COGS118C: Neural Signal Processing

Finale

Lecture 17
August 1, 2019

Course Outline: Road Map

Electrophysiological Data Analyses

L

Math

- Linear Algebra
- Complex Numbers

L

Coding

Git & Python
numpy
scipy

Communication

- Reading Scientific Papers
- Visualization & Writing

"Field Potentials" (Time-Series)

"Spikes" (Point Process)

2*

Brain Physiology

3-11

Time-Series Analyses

- 3 Sampling
- 4 Time-locked Analysis
- 5 Convolution
- 6 Fourier Analysis
- 7-8 Time-Frequency Analysis
- 9 Filtering
- 10 Hilbert
- 11 Nonlinear Techniques

12-14

Spike Analyses

- 12 Spike-LFP Analysis
- 13 Spike-Train Models
- 14 Population Coding Models

15-16 Multi Channel Analysis

- Dimensionality
- Information Theory

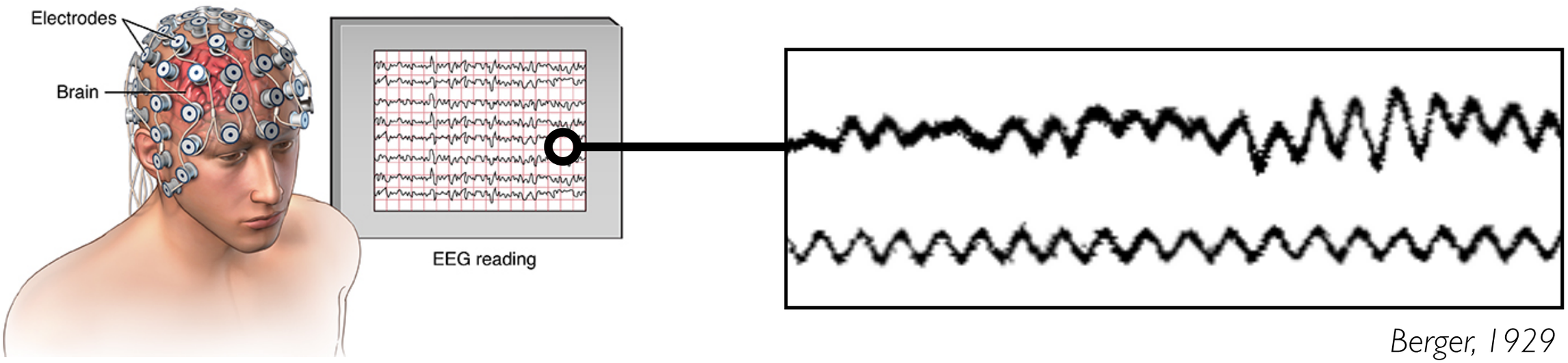
Goals for Today

1. Tell you about my own research

2. Give you examples & practical tips for your project

3. Entertain & motivate your further interest in neural signal processing

Neural Oscillations



Berger, 1929

Opinion
TRENDS in Cognitive Sciences Vol.9 No.10 October 2005
Full text provided by www.sciencedirect.com
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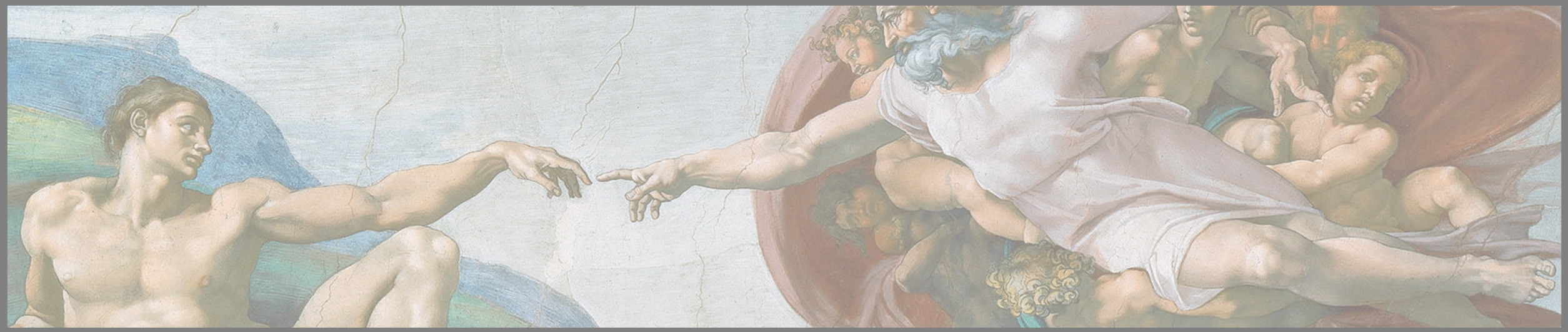
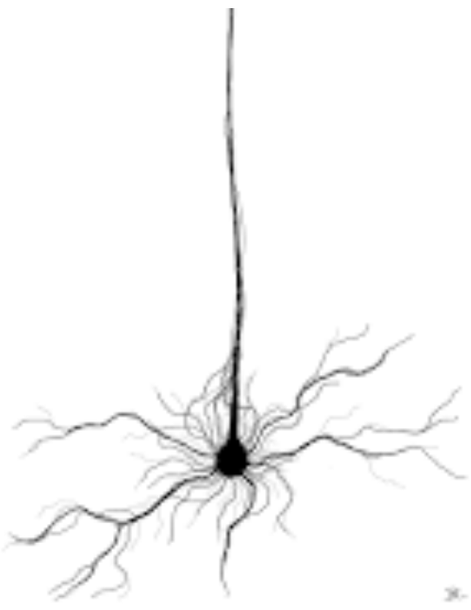
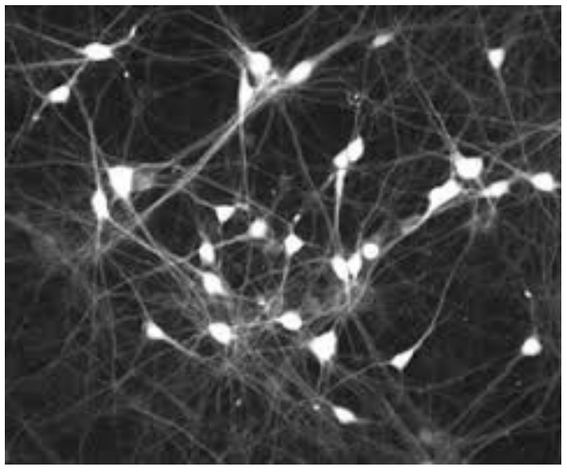
A mechanism for cognitive dynamics: neuronal communication through neuronal coherence

Pascal Fries[1,2]

Synchronous neural oscillations are **ubiquitous** and tightly linked to **behavior, cognition,** and **disease**.







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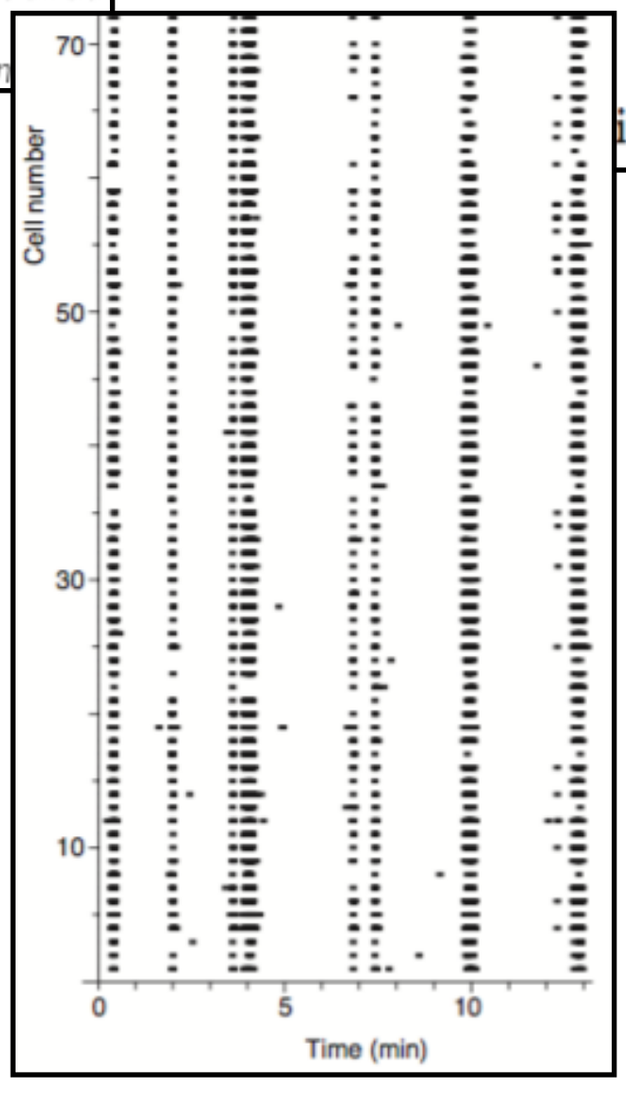
Where does **complex & organized neural activity** begin?

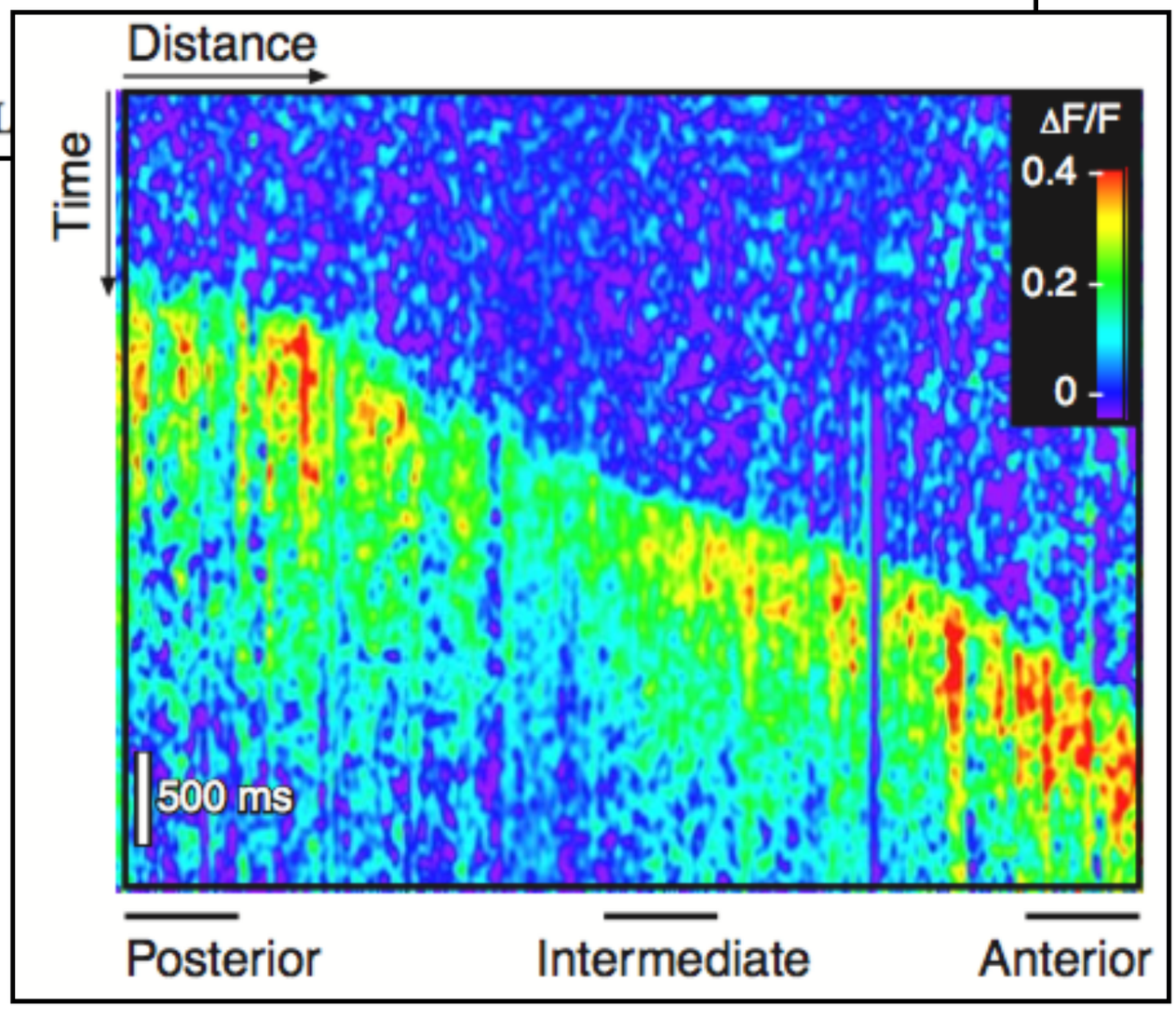
Neural Synchrony & Development

Cortical travelling waves: mechanisms

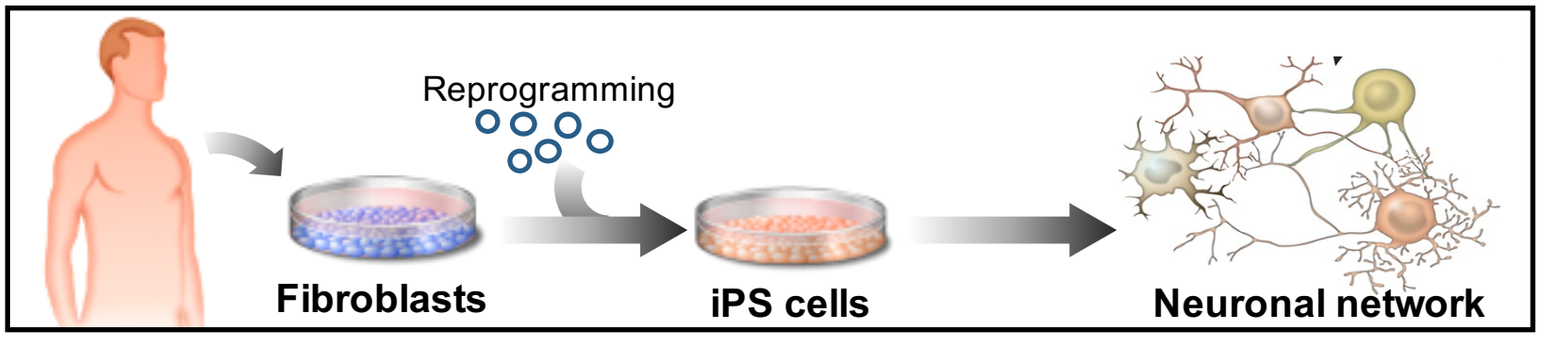
Synchronous bursts of action potentials in ganglion cells

Large-scale oscillatory calcium waves in the immature cortex



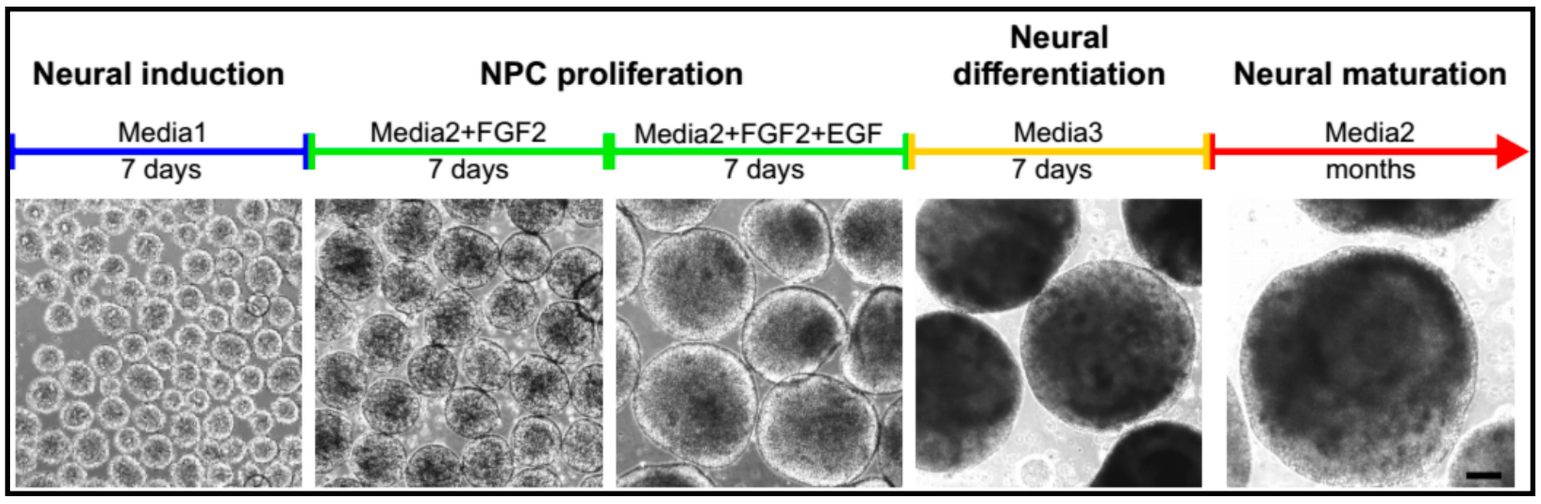


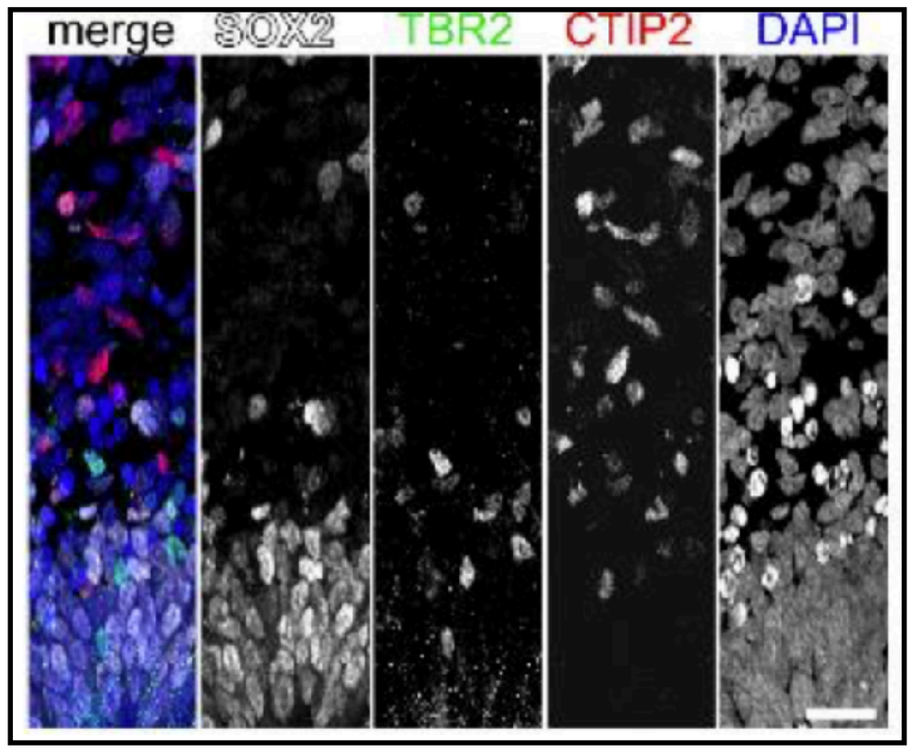
Cerebral Organoids & iPSC

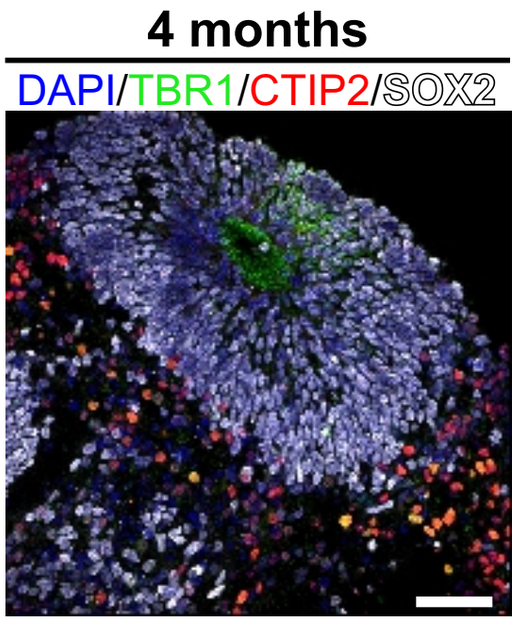


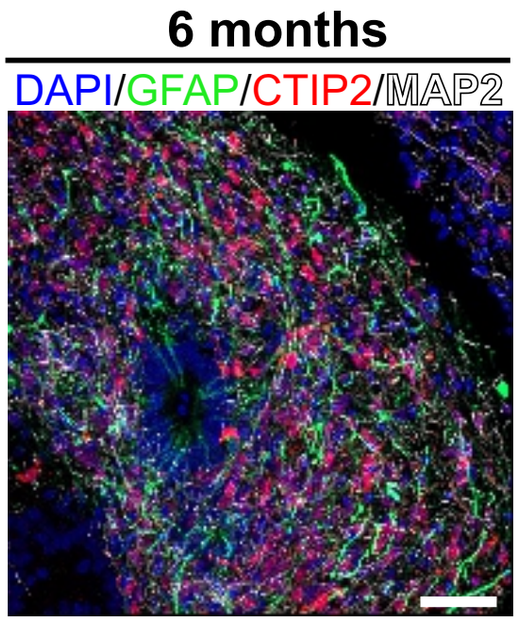
Pri Negraes

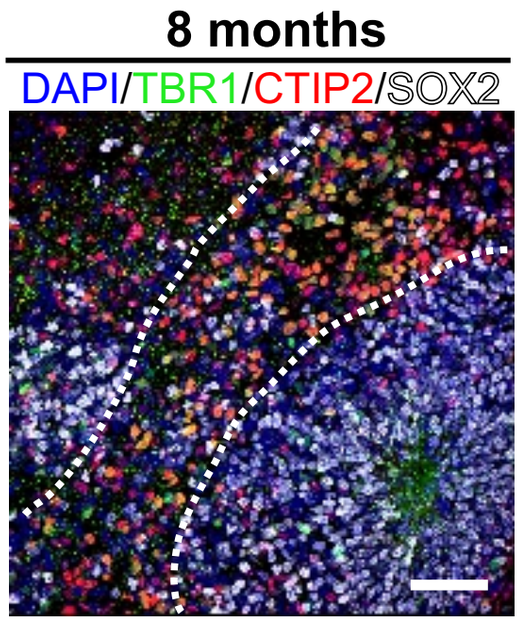
Cleber Trujillo



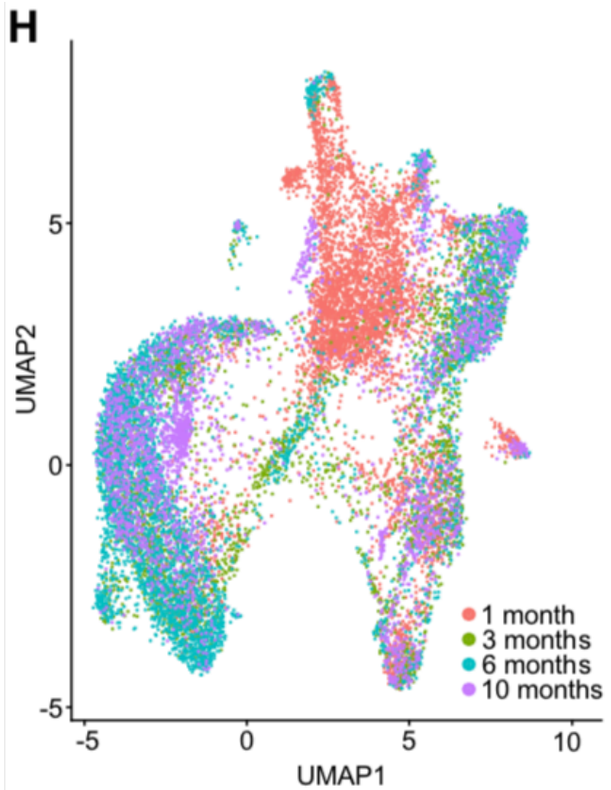


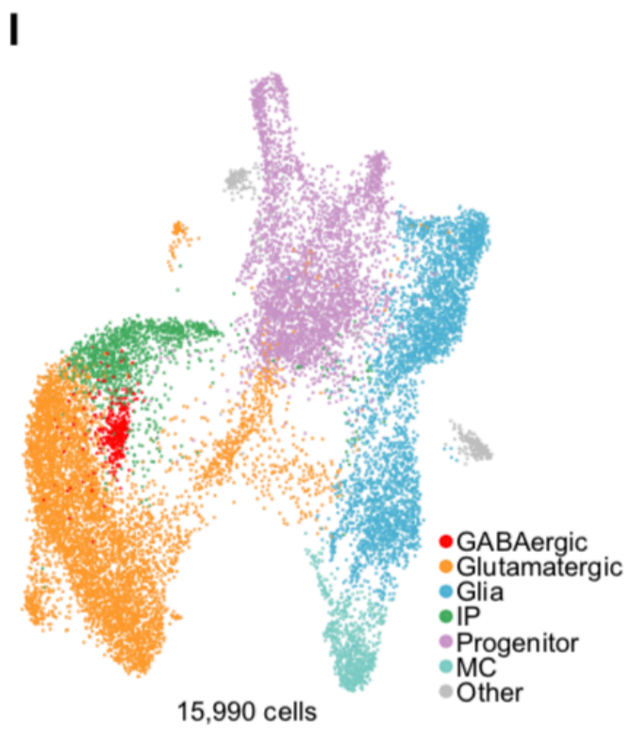


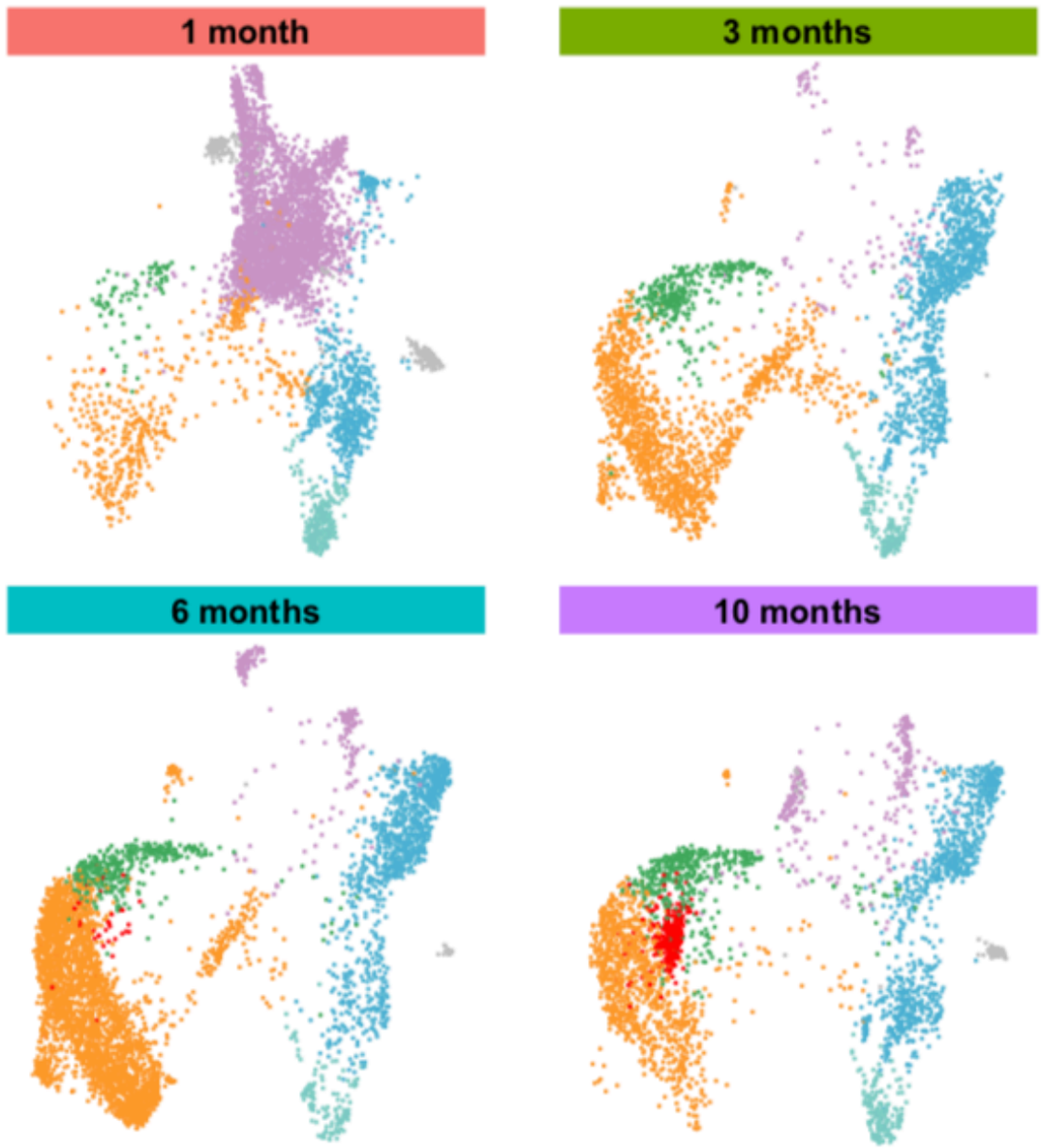


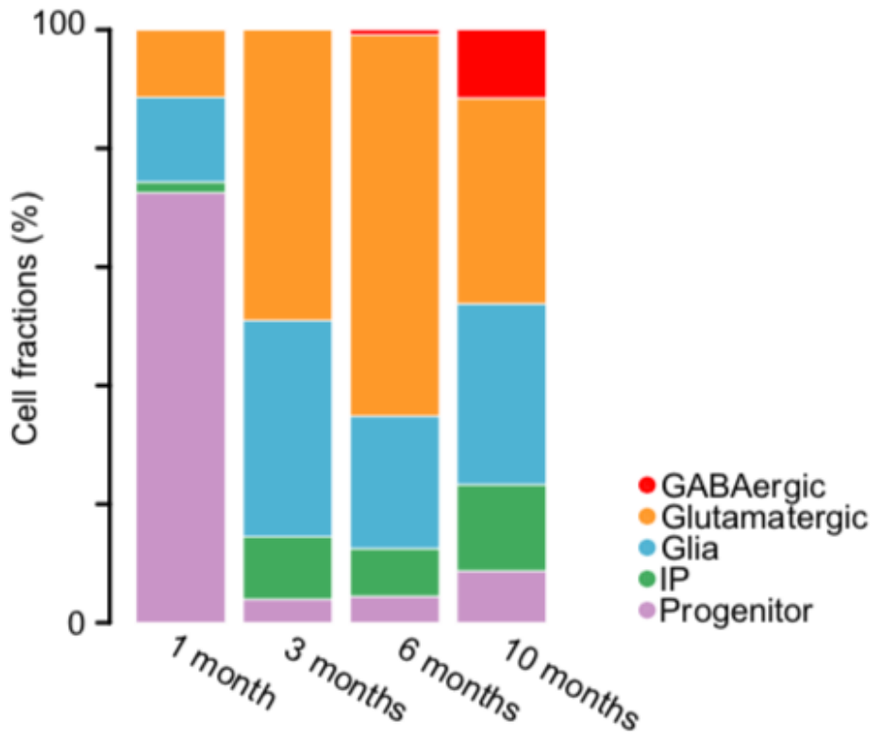


Single Cell RNA Sequencing





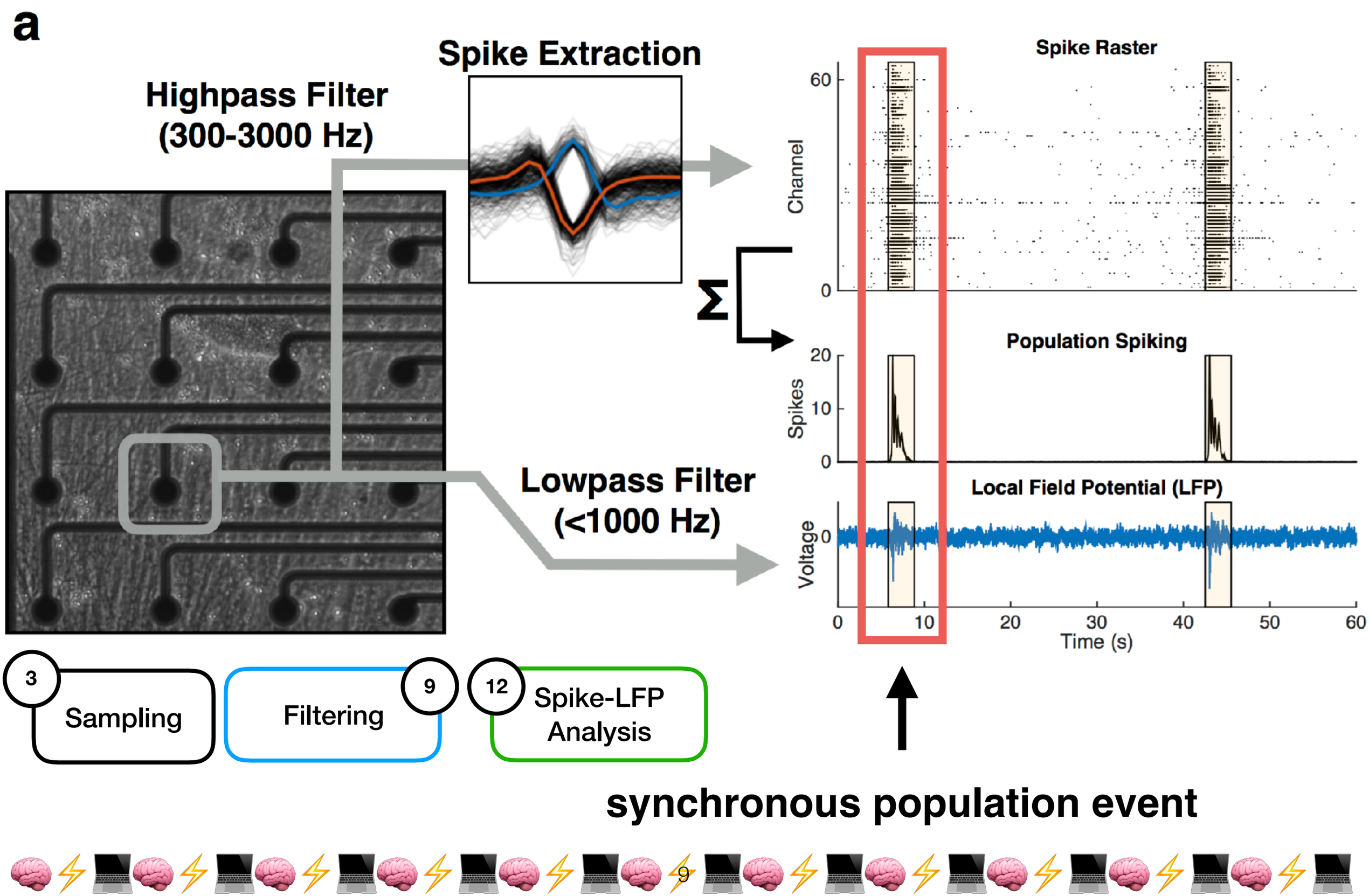




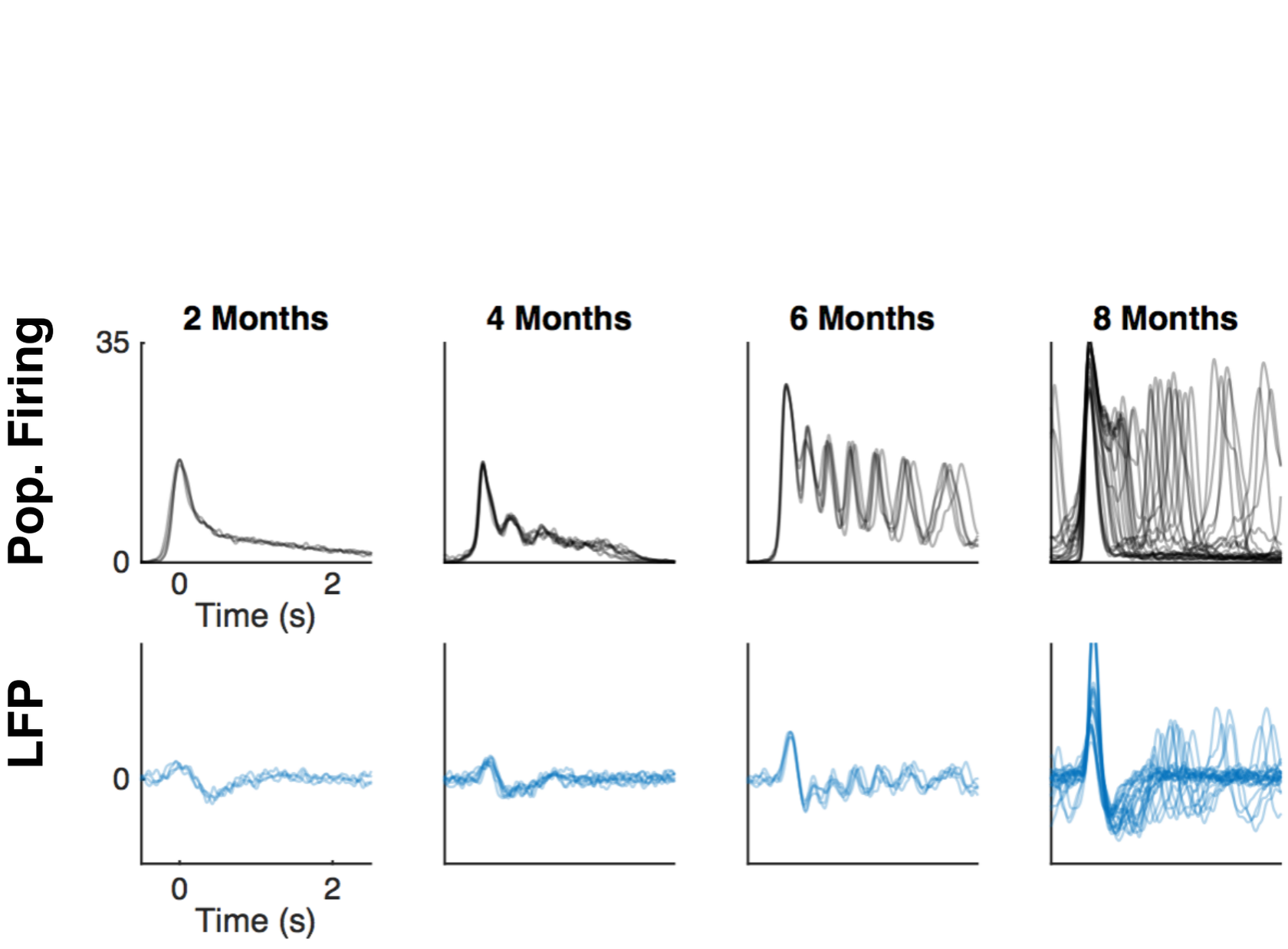
Multi Channel Analysis

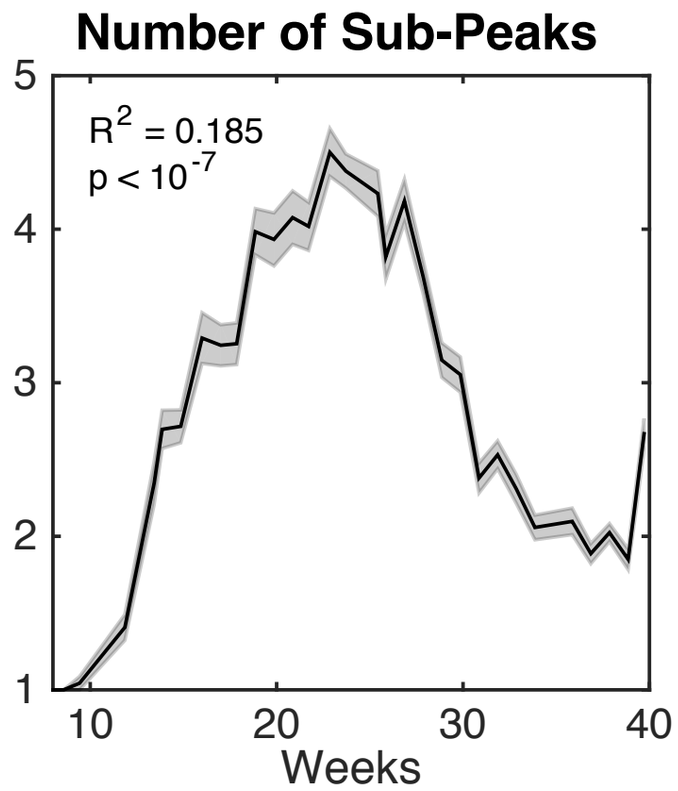
Dimensionality

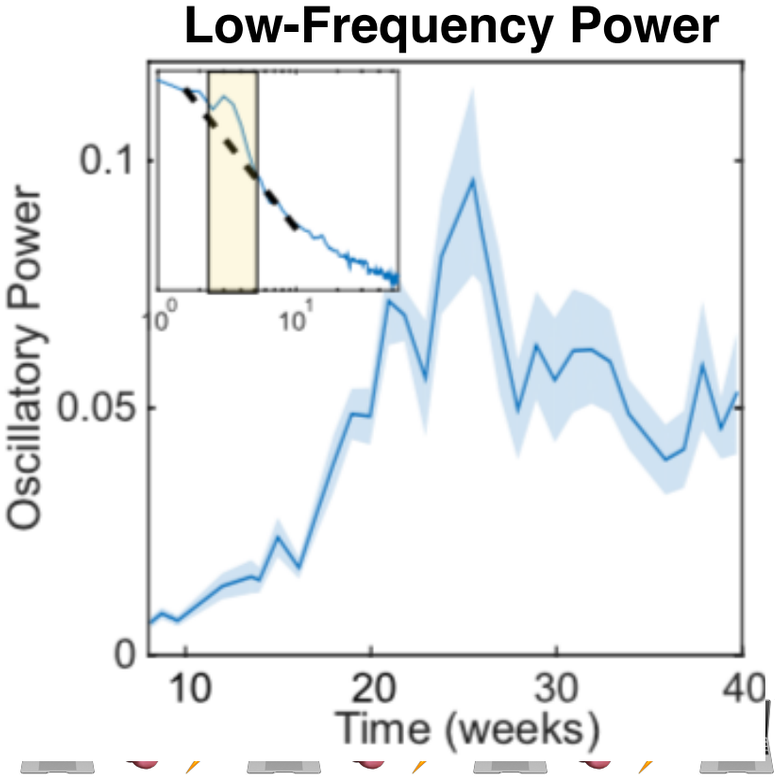
Organoid Electrophysiology



Oscillatory Network Dynamics





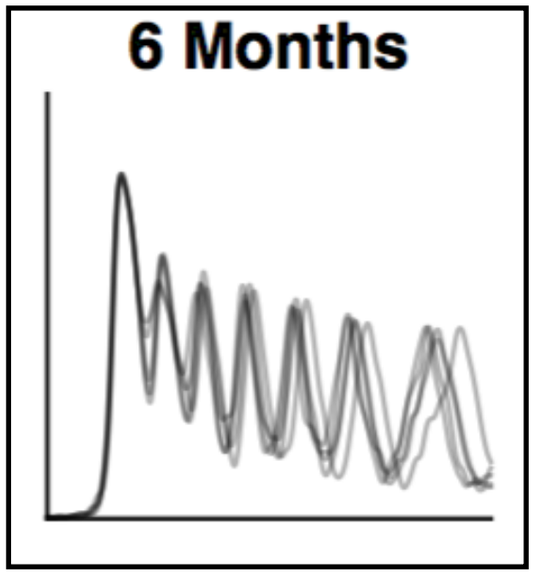


4 Time-locked Analysis

6 Fourier Analysis

13 Spike-Train Models

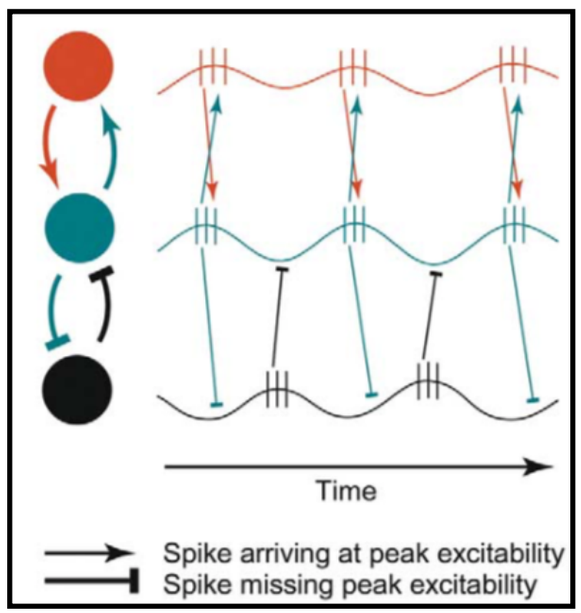
Oscillatory Network Dynamics



3Hz Rhythmic Population Firing

(5 seconds)

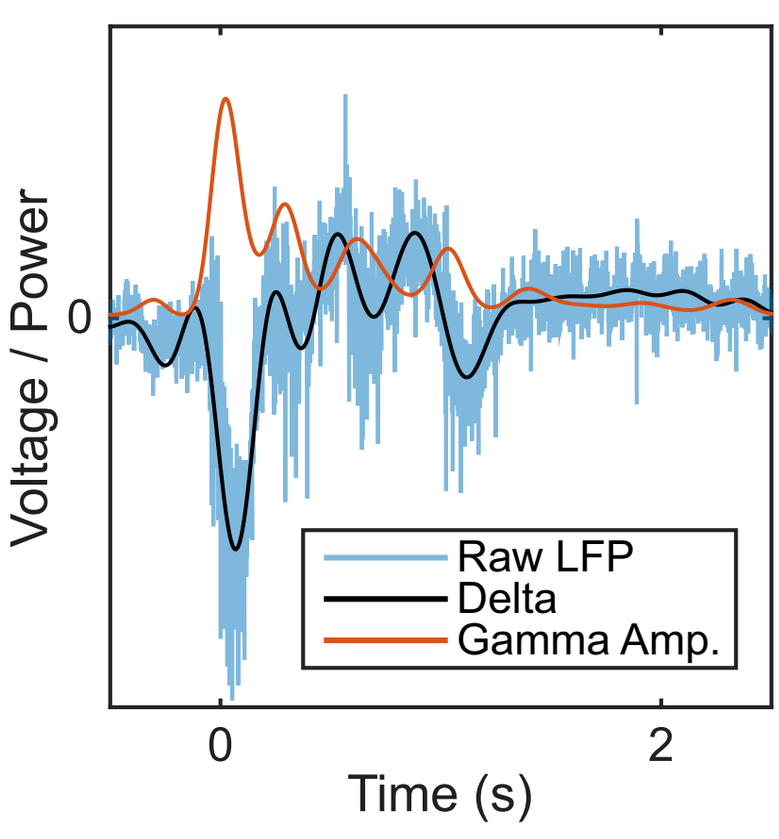
Oscillatory Coordination

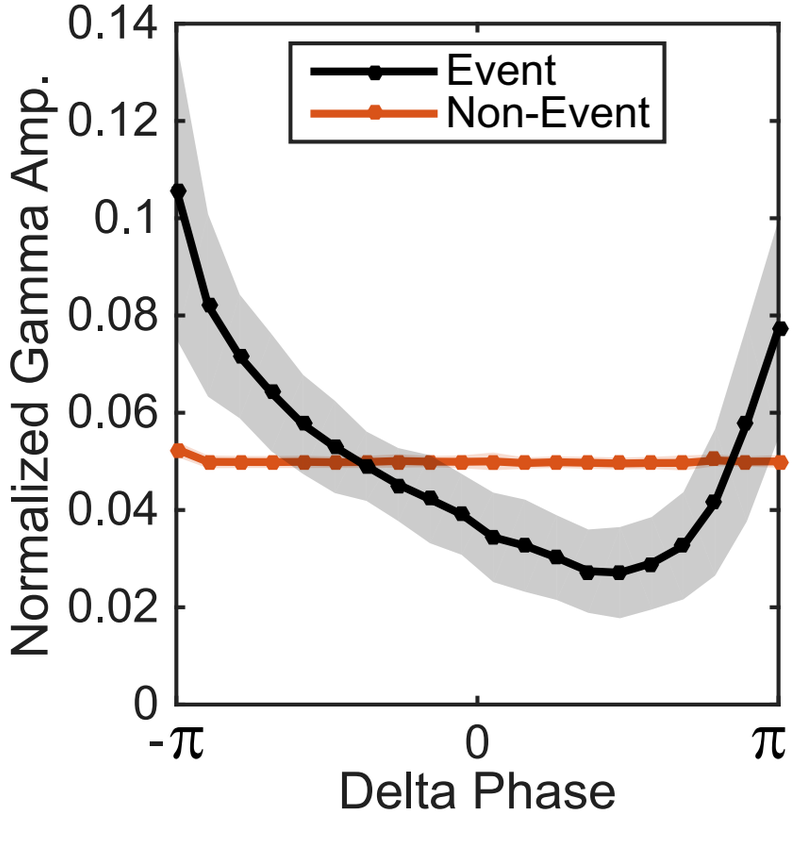


Fries, 2005

Communication Through Coherence

Oscillations are thought to temporally organize spikes, as evidenced by spike-field (SFC) or **phase-amplitude coupling (PAC)**.



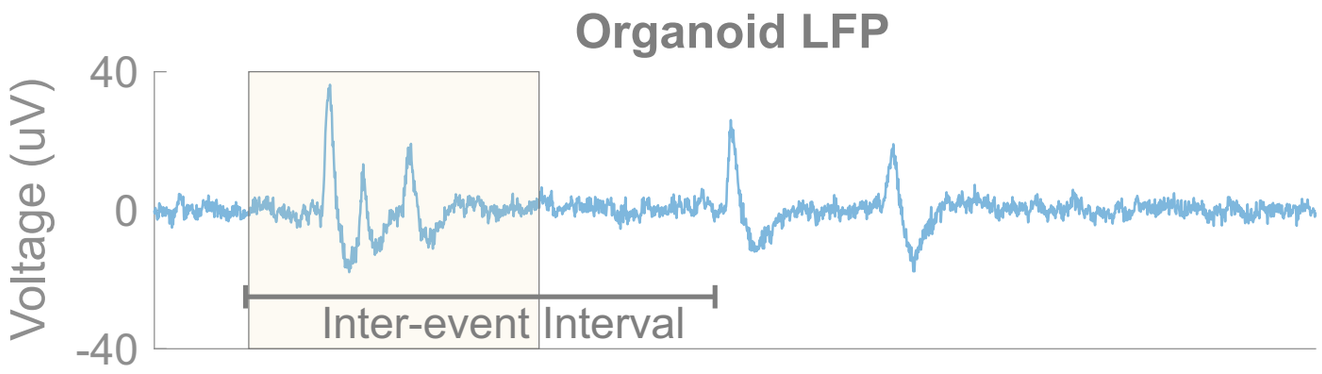


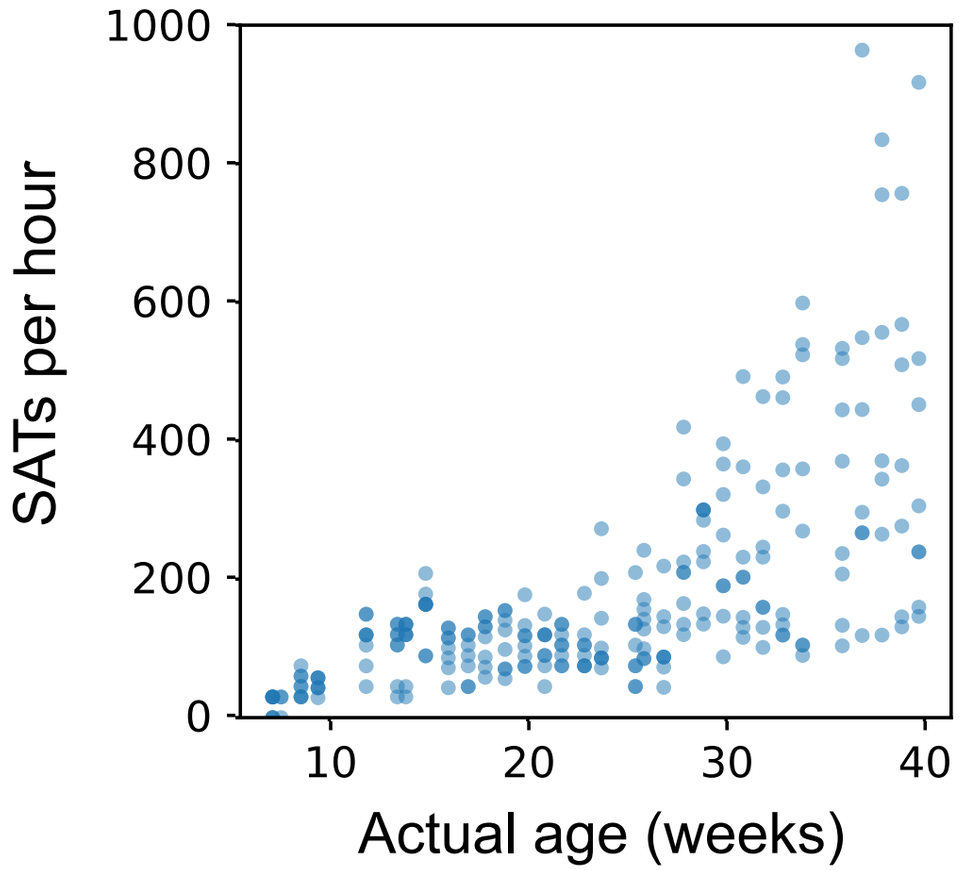
9 Filtering

10 Hilbert

12 Spike-LFP Analysis

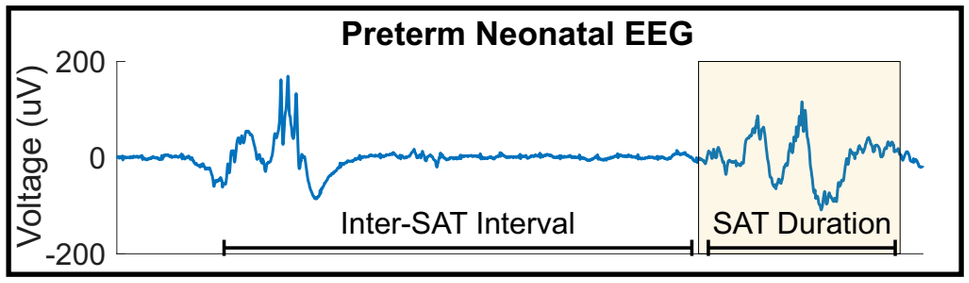
Comparing to Human Electrophysiology



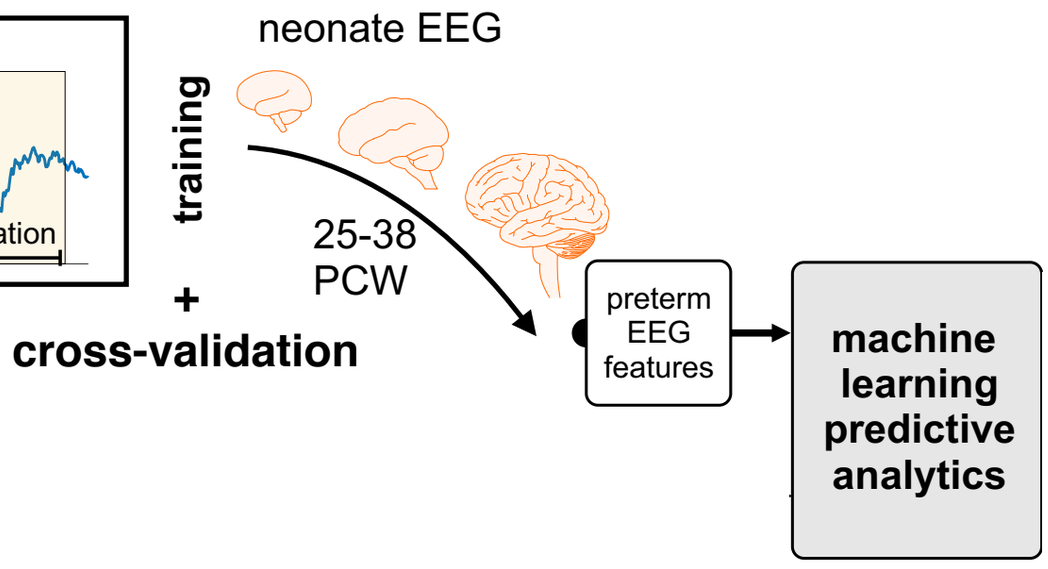


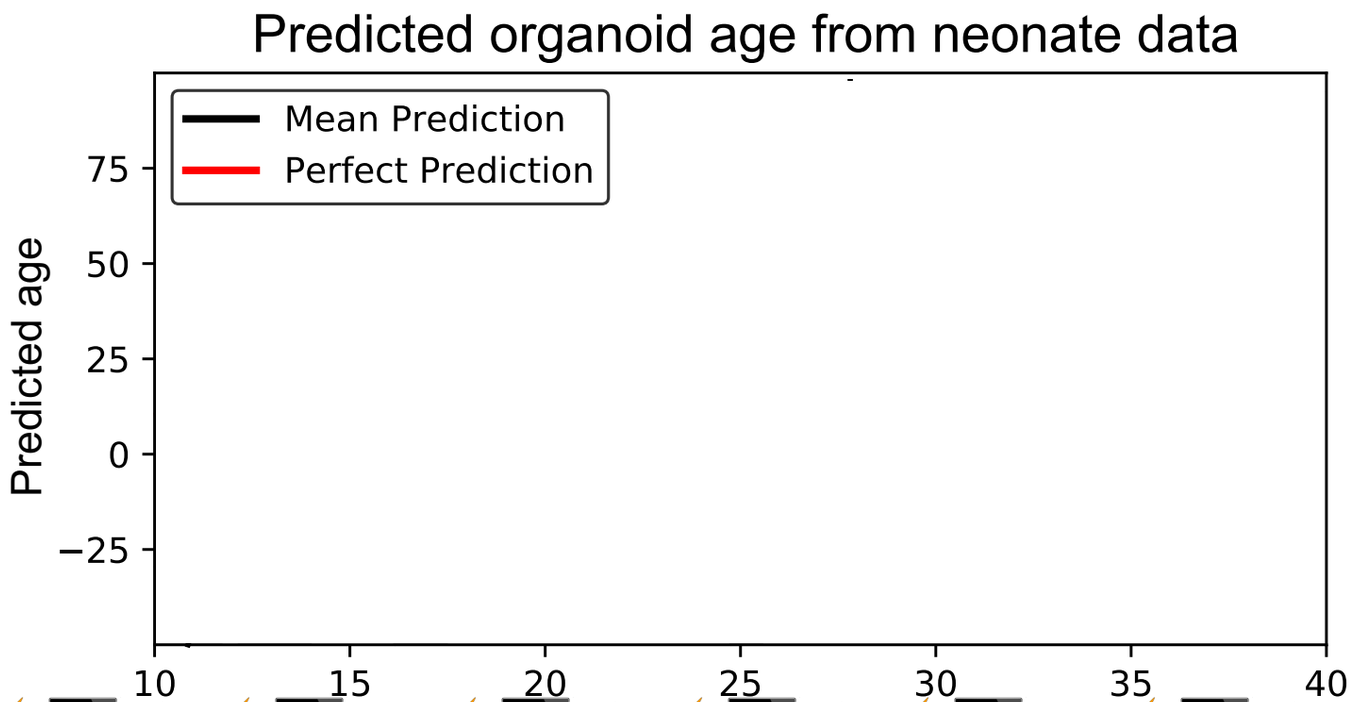
Data: Stevenson et al., 2018.

Predicting Organoid “Brain Age”



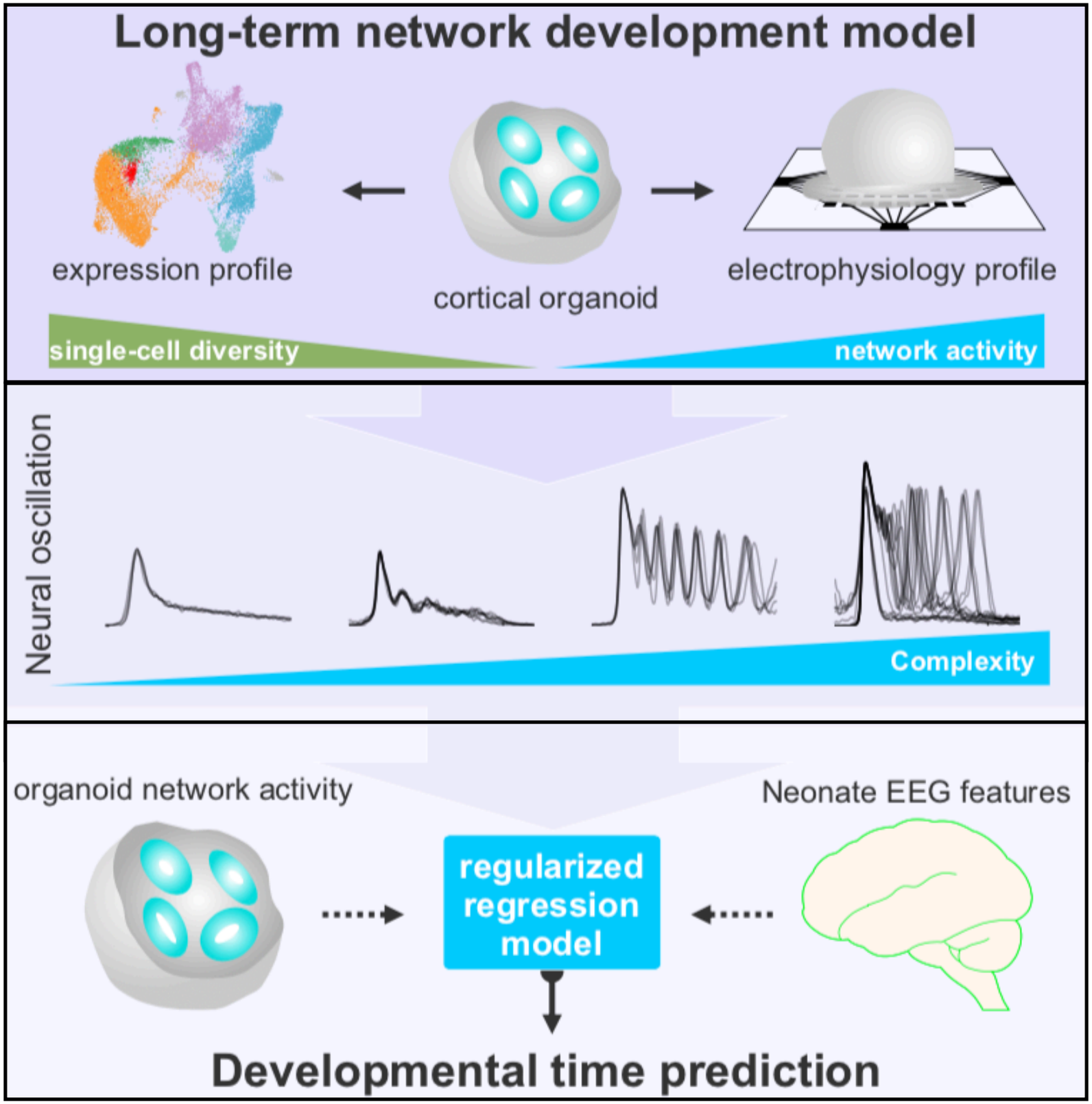
Data: Stevenson et al., 2018.



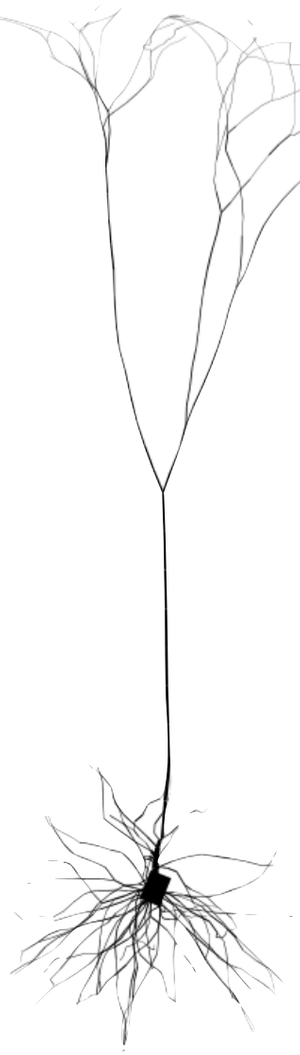


Organoid partially recapitulates the development of electrophysiological features in-vivo.

Developmental Model of Electrophysiology



Complex Dynamical System

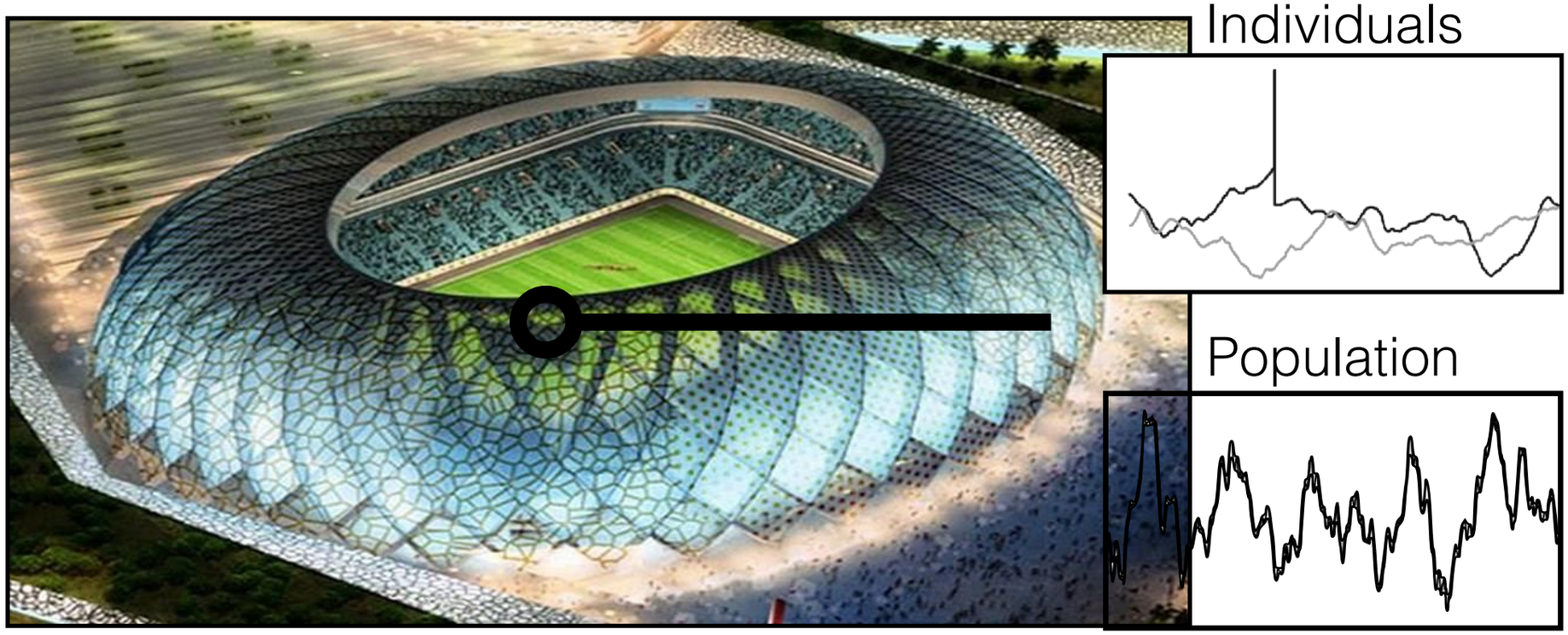


x O(10 billion)

$$\tau_m \frac{dv}{dt} = -v(t) + RI(t)$$

Are we screwed (10 billion ways)?

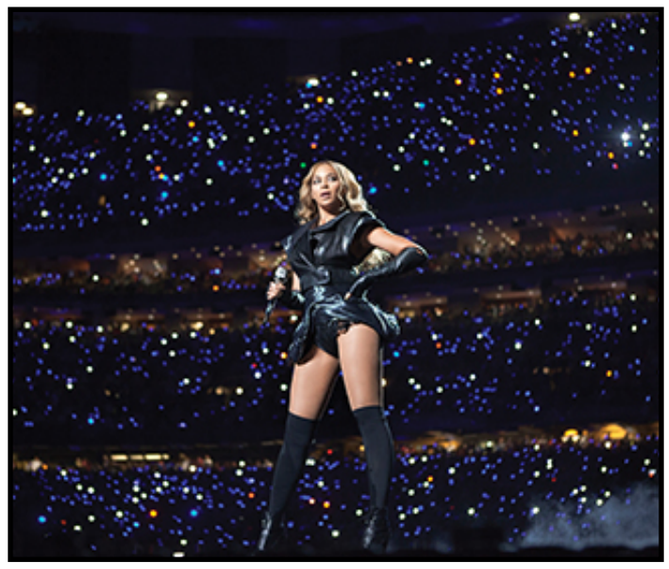
Complex Dynamical System



“asynchronous”

“oscillatory”

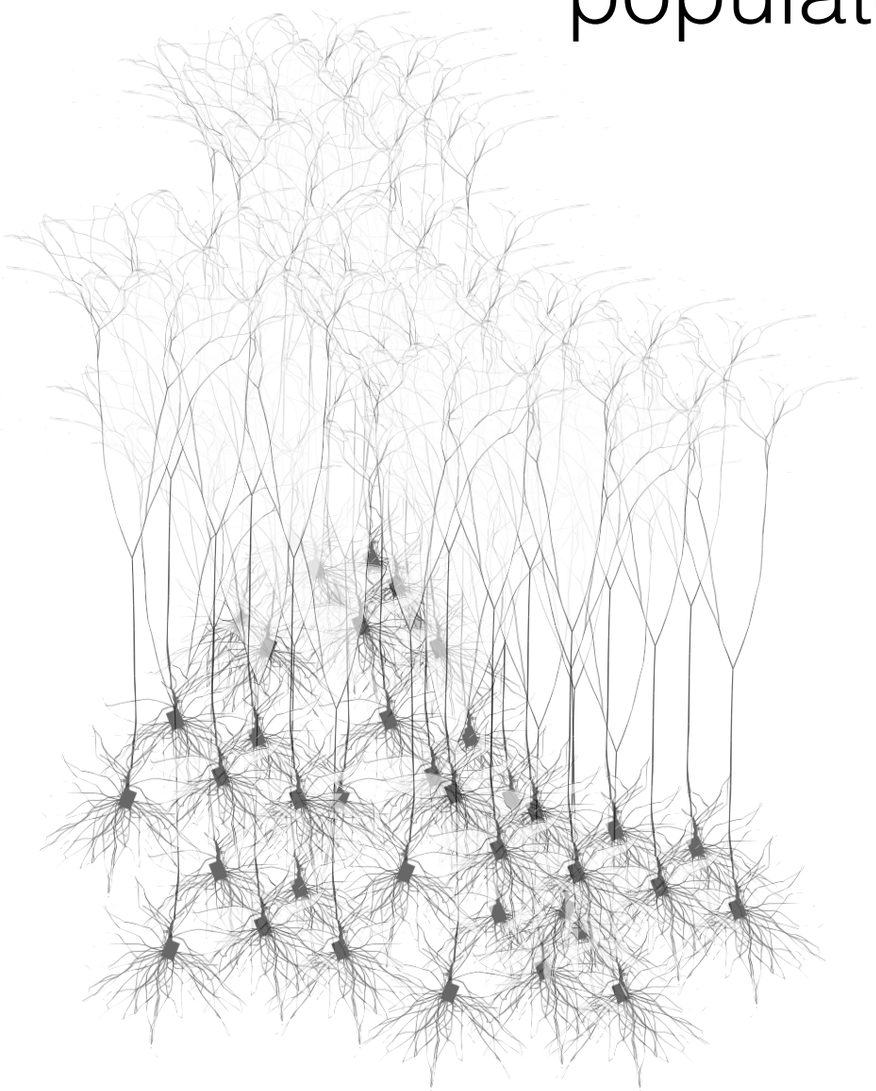
“synchronous”



Low-Dimensional Activity in the Brain

Can we meaningfully study a 10 billion-dimensional system?

Are there low-dimensional attractors in the phase space populated by our ~10 billion neurons?

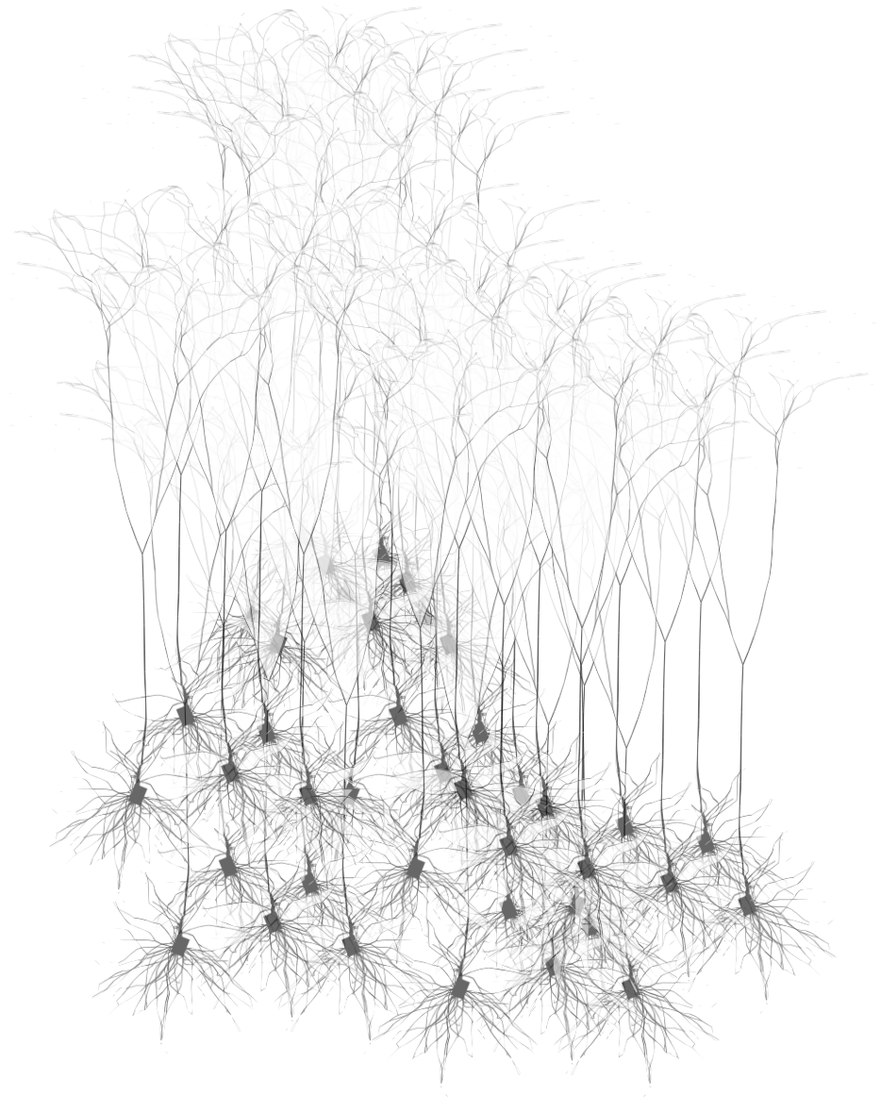


(Probabaly) Yes!

1. Experiential Argument
2. Single Neuron Attractors
3. Neural Population

Low-Dimensional Activity in the Brain

1. **Experiential Argument**
2. Single Neuron Attractors
3. Neural Population



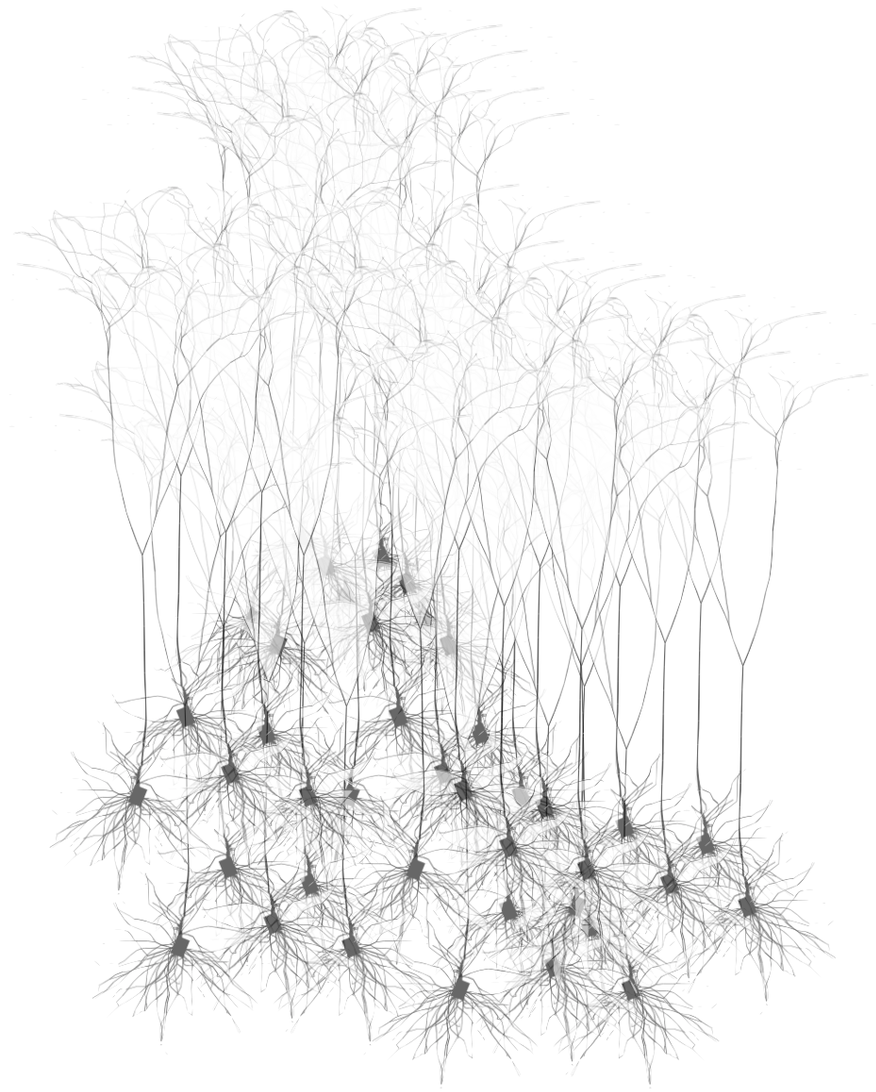
We have:

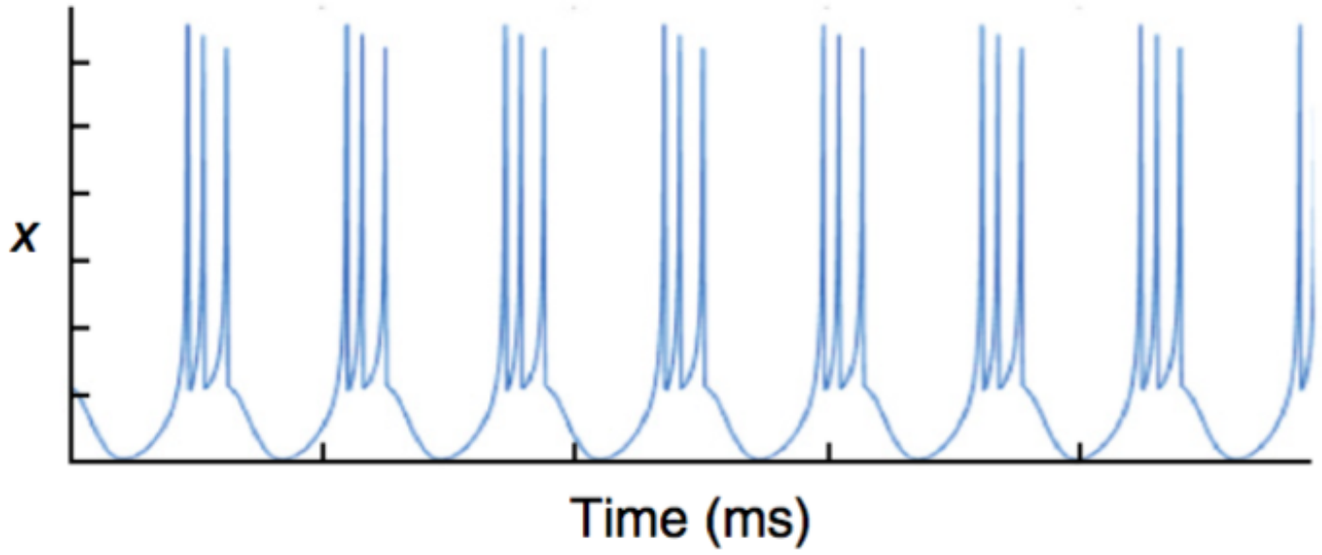
memories
repeatable skills
songs that get stuck in our heads
. . .

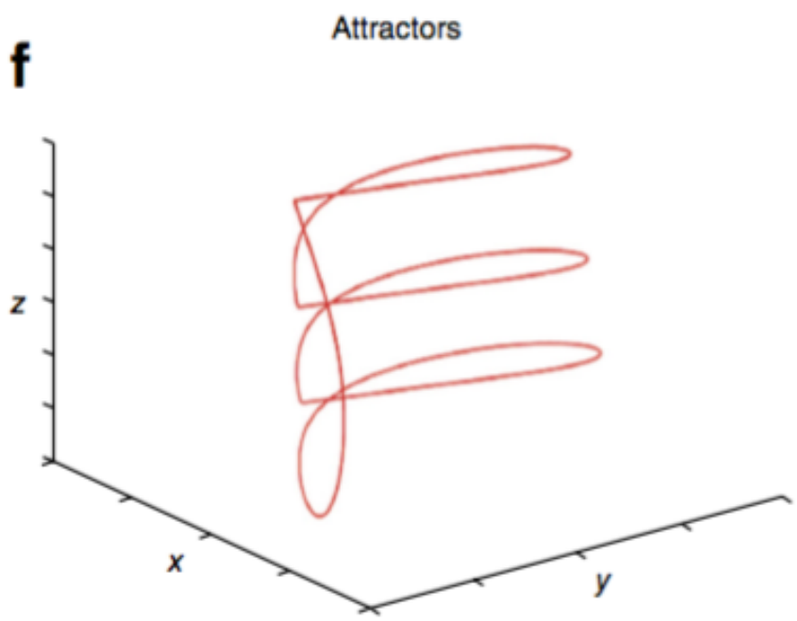
Our experiences (probably) do not span an infinite dimensional space, “limited” by our brains.

Low-Dimensional Activity in the Brain

1. Experiential Argument
2. **Single Neuron Attractors**
3. Neural Population





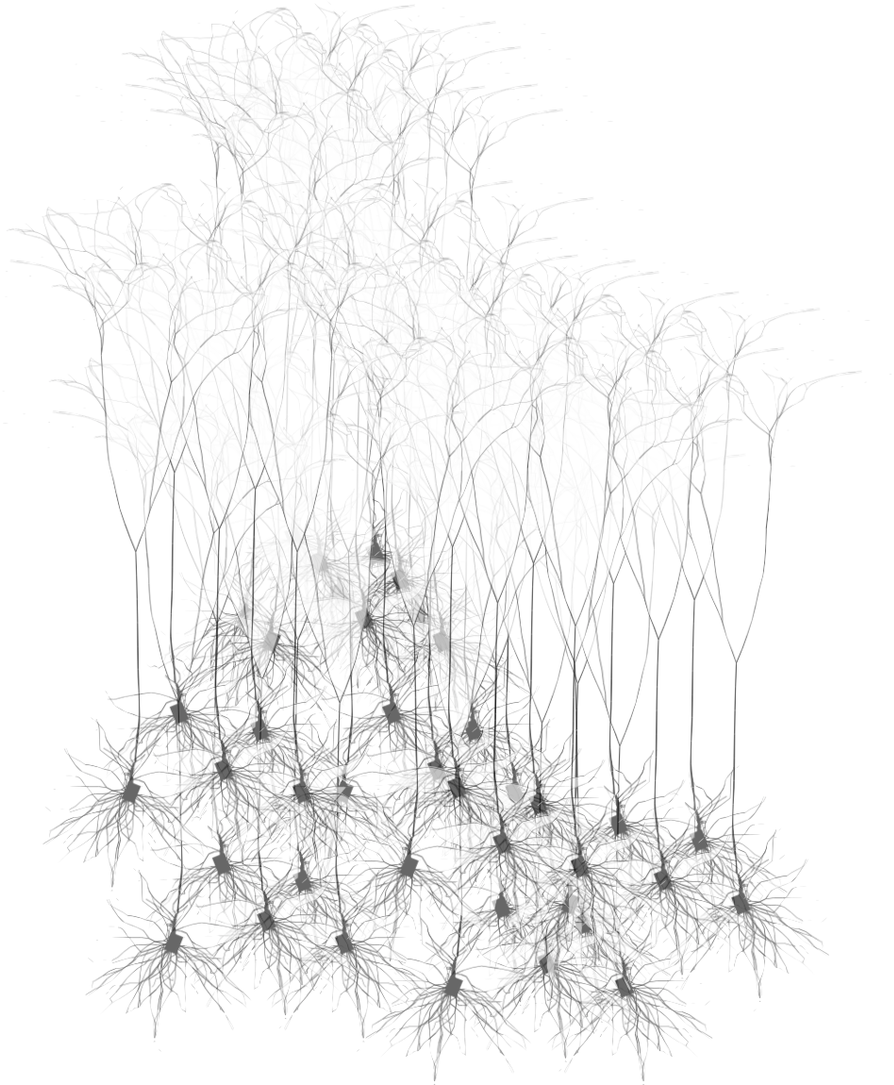


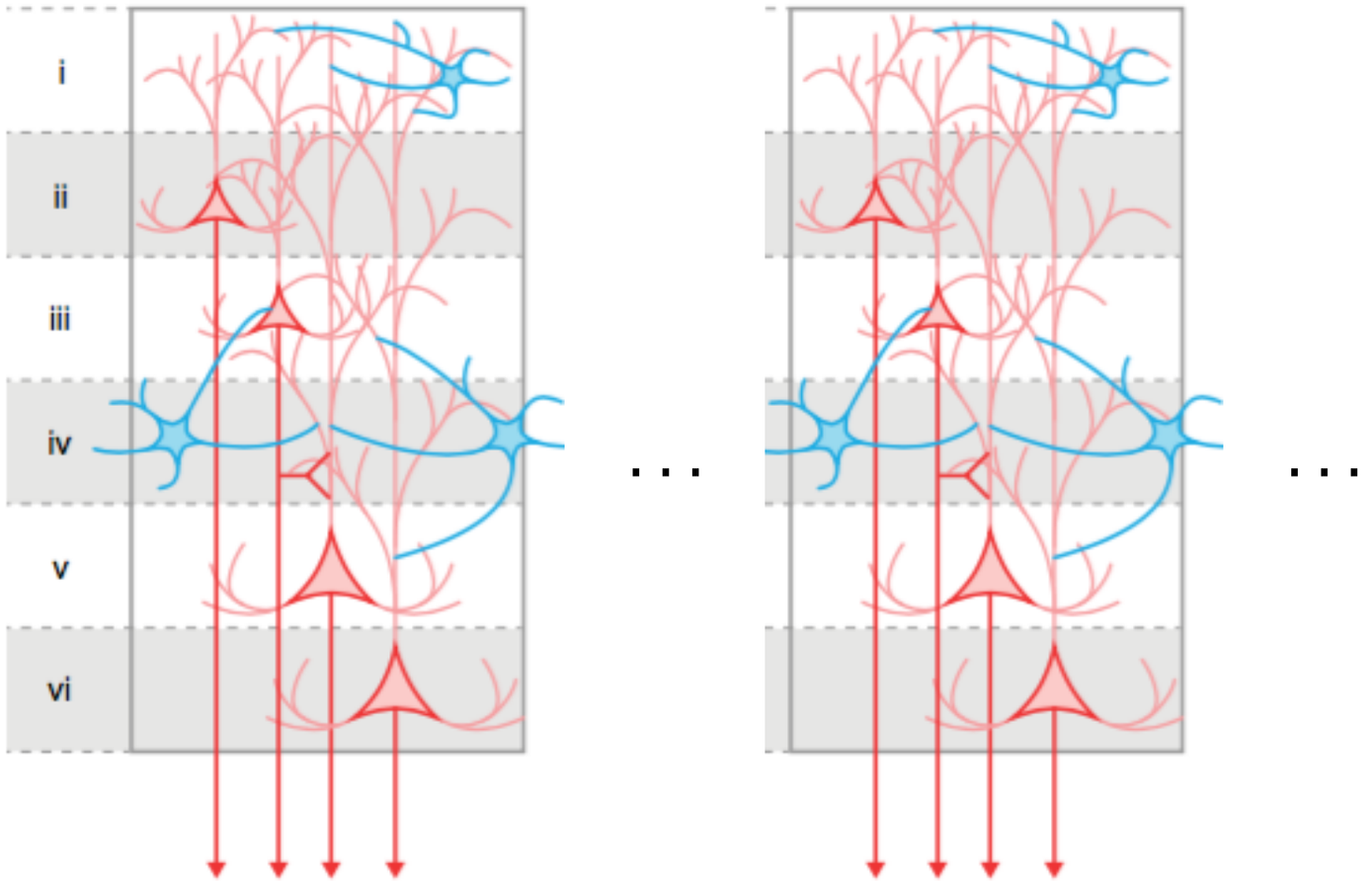
Neurons fire repeated action potentials: dynamics around a limit cycle

images: Breakspear (2017, Nat Neurosci)

Low-Dimensional Activity in the Brain

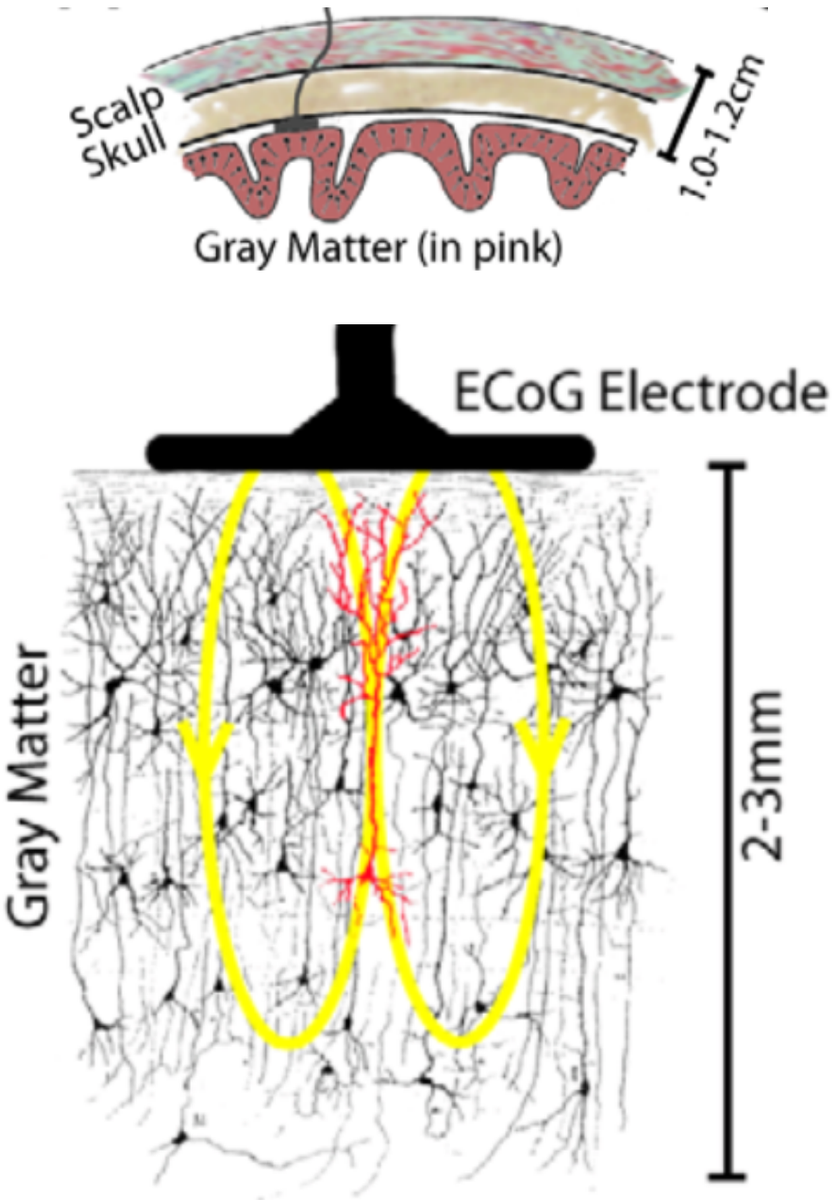
1. Experiential Argument
2. Single Neuron Attractors
3. **Neural Population**





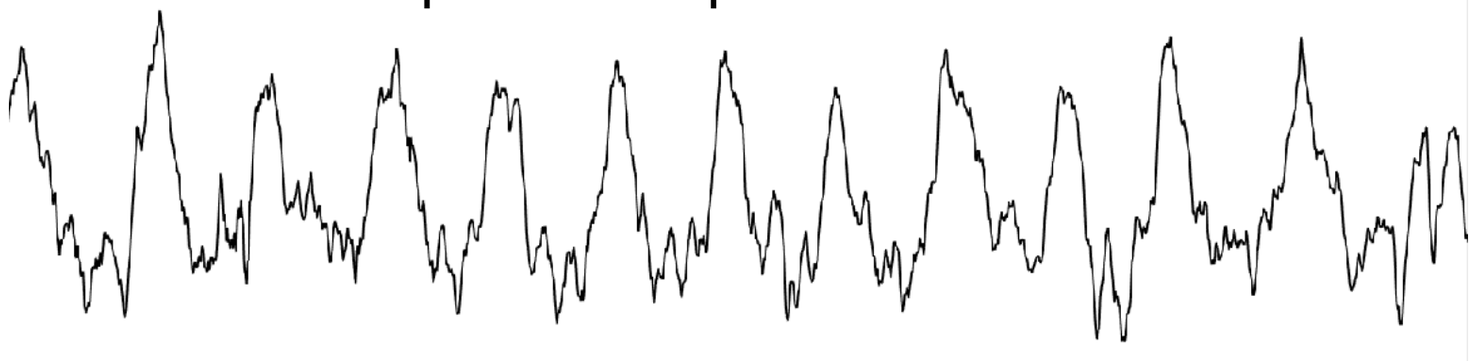
Neurons form ensembles that behave similarly.
(synchronicity, redundancy)

Synchrony Is Low-Dimensionality



Neural Oscillations (Brain Waves!)

Ubiquitous phenomenon



Not individual action potentials, but synchronous (synaptic) current discharges.

Limit Cycles?

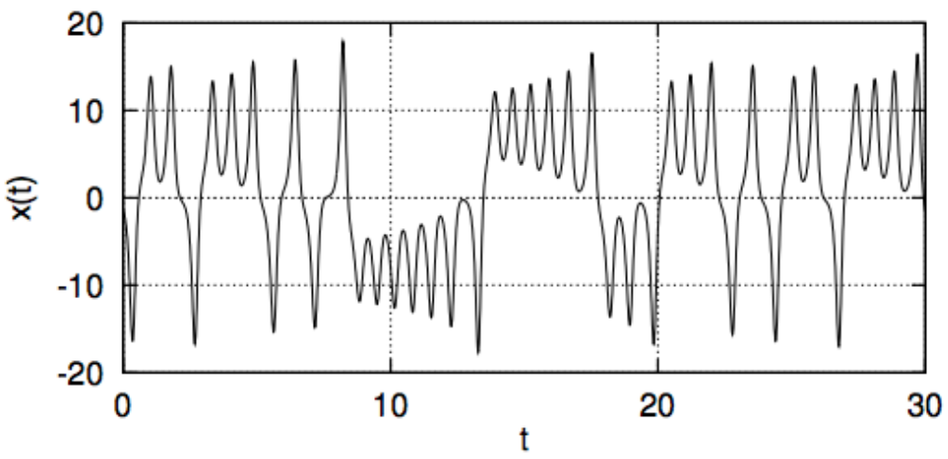
images: Miller et al (PLoS CB, 2009)

Phase Space Reconstruction

Problem:

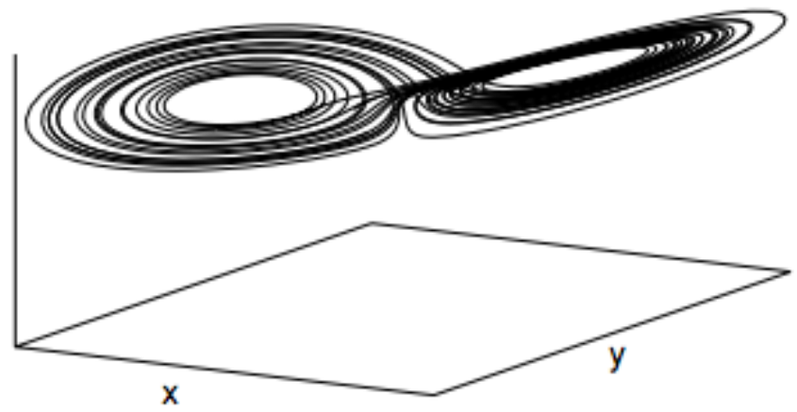
There is attractor dynamics in phase space but we only observe data in time projected along a single dimension.

Can we learn anything about the attractor?



projection

reconstruction?



Phase Space Reconstruction

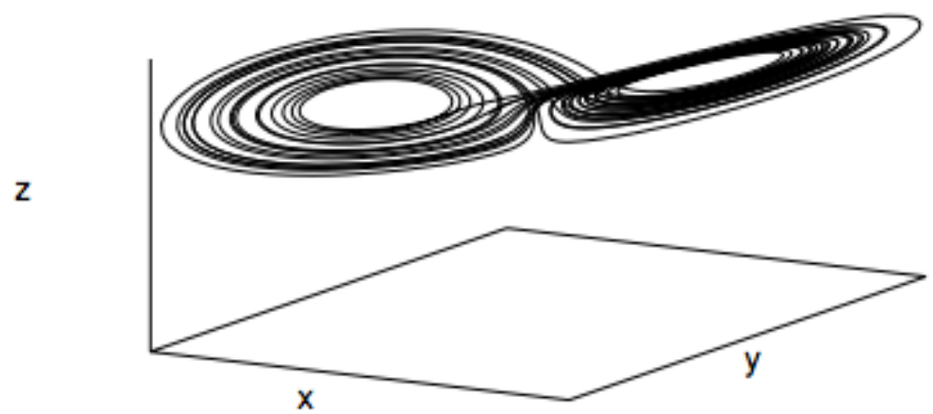
Takens' Theorem

We can reconstruct the attractor dynamics **faithfully** with **delayed** version of the data as "**dimensions**".

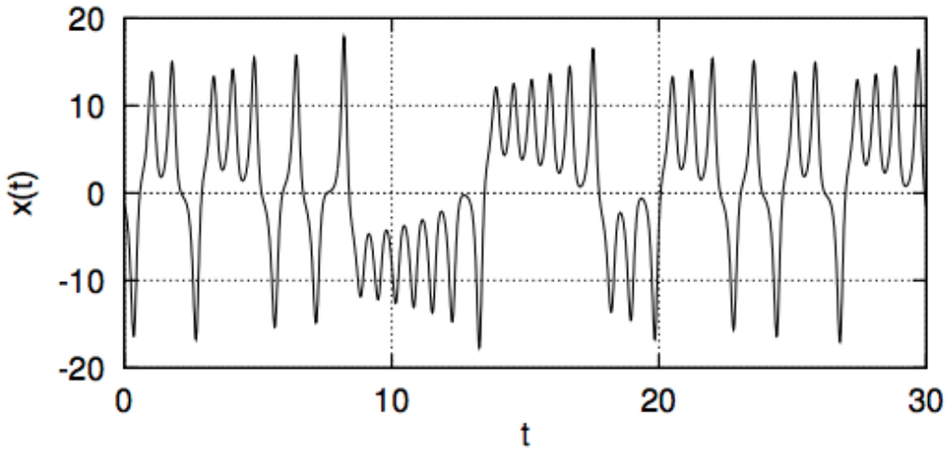
- faithfully: diffeomorphic (warped attractor manifold), preserves topological properties
- delayed: with optimal* time delay
- dimensions: 2D+1 dimensions, D is dimension of **attractor**

note: cannot recover dimension of phase space, only that of the attractor (hence low-D)

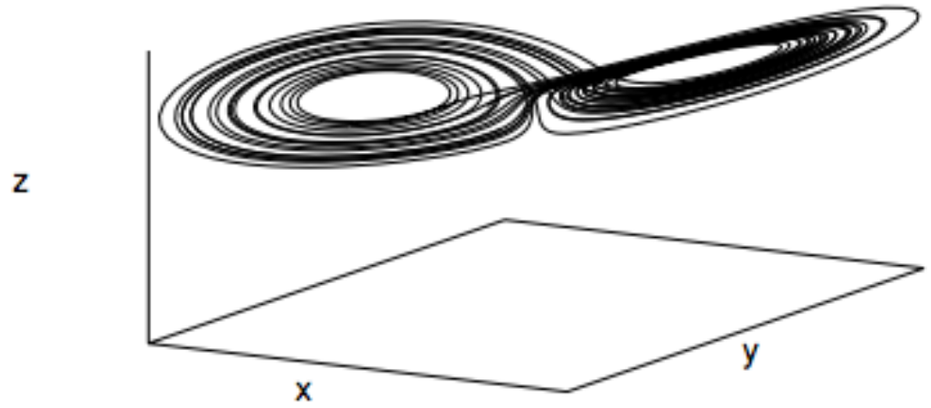
11 Nonlinear Techniques



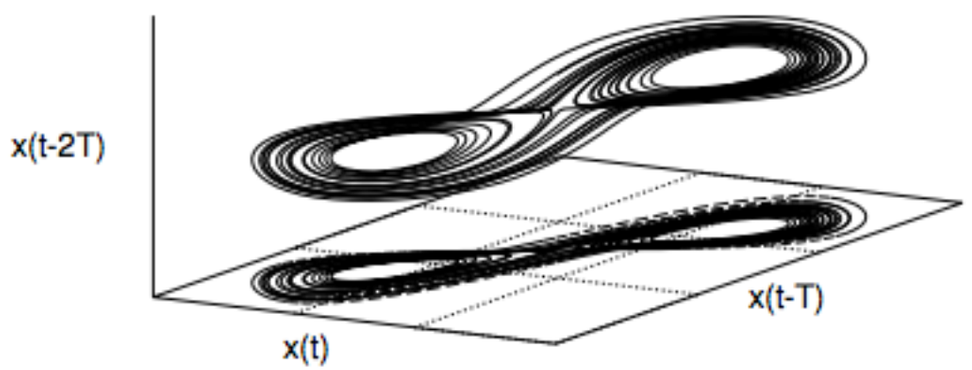
Phase Space Reconstruction



projection



reconstruction



Multi Channel Analysis 15-16

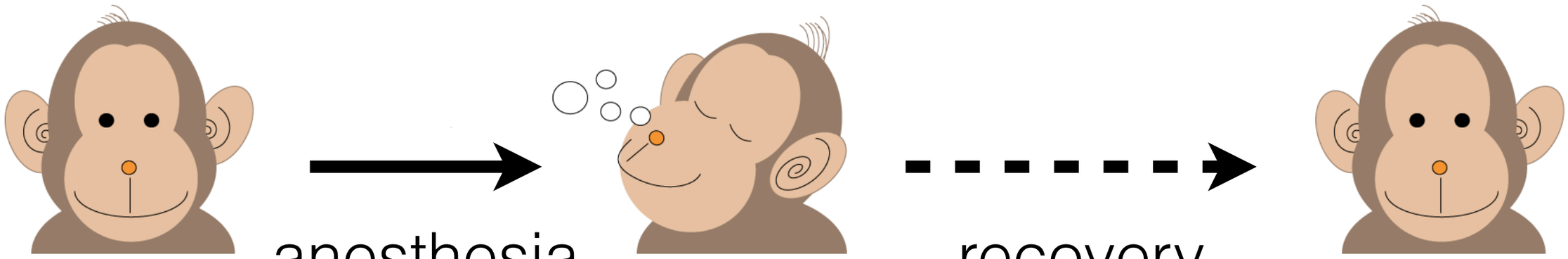
Dimensionality

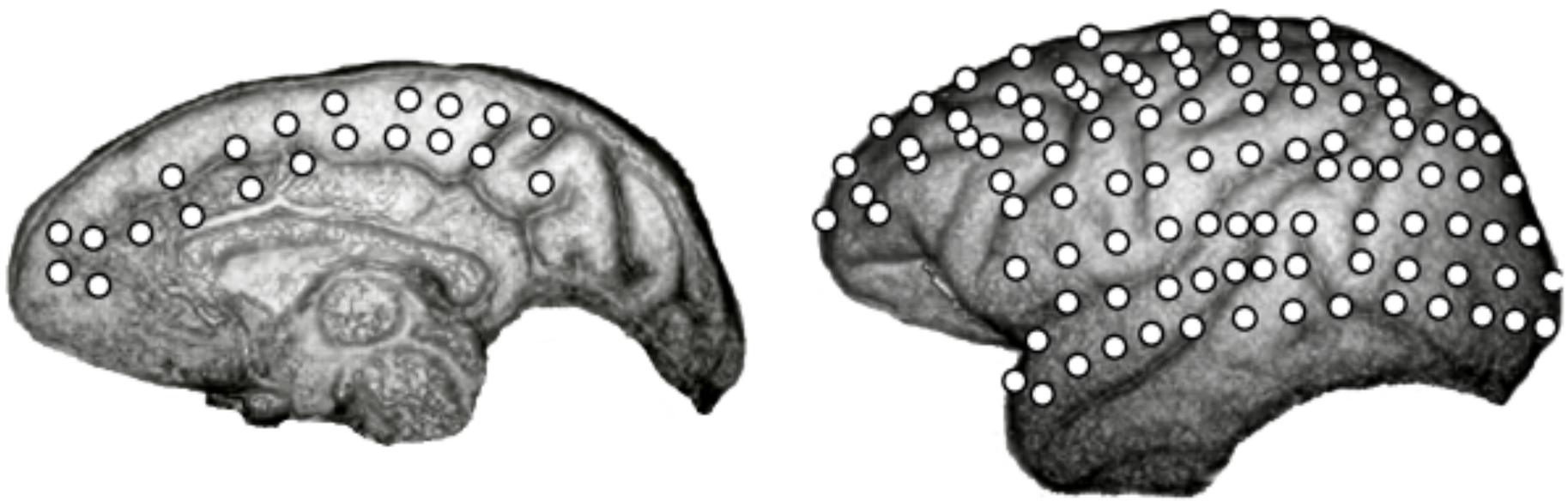
Information Theory

Dimensionality Change in Brain Dynamics

Question:

Does attractor dimension, as estimated via delay embedding, change with different brain states?

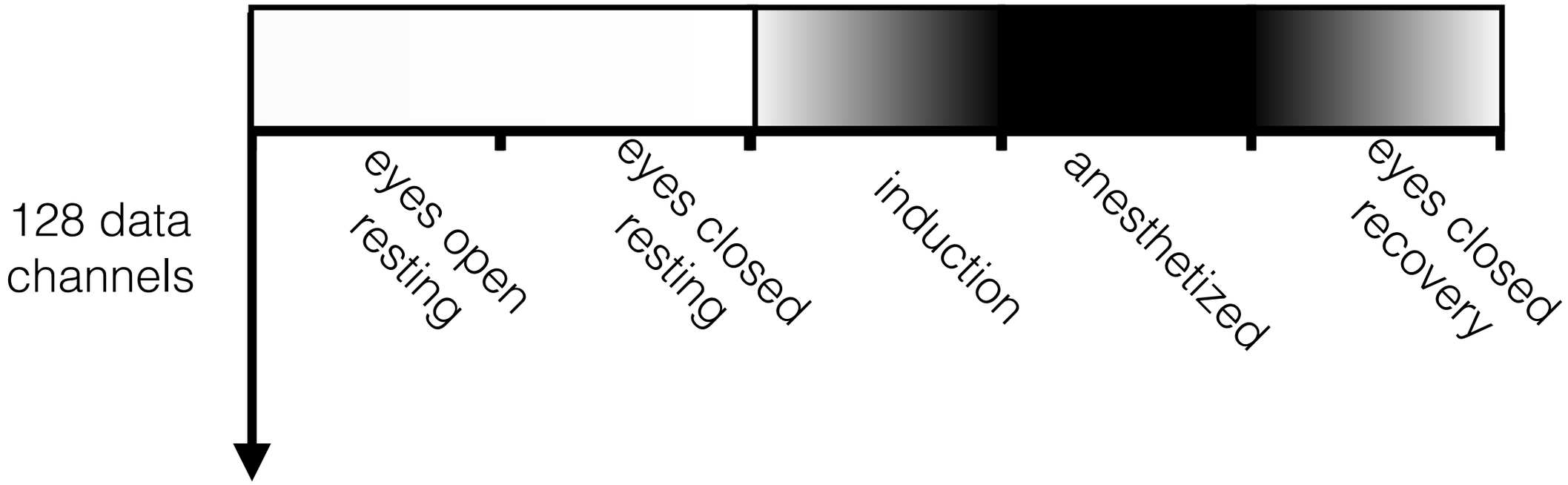




Dimensionality Change in Brain Dynamics

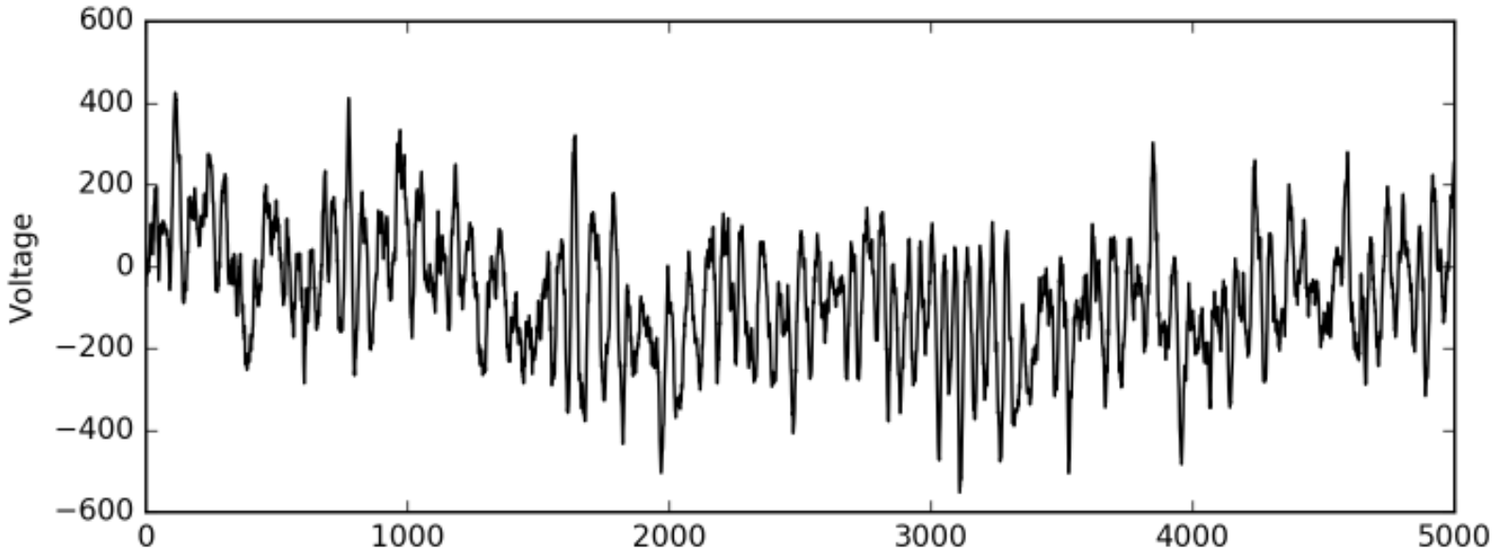
Hypothesis

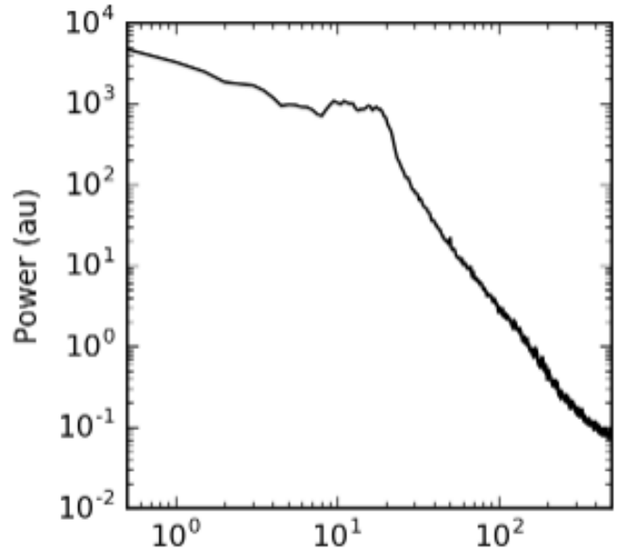
Anesthetized brain should have attractors of lower dimension due to decreased computational needs.



Dimensionality Change in Brain Dynamics

Awake

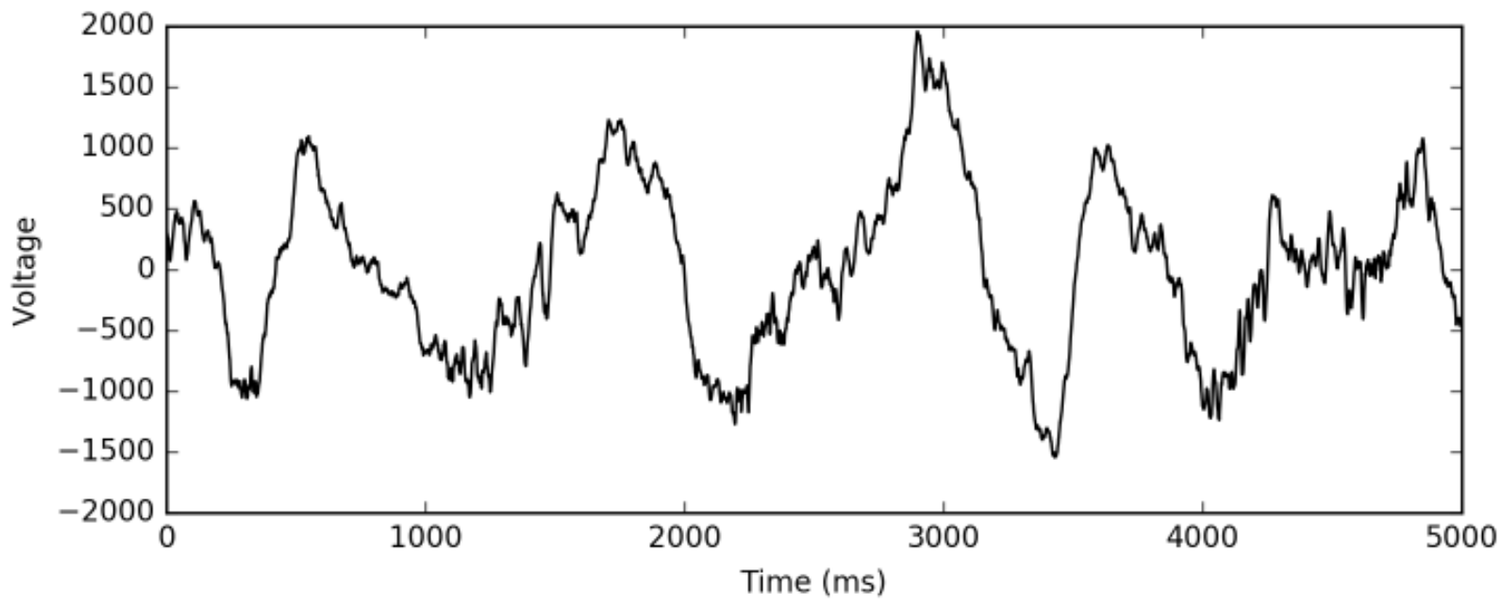


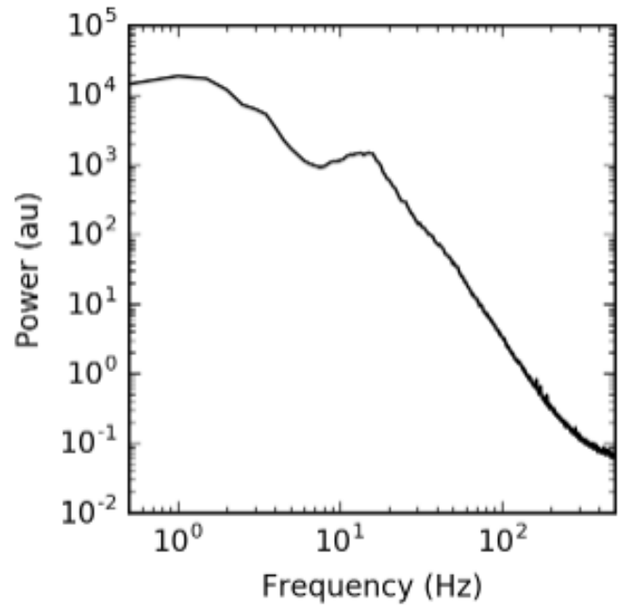


6

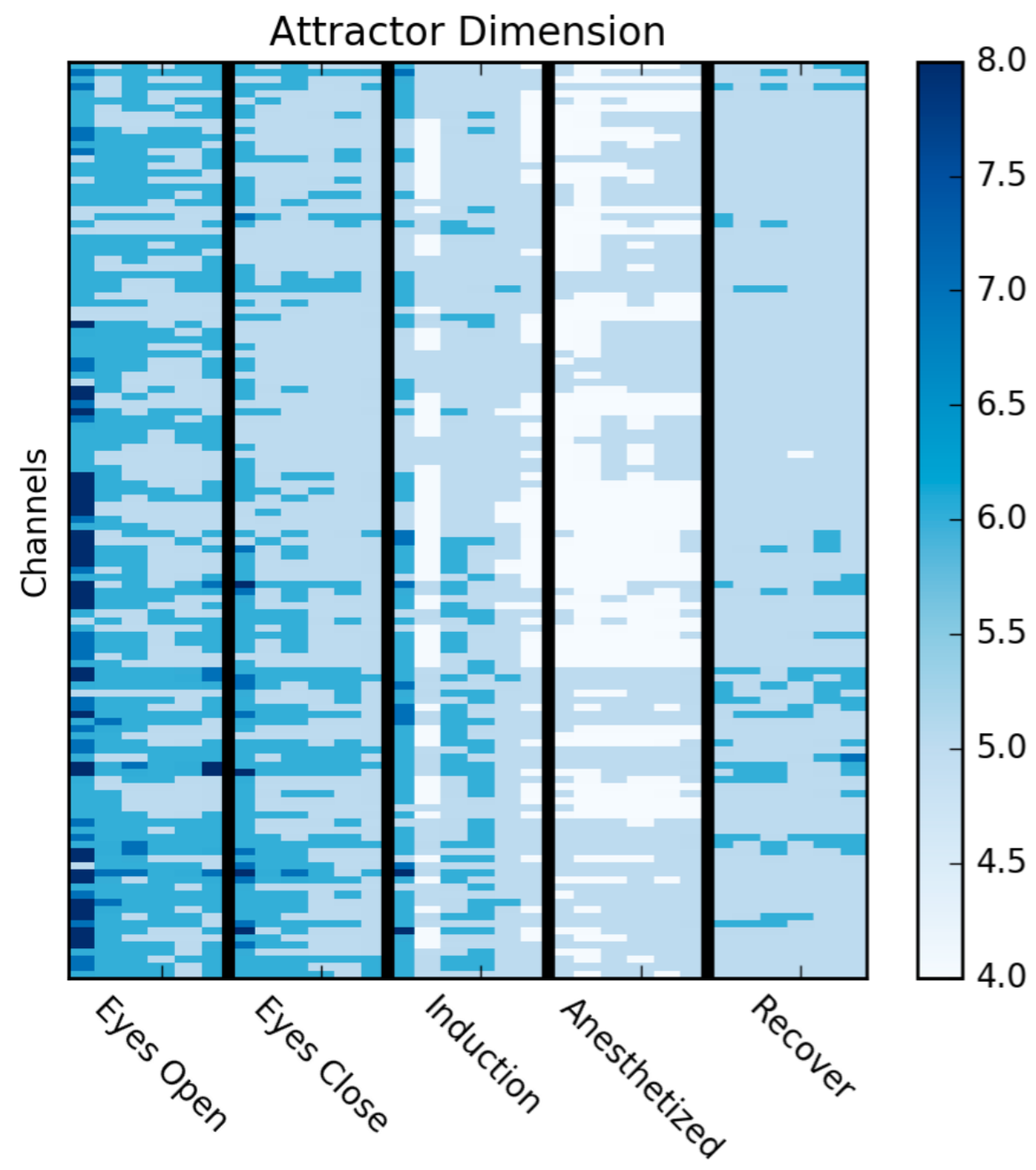
Fourier Analysis

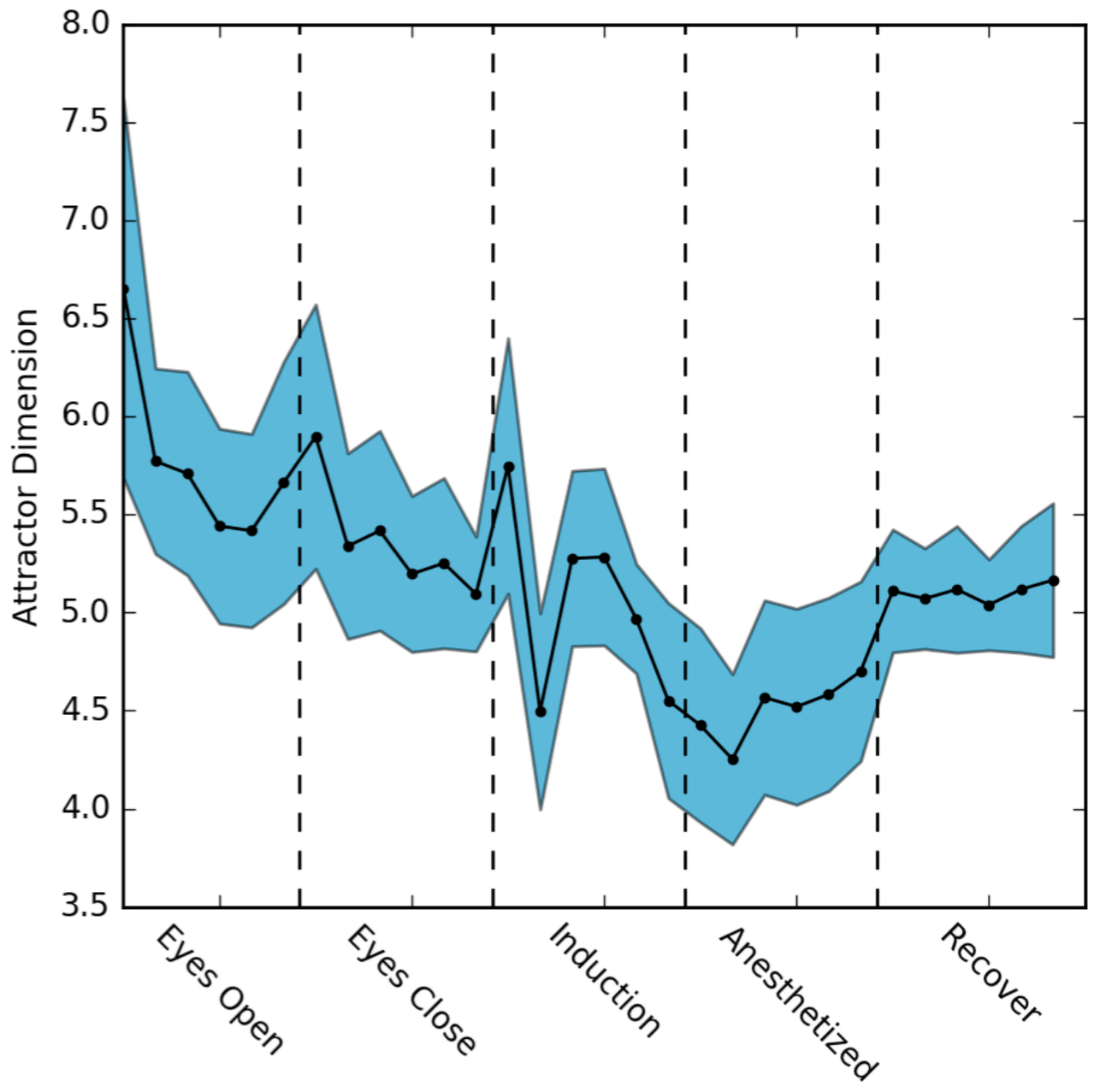
Anesthetized





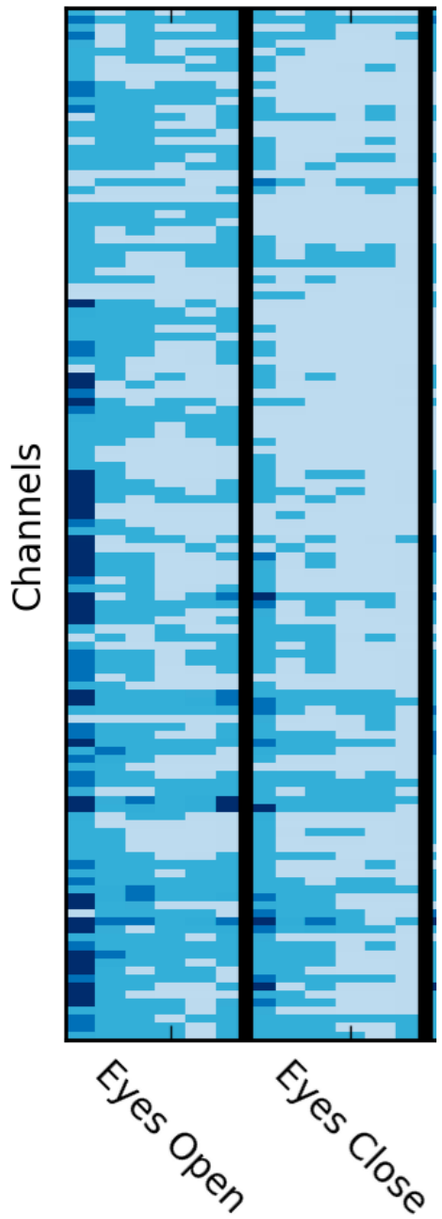
Attractor Dimension

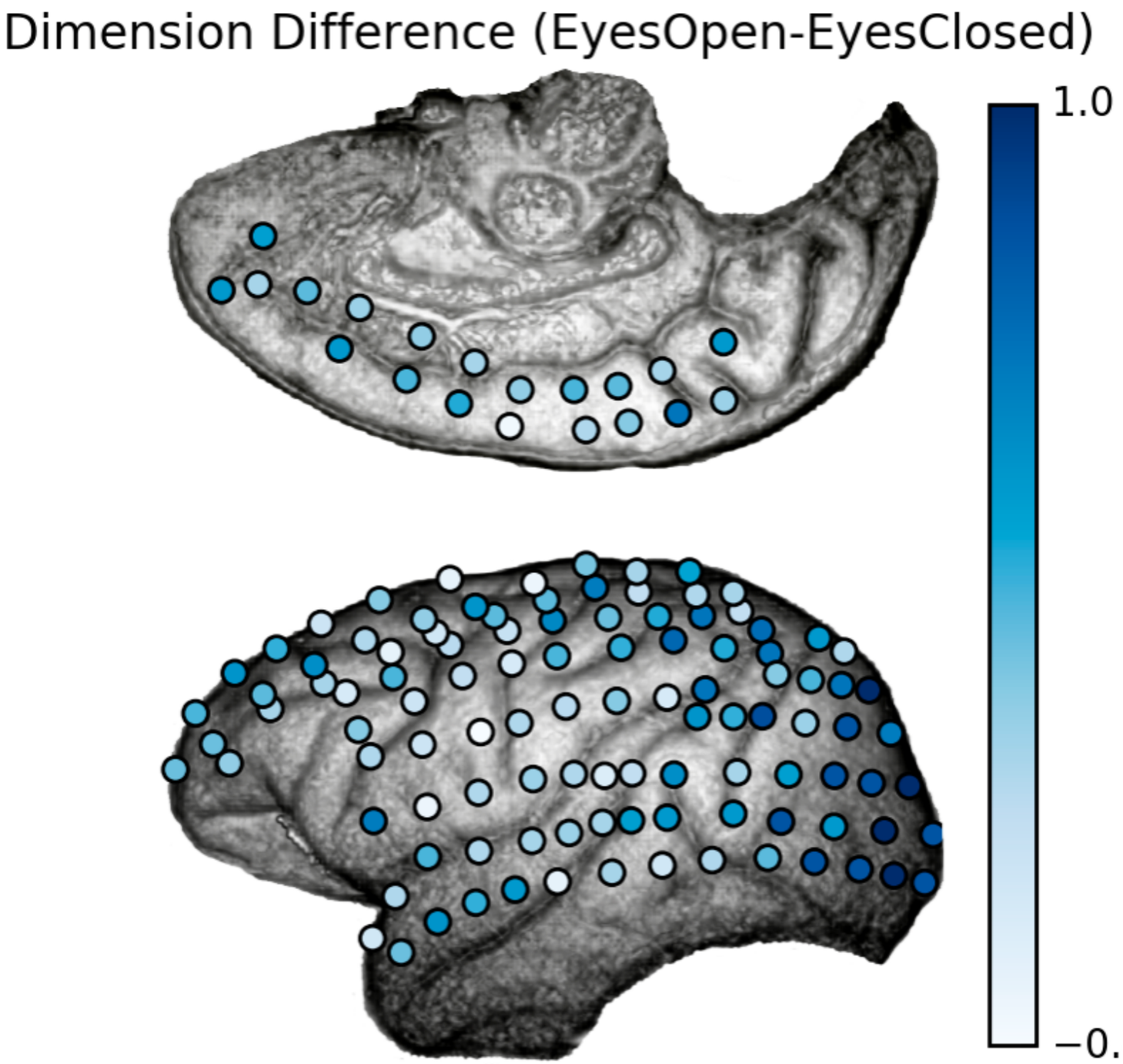




Anesthetized state has lower attractor dimension.

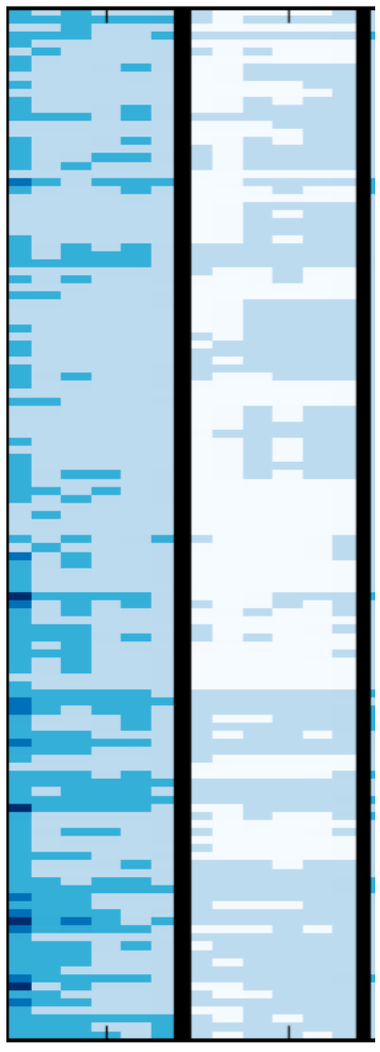
Attractor Dimension

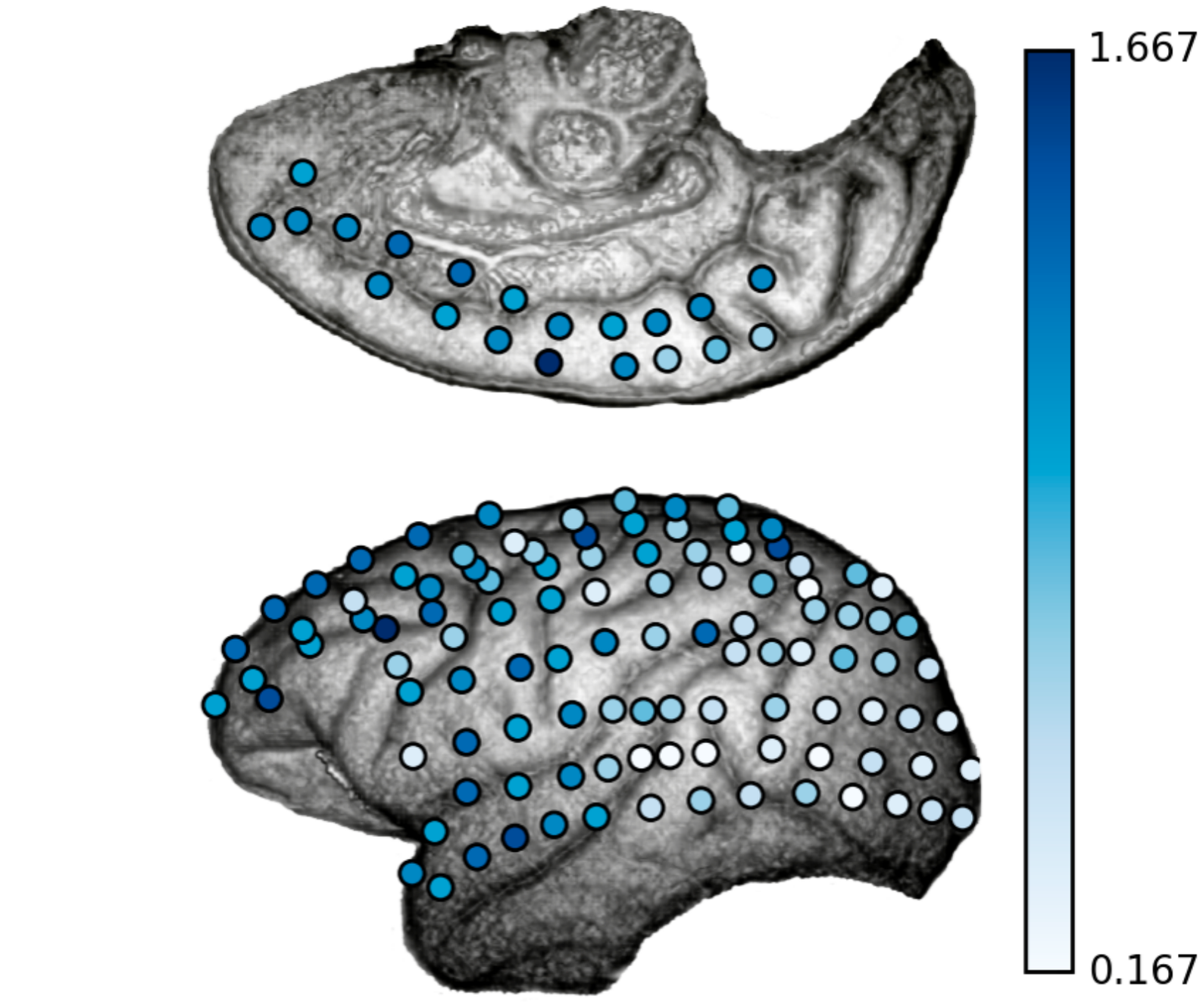




Visual areas have higher dimension when eyes are open.
Some areas actually increase in dimensions.

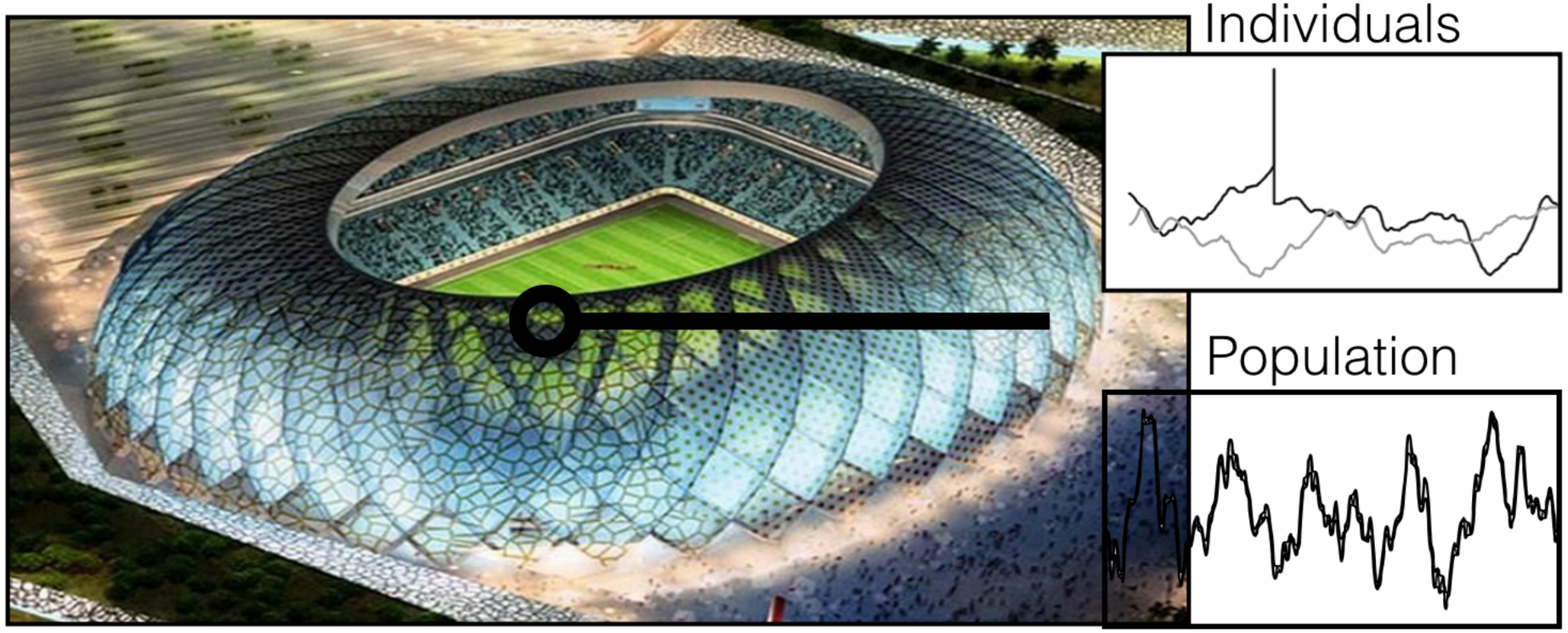
Attractor Dimension





Fronto-temporal areas have higher dimension when awake.

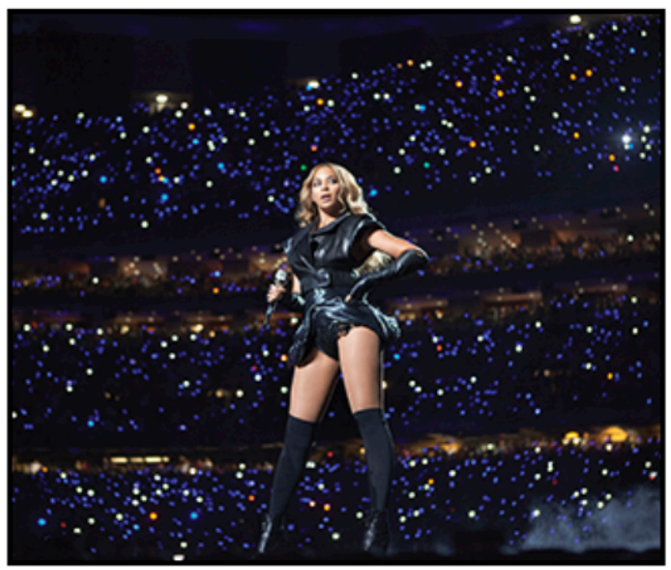
Higher Dimensional Dynamics



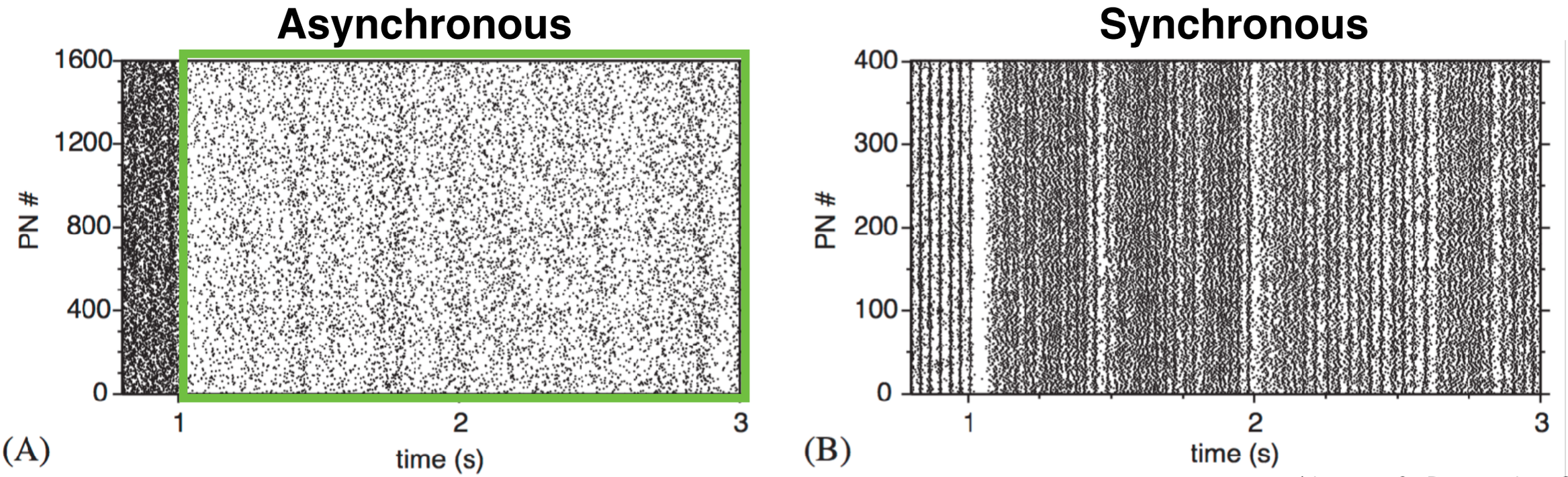
"asynchronous"

"oscillatory"

"synchronous"



Chaos - Noise - Asynchrony

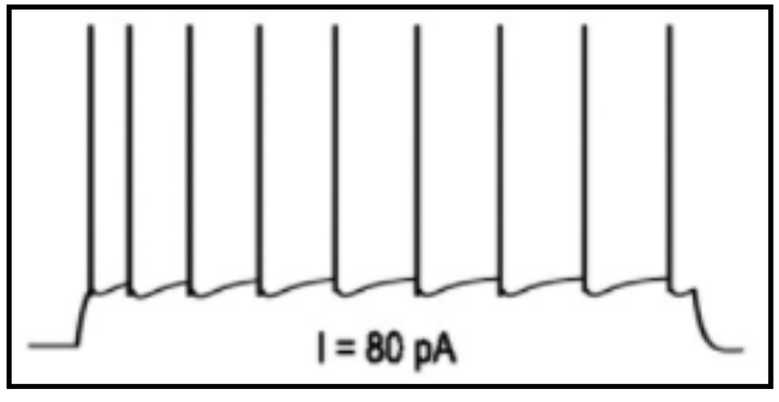


Alvarez & Destexhe, 2004

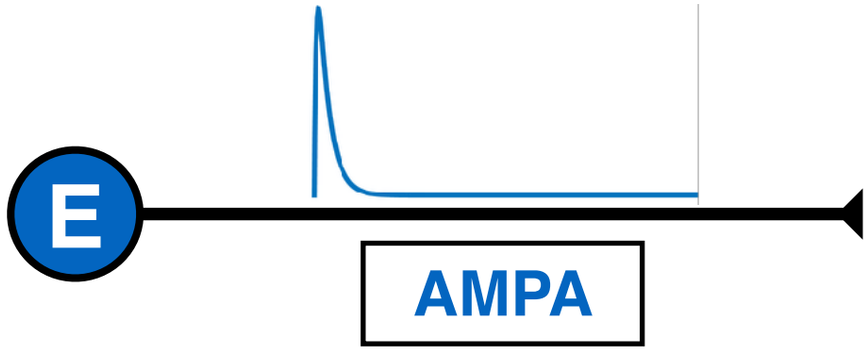
Also referred to as:

- Asynchronous irregular state
- Fluctuation-driven regime
- High conductance state
- Chaotic regime - sensitive but deterministic

In contrast:



EI Balance

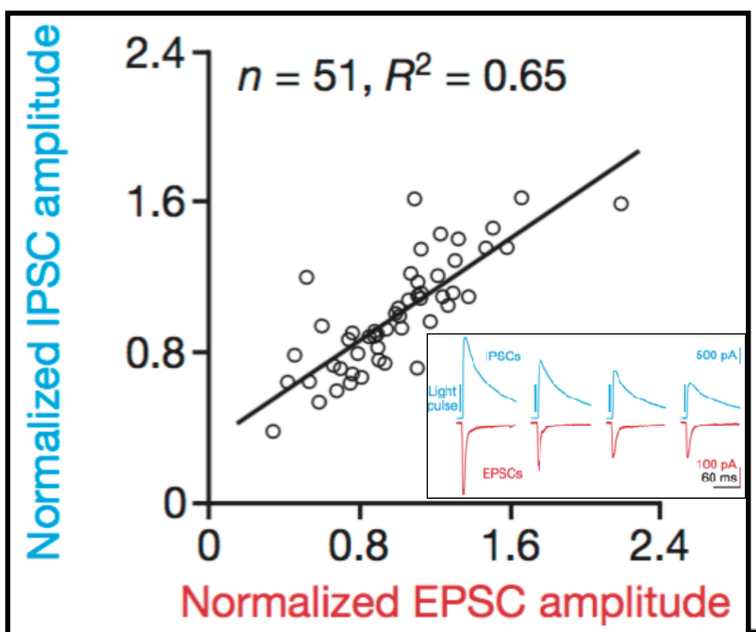


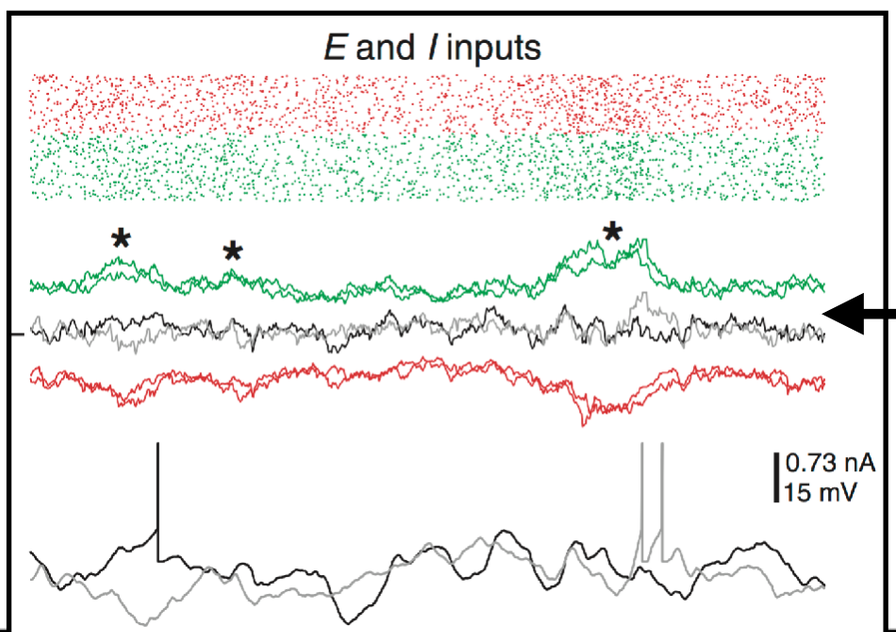
Excitation

- principal cells
- glutamate synapse
- depolarizing
- promote firing

Inhibition

- interneurons
- GABA synapse
- hyperpolarizing
- suppress firing





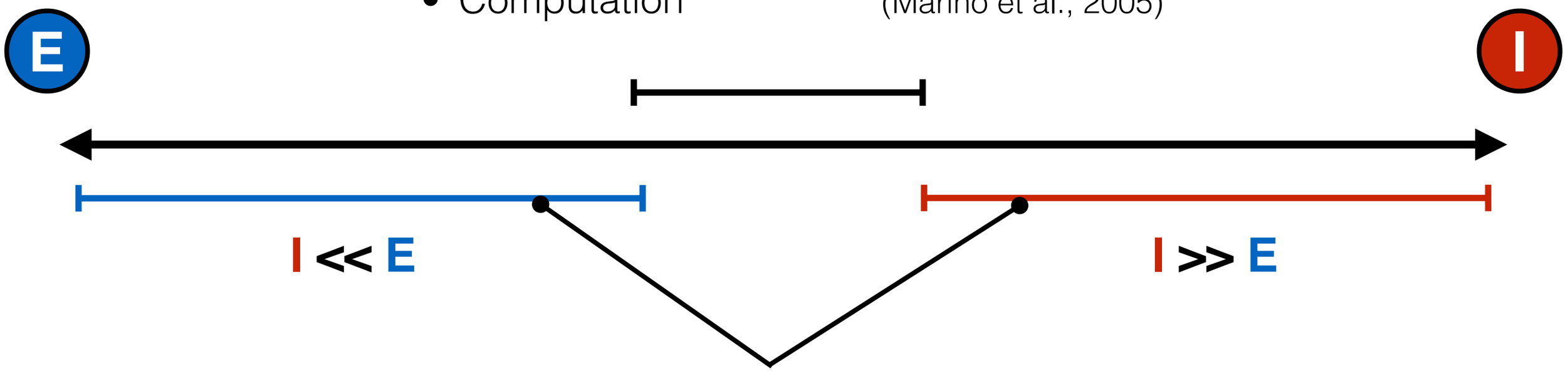
high conductance fluctuations

Renart et al., 2010
Xue et al., 2014

EI Balance

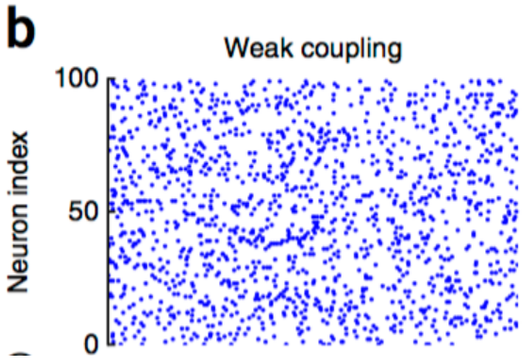
“Balance”

- Spontaneous
- Enable Oscillations (Atallah et al., 2012)
- Information Gating (Vogels & Abbott, 2009)
- Computation (Marino et al., 2005)

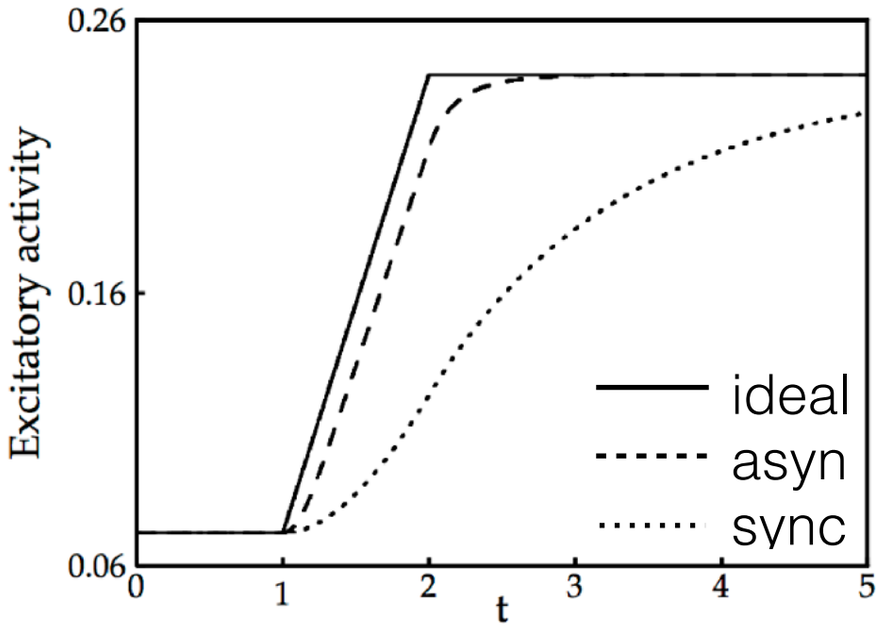


“Imbalance”

- Epilepsy (Symonds, 1959)
- Autism (Rubenstein & Merzenich, 2003)
- Schizophrenia (Uhlhaas & Singer, 2010)
- Social Dysfunction (Yizhar *et al.*, 2011)

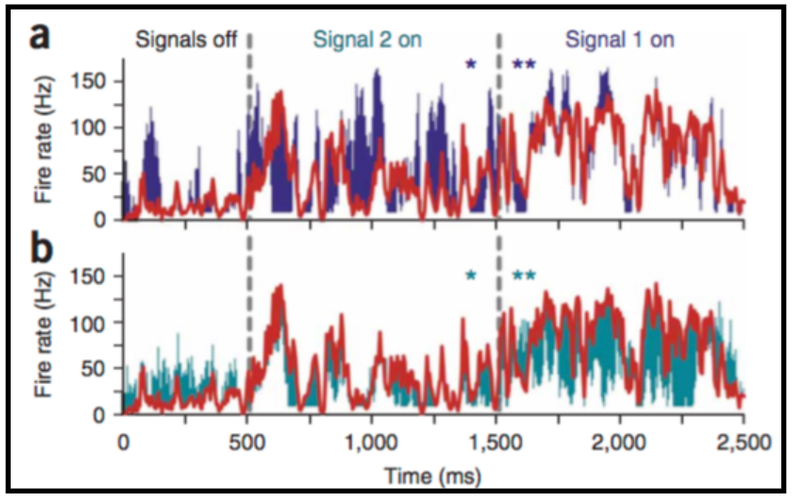


Spike-timing Chaos in EI Balanced Circuits



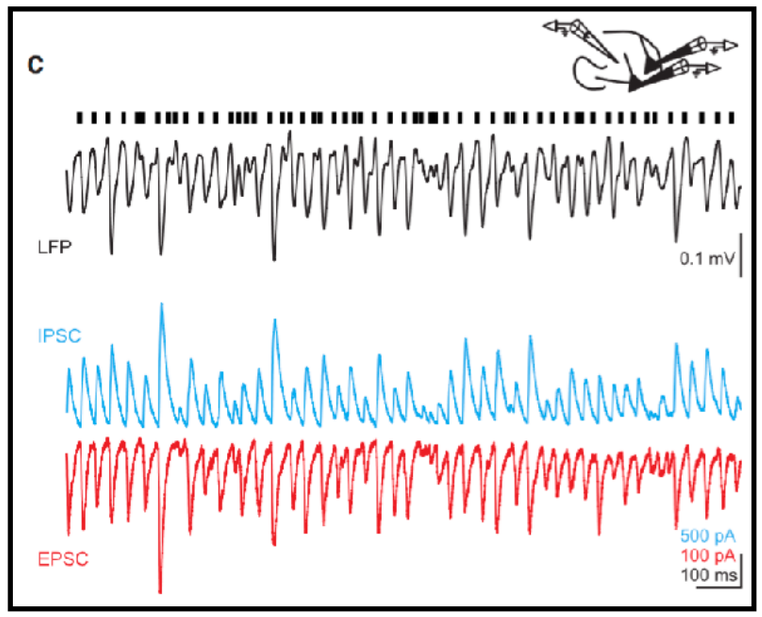
Stimulus Tracking

Van Vreeswijk & Sompolinsky, 1996



Signal Gating & Gain Modulation

Vogels & Abbott, 2009
Chance et al., 2003



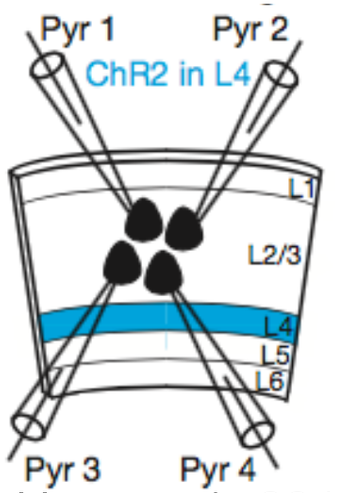
Oscillations

Atallah & Scanziani, 2009

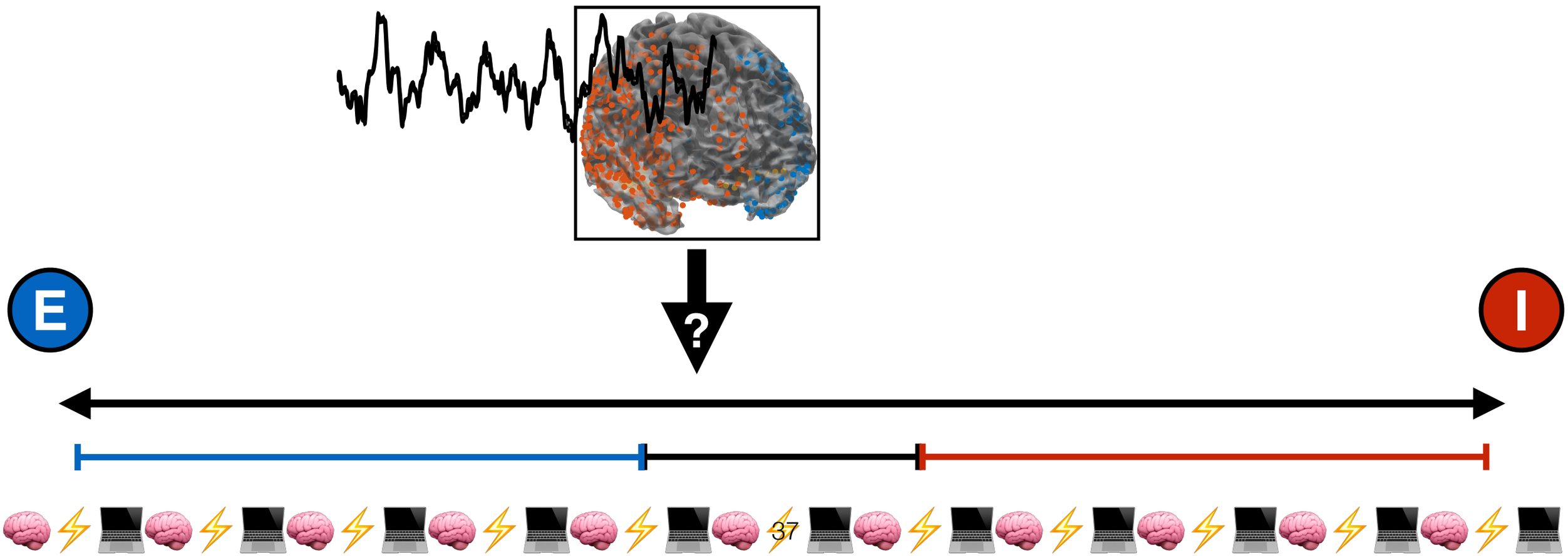
Measuring EI Balance

Motivation

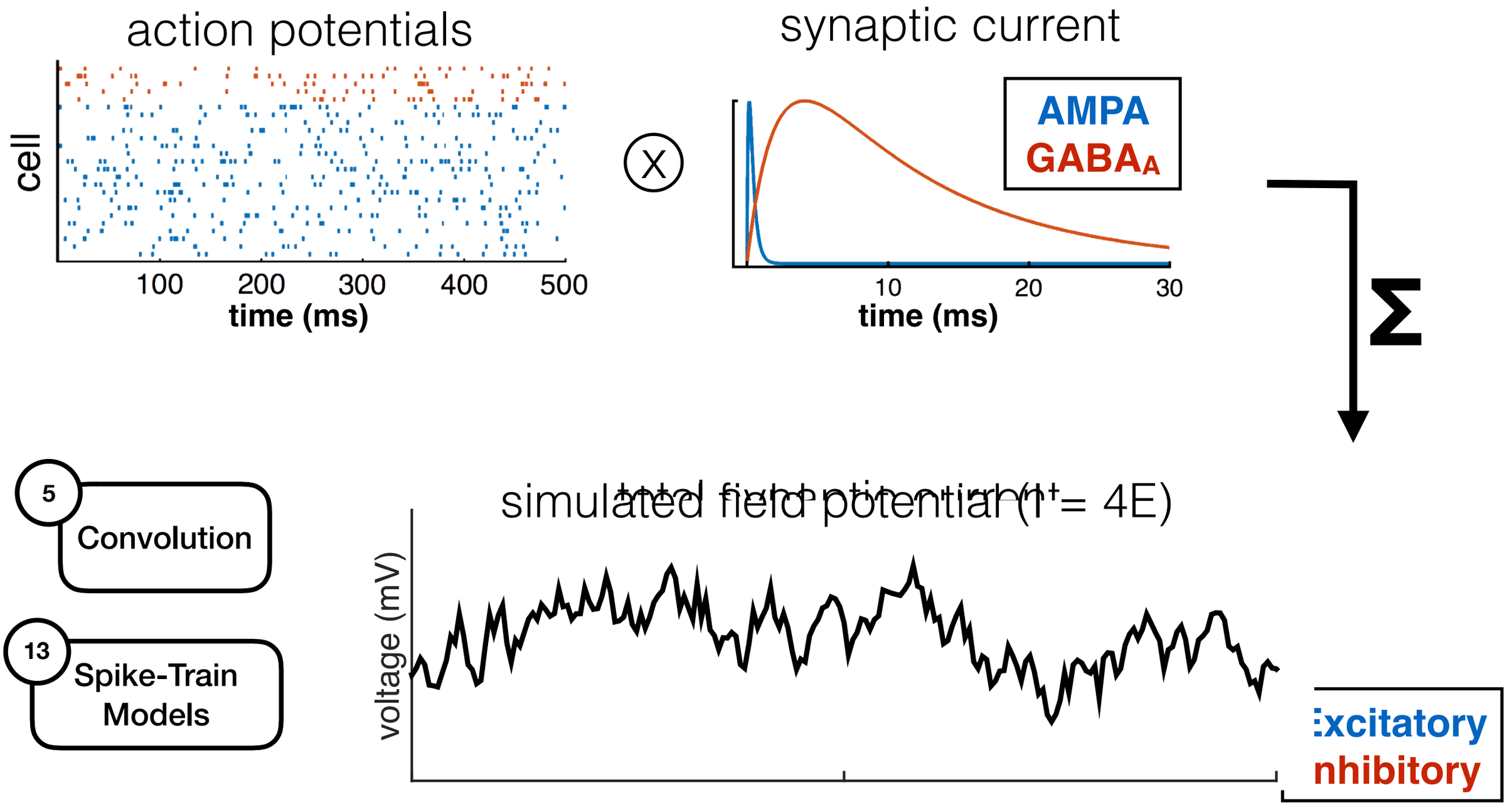
Can we determine E:I ratio without intracellular and/or active manipulation studies?



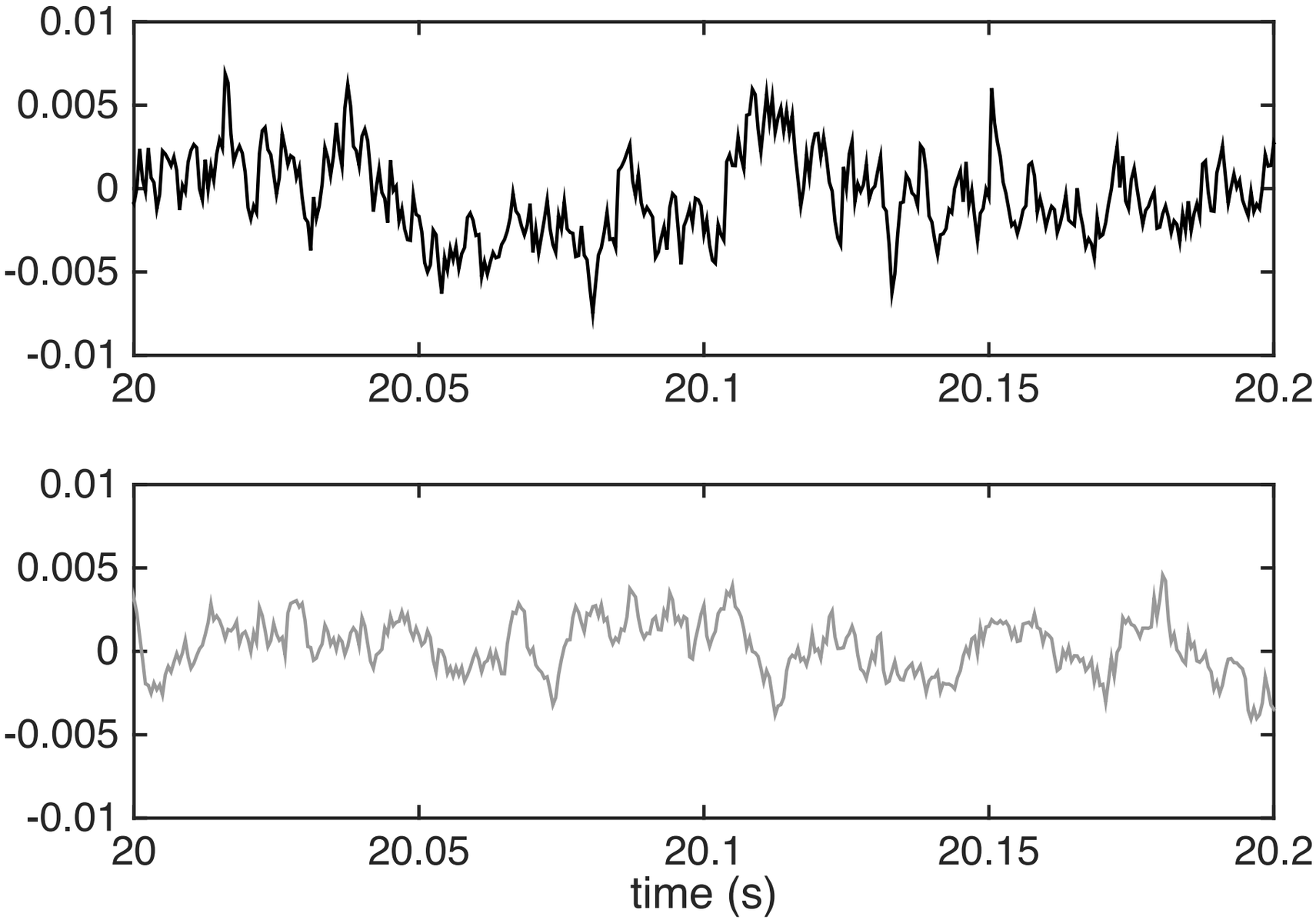
Xue *et al.*, 2014



Simulating Local Field Potentials



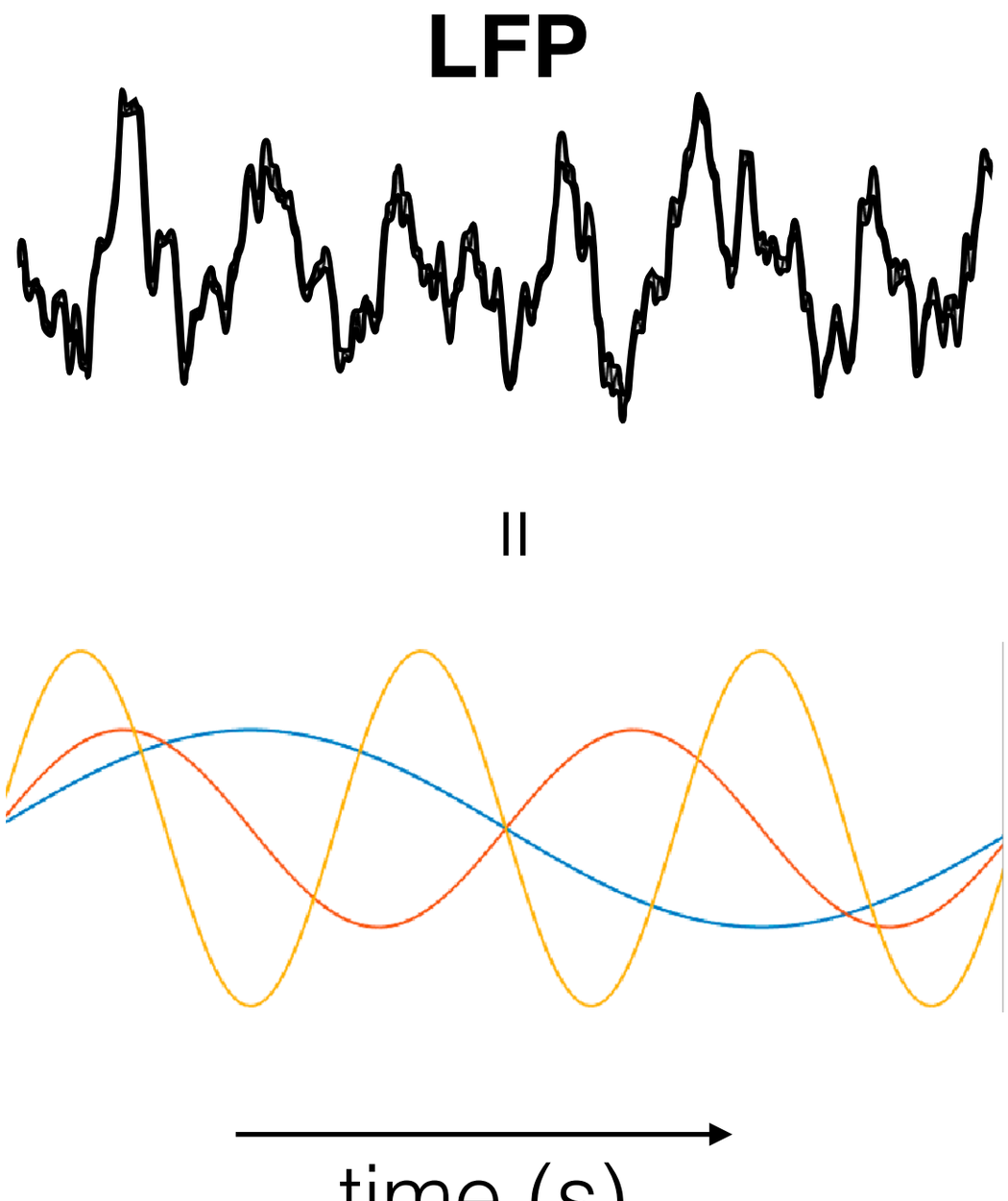
Measuring EI Balance

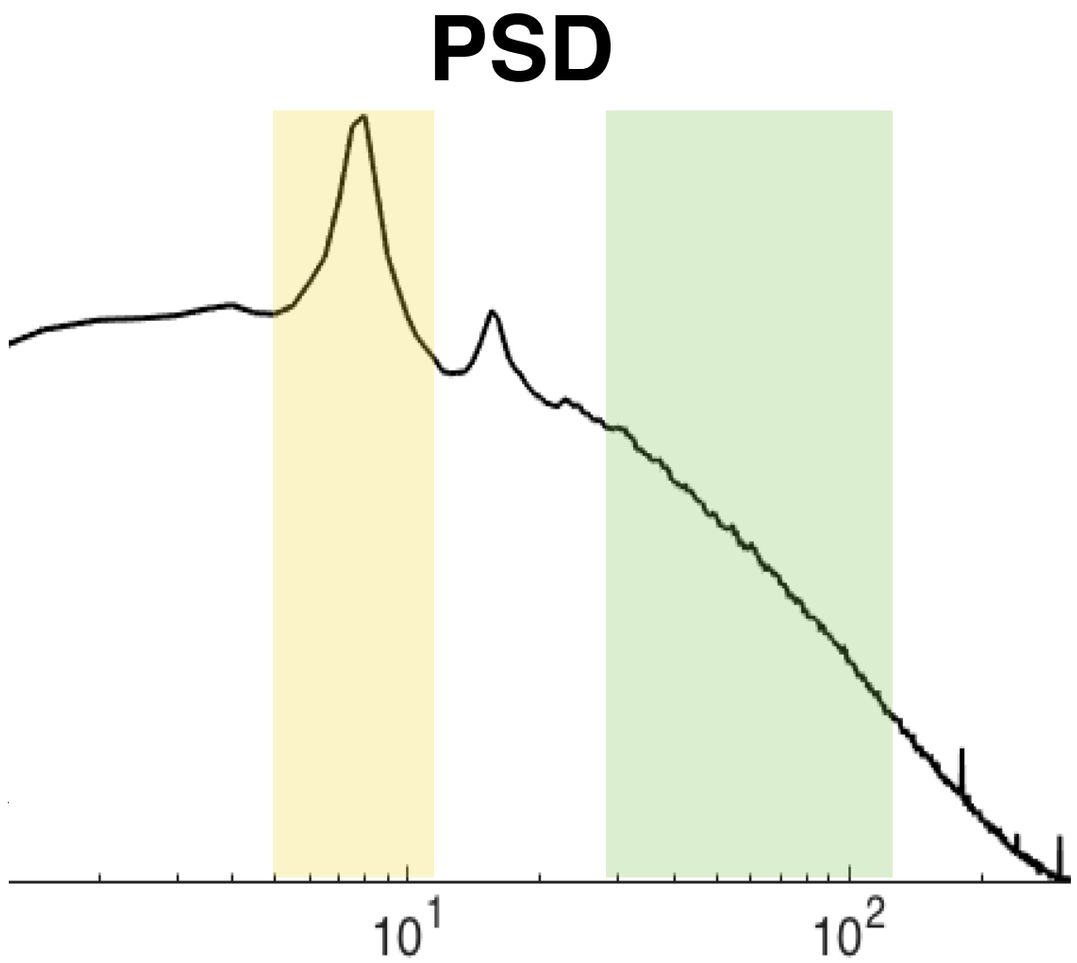


???

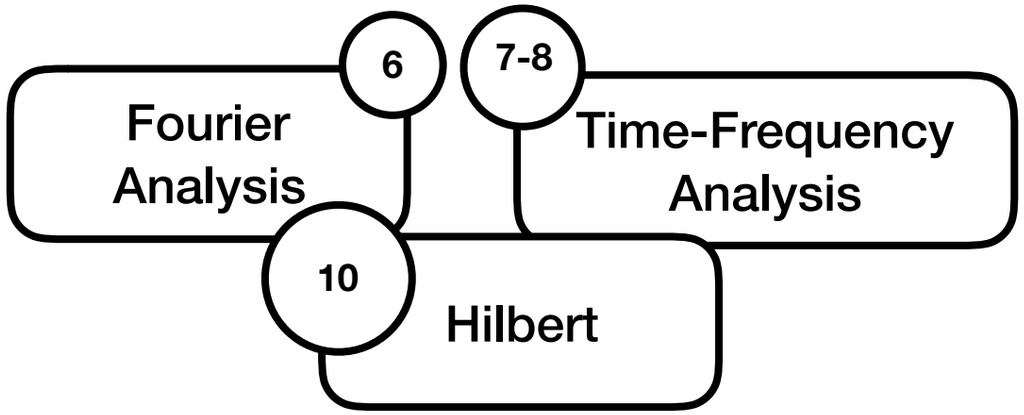
E:I = 1:2 or 1:6

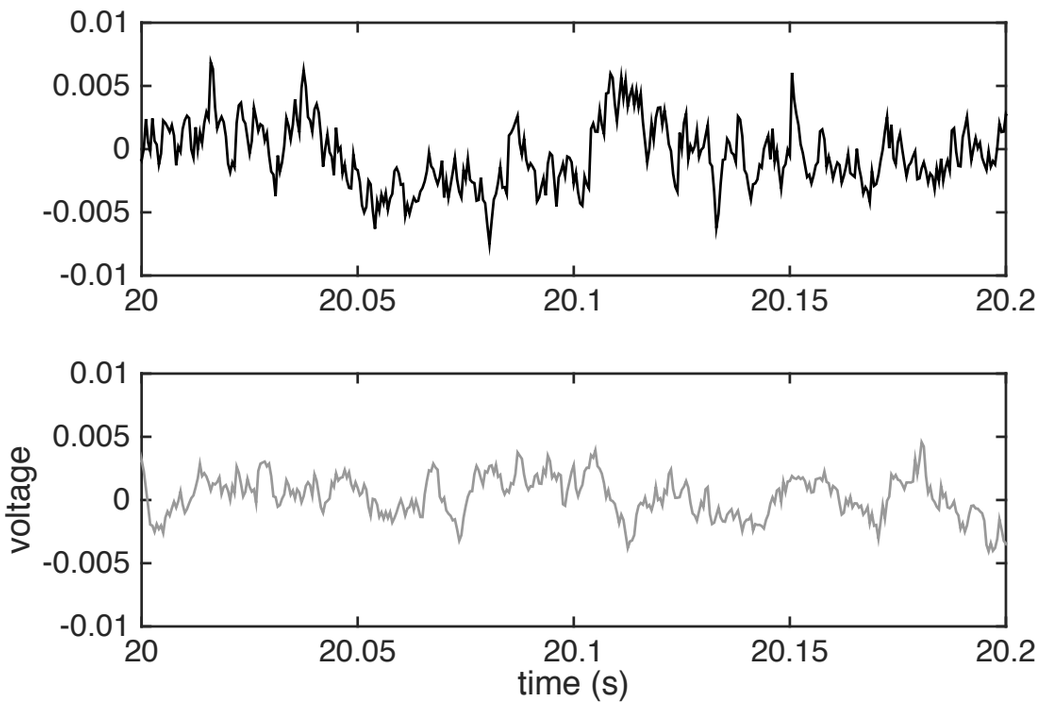
Measuring EI Balance

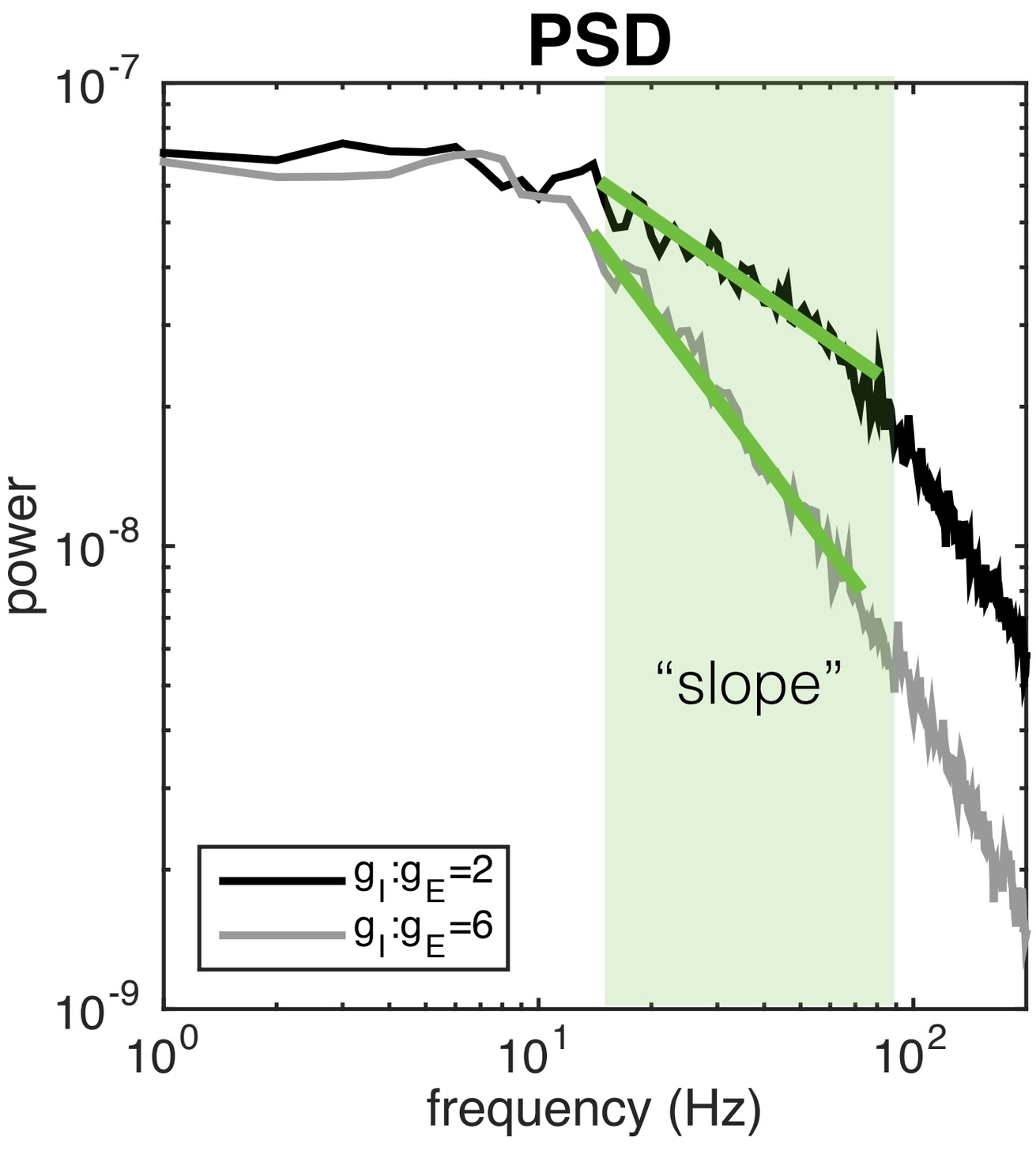




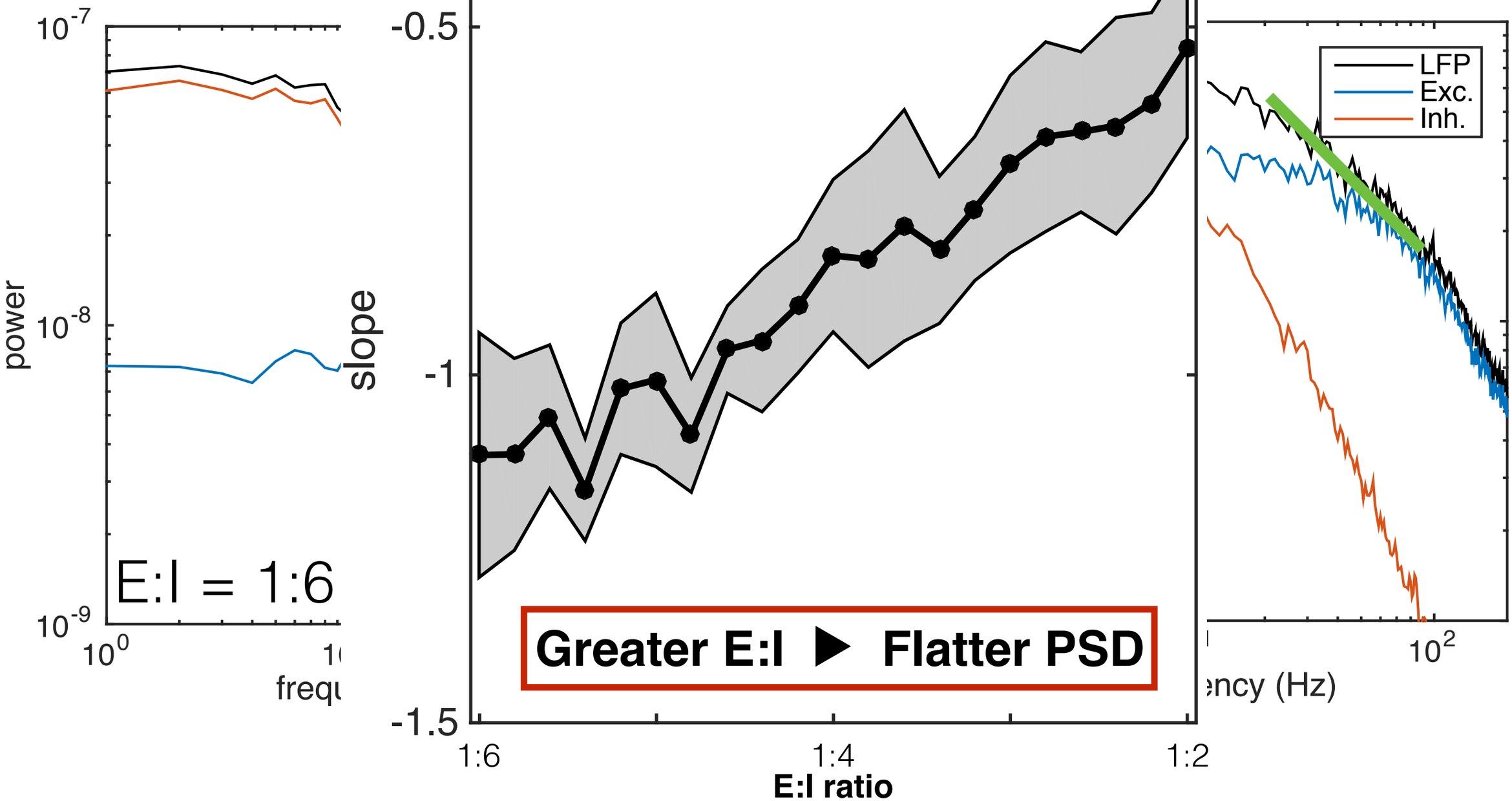
Measuring EI Balance



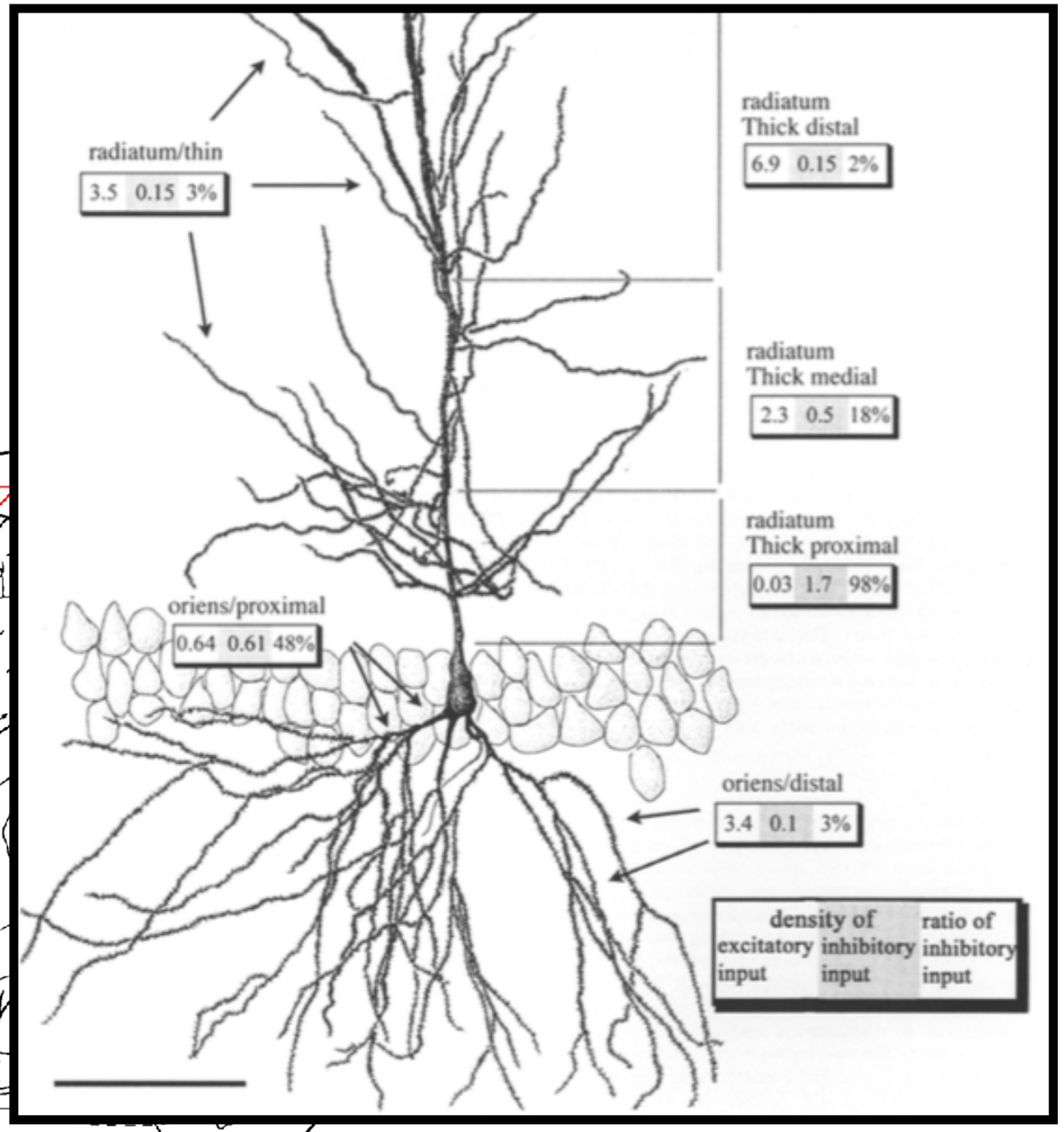


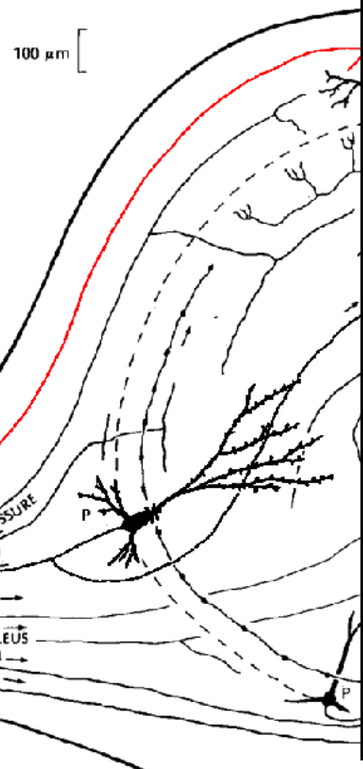


Measuring EI Balance



Measuring EI Balance



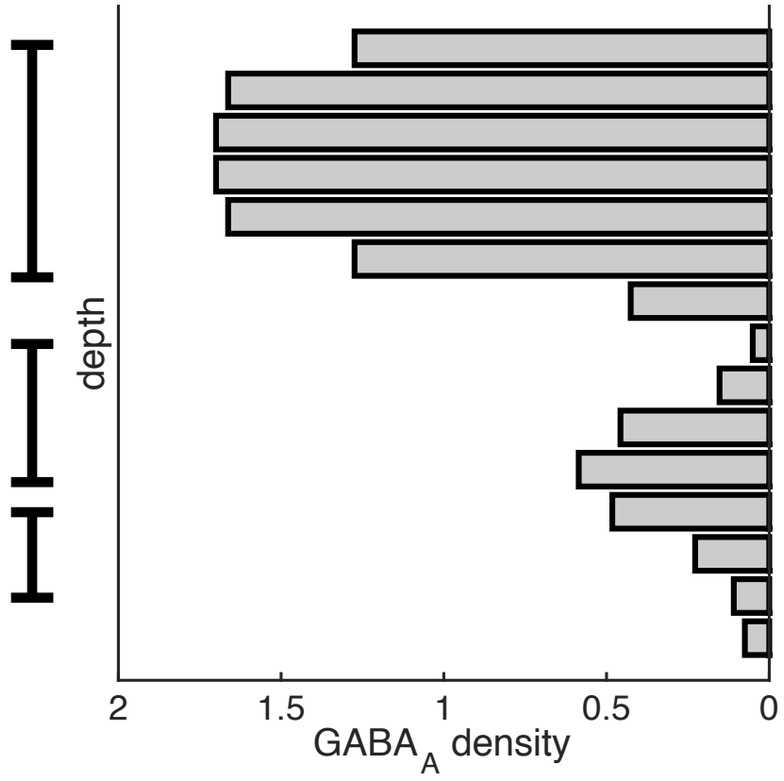


CA 3

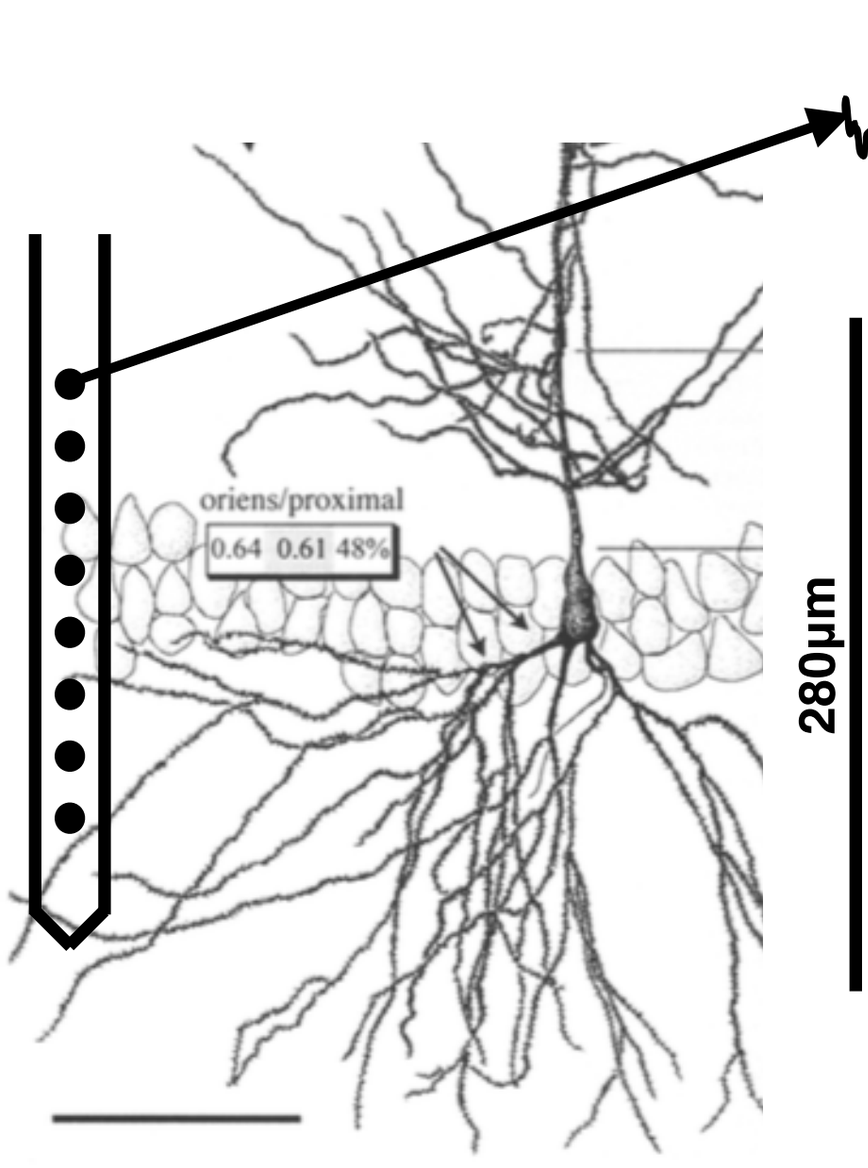
Dentate Gyrus

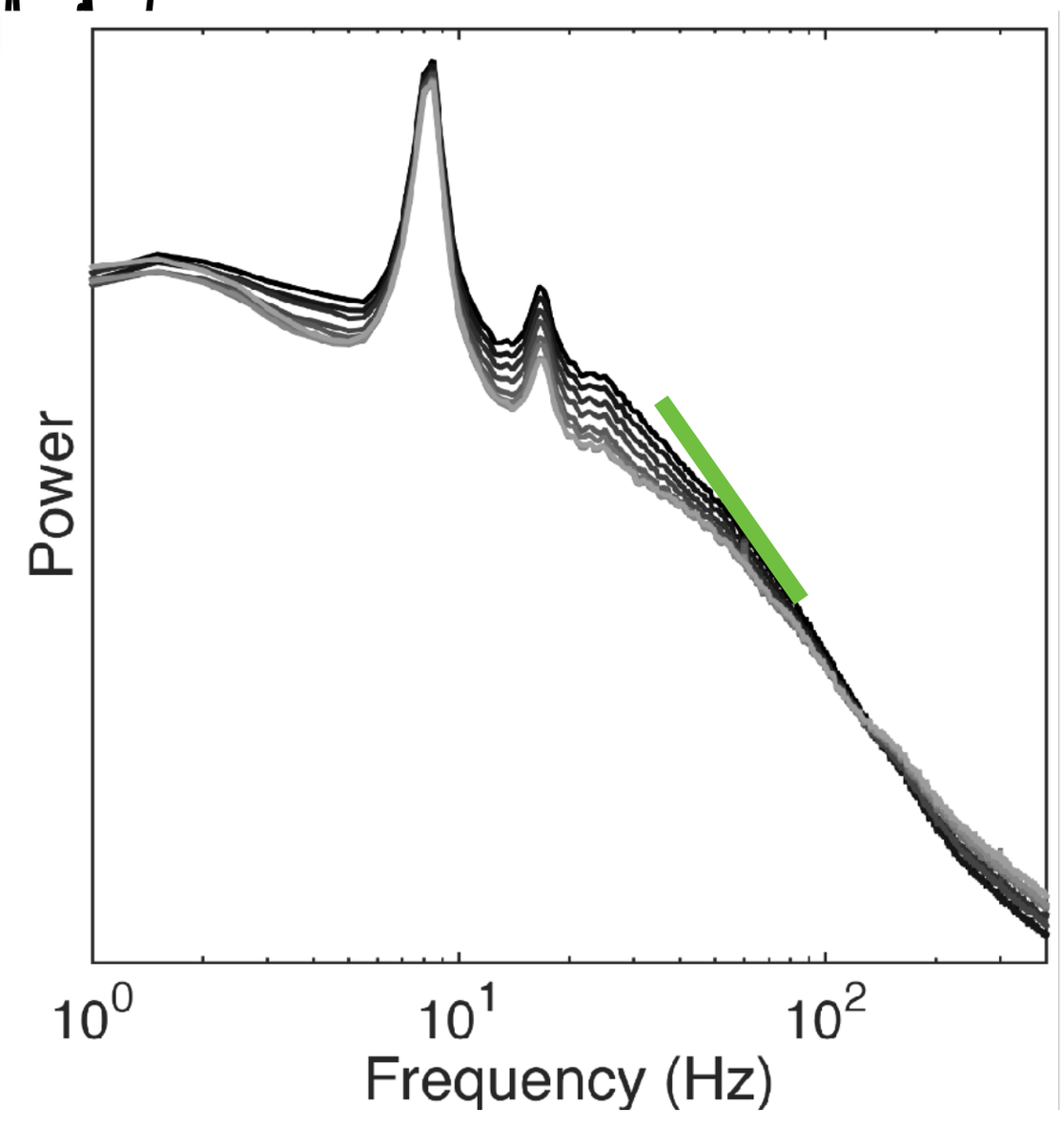
image: senselab@yale

GABA synapse density (per µm)



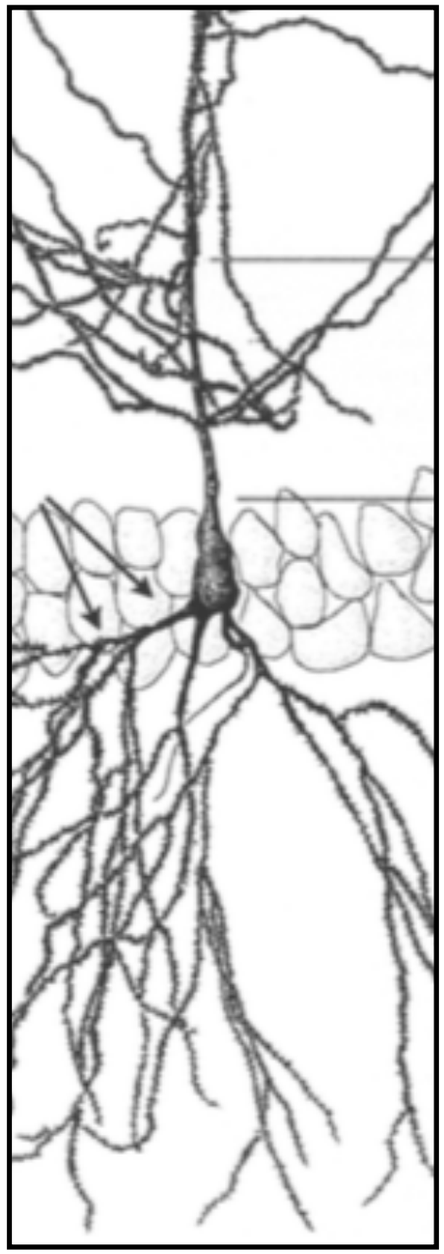
Depth Dependent Inhibition in Hippocampus (CA1)

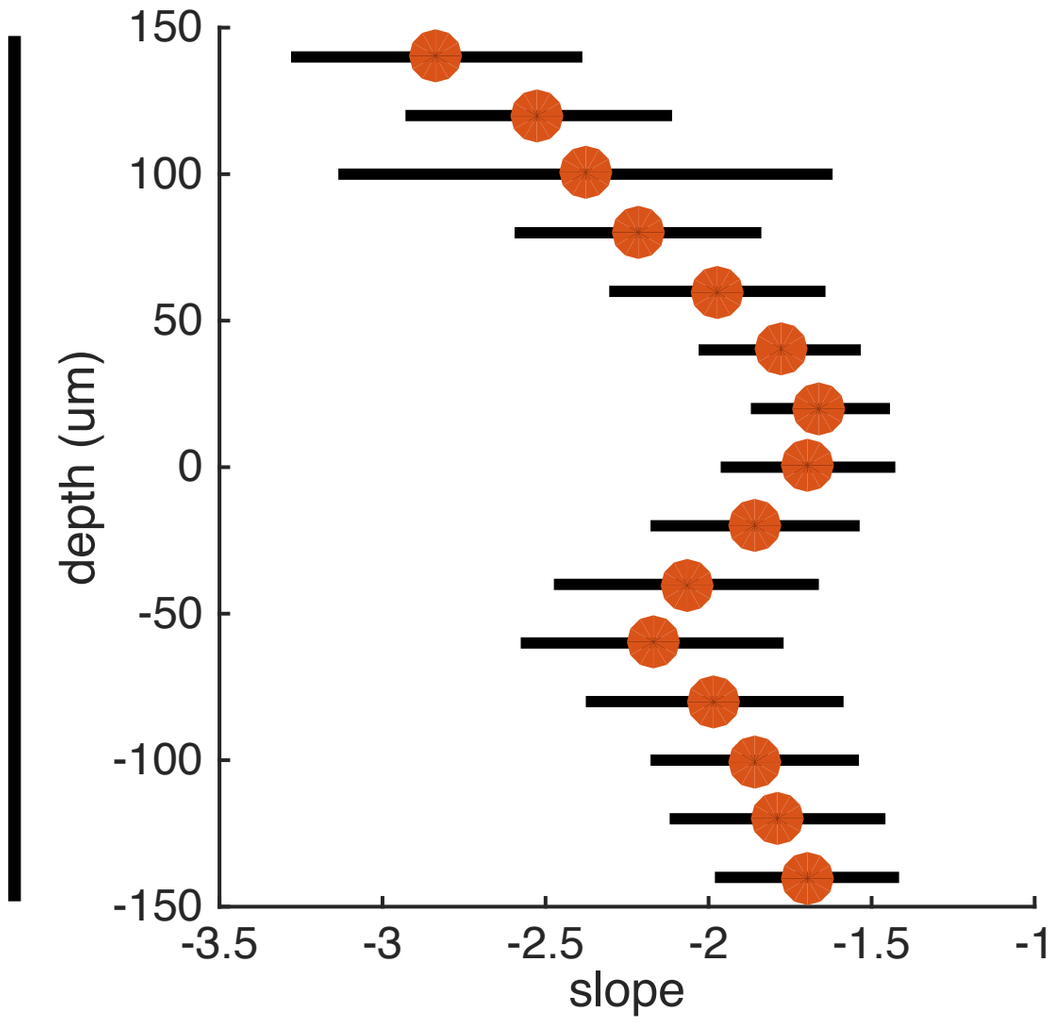




data: CRCNS & Buzsaki Lab

Measuring EI Balance

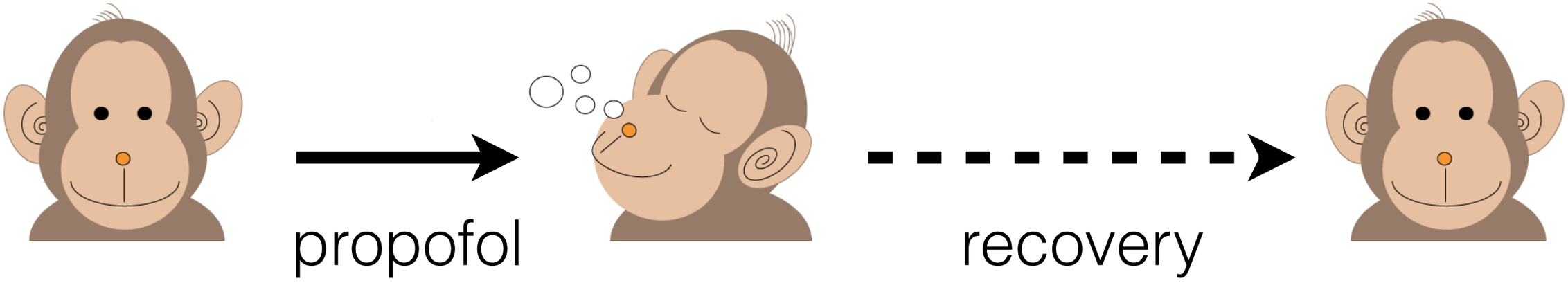




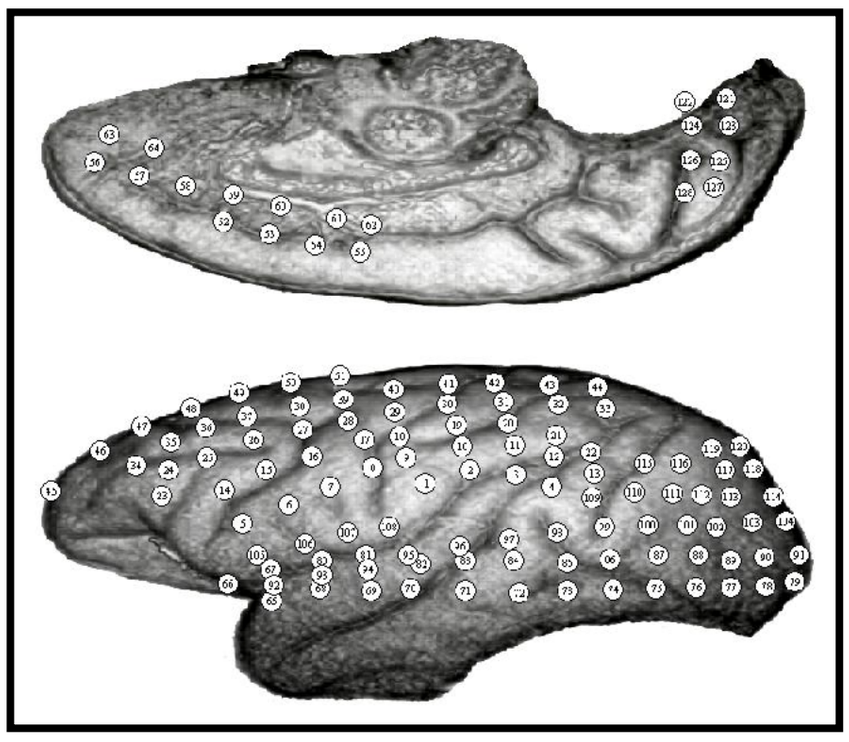
PSD slope across depth reflects density of inhibitory synapses.

Measuring EI Balance

Anesthesia Induced Increase of Inhibition



ECoG

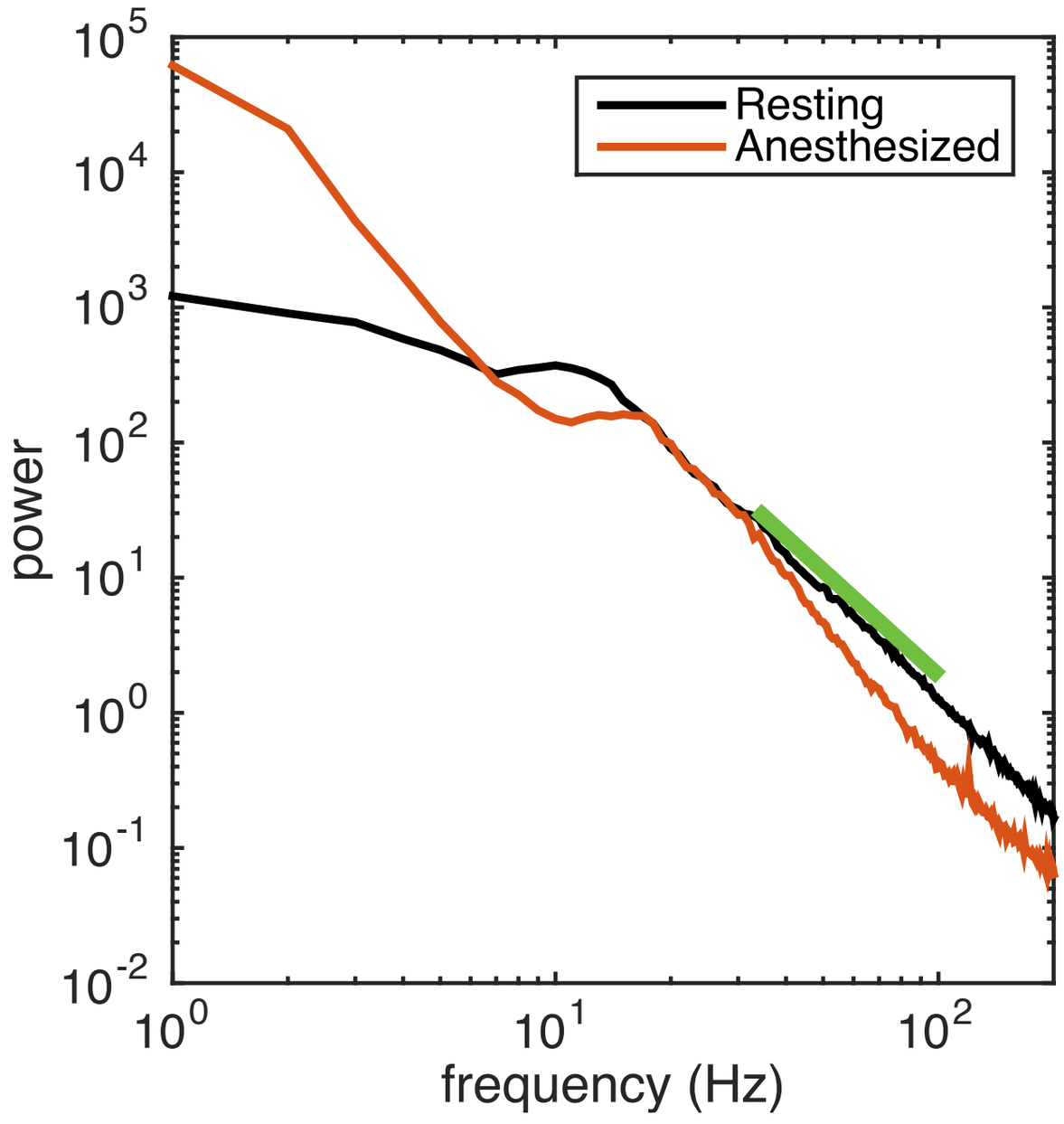


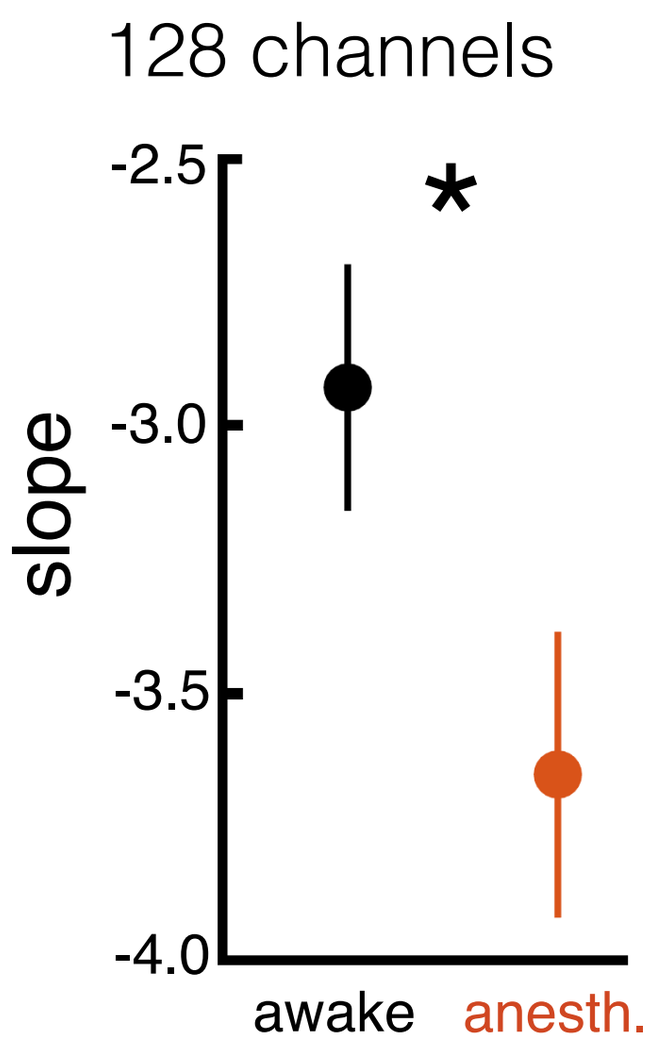
"Propofol significantly increases both the amplitude & frequency of inhibitory post-synaptic potentials."

Wakita *et al*. 2013, & others

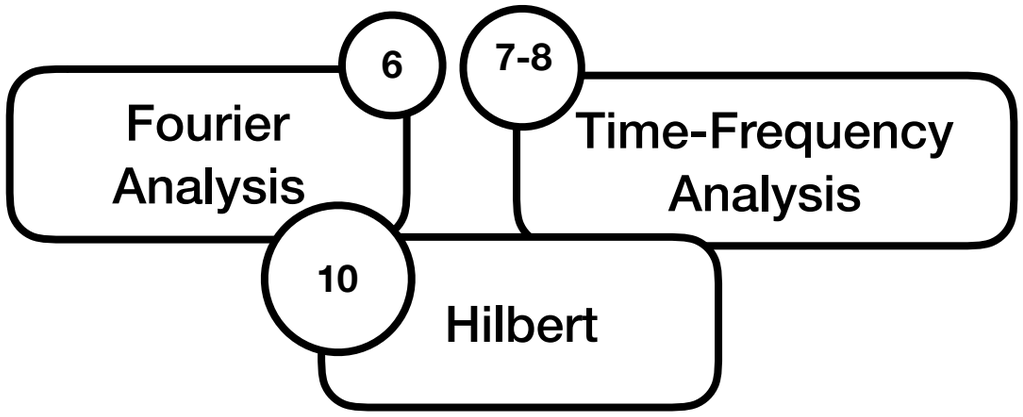
data & images: NeuroTycho

Anesthesia Induced Increase of Inhibition

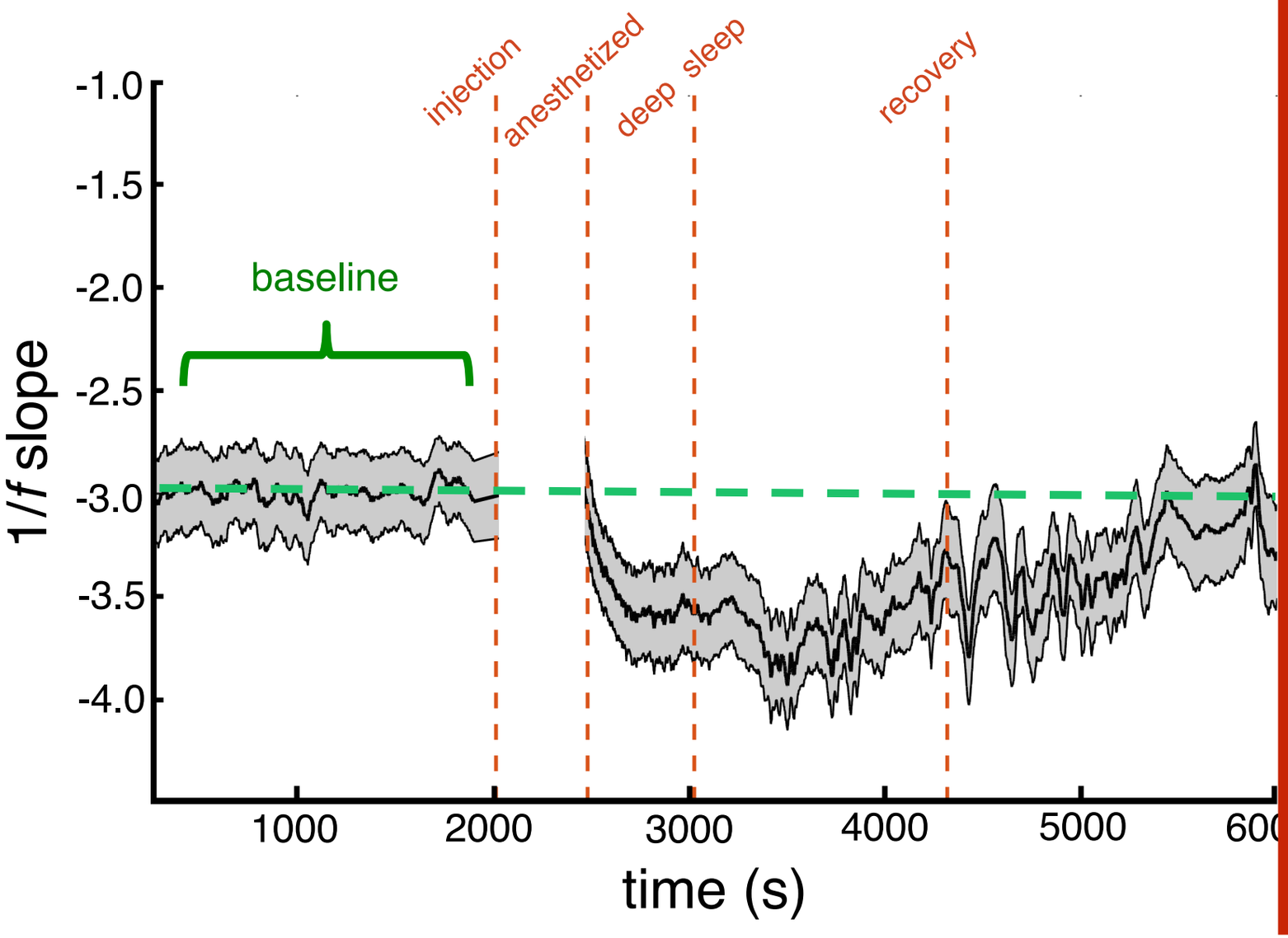




Measuring EI Balance



PSD Slope Time Course

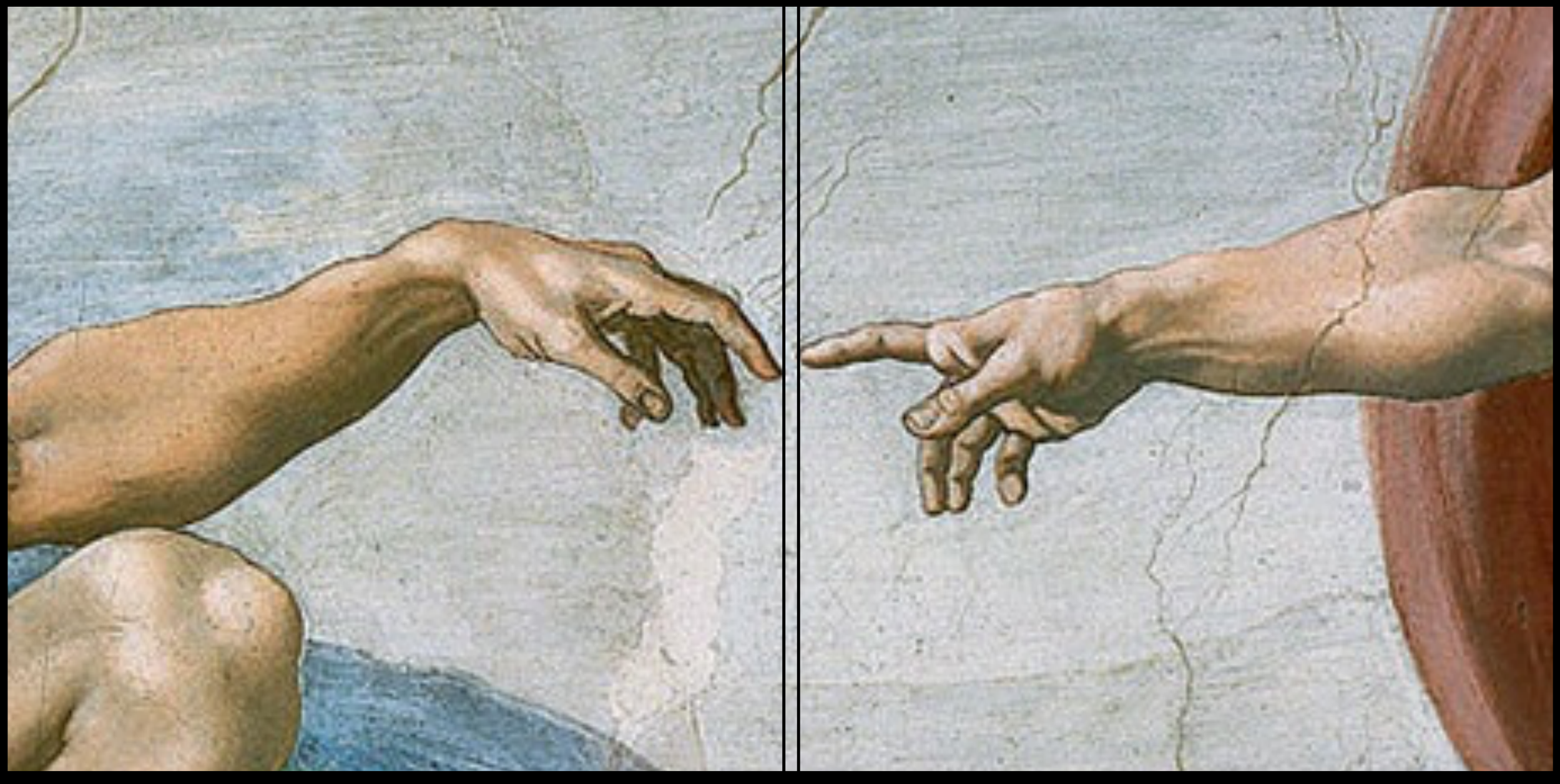


Time-Resolved Estimate

PSD slope tracks anesthesia induced increase of inhibition over cortex.

Human Cognitive Neuroscience

Systems Neuroscience



Data Analysis & Computational Modeling

Course Outline: Road Map

Electrophysiological Data Analyses

"Field Potentials" (Time-Series)

"Spikes" (Point Process)

L

Math

Linear Algebra

Complex Numbers

L

Coding

Git & Python
numpy
scipy

Communication

Reading Scientific Papers

Visualization & Writing

3

Sampling

3-11

4

Time-locked Analysis

5

Convolution

6

Fourier Analysis

7-8

Time-Frequency Analysis

9

Filtering

10

Hilbert

11

Nonlinear Techniques

Time-Series Analyses

2*

Brain Physiology

12-14

12

Spike-LFP Analysis

13

Spike-Train Models

14

Population Coding Models

Spike Analyses

15-16

Multi Channel Analysis

Dimensionality

Information Theory

Summary

Thank you for a great session!

https://tinyurl.com/cogs118c-att

https://cape.ucsd.edu/students/