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Mapping and Modeling Human Brain Networks

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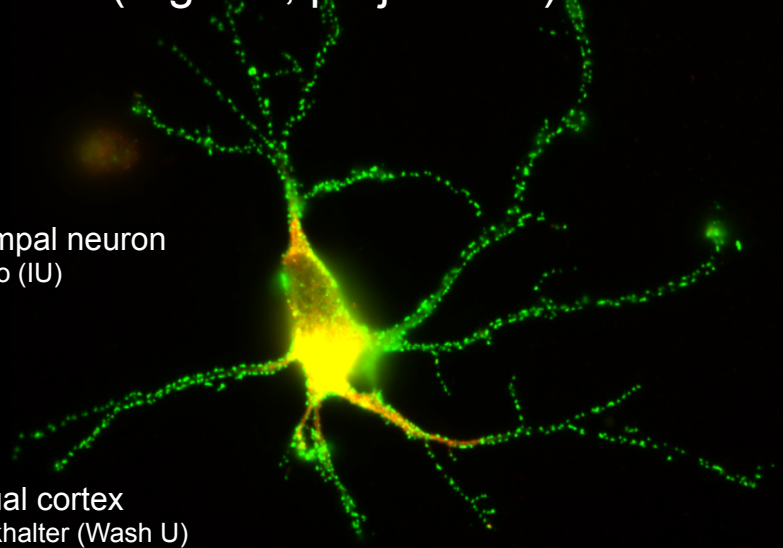
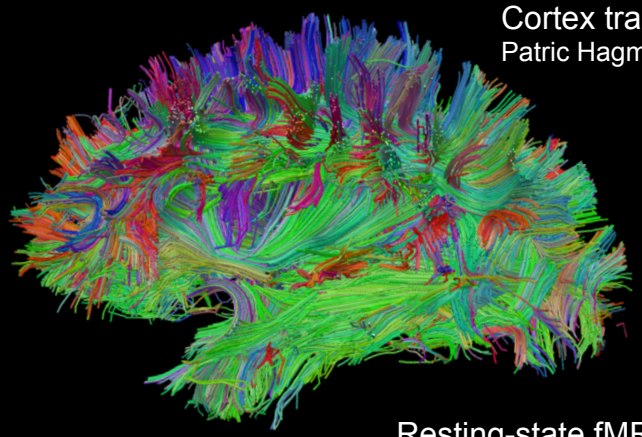
Neural Systems are Complex Networks

Networks across scales:
- micro (neurons, synapses)
- macro (regions, projections)

Networks across modes:
- structural (anatomical couplings)
- functional (dynamic interactions)

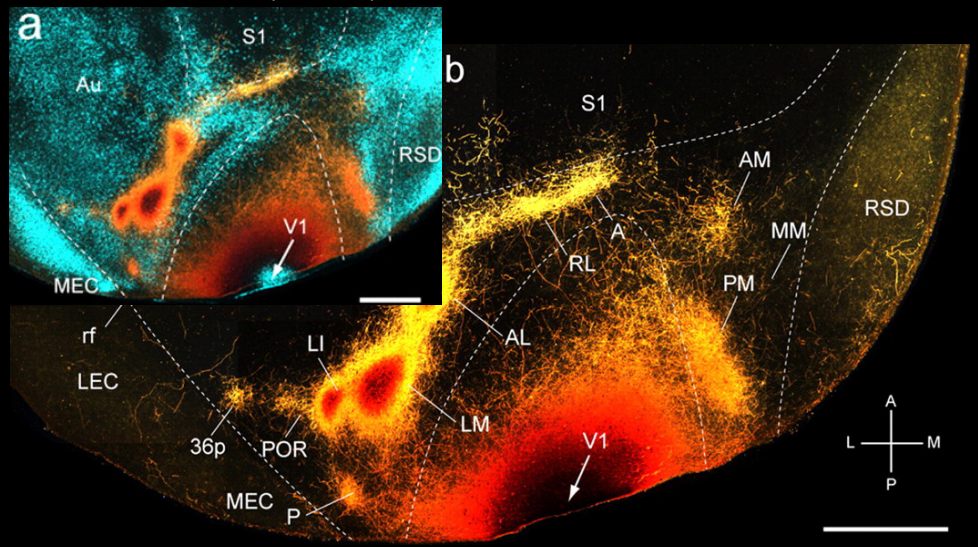


Hippocampal neuron
Anne Prieto (IU)

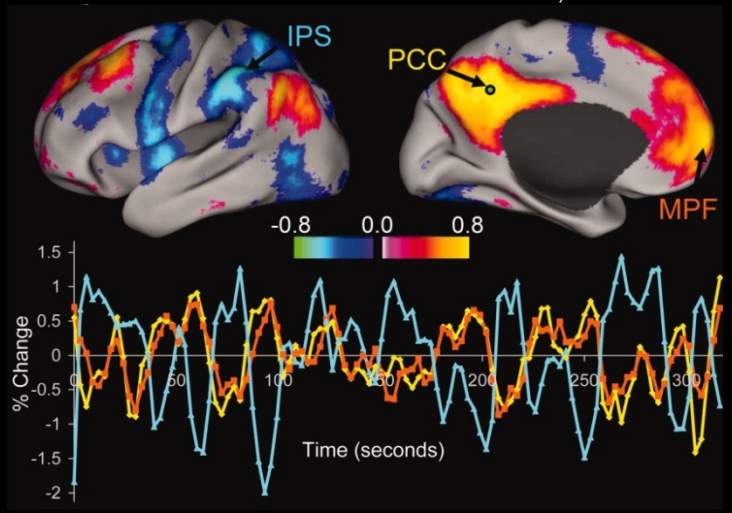


Cortex tractography
Patric Hagmann (EPFL)

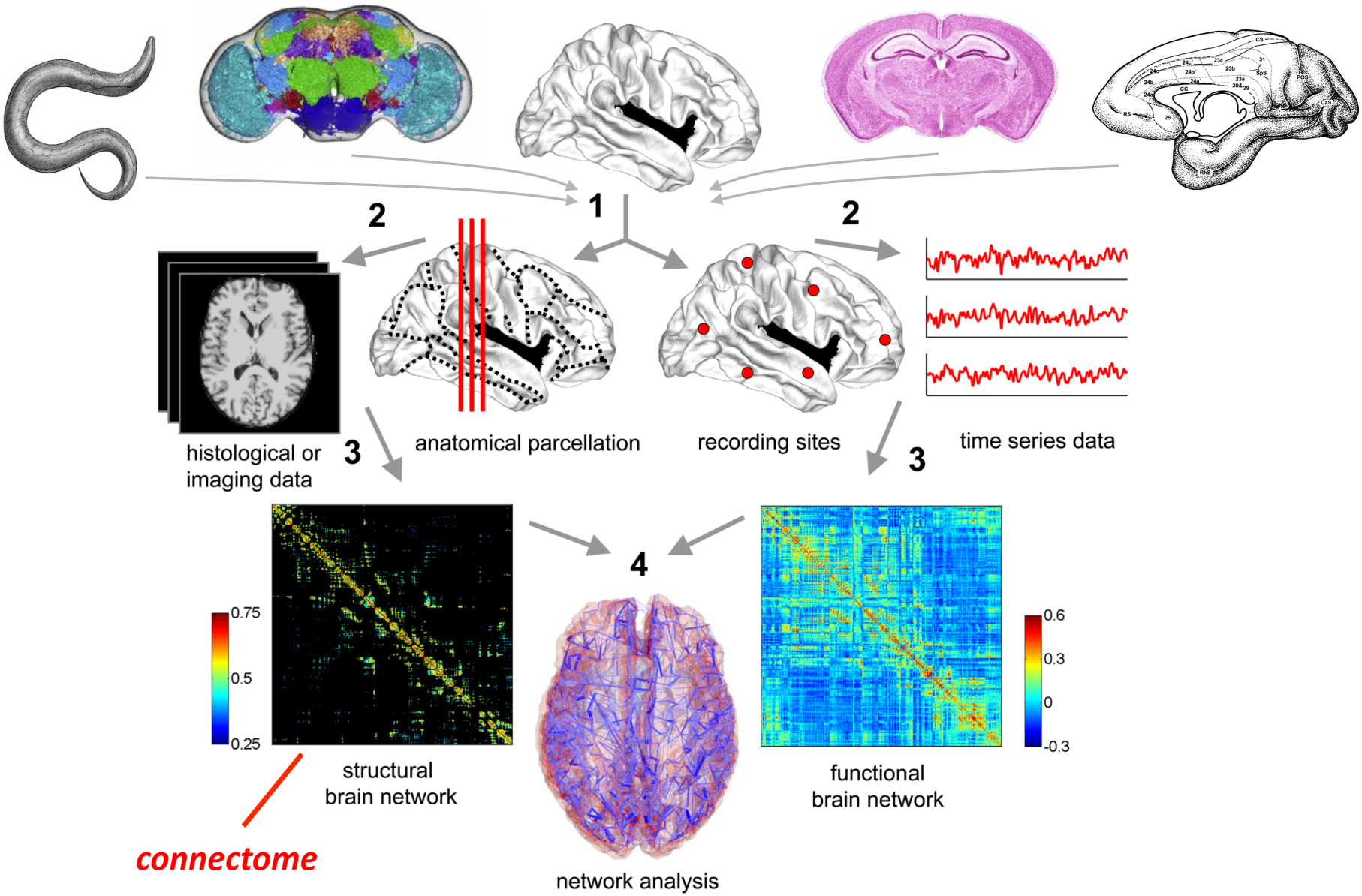
Mouse visual cortex
Andreas Burkhalter (Wash U)



Resting-state fMRI recording
Michael Fox, Marc Raichle (Wash U)

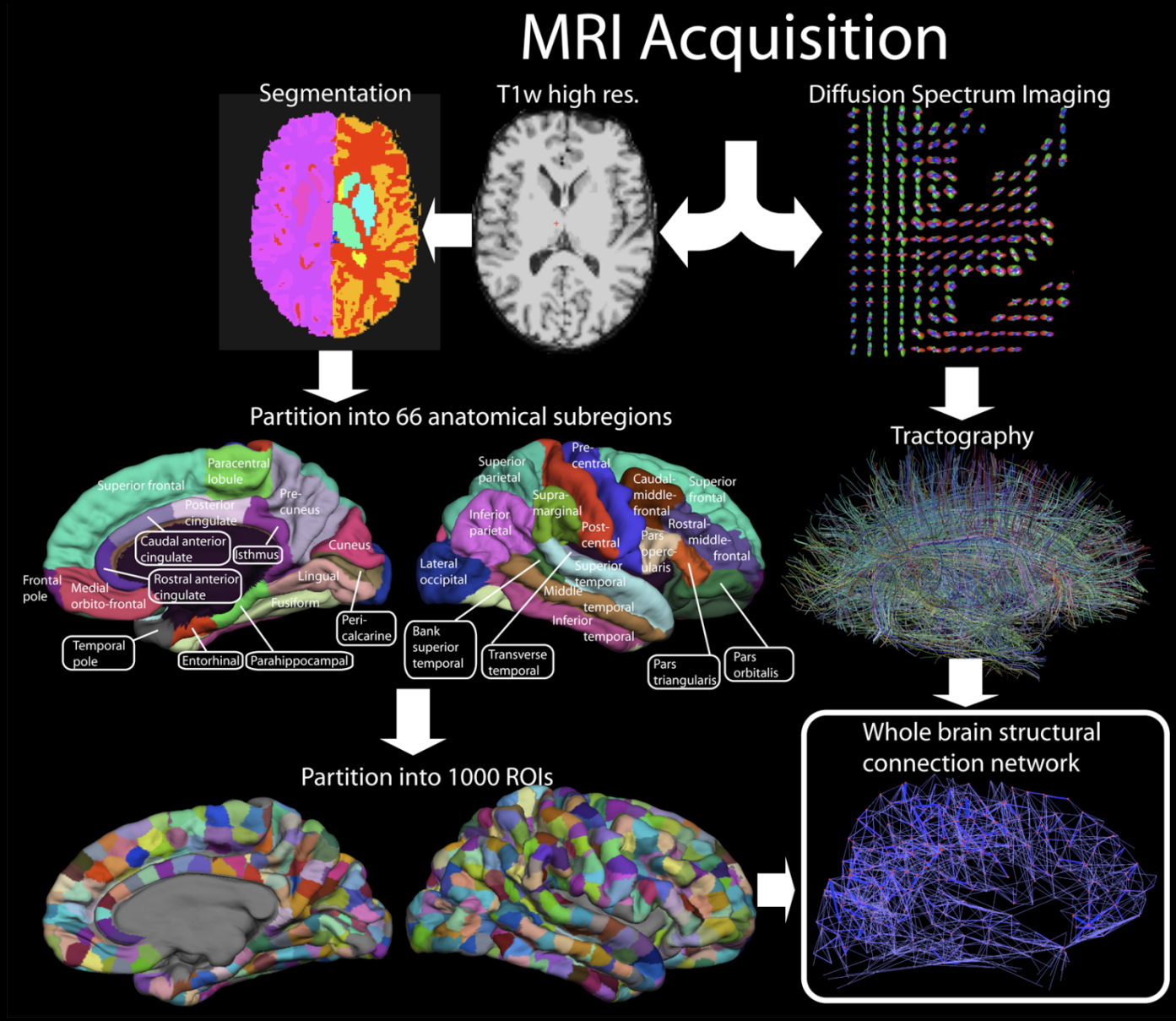


Extraction of Brain Networks from Empirical Data



Bullmore & Sporns (2009) *Nature Rev Neurosci* 10, 186.

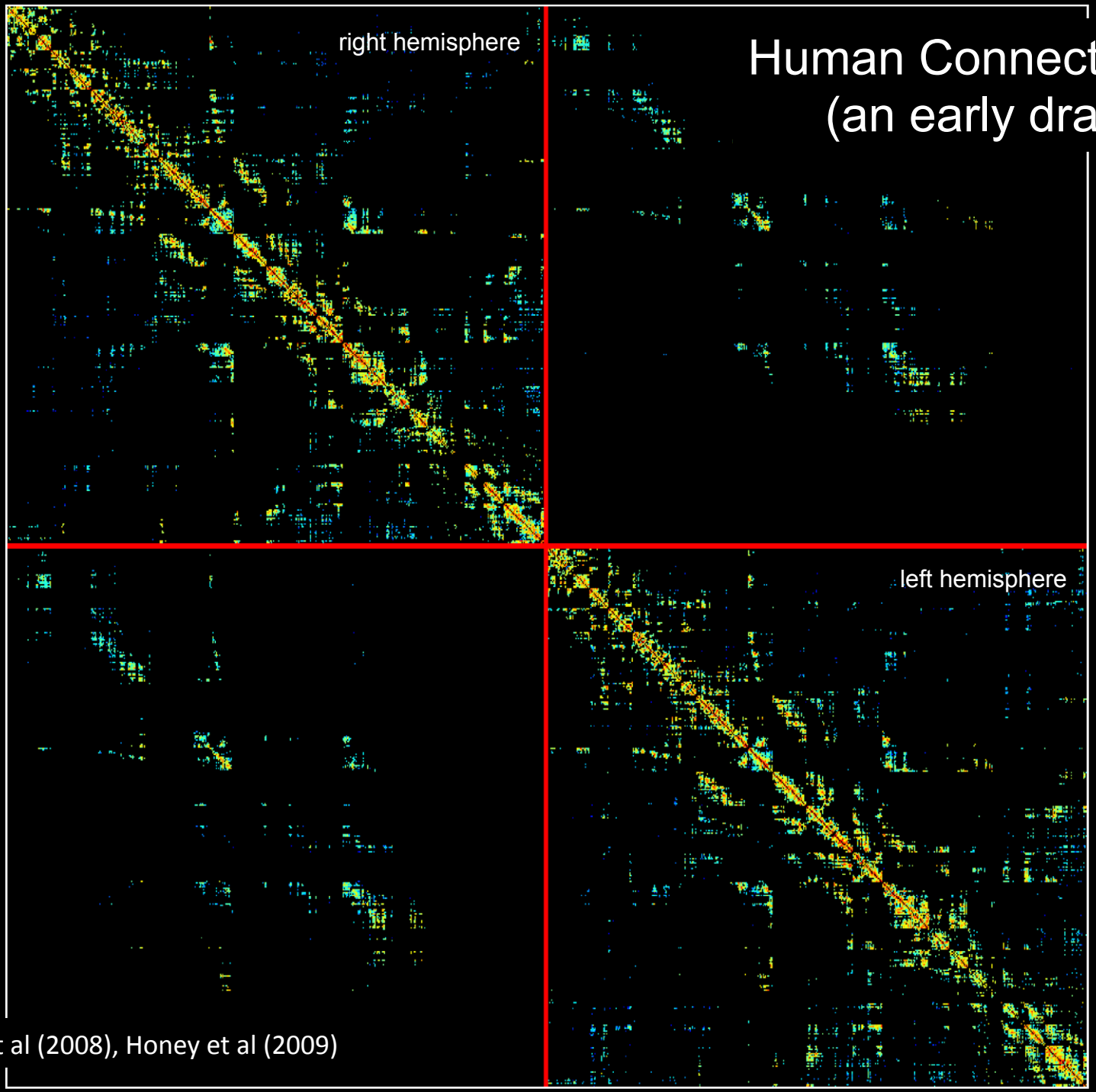
Mapping Human Brain Structural Connectivity



Patric Hagmann

Hagmann et al. (2008) *PLoS Biol.* 6, e159

Human Connectome (an early draft)

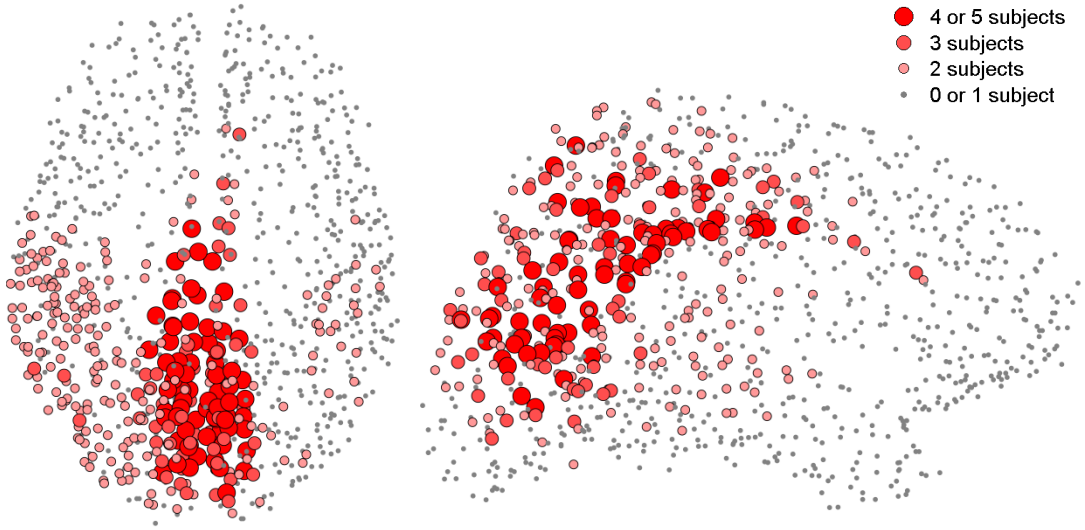


Hagmann et al (2008), Honey et al (2009)

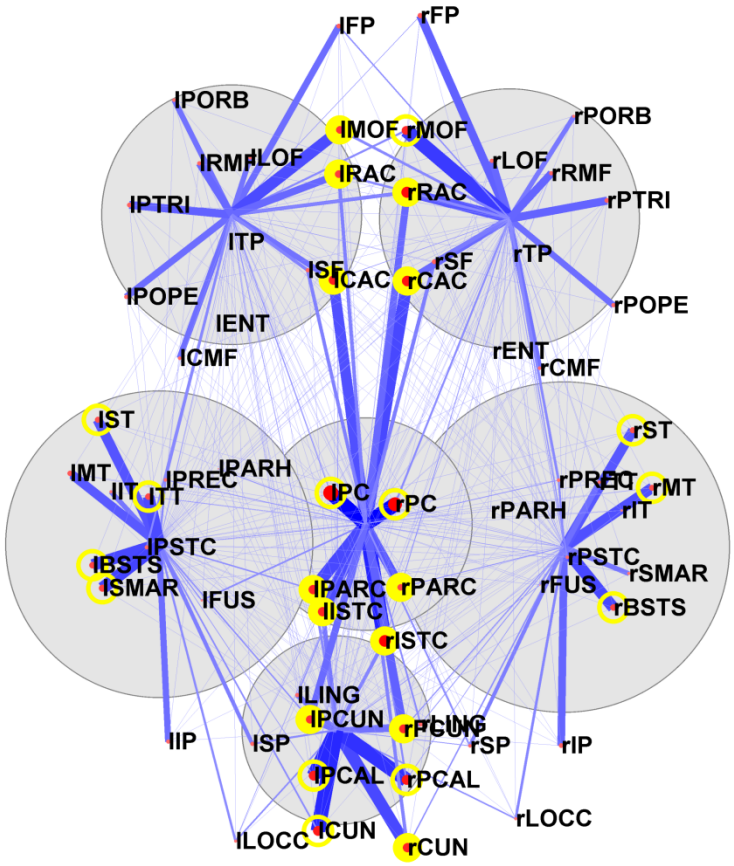
Network Analysis of the Connectome

Network analysis revealed

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



core

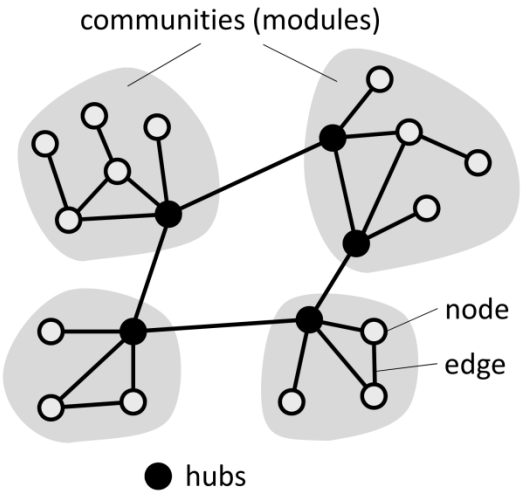


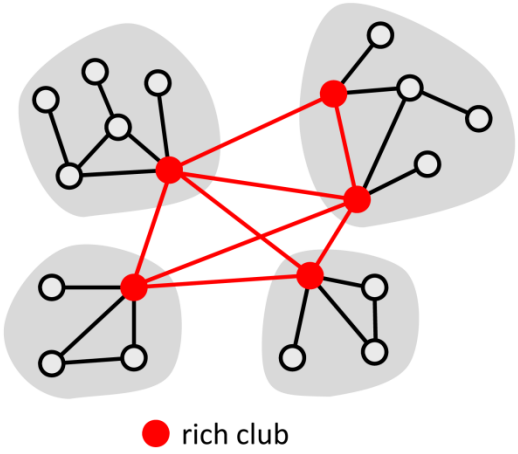
modules

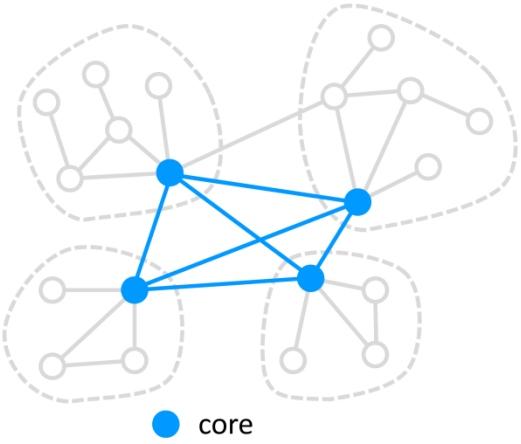
Hagmann et al. (2008) *PLoS Biol.* 6, e159.

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,

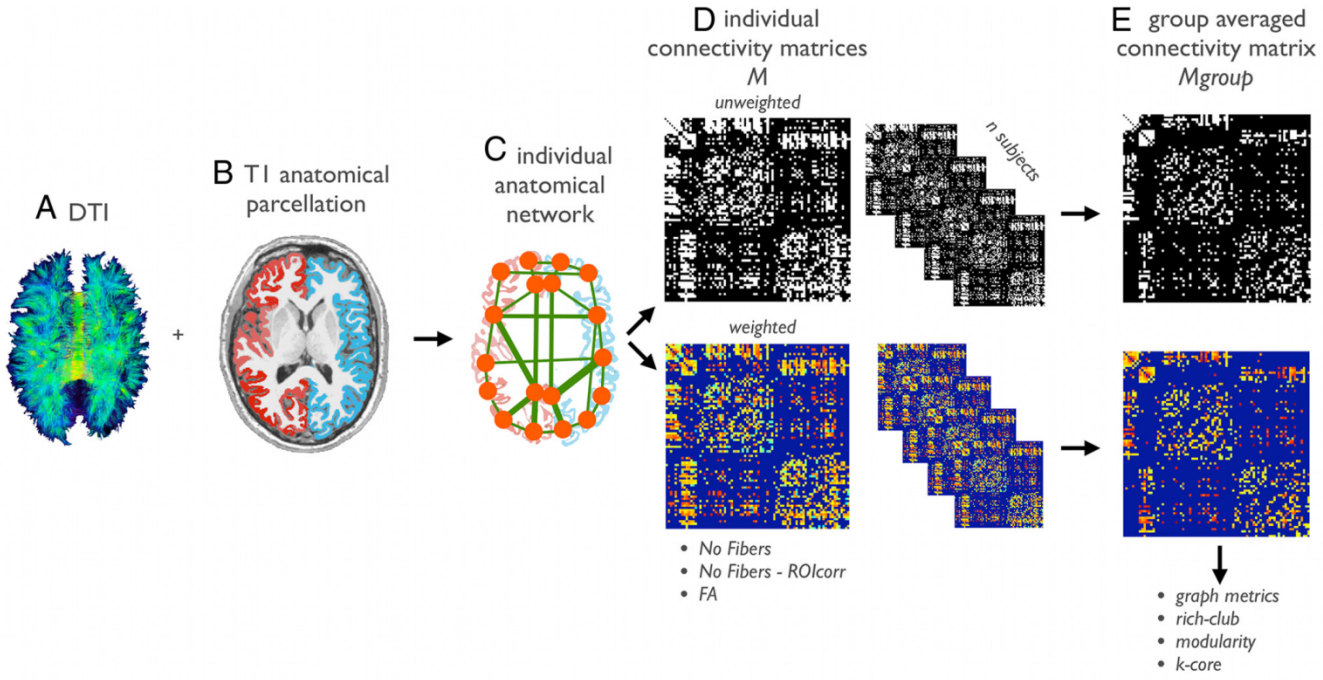
Rich-Club Organization of the Human Connectome

Human connectome data sets exhibit a prominent rich club, comprising cortical and subcortical regions.

Presence of rich-club (RC) organization suggests central role in information integration and communication.

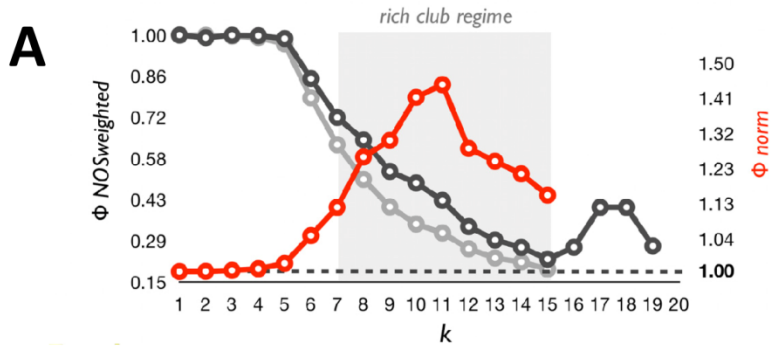
DTI study, 21 participants, low (82 nodes) and high-resolution (1170 nodes) partition, streamline tractography

Martijn van den Heuvel

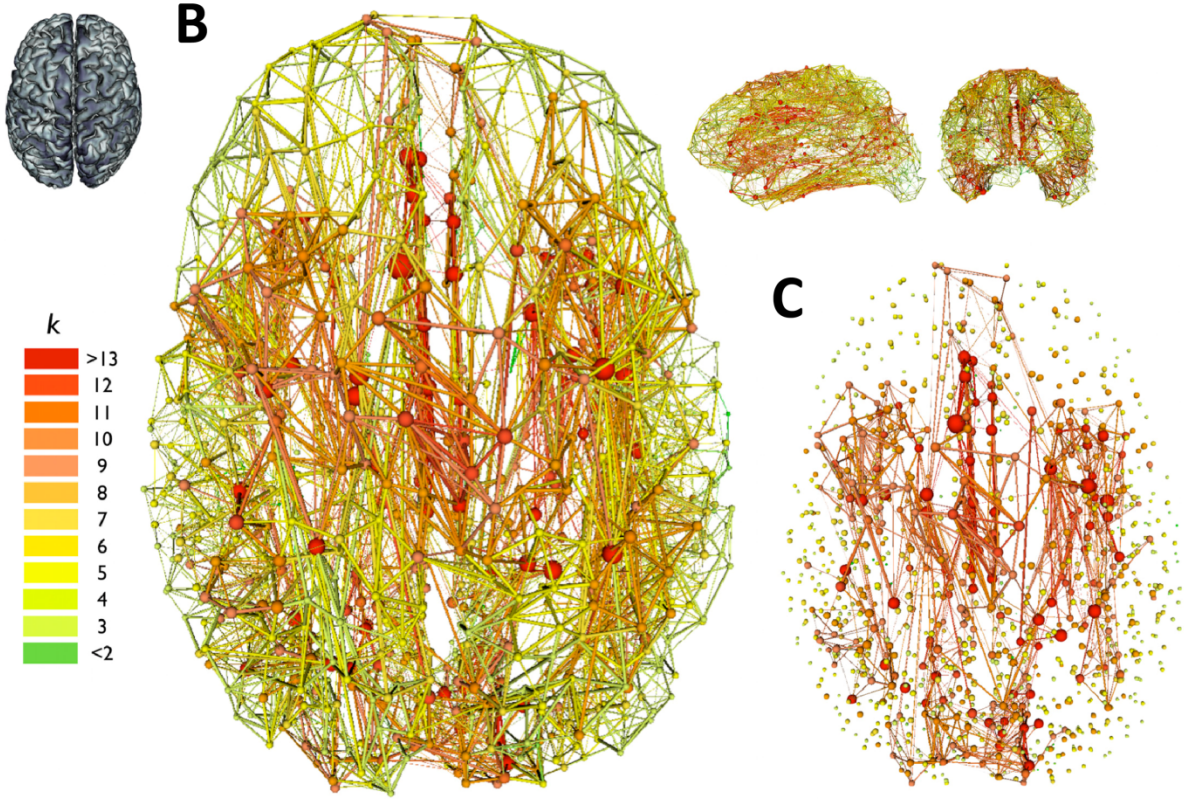


van den Heuvel and Sporns (2011) *J. Neurosci.* 31, 15775.

Rich-Club Organization of the Human Connectome



RC members include:
precuneus, posterior cingulate cortex, superior frontal cortex, medial orbitofrontal cortex, caudal anterior cingulate cortex, insula, portions of medial temporal cortex.



Overlap of RC and structural core.

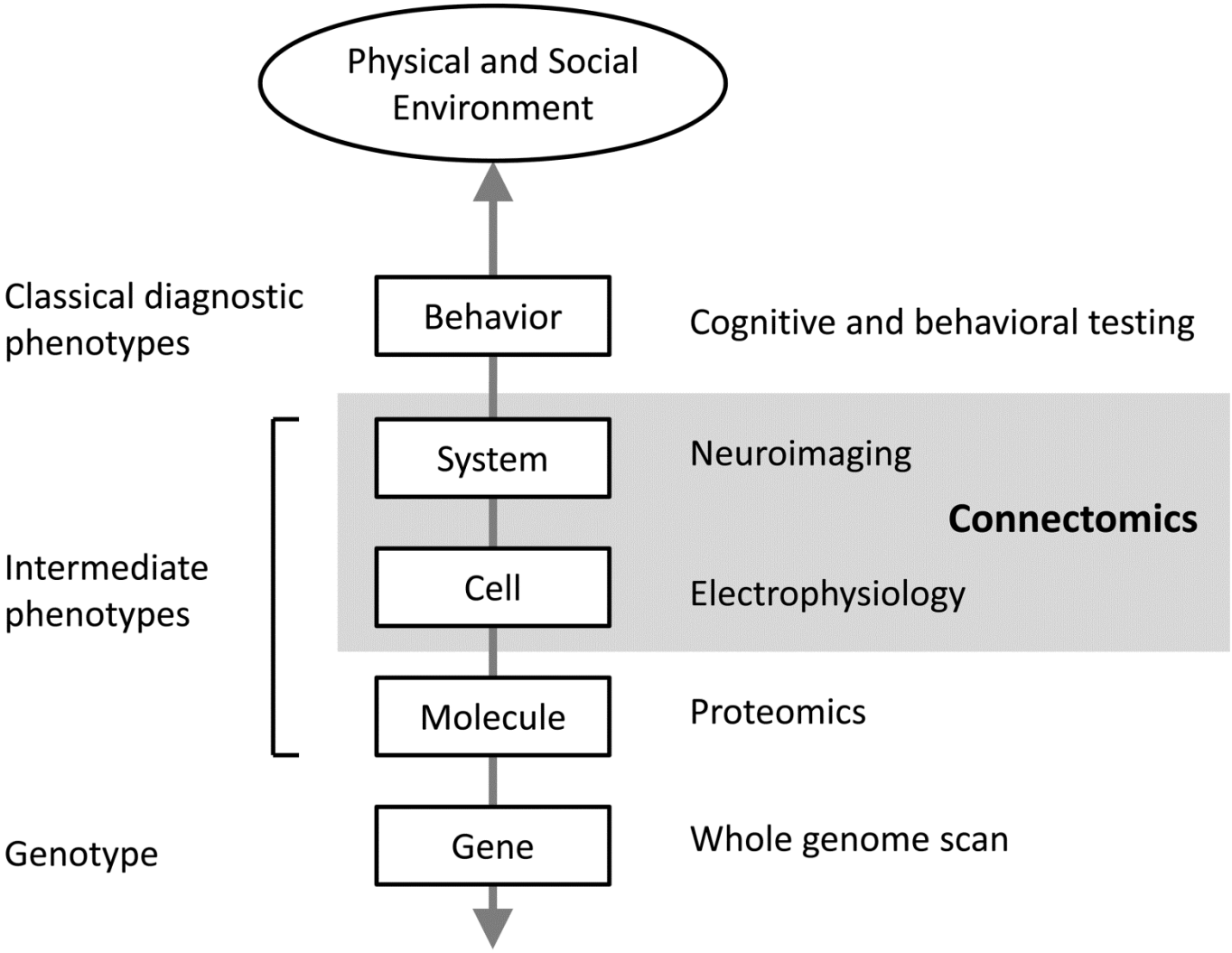
High proportion (89%) of short communication paths travel trough at least one RC node (66% through an RC edge).

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

Linking Networks across Levels

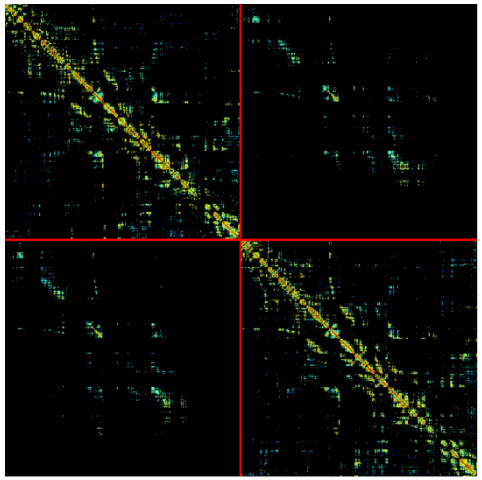


Sporns (2011) *Networks of the Brain.* MIT Press

Sporns (2012) *Discovering the Human Connectome*.

Connectome-Based Models of Functional Connectivity

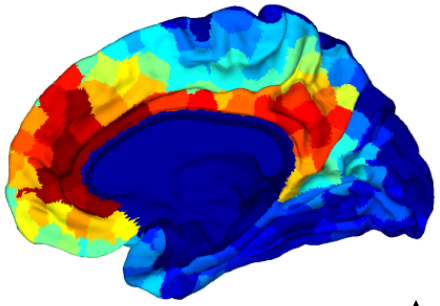
SC



DSI structural connections

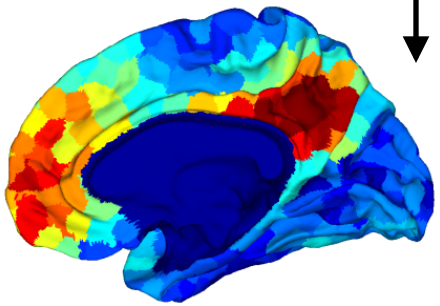
modeling

seeds placed in PCC, MPFC



functional connectivity (rsFC) – nonlinear model

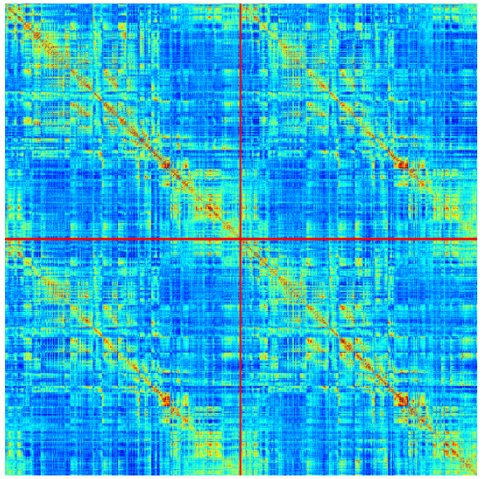
comparison



functional connectivity (rsFC) - empirical

prediction **inference**

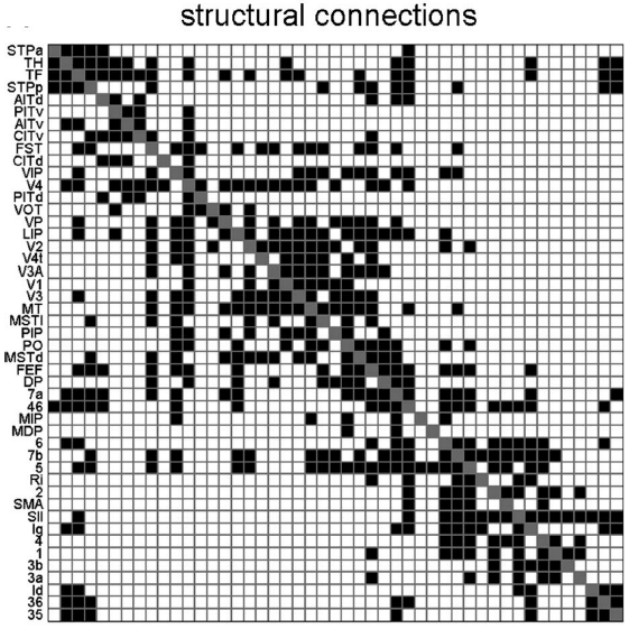
FC



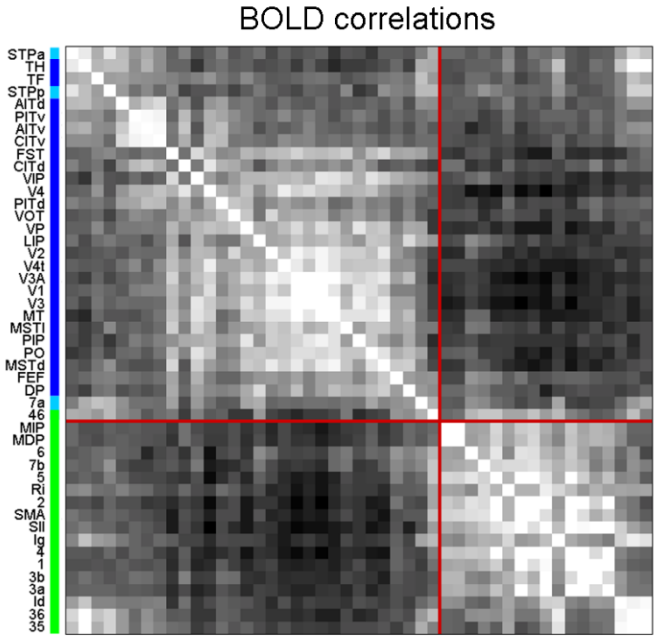
rs-fMRI functional connections

Honey et al. (2009) *PNAS* 106, 2035.

Connectome-Based Models of Functional Connectivity



perturbations



connectome

+

biophysical equations

rest

task

$$\frac{dV}{dt} = -\left(g_{Ca} + r_{NMDA} a_{ee} Q_V\right) m_{Ca}\left(V - V_{Ca}\right) - \left(g_{na} m_{na} + a_{ee} Q_V\right)\left(V - V_{na}\right) - g_K W\left(V - V_K\right) - g_L\left(V - V_L\right) + a_{ie} Z Q_Z + a_{ne} I_\delta ,$$

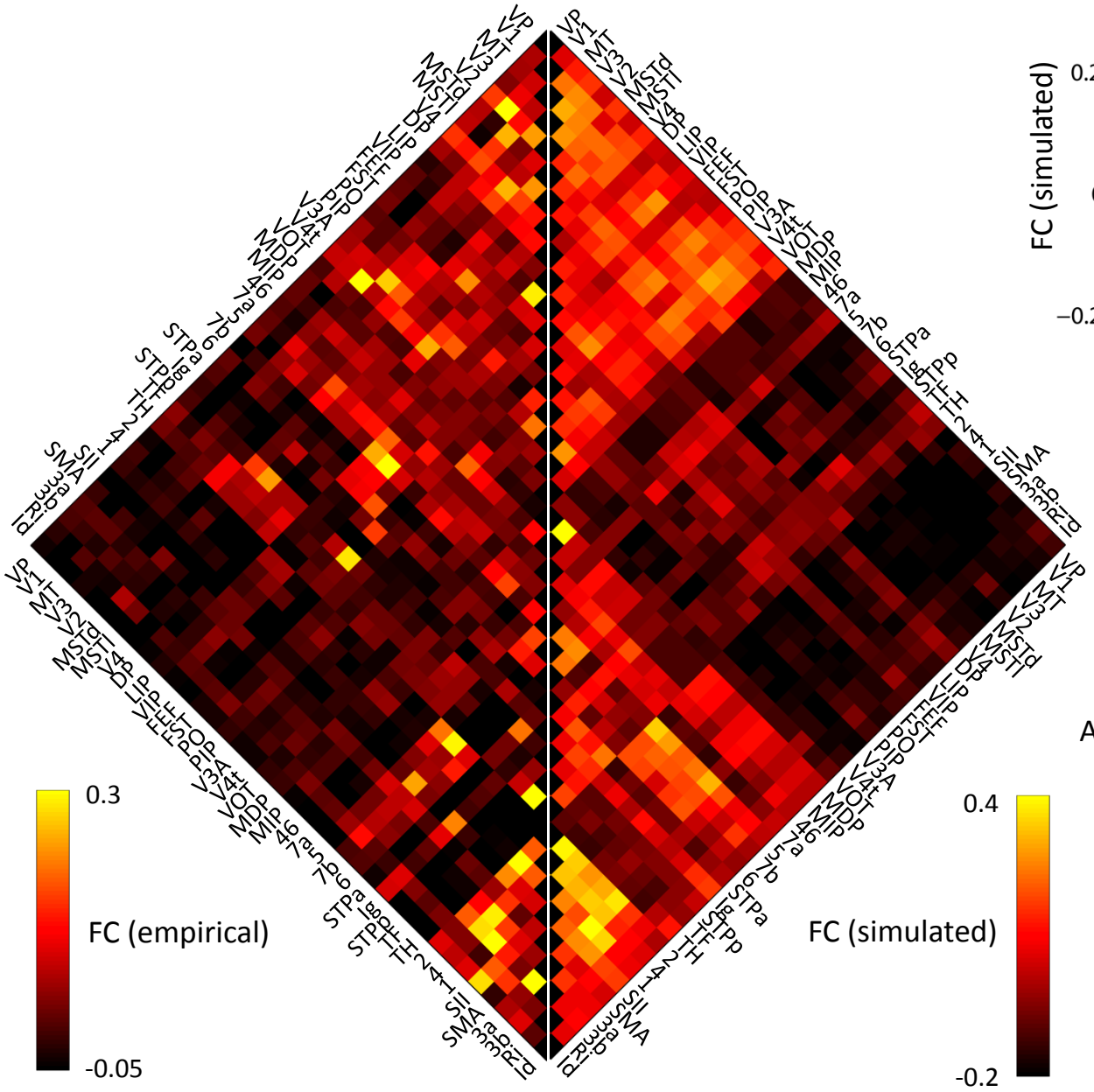
$$\frac{dZ}{dt} = b\left(a_{ni} I_\delta + a_{ei} V Q_V\right),$$

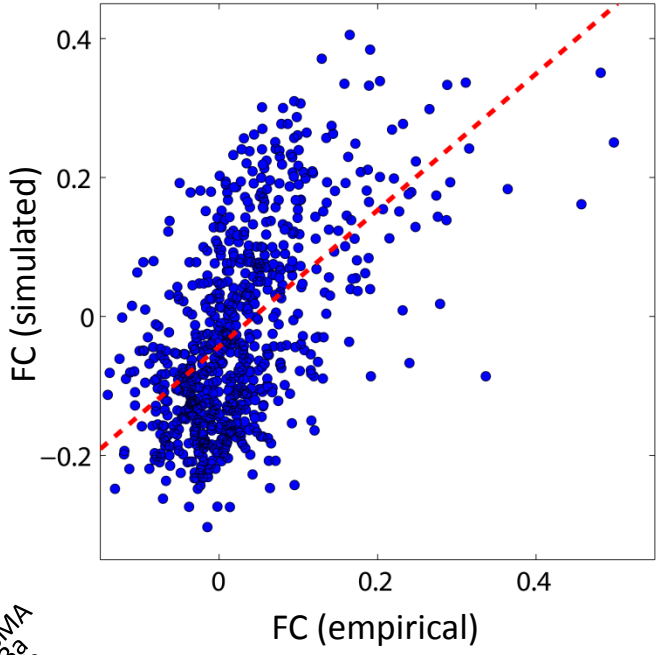
inputs

R = 0.55 correlation with empirical macaque rs-fMRI data
Adachi et al. (2012) *Cereb Cortex*

Honey et al. (2007) *PNAS* 104, 10240.

Deco et al. (2011) *Nature Rev Neurosci* 12,

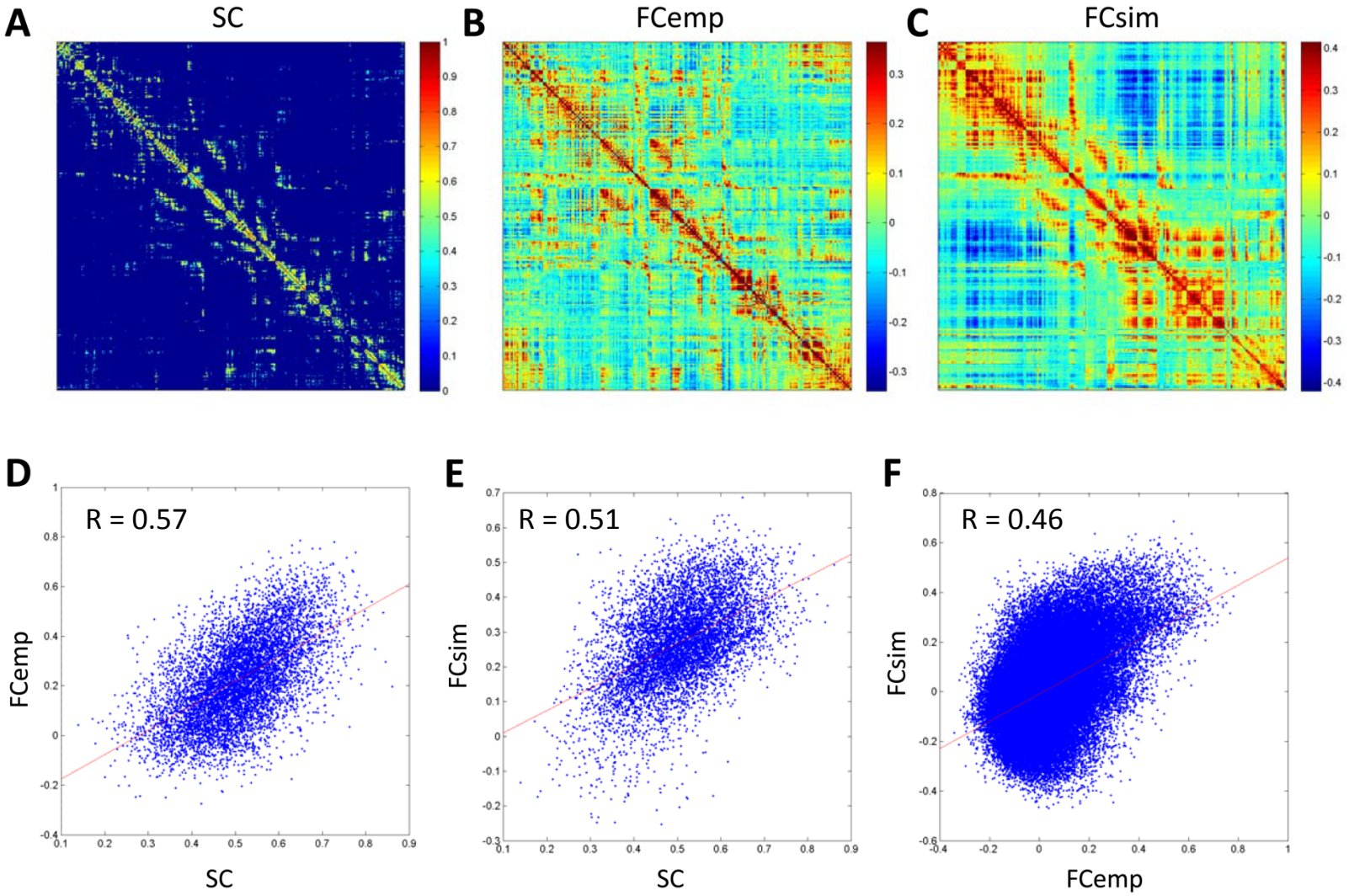




Adachi et al (2012) Cereb Cortex

Connectome-Based Models for Functional Connectivity

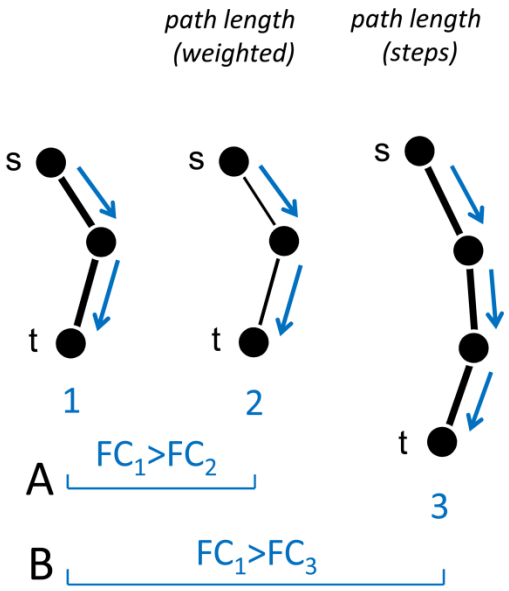
A network model of human resting-state fMRI functional connectivity.



Honey et al. (2009) *PNAS* 106, 2035.

Connectome-Based Models for Functional Connectivity

Role of network topology in shaping patterns of network communication.



Search information quantifies the "hiddenness" of a path, i.e. the information needed to access it.

Path transitivity quantifies the density of "local detours" surrounding a given path.

Predictions:

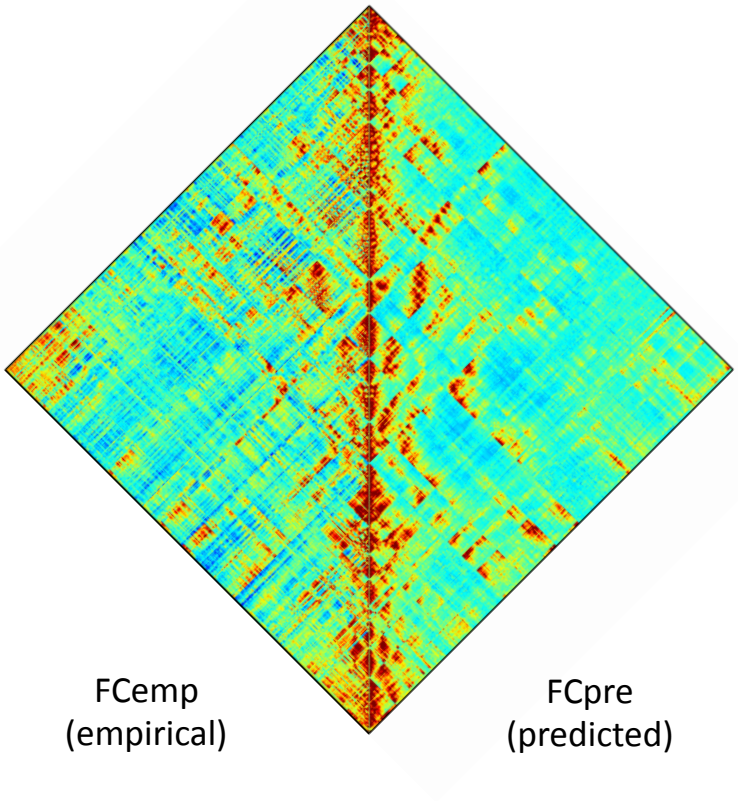
- [s,t] node pairs requiring greater search information exhibit weaker FC*
- [s,t] node pairs with higher path transitivity exhibit stronger FC**

* holding path length constant
** holding path length and search information constant

Goñi et al. (2014) *PNAS* 111, 833.

Connectome-Based Models for Functional Connectivity

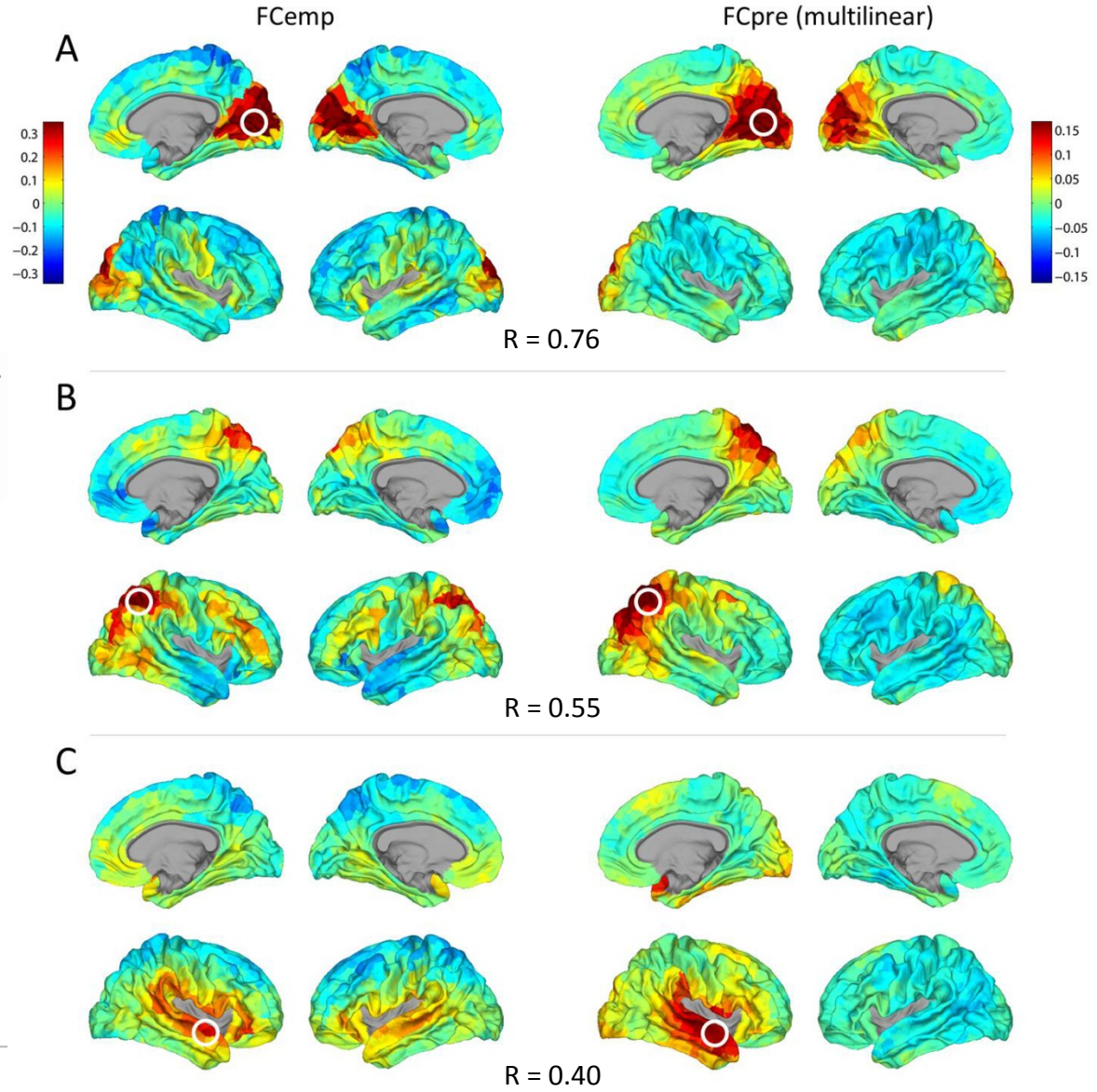
Analytic measures of network communication can predict functional connectivity.



FCemp (empirical)

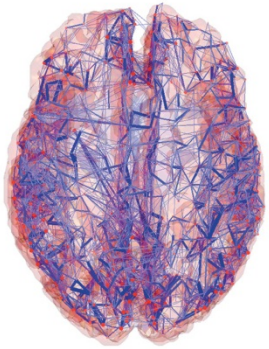
FCpre (predicted)

R = 0.60

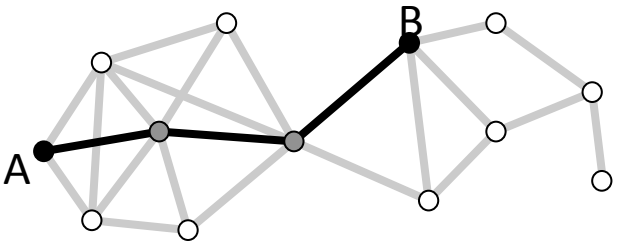


Goñi et al. (2014) *PNAS* 111, 833.

Summary and Conclusion

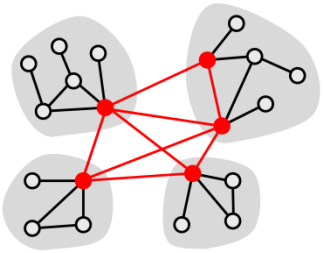


Connectomics is beginning to reveal the network architecture of the human brain.



Network science approaches are increasingly important for analysis and modeling of connectome data.

Highly connected and highly central hub nodes are a prominent feature in human and non-human connectome networks.



Hubs are densely interconnected to form a "rich club" – a high-cost and high-efficiency attribute of the connectome.

Network hubs and their interconnections may provide an important structural substrate for functional integration across segregated brain regions and resting-state networks.

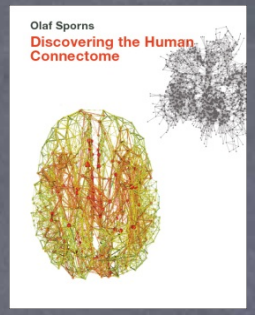
Further Reading and Acknowledgements

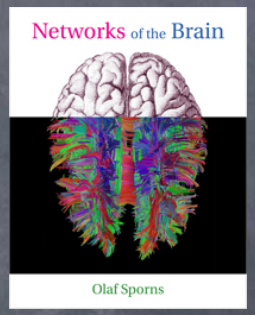
Further Reading:

• van den Heuvel MP, Sporns O (2013) Network hubs in the human brain. *Trends Cogn Sci* 17, 683.
• Bullmore ET, Sporns O (2012) The economy of brain network organization. *Nature Rev Neurosci* 13, 336-349.
• Behrens TEJ, Sporns O (2012) Human connectomics. *Curr Opin Neurobiol* 22, 144-153.
• Rubinov M, Sporns O (2010) Complex network measures of brain connectivity: Uses and interpretations. *Neuroimage* 52, 1059-1069.
• Bullmore, ET, Sporns, O (2009) Complex brain networks: Graph-theoretical analysis of structural and functional systems. *Nature Rev Neurosci* 10, 186-198.

HUMAN Connectome PROJECT

THEVIRTUALBRAIN.





Lab: www.indiana.edu/~cortex

NIH Human Connectome Project: www.humanconnectome.org

The Virtual Brain Project: http://thevirtualbrain.org

Network Analysis Toolbox (Matlab): www.brain-connectivity-toolbox.net

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-- Nieves Velez de Mendizabal (IUPUI)

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