Donders Institute
for Brain, Cognition and Behaviour

Fundamentals of the analysis of neuronal oscillations

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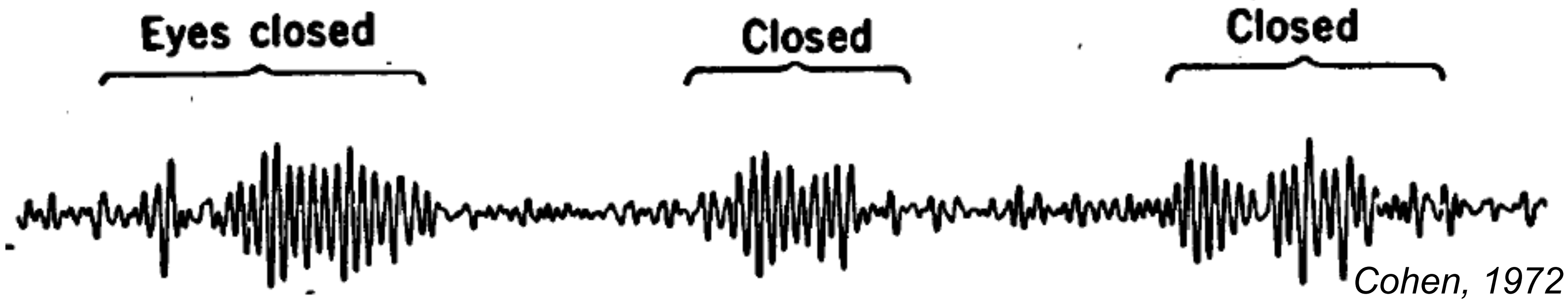
FieldTrip

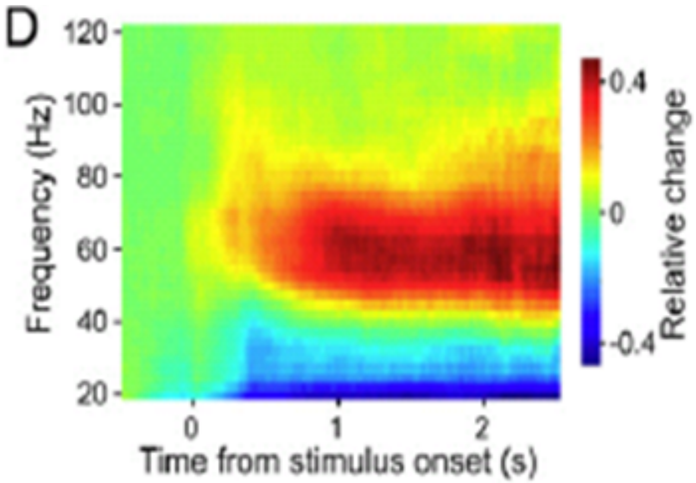
Separating sources

- Use the temporal aspects of the data at the channel level
  - ERF latencies
  - (ERF difference waves)
  - Filtering the time-series
  - Spectral decomposition
- Use the spatial aspects of the data

Brain signals contain oscillatory activity at multiple frequencies



Cohen, 1972

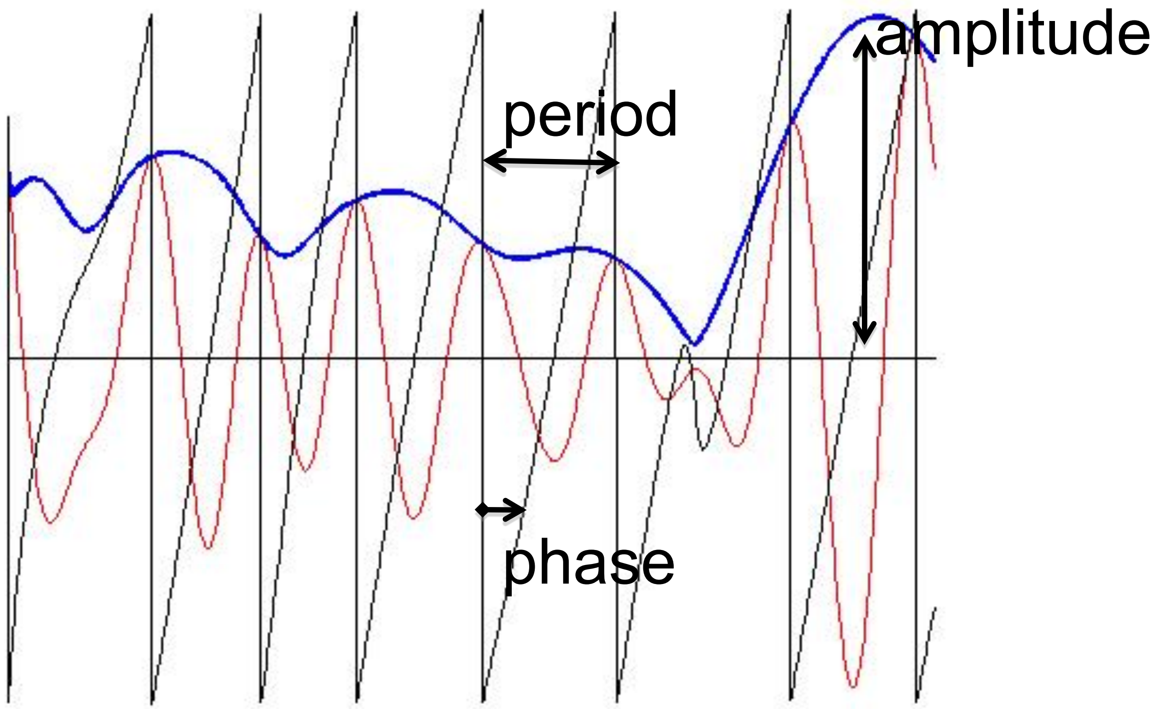


Hoogenboom et al, 2006

Outline

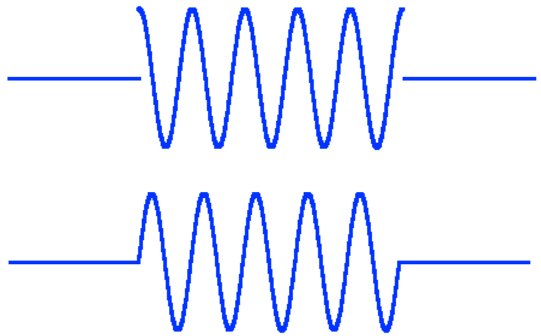
- Spectral analysis: going from time to frequency domain
- Issues with finite and discrete sampling
- Spectral leakage and (multi-)tapering
- Time-frequency analysis

A background note on oscillations

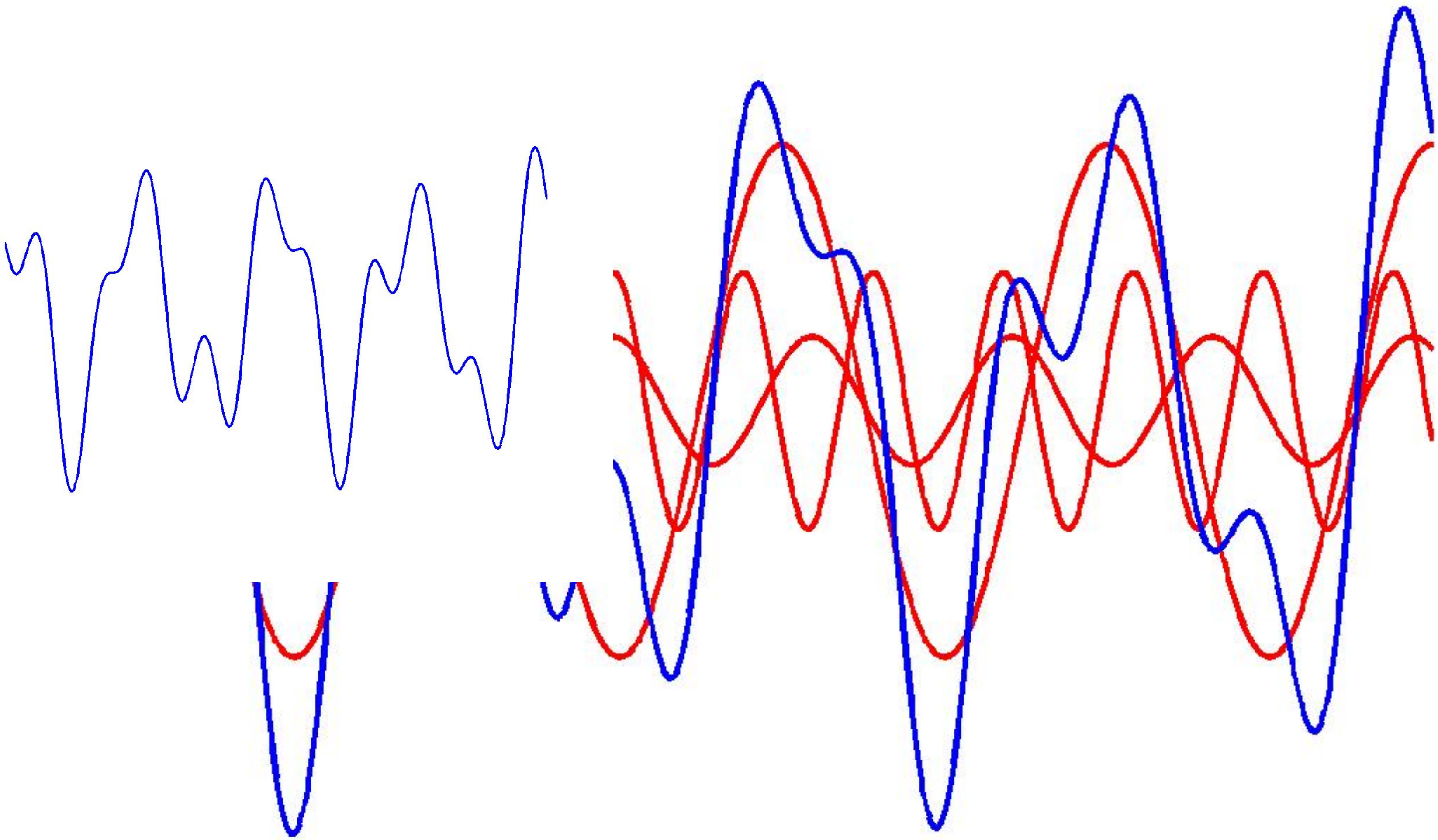


Spectral analysis

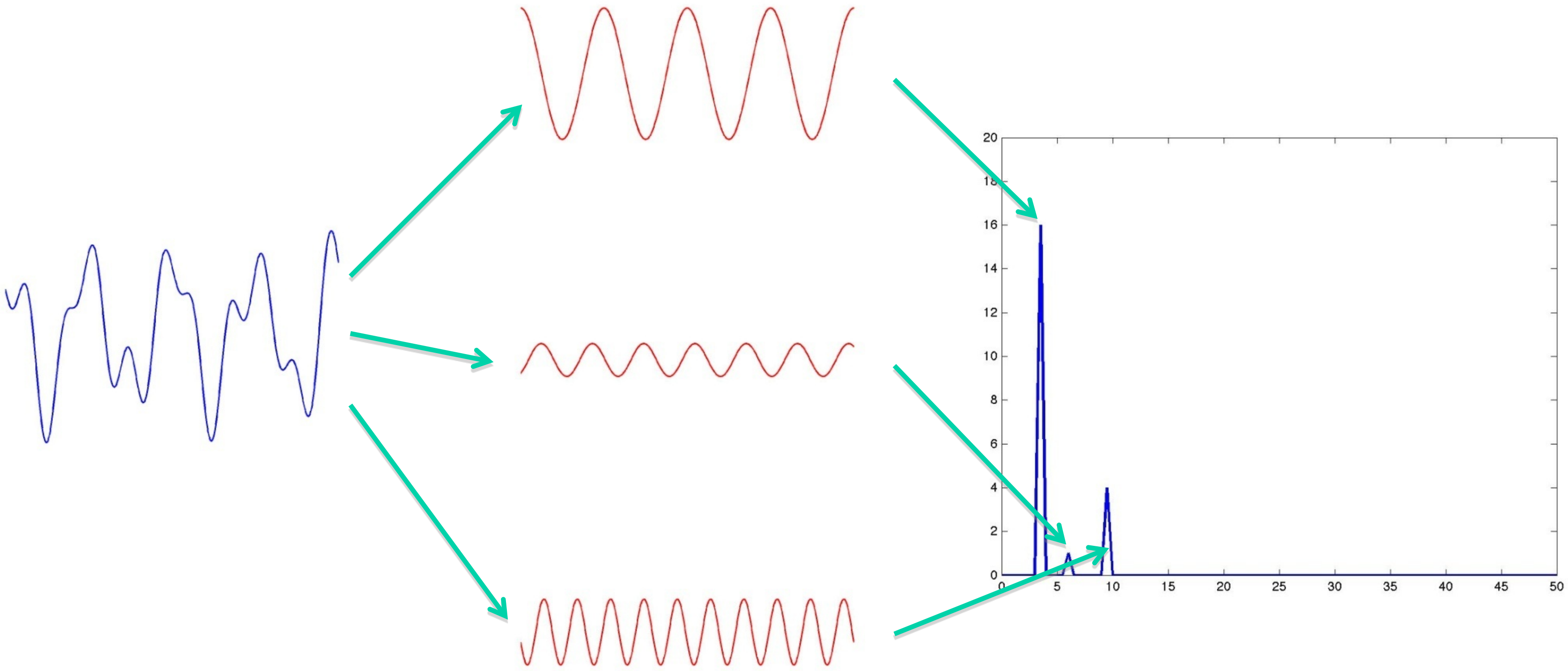
- Deconstructing a time domain signal into its constituent oscillatory components, a.k.a. Fourier analysis
- Using simple oscillatory functions: cosines and sines



Spectral decomposition: the principle



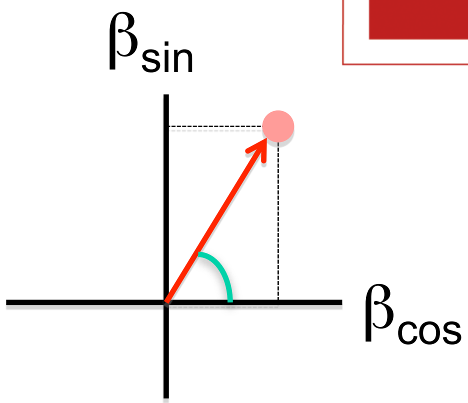
Spectral decomposition: the power spectrum



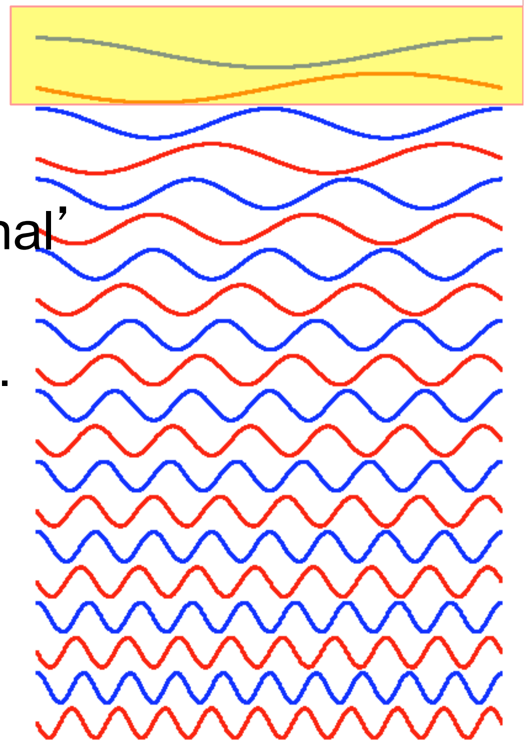
Spectral analysis

- Deconstructing a time domain signal into its constituent oscillatory components, a.k.a. Fourier analysis
- Using simple oscillatory functions: cosines and sines
- Express signal as function of frequency, rather than time
- Concept: linear regression using oscillatory basis functions

Spectral analysis ~ regression



- **Y** = β x **X**
- **X** : set of basis functions
- β_i ~ 'goodness-of-fit' of basis function *i* with data
- β for cosine and sine components for a given frequency map onto amplitude and phase estimate.



- Restriction: basis functions should be 'orthogonal'
- Consequence 1: frequencies not arbitrary -> integer amount of cycles should fit into N points.
- Consequence 2: N-point signal -> N basis functions

Time-frequency relation

- Consequence 1: frequencies not arbitrary -> integer amount of cycles should fit into N points (of length T).
- The frequency resolution is determined by the length of the data segments (T)
- Rayleigh frequency = 1/T = Δf = frequency resolution

Time window: 1 s → **Frequencies: (0) 1 2 3 4 5 6 .. Hz**

Time window: 0.2 s → **Frequencies: (0) 5 10 15 20 .. Hz**

Time-frequency relation

- Consequence 2: N-point signal -> N basis functions
- N basis functions -> N/2 frequencies
- The highest frequency that can be resolved depends on the sampling frequency F
- Nyquist frequency = F/2

Sampling freq 1 kHz

Time window 1 s

→

Frequencies:

(0) 1 2 … 499 500 Hz

Sampling freq 400 Hz

Time window 0.25 s

→

Frequencies:

(0) 4 8... 196 200 Hz

Spectral analysis

- Deconstructing a time domain signal into its constituent oscillatory components, a.k.a. Fourier analysis
- Using simple oscillatory functions: cosines and sines
- Express signal as function of frequency, rather than time
- Concept: linear regression using oscillatory basis functions
- Each oscillatory component has an amplitude and phase
- Discrete and finite sampling constrains the frequency axis

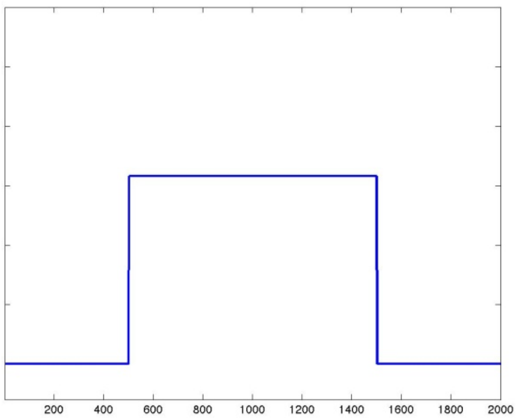
Goal and challenges

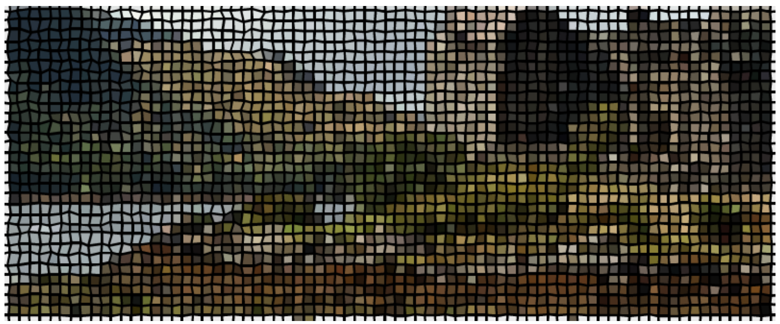
- Estimate the true oscillations from the observed data
- Limited time available for Fourier transform
- You are looking at the activity through a time restricting window

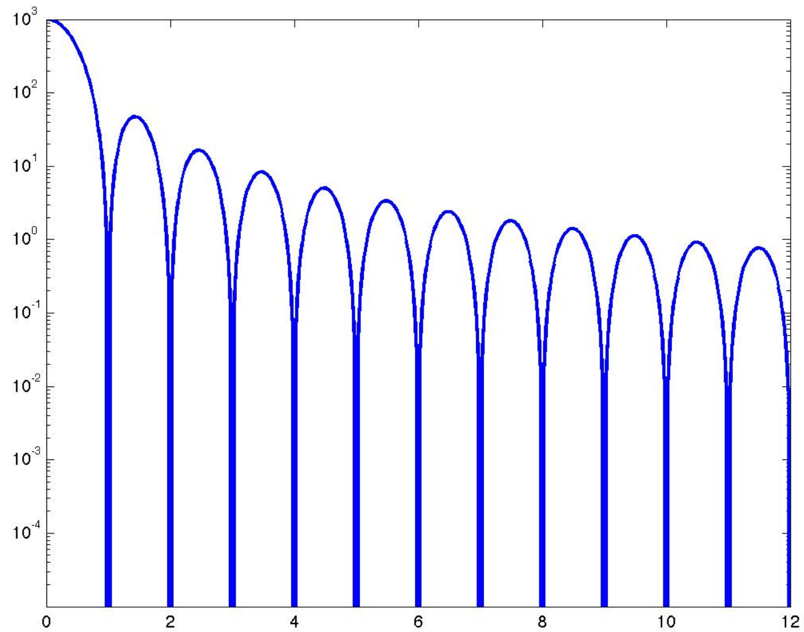
- This implicitly means that the data are ‘tapered’ with a boxcar
- Data are discretely sampled

Spectral leakage and tapering

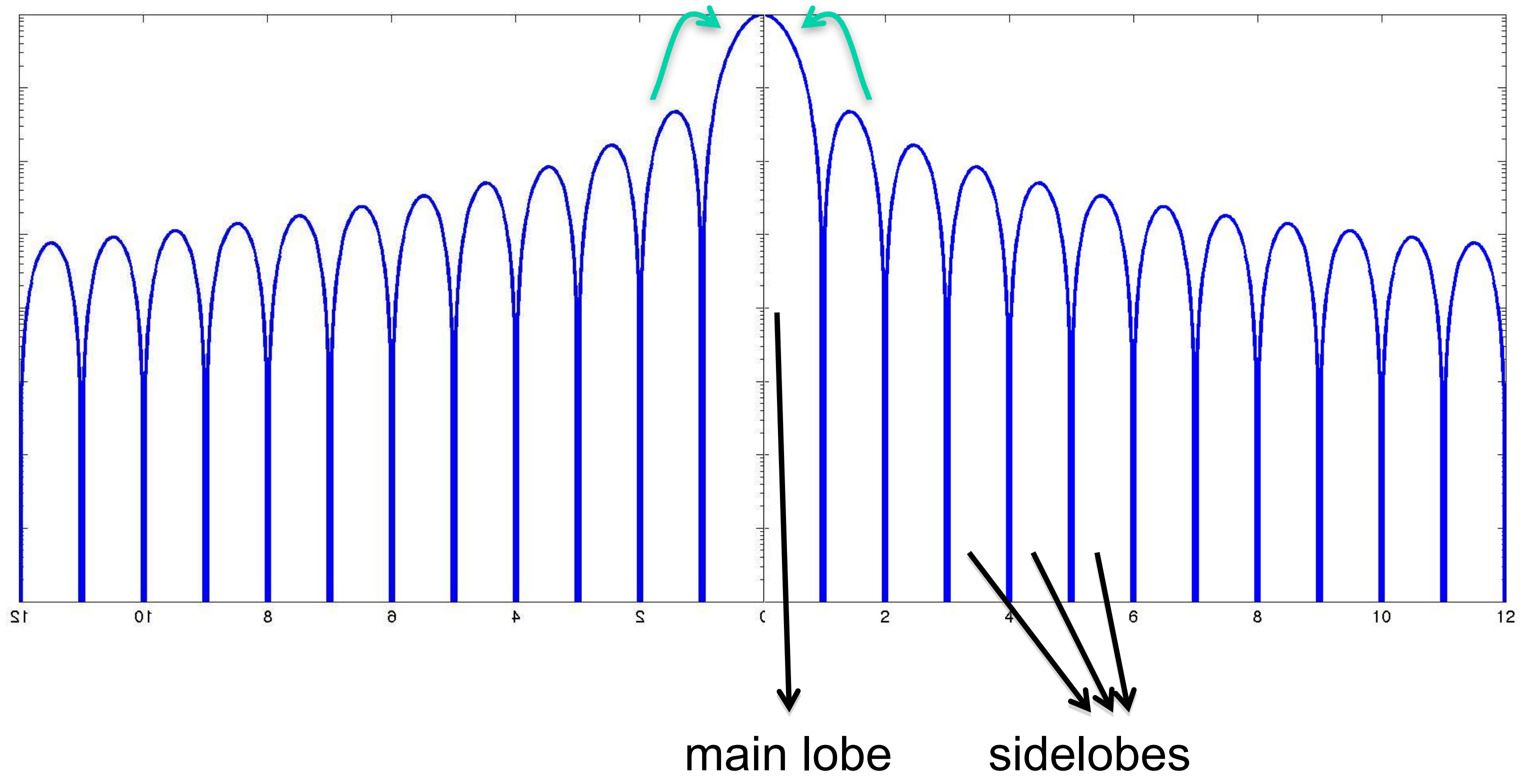
- True oscillations in data at frequencies **not sampled** with Fourier transform **spread their energy** to the sampled frequencies
- Not tapering = applying a boxcar taper
- Each type of taper has a specific leakage profile



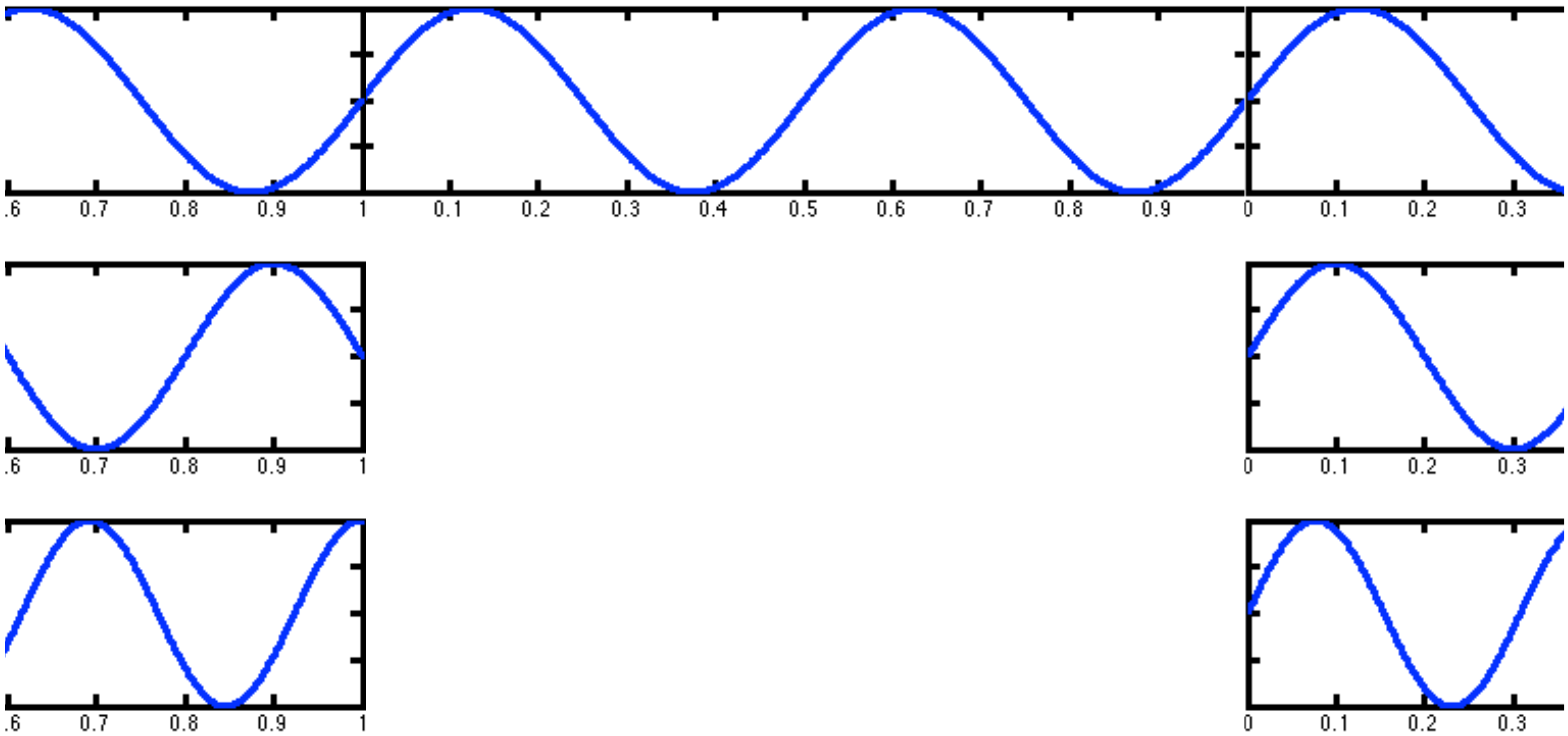




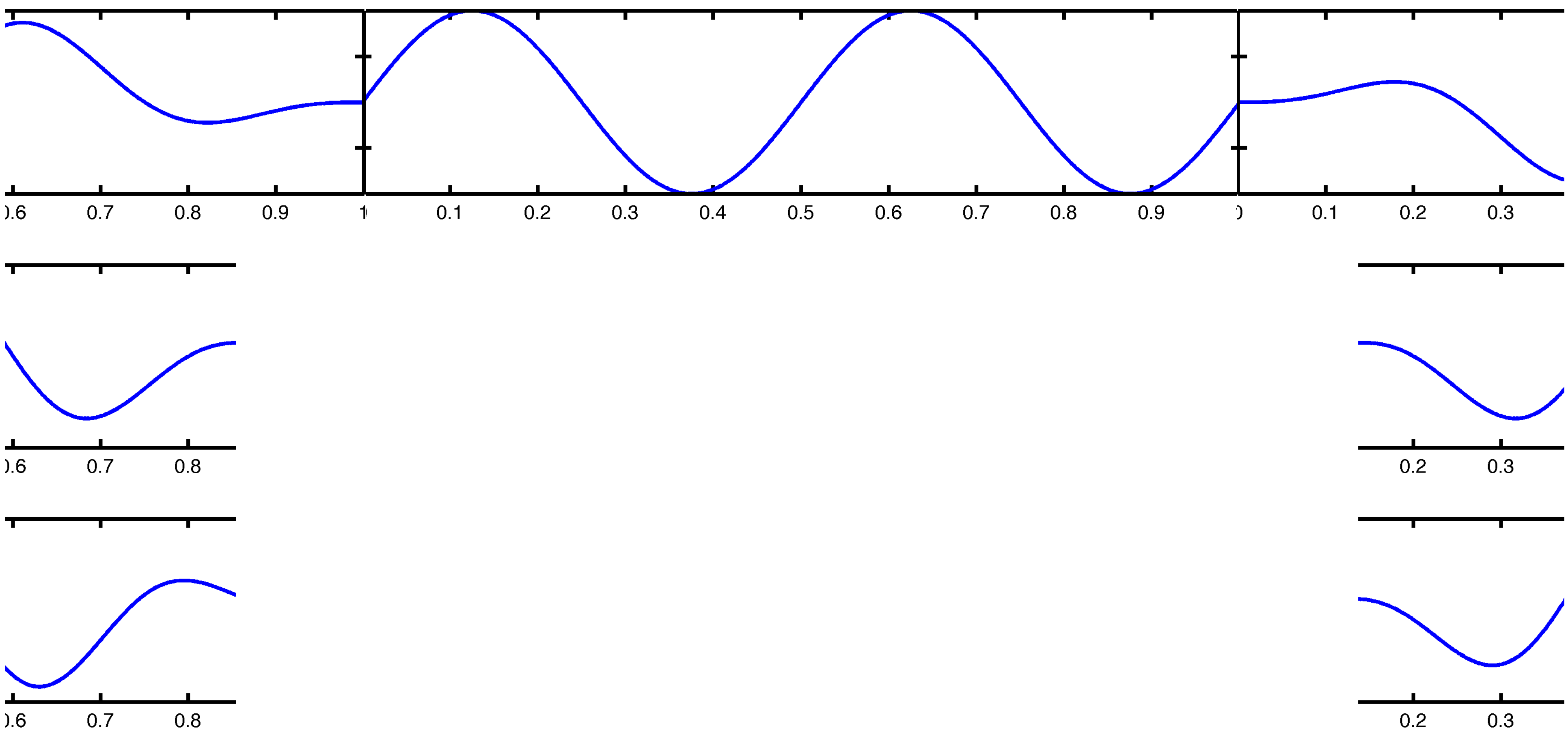
Spectral leakage



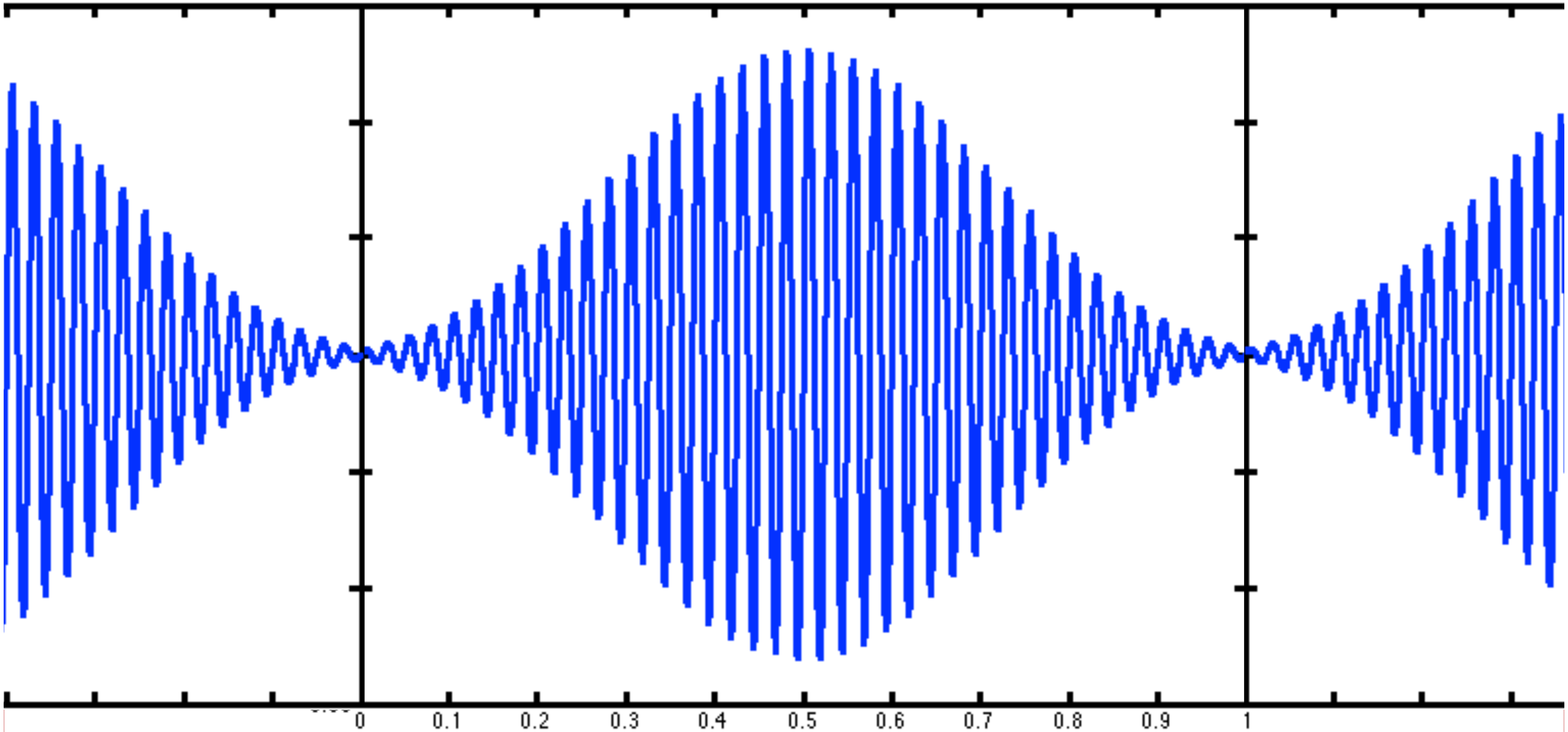
Tapering in spectral analysis



Tapering in spectral analysis



Tapering in spectral analysis



Spectral leakage and tapering

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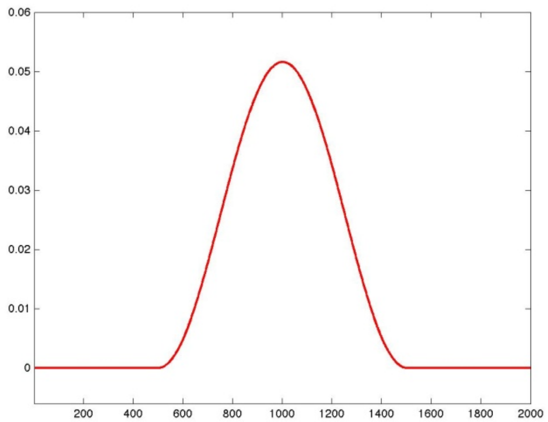
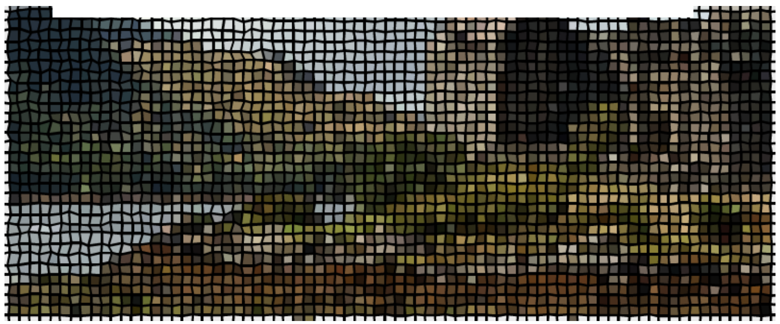
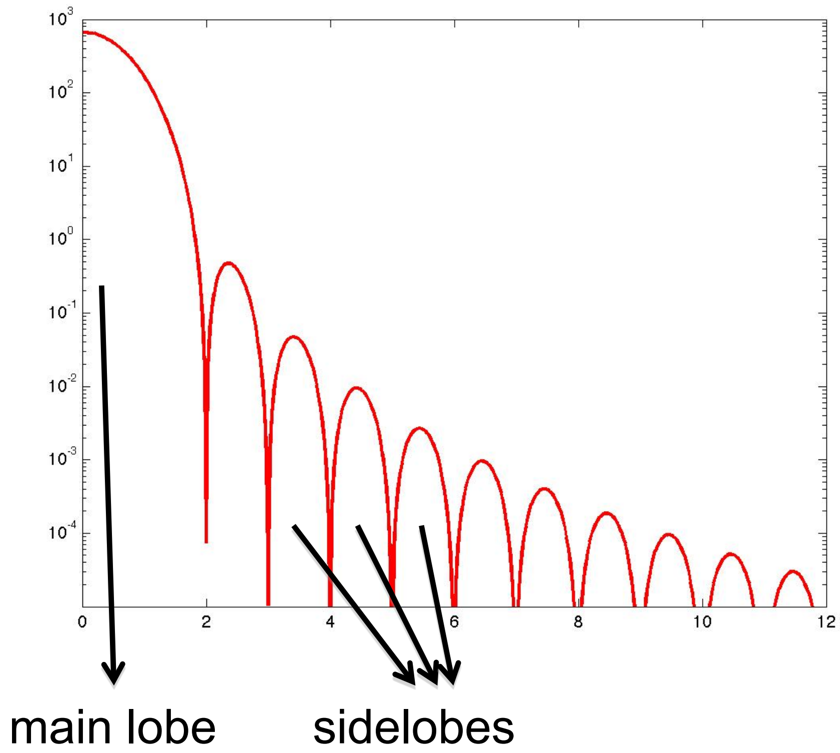


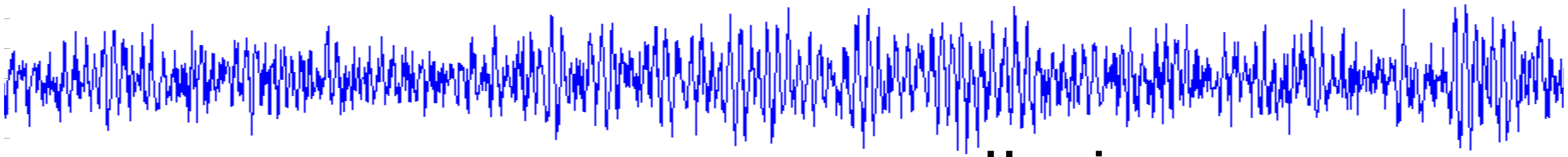




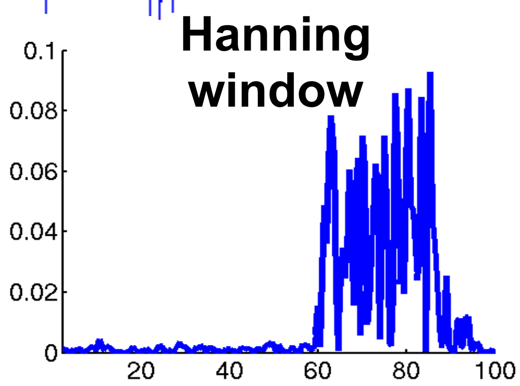
Multitapers

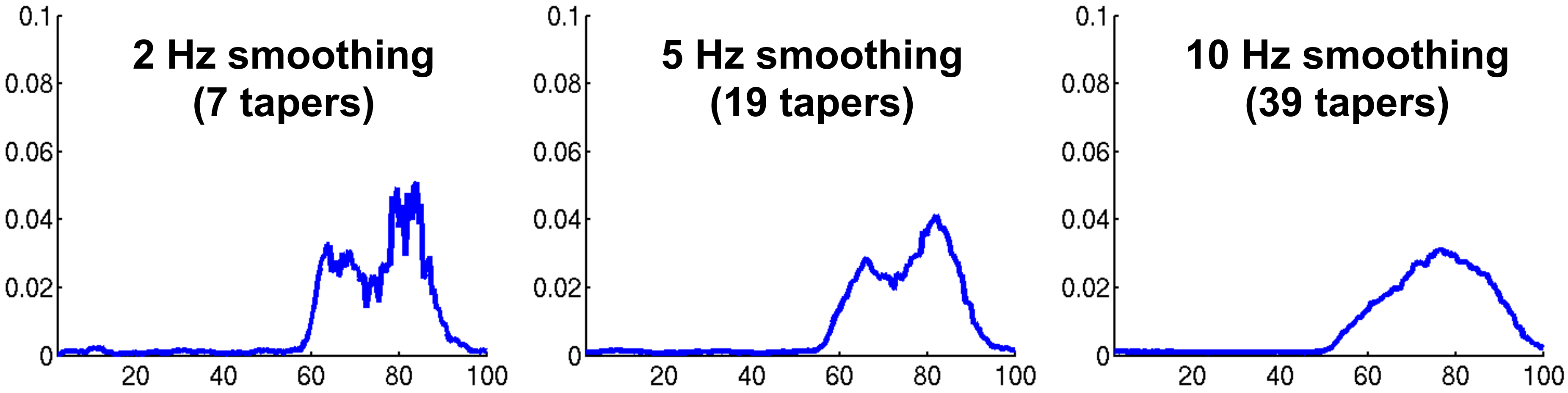
- Make use of more than one taper and combine their properties
- Used for smoothing in the frequency domain
- Instead of “smoothing” one can also say “controlled leakage”

Multitapered spectral analysis



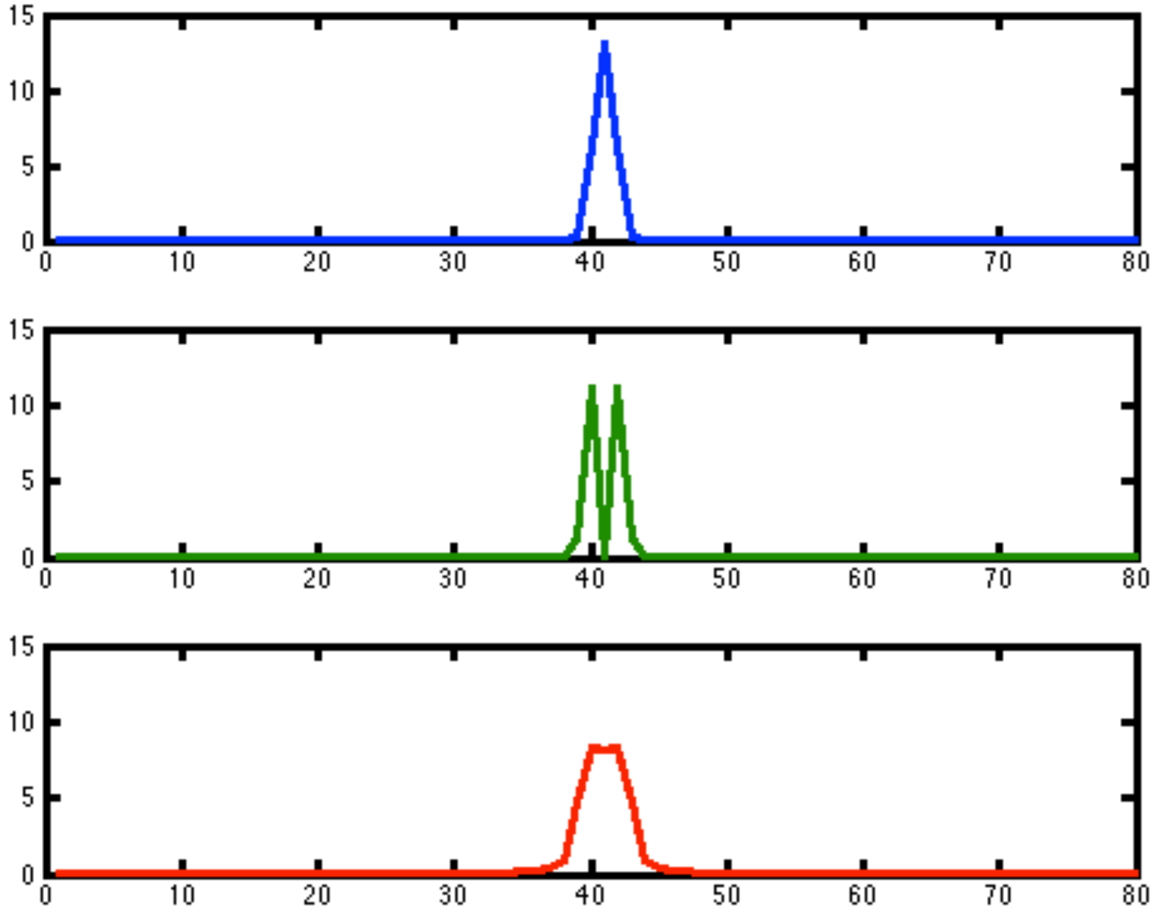
broadband activity between 60-90 Hz



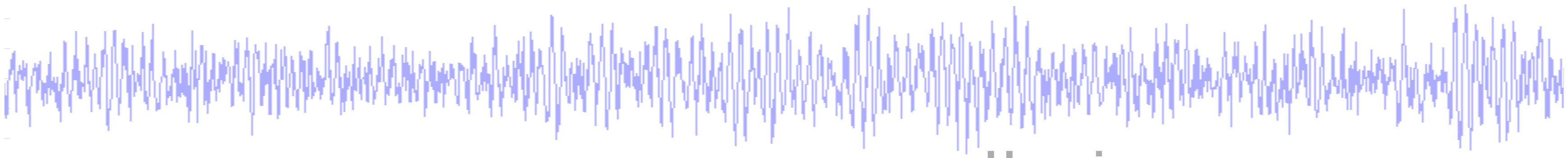


Mitra & Pesaran, 1999, Biophys

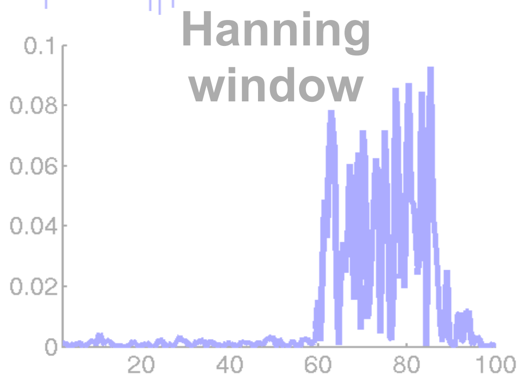
Multitapered spectral analysis

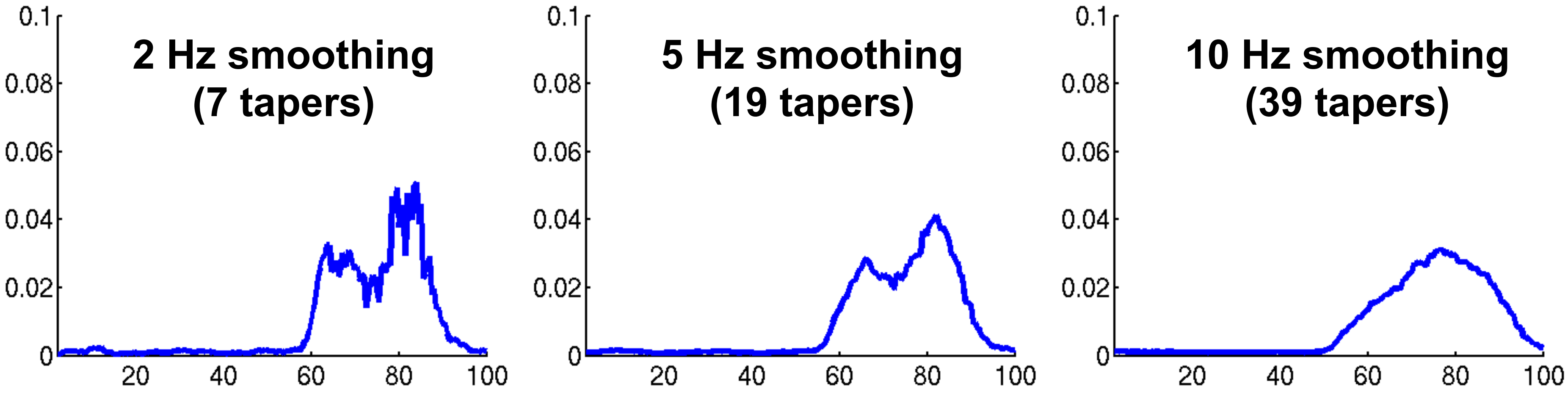


Multitapered spectral analysis



broadband activity
between 60-90 Hz





Multitapers

- Multitapers are useful for reliable estimation of high frequency components
- Low frequency components are better estimated using a single (Hanning) taper

```
%estimate low frequencies

cfg  = [];
cfg.method = 'mtmfft';
cfg.foilim = [1 30];
cfg.taper  = 'hanning';
      .
      .
      .
freq=ft_freqanalysis(cfg, data);
```

```
%estimate high frequencies

cfg  = [];
cfg.method     = 'mtmfft';
cfg.foilim     = [30 120];
cfg.taper      = 'dpss';
cfg.tapsmofrq = 8;
      .
      .
freq=ft_freqanalysis(cfg, data);
```

Sub summary

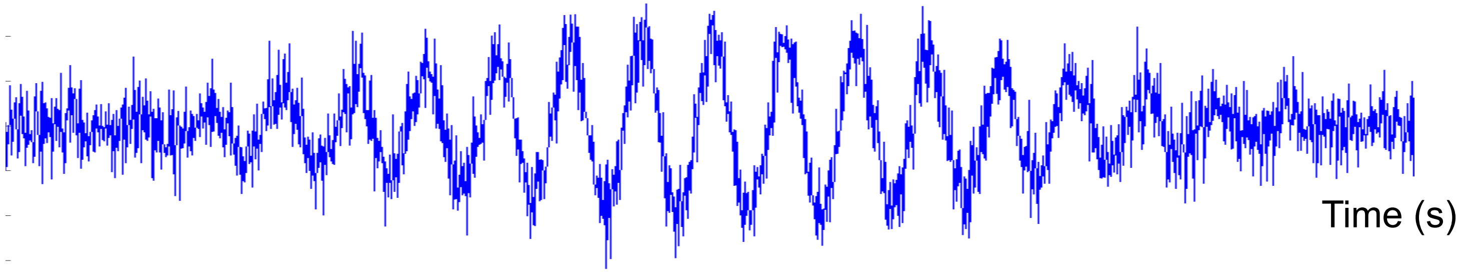
- Spectral analysis
  - Decompose signal into its constituent oscillatory components
  - Focused on 'stationary' power
- Tapers
  - Boxcar, Hanning, Gaussian
- Multitapers
  - Control spectral leakage/smoothing

Time-frequency analysis

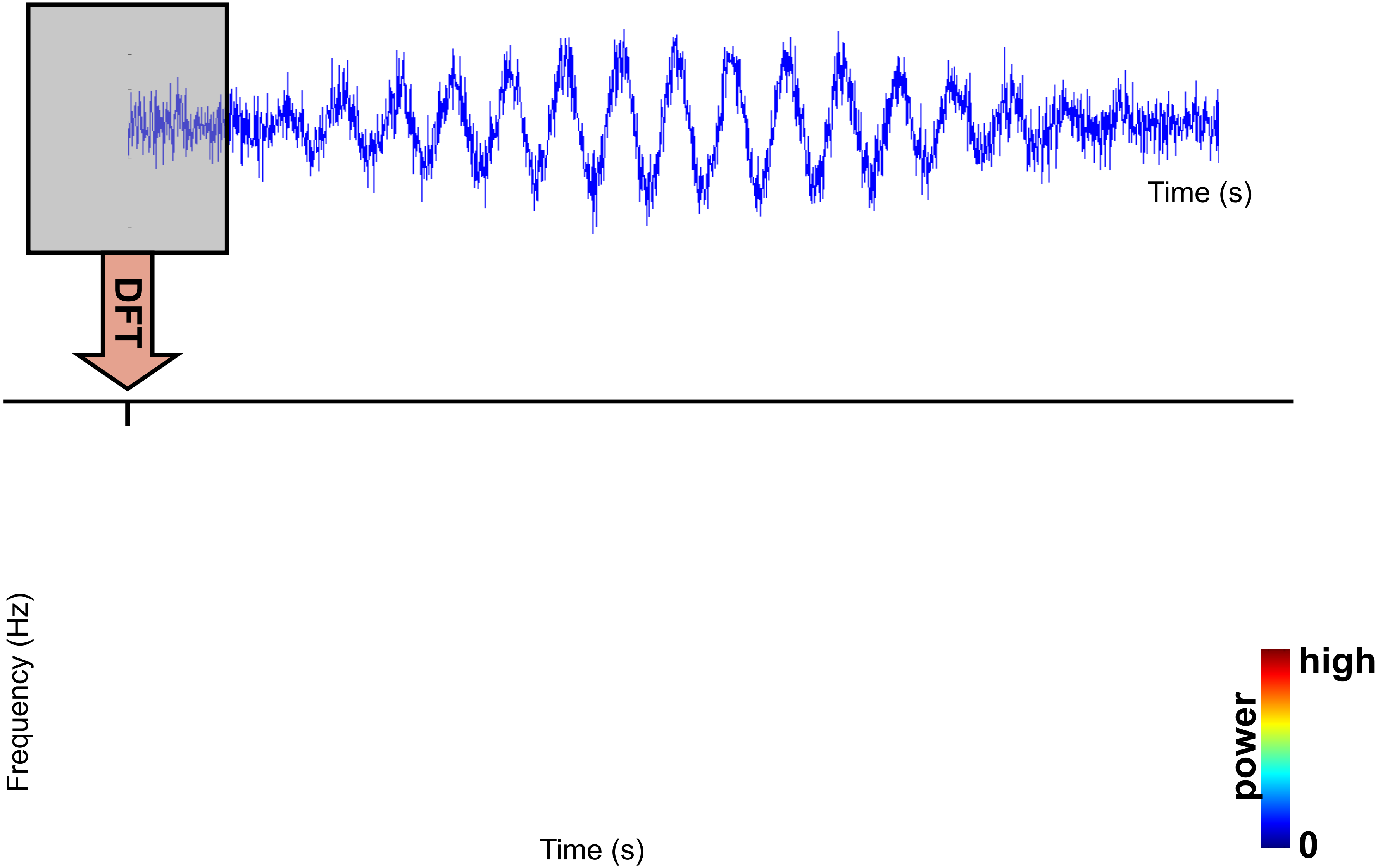
- Typically, brain signals are not ‘stationary’
- Divide the measured signal in shorter time segments and apply Fourier analysis to each signal segment
- Everything we saw so far with respect to frequency resolution applies here as well

```
cfg   = [];
cfg.method = 'mtmconvol';
      .
      .
      .
freq = ft_freqanalysis(cfg, data);
```

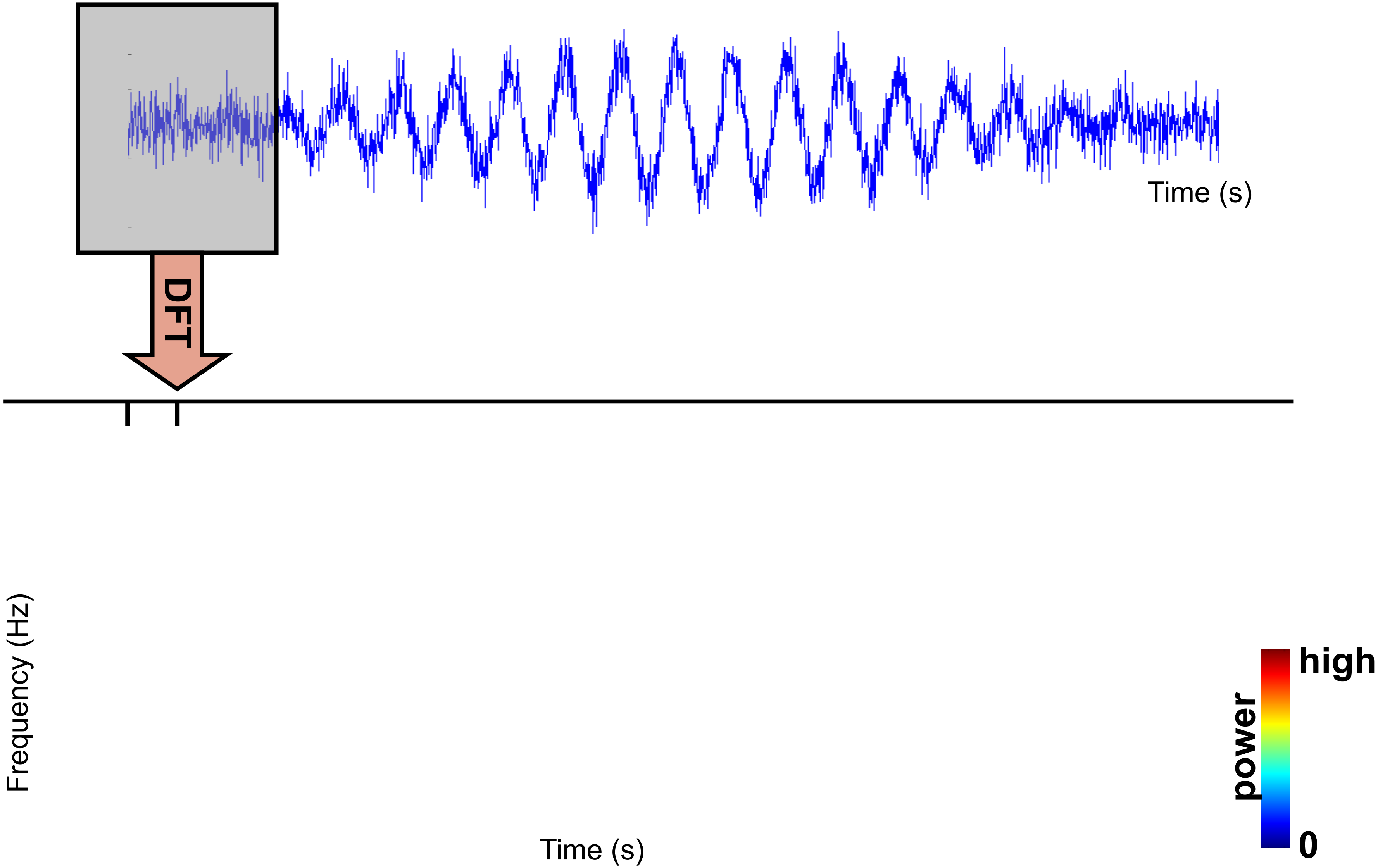
Time frequency analysis



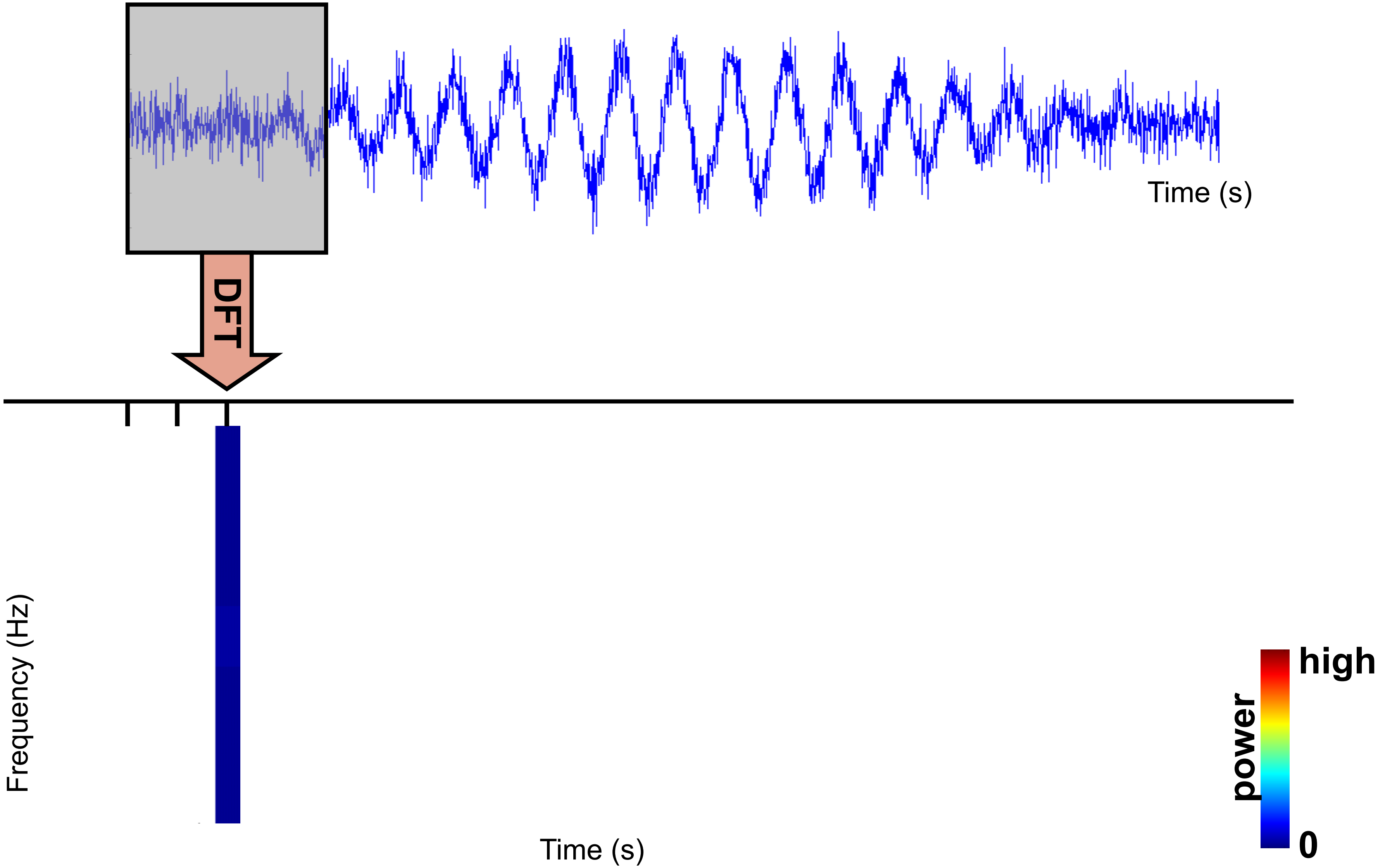
Time frequency analysis



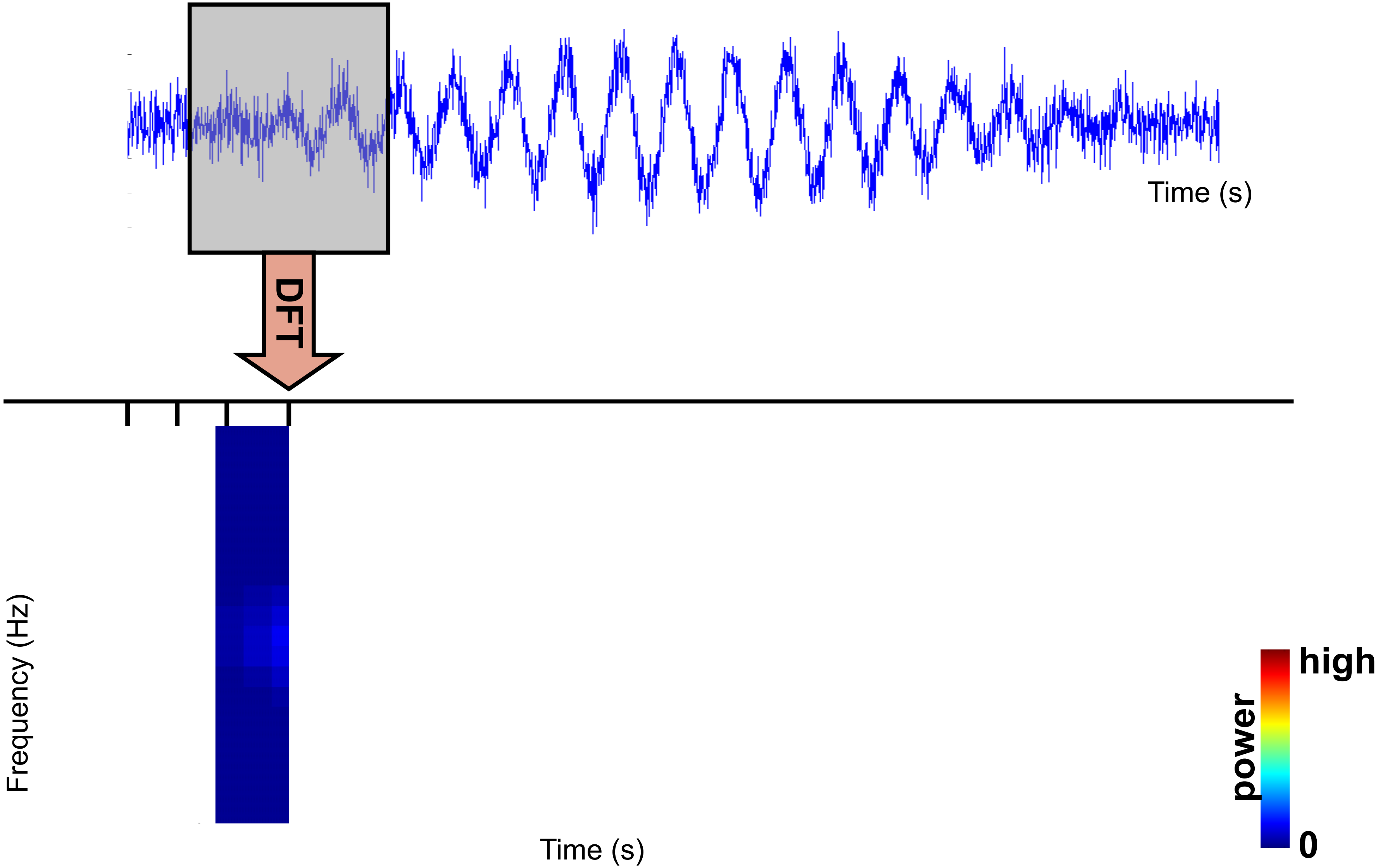
Time frequency analysis



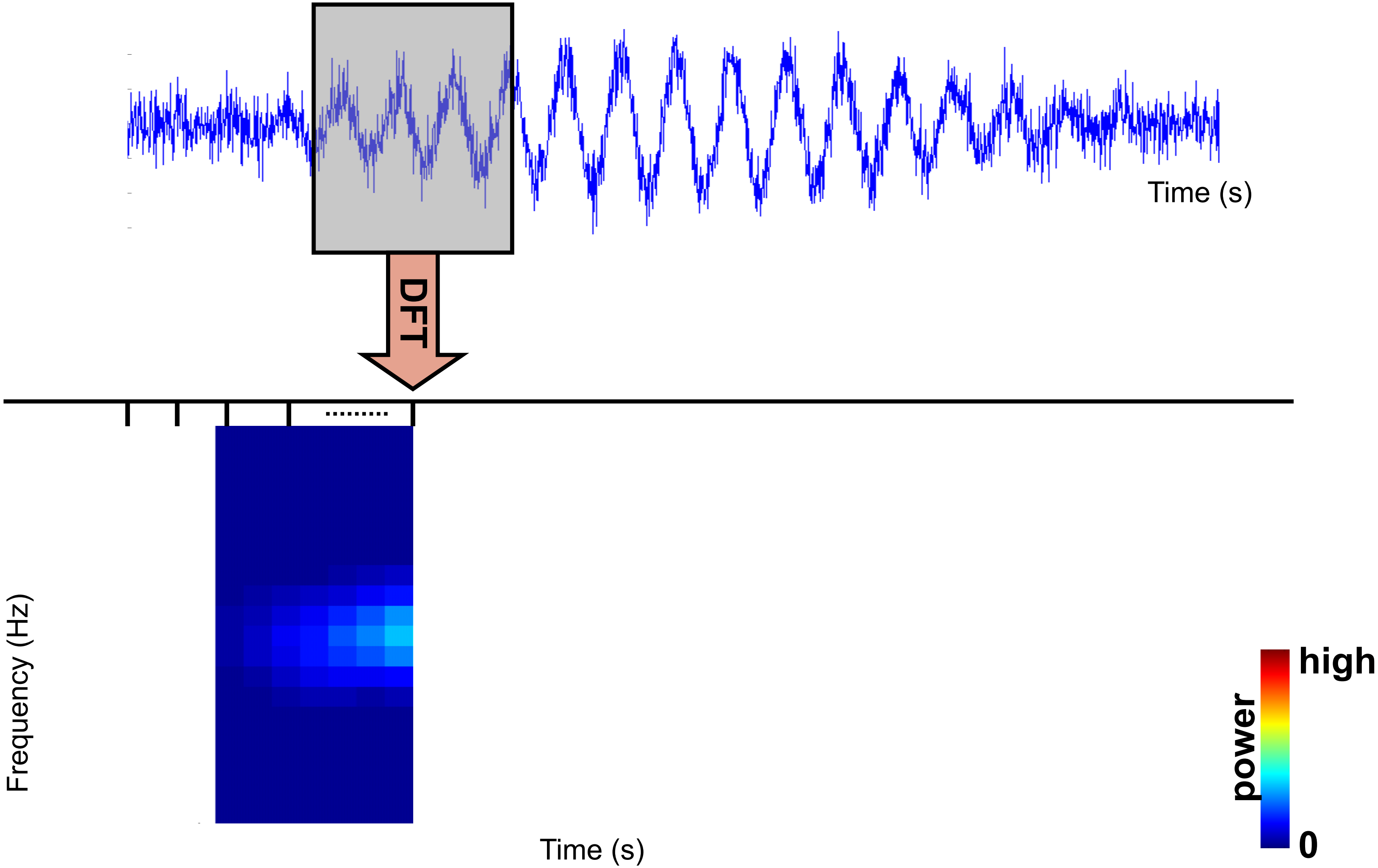
Time frequency analysis



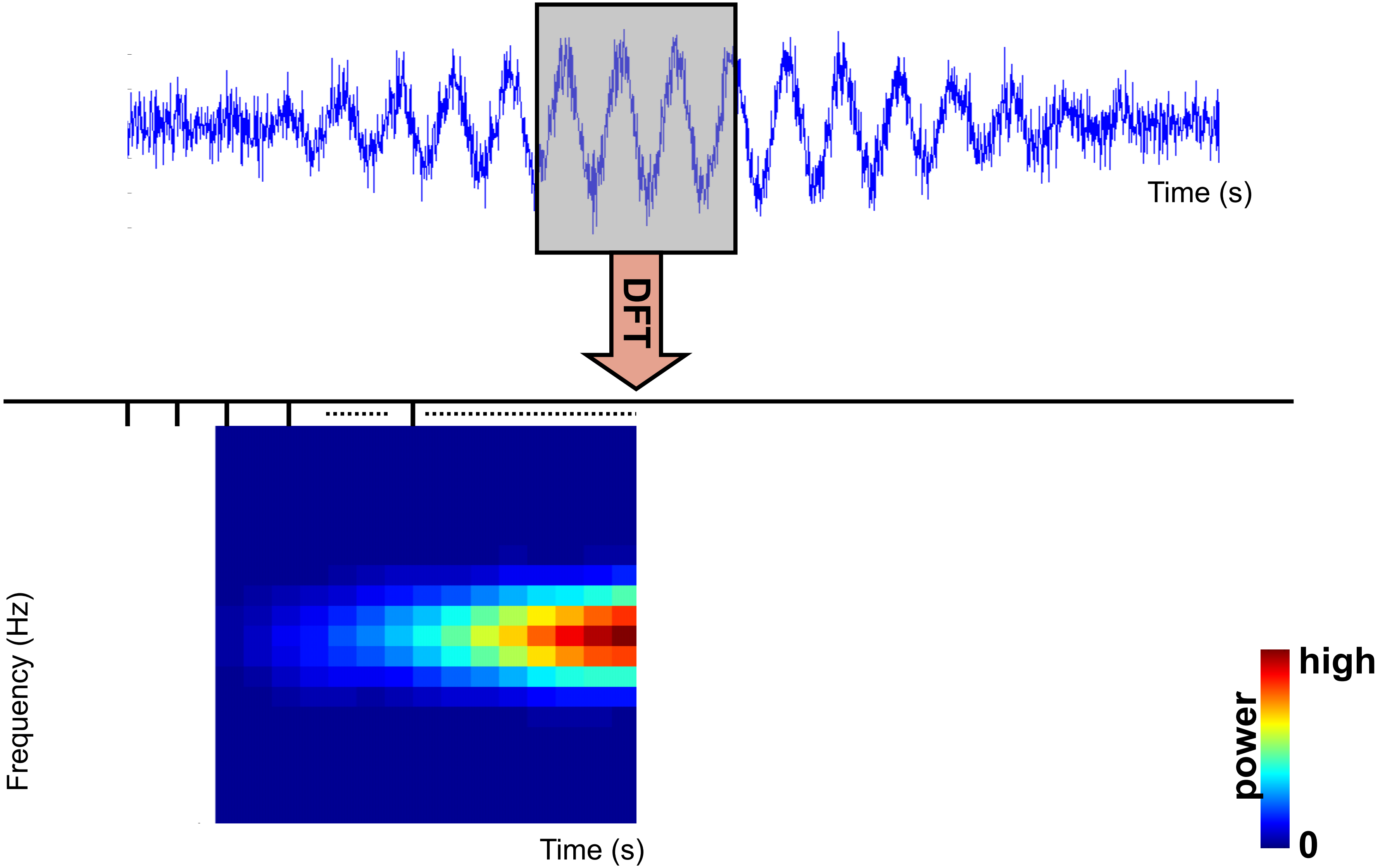
Time frequency analysis



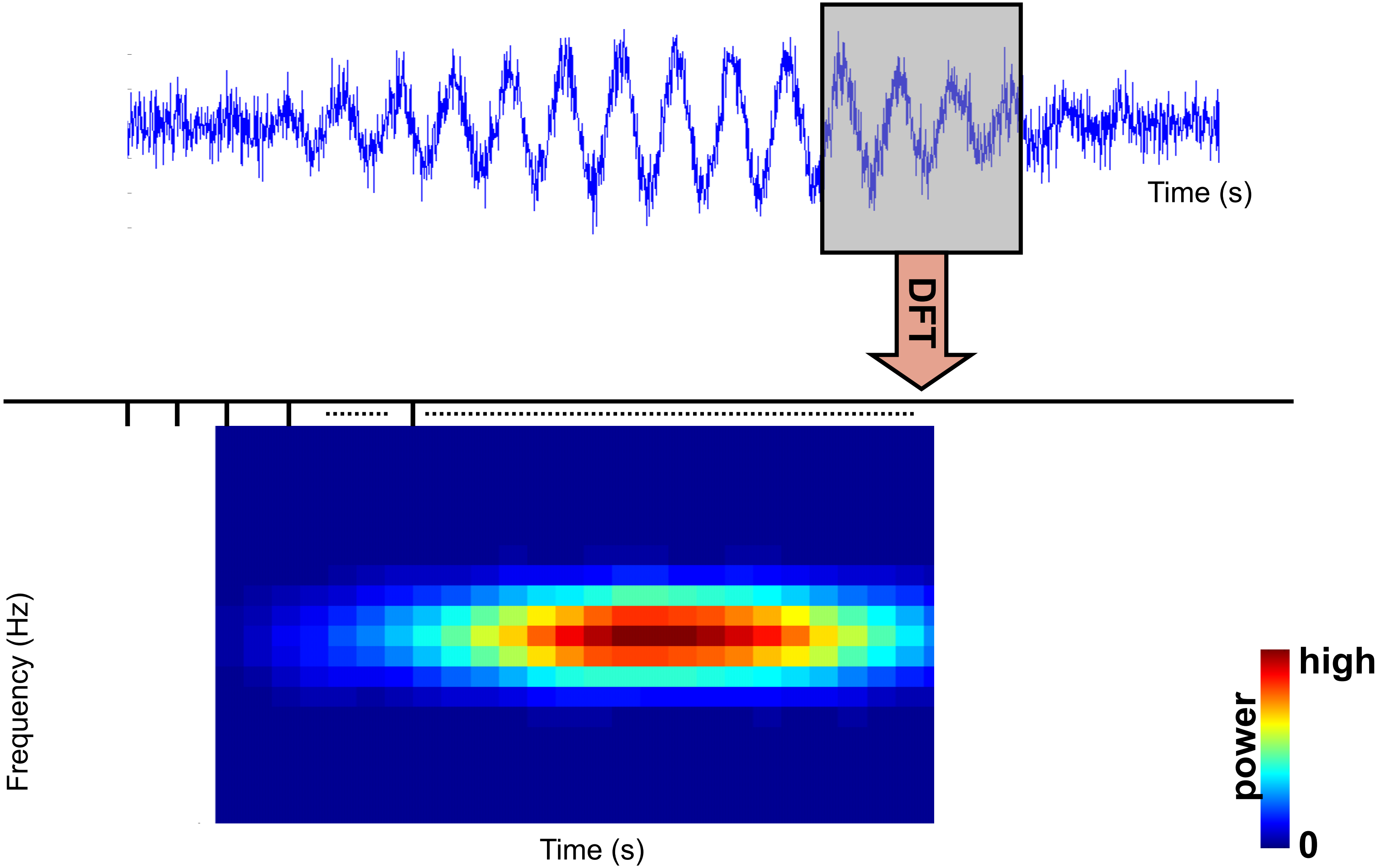
Time frequency analysis



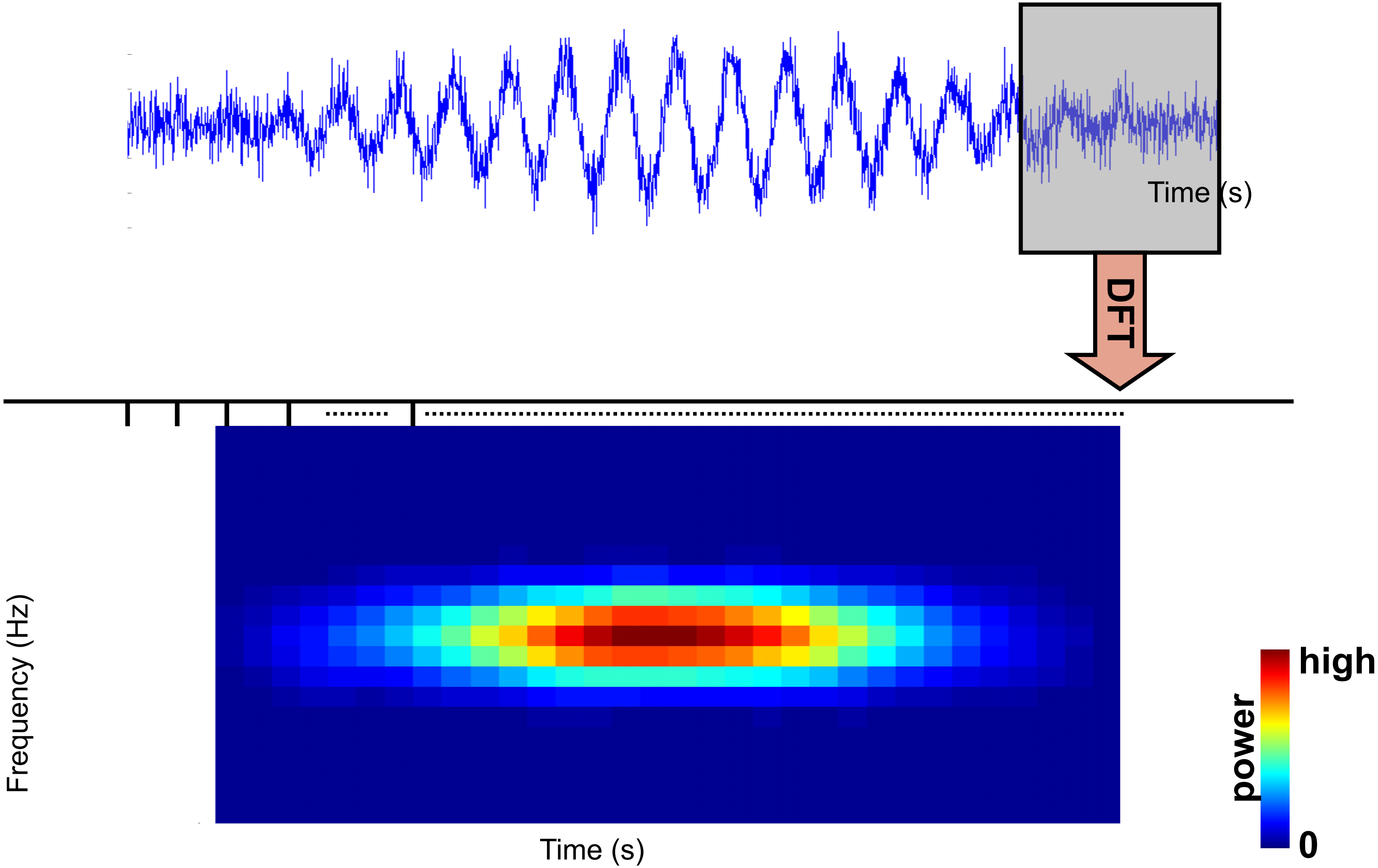
Time frequency analysis



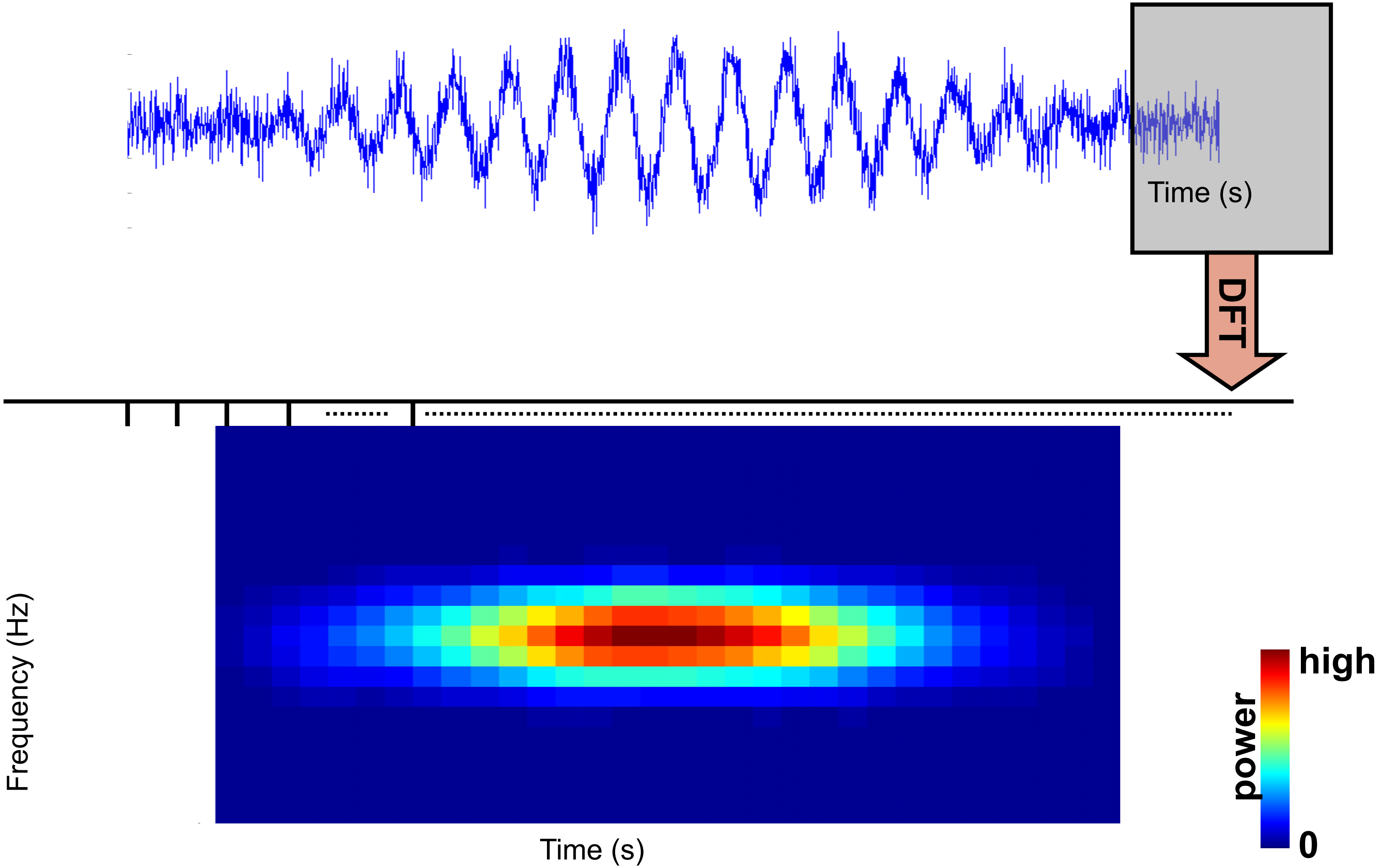
Time frequency analysis



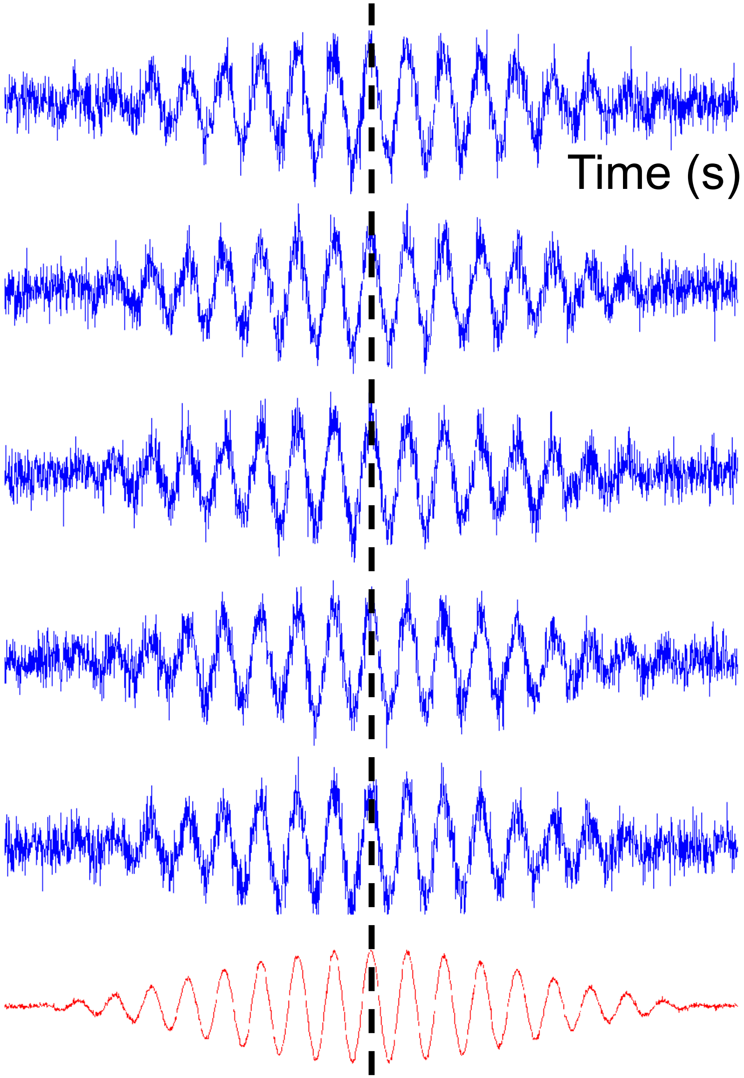
Time frequency analysis

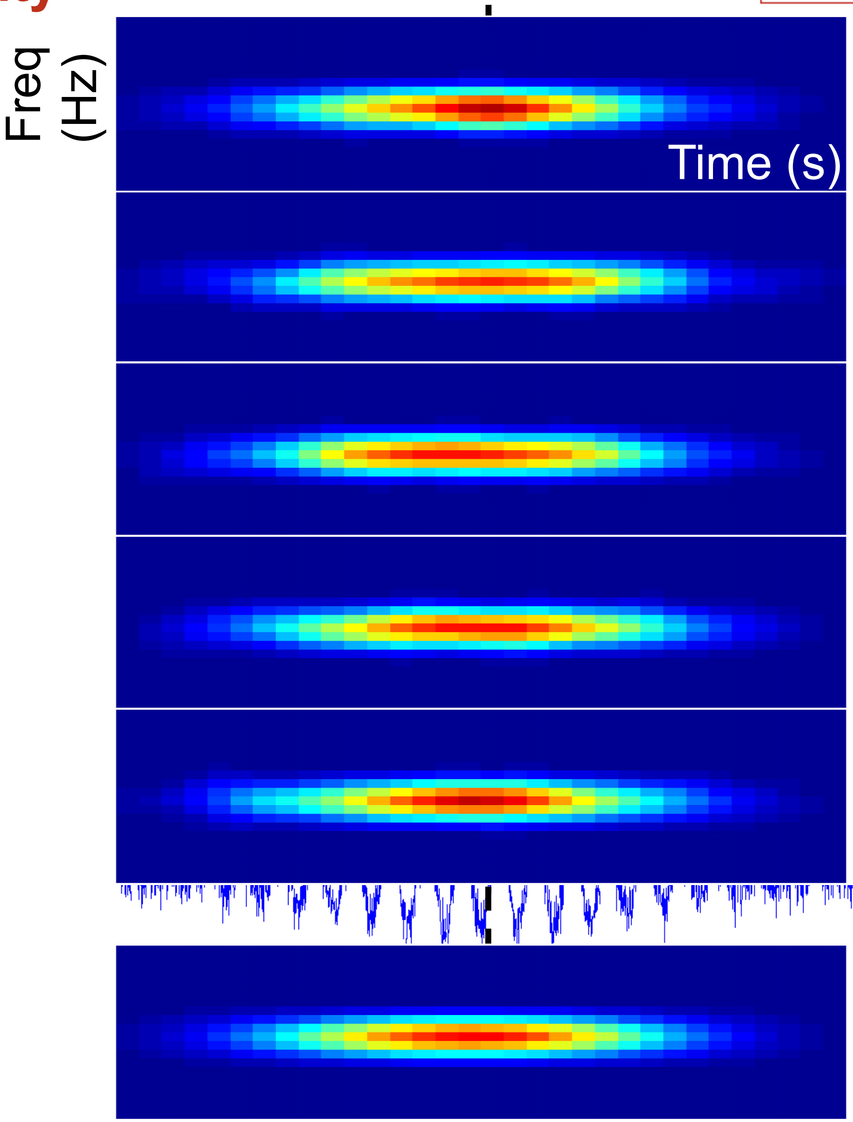


Time frequency analysis

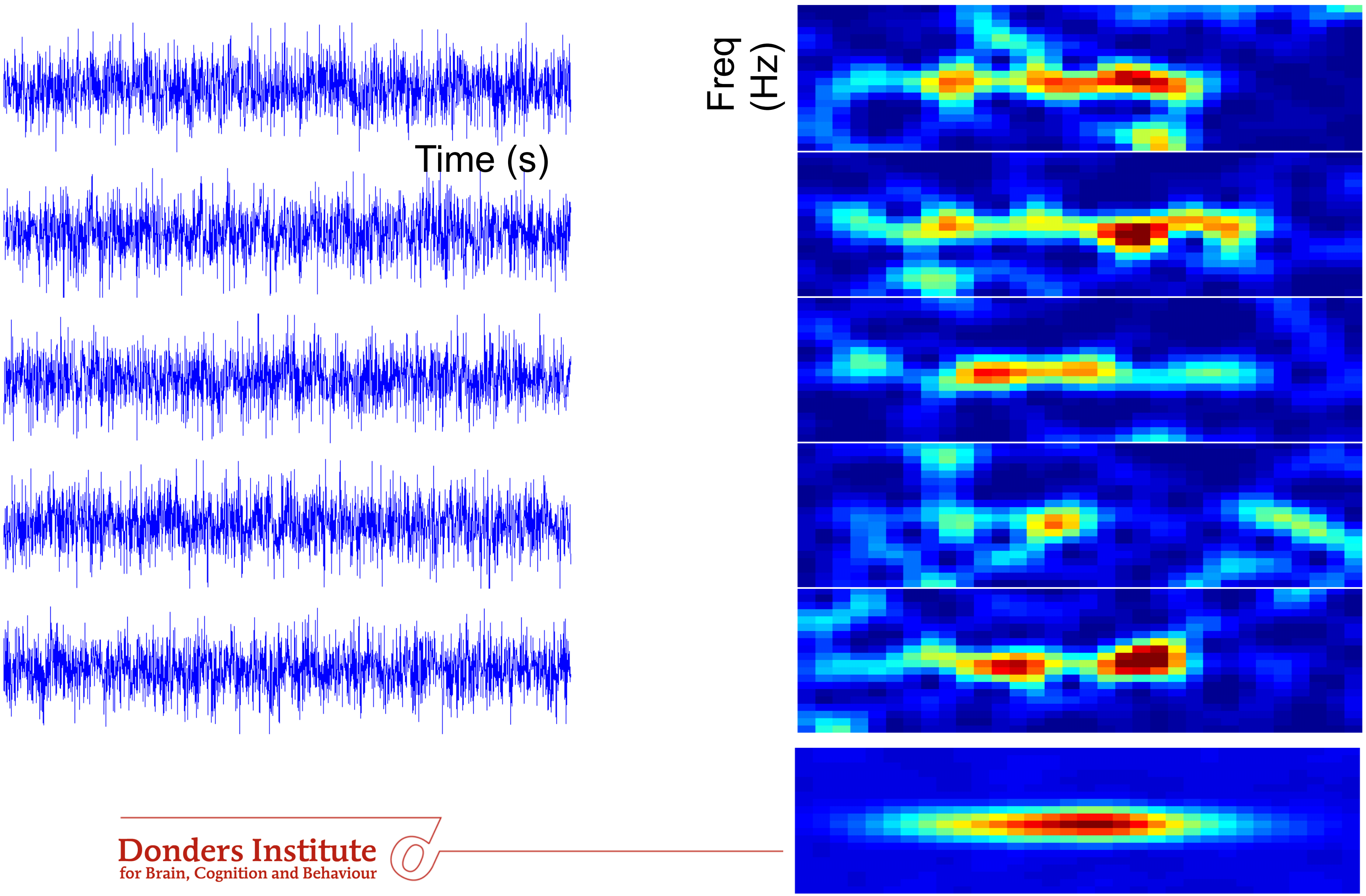


Evoked versus induced activity

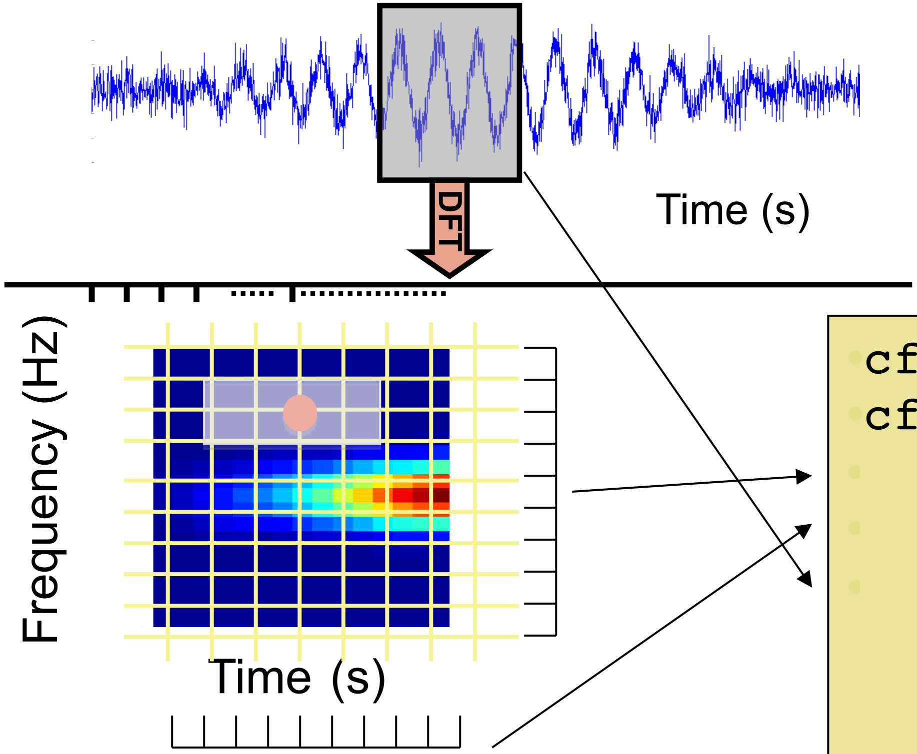




Noisy signal -> many trials needed



The time-frequency plane



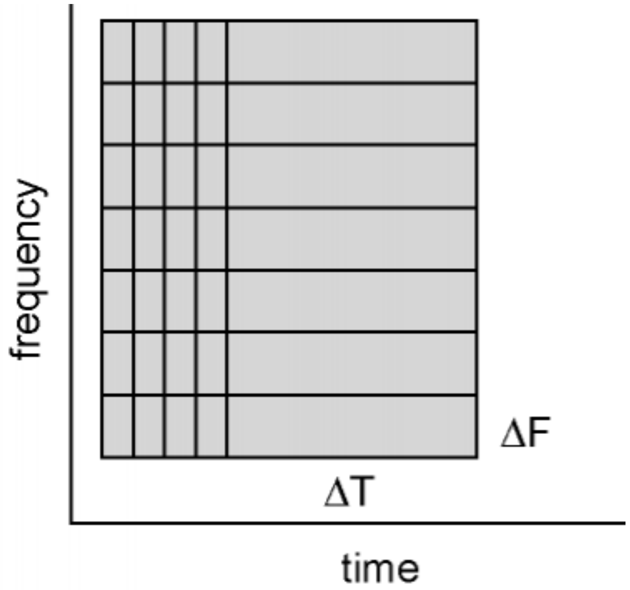

```
cfg  = [];
cfg.method = 'mtmconvol';



              .
              .
              .
freq = freqanalysis(cfg, data);
```

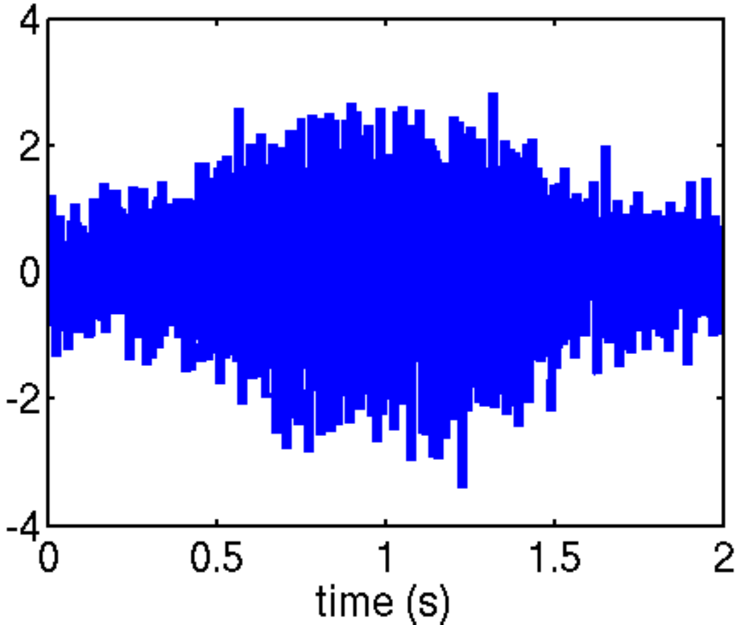
The time-frequency plane

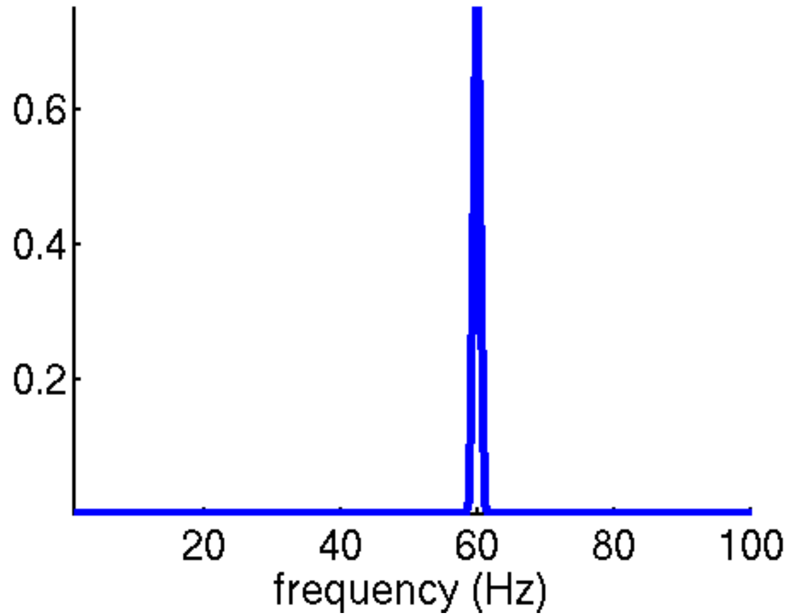
- Division is ‘up to you’
- Depends on the phenomenon you want to investigate
  - Which frequency band?
  - Which time scale?




```
cfg   = [];
cfg.method      = ‘mtmconvol’;
cfg.foi         = [2 4 … 40];
cfg.toi         = [0:0.050:1.0];
cfg.t_ftimwin = [0.5 0.5 … 0.5];
cfg.tapsmofrq = [4 4 … 4];
          .
          .
freq = freqanalysis(cfg, data);
```

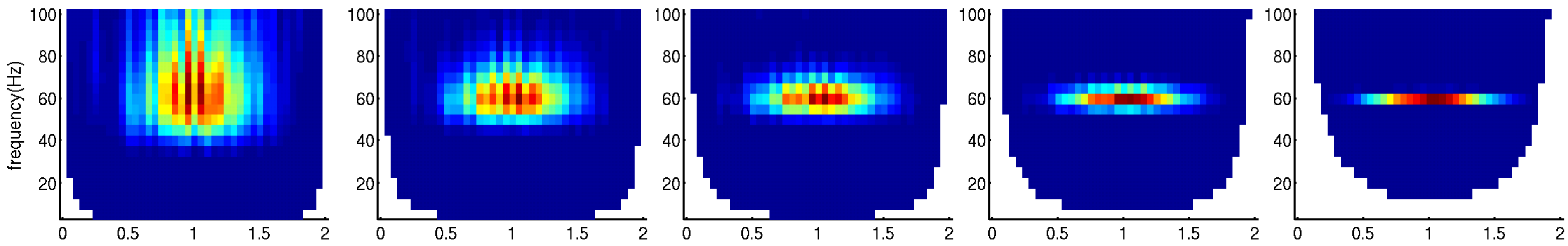
Time versus frequency resolution





short timewindow

long timewindow



Sub summary

- Time frequency analysis
  - Fourier analysis on shorter sliding time window
- Evoked & Induced activity
- Time frequency resolution trade off

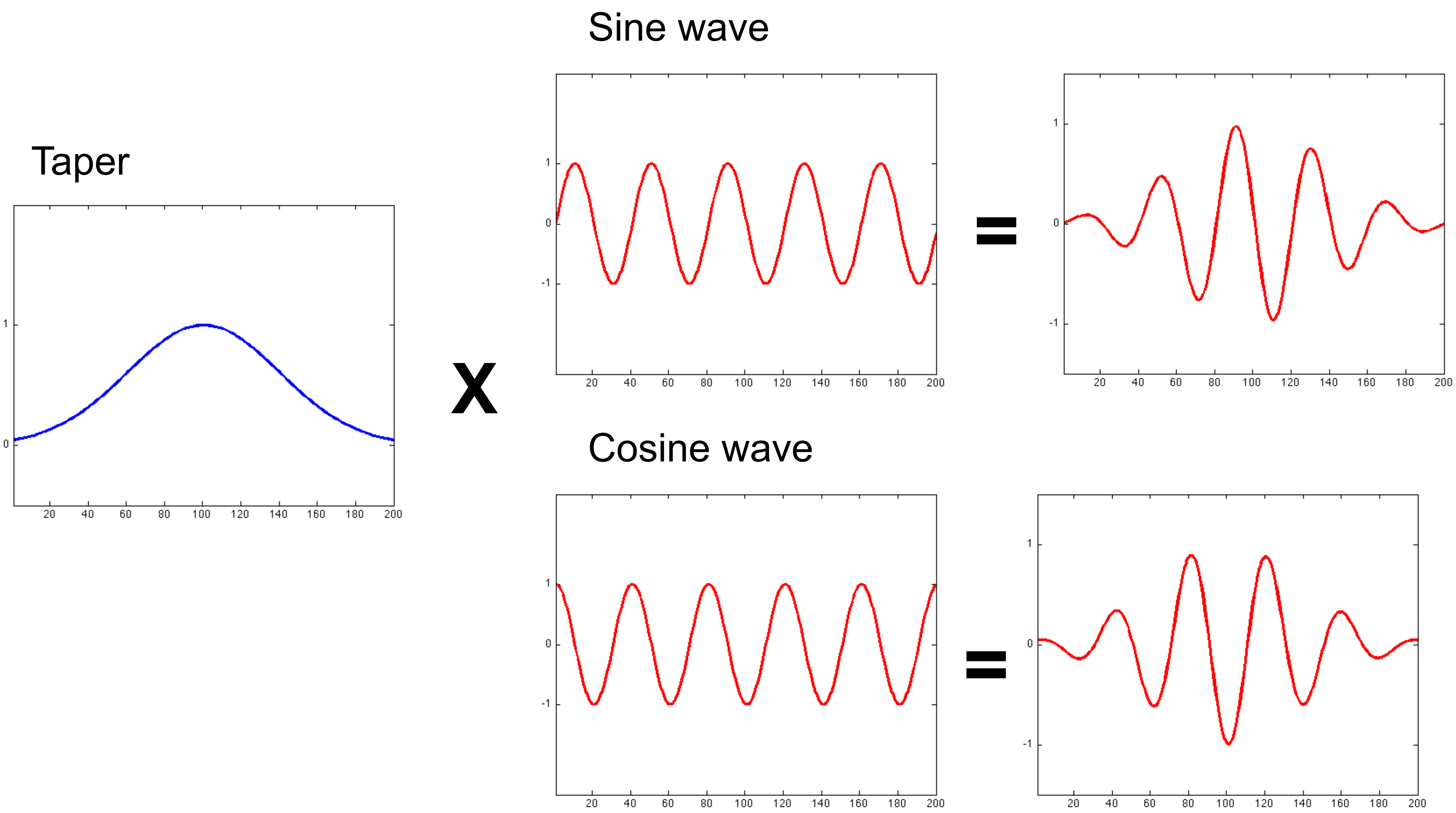
Wavelet analysis

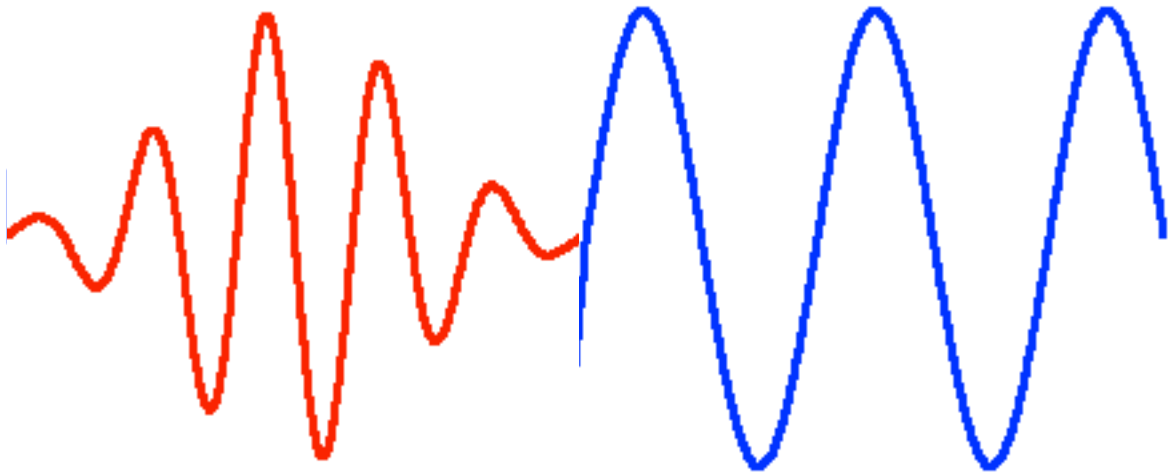
- Popular method to calculate time-frequency representations
- Is based on convolution of signal with a family of ‘wavelets’ which capture different frequency components in the signal
- Convolution ~ local correlation

Wavelet analysis

```
cfg  = [];
cfg.method =  'wavelet';
       .
       .
       .
freq=ft_freqanalysis(cfg, data);
```

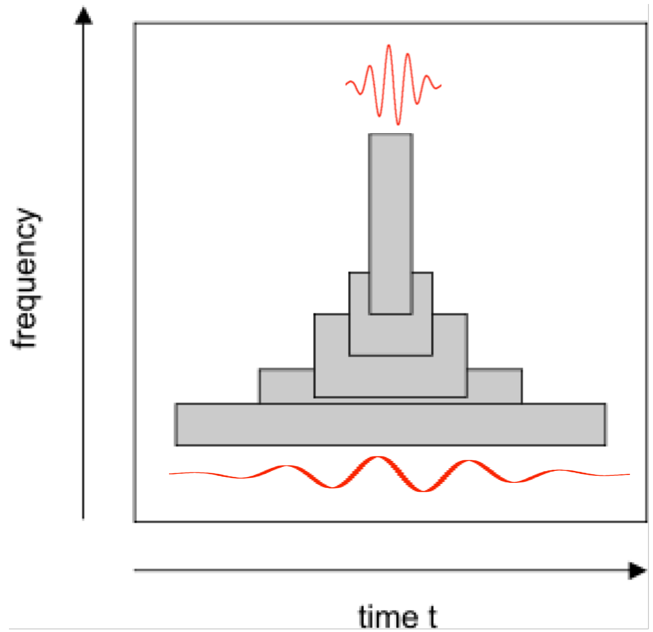
Wavelets


Taper
X
Sine wave
=
Cosine wave
=
1
0
-1
20 40 60 80 100 120 140 160 180 200



Wavelet analysis

- Wavelet width determines time-frequency resolution
- Width function of frequency (often 5 cycles)
- ‘Long’ wavelet at low frequencies leads to relatively narrow frequency resolution but poor temporal resolution
- ‘Short’ wavelet at high frequencies leads to broad frequency resolution but more accurate temporal resolution



Wavelet analysis

- Similar to Fourier analysis, but
  - Computationally slow
  - Tiles the time frequency plane in a particular way with few degrees of freedom

```
%time frequency analysis with
%multitapers

cfg  = [];
cfg.method     = 'mtmconvol';
cfg.toi        = [0:0.05:1];
cfg.foi        = [4 8 … 80];
cfg.t_ftimwin = [0.5 0.5 … 0.5];
cfg.tapsmofrq = [2 2 … 10];
      .
      .
freq=ft_freqanalysis(cfg, data);
```

```
%time frequency analysis with
%wavelets

cfg  = [];
cfg.method = 'wavelet';
cfg.toi    = [0:0.05:1];
cfg.foi    = [4 8 … 80];
cfg.gwidth = 5;
      .
      .
      .
freq=ft_freqanalysis(cfg, data);
```

Summary

Spectral analysis

- Relation between time and frequency domains
- Tapers

Time frequency analysis

- Time vs frequency resolution

Wavelets

Hands-on: Time-frequency analysis of power

- *Hanning window*
  - *fixed and variable length.*
- *Wavelets*
- *Multi-tapers*