

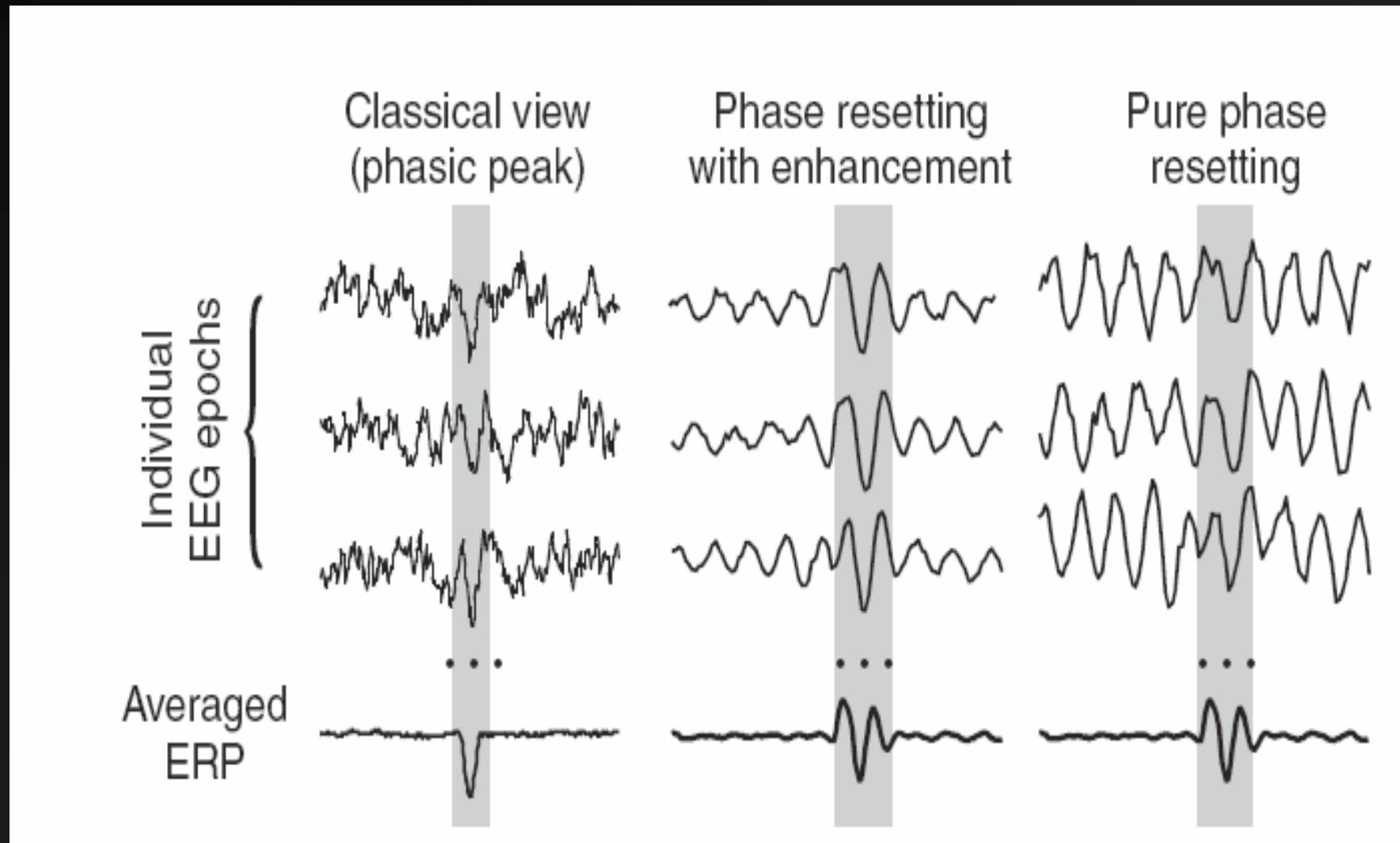
# Advanced Signal Processing I

*Time Frequency Approaches*

*Ocular Artifacts*

*Digital Filters*

# Classic ERPs Vs Phase Resetting



From Yeung et al., *Psychophysiology*, 2004

# Time-Frequency Representations

648

L.T. Trujillo, J.J.B. Allen / Clinical Neurophysiology 118 (2007) 645–668

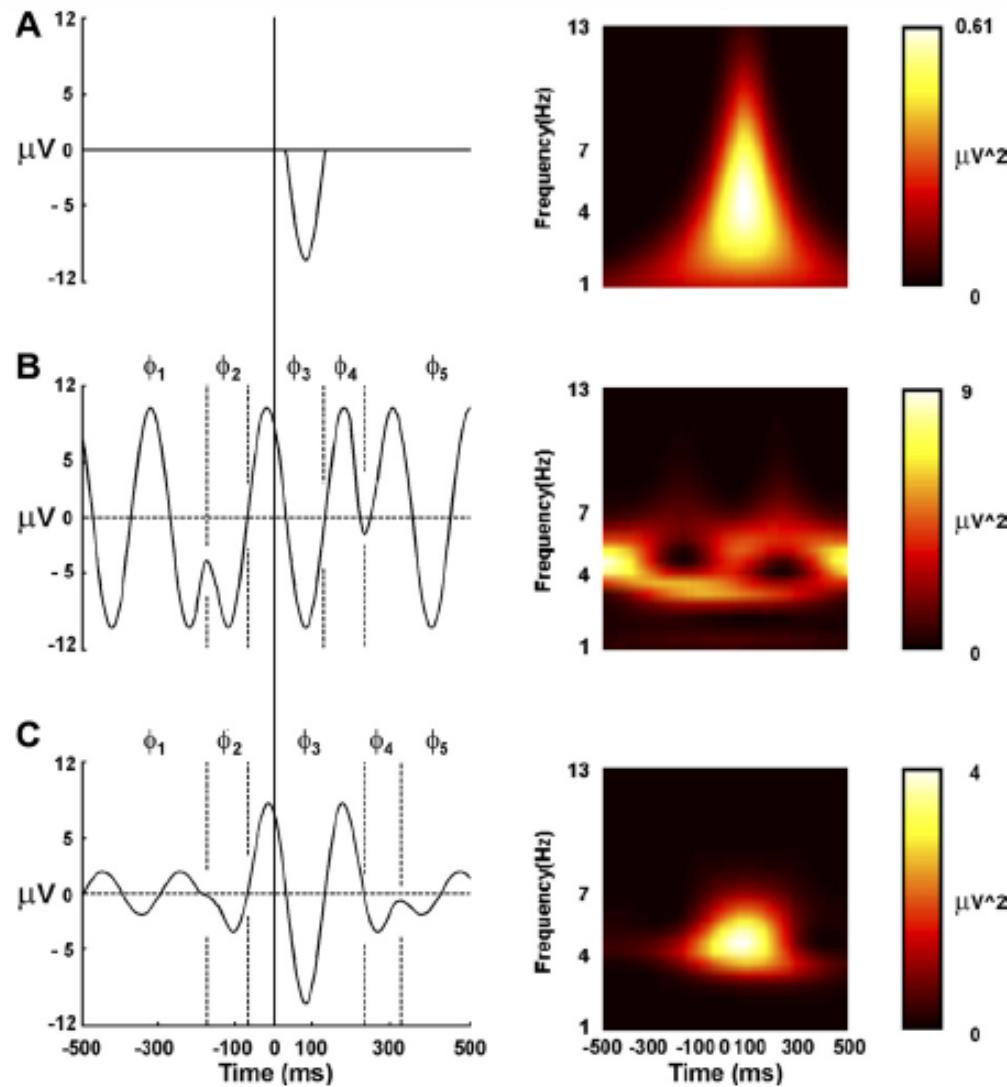
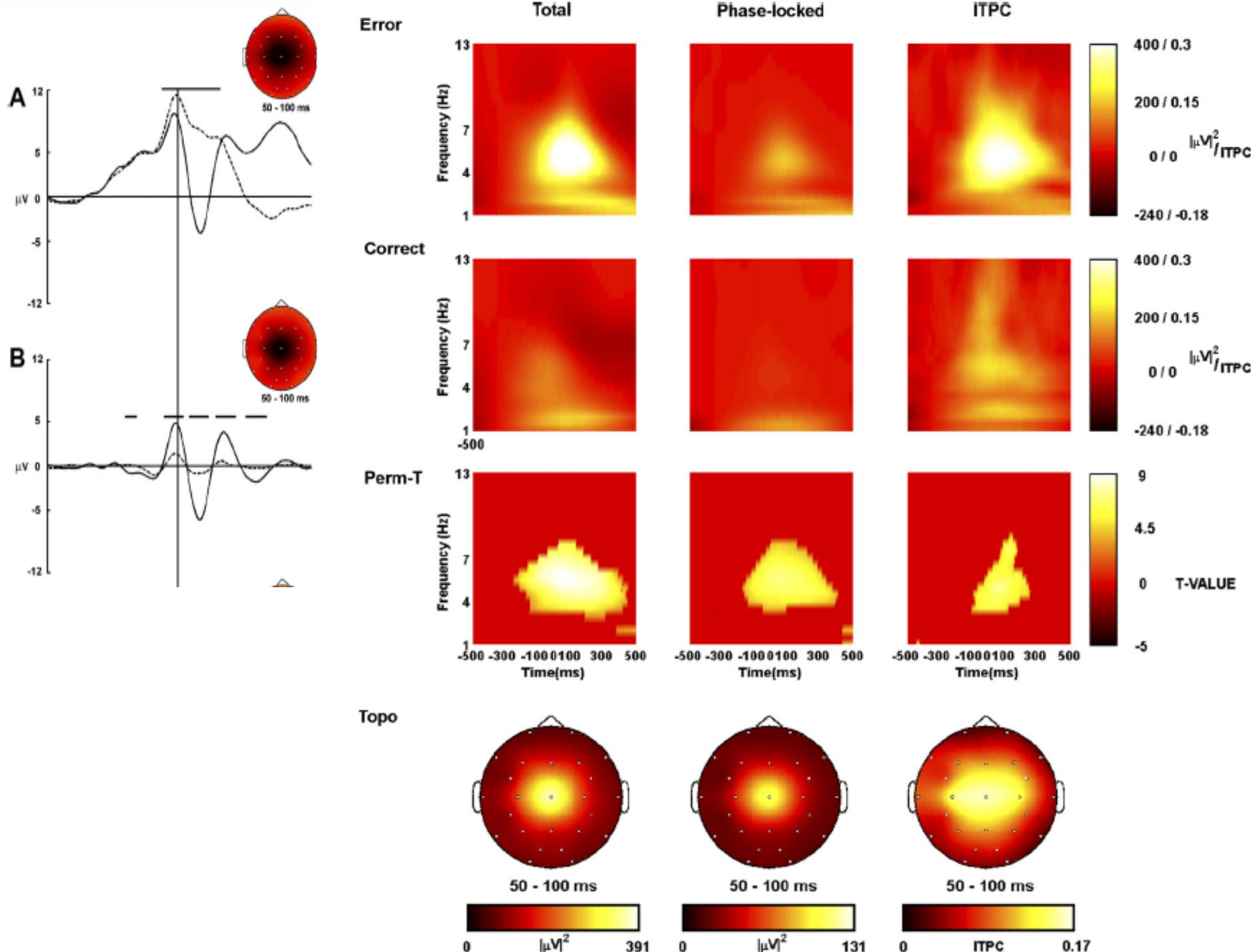
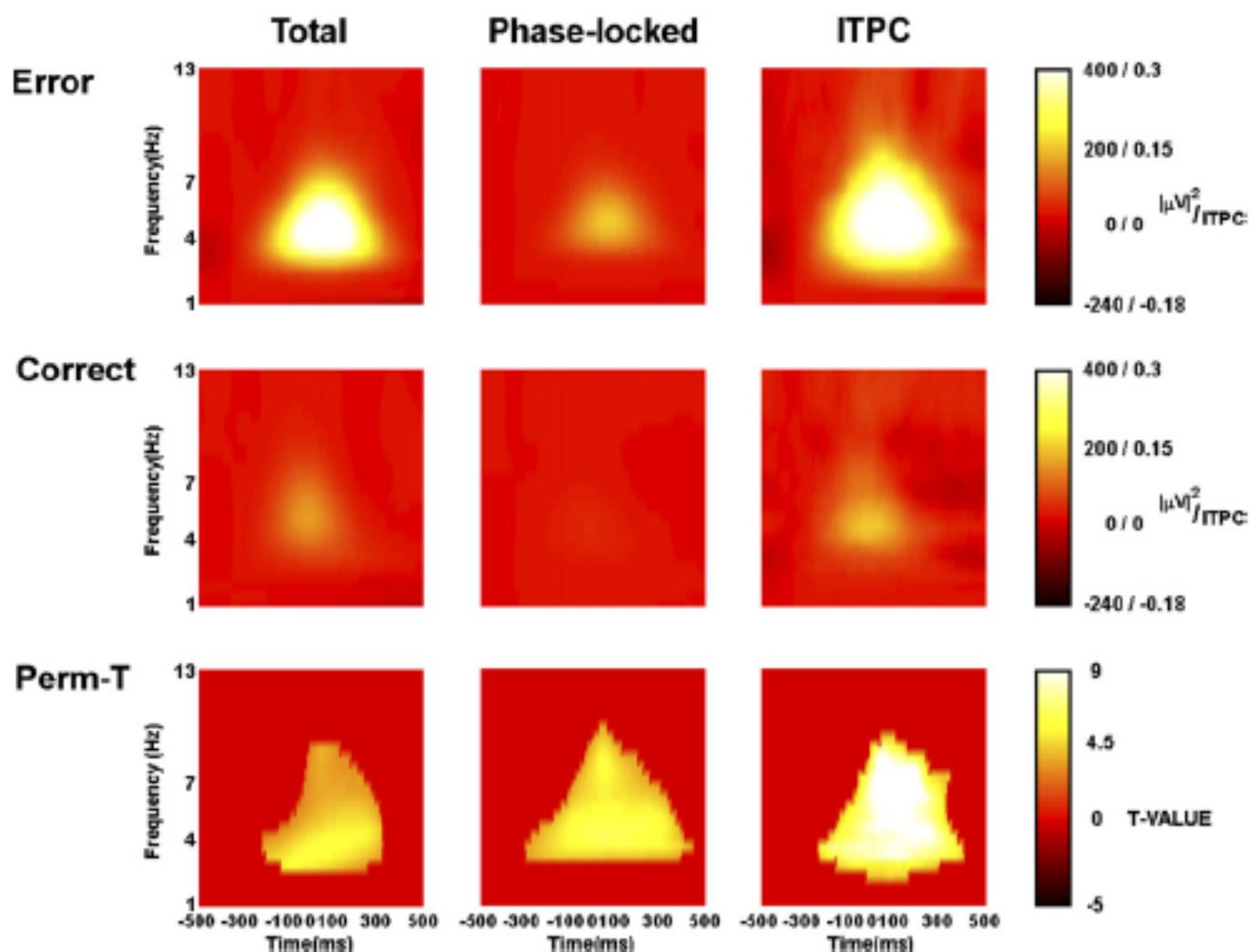
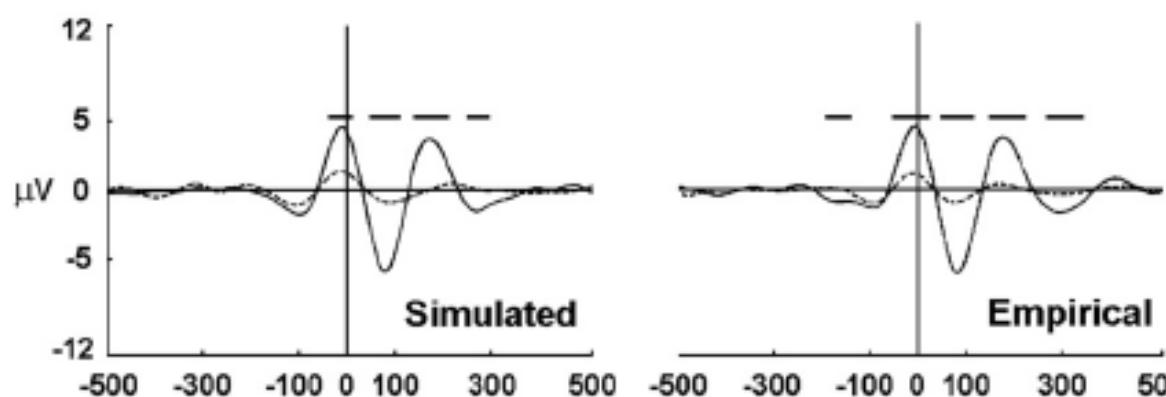


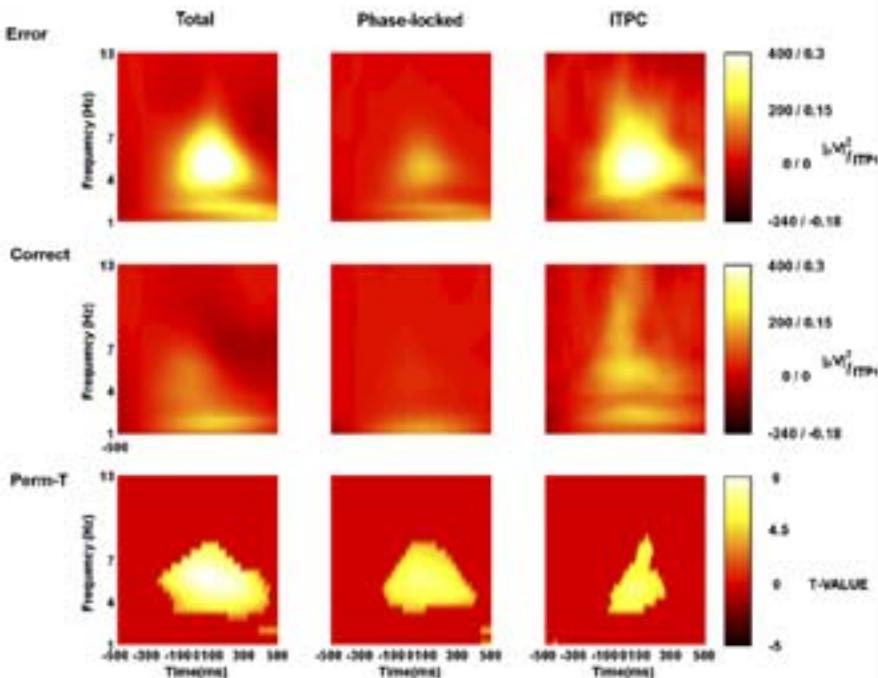
Fig. 1. Left column: Basic oscillatory waveforms used to simulate ERN responses according to the (A) *classic*, (B) *pure phase-resetting*, and (C) *phase-resetting with enhancement* hypotheses of ERN generation. Right column: Corresponding non-baseline-corrected wavelet-based time-frequency representations of these waveforms. The procedures used to create these waveforms and time-frequency representations are described in Sections 2.6 and 2.7.



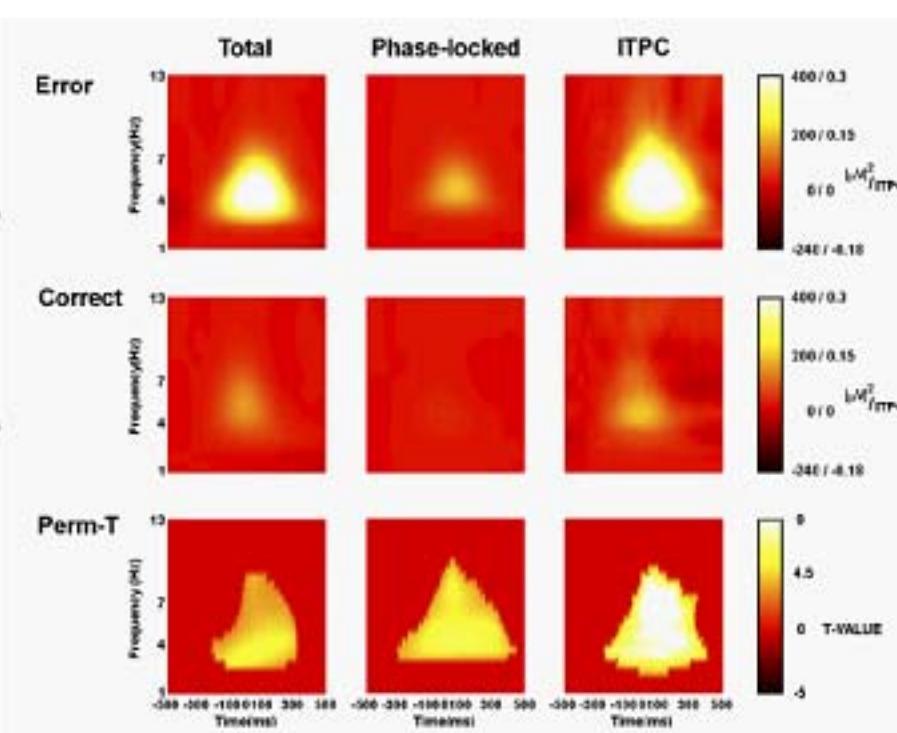
### Simulated Phase-resetting with Enhancement



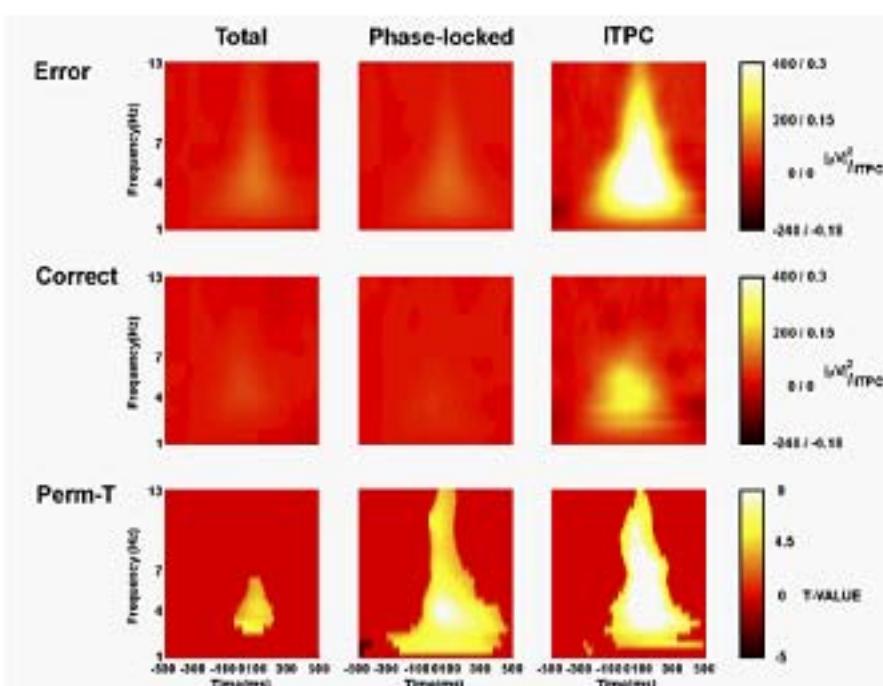
## Empirical



## Simulated Phase + Amp Enhance



## Simulated Classic





# Psychology



**EVERYTHING YOU EVER  
WANTED TO KNOW ABOUT  
ADVANCED EEG ANALYSES  
BUT WERE AFRAID OR DIDN'T  
KNOW ENOUGH TO ASK.**



Dr. Mike X Cohen

# 1-hour boot camp for advanced EEG analyses

**BY THE END OF TODAY, YOU WILL BE ABLE TO:**

- 1. Know what EEG oscillations are, where they come from, and how to extract them from EEG data.**
- 2. Know the differences among band-pass filtered EEG, power, phase, inter-trial phase coherence, and inter-site phase coherence.**
- 3. Understand and interpret time-frequency plots.**
- 4. Understand what cross-frequency coupling is, different ways to measure it, and how to interpret results.**
- 5. (optional) Renounce ERPs forever!!**

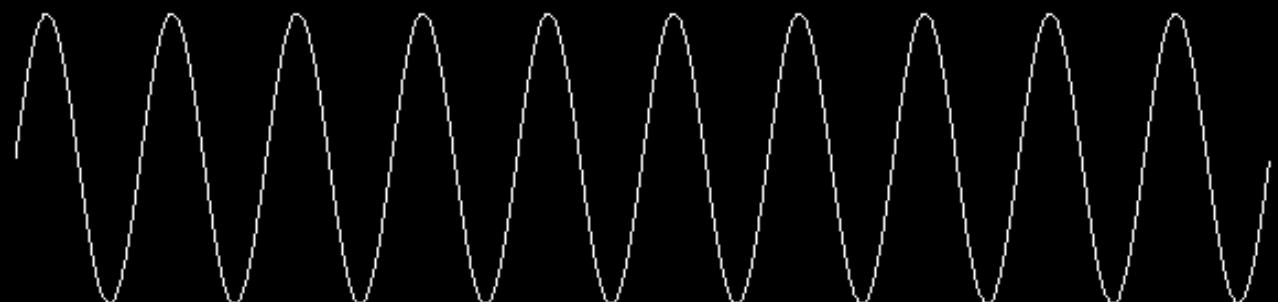
# 1-hour boot camp for advanced EEG analyses

**ACT NOW TO RECEIVE – AT NO ADDITIONAL COST:**

- These slides
- Sample matlab code
- Sample EEG datasets from intracranial and surface EEG
- (optional) Hats that say “Down with ERPs!!”

# 1. What are EEG oscillations?

But first, what is an oscillation?



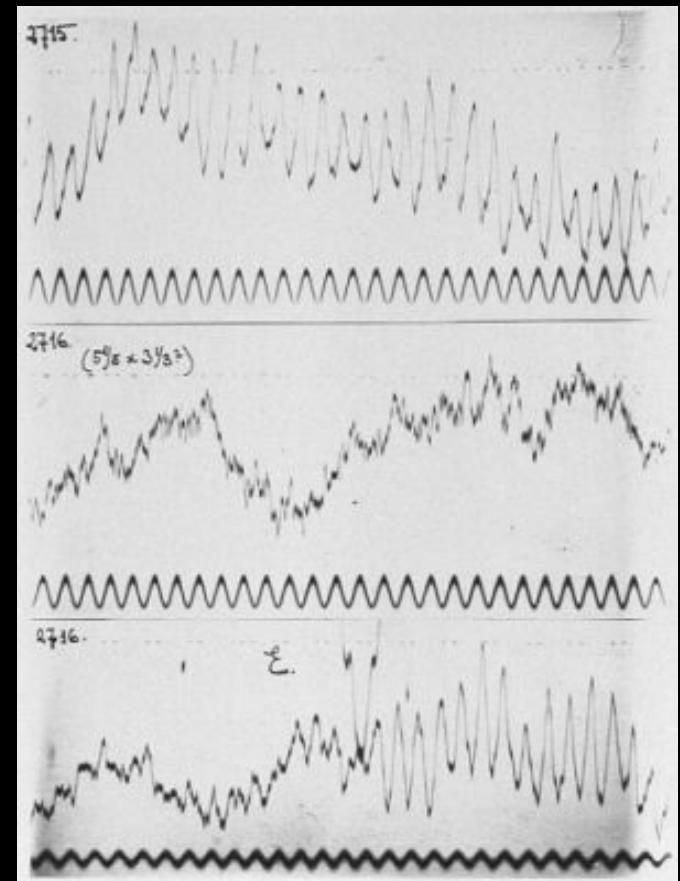
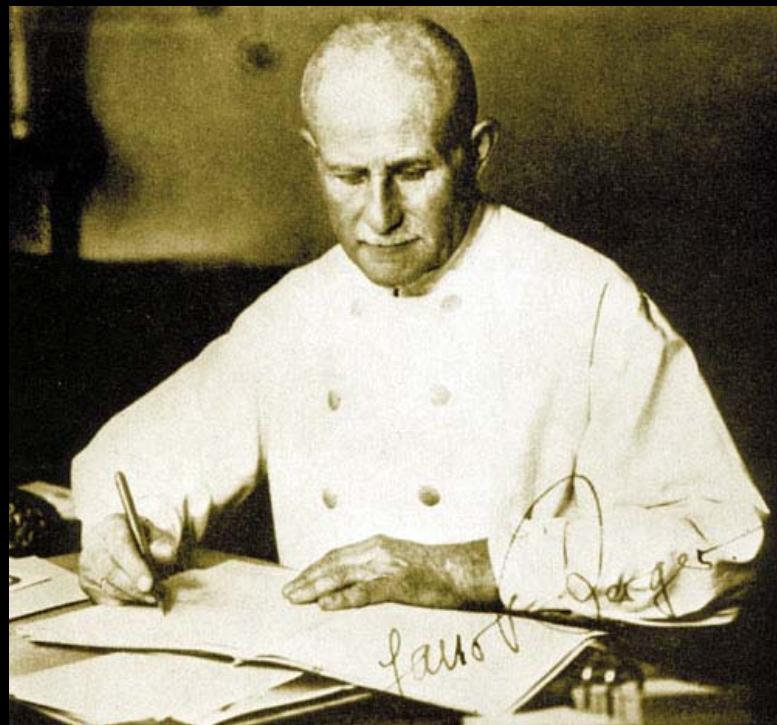
Math of oscillations:

```
> sin(2*pi*freq*time);
```

Most things in the universe oscillate...

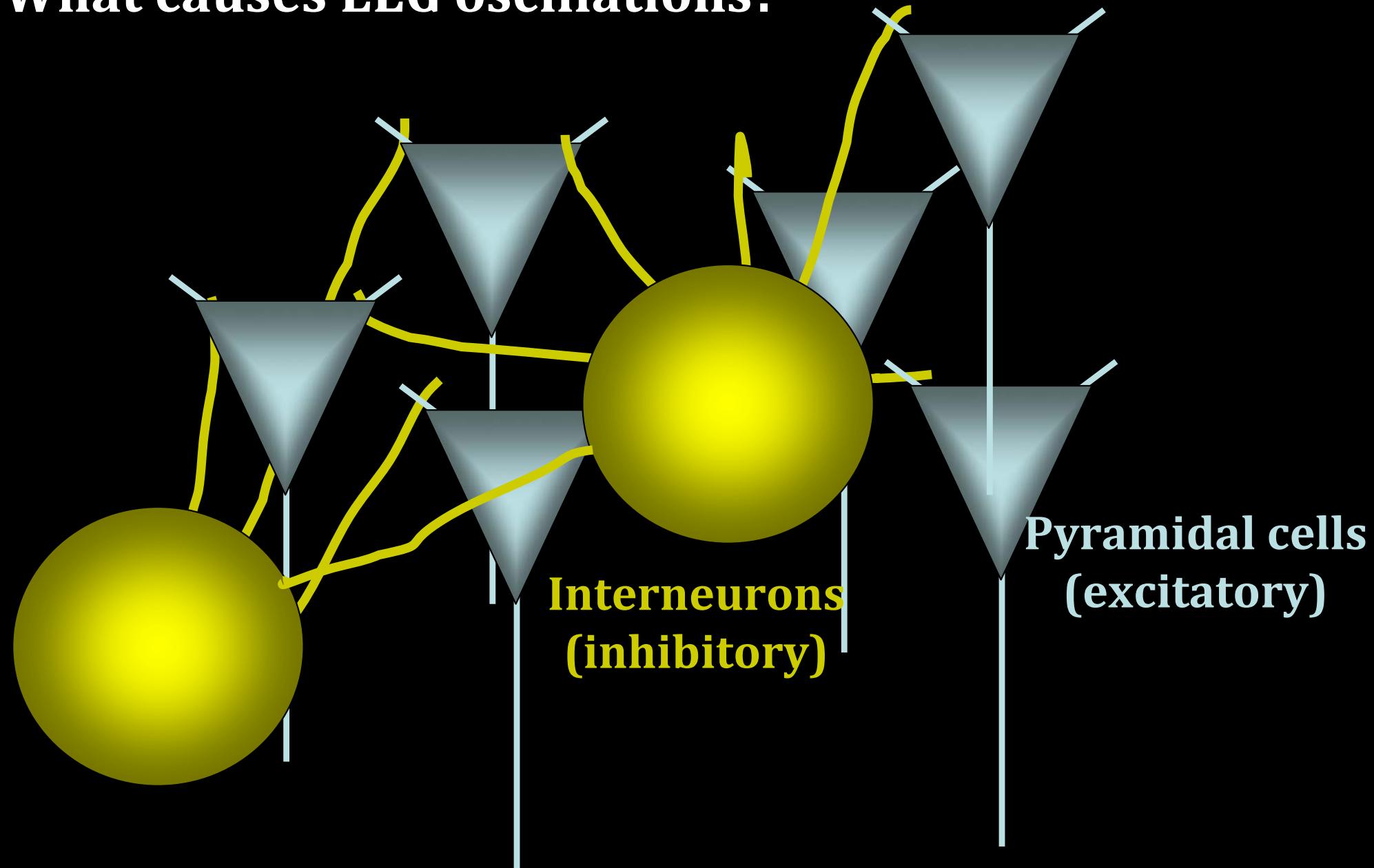
# 1. What are EEG oscillations?

Hans Berger, the dude who started it all...



# 1. What causes EEG oscillations?

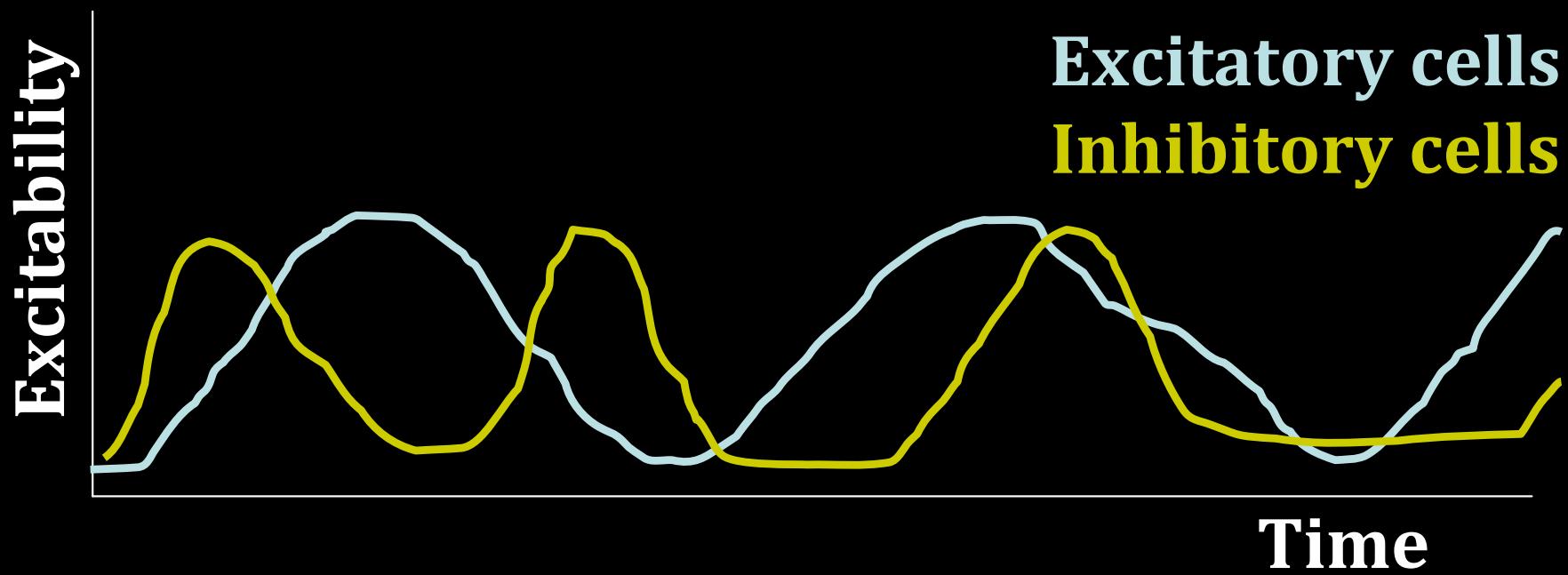
What causes EEG oscillations?



# 1. What causes EEG oscillations?

Oscillations arise from the dynamic interplay between inhibitory interneurons and excitatory cells.

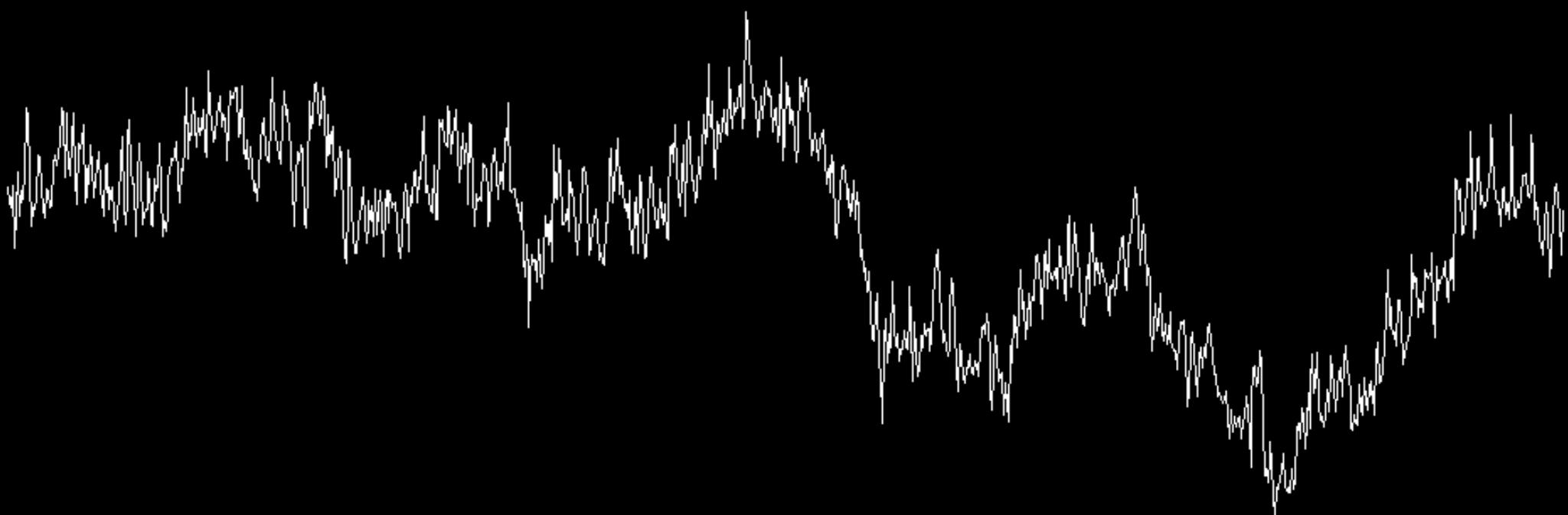
Inhibitory interneurons entrain excitatory cells by modulating excitability, which might serve to coordinate information processing in local and distal neural networks.



# **1. What are EEG oscillations?**

---

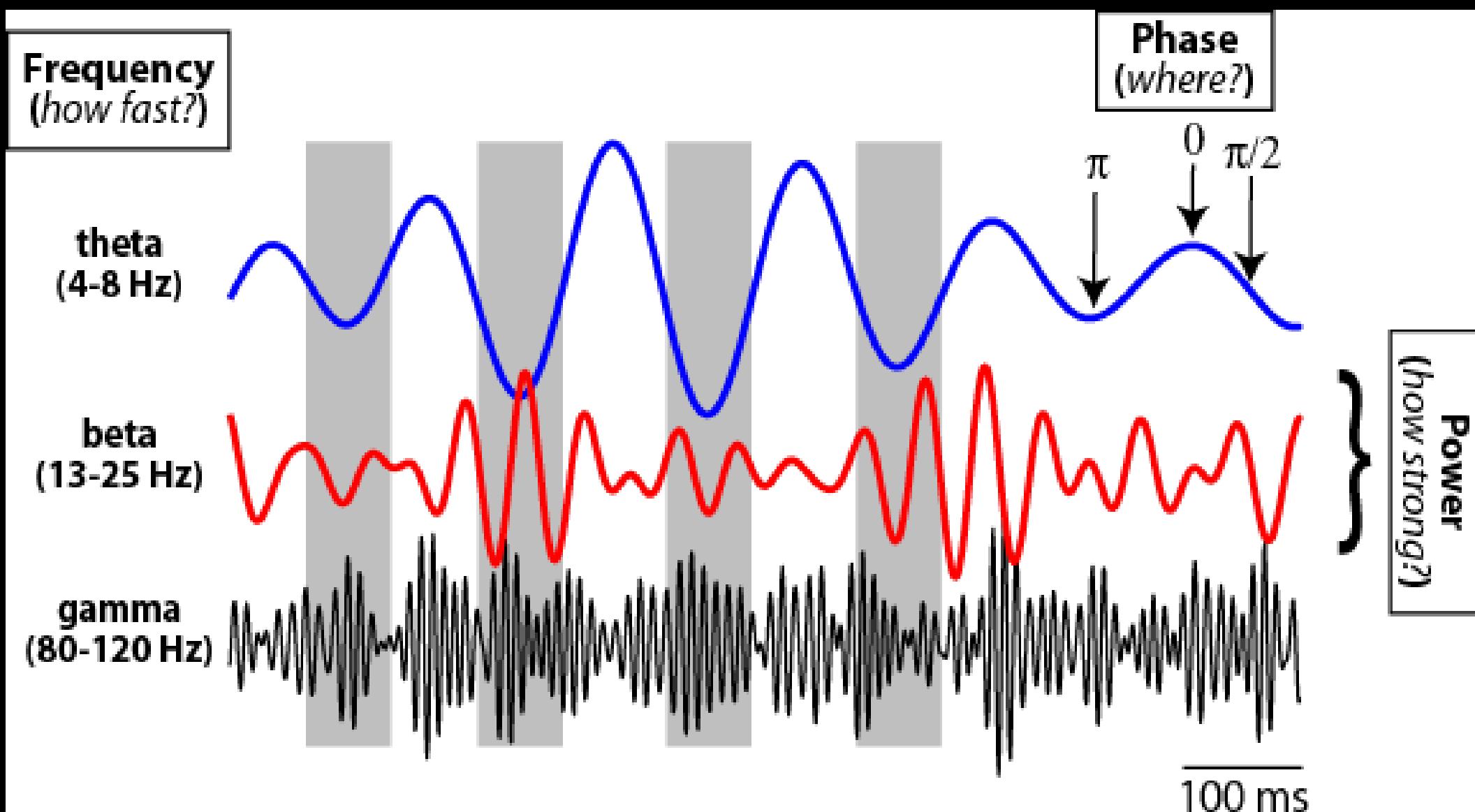
**Some unfiltered (“raw”) EEG data**



**You can see fast and slow oscillations...**

# 1. What are EEG oscillations?

Some nomenclature.



# 1. What are EEG oscillations?

**Problem:** Lots of overlapping frequencies in EEG.

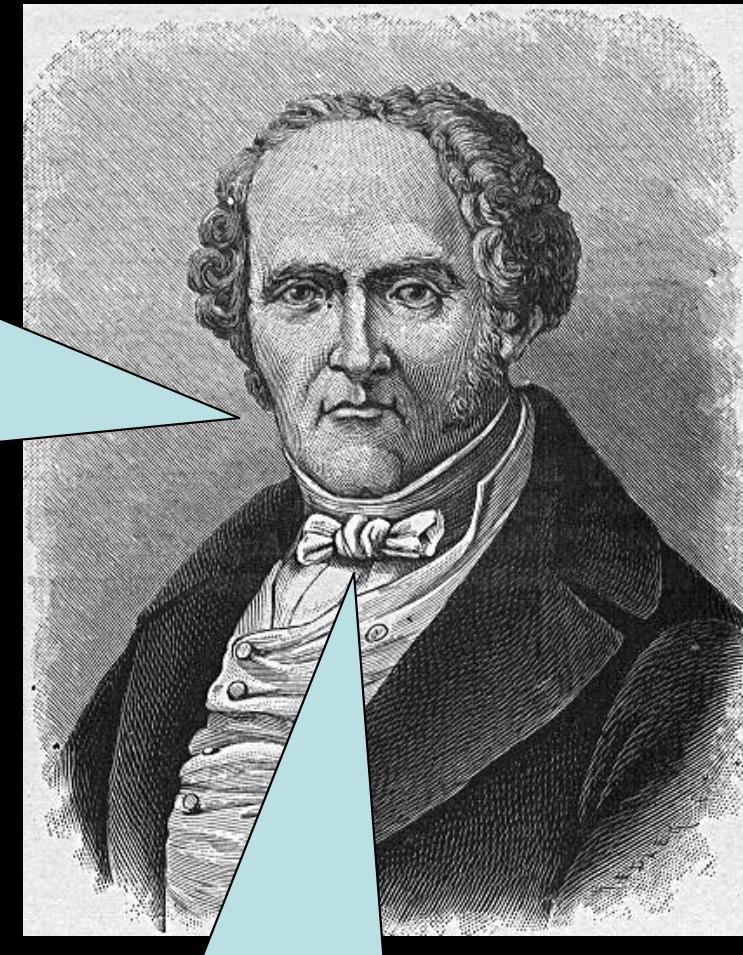
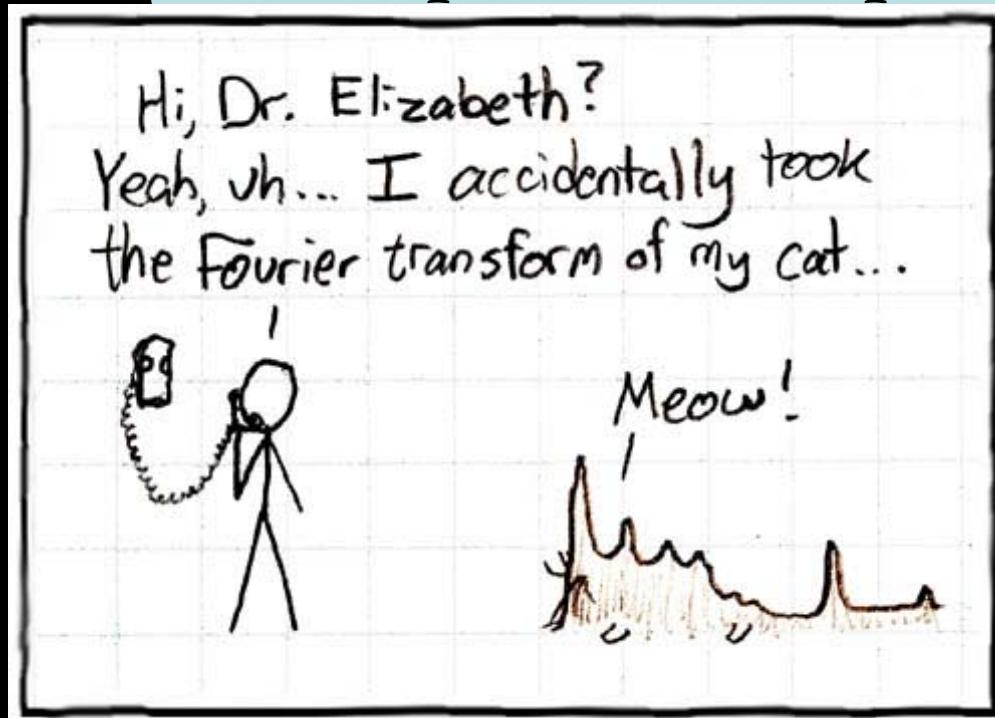
Fourier to the rescue!

How can we tell what frequencies are happening when and to what extent??



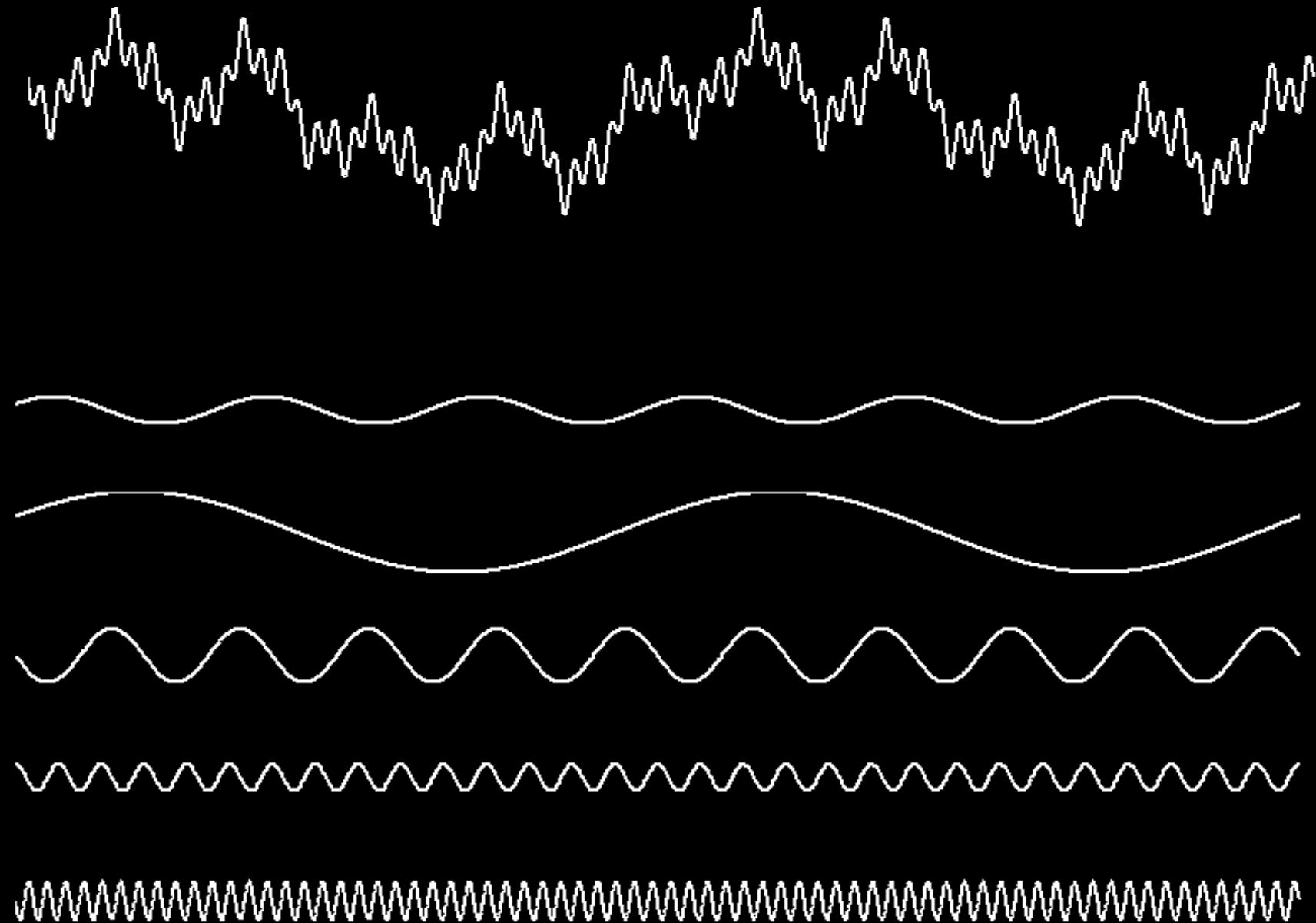
# 1. What are EEG oscillations?

Any signal can be expressed as a combination of different sine waves, each with its own frequency, amplitude, and phase!

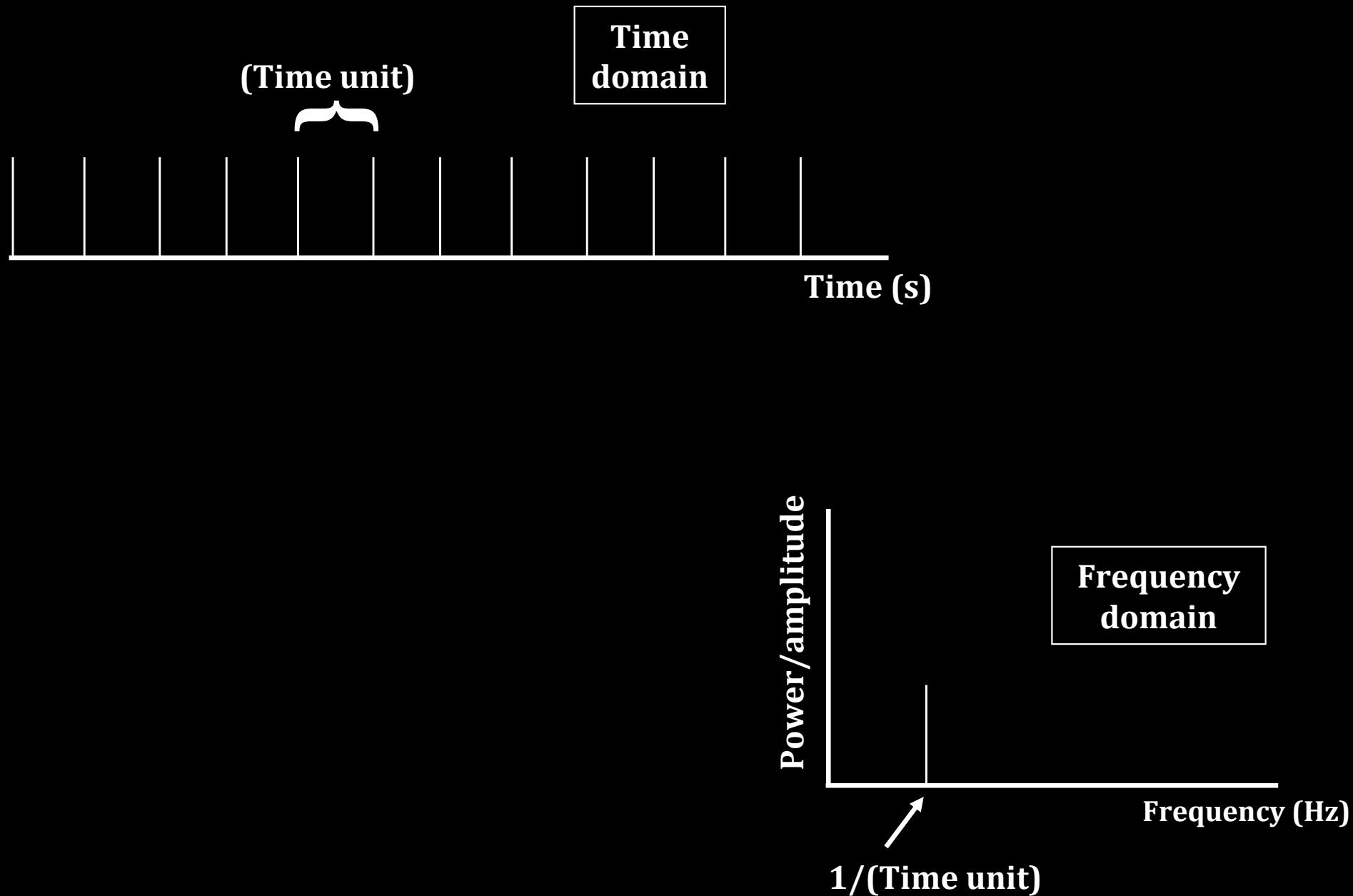


Zut allor! C'est magnifique!  
Tu as le coeur d'un lion!

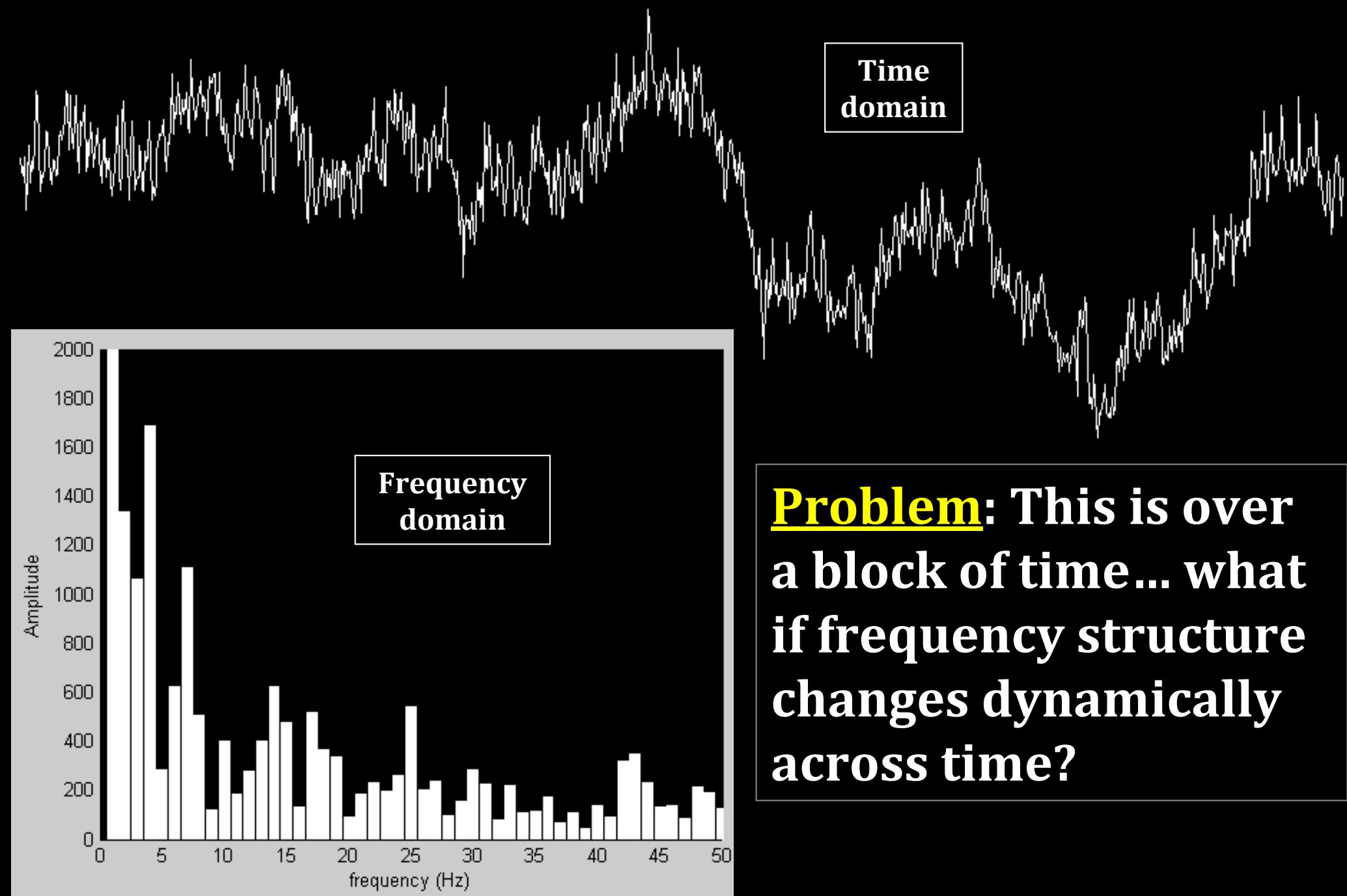
# 1. Representing time series data as the sum of sine waves



# 1. Going from the time to frequency domains



# 1. What are EEG oscillations?



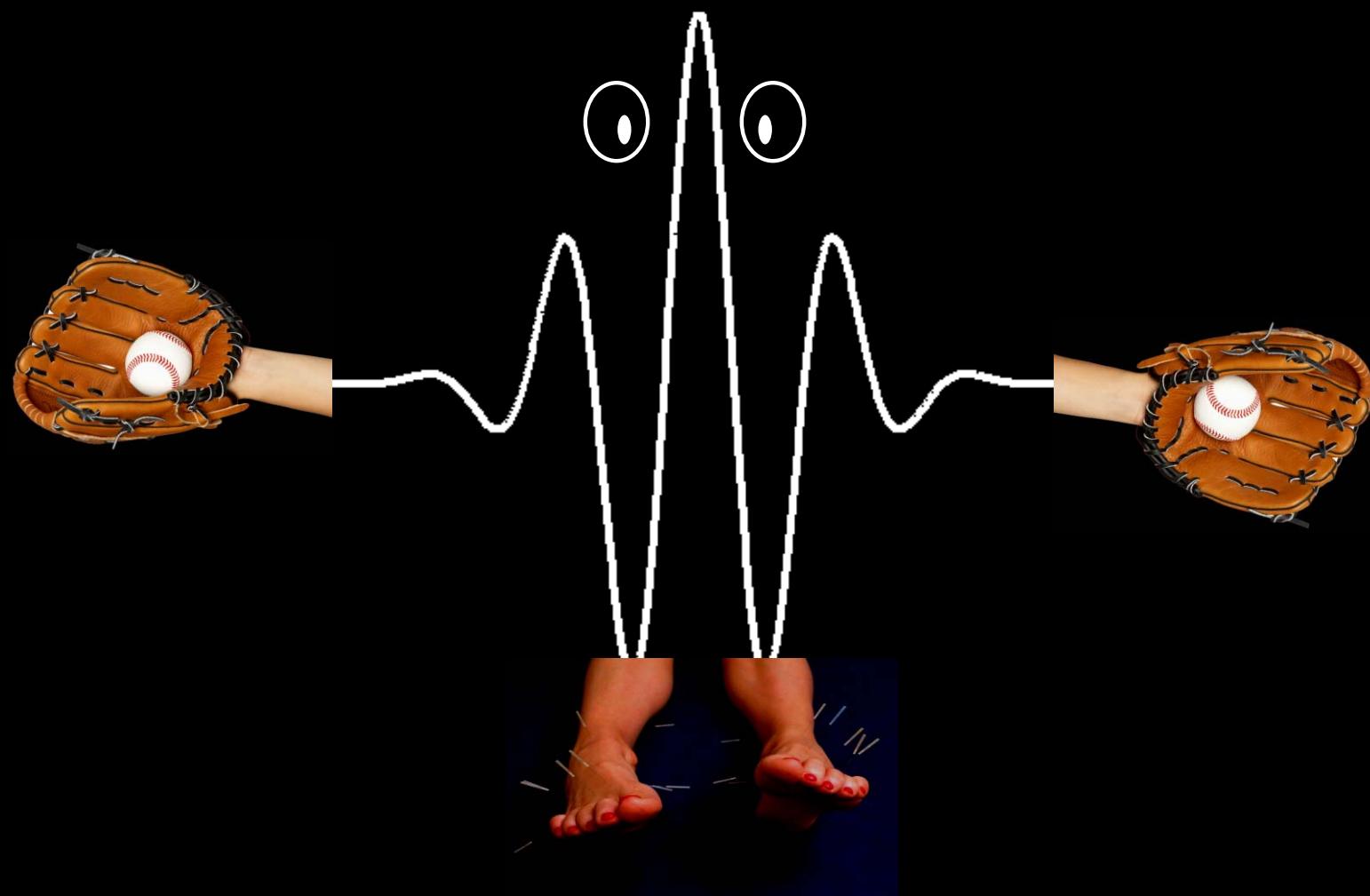
Time  
domain

Frequency  
domain

**Problem:** This is over  
a block of time... what  
if frequency structure  
changes dynamically  
across time?

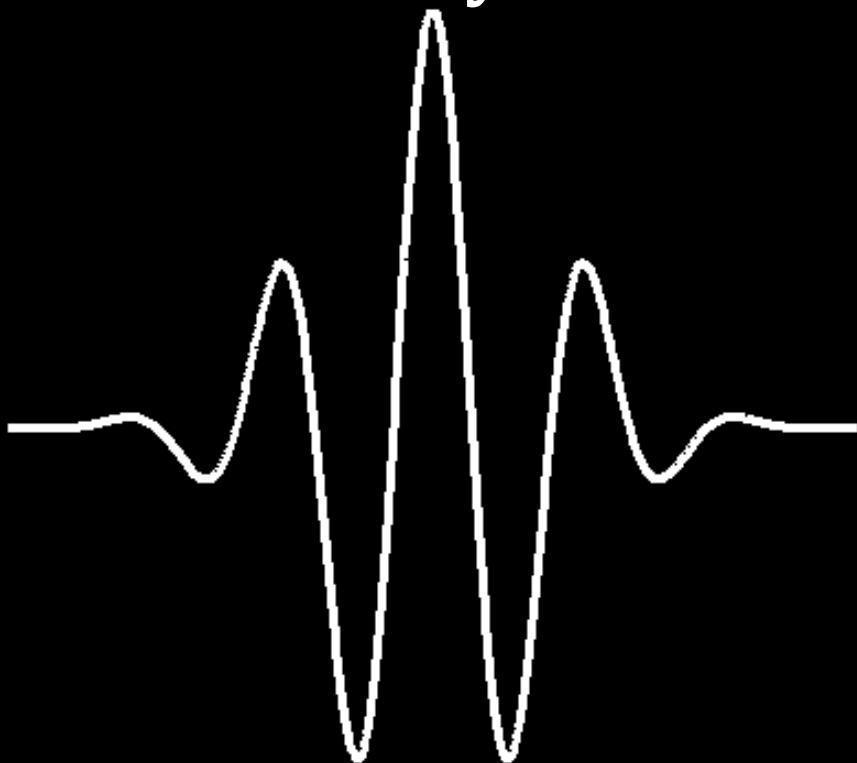
# 1. Introduction to Wavelets and wavelet convolution

Mr. Wavelet and his  
family to the rescue!

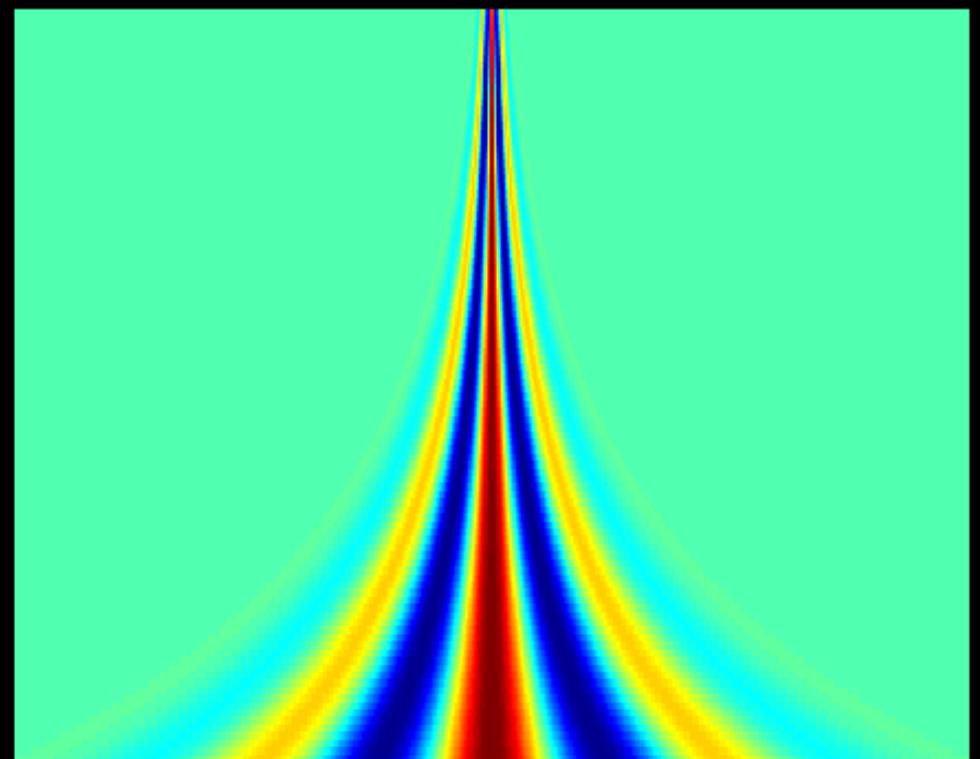


# 1. Introduction to Wavelets and wavelet convolution

**Mr. Wavelet in his  
birthday suit:**



**And his family:**



# 1. Introduction to Wavelets and wavelet convolution

Mr. Wavelet, meet EEG.

Greetings,  
Earthican.

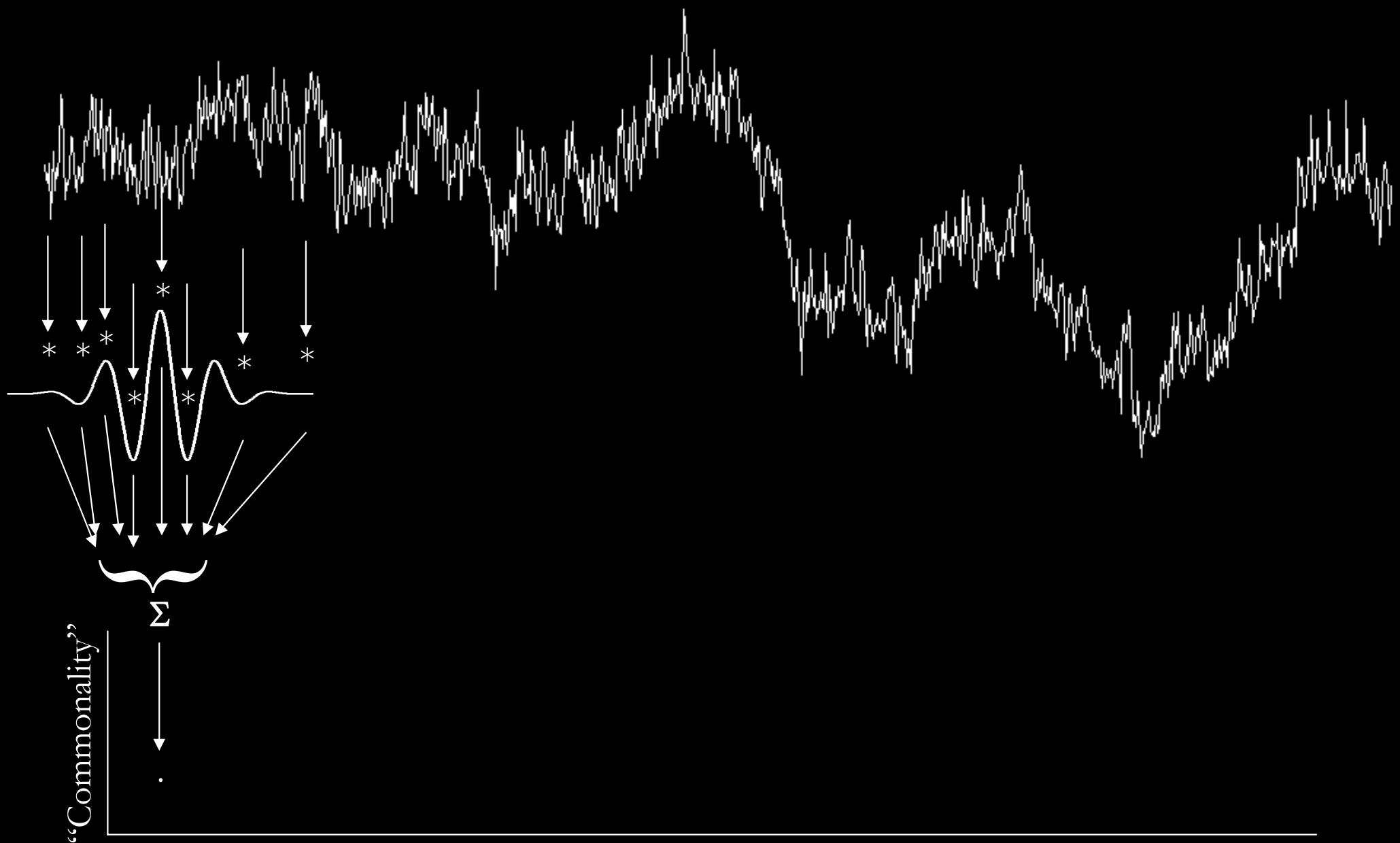
At least he's not  
wearing that  
ridiculous costume.

Hiya!

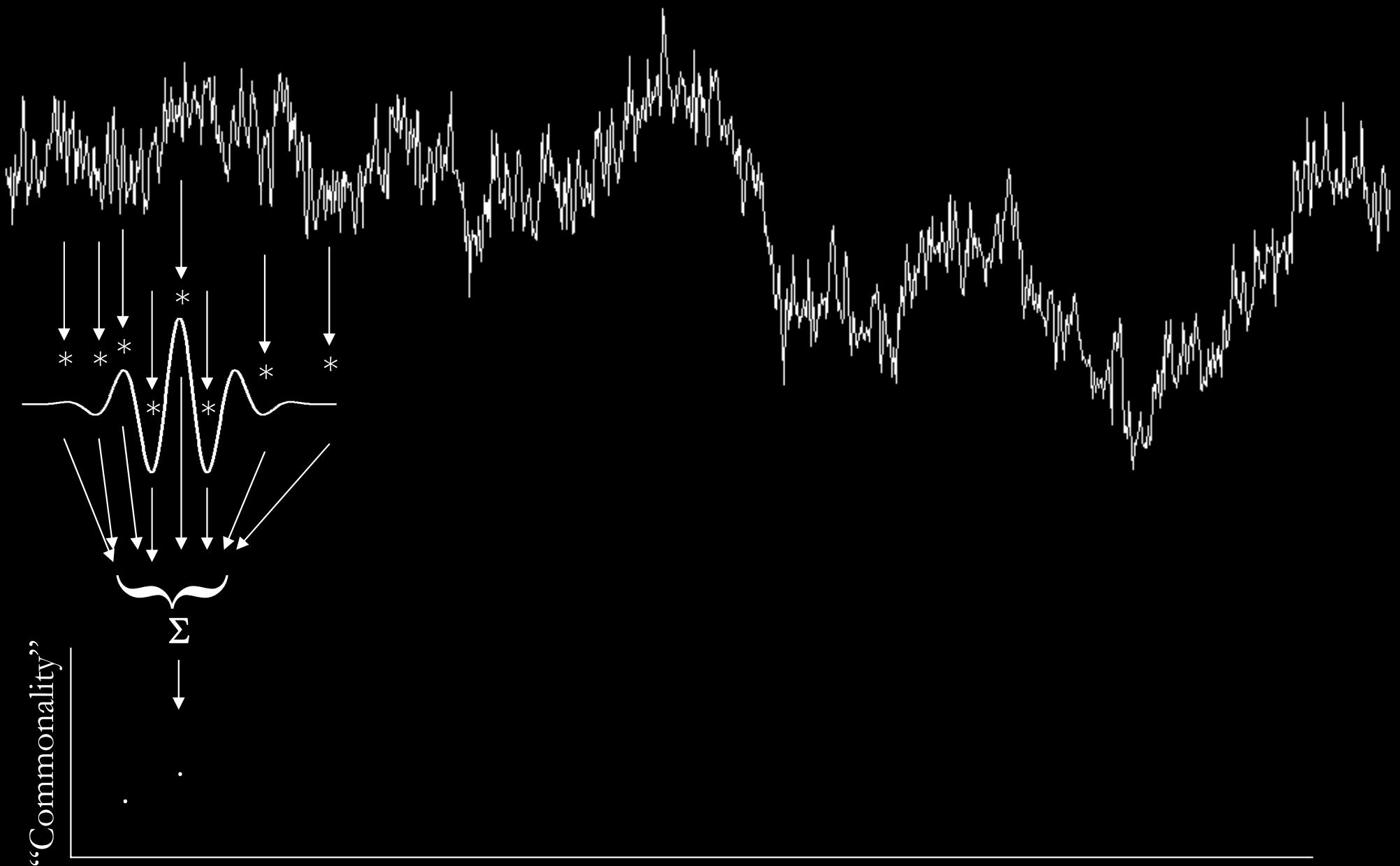
Hey baby, do  
we have any  
common  
interests?

Let's *convolve*  
and find  
out!

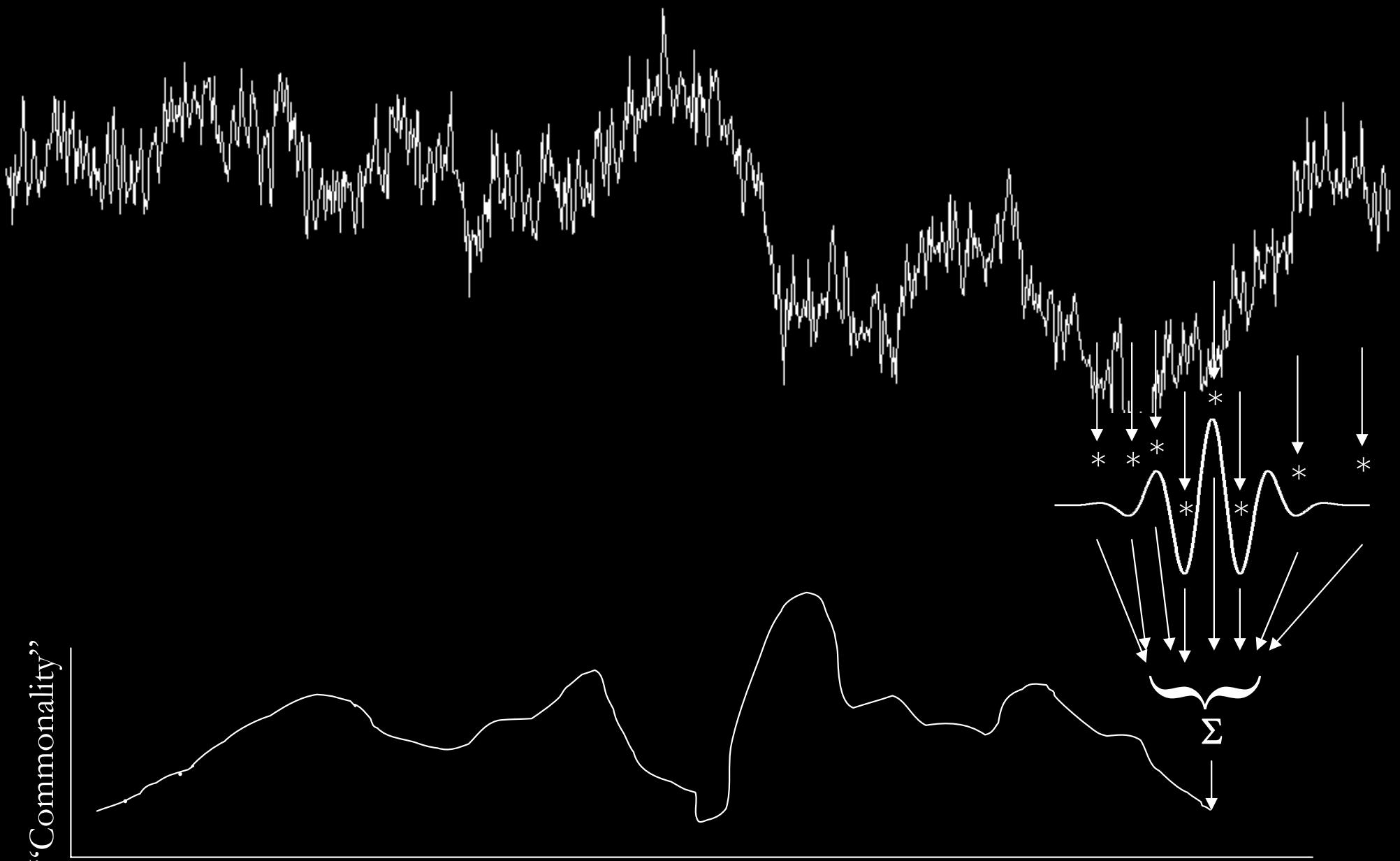
# 1. What is convolution?



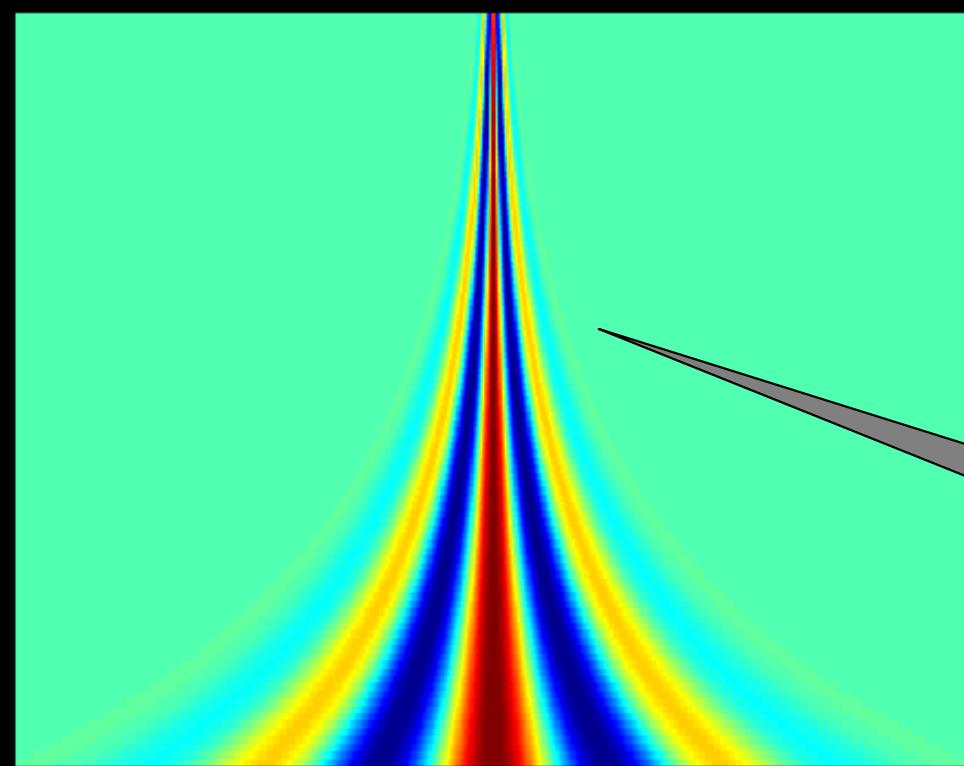
# 1. What is convolution?



# 1. What is convolution?



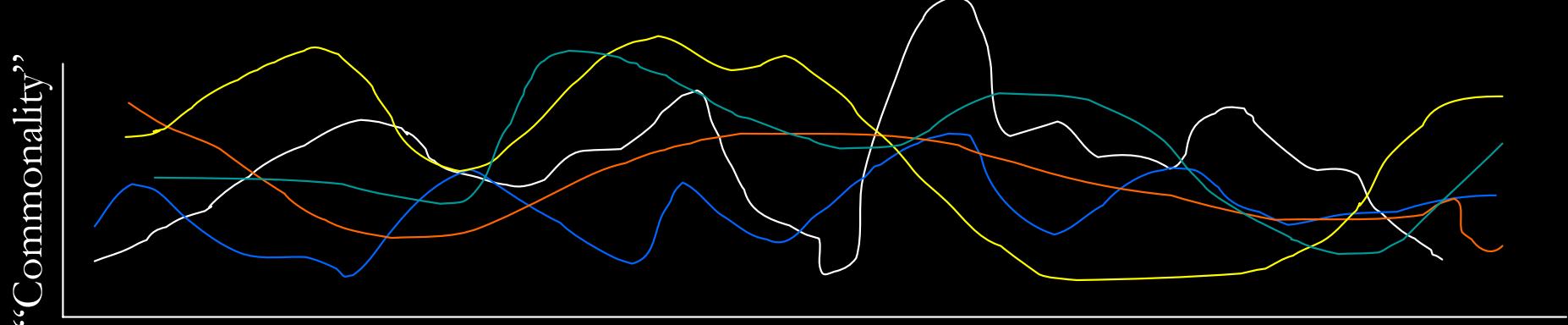
# 1. What is convolution?



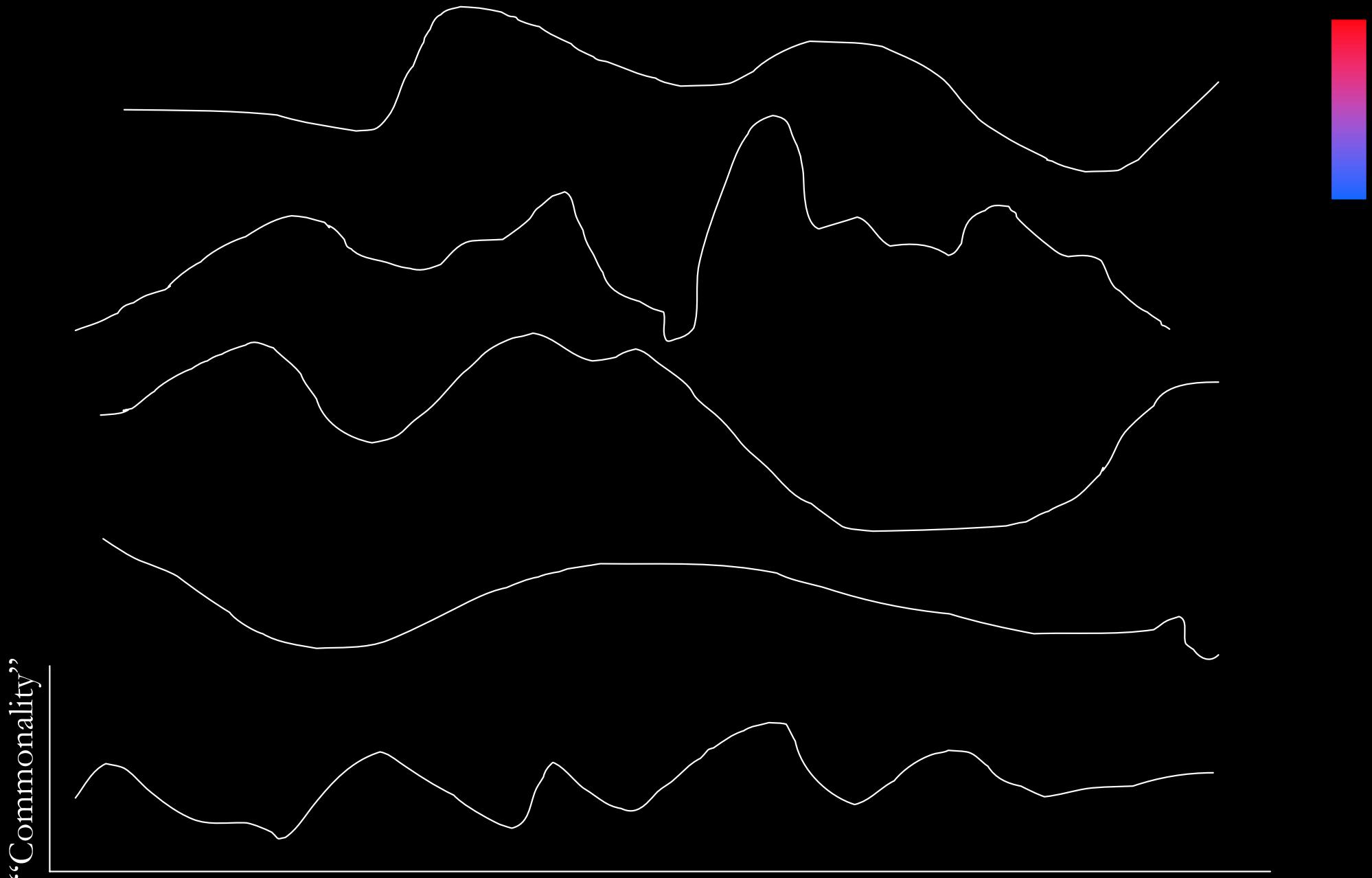
Uh oh...

Here we  
come!!

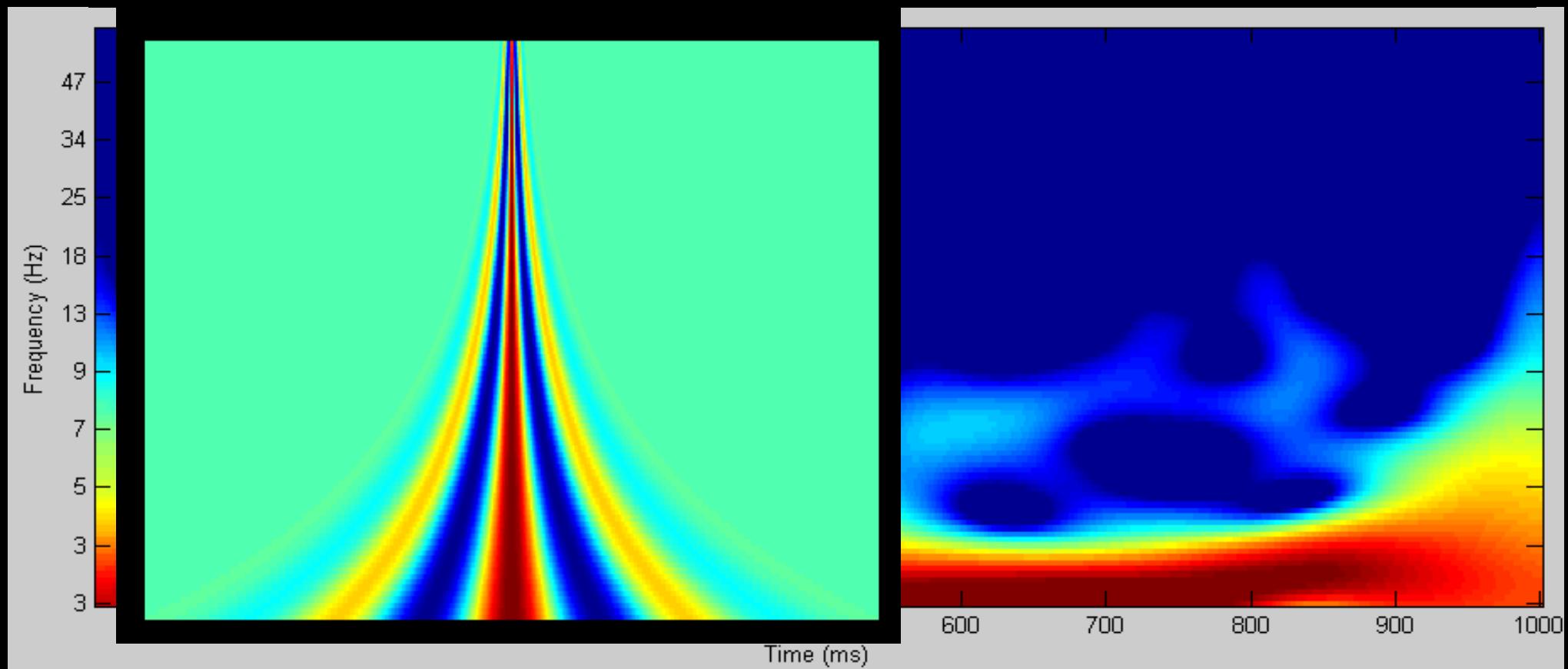
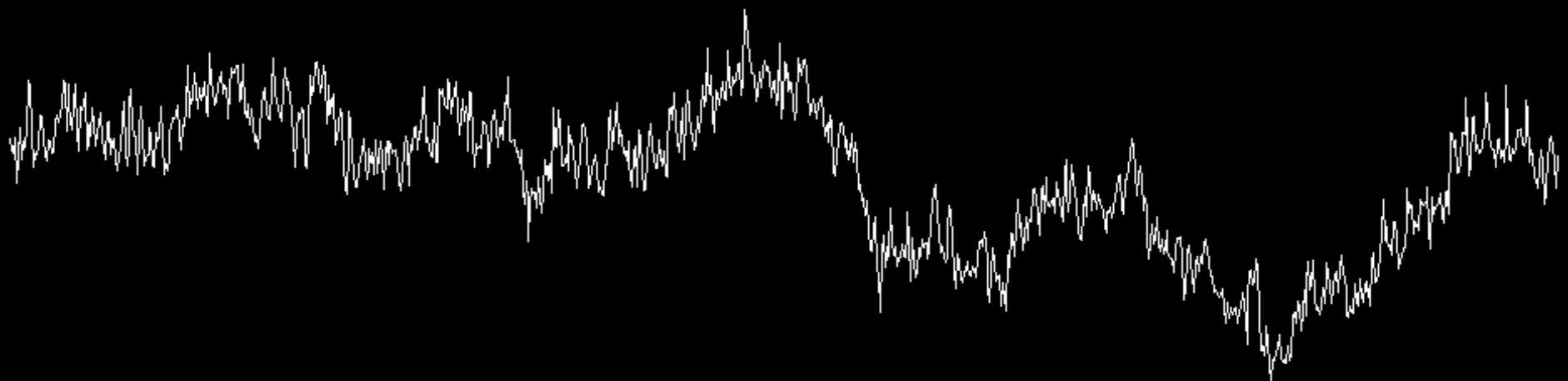
# 1. What is convolution?



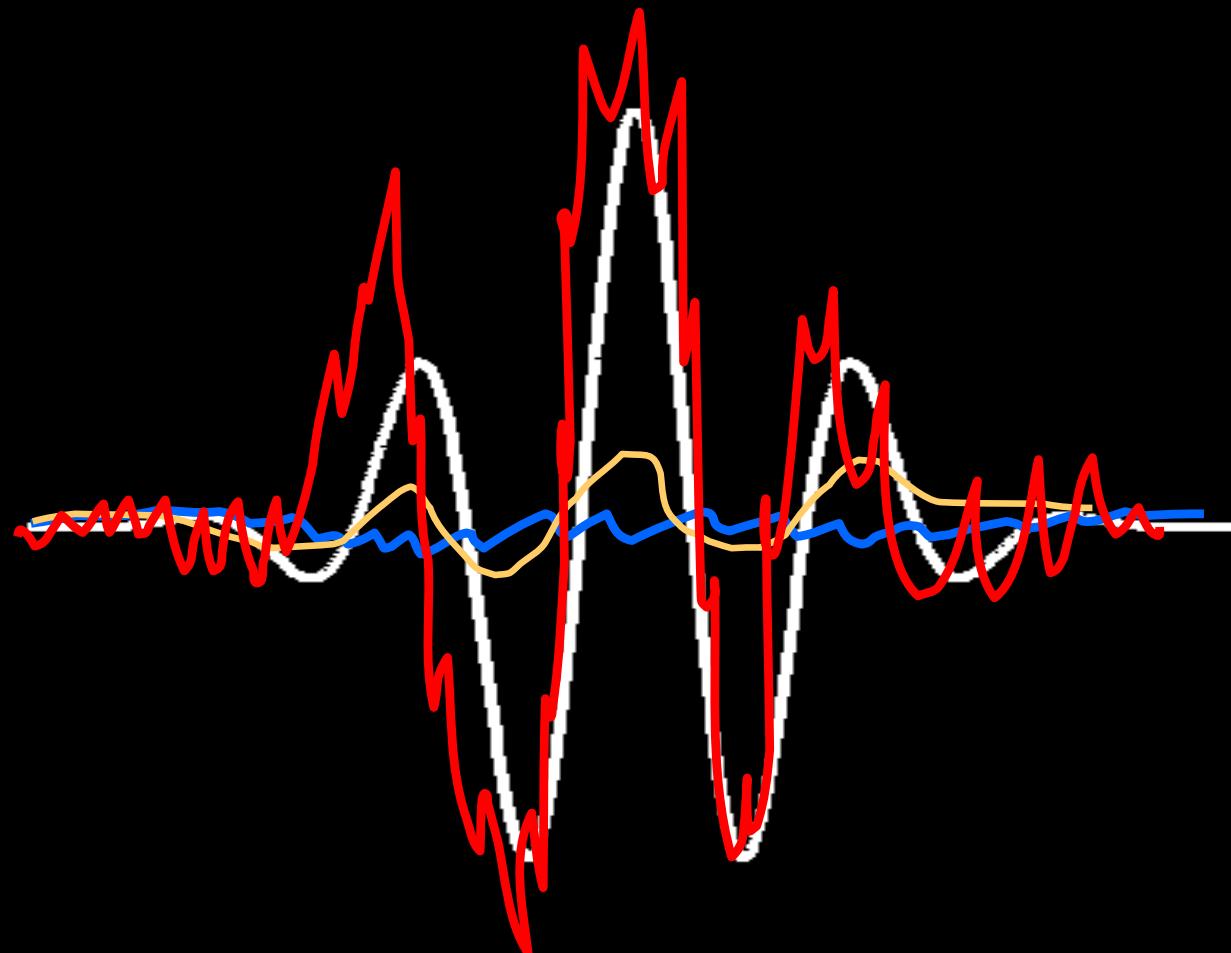
# 1. What is convolution?



# 1. What is convolution?



# 1. Why does it work?



<http://www.jhu.edu/signals/convolve/index.html>

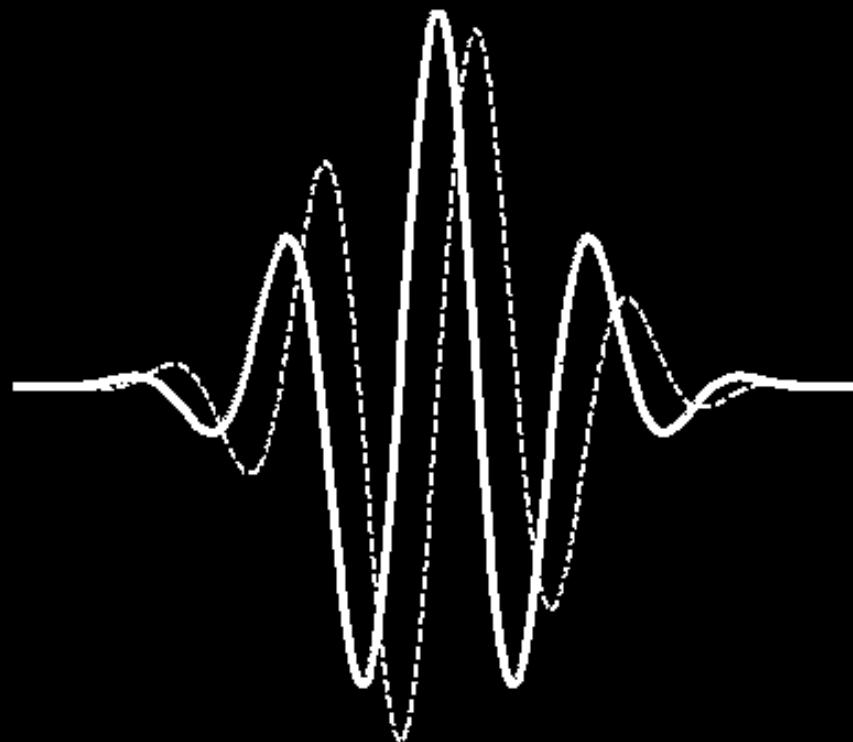
# 1-hour boot camp for advanced EEG analyses

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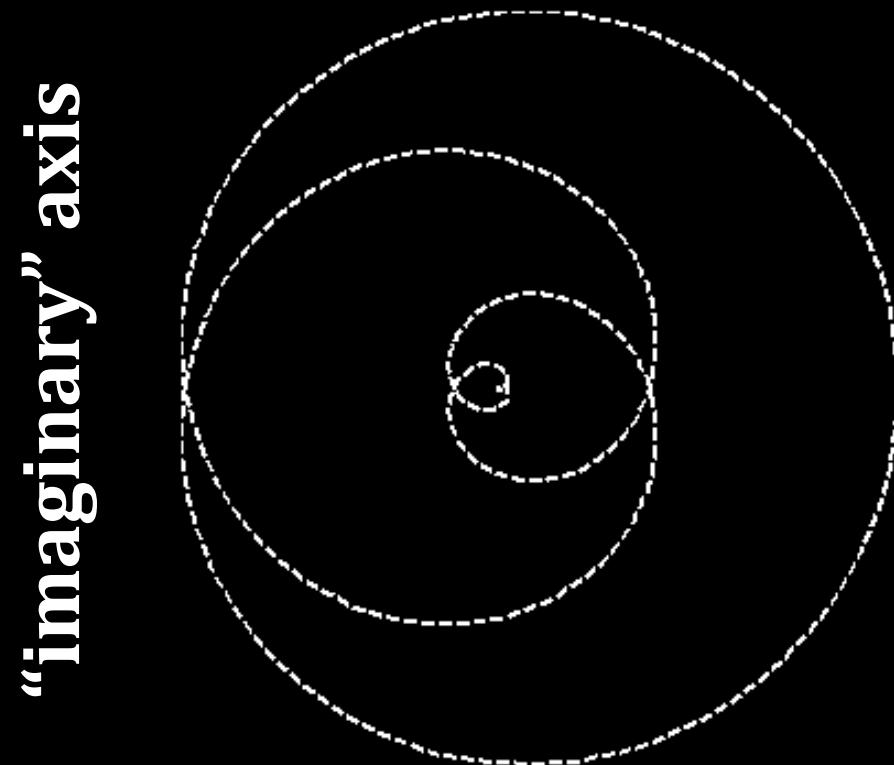
## **2. Different kinds of oscillation information.**

**Mr. Wavelet lives a double life:  
in the real world and in the imaginary world.**



## 2. Different kinds of oscillation information.

When he doesn't take his "happy pills"  
he looks like this:

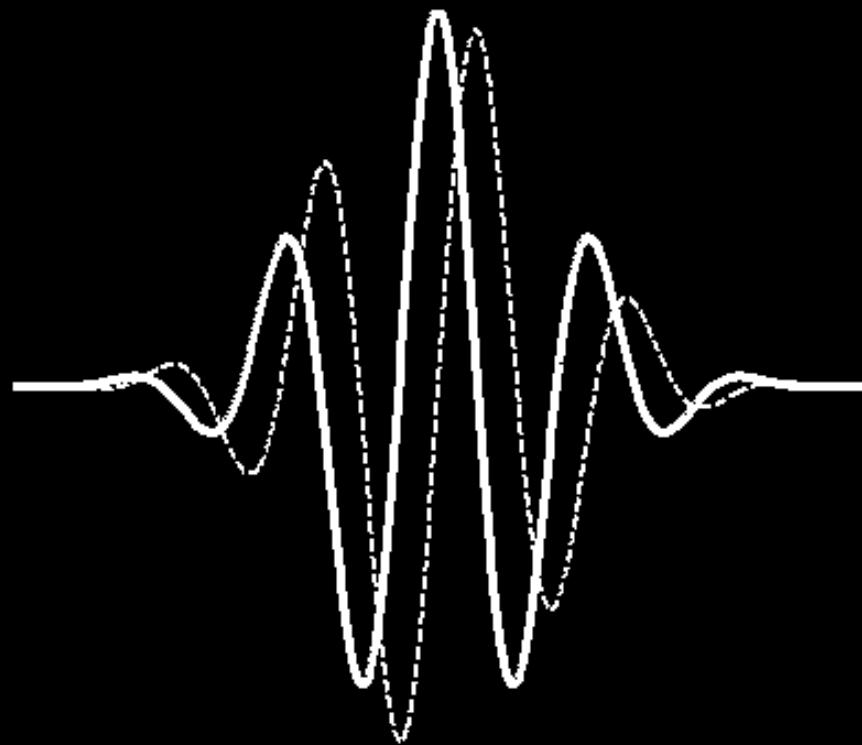


"real" axis

## 2. Different kinds of oscillation information.

**Cartesian space**

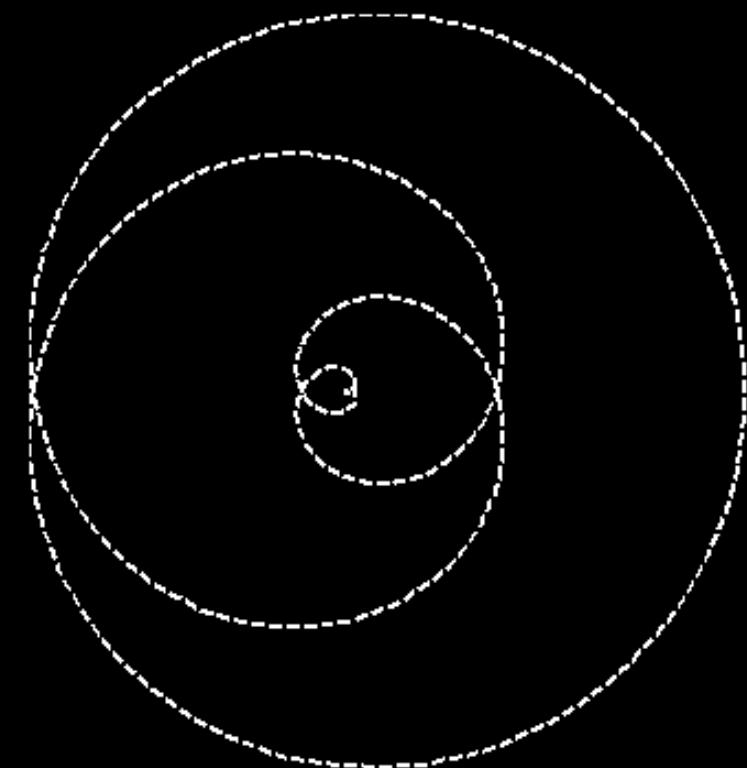
“Y” axis



“X” axis

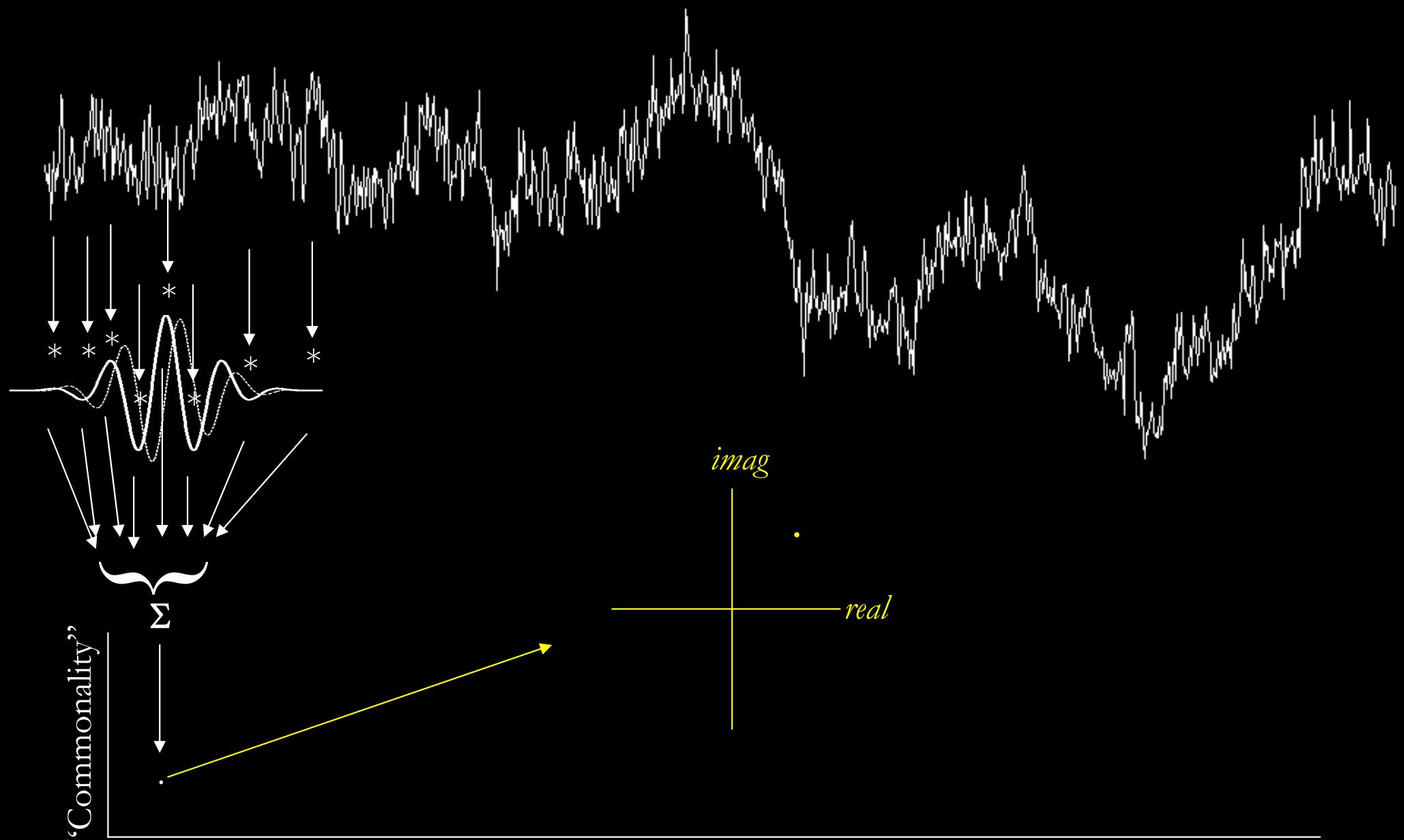
**Complex space**

“imaginary” axis

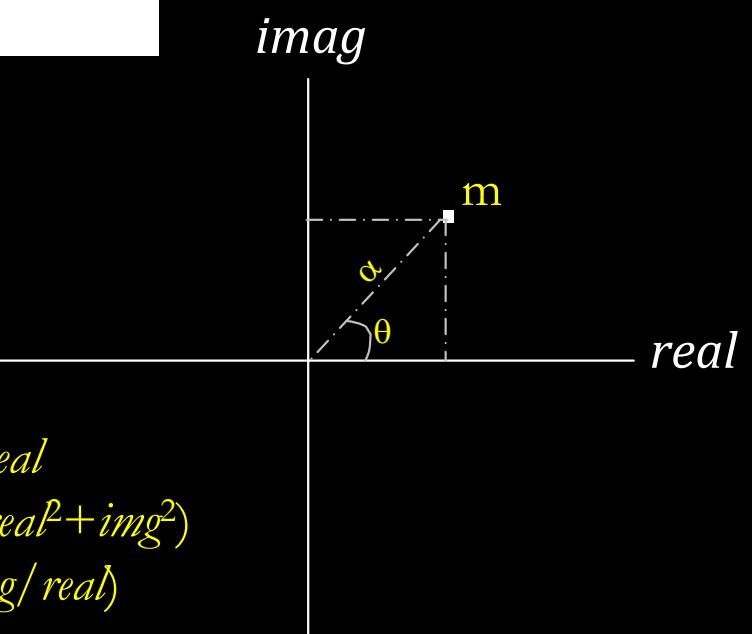
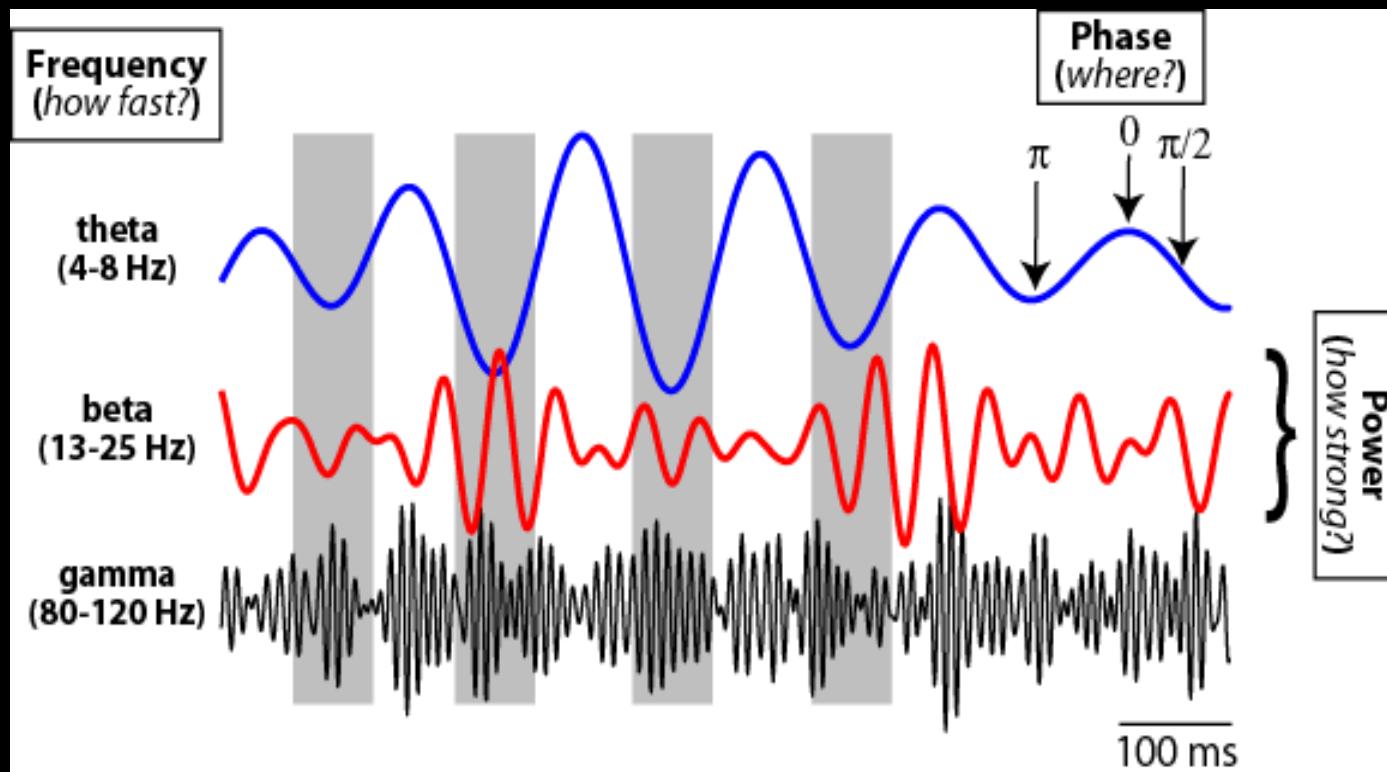


“real” axis

## 2. Ugh. It gets *more* complicated??



## 2. Ok, it's cool. But why should I care?



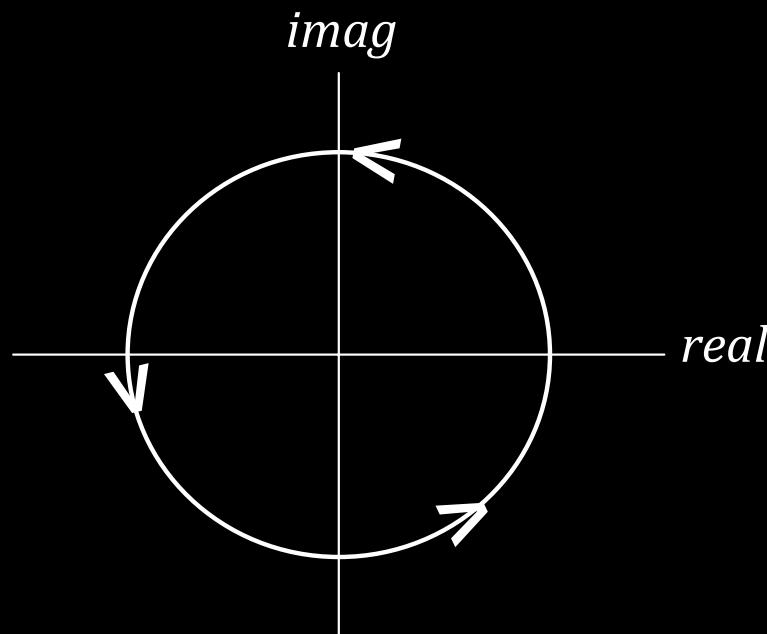
Filtered EEG = *real*

Magnitude =  $\sqrt{real^2 + img^2}$

Angle =  $\arctan(img / real)$

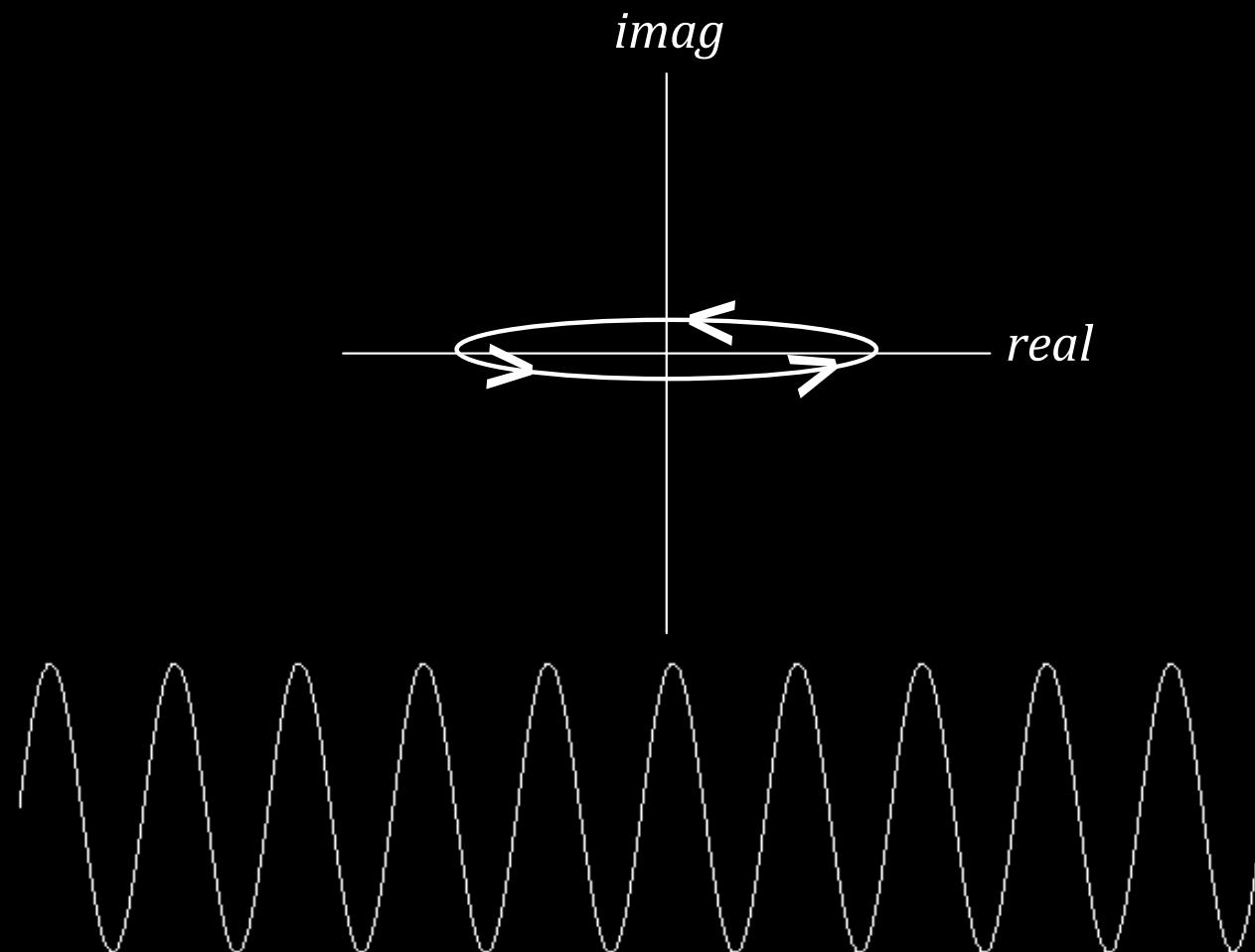
## 2. An aside on why oscillations *oscillate*.

Consider a Sisyphean process.

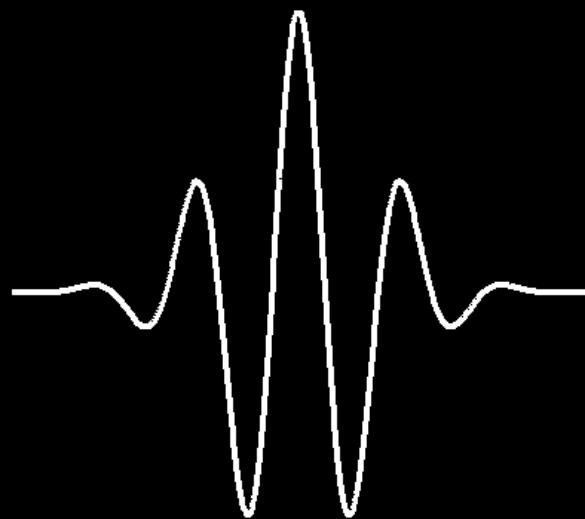


## 2. An aside on why oscillations *oscillate*.

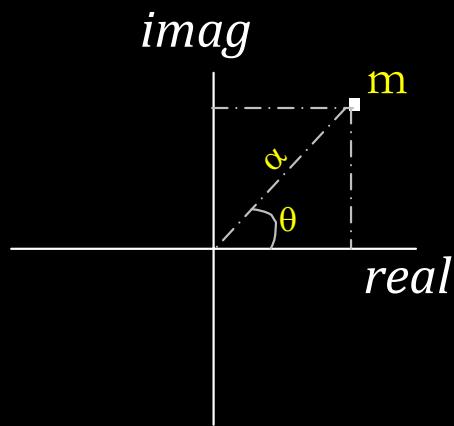
Now consider viewing this process as an adult  
(i.e., no imaginary component).



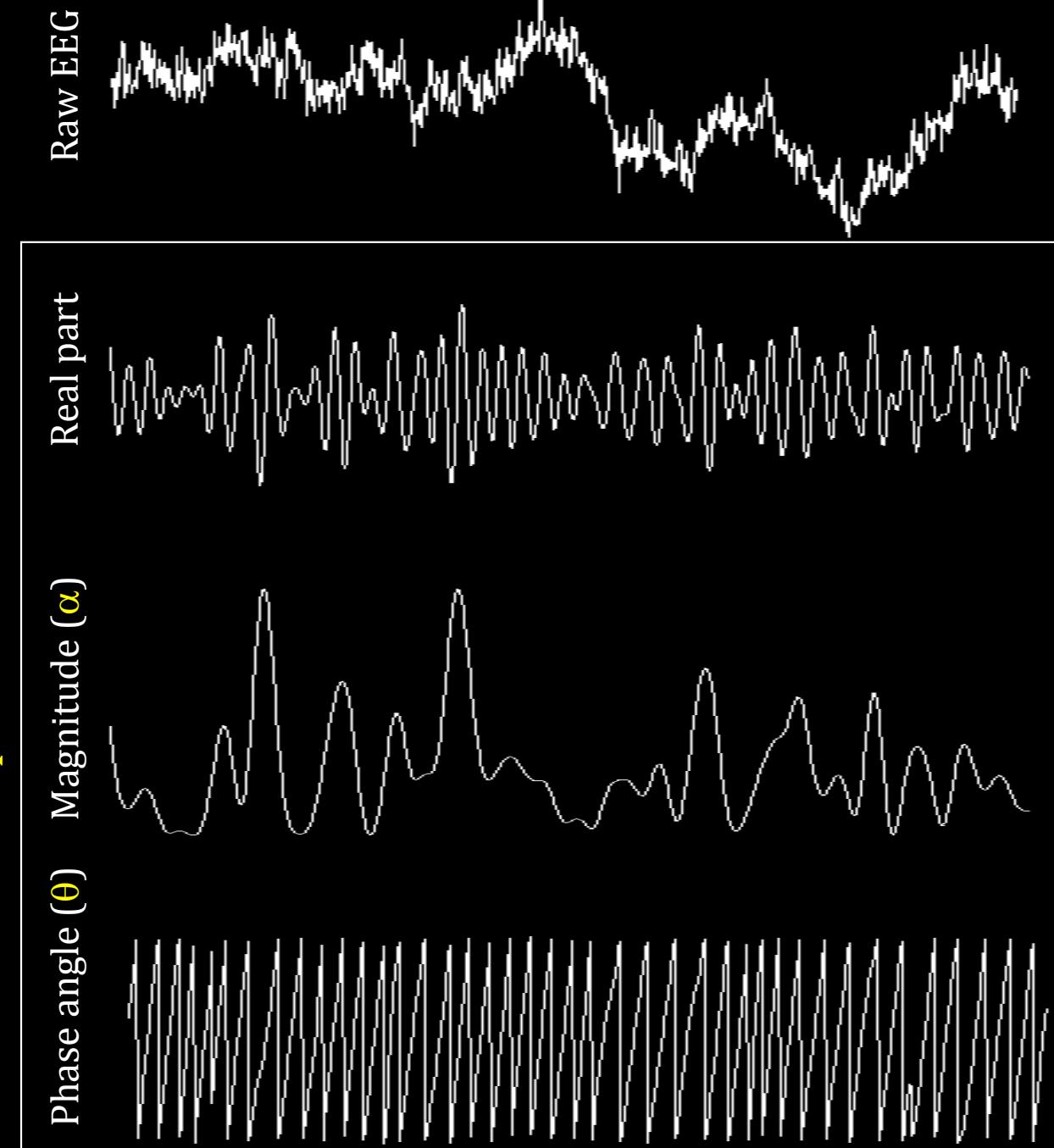
## 2. Different kinds of oscillation information.



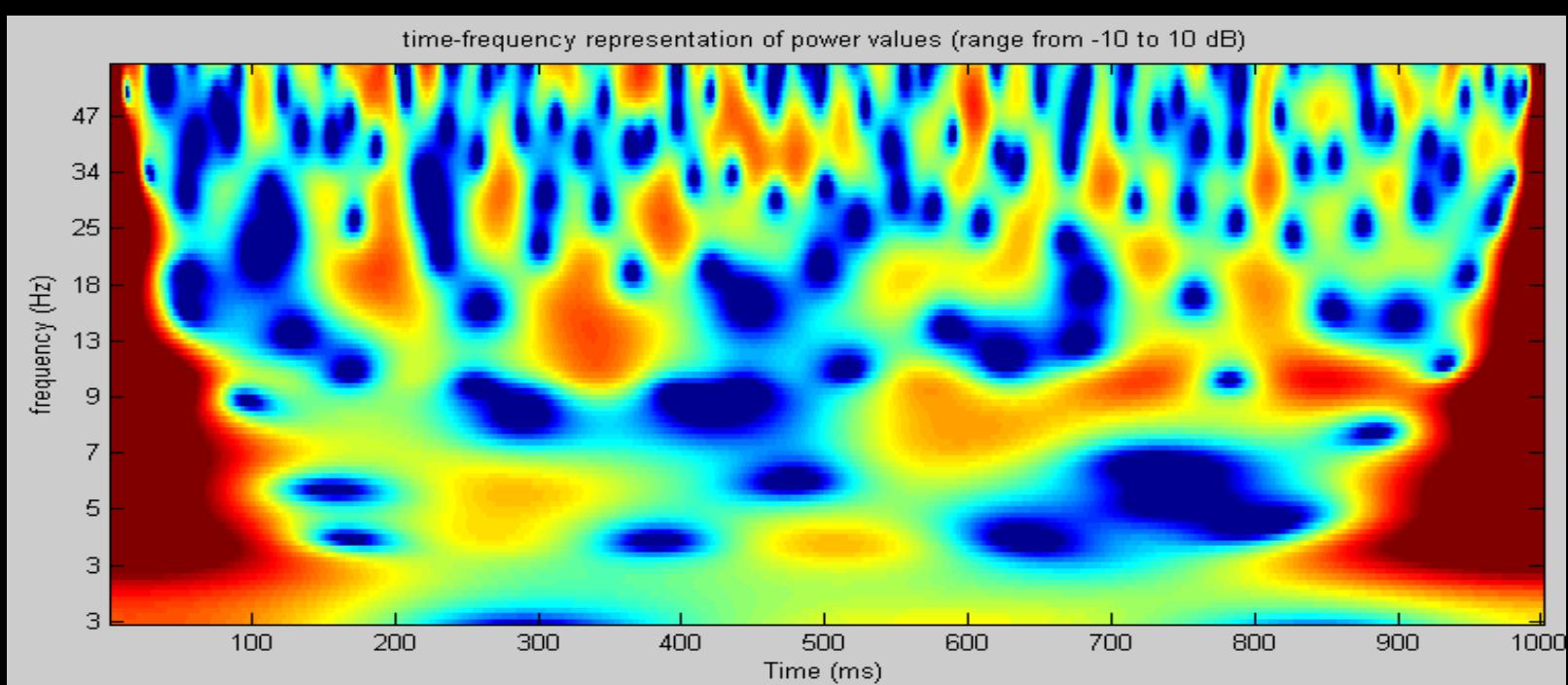
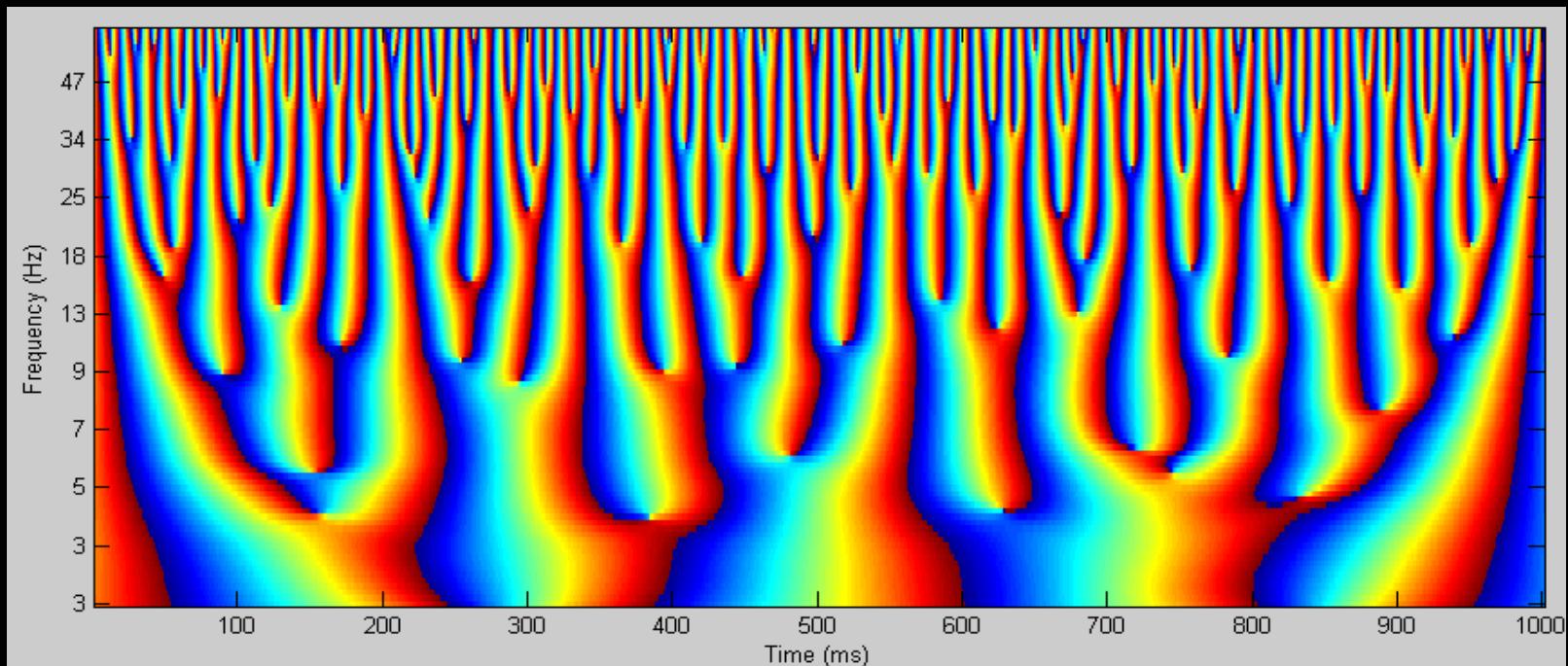
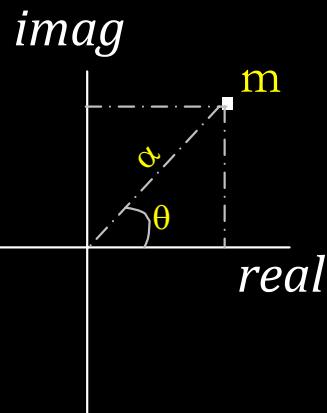
Center  
frequency:  
23.7 Hz



### Results from complex wavelet convolution



## 2. Different kinds of oscillation information.

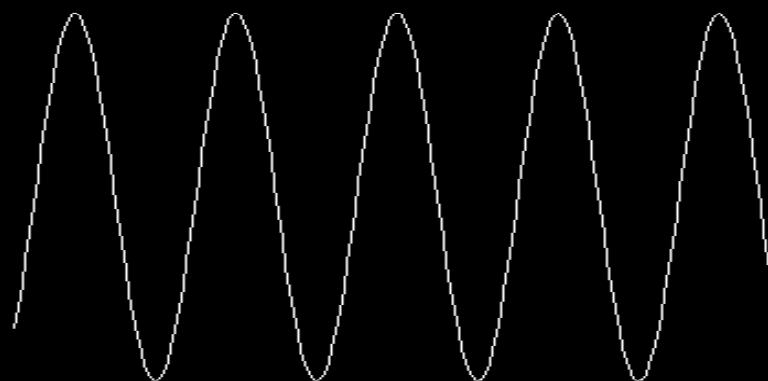


## 2. Where do wavelets come from?

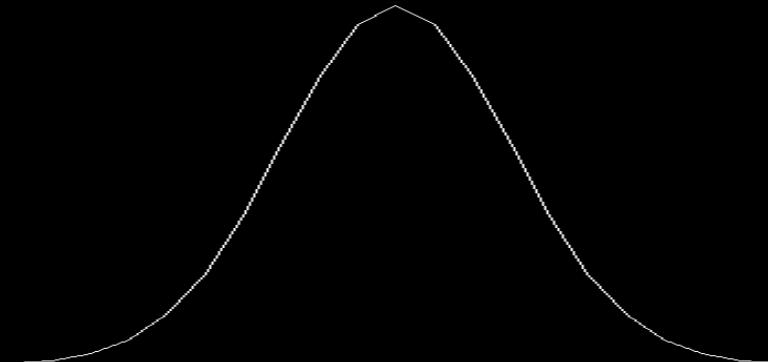


## 2. Where do wavelets come from?

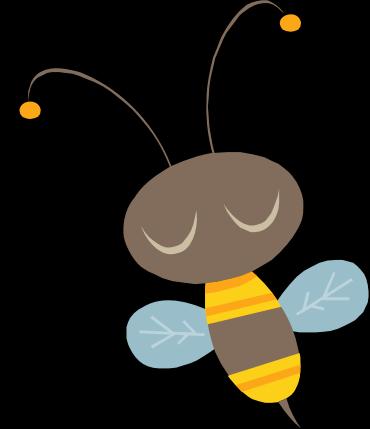
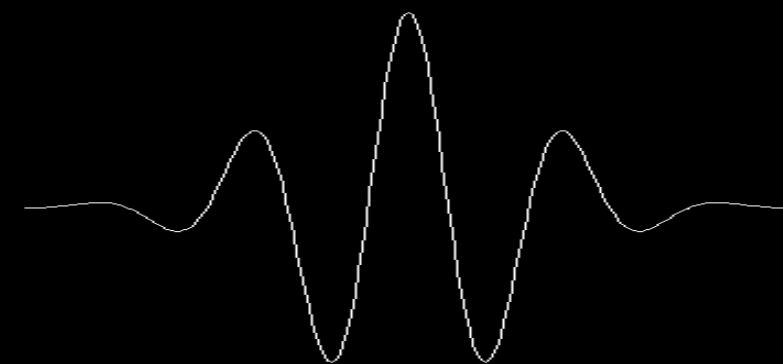
Sine wave



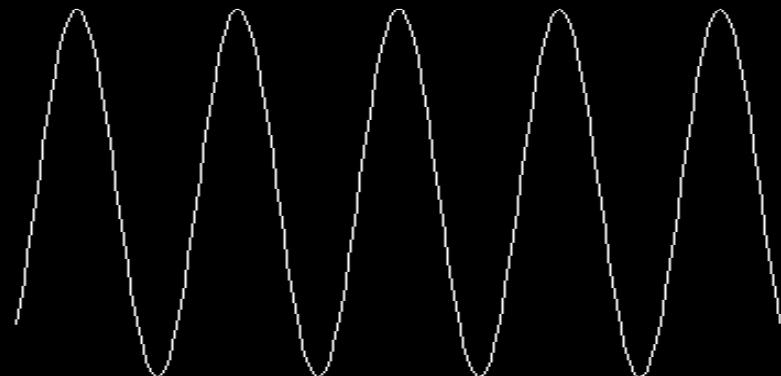
Gaussian



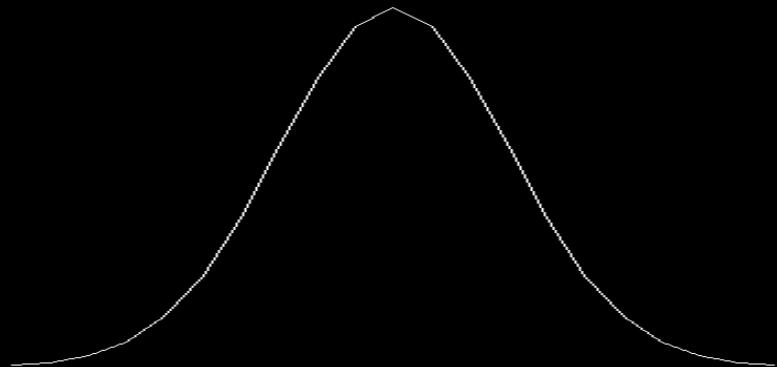
Morelet  
wavelet



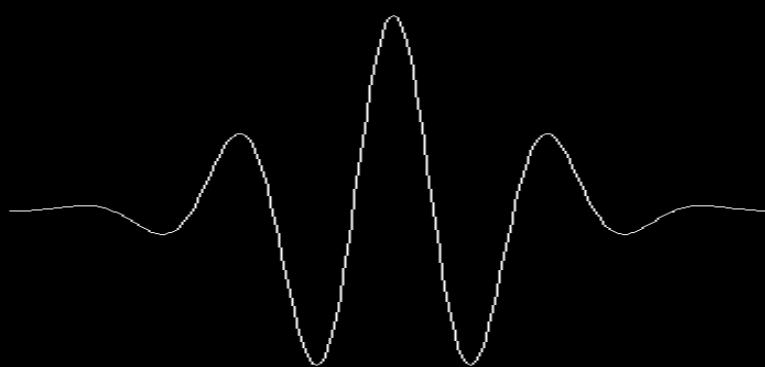
## 2. Wavelet origins: The math behind the magic



```
> sin( 2*pi*freq*time );
```



```
> exp( -time^2 / ( 2*s^2 ) );
```



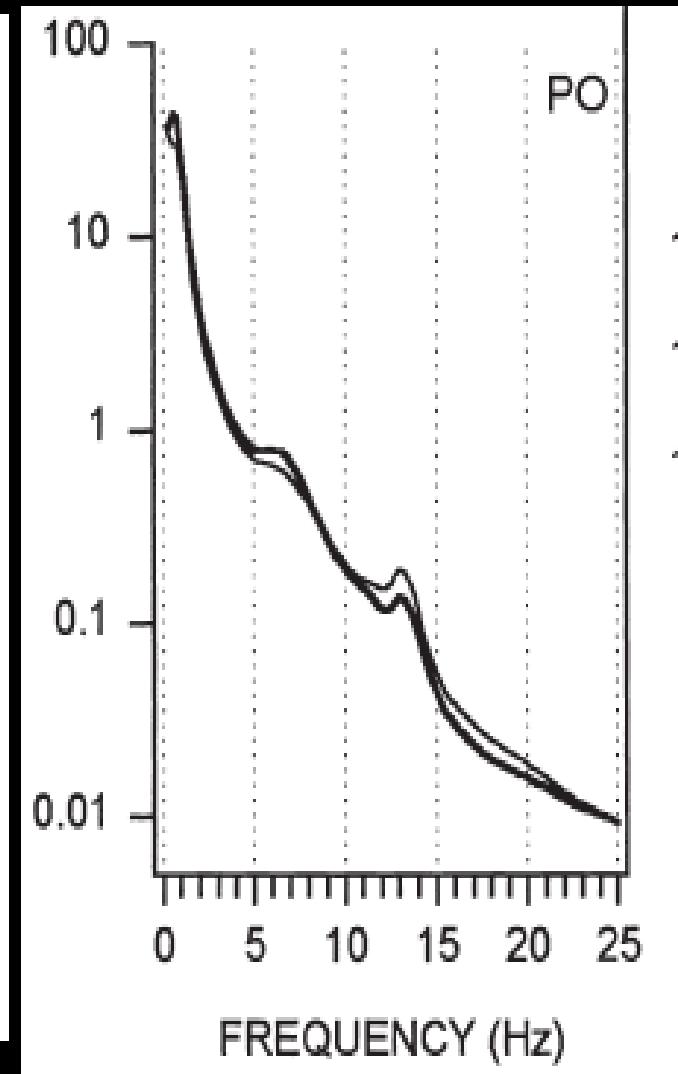
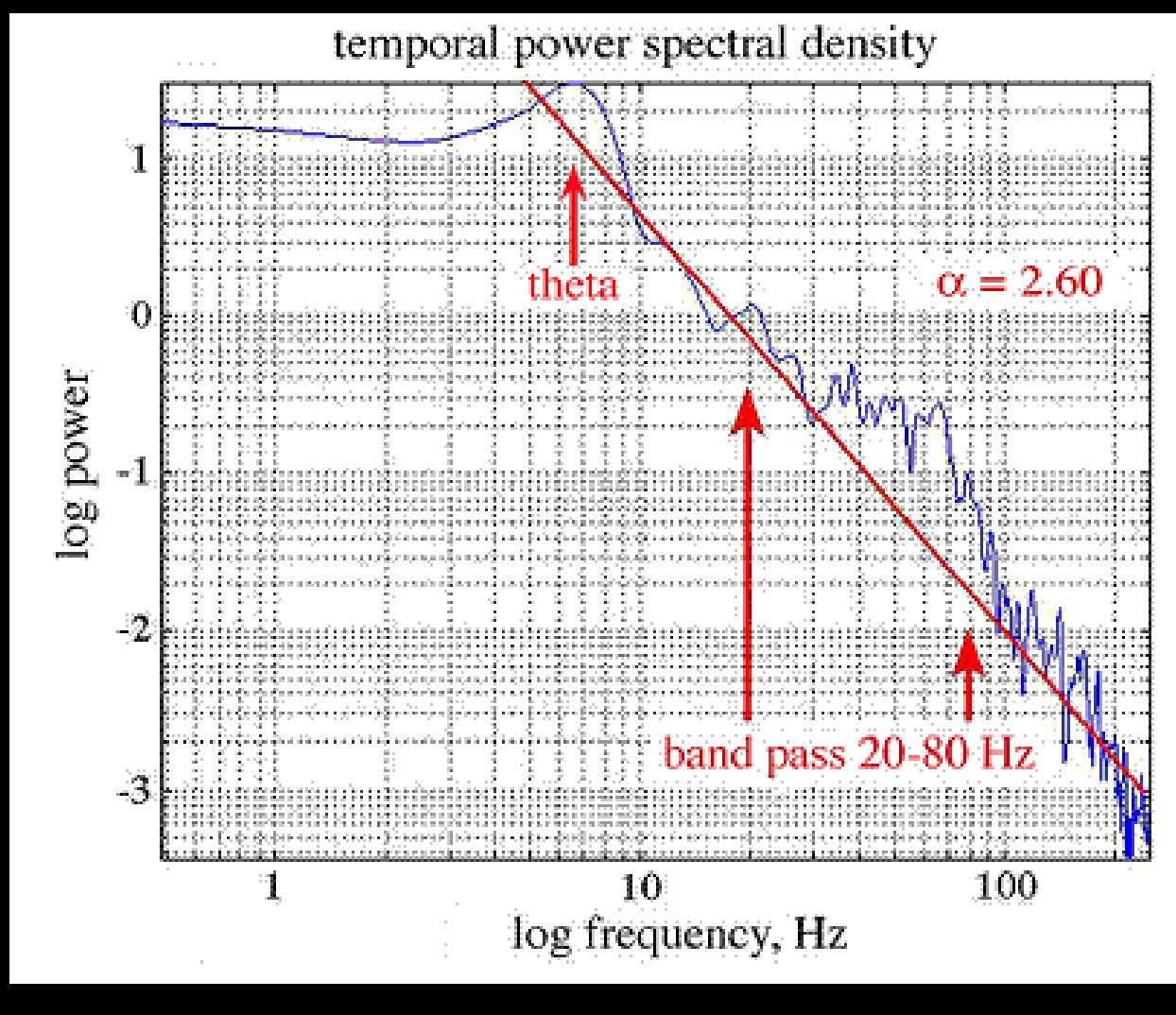
```
> sin( 2*pi*freq*time ) ./  
exp( -time^2 / ( 2*s^2 ) );
```

## 2. Power normalization and the power law

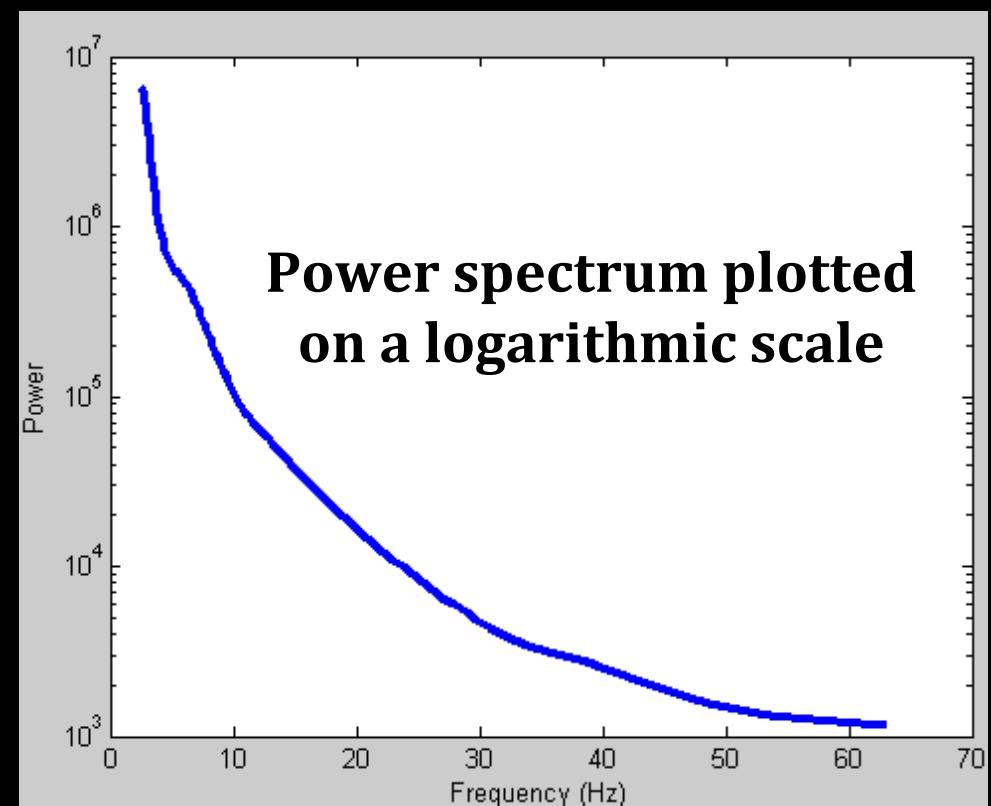
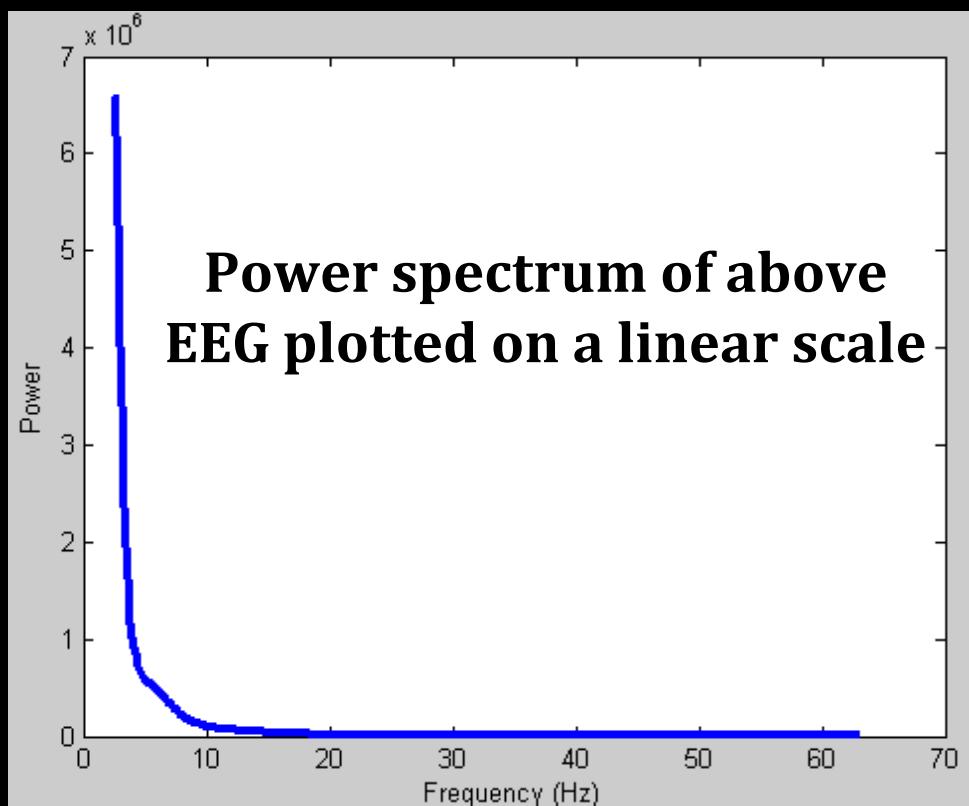
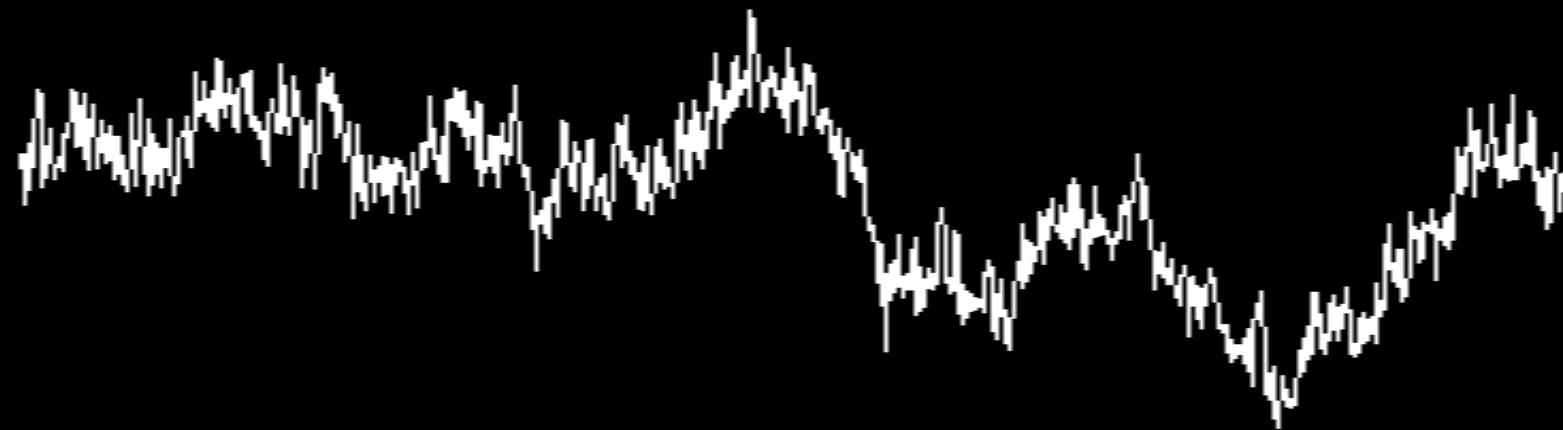


## 2. Power normalization and the power law

The power law: Power decreases with increasing frequency  
(at low frequencies, power approaches a  $1/f$  function).



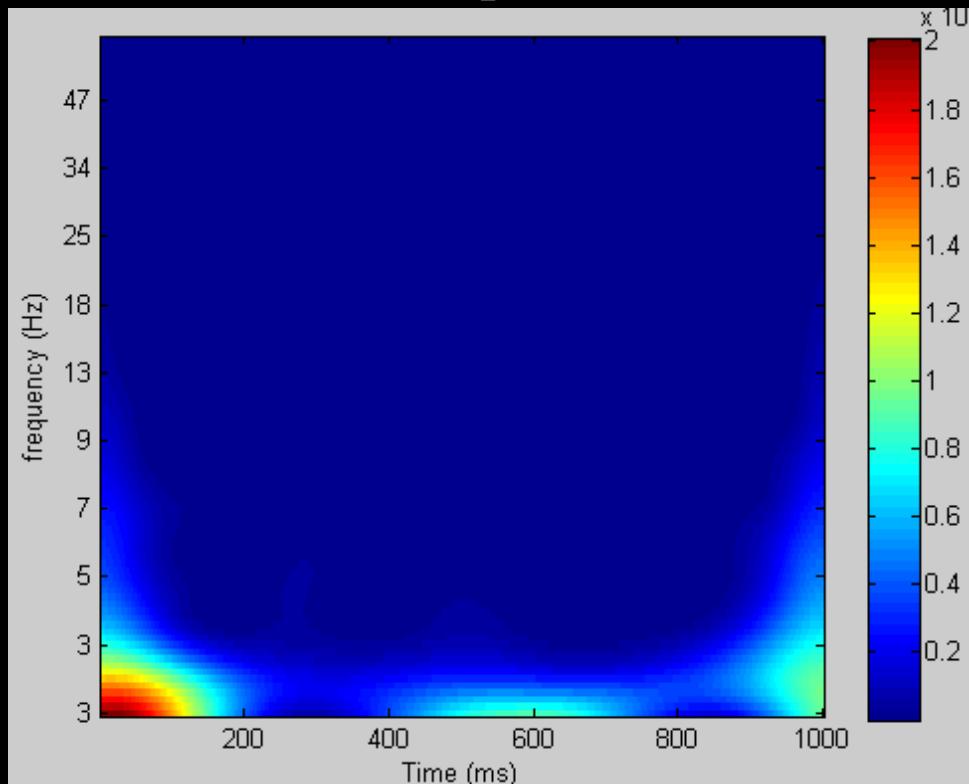
## 2. Power Law in da house!



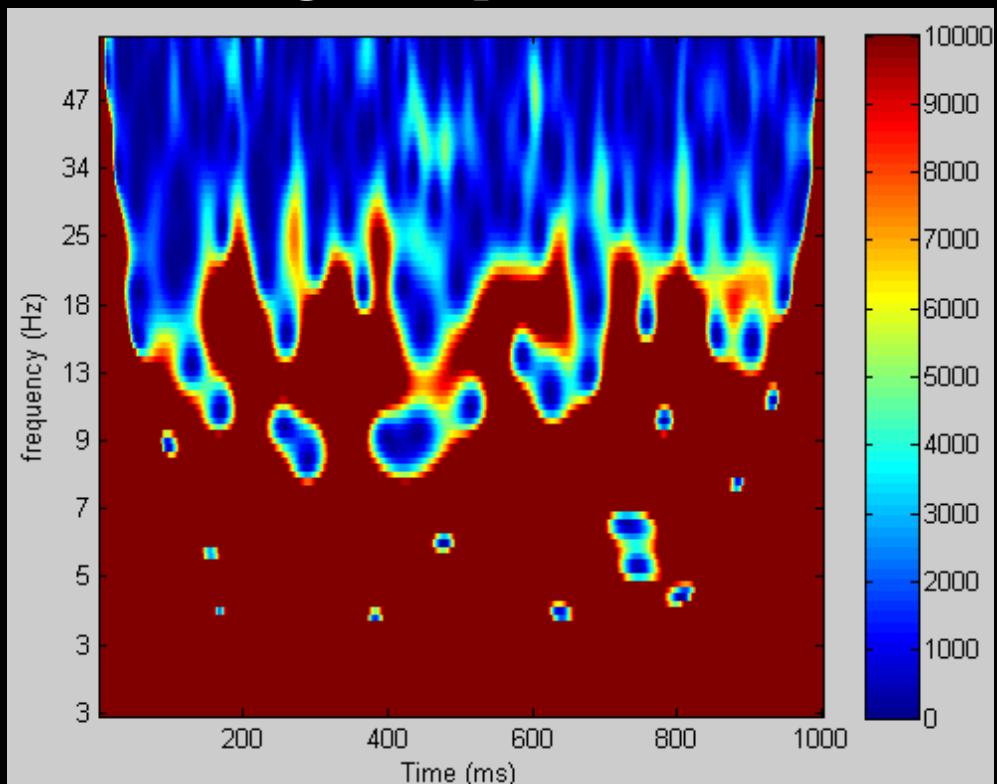
## 2. Power normalization and the power law

The power law introduces a problem, because possible effects in higher frequencies will be nearly impossible to see when plotted simultaneously with lower frequencies.

Colorscale optimized for  
low frequencies



Colorscale optimized for  
high frequencies



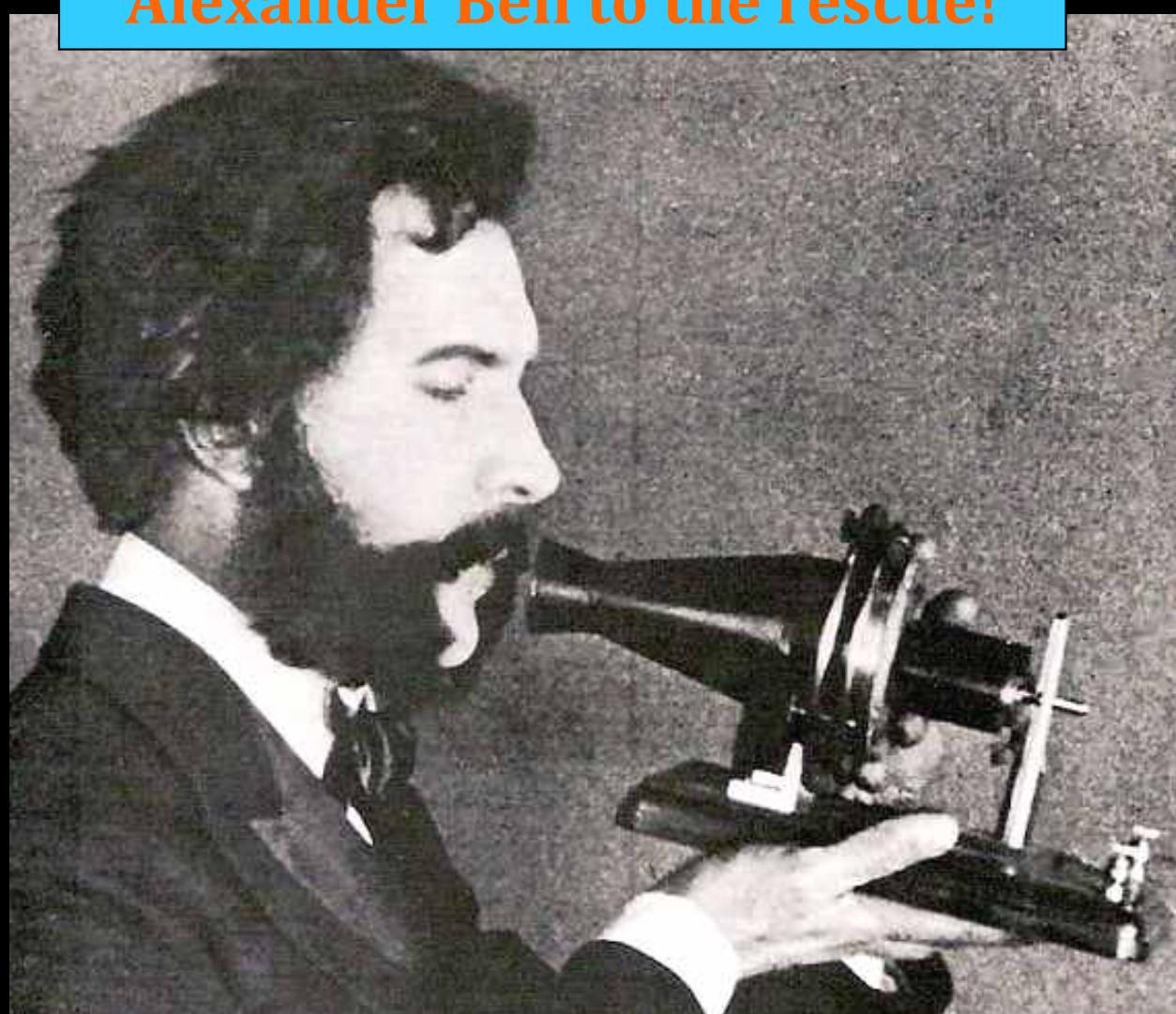
## 2. Power normalization and the power law

What to do?

Can't use a linear baseline correction (e.g., subtracting pre-stimulus power). We need a *nonlinear* correction that takes the Power Law into account.

Solution??

Alexander Bell to the rescue!



## 2. Power normalization and the power law

---

A Decibel (dB) is a *ratio*.

Ratios are useful because they are  
*scale-free!*

Formula:

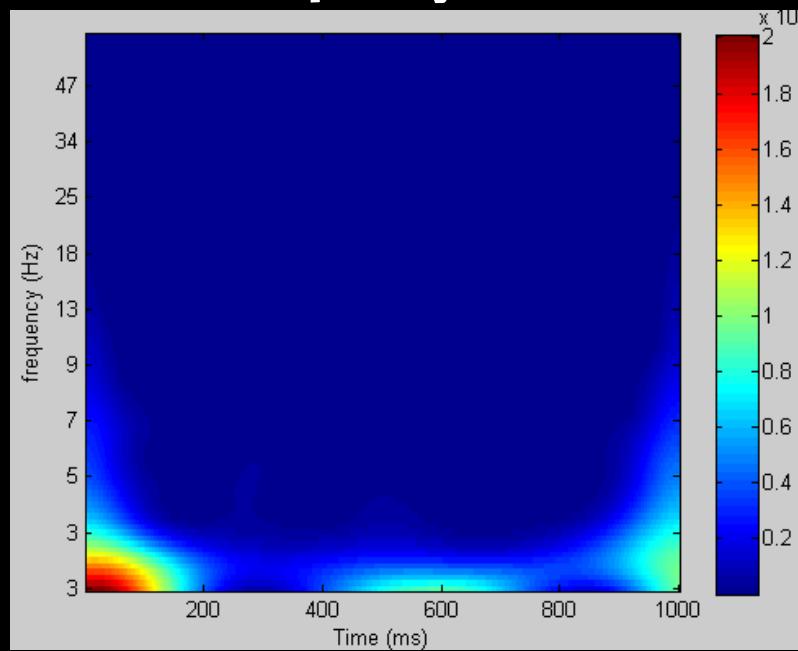
$$\text{dB} = 10 * \log_{10}(\text{baseline}/\text{activity})$$

Or:

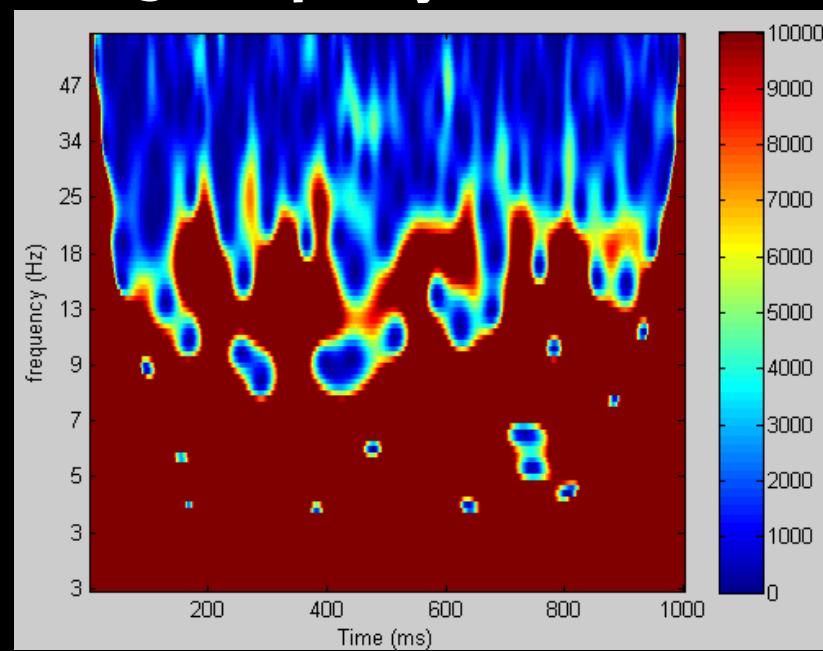
$$\text{dB} = 10 * ( \log_{10}(\text{baseline}) - \log_{10}(\text{activity}) )$$

## 2. Power normalization and the power law

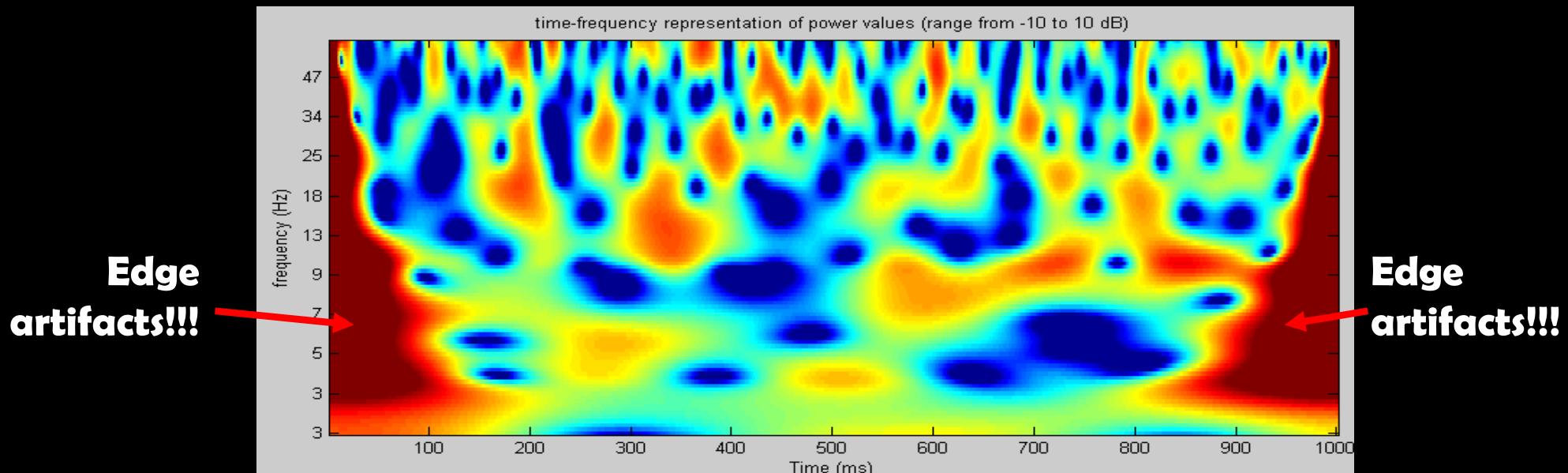
Low frequency colorscale



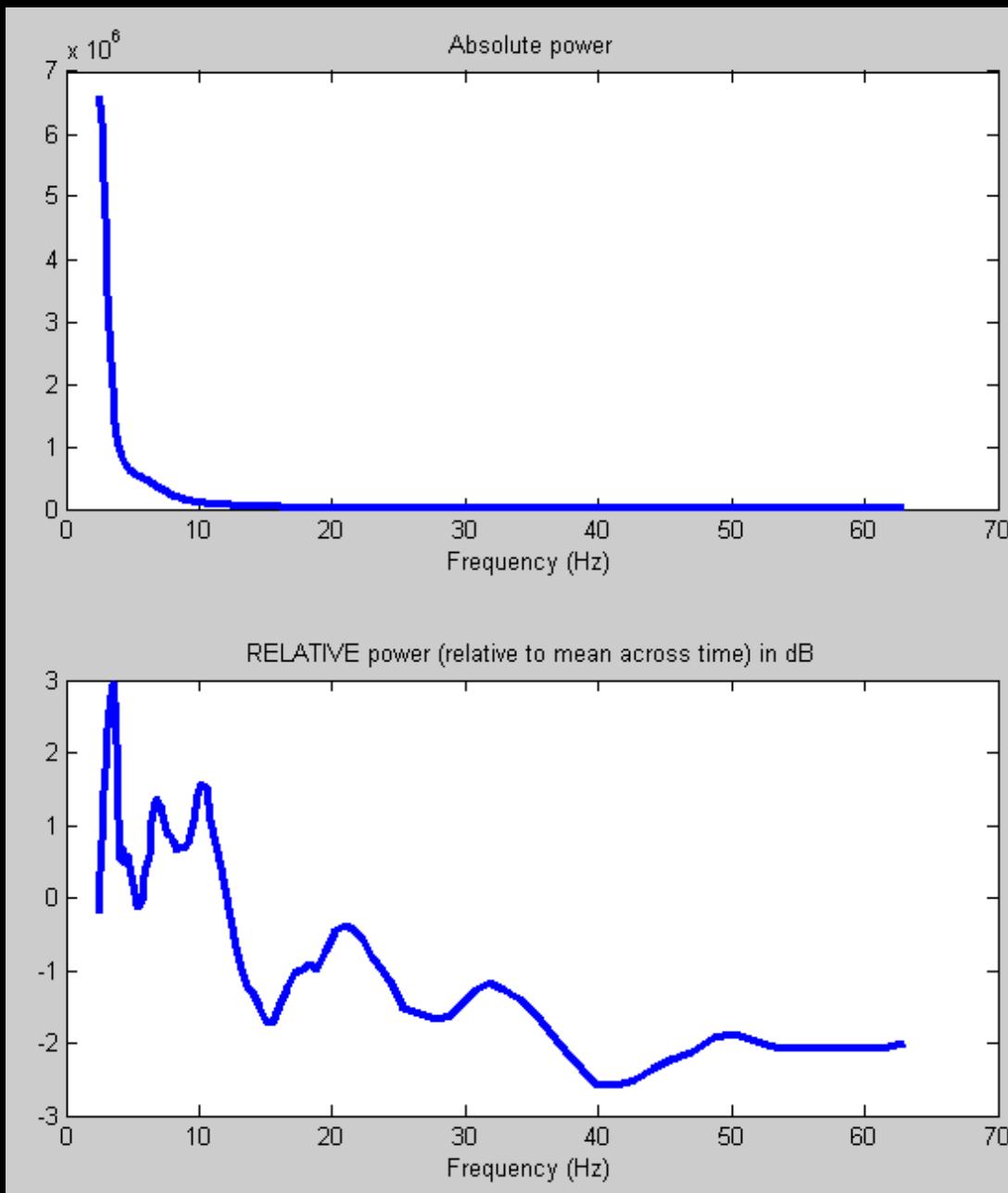
High frequency colorscale



**dB scaled!**



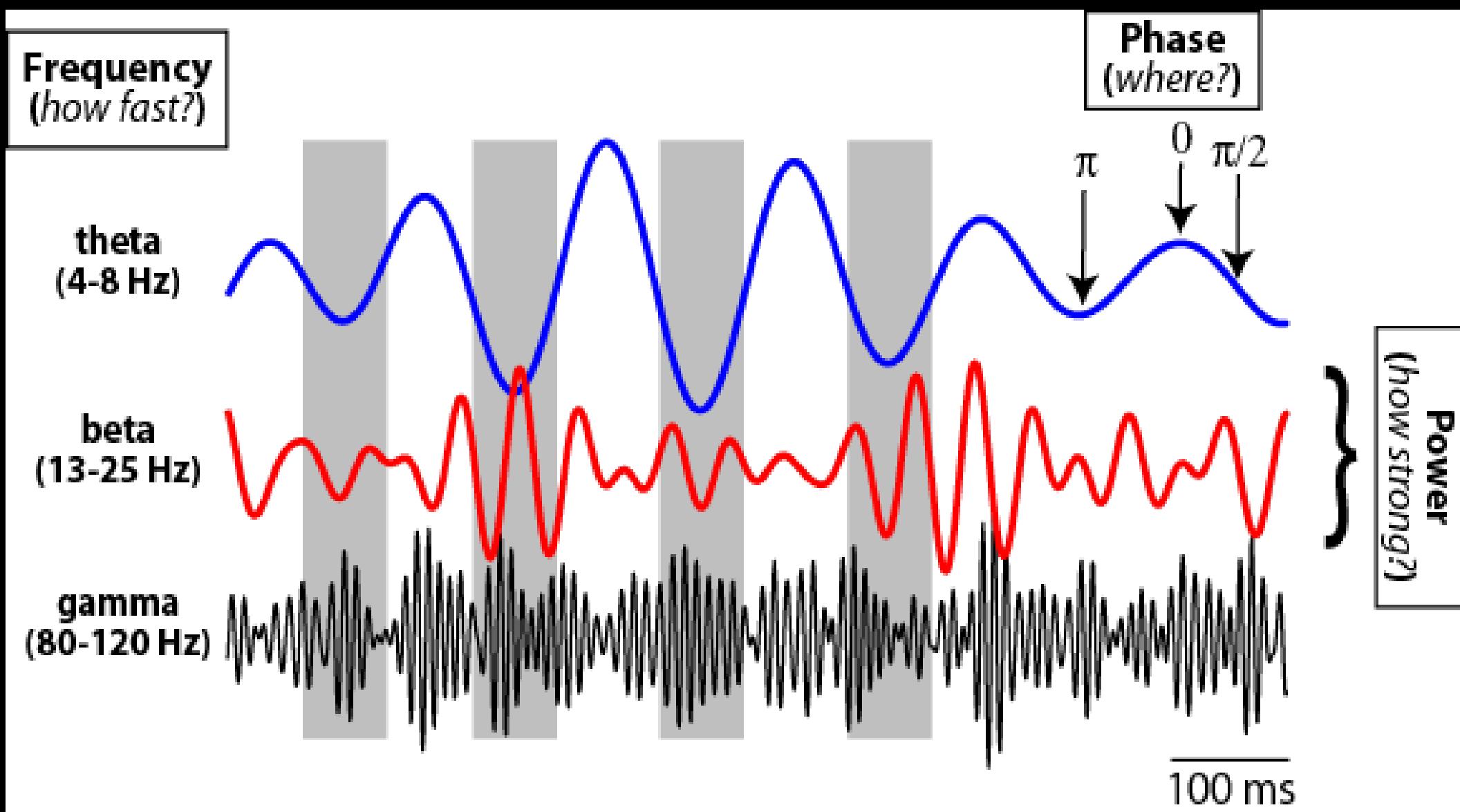
## 2. Power normalization and the power law



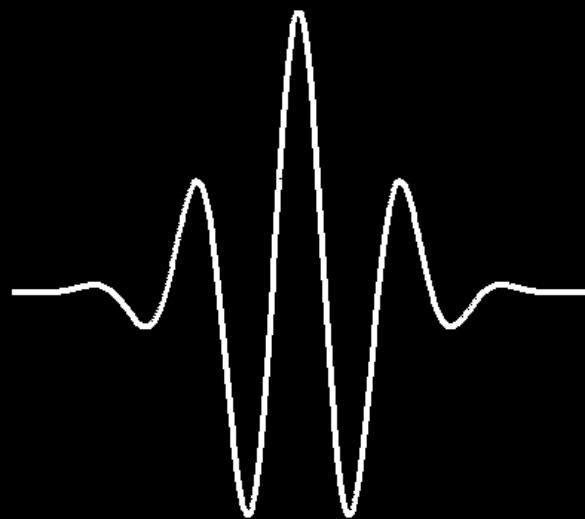
**Note that these two plots come from the same EEG data!**

**dB scaling is also useful when comparing findings across subjects, because different individuals will have different levels of absolute oscillation power, due a variety of factors including skull thickness and cortical folding.**

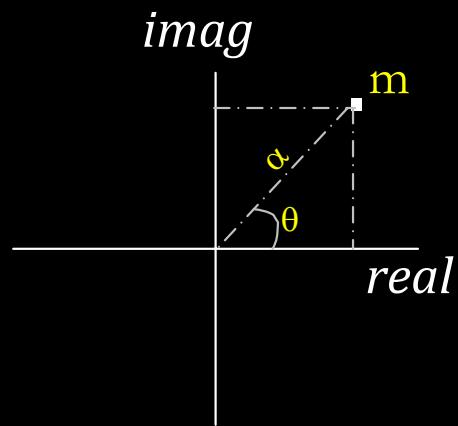
## 2. Summary of oscillation properties



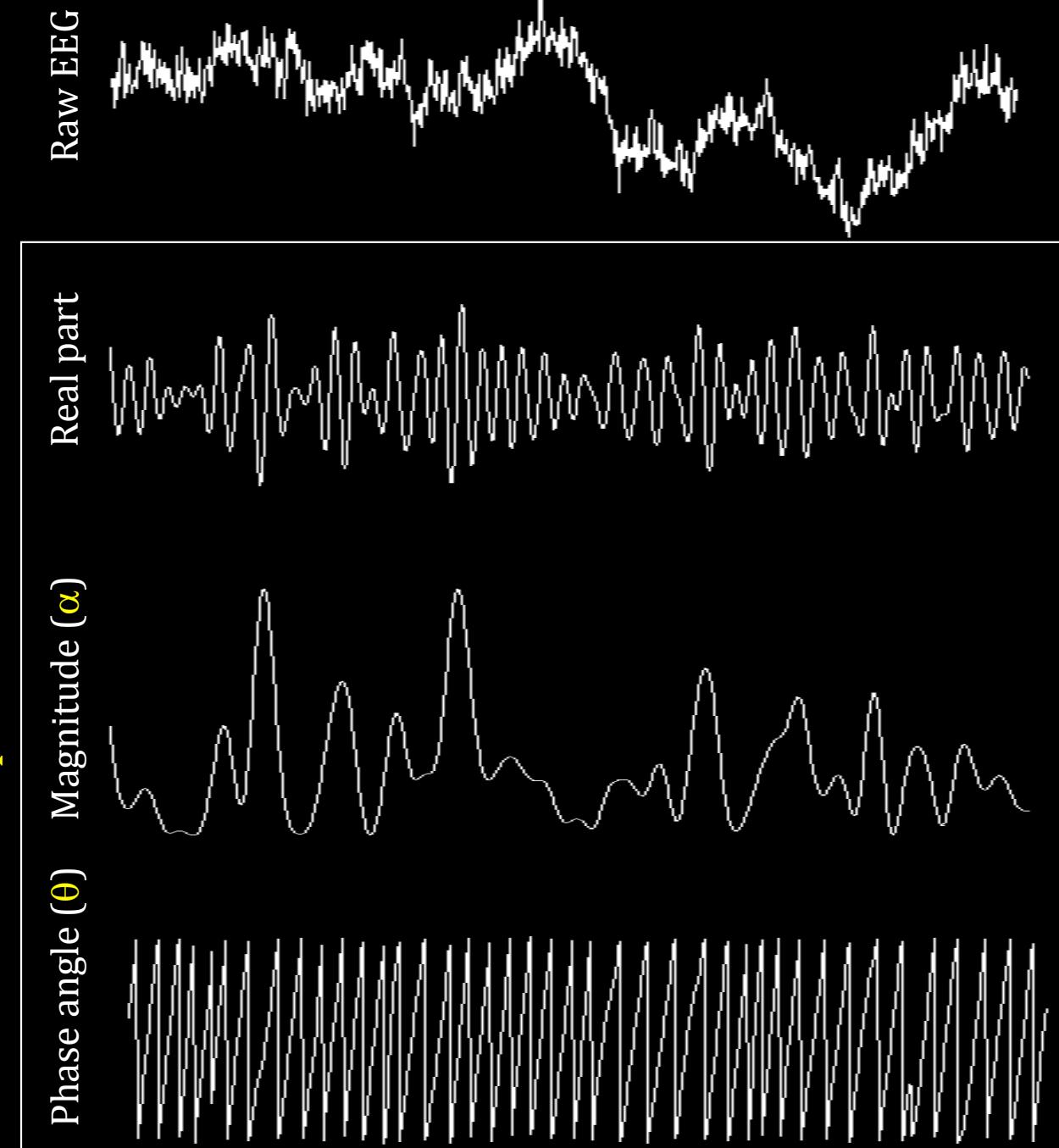
## 2. Different kinds of oscillation information.



Center  
frequency:  
23.7 Hz



### Results from complex wavelet convolution

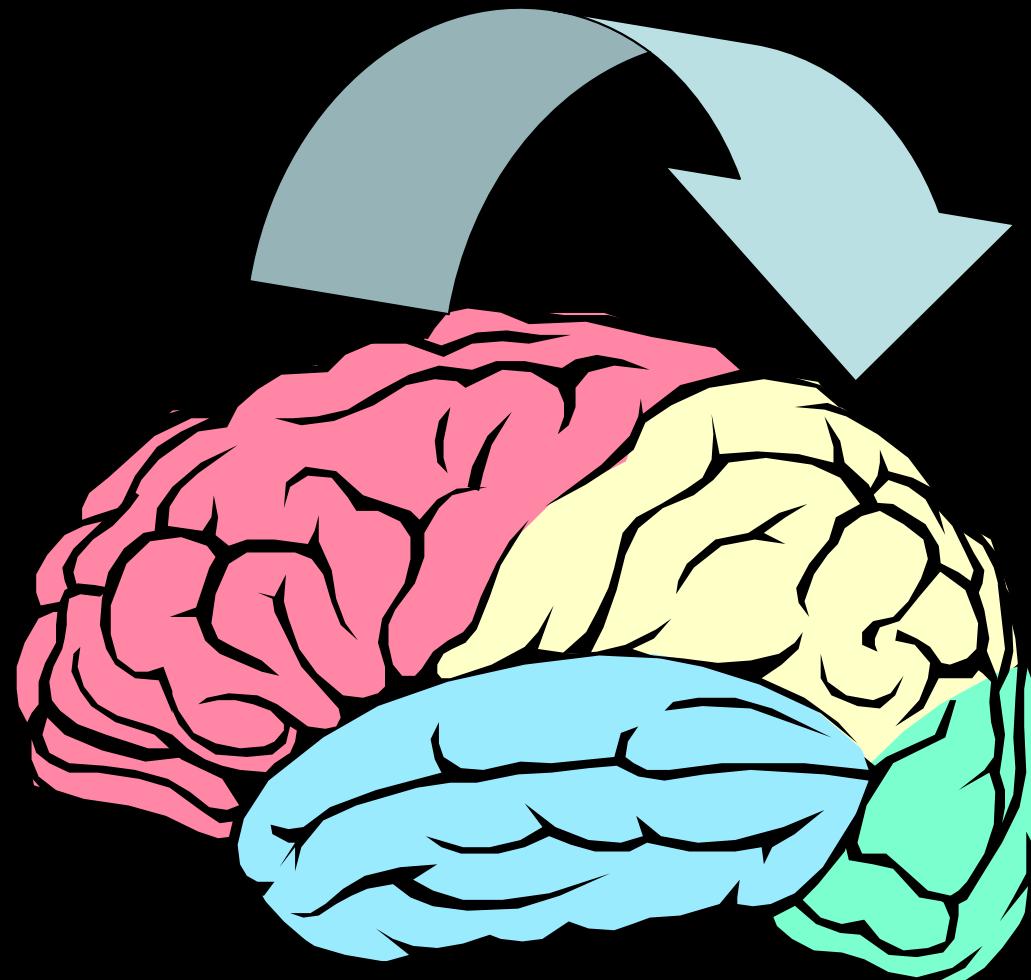


# 1-hour boot camp for advanced EEG analyses

**BY THE END OF TODAY, YOU WILL BE ABLE TO:**

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- 5. (optional) Renounce ERPs forever!!**

## 2. How do brain regions “talk” to each other?

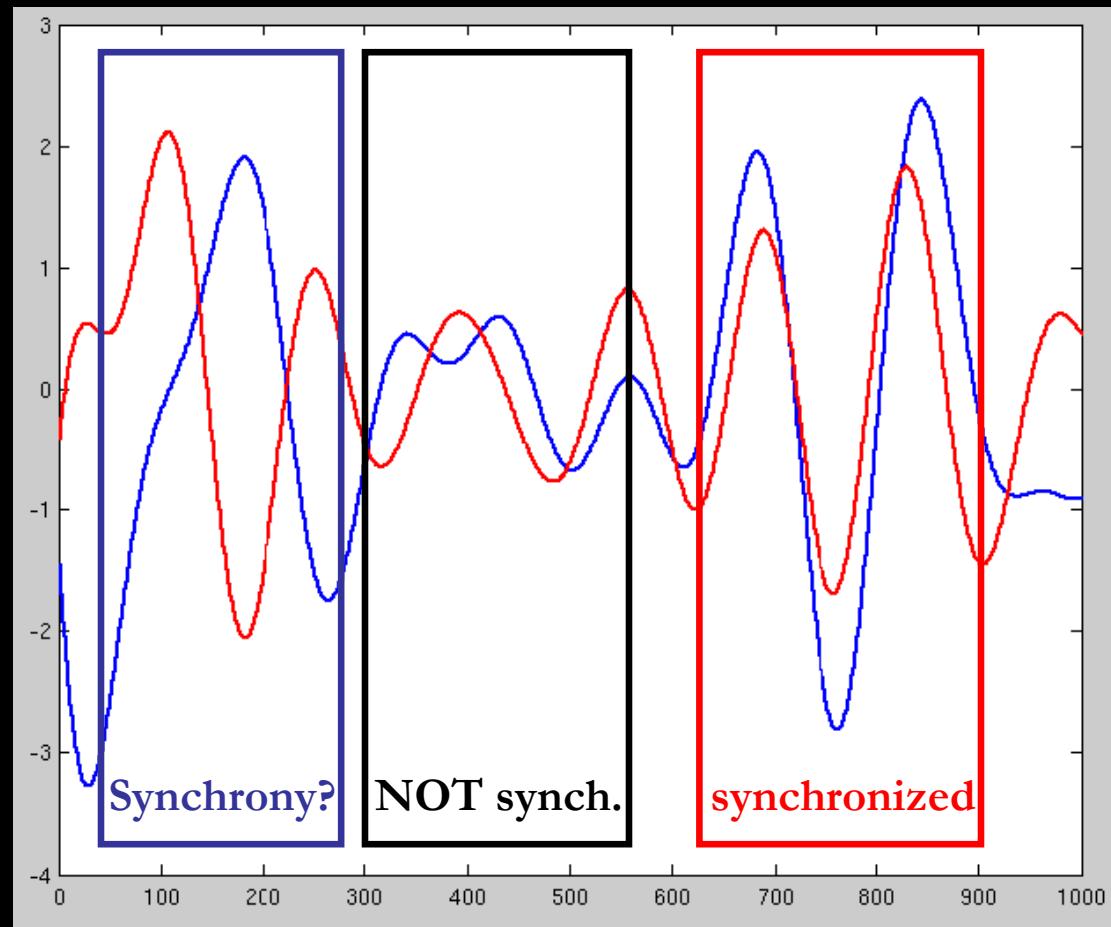


**Perhaps through synchronized oscillations!**

See empirical work and reviews by:  
Rubino, Lisman, Singer, Engels, etc.

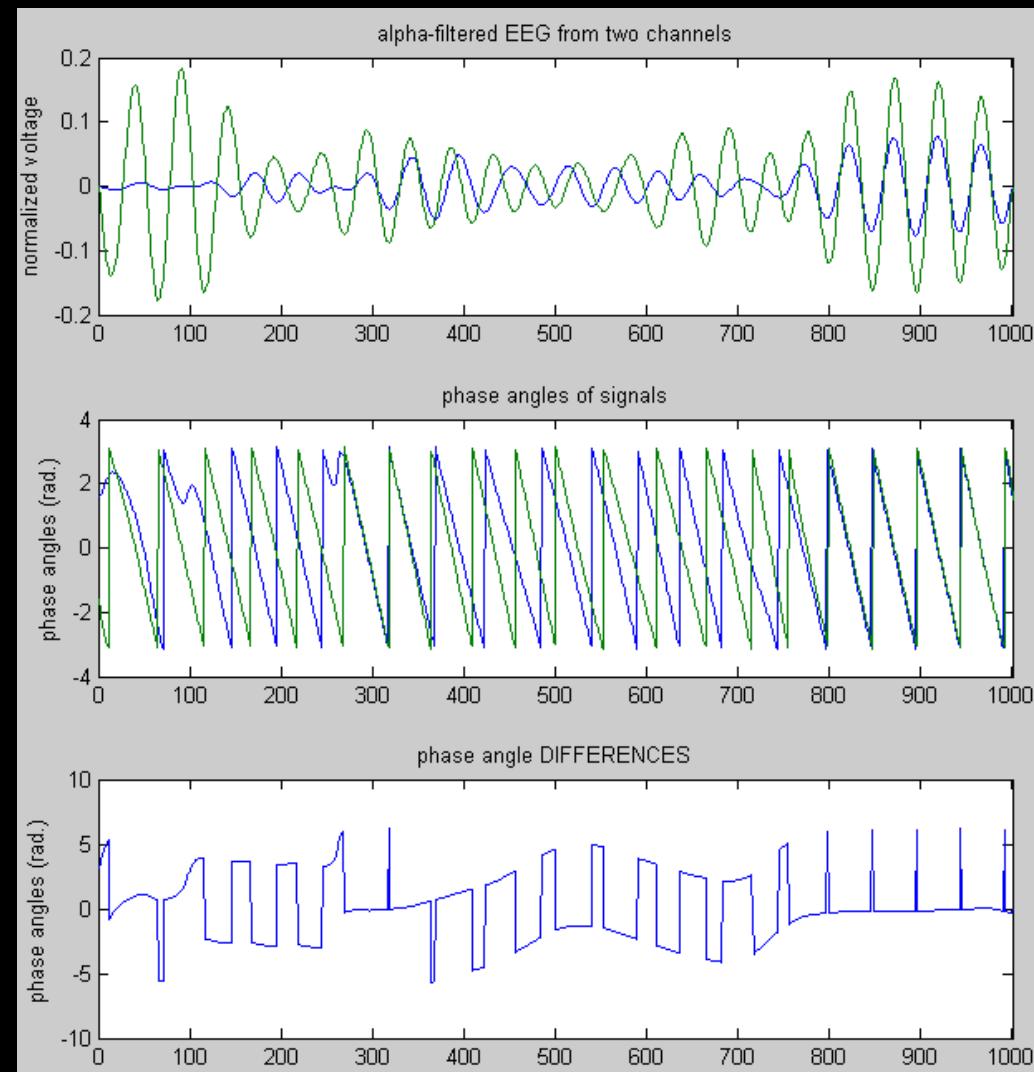
## 2. How do brain regions “talk” to each other?

Synchronized oscillations is an intuitive concept,  
but how to measure it quantitatively?

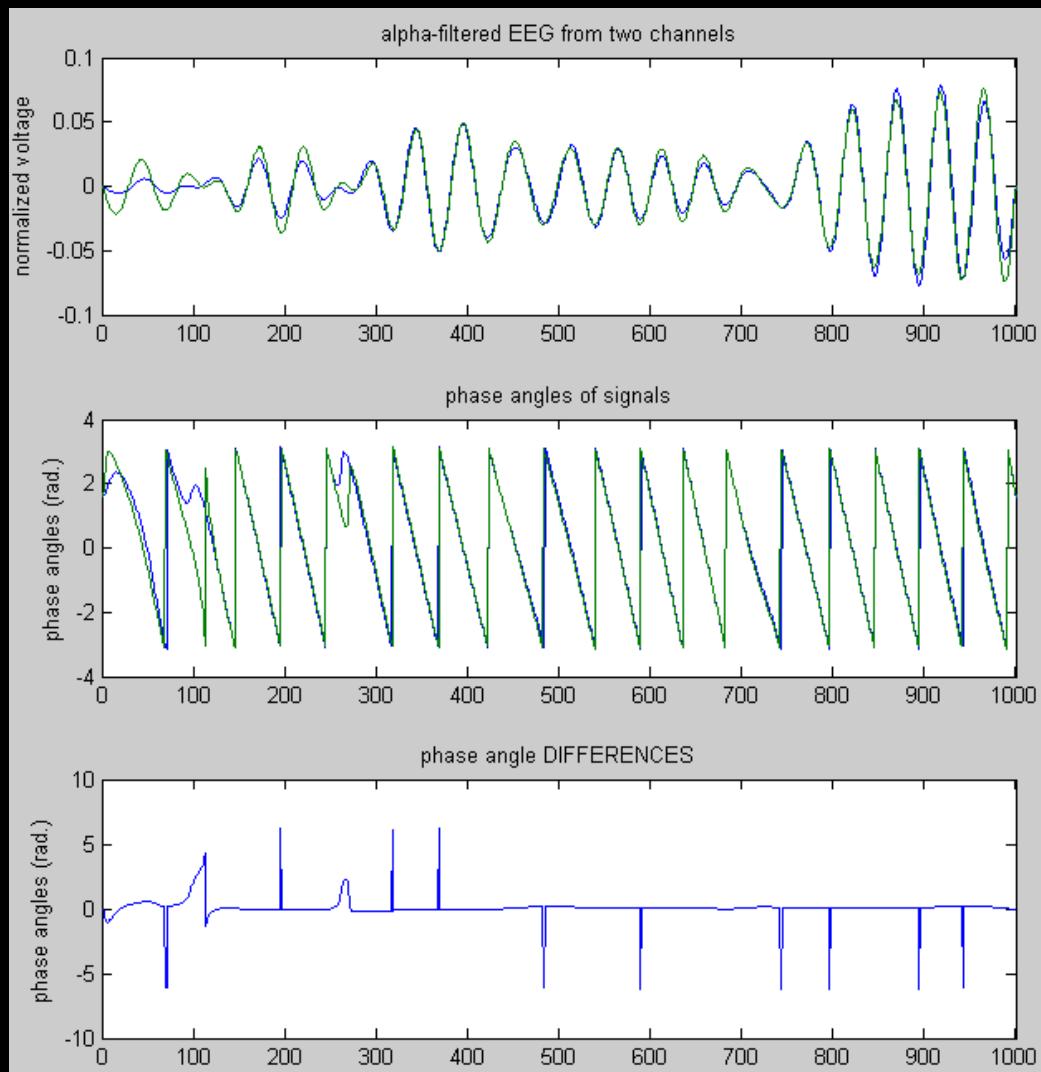


## 2. Inter-site phase coherence.

Electrodes: Fp1 & C4

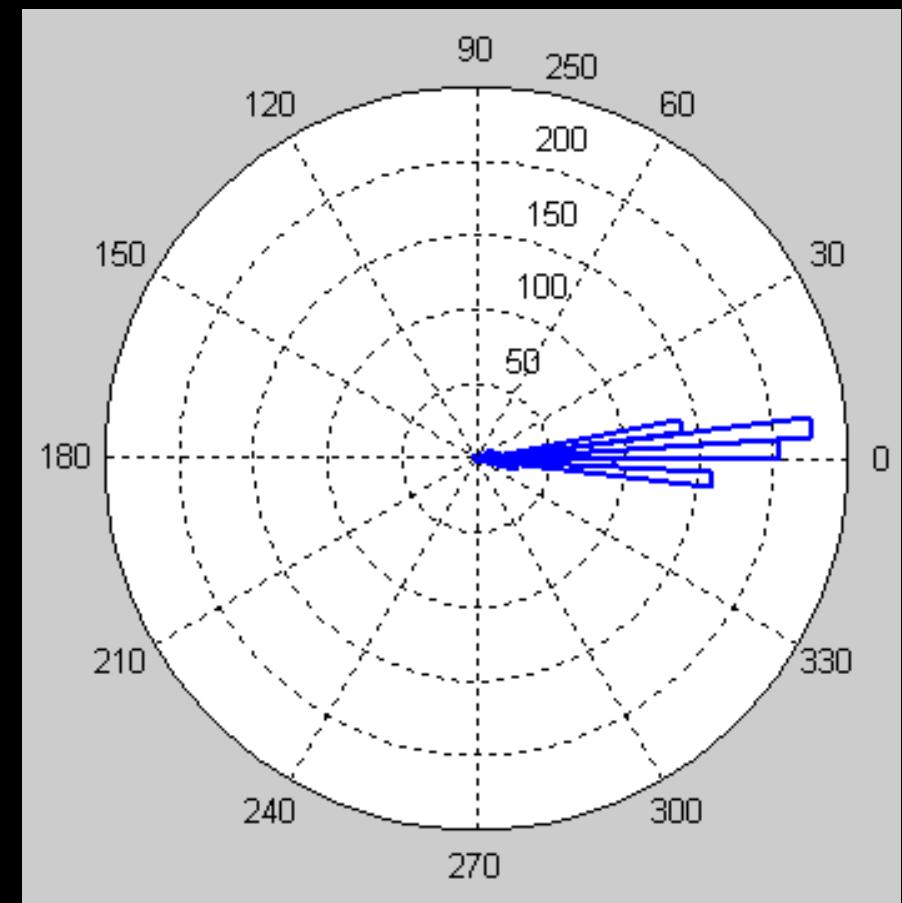
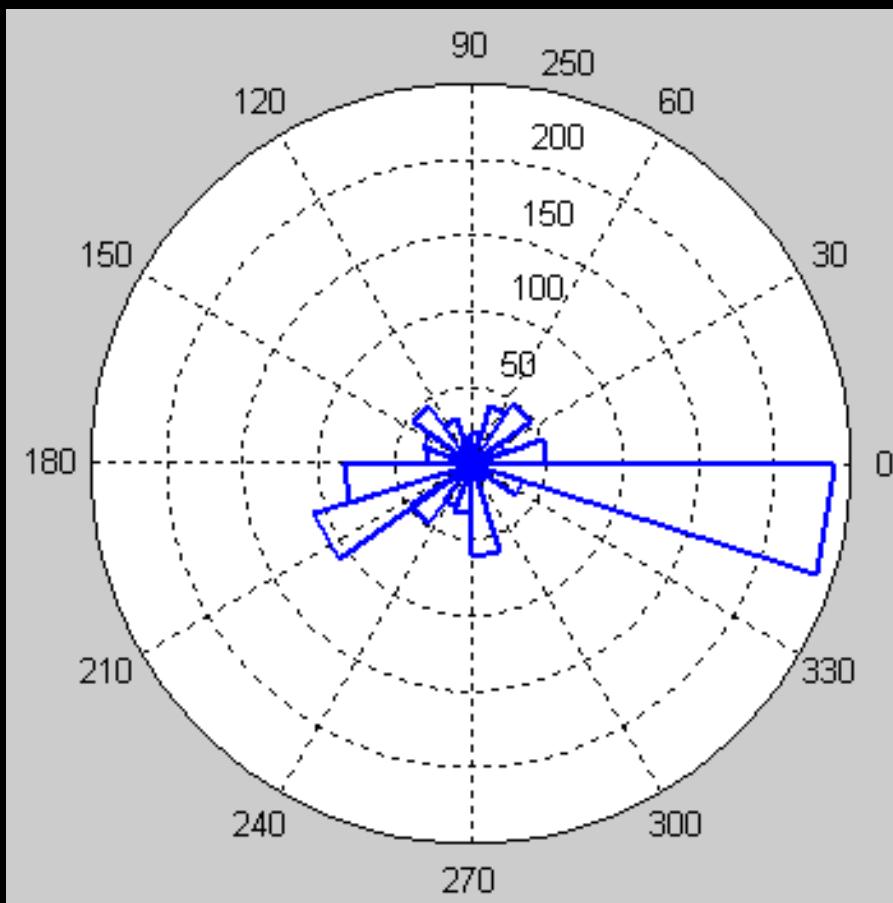


Electrodes: Fp1 & Fp2



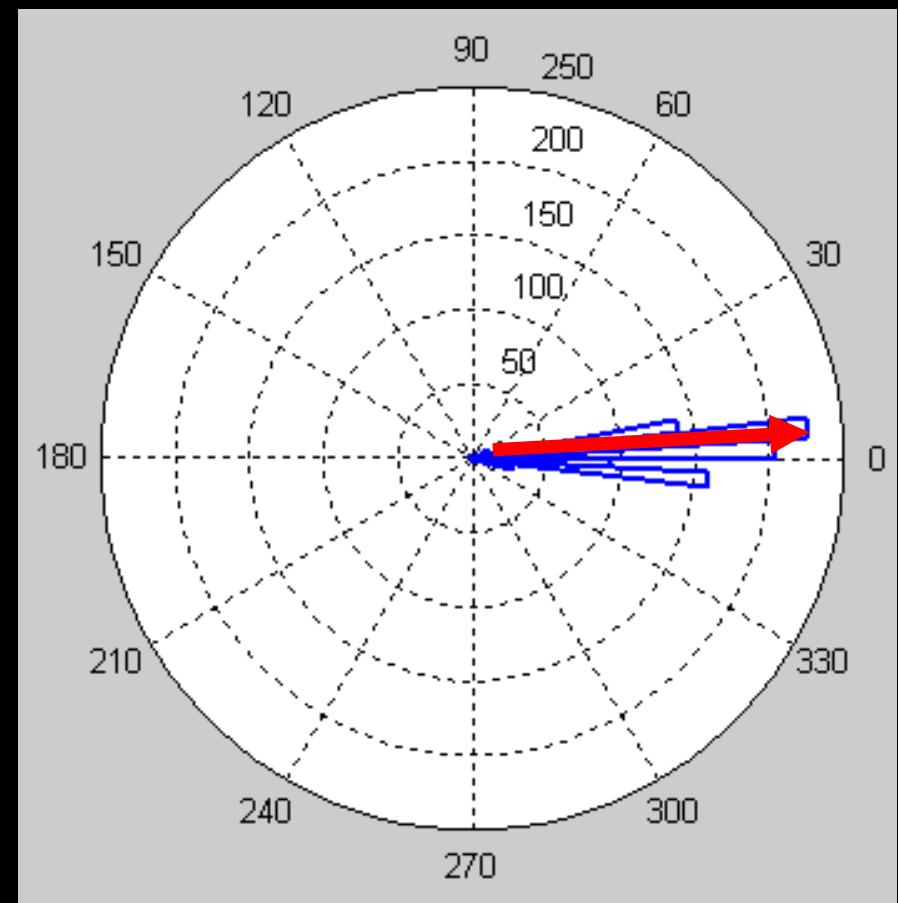
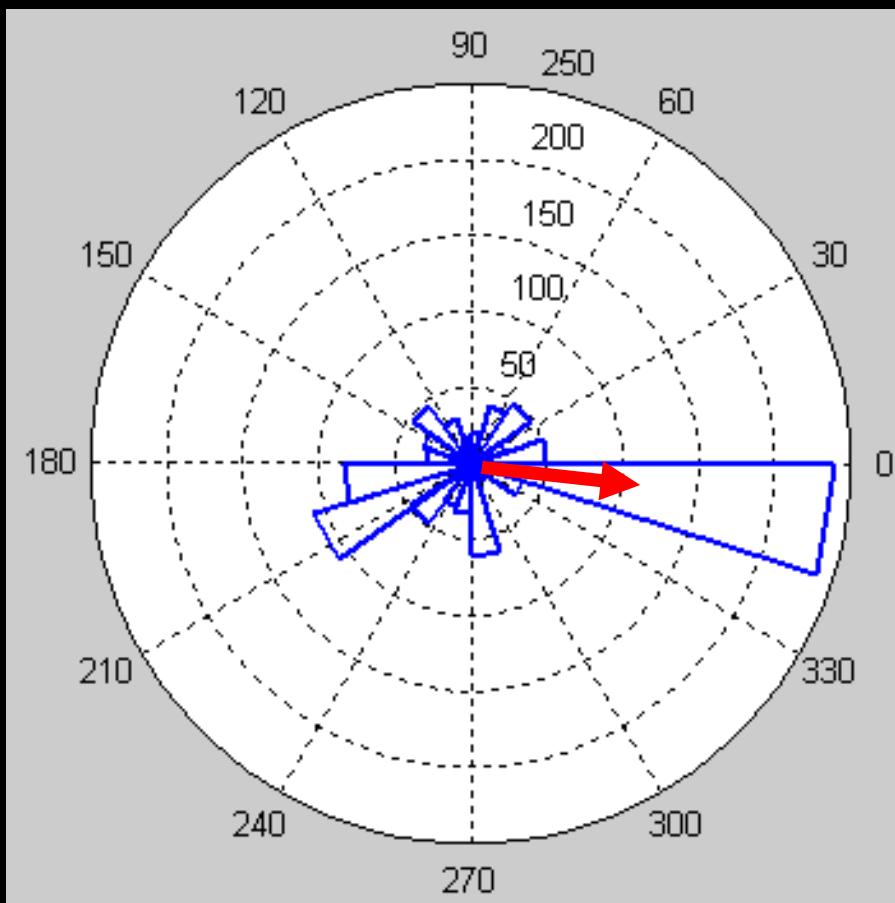
## 2. Inter-site phase coherence?

“Polar plot” of phase angle differences.



## 2. Circular variance.

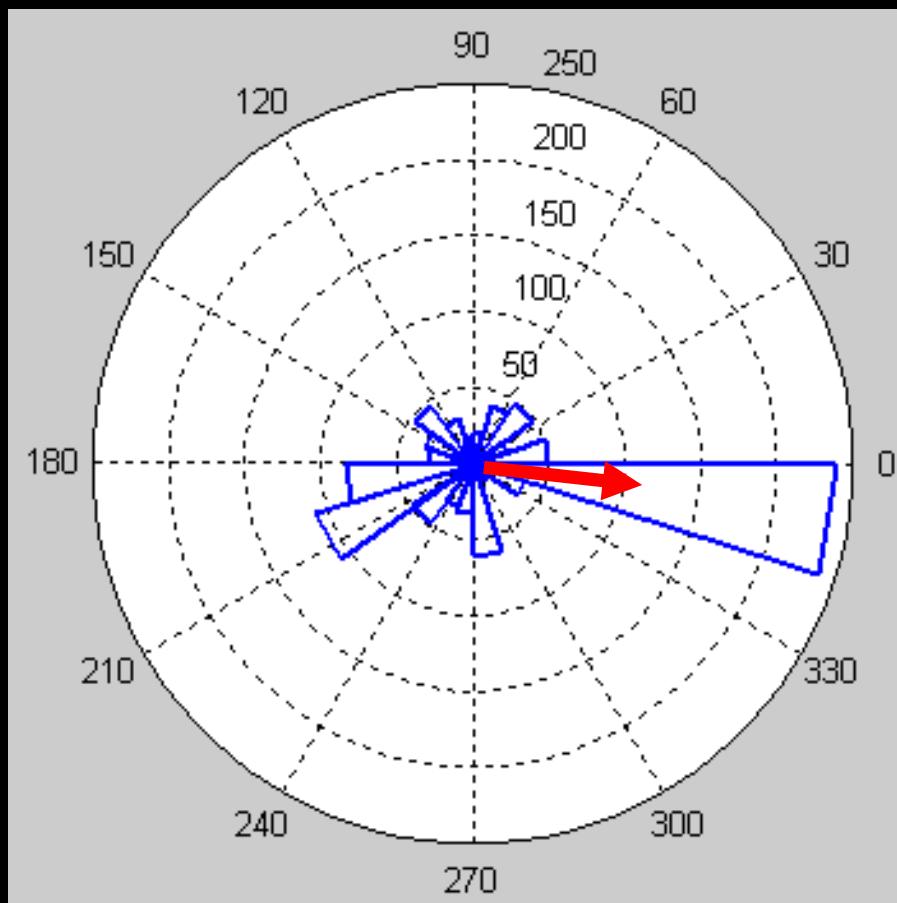
Draw a line through the “average” of vectors.



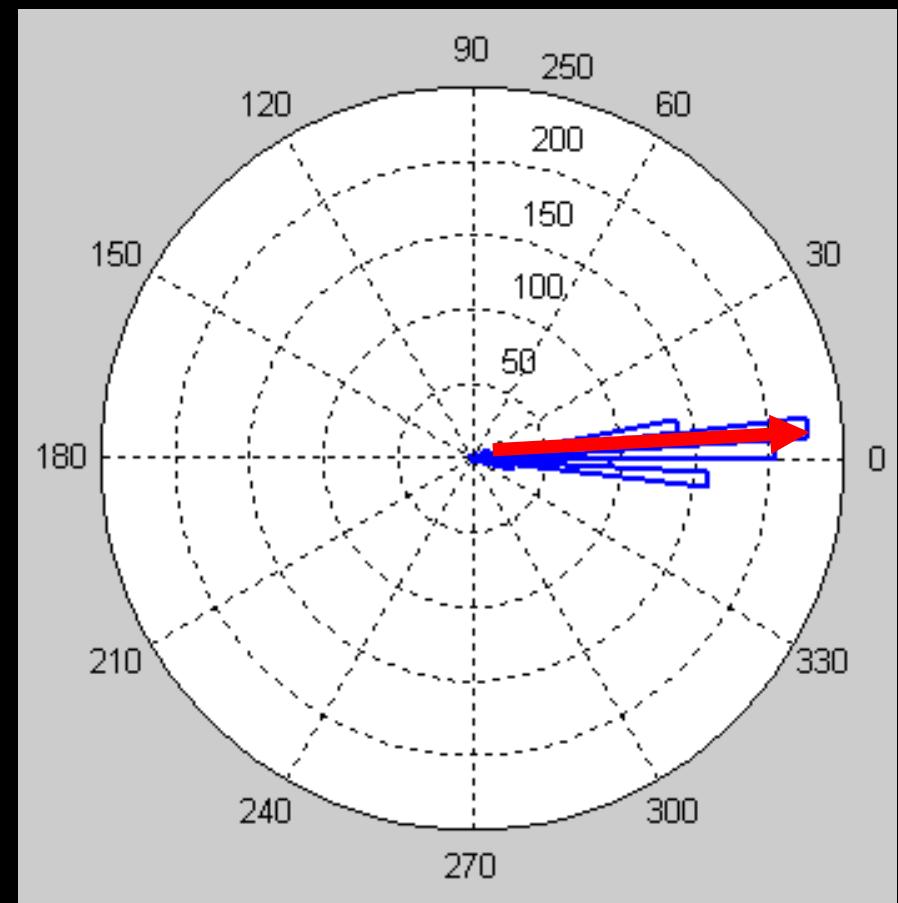
## 2. Circular variance.

The length (magnitude) of that vector varies from 0 to 1, and is the phase coherence.

Phase coherence: 0.11



Phase coherence: 0.94



## 2. Circular variance.

The equation for phase coherence is simple:

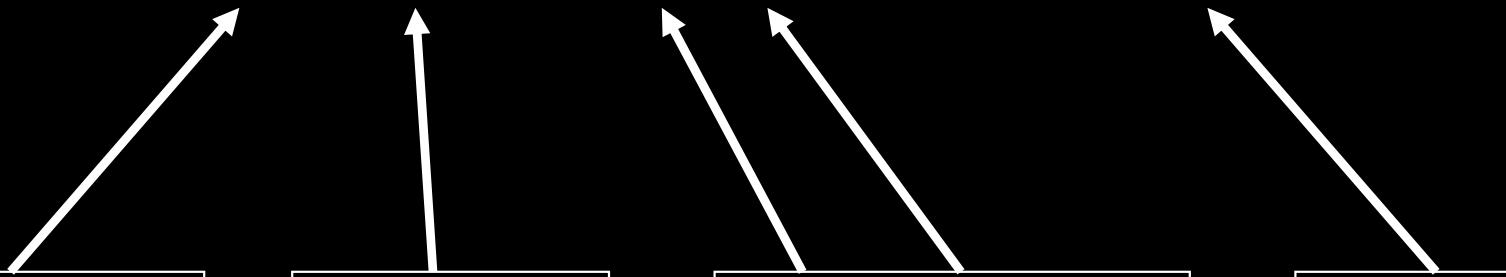
```
> abs(mean(exp(i*angle_differences))) ;
```

Magnitude  
of vector

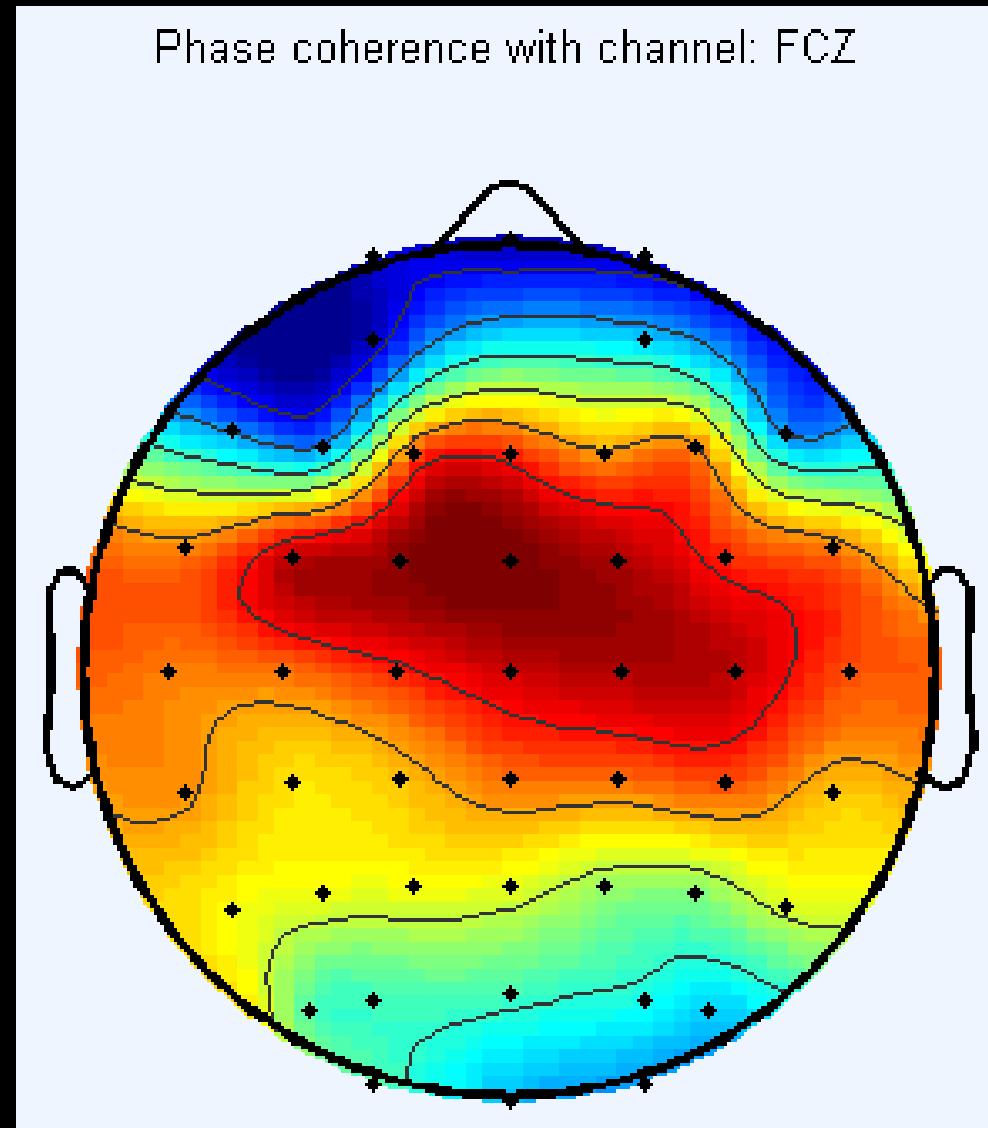
Average  
across  
values

Transform to  
complex plane

Phase angle  
differences  
between  
channels

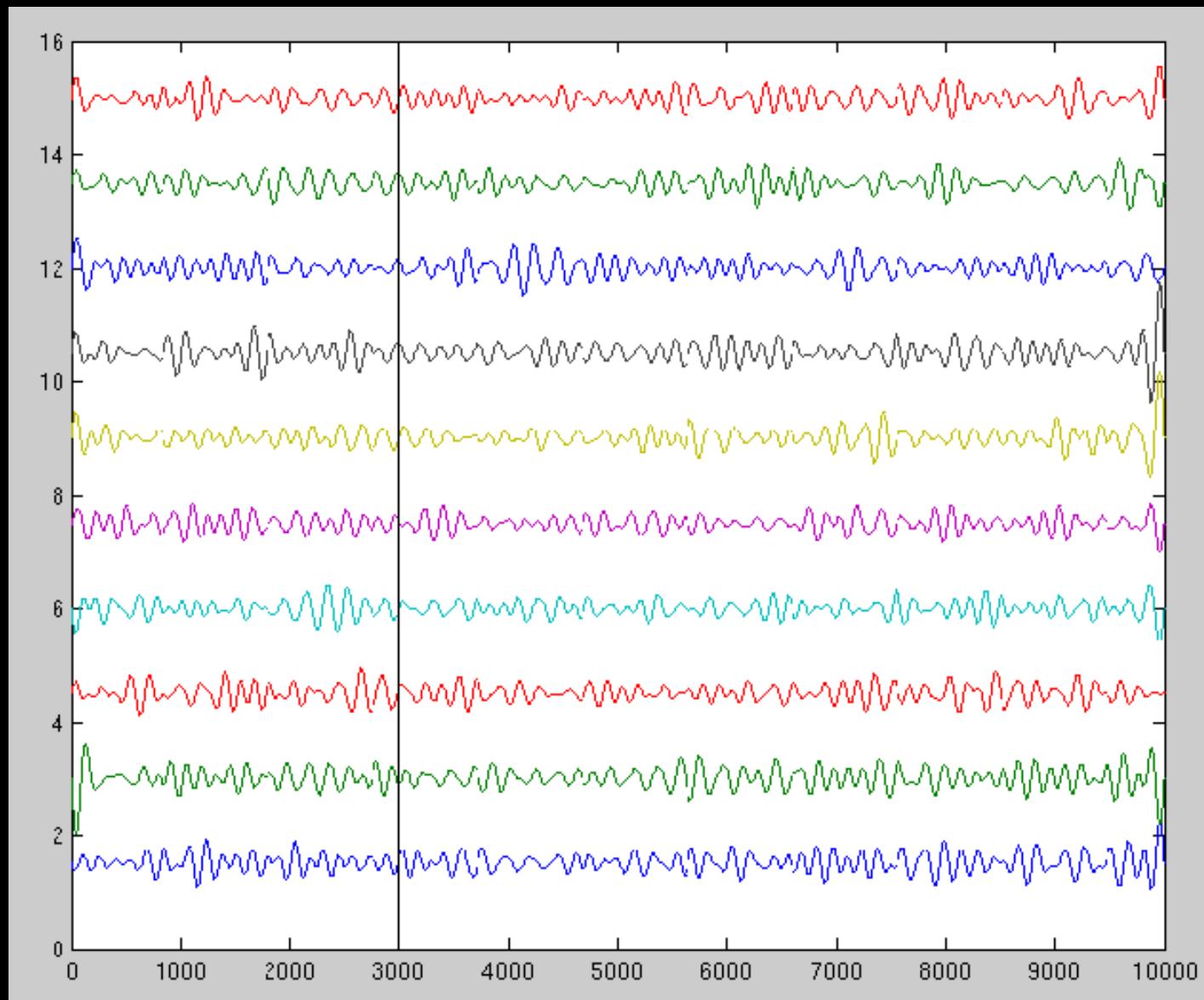


## 2. Inter-site phase synchrony with one “seed” site.

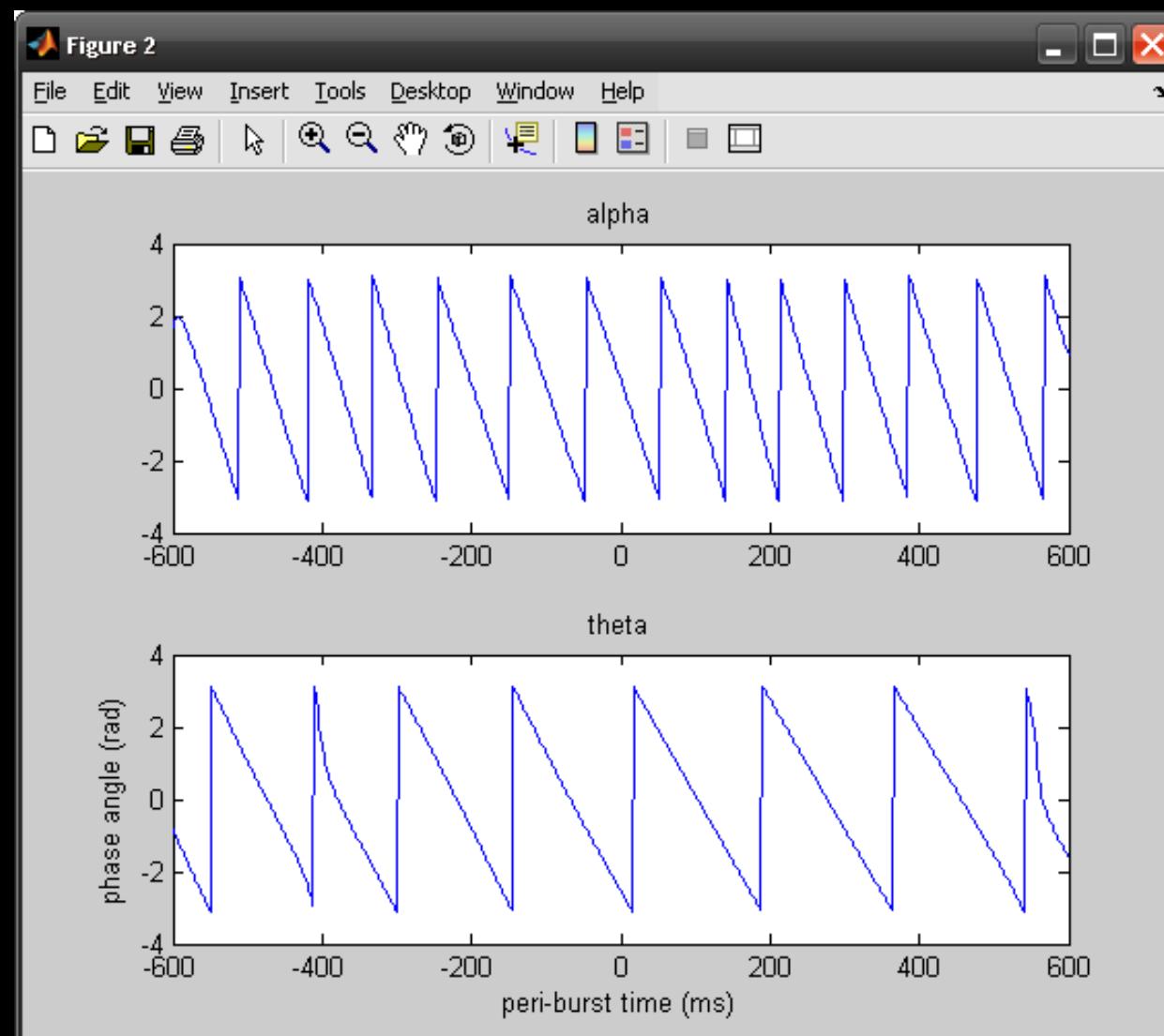


## **2. Inter-trial phase synchrony within one electrode.**

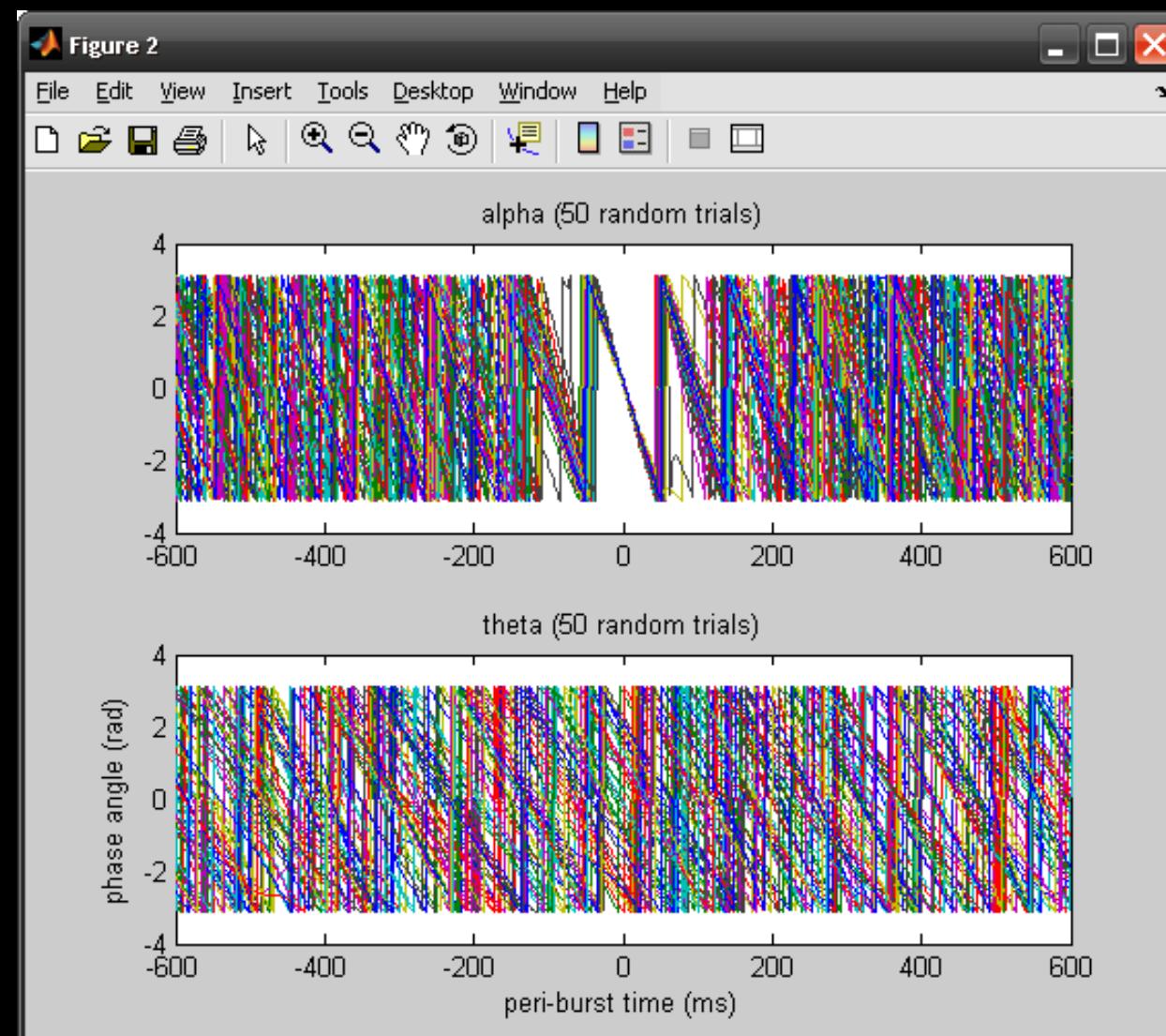
**Many trials from the same electrode:**



## 2. Inter-trial phase coherence



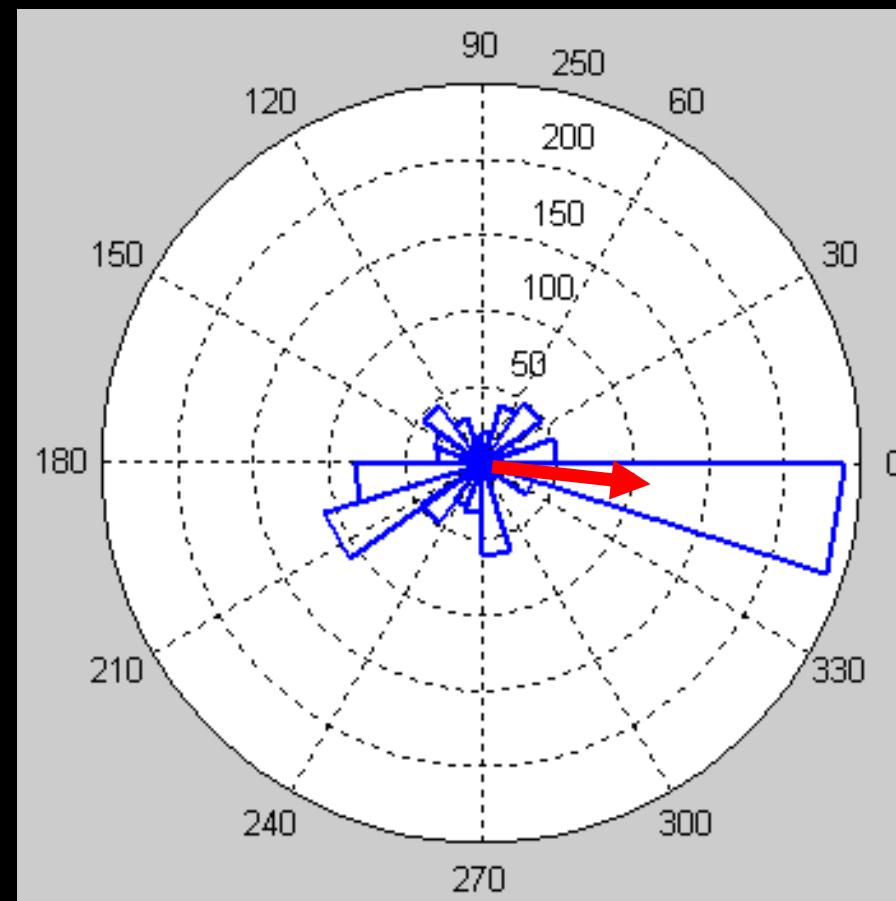
## 2. Inter-trial phase coherence



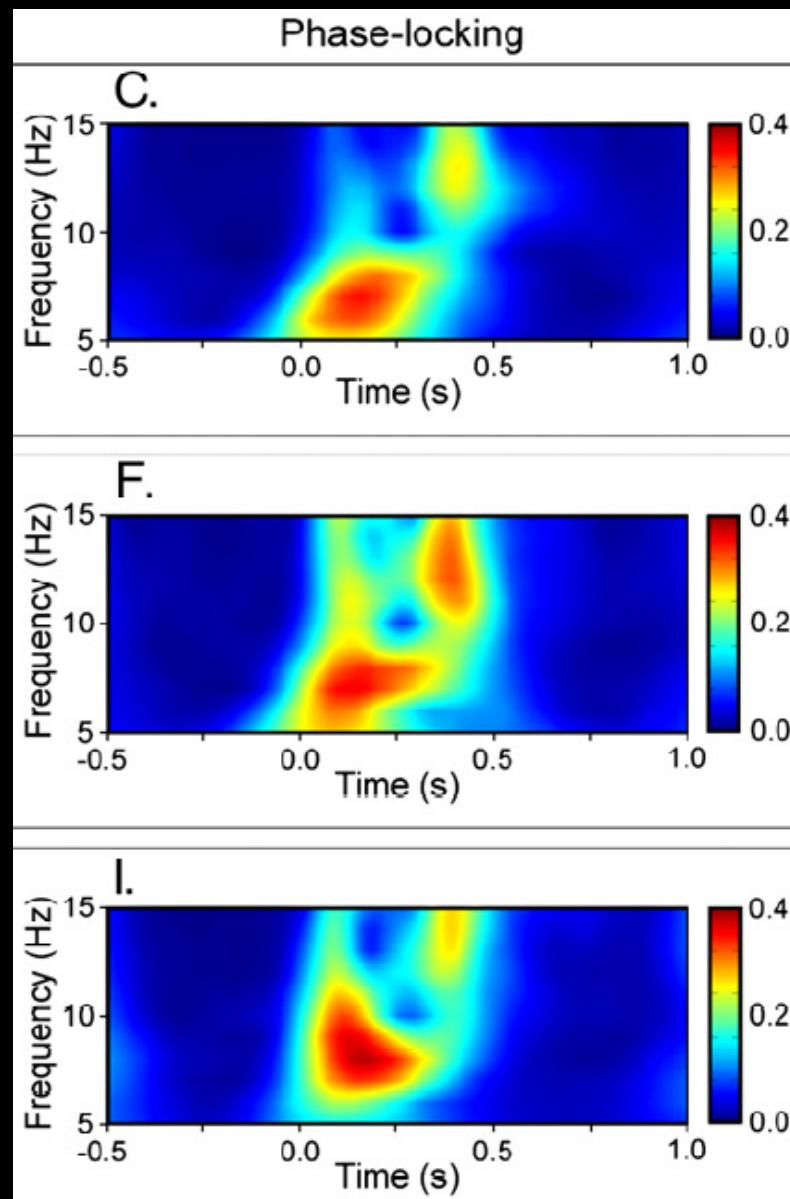
## 2. Inter-trial phase coherence

Calculate phase coherence across trials at each time point

Phase coherence, 154 ms: 0.11



## 2. Inter-trial phase coherence



## Measures of synchronization

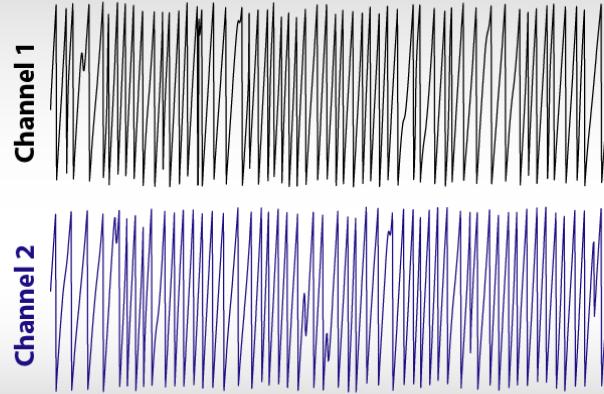
### Data

#### Filtered ECoG (30-80 Hz)



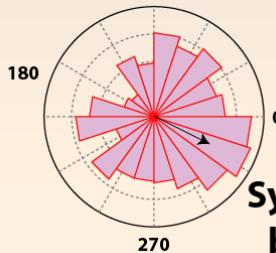
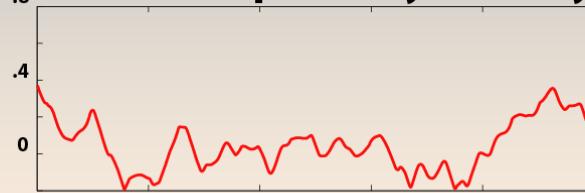
Apply Hilbert transform to obtain power and phase:

#### Analytic phase



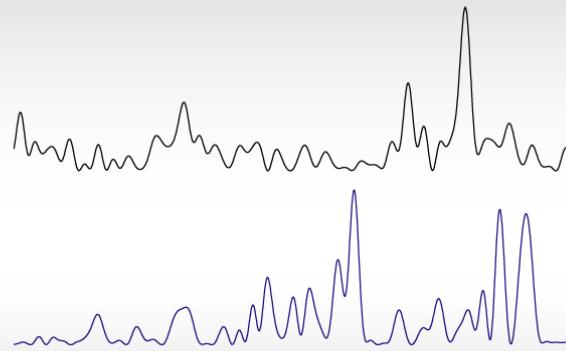
$$\text{Phase synchrony} = \left| \sum_{t=1}^n e^{i(\theta_1 t - \theta_2 t)} \right| * 1/n$$

#### Windowed phase synchrony



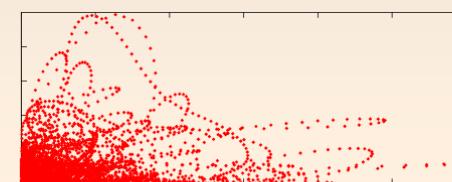
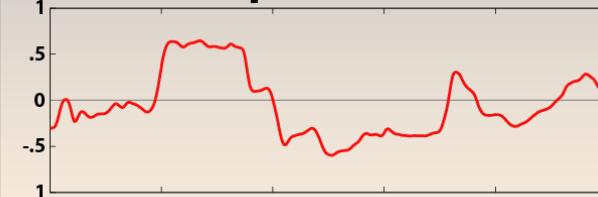
Synchrony over block of time

#### Power envelope



$$\text{Power correlation} = \frac{\sum_{t=1}^n (x_t - \bar{x})(y_t - \bar{y})}{(n-1)s_x s_y}$$

#### Windowed power correlations



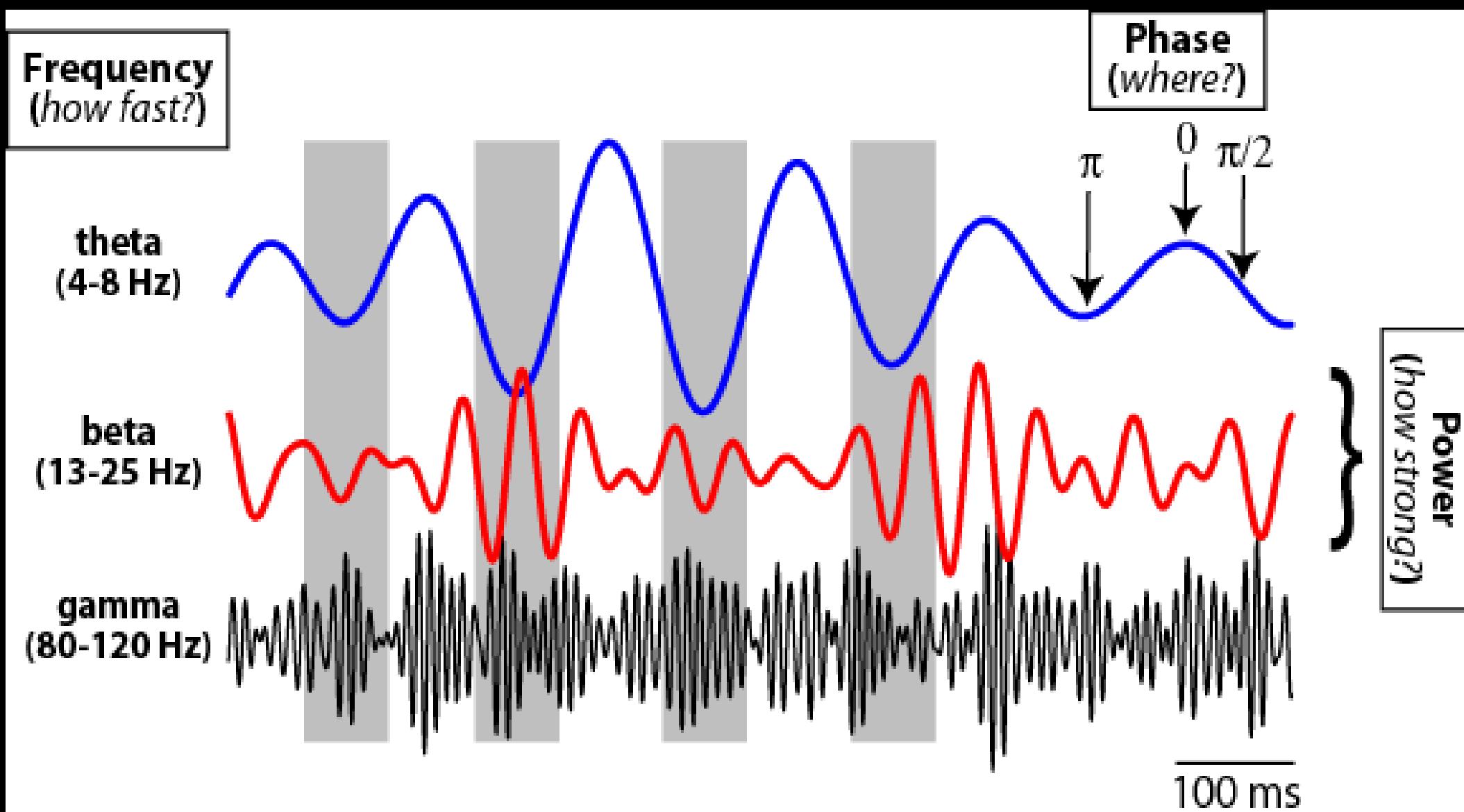
Power correlation over block of time

# 1-hour boot camp for advanced EEG analyses

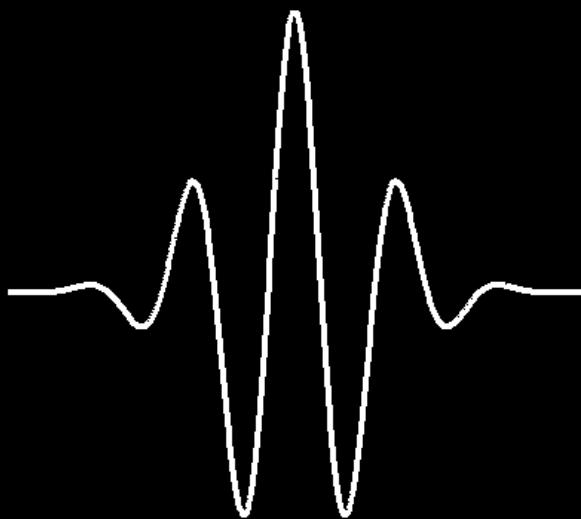
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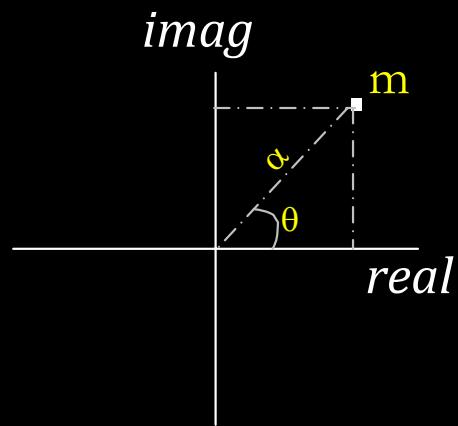
### 3. Review: Nomenclature of oscillation properties



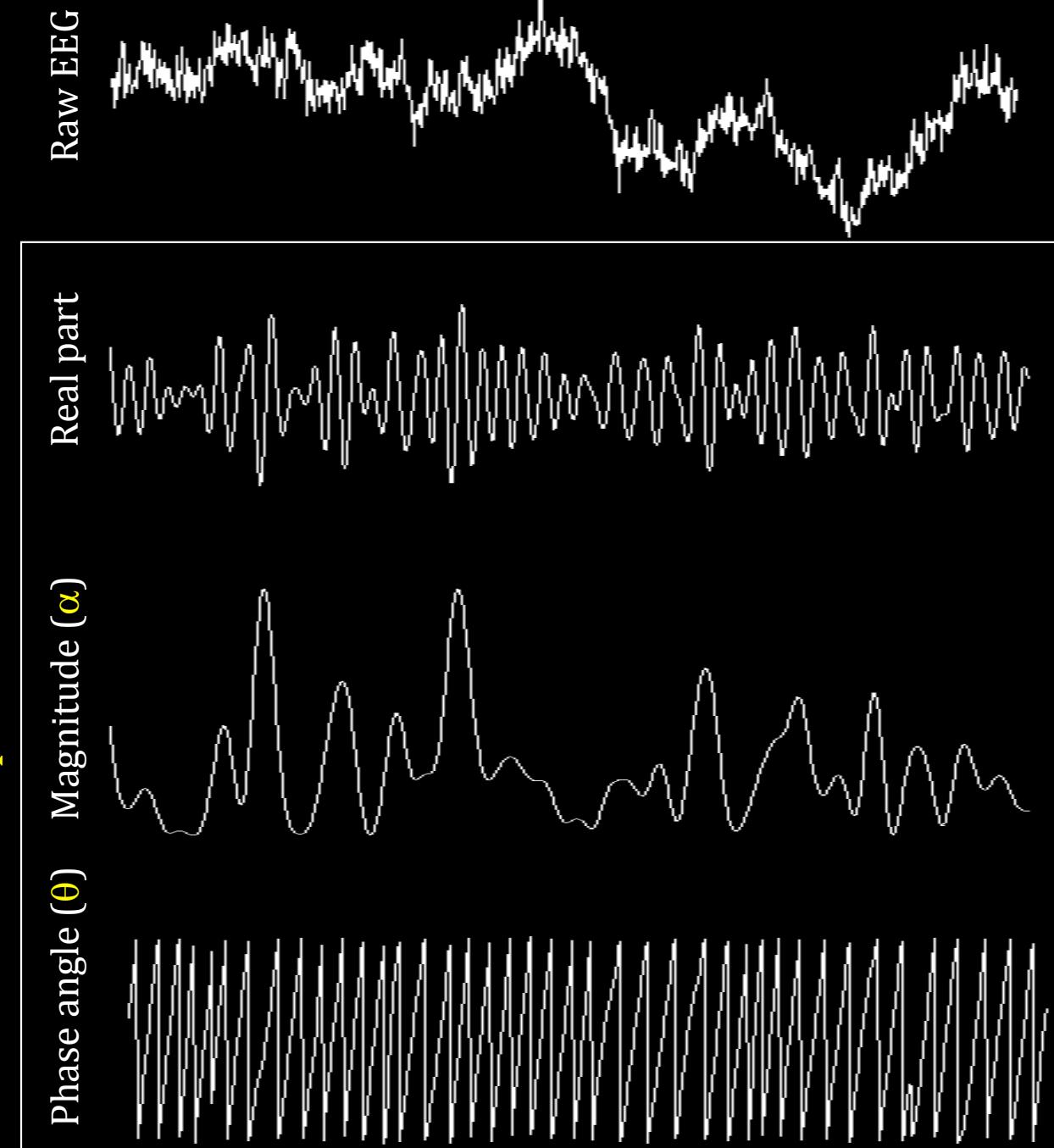
### 3. Review: information obtained from wavelet transform



Center  
frequency:  
23.7 Hz

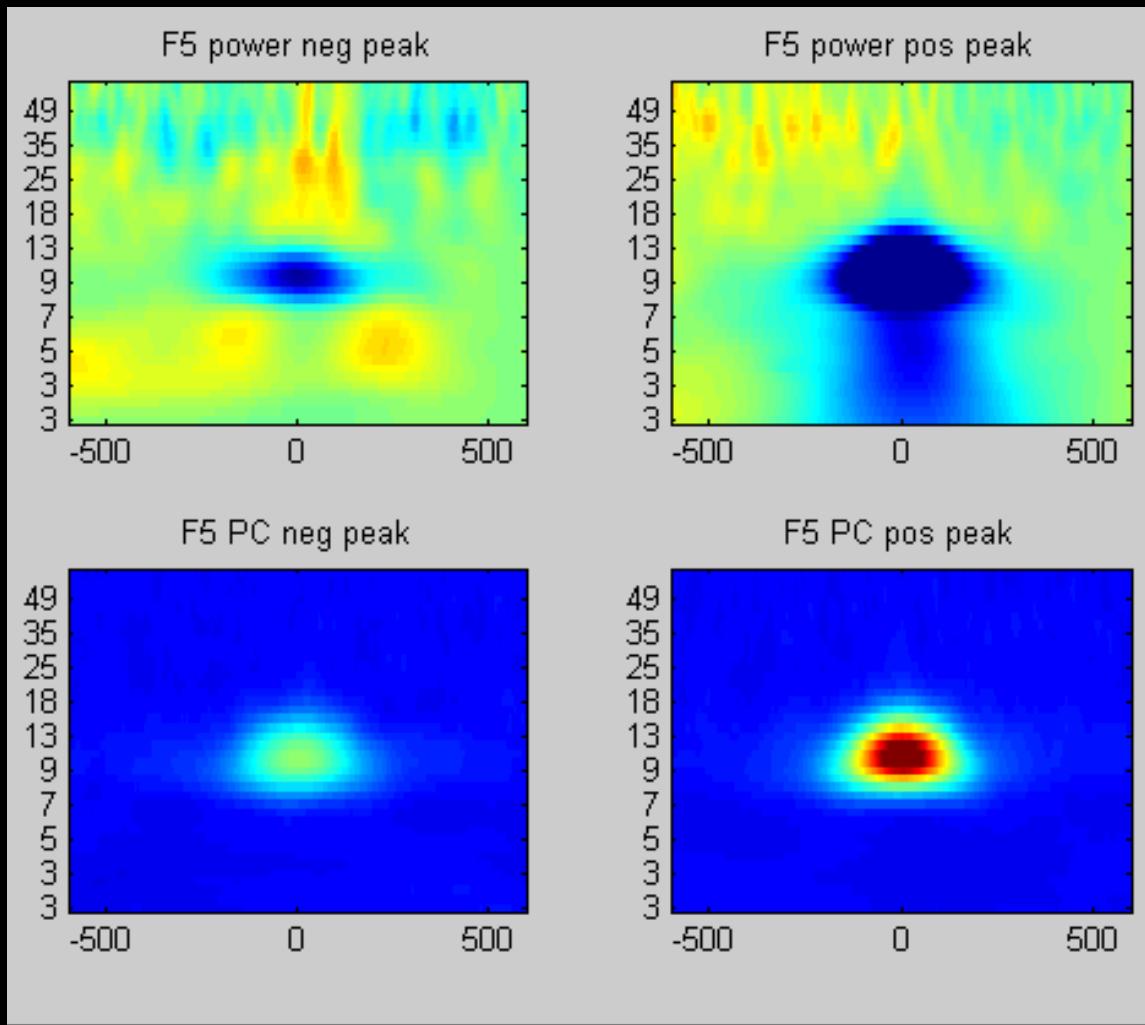


#### Results from complex wavelet convolution



### 3. Review on interpreting time-frequency plots

Power      Phase coher



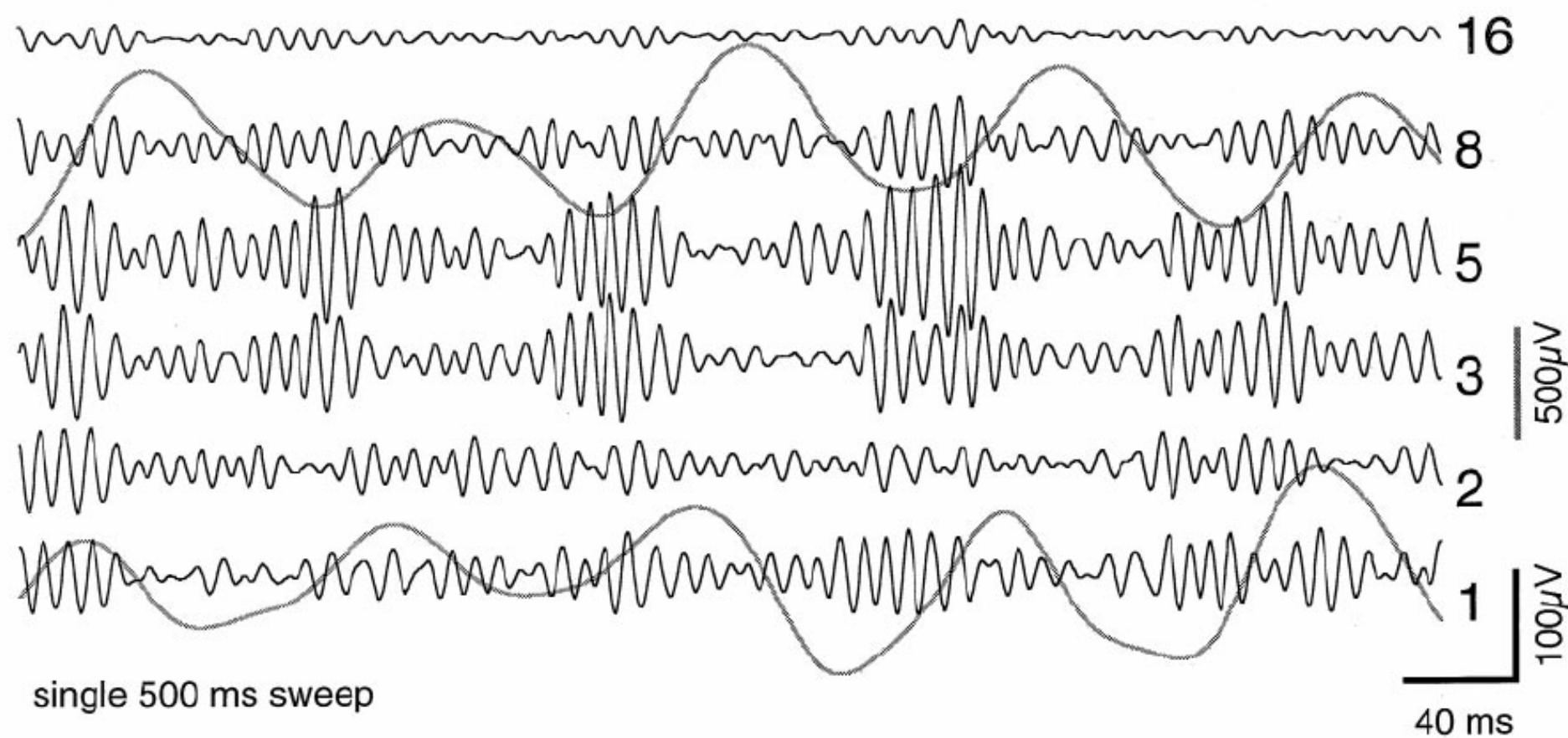
# 1-hour boot camp for advanced EEG analyses

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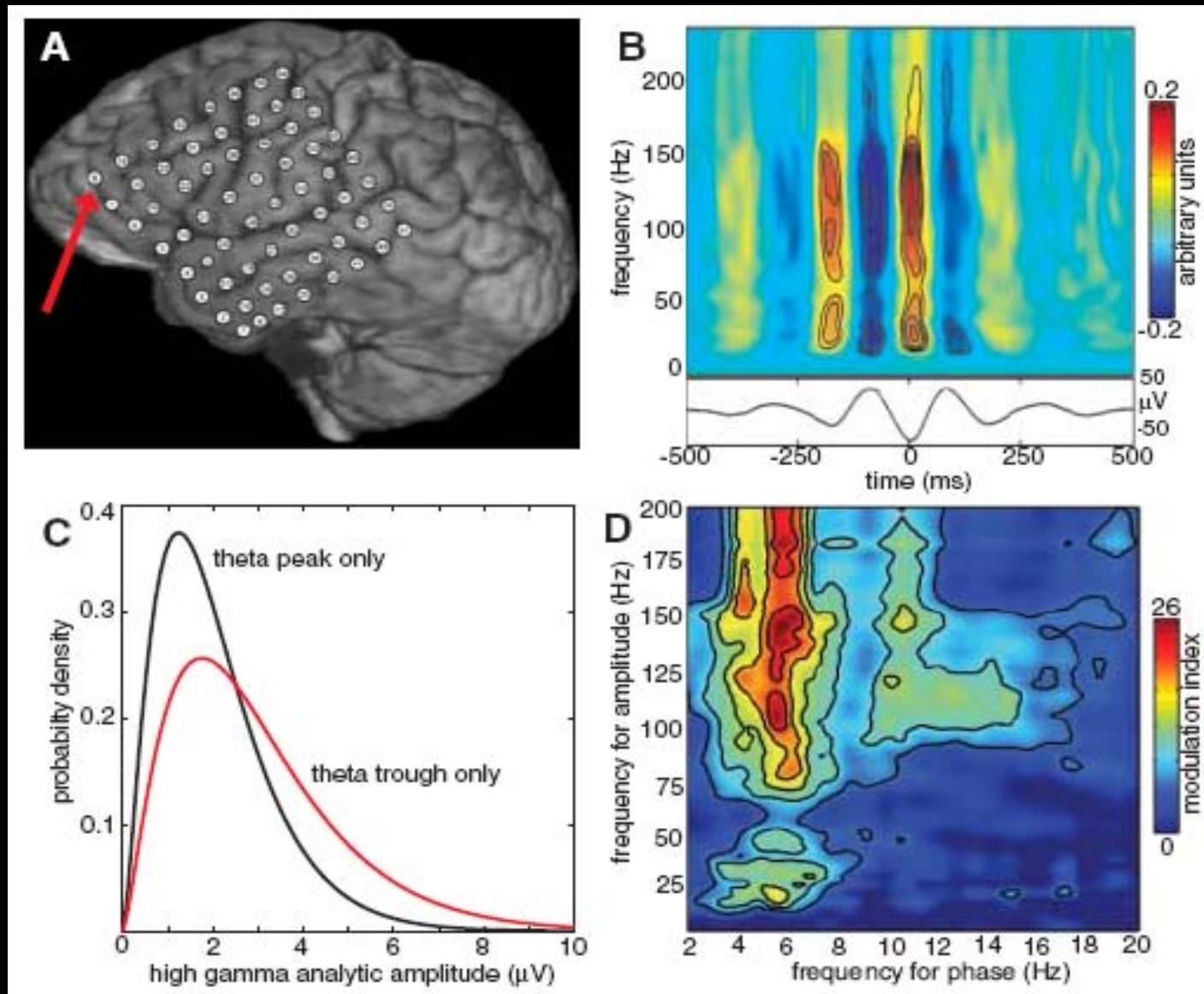
## 4. Introduction to cross-frequency coupling

A



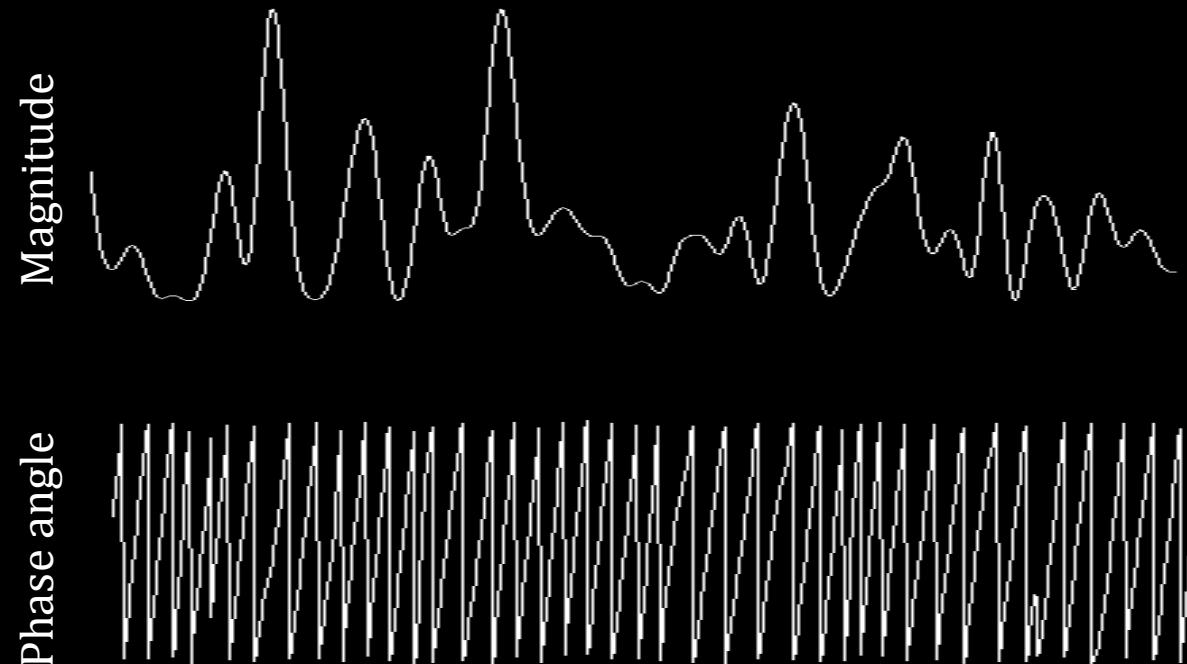
Chrobak et al., 1998

## 4. Introduction to cross-frequency coupling



## 4. How to measure cross-frequency coupling

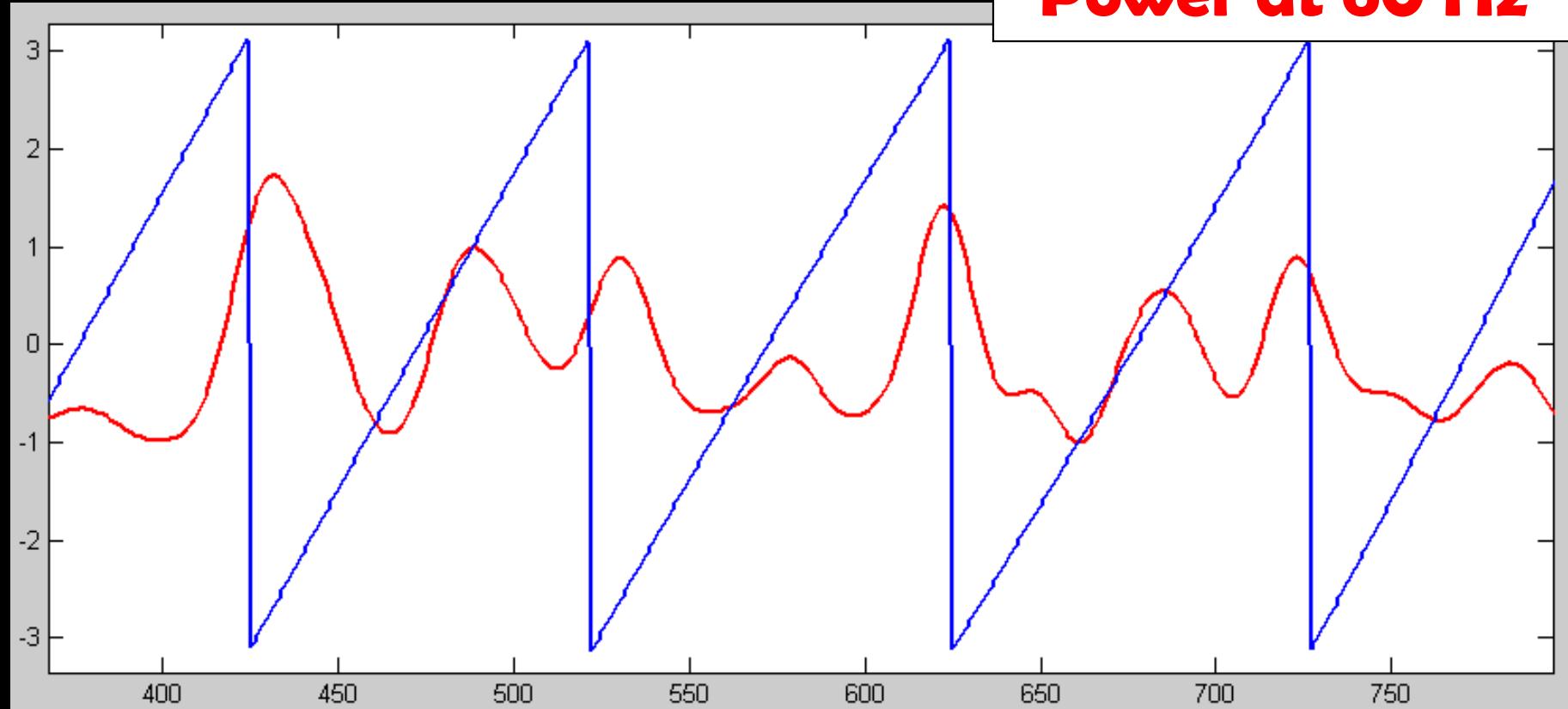
### Method 1: Phase-amplitude coupling



Here, phase and amplitude are taken from the *same* frequency band. What if we were to take them from *different* frequency bands??

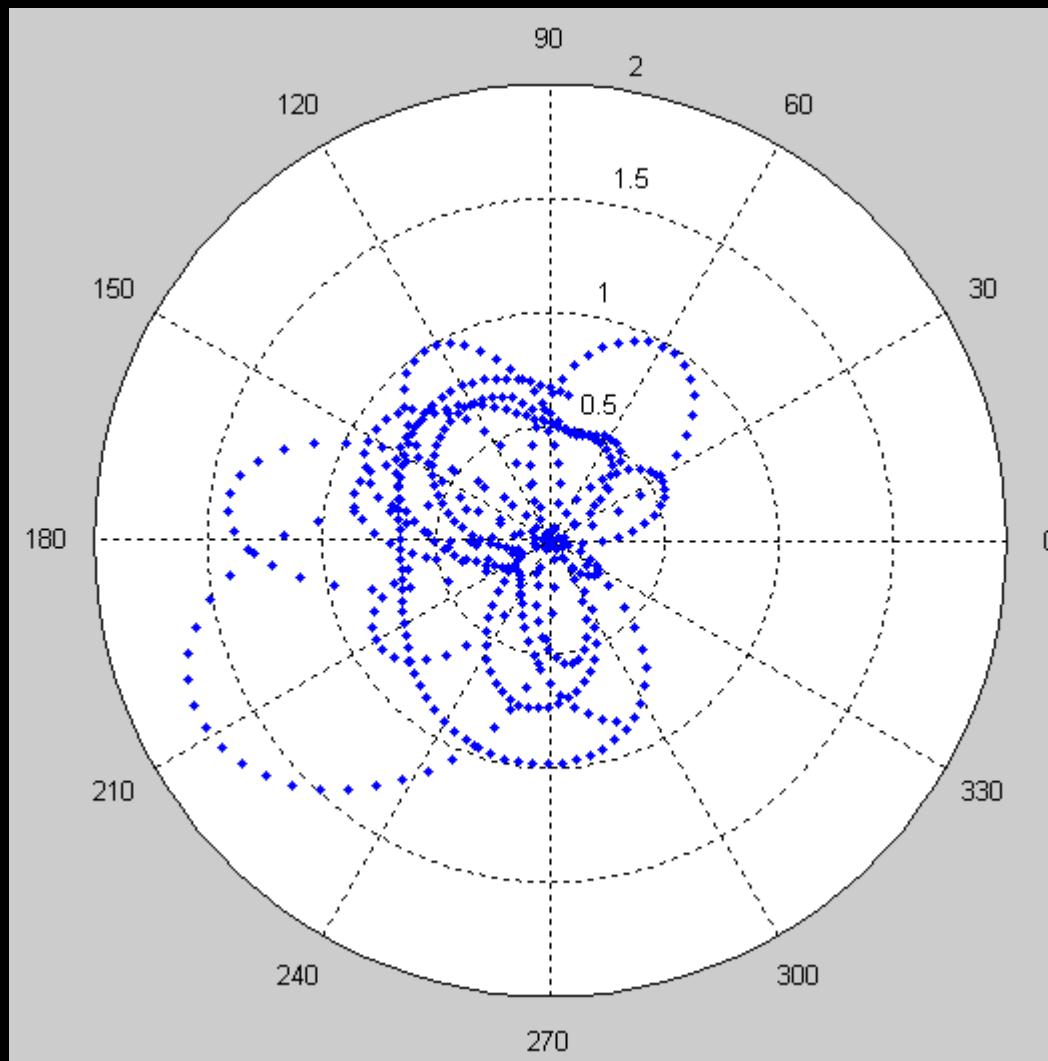
## 4. Phase-amplitude cross-frequency coupling

Phase of 8-12 Hz  
Power at 60 Hz



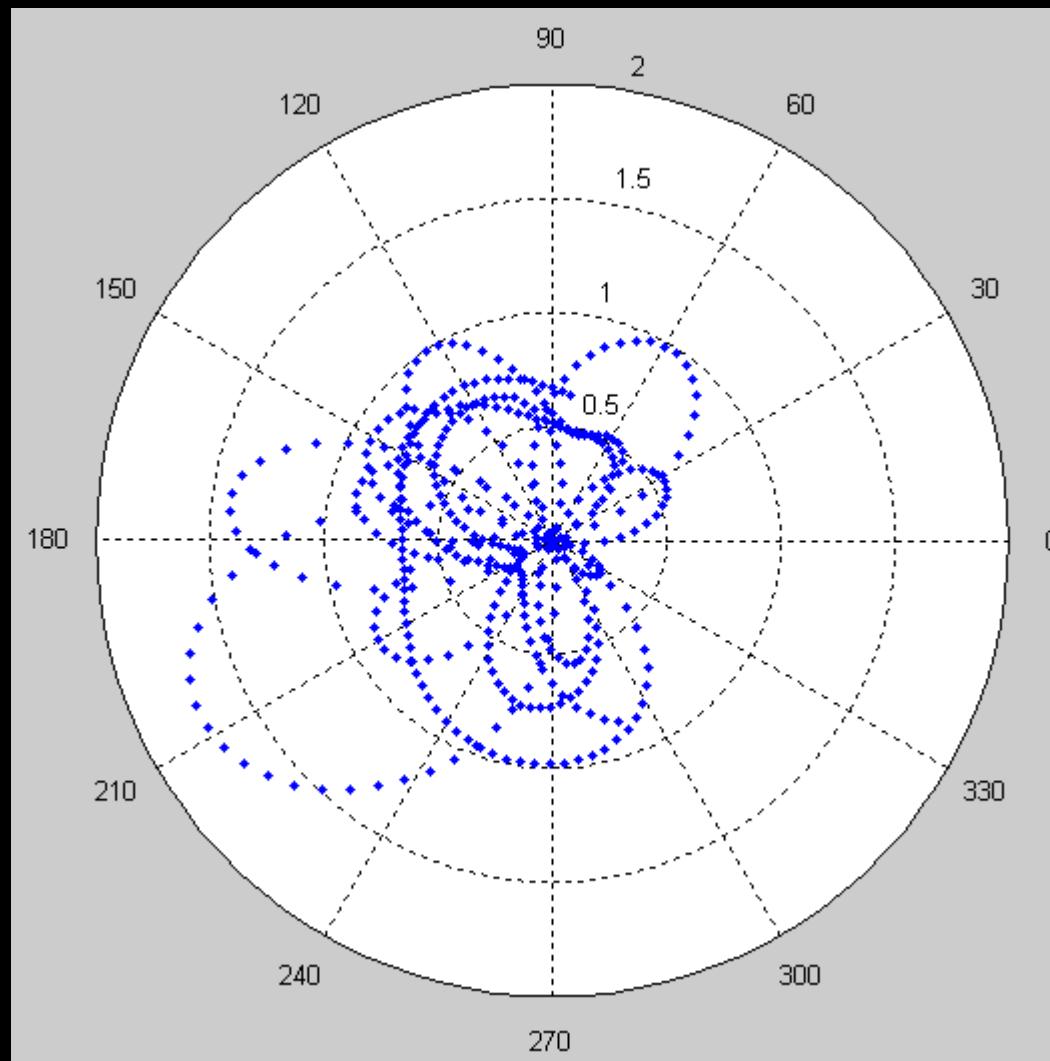
Notice that gamma power seems to be maximal during specific alpha phases!

## 4. Phase-amplitude cross-frequency coupling



Let's examine this in polar space: *Gamma power* is plotted as a function of *alpha phase*

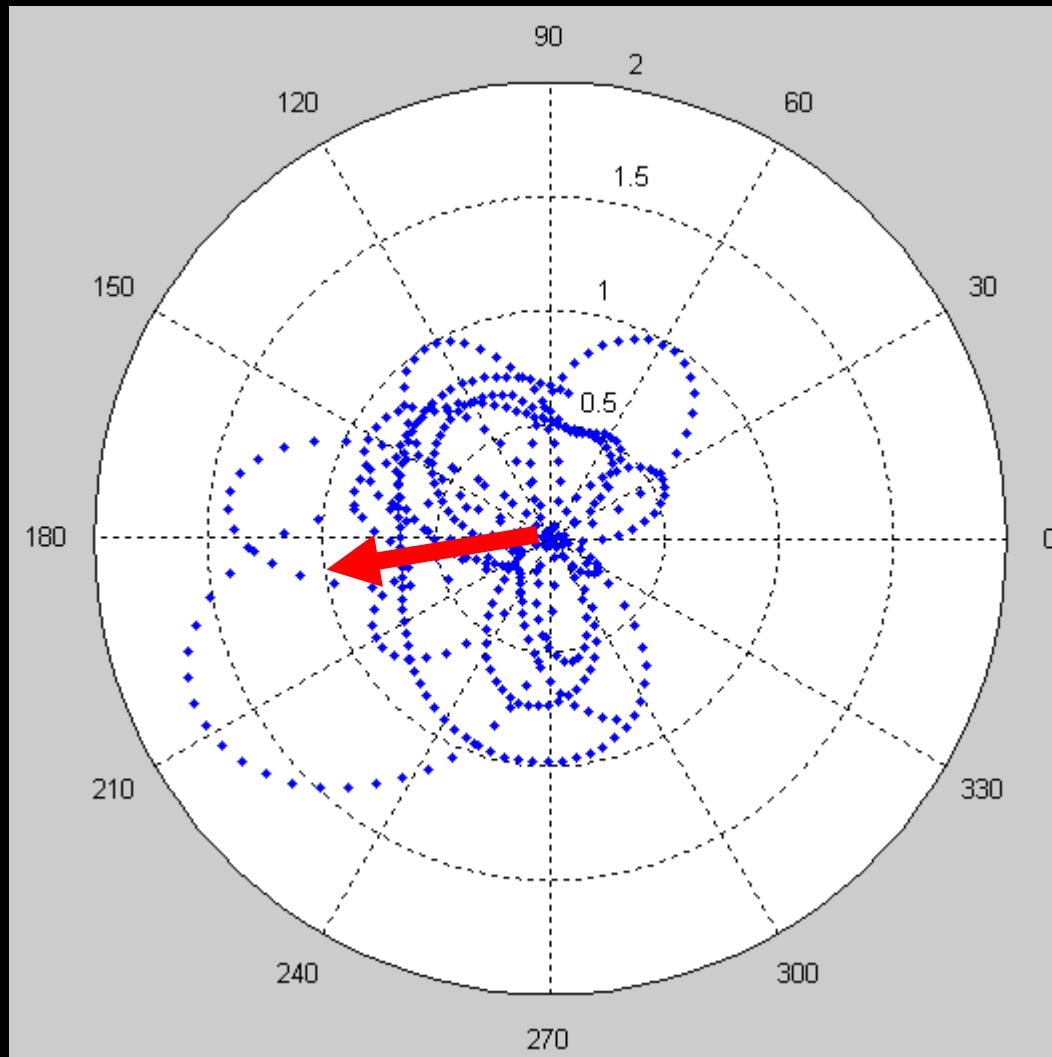
## 4. Phase-amplitude cross-frequency coupling



**Gamma power is NOT uniformly distributed throughout alpha phase!!**

**Thus, gamma power is coupled with alpha phase.**

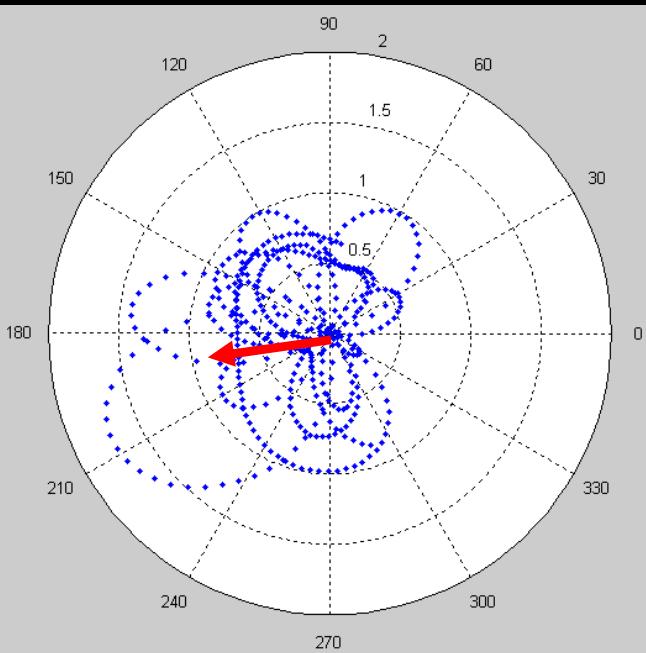
## 4. Phase-amplitude cross-frequency coupling



**How can we test this quantitatively?**

**Answer: By measuring the vector magnitude,  
just like in phase coherence!**

## 4. Phase-amplitude cross-frequency coupling



(it's called modulation index instead of phase coherence)

**Modulation index = .244**

**The equation is slightly different than that for phase coherence, but it is similar in essence:**

```
> abs( mean( power . * exp( i * phase ) ) );
```

Magnitude  
of vector

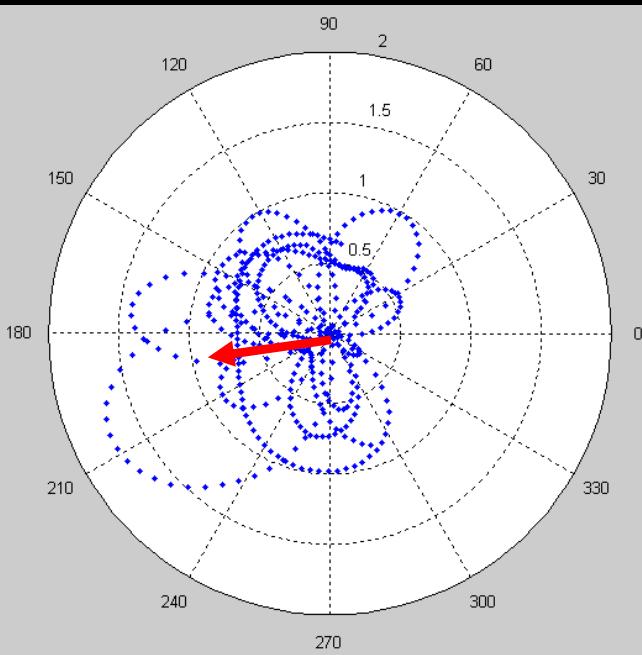
Average  
across  
values

Power of  
higher  
frequency

Transform to  
complex plane

Phase angle  
of lower  
frequency

## 4. Phase-amplitude cross-frequency coupling

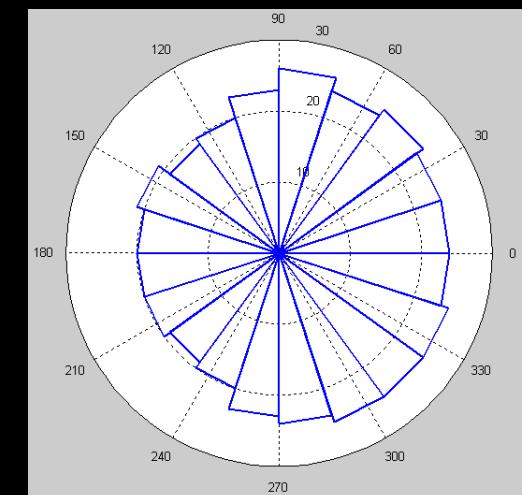


**Modulation index = .244**

**Potential problem:**  
**If alpha phase values are not uniformly distributed, a large modulation index could result.**

**This is not the case in this example, but it could happen (especially if the phase values are reset by a stimulus).**

**Distribution of alpha phase**



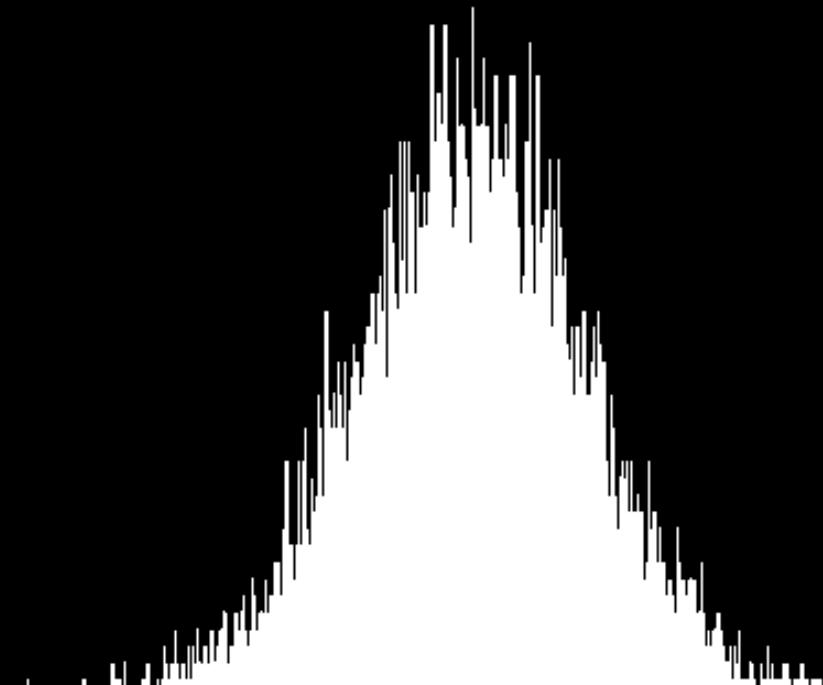
## 4. Phase-amplitude cross-frequency coupling

### So what to do?

**Permutation testing is useful for null-hypothesis testing when assumptions of parametric statistics cannot be met.**

**The Law of Large Numbers states that randomly sampled data approach a normal distribution as the number of samples increases.**

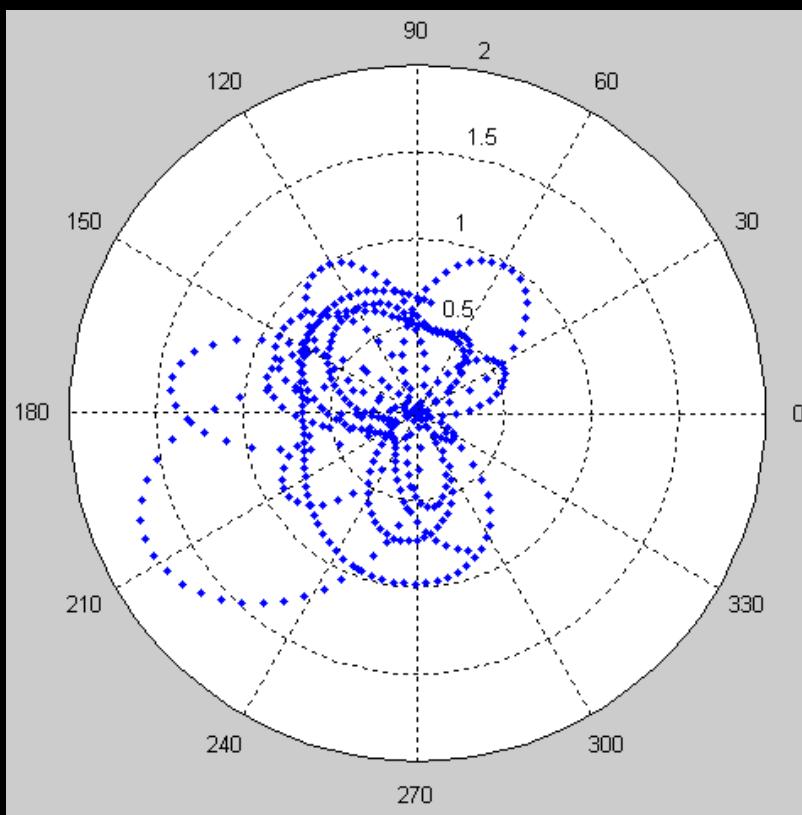
**Permutation tests in combination with the Law of Large Numbers to the rescue!**



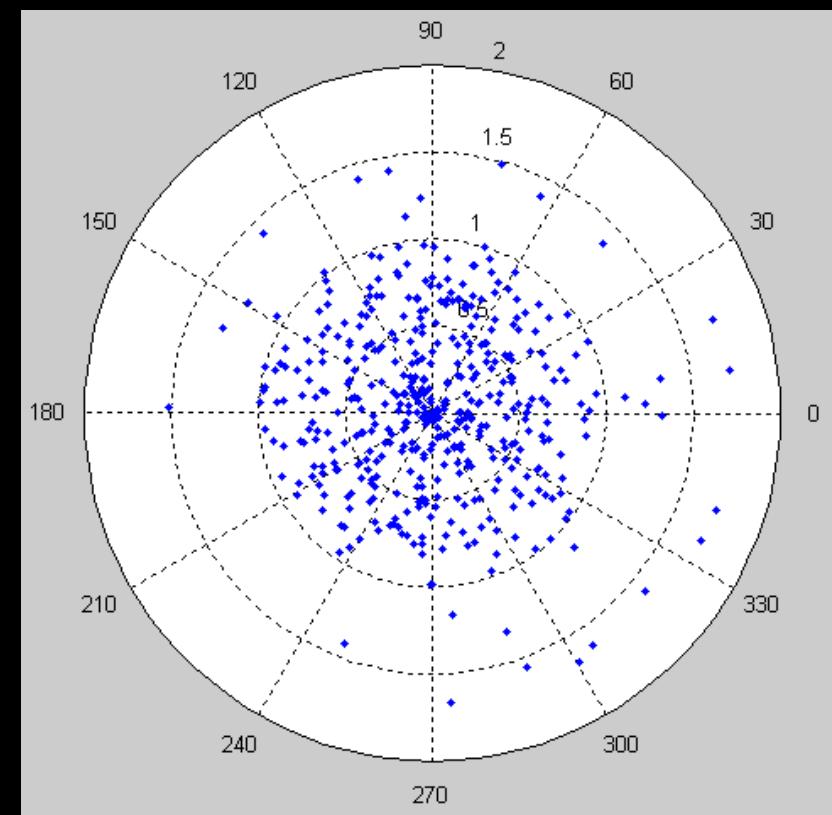
## 4. Phase-amplitude cross-frequency coupling

**Here's what we do: Re-calculate the modulation index many many times, each time randomly re-assigning power-to-phase couples.**

**Observed data (M=.244)**

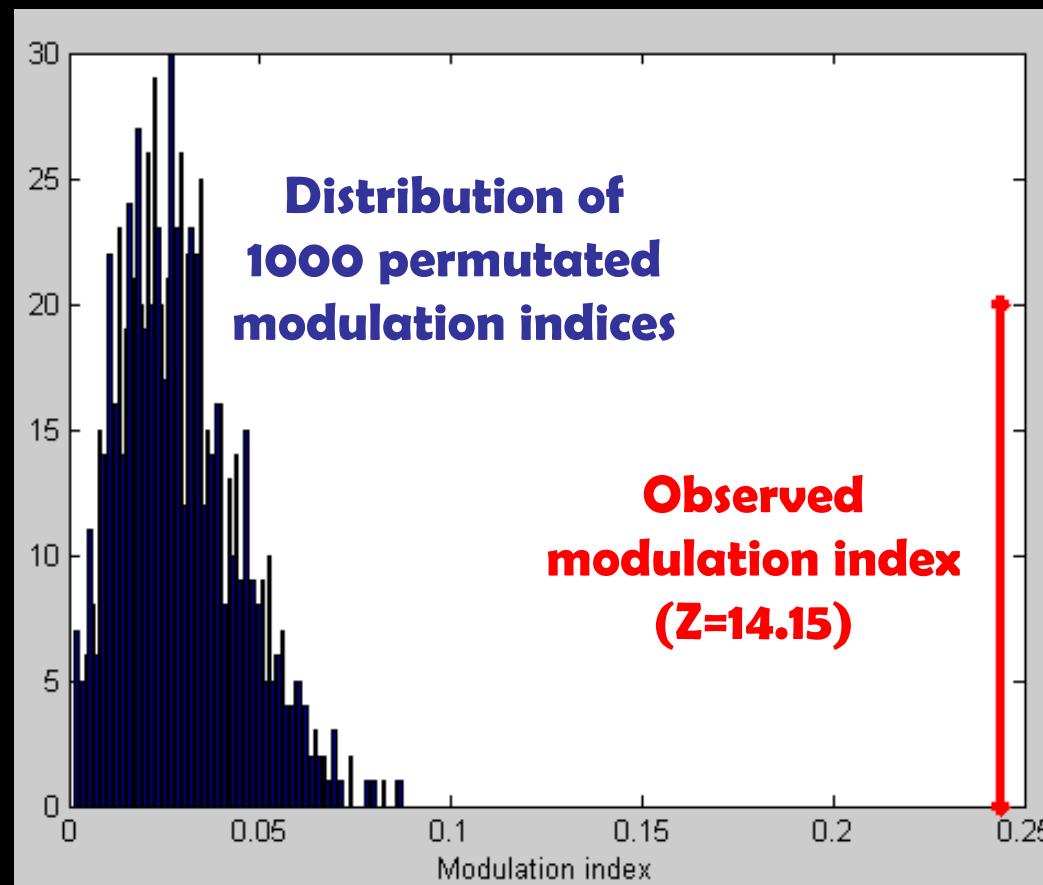


**Shuffled data (M=.033)**

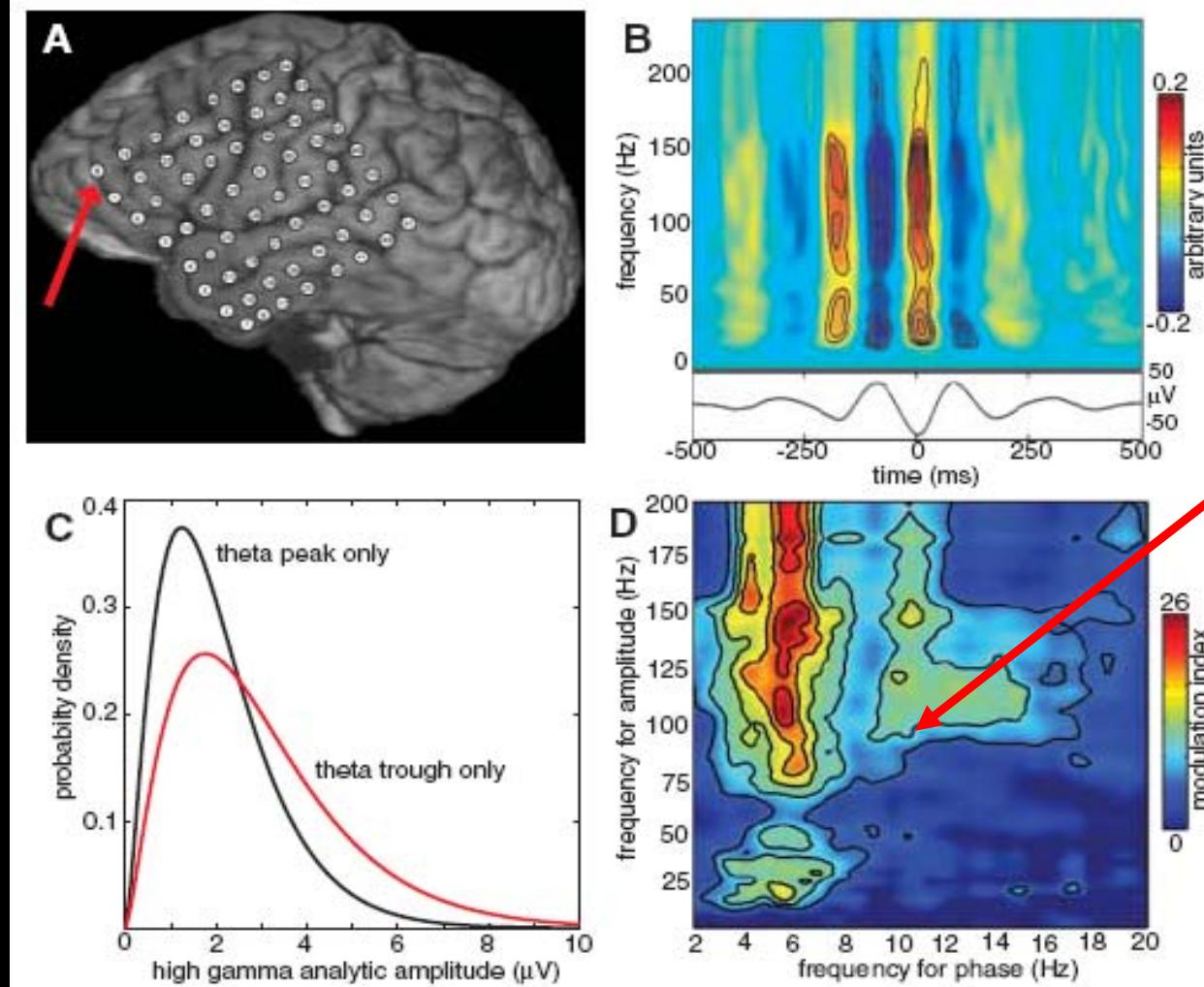


## 4. Phase-amplitude cross-frequency coupling

Because permuted modulation indices approach a normal distribution, we can define a normalized modulation index as the distance (in standard deviation units) away from the mean of the distribution.



## 4. Phase-amplitude cross-frequency coupling



The previous few slides showed you how to create one modulation index.

This procedure can be done over many phase and amplitude frequency pairs, as in Canolty et al., 2006.

High Gamma Power Is Phase-Locked to Theta Oscillations in Human Neocortex

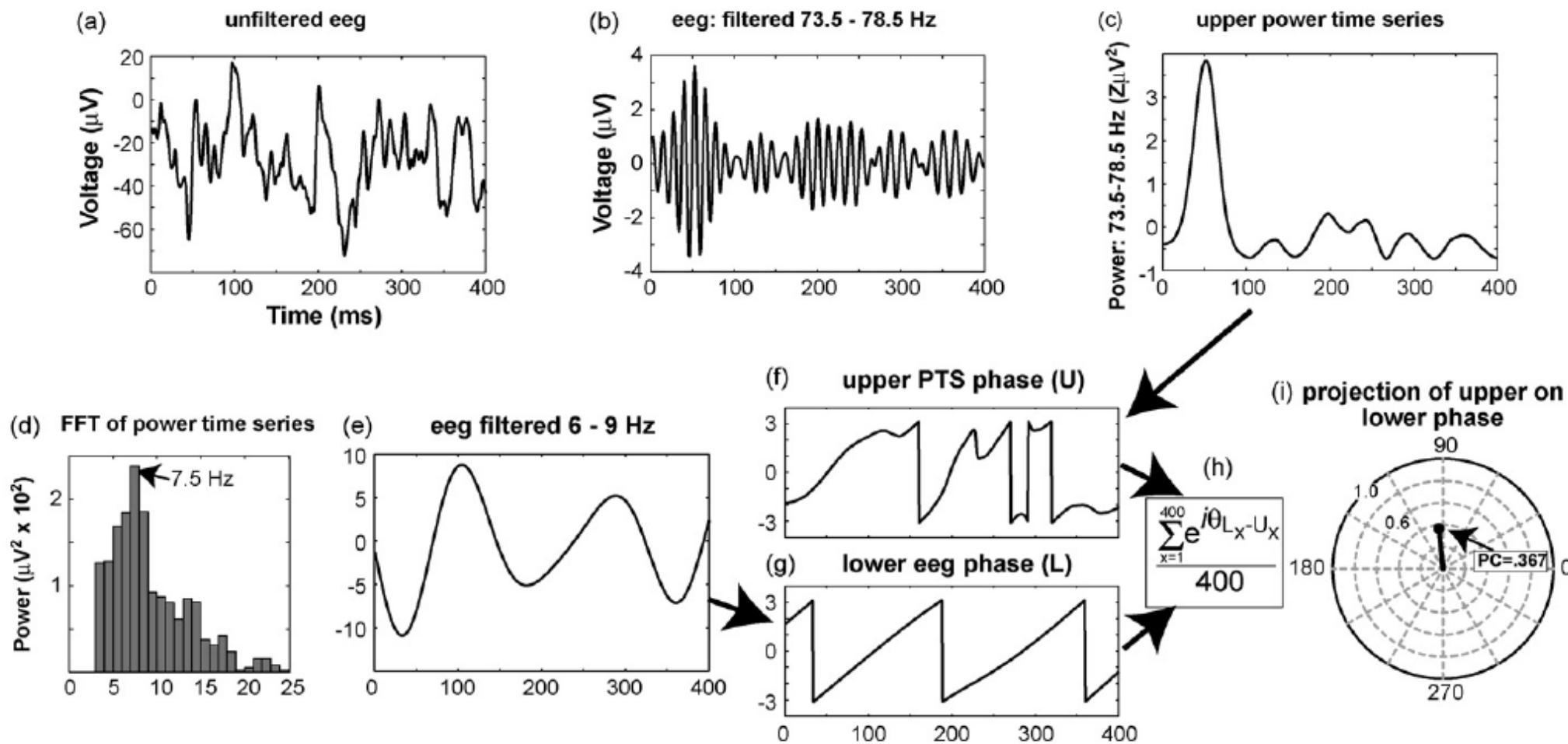
R. T. Canolty,<sup>1,\*</sup> E. Edwards,<sup>1,2</sup> S. S. Dalal,<sup>3</sup> M. Soltani,<sup>1,2</sup> S. S. Nagarajan,<sup>3,4</sup> H. E. Kirsch,<sup>5</sup> M. S. Berger,<sup>6</sup> N. M. Barbaro,<sup>5,6</sup> R. T. Knight<sup>1,2,3,5,6</sup>

# 4. How to measure cross-frequency coupling

## Method 2: Phase-phase coupling

496

M.X. Cohen / Journal of Neuroscience Methods 168 (2008) 494–499



## **4. How to measure cross-frequency coupling**

---

**There are several other methods of assessing cross-frequency coupling (e.g., Bruns et al., 2000, Mormann et al., 2005, Palva & Palva, 2006).**

**Each method has benefits and limitations, and each is suited for particular analyses, datasets, and assumptions.**

**However, all methods are similar in that they rely on measures of power and phase in different frequency bands.**

# 1-hour boot camp for advanced EEG analyses

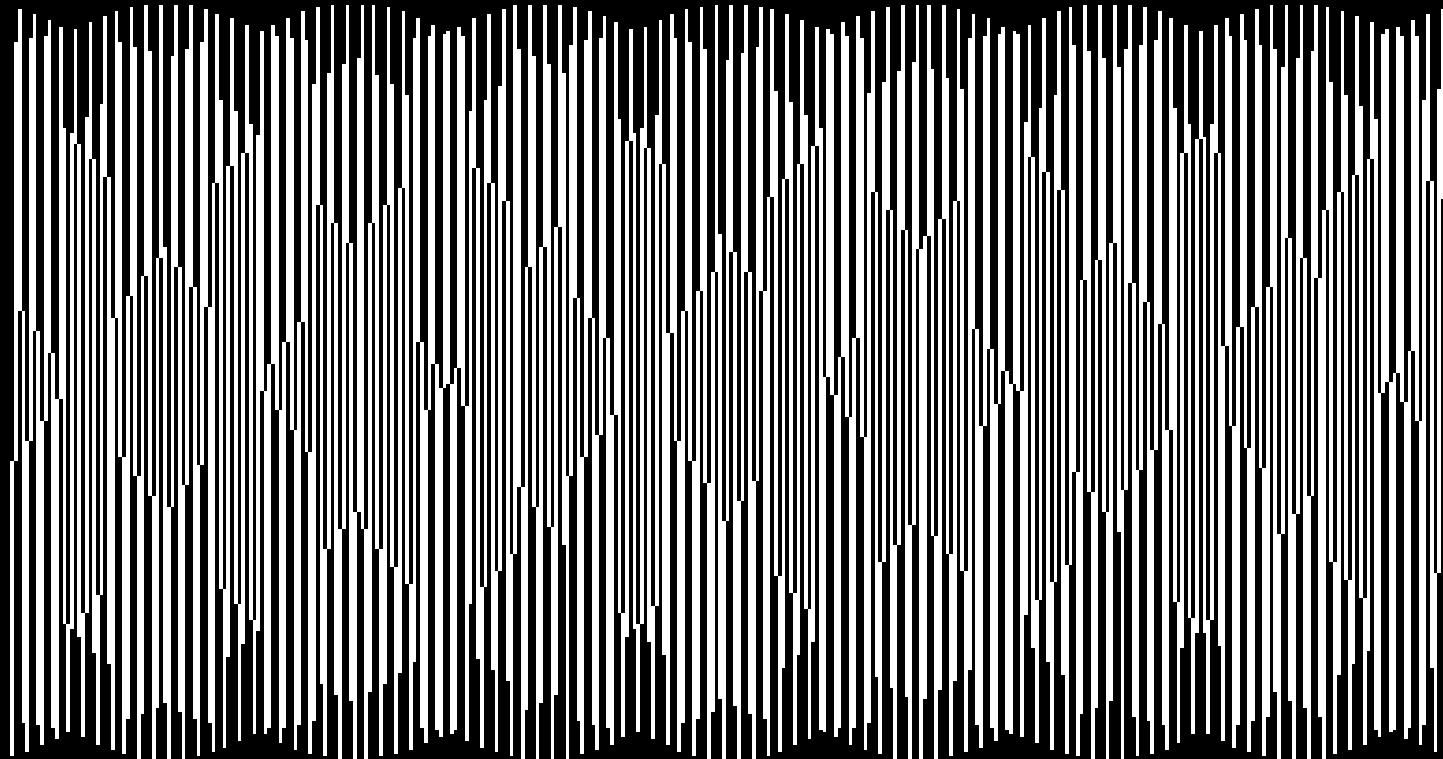
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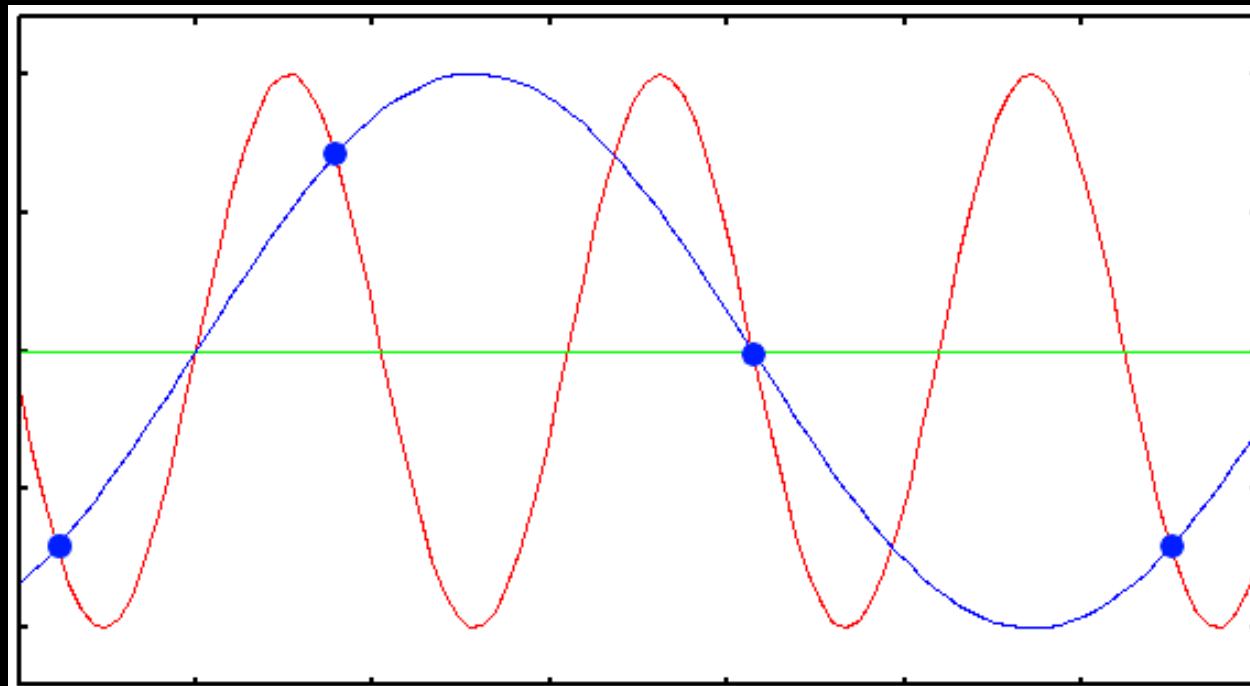
# **Some practical issues that arise during oscillation analyses**

# Practical issues: That darned tootin' Nyquist frequency!



# Practical issues: That darned tootin' Nyquist frequency!

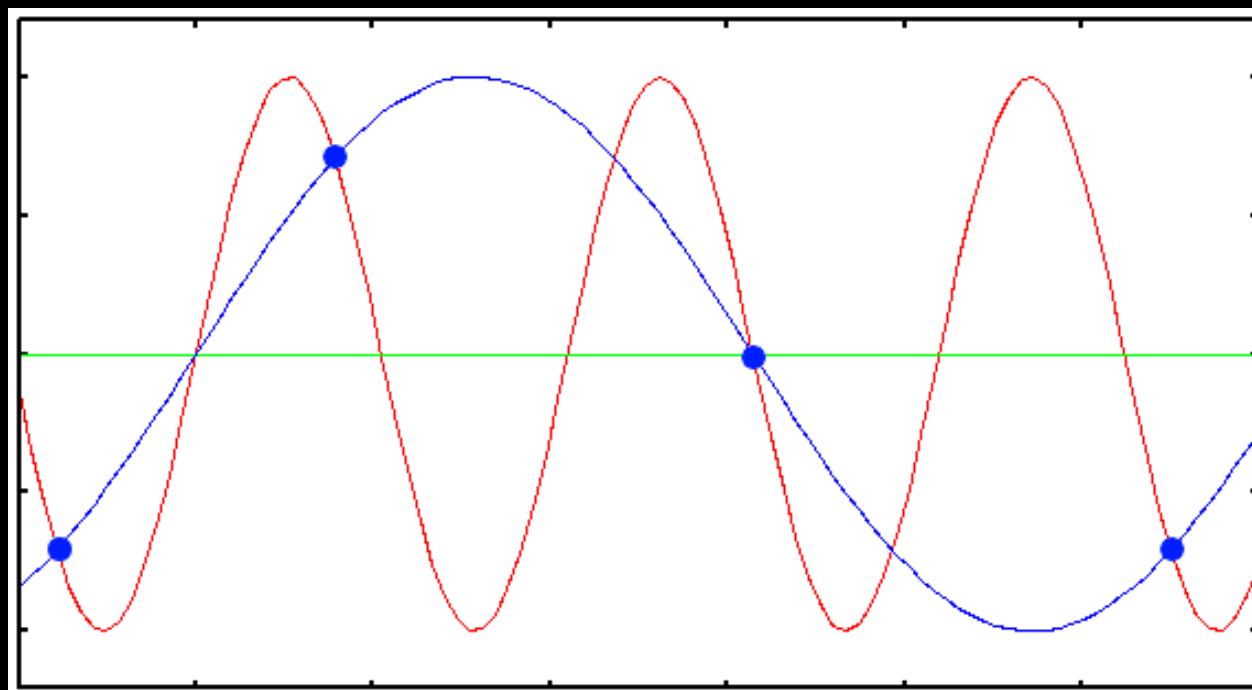
**Oscillations that are faster than the sampling rate may induce artificial slow oscillations!**



# Practical issues: That darned tootin' Nyquist frequency!

You **must** sample at least twice the highest frequency you want to analyze!

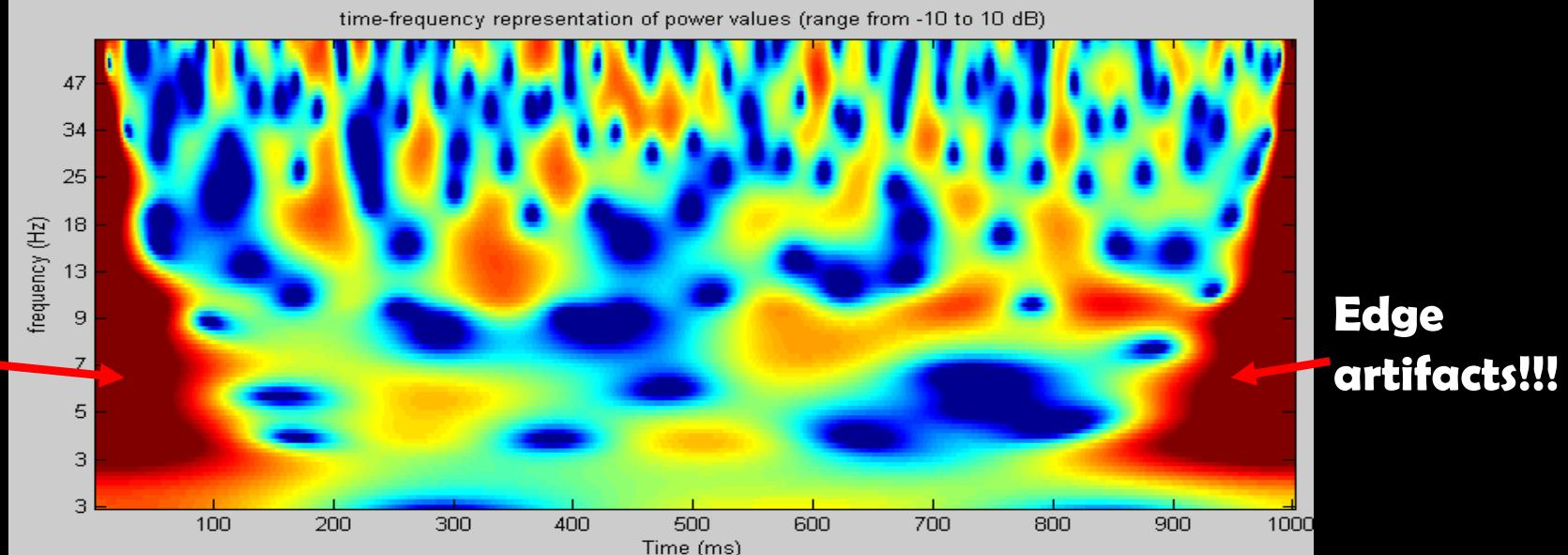
(I recommend sampling at least four times; this also helps with phase coherence analyses)



# Practical issues: Life on the fringe...

Edge artifacts!!!

time-frequency representation of power values (range from -10 to 10 dB)

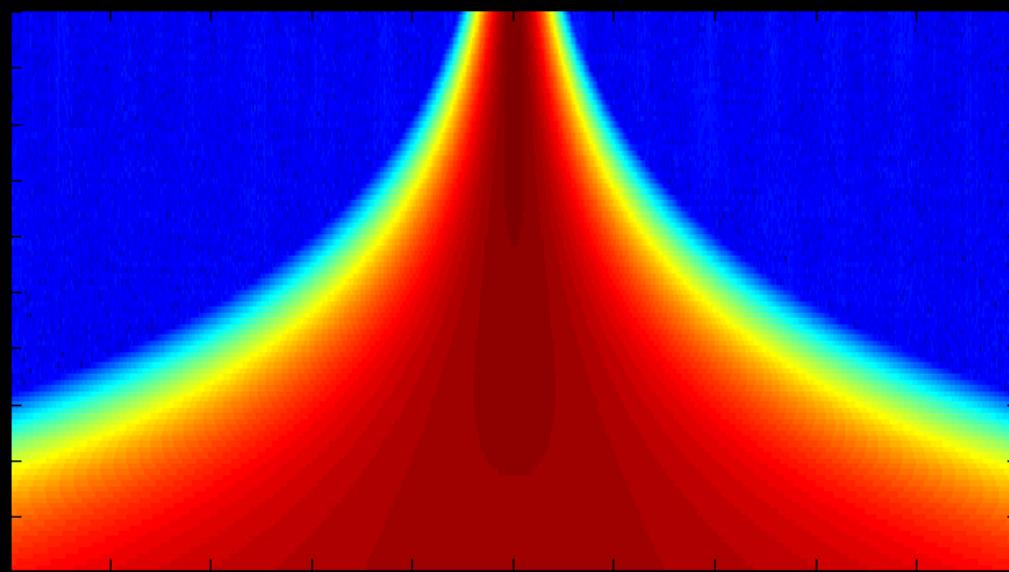


Edge artifacts!!!

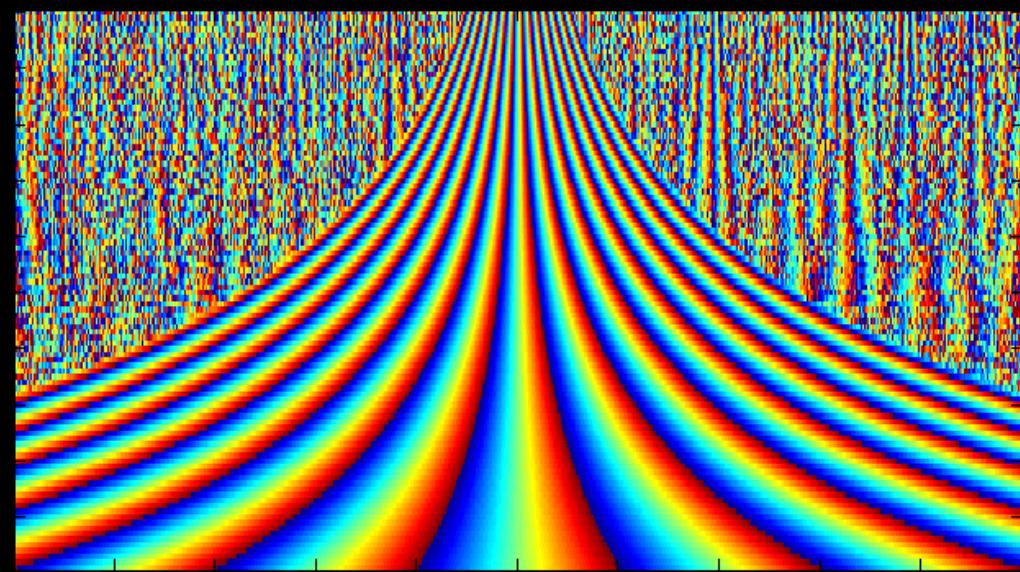
# Practical issues: Life on the fringe...

Time course with sharp edge

Power



Phase



# Practical issues: Life on the fringe...

**Solution: Perform convolution on a large window of time, then discard the edges.**

**I recommend at least 2 seconds on either side, but at least enough time for 5 cycles.**

