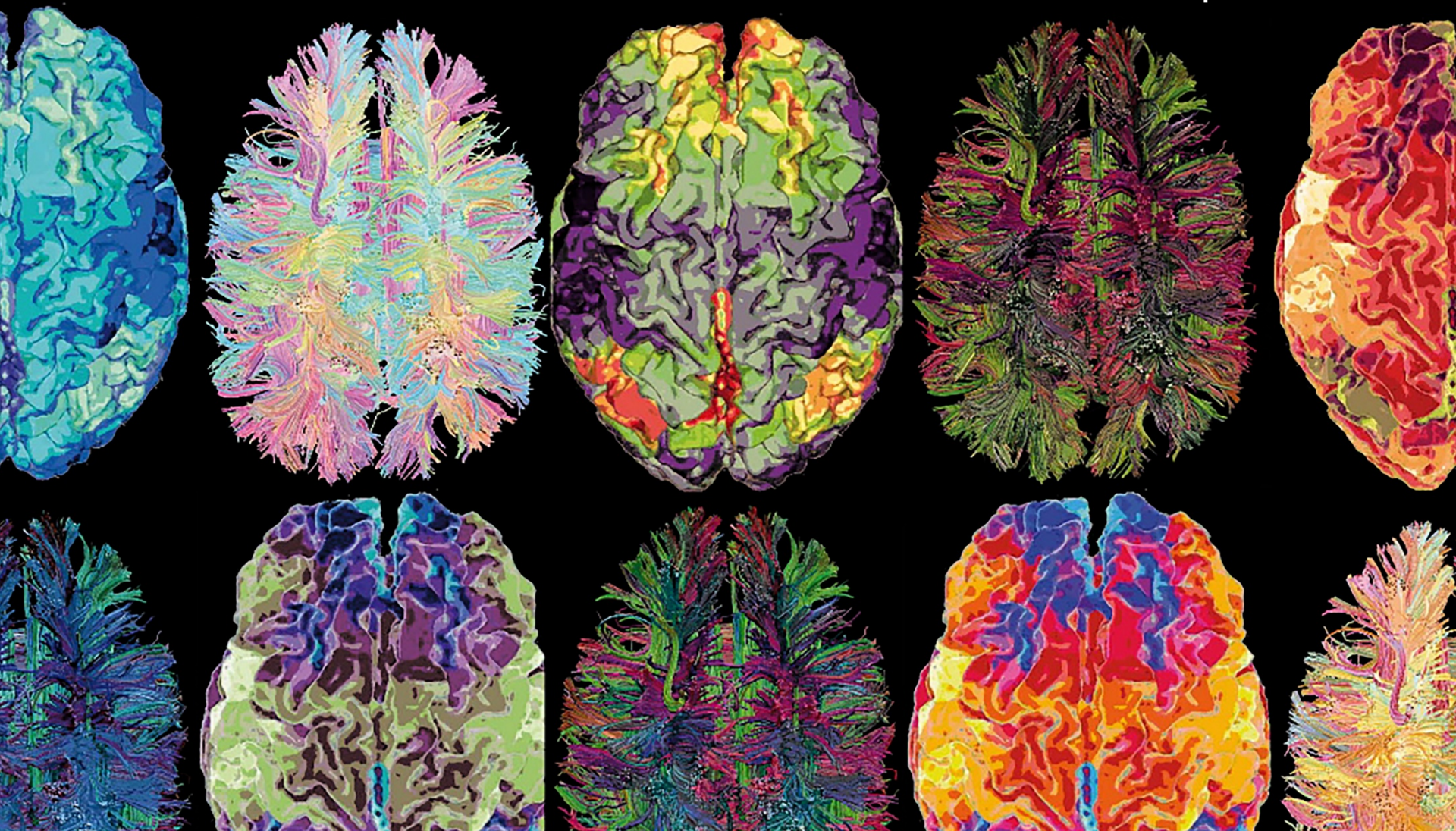
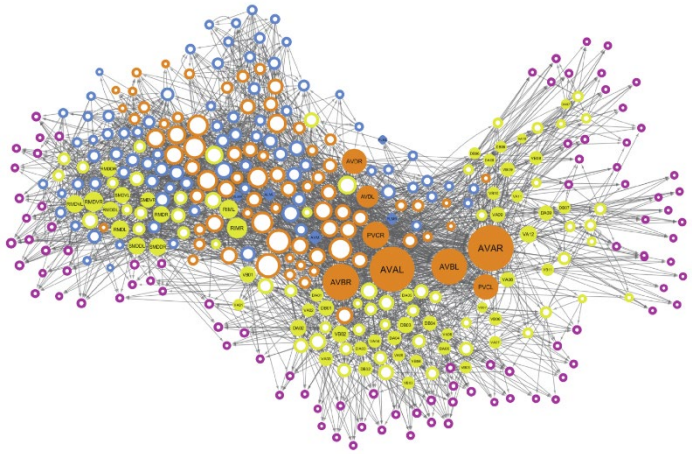
Brain Networks: Structural and Dynamic Substrates of Cognitive Architectures?

VISCA – 06/09/2021

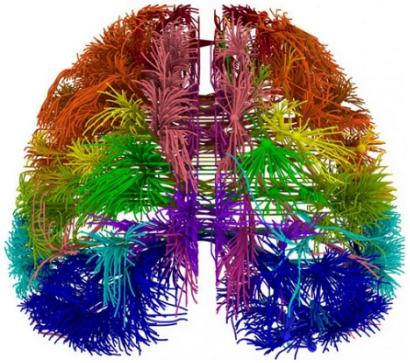
Olaf Sporns



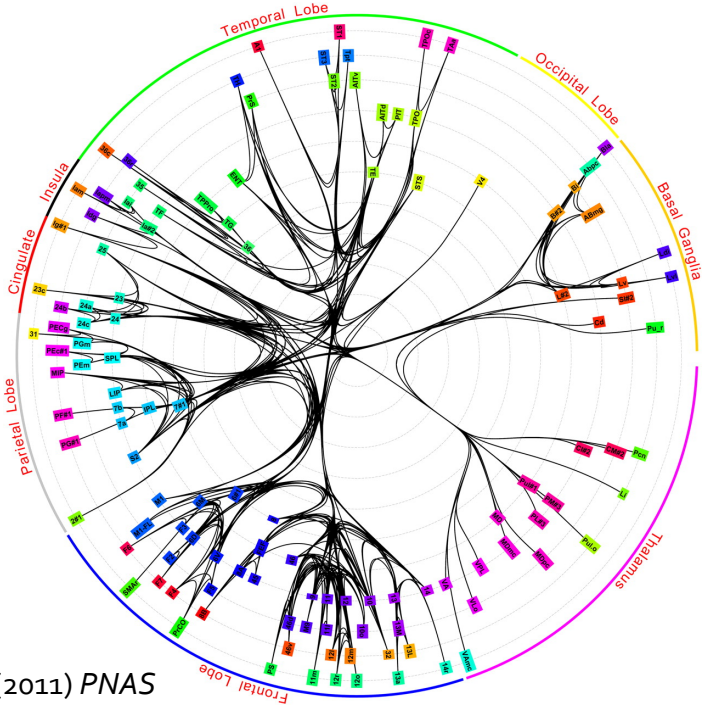
Brain Networks



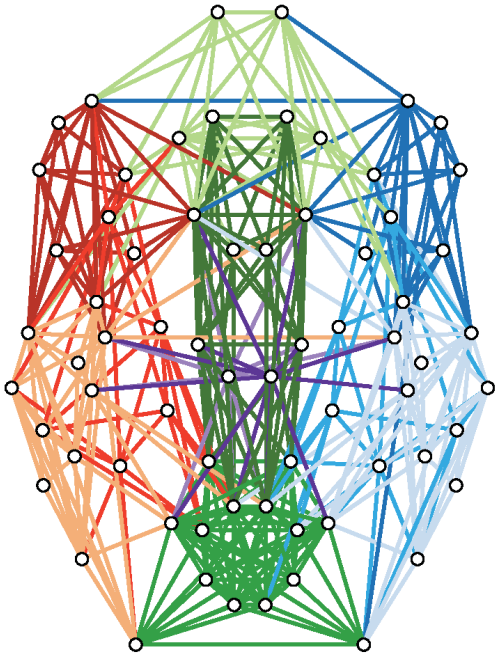
Emma Towlson



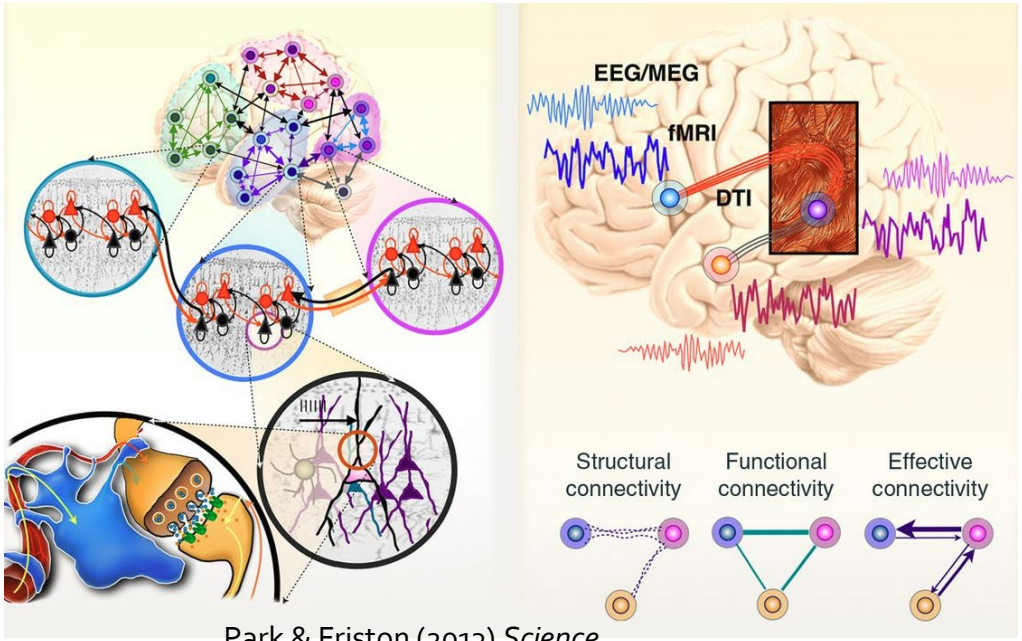
Allen Institute



Modha & Singh (2011) *PNAS*

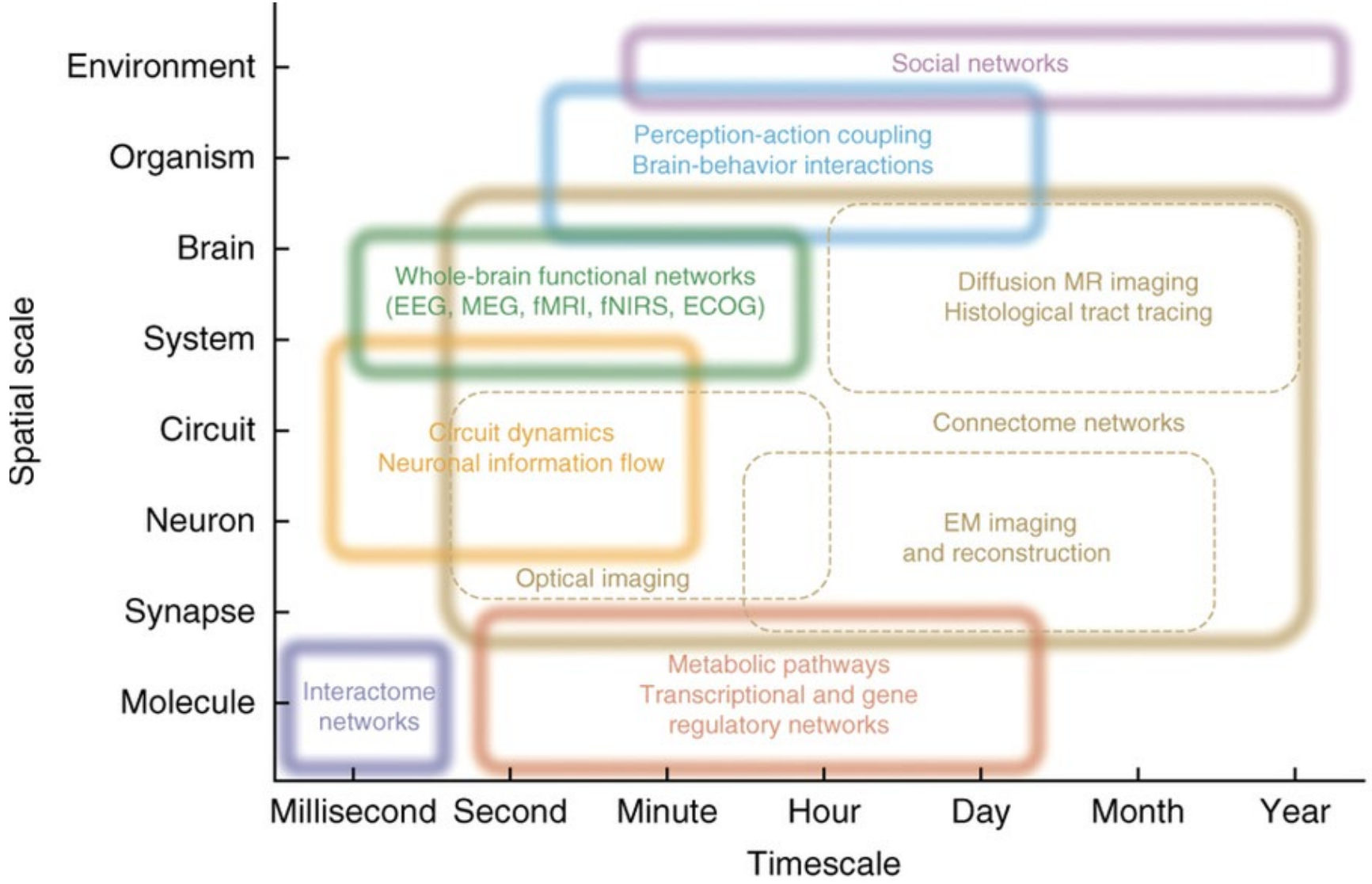


de Reus et al (2014) *Phil Trans R Soc*



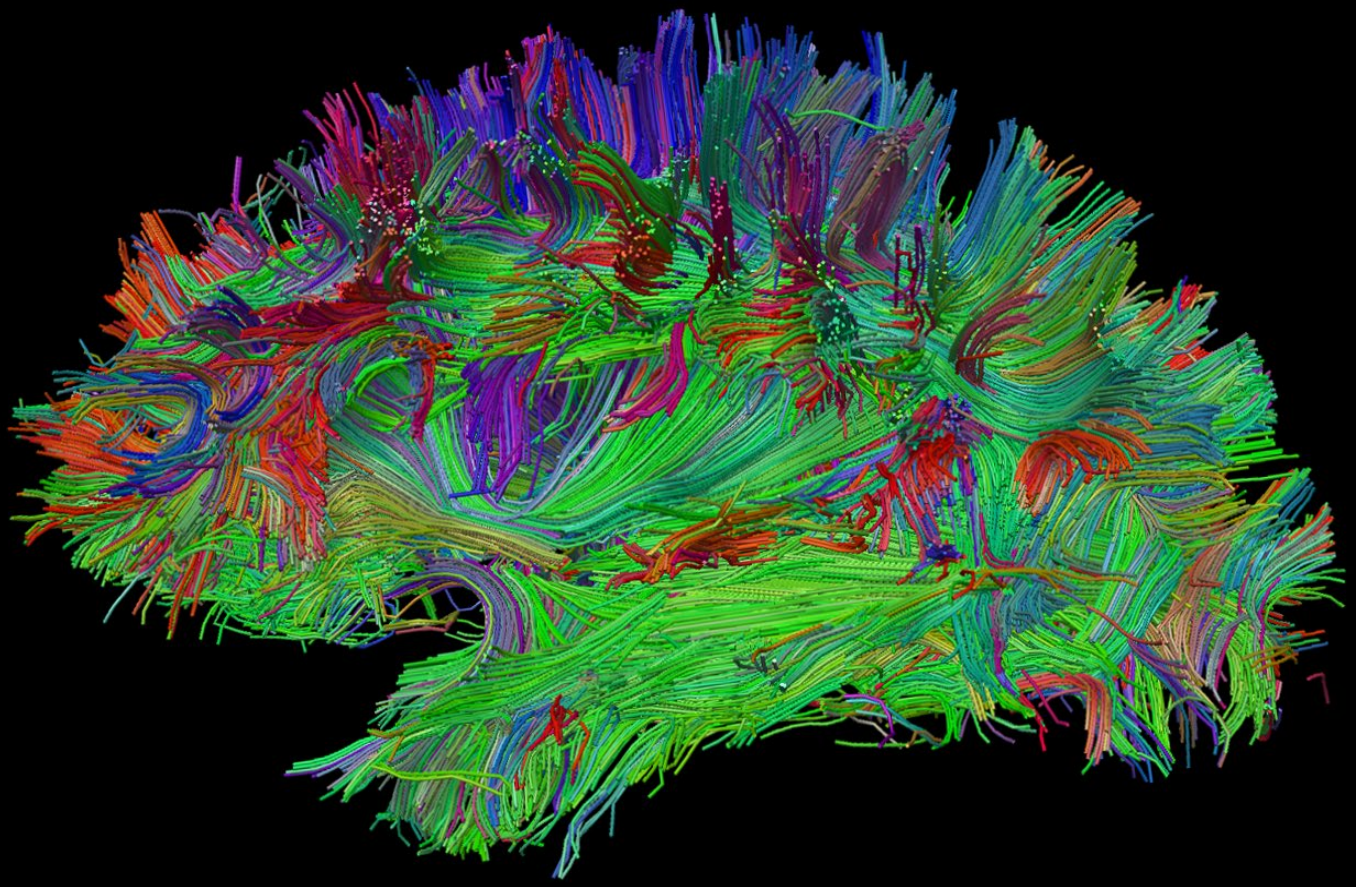
Park & Friston (2013) *Science*

Network Neuroscience



Bassett & Sporns (2017) *Nature Neuroscience* 20, 353

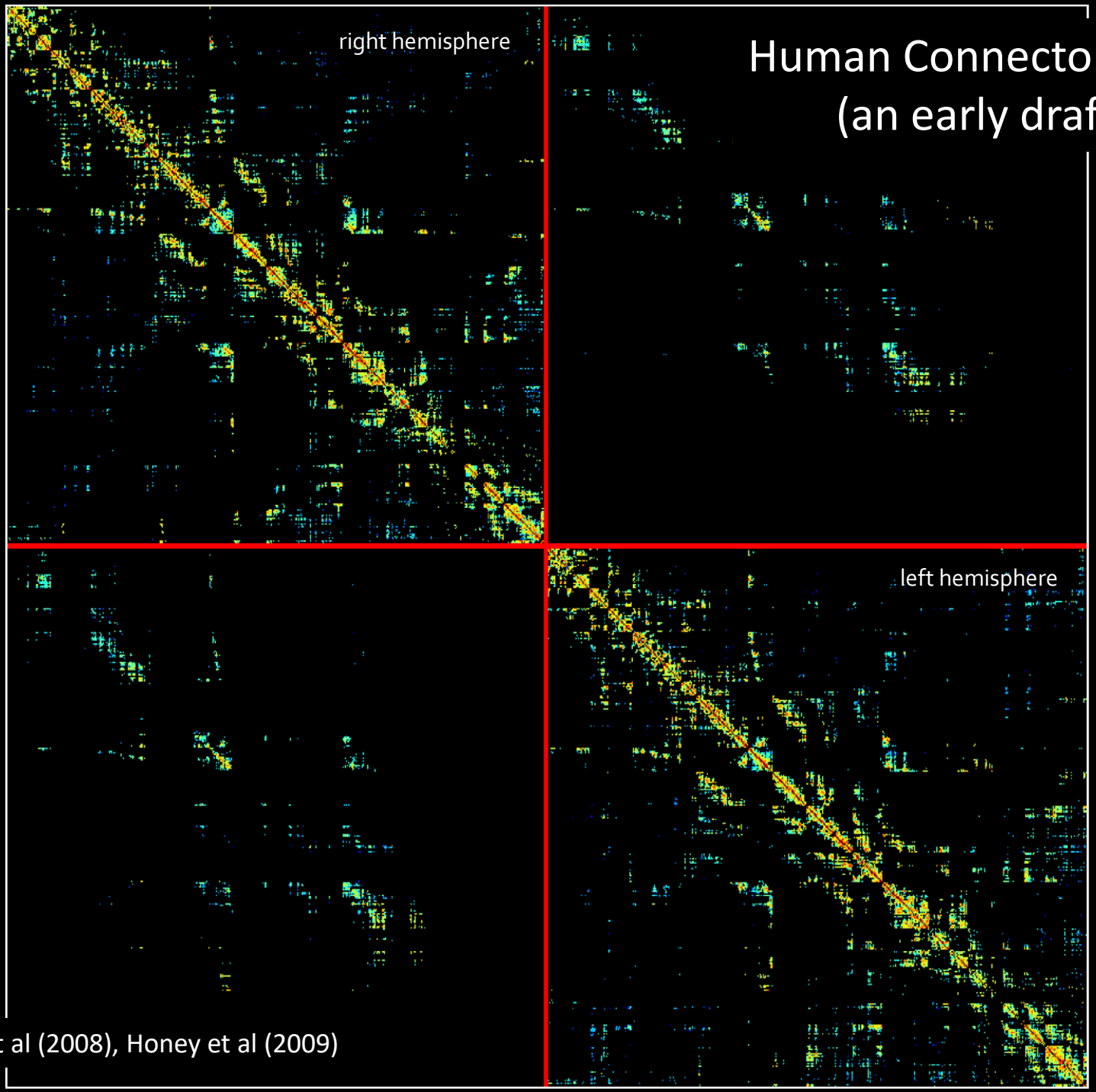
Changing Views of Human Brain Anatomy



Ludwig Klingler - 1956

Patric Hagmann - 2008

Human Connectome (an early draft)

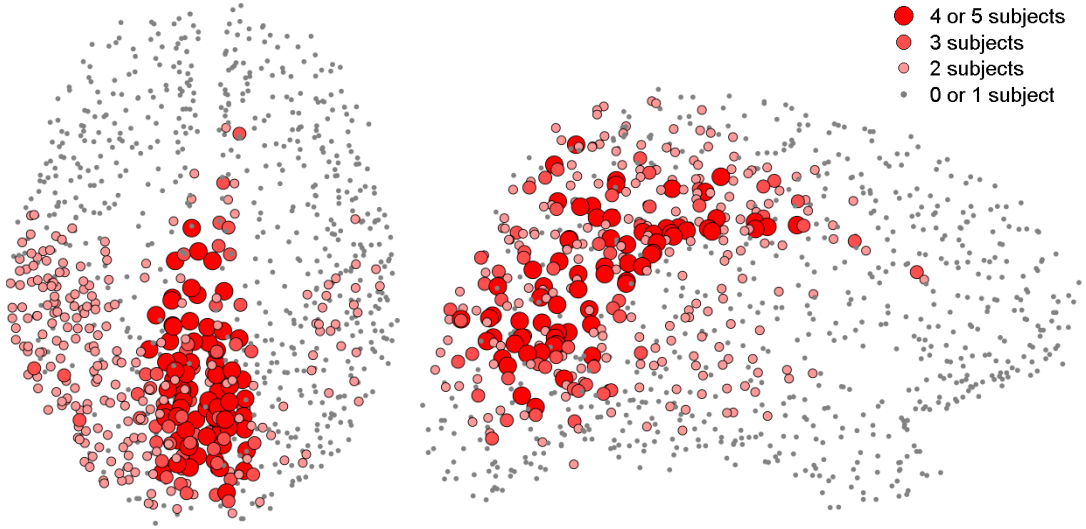


Hagmann et al (2008), Honey et al (2009)

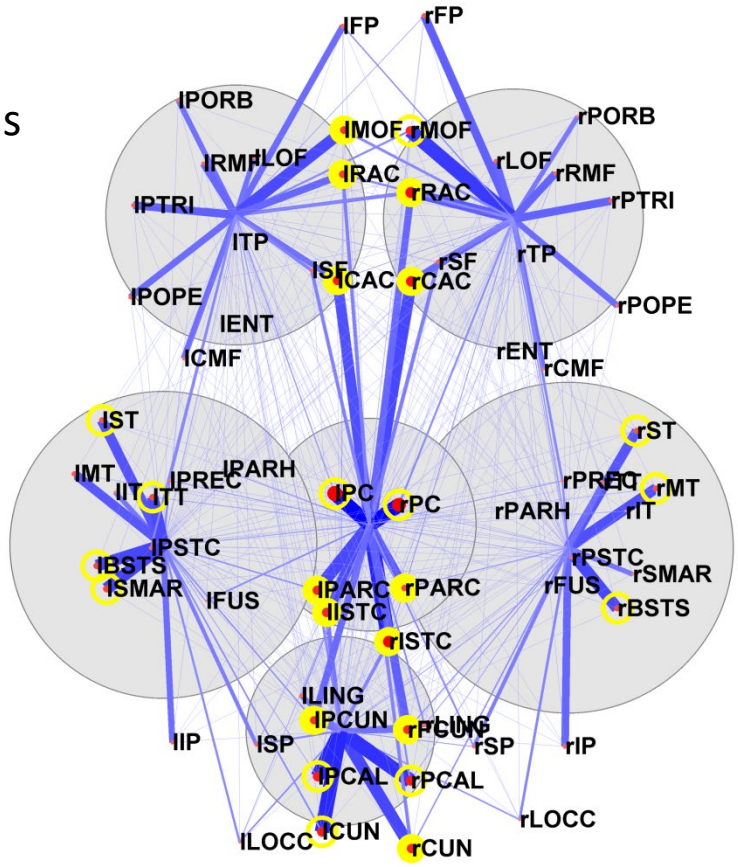
Network Analysis of the Human Connectome

Prominent network attributes of the human connectome (Hagmann et al. 2008)

- Unique regional connectivity fingerprints
- Broad (log-normal?) degree distribution
- High clustering, short path length
- Existence of modules interlinked by hub regions
- A prominent structural core



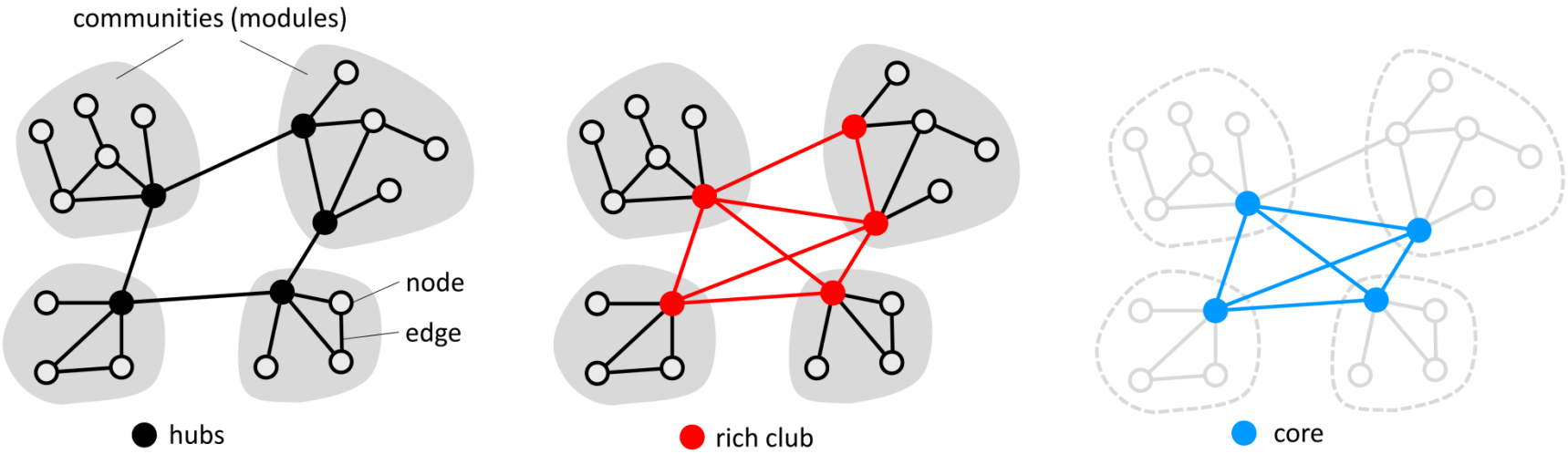
core



modules

Modules, Cores and Rich Clubs

In some networks, highly connected/central hub nodes have a tendency to be highly connected to each other ("rich-club" organization).



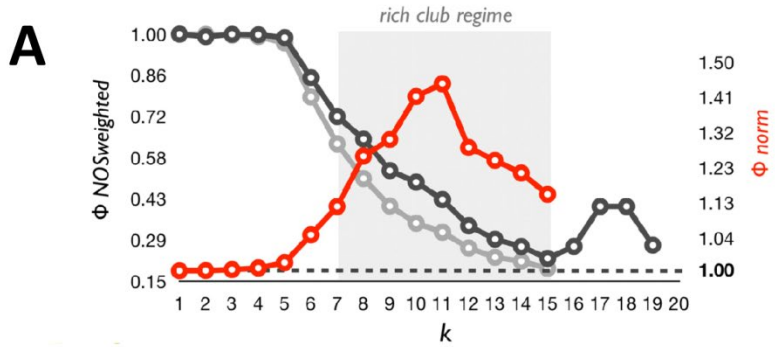
Hubs, cores and rich clubs may play important roles in global communication:

- By creating short (efficient) paths
- By supporting integration of information across diverse brain systems

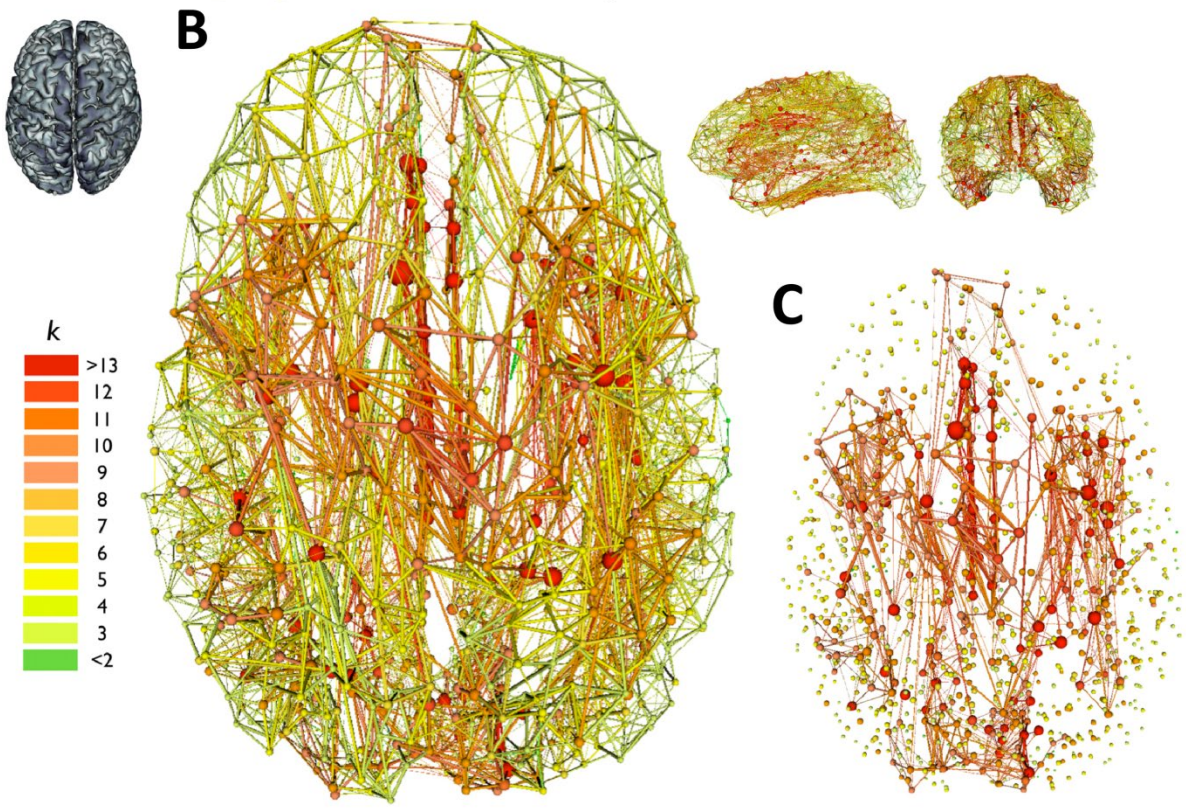
Colizza et al. (2006) *Nature Physics* 2, 110.

Bullmore & Sporns (2012) *Nature Rev. Neurosci.* 13, 336.

Rich-Club Organization of the Human Connectome



Martijn van den Heuvel



The human connectome exhibits rich club organization

High proportion (89%) of short communication paths travel trough at least one RC node (66% through an RC edge).

RC damage (node/edge deletion) has large effects on network integrity and efficiency.

van den Heuvel and Sporns (2011) *J. Neurosci*. 31, 15775.

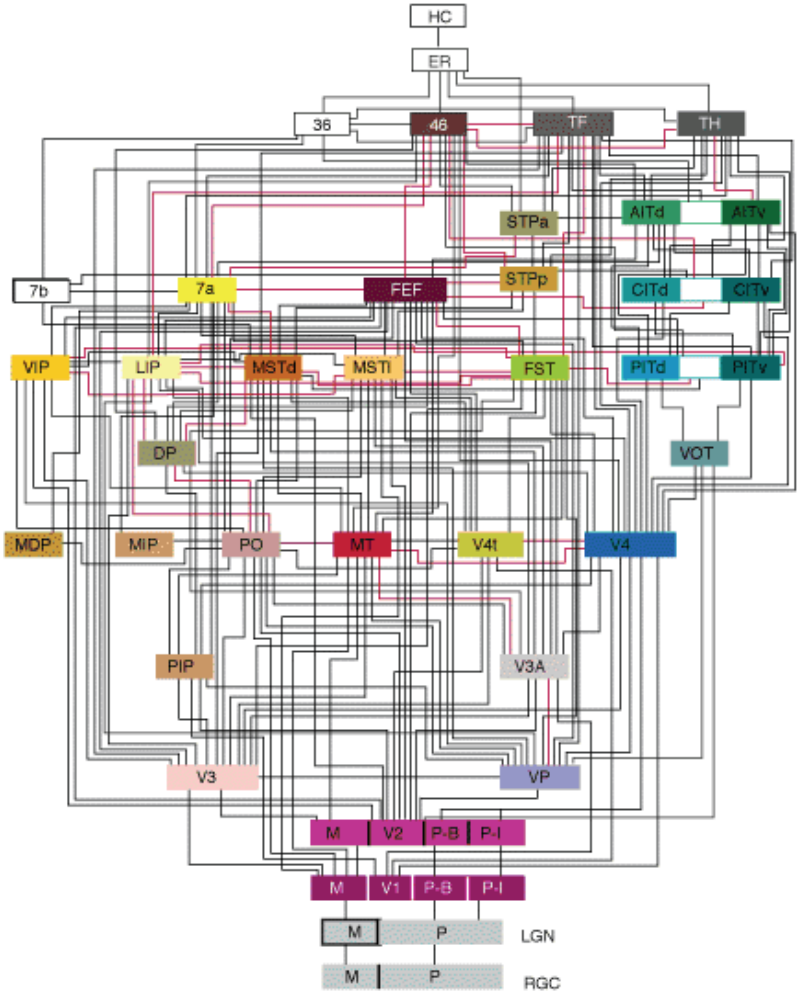
van den Heuvel et al (2012) *PNAS* 109, 11372.

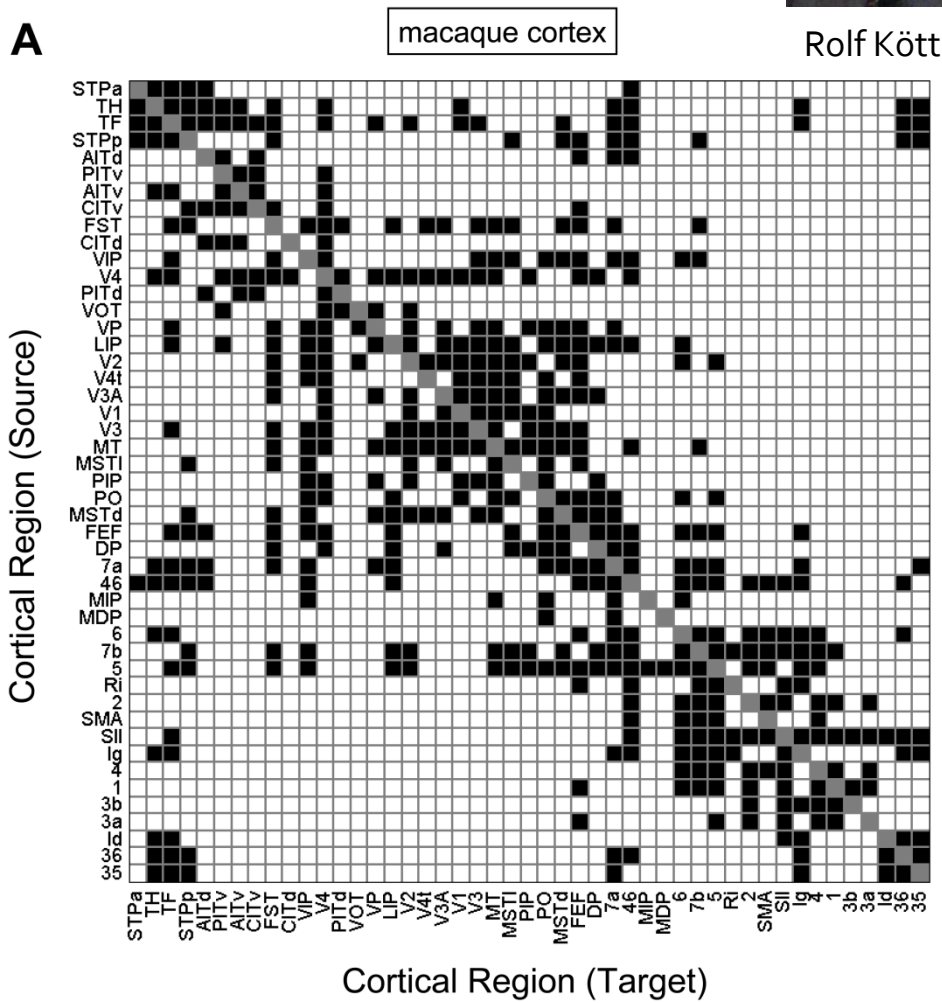
Comparative Connectomics

van den Heuvel, Bullmore, Sporns (2016) Trends Cogn Sci

Macaque Cortex

Rolf Kötter



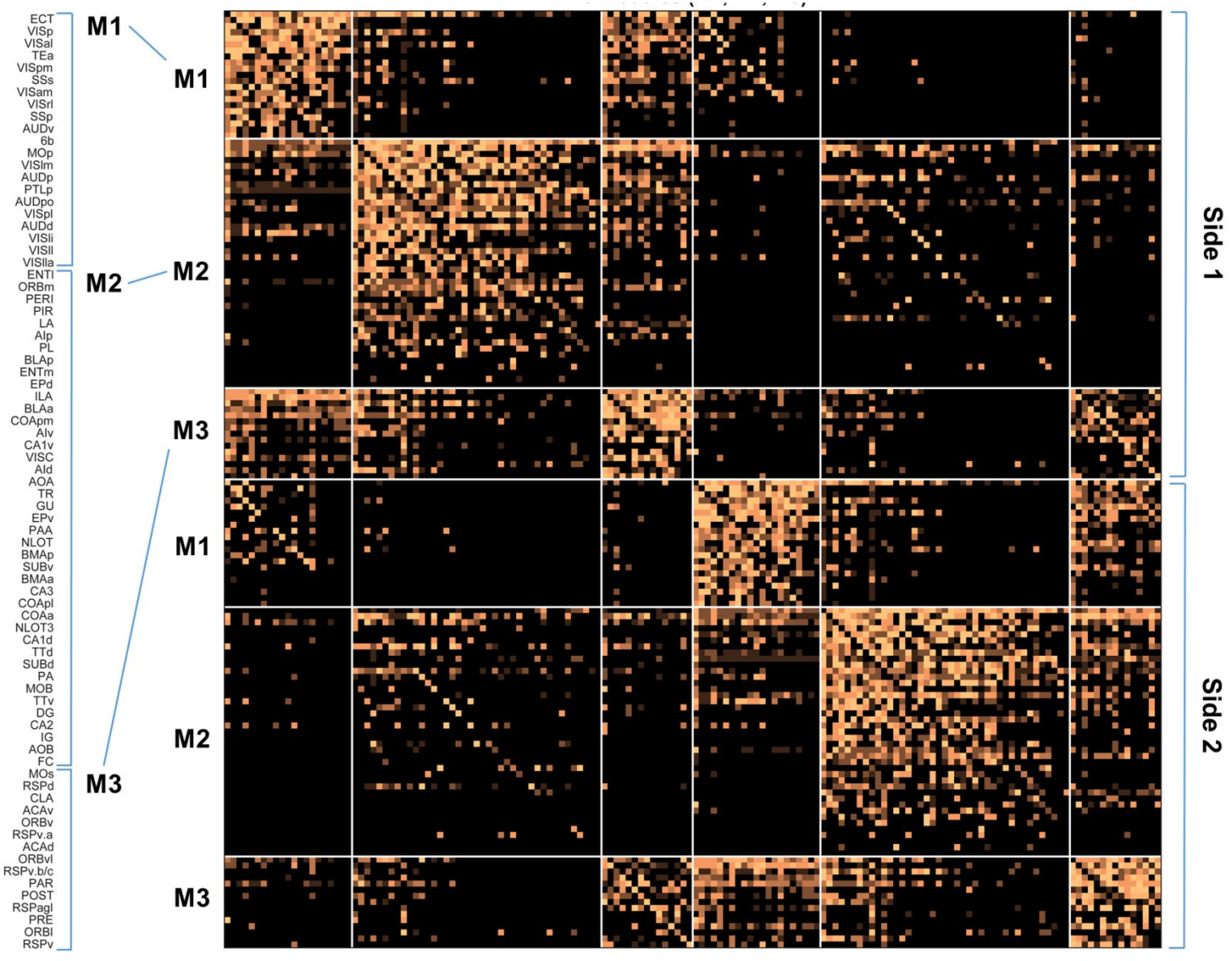


Felleman & van Essen (1991) *Cerebral Cortex*.

Sporns & Kotter (2004) *PLOS Biol*

Rat Cortex

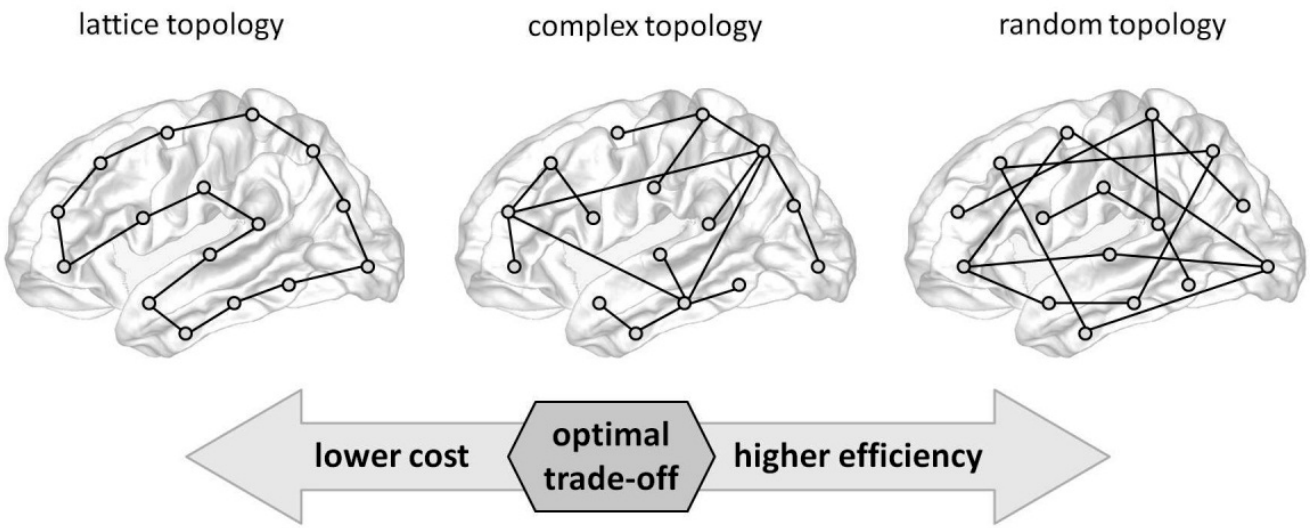
Larry Swanson



Modular organization

Swanson, Hahn, Sporns (2017) PNAS

Cost-Efficiency Trade-Off



Ed Bullmore

Two major driving forces shaping brain connectivity:

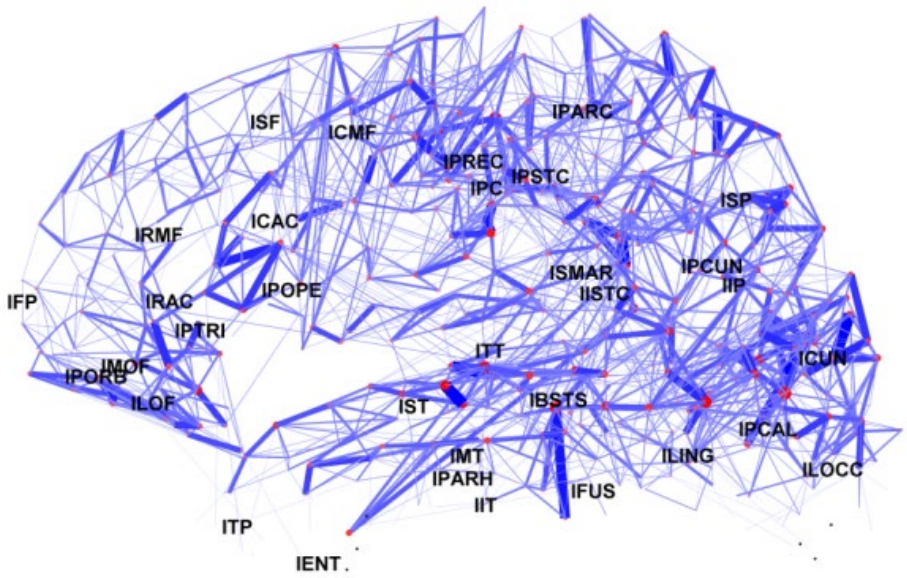
- Minimization of cost (wiring volume, energy use)
- Maximization of efficiency (communication, information flow)

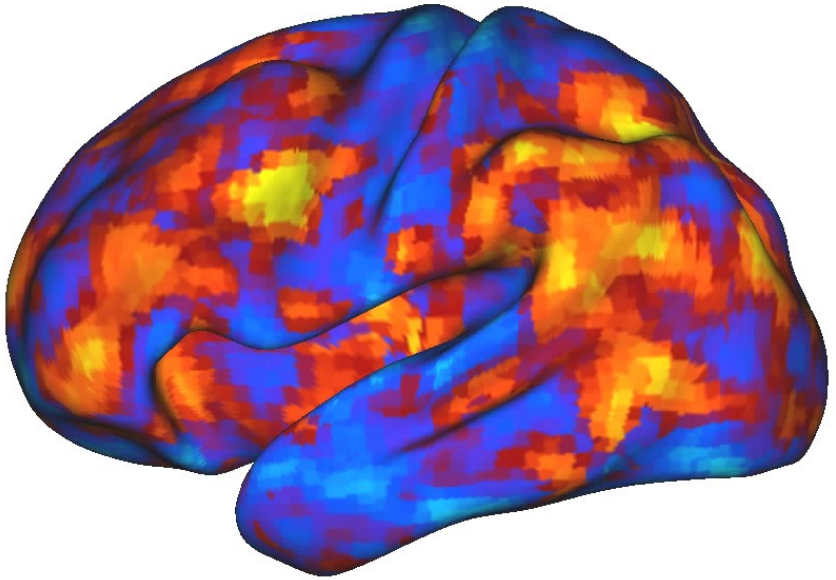
Cost minimization and efficiency maximization promote different network attributes.

Hypothesis: The architecture of brain networks represents an optimal trade-off between the competing demands of cost and efficiency.

Bullmore & Sporns (2012) *Nature Rev. Neurosci.* 13, 336.

Linking Anatomy and Dynamics





Hagmann et al. (2008)

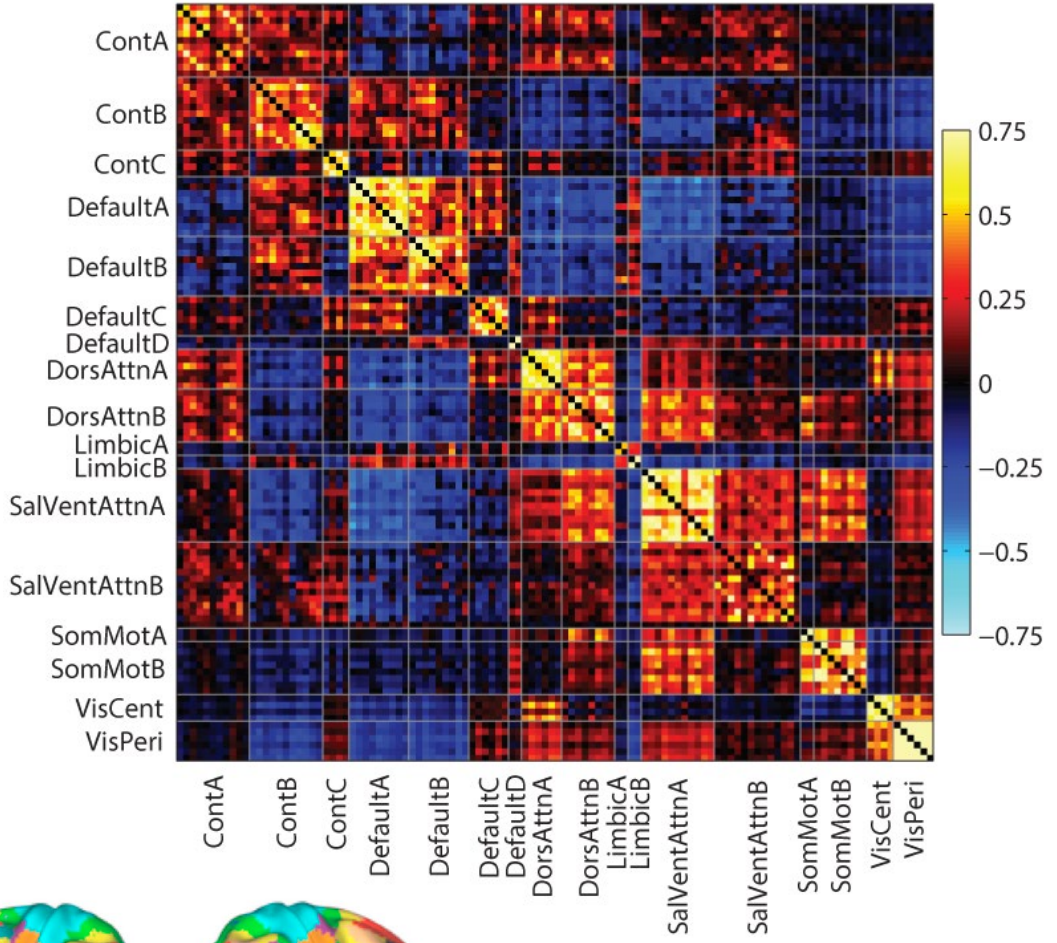
Vincent et al. (2007)

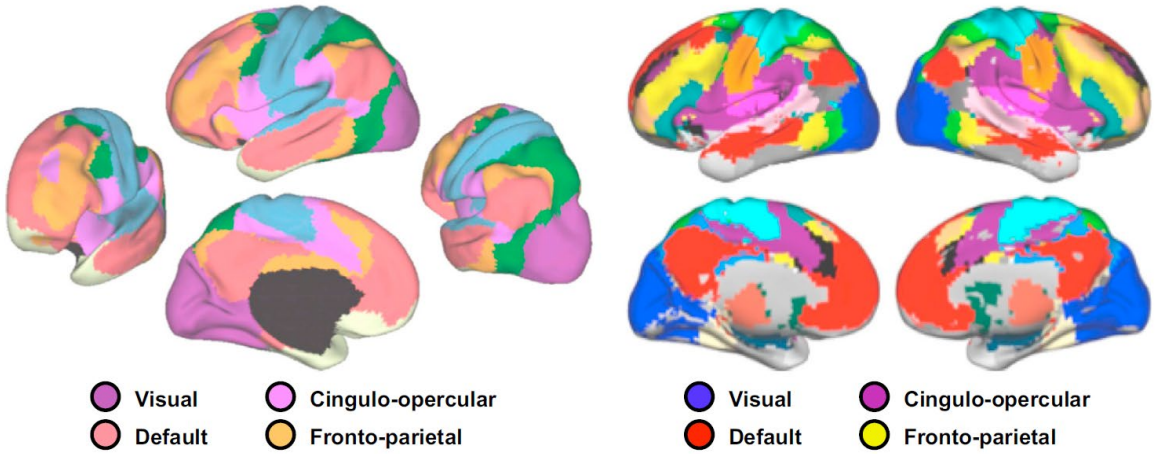
Structural Connectivity ? Functional Connectivity

Resting-State Networks

Patterns of coherent brain activity during extended periods of resting-state: "resting-state networks" (functional brain modules)…

Betzel et al. (2014) Neuroimage 102, 345

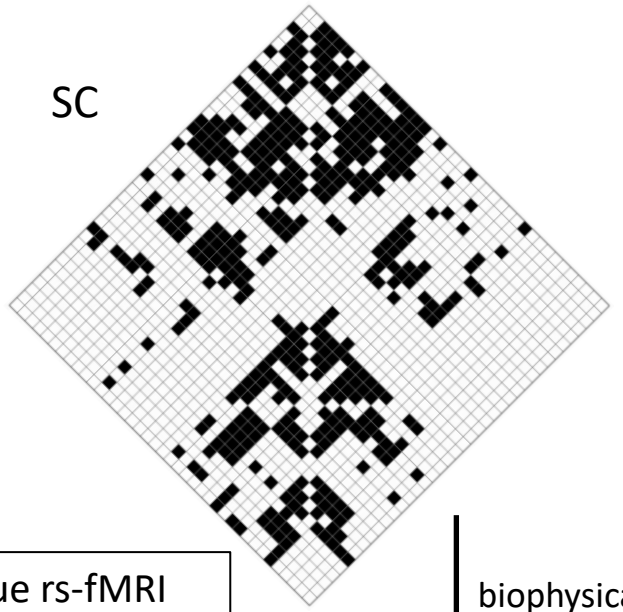




Power et al. (2011) Neuron
Yeo et al. (2011) J Neurophysiol.
Petersen & Sporns (2015) Neuron

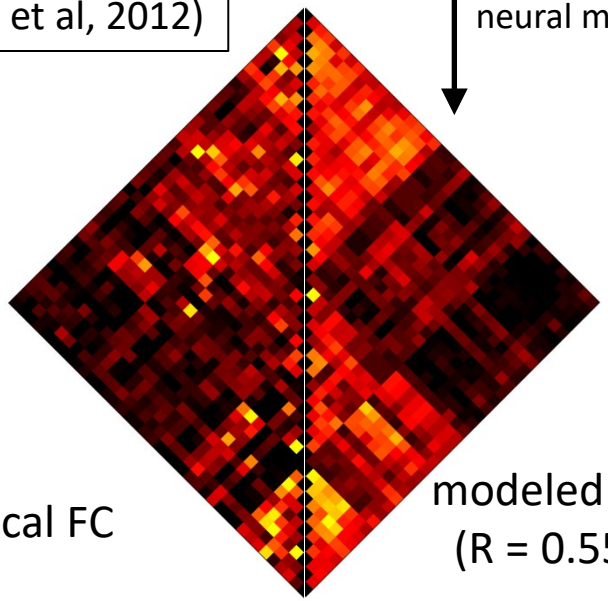
Generative Models for Functional Networks

Structural connectivity (SC) constrains & shapes functional connectivity (FC)



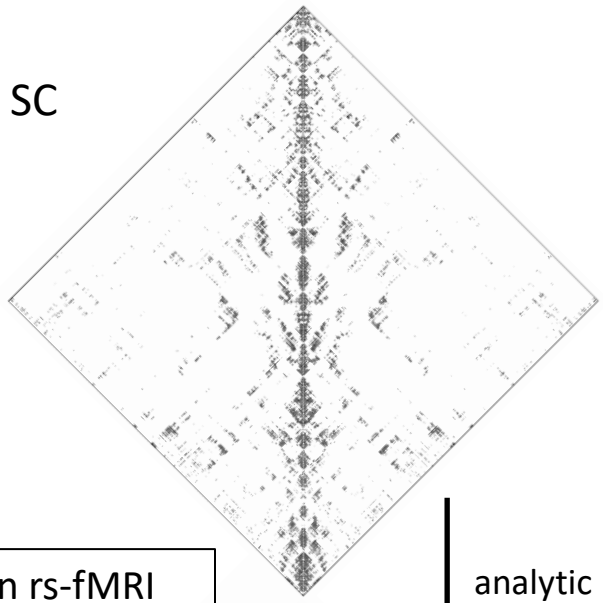
macaque rs-fMRI
(Adachi et al, 2012)

biophysical
neural model



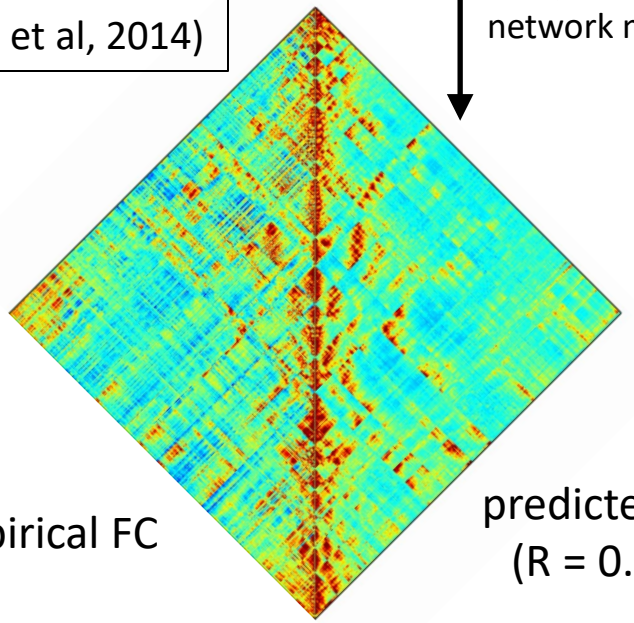
empirical FC

modeled FC
(R = 0.55)



Human rs-fMRI
(Goni et al, 2014)

analytic
network model



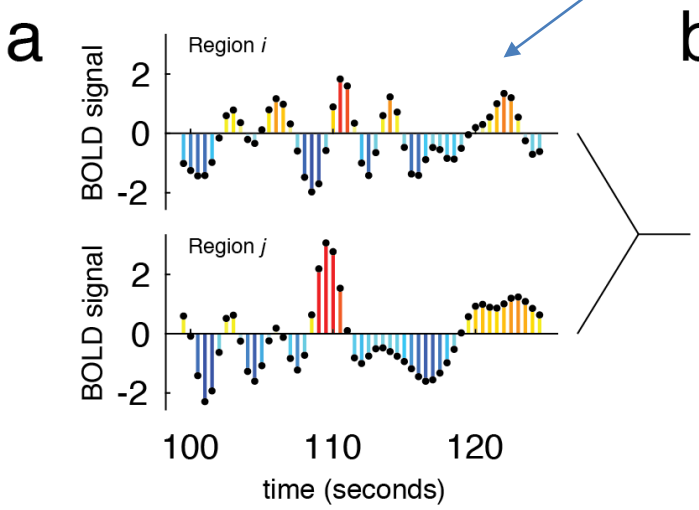
empirical FC

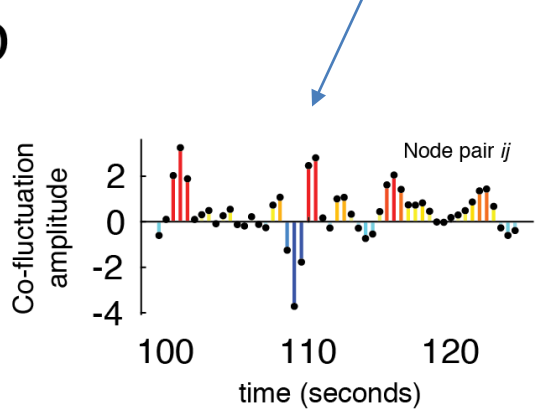
predicted FC
(R = 0.60)

Going from Nodes to Edges

"Classic" fMRI functional connectivity is based on similarity of (node-based) activation patterns (Pearson correlation of node time series)

Proposal: "edge functional connectivity" based on similarity of (edge-based) co-fluctuation patterns (Pearson correlation of edge time series)





Classic FC is the average of this edge time series

Josh Faskowitz

Rick Betzel

Farnaz Zamani Esfahlani

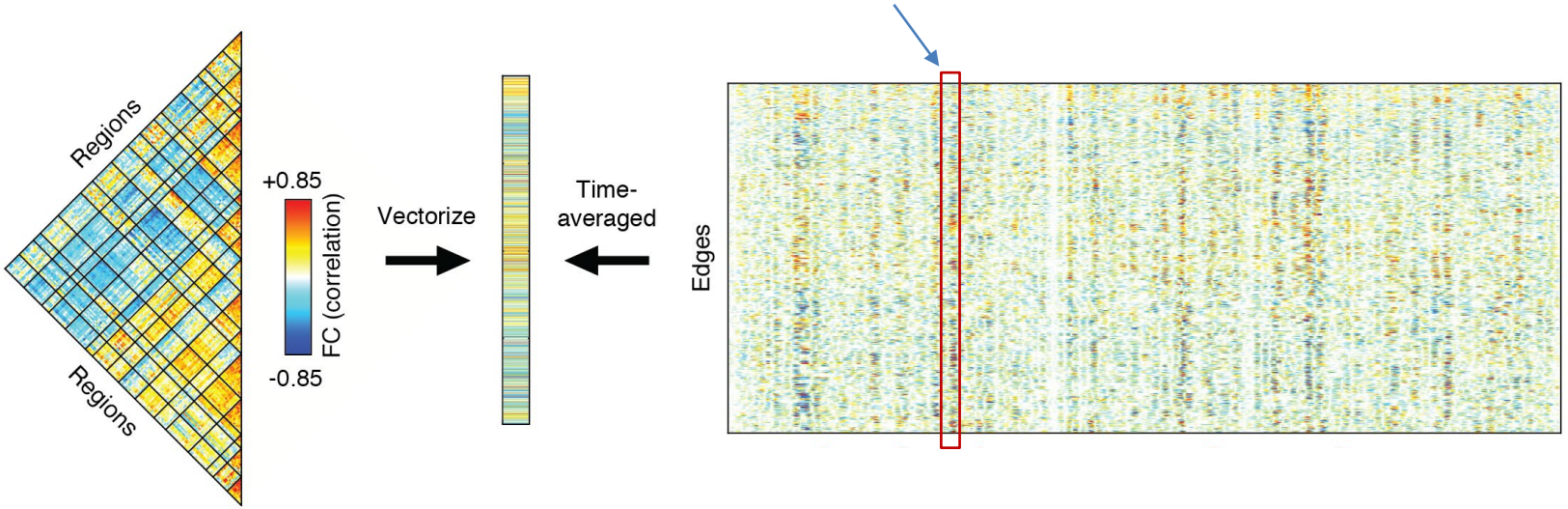
Youngheun Jo

Faskowitz et al (2020) Nature Neuroscience

Esfahlani et al (2020) PNAS

High-Resolution fMRI Dynamics

Edge time series deliver moment-to-moment co-fluctuations

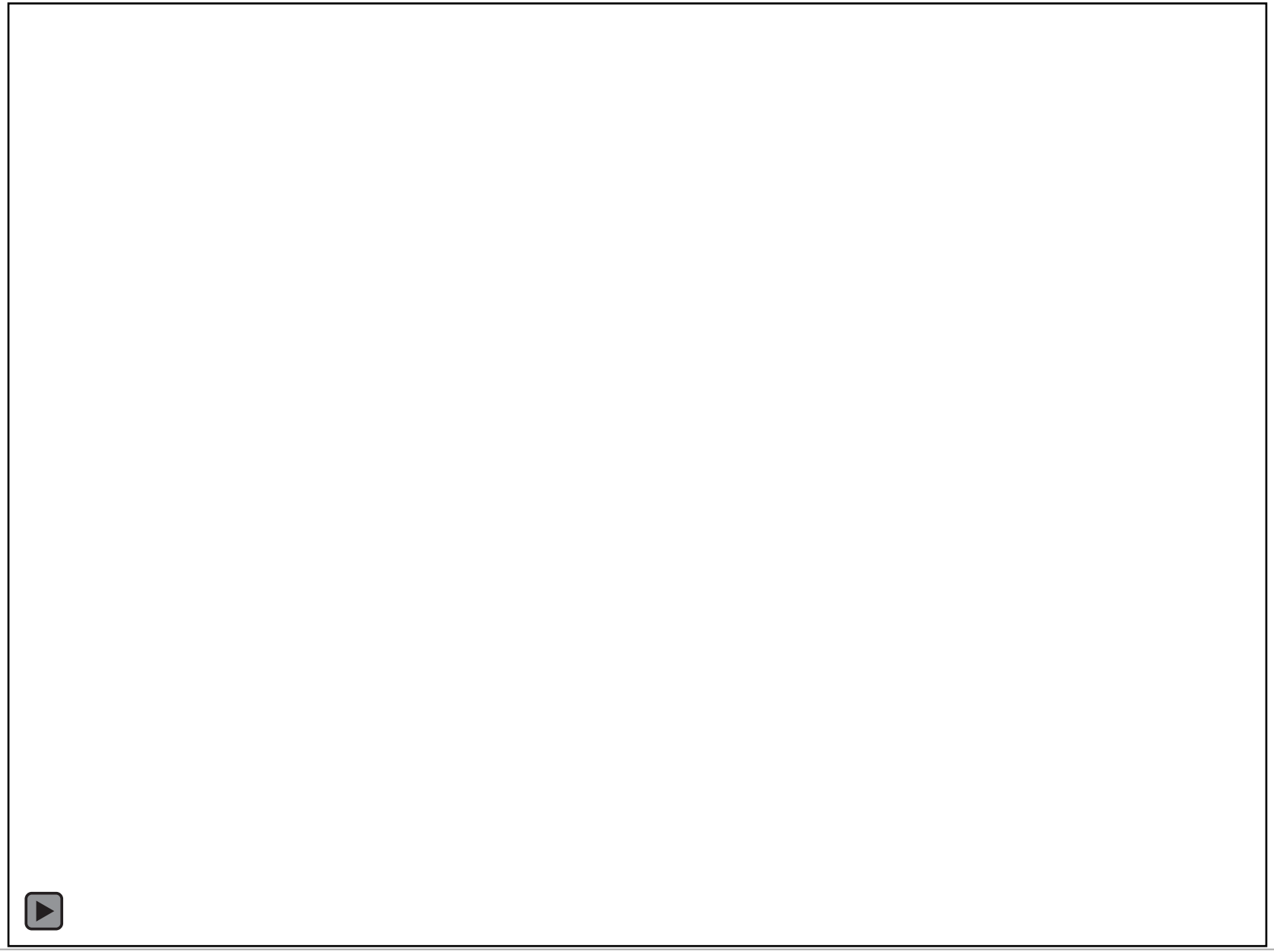


Edge time series exhibit “bursty” behavior (events)

…unrelated to head motion or cardiac/respiratory cycles

Events are intermittent, short-lasting, present in movie data, can be extracted from “standard” BOLD time series, and are present in all individuals

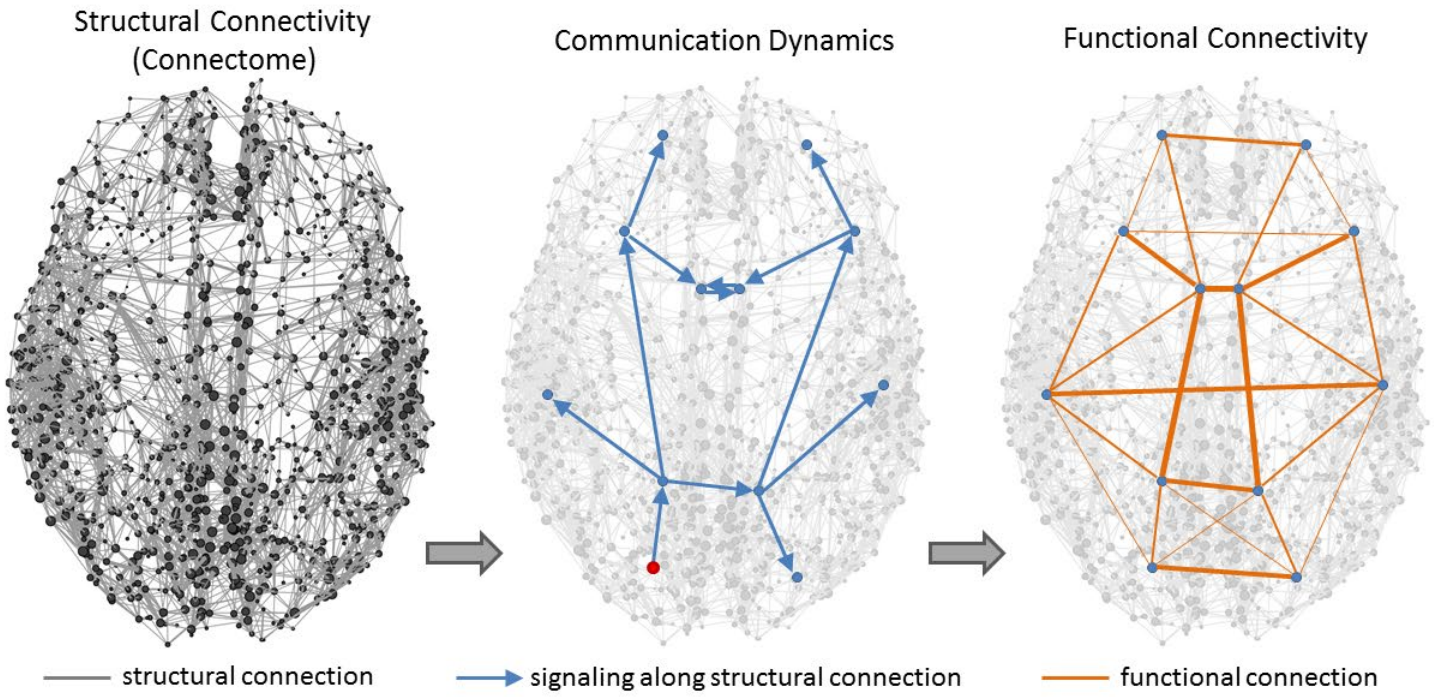
High-Resolution fMRI Dynamics



Faskowitz et al (2020) Nature Neuroscience Esfahlani et al (2020) PNAS Sporns et al (2021) Netw Neurosci

Networks Link Structure and Function

- Structural connectivity: anatomical links (weighted, directed, multi-scale)
- Communication dynamics: the spatiotemporal flow of communication events unfolding along structural connections
- Functional connectivity: expresses the effect of communication dynamics in statistical dependencies among time series



Avena-Koenigsberger, Misic, Sporns (2018) *Nature Rev Neurosci*

Cognition emerges from Brain Networks

Many Features of Brain Networks are shared across Species

Evolving Networks trade off Cost and Efficiency – Cognition is subject to same Constraints

Functional Connectivity (Rest and Task) is Dynamic and Flexible

NETWORK NEUROSCIENCE