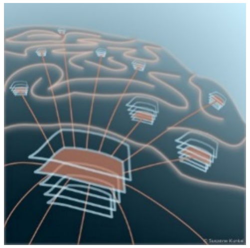
LARGE-SCALE SPIKING NEURAL NETWORK MODELS OF RESTING-STATE DYNAMICS IN PRIMATE CORTEX

BigBrain Workshop, 26 June 2020 | Sacha van Albada

Institute of Neuroscience and Medicine (INM-6), Jülich Research Centre & Institute of Zoology, University of Cologne, Germany



Human Brain Project

SPP 2041 Computational Connectomics

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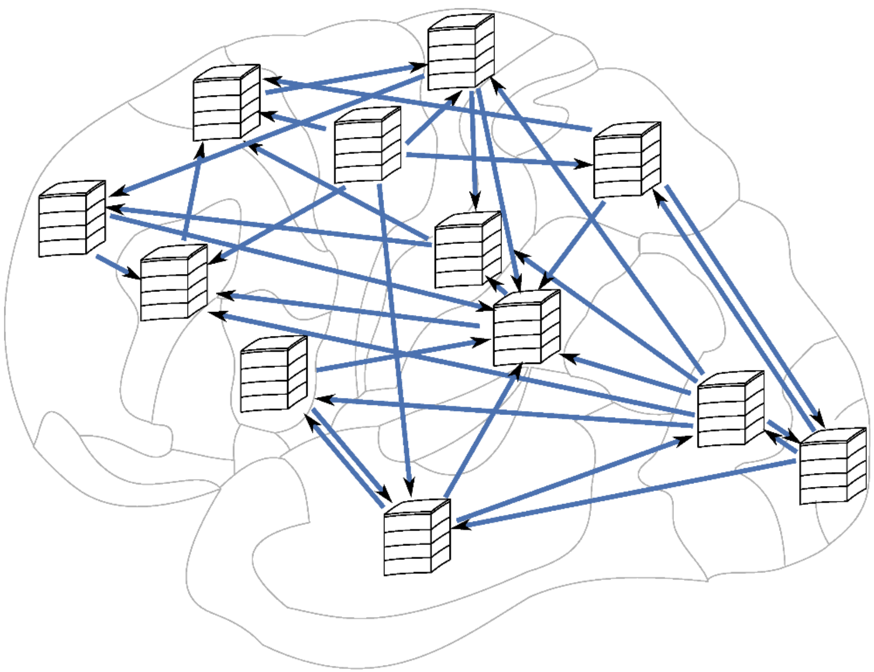
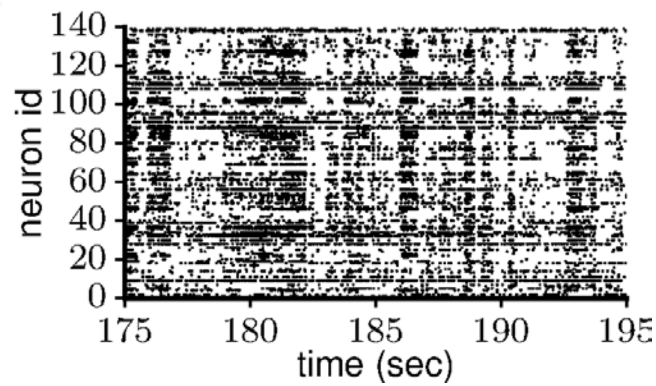
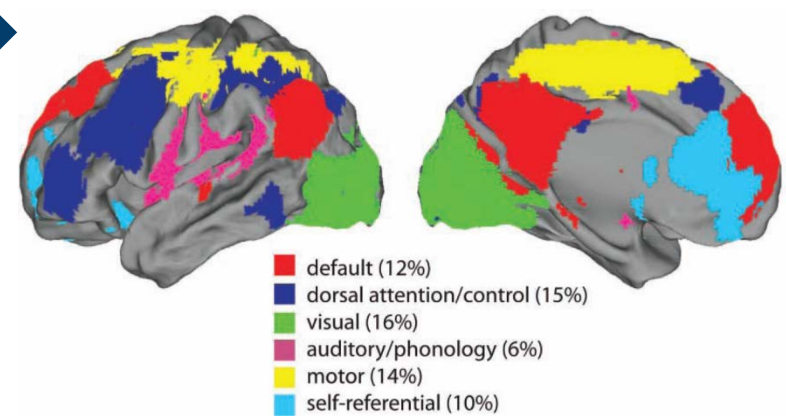
GOAL



?



Chu et al. (2014) *Vision Res*



Deco and Corbetta (2011)
The Neuroscientist

cortical connectivity

multi-scale resting-state dynamics

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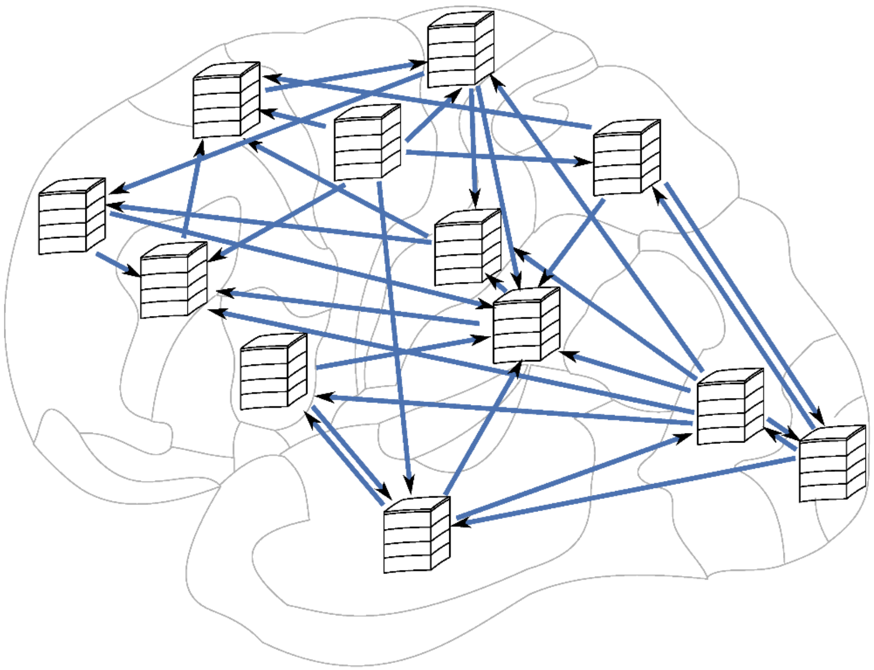
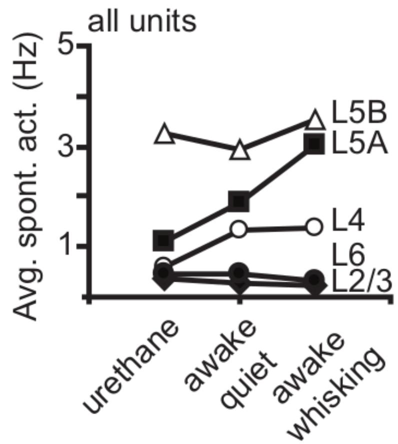
GOAL



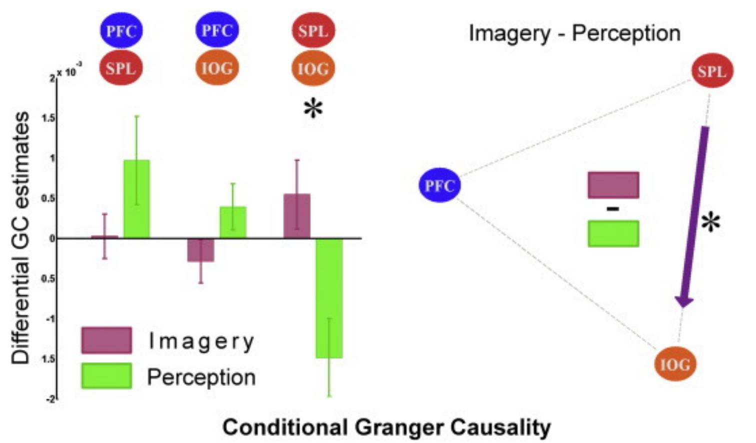
cortical connectivity

?



De Kock & Sakmann (2009) *PNAS*

cell-type specific spike rates



Dentico et al. (2014) *NeuroImage*

inter-area propagation

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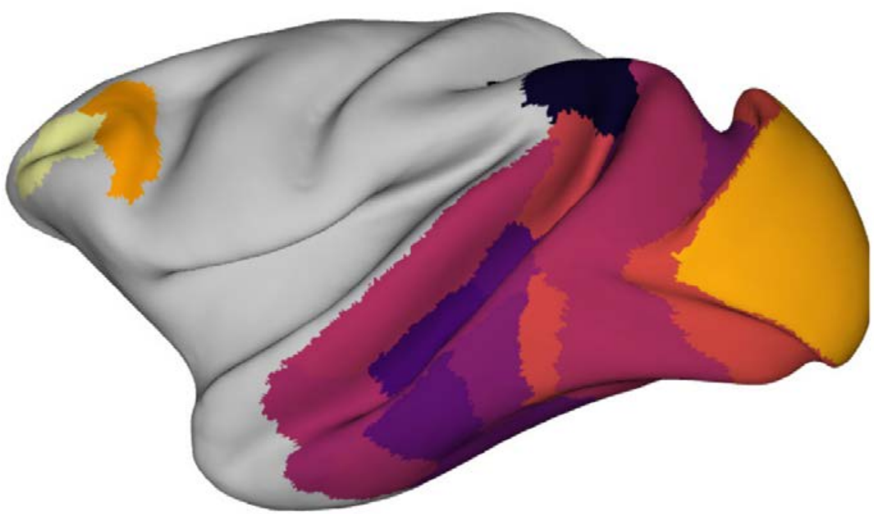
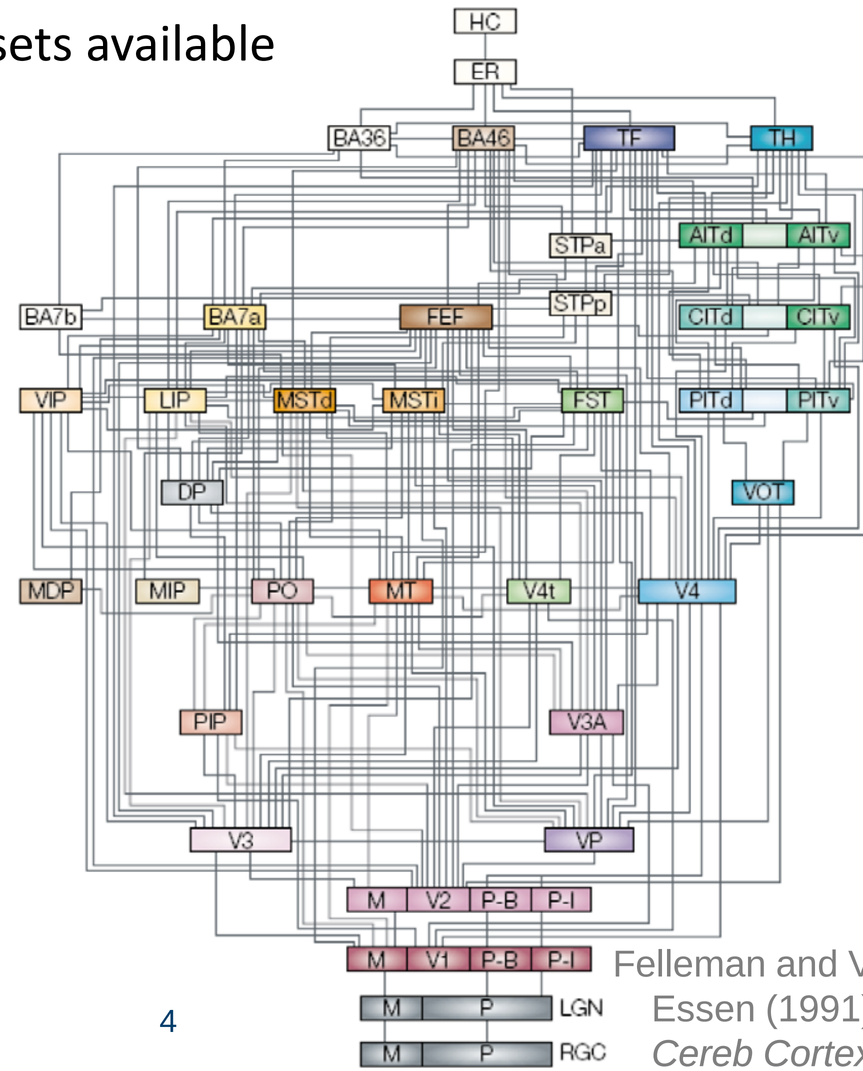
MULTI-AREA MODEL OF MACAQUE VISION-RELATED CORTEX

- rich anatomical and physiological data sets available
- stepping stone to human
- regularities of organization



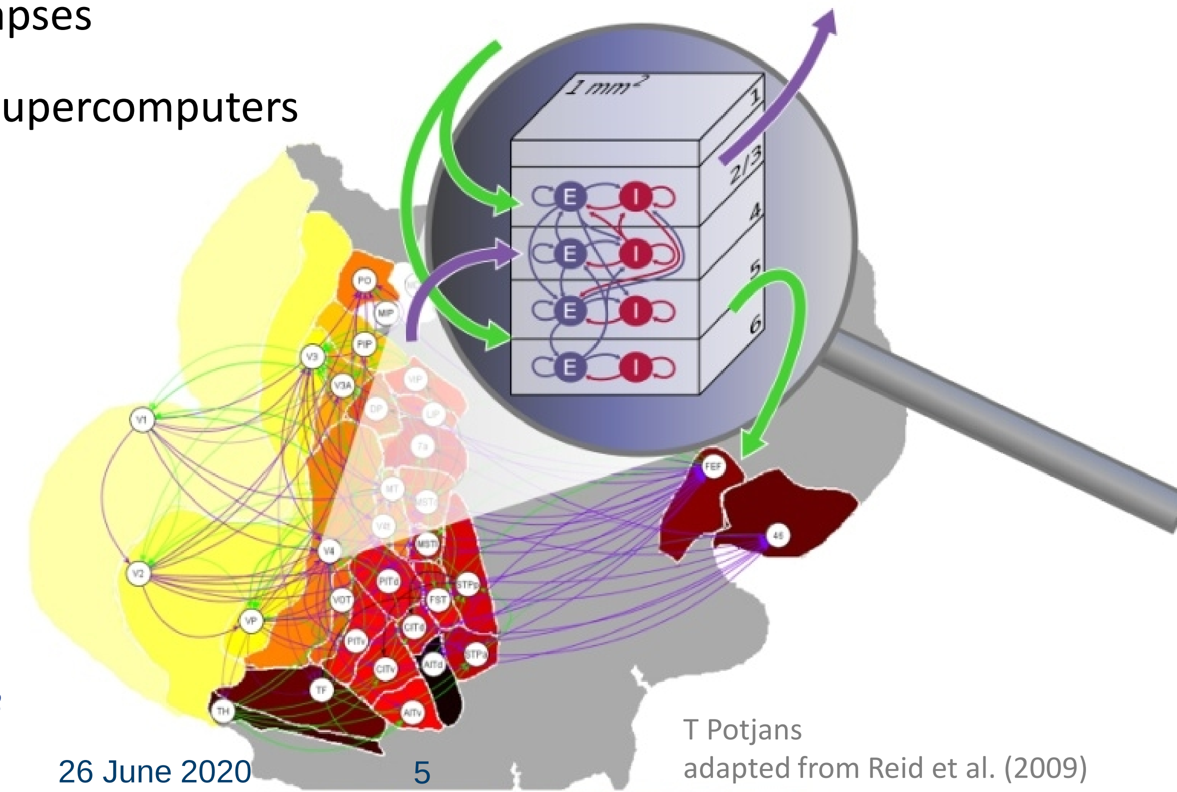


Felleman and Van Essen (1991) *Cereb Cortex*

MULTI-AREA MODEL OF MACAQUE VISUAL CORTEX

- 800 million neurons in one hemisphere
- 32 areas in Felleman & Van Essen parcellation
- representing each area by a 1 mm^2 microcircuit
- $4 \cdot 10^6$ neurons and $2.4 \cdot 10^{10}$ synapses
- simulated using NEST on Jülich supercomputers

Maximilian Schmidt

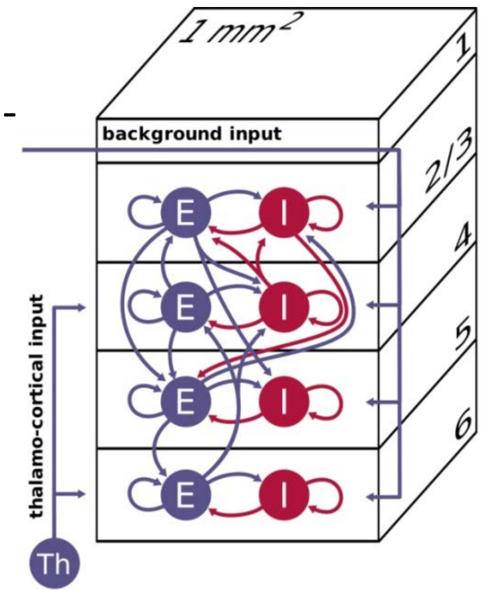


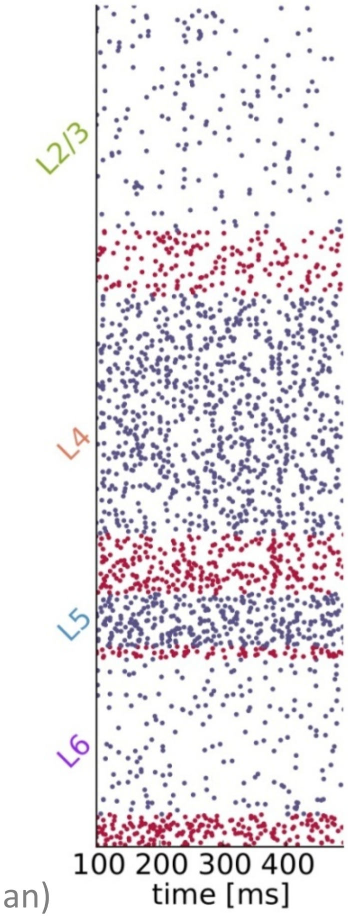
T Potjans
adapted from Reid et al. (2009)

Schmidt M, Bakker R, Shen K, Bezgin G, Diesmann M, van Albada SJ (2018) *PLOS CB*

MINIMAL LAYERED CORTICAL NETWORK MODEL

- 1 mm^2
- 0.3 billion synapses; 80,000 leaky integrate-and-fire neurons
- 2 populations of neurons per layer:
  - E: Excitatory
  - I: Inhibitory
- E and I identical neuronal dynamics
- laterally homogeneous connectivity
- layer- and type-specific connection probability based on collation of experimental data
- Poisson drive

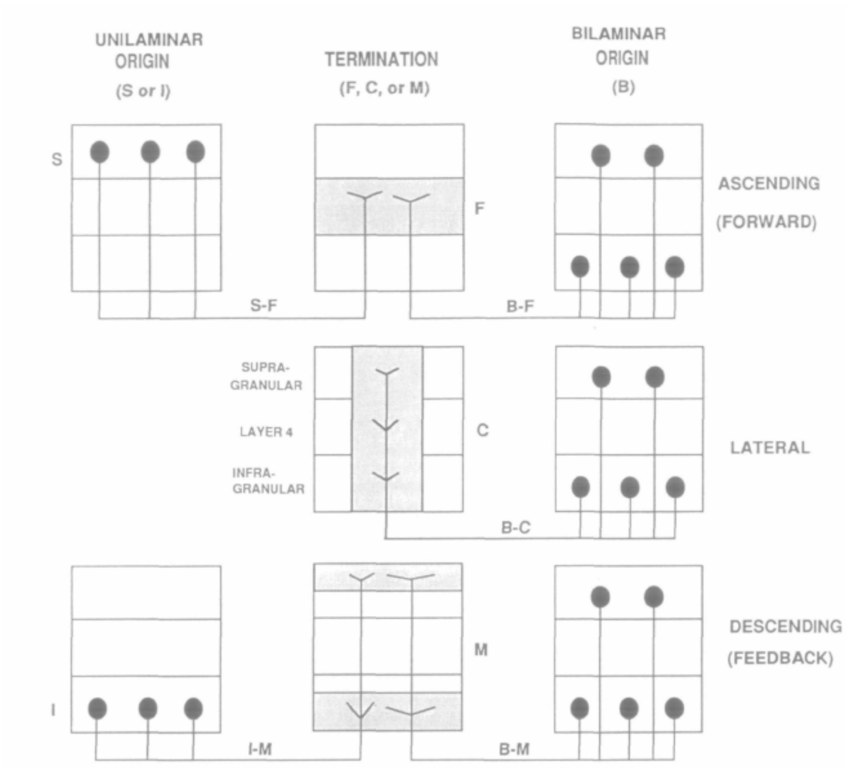


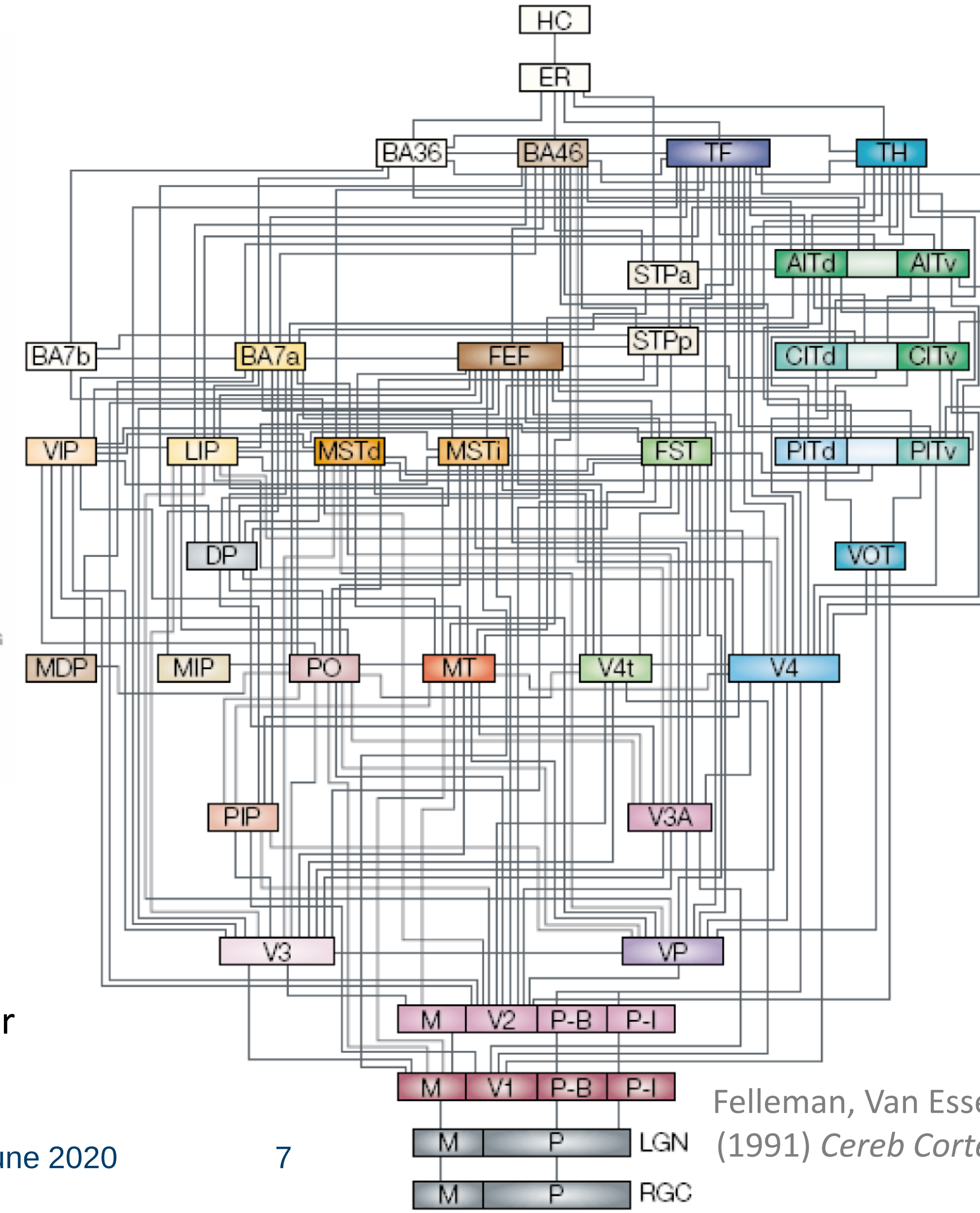


Potjans & Diesmann (2014)
Cereb Cortex

now available in various simulators (NEST, PyNN, NetPyNE/NEURON, Brian) and in Open Source Brain
Gleeson…van Albada et al. (2019)
Neuron

HIERARCHY OF VISUAL CORTICAL AREAS



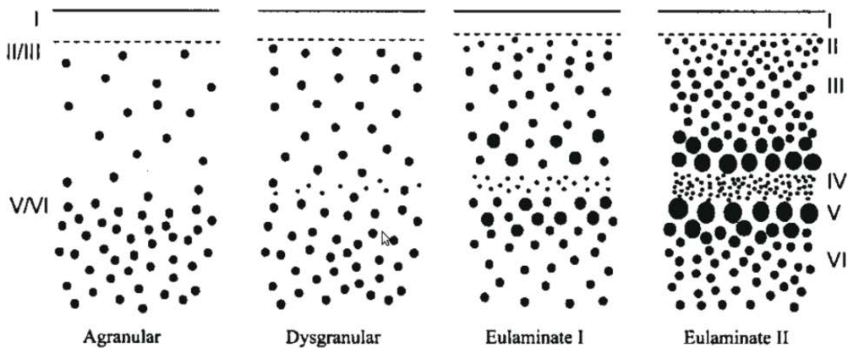


Felleman, Van Essen (1991) *Cereb Cortex*

- this is only one of thousands of possible orderings fitting the pairwise connection patterns equally well Hilgetag et al., 1996
- alternatively, can use `architectural types' or neuron densities to define hierarchy

DIFFERENTIAL LOCAL ARCHITECTURE

architectural types



Dombrowski et al. (2001) *Cereb Cortex*

synapse density remains roughly constant

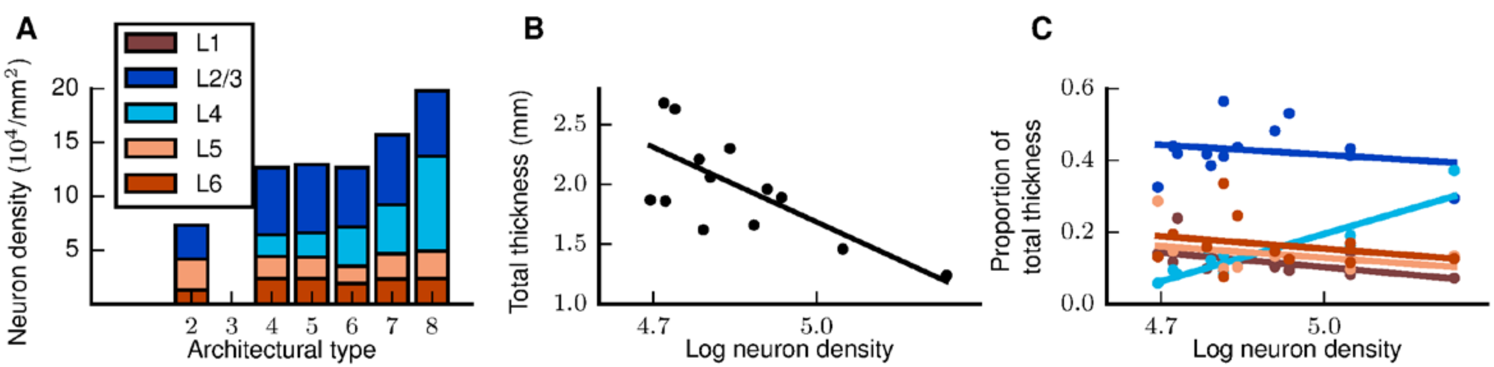
→ higher areas receive more synapses per neuron

review on relationship between cortical architecture and connectivity: Hilgetag, Beul, van Albada, Goulas (2019) *Network Neurosci*

- total cortical thicknesses and overall neuron densities for 14 areas
- estimated for remaining areas based on architectural types

} Hilgetag et al. (2016) *NeuroImage*

- reduction in L4 thickness toward higher areas based on micrographs from the literature



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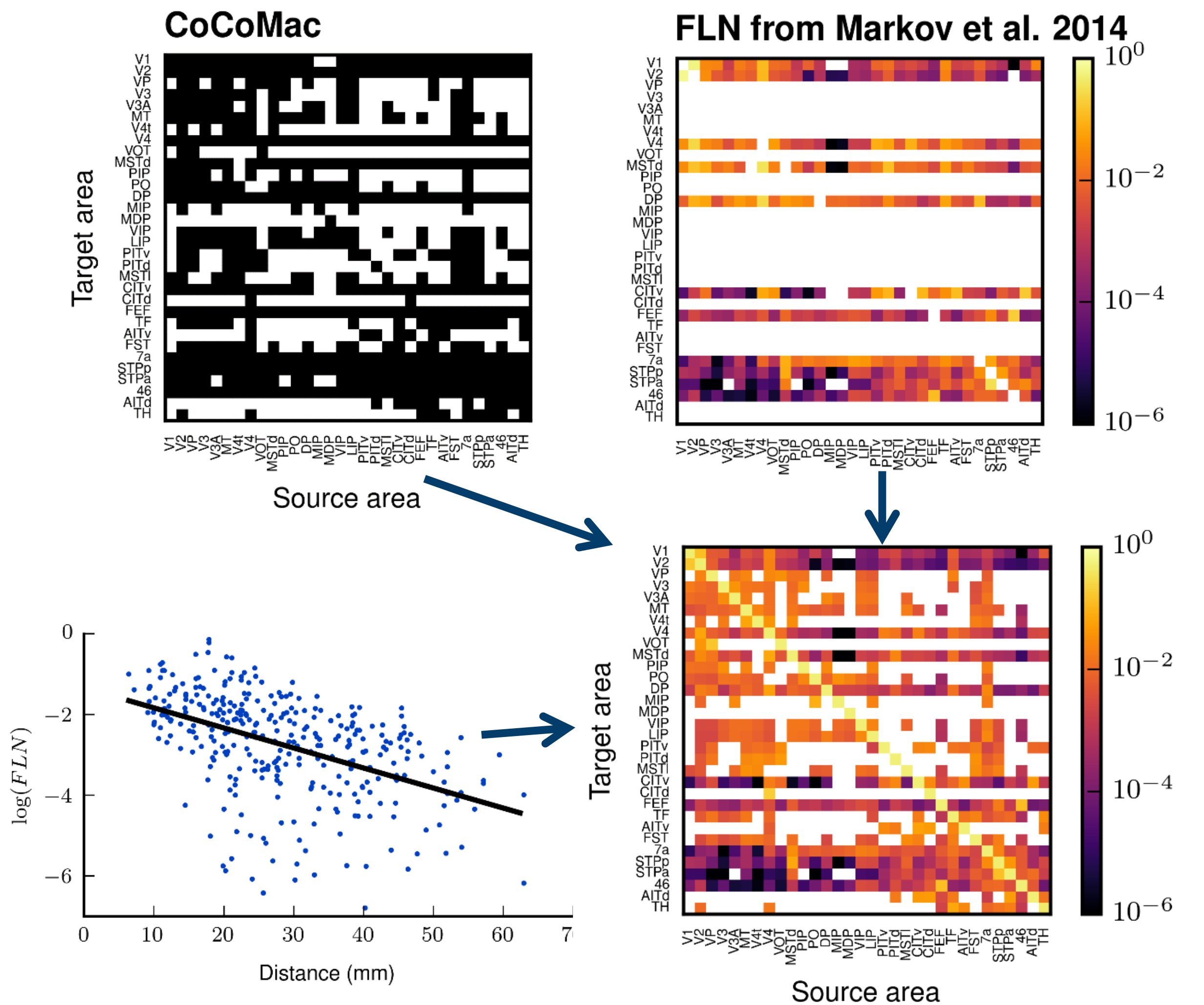
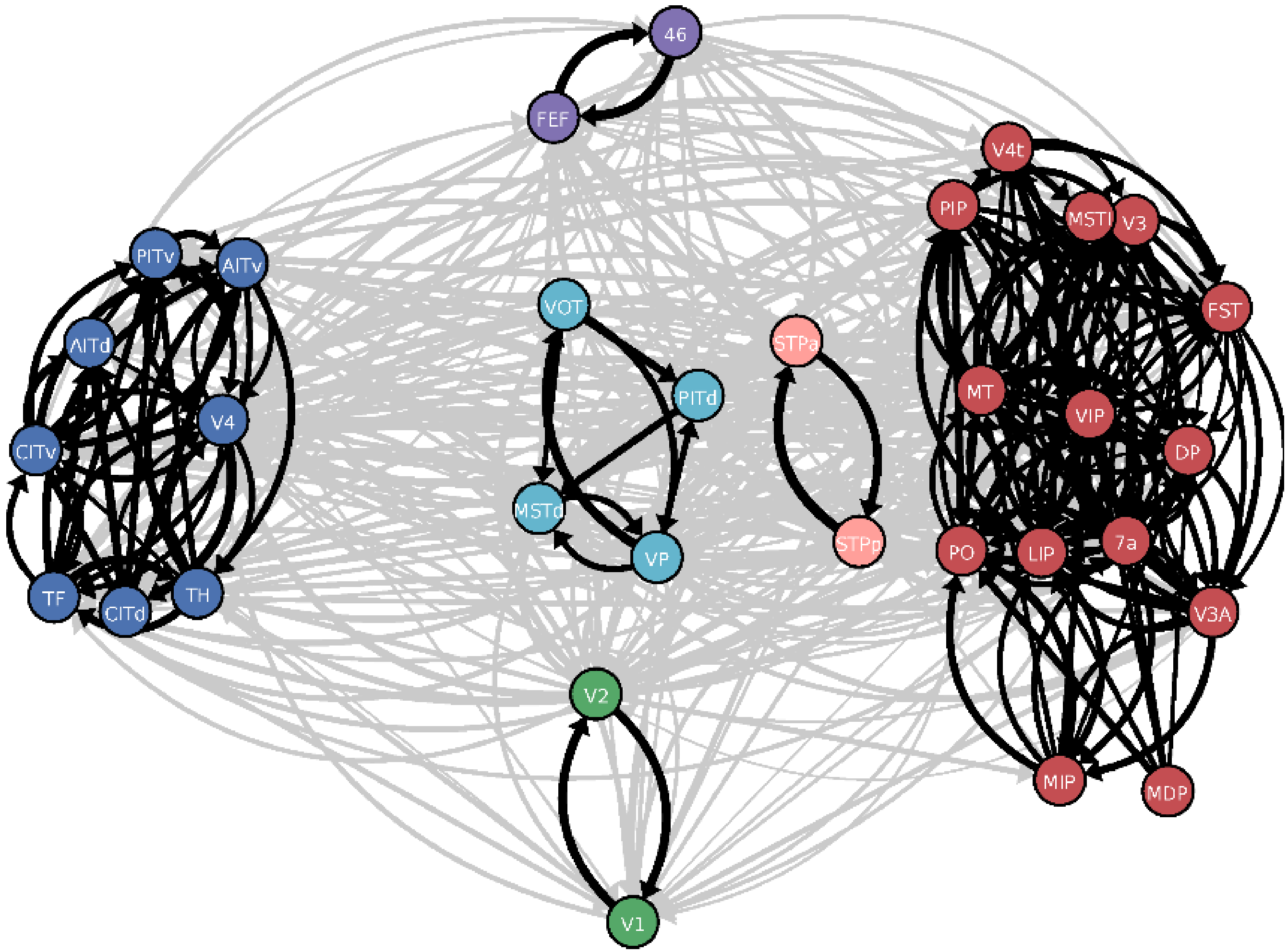
CONNECTIVITY MAP FROM TRACING DATA

- partly binary, partly quantitative data
- connection probability decays with distance also for inter-area connections
- use this decay to estimate missing data based on distance between areas
- roughly 2/3 of area pairs are connected
- more important: connection density, spanning ~6 orders of magnitude



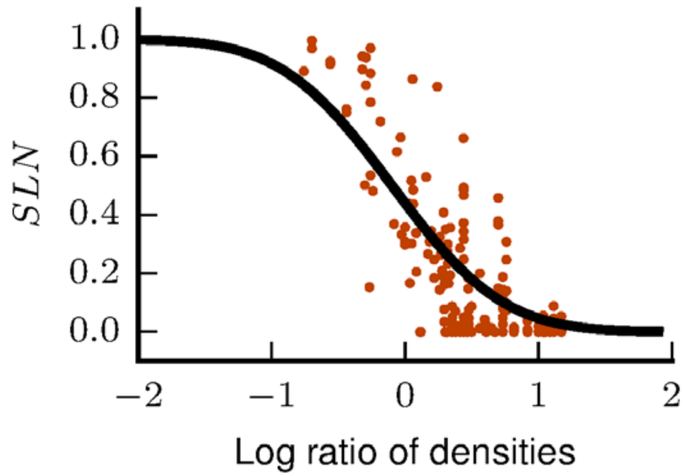
Ercsey-Ravasz et al. (2013) *Neuron*

PLAUSIBILITY CHECK

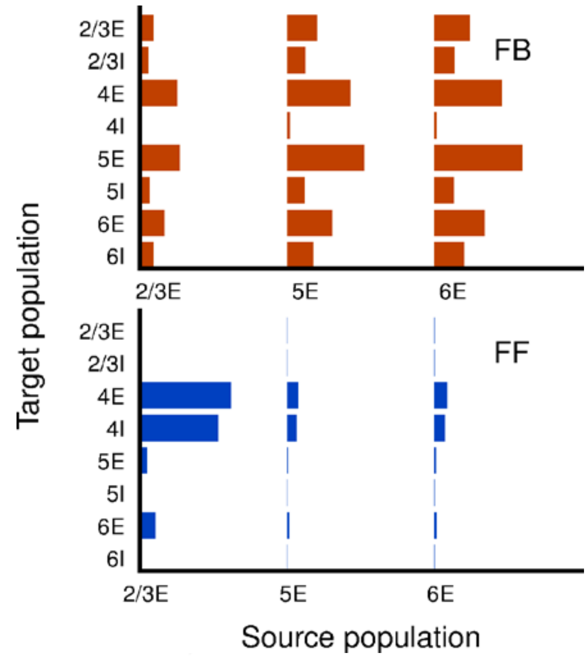


structural connectivity exhibits functionally relevant community structure

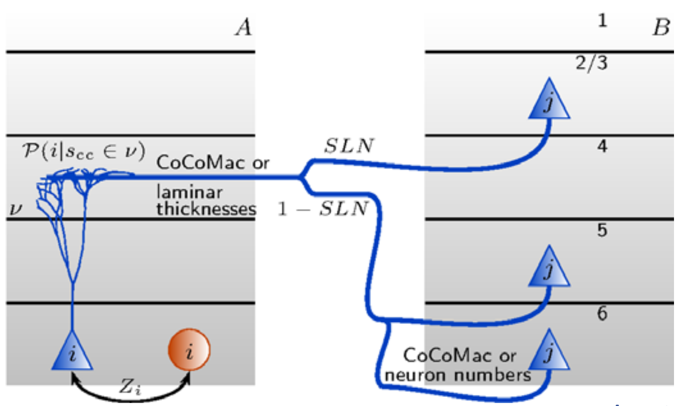
LAMINAR PATTERNS

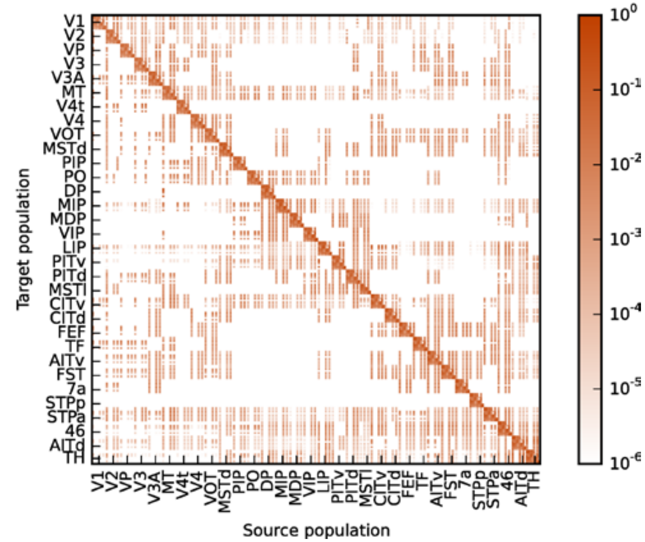


SLN = fraction of supragranular labeled neurons



statistical mapping of synapses to target cell bodies according to Binzegger et al. (2004) cat V1 morphologies





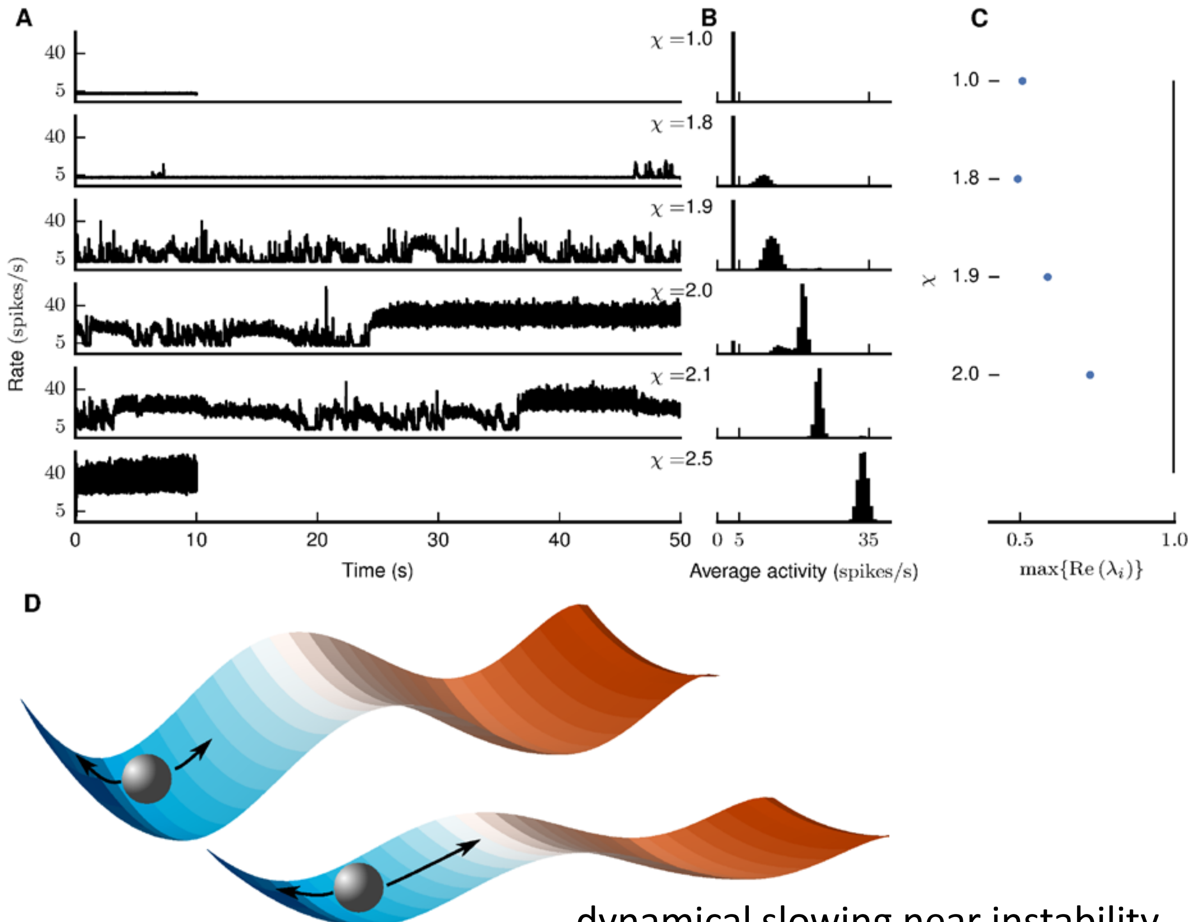
Schmidt M, Bakker R, Hilgetag CC, Diesmann M, van Albada SJ (2018) *Brain Struct Func*

INTER-AREA INTERACTIONS CAUSE SLOW FLUCTUATIONS

- stable ground state obtained after mean-field-based stabilization

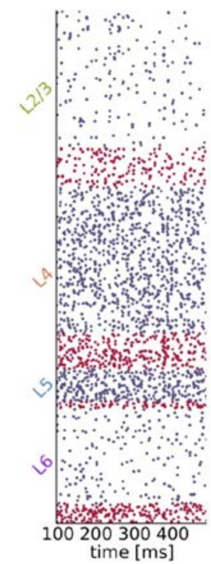
Schuecker J, Schmidt M, van Albada SJ, Diesmann M, Helias M (2017) *PLOS CB*

- scaling cortico-cortical synaptic strengths evokes inter-area interactions

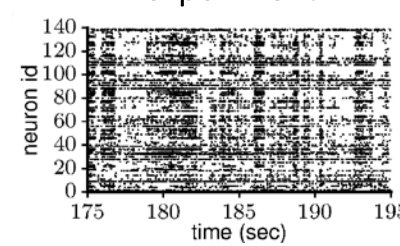


dynamical slowing near instability

isolated microcircuit model



experiment



Chu et al. (2014) *Vision Res*

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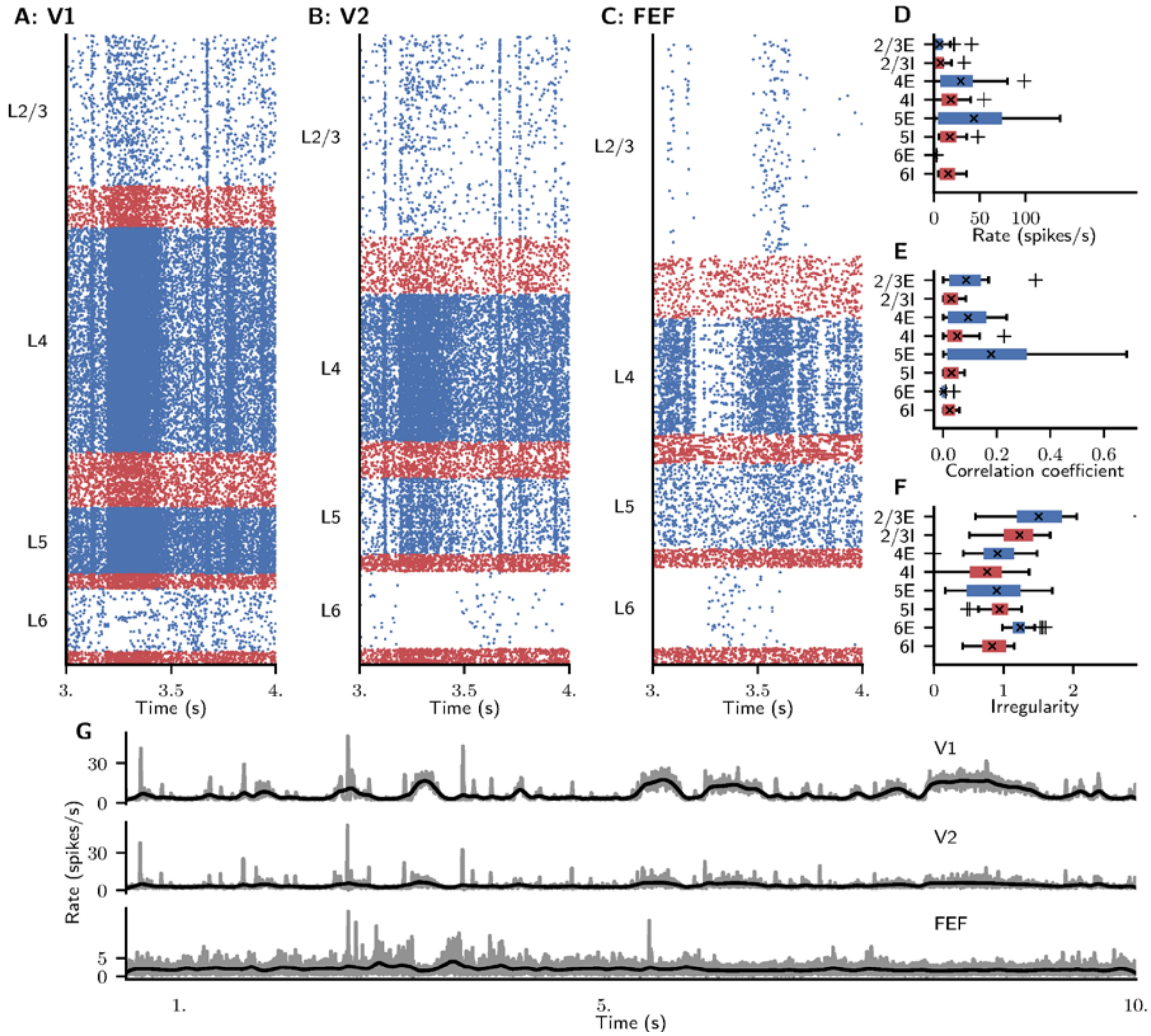
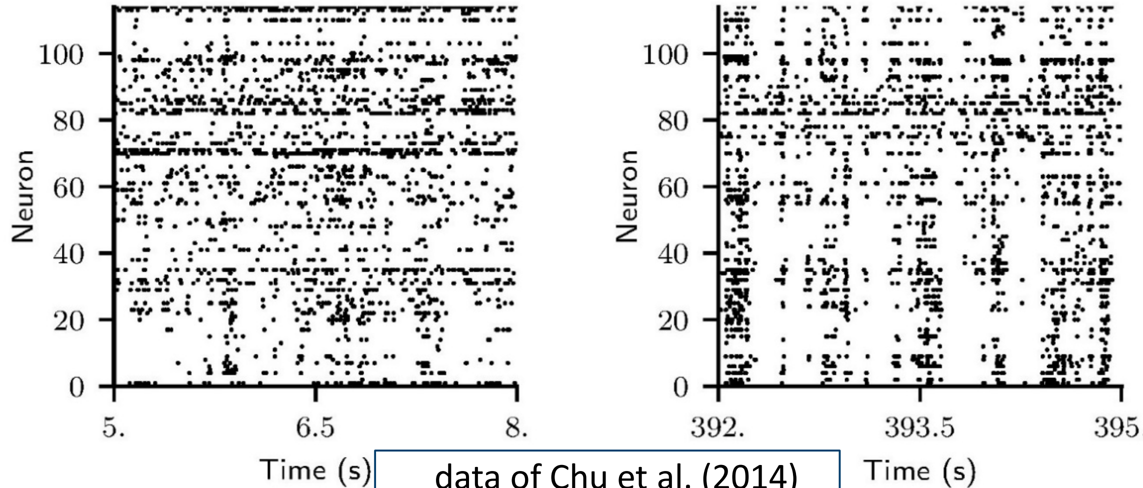
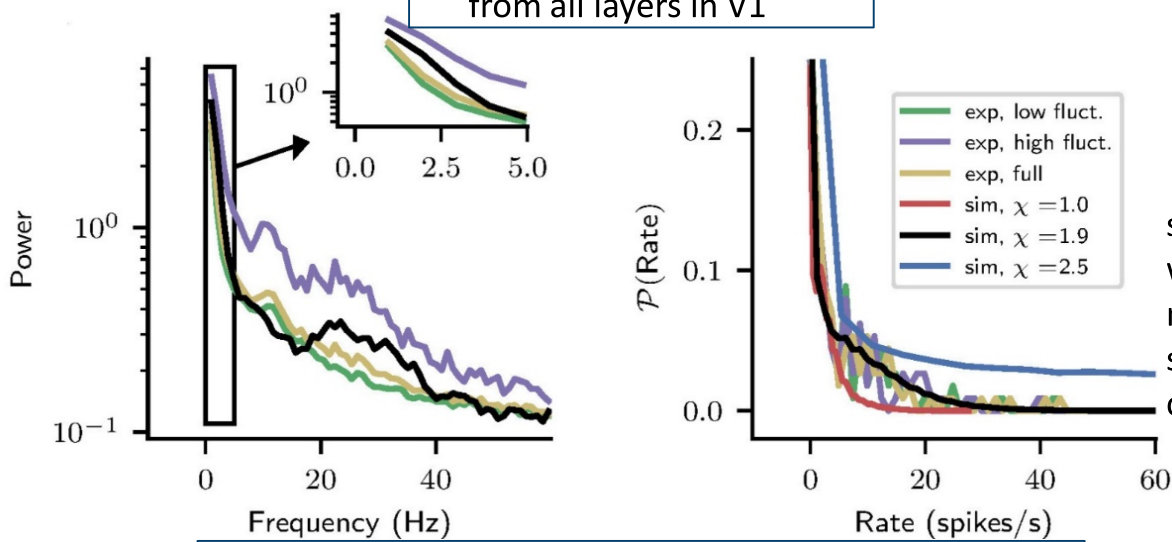
GROUND STATE WITH MULTIPLE TIME SCALES



V1 SPIKING STATISTICS



data of Chu et al. (2014)
from all layers in V1



experiment
simulation

simulations with
weak (red),
medium (black/gray),
strong (blue)
cortico-cortical interactions

comparison of power spectra and rate distributions
between simulation and experiment

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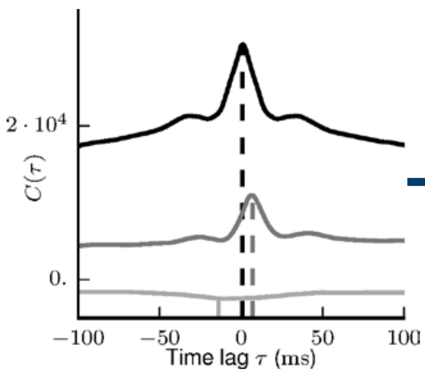
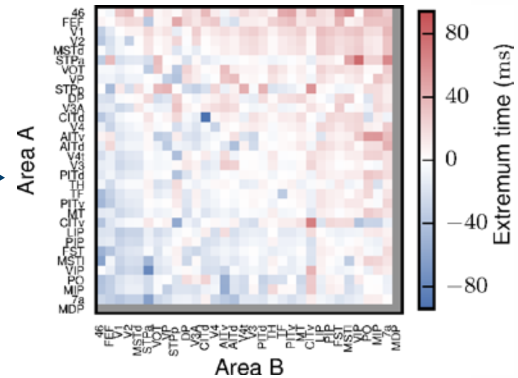
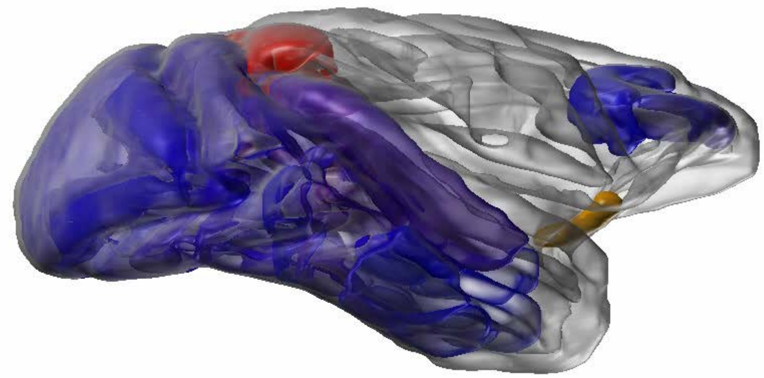
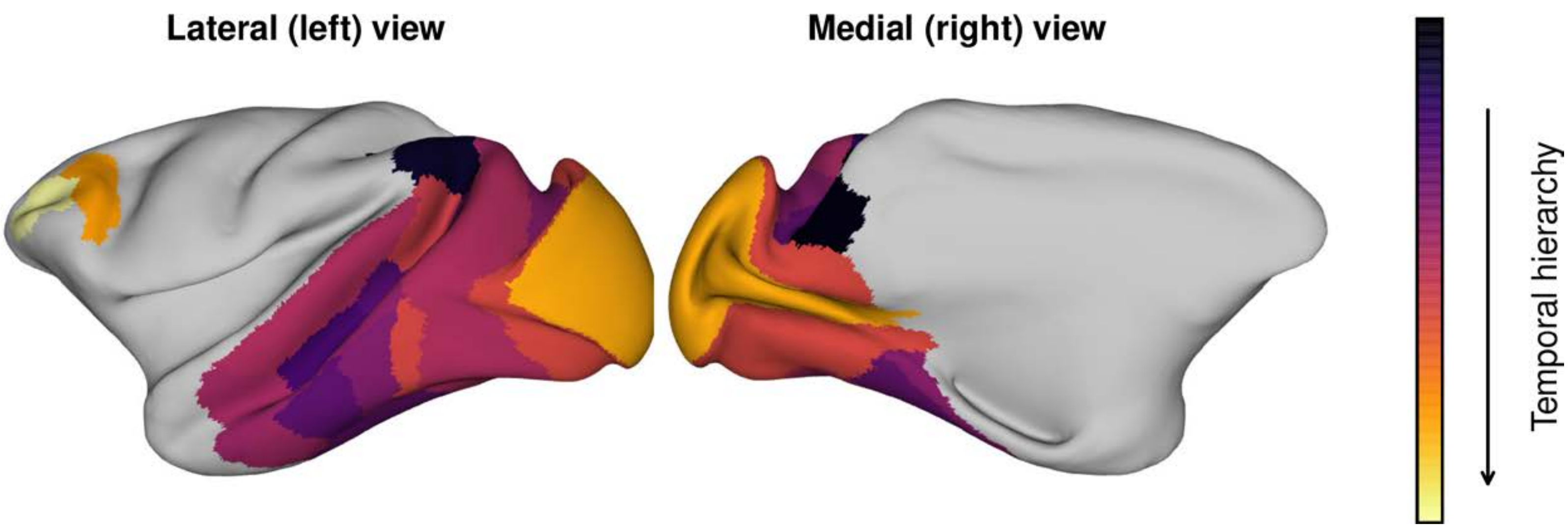
TEMPORAL HIERARCHY







Nowke C, Schmidt M, van Albada SJ, Eppler JM, Bakker R, Diesmann M, Hentschel B, Kuhlen T (2013) *IEEE BioVis*

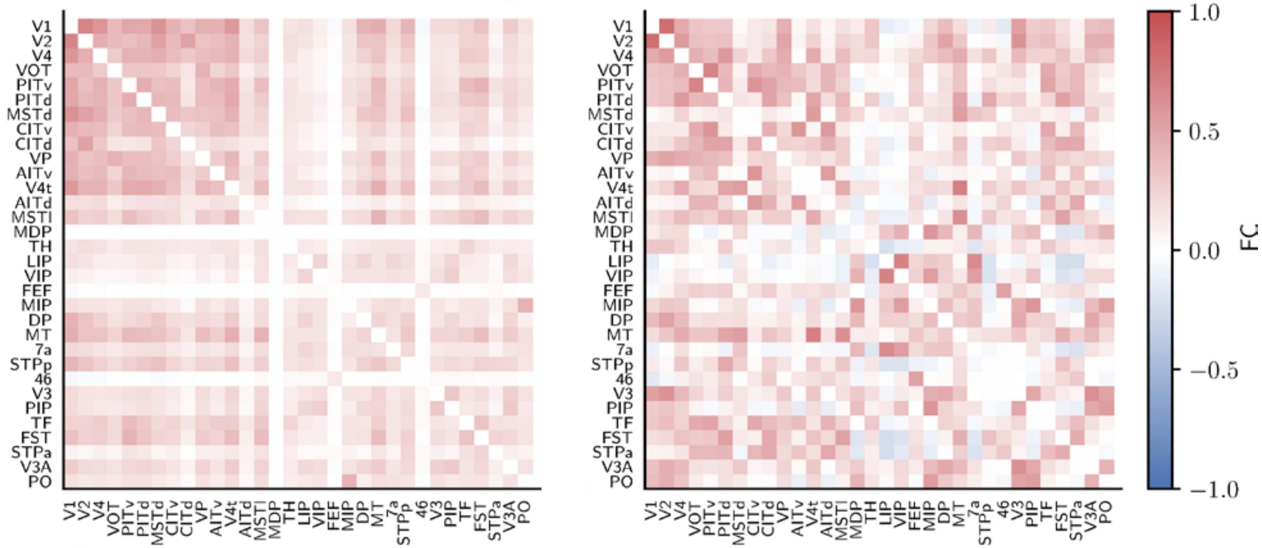


FUNCTIONAL CONNECTIVITY

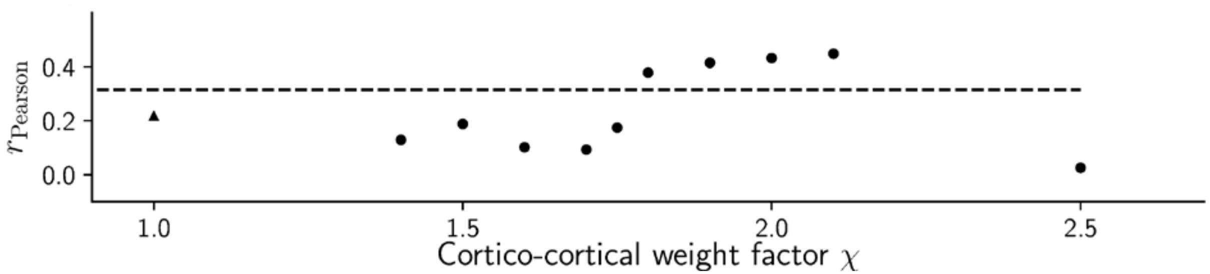
inter-area interactions in metastable state resemble experimental resting-state fMRI

correlations between simulated synaptic inputs

fMRI functional connectivity averaged over six monkeys



match between experiment and simulation



Schmidt M, Bakker R, Shen K, Bezgin G, Diesmann M, van Albada SJ (2018) *PLOS CB*

GITHUB REPOSITORY

https://inm-6.github.io/multi-area-model/

multi-area-model

A large-scale spiking model of the vision-related areas of macaque cortex.

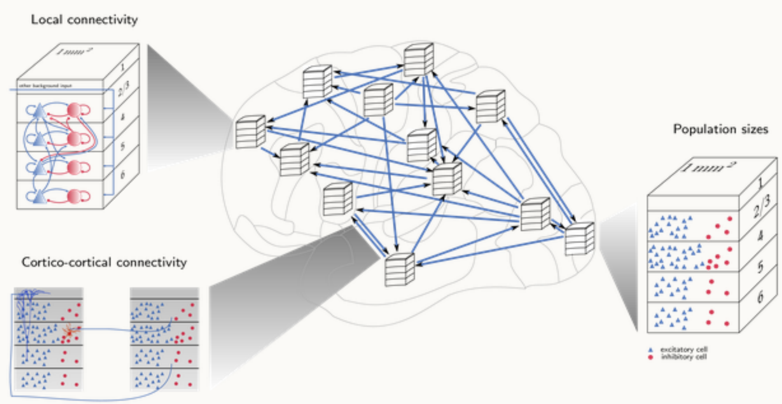
View On GitHub

This project is maintained by INM-6

Hosted on GitHub Pages

Multi-scale spiking network model of macaque visual cortex

python 3.6 | nest::simulated() | license CC BY-NC-SA 4.0



This code implements the spiking network model of macaque visual cortex developed at the Institute of Neuroscience and Medicine (INM-6), Research Center Jülich. The model has been documented in the following publications:

1. Schmidt M, Bakker R, Hilgetag CC, Diesmann M & van Albada SJ Multi-scale account of the network structure of macaque visual cortex Brain Structure and Function (2018), 223: 1409 https://doi.org/10.1007/s00429-017-1554-4

2. Schuecker J, Schmidt M, van Albada SJ, Diesmann M & Helias M (2017) Fundamental Activity Constraints Lead to Specific Interpretations of the Connectome. PLOS Computational Biology, 13(2): e1005179. https://doi.org/10.1371/journal.pcbi.1005179

3. Schmidt M, Bakker R, Shen K, Bezgin B, Diesmann M & van Albada SJ (accepted) A multi-scale layer-resolved spiking network model of resting-state dynamics in macaque cortex. PLOS Computational Biology, 14(9): e1006359.

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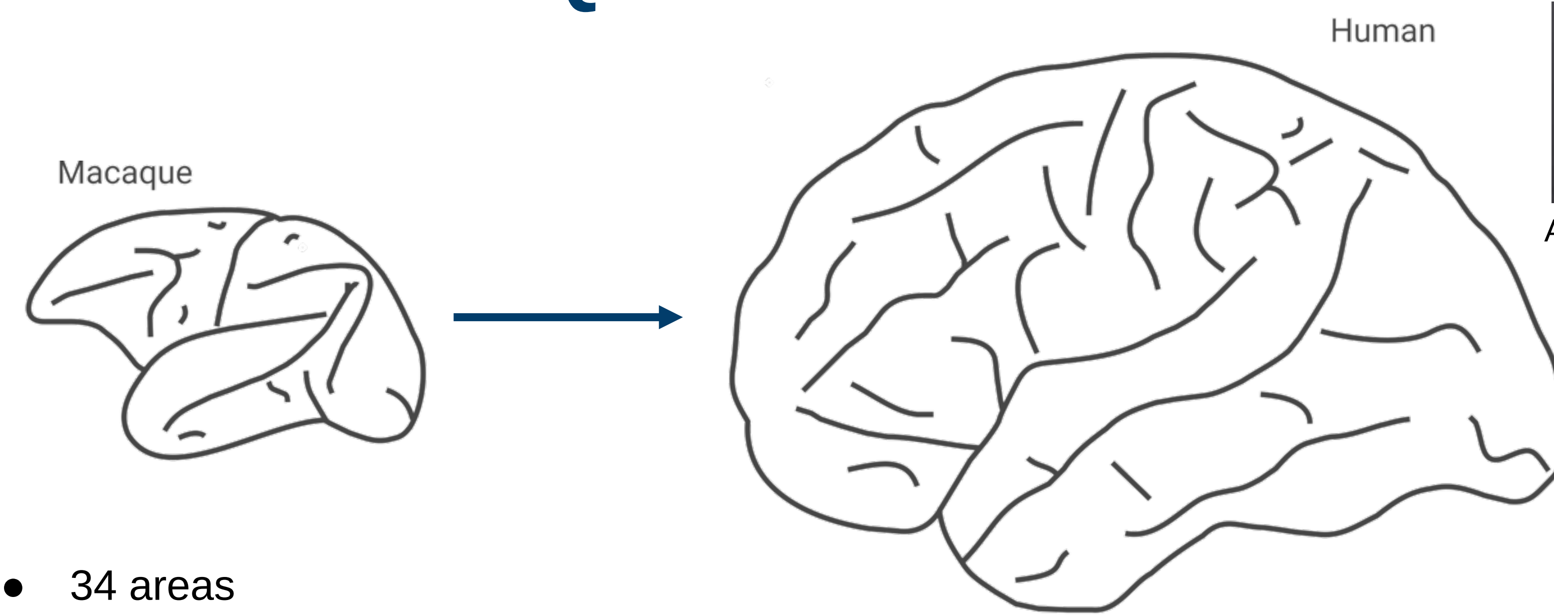
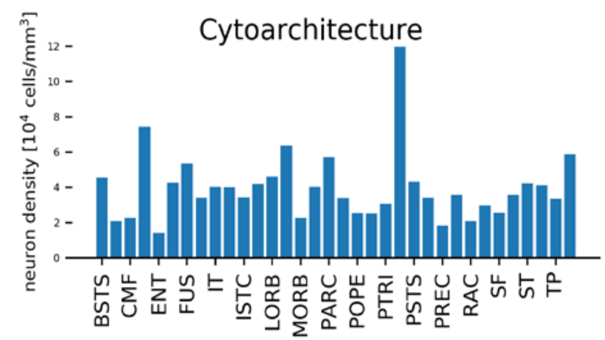
FROM MACAQUE TO HUMAN CORTEX

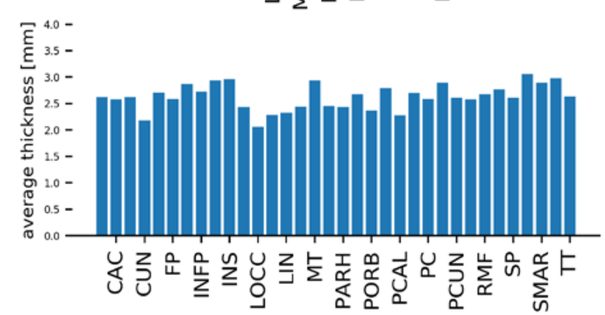



Alexander van Meegen

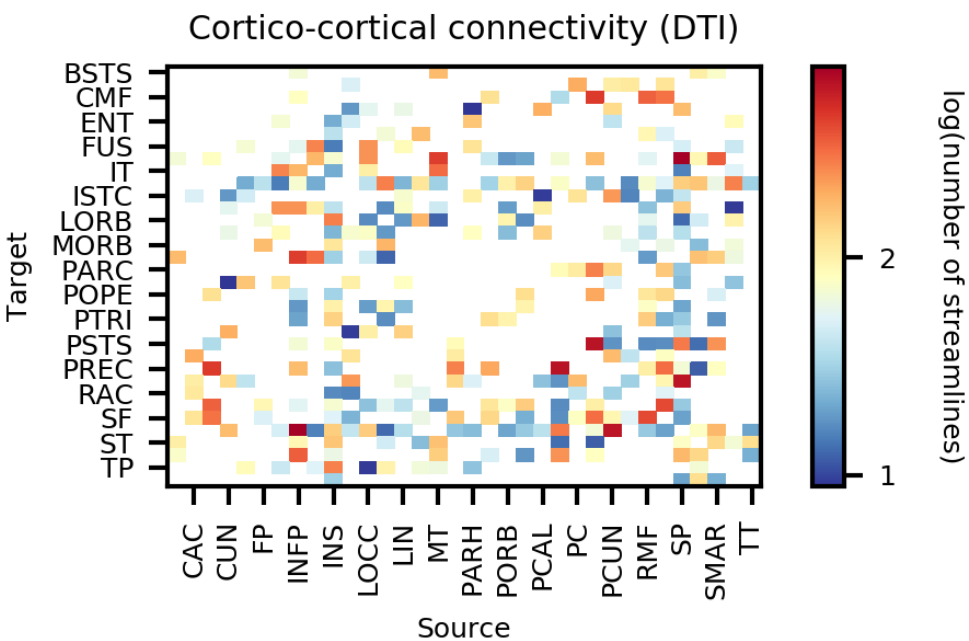
Jari Pronold

- 34 areas
- one hemisphere of human cortex
- Desikan-Killiany parcellation
- 3.6 million neurons
- 44 billion synapses
- cytoarchitectonic data
  - von Economo & Koskinas (1925)
  - layer thicknesses (Wagstyl et al. 2020 *PLOS Biol*) extracted from BigBrain
  - neuron densities measured by Timo Dickscheid et al. extracted from BigBrain where available

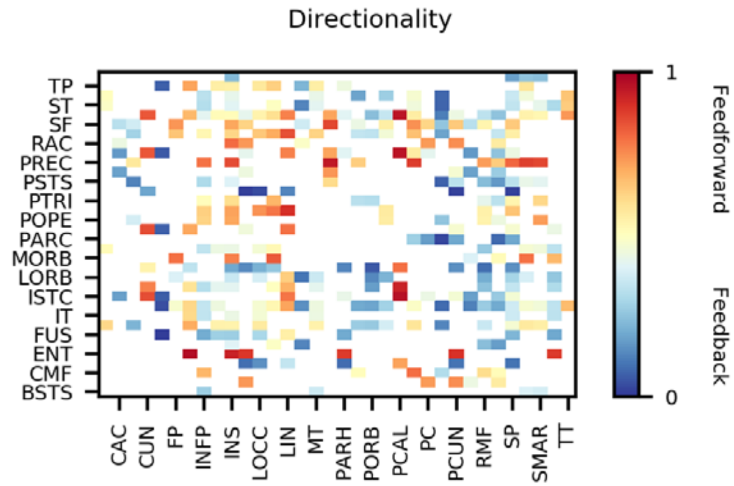




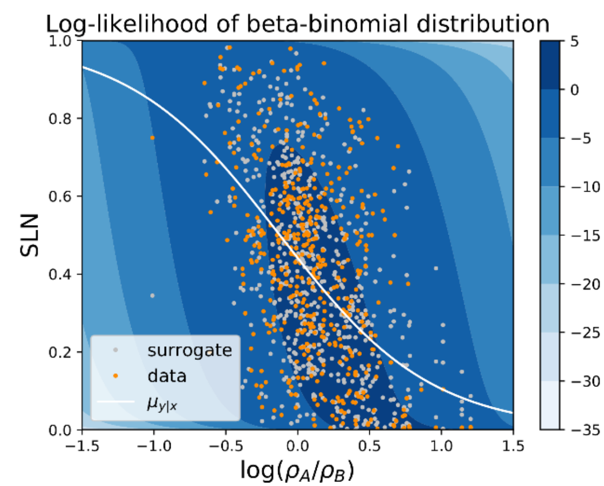
HUMAN CONNECTIVITY DATA AND PREDICTIVE CONNECTOMICS



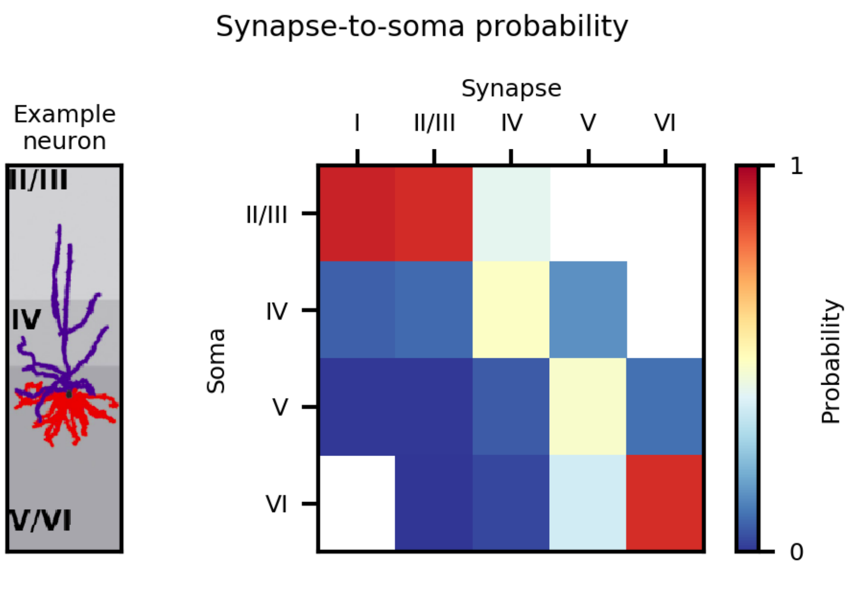
Data: *Van Essen et al. (2013) NeuroImage*



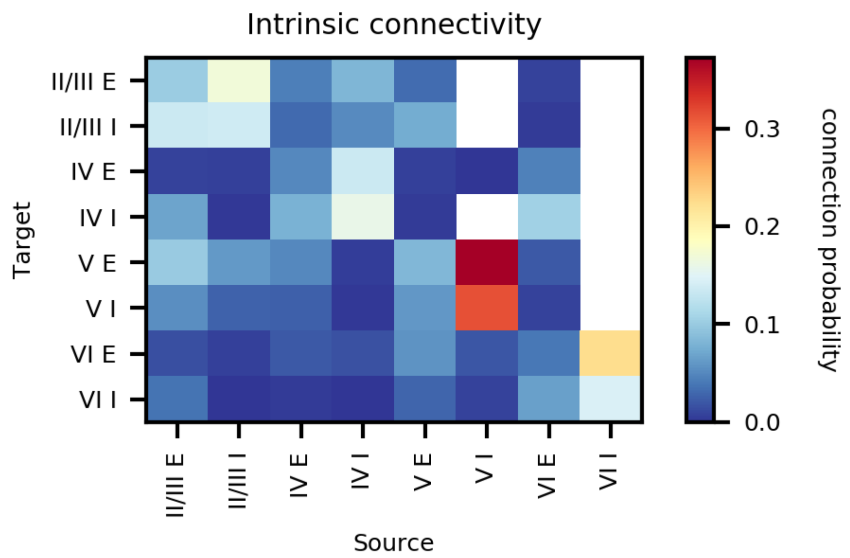
Directionality of cortico-cortical connections based on fit of macaque tracing data



ASPECTS OF LOCAL CONNECTIVITY



Data: *Mohan et al. (2015) Cereb Cortex*



Data: *Potjans & Diesmann (2014) Cereb Cortex*

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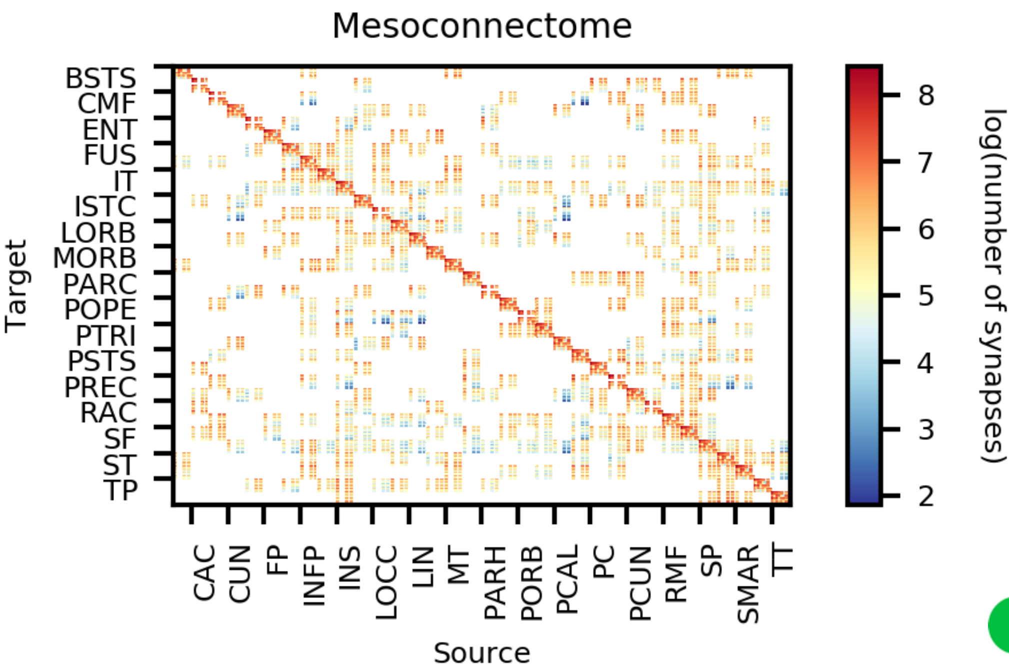
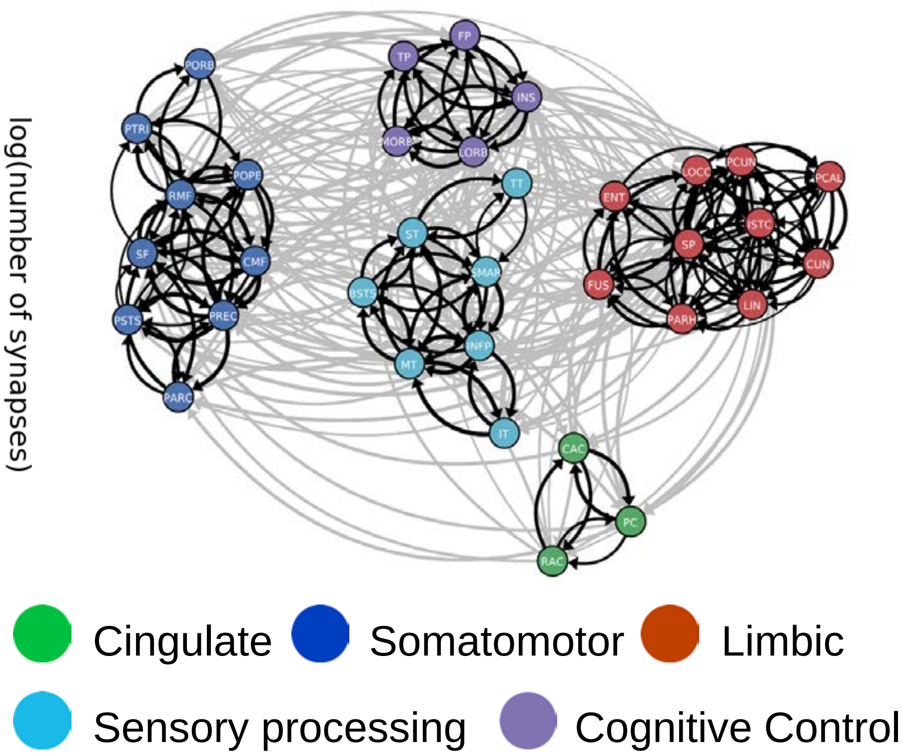
STRUCTURAL CONNECTIVITY





Data: *Van Essen (2013) NeuroImage*

MEAN-FIELD DYNAMICS

Alexander van Meegen

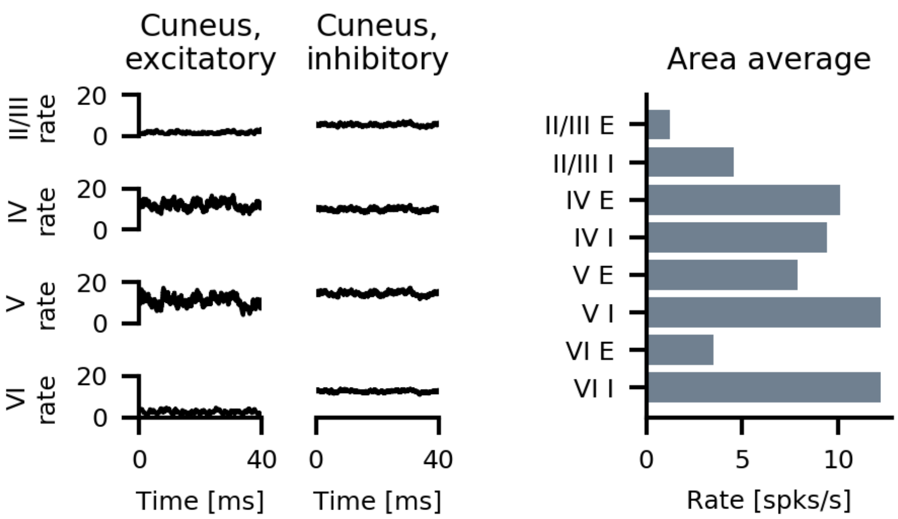
- mean-field theory describes population-averaged rates:

$$\frac{d\nu_i}{dt} = -\nu_i + \phi(\mu_i, \sigma_i),$$

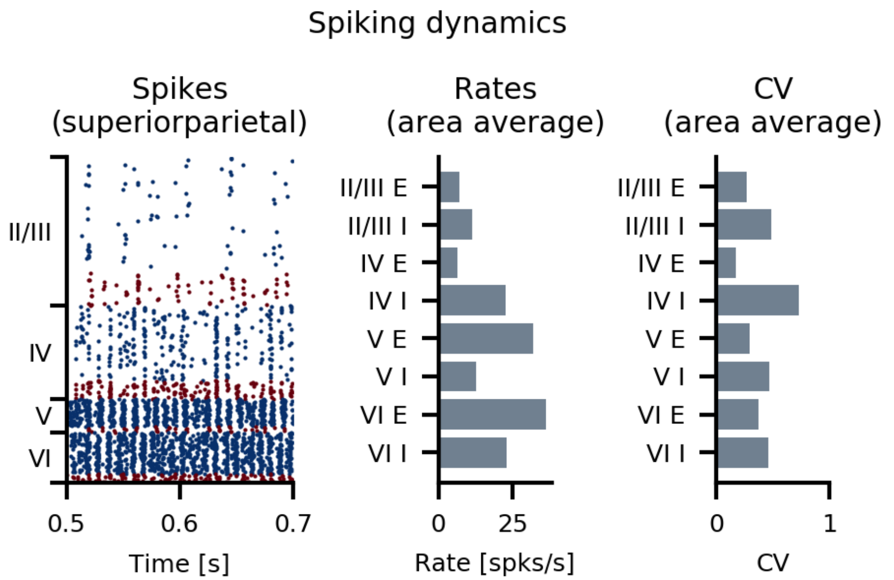
$$\mu_i = \tau_m \sum_j J_{ij}\nu_j + \tau_m J_{ext}\nu_{ext} + \xi_i(t),$$

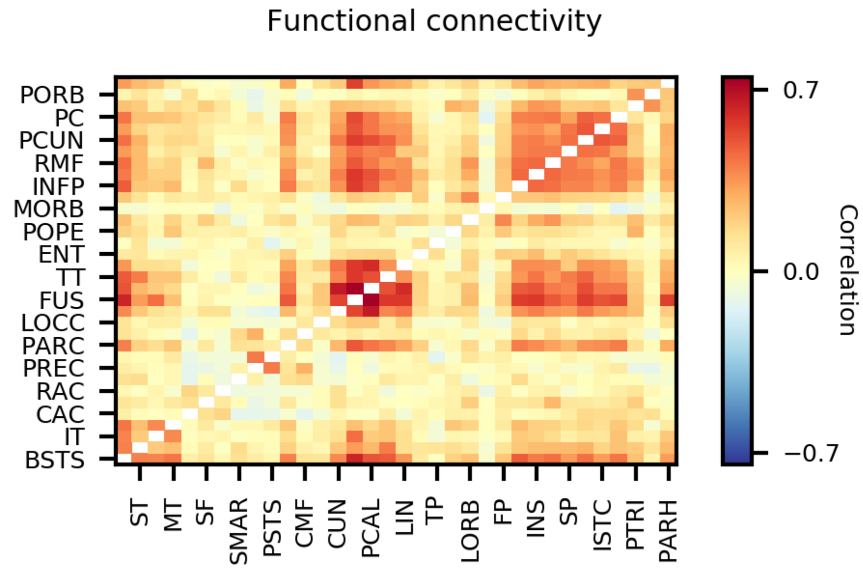
$$\sigma_i^2 = \tau_m \sum_j J_{ij}^2\nu_j + \tau_m J_{ext}^2\nu_{ext}.$$

- enables systematic exploration of parameter space
- strong effect of inhibitory connections onto layer 5 excitatory neurons



SIMULATED DYNAMICS





ACKNOWLEDGMENTS

Jülich

modeling, theory

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modeling, benchmarking

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modeling

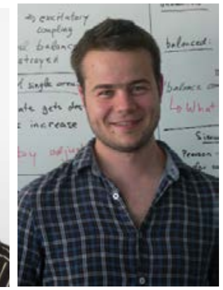
Hannah Vollenbröker

Aitor Morales-Gregorio

anatomical data

Rembrandt Bakker

theory



Jannis Schuecker

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fMRI data

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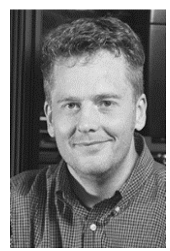
McGill, Montreal

anatomy

Claus Hilgetag
UKE Hamburg

visualization

Christian Nowke



Bernd Hentschel

Torsten Kuhlen

RWTH Aachen University

Human Brain Project

SPP 2041 Computational Connectomics

grant JINB33 for compute time on the Jülich supercomputers

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