

# Oscillations & Connectivity in MEG/EEG/LFP

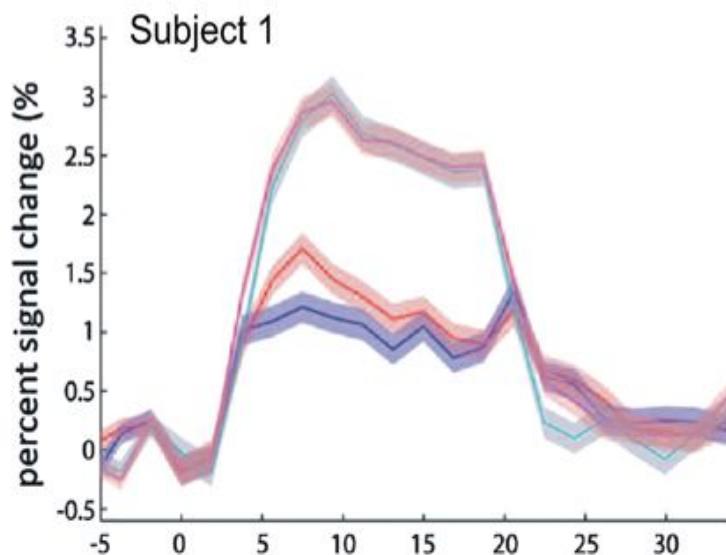
Signal processing introduction

Peter Donhauser, PhD student, Baillet  
lab

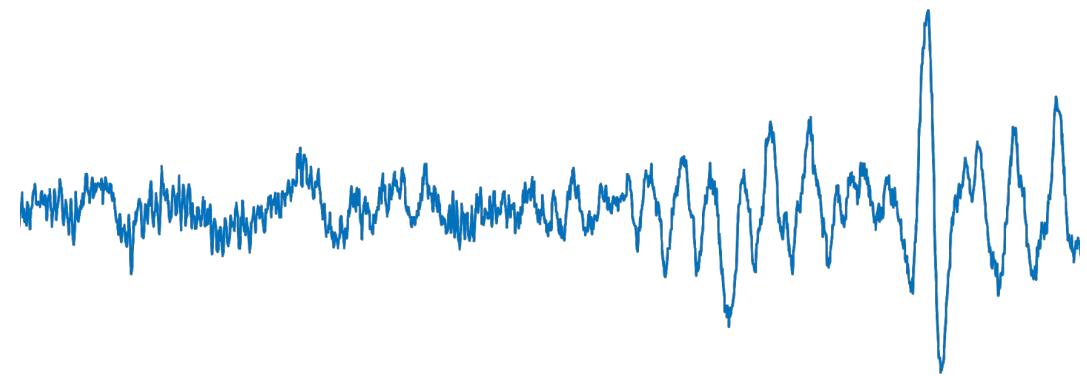
Computational Neuroscience  
class - Winter term 2018

# Why spectral analysis?

- Electrophysiological signals contain a wide range of components
- Electrophysiology vs. BOLD: what is 'activity'?

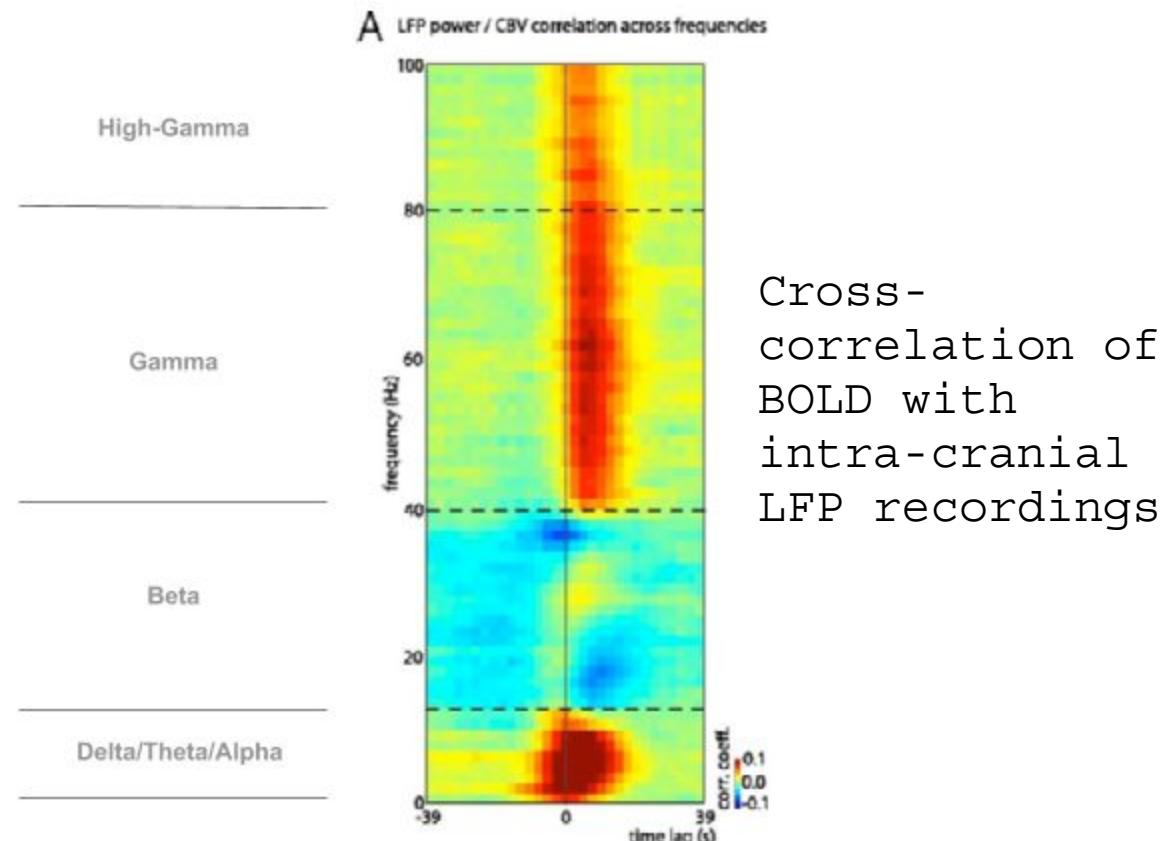
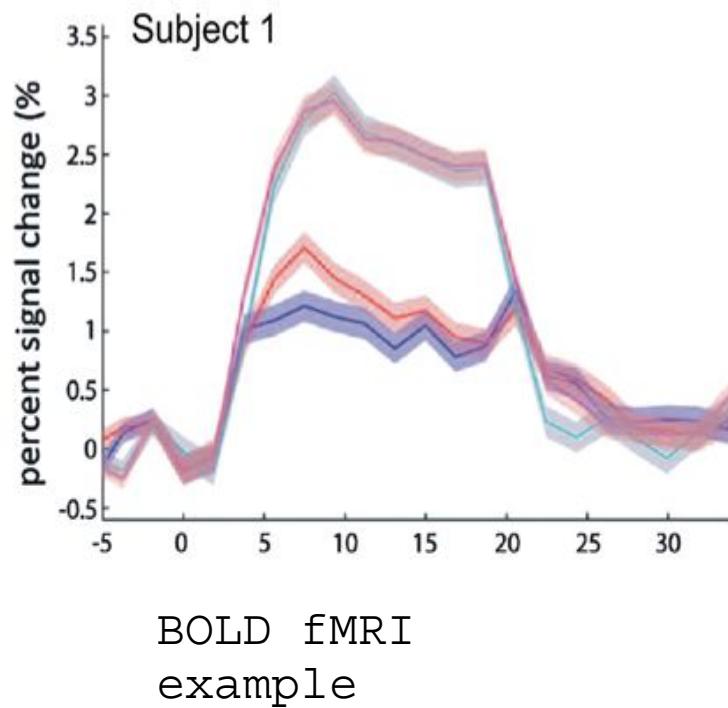


BOLD fMRI  
example



# Why spectral analysis?

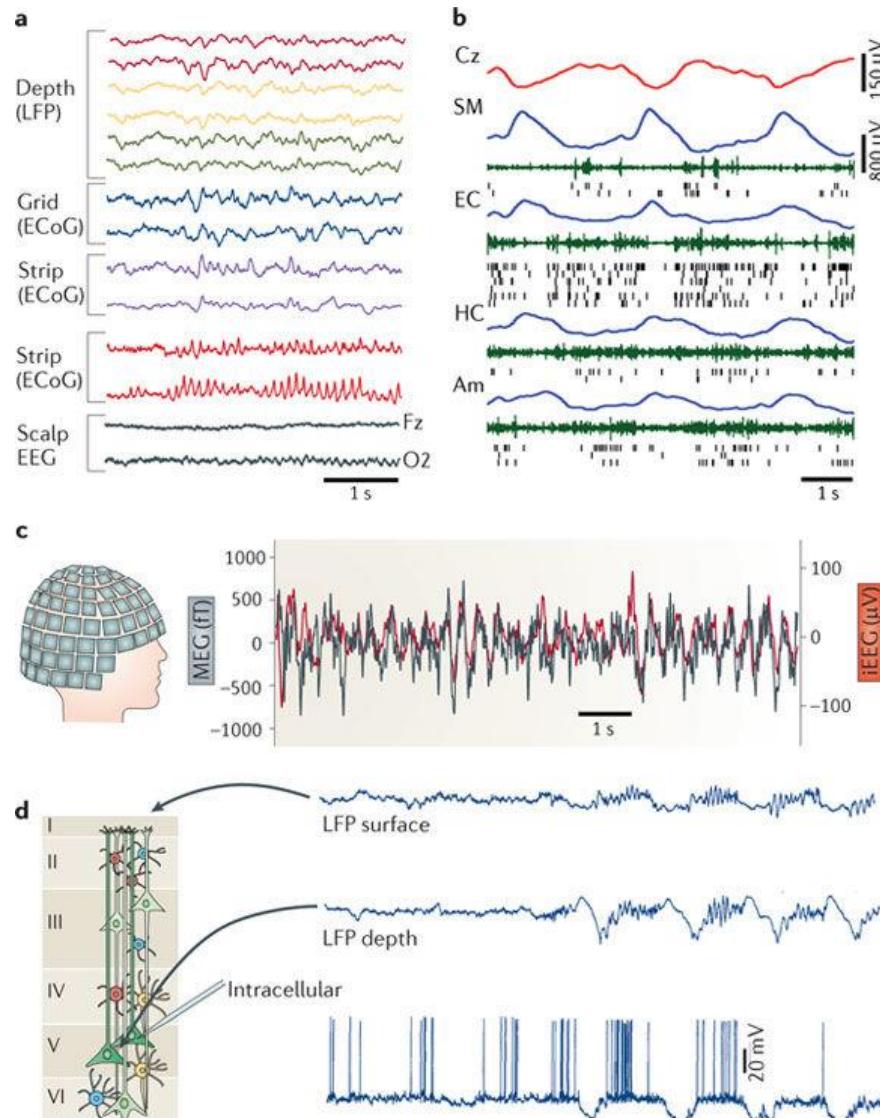
- Electrophysiological signals contain a wide range of components
- Electrophysiology vs. BOLD: what is 'activity'?



Schölvinck et al., PNAS (2010)

Cross-correlation of BOLD with intra-cranial LFP recordings

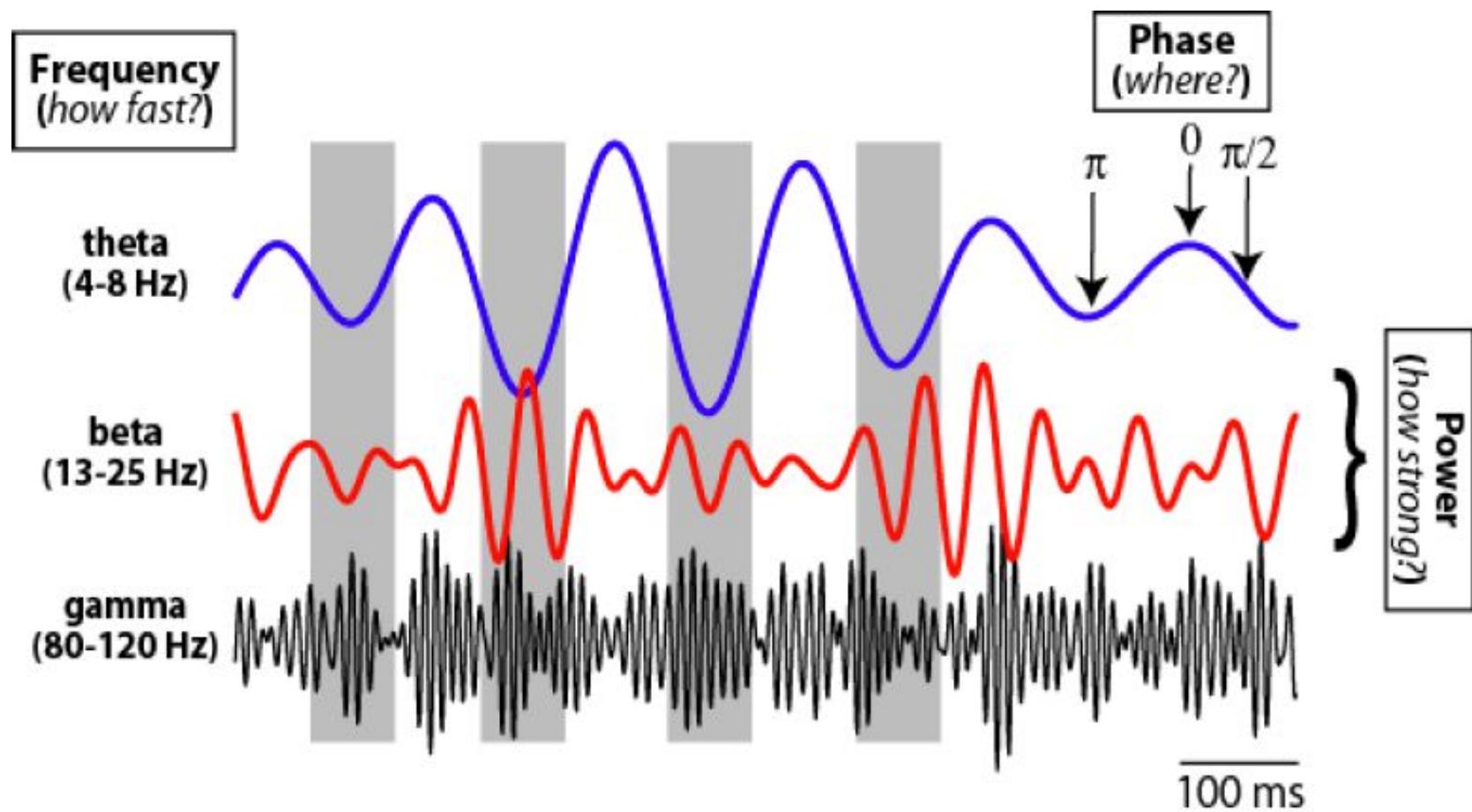
# What are the signals?



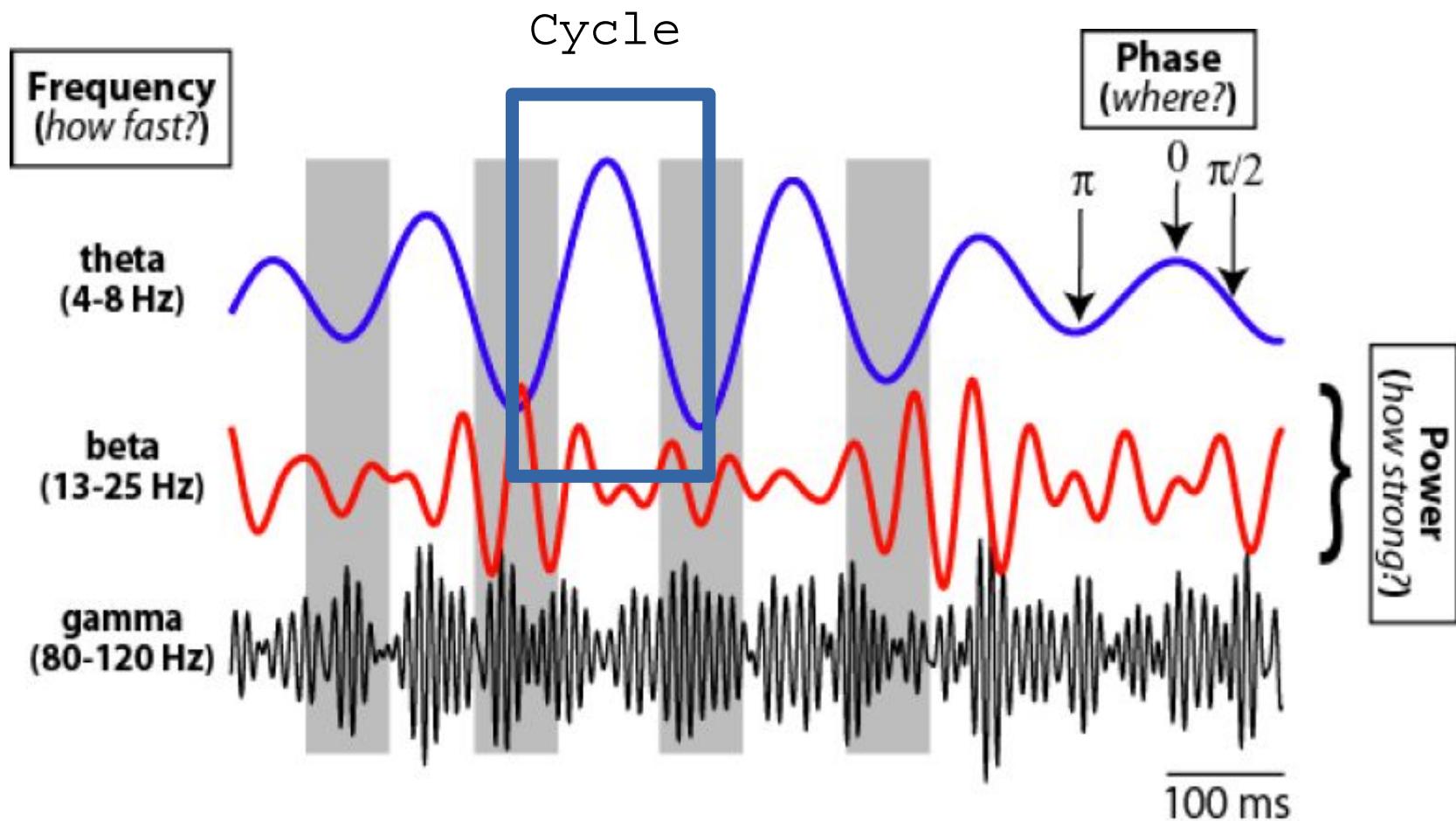
Extracellular traces using different recording methods are fundamentally similar.

LFP/ECoG/EEG/MEG

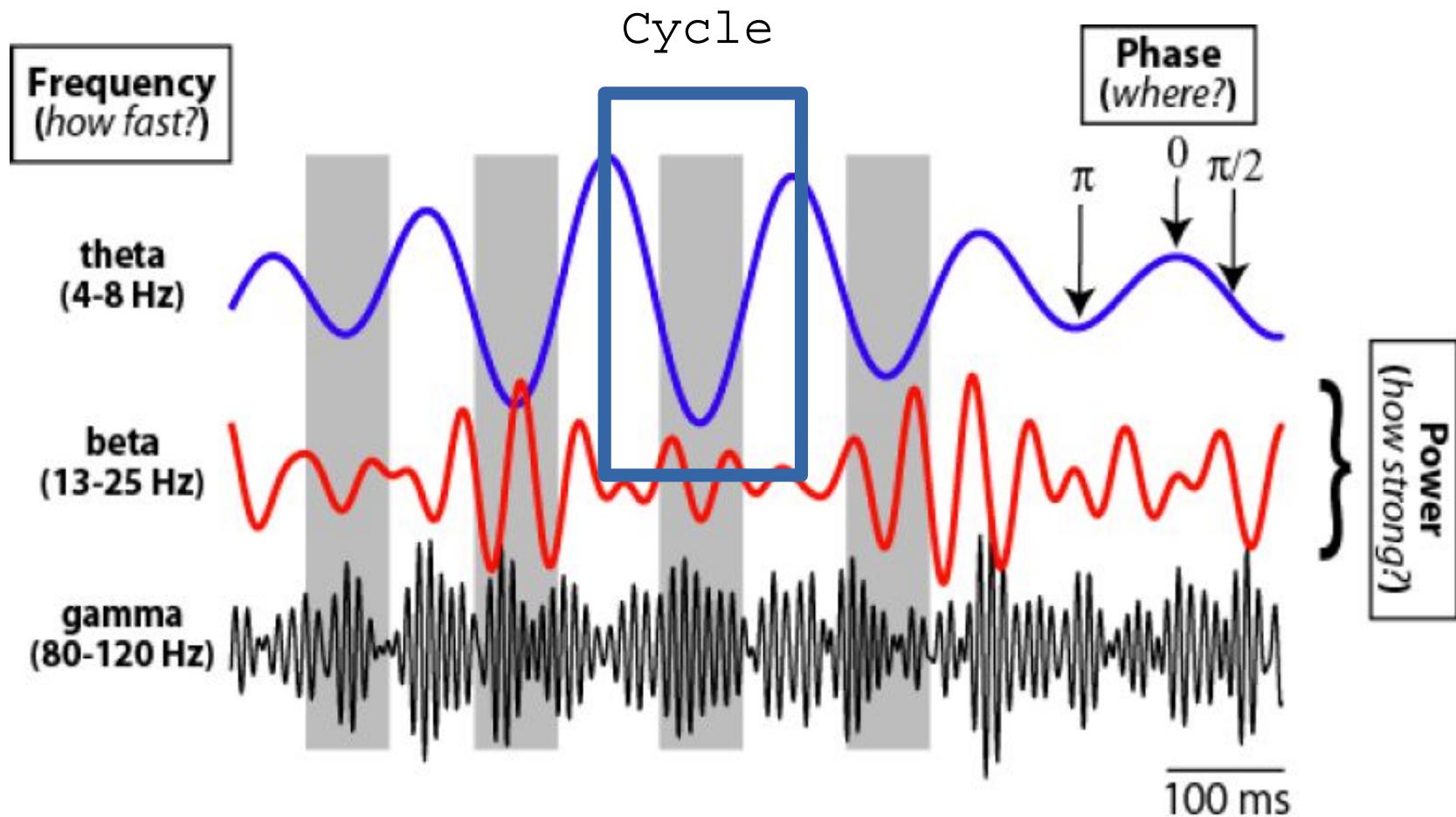
# Basic concepts



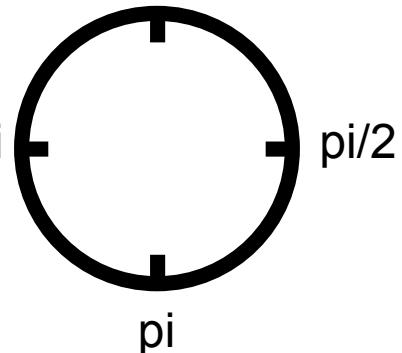
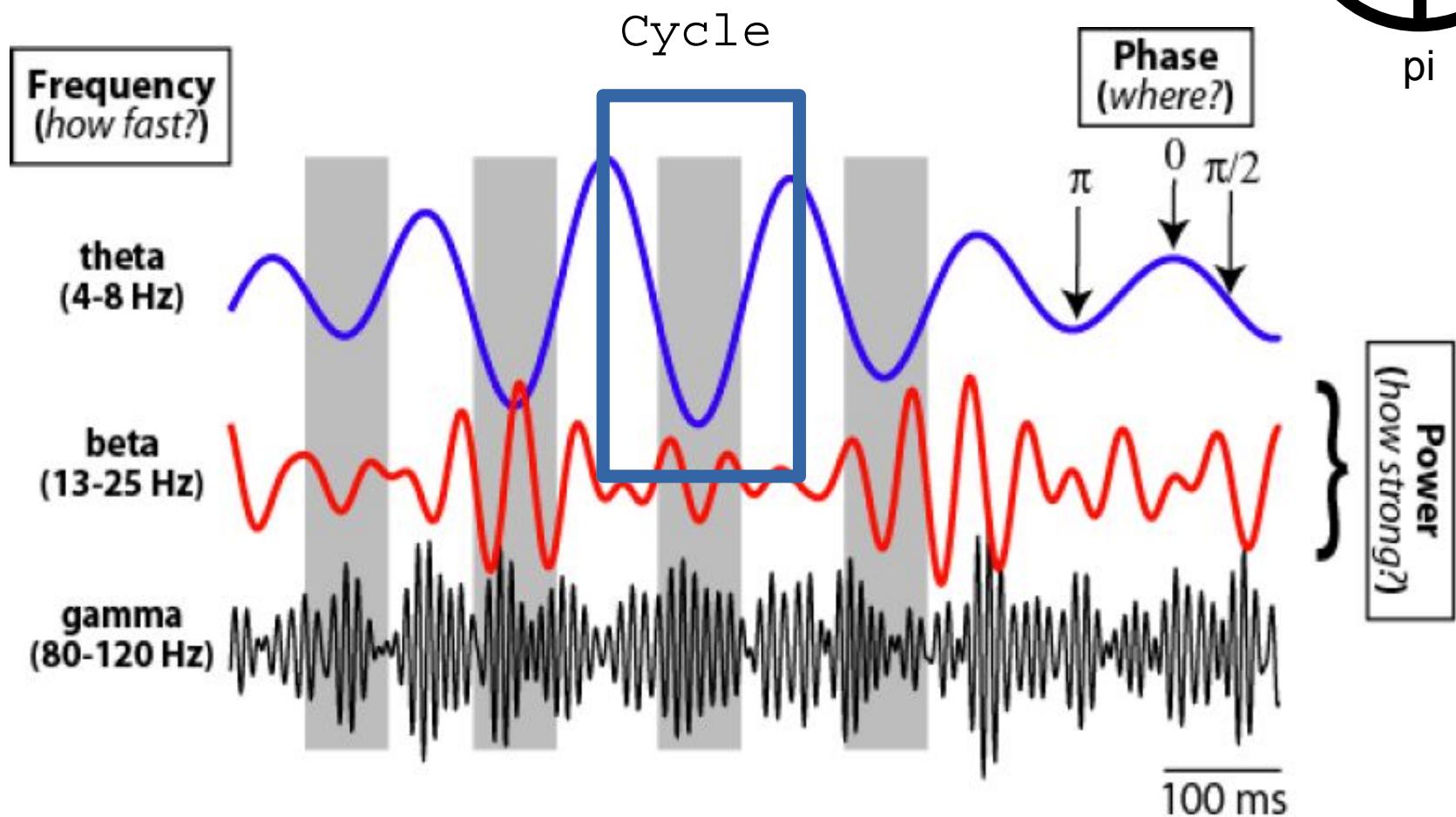
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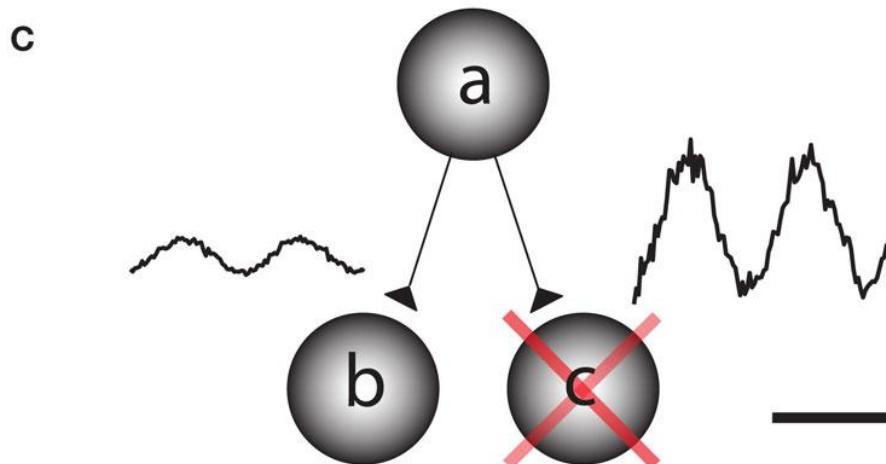
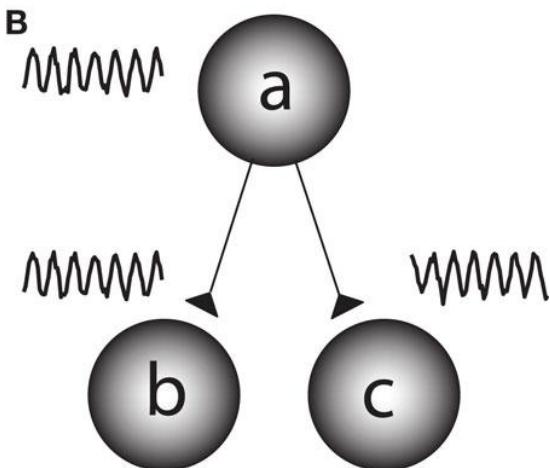
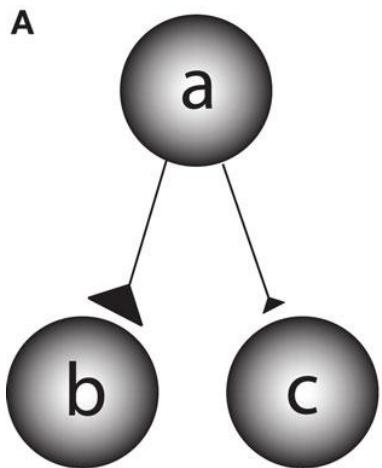
# Basic concepts



# Basic concepts



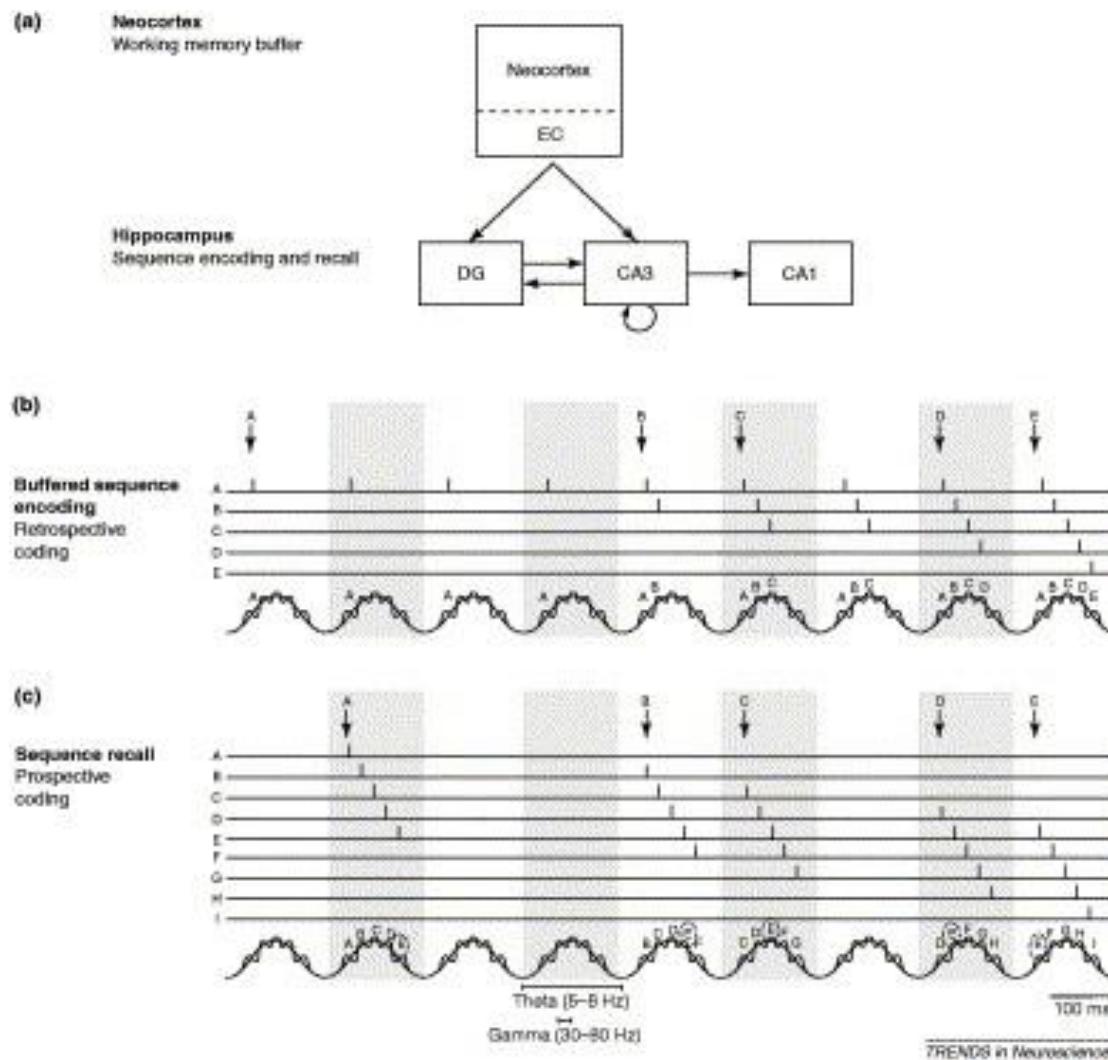
# Oscillations & routing of information



How can two regions transiently increase their communication efficiency?

- A: strengthening of synapses
- B: phase synchronization
- C: functional inhibition by alpha oscillations

# Phase coding



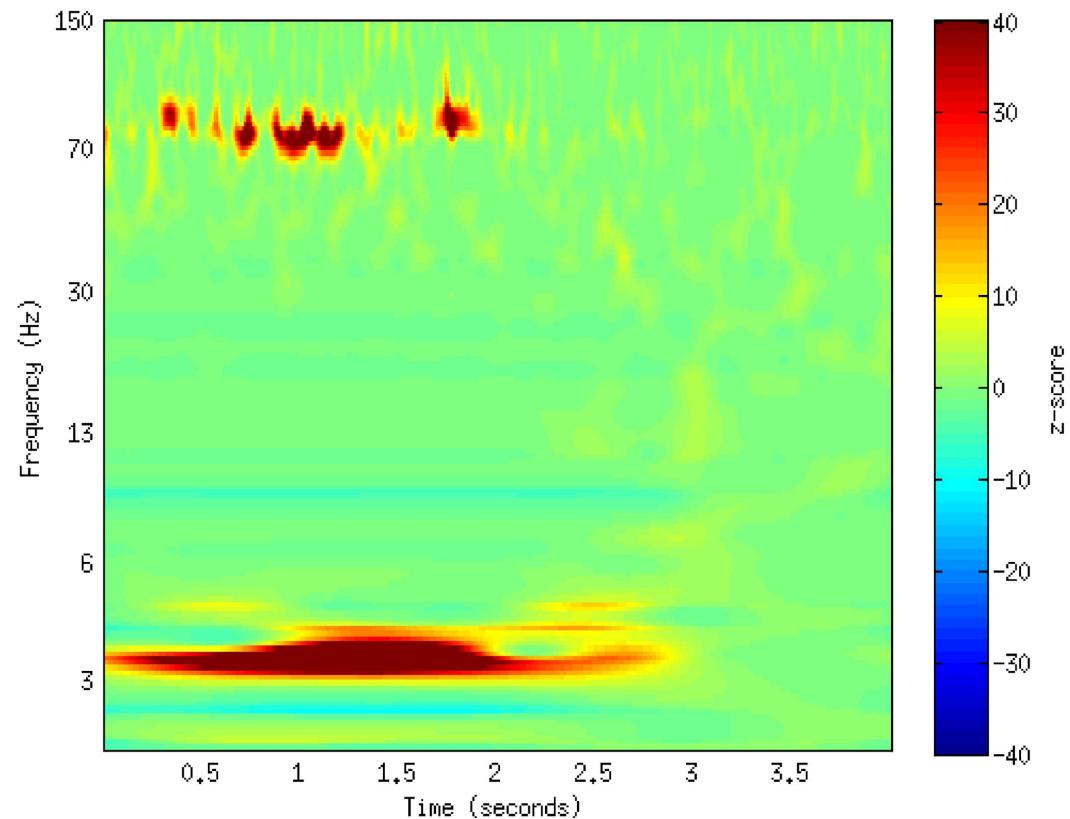
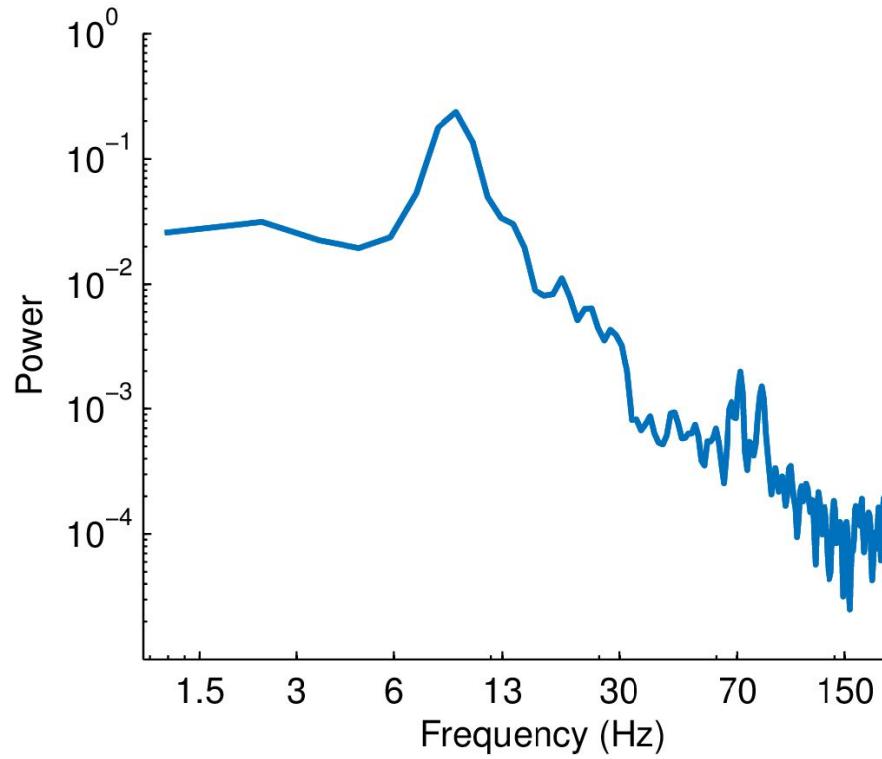
Action potentials occurring at specific phases of a lower frequency rhythm

- Sequences of items in memory can be represented by a phase code
- Theta rhythm as a temporal reference frame

# Methods covered today

Two main groups:

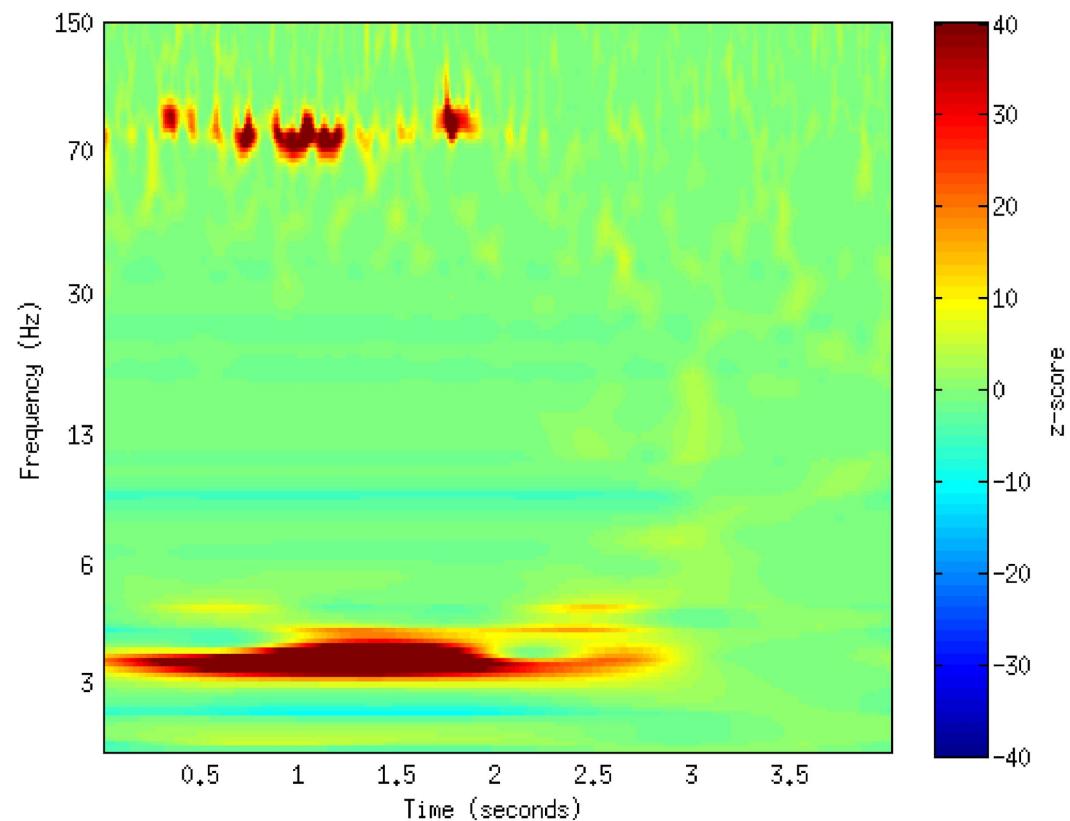
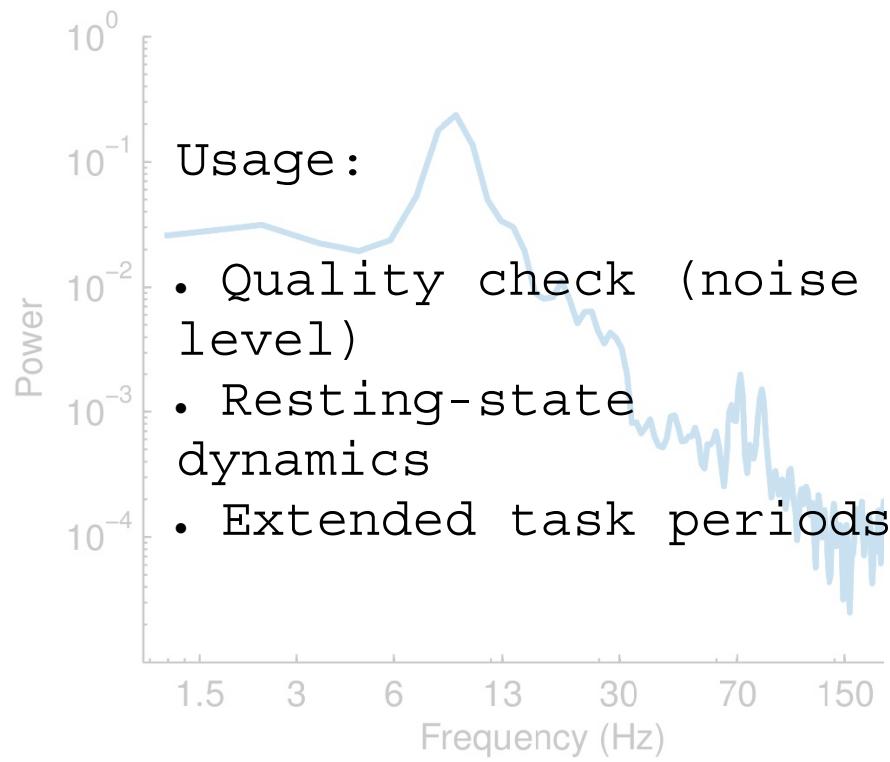
- Estimation of spectral power (stationary) vs.
- Localization of Power in time & frequency



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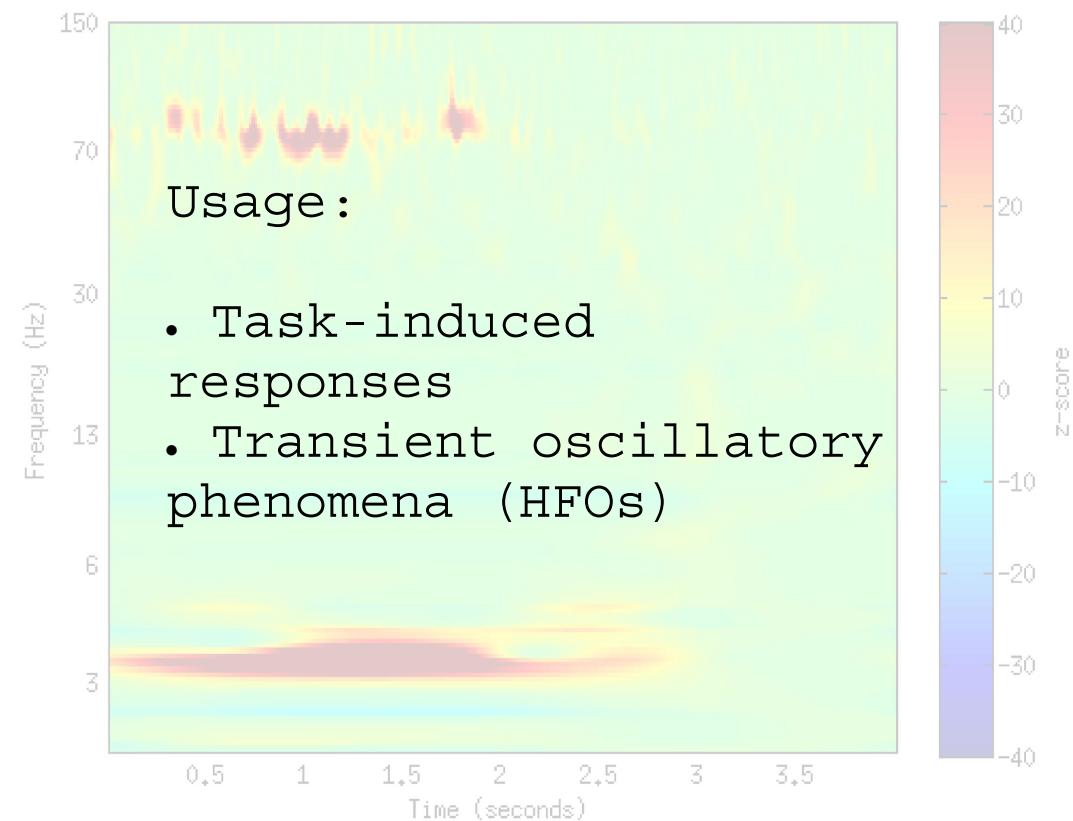
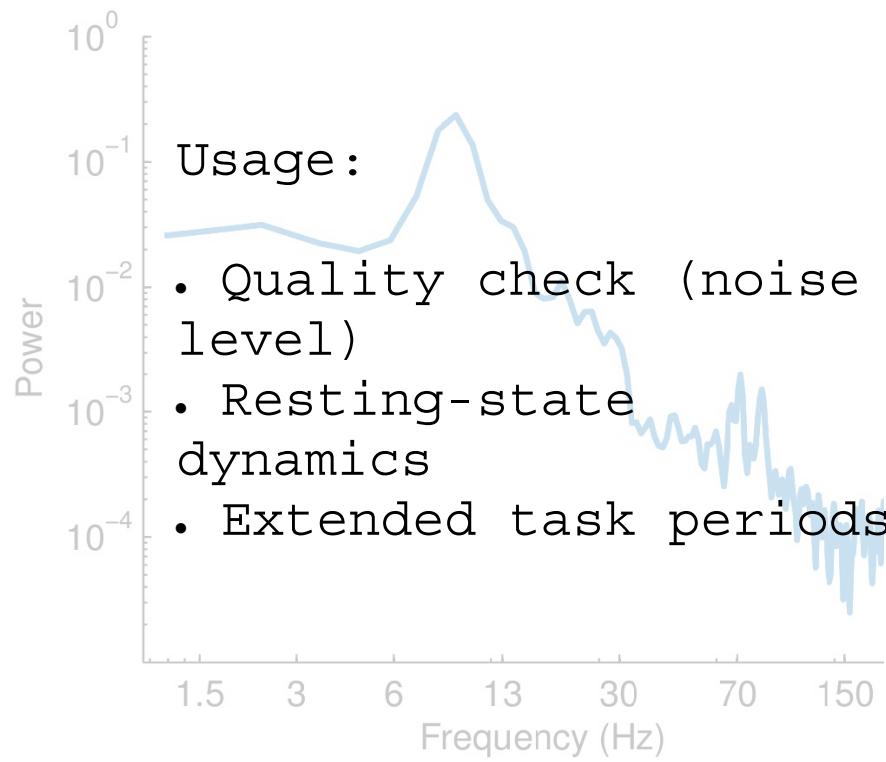
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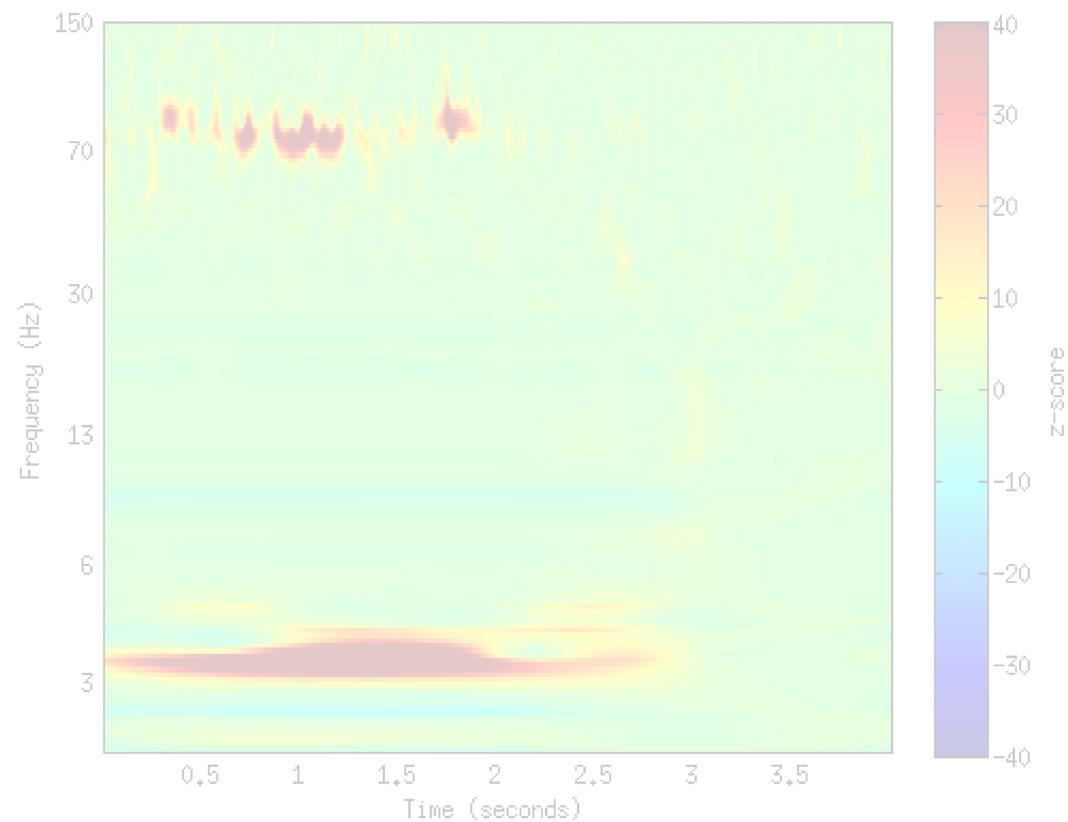
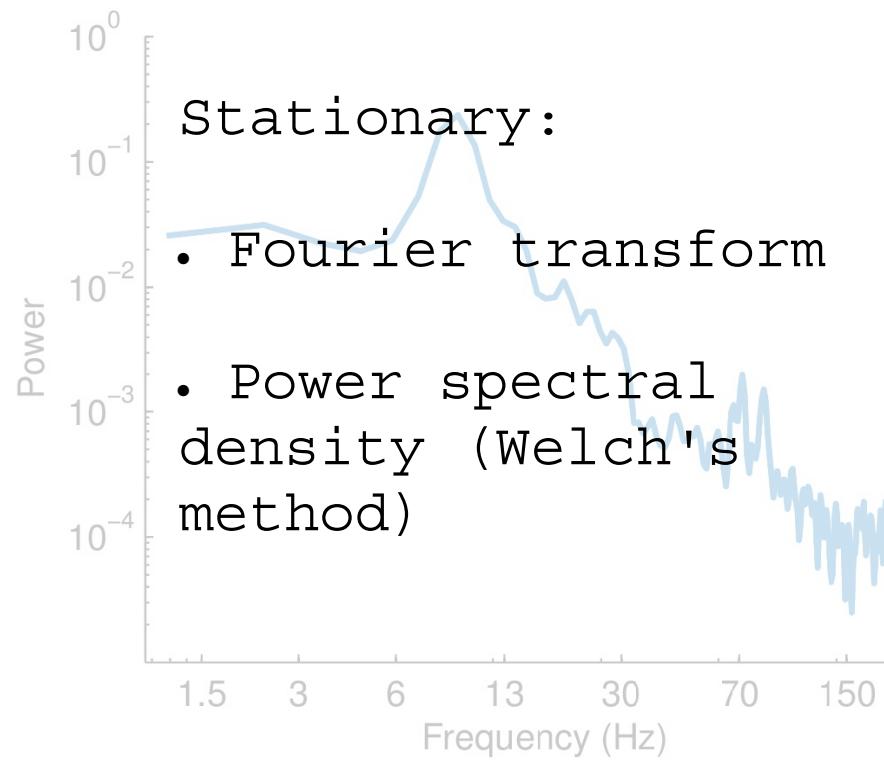
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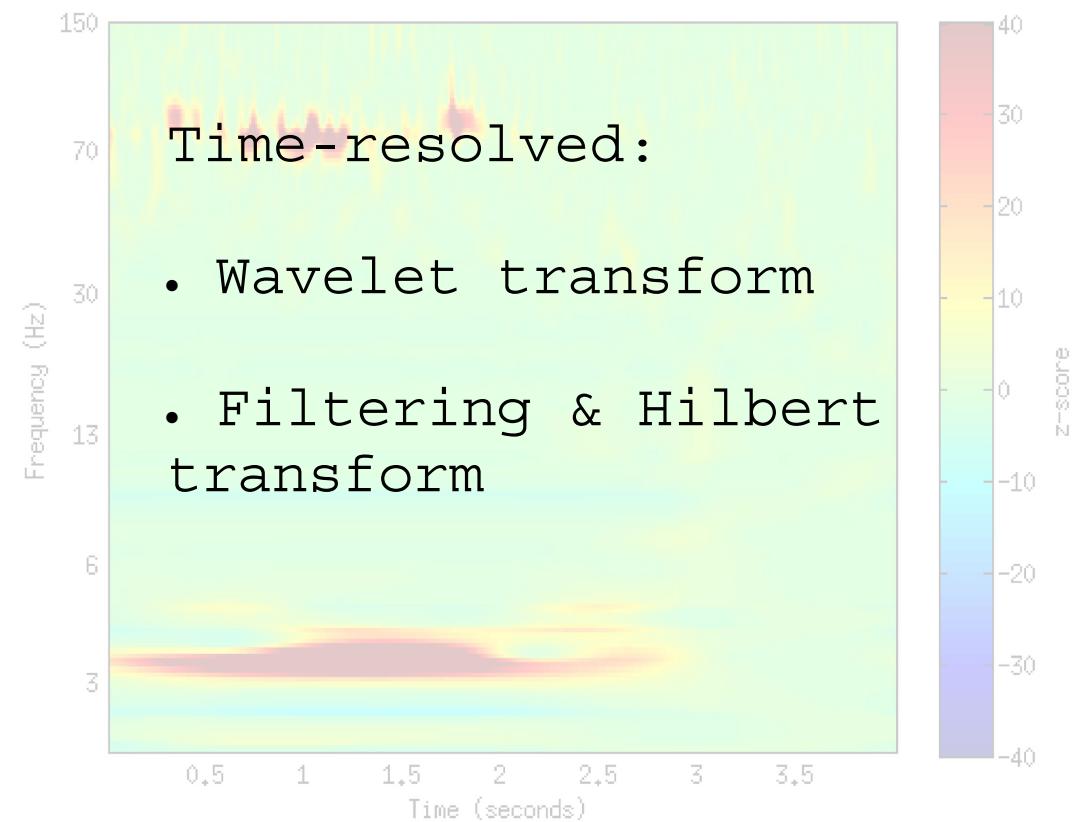
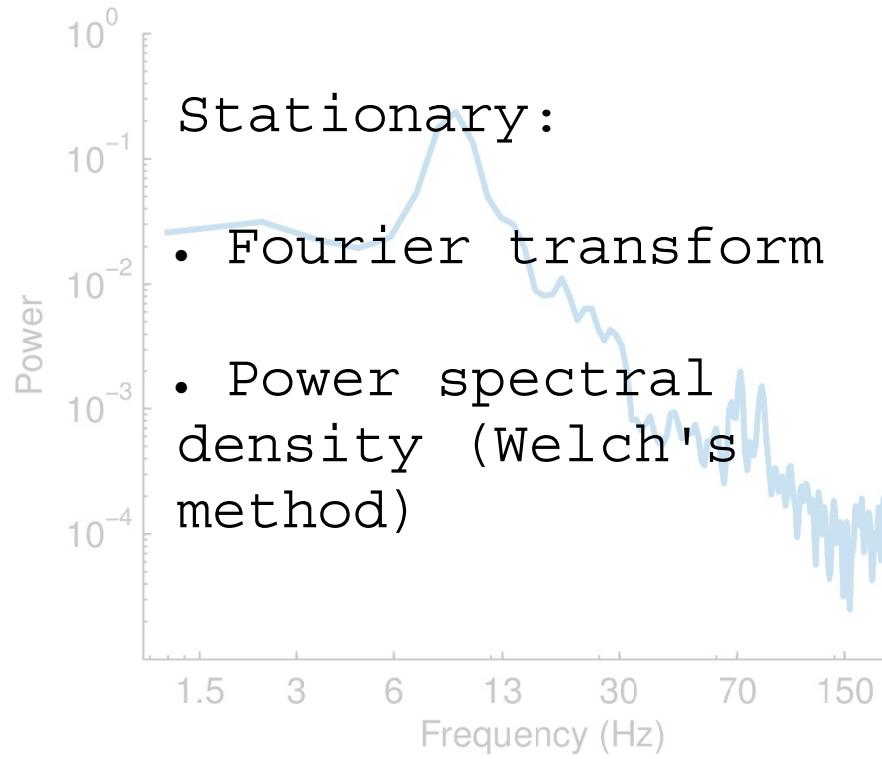
- Estimation of spectral power (stationary) vs.
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# Methods covered today

Two main groups:

- Estimation of spectral power (stationary) vs.
- Localization of Power in time & frequency



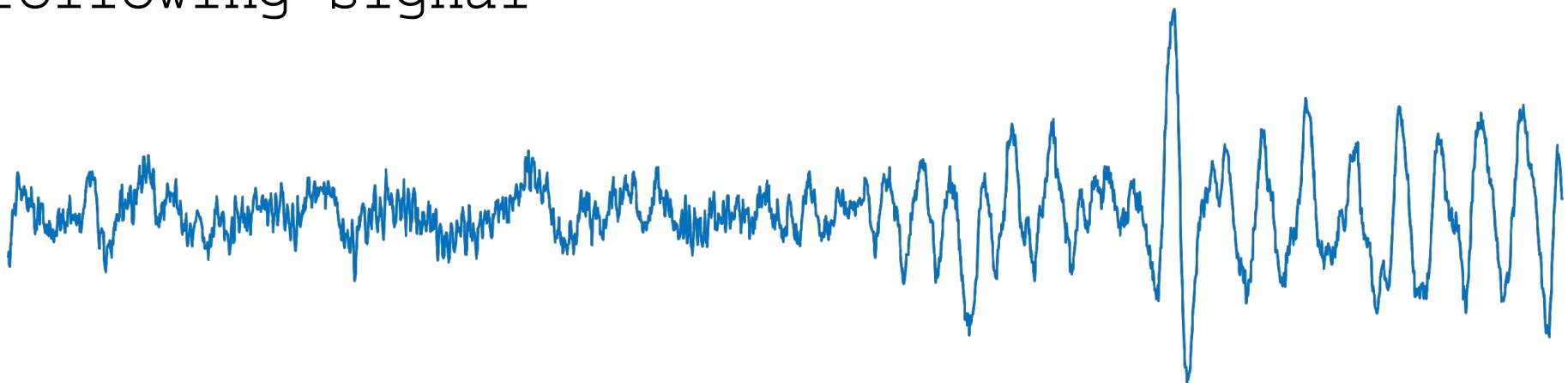
# Methods covered today

Two main groups:

- Estimation of spectral power (stationary) vs.
- Localization of Power in time & frequency
- Examples of connectivity measures

# Example signal

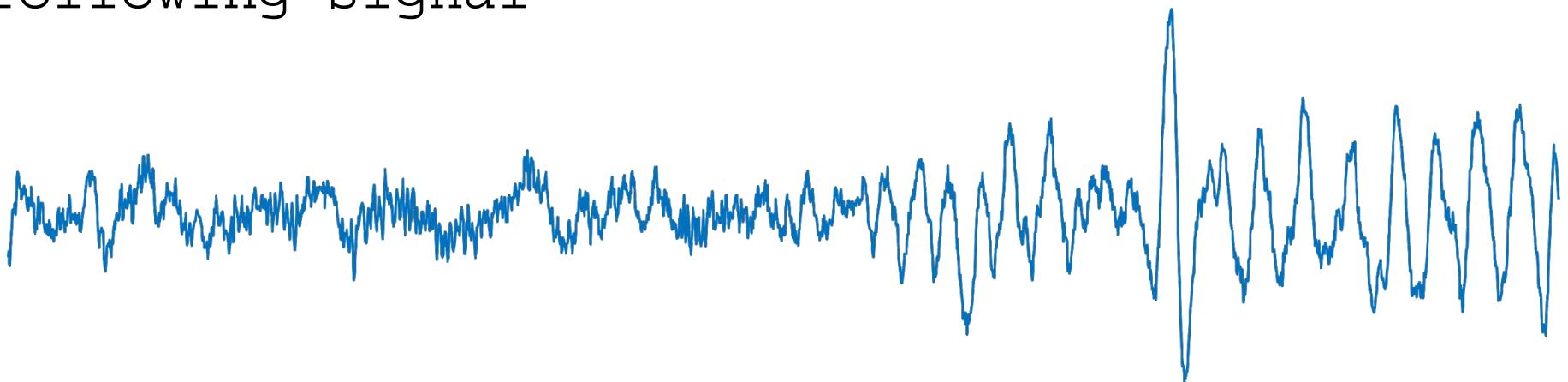
- Concepts will be illustrated using the following signal



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# Example signal

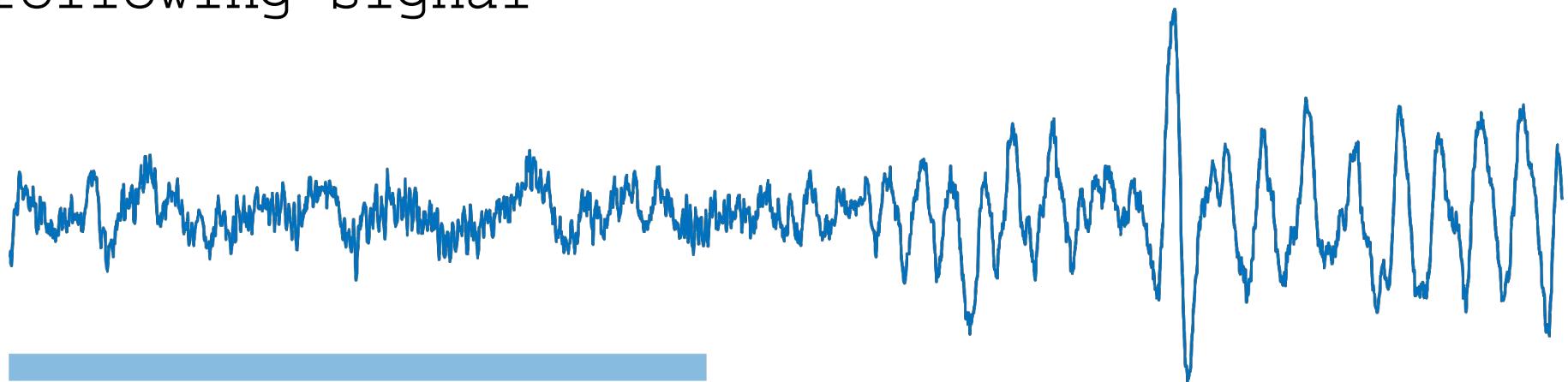
- Concepts will be illustrated using the following signal



- MEG source signal from visual cortex
- 4 seconds
- Sampling frequency: 600 Hz
-

# Example signal

- Concepts will be illustrated using the following signal



- MEG source signal from visual cortex
- 4 seconds
- Sampling frequency: 600 Hz
- Visual stimulus

# Contents

## Stationary:

- Fourier transform
- Power spectral density (Welch's method)

## Time-resolved:

- Wavelet transform
- Filtering & Hilbert transform

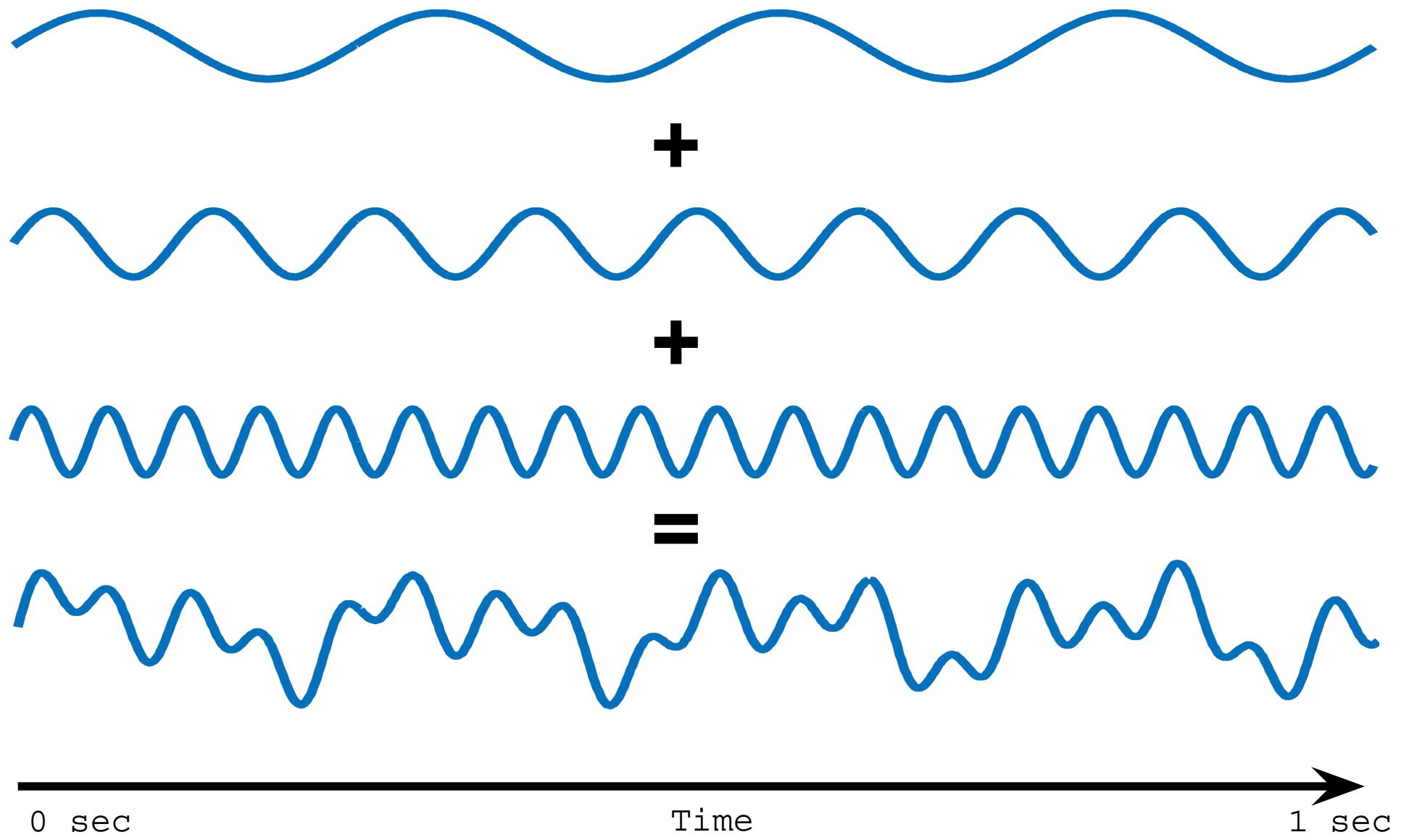
## Connectivity:

- Amplitude correlation
- Phase-locking value

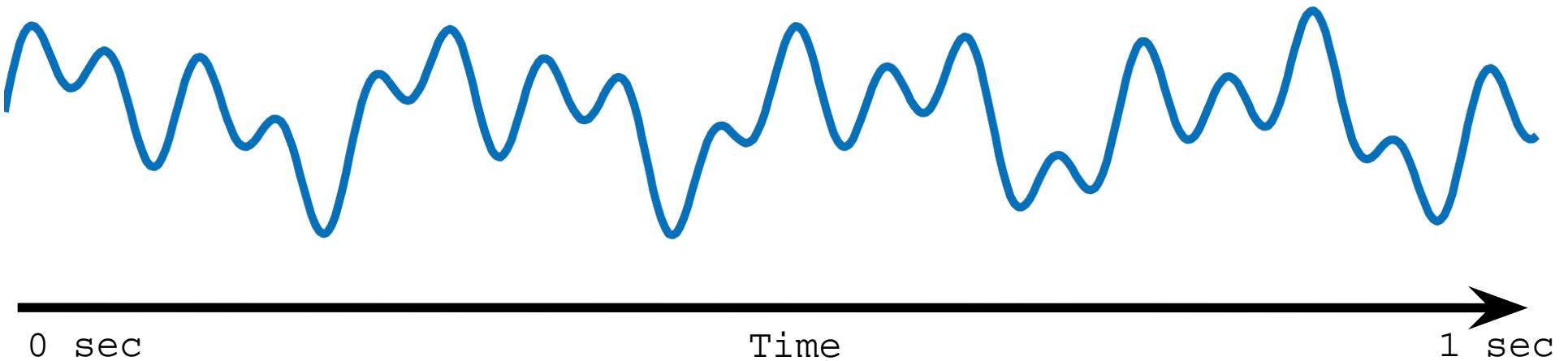
# (Fast) Fourier Transform, FFT

- Transforms a signal from time to frequency domain.
- Hugely important in many fields of science and engineering.
- Not so powerful in its raw form for estimating spectral components in neural signals
- BUT: forms the basis for many of the following methods

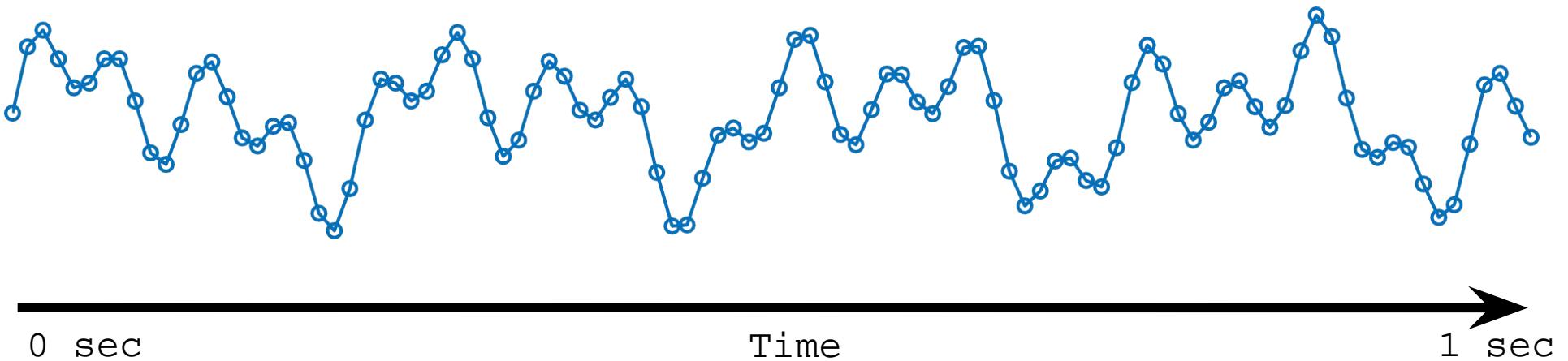
# (De- ) Composing a signal



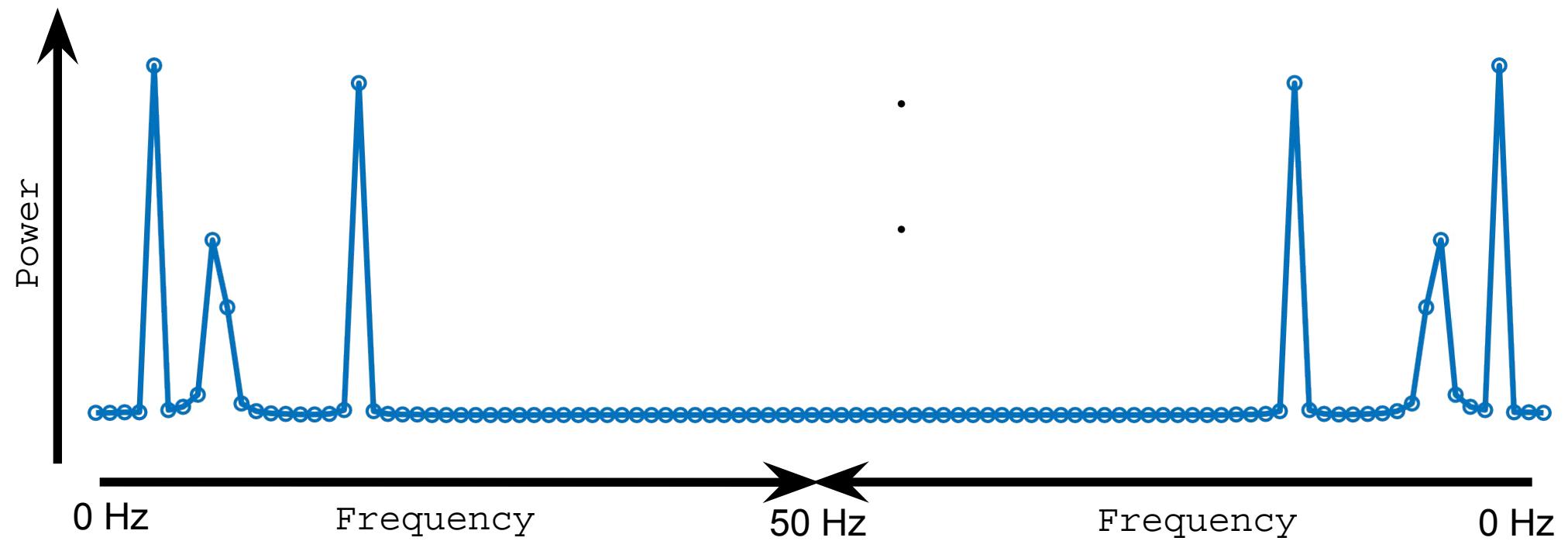
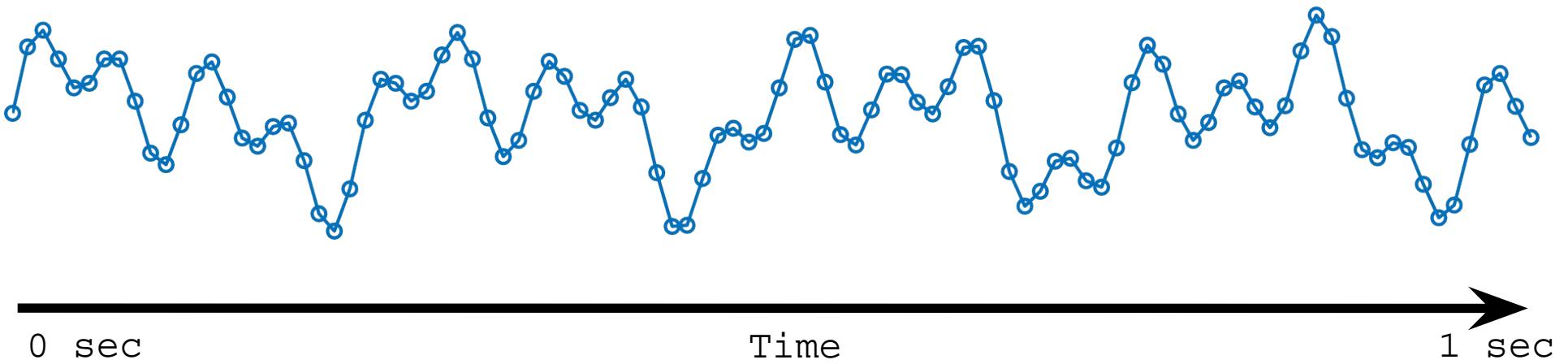
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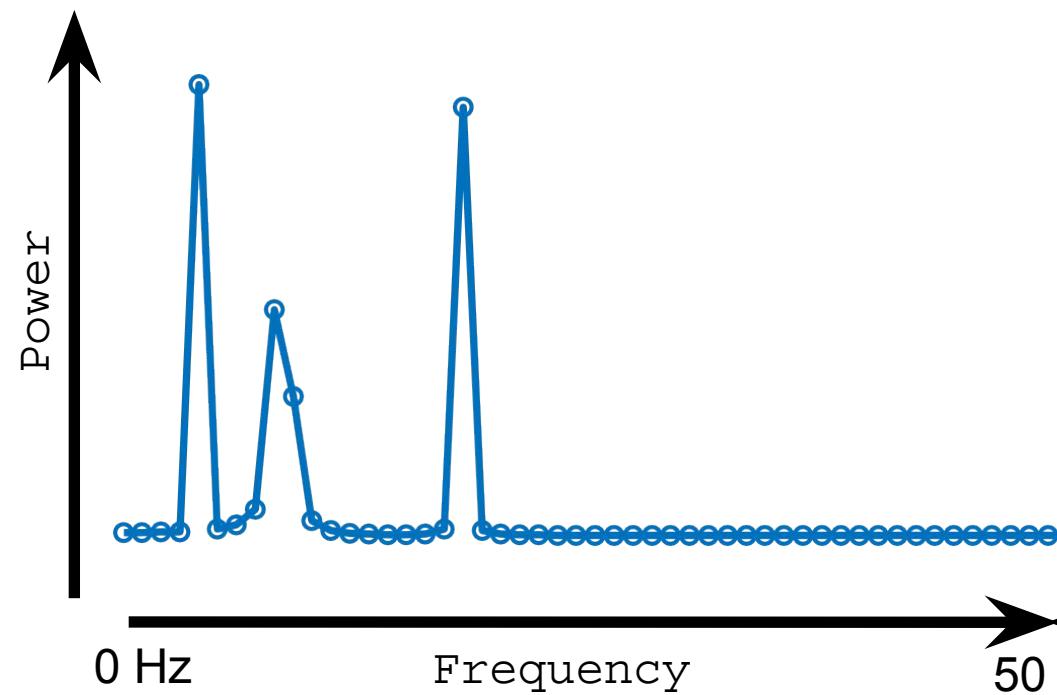
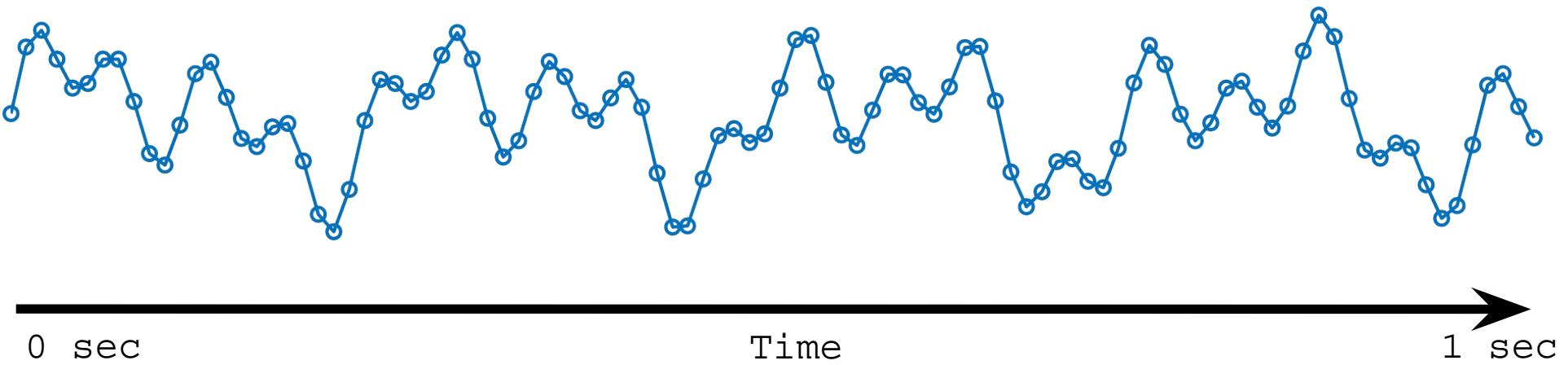
# (De-)Composing a signal



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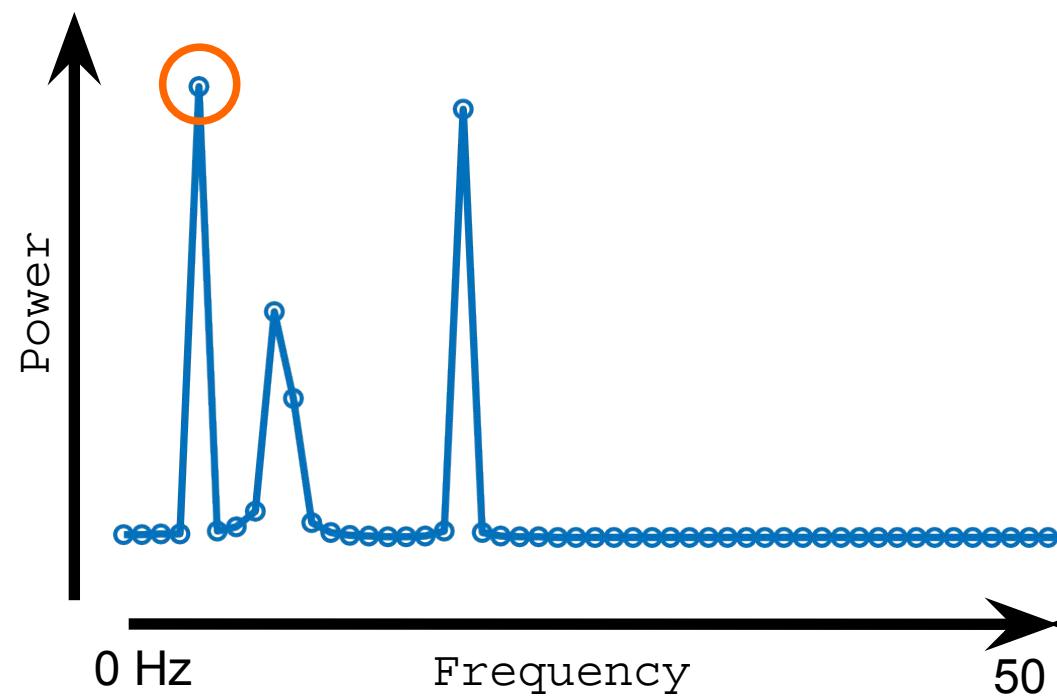
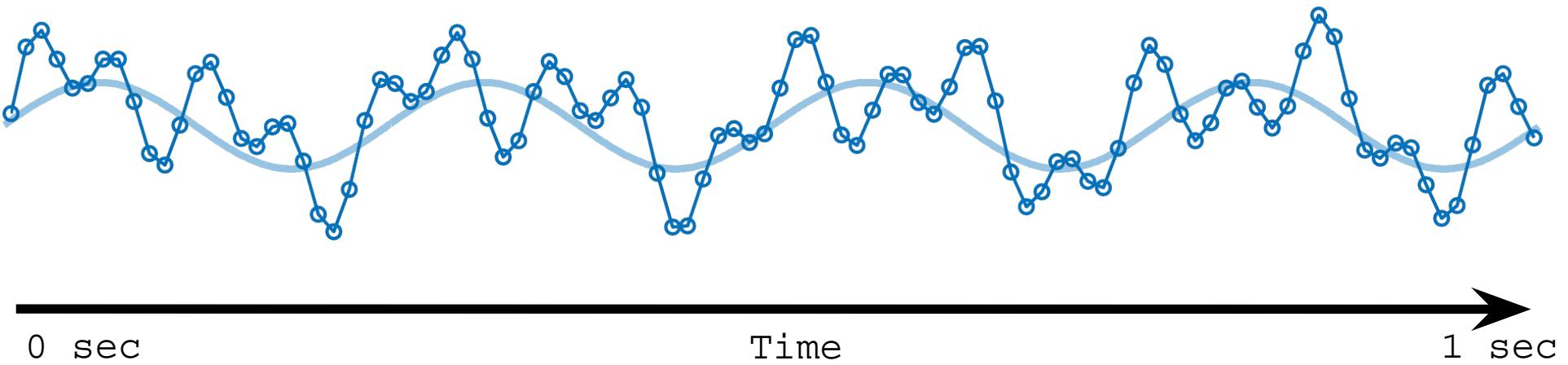
# (De-)Composing a signal



- FFT output is symmetric, second half usually removed

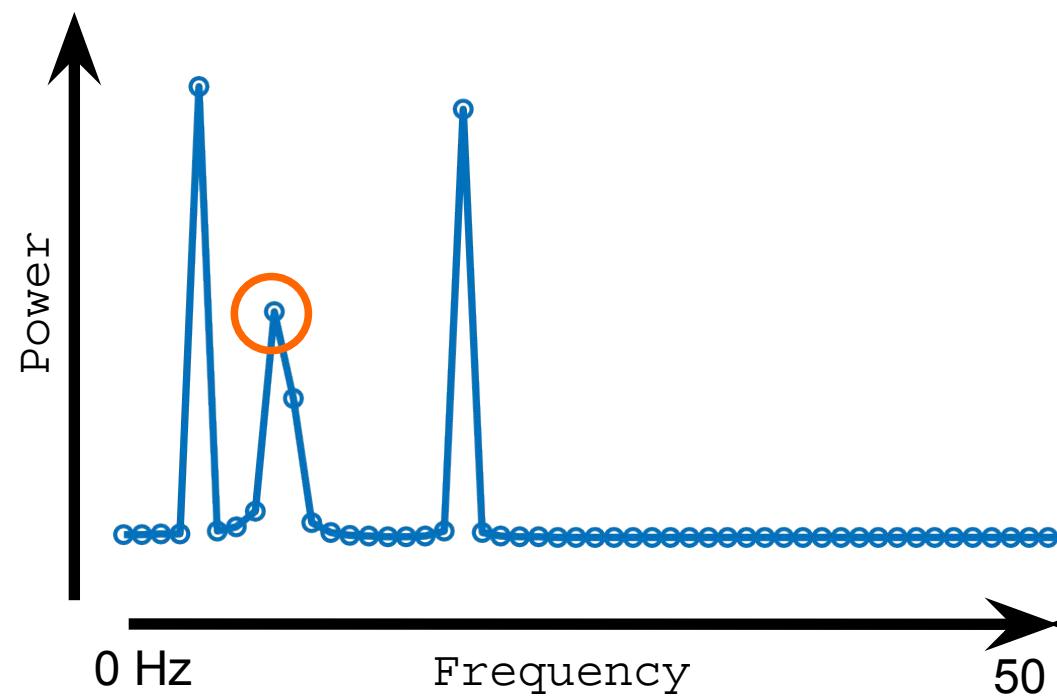
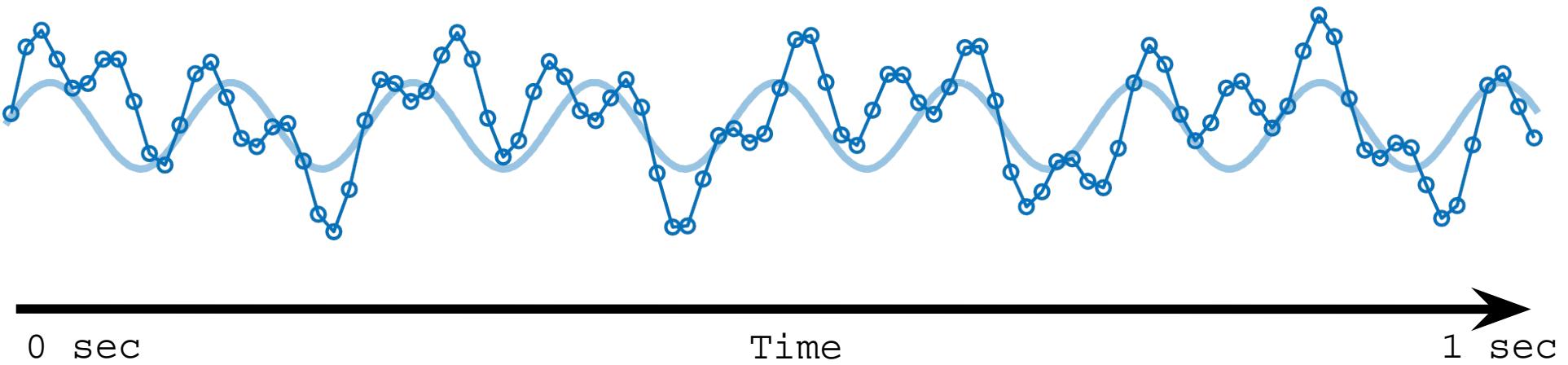
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# (De-)Composing a signal



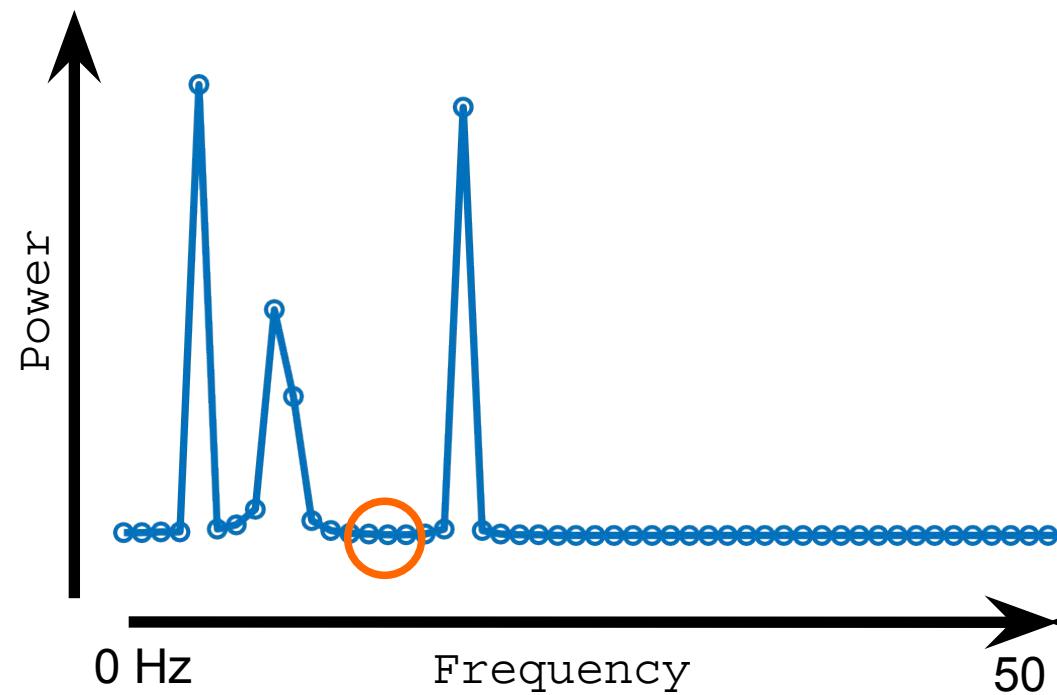
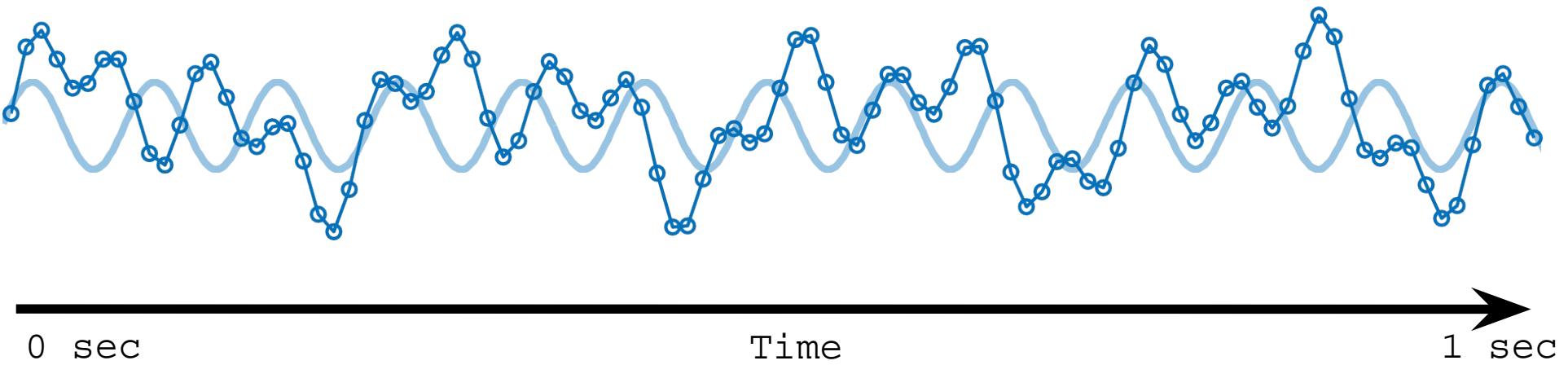
- FFT output is symmetric, second half usually removed
- Peaks in frequency domain correspond to an oscillatory component in time domain

# (De-)Composing a signal



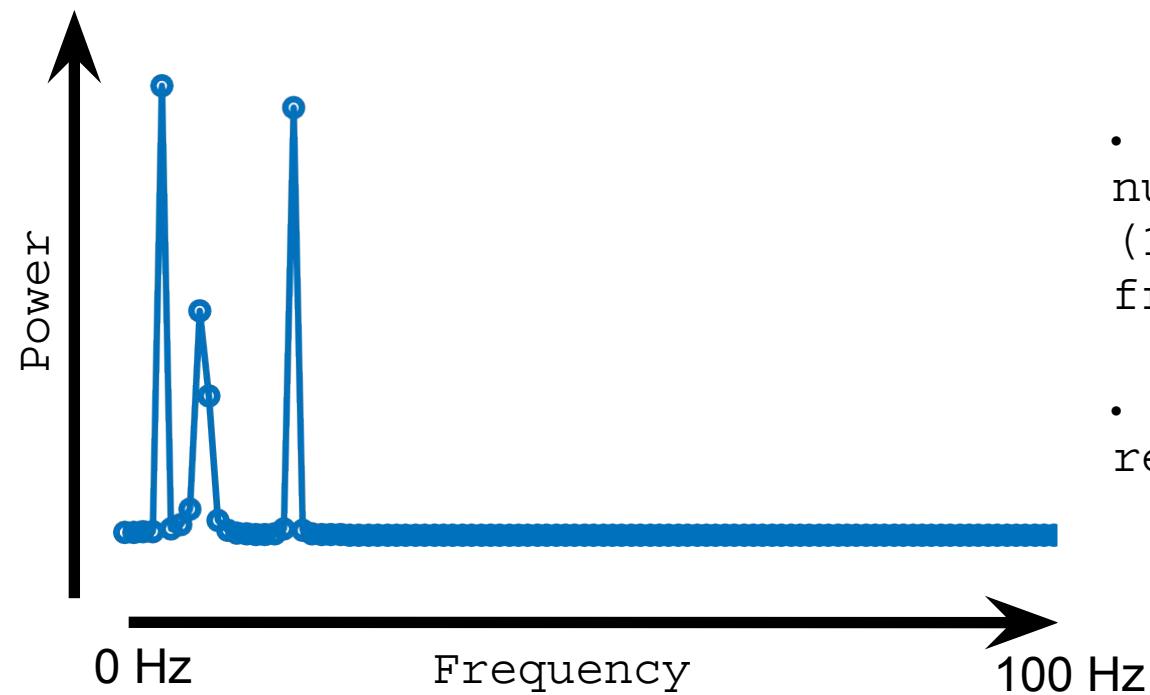
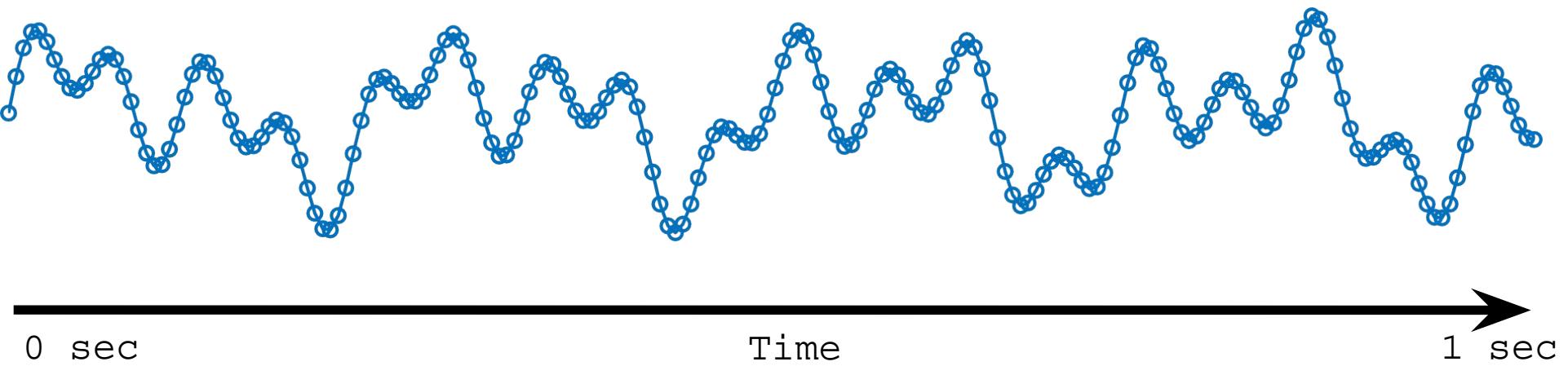
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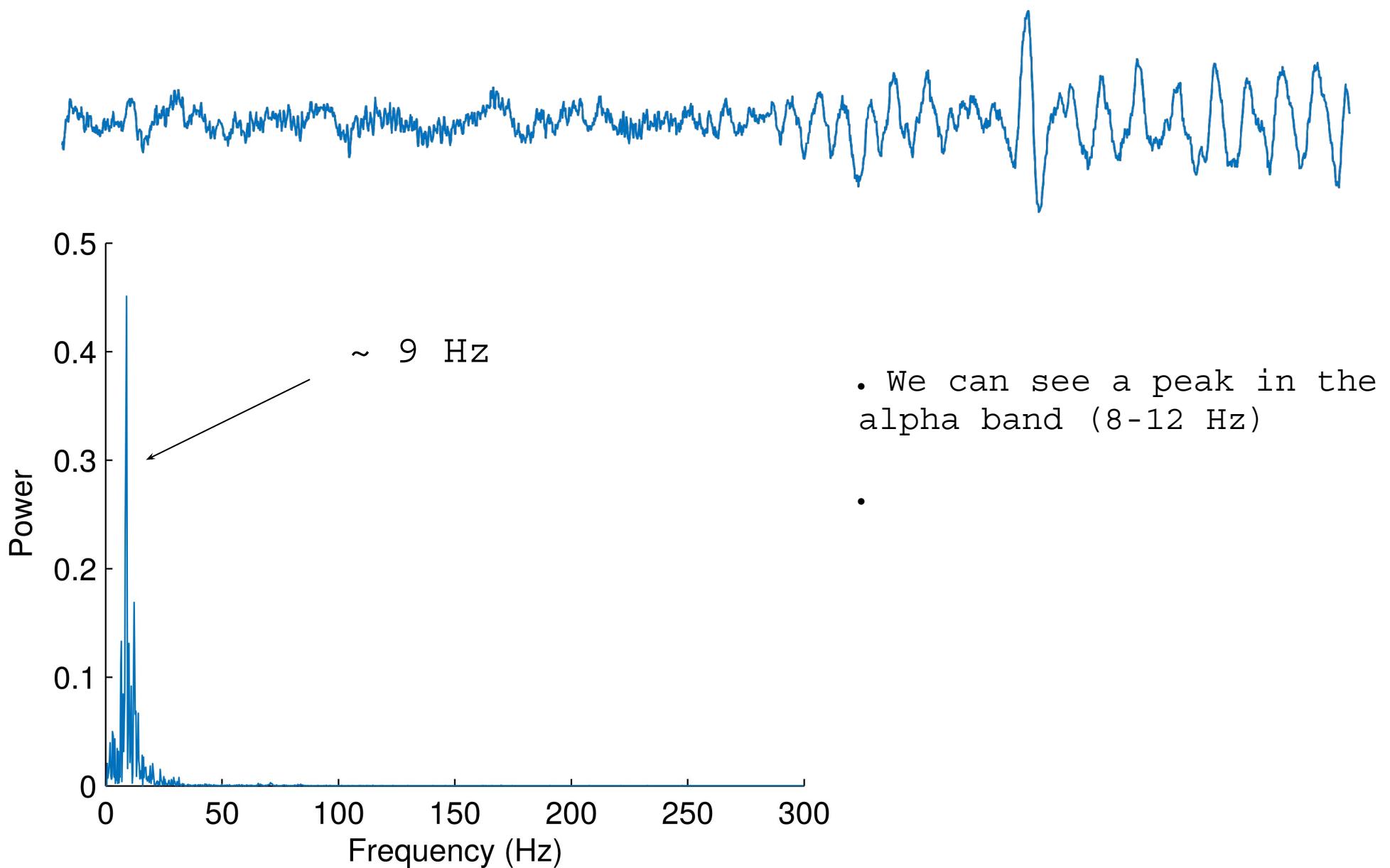
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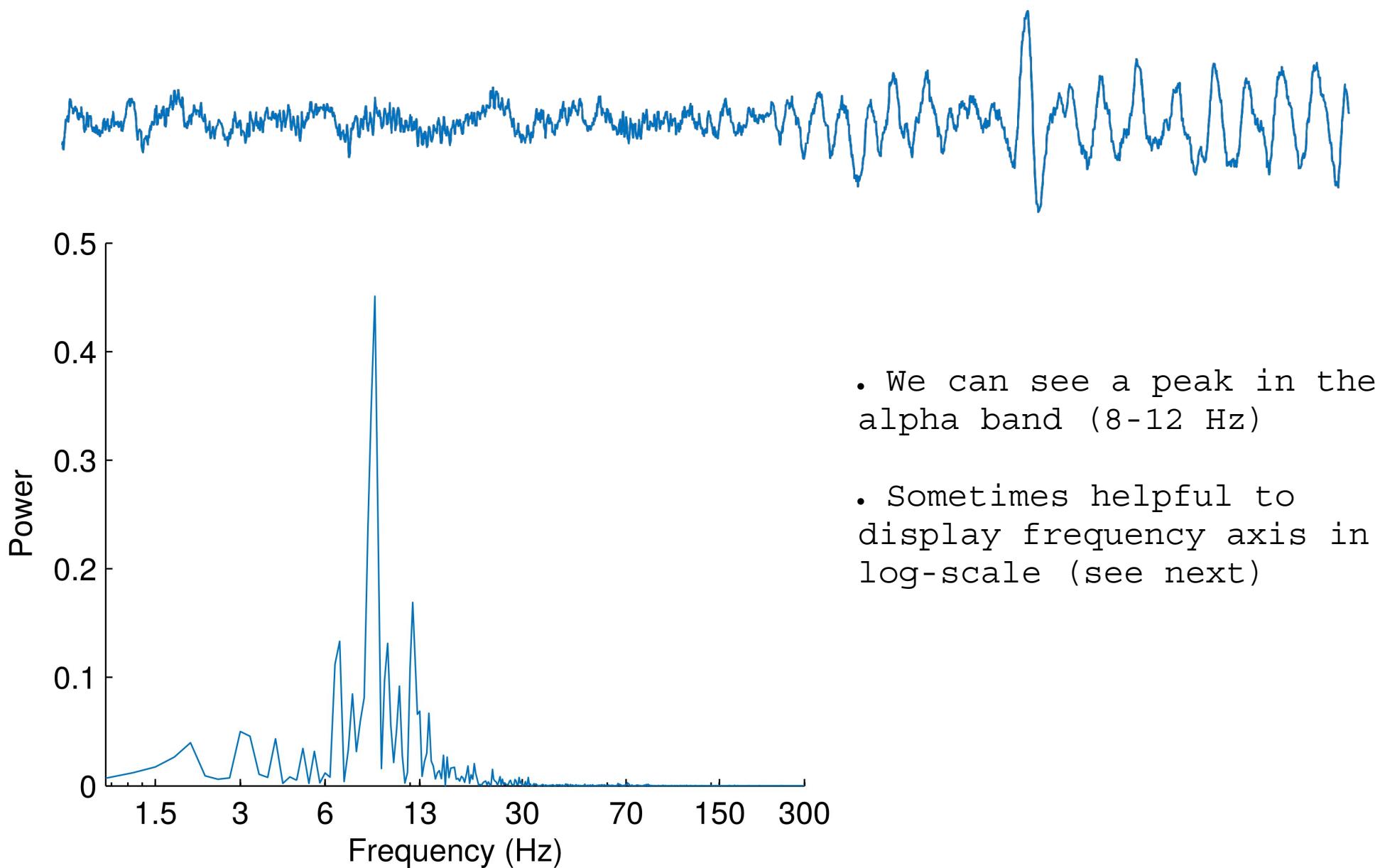


- Number of samples in time = number of samples in frequency (1/2 without 'negative frequencies')
- Higher sampling rate can resolve higher frequencies

# Fourier Transform



# Fourier Transform



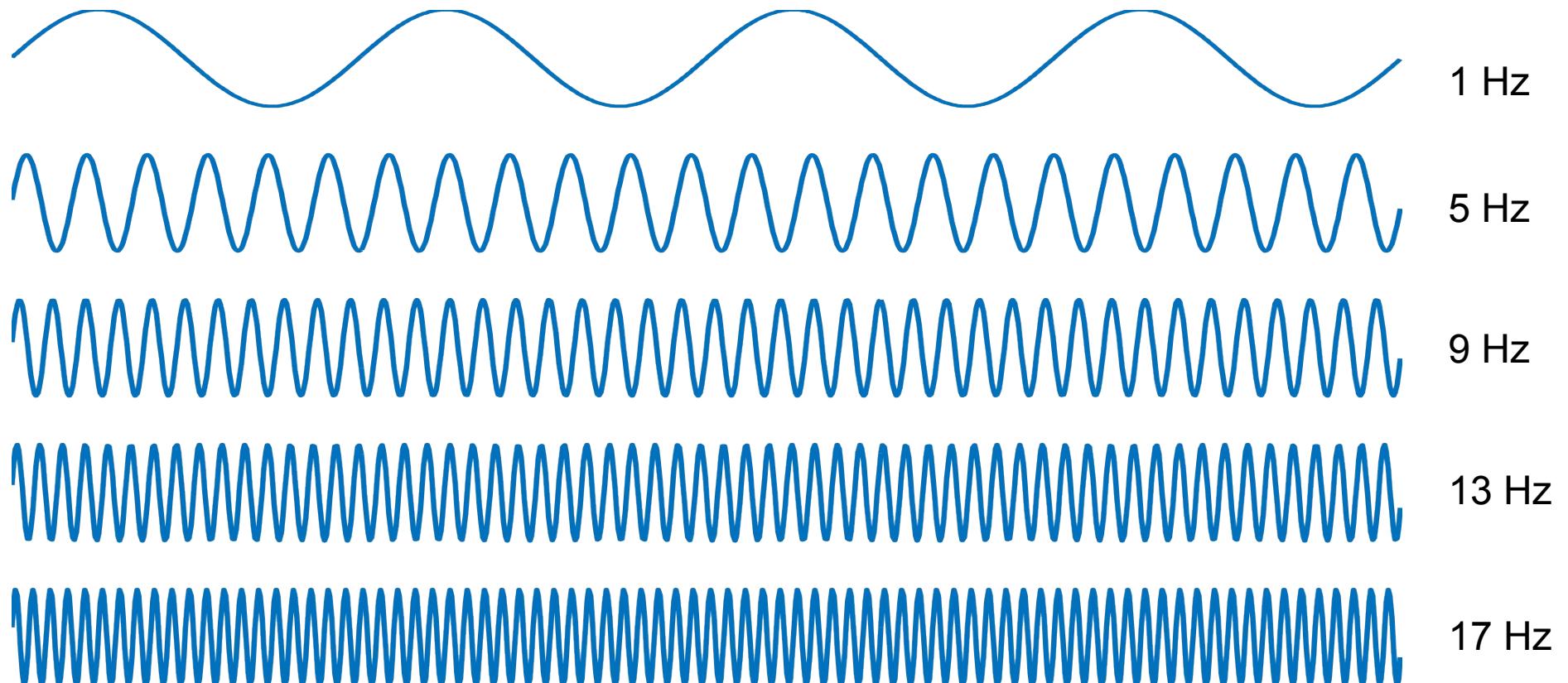
# Linear- vs. Log-scaled spectrum

Compare:

1 or 2 cycles per second

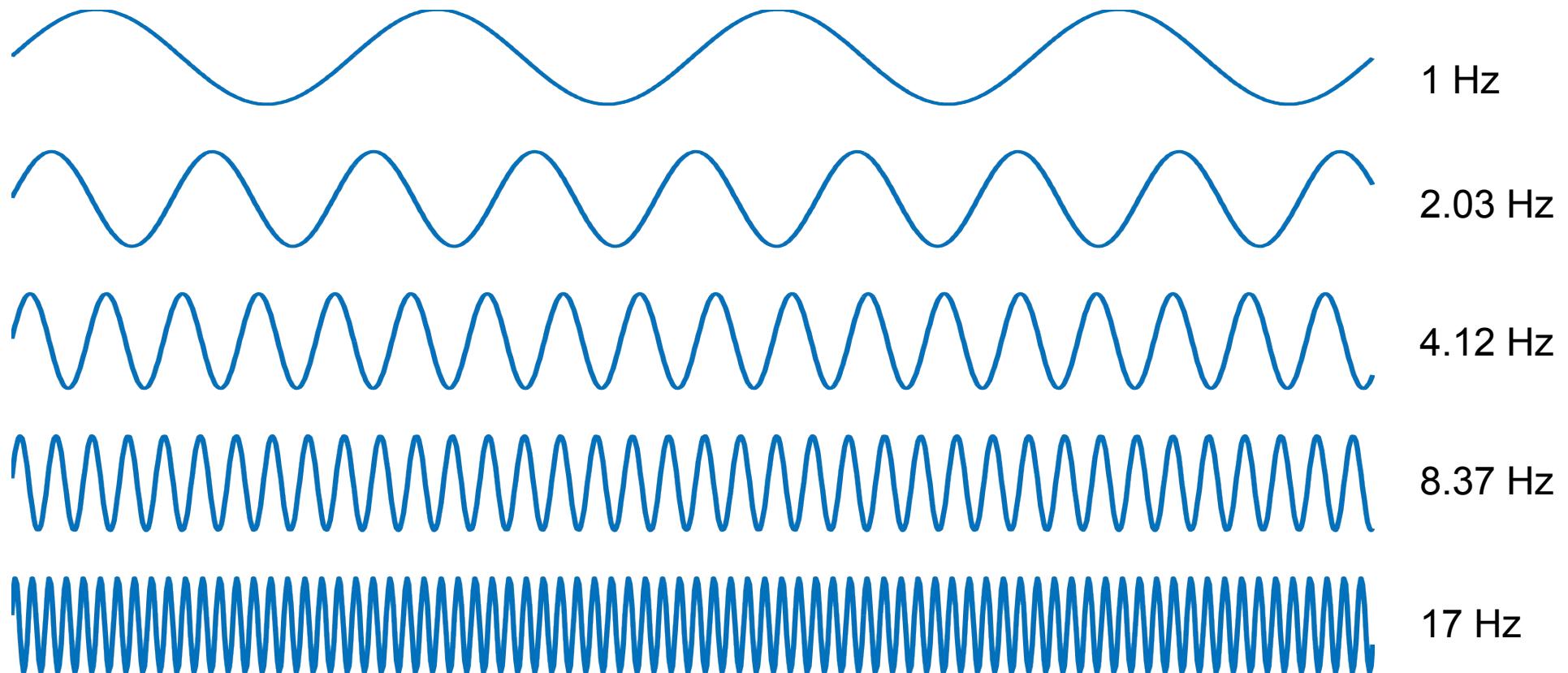
50 or 51 cycles per second

# Linear- vs. Log-scaled spectrum



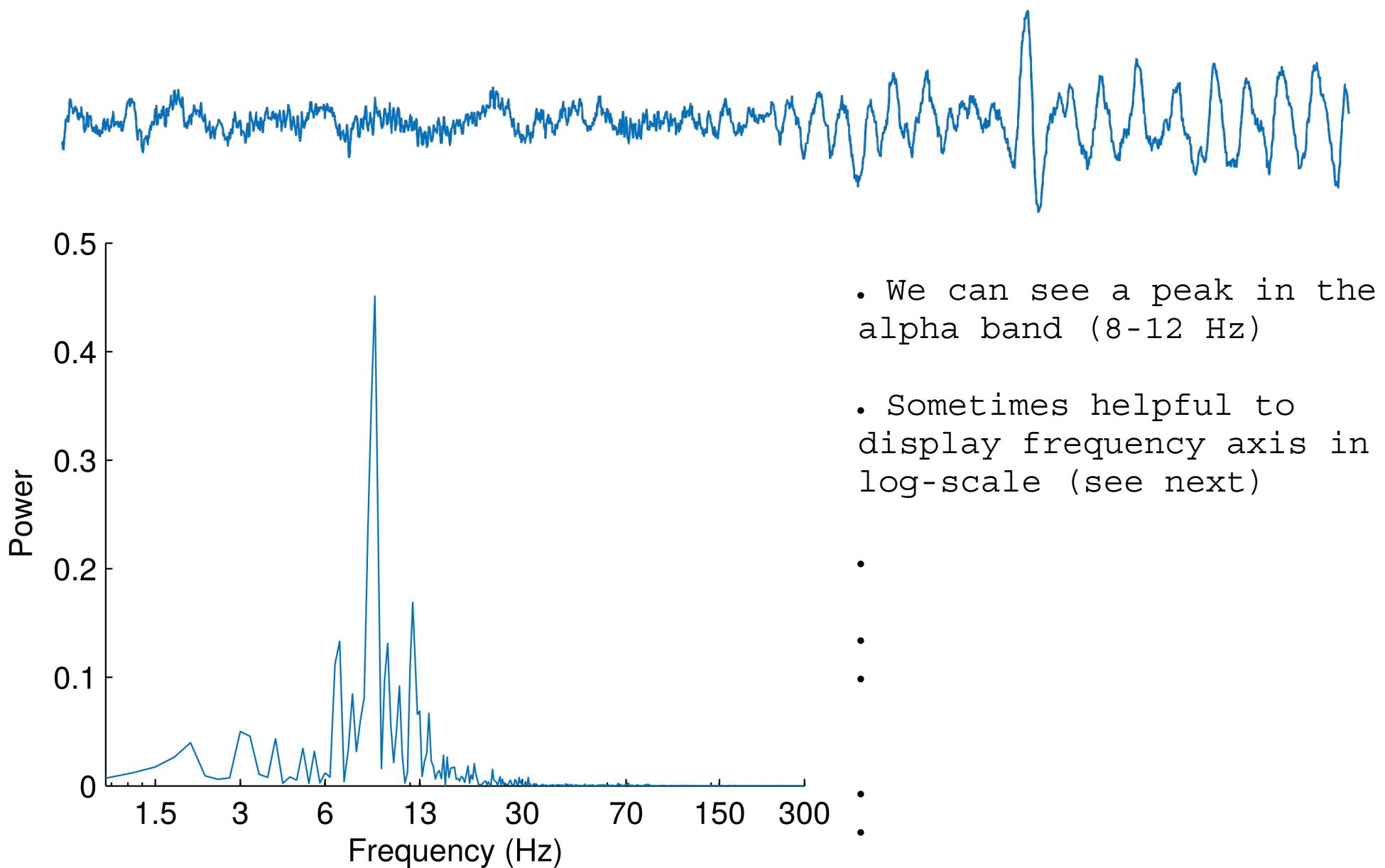
Sinusoids linearly spaced from 1 Hz to 17 Hz

# Linear- vs. Log-scaled spectrum

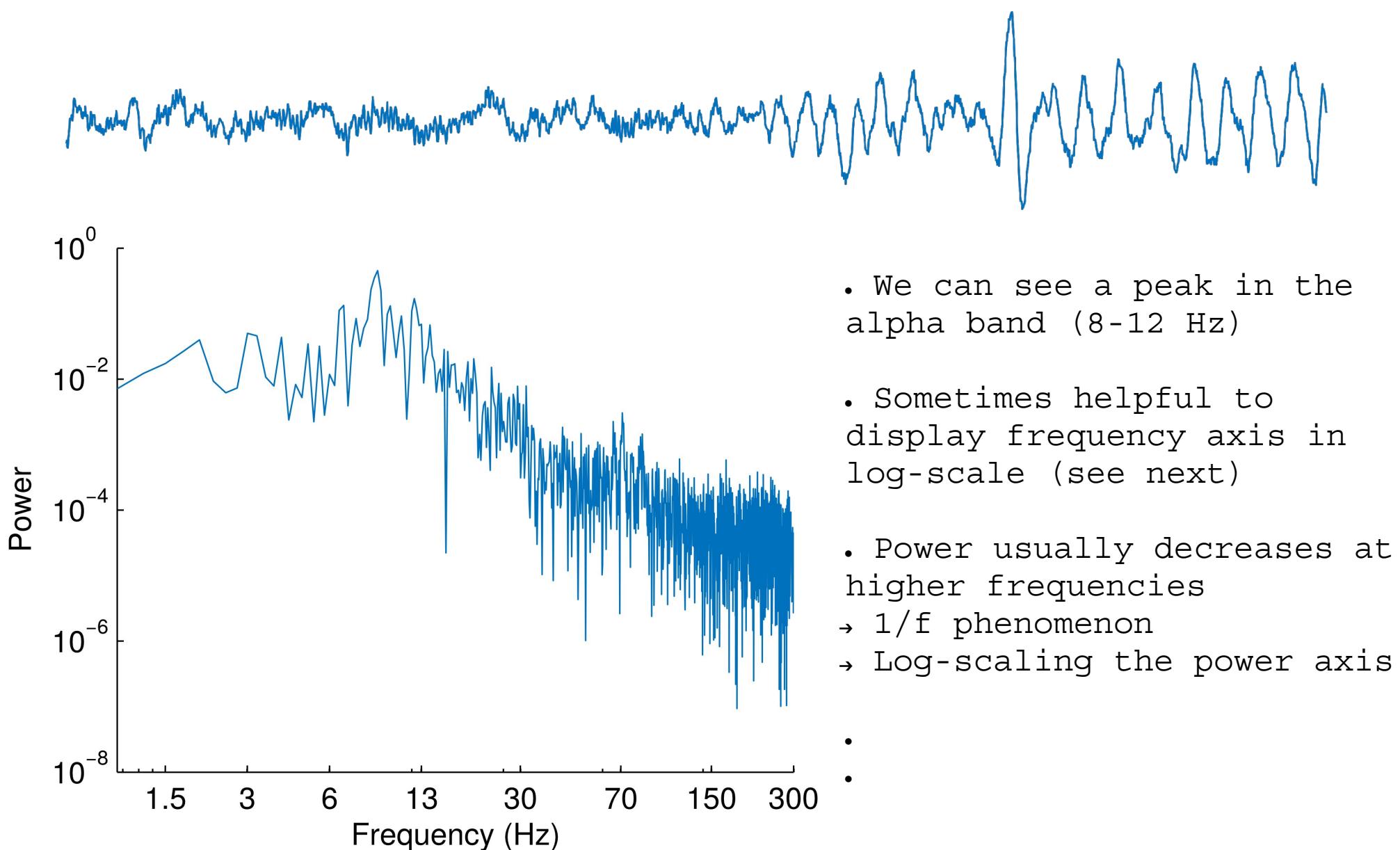


Sinusoids log spaced from 1 Hz to 17 Hz

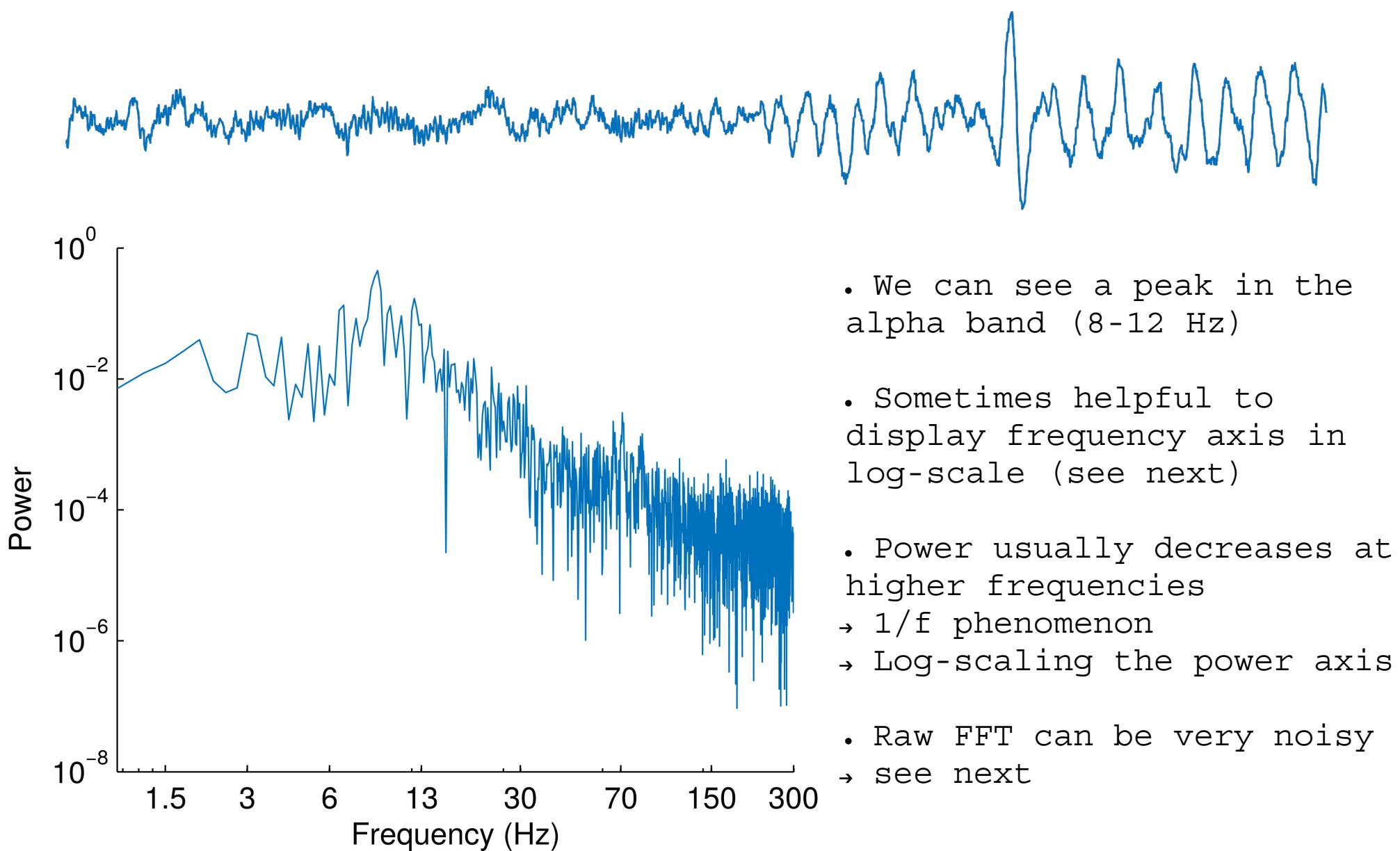
# Fourier Transform



# Fourier Transform



# Fourier Transform



# Contents

## Stationary:

- Fourier transform
- Power spectral density (Welch's method)

## Time-resolved:

- Wavelet transform
- Filtering & Hilbert transform

## Connectivity:

- Amplitude correlation
- Phase-locking value

# Power spectral density



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# Power spectral density



# Power spectral density



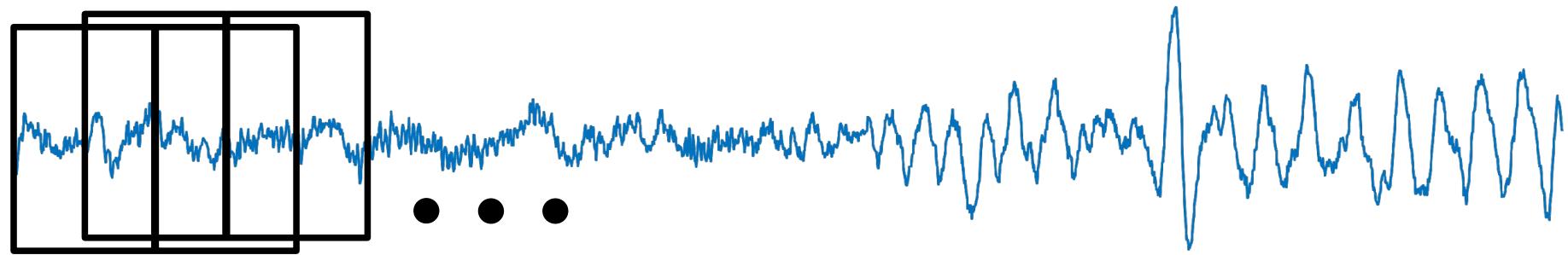
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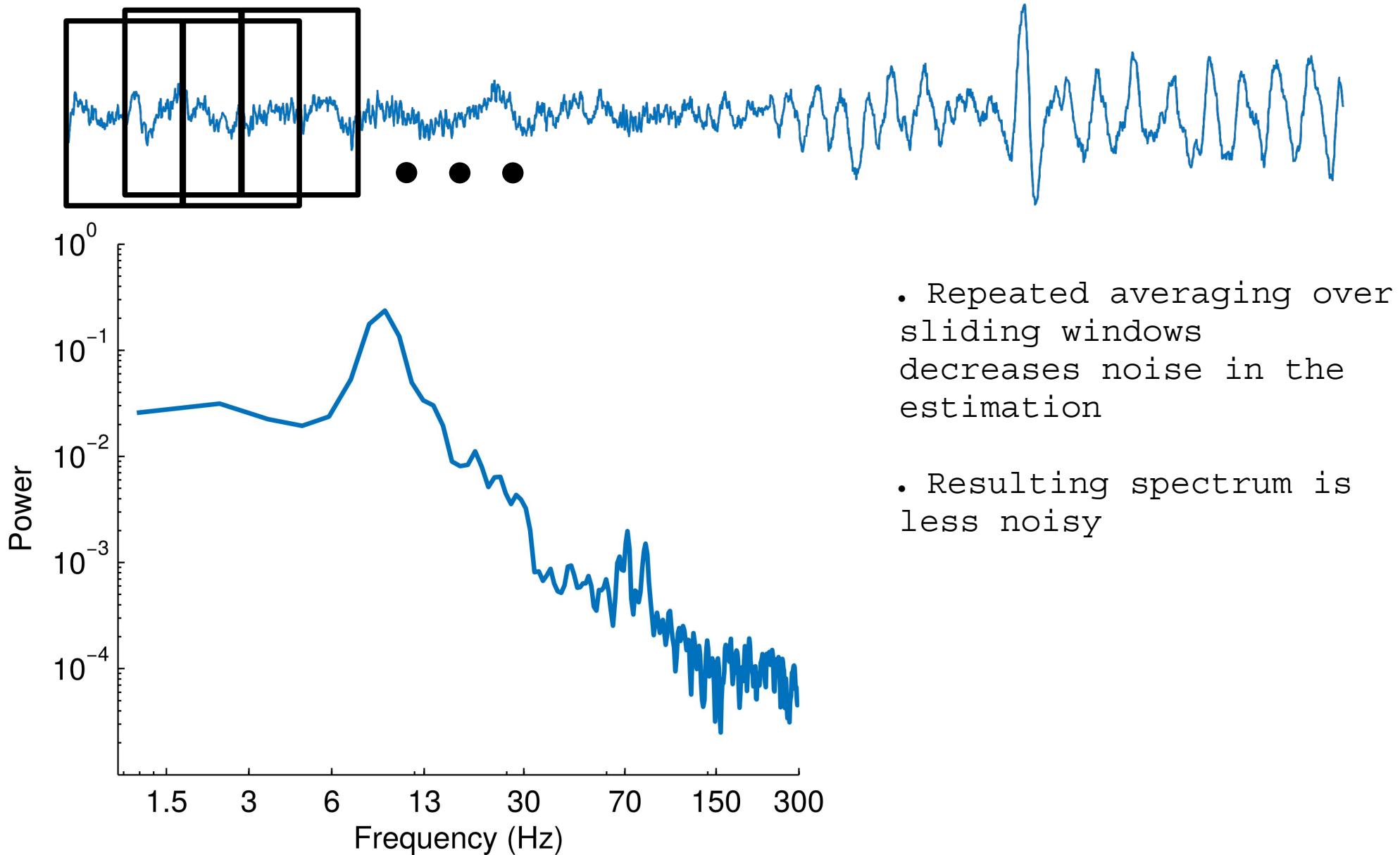
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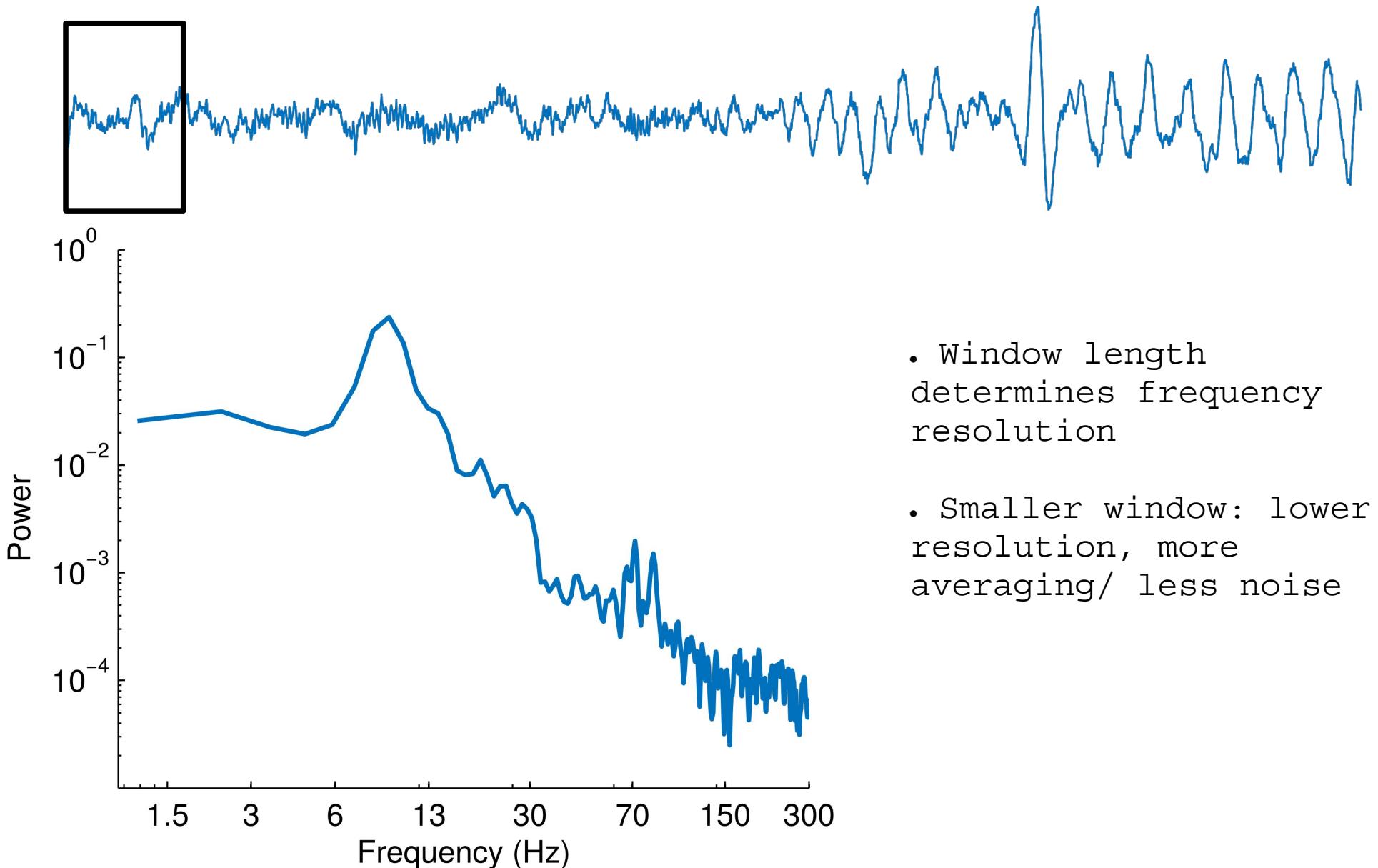
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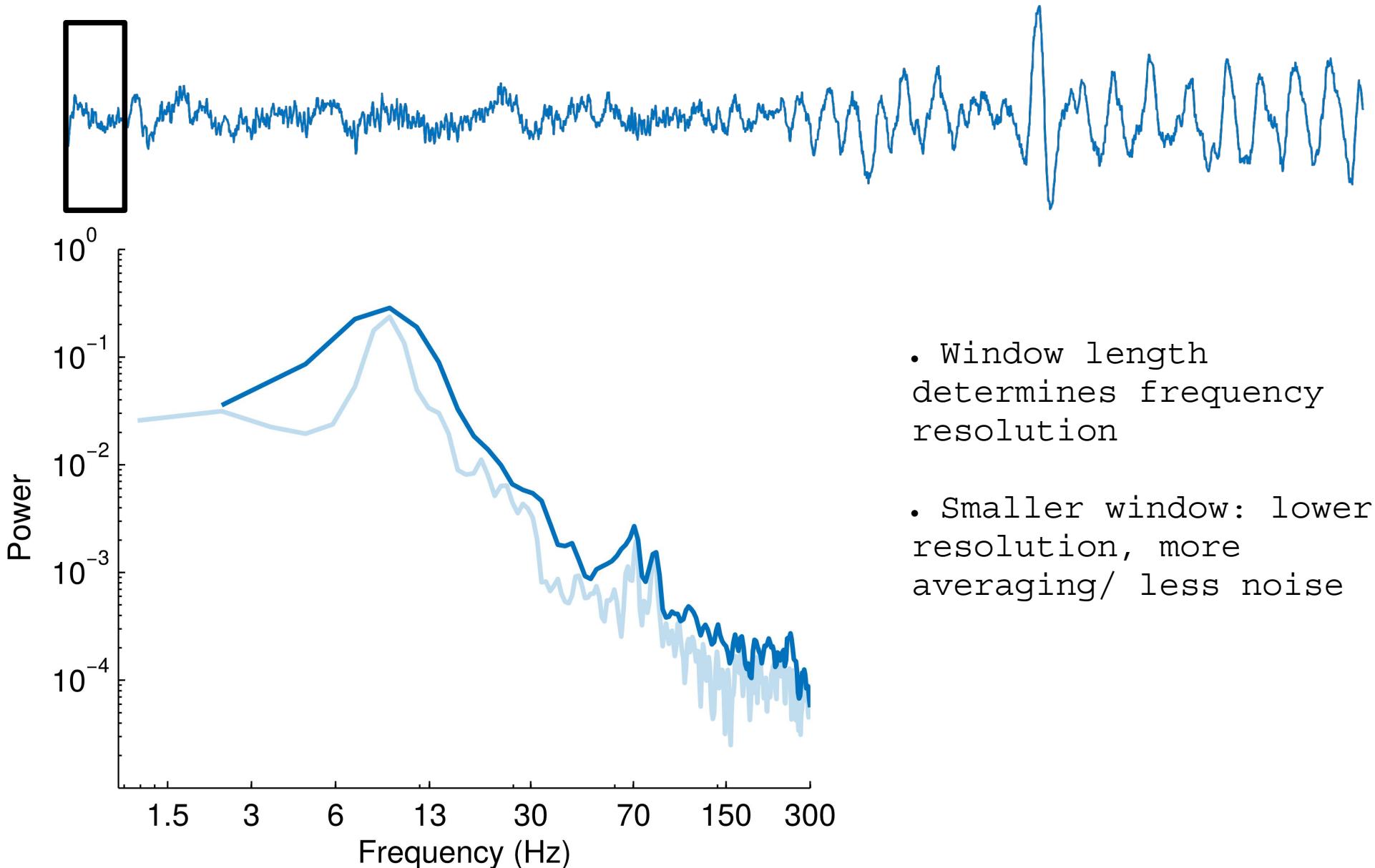
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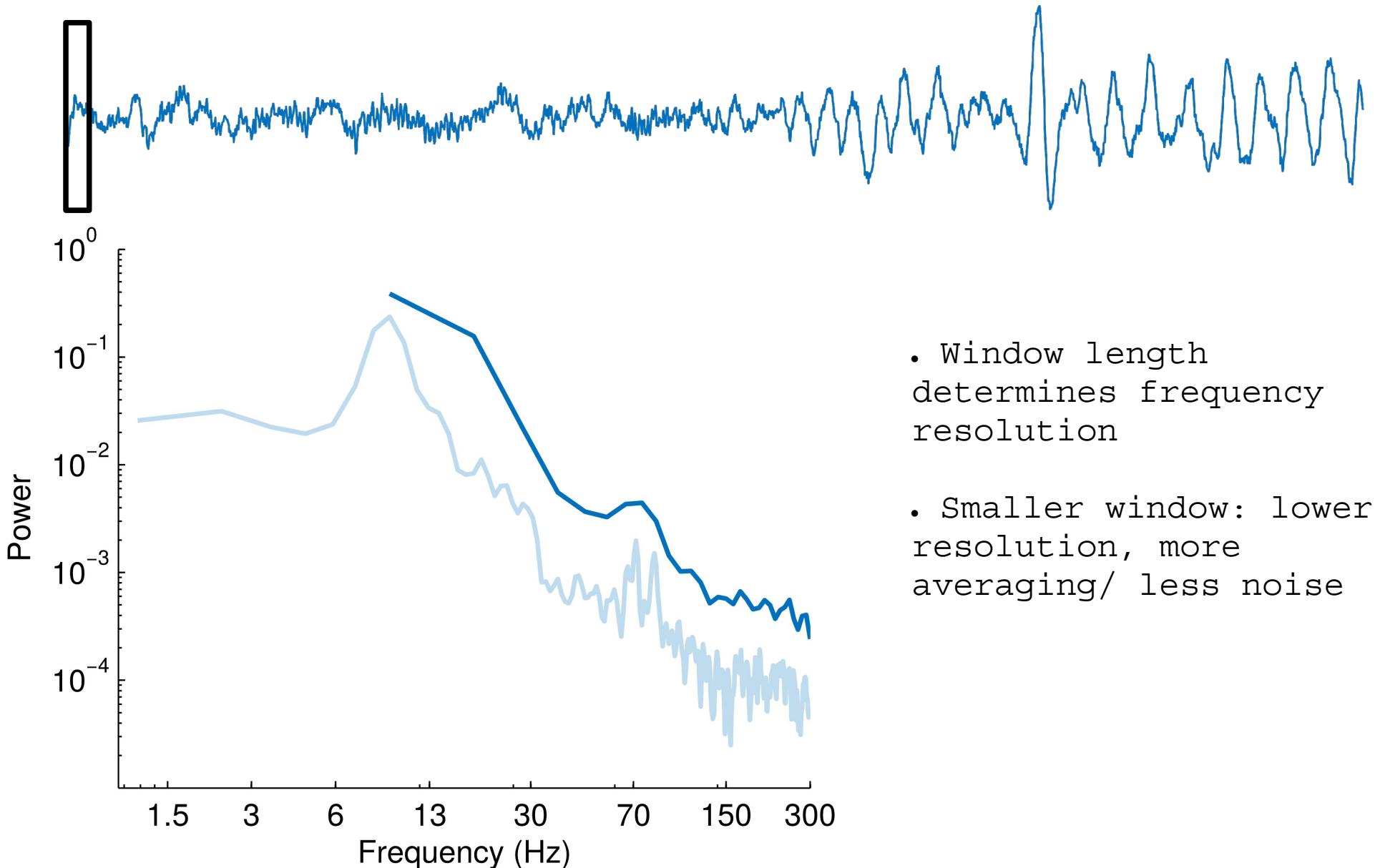
# PSD: effect of window size



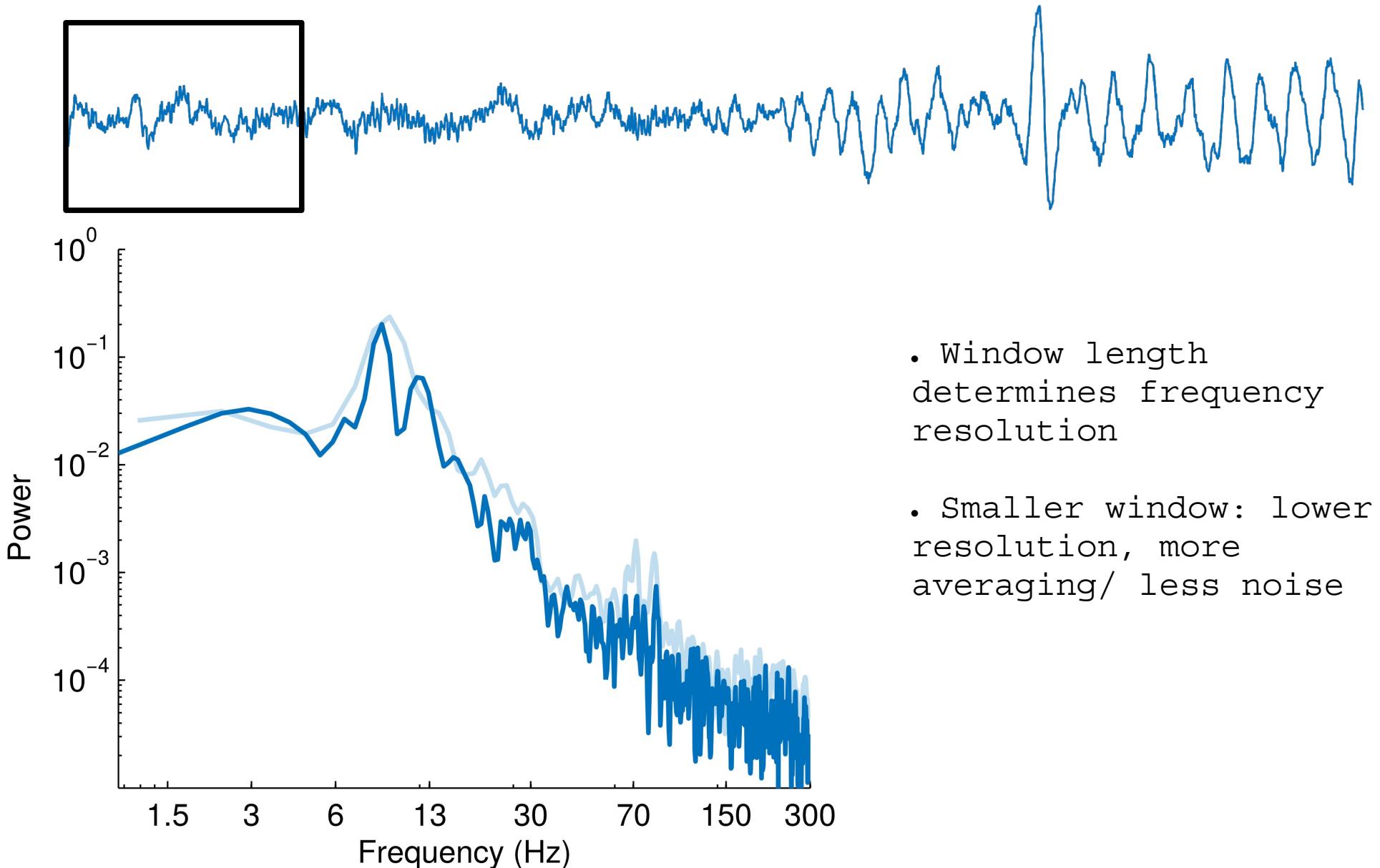
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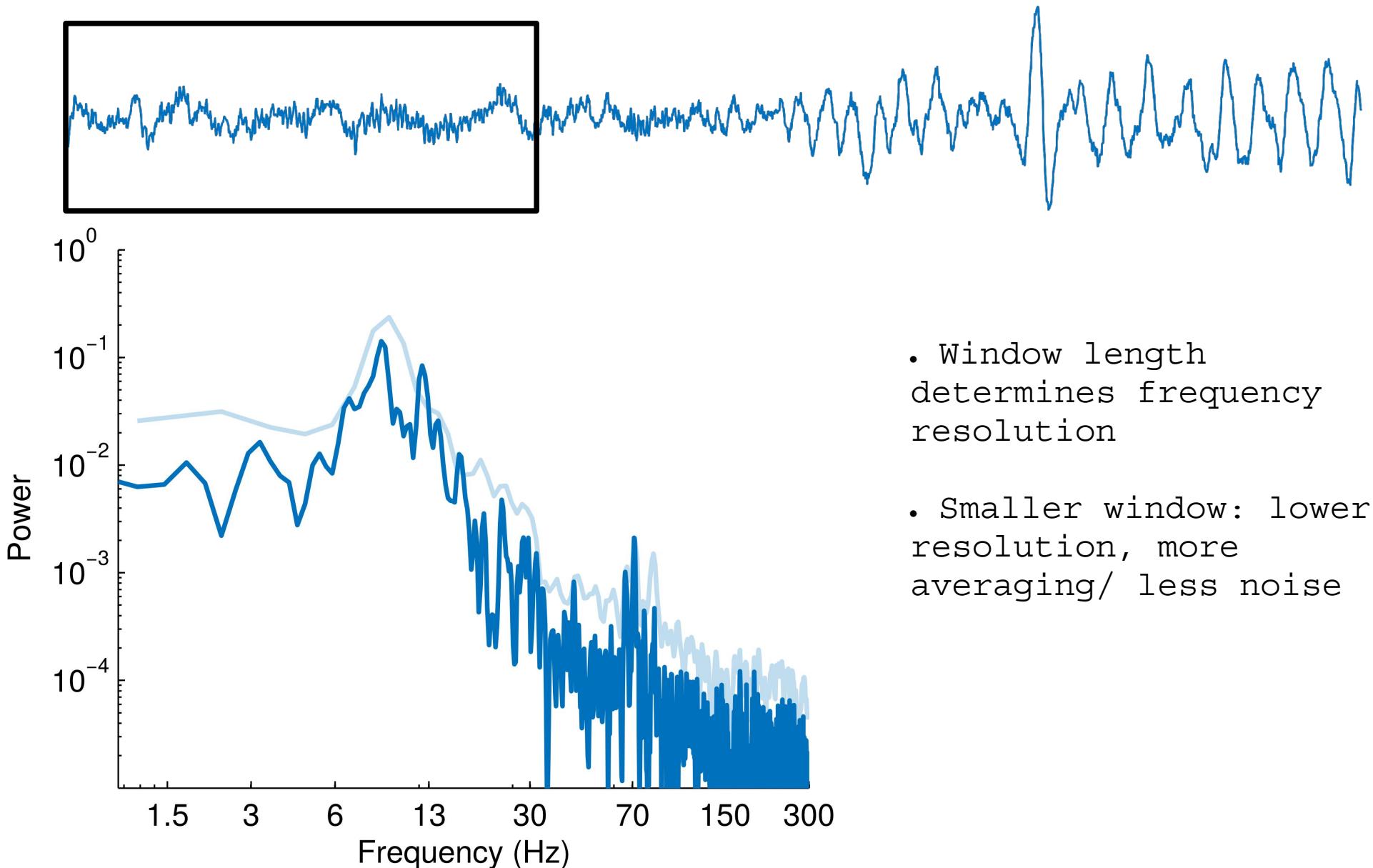
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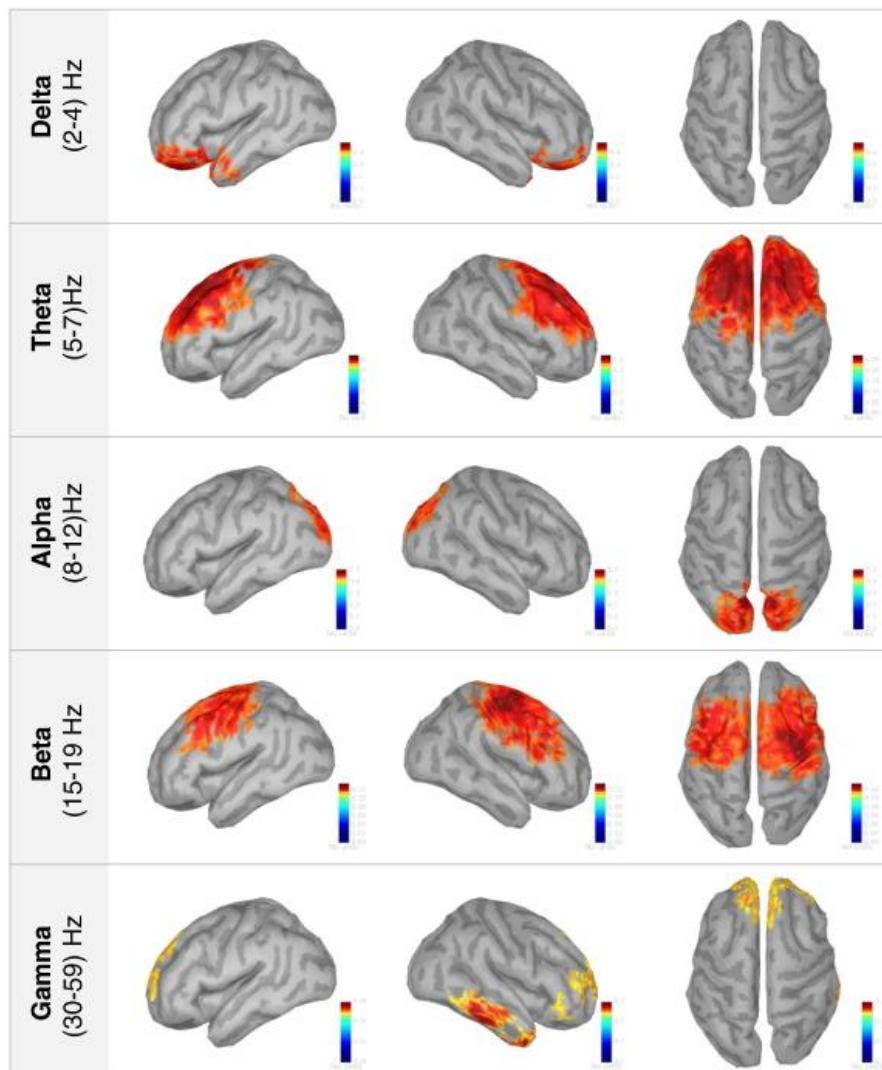
# PSD: effect of window size



# PSD: effect of window size



# PSD: application



- Spontaneous rhythms during rest
- Shown is the proportion of power in different frequency bands (MEG source imaged)

# Contents

## Stationary:

- Fourier transform
- Power spectral density (Welch's method)

## Time-resolved:

- **Wavelet transform**
- Filtering & Hilbert transform

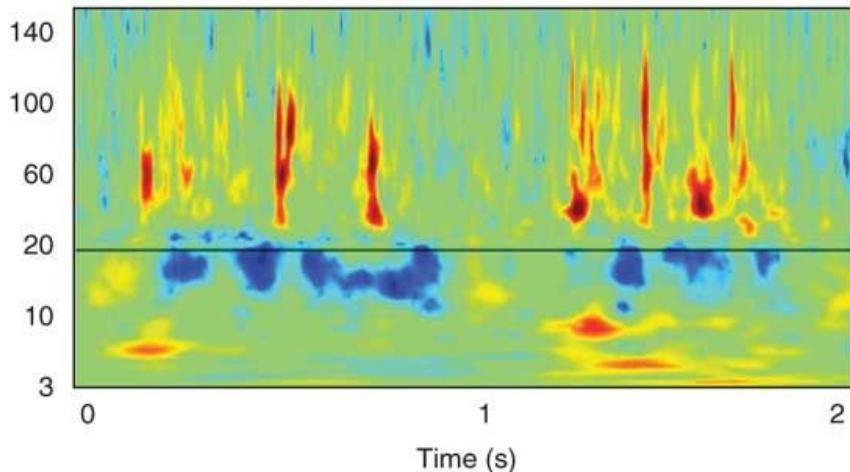
## Connectivity:

- Amplitude correlation
- Phase-locking value

# Time-frequency analysis

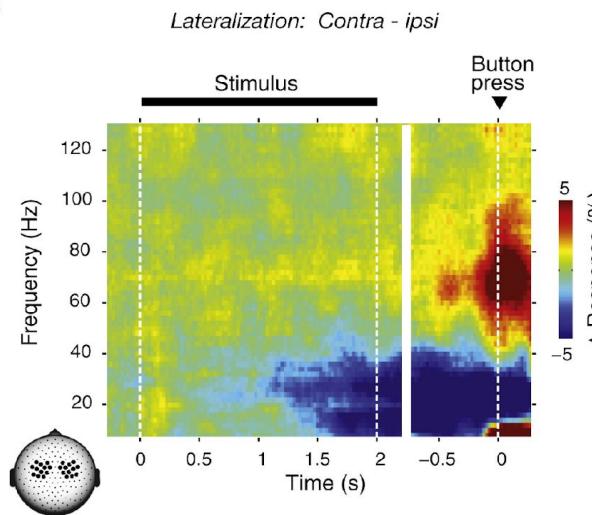
- Analysis of transient oscillatory activity
- Examples: auditory cortex / motor cortex
- Event-related synchronization vs. desynchronization

a



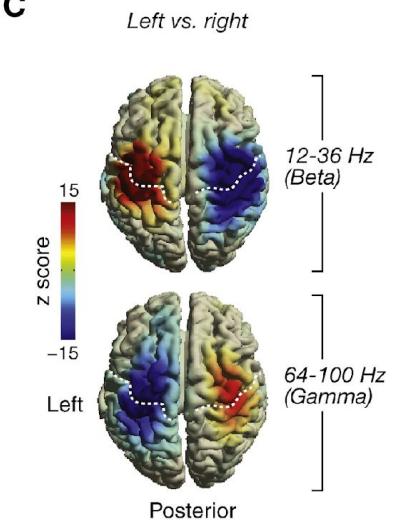
Spoken sentence, auditory cortex responses (Fontolan, Morillon et al., 2014)

b

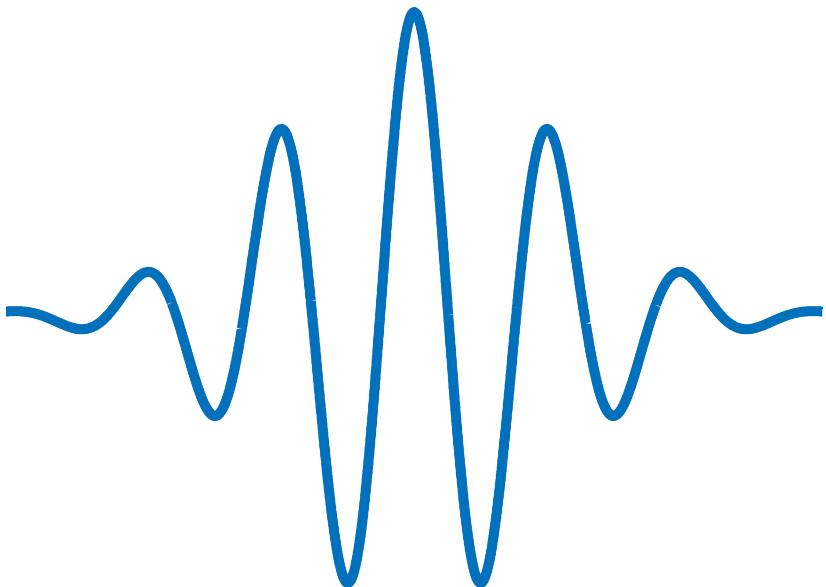


Build-up of choice predictive activity in motor cortex (Donner et al., 2009)

c



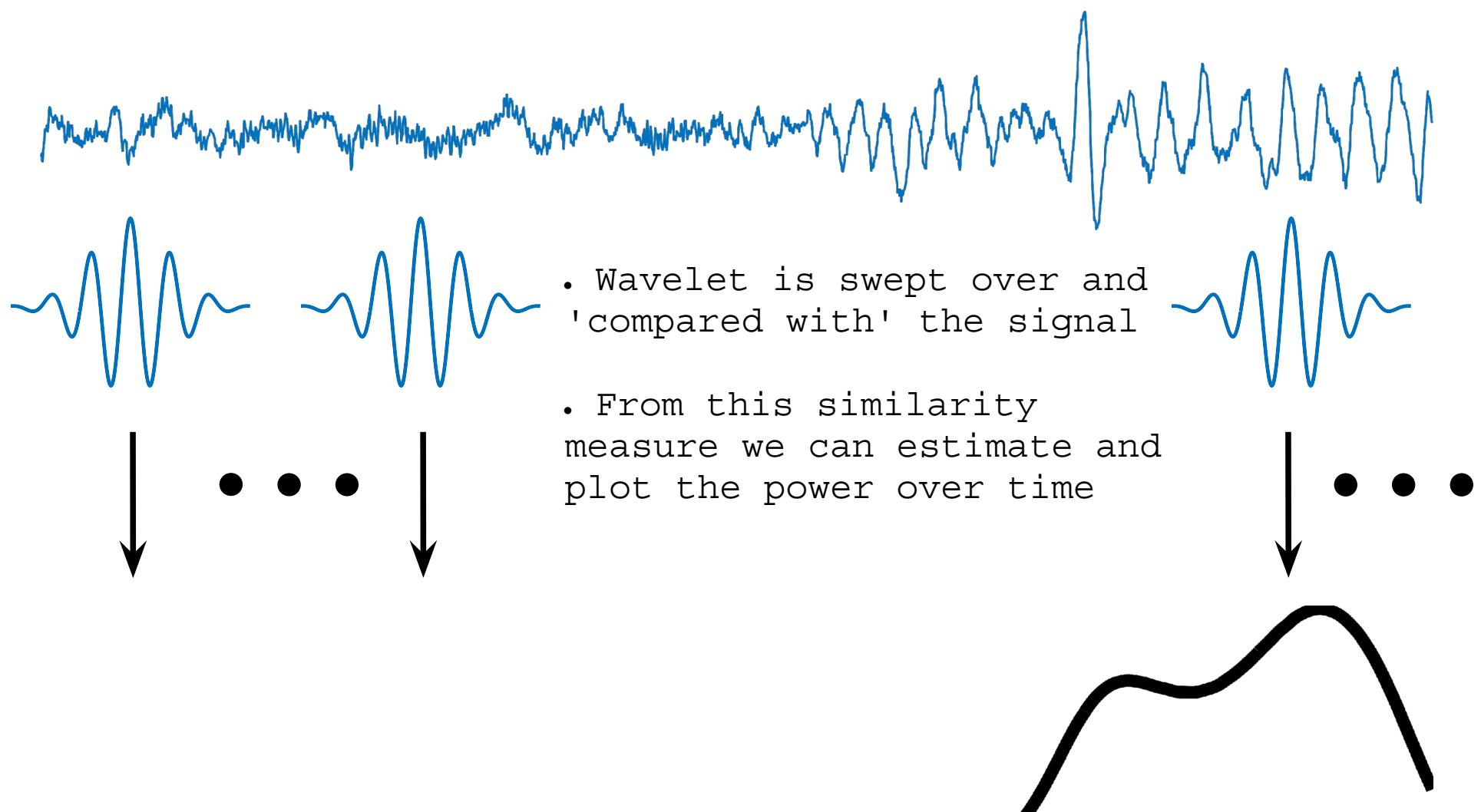
# Wavelet transform



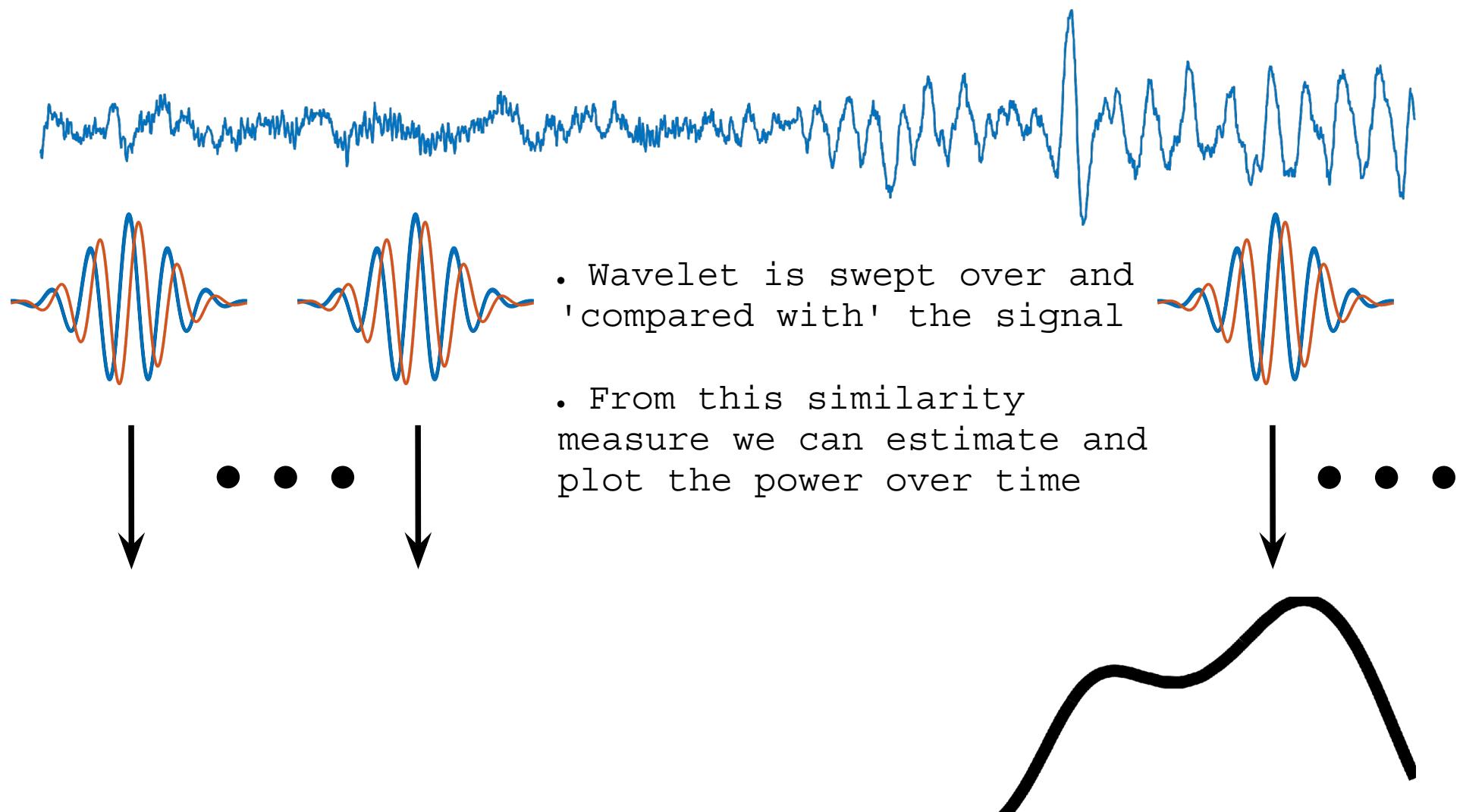
Morlet wavelet (most popular in neuroscience) :

- Sine wave, power is modulated in time with a gaussian centered at time zero
- Serves as a 'template'

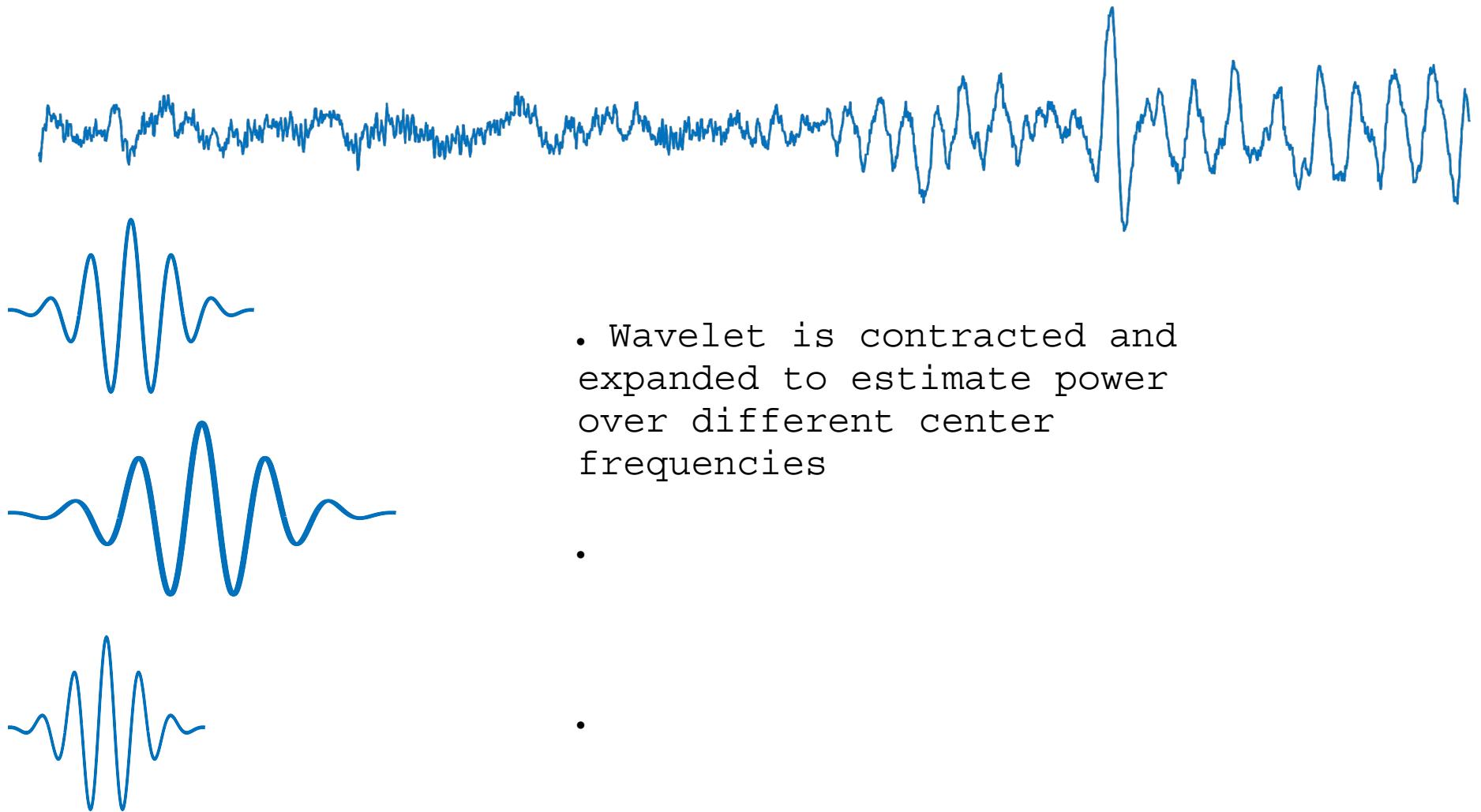
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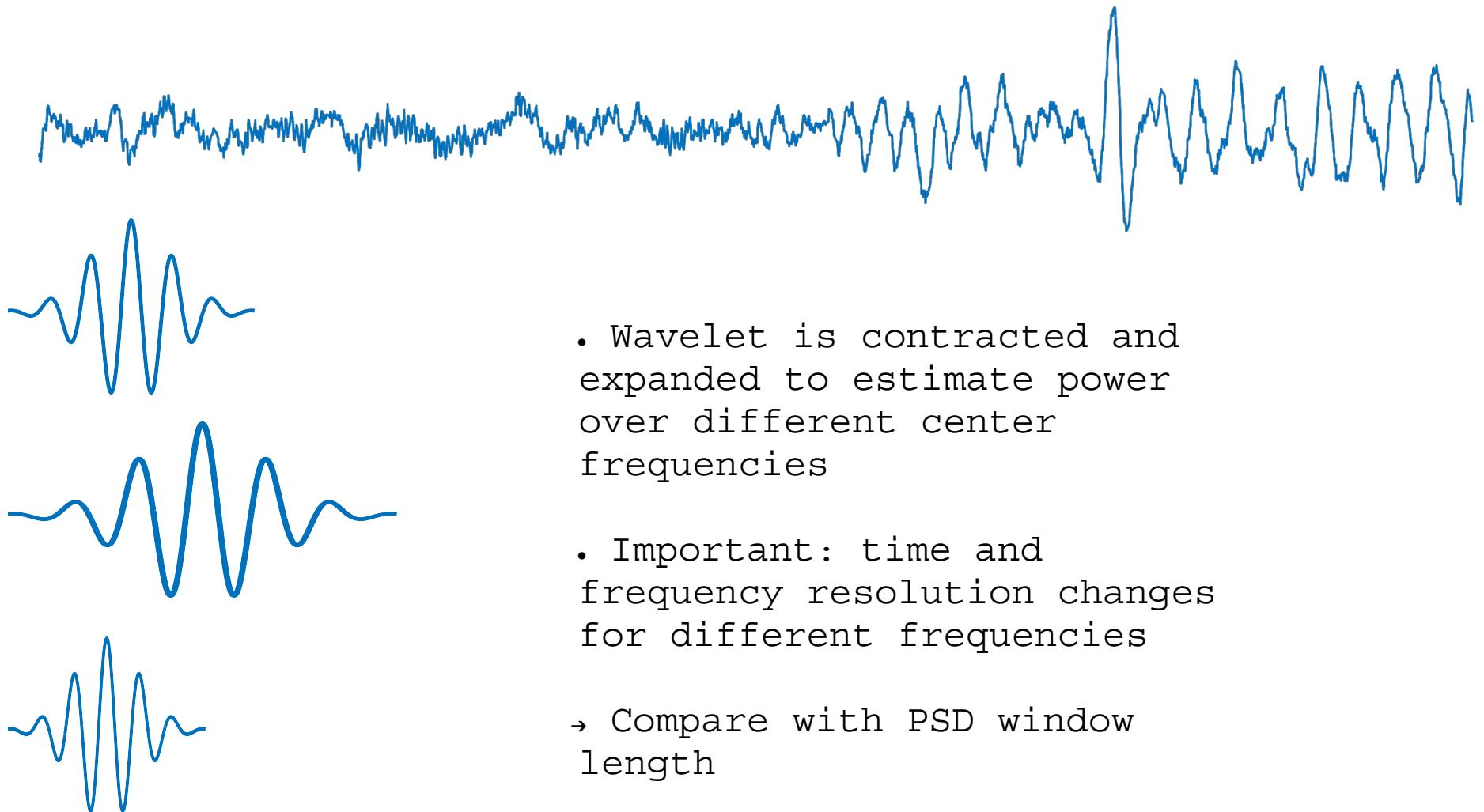
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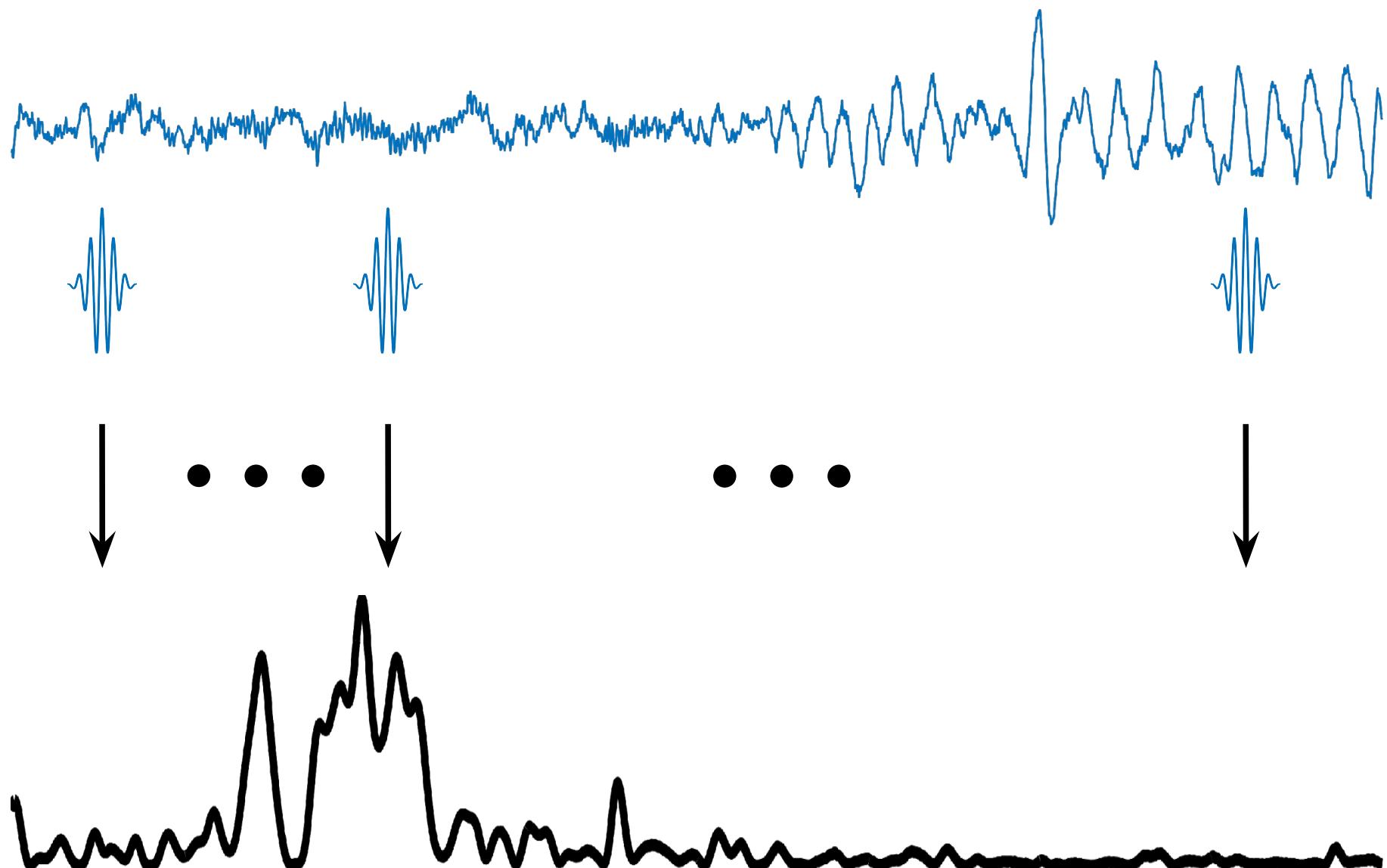
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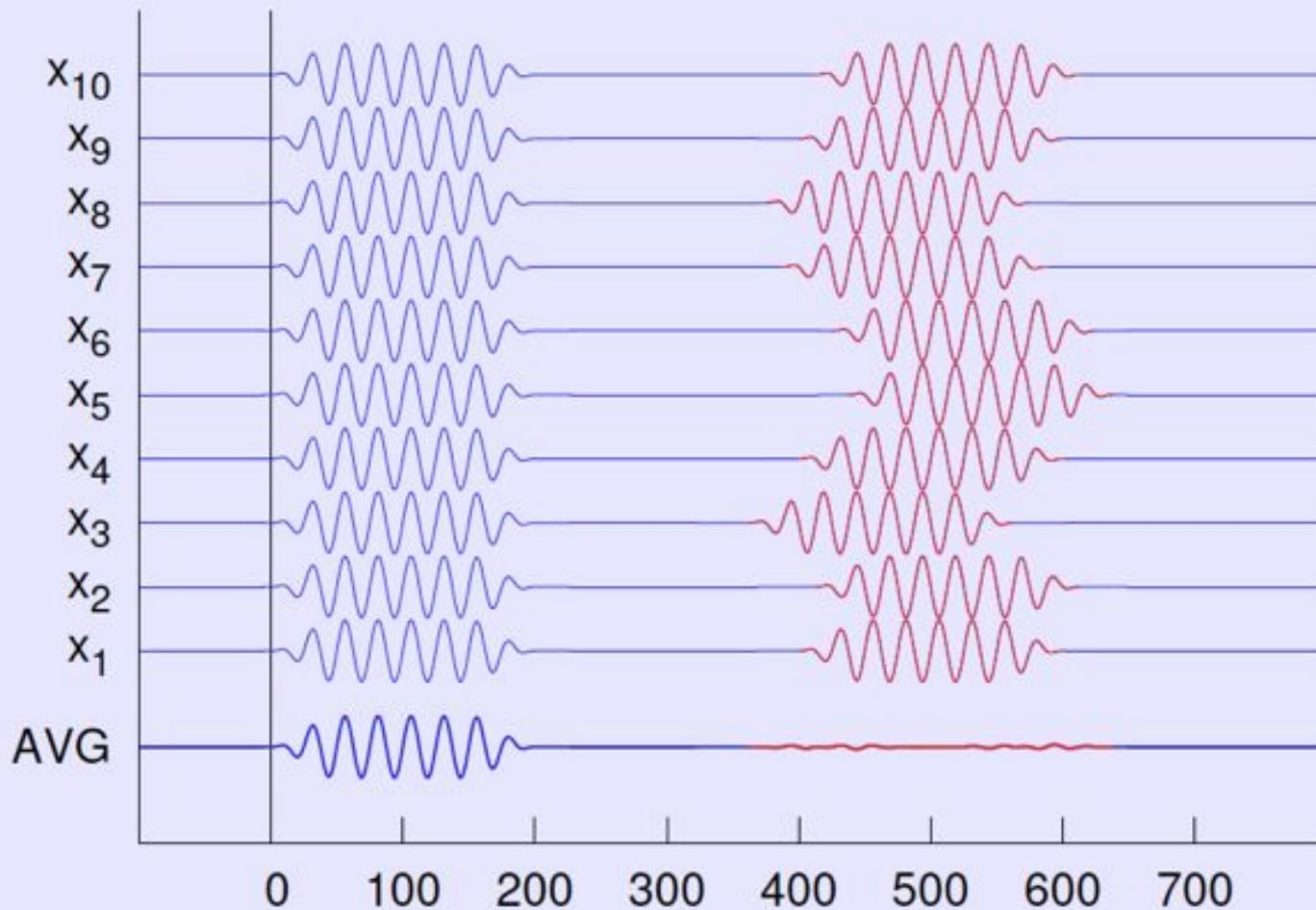


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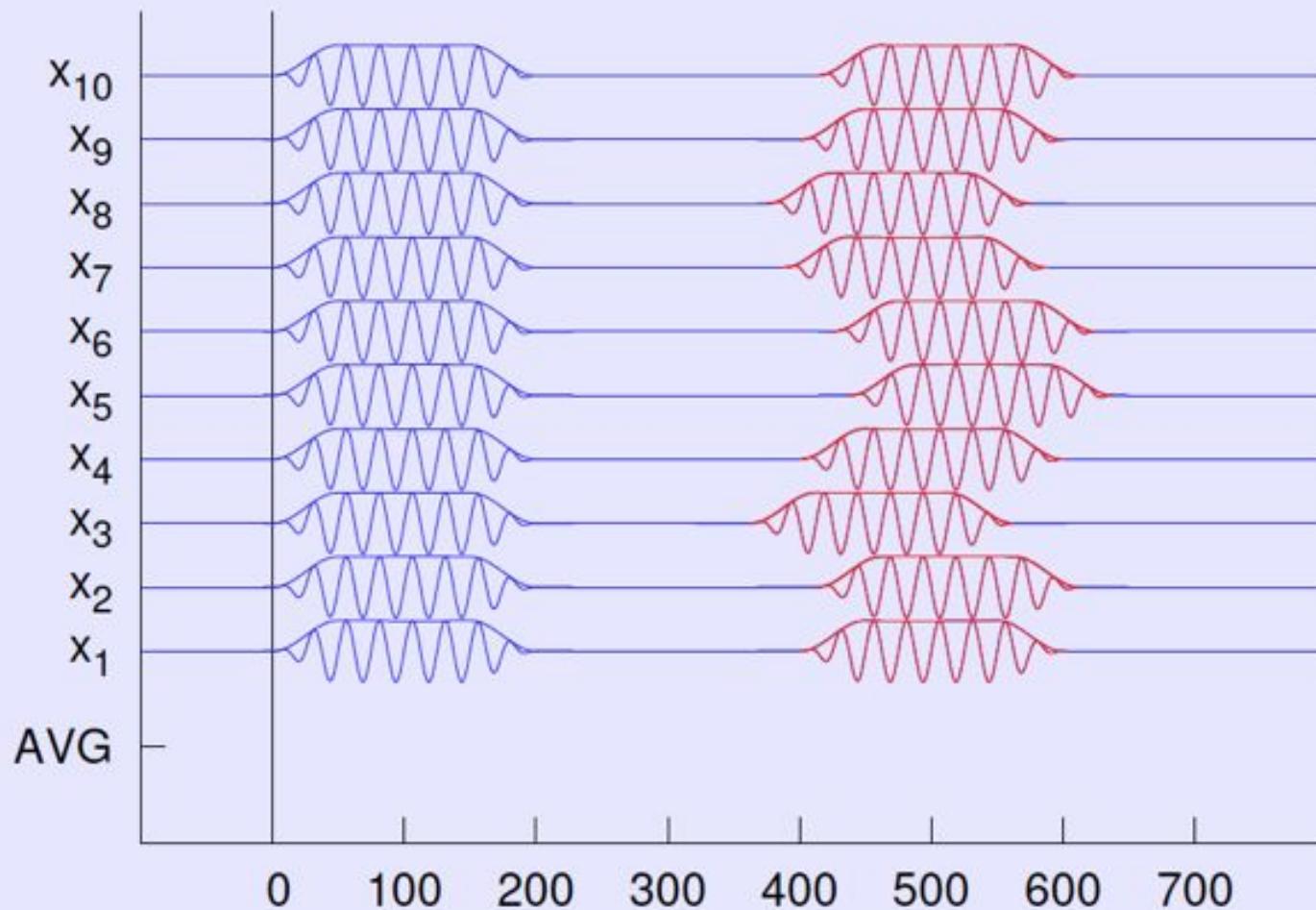
# Evoked vs induced responses

Event related oscillator activity



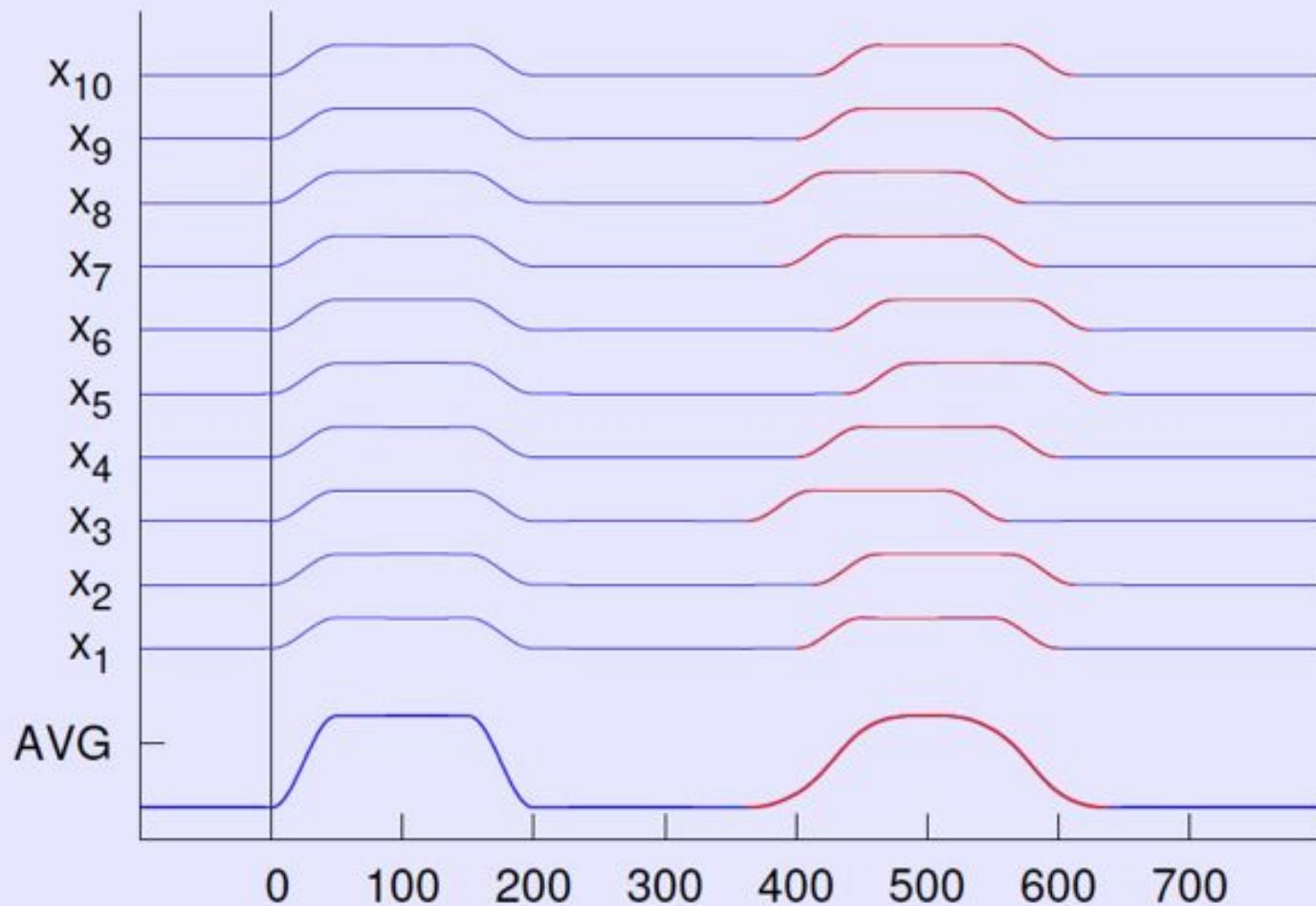
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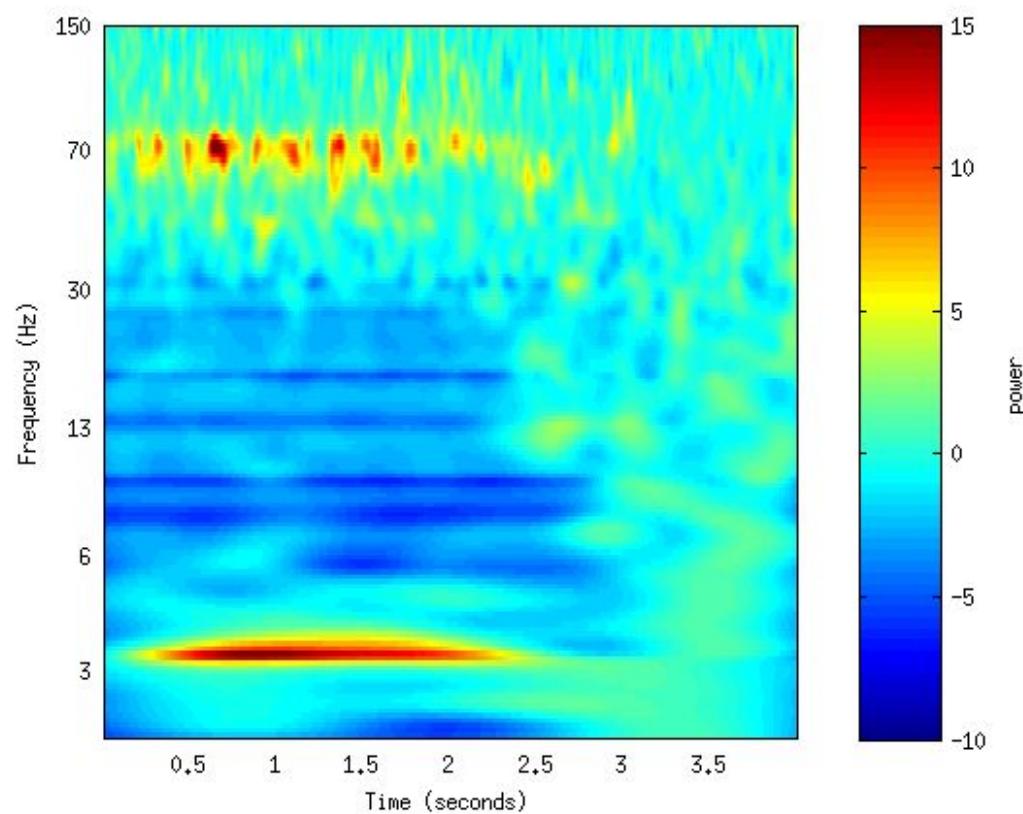
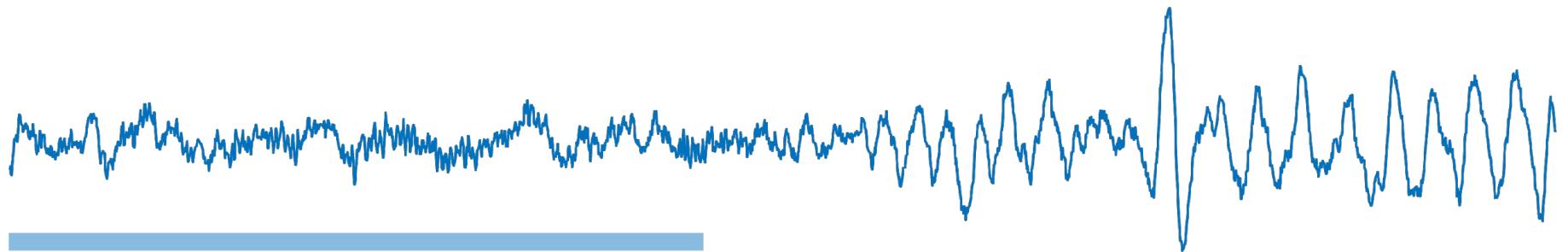


# Evoked vs induced responses

Event related oscillator activity

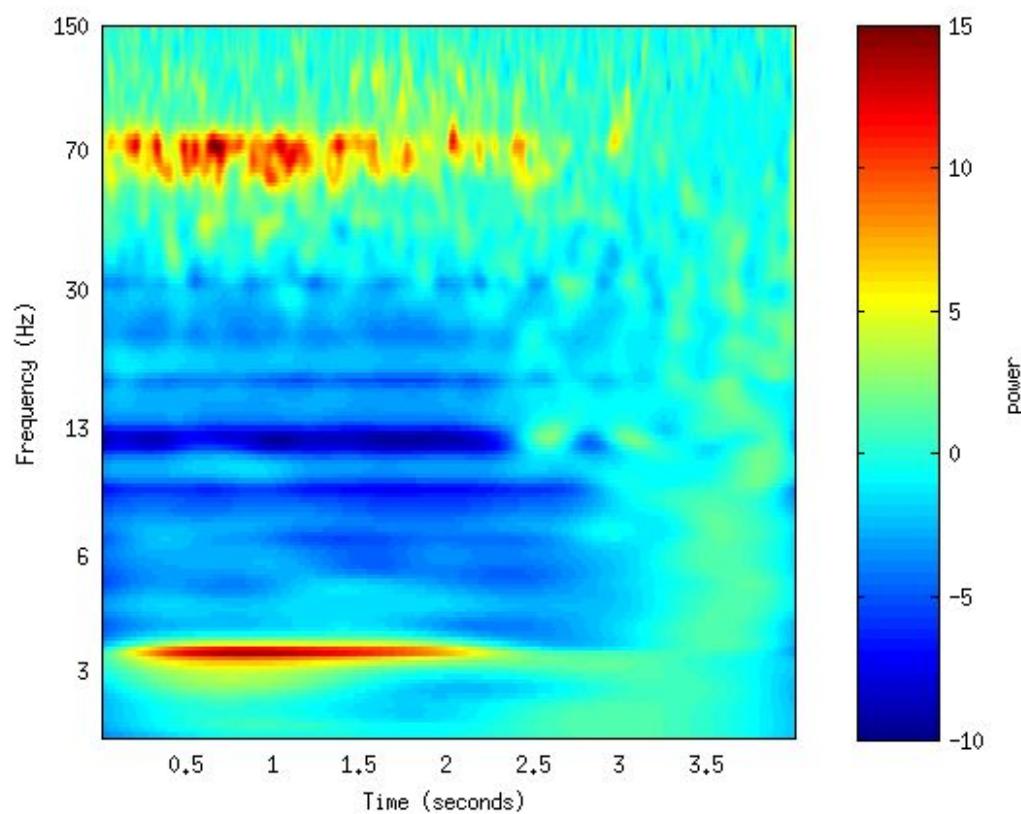
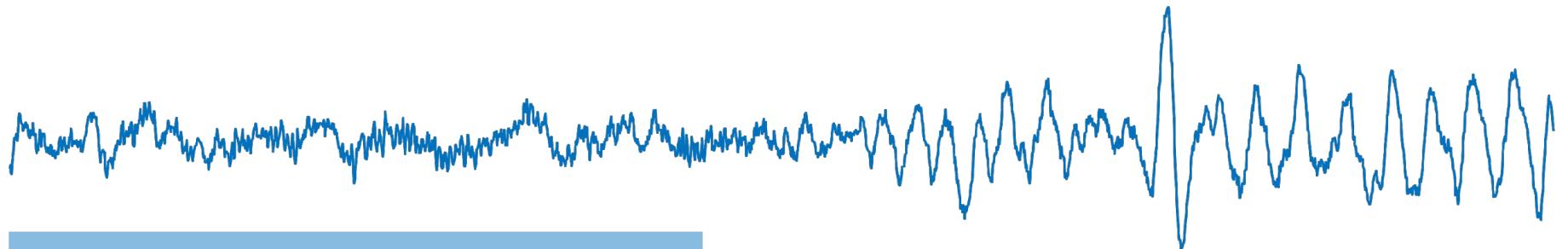


# Evoked vs induced responses



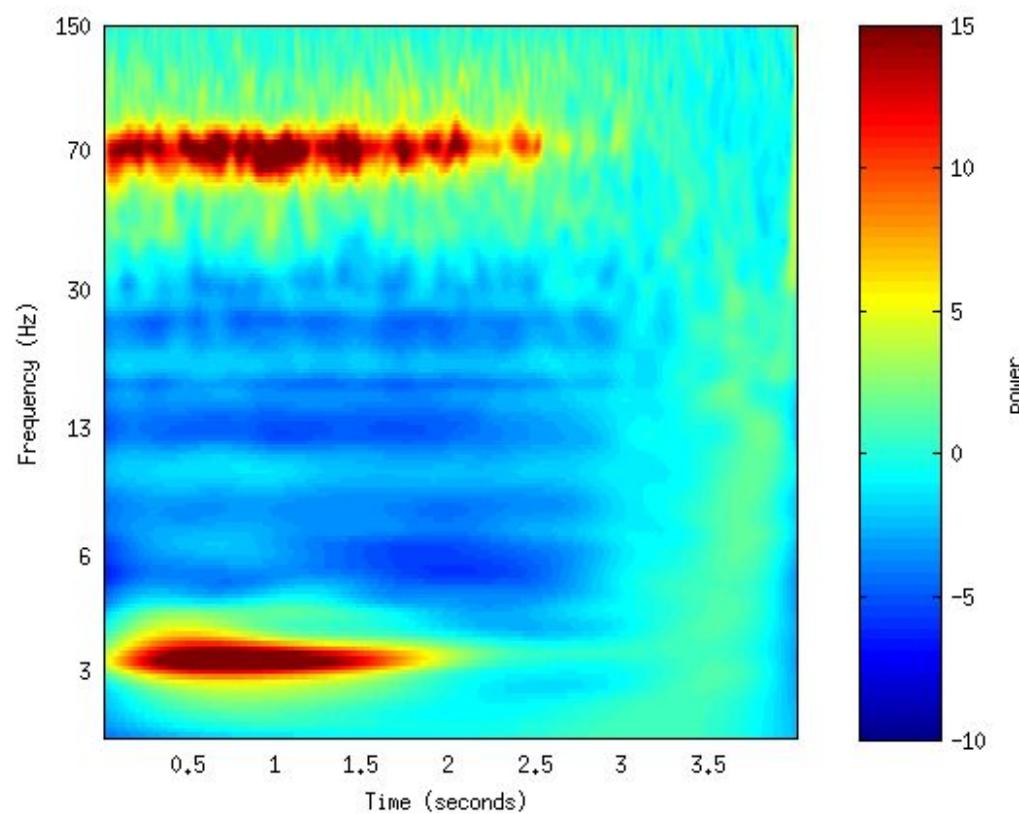
- Averaging
  - 10 trials

# Evoked vs induced responses



- Averaging
  - 10 trials
  - 20 trials

# Evoked vs induced responses



- Averaging
  - 10 trials
  - 20 trials
  - 100 trials

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## Stationary:

- Fourier transform
- Power spectral density (Welch's method)

## Time-resolved:

- Wavelet transform
- **Filtering & Hilbert transform**

## Connectivity:

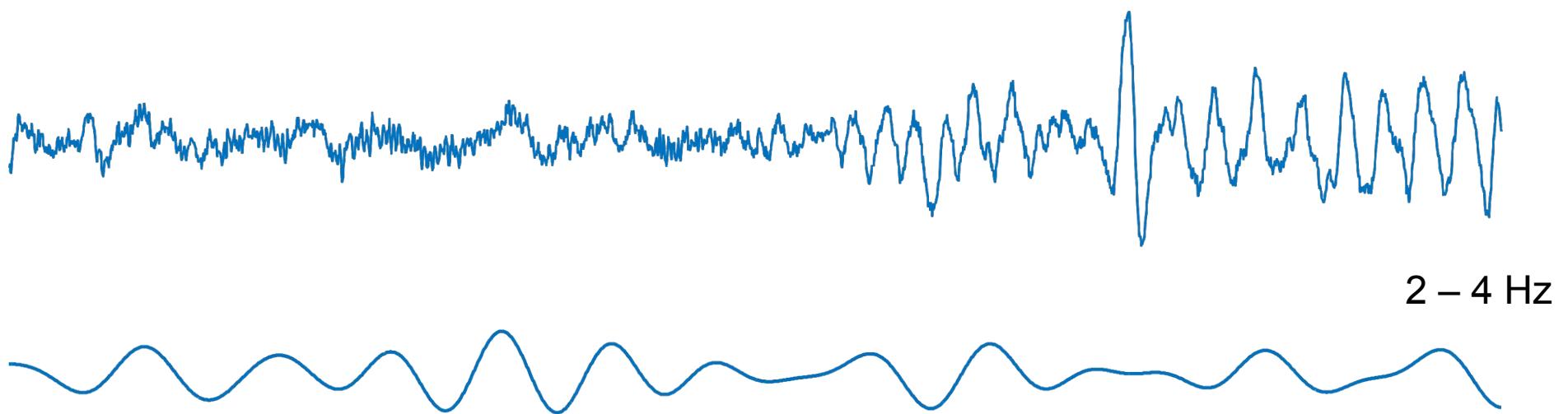
- Amplitude correlation
- Phase-locking value

# Hilbert transform



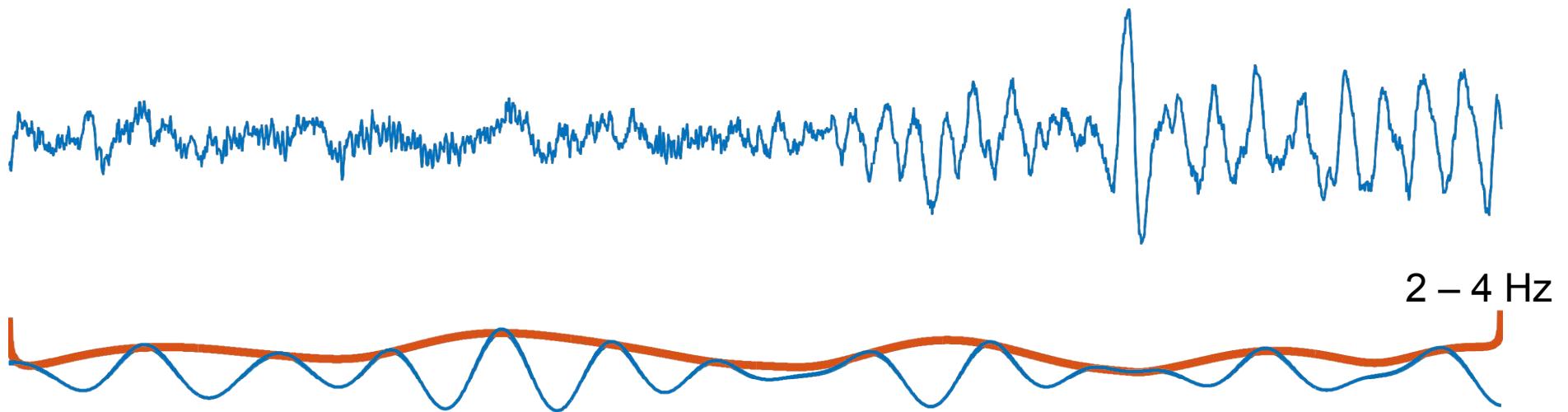
- Useful for estimating time-resolved power (or phase) in a pre-defined frequency band (e.g. Delta: 2-4 Hz)
- 
-

# Hilbert transform



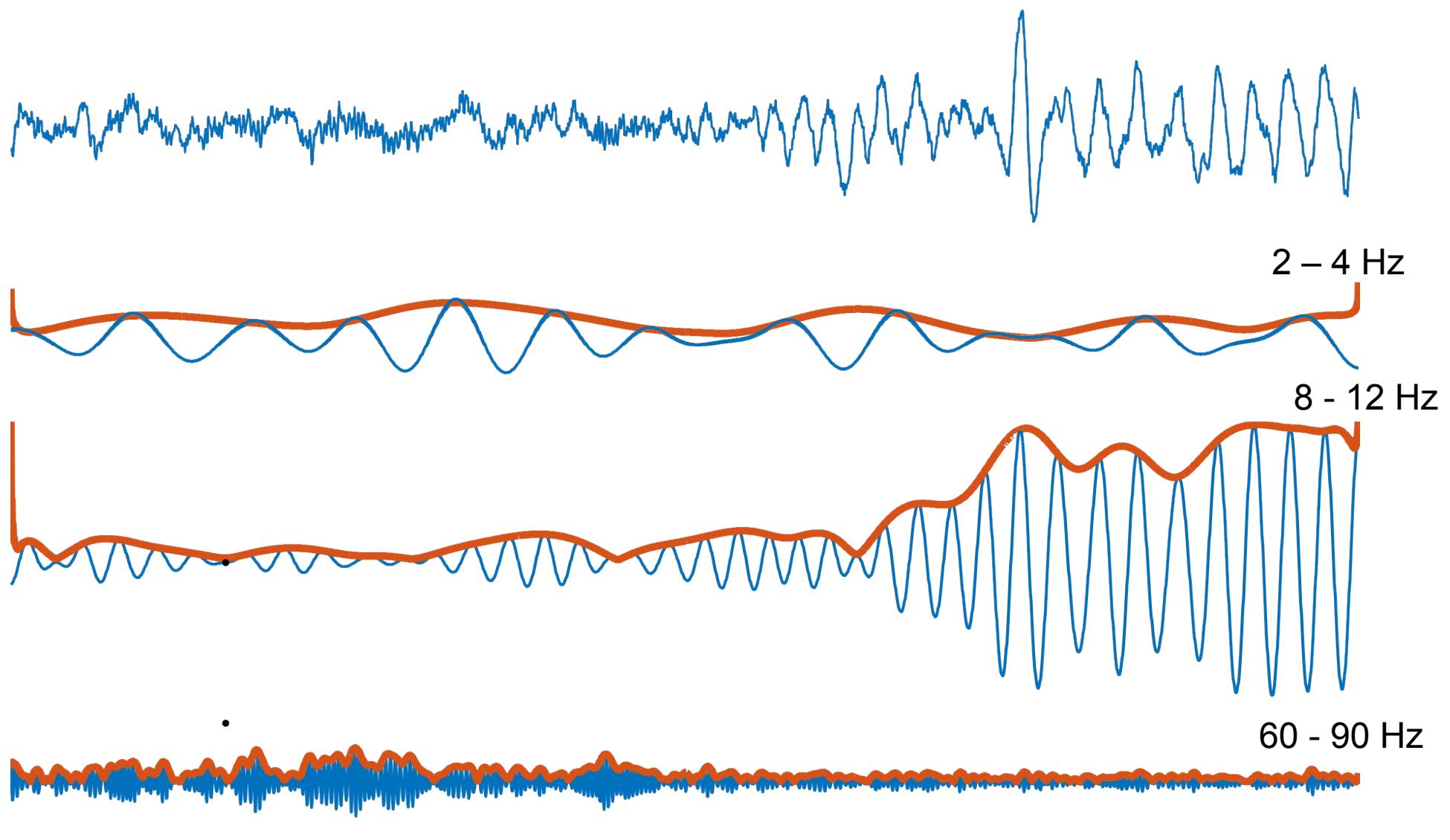
- Useful for estimating time-resolved power (or phase) in a pre-defined frequency band (e.g. Delta: 2-4 Hz)
- Signal is first filtered in the specified band
-

# Hilbert transform

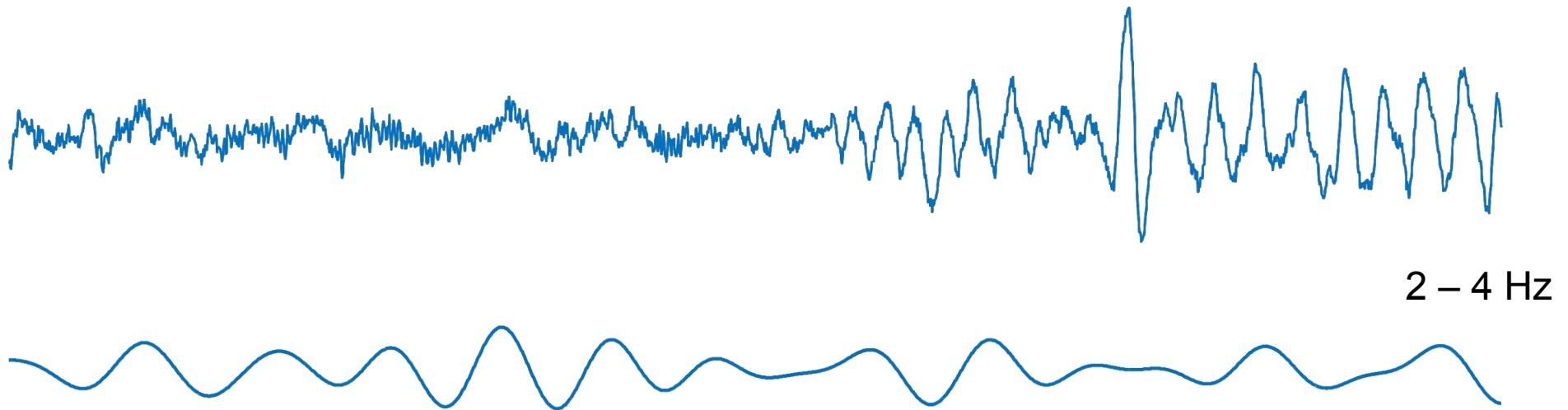


- Useful for estimating time-resolved power (or phase) in a pre-defined frequency band (e.g. Delta: 2-4 Hz)
- Signal is first filtered in the specified band
- Envelope (power) is computed using the Hilbert transform

# Hilbert transform

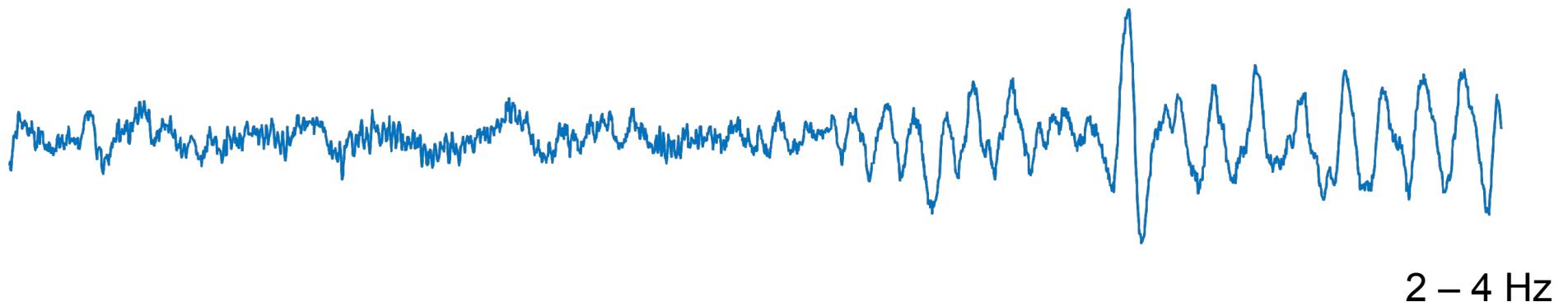


# Hilbert transform

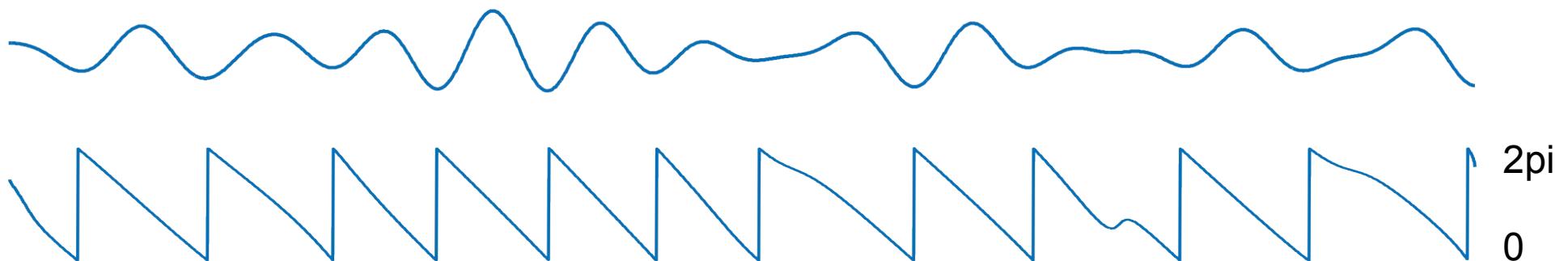


- The hilbert transform can also extract the phase of the bandpassed signal in time
-

# Hilbert transform

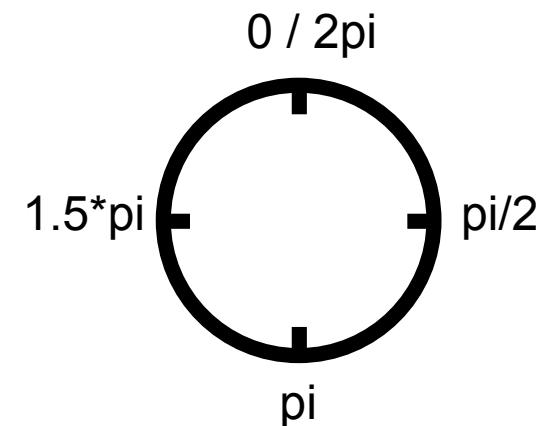


2 – 4 Hz

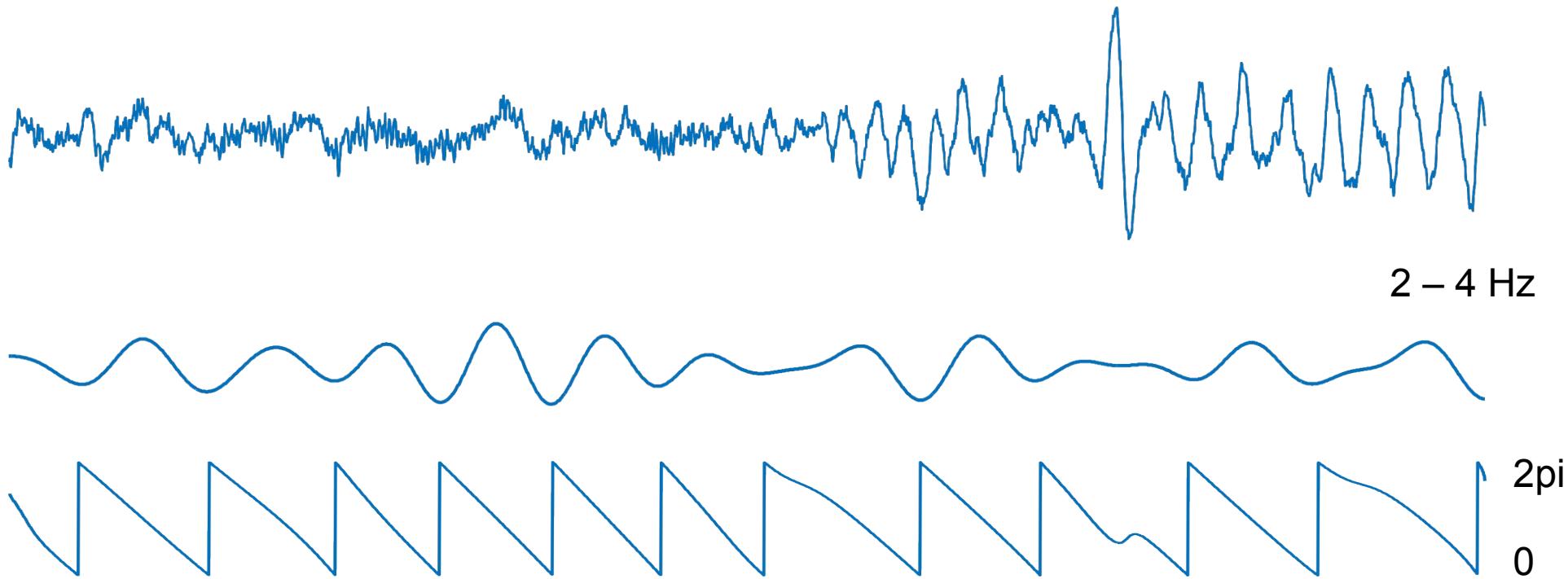


2pi  
0

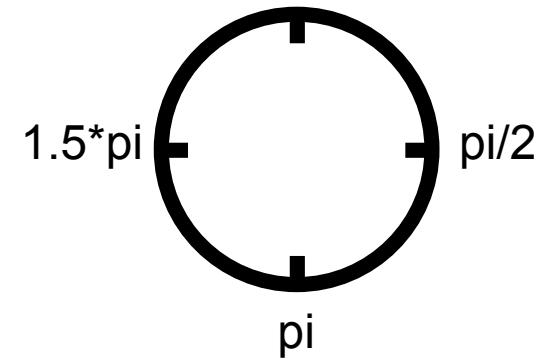
- The hilbert transform can also extract the phase of the bandpassed signal in time
- 



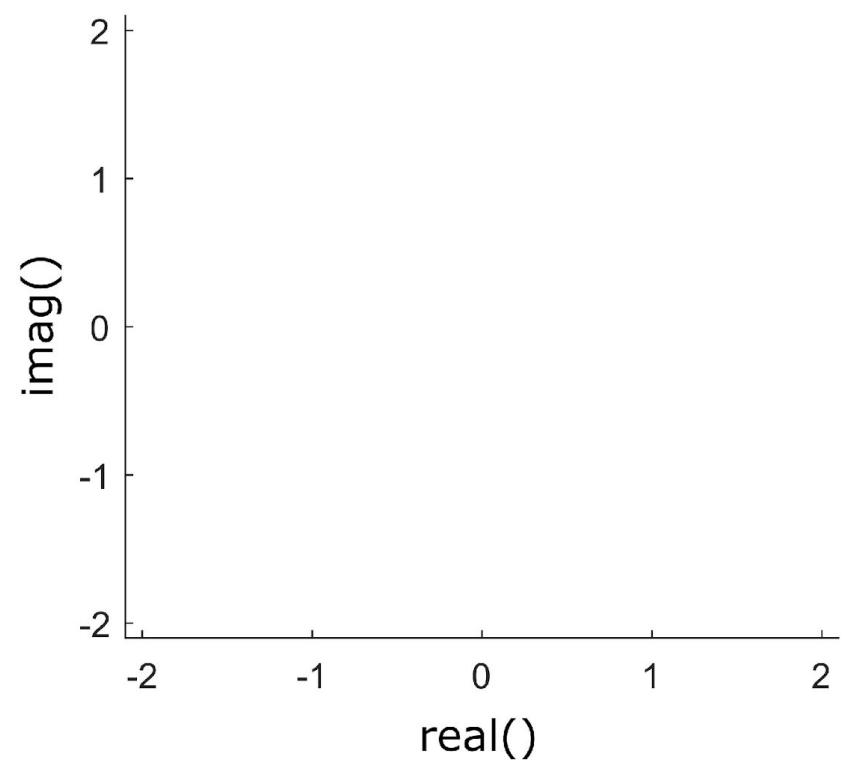
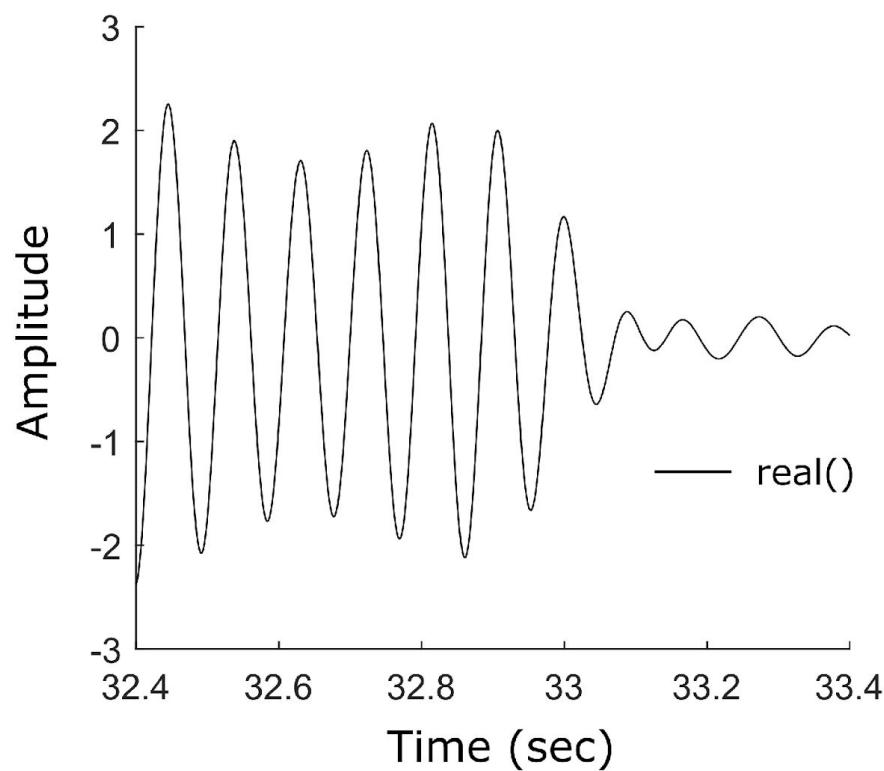
# Hilbert transform



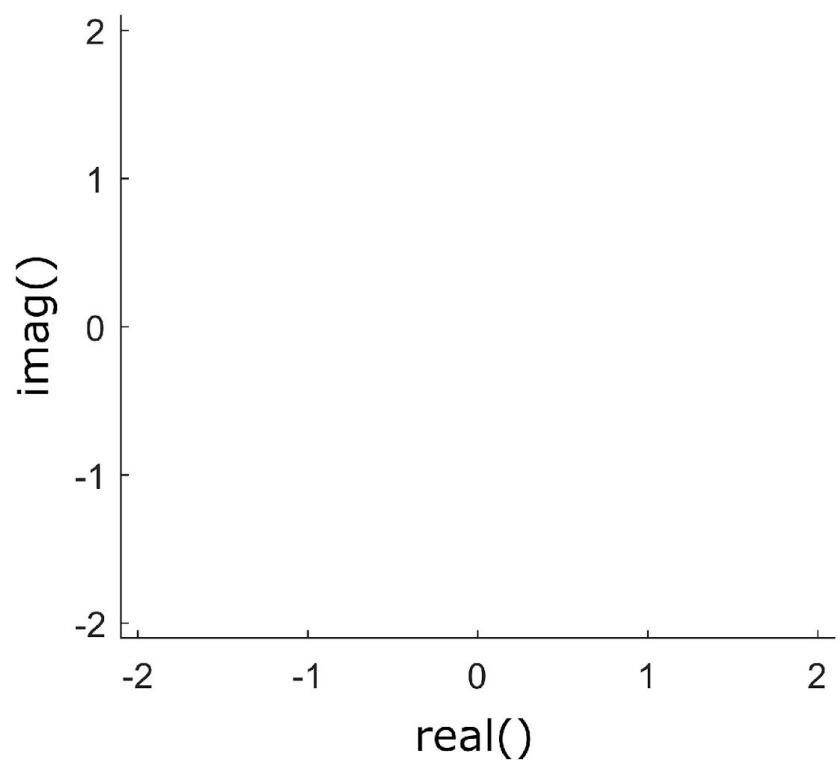
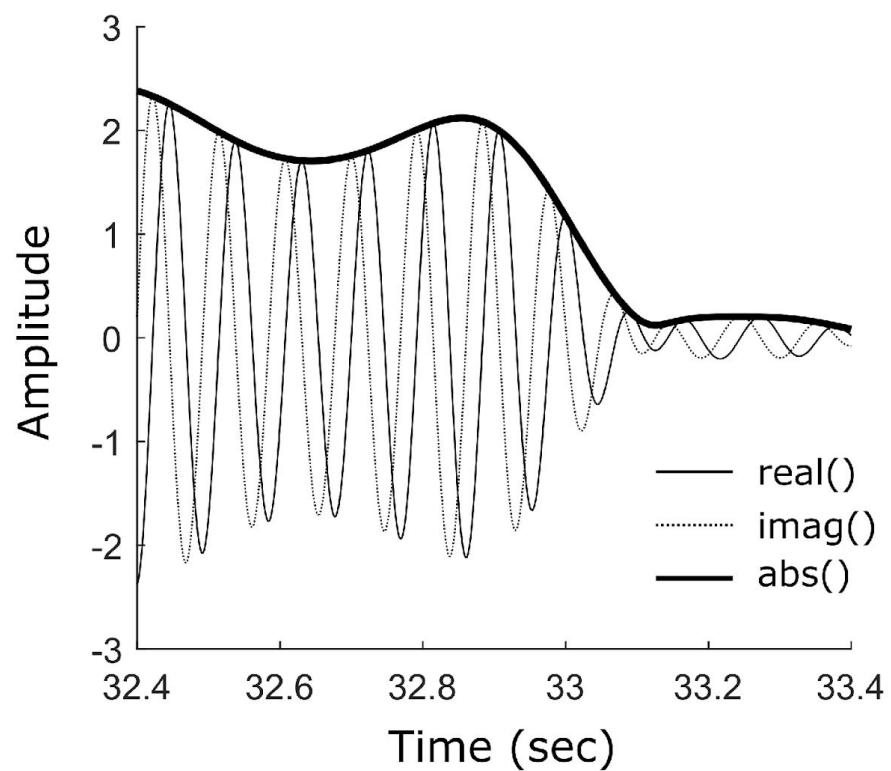
- The hilbert transform can also extract the phase of the bandpassed signal in time
- Usage: phase-locking value, stimulus-brain coupling, phase-amplitude coupling



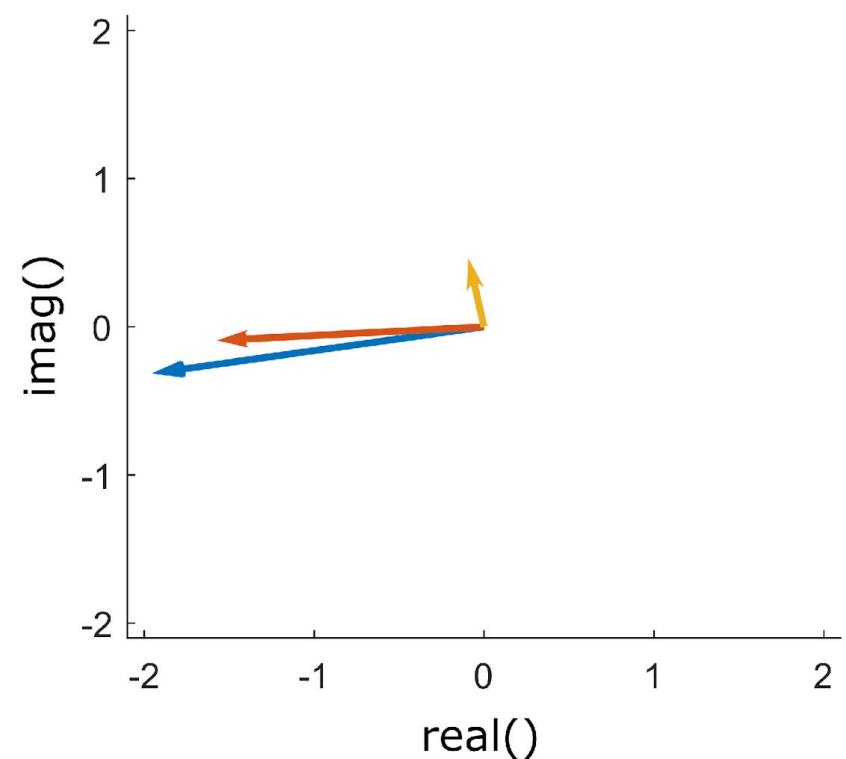
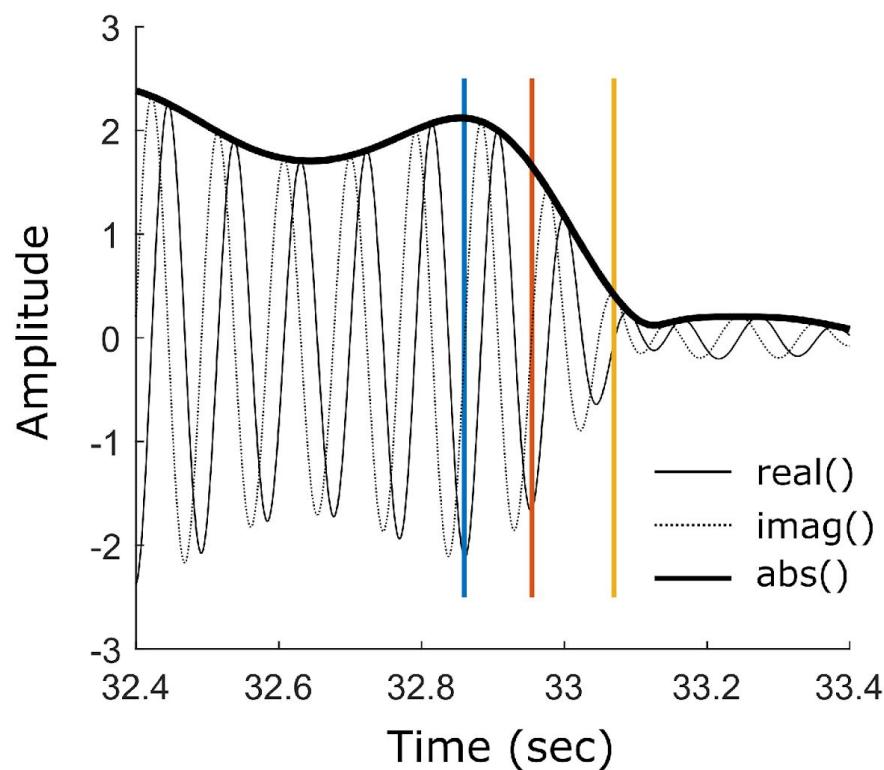
# Hilbert transform



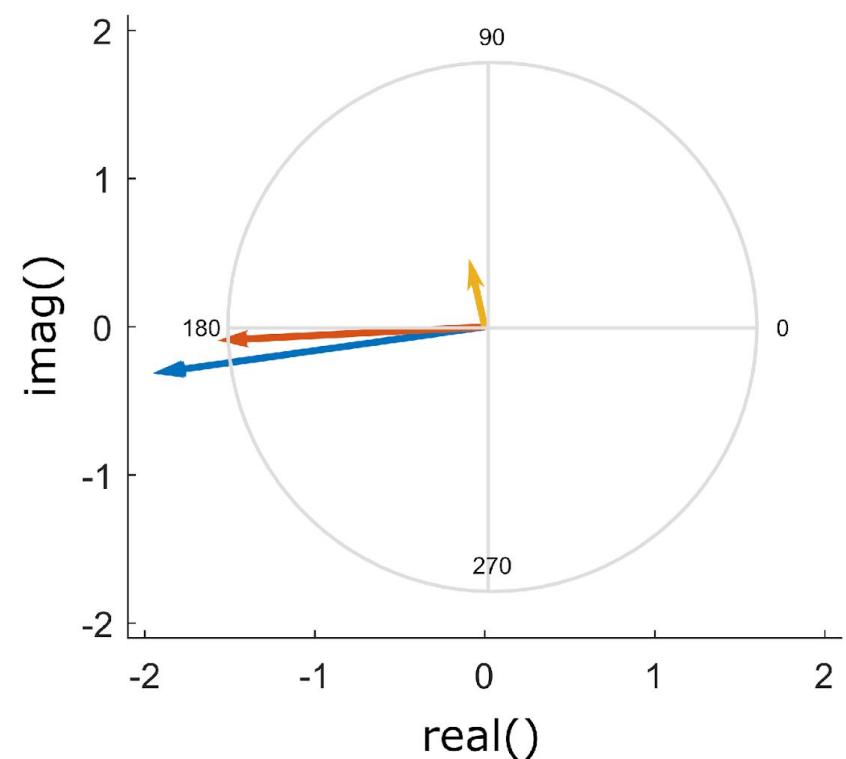
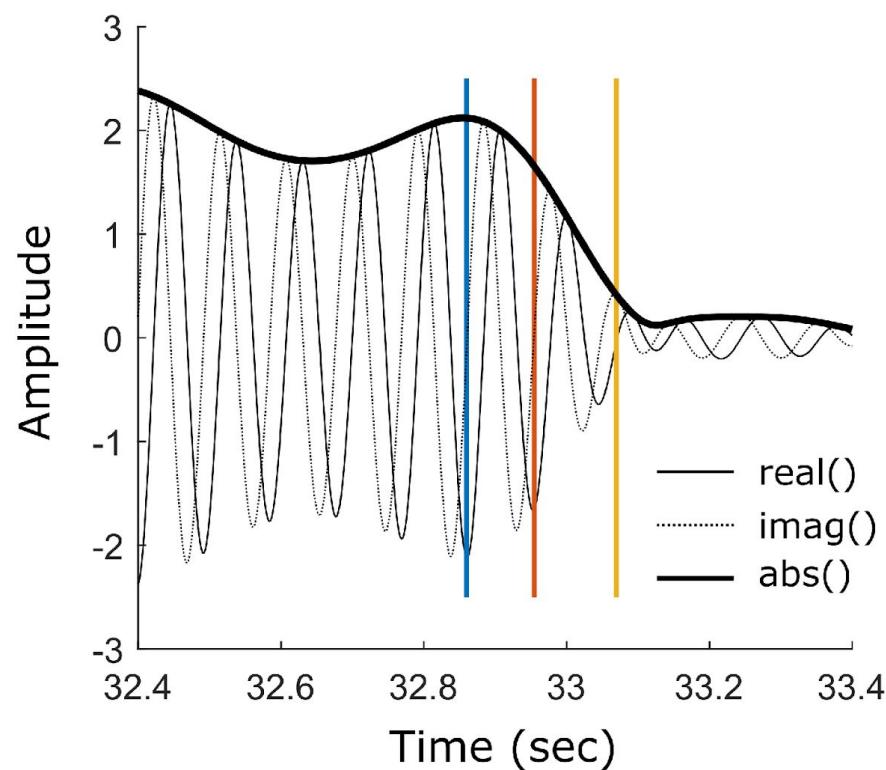
# Hilbert transform



# Hilbert transform

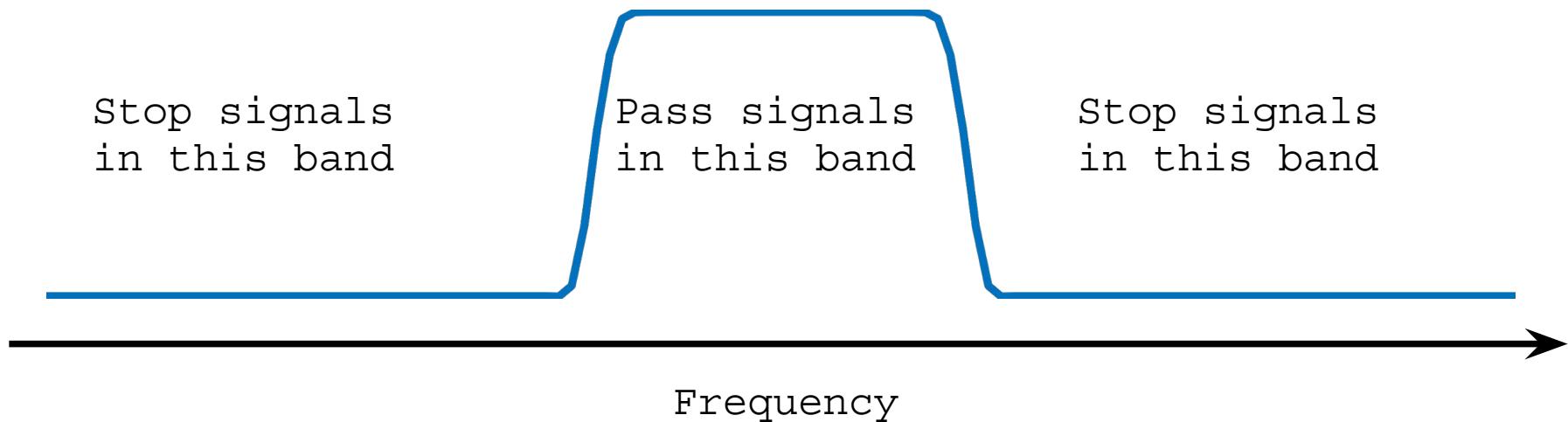


# Hilbert transform



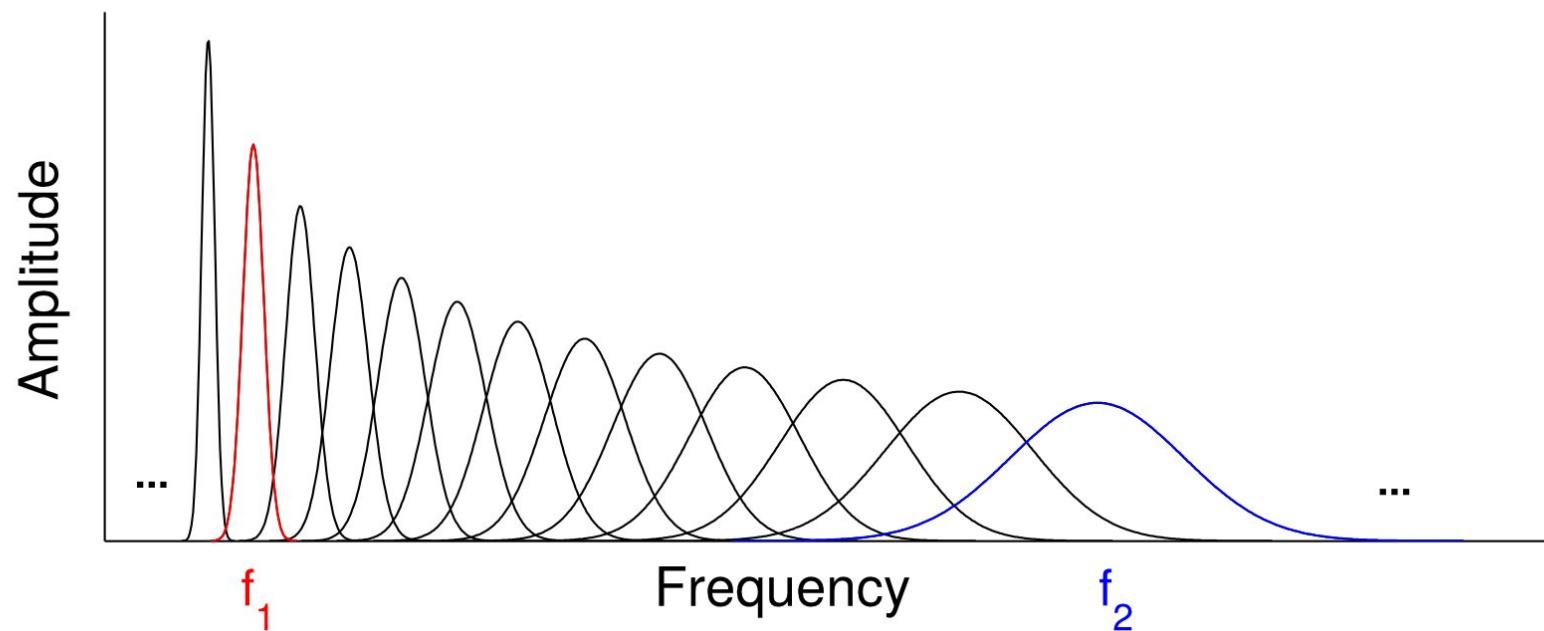
# Hilbert vs. Wavelet

- Important: frequency response of the bandpass filter
- 



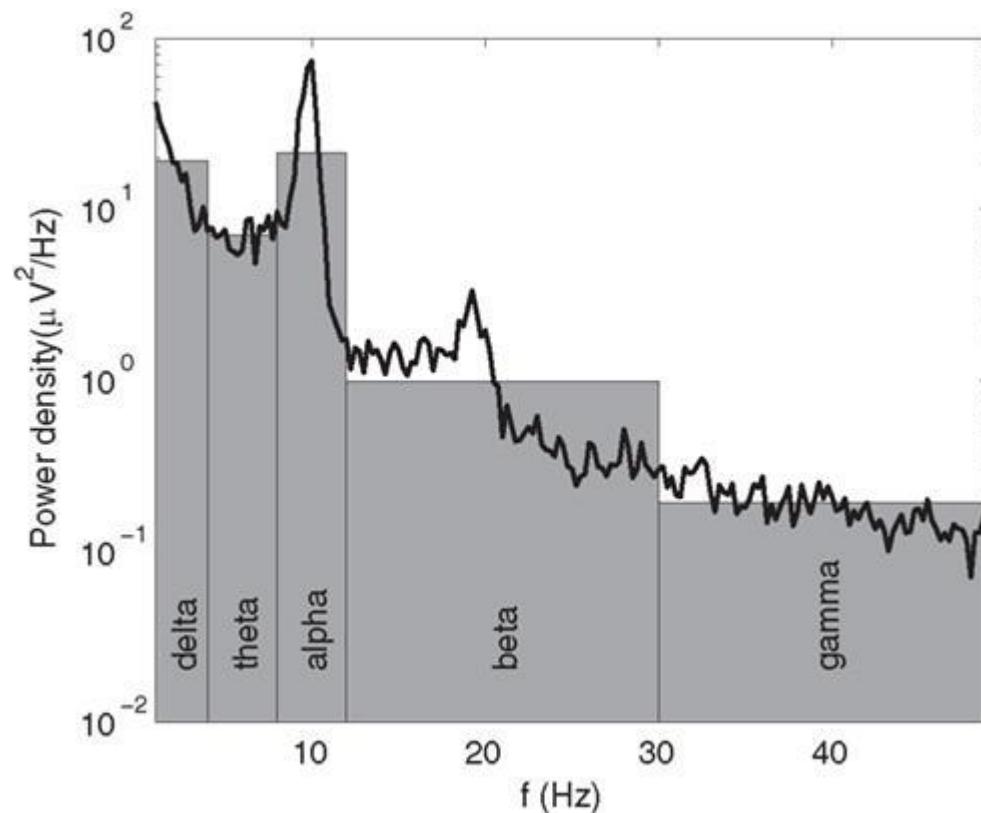
# Hilbert vs. Wavelet

- Important: frequency response of the bandpass filter
- Morlet wavelets more localized around center frequency



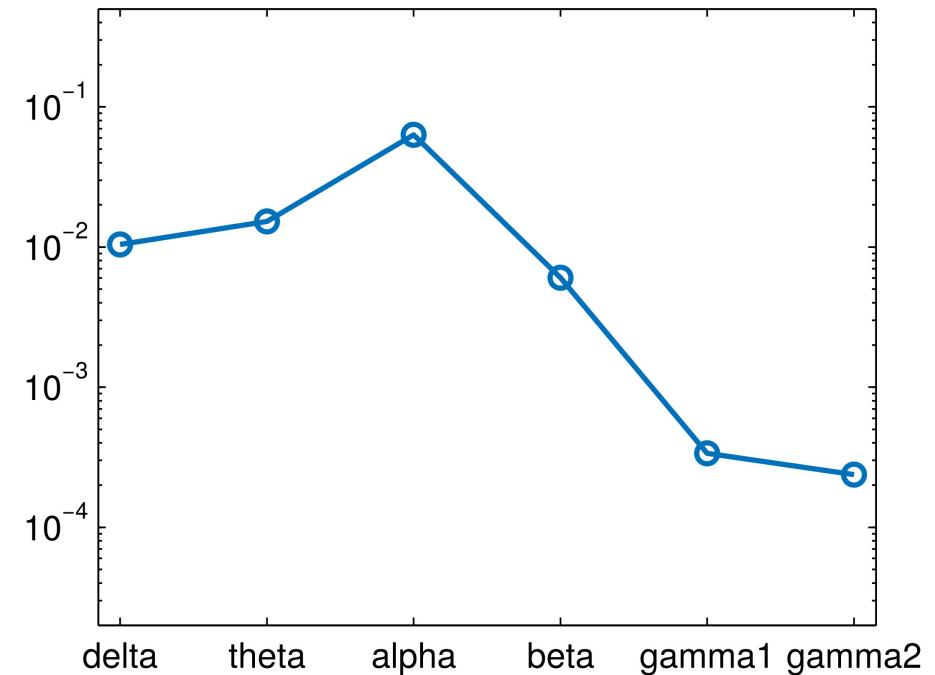
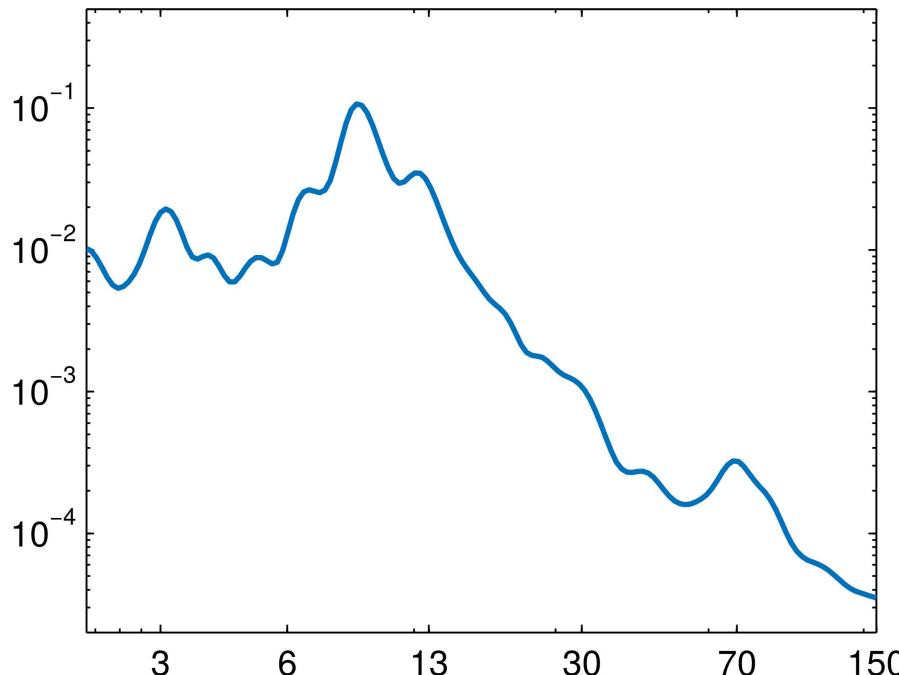
# Defining frequency bands

- 'Based on the literature': many definitions



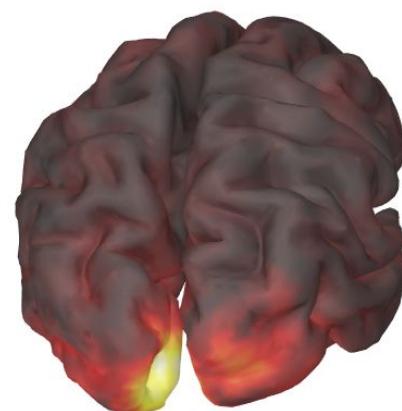
# Defining frequency bands

- Should I collapse over frequency bands or keep the full spectrum?
- Information might be lost (peaks)

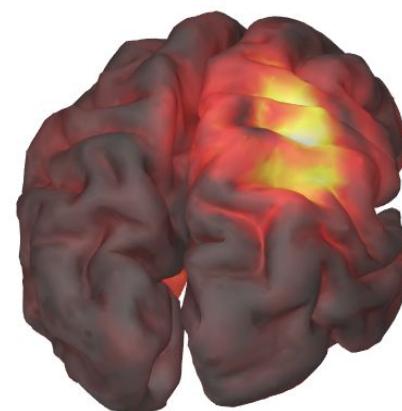


# Defining frequency bands

- Should I collapse over frequency bands or keep the full spectrum?
- Sometimes necessary for reducing dimensionality (e.g. in MEG source space)
- Can increase sensitivity (due to averaging)



Gamma 60-90  
Hz



Beta 15-30  
Hz

# Contents

## Stationary:

- Fourier transform
- Power spectral density (Welch's method)

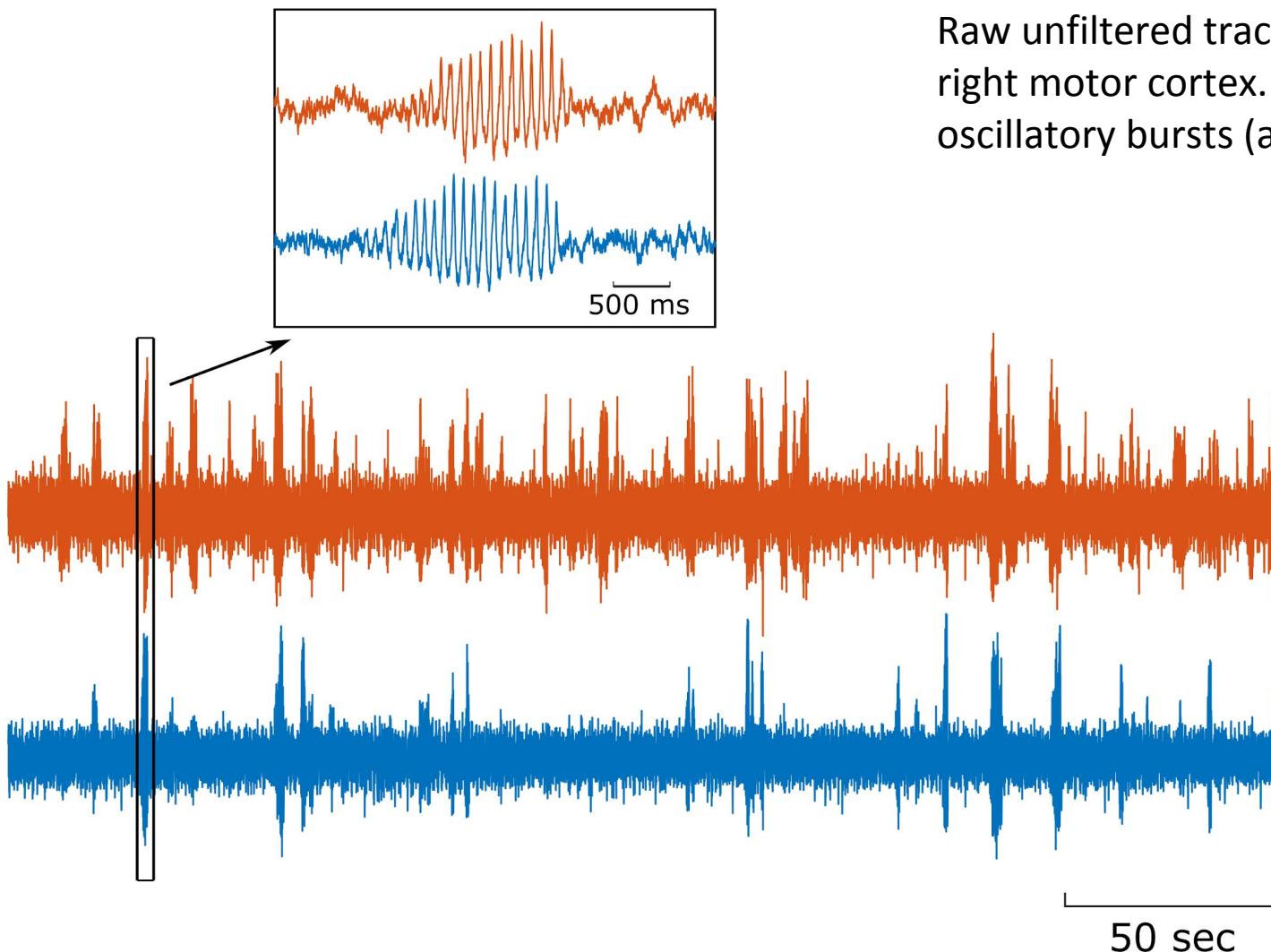
## Time-resolved:

- Wavelet transform
- Filtering & Hilbert transform

## Connectivity:

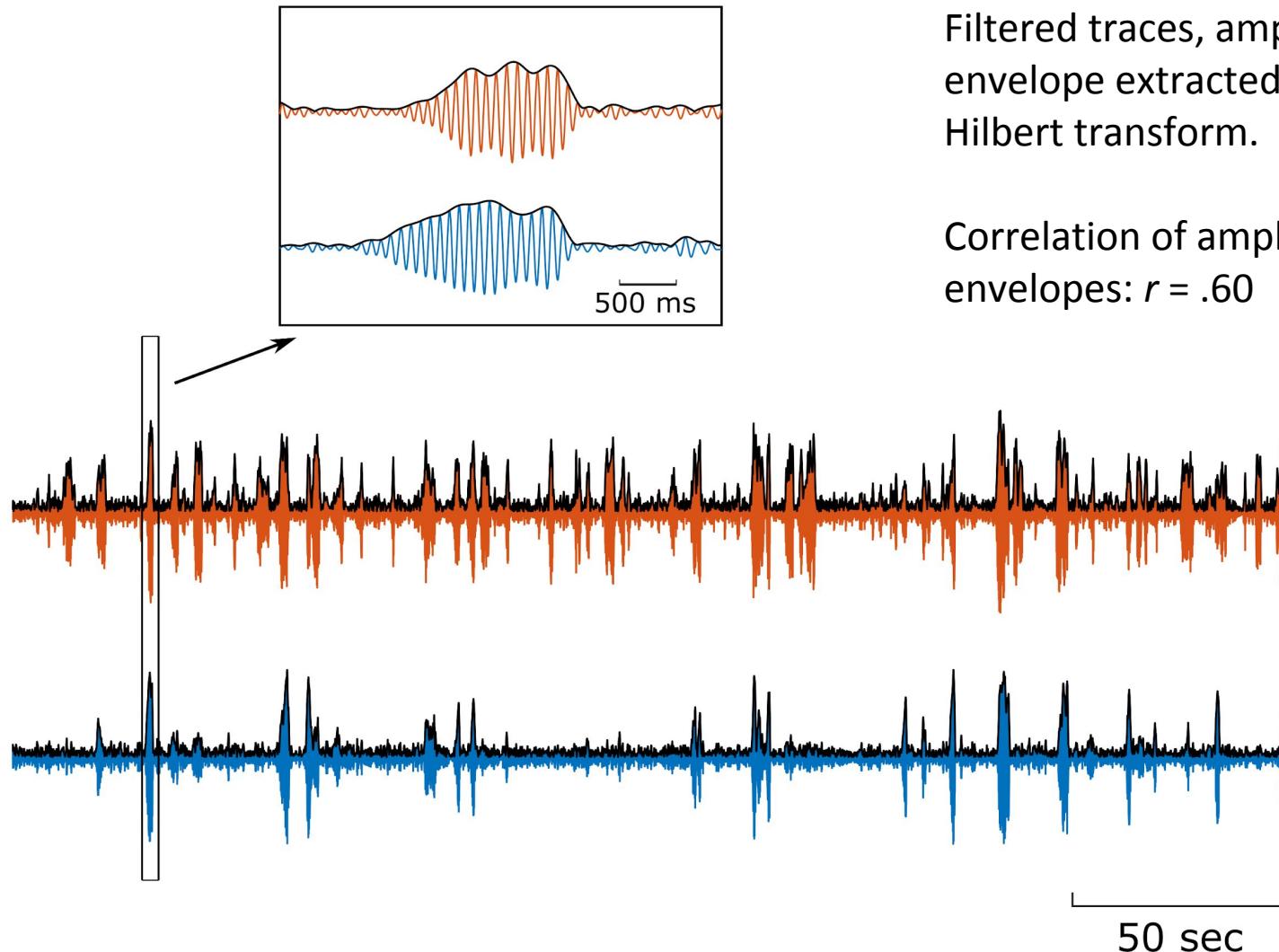
- Amplitude correlation
- Phase-locking value

# Amplitude correlation



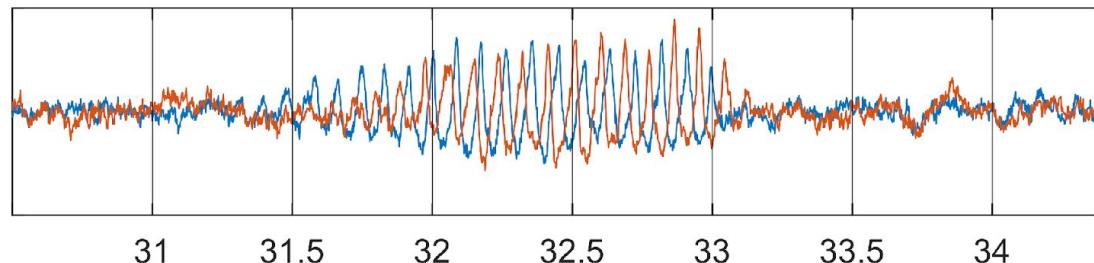
Raw unfiltered traces, left and right motor cortex. Co-occurring oscillatory bursts (around 10Hz)

# Amplitude correlation

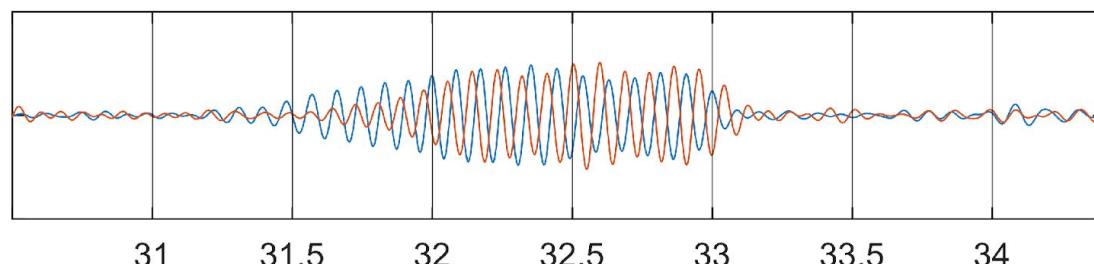


# Phase-locking value

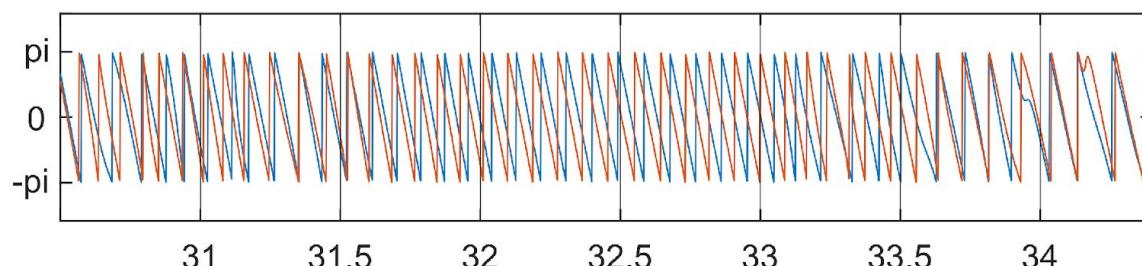
- Raw and filtered traces of an oscillatory burst, phase angle extracted using the Hilbert transform



31    31.5    32    32.5    33    33.5    34



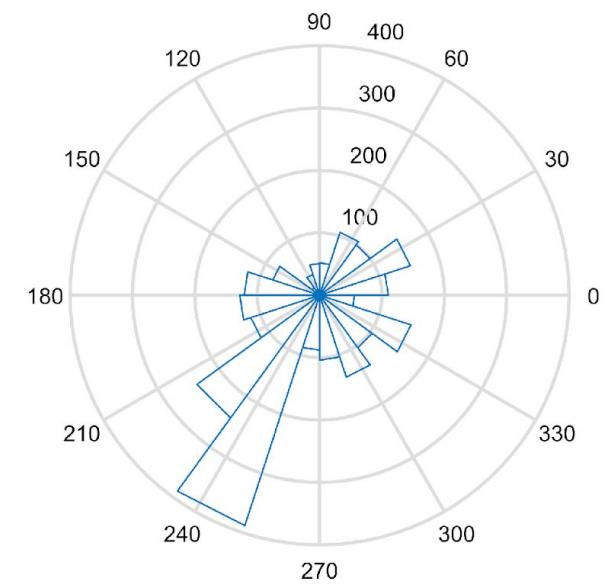
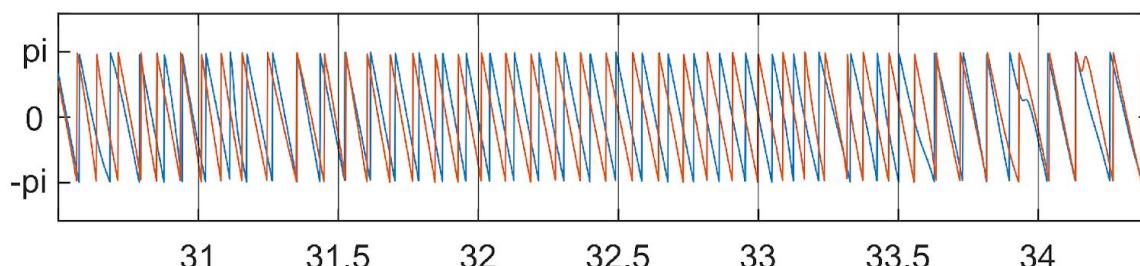
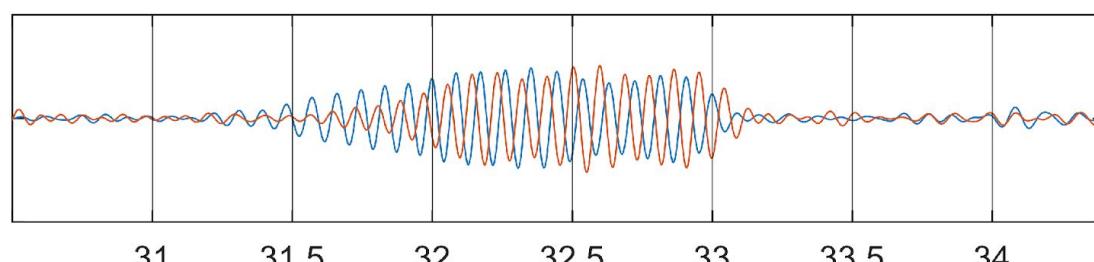
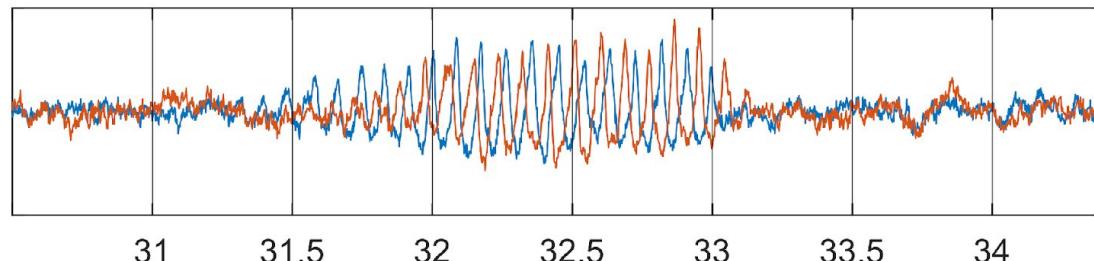
31    31.5    32    32.5    33    33.5    34



31    31.5    32    32.5    33    33.5    34

# Phase-locking value

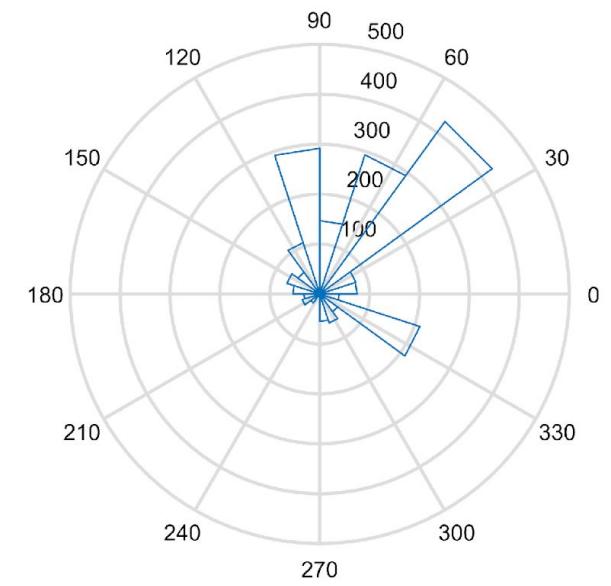
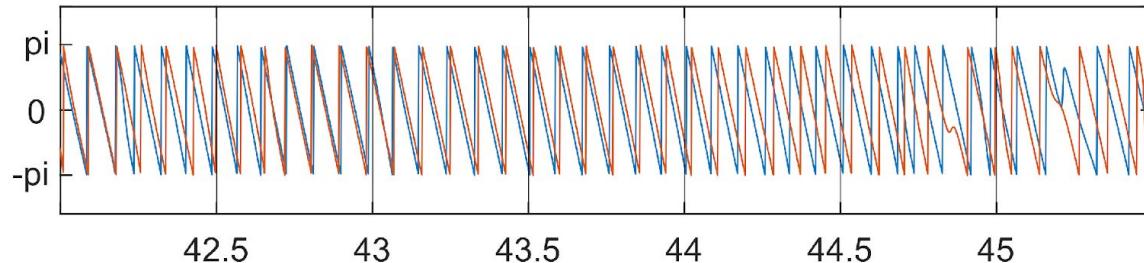
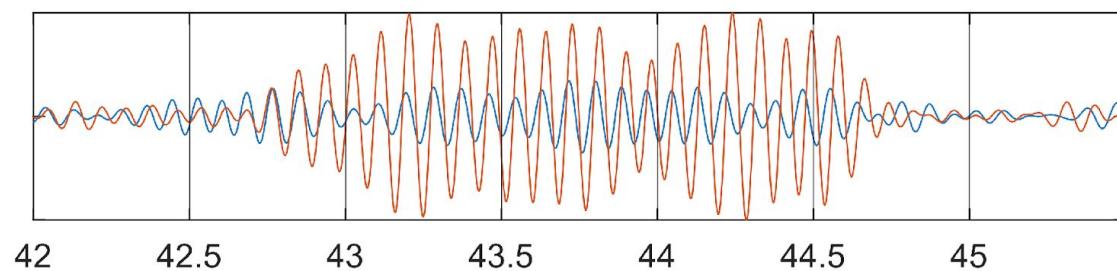
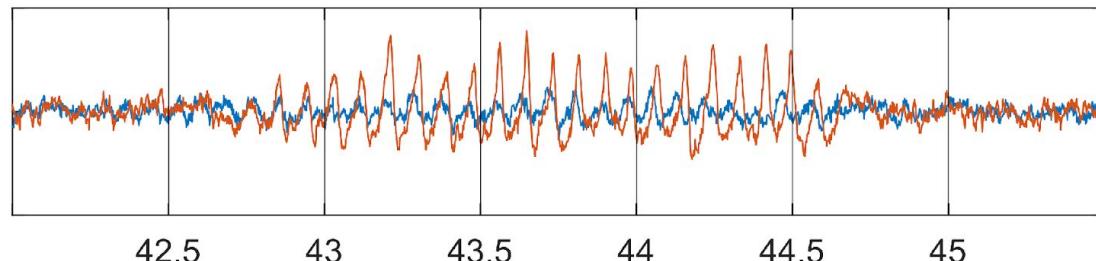
- Raw and filtered traces of an oscillatory burst, phase angle extracted using the Hilbert transform
- Phase differences are used to calculate PLV



PLV: .26

# Phase-locking value

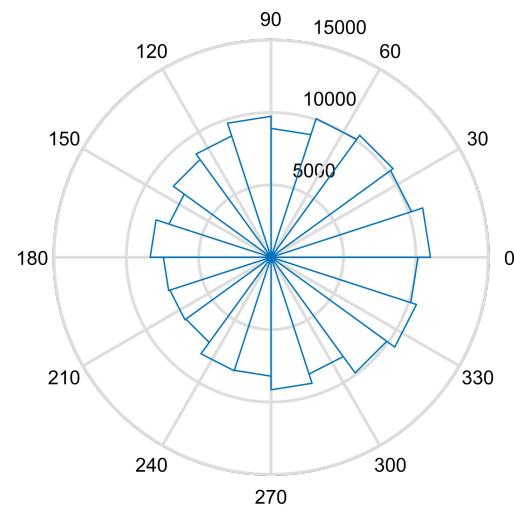
- Different burst, 10 seconds later > phase difference has changed



PLV: .52

# Phase-locking value

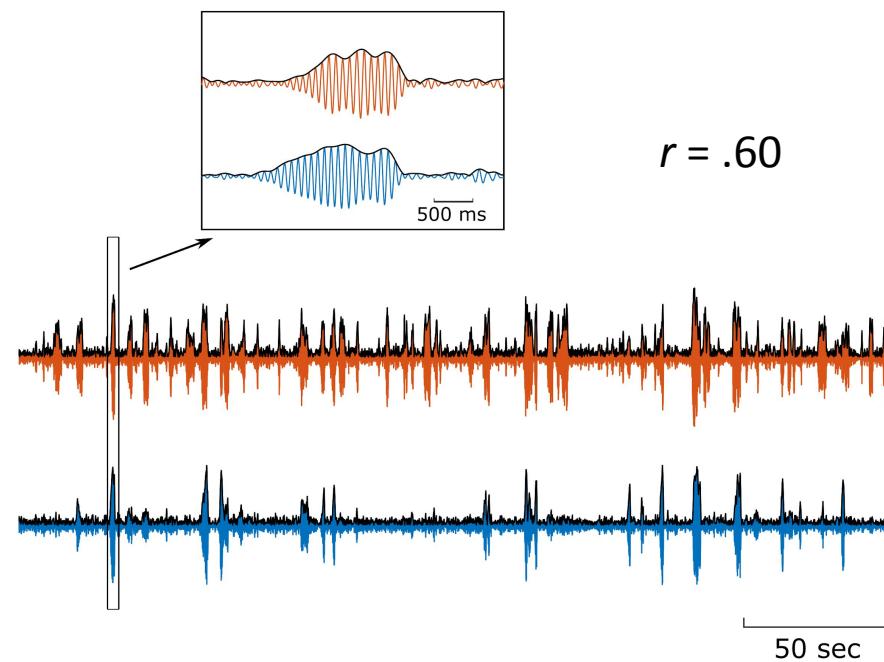
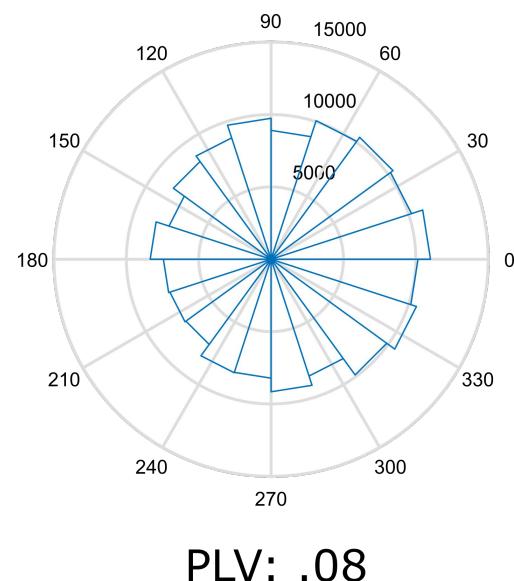
- Histogram of phase differences for the whole five minute period



PLV: .08

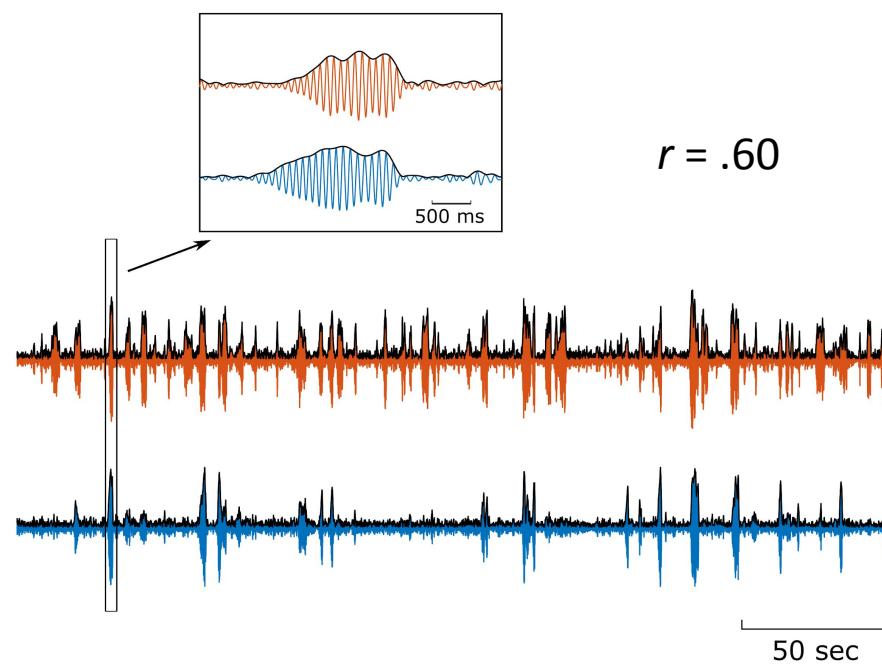
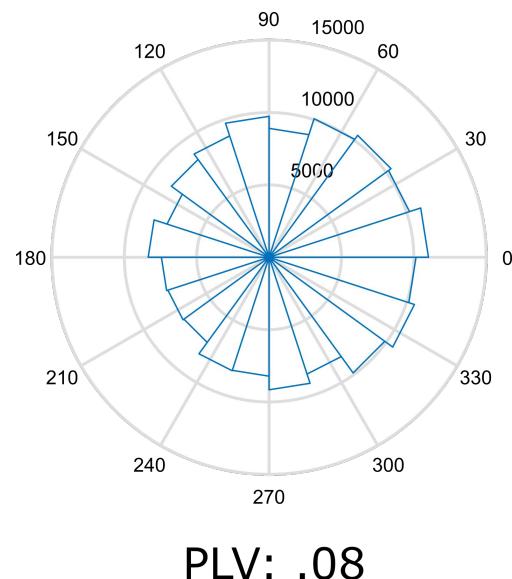
# Phase-locking value

- Histogram of phase differences for the whole five minute period
- PLV is low, whereas amplitude correlation is high



# Phase-locking value

- Histogram of phase differences for the whole five minute period
- PLV is low, whereas amplitude correlation is high
- ‘Connectivity’ in electrophysiological signals is complicated / and interesting (compared to BOLD-fMRI)



# Summary

## Stationary:

- Fourier transform
- Power spectral density (Welch's method)

## Time-resolved:

- Wavelet transform
- Filtering & Hilbert transform

## Connectivity:

- Amplitude correlation
- Phase-locking value

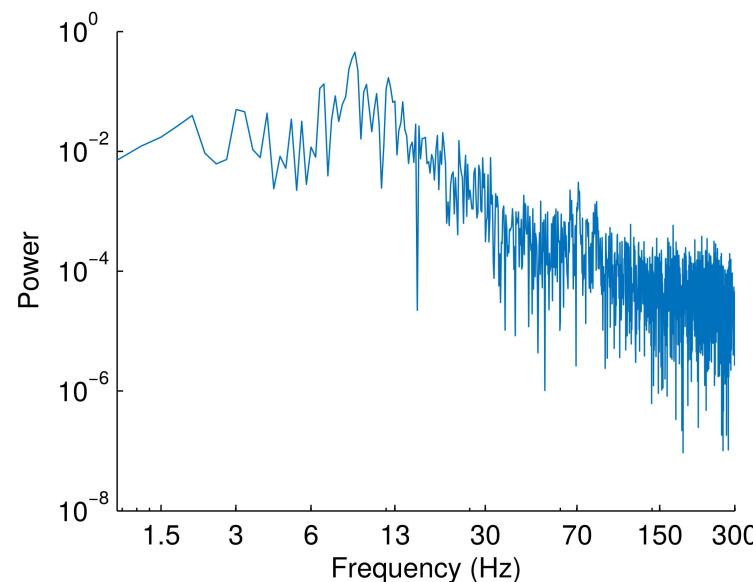
# Summary

## Stationary:

- Fourier transform
- Power spectral density (Welch's method)

## Time-resolved:

- Wavelet transform
- Filtering & Hilbert transform



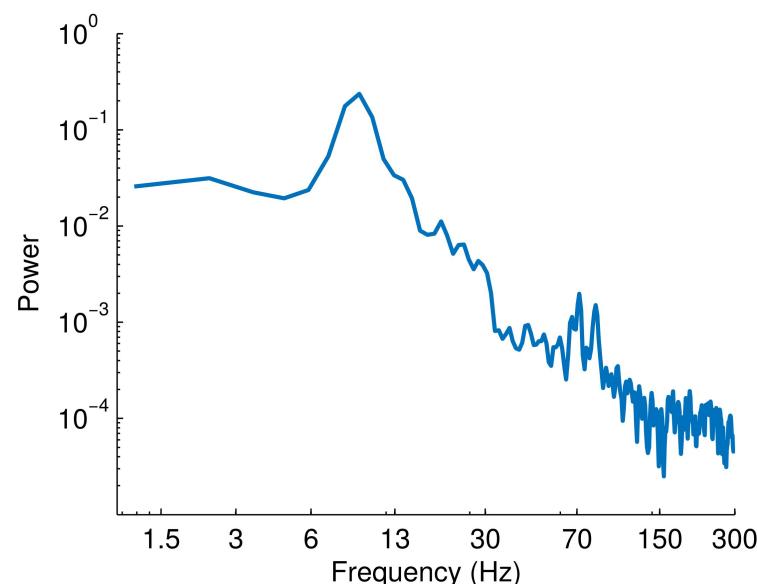
# Summary

## Stationary:

- Fourier transform
- **Power spectral density (Welch's method)**

## Time-resolved:

- Wavelet transform
- Filtering & Hilbert transform



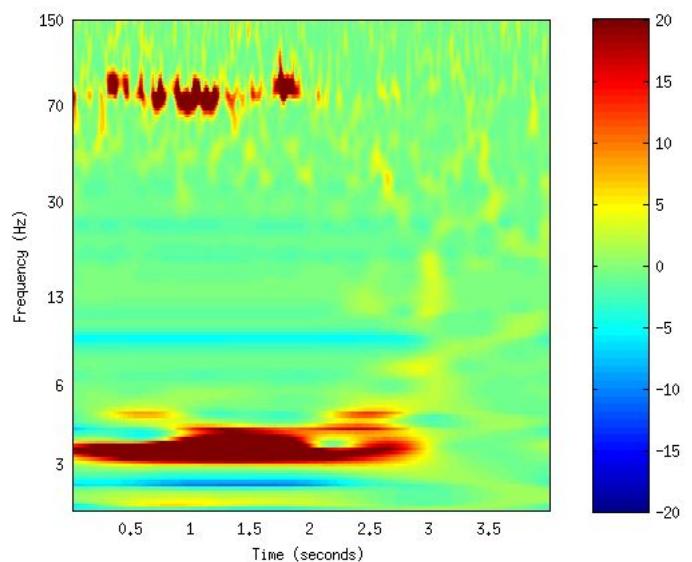
# Summary

## Stationary:

- Fourier transform
- Power spectral density (Welch's method)

## Time-resolved:

- **Wavelet transform**
- Filtering & Hilbert transform



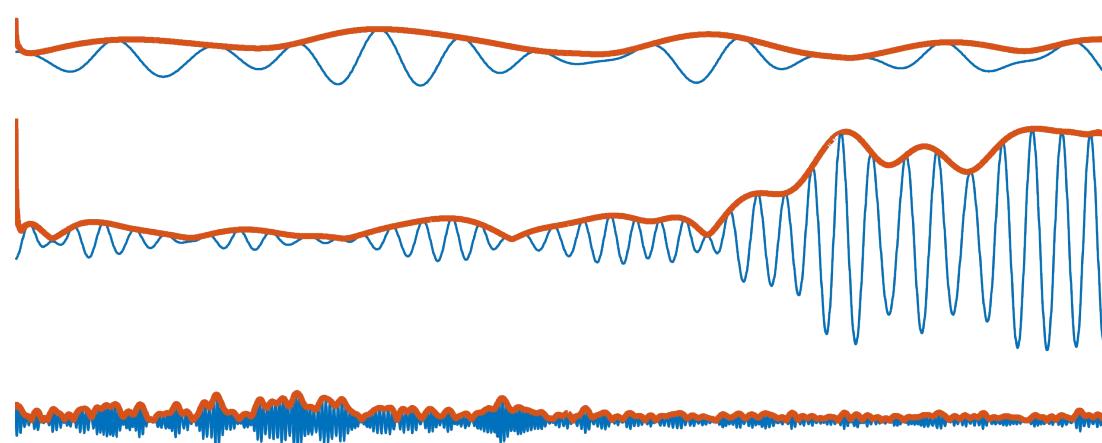
# Summary

## Stationary:

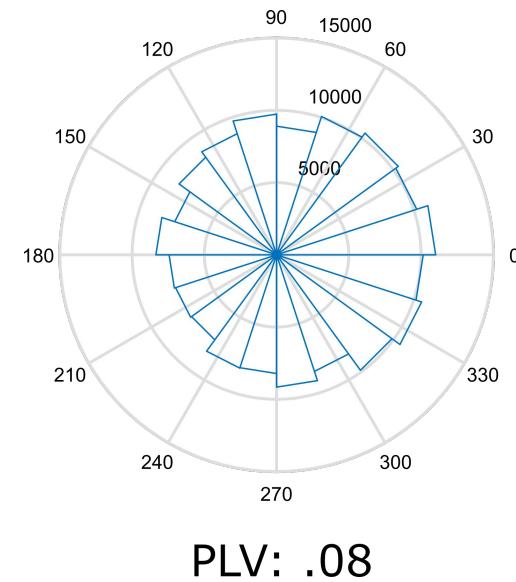
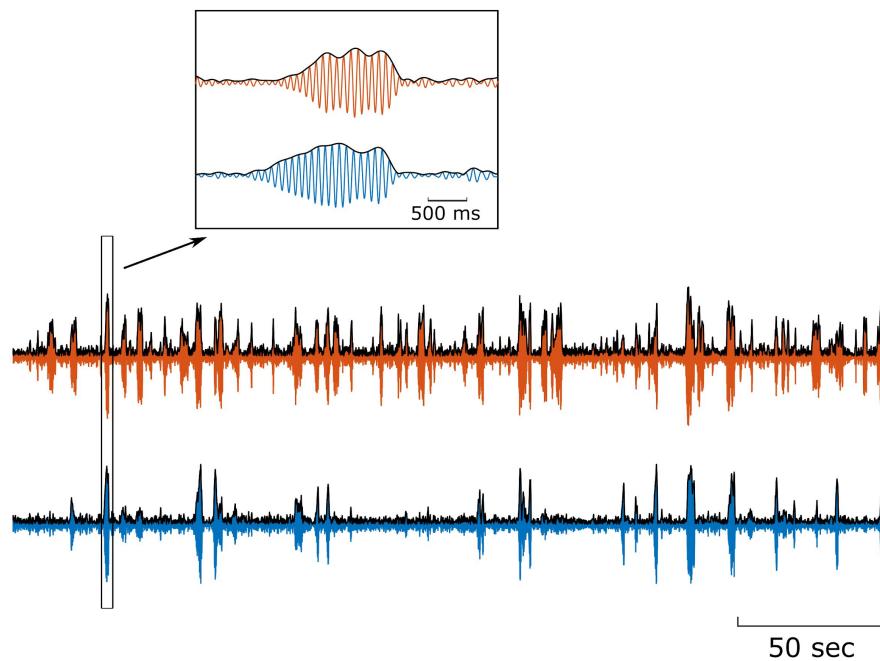
- Fourier transform
- Power spectral density (Welch's method)

## Time-resolved:

- Wavelet transform
- **Filtering & Hilbert transform**



# Summary



## Connectivity:

- Amplitude correlation
- Phase-locking value

