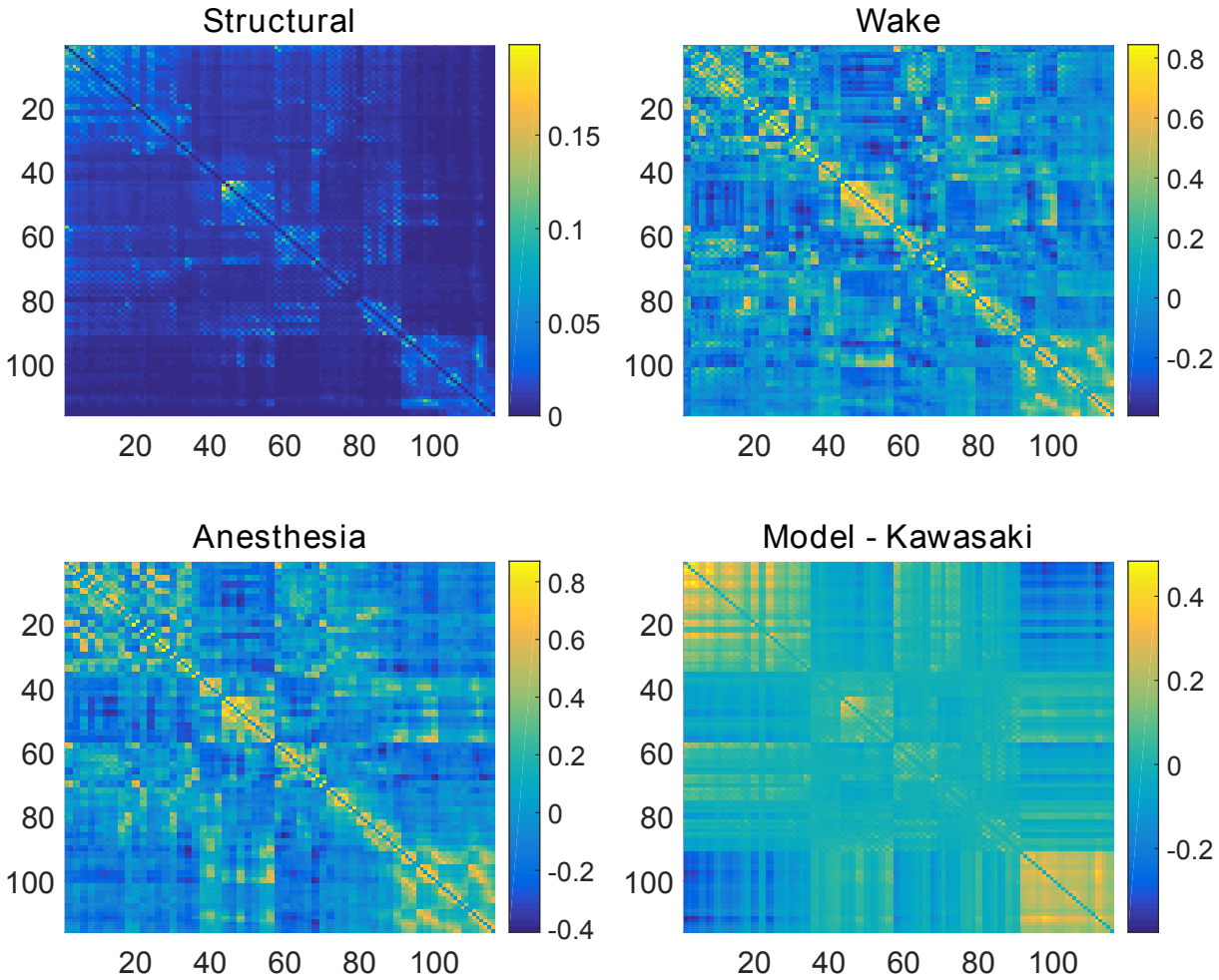
Case study: induced loss of consciousness

- 18 subjects
- wakefulness and propofol anesthesia
- how is the relation structure-function modified by anesthesia?
- does the conserved model add insight in this relation?

Correlation between the model spin correlations and the empirical functional connectivities

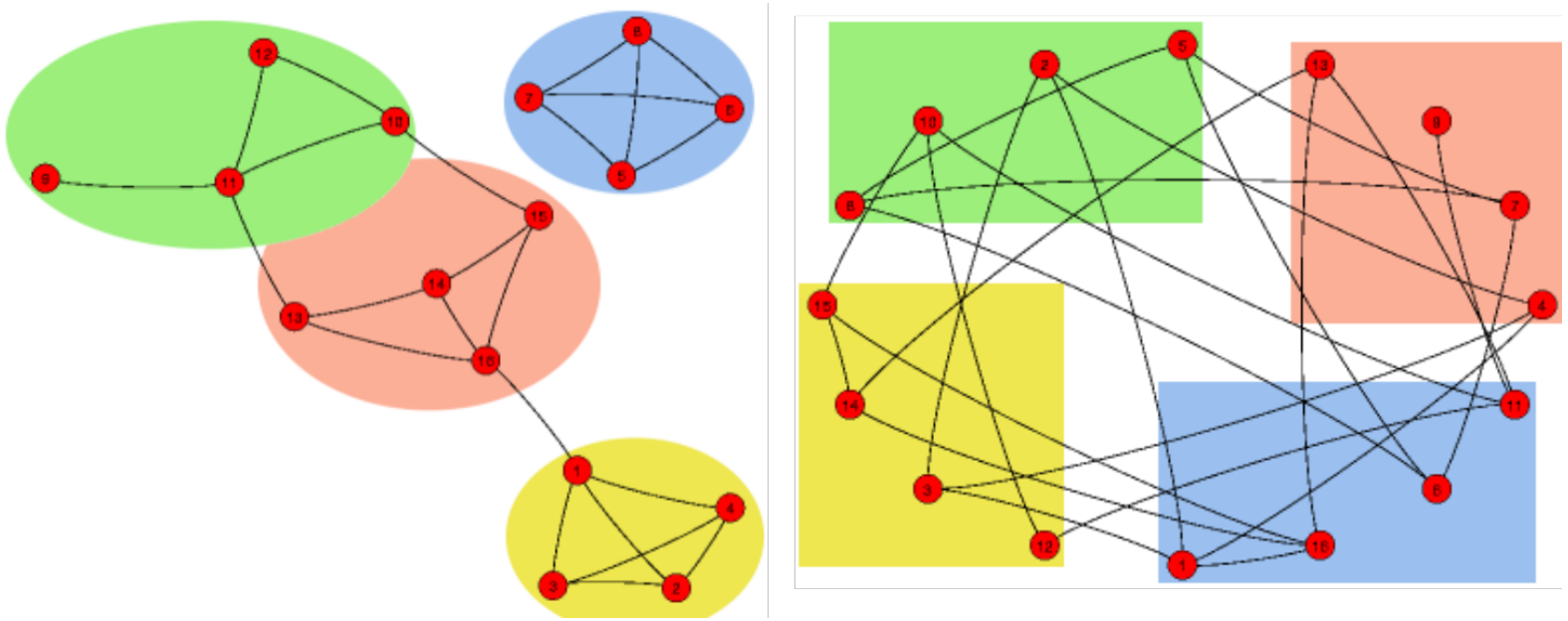


Connectivity matrices from a parcellation in 116 regions



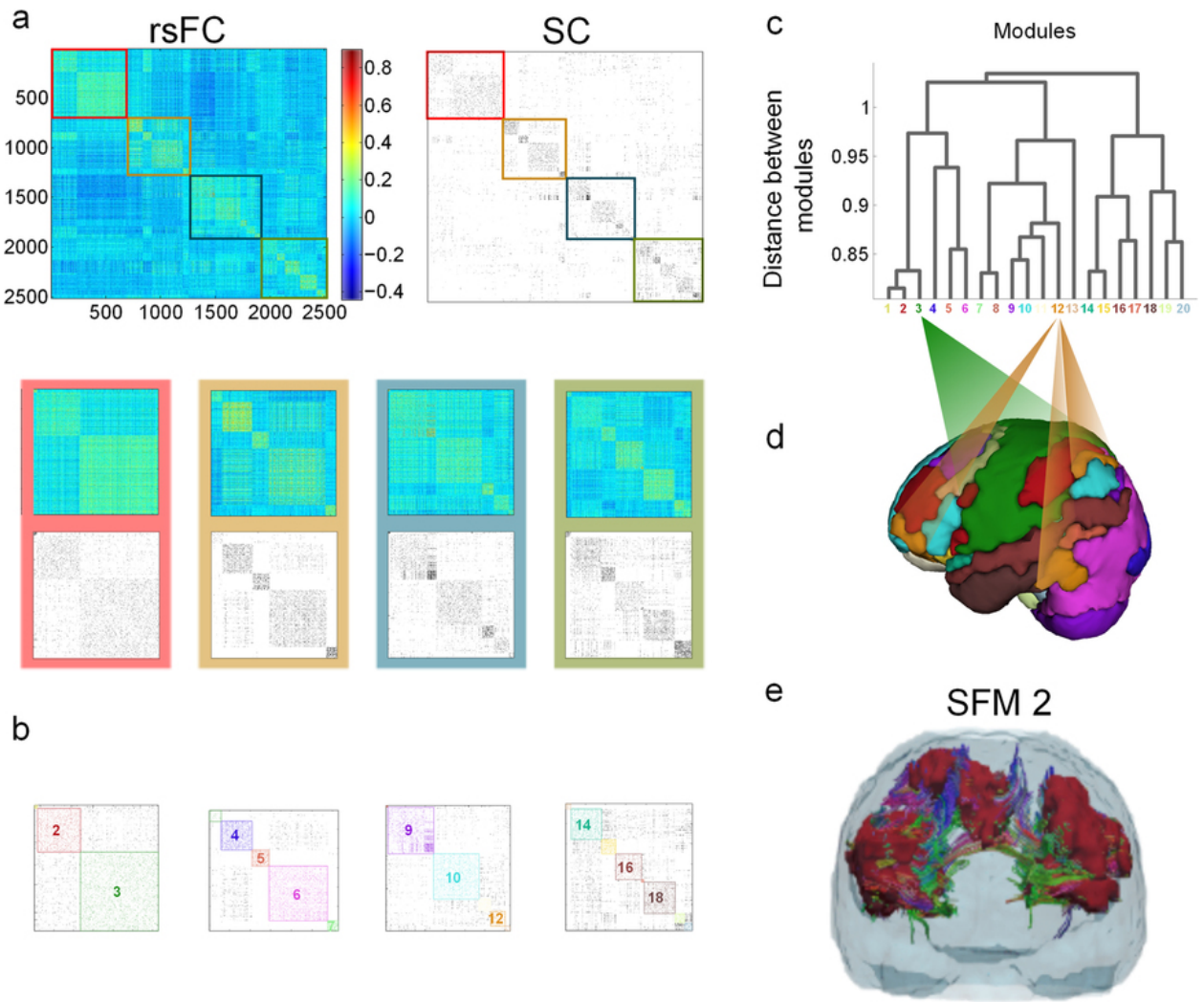
Interplay between segregation and integration: modularity

Modularity defines how a network is split in subnetworks



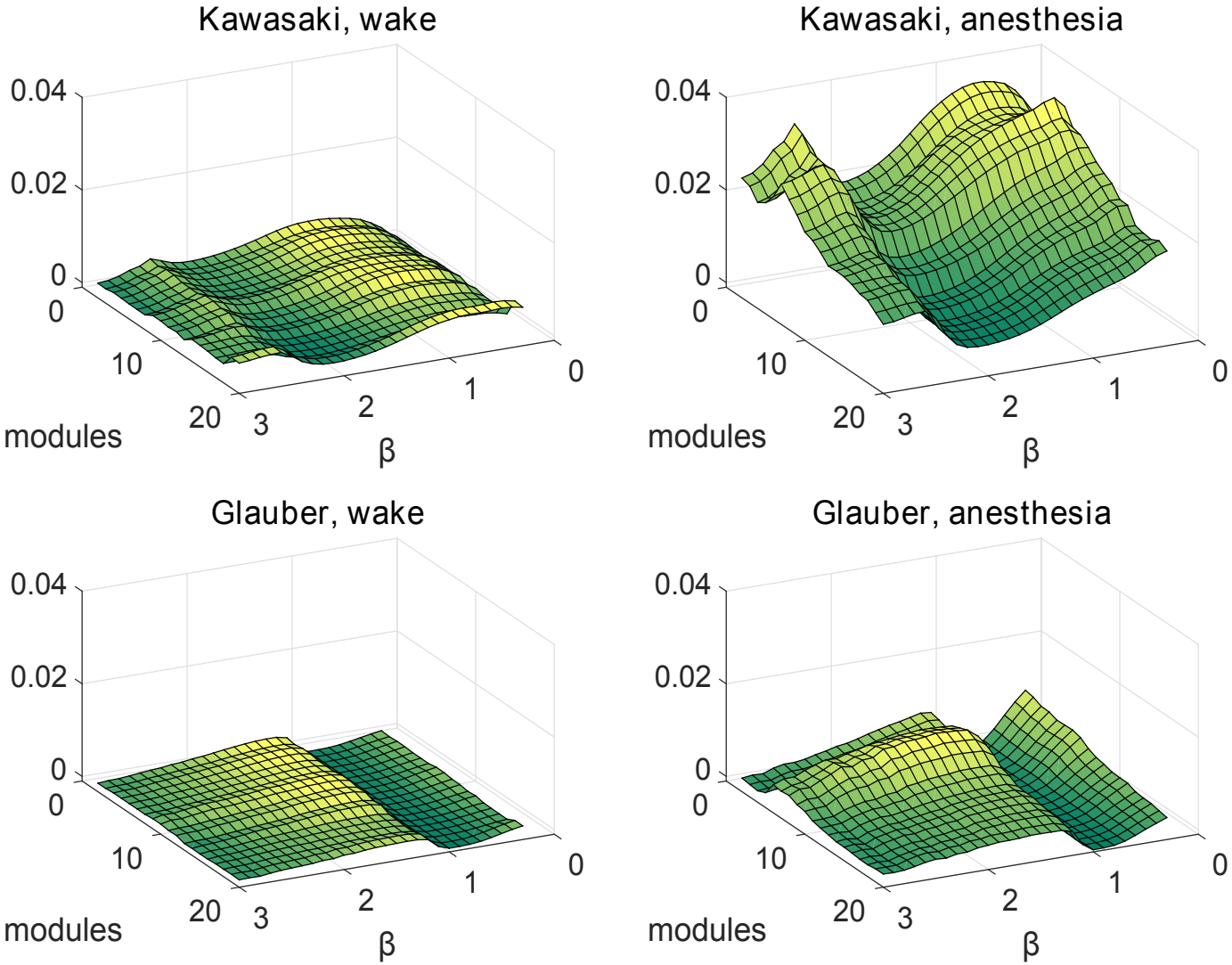
The idea is that the efficient organization in the brain is mapped by anatomically segregated subnetworks, connected to each other giving rise to complex function.

Cross-modularity: looking for a common skeleton

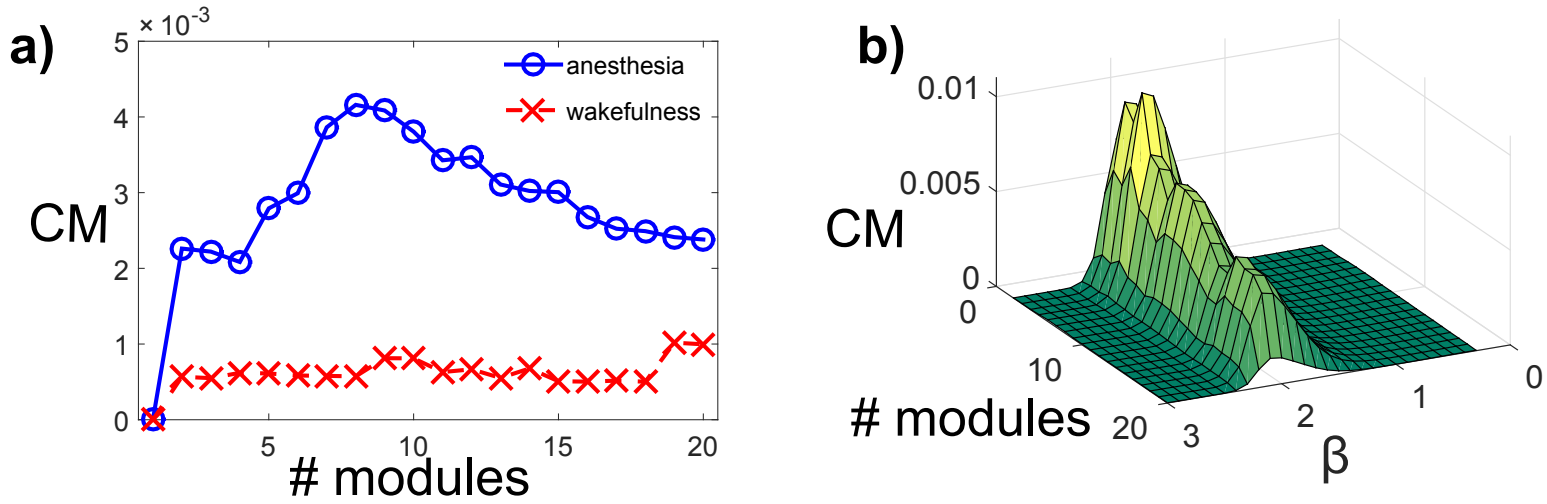


Diez et al., Sci Rep 2015

The conserved dynamics maximizes cross-modularity between simulated and empirical dynamics in anesthesia

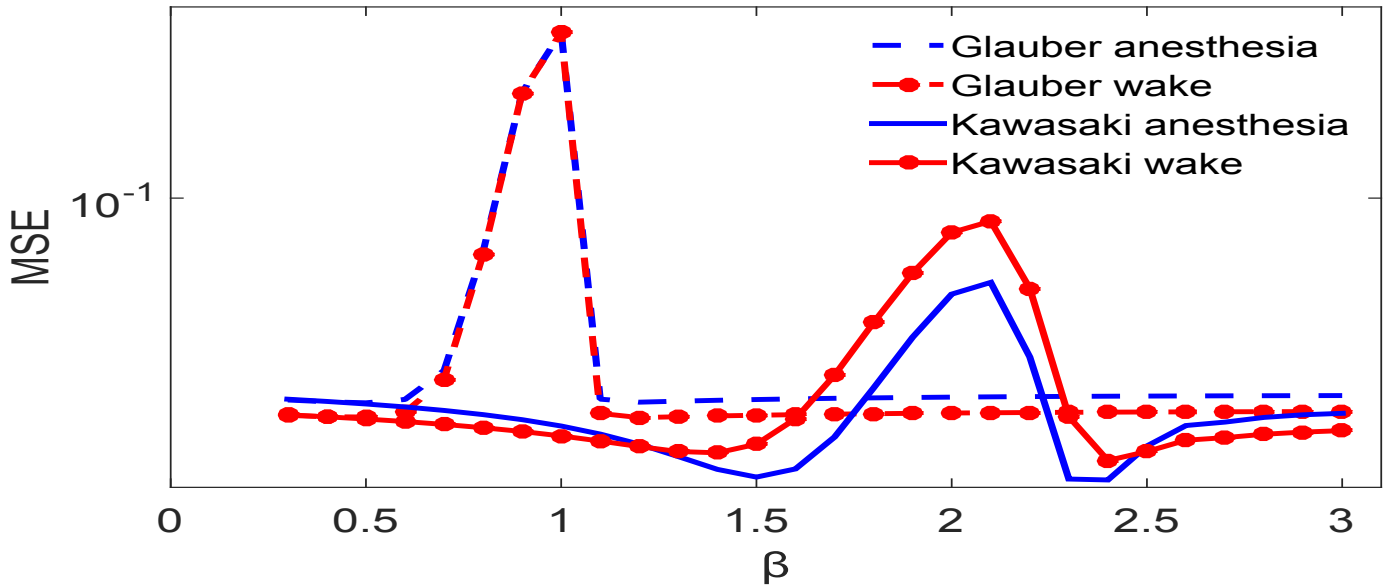


Anesthesia shapes the cross-modularity between structure and function in real data



and between structure and simulated data.

At criticality the distance between model and empirical data is maximized



When the dynamical repertoire is maximized, the underlying structure is forgotten.

At criticality most evident properties are preserved, but looking for a link-to-link correspondence between structure and function makes little sense

Conclusions

- The total amount of information transfer is maximized at criticality when Ising model is connected according to the brain connectome
- Under anesthesia the cross-modularity between structure and function is maximized
- Conserving the magnetization (activity) leads to a better fit with real data, in particular under anesthesia
- At the peak of criticality the pattern of functional correlations are minimally shaped by the structural underlying network

Thanks to

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