# On the waveform shape of brain oscillations

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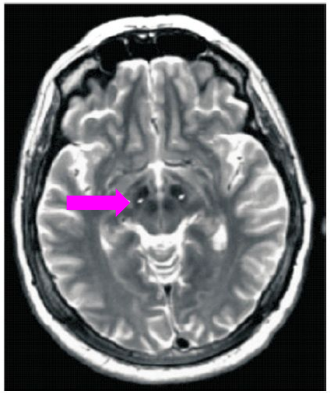
**13 December 2018**
**PhD Defense**
**Voytek Lab**
**Neurosciences Graduate Program**
**UC San Diego**

# Parkinson’s Disease (PD) and Deep Brain Stimulation (DBS)

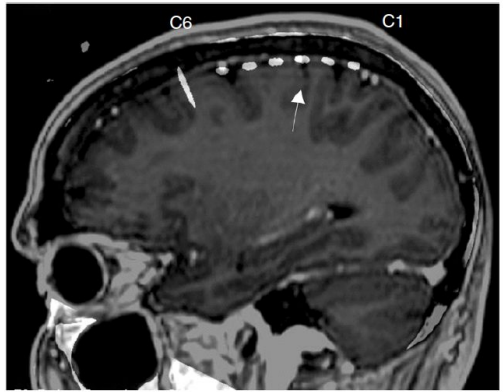
How does DBS modify neural activity to improve motor symptoms?

# Motor cortical recordings in PD patients

DBS



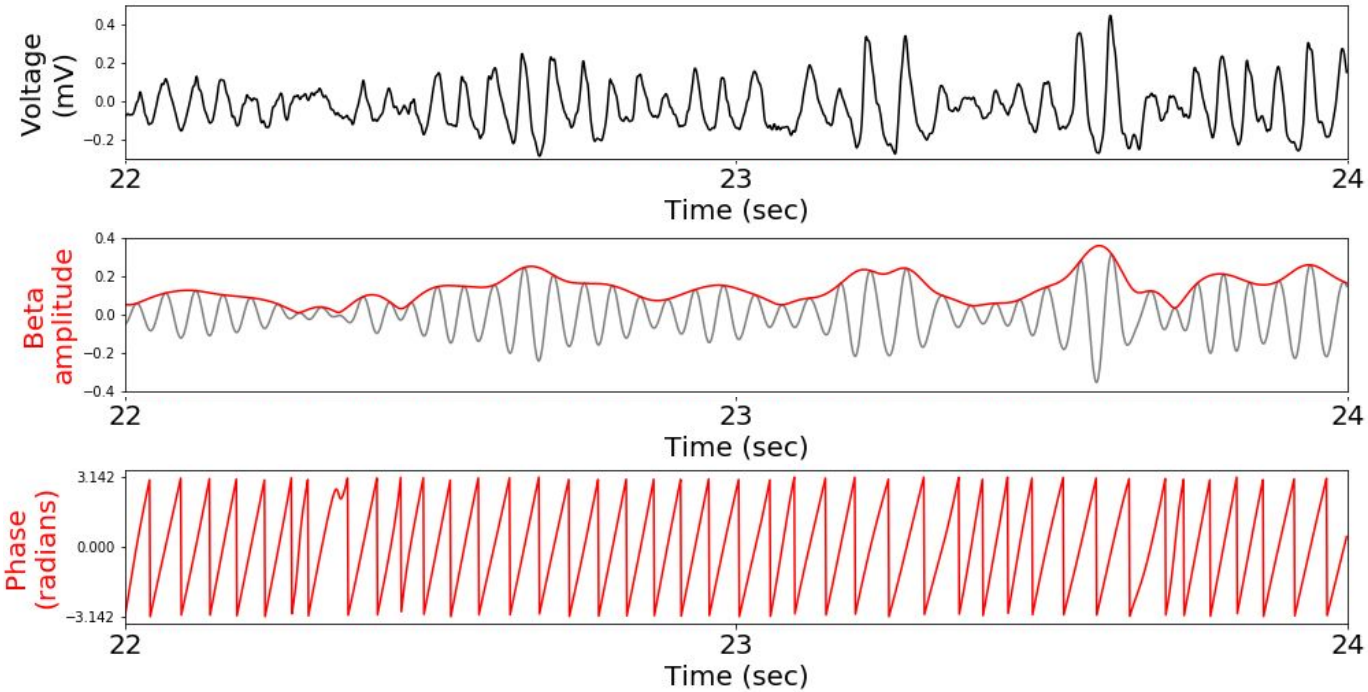
Electrocorticography

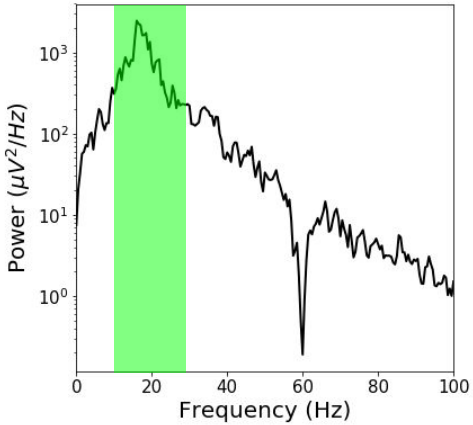



**How does DBS affect electrical activity in motor cortex?**

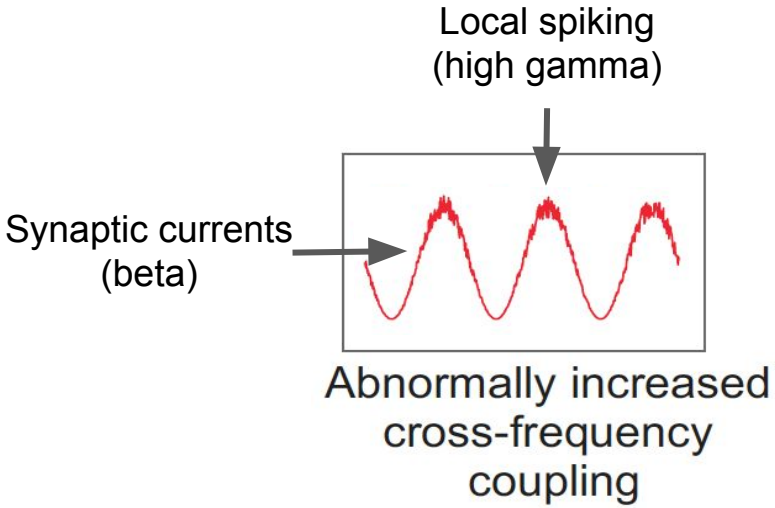
de Hemptinne et al., Nat Neuro 2015

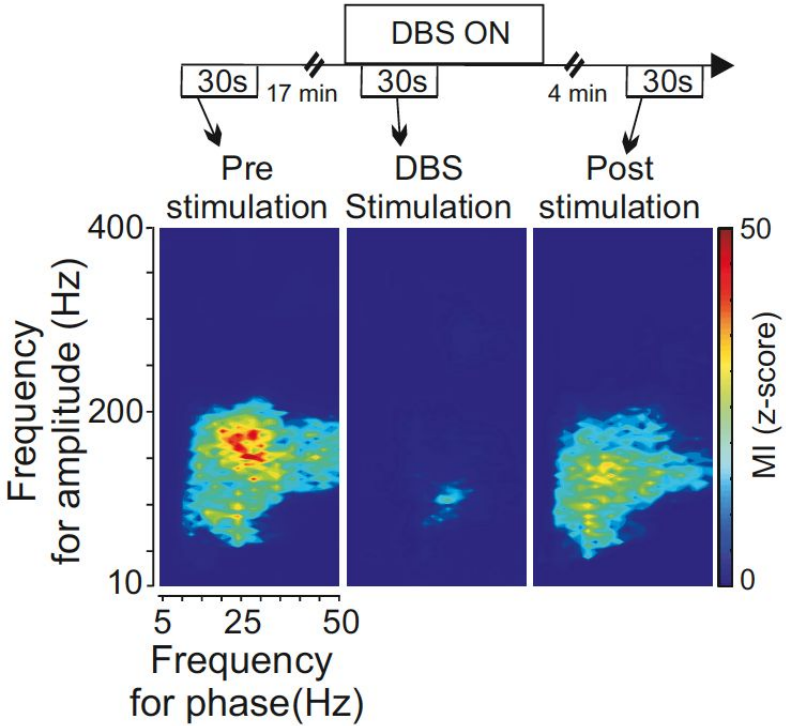
# Analyzing motor cortical beta oscillations



# Phase-amplitude coupling in PD



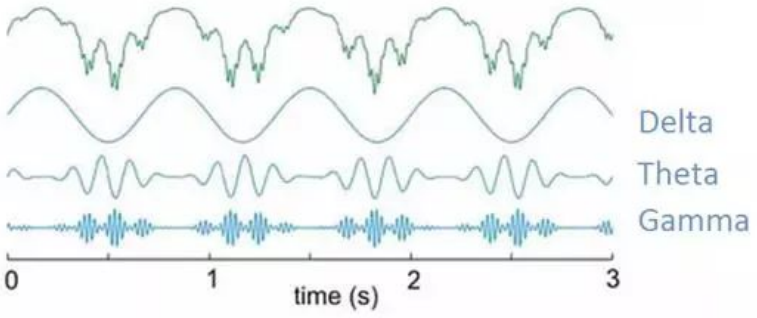

de Hemptinne et al., PNAS 2013

# Review

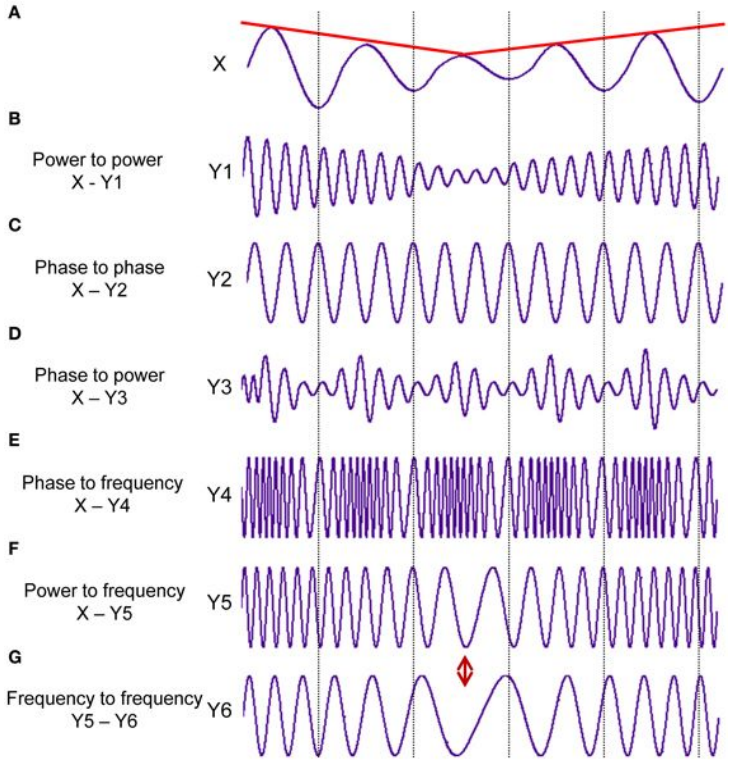
Biological Psychiatry

## Dynamic Network Communication as a Unifying Neural Basis for Cognition, Development, Aging, and Disease

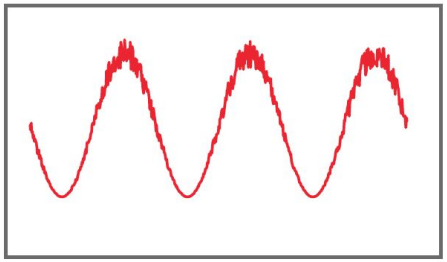
Bradley Voytek and Robert T. Knight

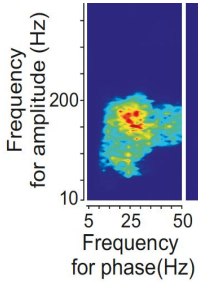



Lizarazu, 2017




Jirsa & Muller, 2013, *Front. Comp. Neuro.*

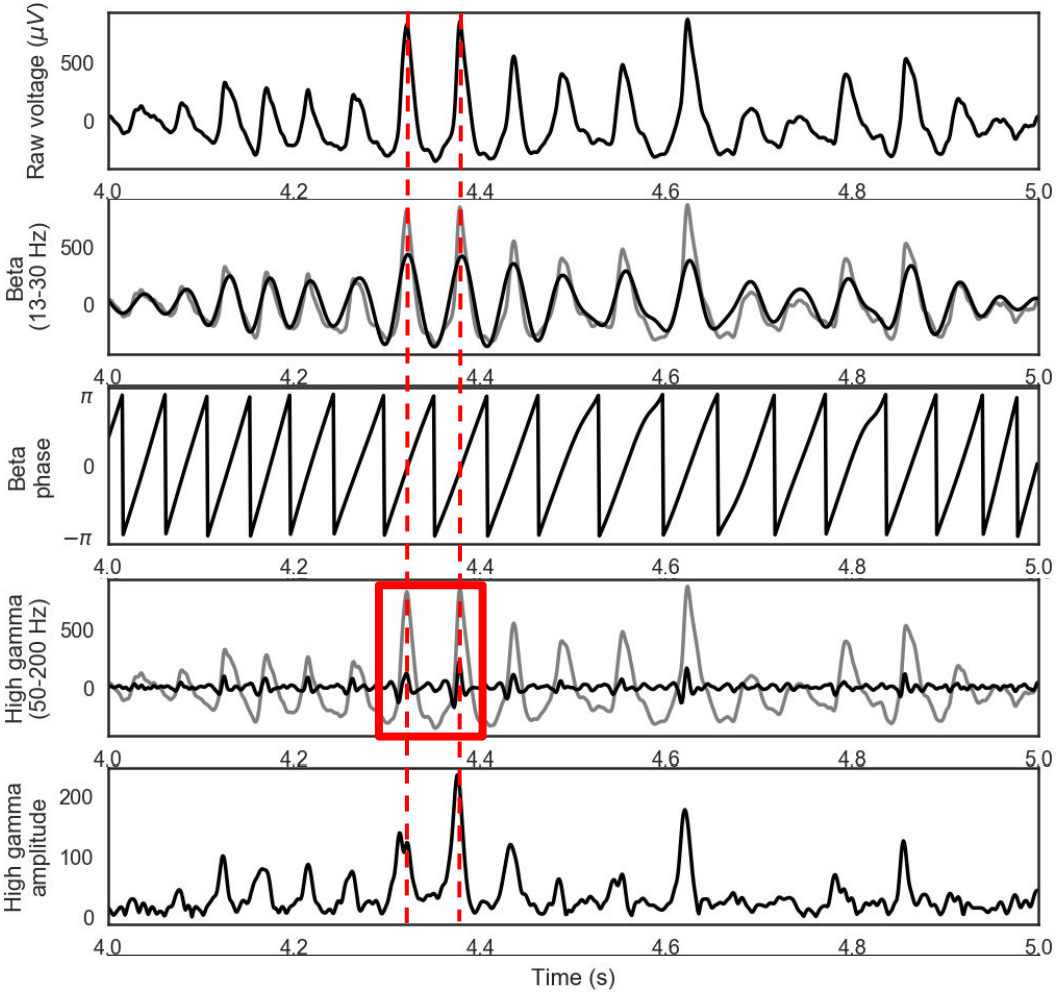




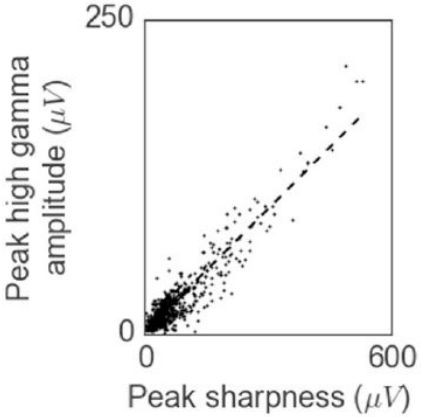

~~2 periodic components (beta, high gamma)~~

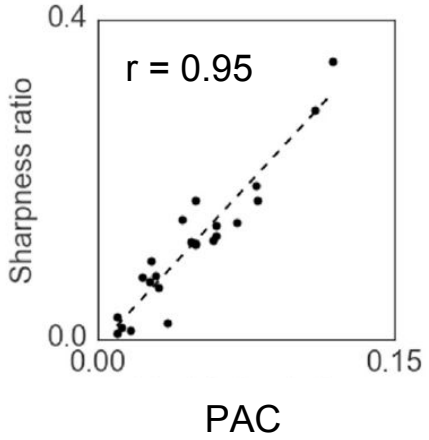
1 periodic component (nonsinusoidal) beta

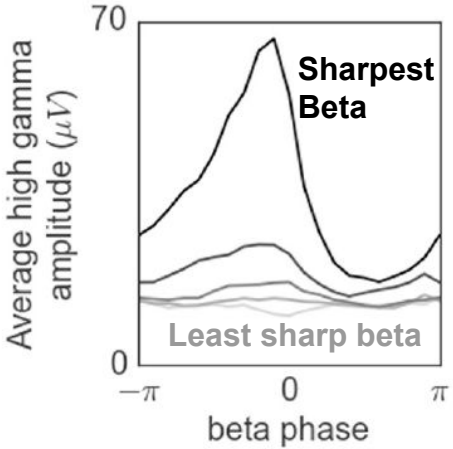
No high gamma “fuzz” signature of spiking



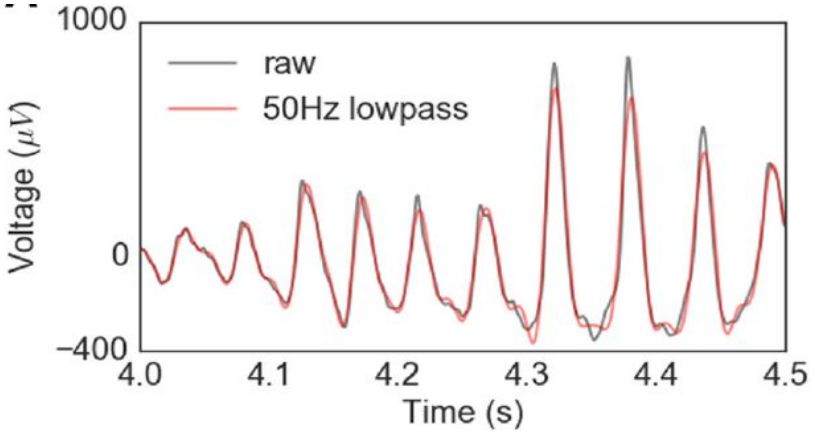
# Are sharp waveforms a prominent contributor to the PAC metric?

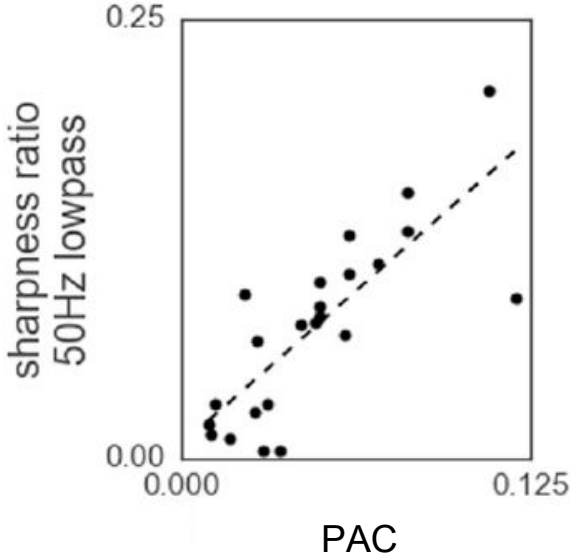


# Could sharpness be caused by gamma rhythms?

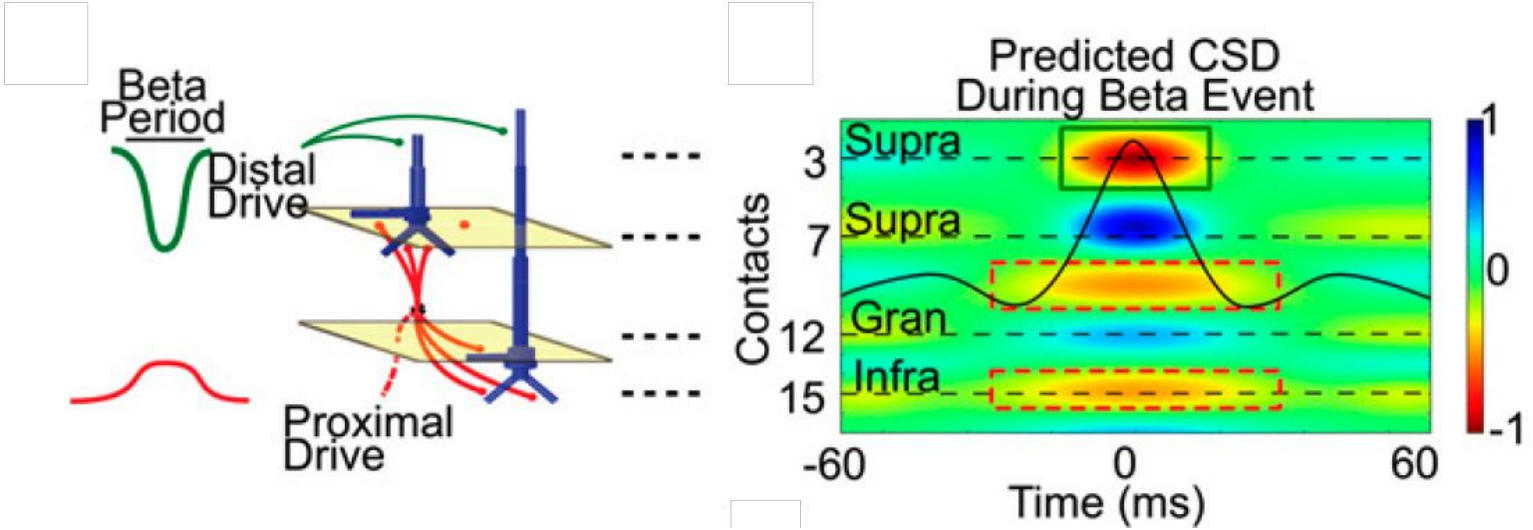



**High PAC is a consequence of sharp beta oscillations**

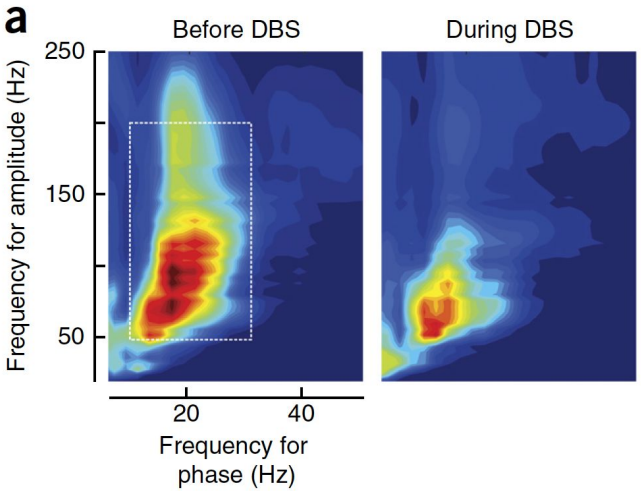
# What does a sharp oscillation reflect?

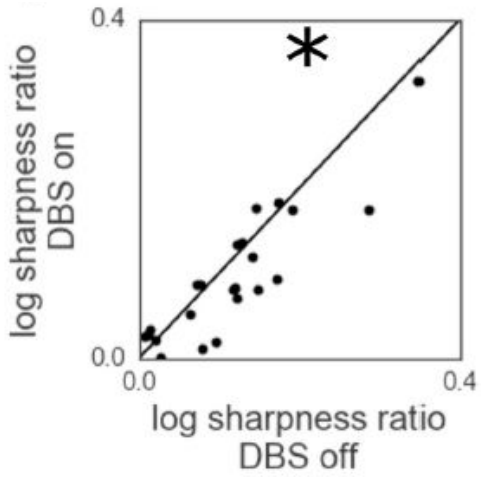
1. Field potentials: spatiotemporal summations of synaptic currents
2. Sharp transients: synchronous synaptic activity




Sherman et al., 2016, *PNAS*

# DBS → Less sharp beta oscillations




Coupled spiking and synaptic input

Synchronous synaptic input

de Hemptinne et al., Nat Neuro 2015

# Outline

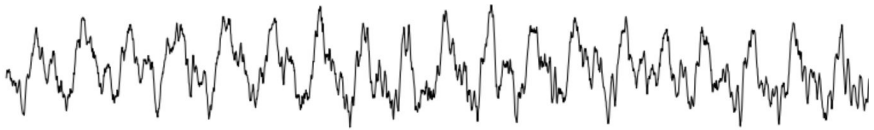
1. **Beta waveform sharpness as biomarker for Parkinson's Disease**

2. Framework to study neural oscillation waveform shape

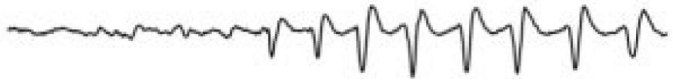
3. Relationship between waveform shape and neuronal activation patterns

# Waveform shape beyond “sharpness”

Hippocampal theta



Spike-wave discharge

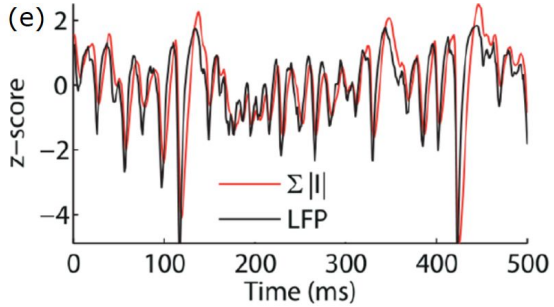


Slaght et al., 2004, *J Neuro*

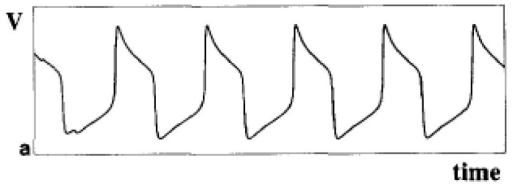
Cortical slow oscillation

Ouedraogo et al., 2016, *eNeuro*

Simulations

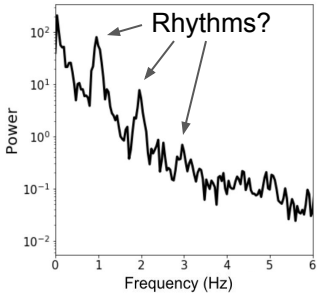


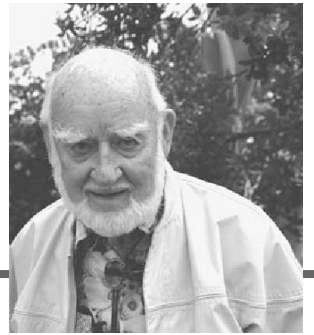

Mazzoni et al., 2015, *PLoS Comp Bio*




Somers & Kopell, 1993, *Biol Cybern*

# “Fourier fallacy”



**Virginie van Wassenhove**
@virginie_vw

Follow

“Even though it may be possible to analyze the complex forms of brain waves into a number of different sine-wave frequencies, this may lead only to what might be term a “Fourier fallacy”" - Jasper (1948)

1:29 AM - 15 Jul 2018

**35** Retweets **107** Likes

*Neuroscience* 121 (2003) 233–252

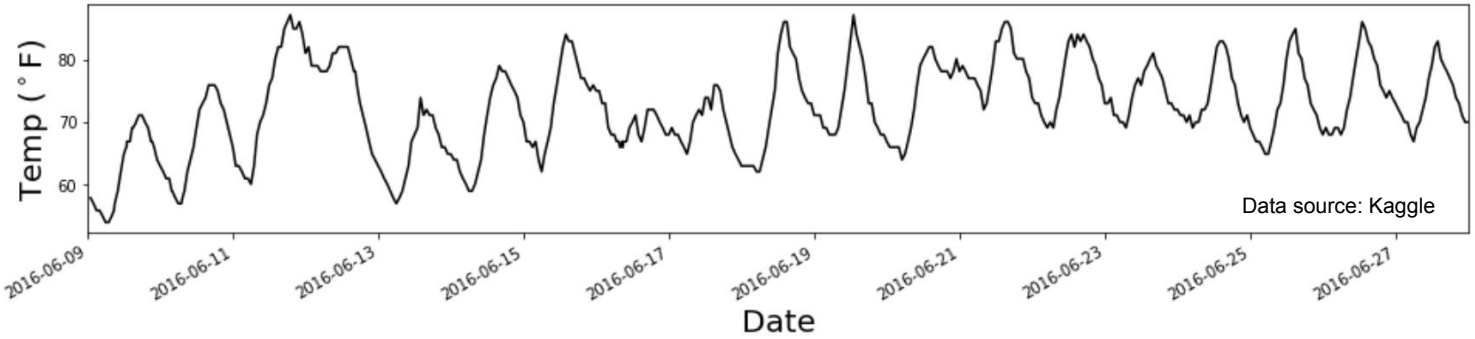
**ARE THE ELECTROENCEPHALOGRAMS MAINLY RHYTHMIC? ASSESSMENT OF PERIODICITY IN WIDE-BAND TIME SERIES**

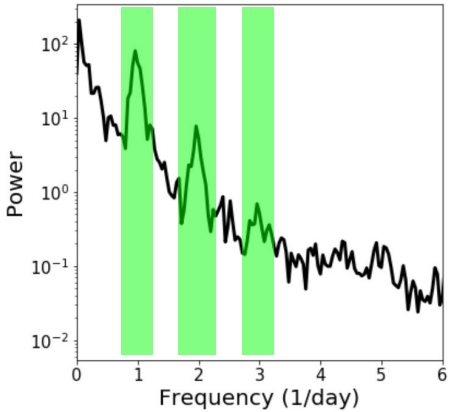
**T. H. BULLOCK,* M. C. McCLUNE AND J. T. ENRIGHT**

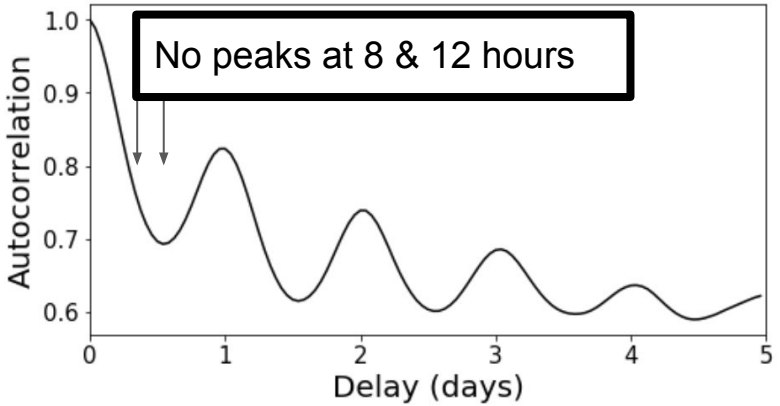
*Department of Neurosciences, School of Medicine and Neurobiology Unit 0240, Scripps Institution of Oceanography, University of California, San Diego, 9500 Gilman Drive, La Jolla, CA 92093, USA*

**Although the principal peaks in the two spectra agree most of the time, quite often a peak in the power spectrum accompanies no periodicity peak and some periodicity peaks have no power spectral peak. The Fourier spectrum is not a reliable indication of rhythms. EEG samples from patients**

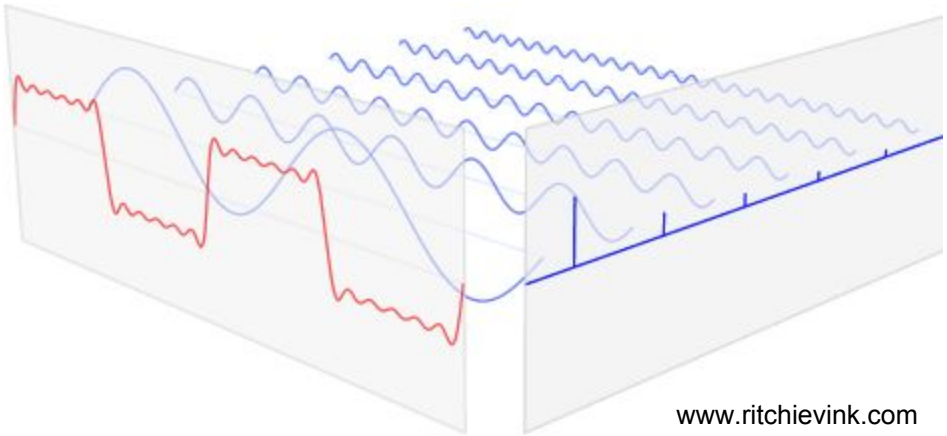
# “Fourier fallacy” in daily temperature fluctuation



# Complementary methods to the Fourier transform?



# Outline

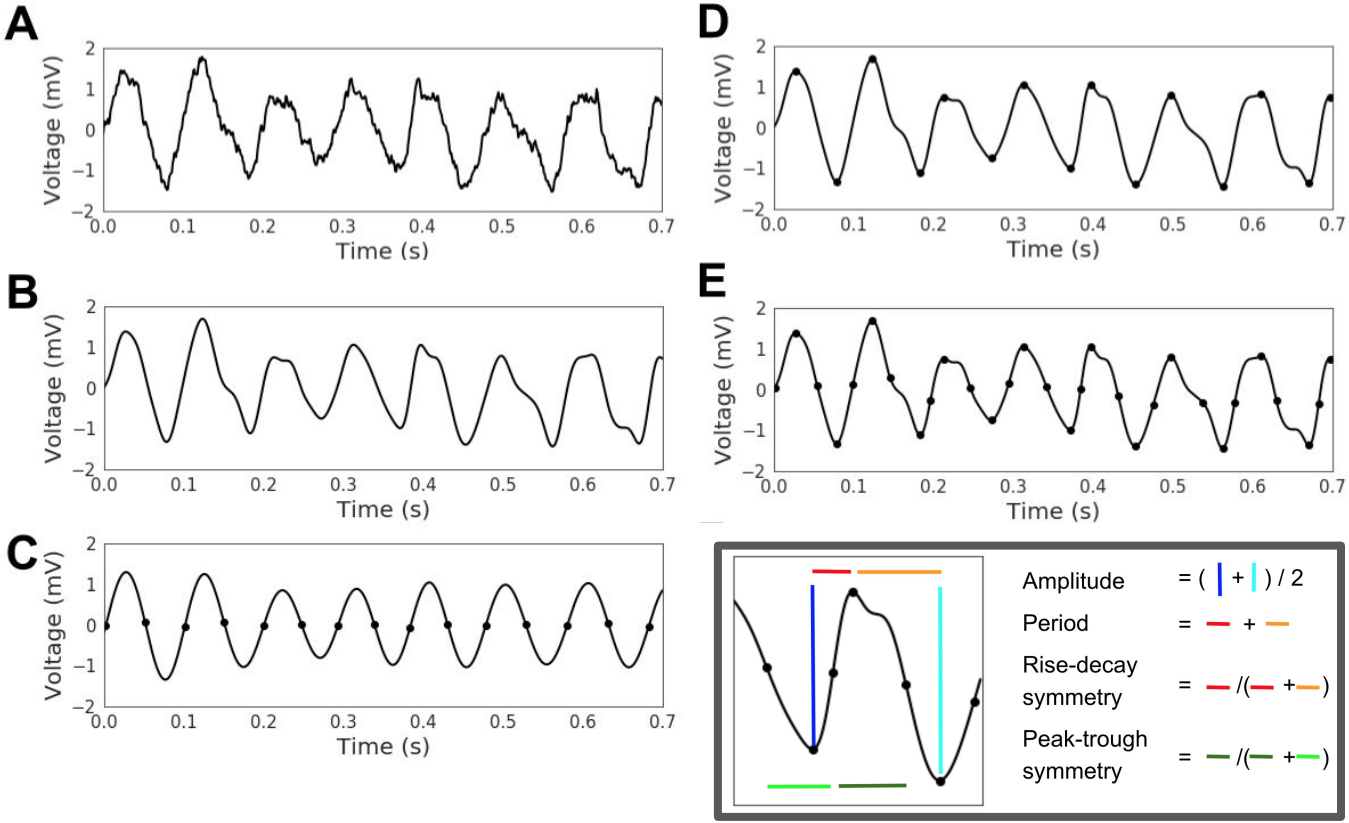
1. Beta waveform sharpness as biomarker for Parkinson's Disease

2. **Framework to study neural oscillation waveform shape**

3. Relationship between waveform shape and neuronal activation patterns

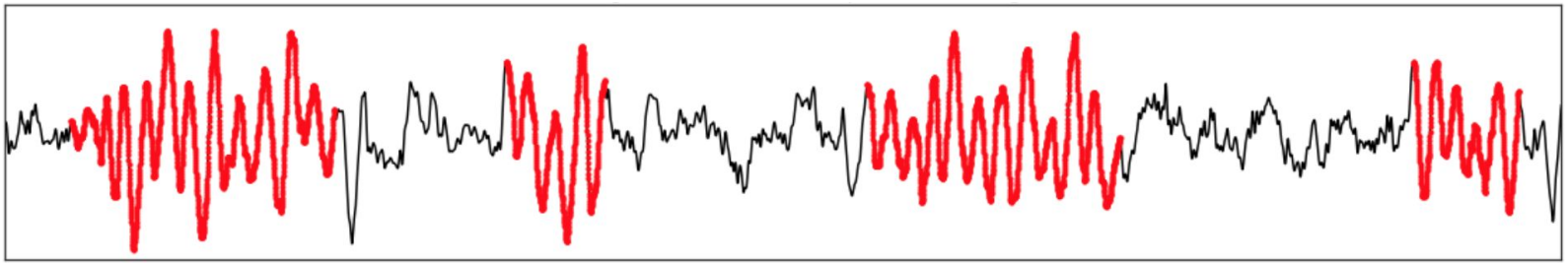
# Cycle-by-cycle analysis

voytekresearch/bycycle

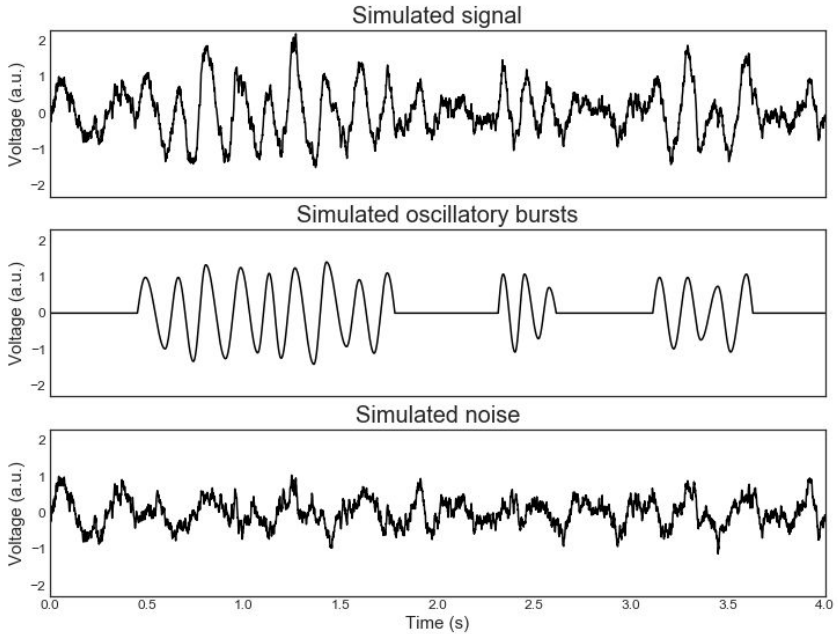



| Peak time | Amplitude | Period | rdsym | ptsym |
|---|---|---|---|---|
| 0.12 | 2.9 | 105 | 0.43 | 0.51 |
| 0.21 | 1.7 | 89 | 0.34 | 0.5 |
| 0.31 | 1.9 | 99 | 0.4 | 0.49 |
| 0.4 | 2.2 | 82 | 0.32 | 0.52 |
| 0.5 | 2.2 | 109 | 0.4 | 0.58 |
| 0.61 | 2.2 | 108 | 0.44 | 0.57 |

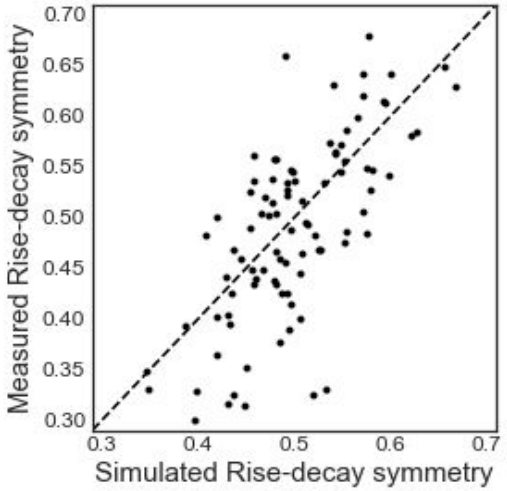
# Oscillation detection

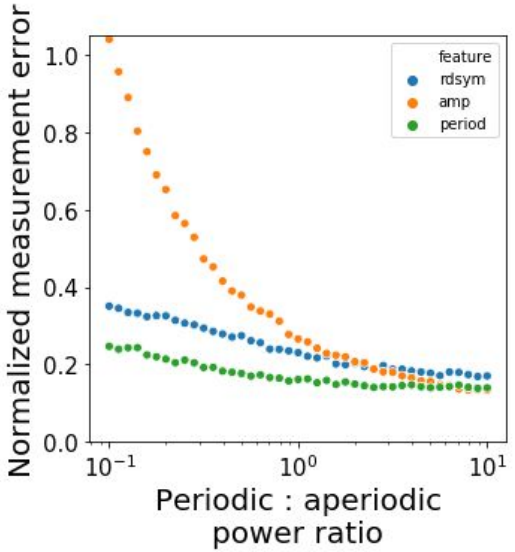


# Oscillation feature accuracy




voytekresearch/neurodsp

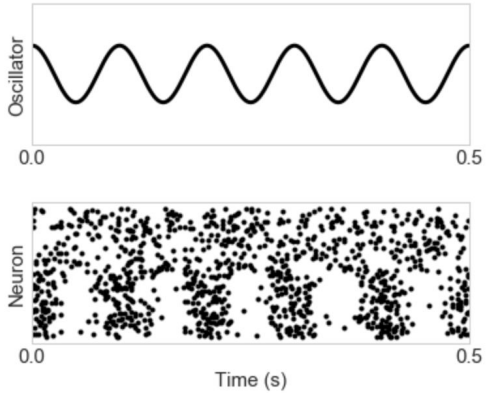


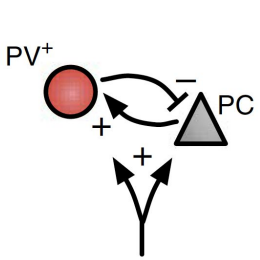
# Benefits of cycle-by-cycle approach

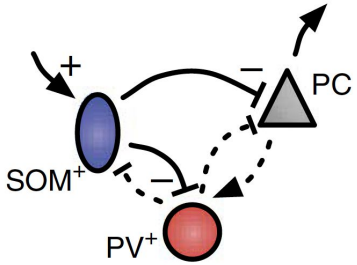
1. Quantifies waveform symmetries
2. Appropriate segments only
3. Time-resolved measurements
4. Direct measurements of amplitude and frequency
    a. Not confounded by oscillation presence
    b. More sensitive to changes

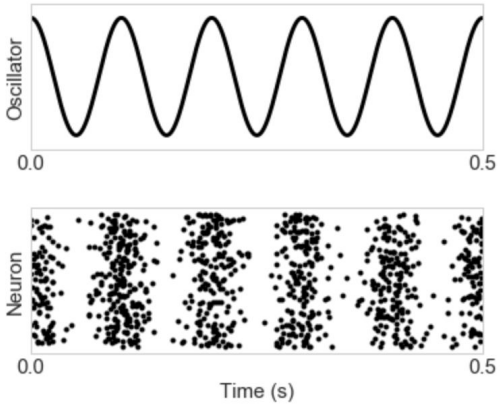
# What might waveform shape reflect?

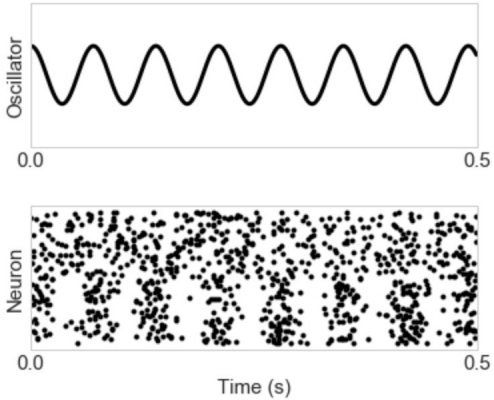


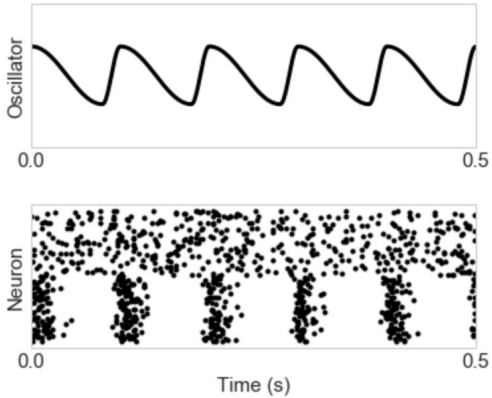

Womelsdorf et al., 2014



# Outline

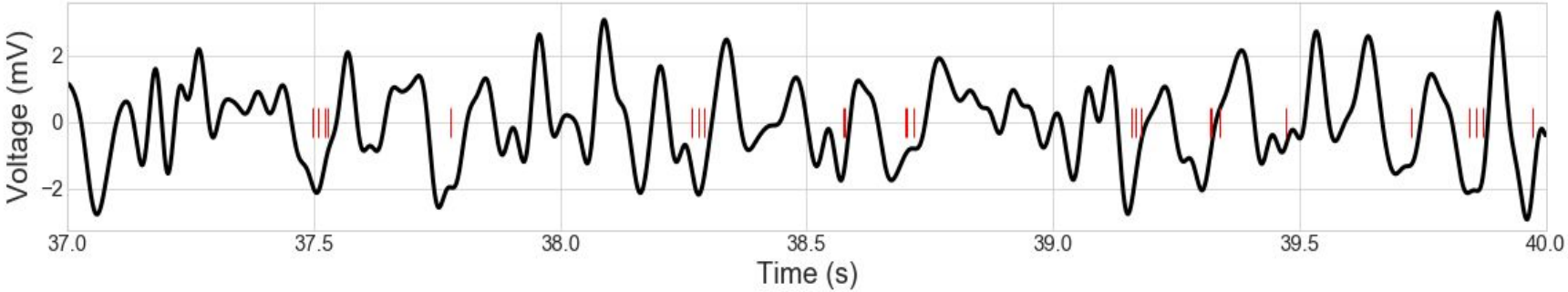
1. Beta waveform sharpness as biomarker for Parkinson's Disease

2. Framework to study neural oscillation waveform shape

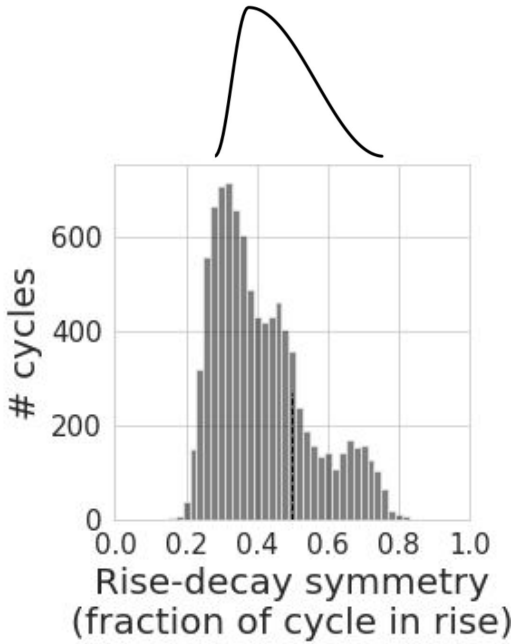
3. **Relationship between waveform shape and neuronal activation patterns**

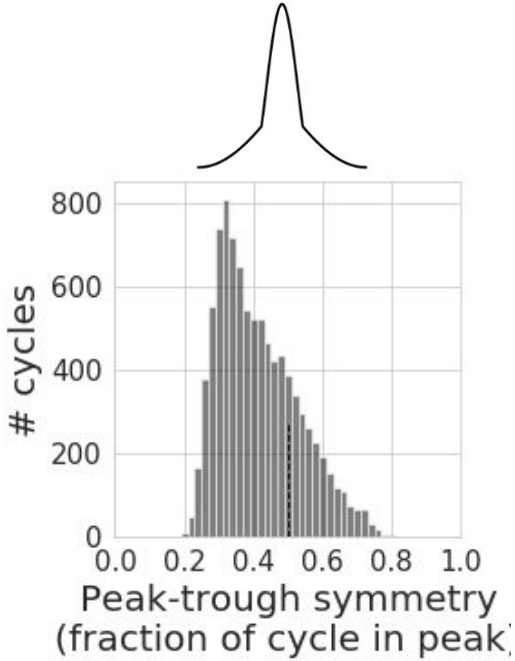
Extracellular recordings: rat hippocampus (CA1)
Online data source: CRCNS (hc3 dataset; Mizuseki et al., 2014, *F1000 Research*)

# Spike-field coupling (SFC)



# Hippocampal theta is asymmetric



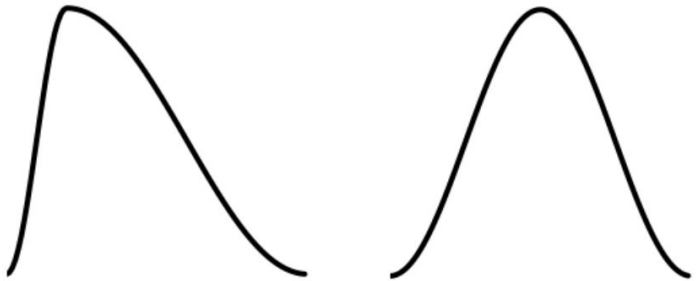
# Hippocampal theta asymmetry & behavior

- ↑ asymmetry, ↑ memory encoding (Trimper et al., 2014, *Hippocampus*)
- asymmetry ~ location representation (Amemiya & Redish, 2018, *Cell Reports*)

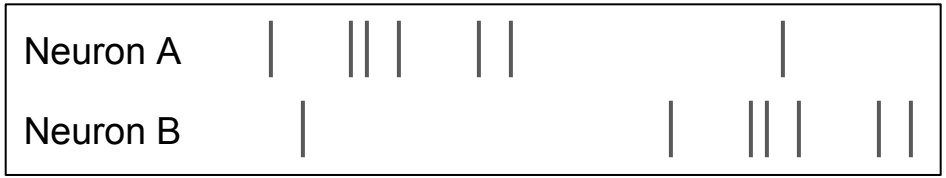
Rat currently in neuron place field

Rat heading to neuron place field

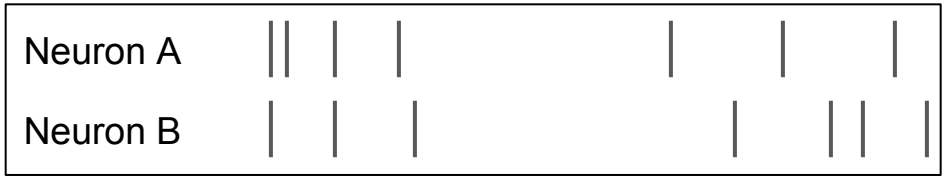
**Hypothesis:**
Waveform shape contains information of local spiking patterns.



Firing rates

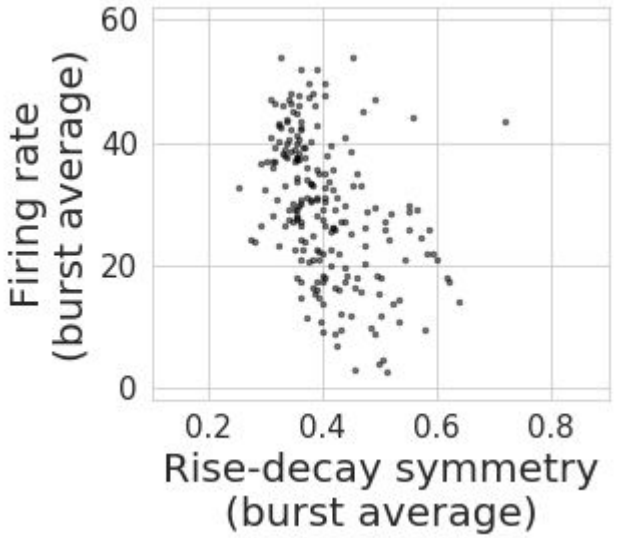


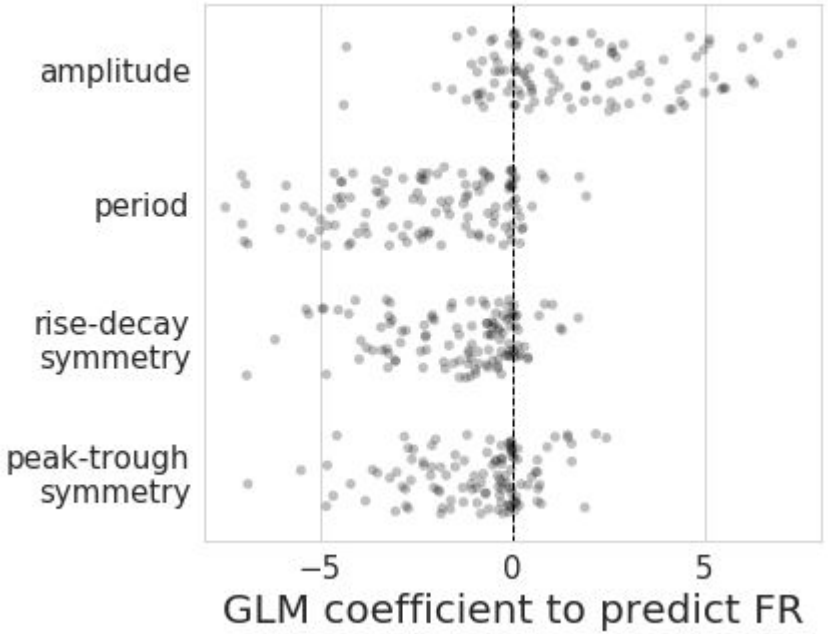

Synchrony




Sequence

# Theta asymmetry ~ neuronal firing rates

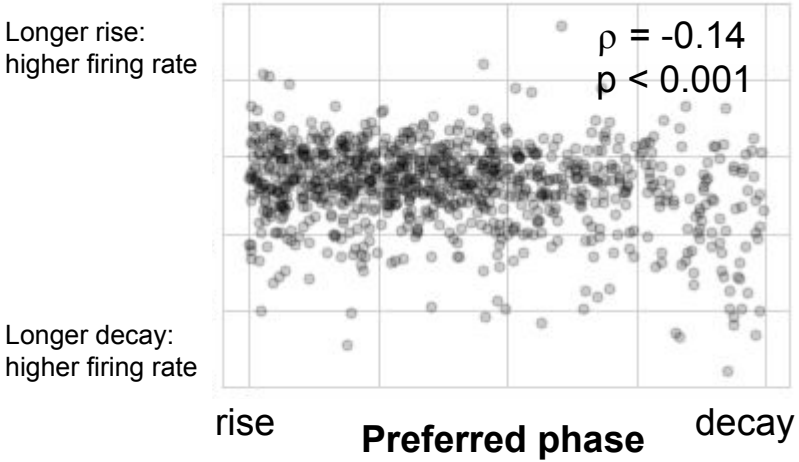


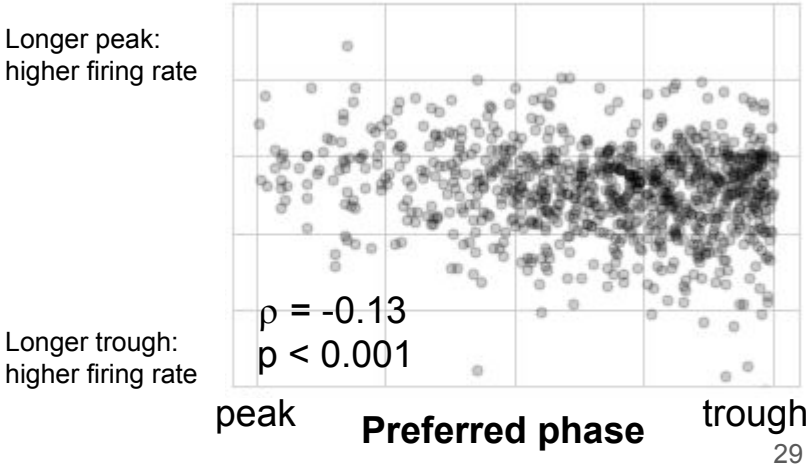



# Spike-field coupling & waveform shape

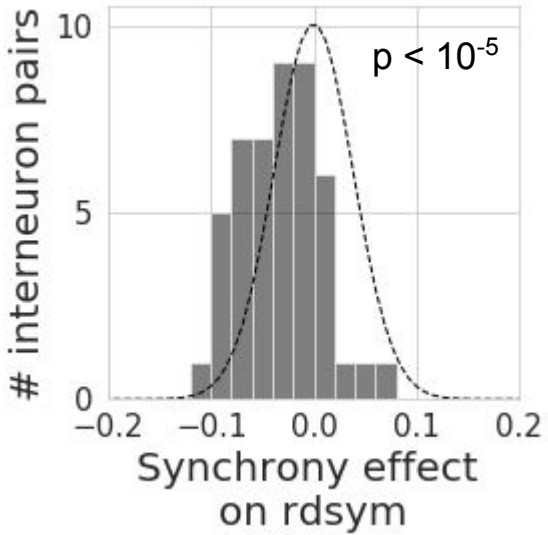
Neuron A
preferred firing phase: decay

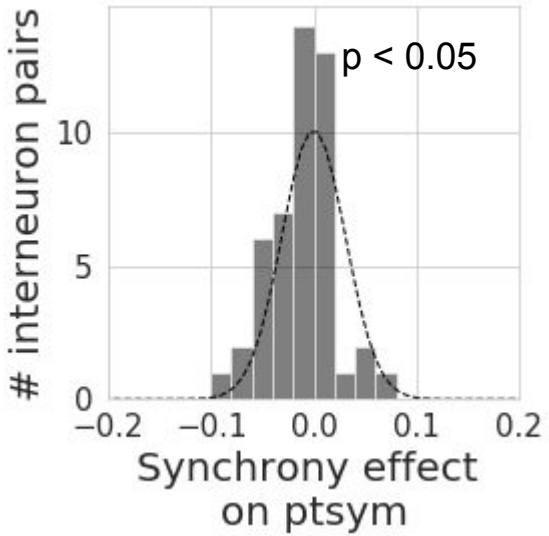
Waveform symmetry indexes relative subpopulation activations



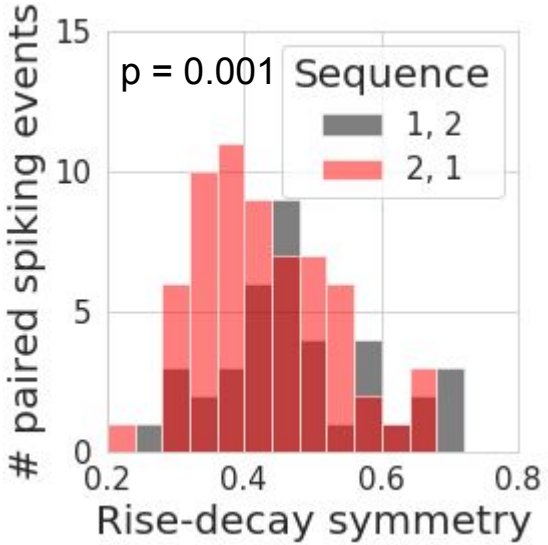



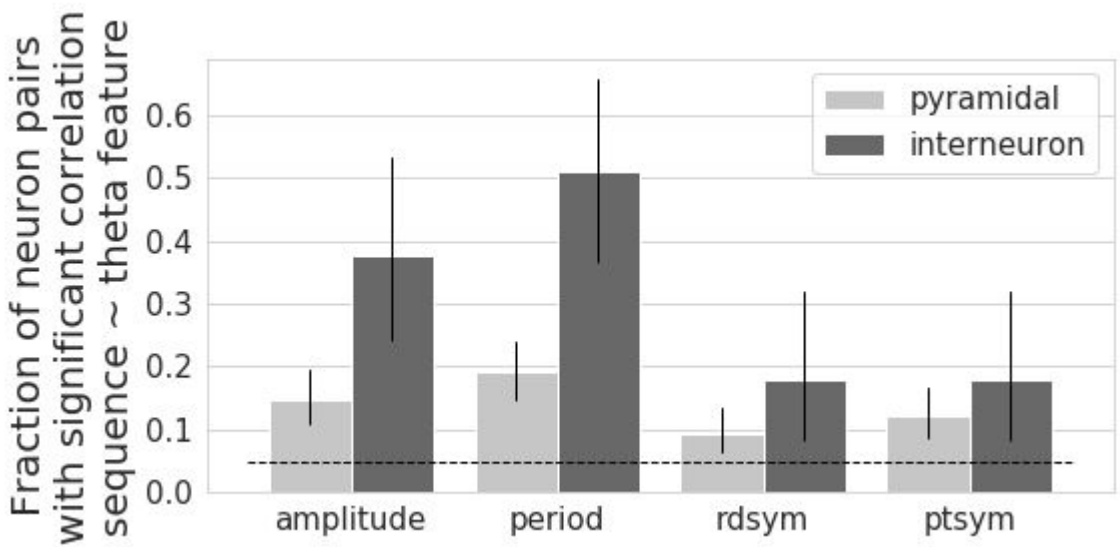
# Increased interneuronal synchrony during asymmetric theta oscillations



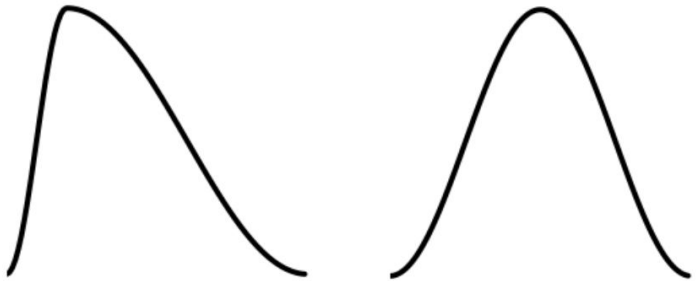



# Theta asymmetry ~ neuronal sequence

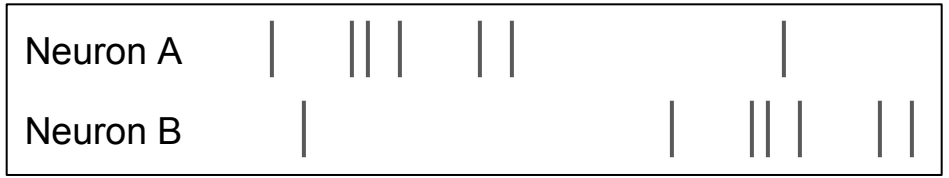


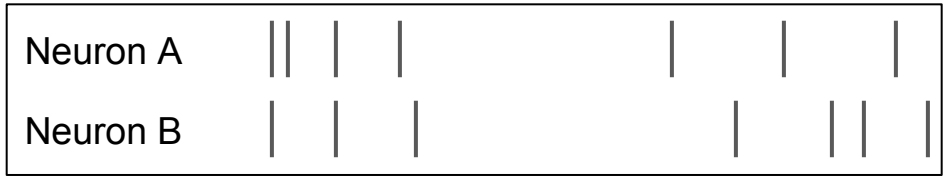
# Theta asymmetry correlates with CA1 neuronal firing patterns



✓ Firing rates




✓ Synchrony




✓ Sequence

# Summary

1. Beta waveform sharpness as biomarker for Parkinson's Disease

   Cole et al., 2017, *J Neurosci*

2. Framework to study neural oscillation waveform shape

   Cole & Voytek, 2018a, *bioRxiv*,  Cole & Voytek, 2017, *Trends in Cog. Sci.*

3. Relationship between waveform shape and neuronal activation patterns

   Cole & Voytek, 2018b, *bioRxiv*

# Outlook: Neural oscillation waveform shape

- More examples of information in waveform shape
  - Decreased bicoherence of mu rhythms in Schizophrenia (Bartz et al., 2018, *NeuroImage*)
- Analysis of spatial patterns in waveform shape
  - Multivariate convolutional sparse coding (Dupre La Tour et al., 2018, *Arxiv*; Agarwal et al., 2014, *Science*)
- Cycle-by-cycle spectral coupling (Lopes Dos Santos et al., 2018, Neuron)
- Probabilistic oscillation detection (Andrew Watrous, in prep.)