Theoretical Neuroscience Group

Institut de Neurosciences des Systèmes

From structural to functional connectivity, via dynamics

LASCON VIII - Part 1 - The connectome is not enough

Demian Battaglia

Institut de Neurosciences des Systèmes

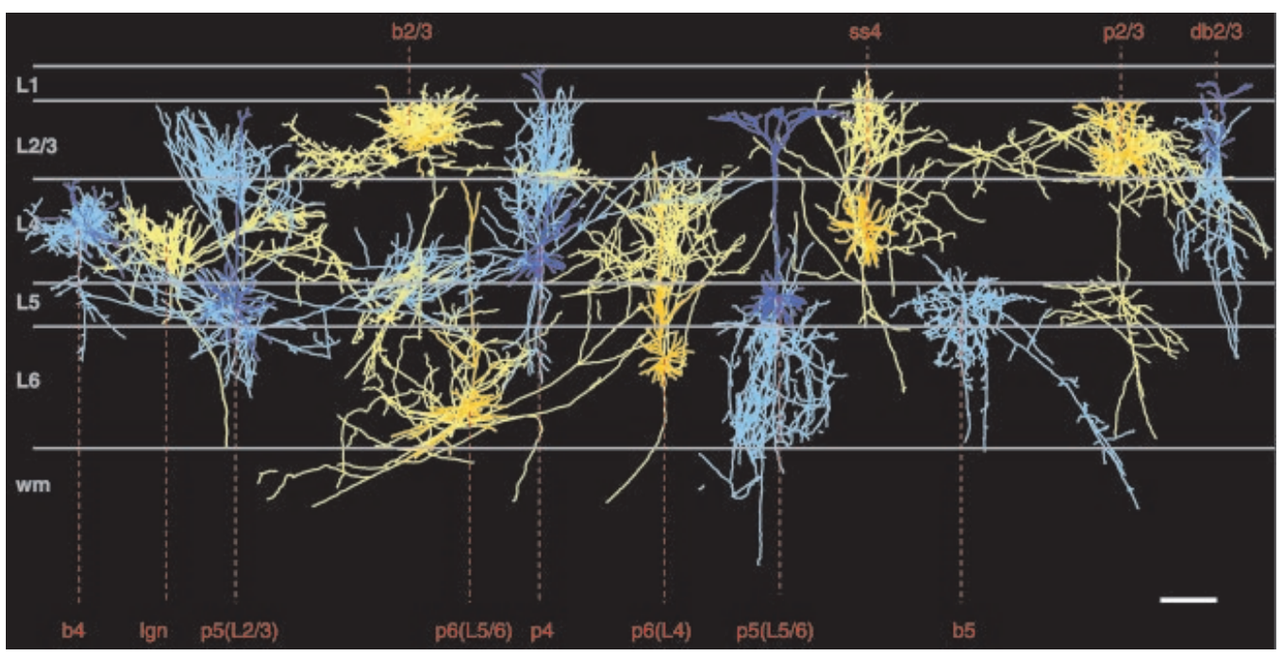
UMR1106, Université Aix-Marseille, France

Aix*Marseille université

cnrs dépasser les frontières

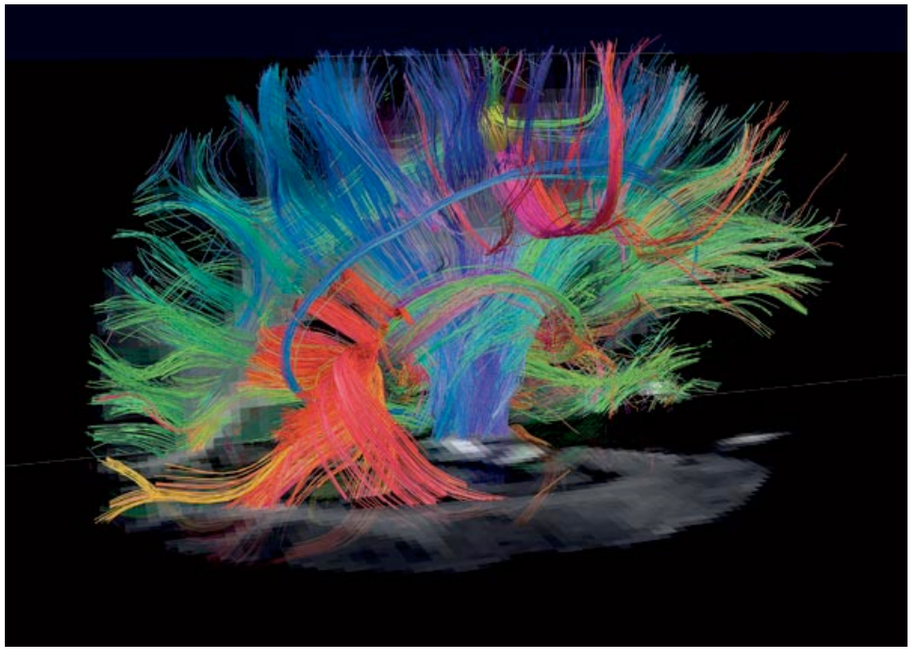
Structure

A column	*Few columns*	*Few areas*	*Brain-wide*
< 1 mm	*1-10 mm*	*(< 10 cm)*	*(10 cm)*



Binzegger et al. (2004)

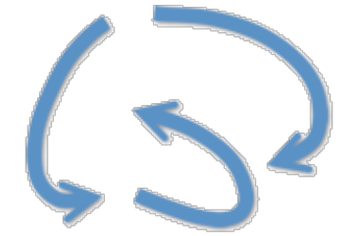
Local microcircuits



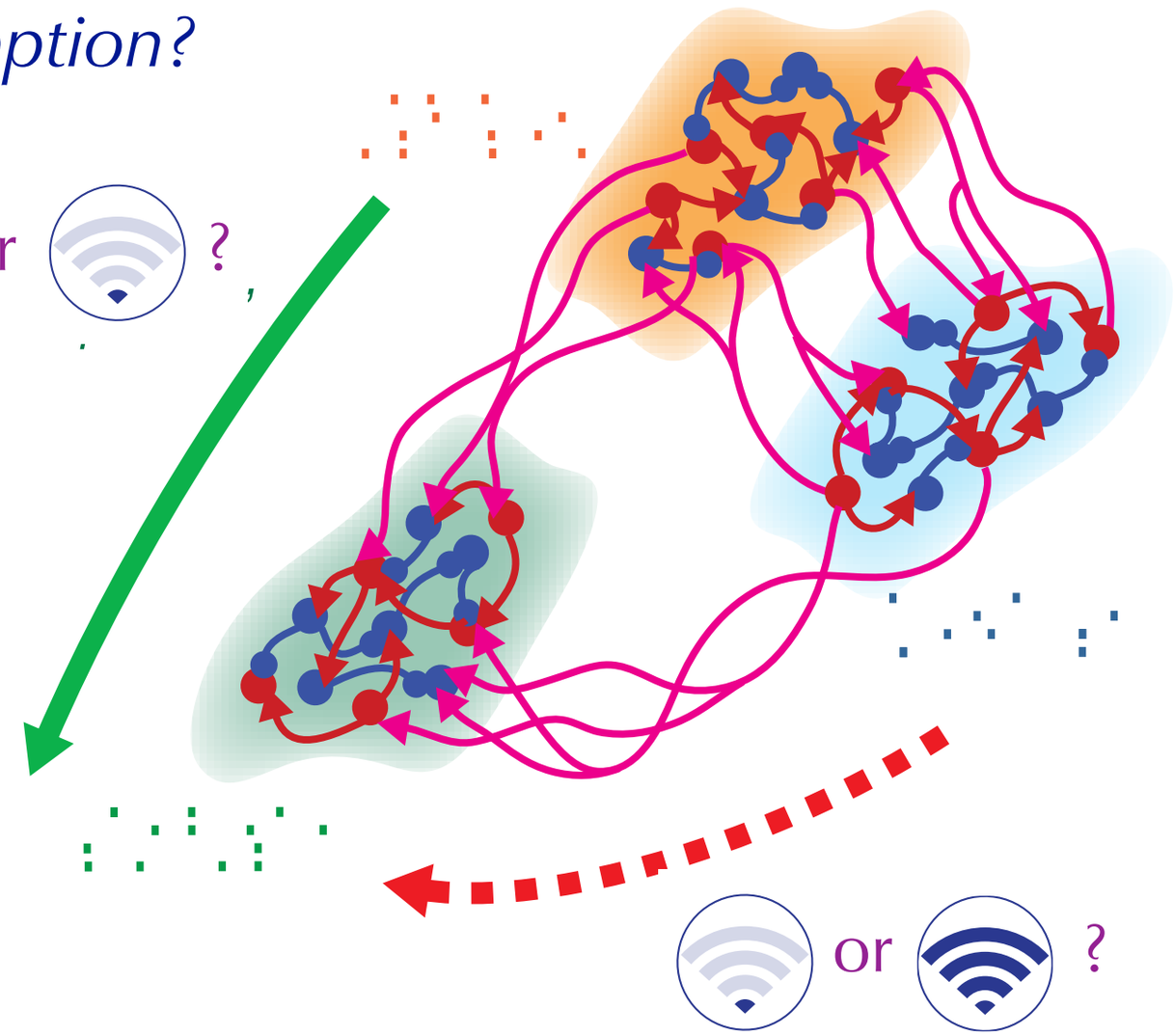
Brain tractography by DTI (Filler 2009)

Inter-areal connections

Function



Bad or good reception?



Directed functional *connectivity*

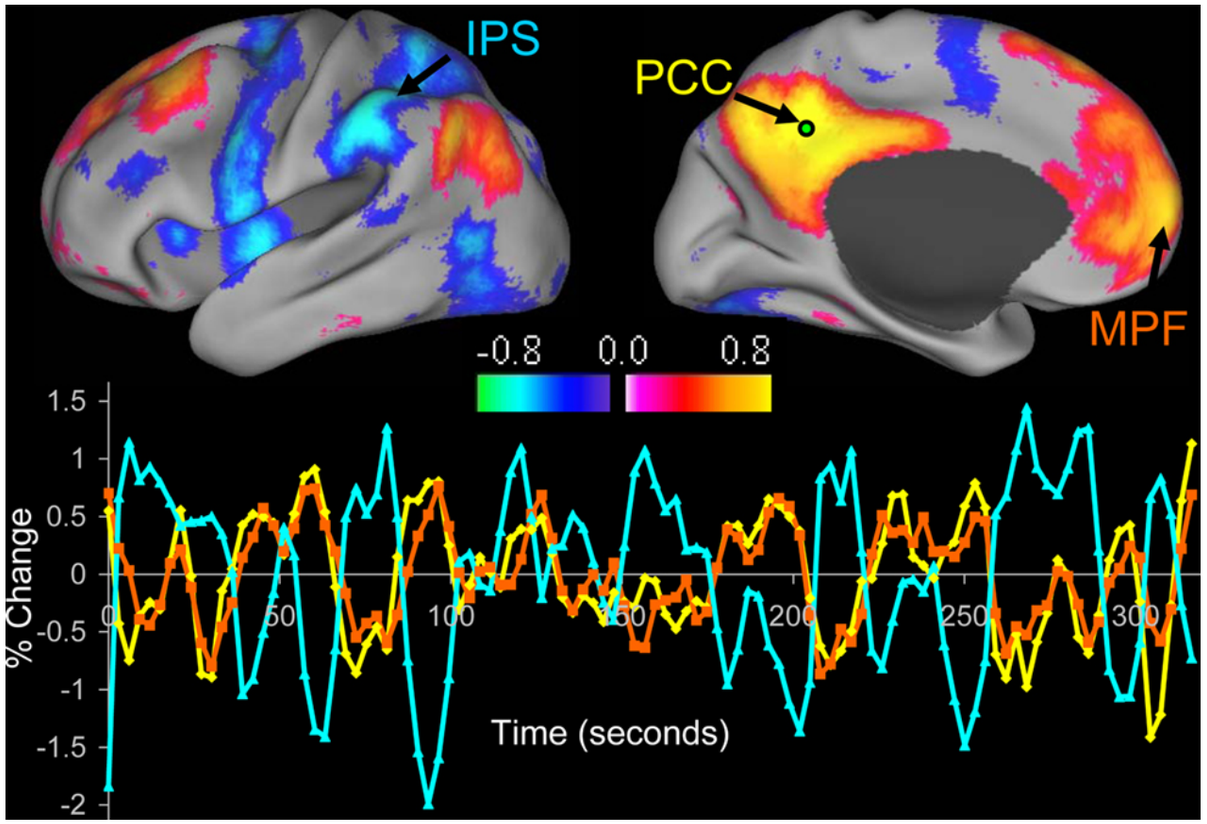
Functional *connectivity*

Effective *connectivity*

Causal *connectivity*

Flexible ***patterns of communication***

"Function"



Directed functional *connectivity*

Functional *connectivity*

Effective *connectivity*

Causal *connectivity*

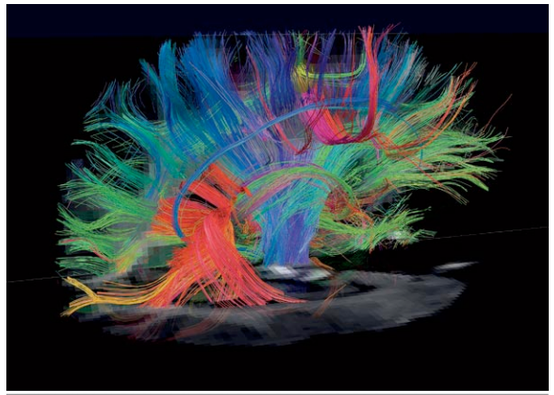
Resting-state fMRI fluctuations

Correlated or anti-correlated clusters of voxels

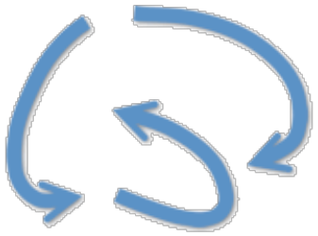
Flexible ***patterns of "interaction"***

Structural Connectivity

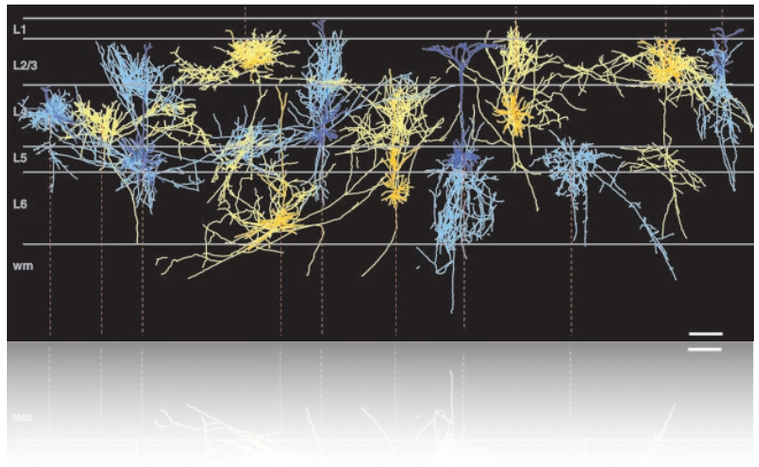
Anatomy,
synaptic connections,…



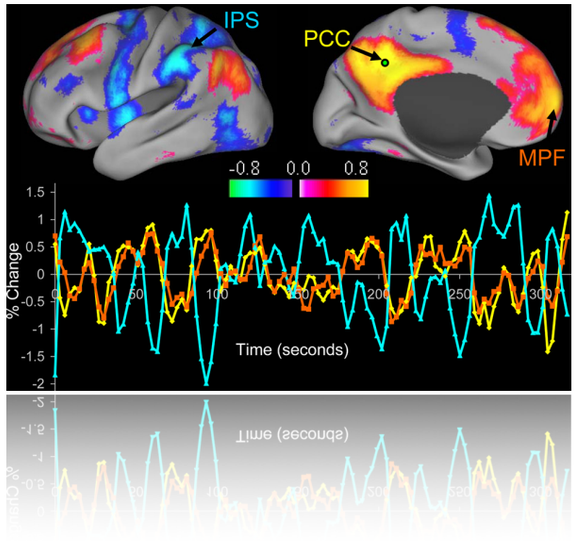
Macro-scale
DTI, tracing studies



Micro-scale
Detailed
reconstructions

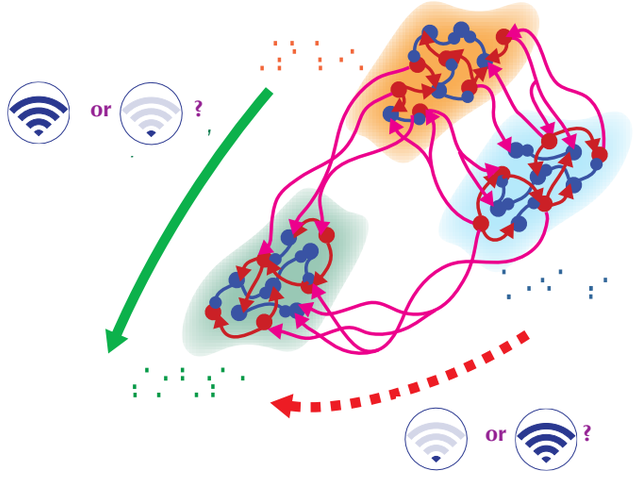


Resting state

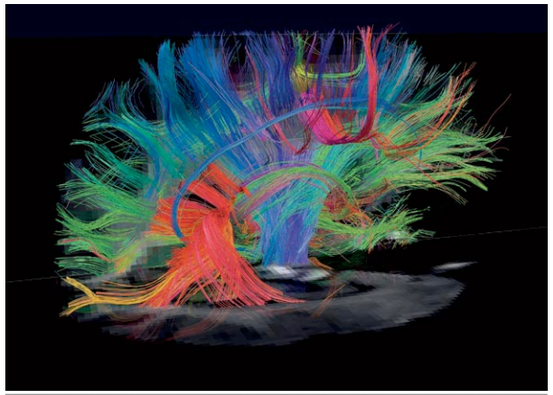


Functional Connectivities

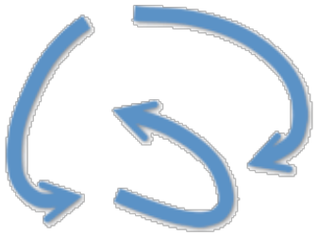
Information routing,
dynamic interaction patterns,…



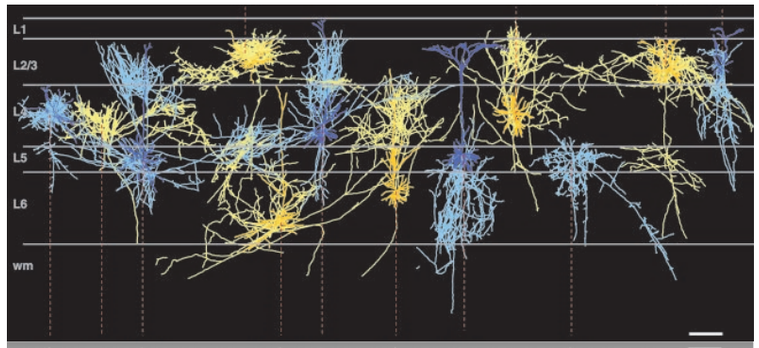
"Bad or good reception?"



Macro-scale
DTI, tracing studies

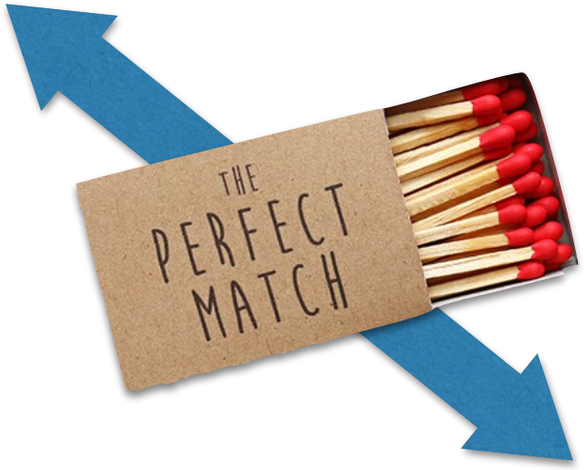


Micro-scale
Detailed
reconstructions



Structural Connectivity

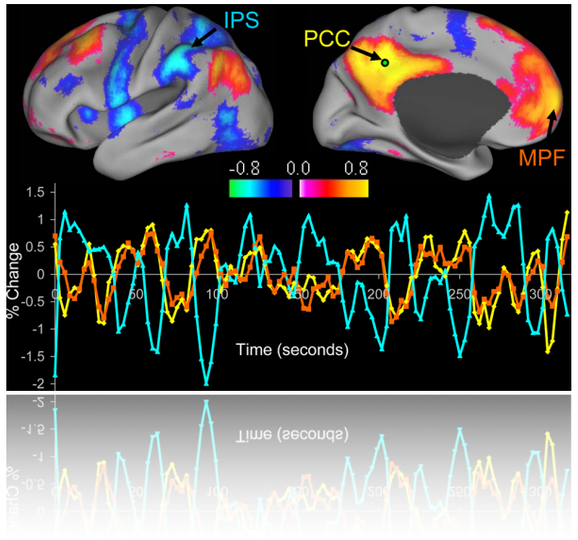
Anatomy,
synaptic connections,…

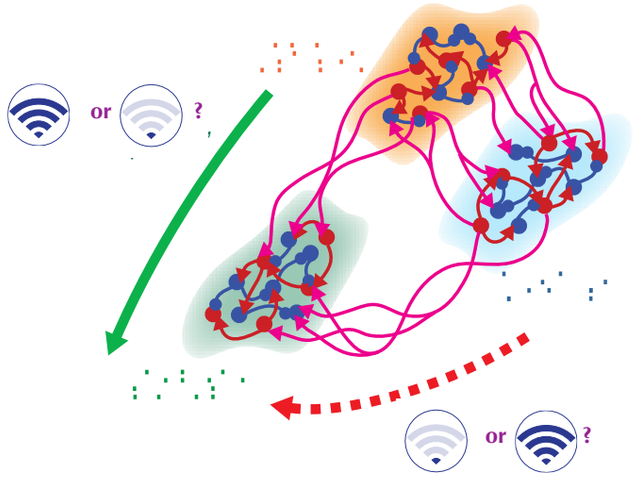


Functional Connectivities

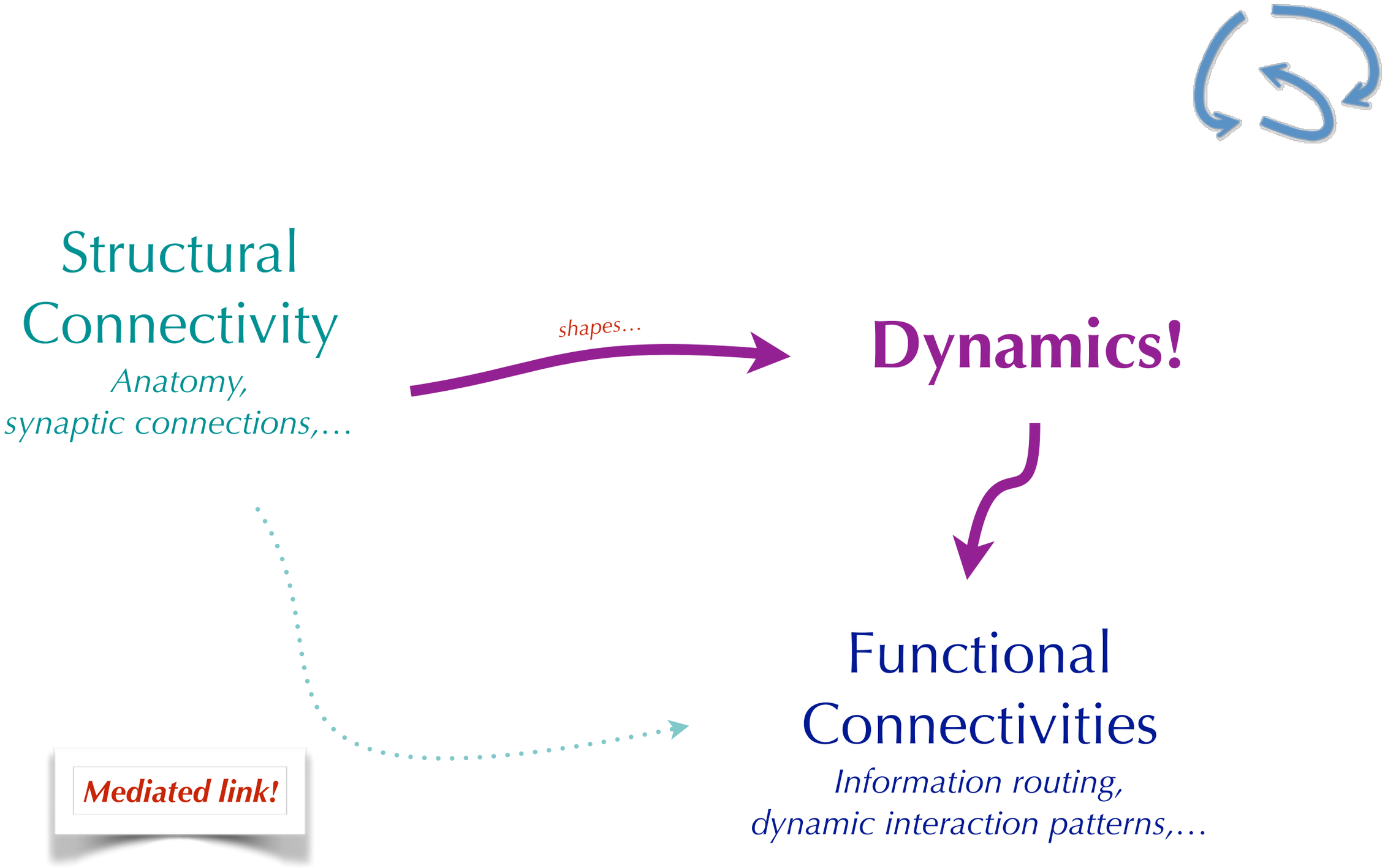
Information routing,
dynamic interaction patterns,…

Resting state





"Bad or good reception?"


Structural Connectivity
Anatomy, synaptic connections,…
shapes…
Dynamics!
Functional Connectivities
Information routing, dynamic interaction patterns,…
Mediated link!

From the connectome to the "dynome"

(Kopell et al. 2014)

Connect
Gnome

Neuron
Perspective

Beyond the Connectome: The Dynome

Nancy J. Kopell,[1,*] Howard J. Gritton,[2] Miles A. Whittington,[3] and Mark A. Kramer[1]
[1]Department of Mathematics and Statistics, Boston University, Boston, MA 02215, USA
[2]Department of Biomedical Engineering, Boston University, Boston, MA 02215, USA
[3]The Hull York Medical School, University of York, Heslington, York YO10 5DD, UK
*Correspondence: nk@math.bu.edu
http://dx.doi.org/10.1016/j.neuron.2014.08.016

Dyn
Gnome

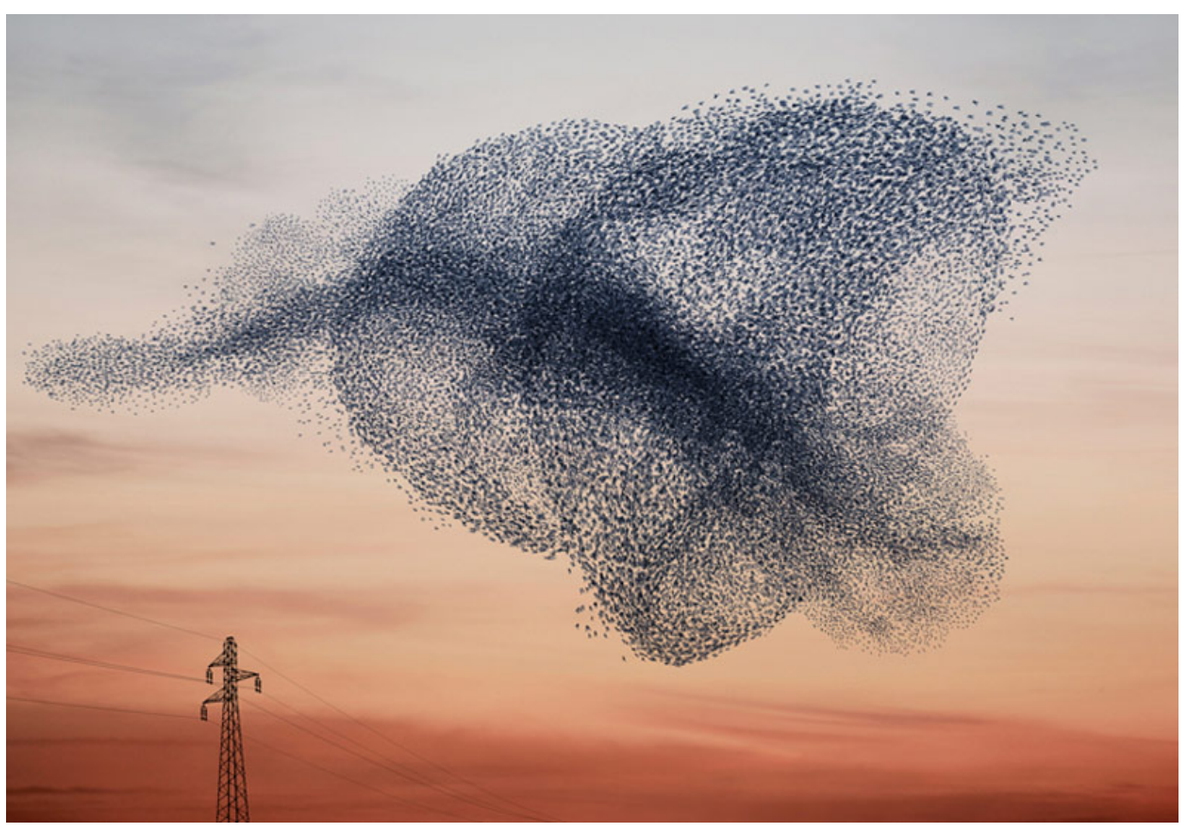
"Emergence"
"Collective behaviors"

Structural Connectivity

Anatomy,
synaptic connections,…

shapes…

Dynamics!



Functional Connectivities

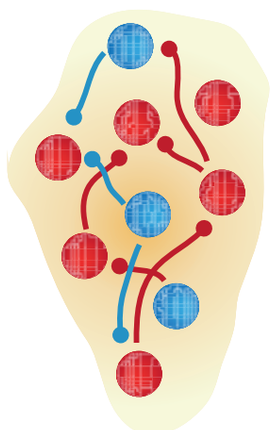
Information routing,
dynamic interaction patterns,…

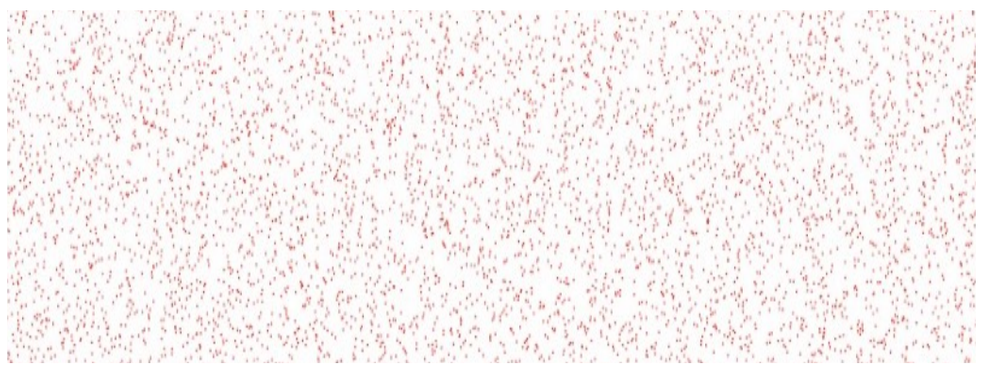
Sparse synchronization in each local region

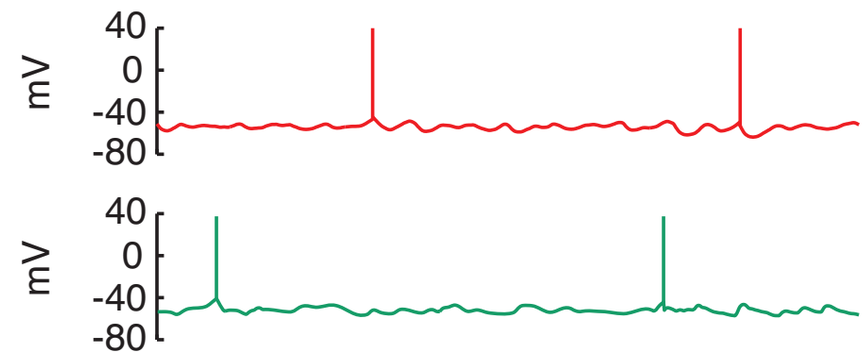
POPULATION
(random excitatory and inhibitory connectivity)

SINGLE NEURONS
(Conductance-based point neutrons)

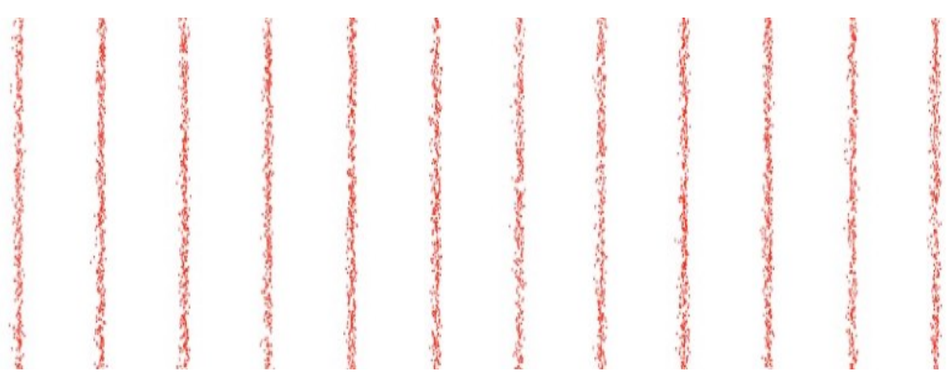
Weak
local inhibition

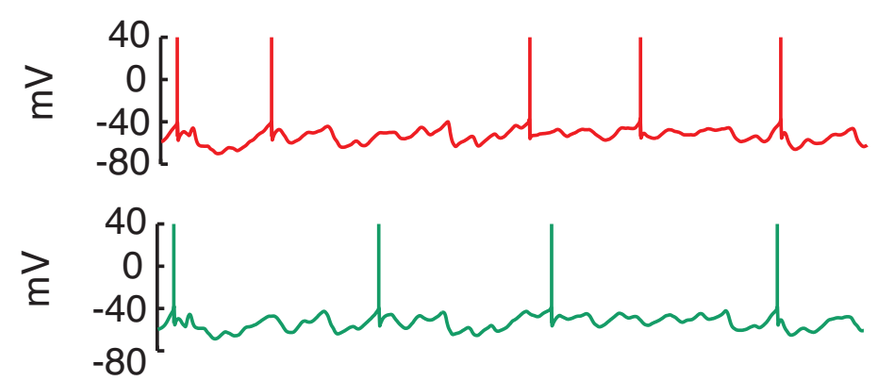






Stronger
local inhibition

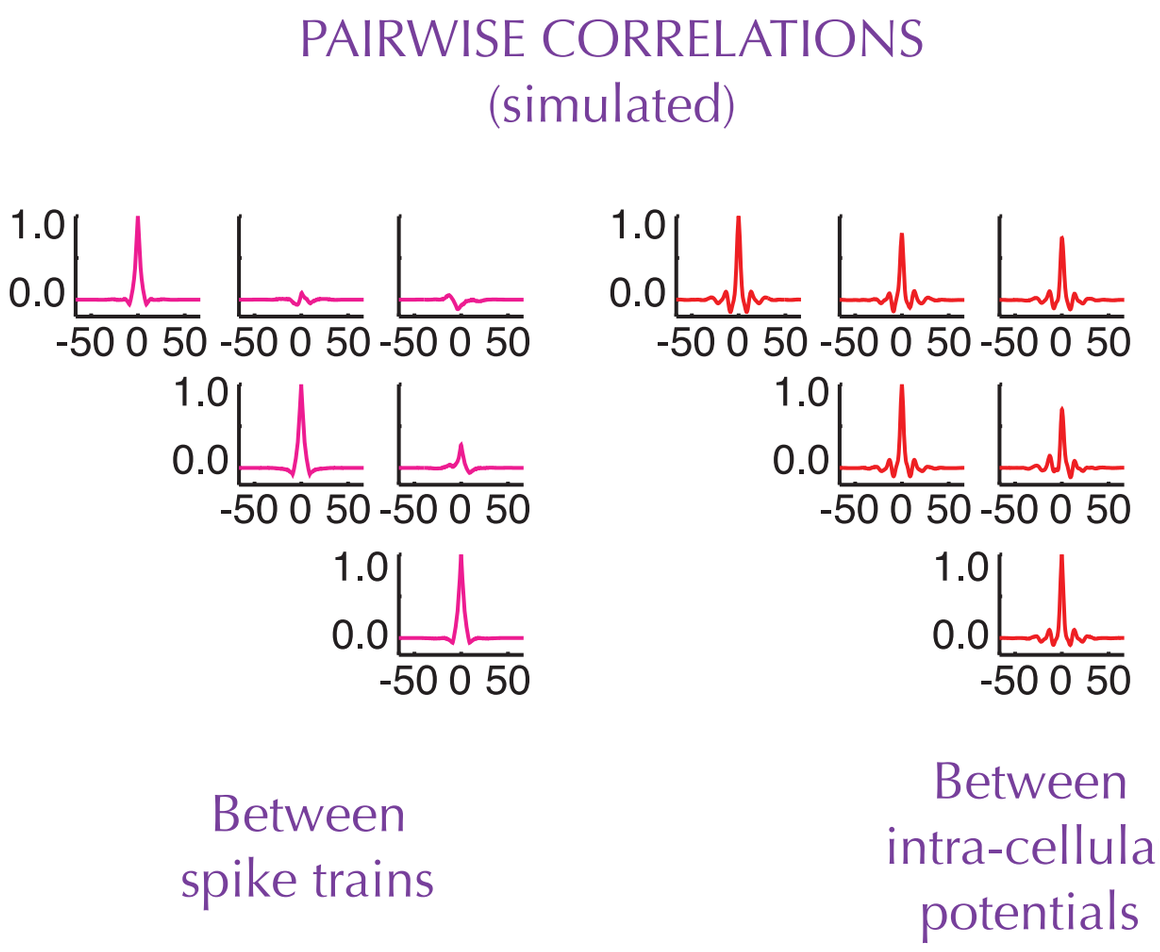


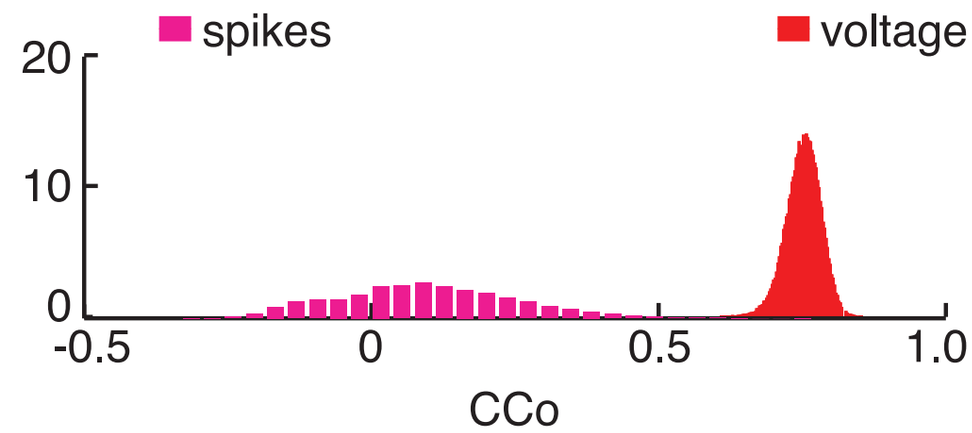


Brunel & Hakim (1999),
Brunel & Wang (2003),
Brunel & Hansel (2006),
DB, Brunel & Hansel (2007), etc.

"ING and PING"

Sparse synchronization in each local region

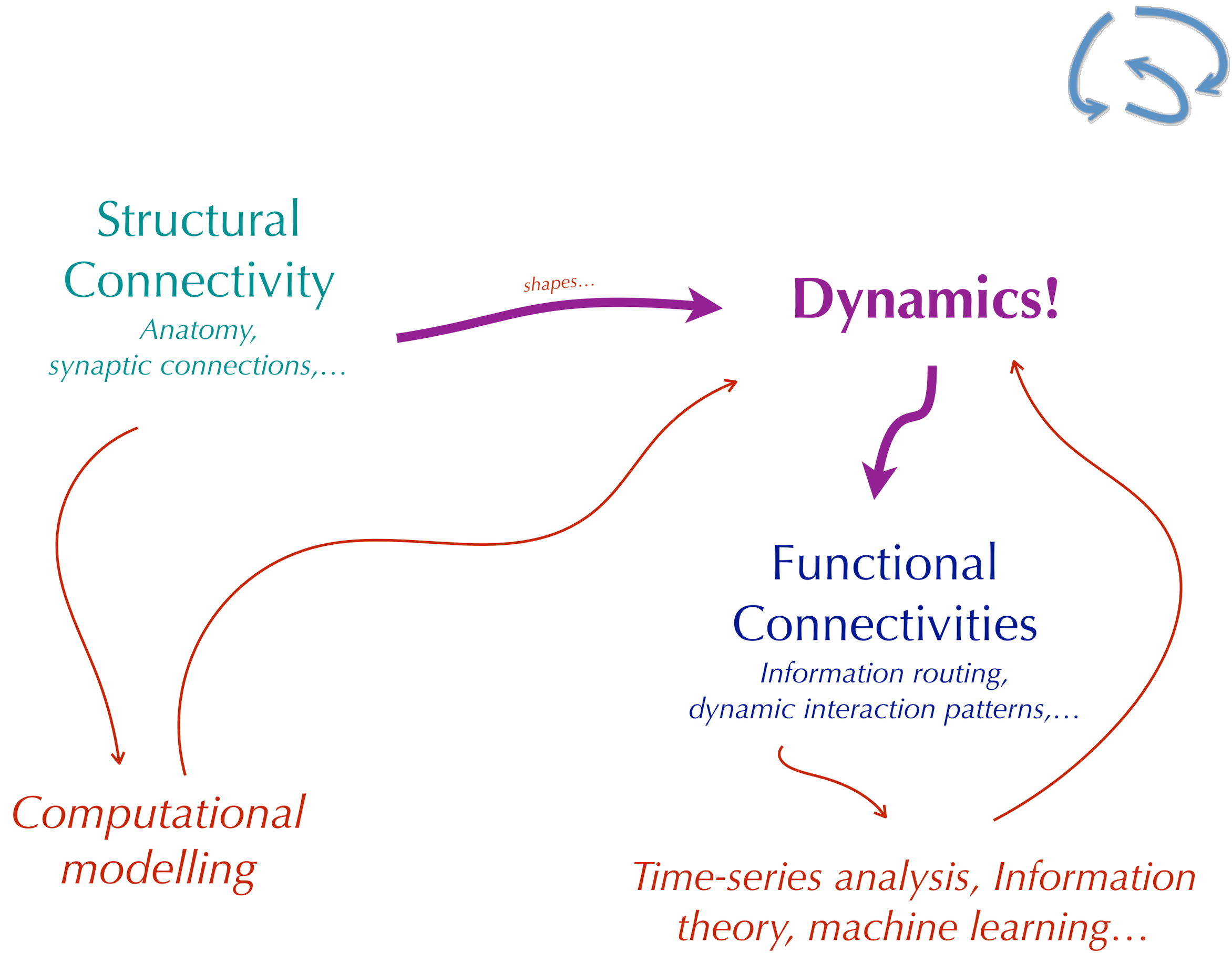




Weak inter-spike correlations coexist with strong sub-threshold correlations

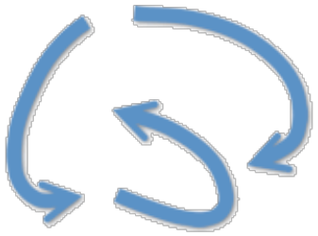
cf. empirical results, e.g. Yu and Ferster, Neuron, 2010

DB & Hansel (2011), etc.


Structural Connectivity
Anatomy, synaptic connections,…
shapes…
Dynamics!
Functional Connectivities
Information routing, dynamic interaction patterns,…
Computational modelling
Time-series analysis, Information theory, machine learning…

Questions

How to quantify functional interactions?



How to change functional connections without changing structural connections?

"Functional multiplicity"

Are functional dynamics analyses useful for concrete applications?

Can we detect complex dynamics in neuronal activity and explain it through models?

Can we infer structural connectivity from neuronal activity?

"Structural degeneracy"

Can we build models of realistic circuits? Do their structure really matters?

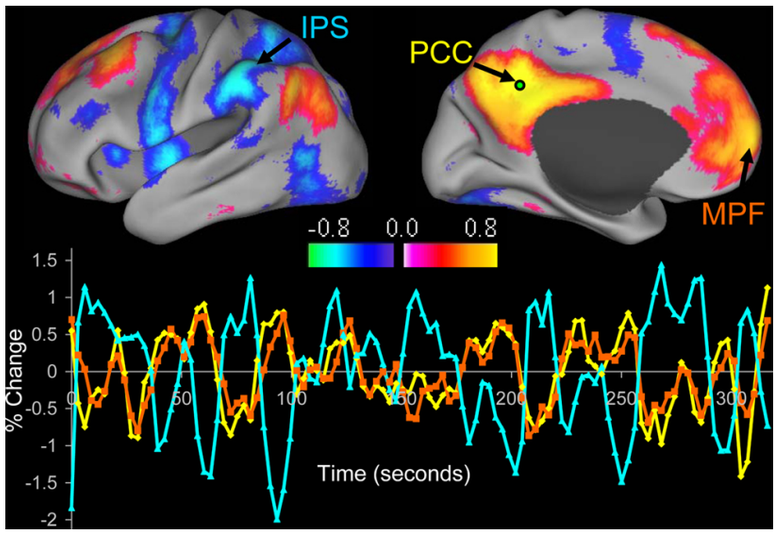
How to quantify functional interactions?

How to change functional connections without changing structural connections?

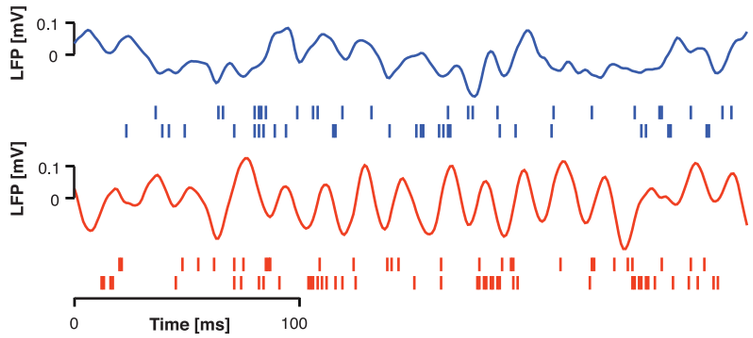
A zoo of measures

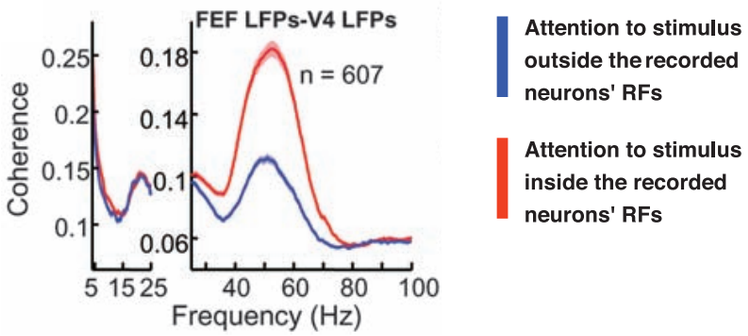
Correlation

(lagged or not lagged, time-domain or spectral coherence)



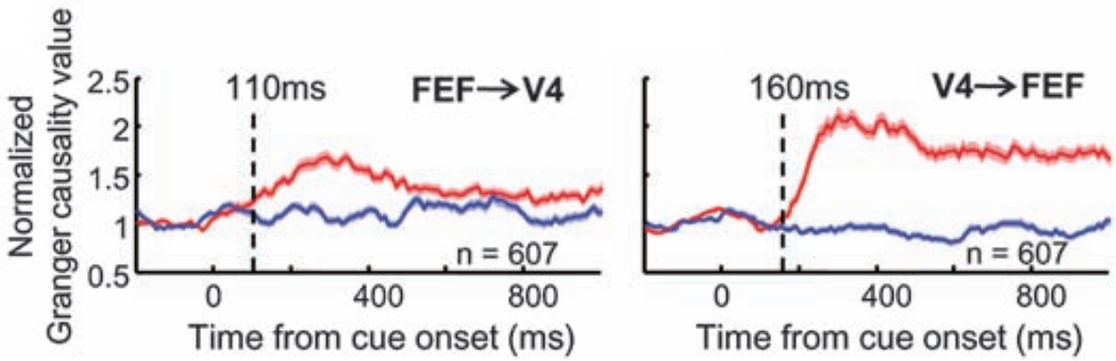
Resting state





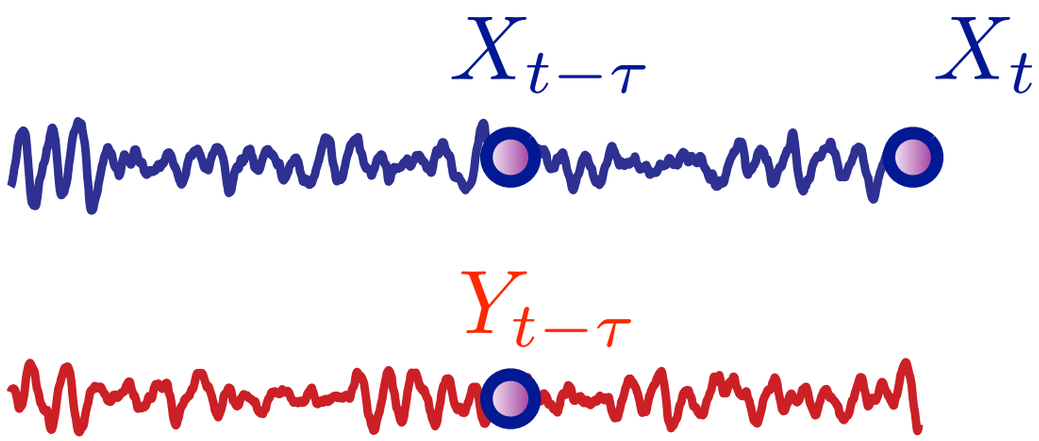
Electrophysiology

Directed coupling, Granger causality



Adapted from Gregoriou et al., 2009

Probing information!



How much information is present in neural activity?

(at a given location, in a given time range?)

How much information is shared between two sites?

Information about which input stream?

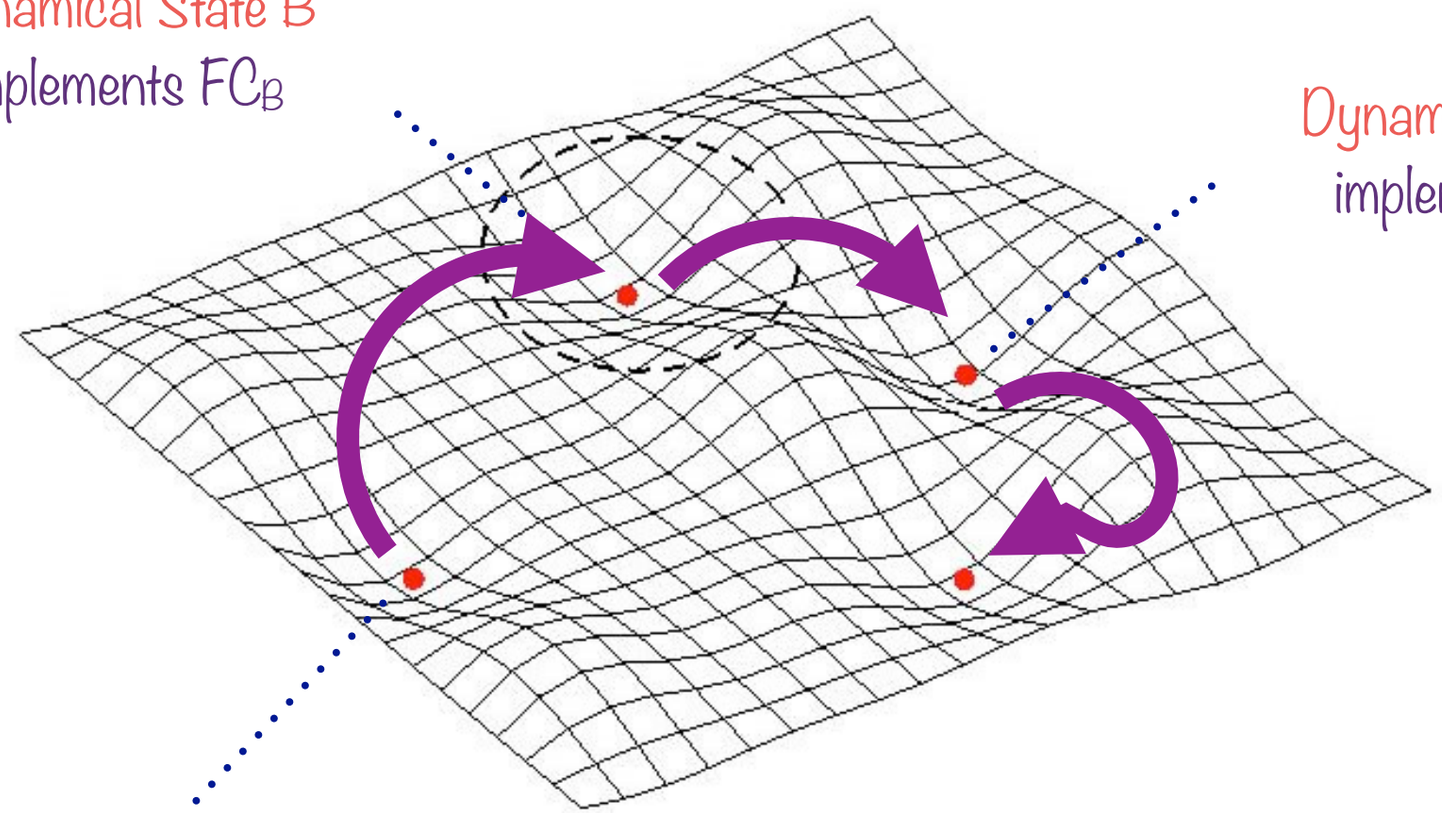
What is the "algorithmic role" of a network node? Storing, transferring or modifying information?

How to quantify functional interactions?

How to change functional connections without changing structural connections?

"Functional multiplicity"

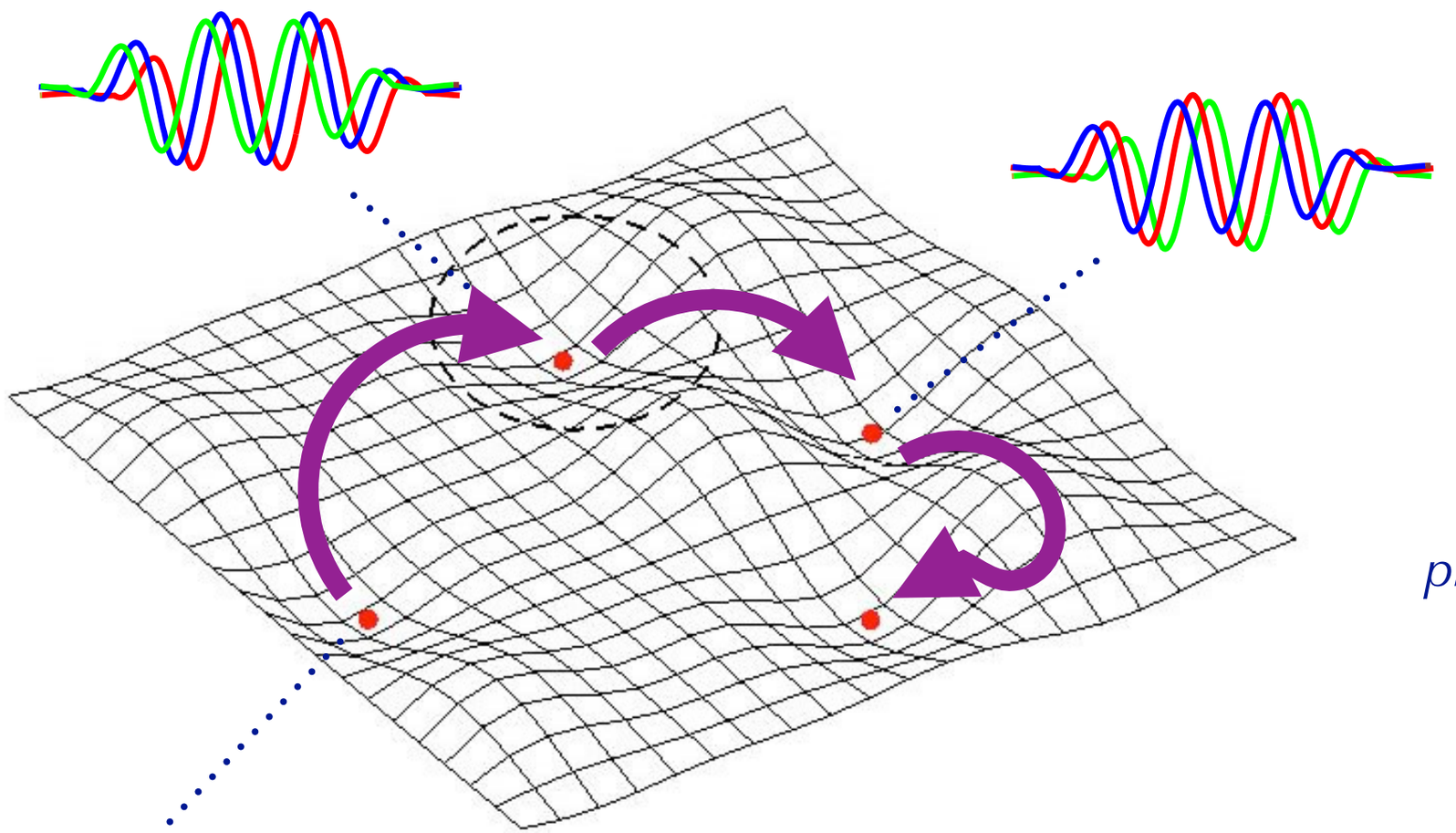
Flexible interactions from dynamical state switching



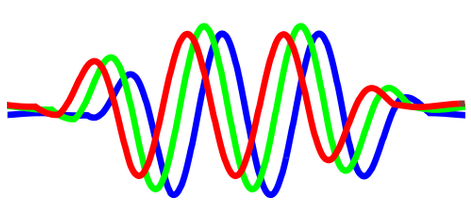
NB: collective states of the system, not of the components

One structural network ➠ many dynamical states

Flexible interactions from flexible oscillatory patterns

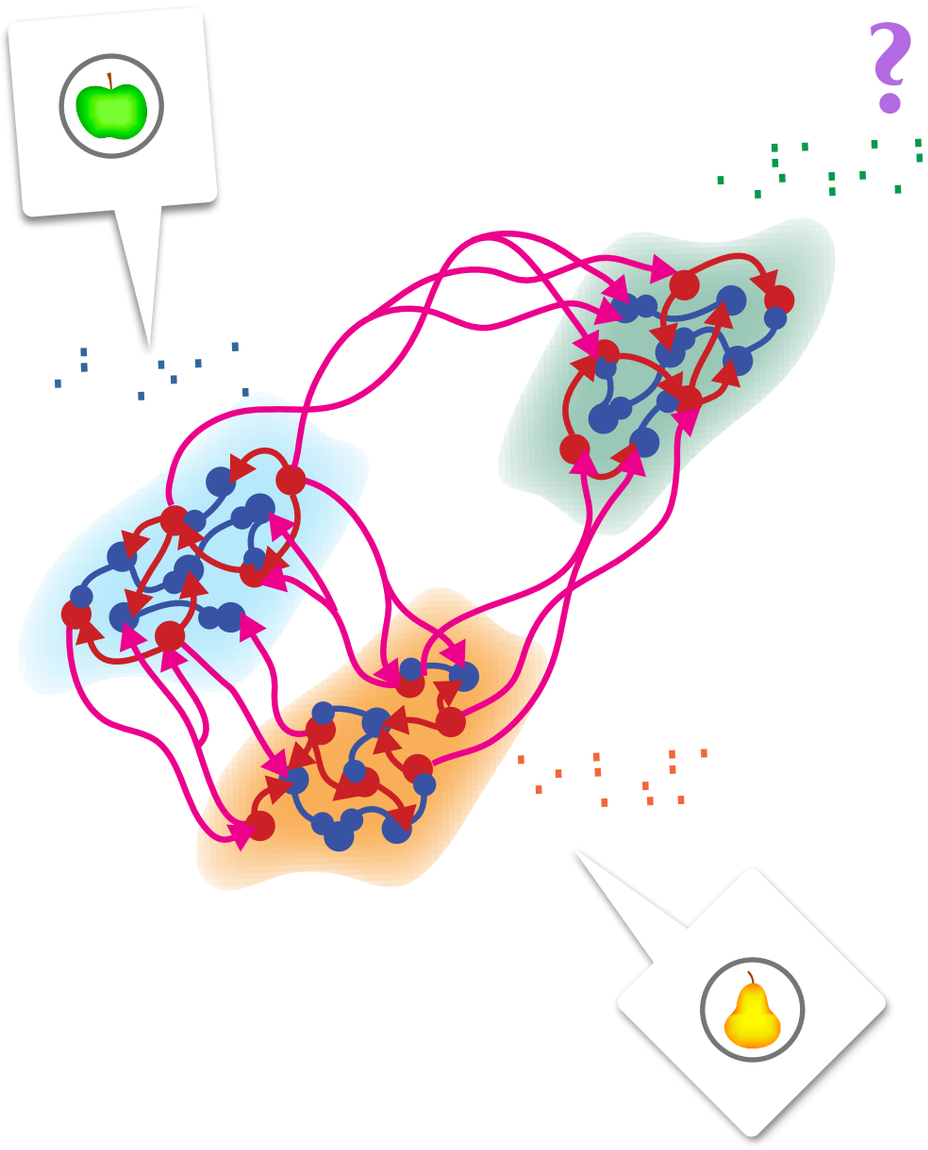


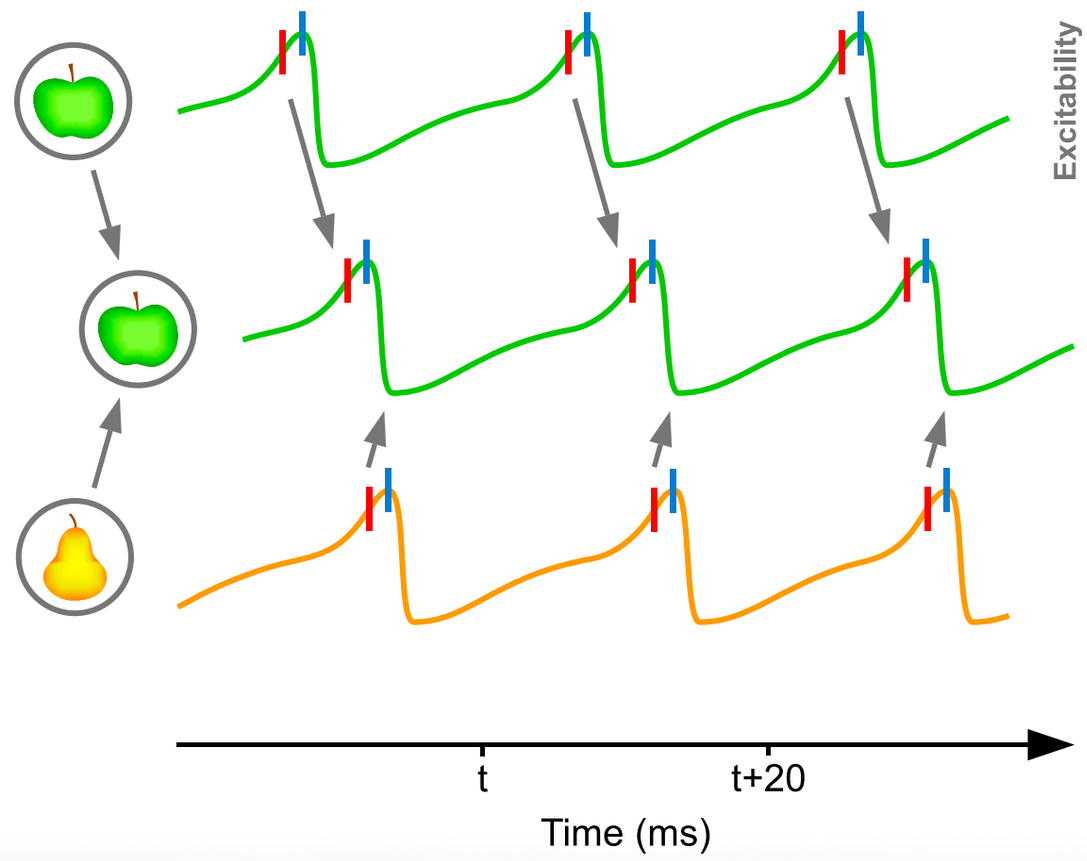
e.g. multistable phase locking patterns, periodic vs chaotic rhythms, etc.

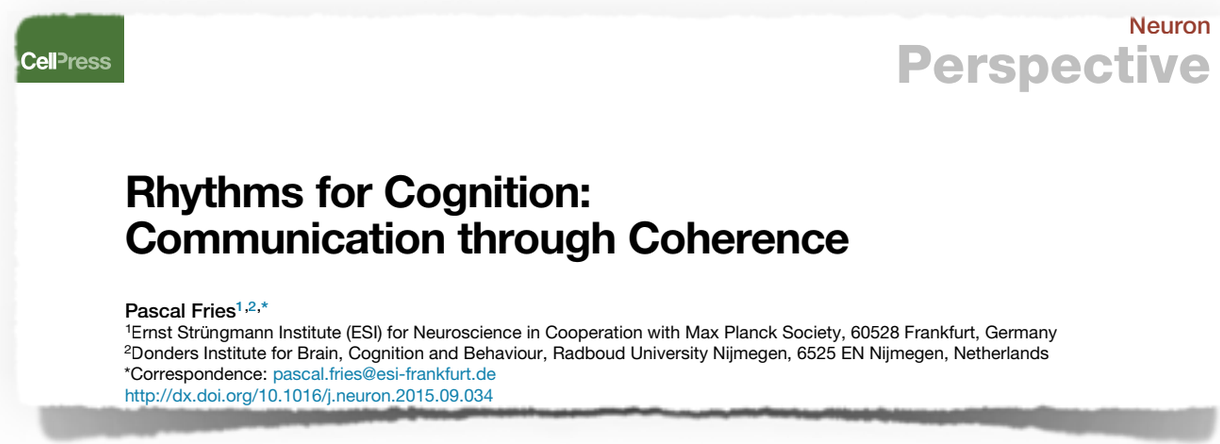


One structural network ➠ many oscillatory states

Communication-through-coherence







CellPress

Neuron

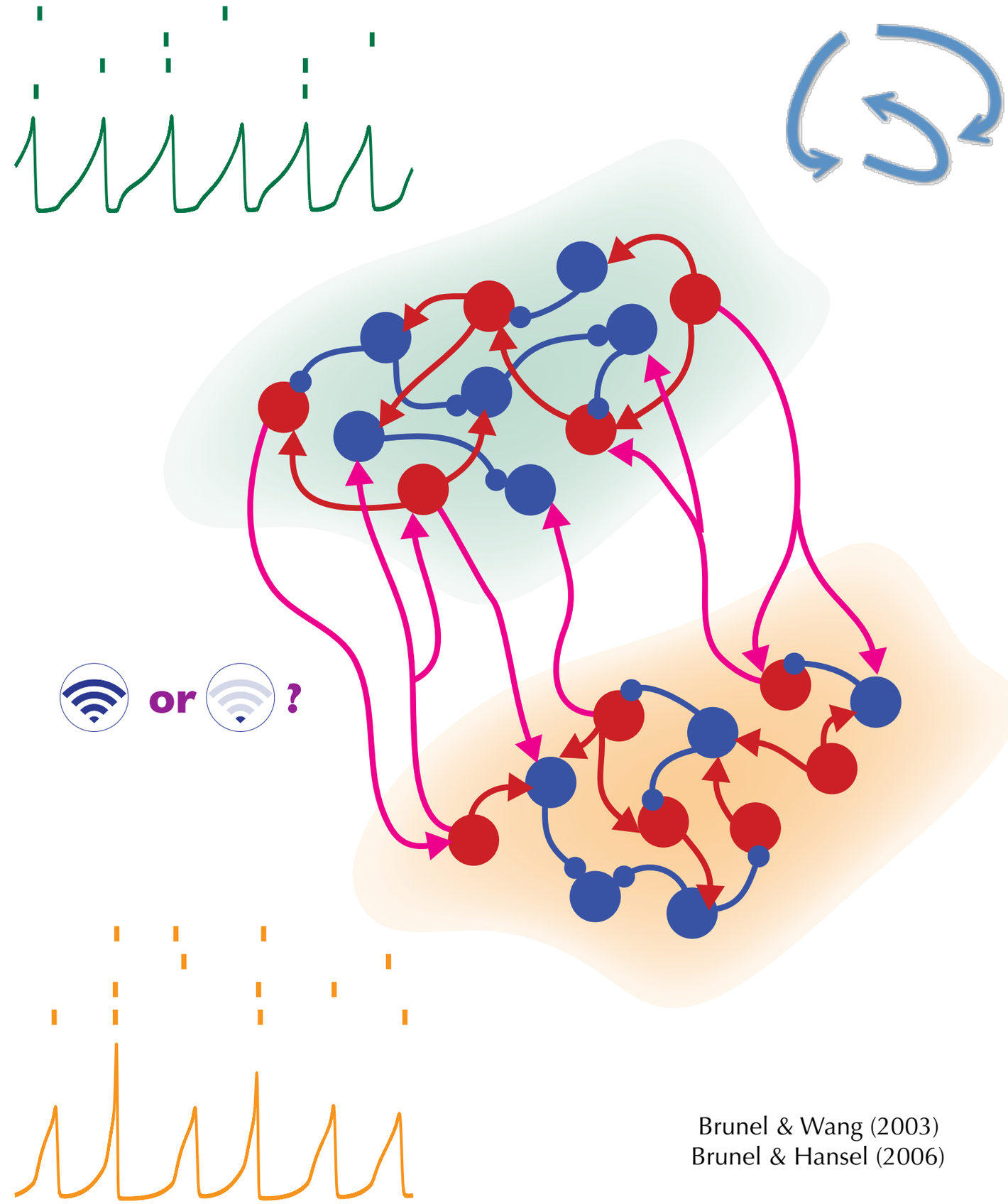
Perspective

Rhythms for Cognition: Communication through Coherence

Pascal Fries[1,2,*]
[1]Ernst Strüngmann Institute (ESI) for Neuroscience in Cooperation with Max Planck Society, 60528 Frankfurt, Germany
[2]Donders Institute for Brain, Cognition and Behaviour, Radboud University Nijmegen, 6525 EN Nijmegen, Netherlands
*Correspondence: pascal.fries@esi-frankfurt.de
http://dx.doi.org/10.1016/j.neuron.2015.09.034

Let's build a model!

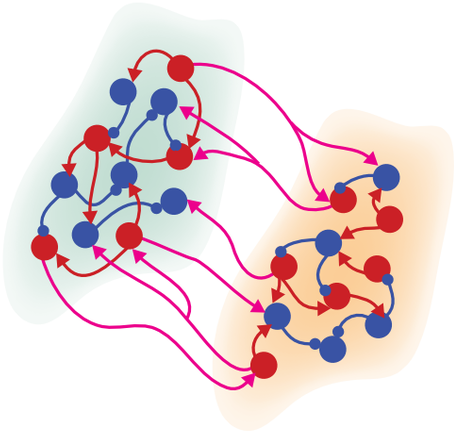
- **Network models** of interacting populations
  - **Locally-generated oscillations (e.g. γ)**
  - **Sparse synchronization**
- Quantify directed **functional interactions** from **simulated** LFPs and spike trains



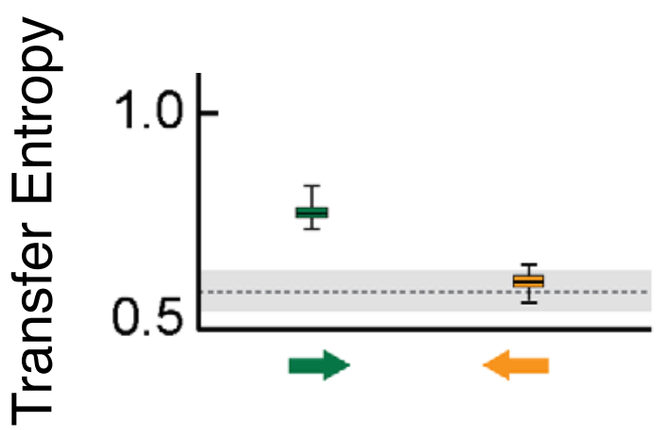
Brunel & Wang (2003)
Brunel & Hansel (2006)

DB, Brunel & Hansel (2007)

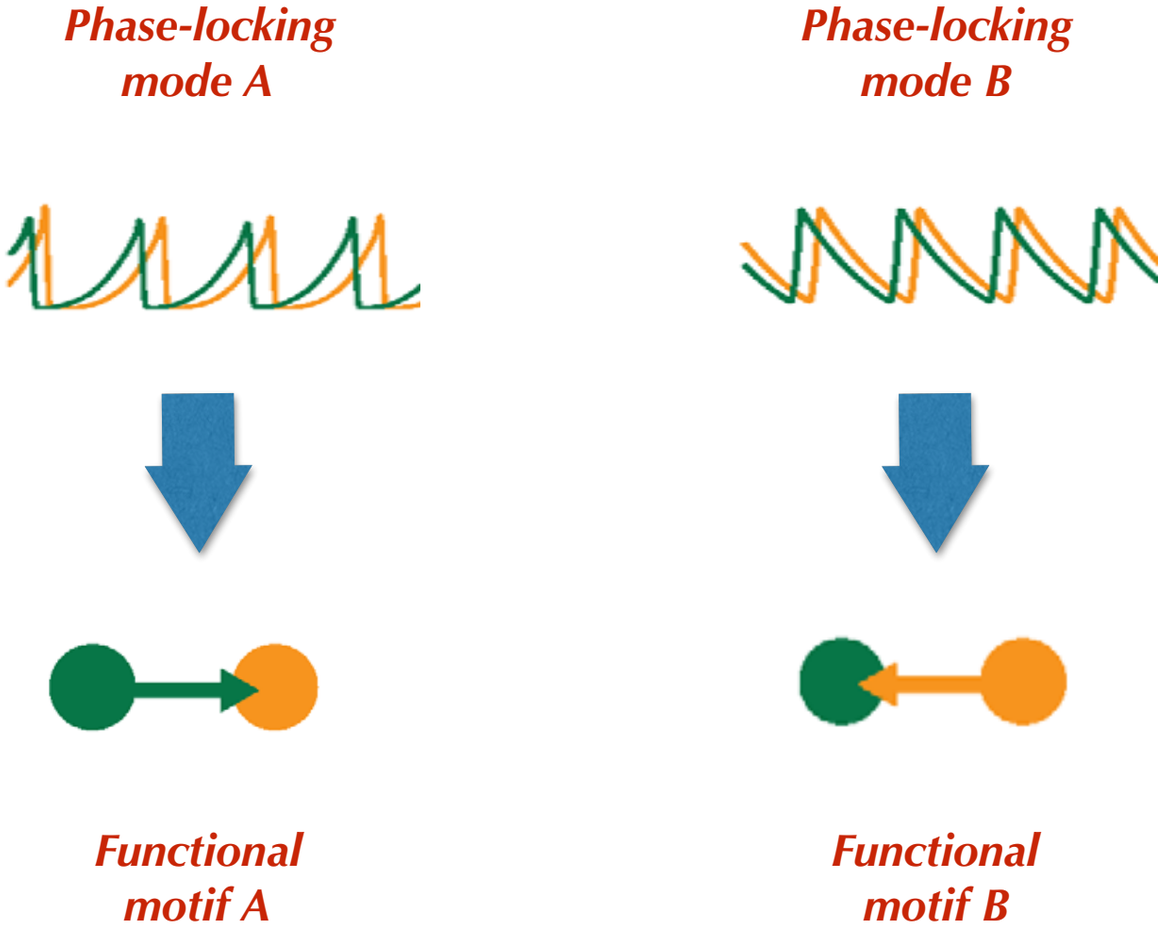
Rich routing repertoire



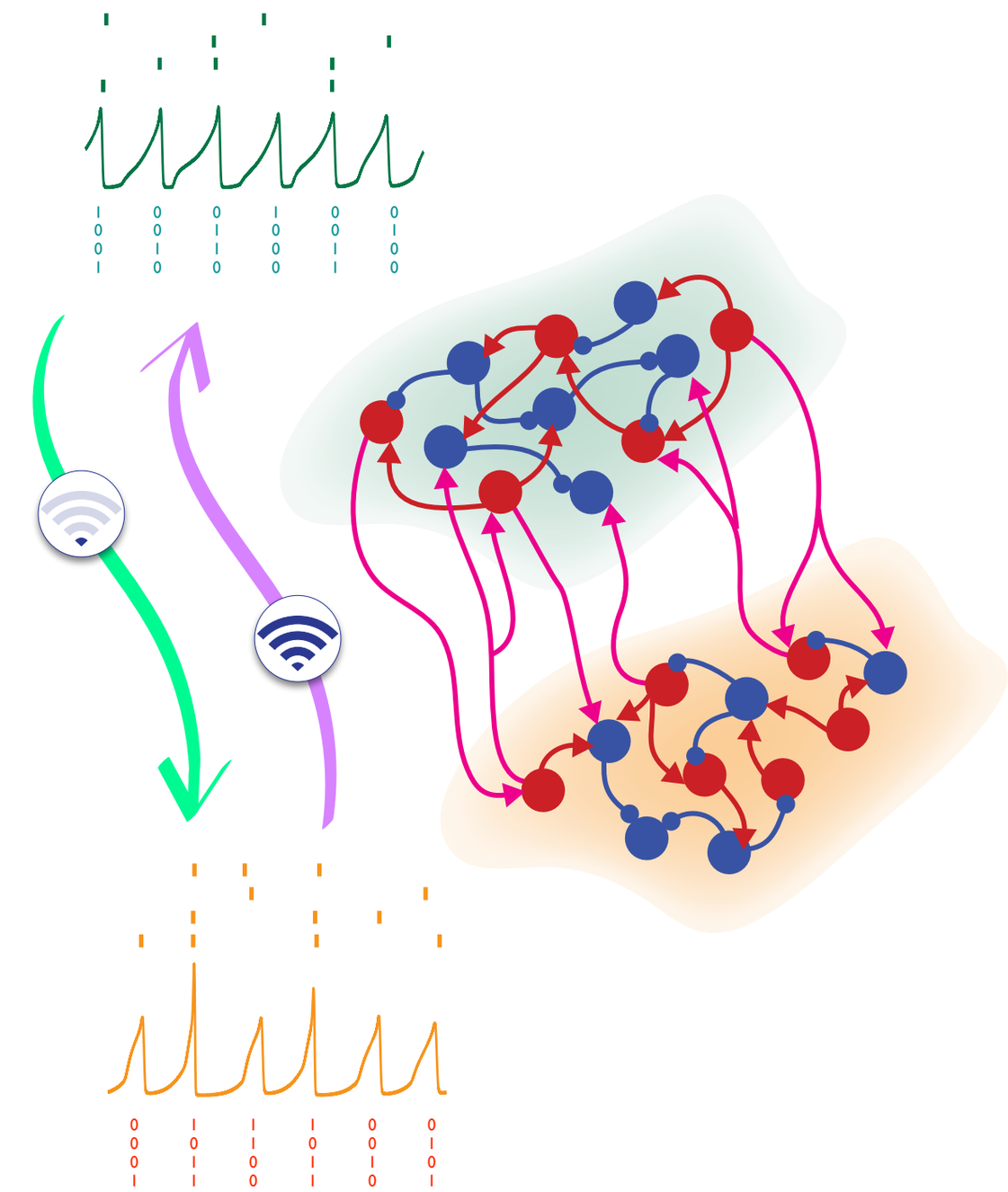
Dynamic multi-stability



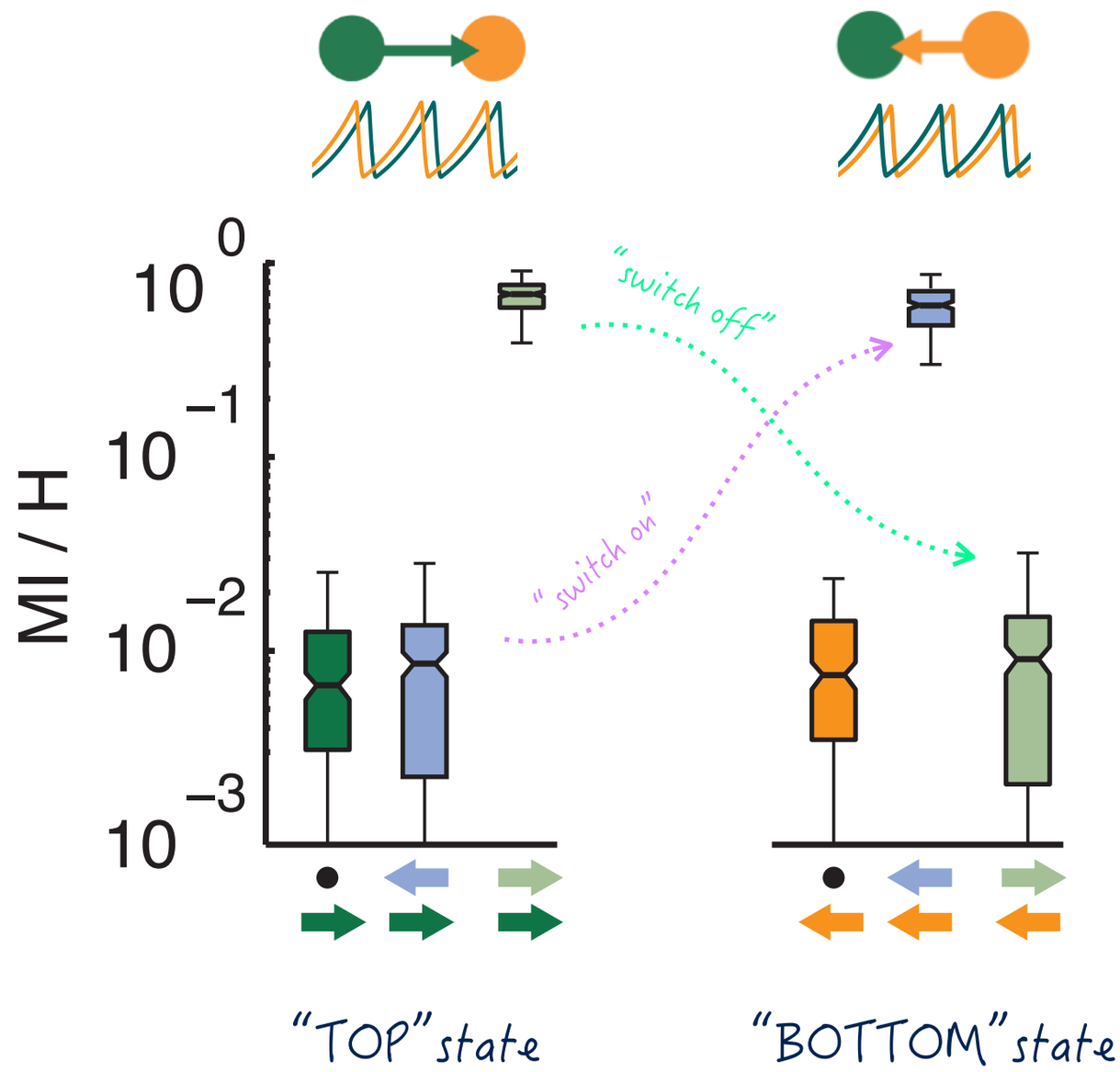
State-dependent information transfer



Re-routing via multi-stability

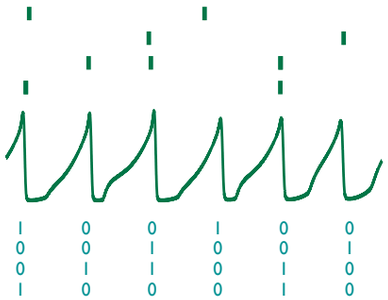


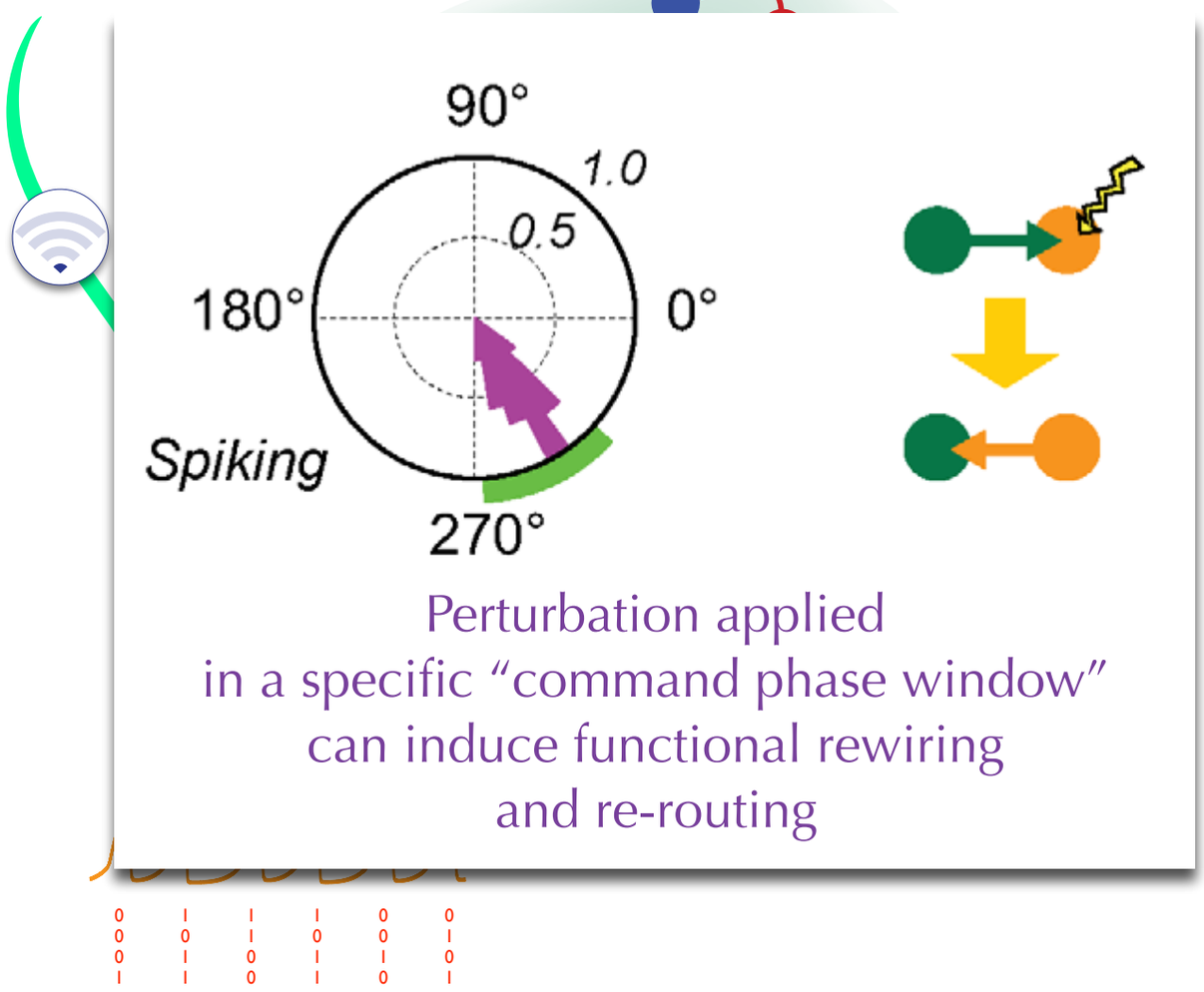
FUNCTIONAL STATE
in which the system is prepared



DB, Witt, Wolf & Geisel, PLoS CB (2012)
Witt et al., Front Neural Circuits (2014)

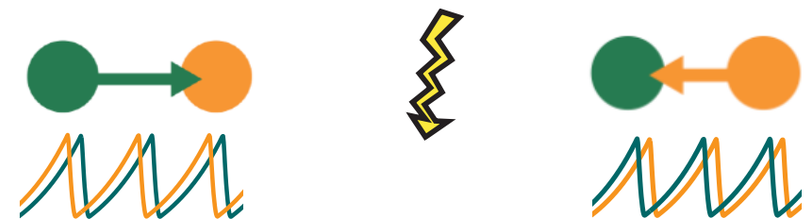
Re-routing via multi-stability

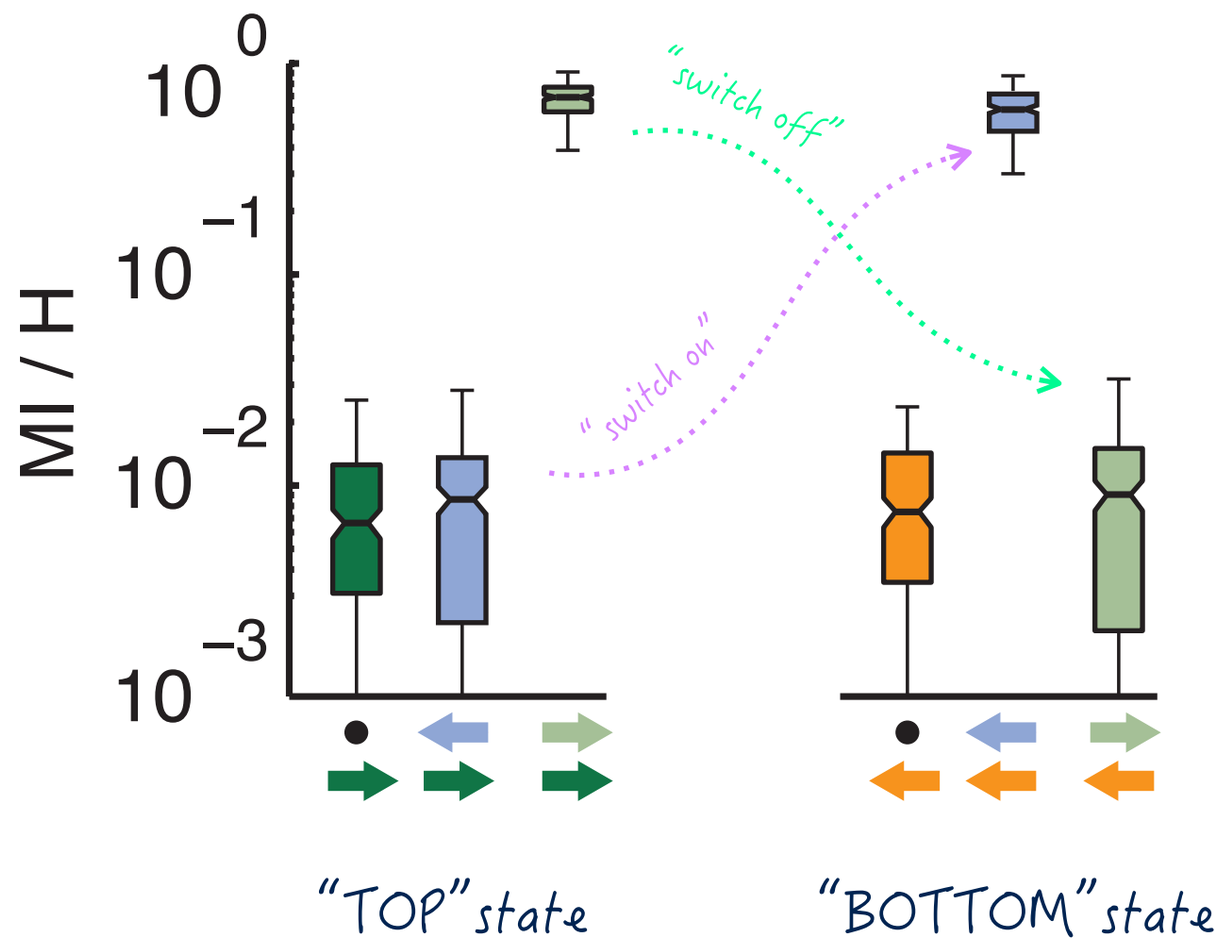




Perturbation applied
in a specific "command phase window"
can induce functional rewiring
and re-routing

FUNCTIONAL STATE
in which the system is prepared

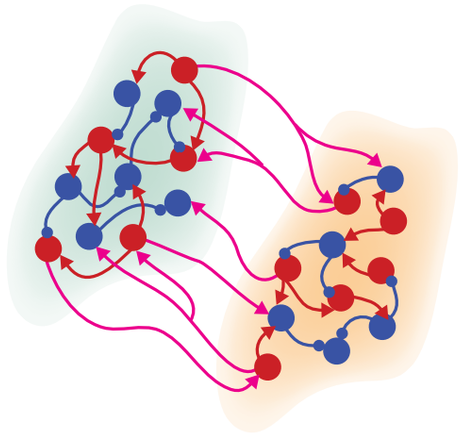


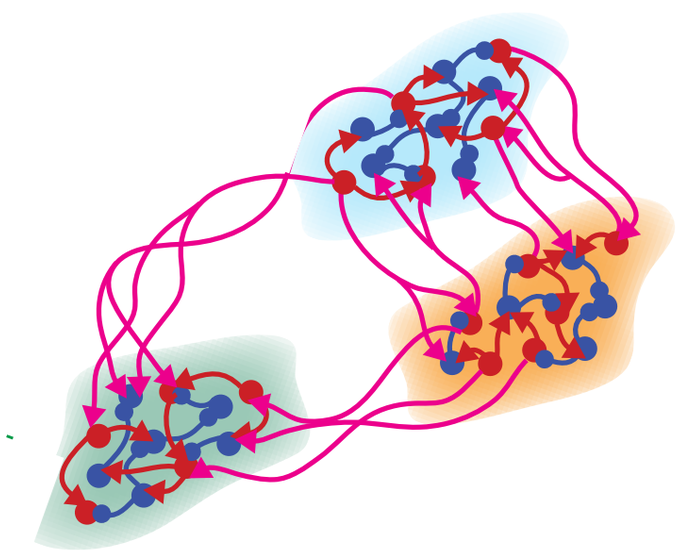


DB, Witt, Wolf & Geisel, PLoS CB (2012)
Witt et al., Front Neural Circuits (2014)

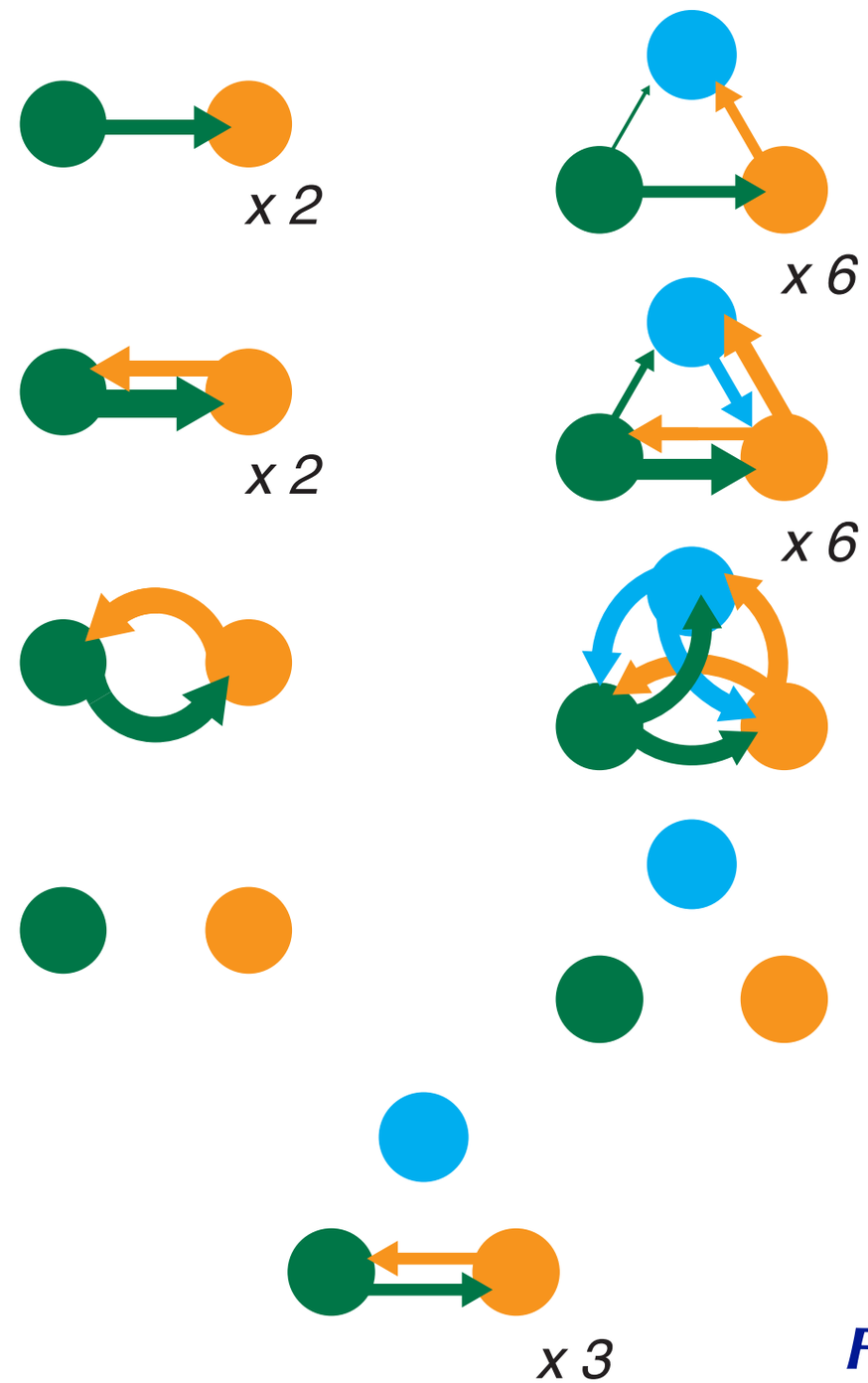
Structural motifs

Actual information transfer measured through information theory tools





Transfer Entropy
from collective "LFP"

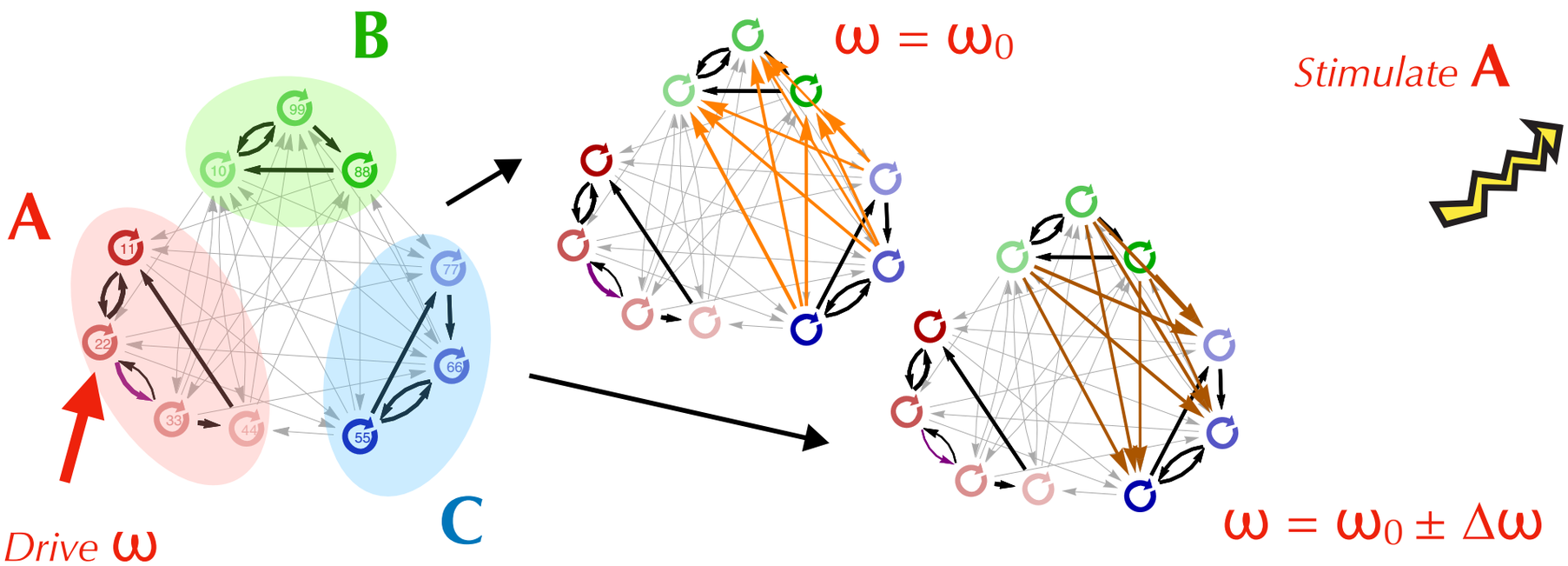


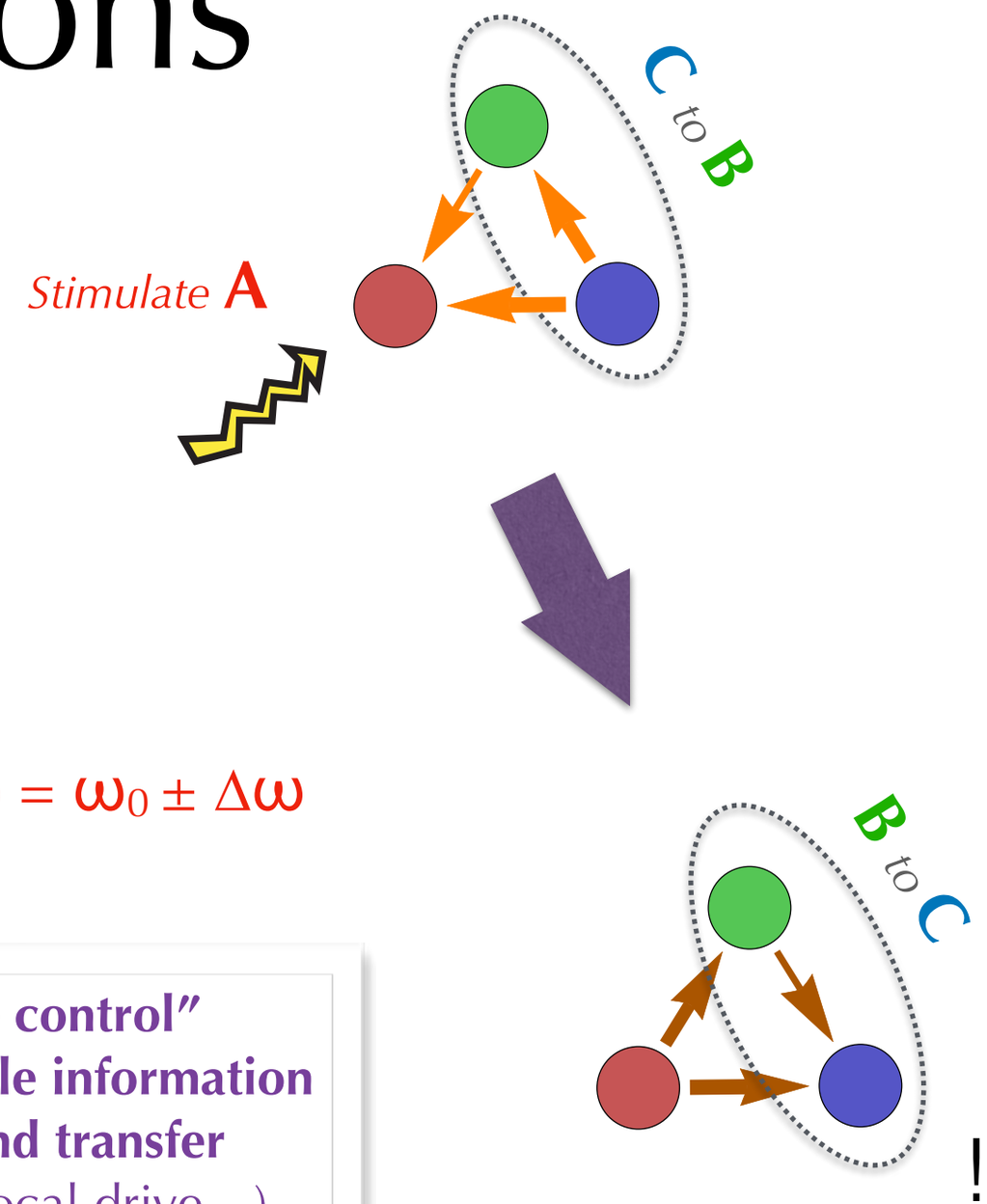
Functional motifs

A zoo of functional motifs!

DB, Witt, Wolf & Geisel, PLoS CB (2012)

Non-local effects of local manipulations





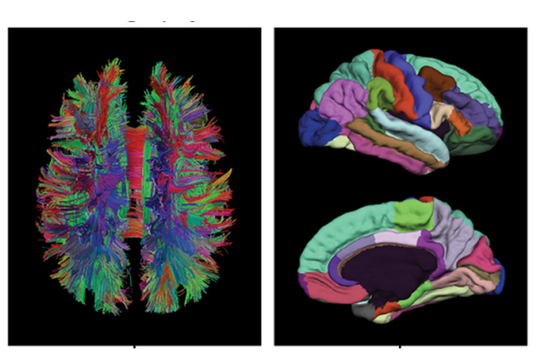
Christoph Kirst

"Remote control" of inter-module information sharing and transfer
(plasticity, local drive…)

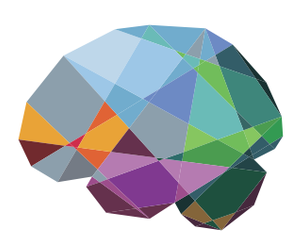
Kirst, Timme, DB, Nature Communications (2016)

If it is already a mess with $N = 2,3$ regions, let's think about $N \sim 100$…

Structural Connectome

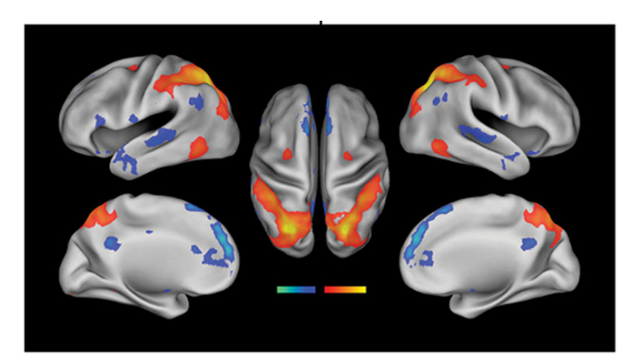


Dynome!



THEVIRTUALBRAIN.

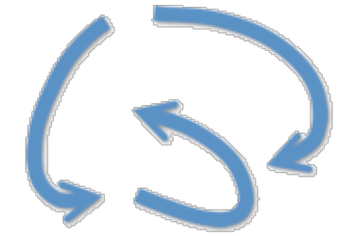
Functional Connectome



Are functional dynamics analyses useful for concrete applications?

Can we detect complex dynamics in neuronal activity and explain it through models?

Dyn
Gnome



From the “dynome" to the “chronnectome”

(Calhoun et al. 2014)

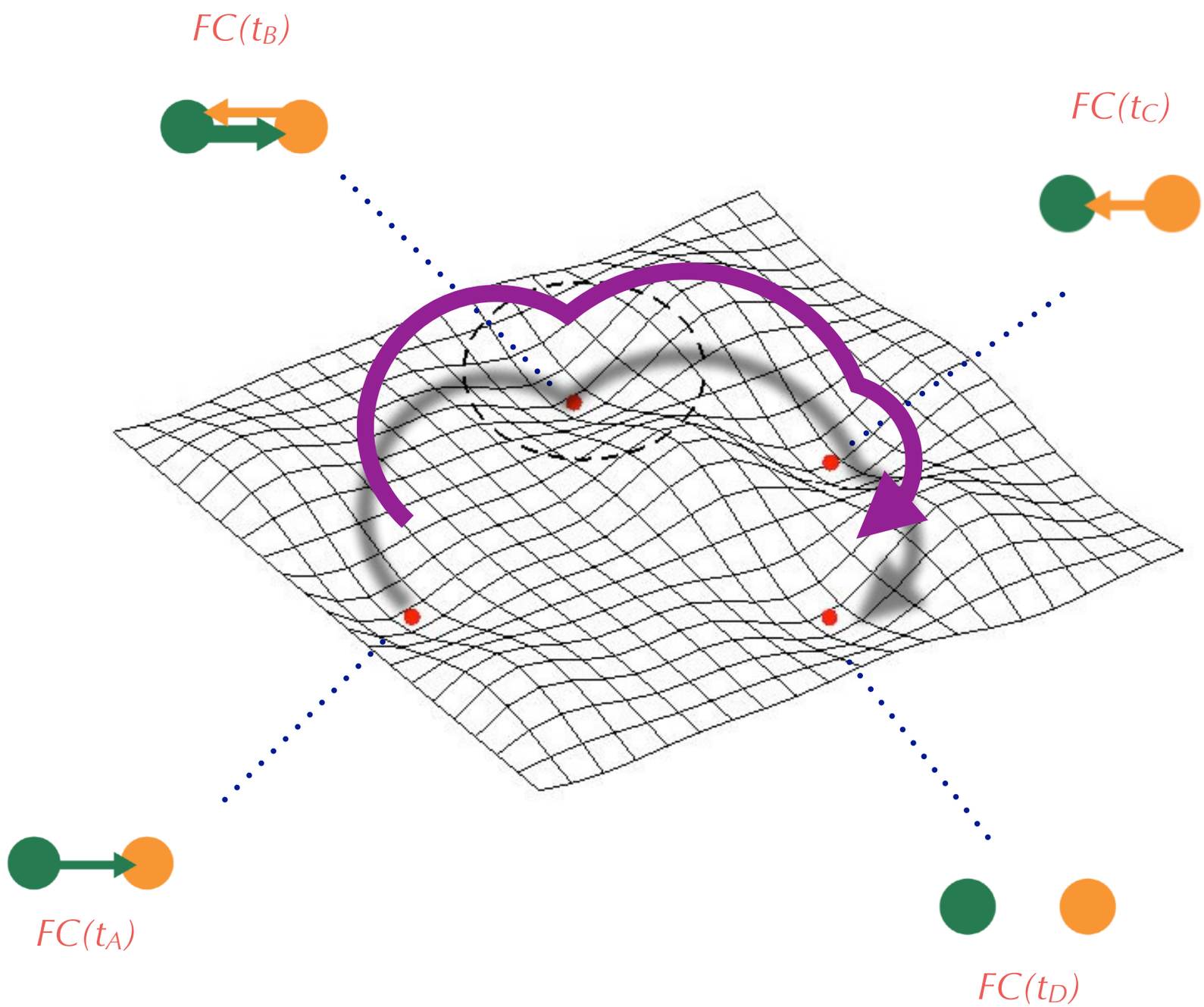
Chronnect
Gnome

Connect
Gnome

The Chronnectome: Time-Varying Connectivity Networks as the Next Frontier in fMRI Data Discovery

Vince D. Calhoun,[1,2,*] Robyn Miller,[1] Godfrey Pearlson,[4] and Tulay Adalı[3]
[1]The Mind Research Network & LBERI, Albuquerque, NM 87106, USA
[2]Department of ECE, University of New Mexico, Albuquerque, NM 87131, USA
[3]Department of CSEE, University of Maryland, Baltimore County, Baltimore, MD 21250, USA
[4]Olin Neuropsychiatry Research Center, Hartford, CT 06114, USA
*Correspondence: vcalhoun@unm.edu

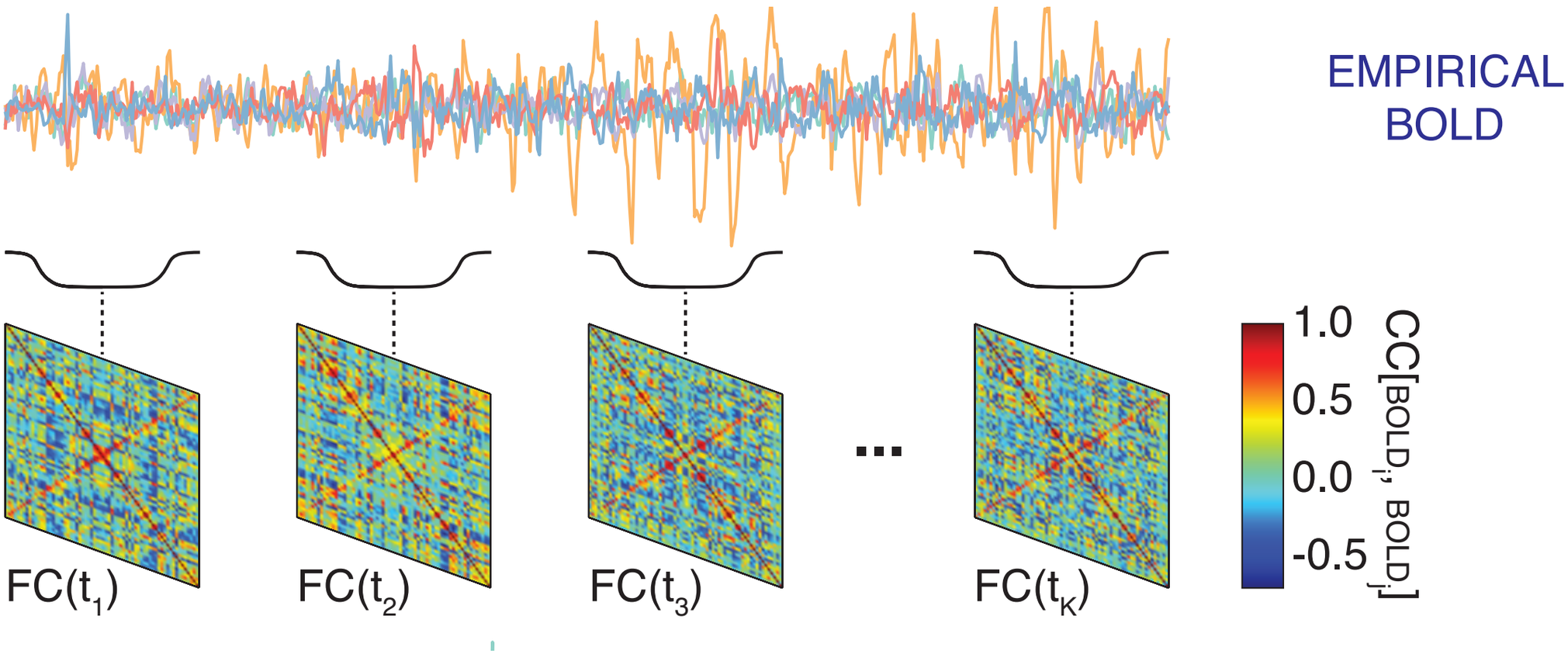
Noise-driven sampling ➠ time-dependent connectivity



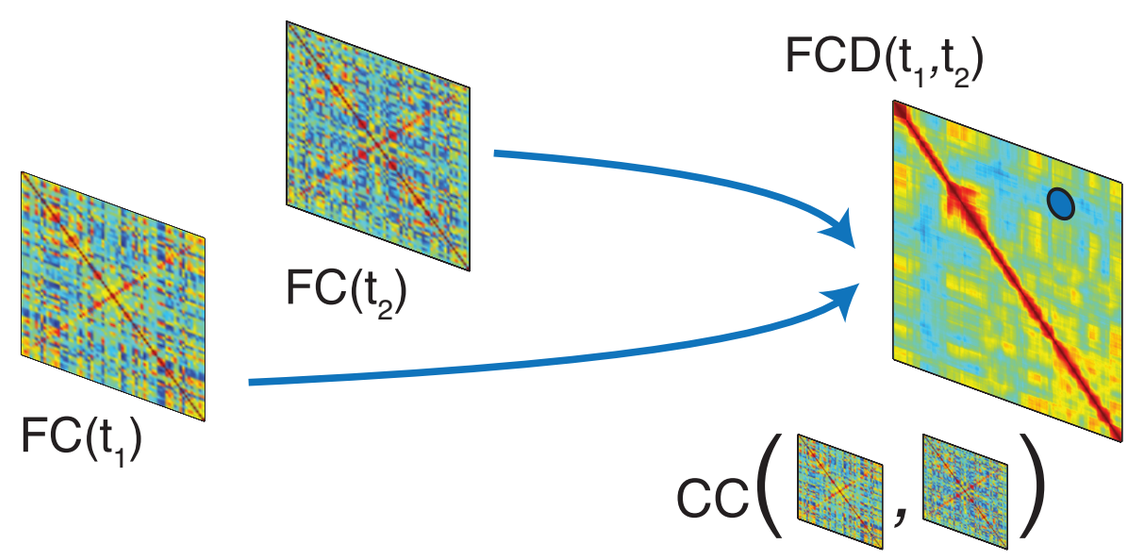
Completely different scales…

Resting state BOLD

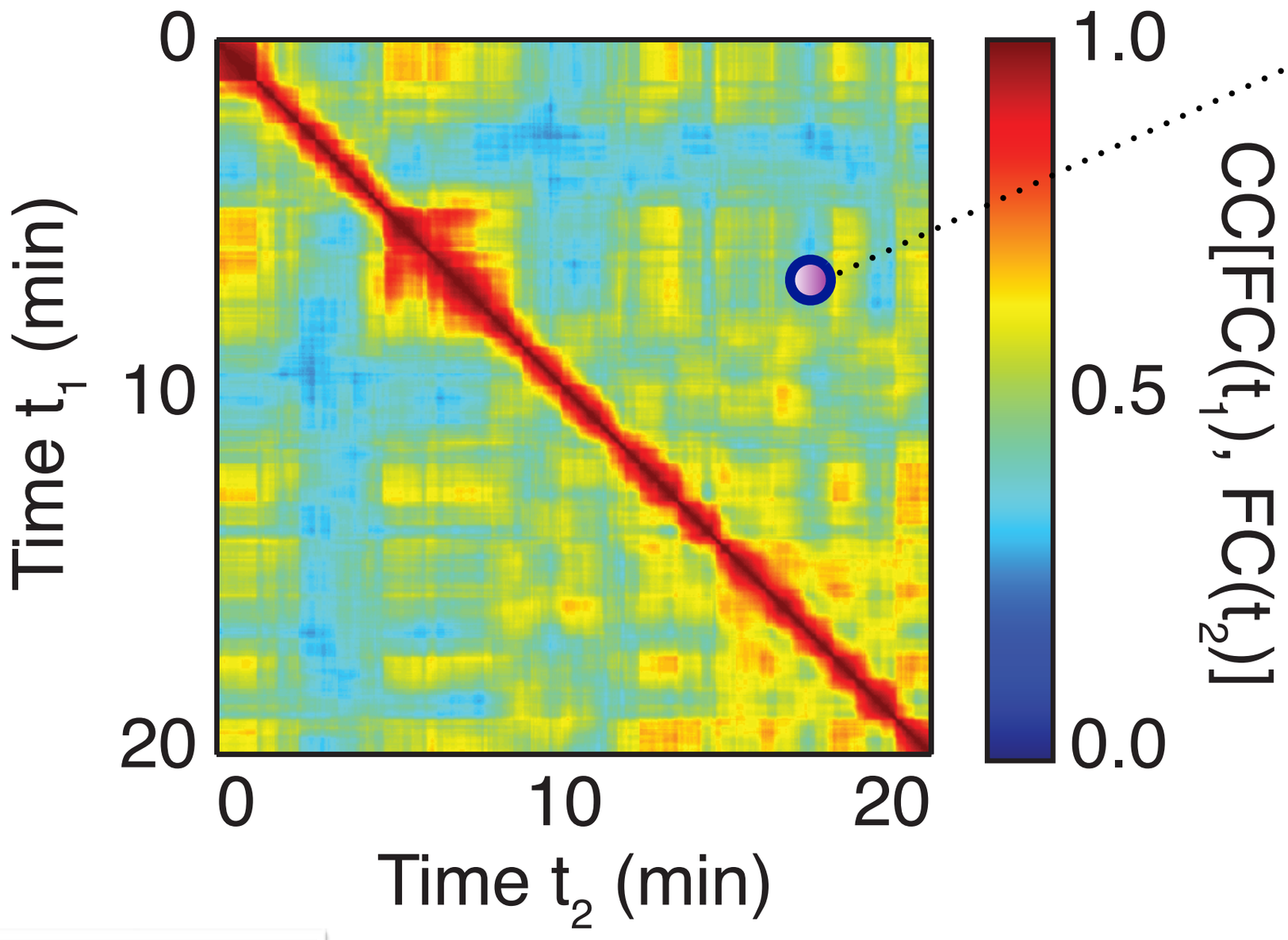
Seeking for rs FCD…

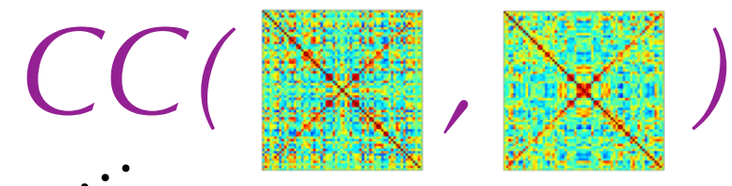


Sliding window analysis reveals time-dependent FC



Transiently stable FC states?





"Checker-board" correlations between FC networks at different times

"Clusters" of FC matrices

Allen et al. 2012
Hutchison et al. 2013
Hansen et al. 2015

rsfMRI data from Petra Ritter
66 regions parcelation

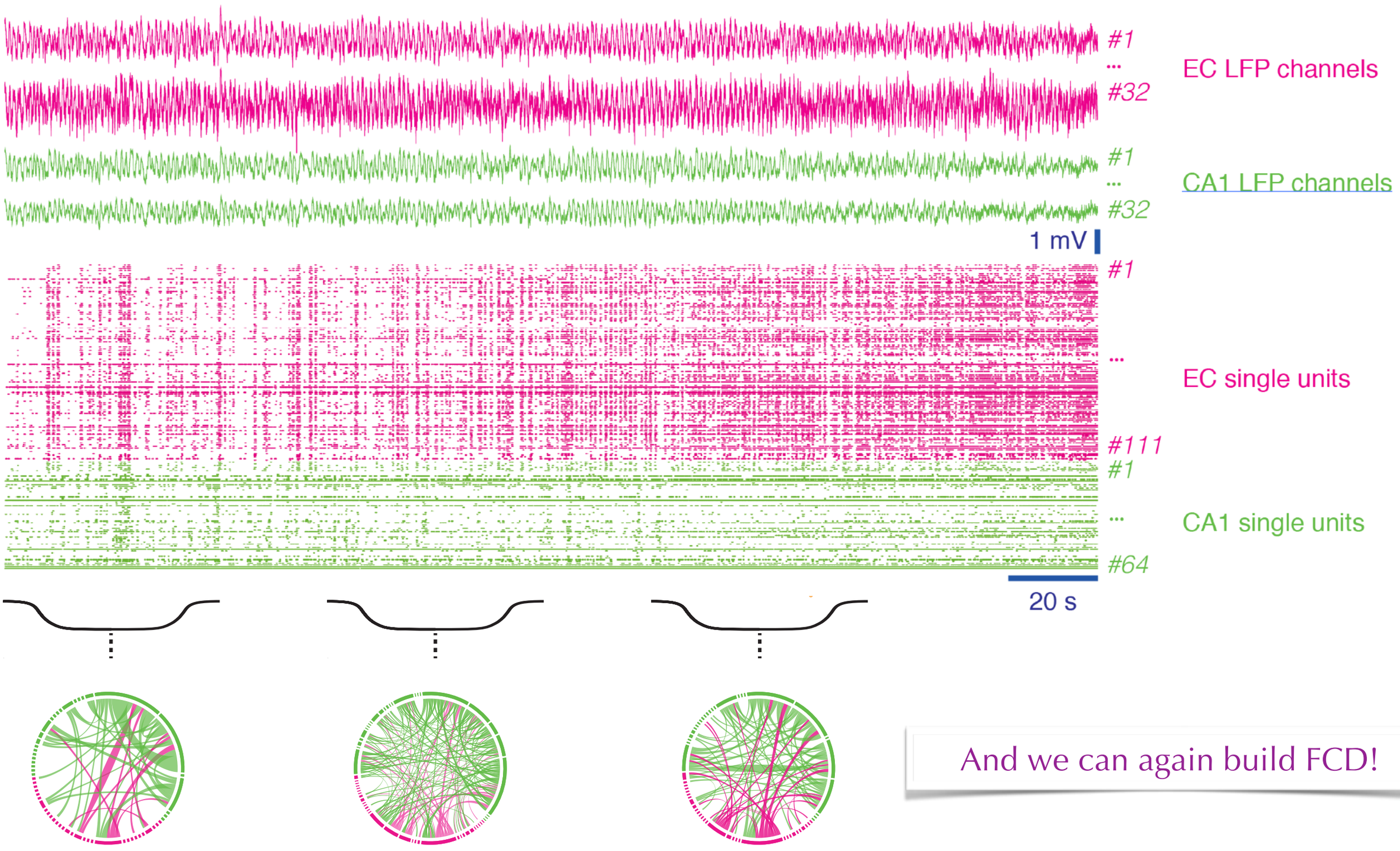
FCD matrix

Battaglia et al., bioRxiv (2020); Lombardo et al., bioRxiv (2020)

But we are not bound to one scale!

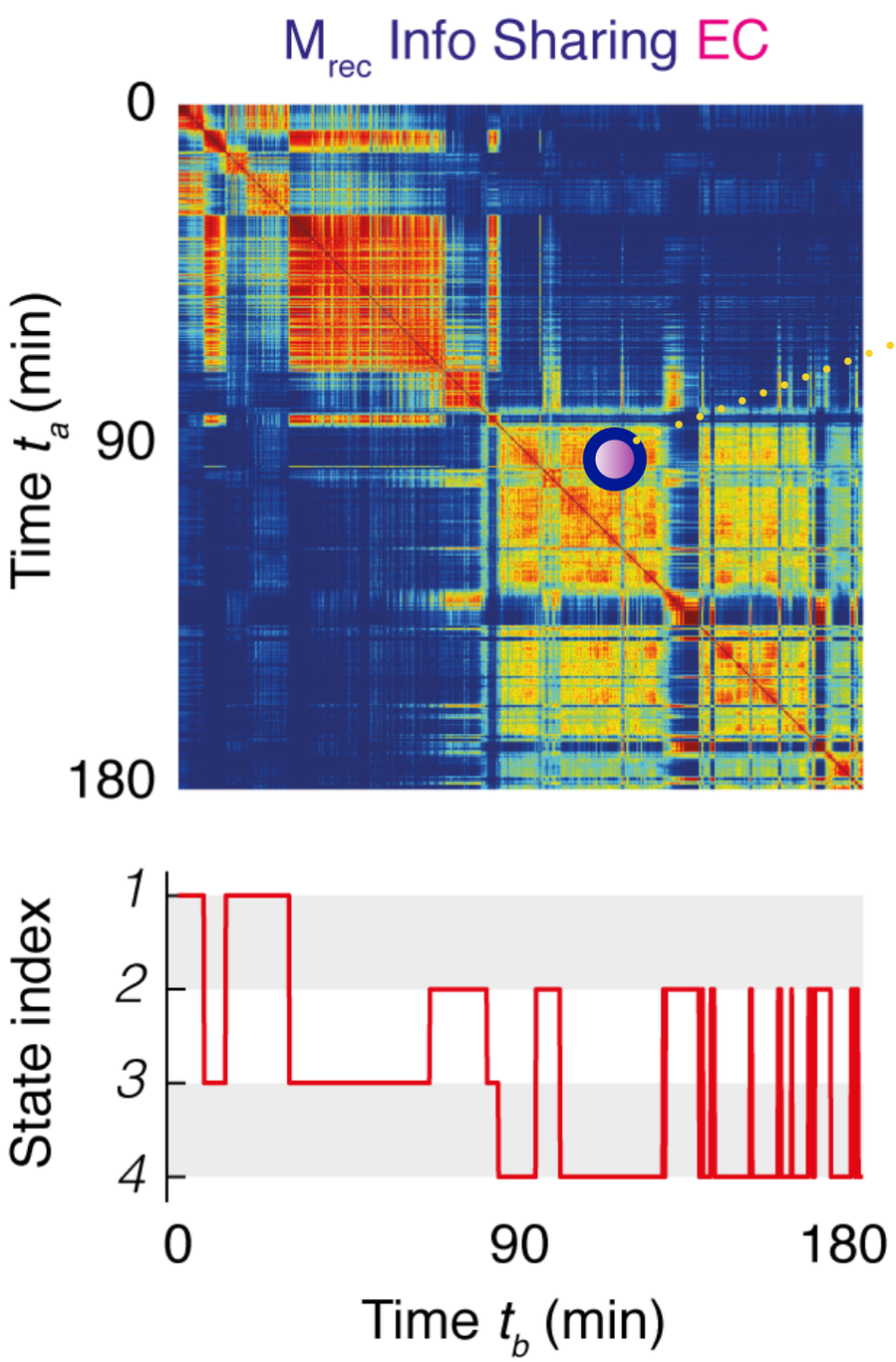
Back to electrophysiology!

Seeking for FCD…



And we can again build FCD!

Discrete FC states



CC( , )

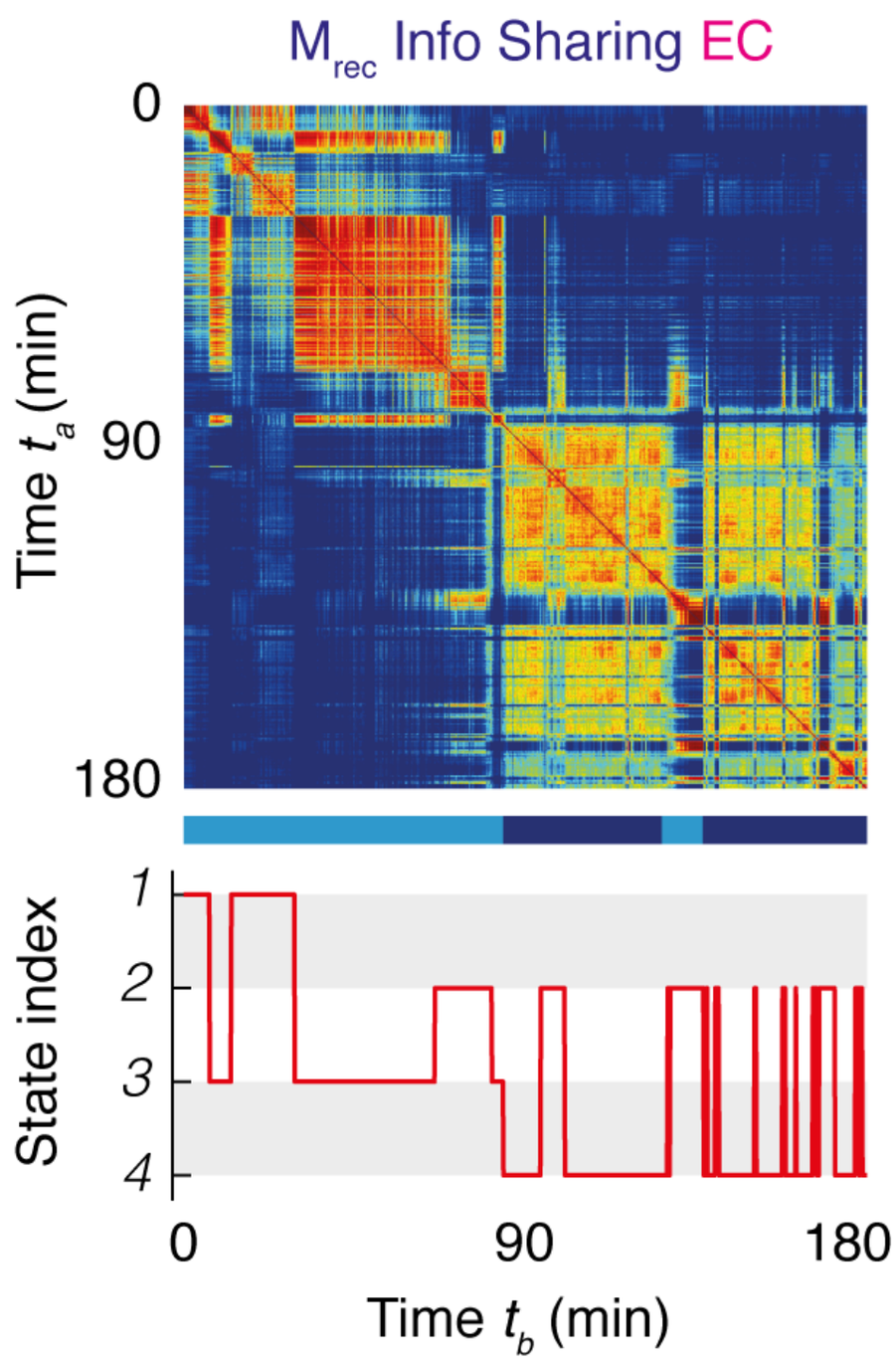
"Checker-board" correlations between FC networks at different times

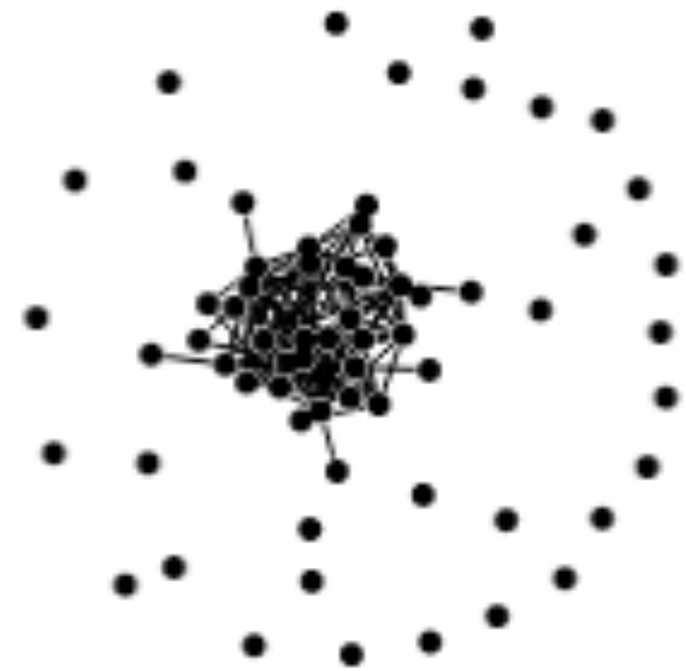
"Clusters" of FC matrices

Pretty much the same as for BOLD!

Clawson et al., Science Advances (2019)
Pedreschi et al., bioRxiv (2020)

Discrete FC states

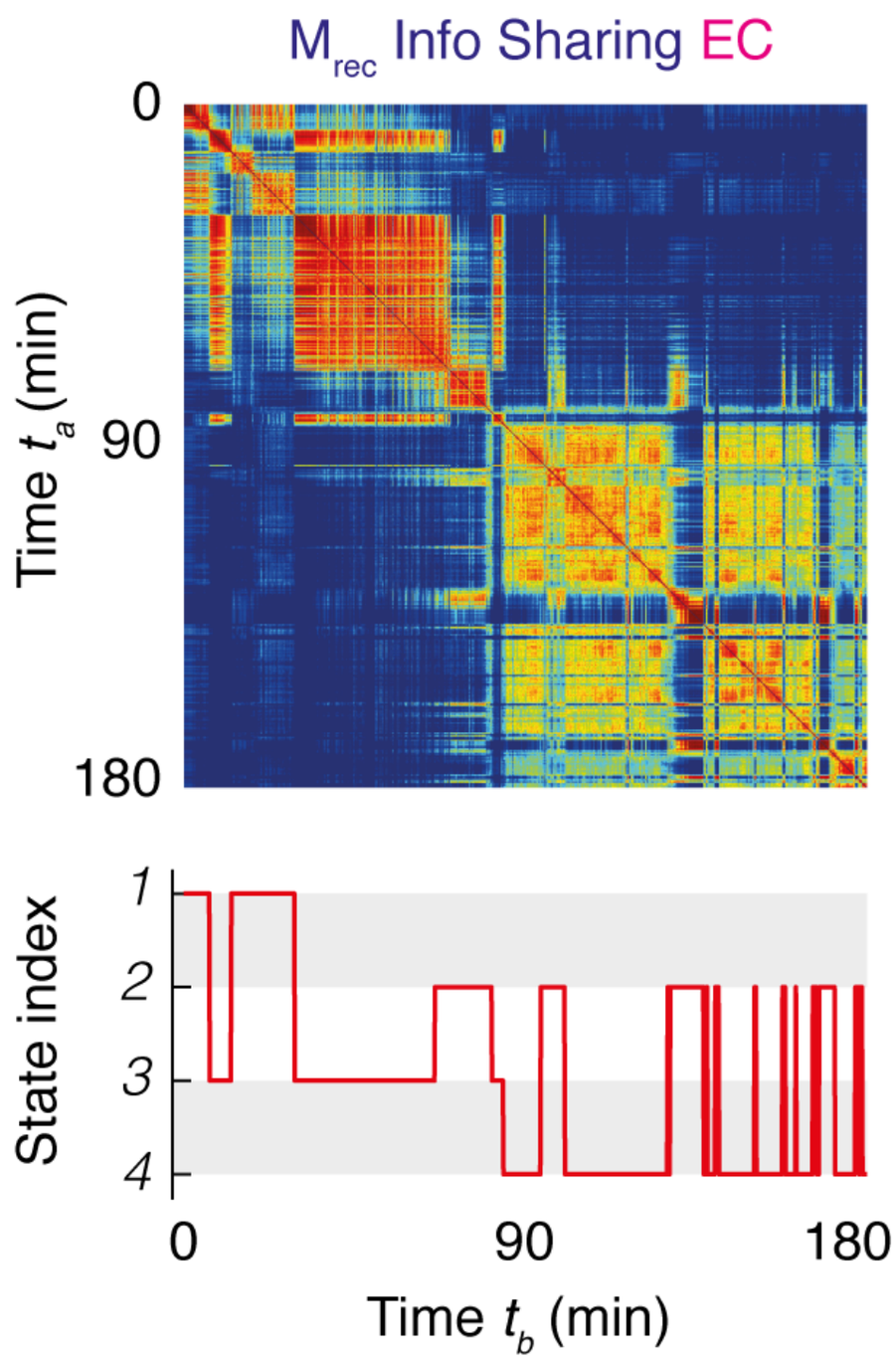


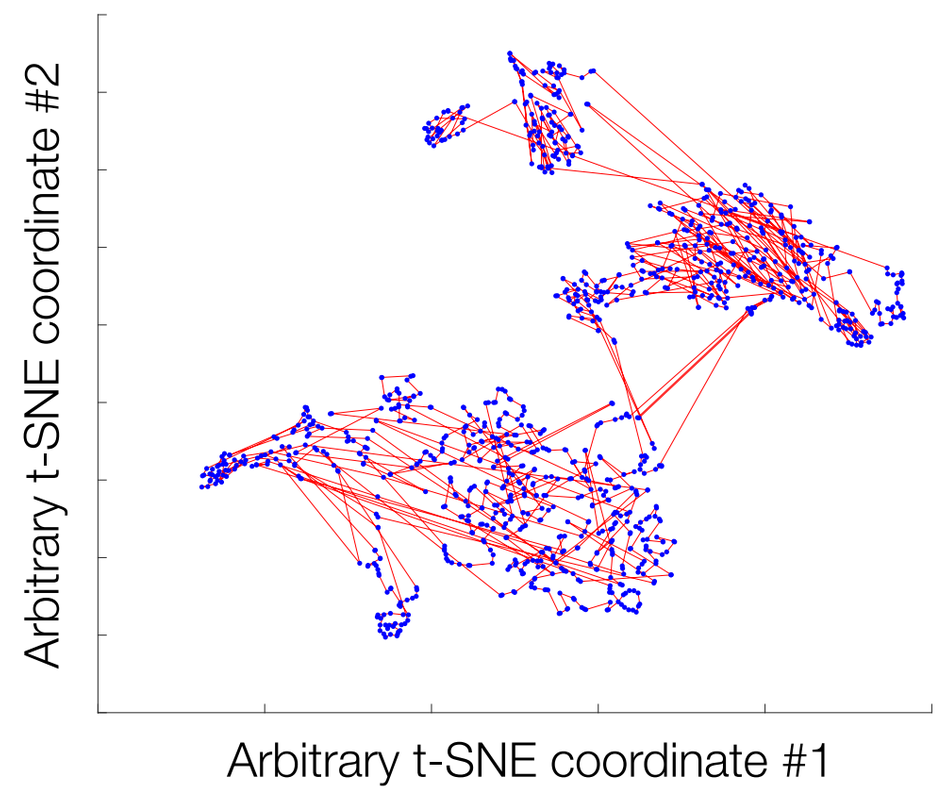


Liquid core-periphery temporal network

Nicola Pedreschi
(in collaboration with Alain Barrat, CPT)

Discrete FC states





Stochastic exploration of FC space

Clawson et al., Science Advances (2019)
Pedreschi et al., bioRxiv (2020)

Dynamic functional connectivity analyses can reveal multiplicity of internal states

Can we detect complex dynamics in neuronal activity and explain it through models?