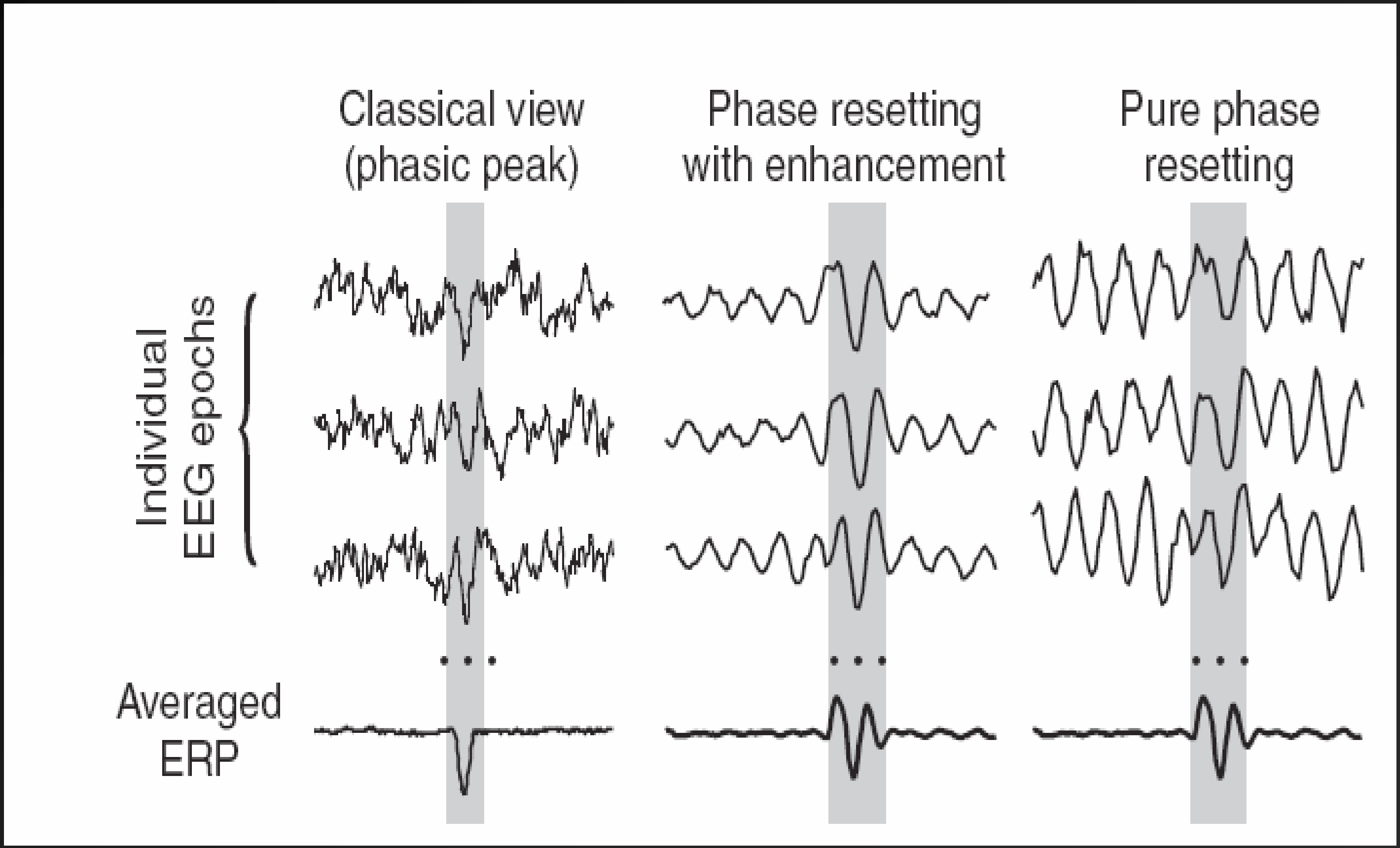
Advanced Signal Processing I

Time Frequency Approaches

Ocular Artifacts

Digital Filters

Classic ERPs Vs Phase Resetting



From Yeung et al., *Psychophysiology*, 2004

Time-Frequency Representations

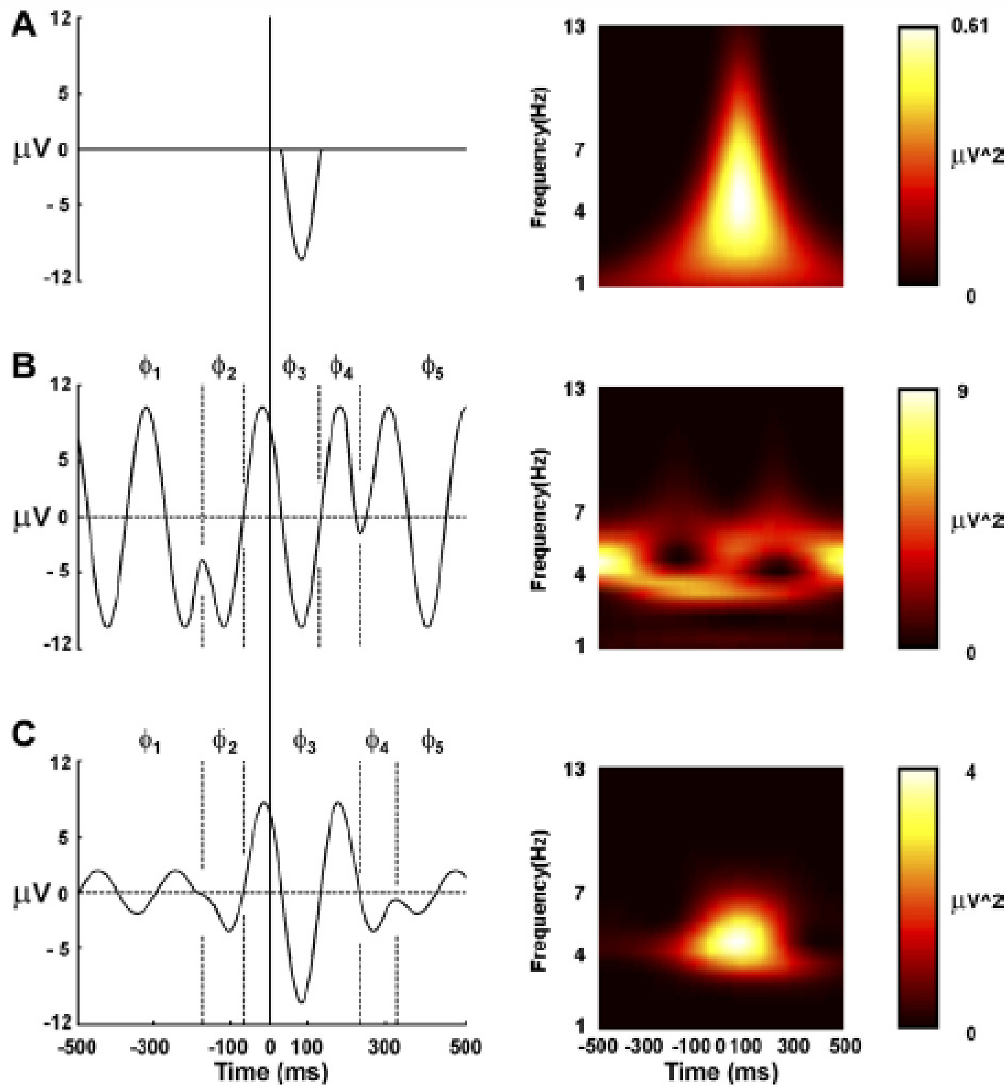
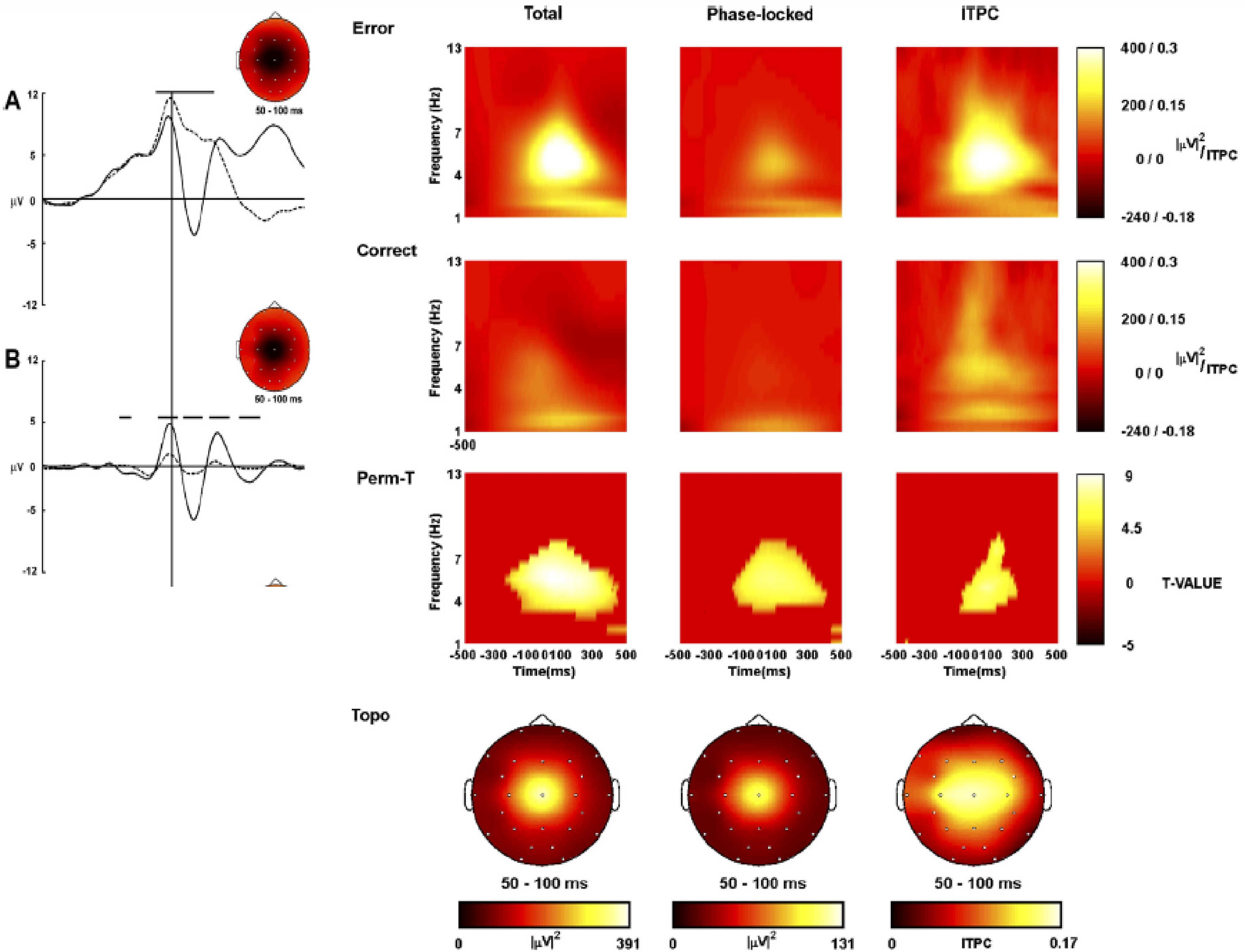
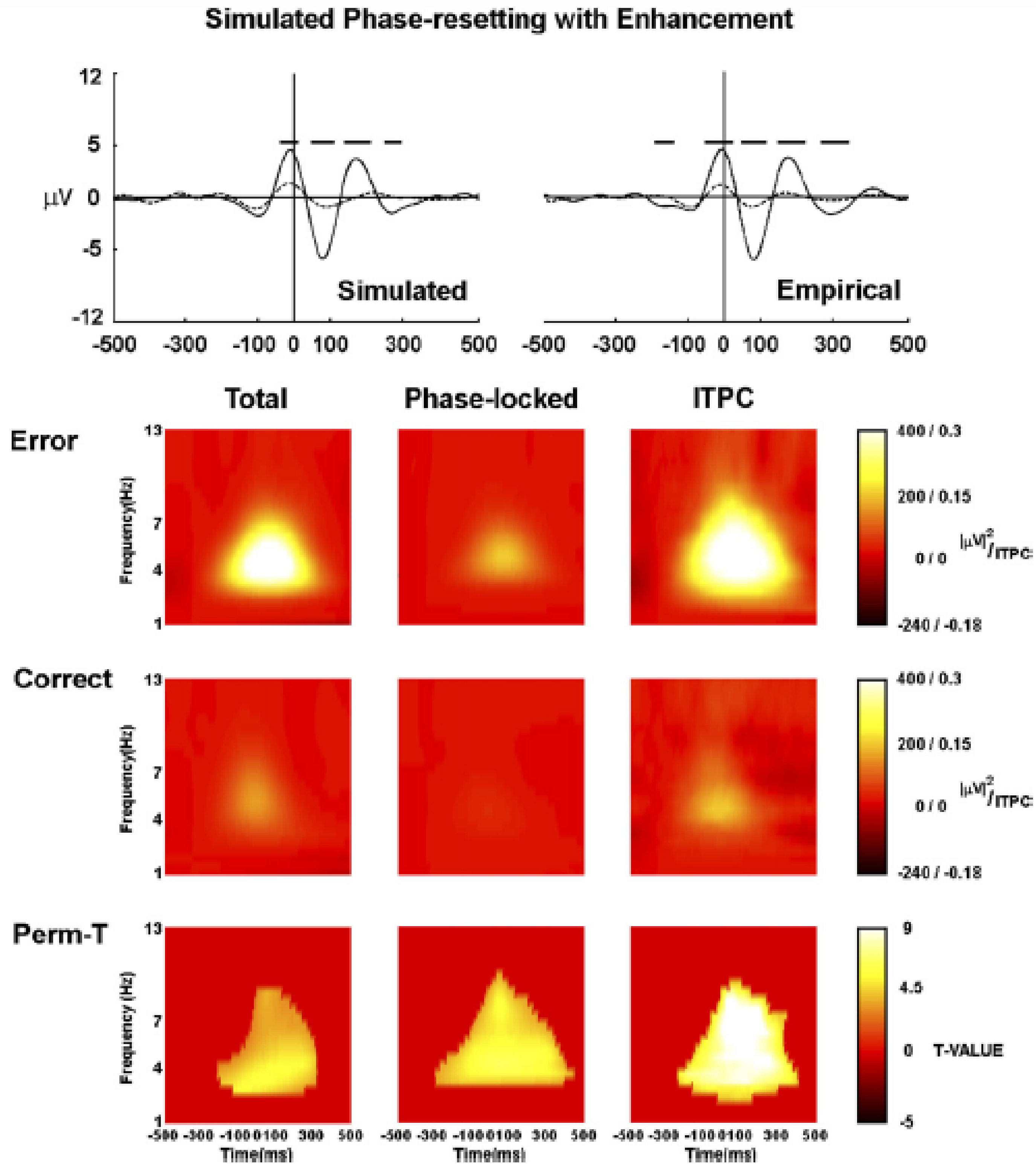


Fig. 1. Left column: Basic oscillatory waveforms used to simulate ERN responses according to the (A) *classic*, (B) *pure phase-resetting*, and (C) *phase-resetting with enhancement* hypotheses of ERN generation. Right column: Corresponding non-baseline-corrected wavelet-based time–frequency representations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

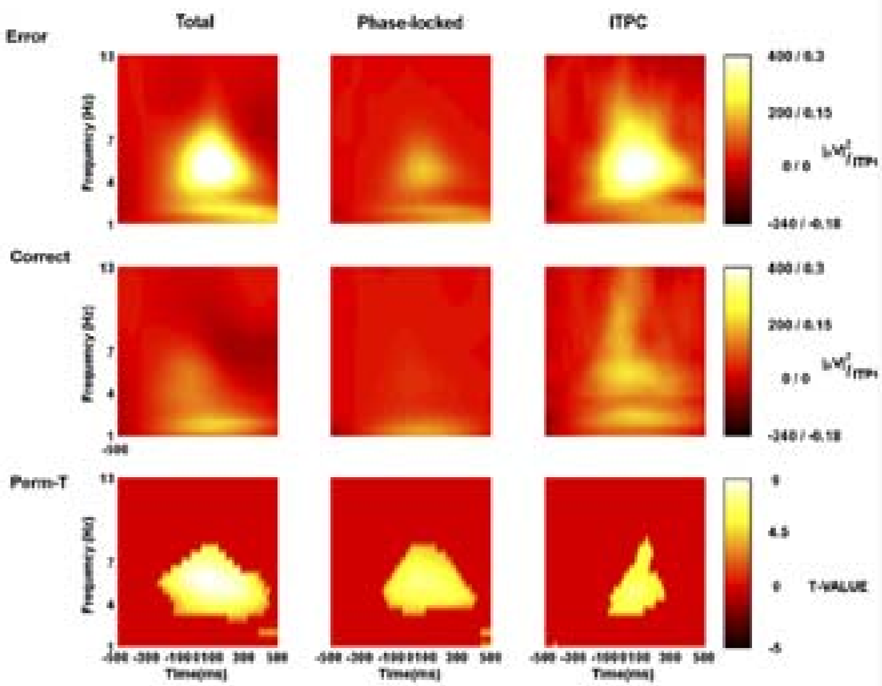


A
B
50 - 100 ms
50 - 100 ms
μV 0
12
5
-5
-12
Error
Correct
Perm-T
Topo
Total
Phase-locked
ITPC
Frequency (Hz)
13
7
4
1
-500
-500 -300 -100 0 100 300 500
Time(ms)
400 / 0.3
200 / 0.15
0 / 0
-240 / -0.18
|μV|²/ITPC
9
4.5
0
-5
T-VALUE
50 - 100 ms
0
|μV|²
391
131
ITPC
0.17

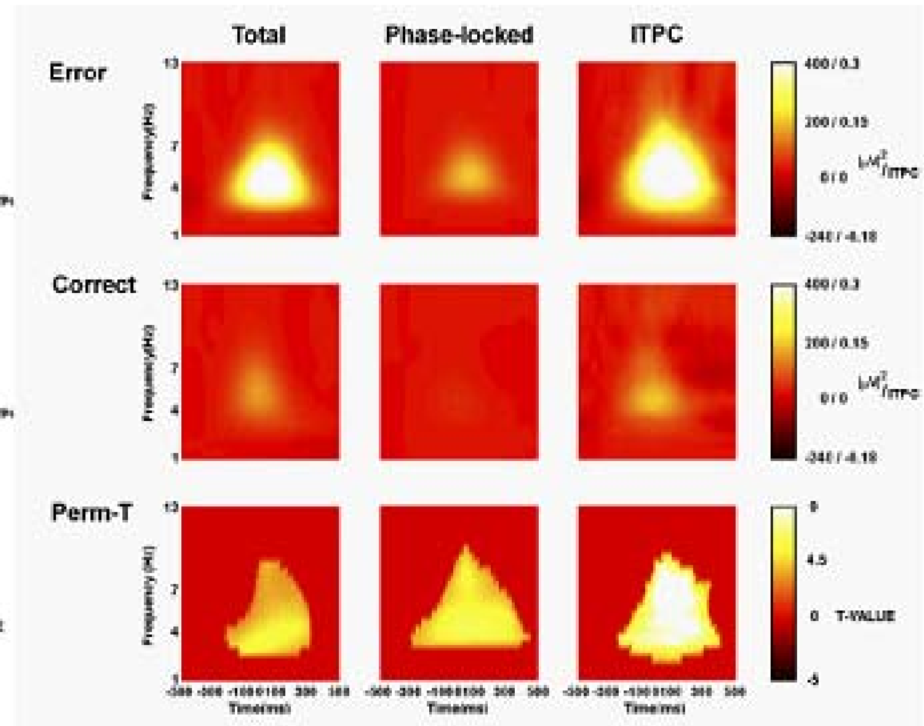


Simulated Phase-resetting with Enhancement
12
5
μV 0
-5
-12
-500 -300 -100 0 100 300 500
Simulated
Empirical
Total
Phase-locked
ITPC
Error
Correct
Perm-T
Frequency(Hz)
13
7
4
1
400 / 0.3
200 / 0.15
0 / 0
-240 / -0.18
$|\mu V|^2$/ITPC
9
4.5
0
-5
T-VALUE
Time(ms)

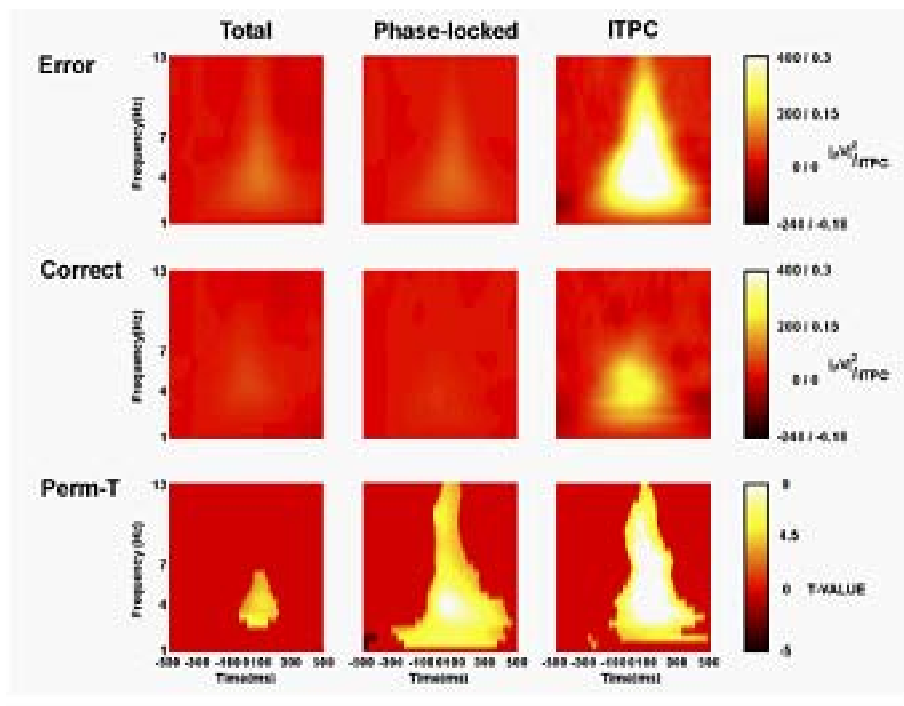
Empirical



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.

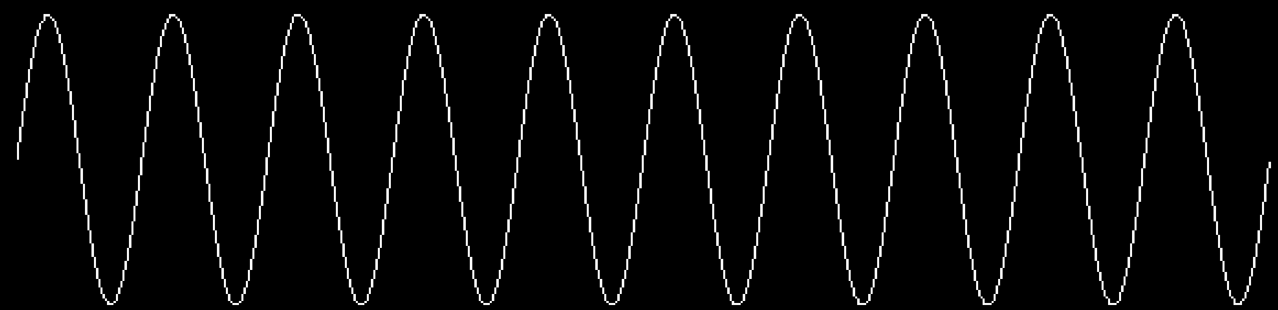
Dr. Mike X Cohen

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. What are EEG oscillations?

But first, what is an oscillation?



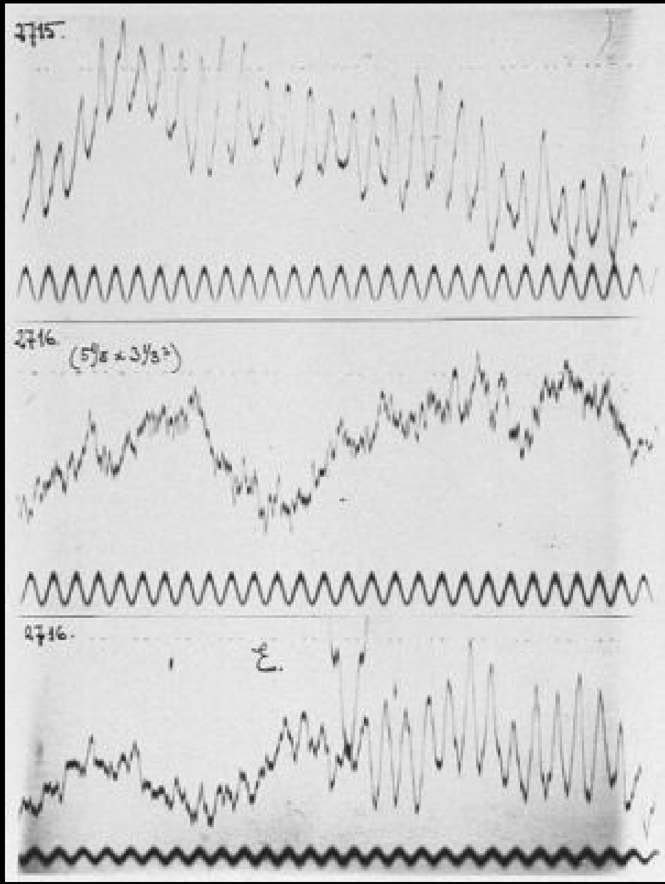
Math of oscillations:

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

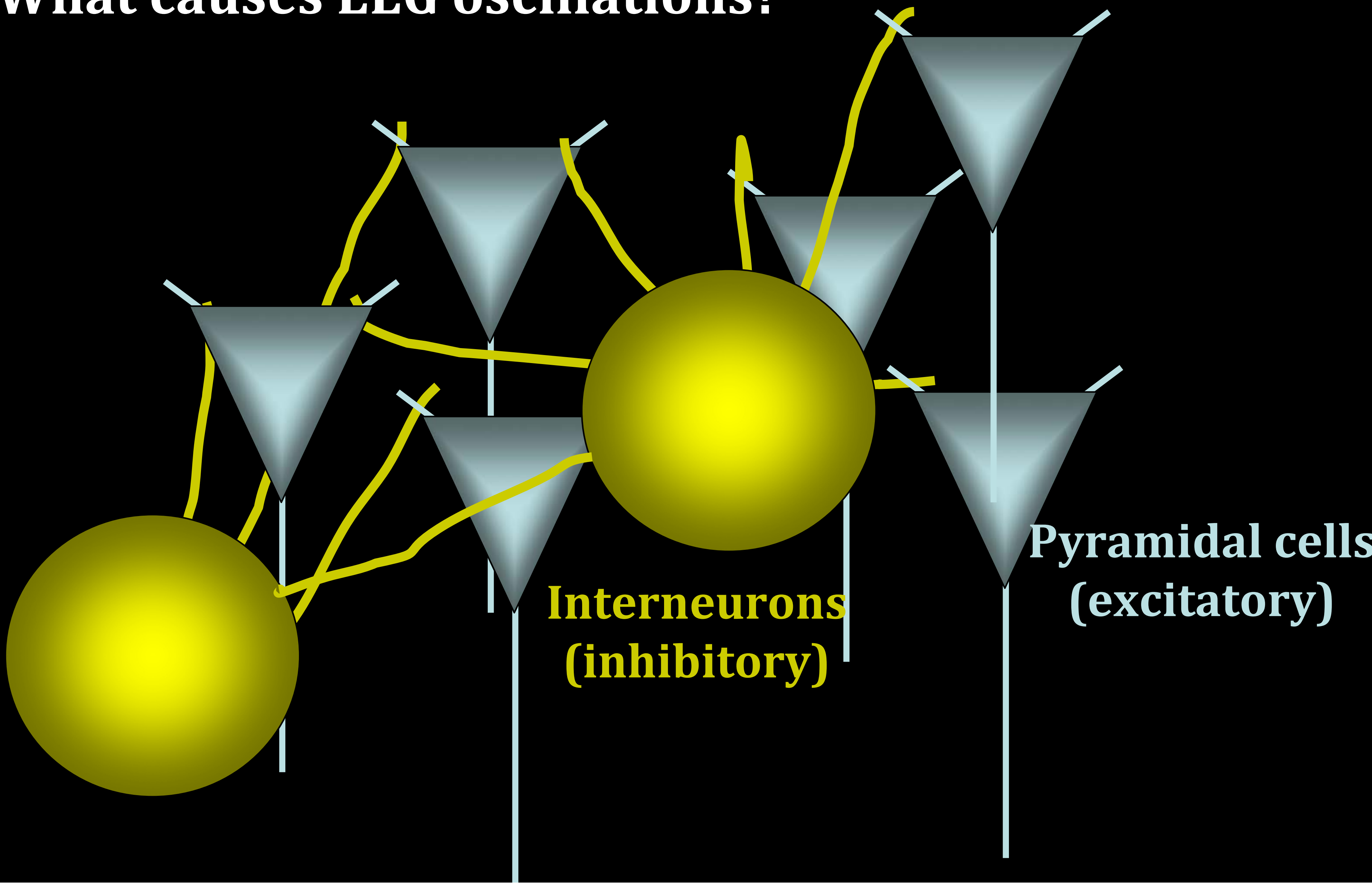
Most things in the universe oscillate…

1. What are EEG oscillations?

Hans Berger, the dude who started it all…



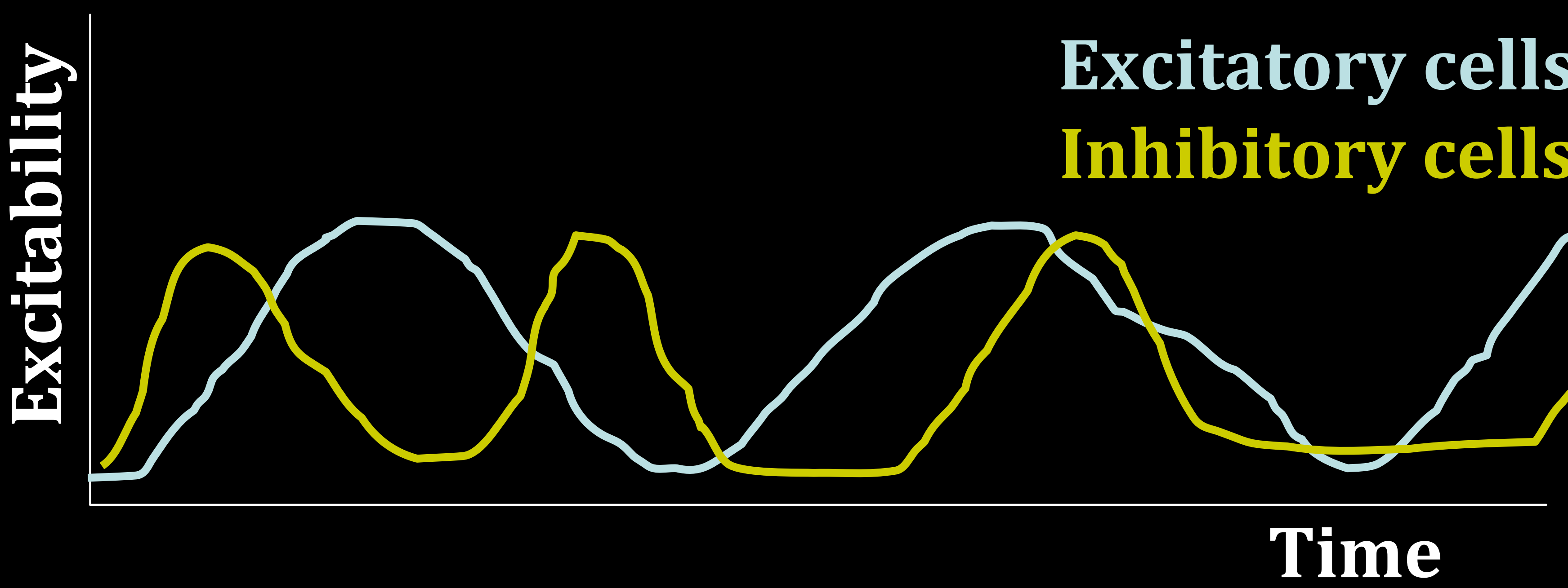
What causes EEG oscillations?



1. What causes EEG oscillations?

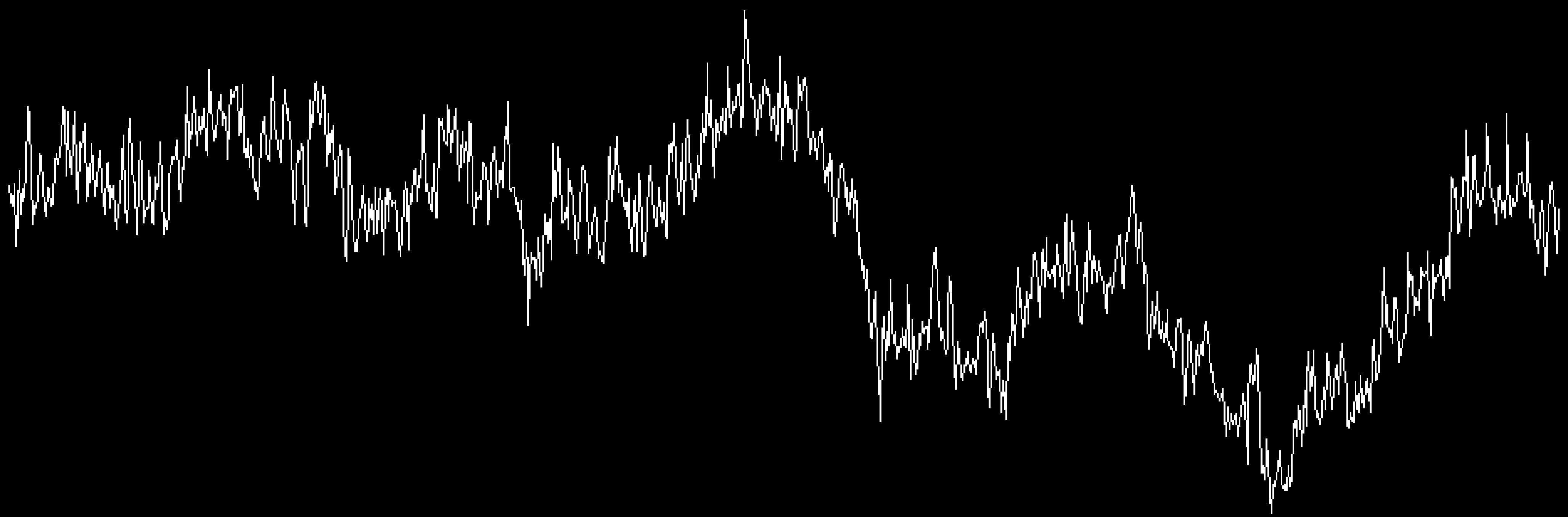
Oscillations arise from the dynamic interplay between inhibitory interneurons and excitatory cells.

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?

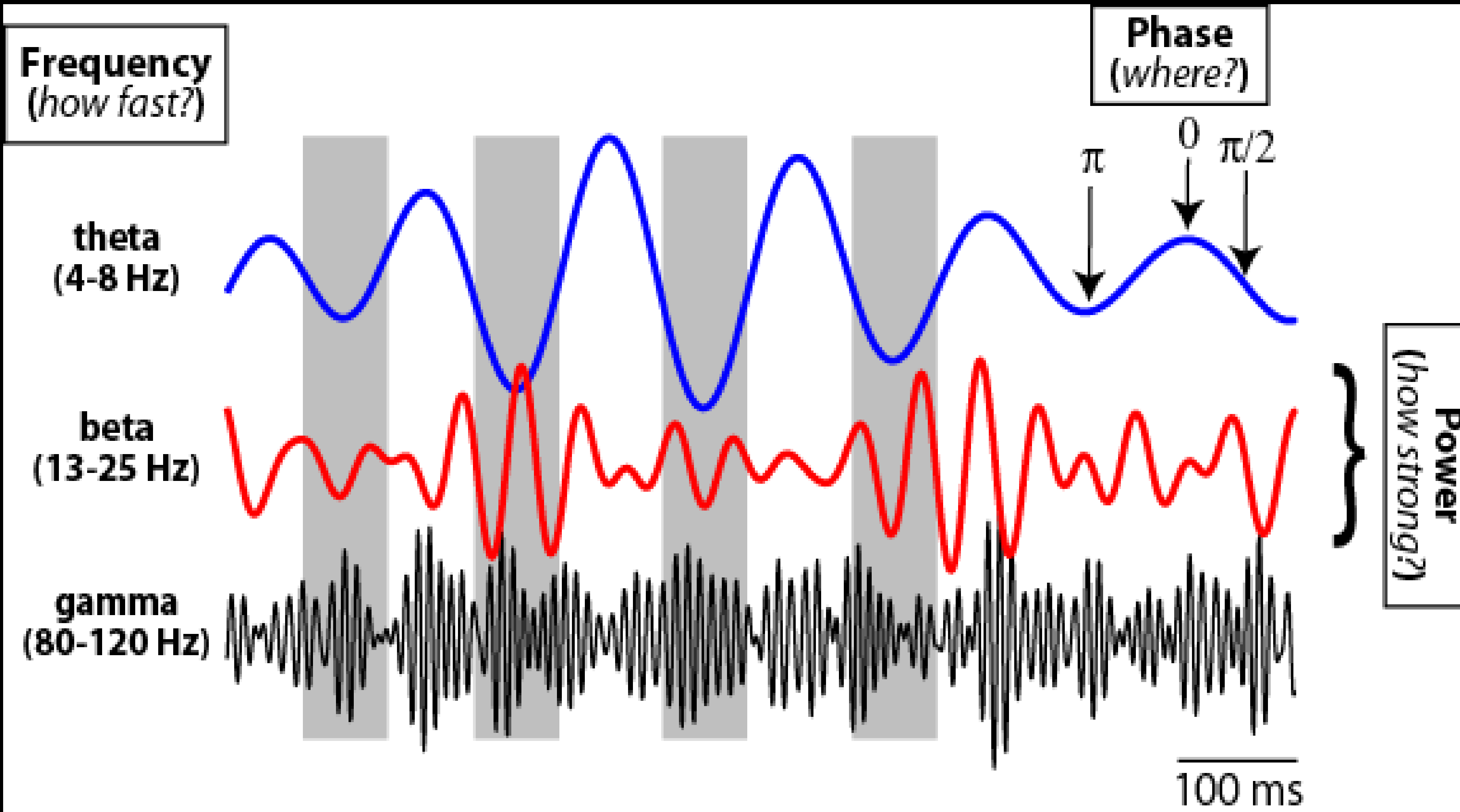
Some unfiltered ("raw") EEG data



You can see fast and slow oscillations…

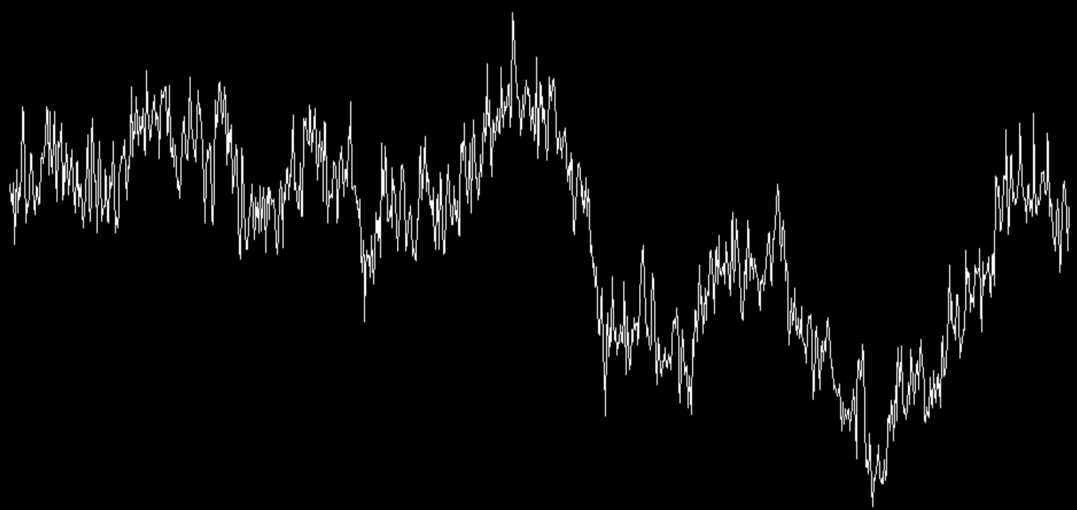
1. What are EEG oscillations?

Some nomenclature.



1. What are EEG oscillations?

Problem: Lots of overlapping frequencies in EEG.

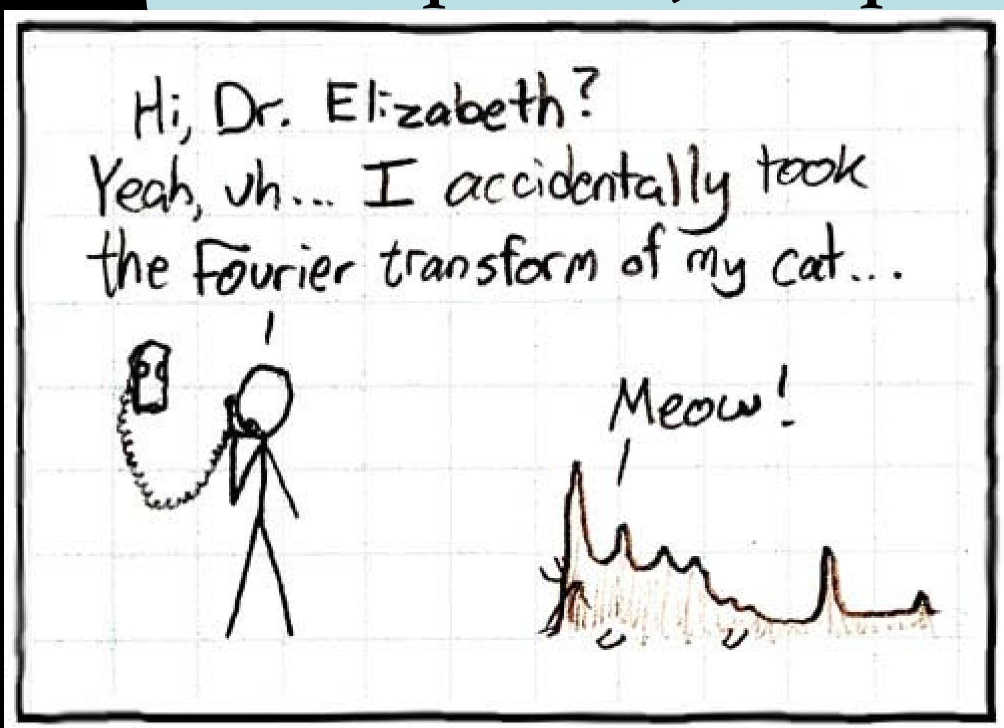


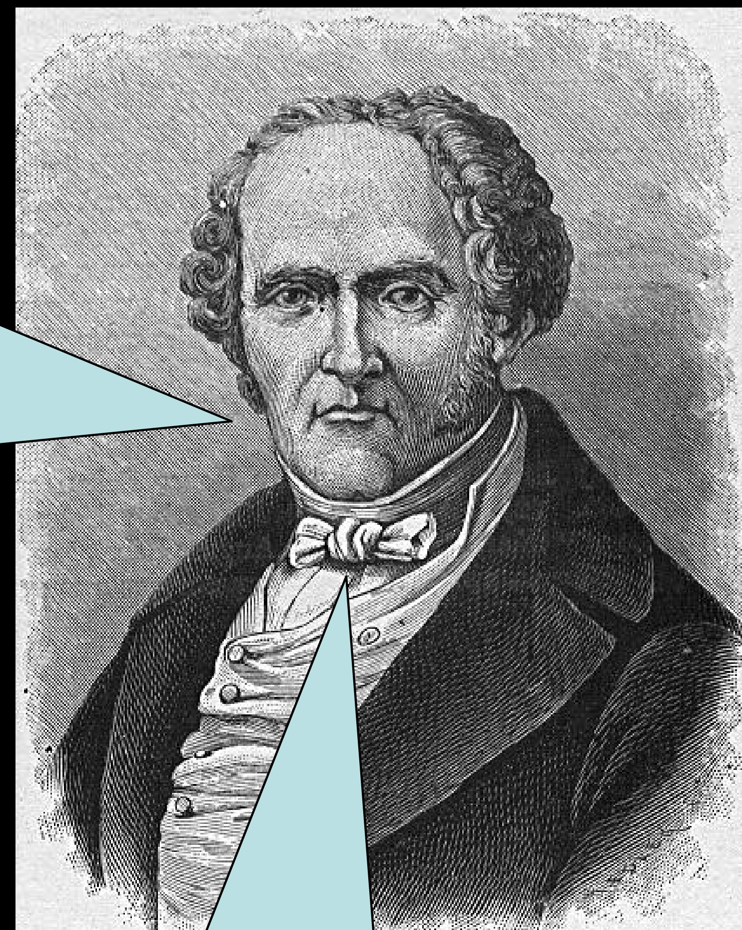
Fourier to the rescue!

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

1. What are EEG oscillations?

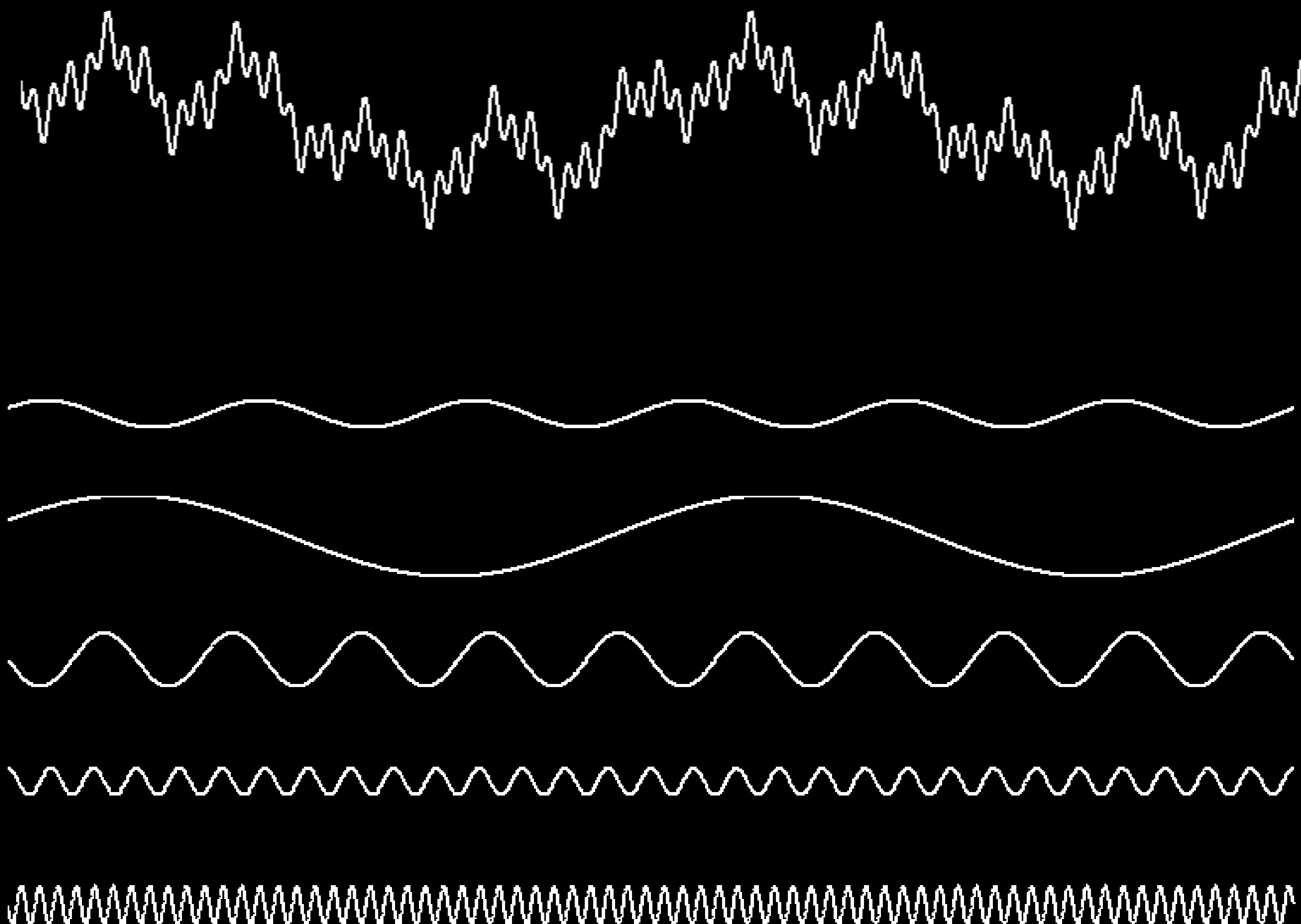
<u>Any</u> signal can be expressed as a <u>combination of different sine waves</u>, each with its own frequency, amplitude, and phase!



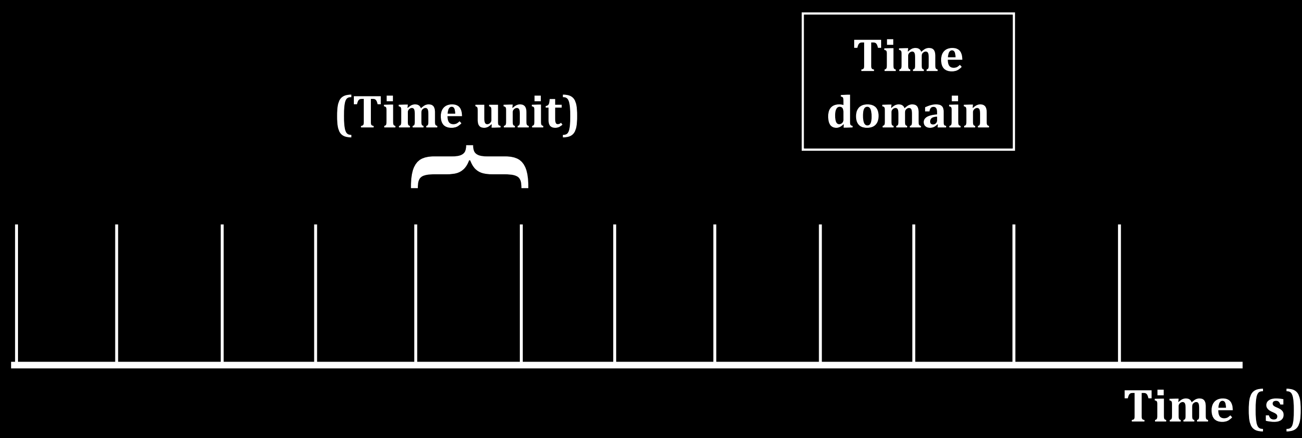


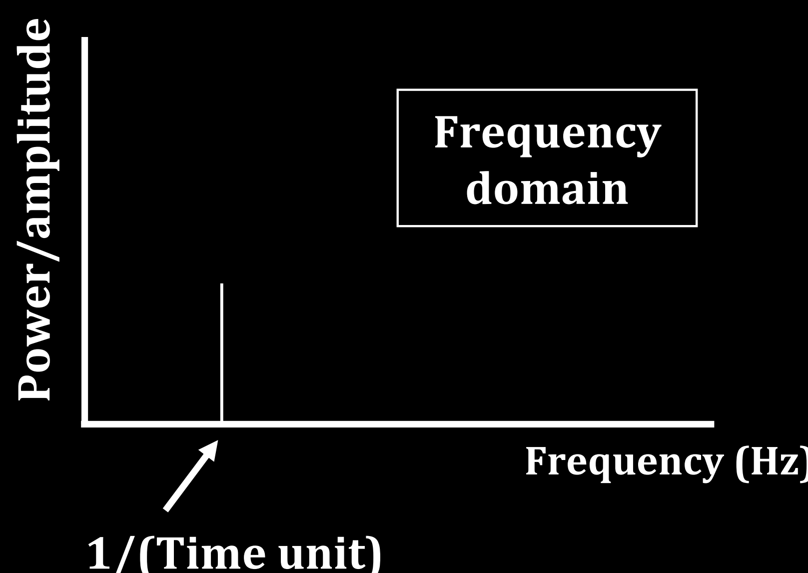
Zut allor! C'est magnifique! Tu as le coeur d'un lion!

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

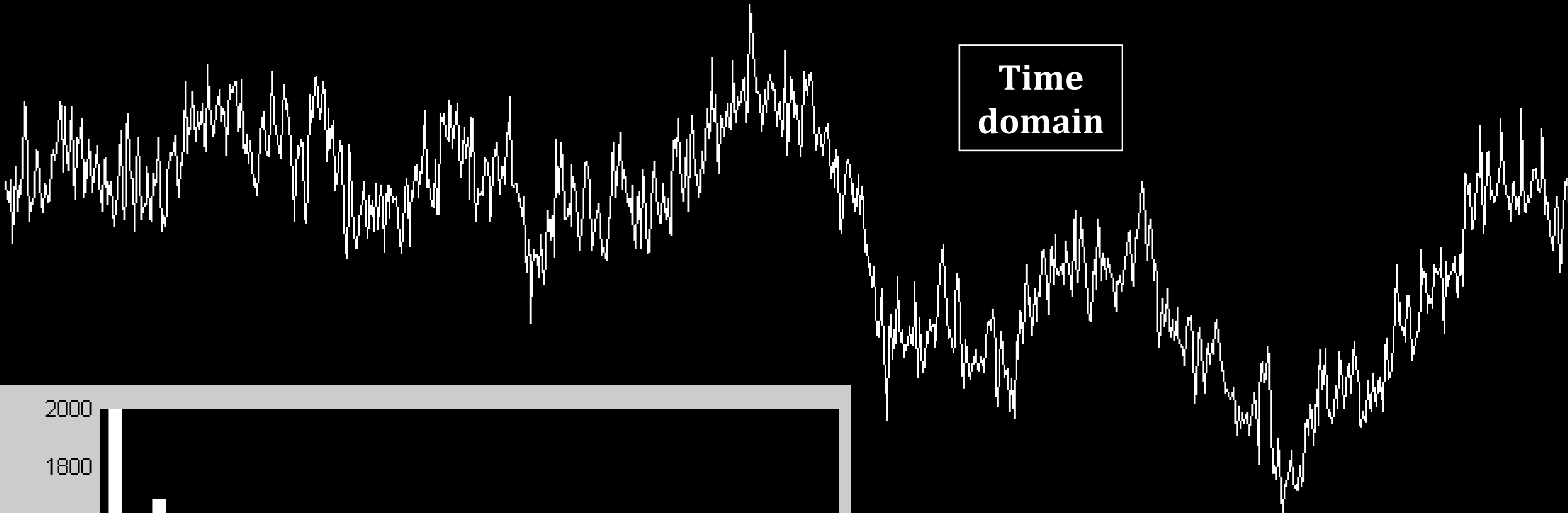


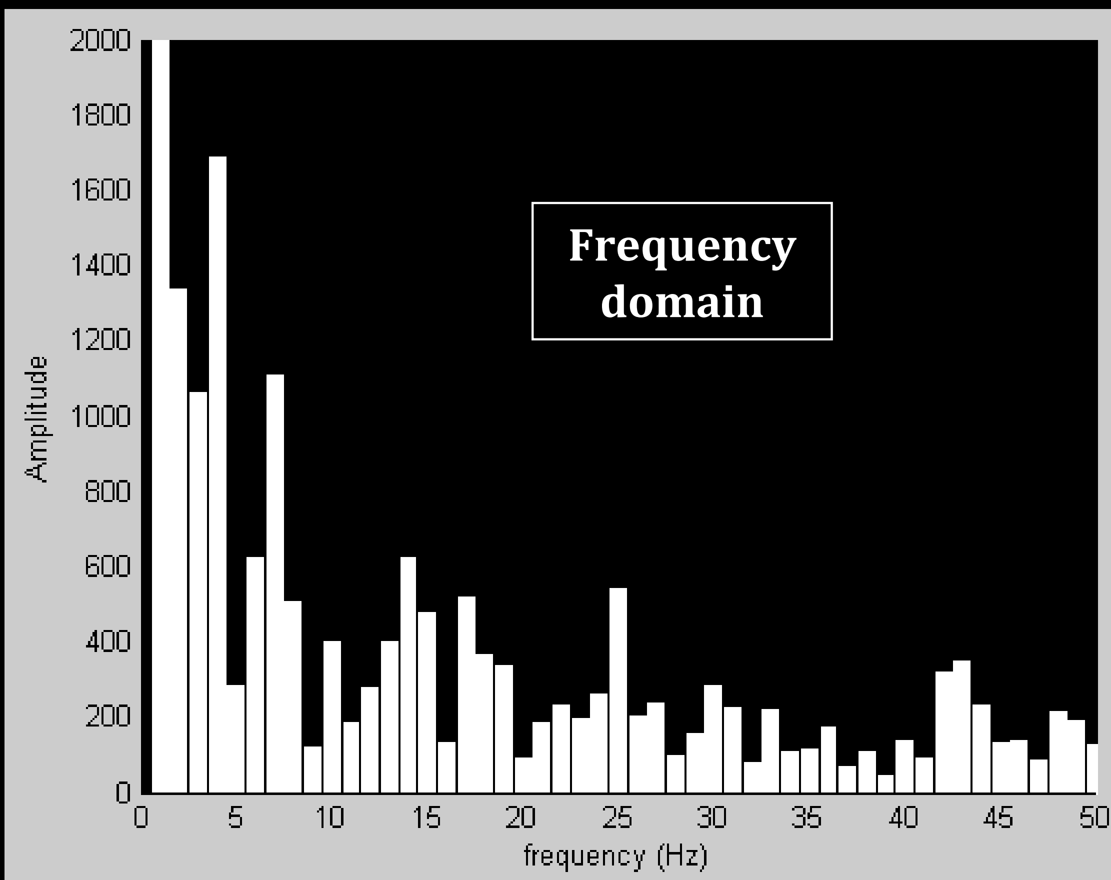
1. Going from the time to frequency domains





1. What are EEG oscillations?

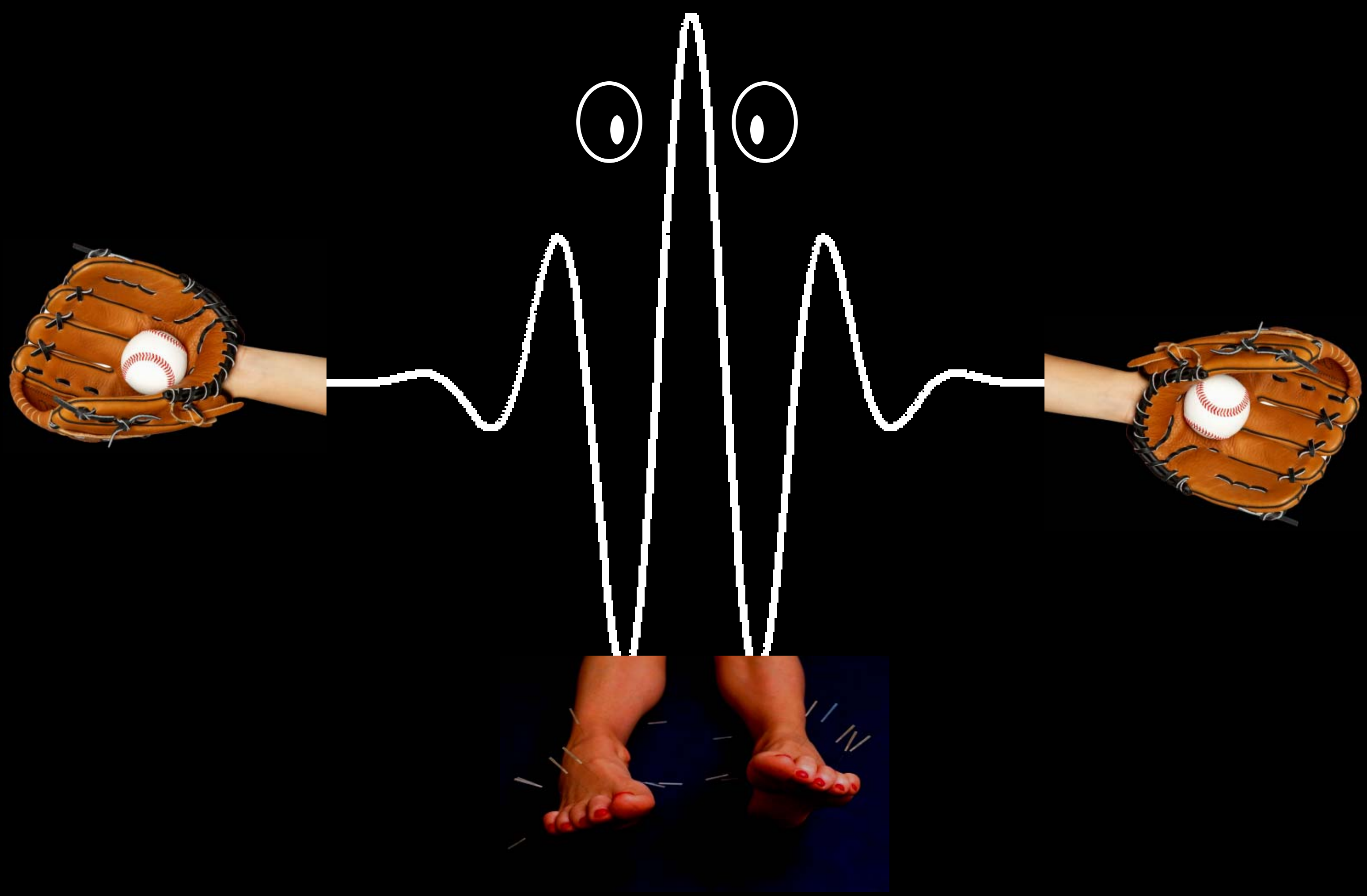




Problem: This is over a block of time… what if frequency structure changes dynamically across time?

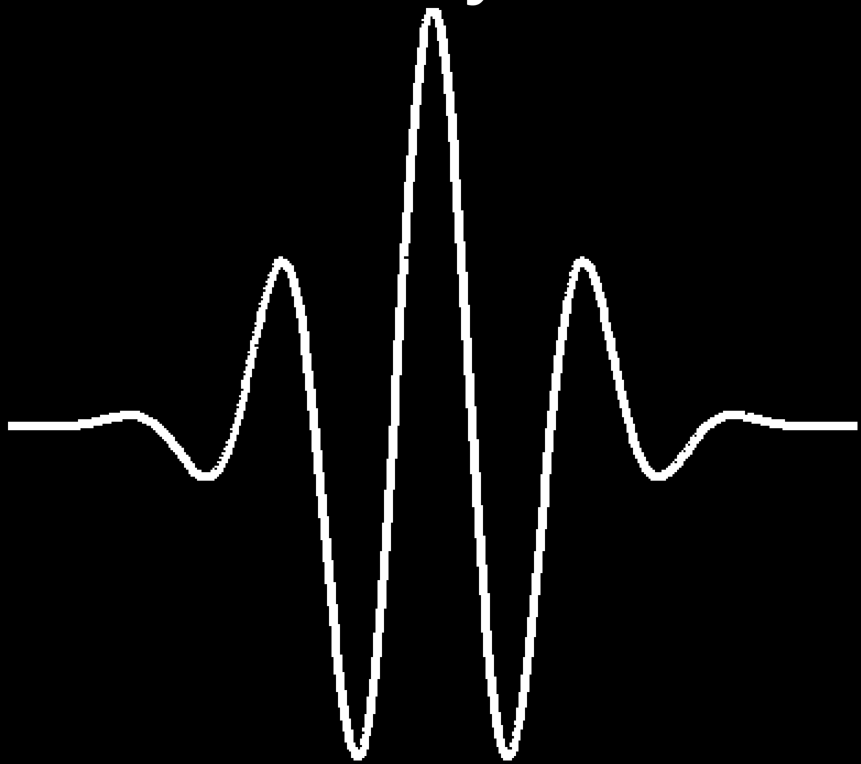
1. Introduction to Wavelets and wavelet convolution

Mr. Wavelet and his family to the rescue!

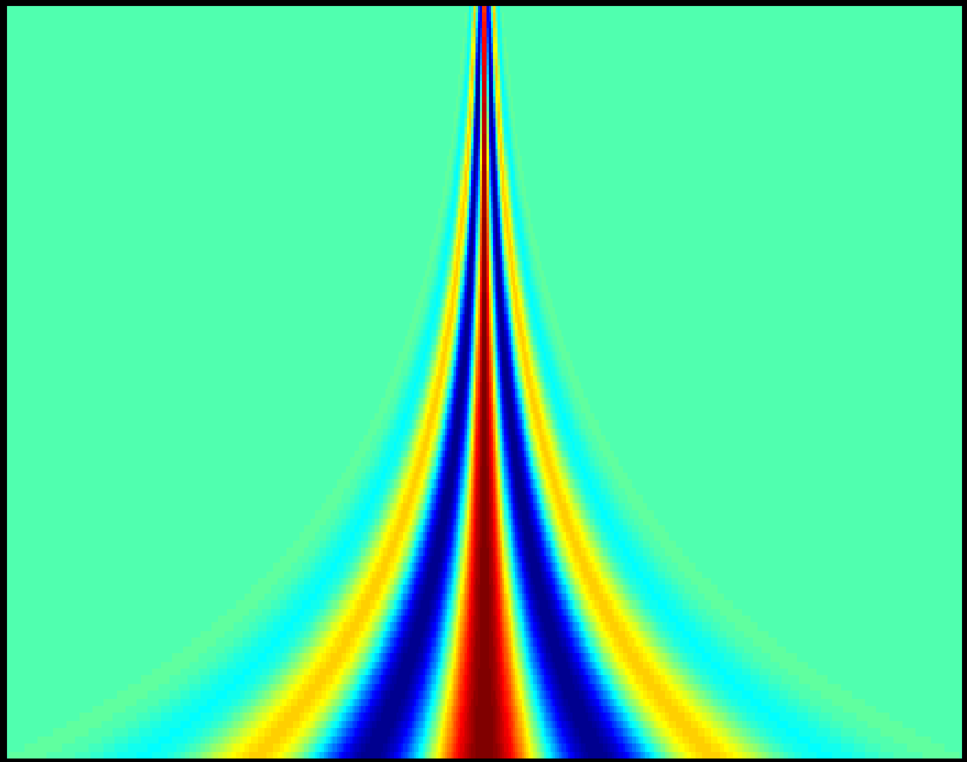


1. Introduction to Wavelets and wavelet convolution

Mr. Wavelet in his birthday suit:

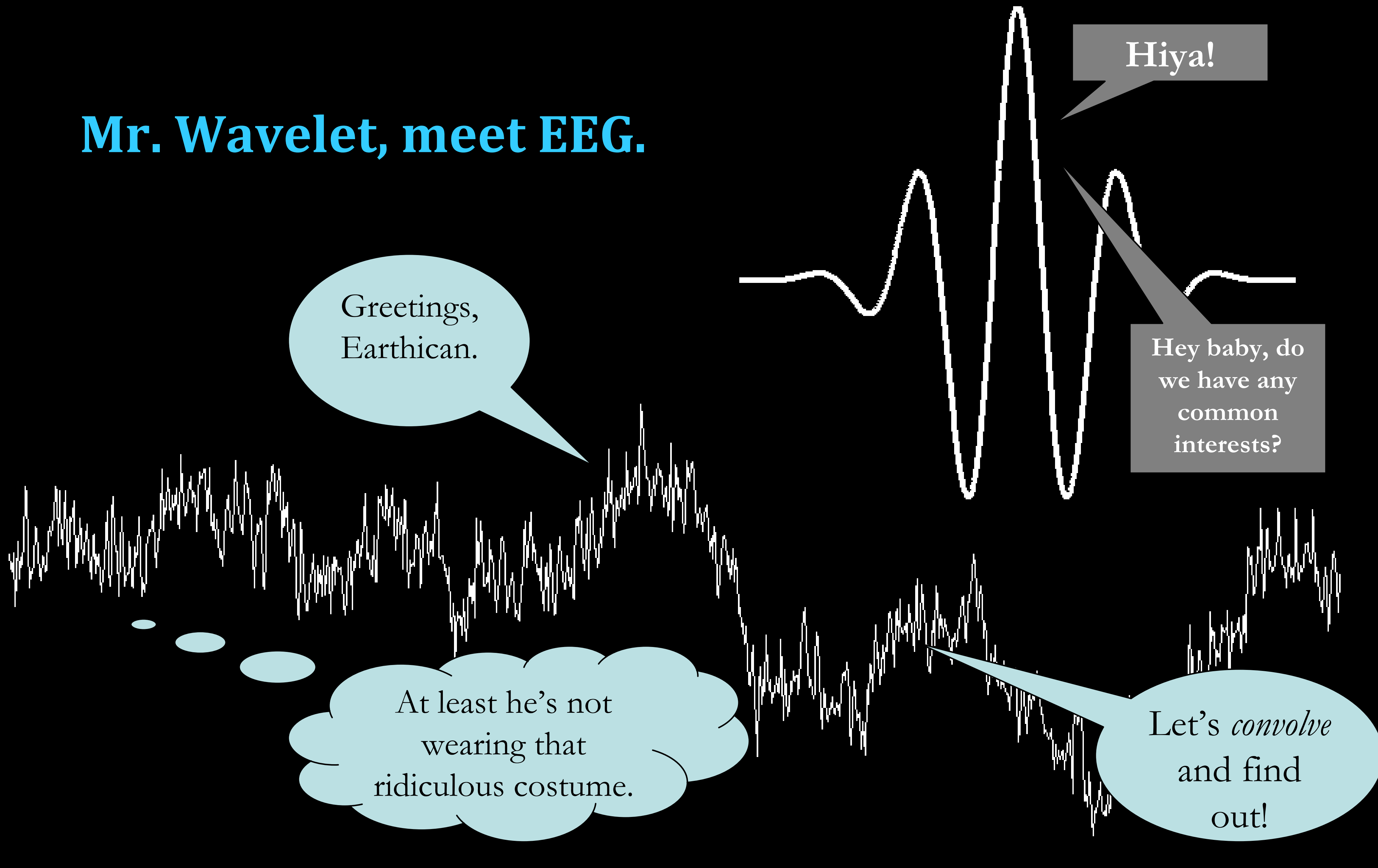


And his family:

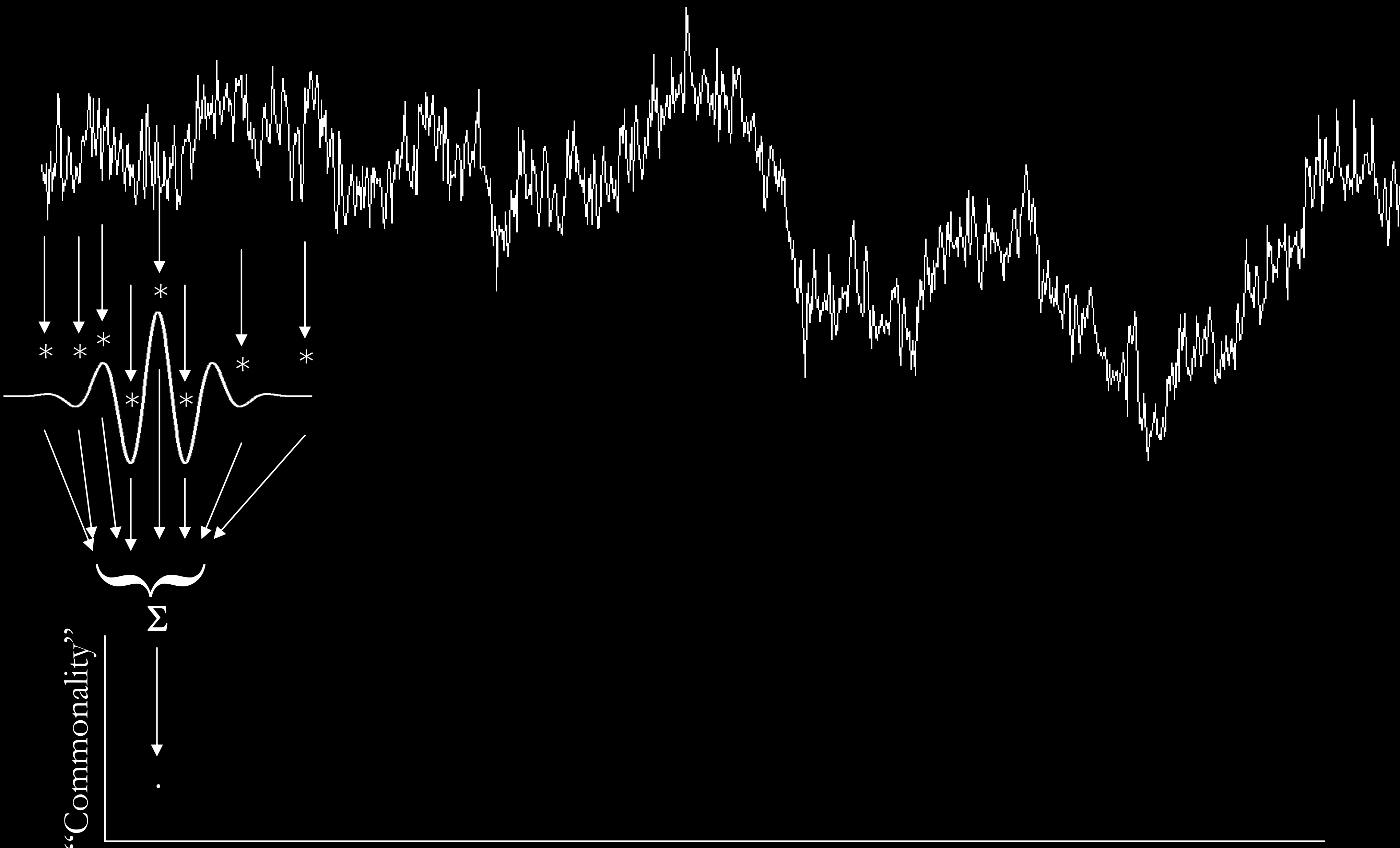


1. Introduction to Wavelets and wavelet convolution

Mr. Wavelet, meet EEG.



1. What is convolution?



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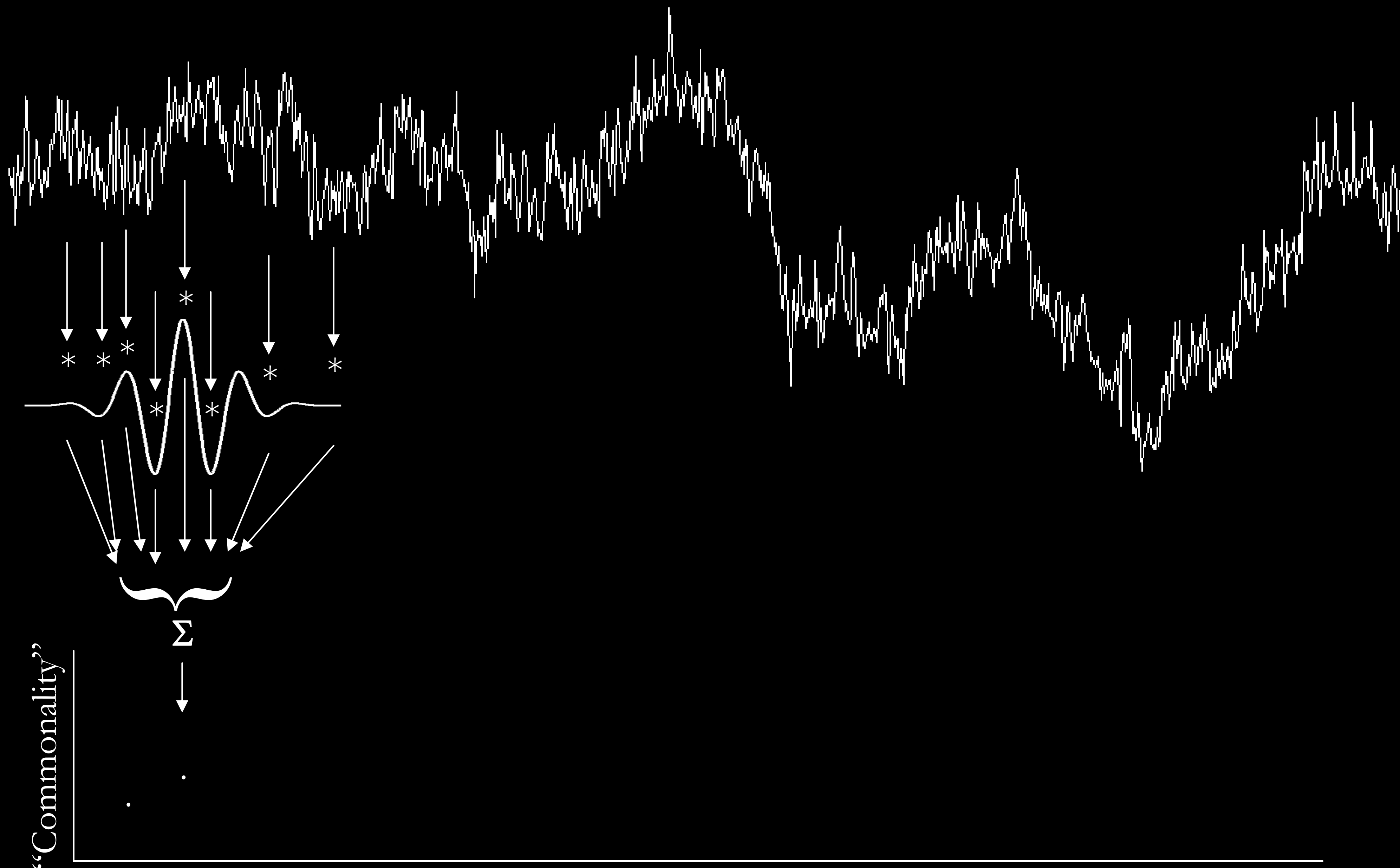

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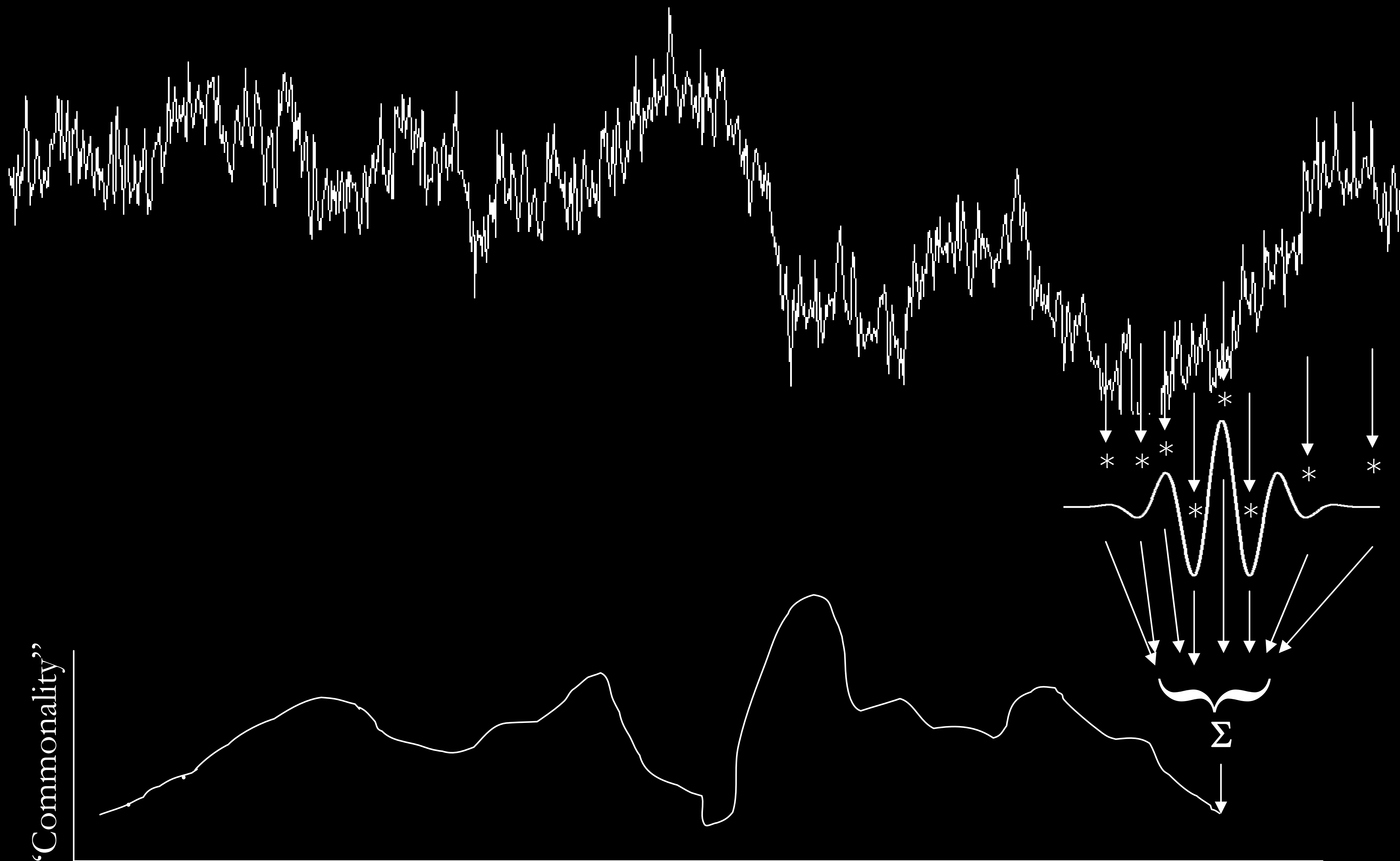

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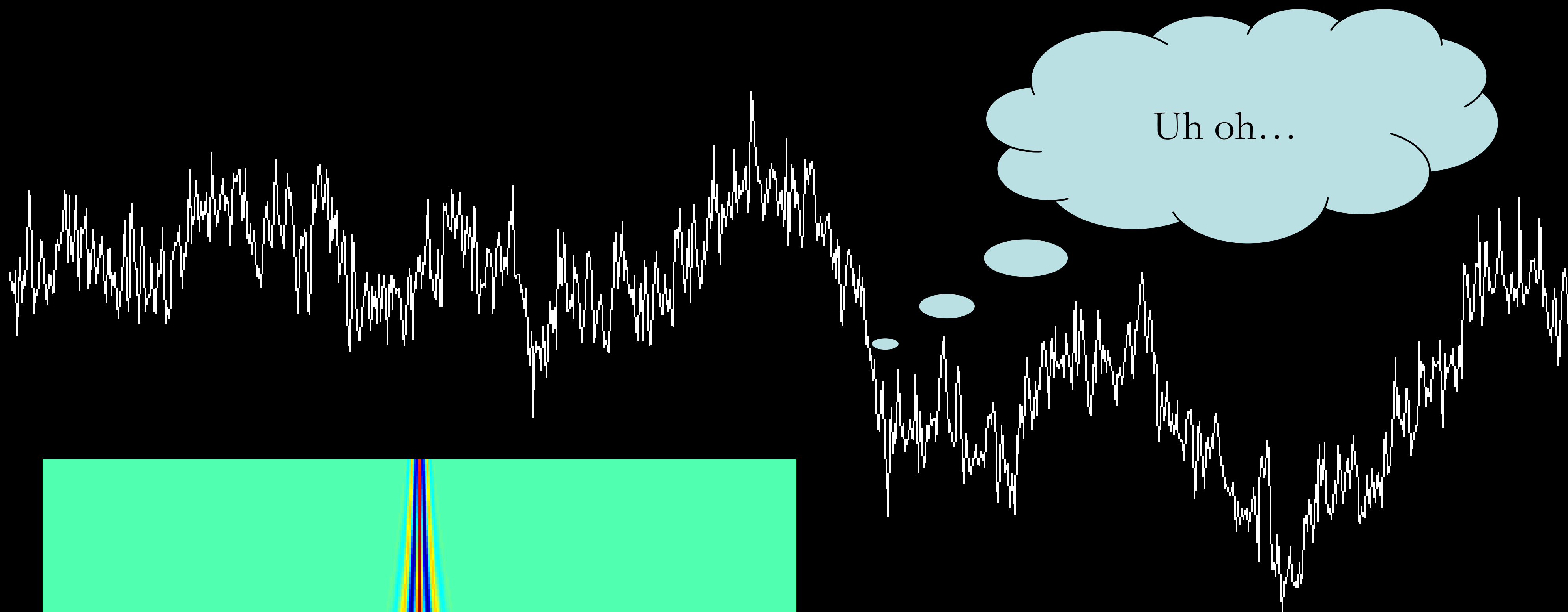

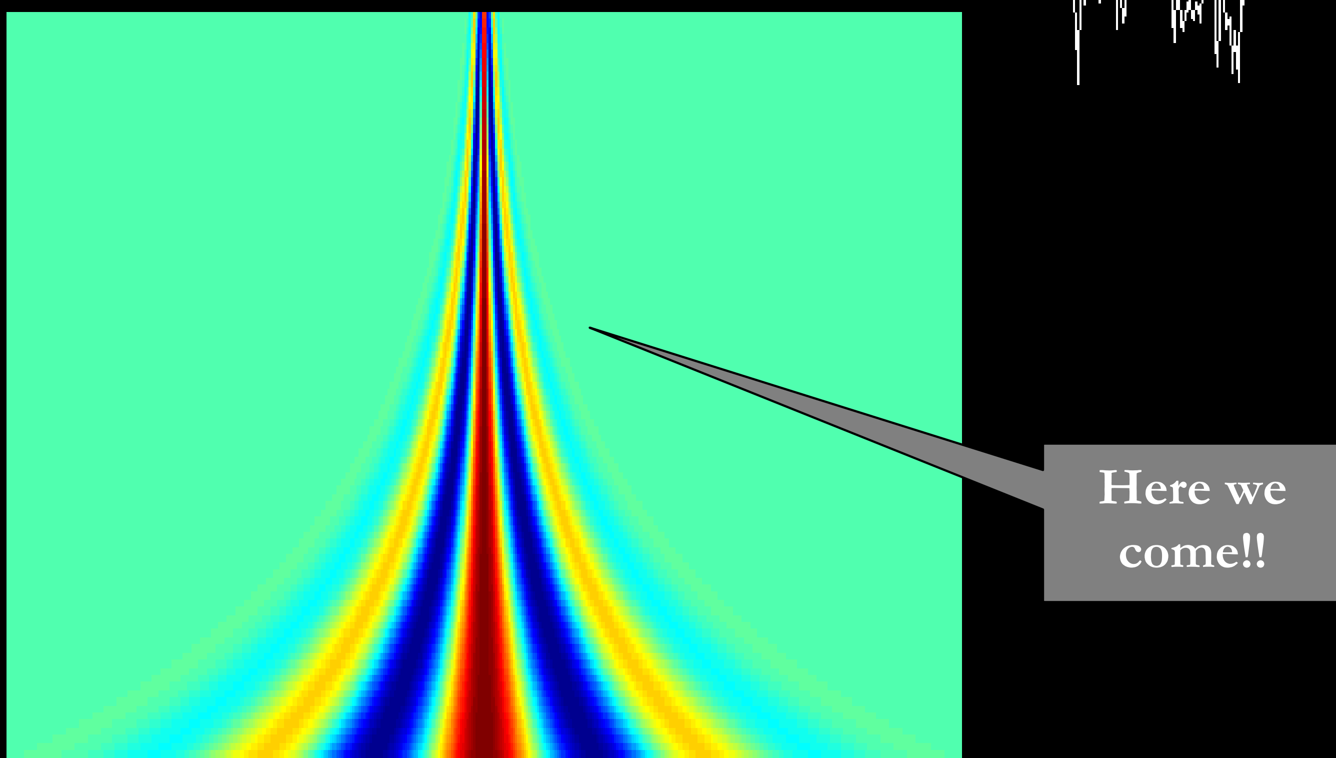

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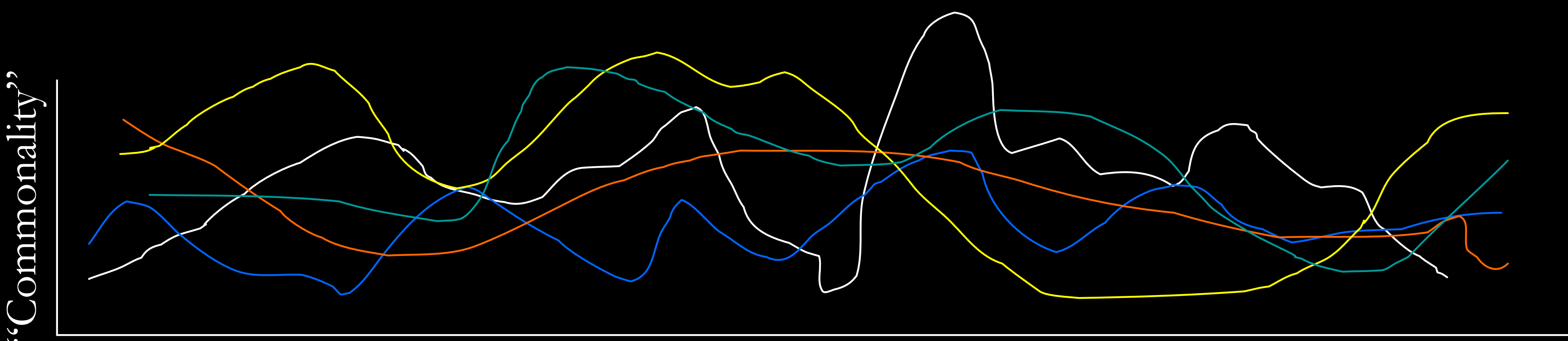

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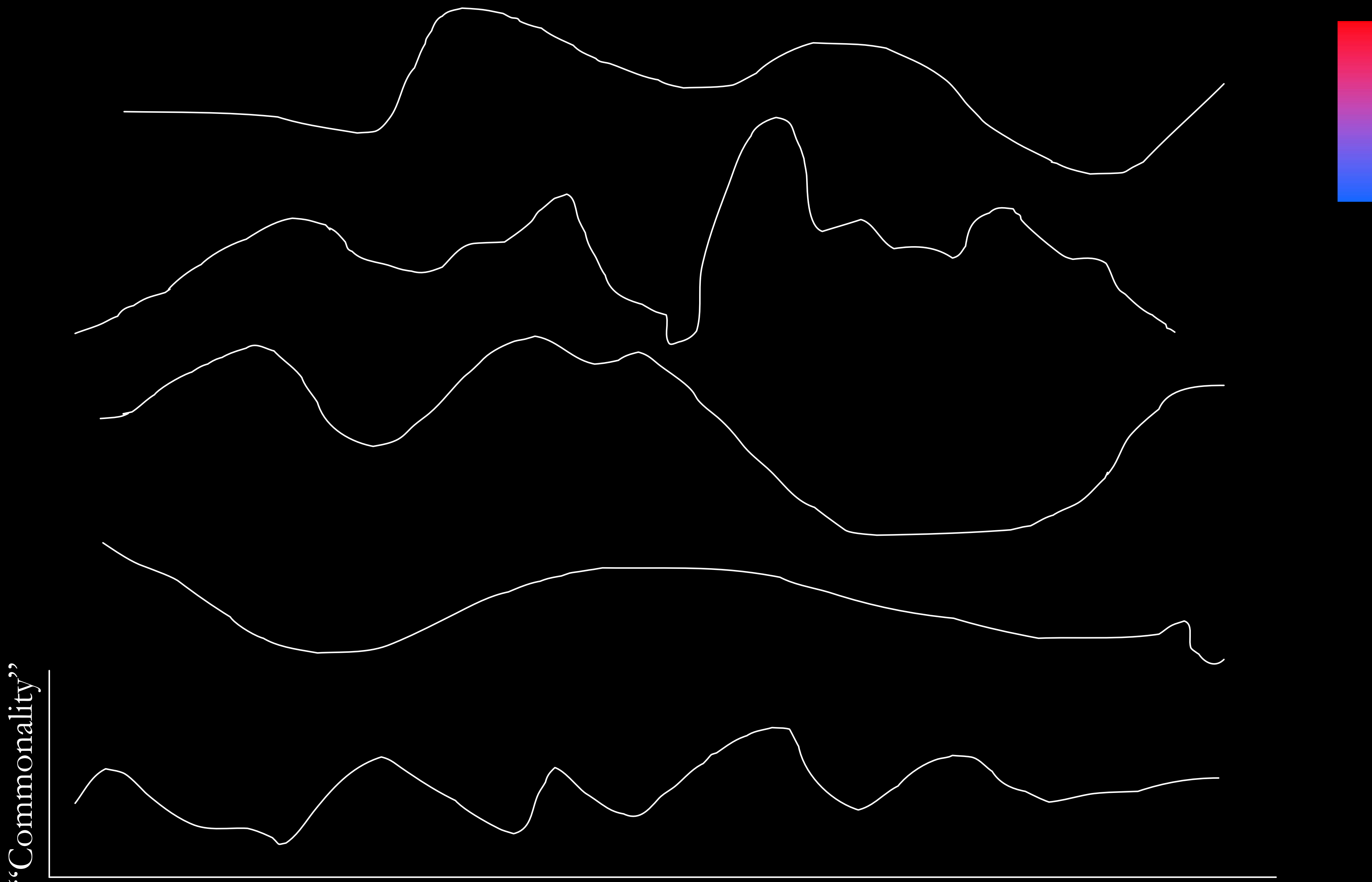

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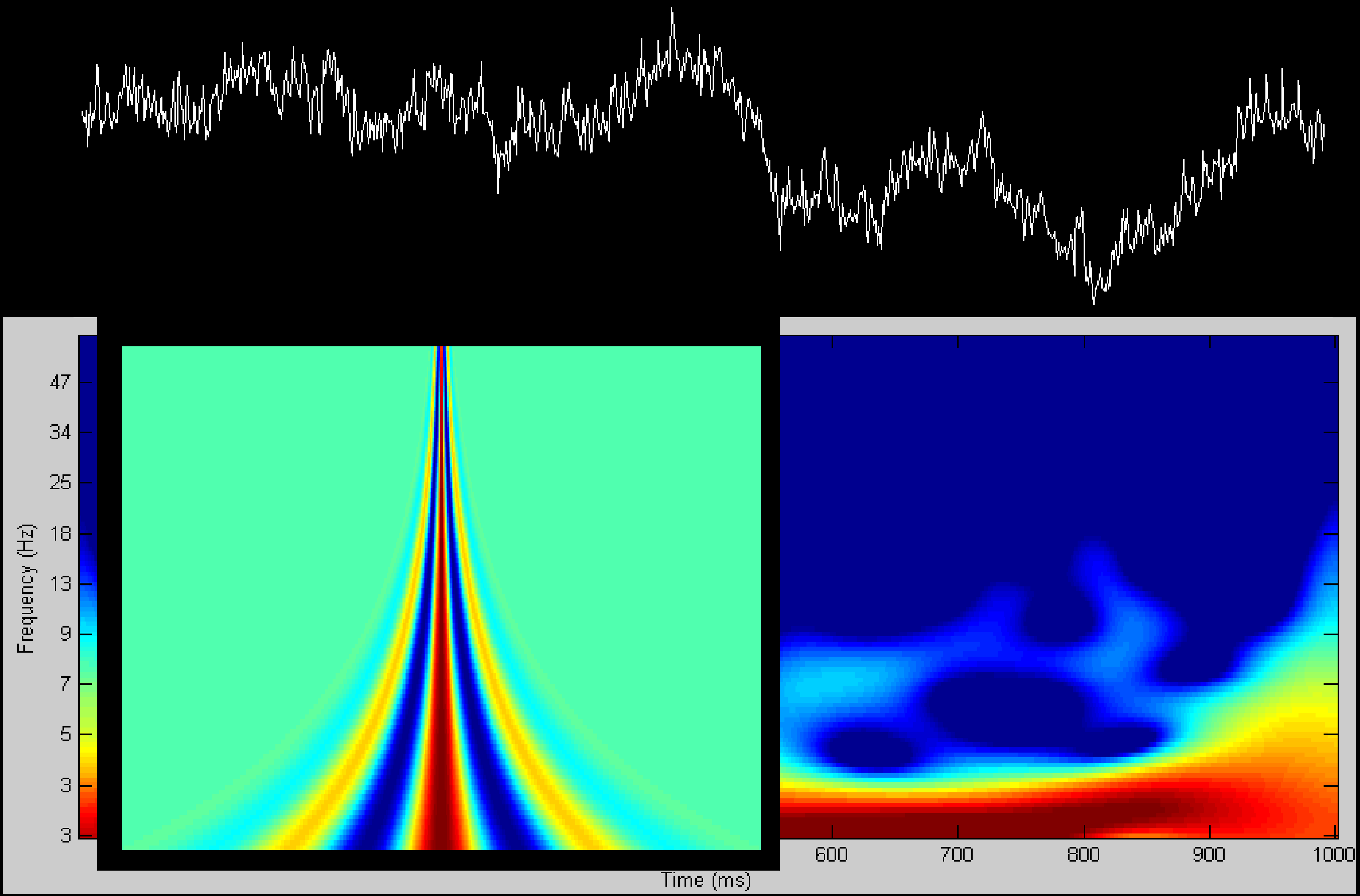
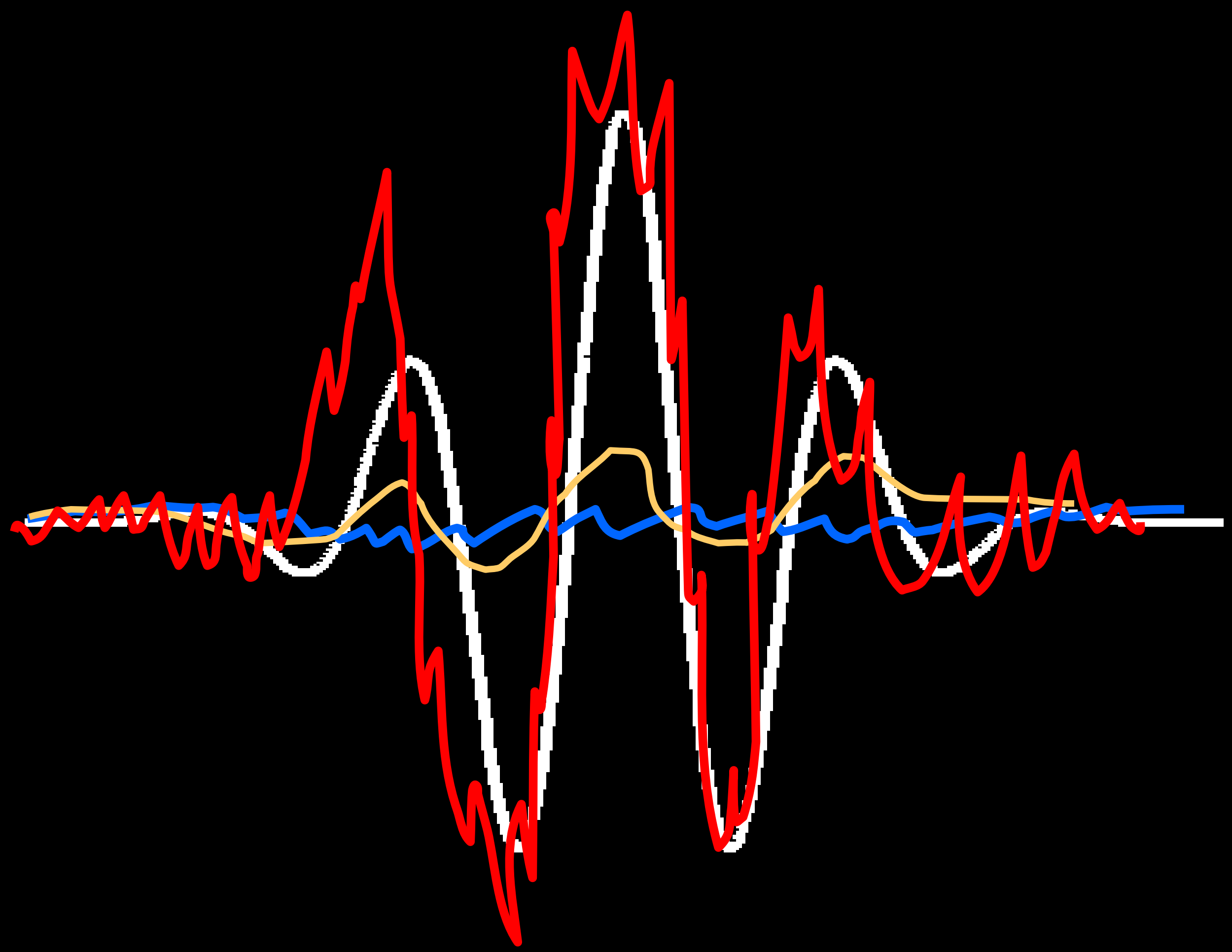


1. Why does it work?



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

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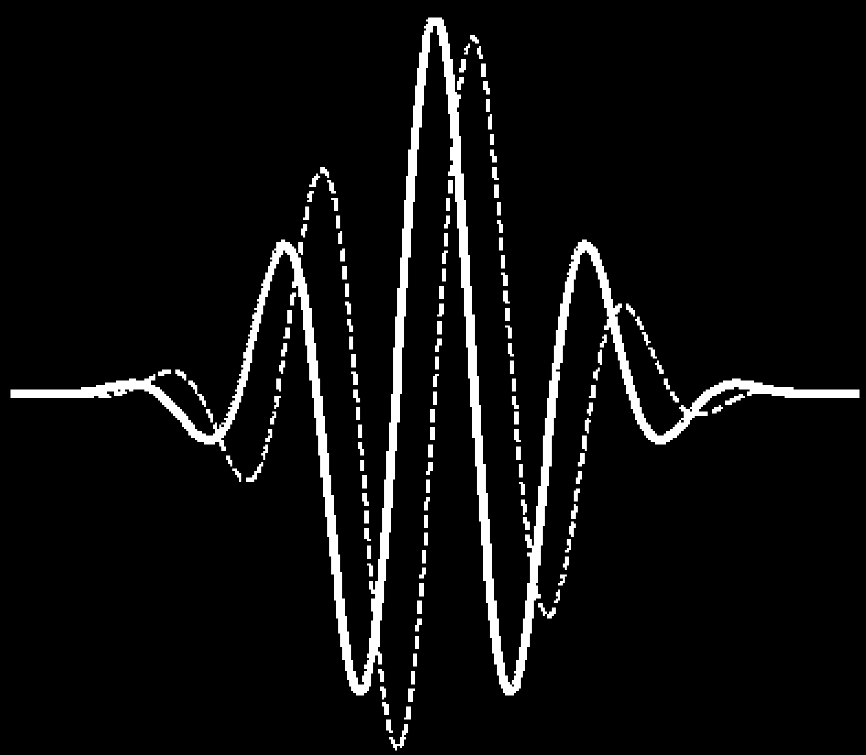
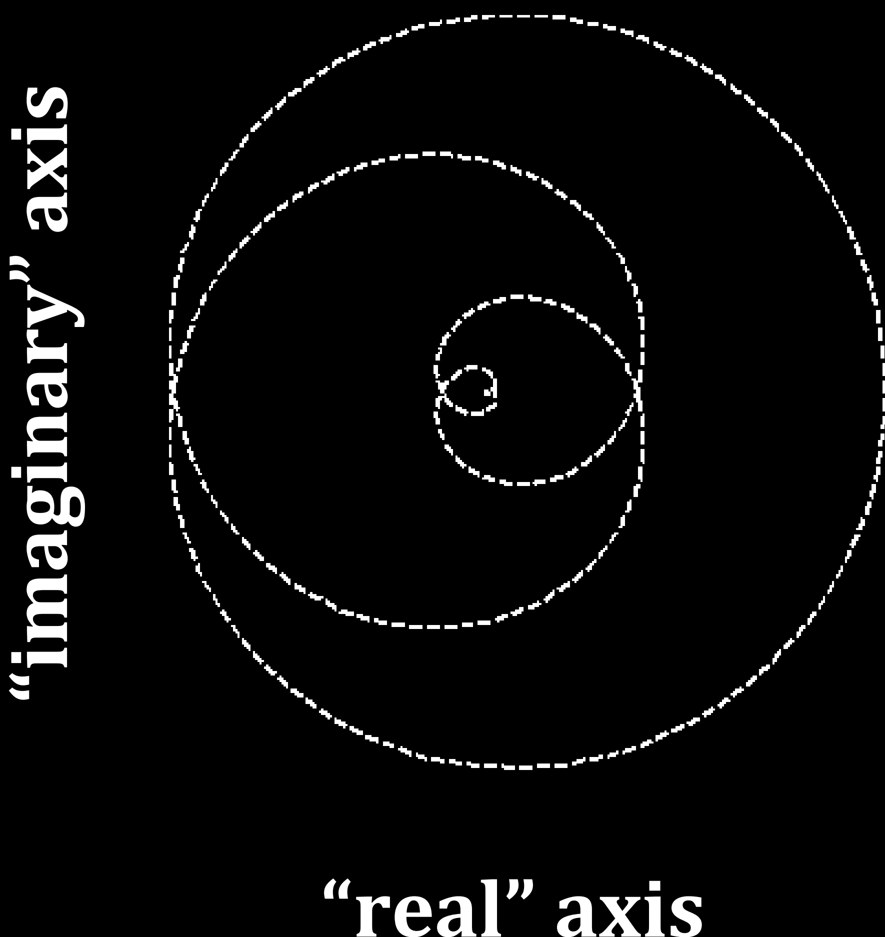
2. Different kinds of oscillation information.

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



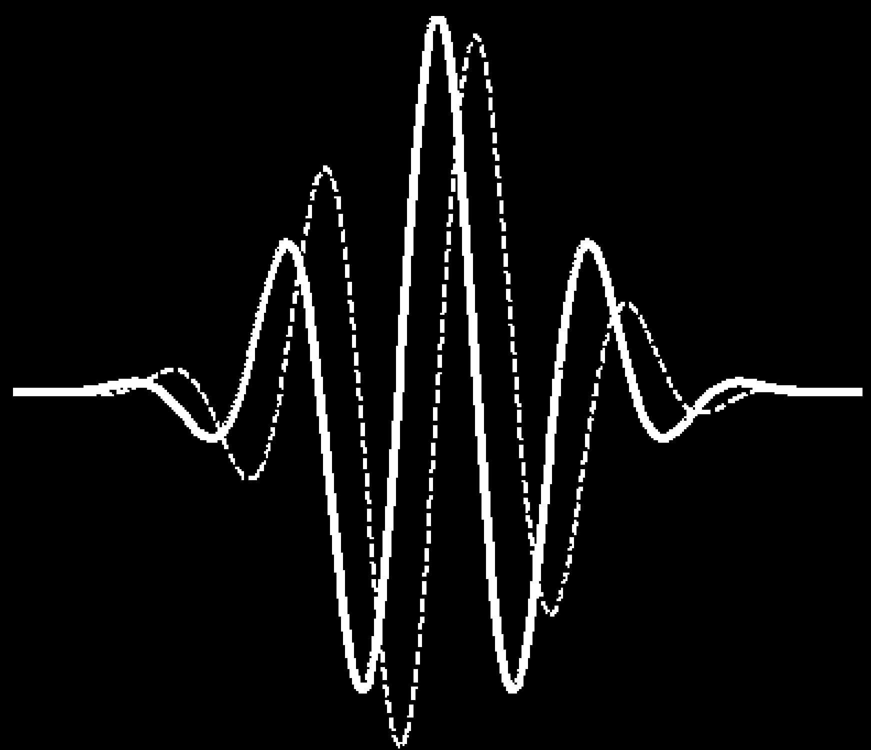
2. Different kinds of oscillation information.

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

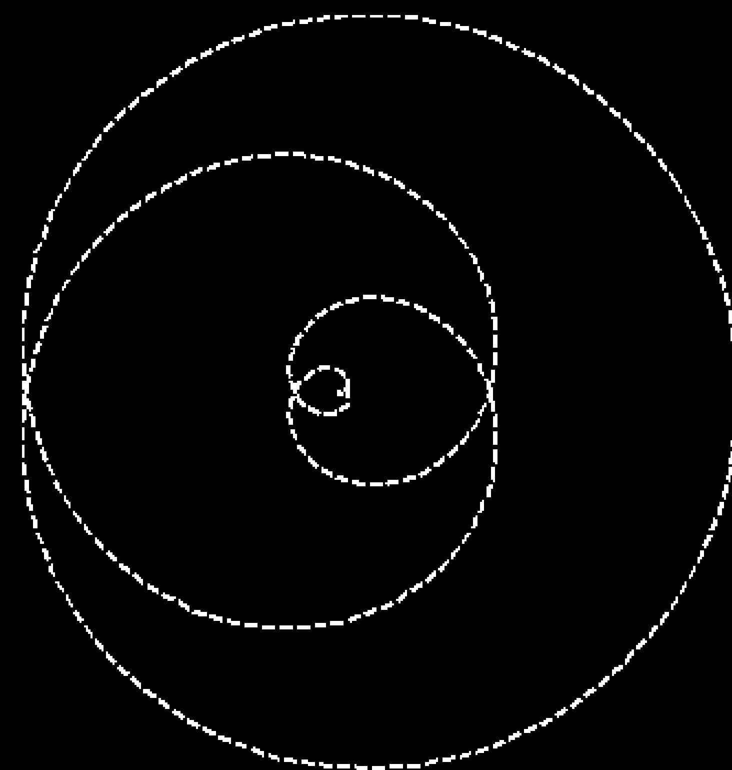


2. Different kinds of oscillation information.

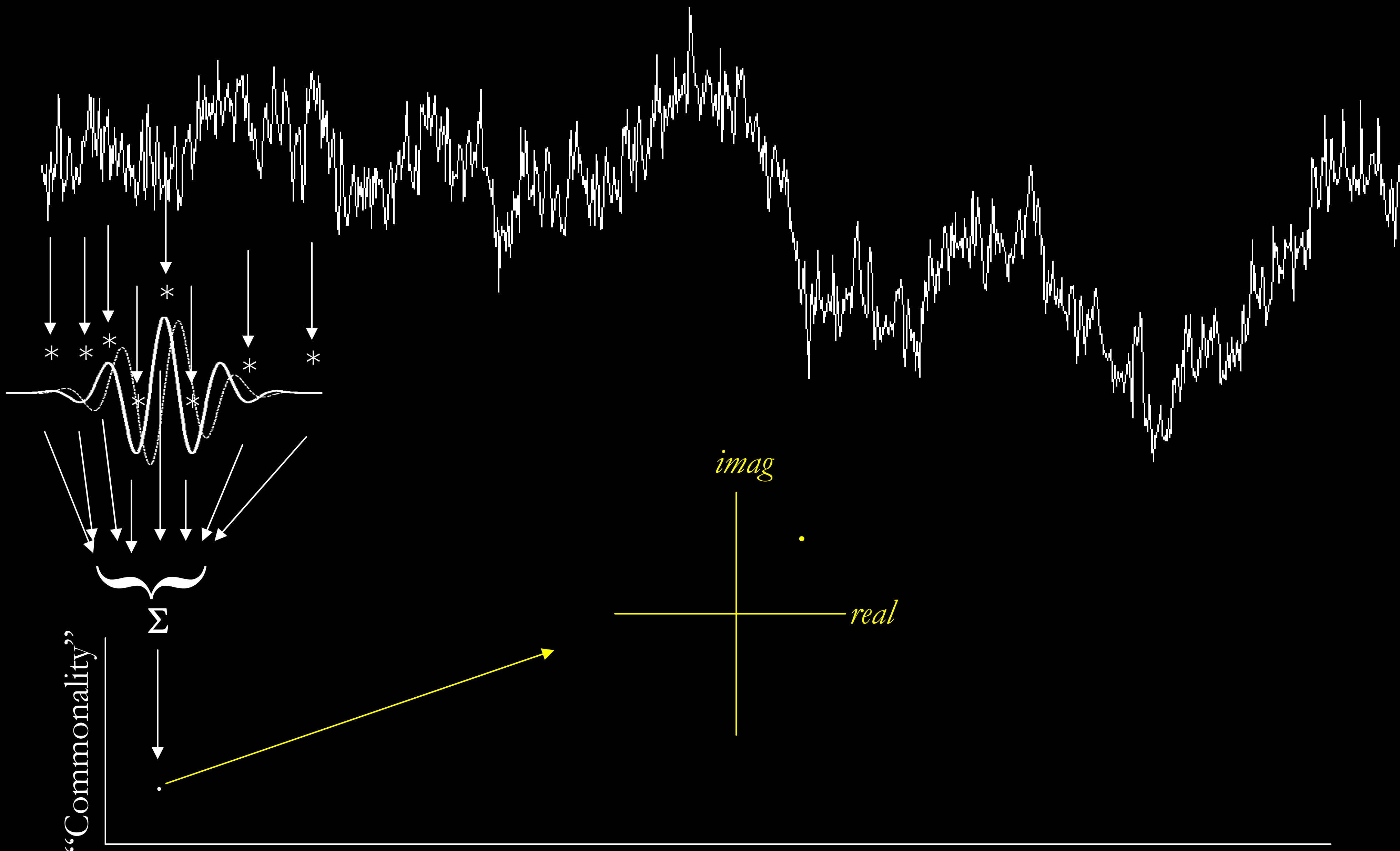
Cartesian space



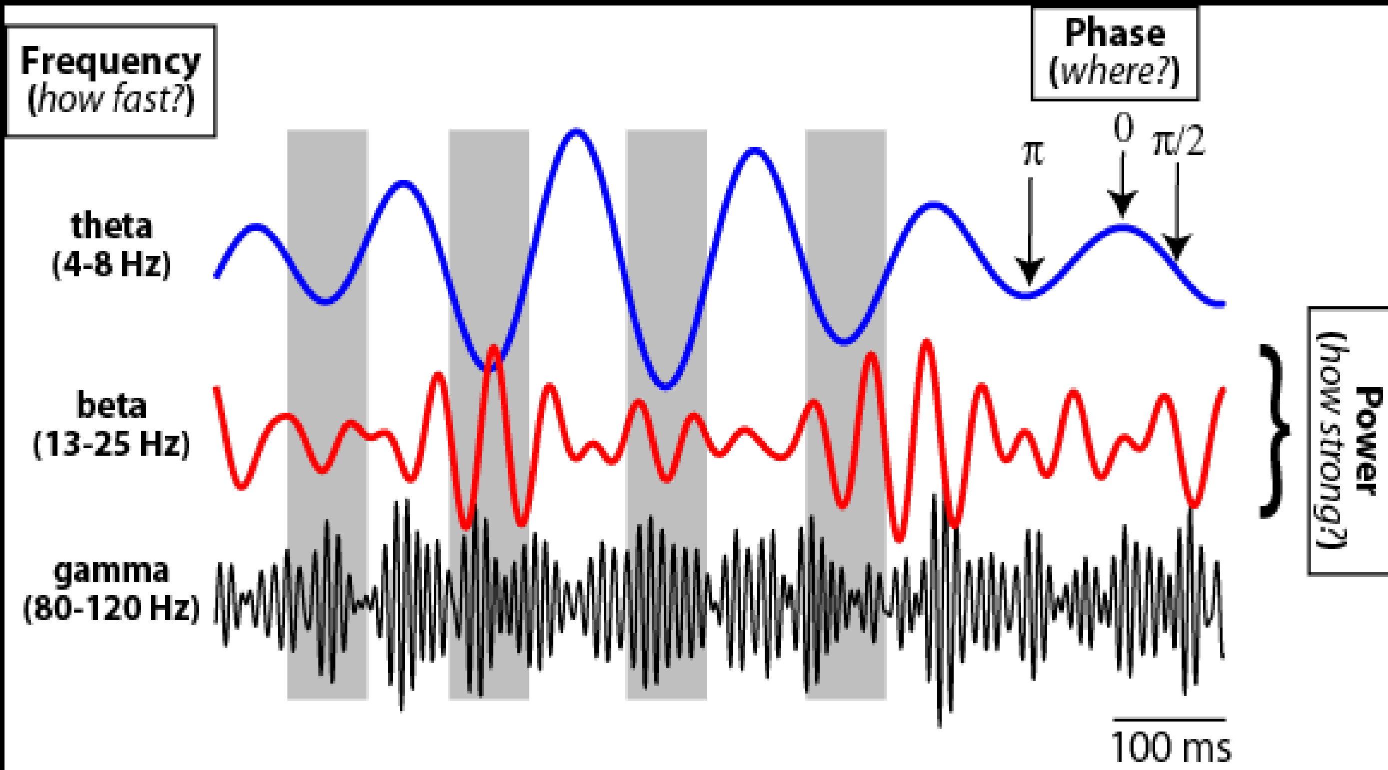
Complex space

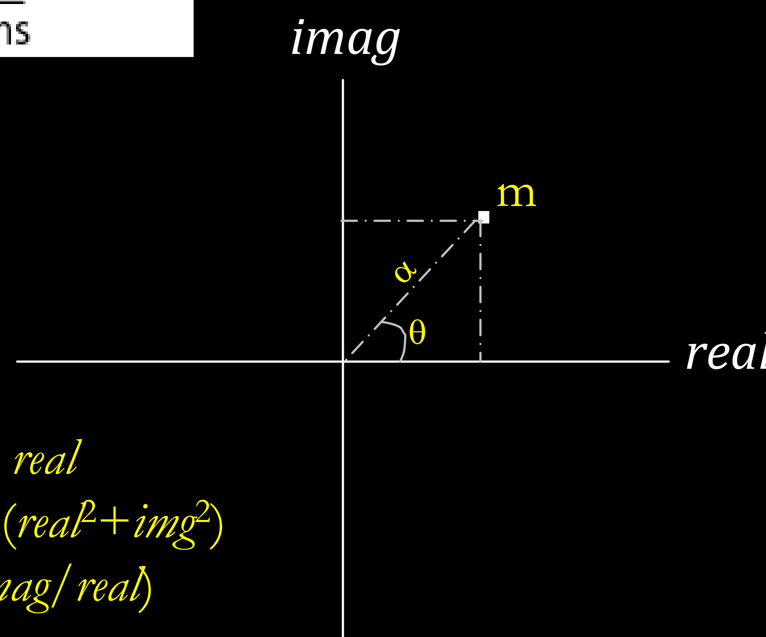


2. Ugh. It gets *more* complicated??



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





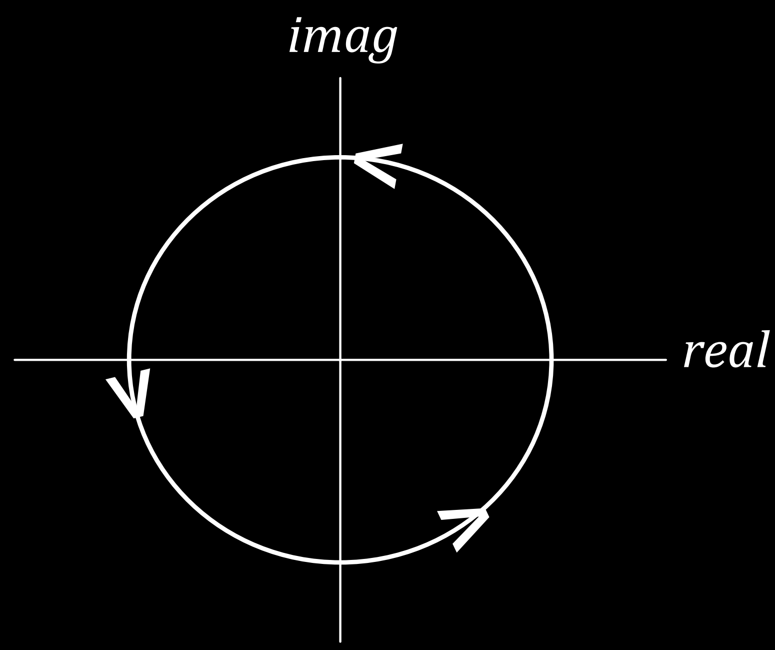
Filtered EEG = *real*

Magnitude=sqrt($real^2+img^2$)

Angle=arctan(*imag*/ *real*)

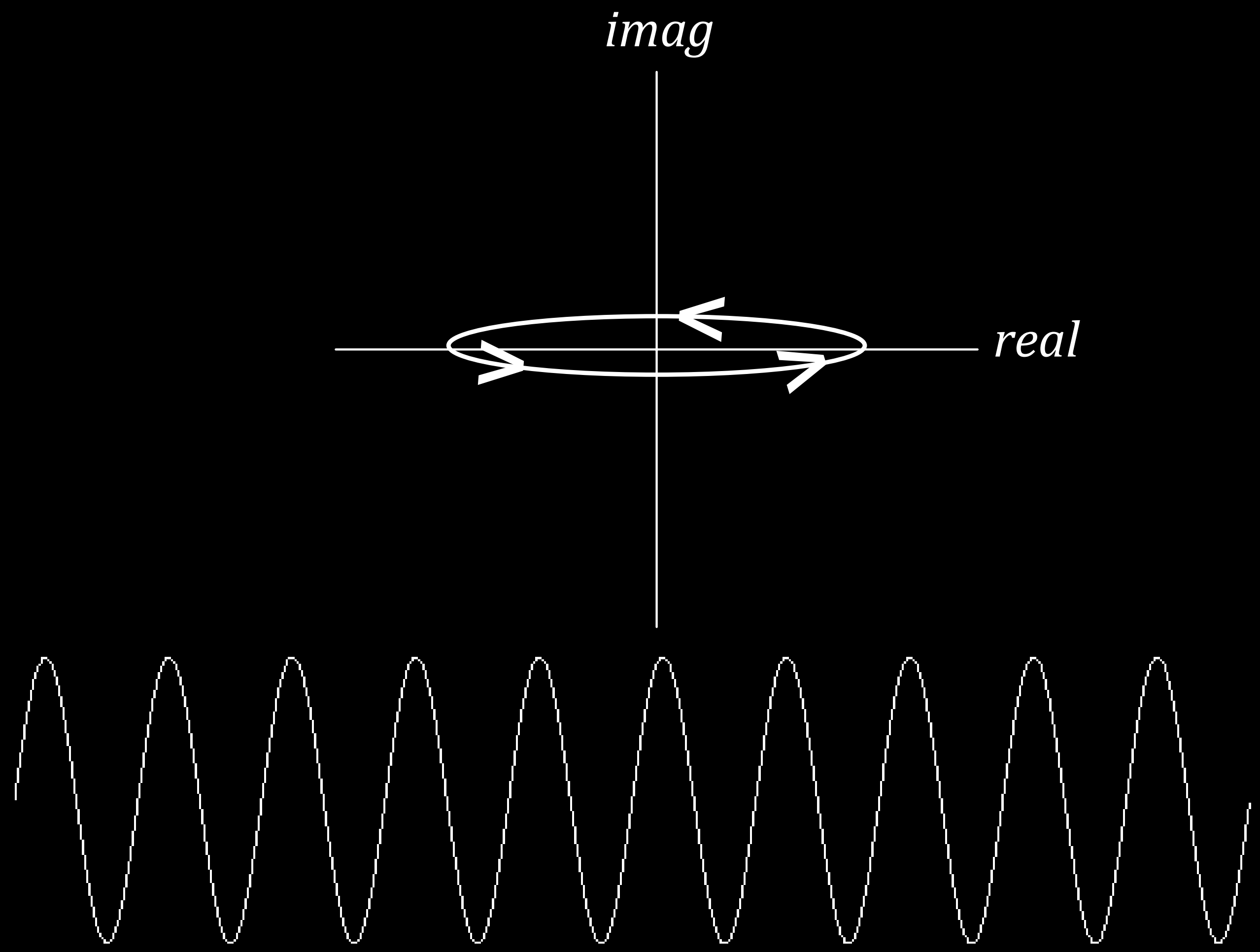
2. An aside on why oscillations *oscillate*.

Consider a Sisyphisian process.

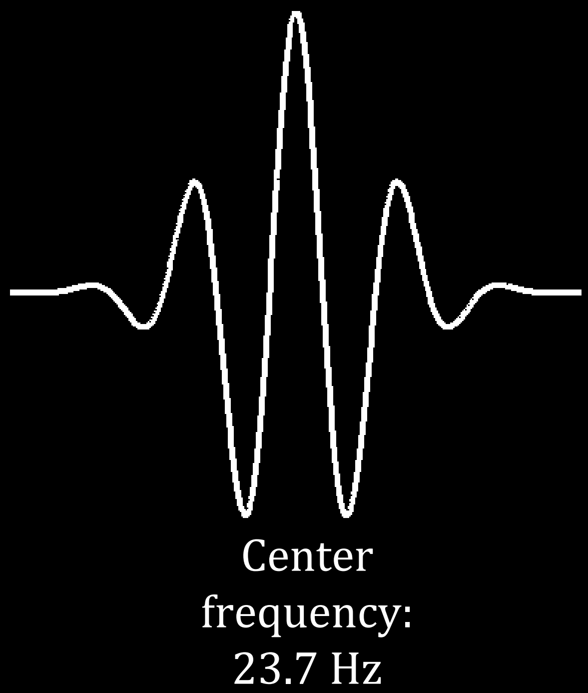


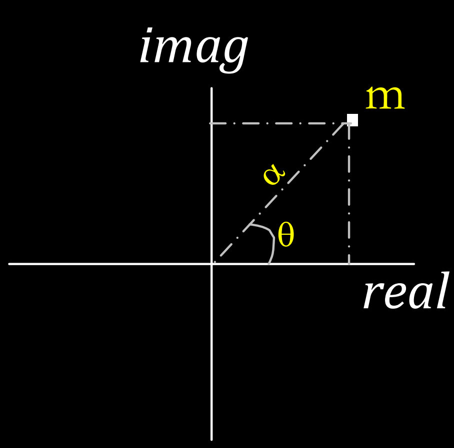
2. An aside on why oscillations *oscillate*.

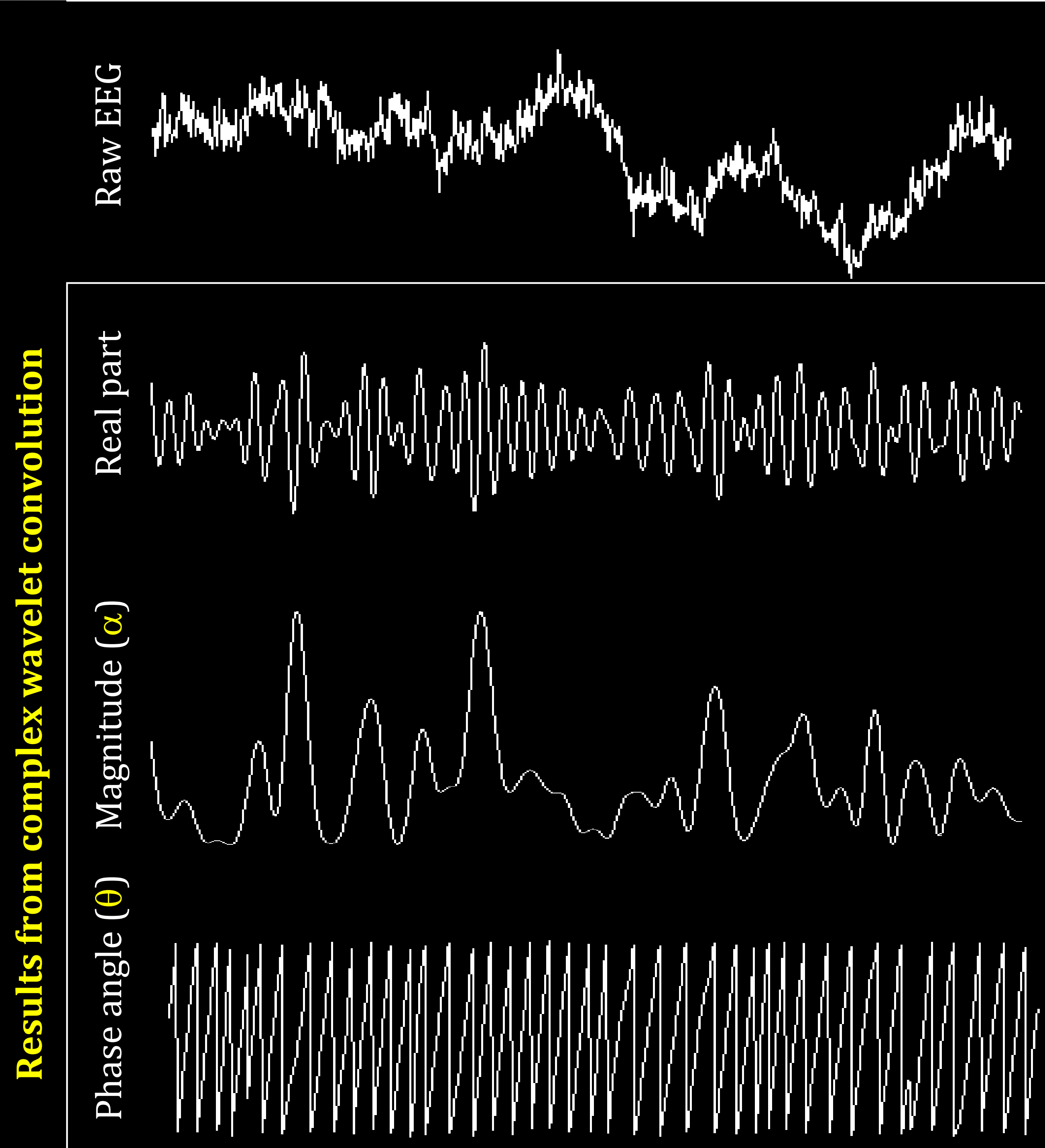
Now consider viewing this process as an adult (i.e., no imaginary component).



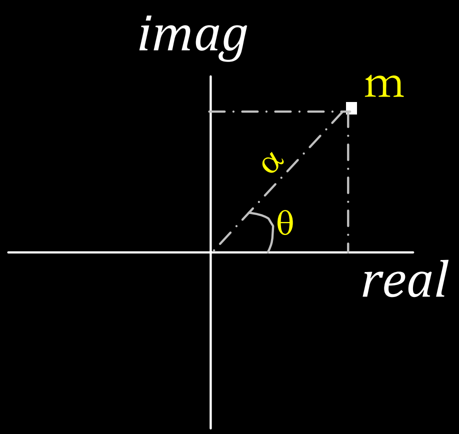
2. Different kinds of oscillation information.

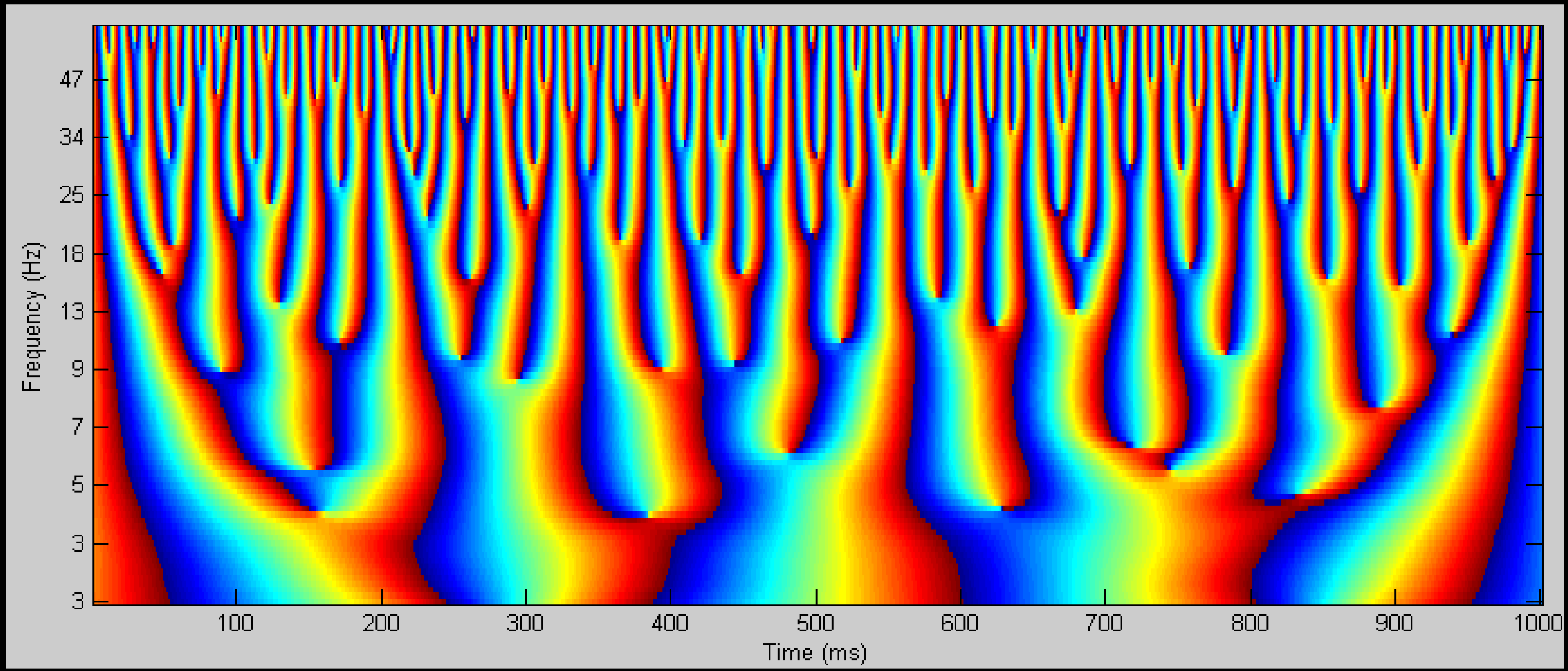


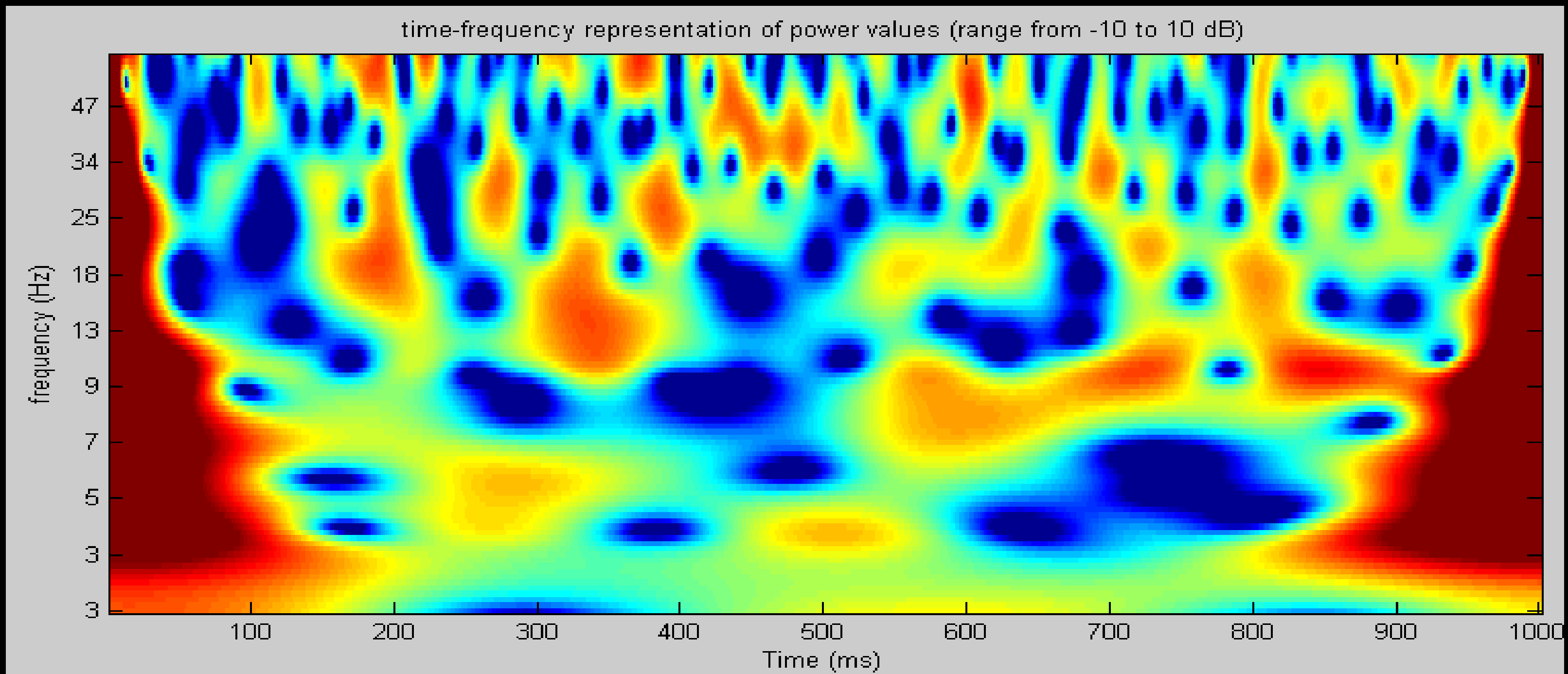




2. Different kinds of oscillation information.







2. Where do wavelets come from?

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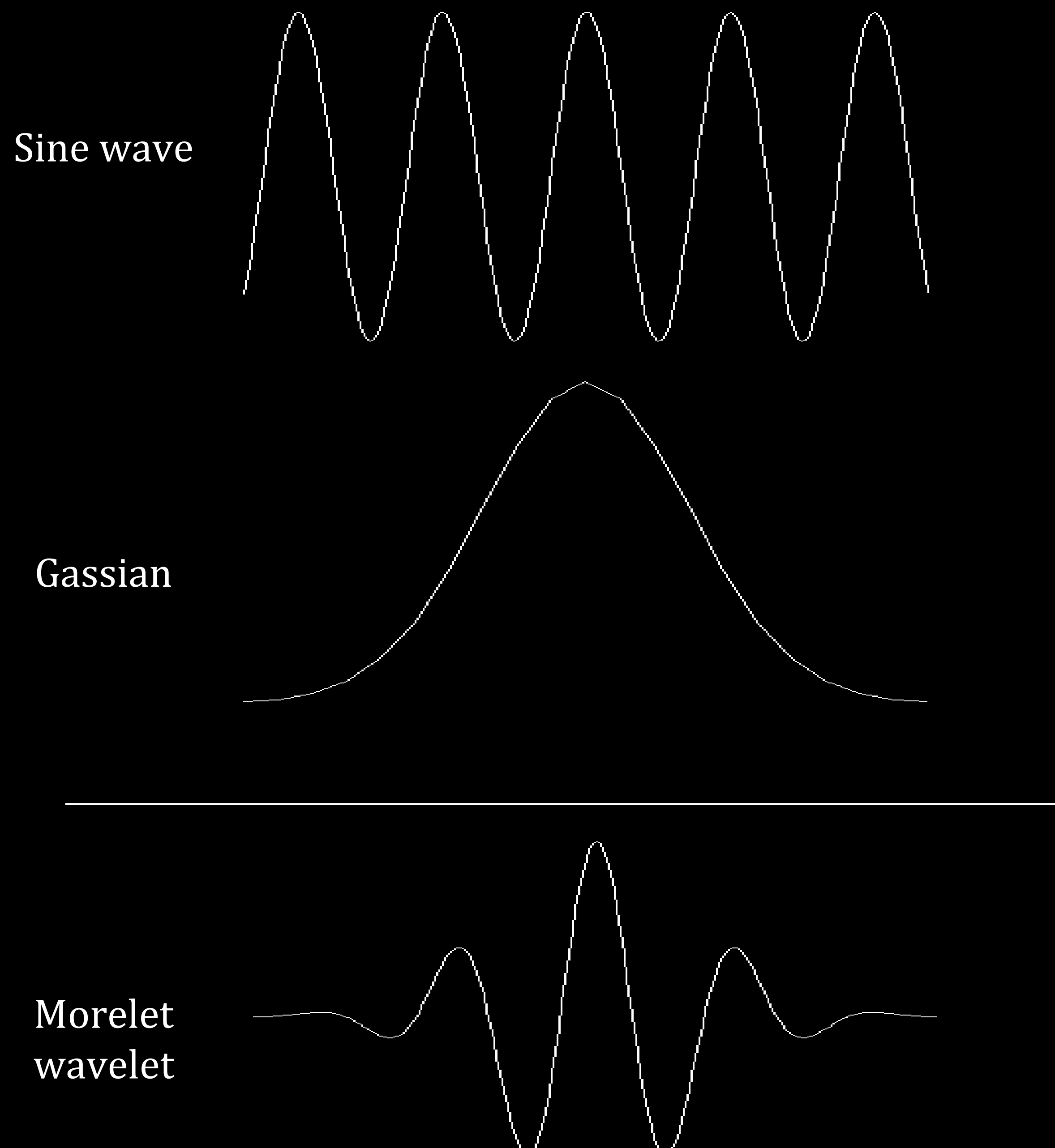
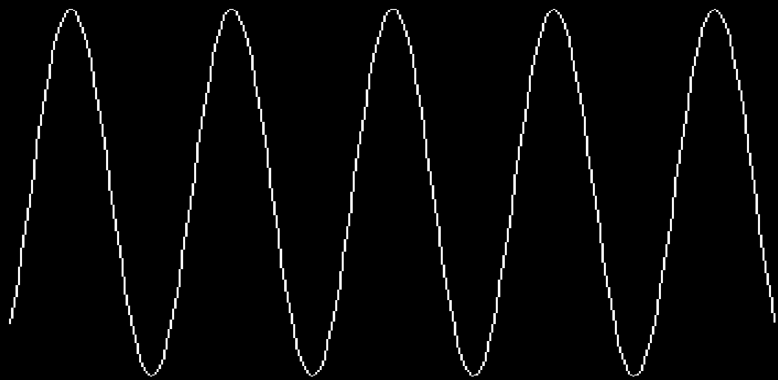
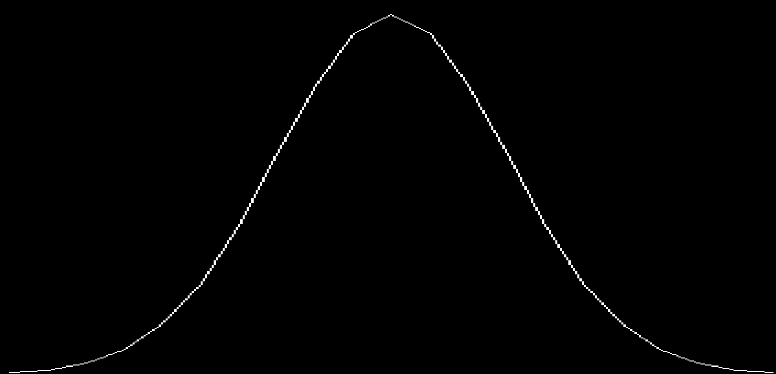


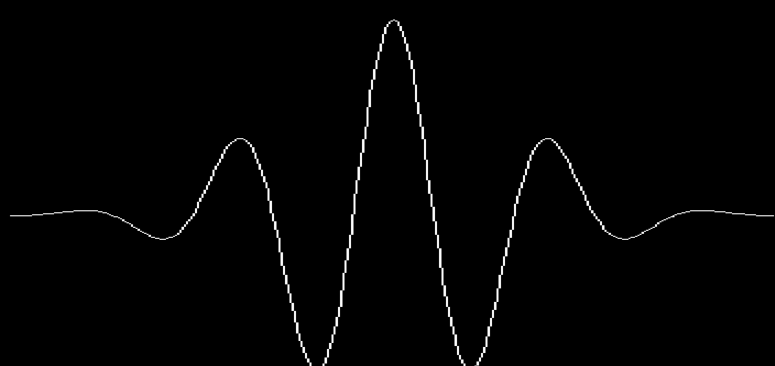
2. Wavelet origins: The math behind the magic



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



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

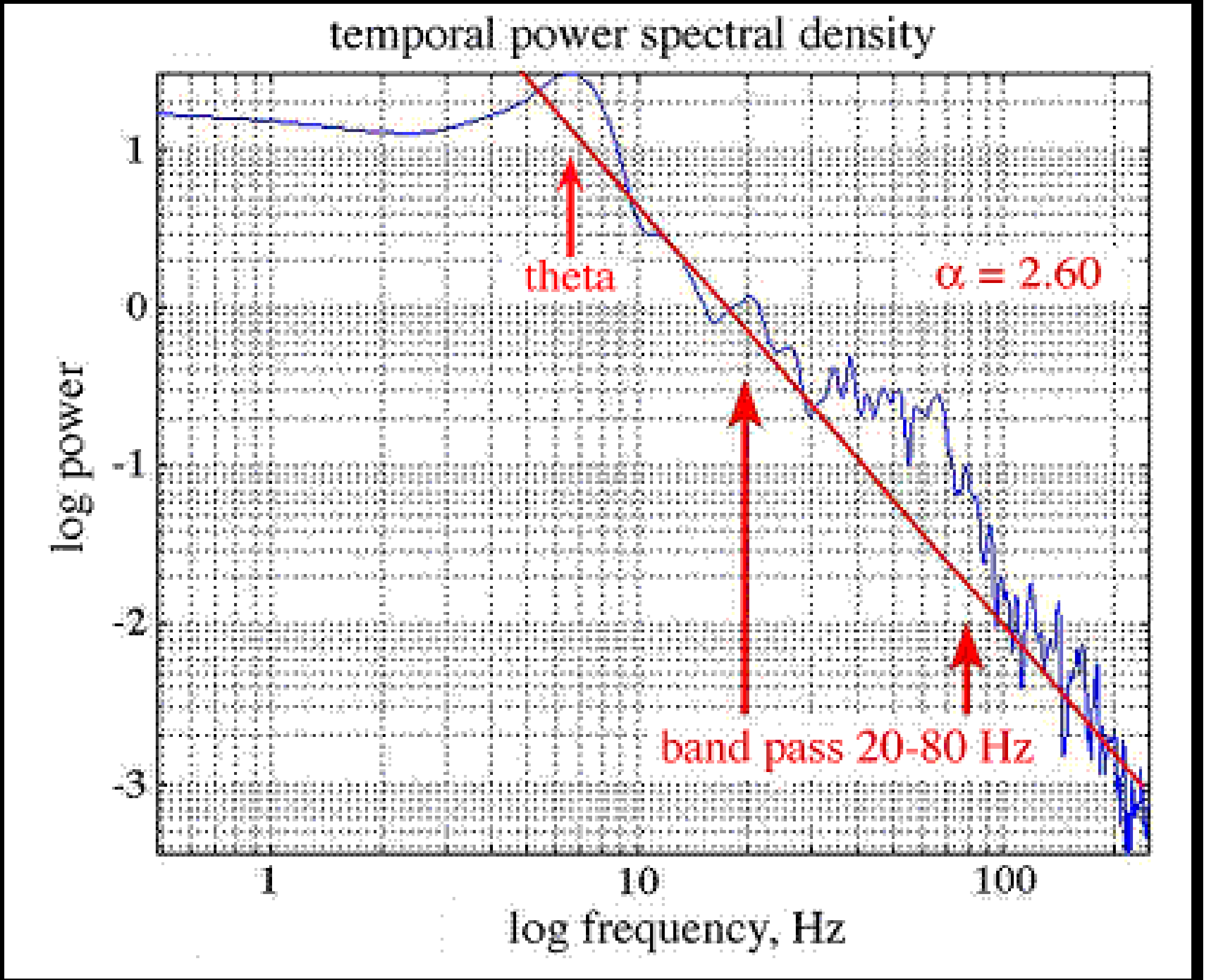


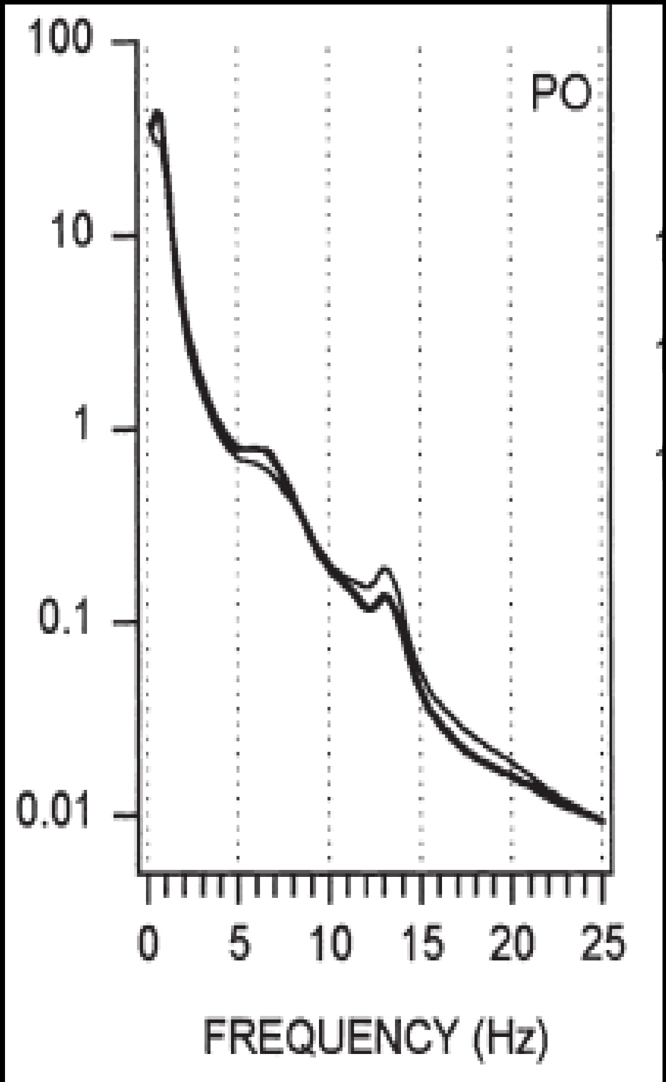
```
> sin(2*pi*freq*time)./
  exp(-time2/(2*s2));
```

2. Power normalization and the power law

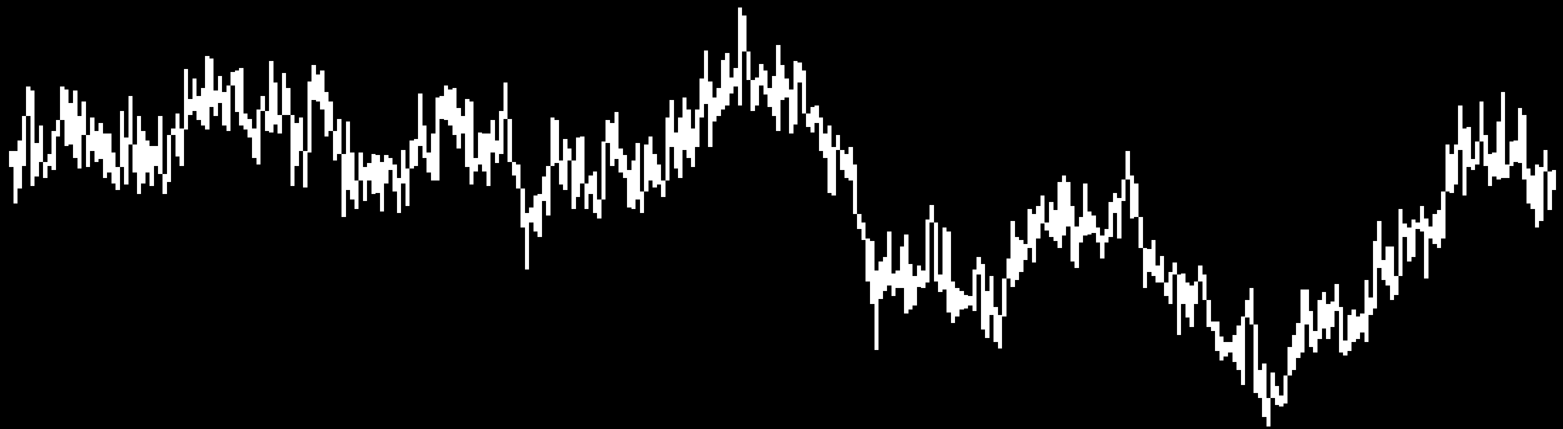
2. Power normalization and the power law

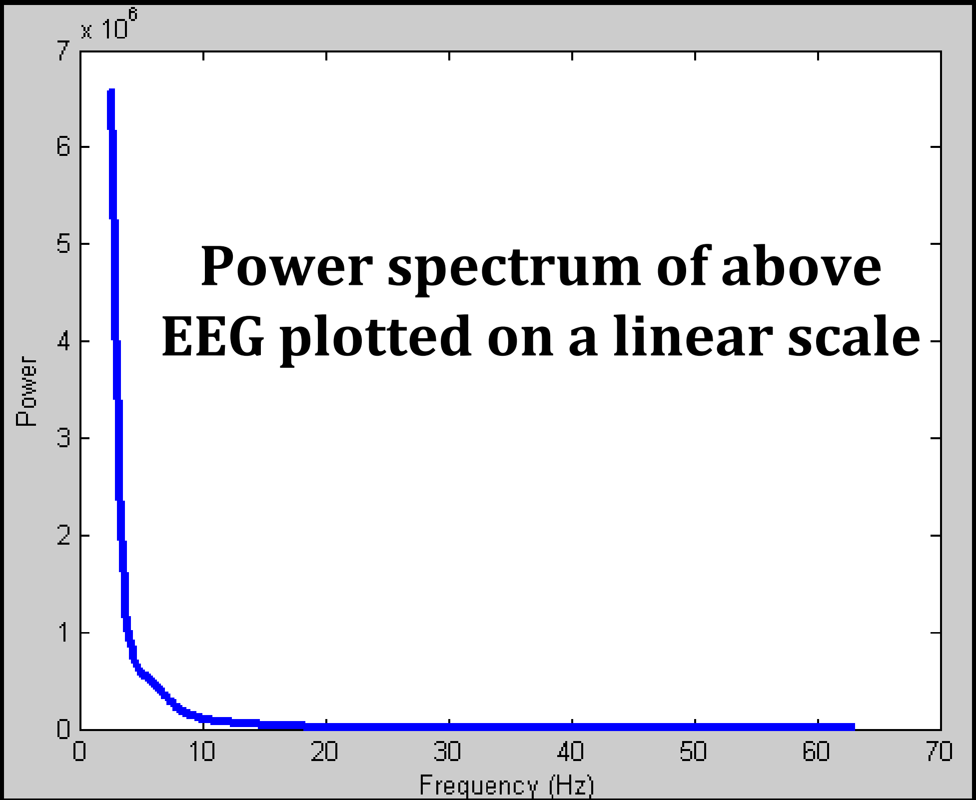
The power law: Power decreases with increasing frequency (at low frequencies, power approaches a 1/f function).

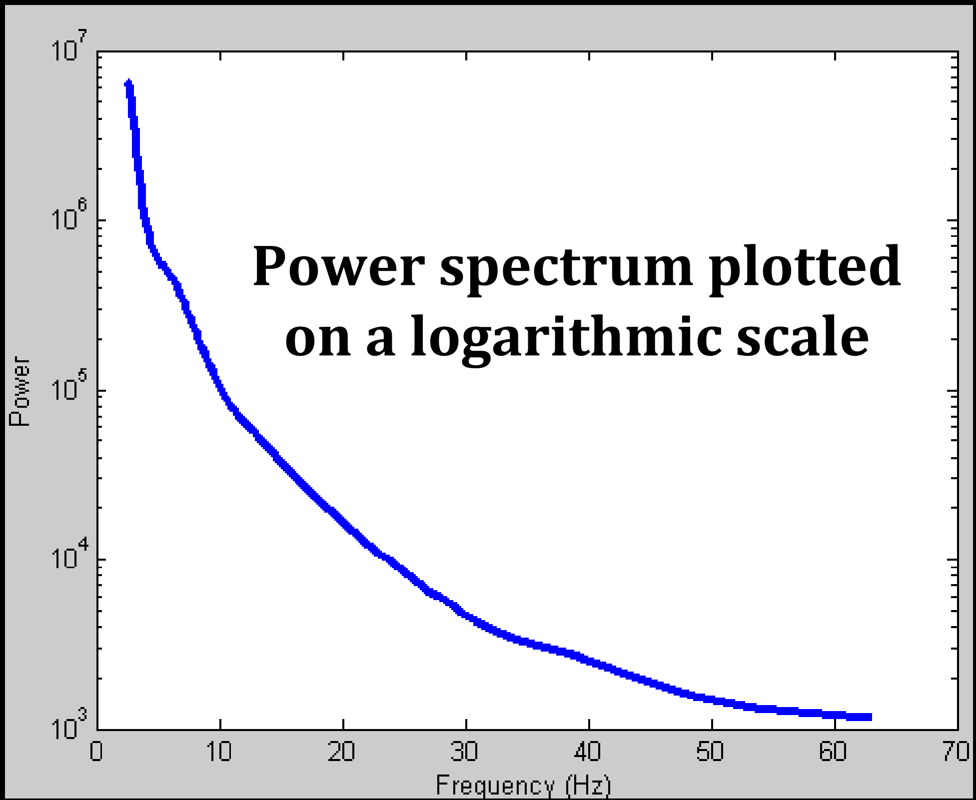




2. Power Law in da house!



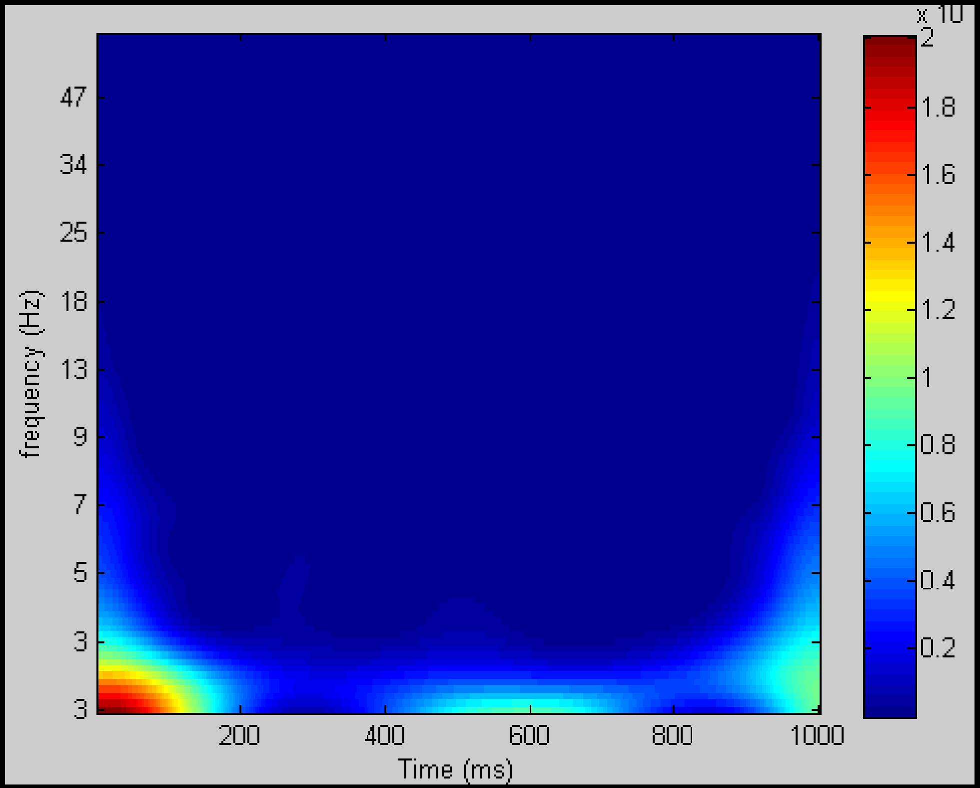




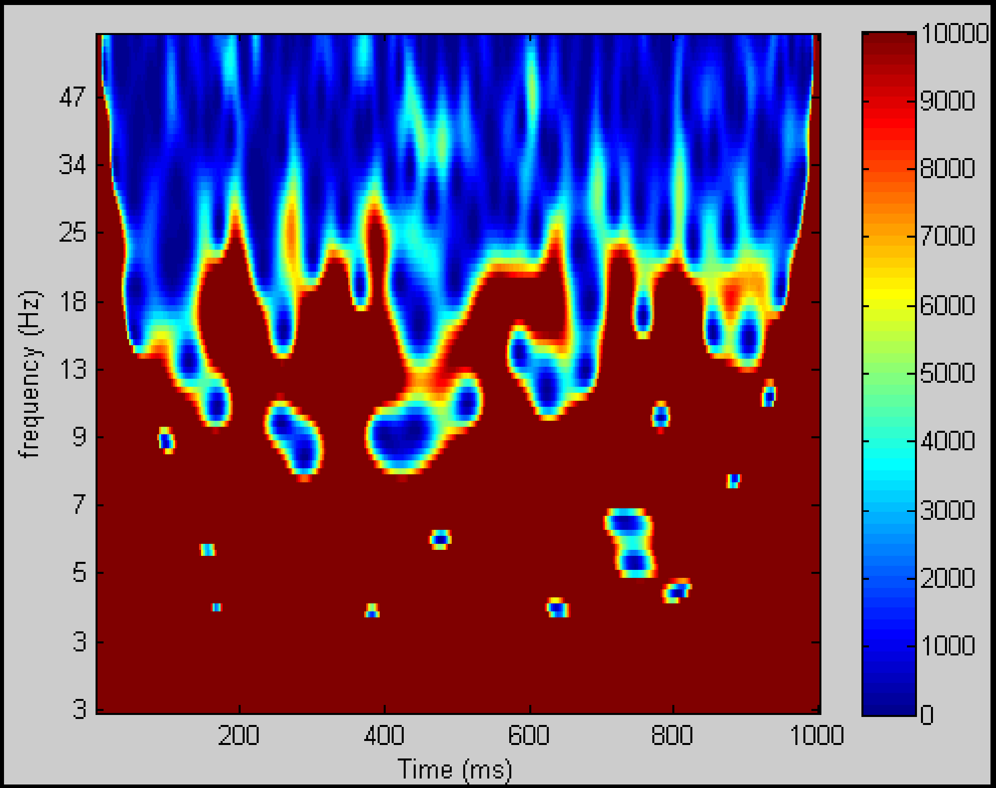
2. Power normalization and the power law

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



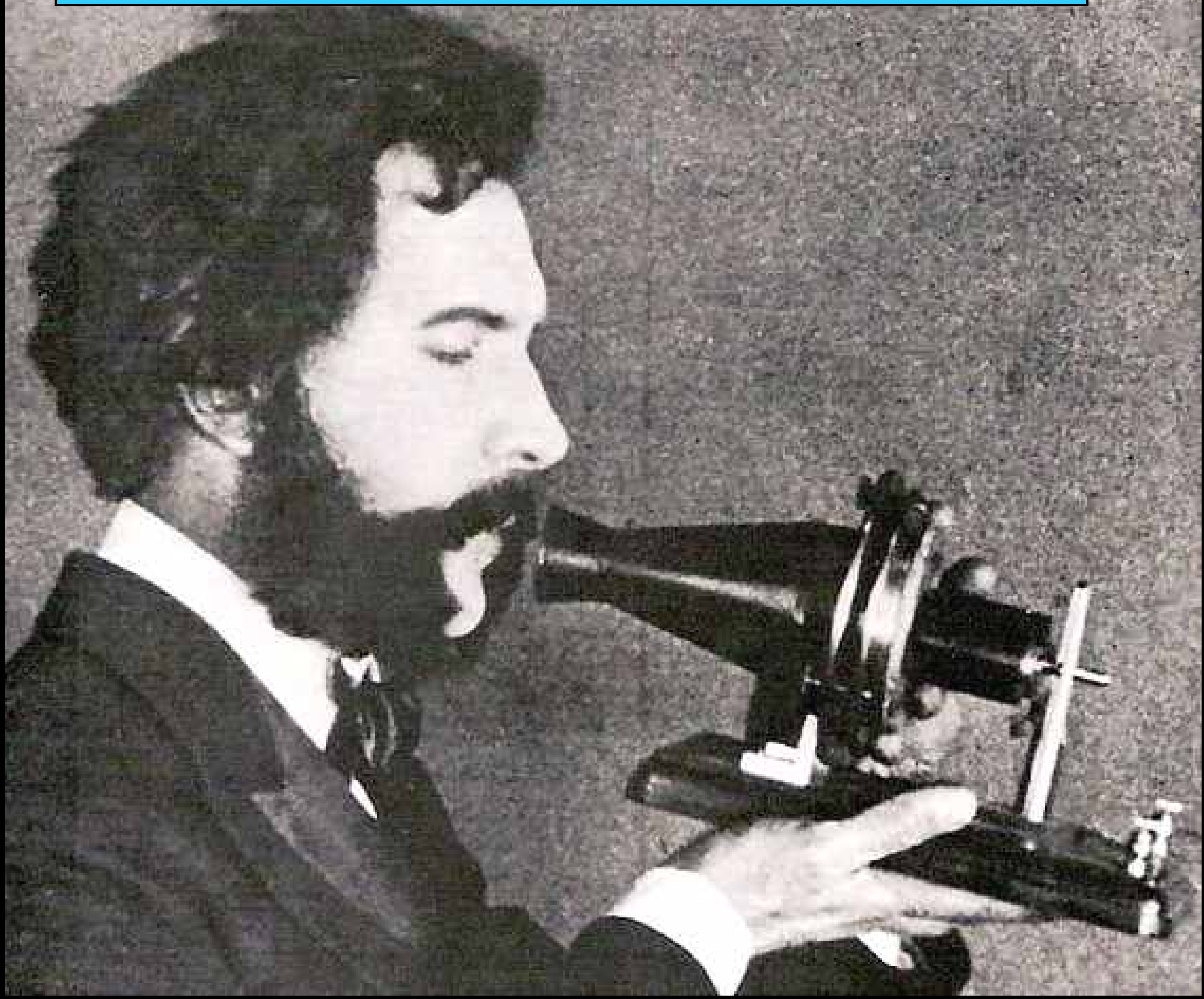
2. Power normalization and the power law

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:

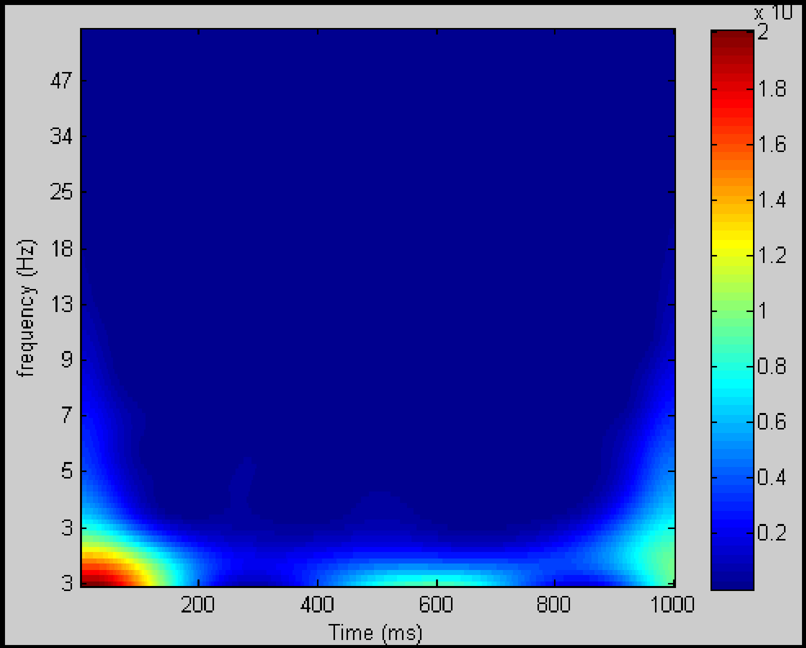
dB = 10*log10(baseline/activity)

Or:

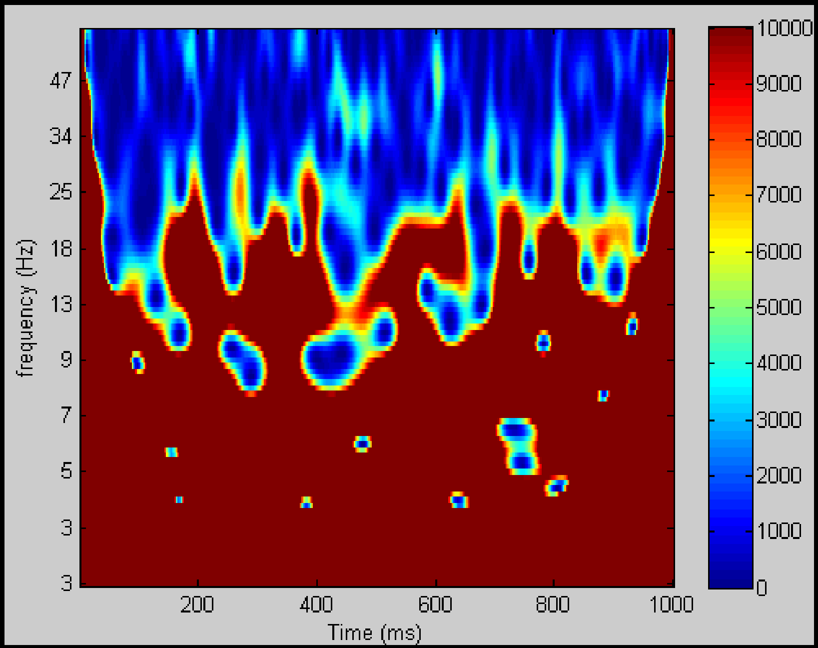
dB = 10*(log10(baseline) – log10(activity))

2. Power normalization and the power law

Low frequency colorscale

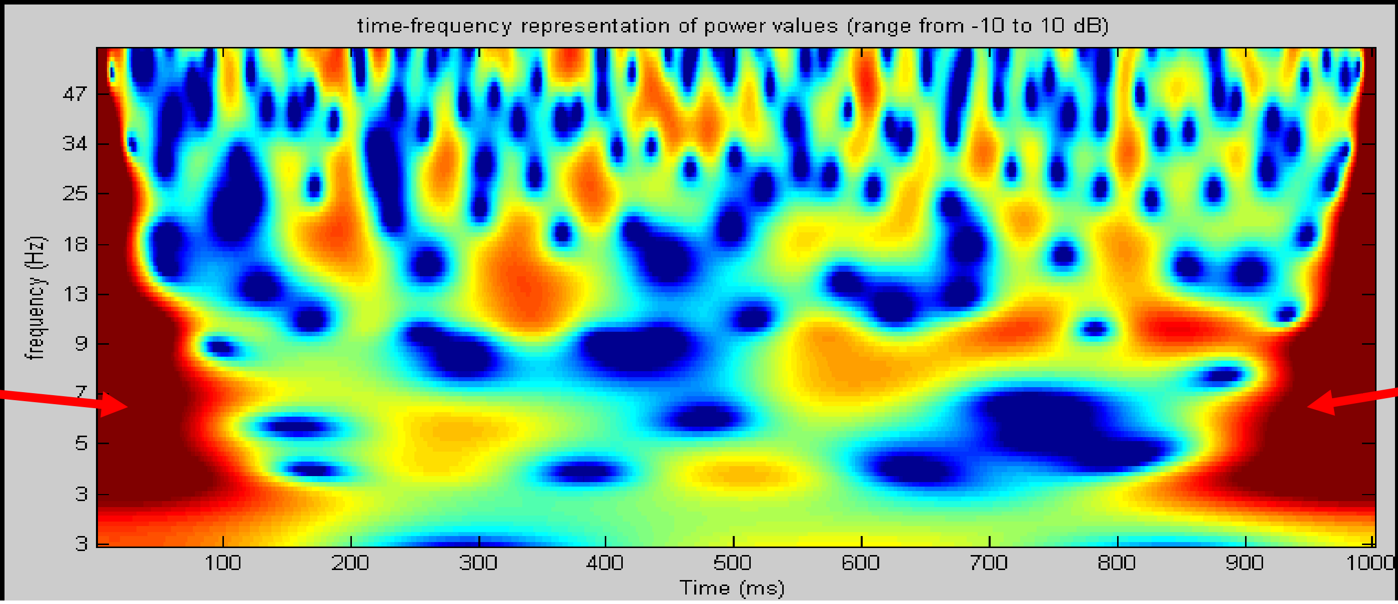


High frequency colorscale



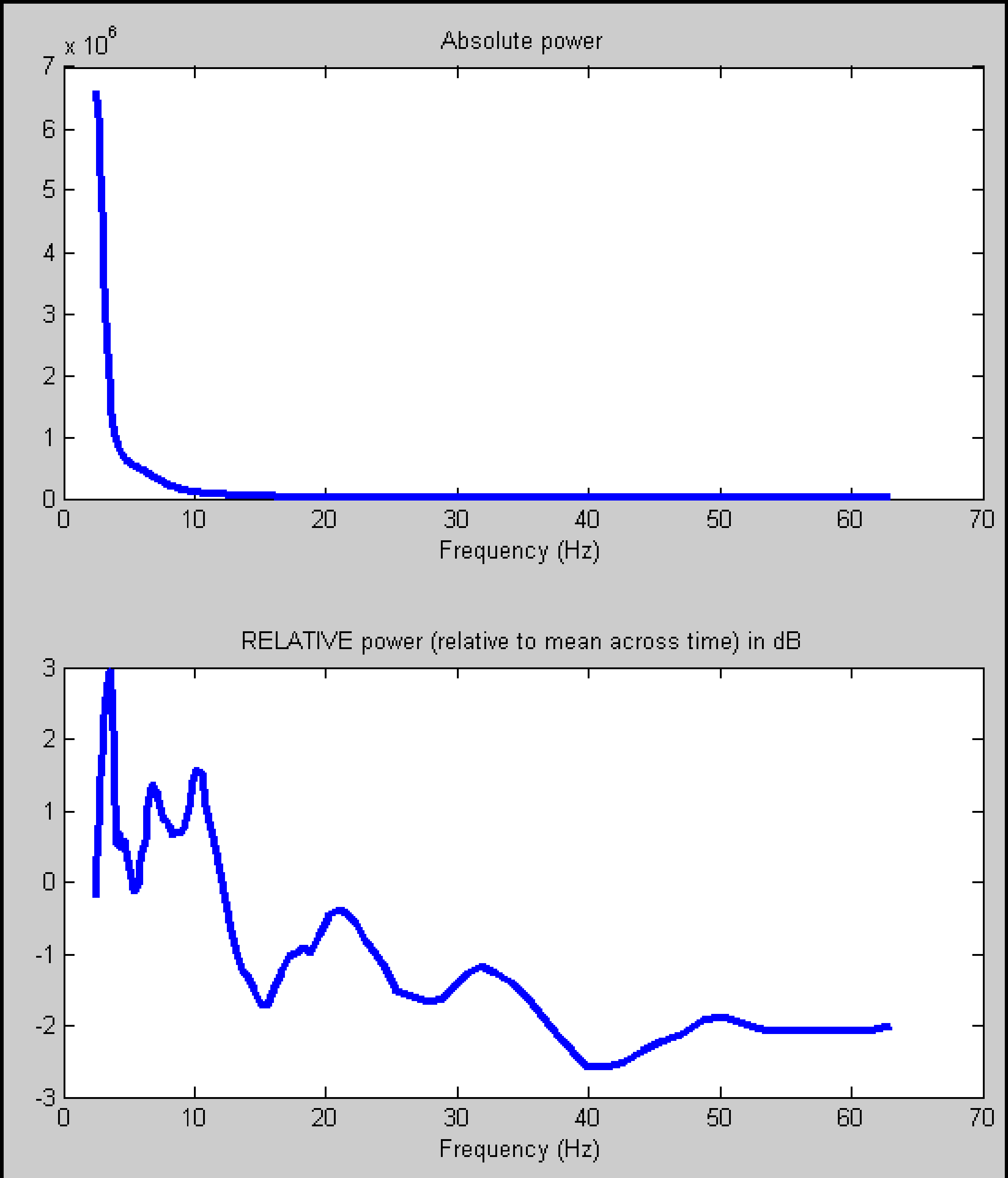
dB scaled!

Edge artifacts!!!



Edge artifacts!!!

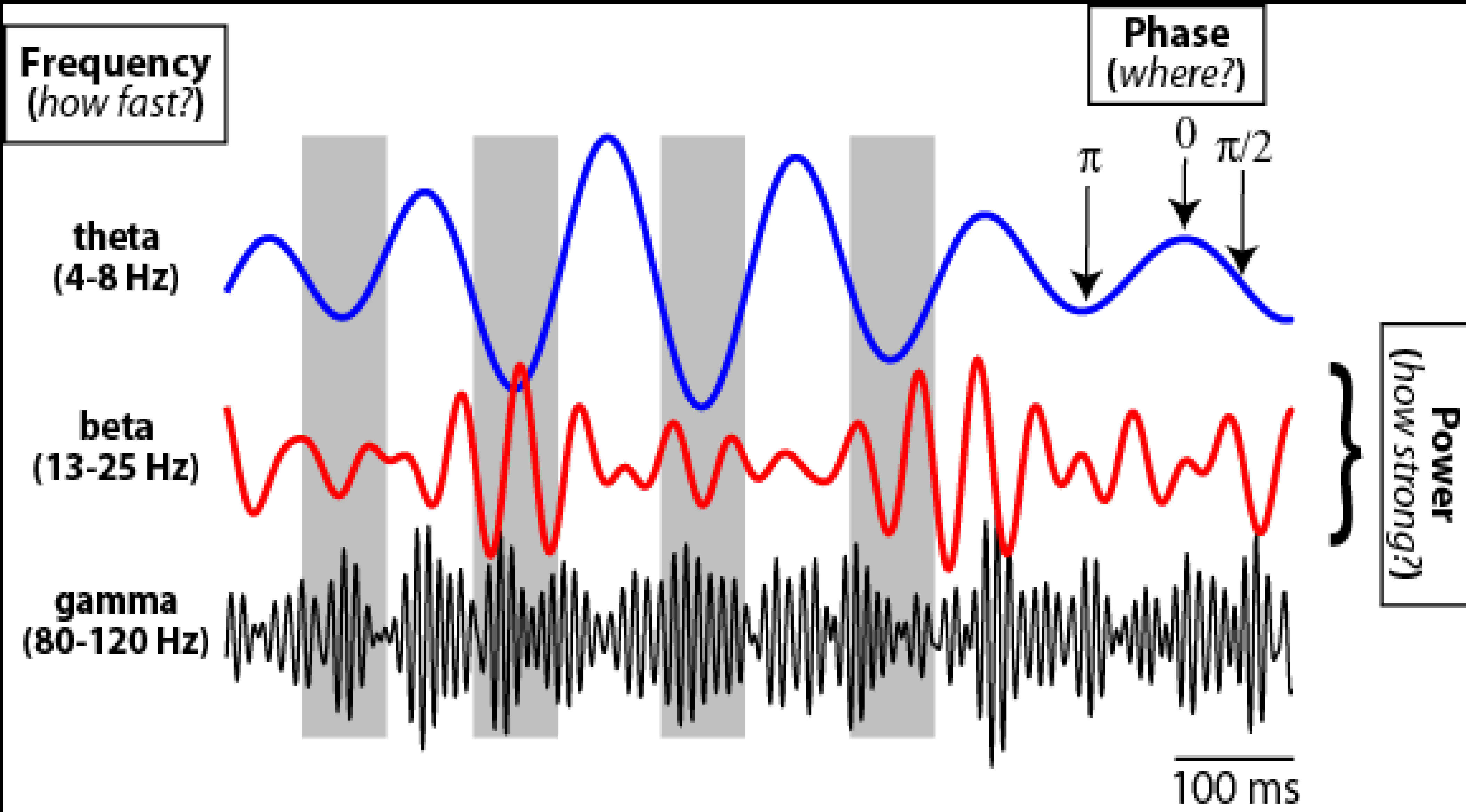
2. Power normalization and the power law



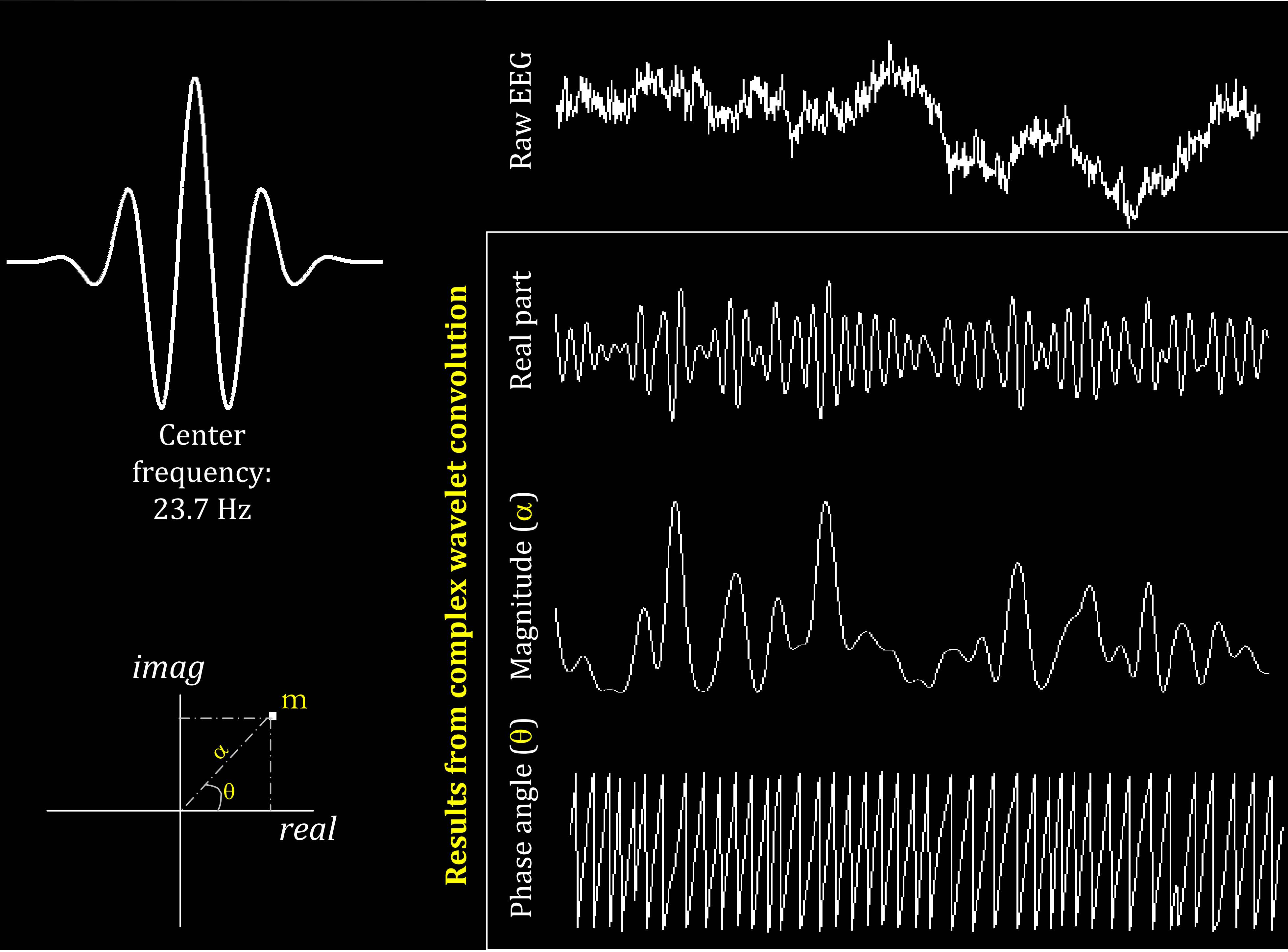
Note that these two plots come from the same EEG data!

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.



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

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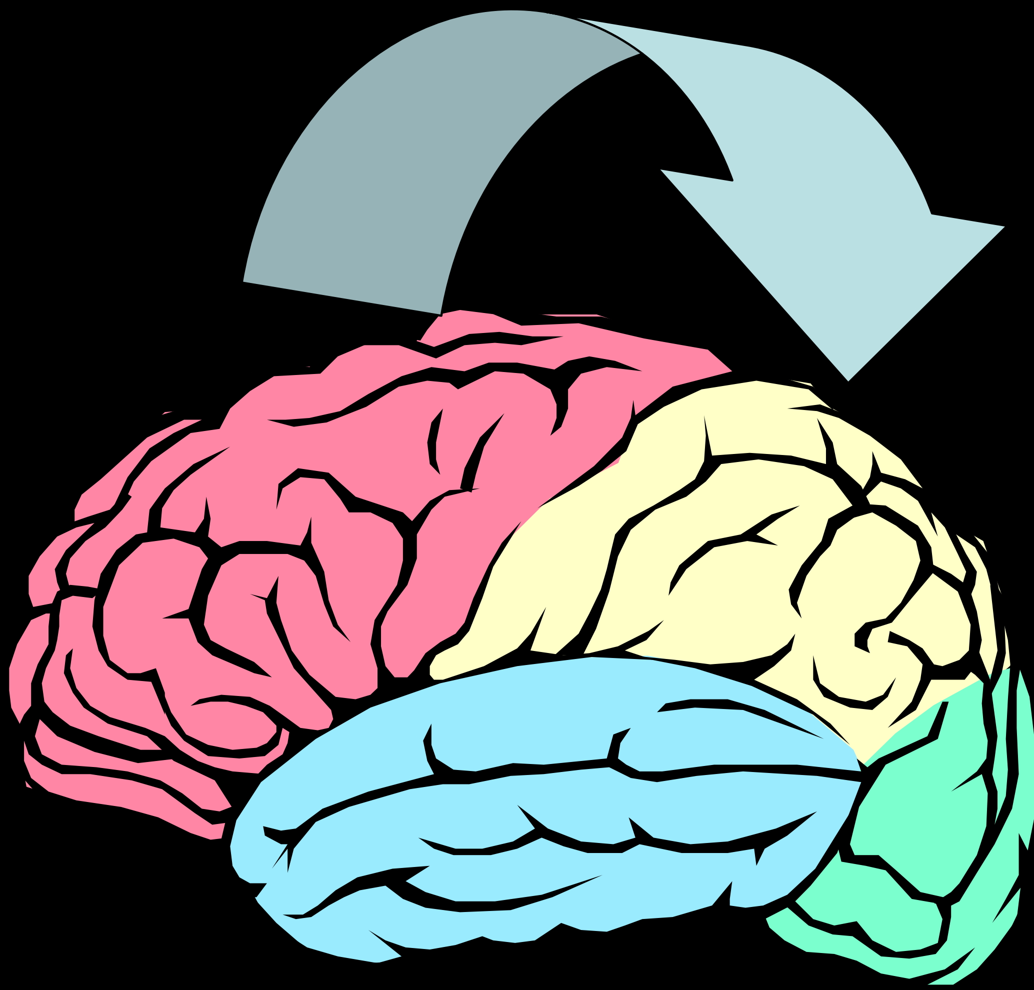
4. Understand what cross-frequency coupling is, different ways to measure it, and how to interpret results.
5. (optional) Renounce ERPs forever!!

2. How do brain regions "talk" to each other?

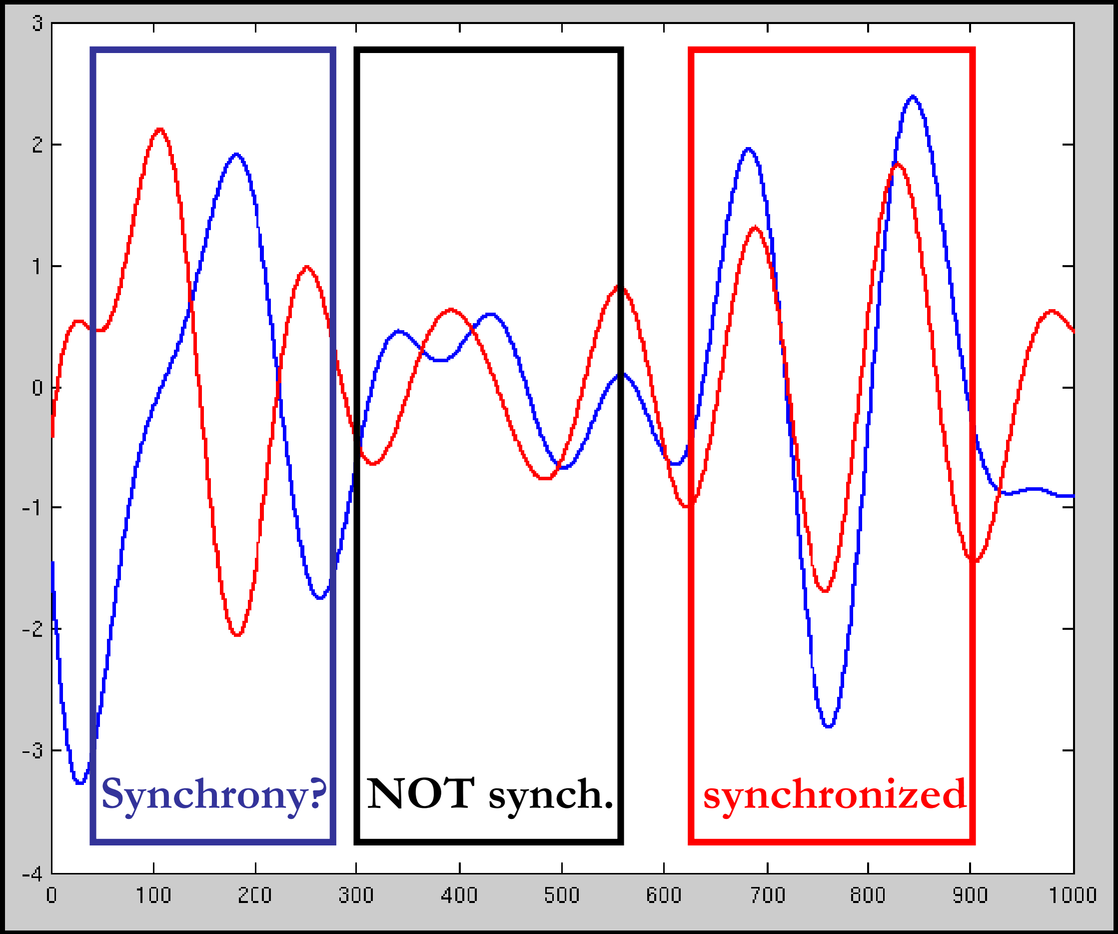


Perhaps through synchronized oscillations!

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

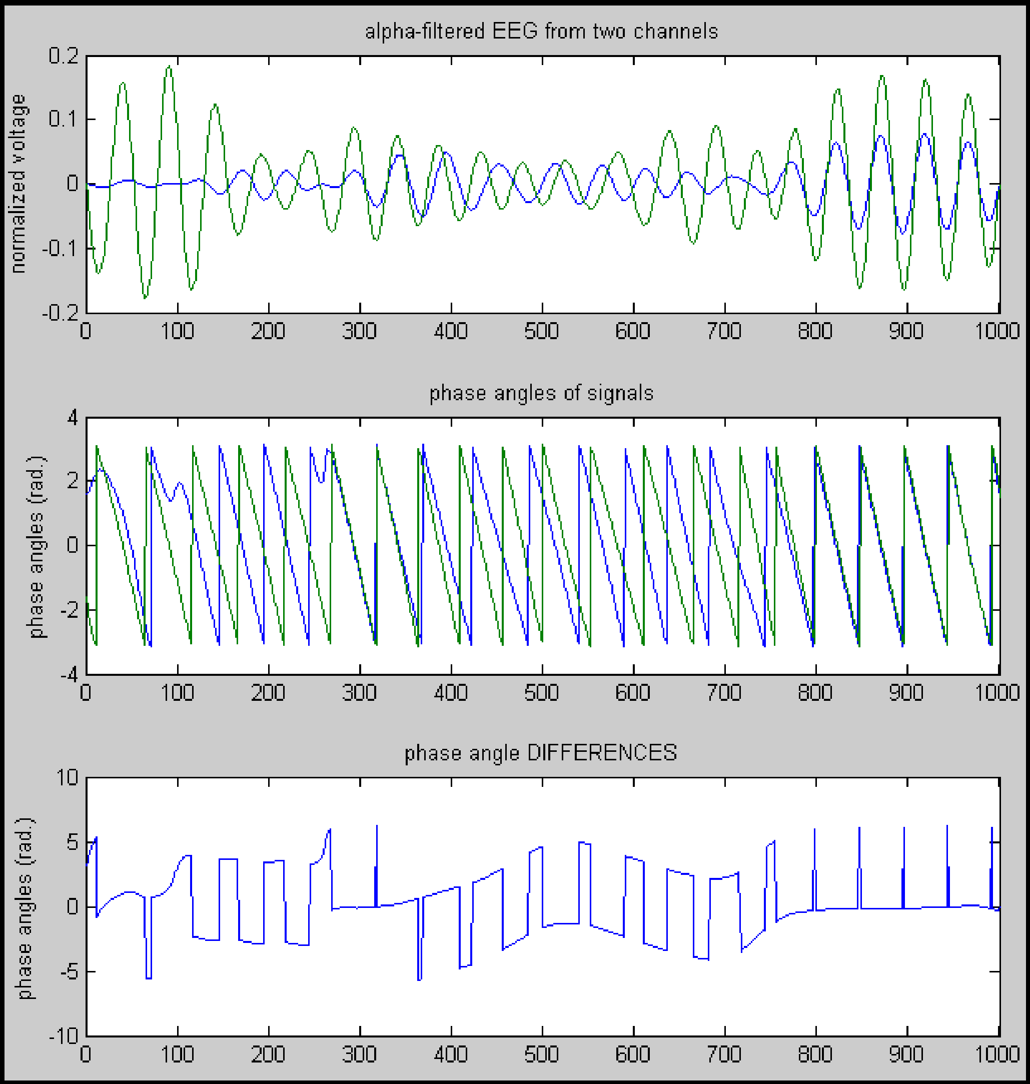
2. How do brain regions “talk” to each other?

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

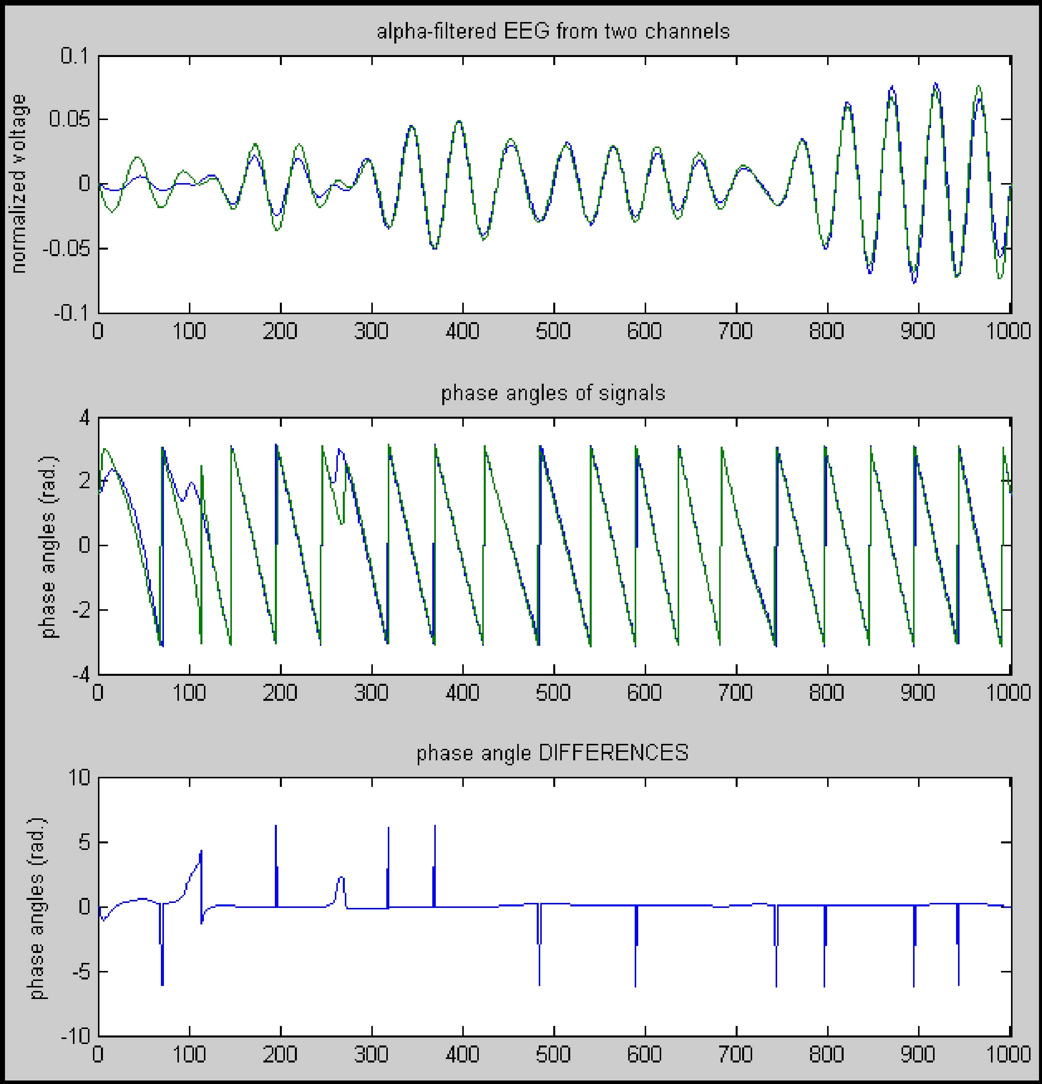


2. Inter-site phase coherence.

Electrodes: Fp1 & C4

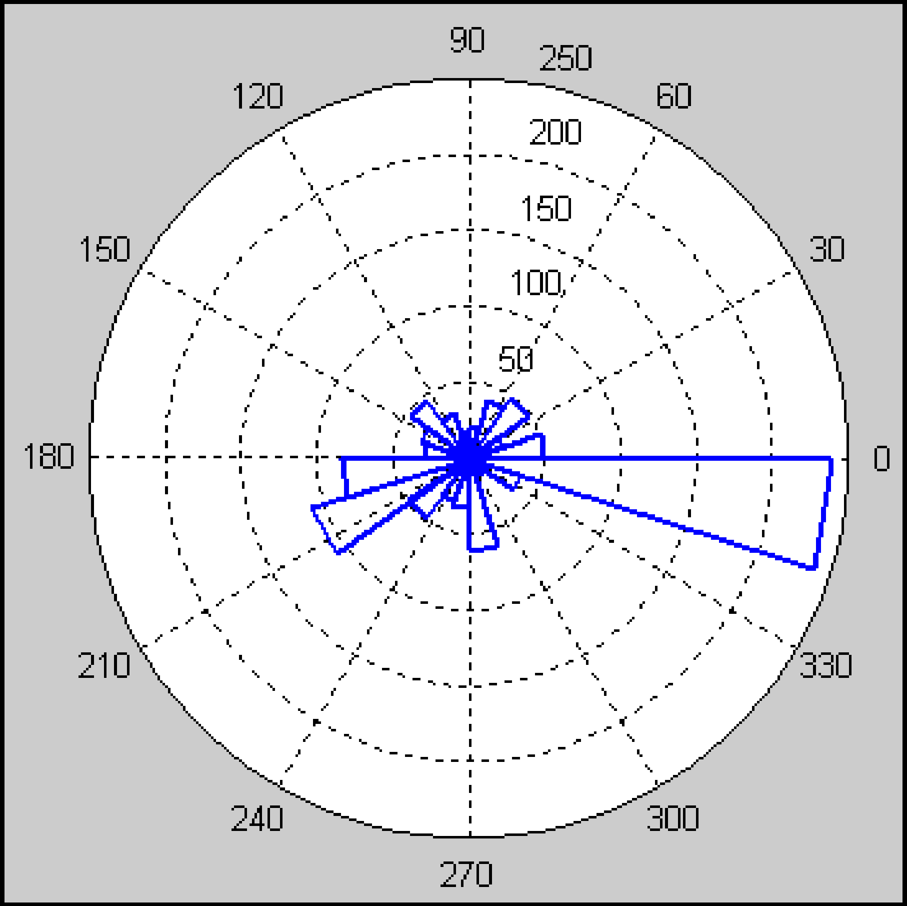


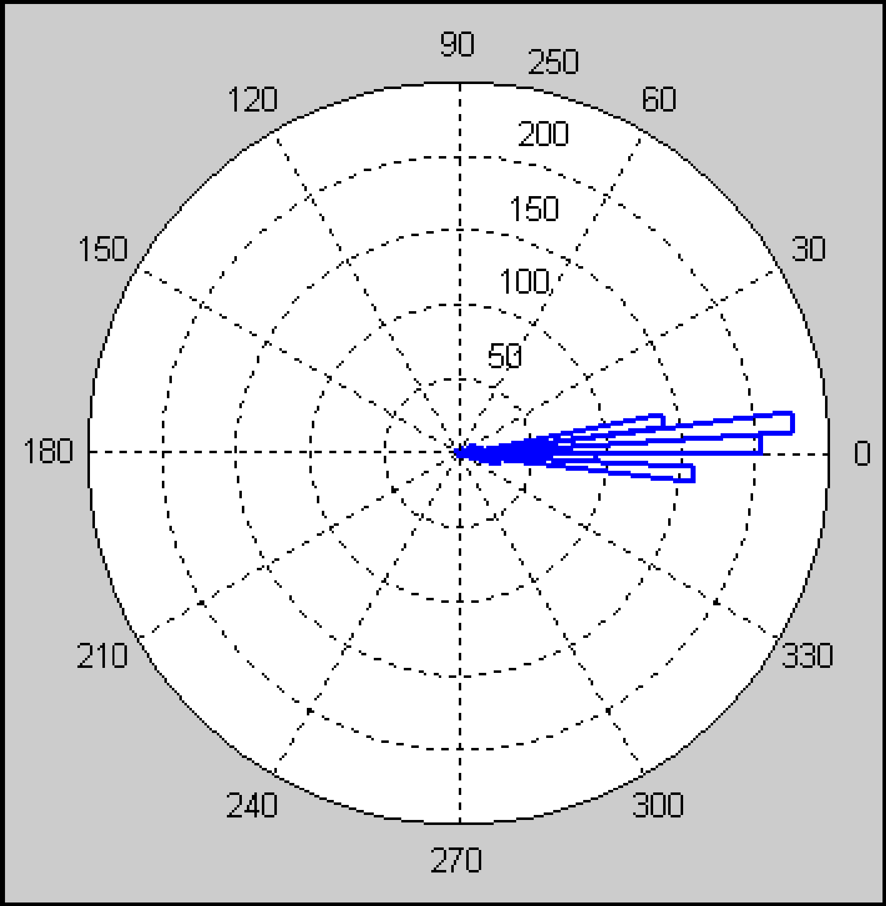
Electrodes: Fp1 & Fp2



2. Inter-site phase coherence?

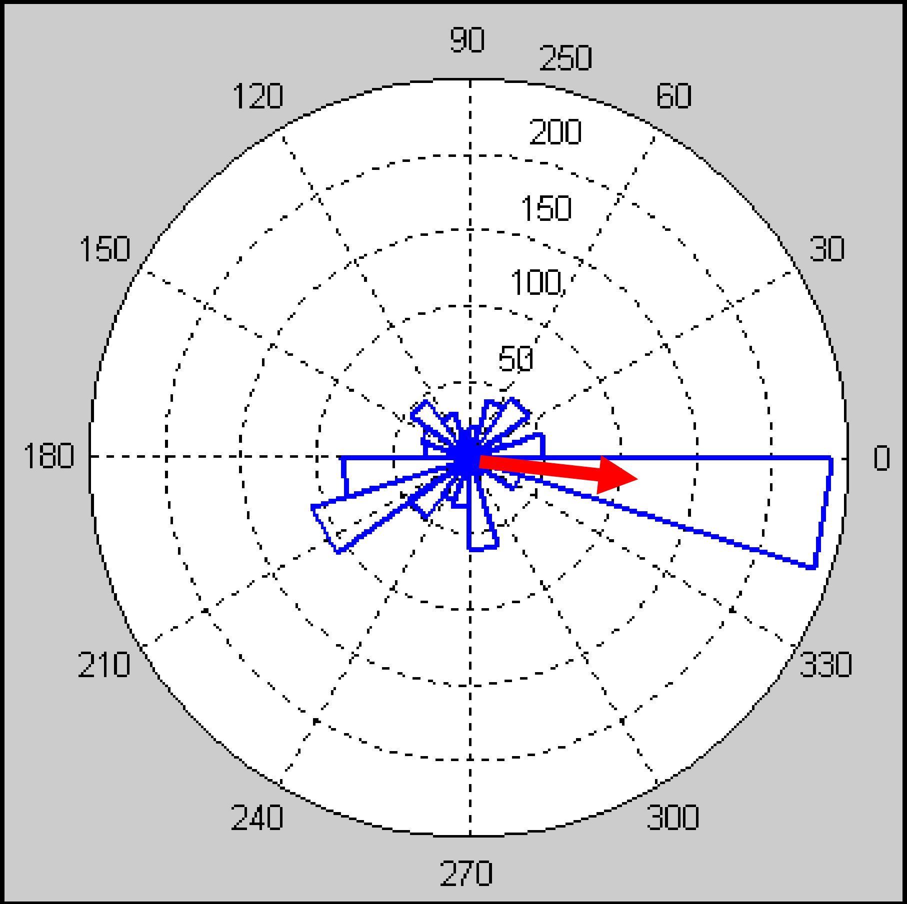
"Polar plot" of phase angle differences.

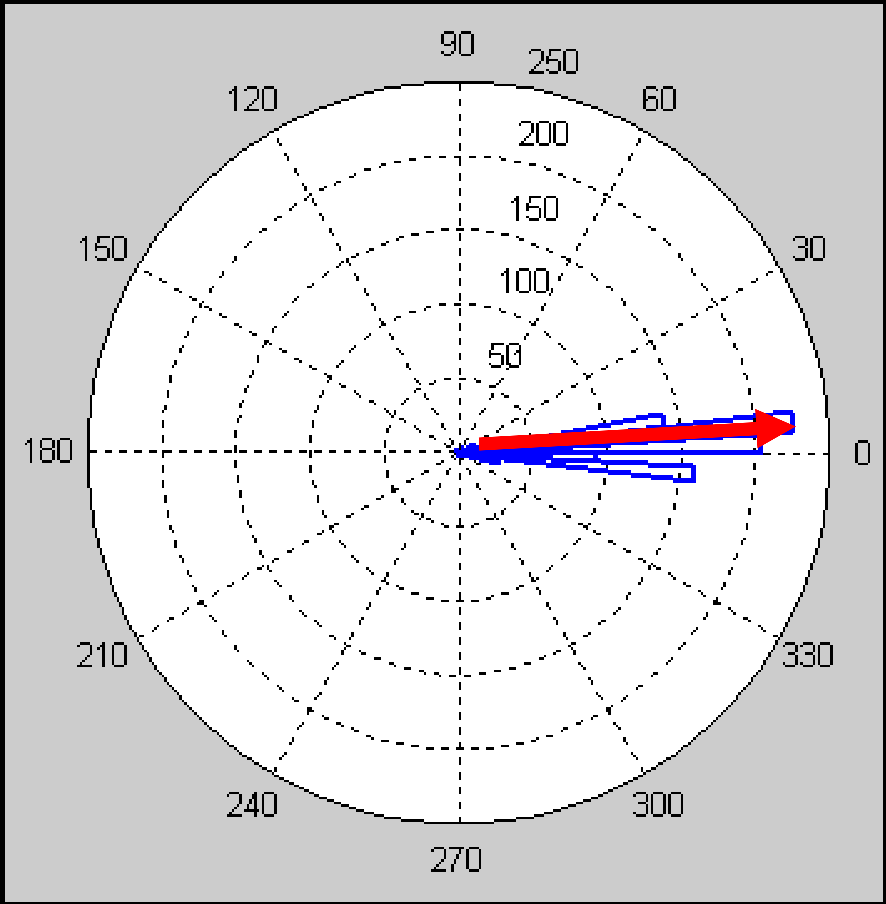




2. Circular variance.

Draw a line through the "average" of vectors.

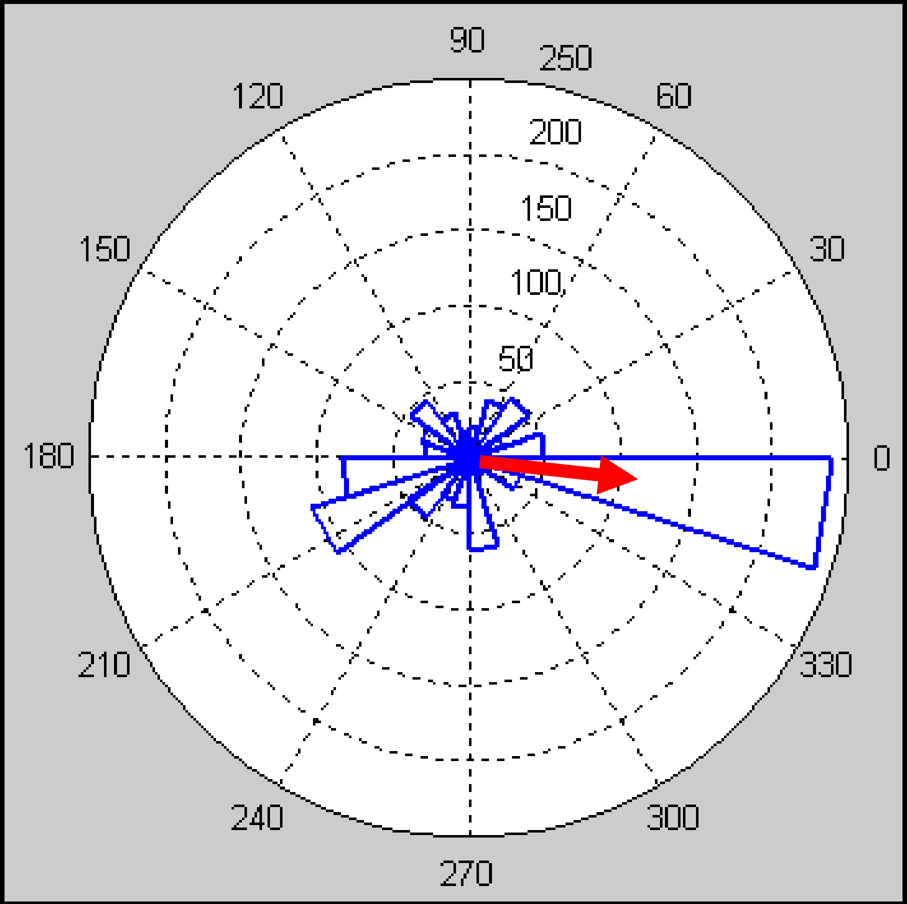




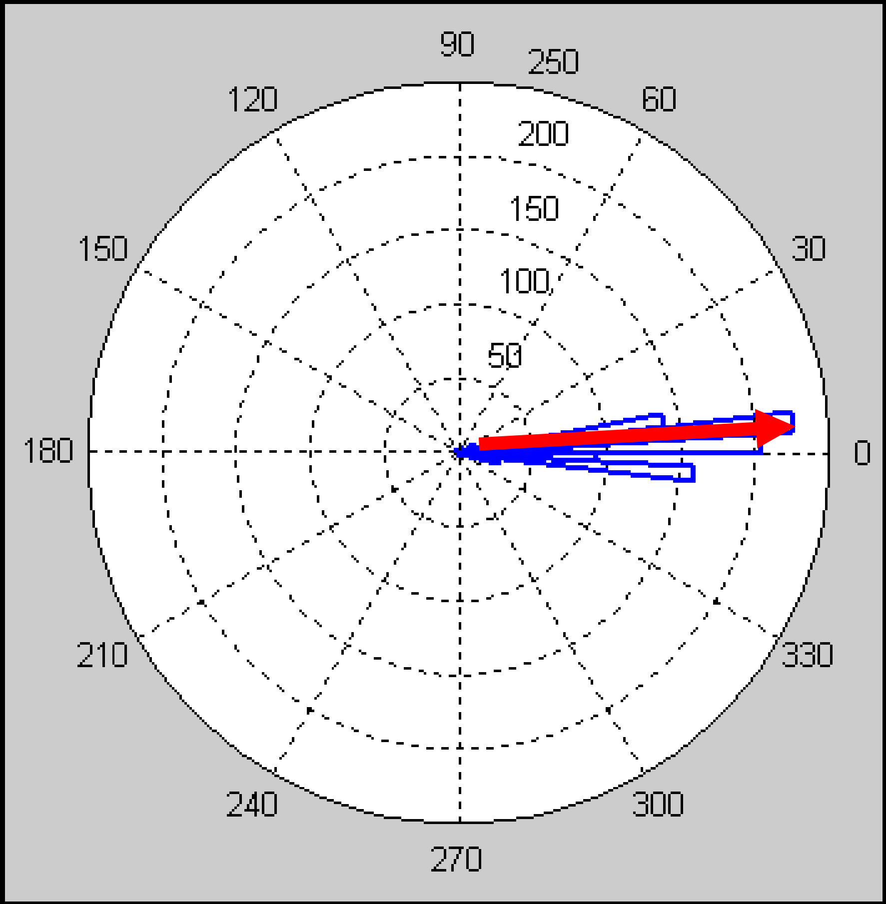
2. Circular variance.

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

Phase coherence: 0.11



Phase coherence: 0.94



2. Circular variance.

The equation for phase coherence is simple:

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

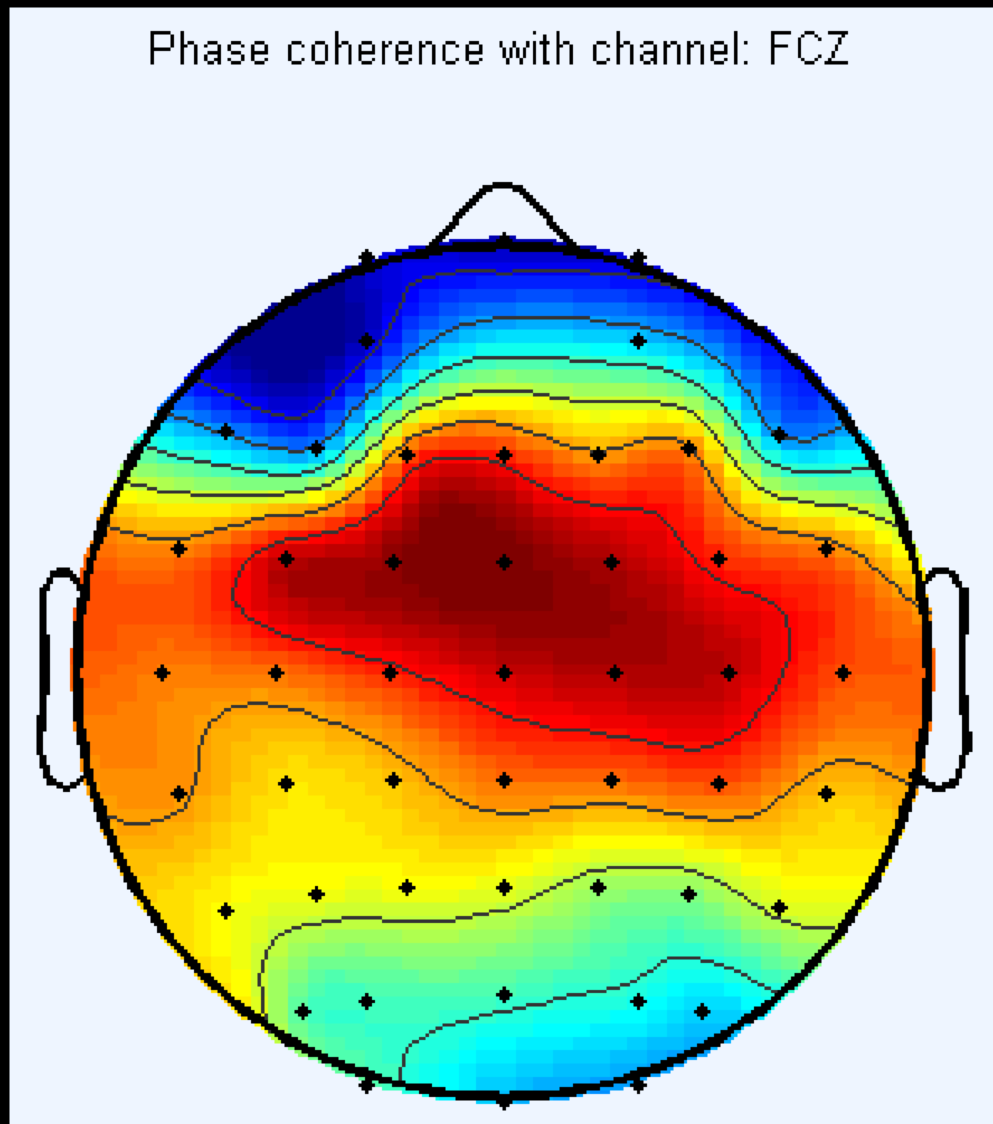
Magnitude of vector

Average across values

Transform to complex plane

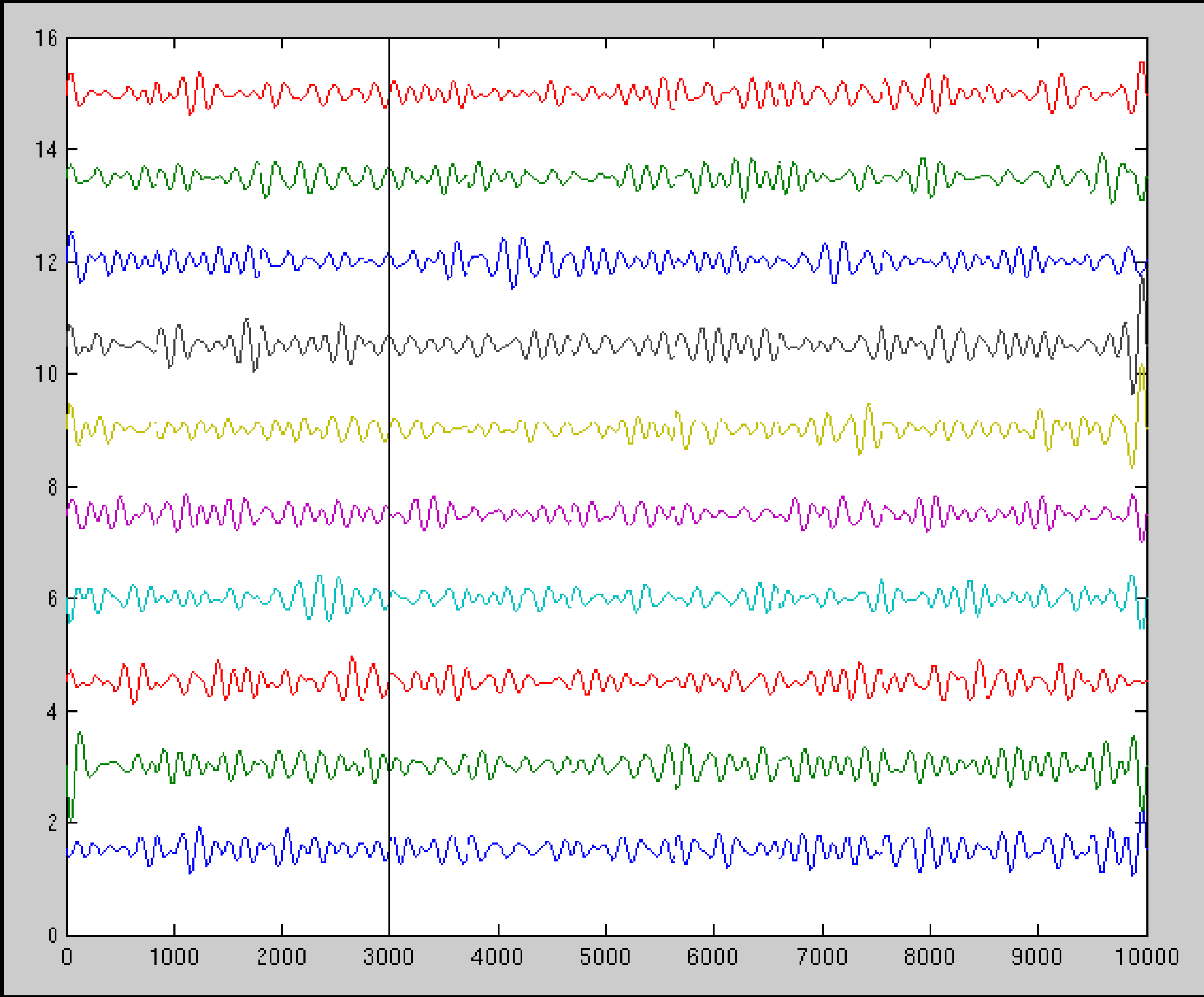
Phase angle differences between channels

2. Inter-site phase synchrony with one "seed" site.

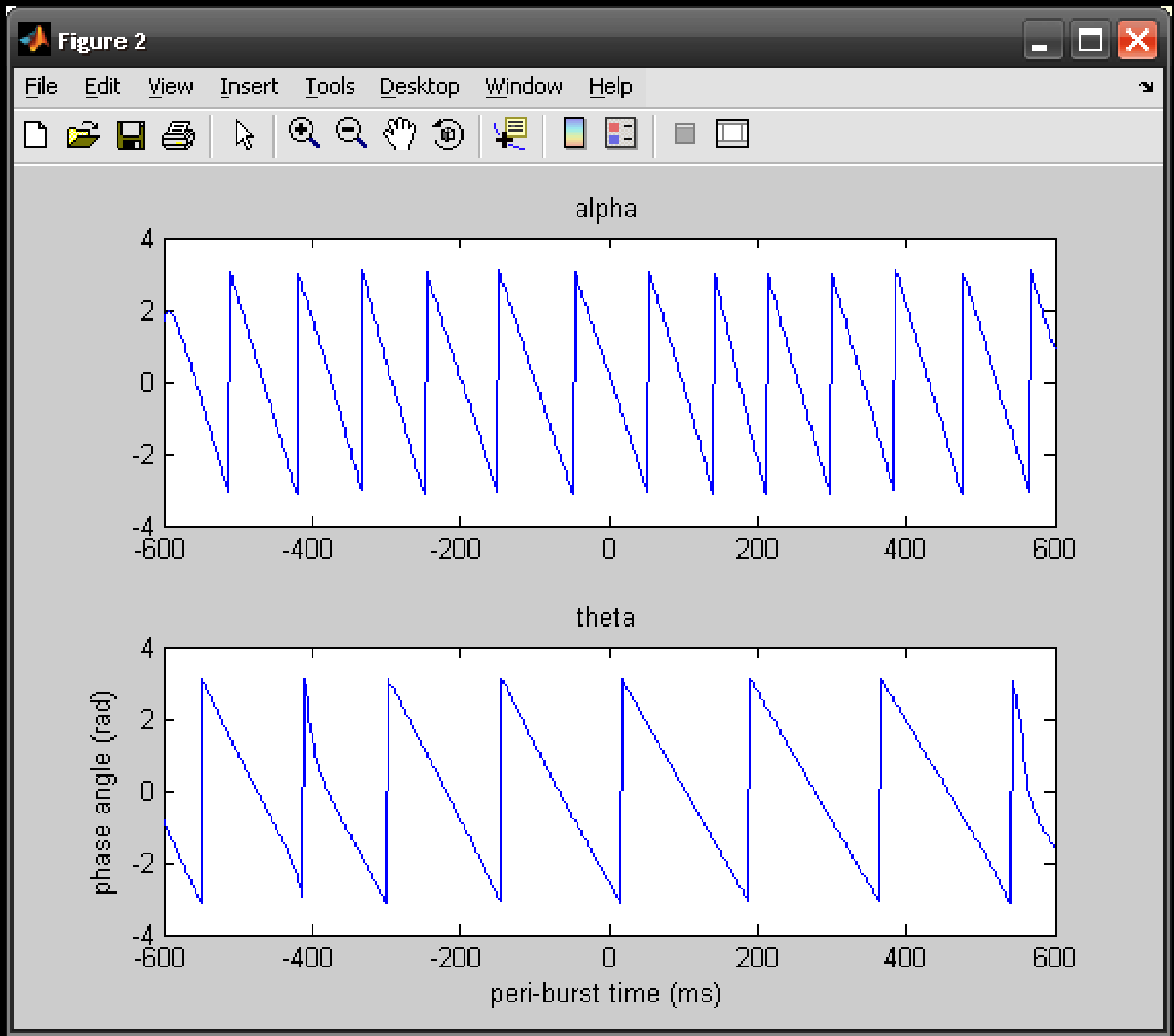


2. Inter-trial phase synchrony within one electrode.

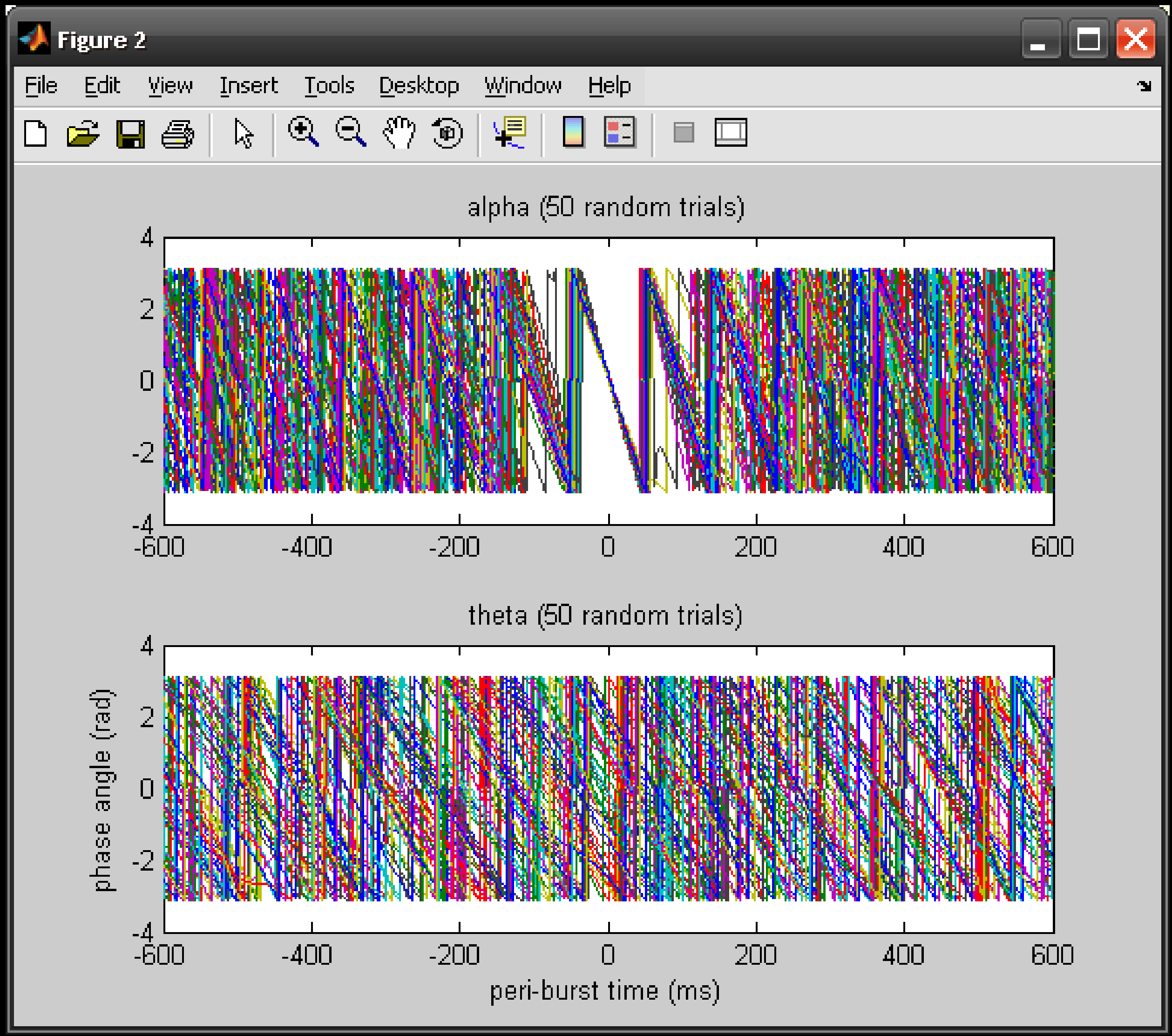
Many trials from the same electrode:



2. Inter-trial phase coherence



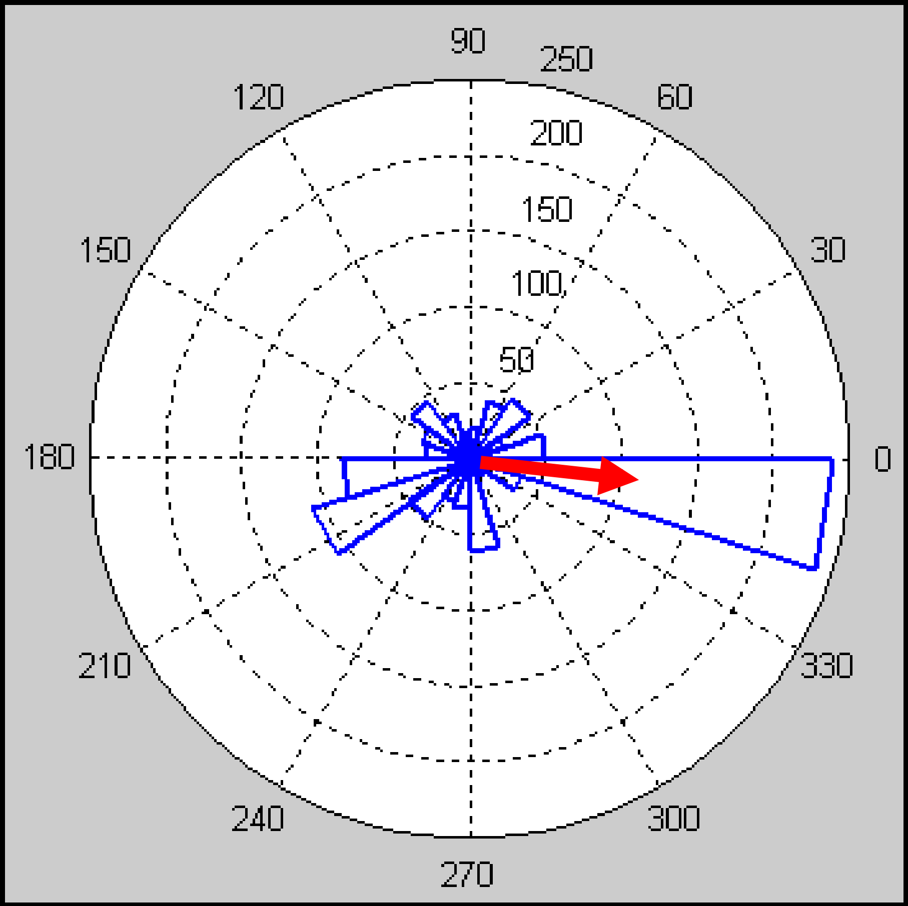
2. Inter-trial phase coherence



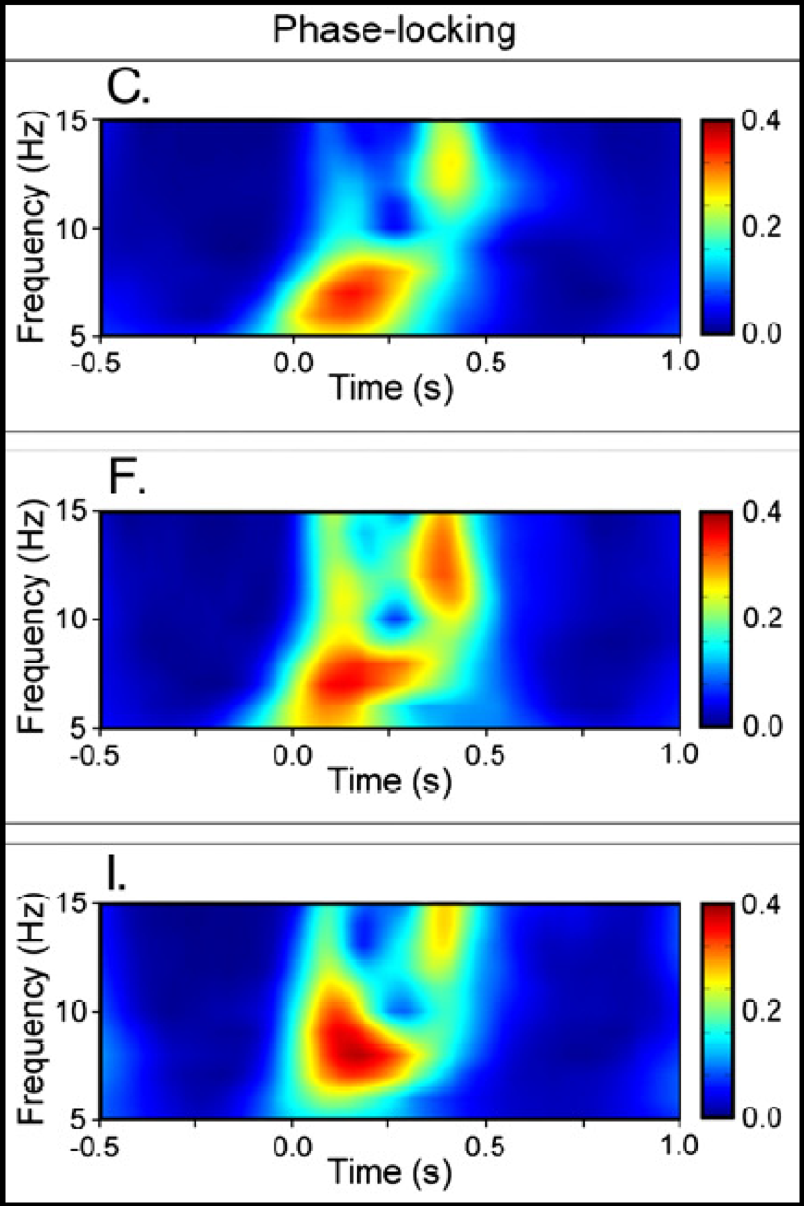
2. Inter-trial phase coherence

Calculate phase coherence across trials at each time point

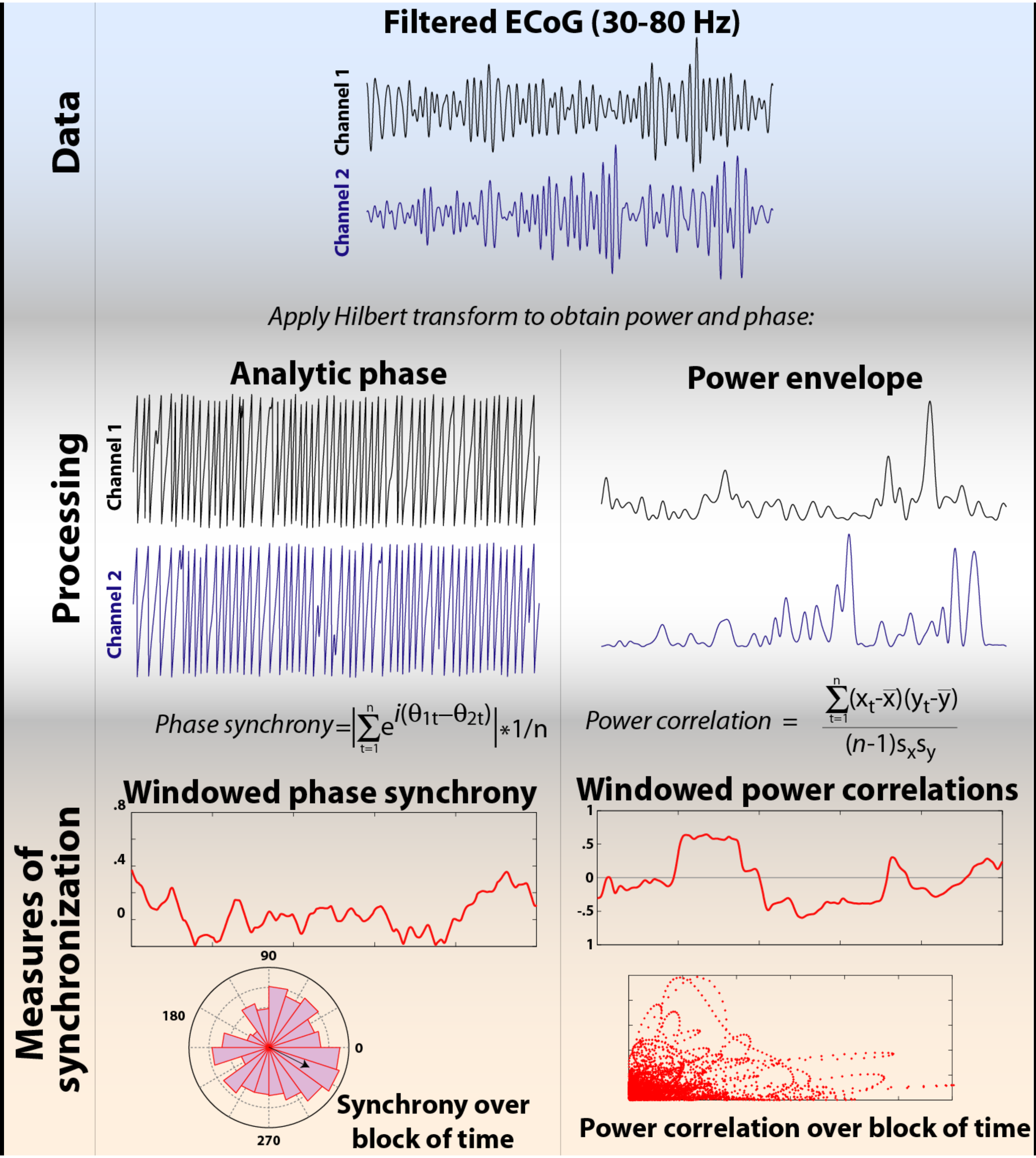
Phase coherence, 154 ms: 0.11



2. Inter-trial phase coherence



B.-K. Min et al. / International Journal of Psychophysiology 65 (2007) 58–68


Data
Filtered ECoG (30-80 Hz)
Channel 1
Channel 2
Apply Hilbert transform to obtain power and phase:
Processing
Analytic phase
Channel 1
Channel 2
Power envelope
$Phase\ synchrony = \left|\sum_{t=1}^{n} e^{i(\theta_{1t}-\theta_{2t})}\right| * 1/n$
$Power\ correlation = \frac{\sum_{t=1}^{n}(x_t-\bar{x})(y_t-\bar{y})}{(n-1)s_x s_y}$
Measures of synchronization
Windowed phase synchrony
.8
.4
0
90
180
0
270
Synchrony over block of time
Windowed power correlations
1
.5
0
-.5
1
Power correlation over block of time

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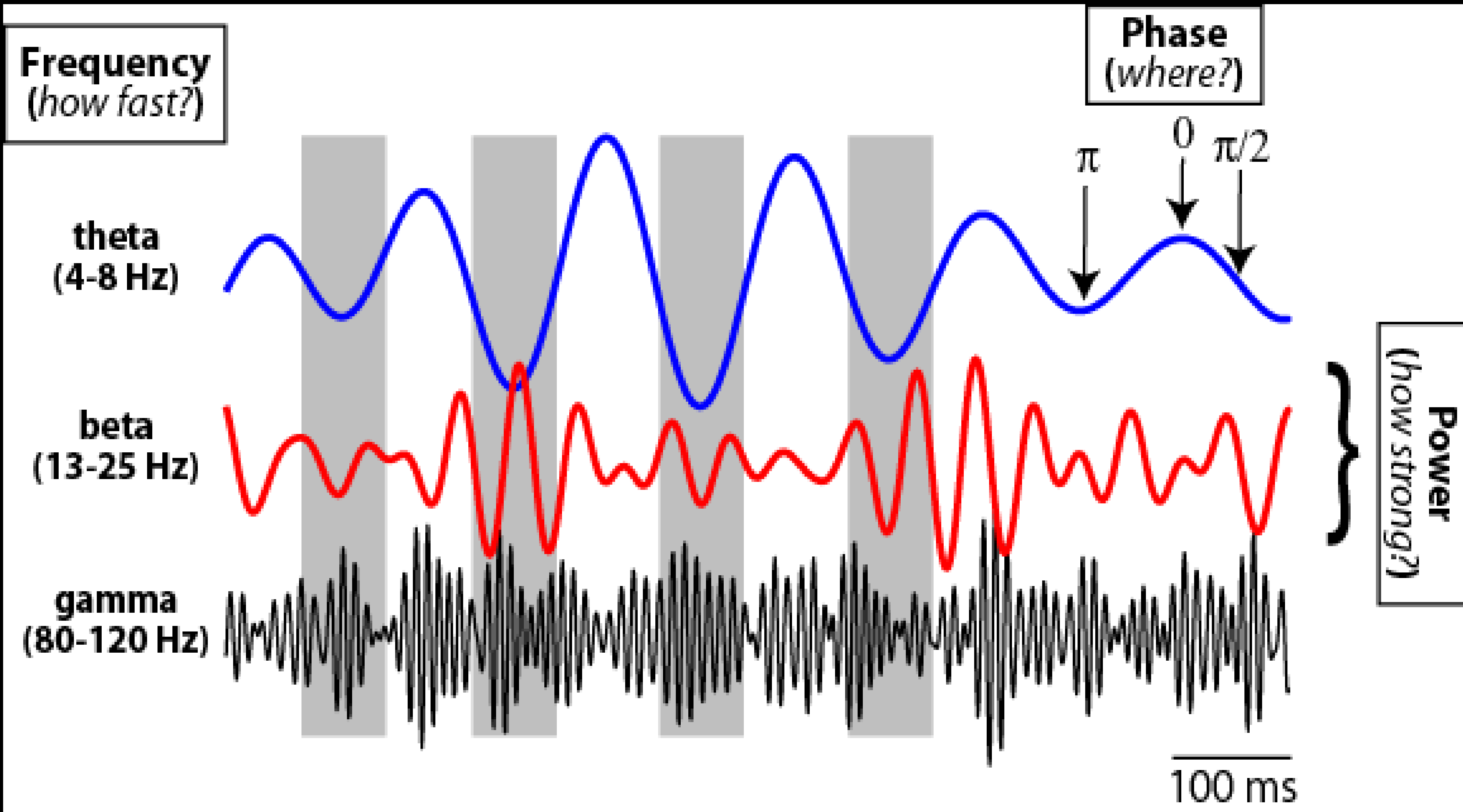
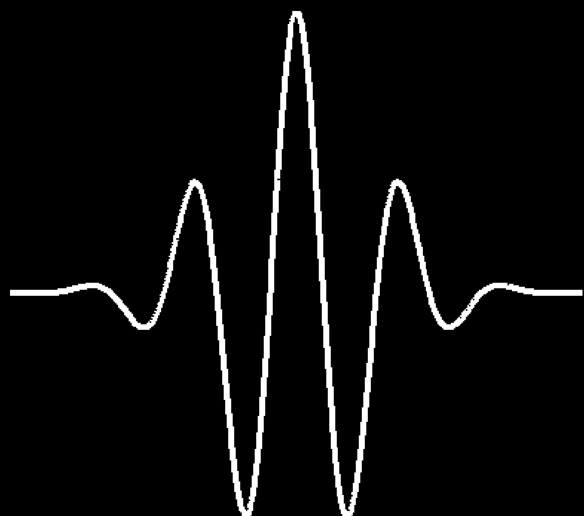
5. (optional) Renounce ERPs forever!!

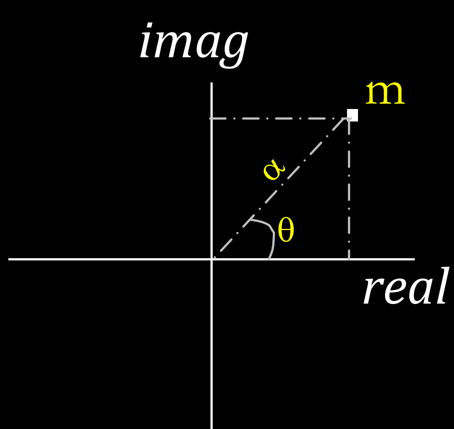
3. Review: Nomenclature of oscillation properties

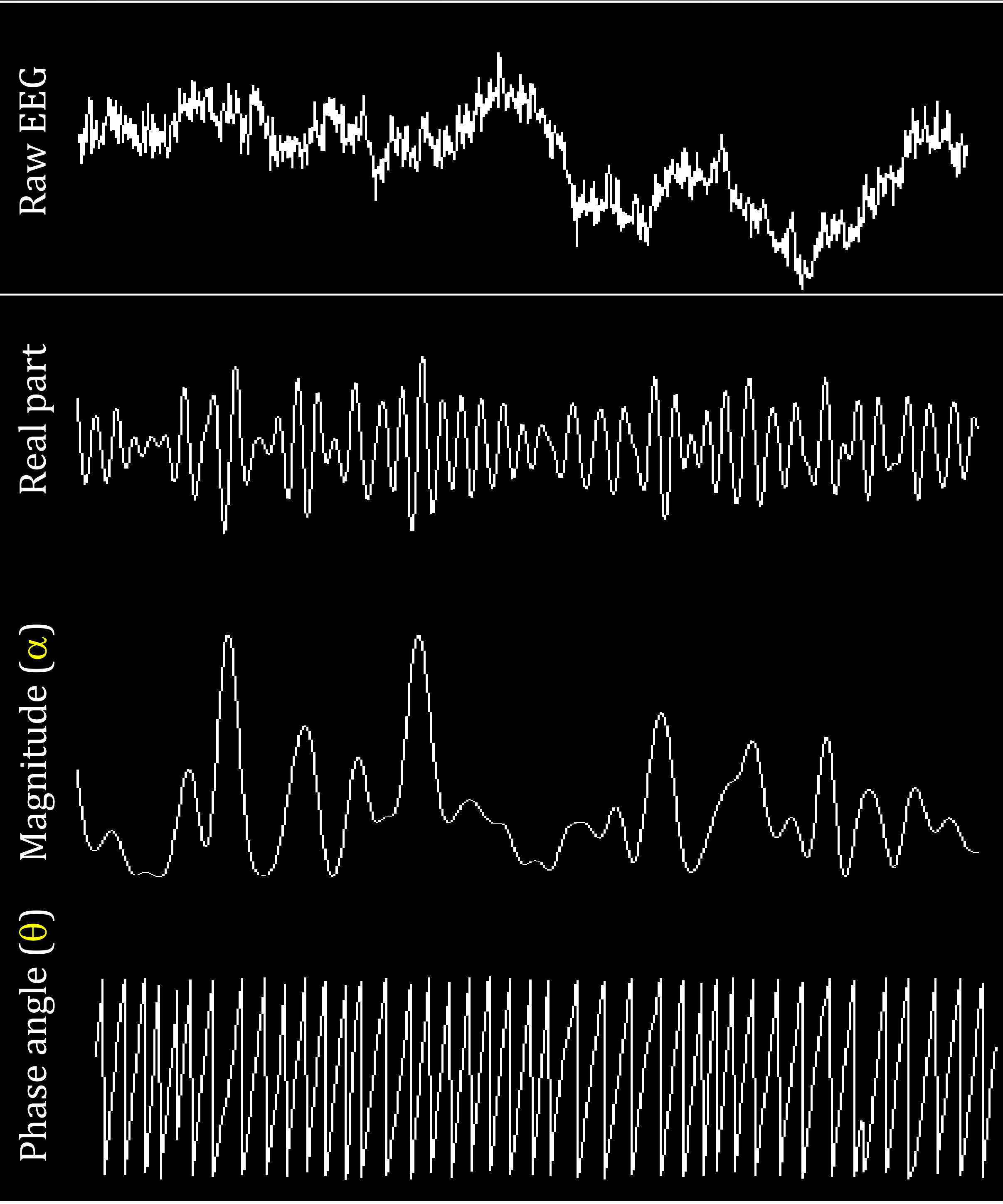


3. Review: information obtained from wavelet transform

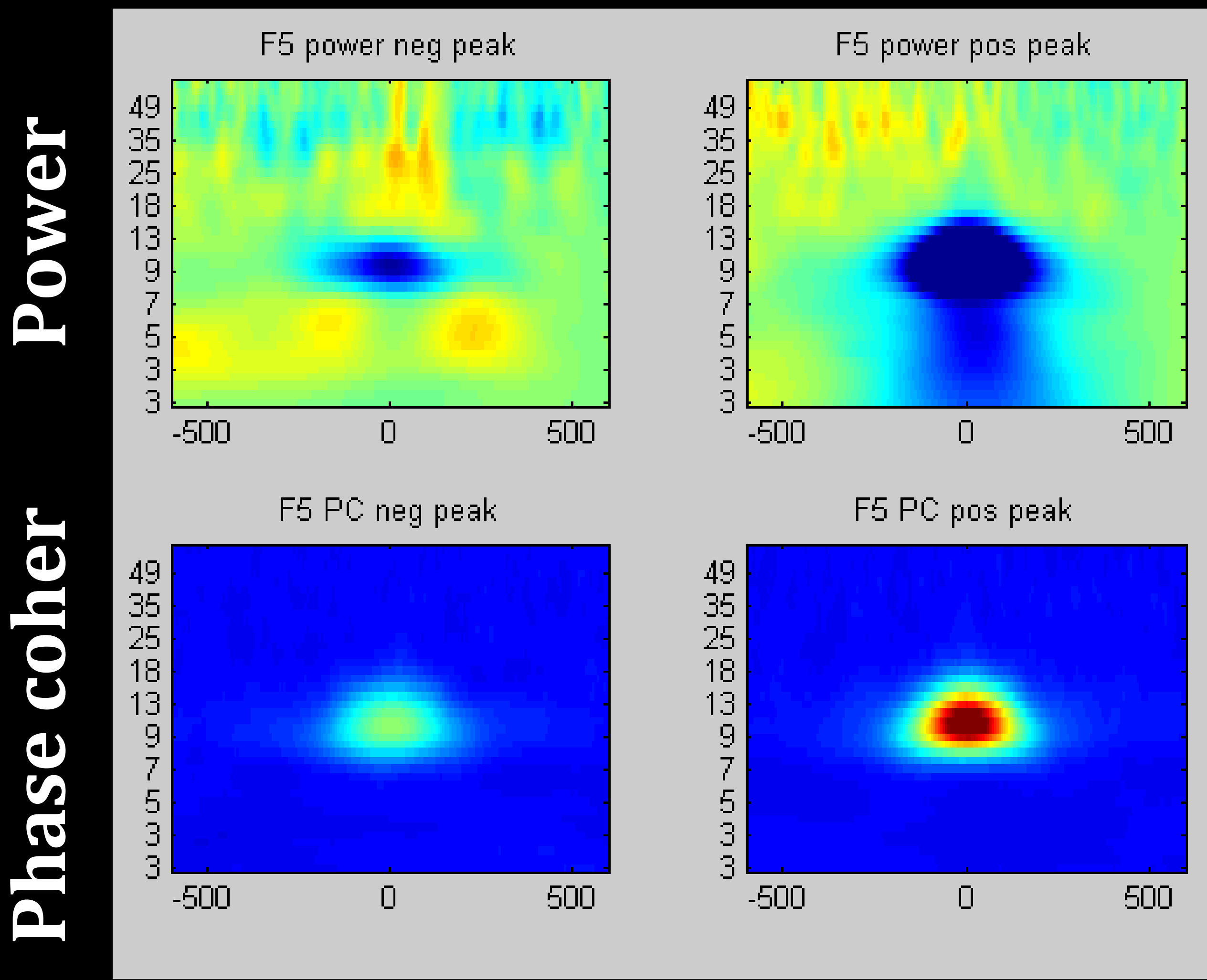


Center frequency: 23.7 Hz





3. Review on interpreting time-frequency plots



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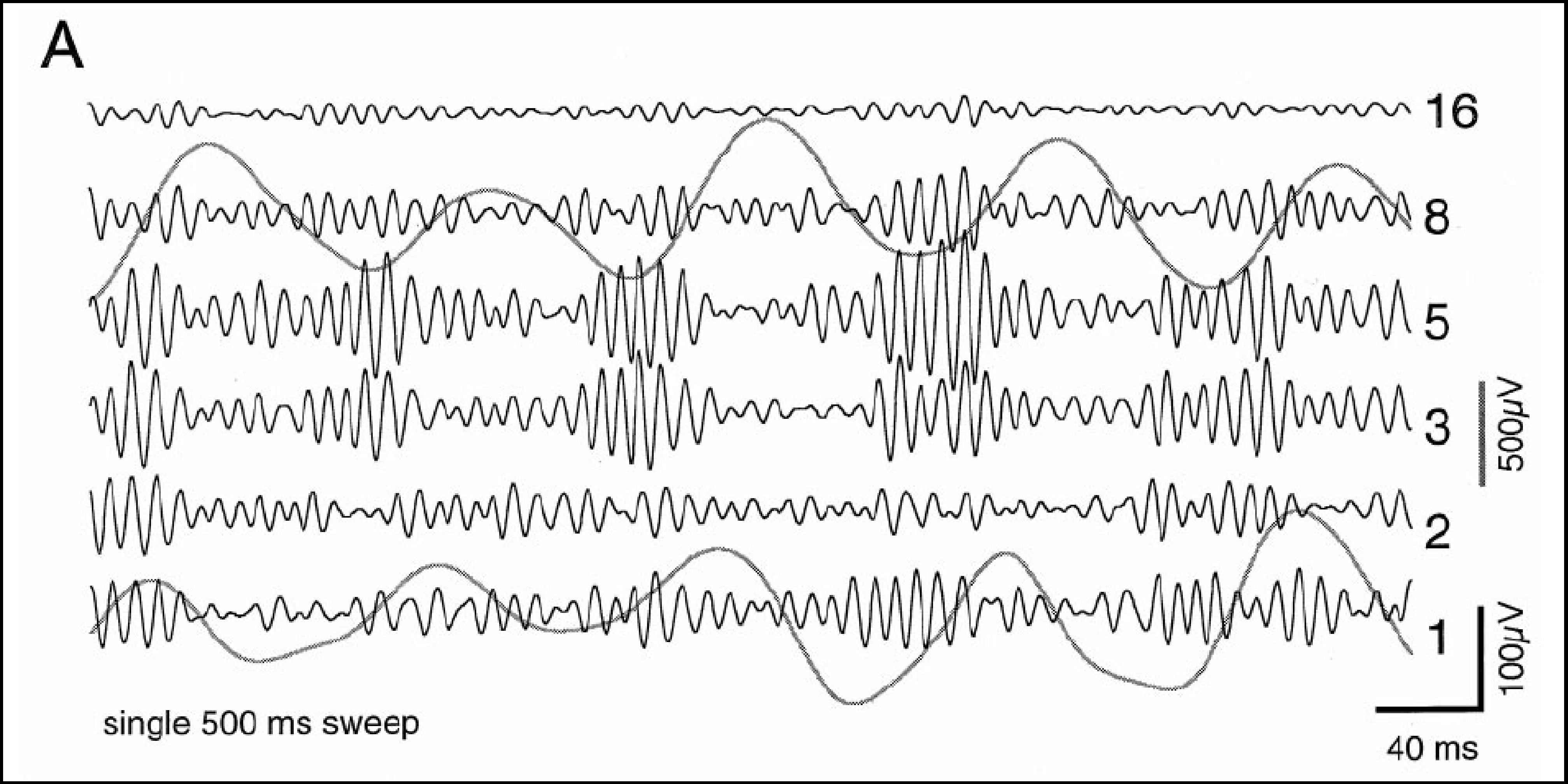
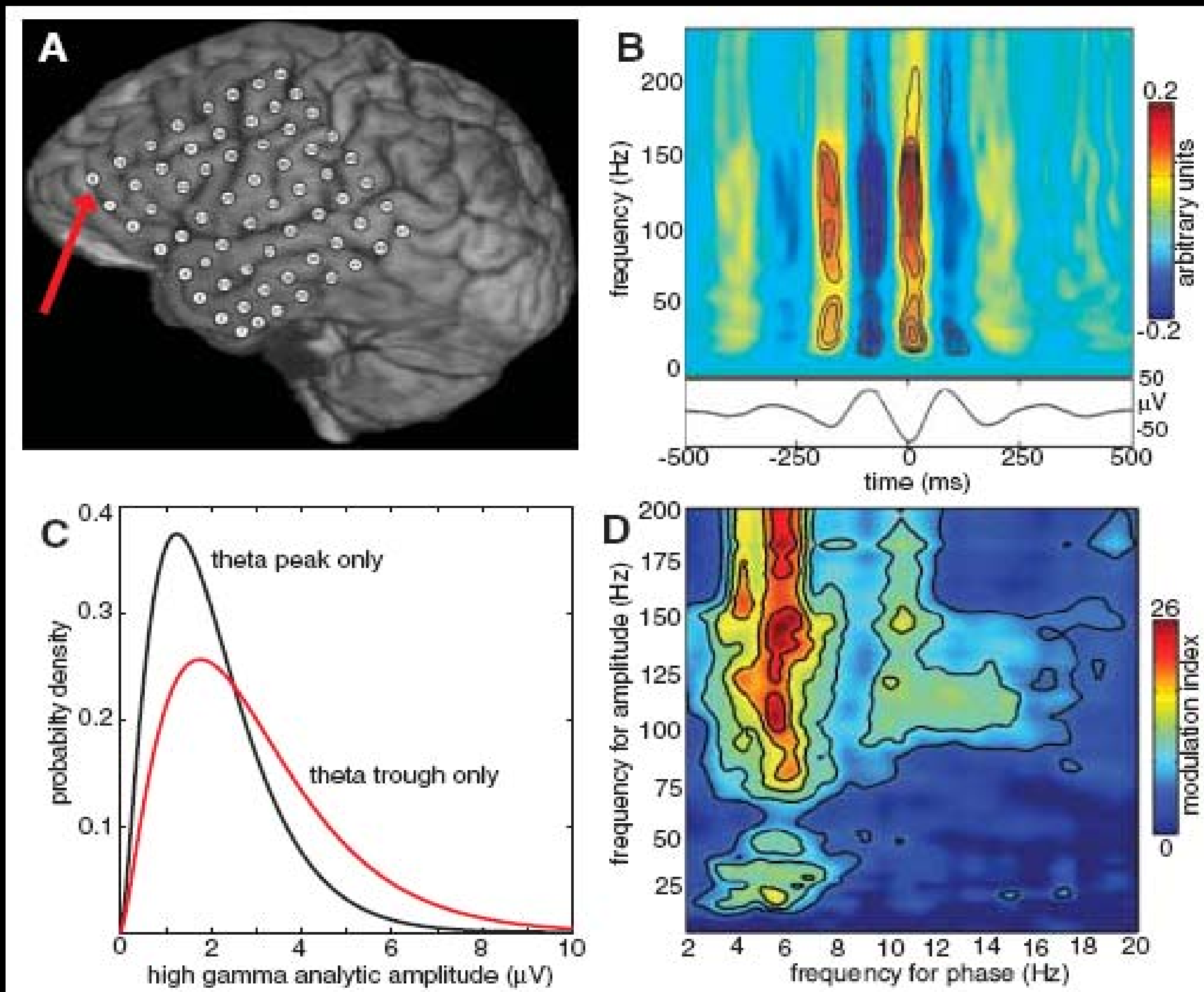
4. Introduction to cross-frequency coupling



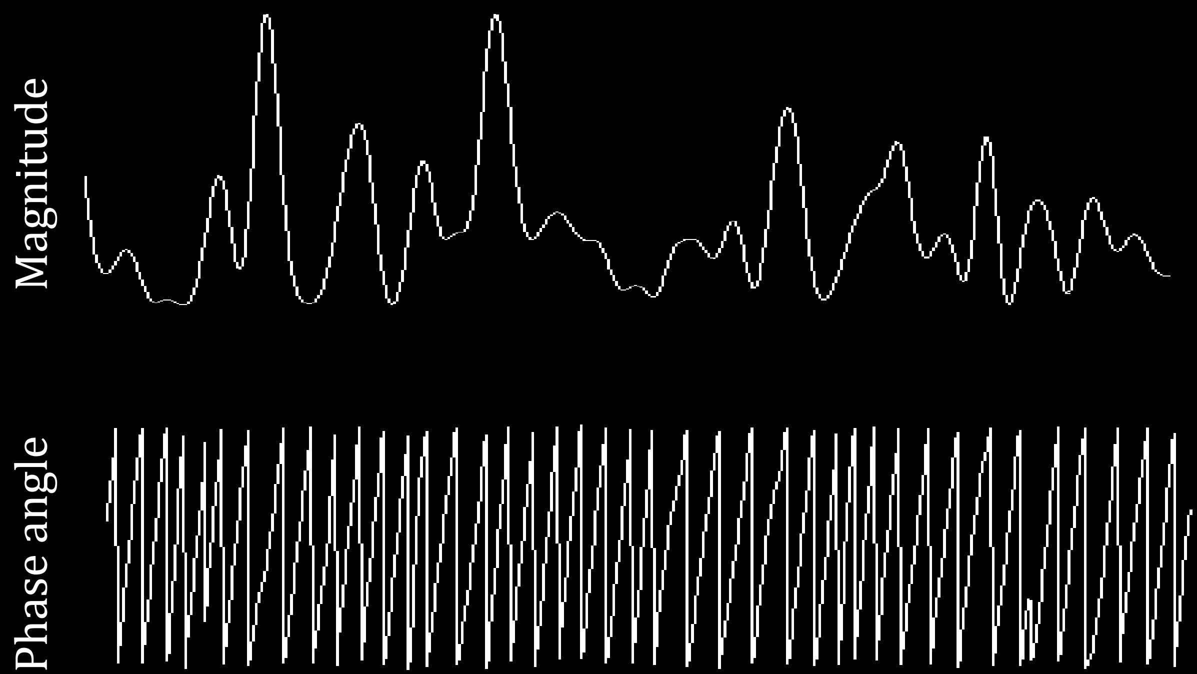
Chrobak et al., 1998

4. Introduction to cross-frequency coupling



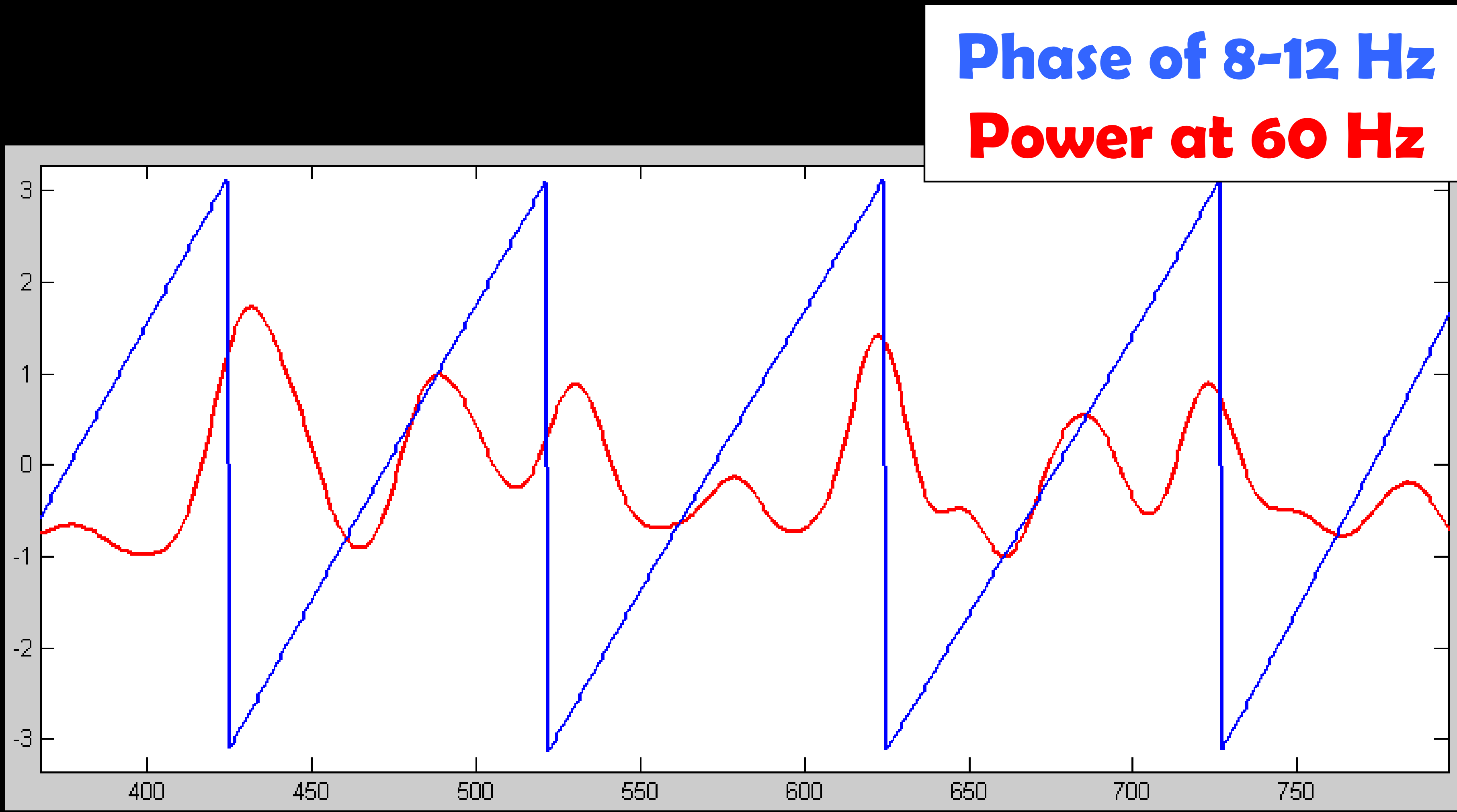
4. How to measure cross-frequency coupling

Method 1: Phase-amplitude coupling



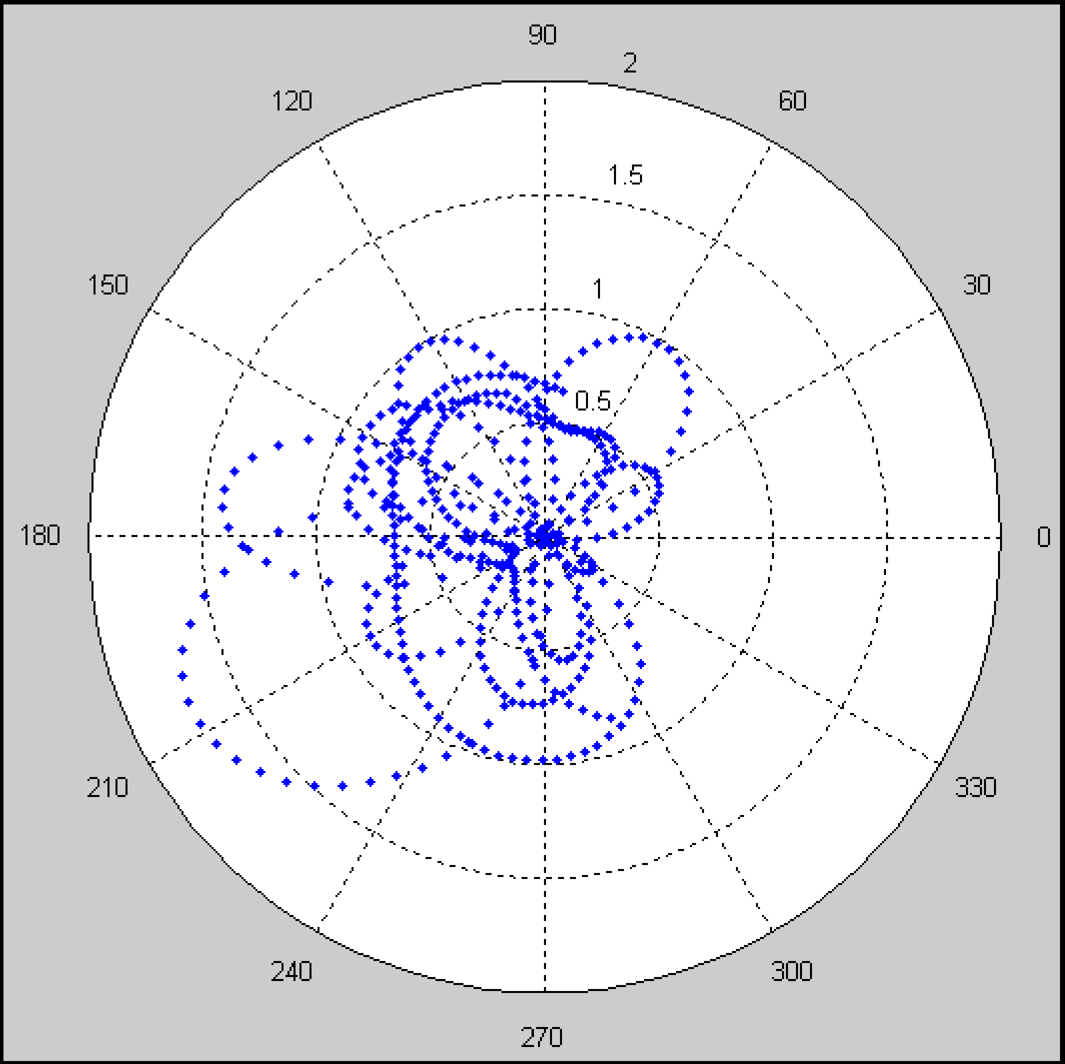
Here, phase and amplitude are taken from the *same* frequency band. What if we were to take them from *different* frequency bands??

4. Phase-amplitude cross-frequency coupling



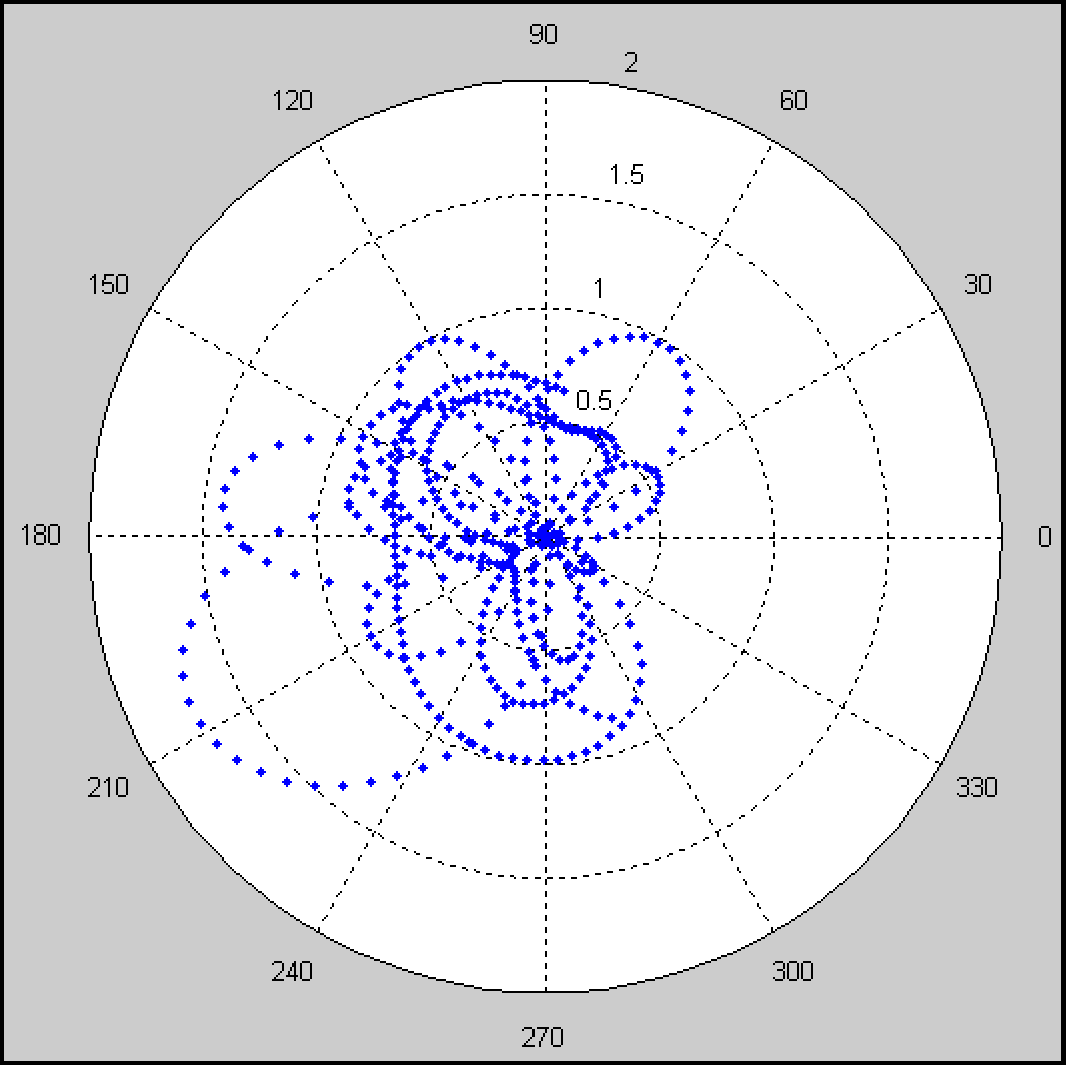
Notice that gamma power seems to be maximal during specific alpha phases!

4. Phase-amplitude cross-frequency coupling



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

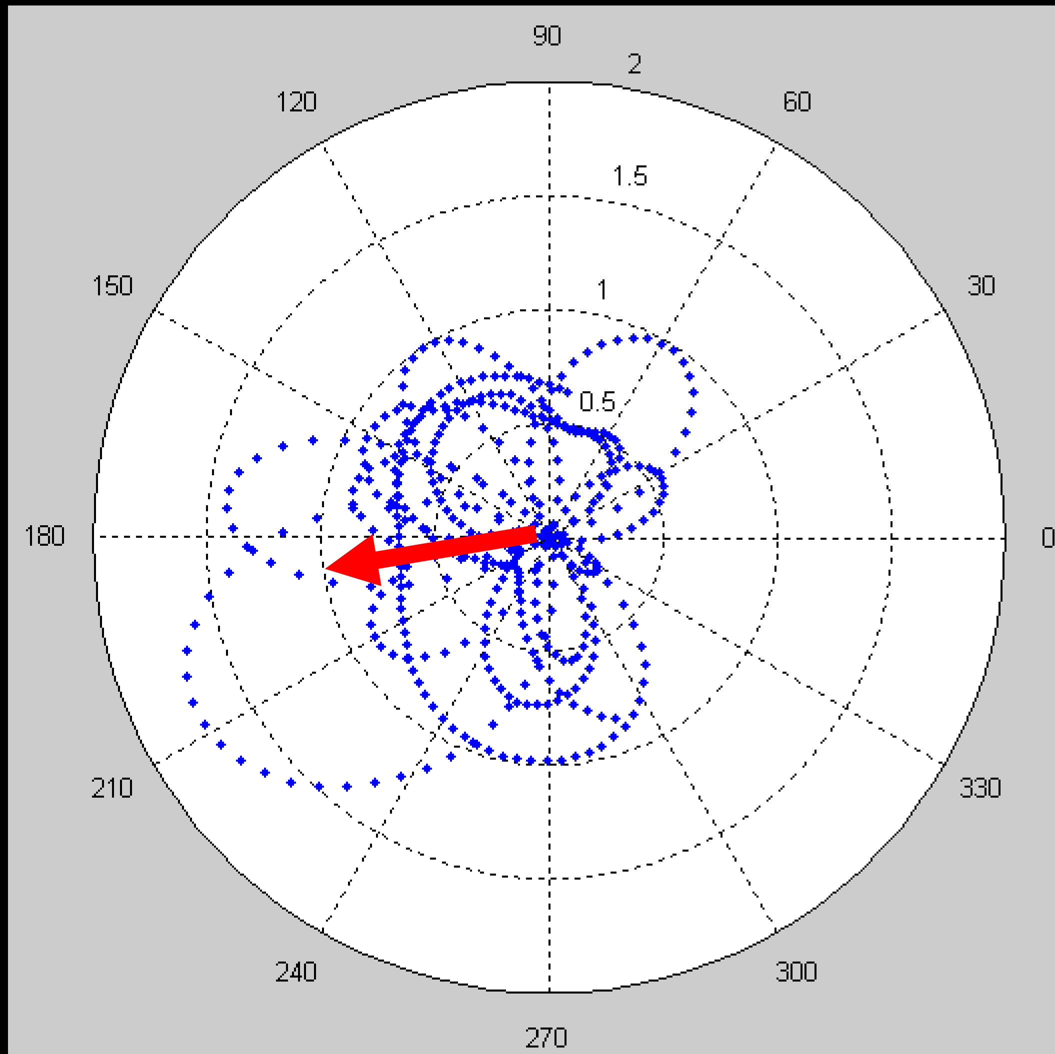
4. Phase-amplitude cross-frequency coupling



Gamma power is NOT uniformly distributed throughout alpha phase!!

Thus, gamma power is coupled with alpha phase.

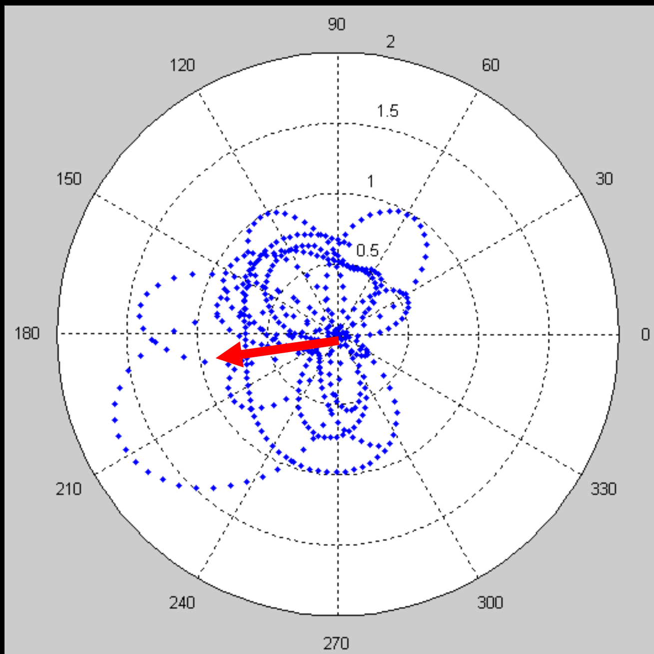
4. Phase-amplitude cross-frequency coupling



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)

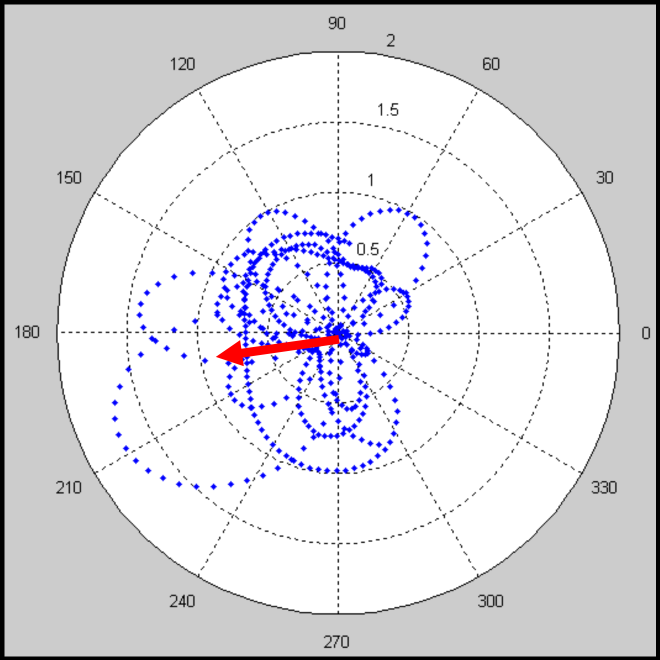
Modulation index = .244

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 → abs
- Average across values → mean
- Power of higher frequency → power
- Transform to complex plane → exp(i*
- Phase angle of lower frequency → phase

4. Phase-amplitude cross-frequency coupling

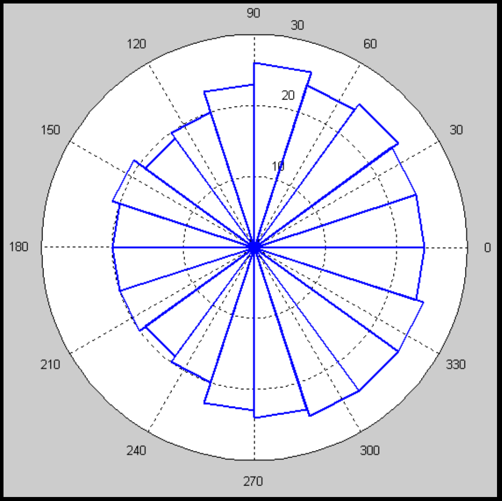


Modulation index = .244

Potential problem:

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

Distribution of alpha phase



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

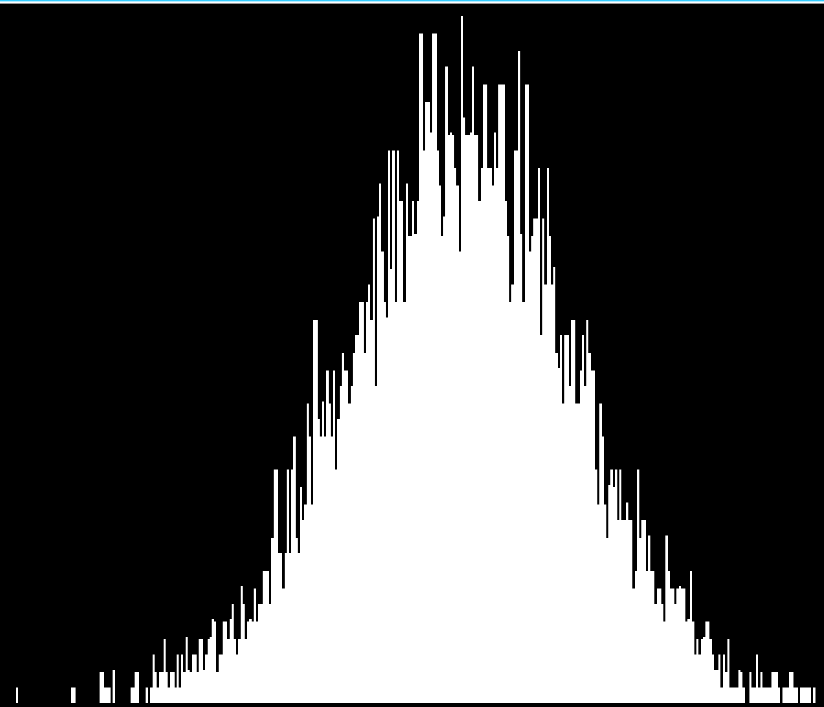
4. Phase-amplitude cross-frequency coupling

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.

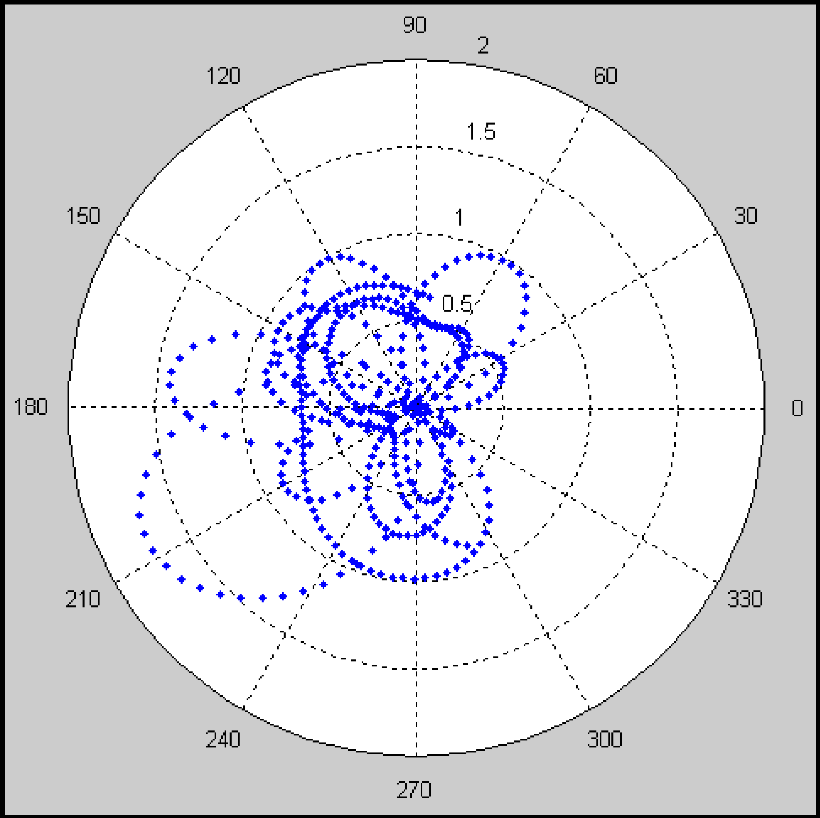
Permutation tests in combination with the Law of Large Numbers to the rescue!



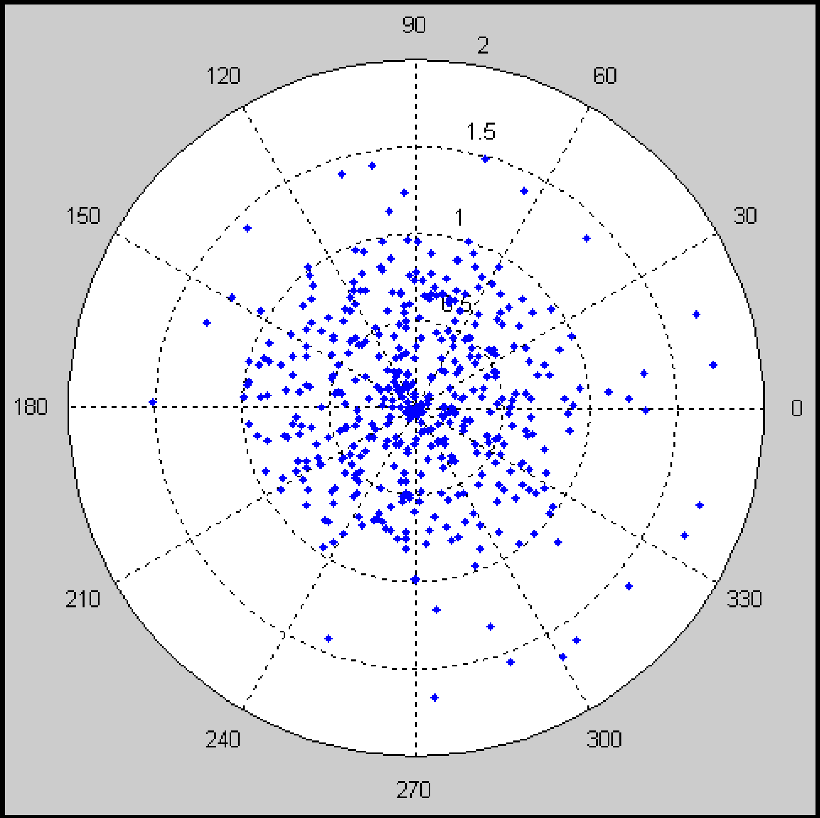
4. Phase-amplitude cross-frequency coupling

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)

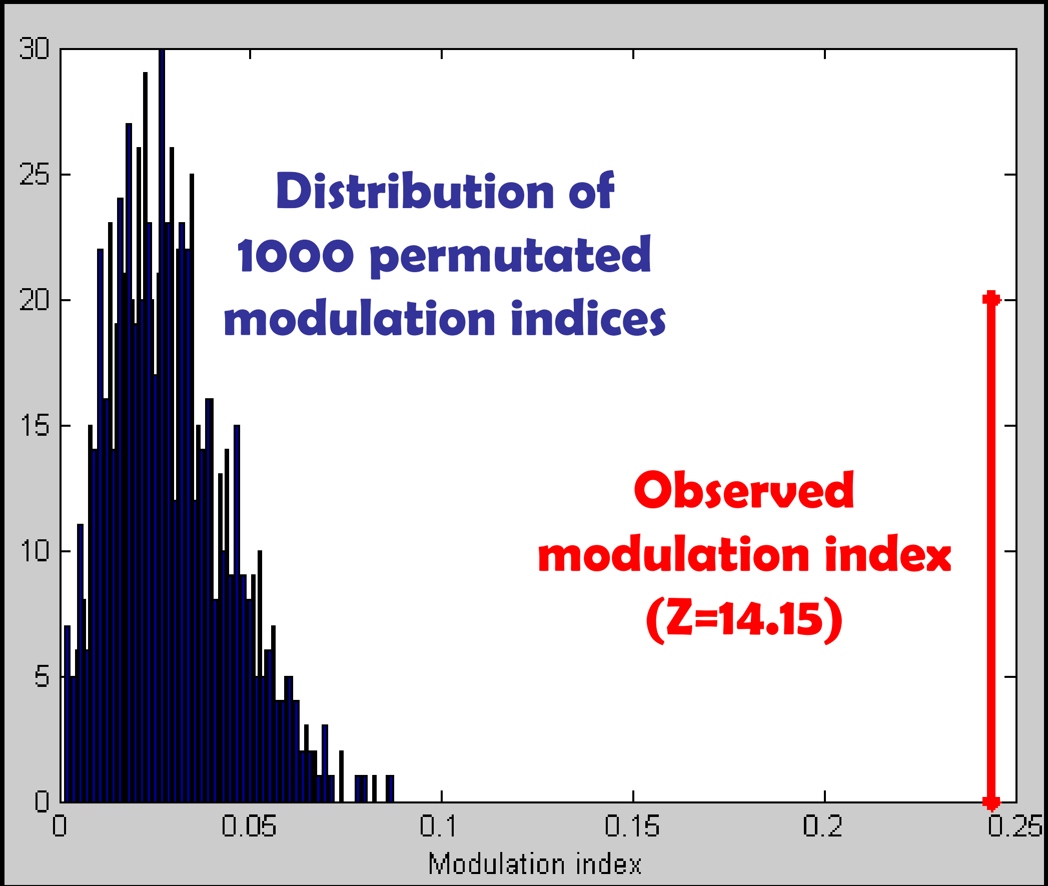


Shuffled data (M=.033)

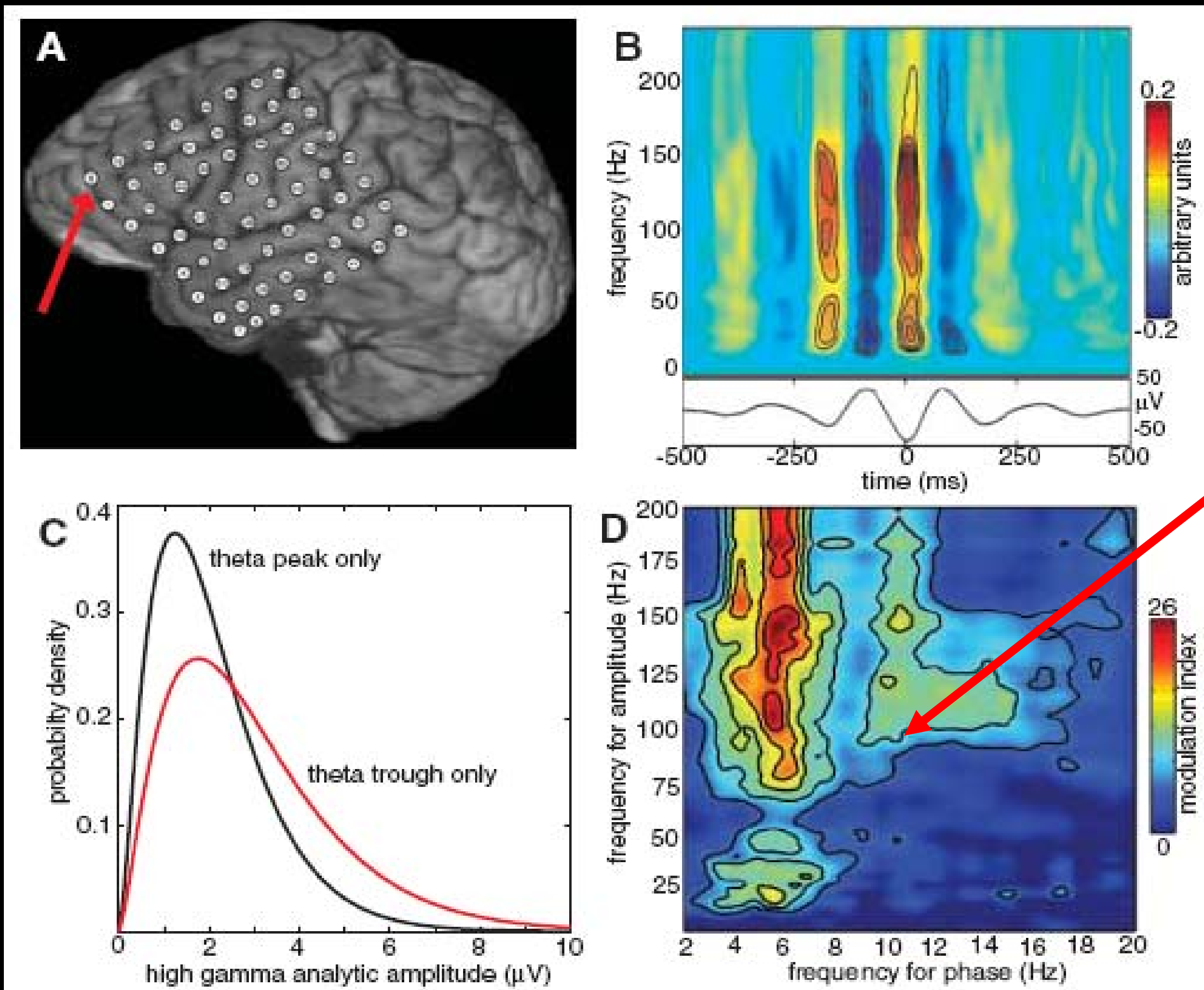


4. Phase-amplitude cross-frequency coupling

Because permutated 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.

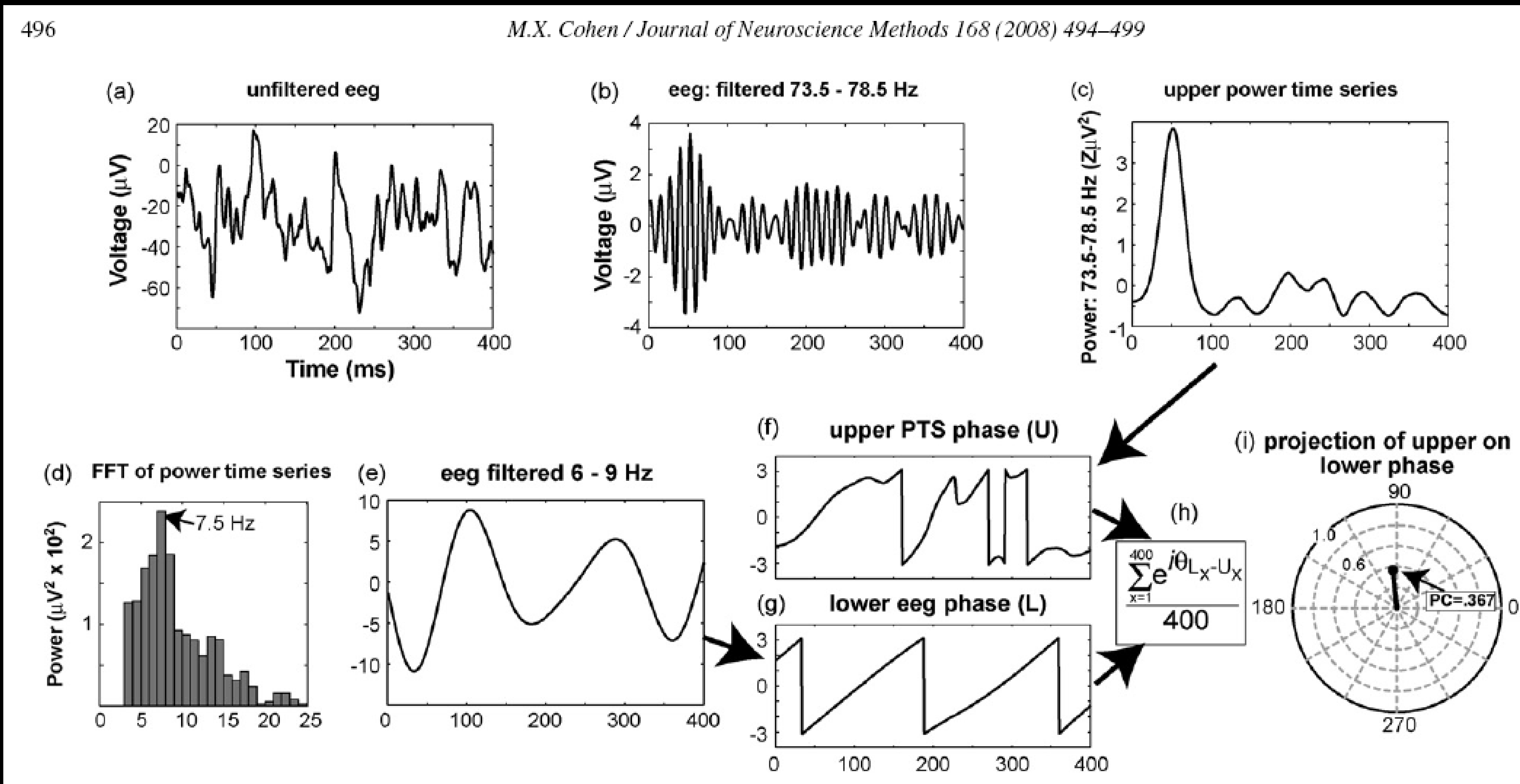
This procedure can be done over many phase and amplitude frequency pairs, as in Canolty et al., 2006.

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

R. T. Canolty,[1*] E. Edwards,[1,2] S. S. Dalal,[3] M. Soltani,[1,2] S. S. Nagarajan,[3,4] H. E. Kirsch,[5] M. S. Berger,[6] N. M. Barbaro,[5,6] R. T. Knight[1,2,3,5,6]

4. How to measure cross-frequency coupling

Method 2: Phase-phase coupling



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.

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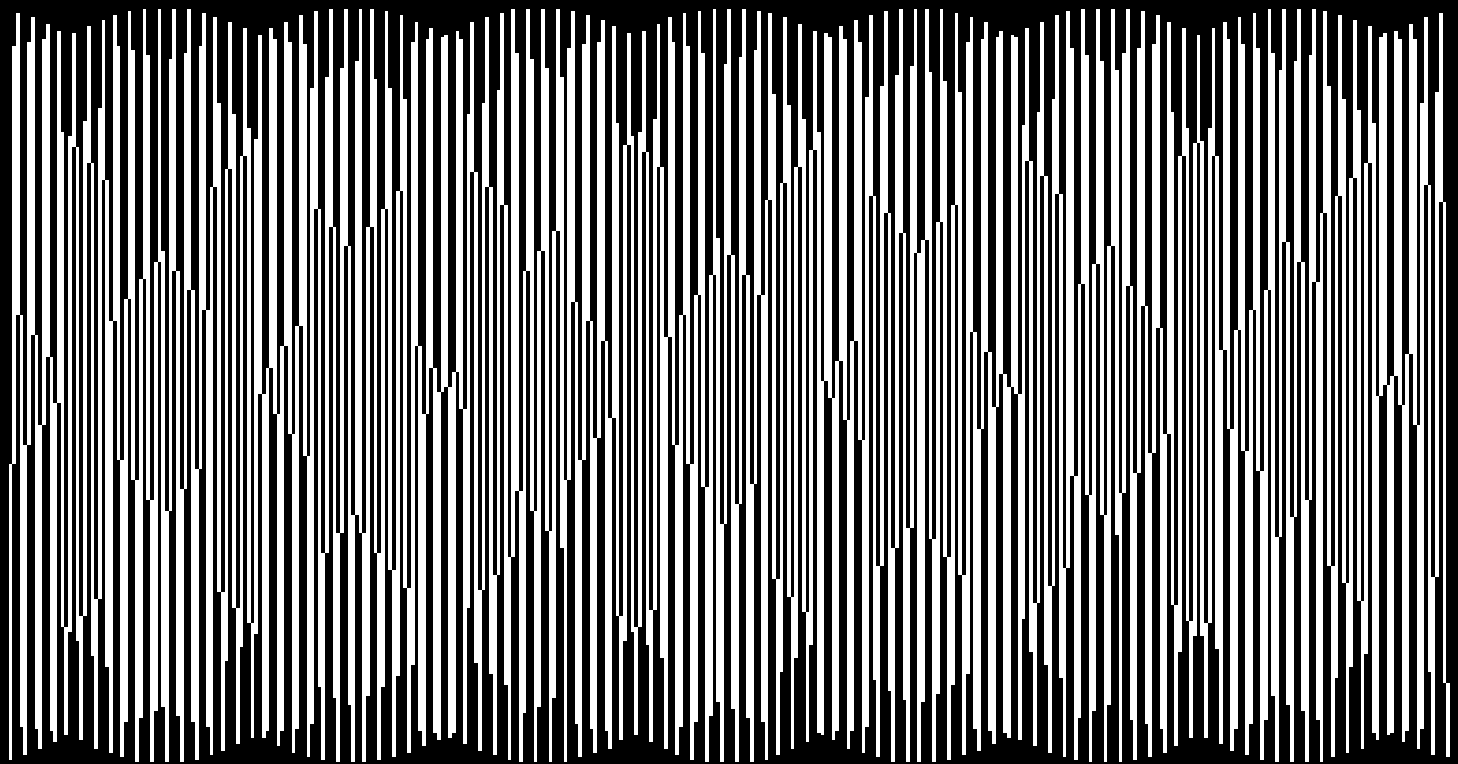
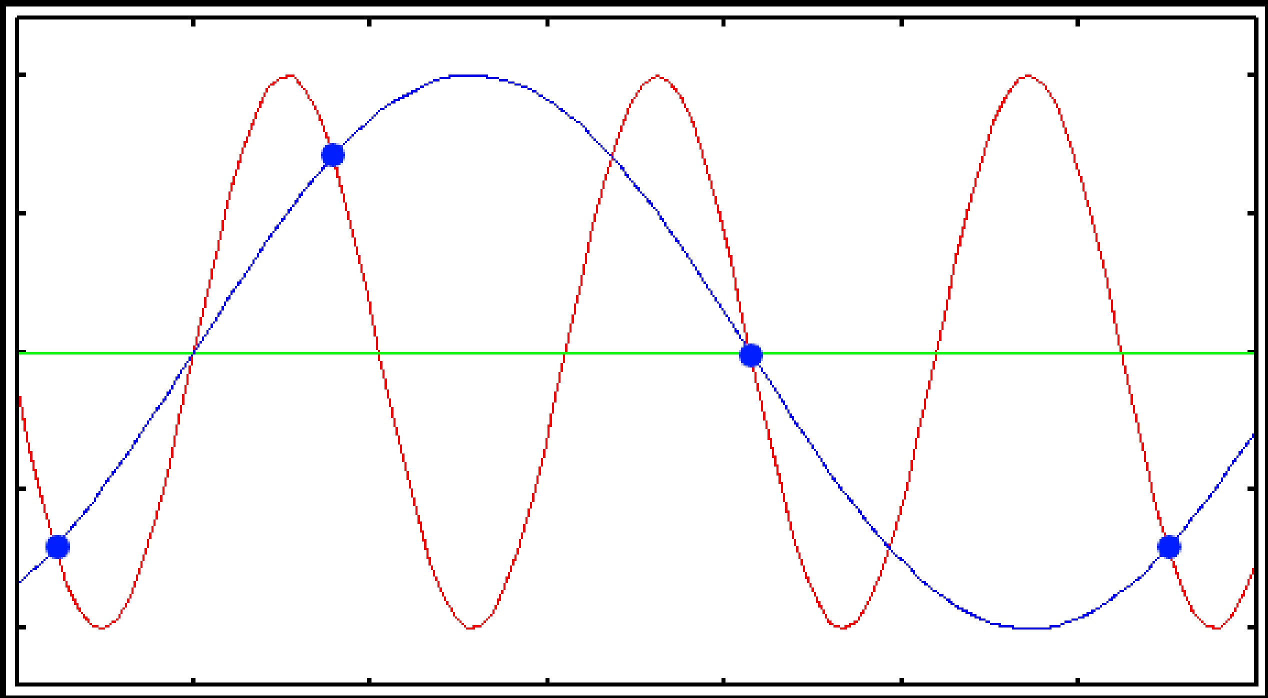
Some practical issues that arise during oscillation analyses

Practical issues: That darned tootin' Nyquist frequency!



Practical issues: That darned tootin' Nyquist frequency!

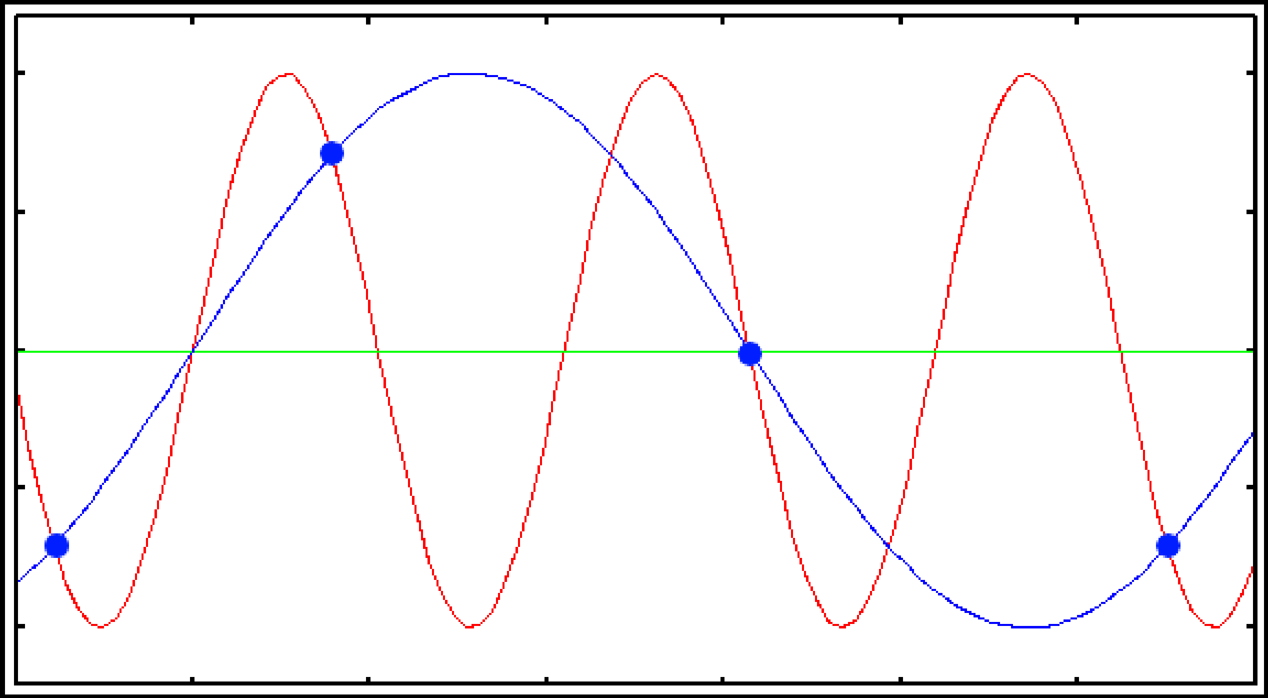
Oscillations that are faster than the sampling rate may induce artificial slow oscillations!



Practical issues: That darned tootin' Nyquist frequency!

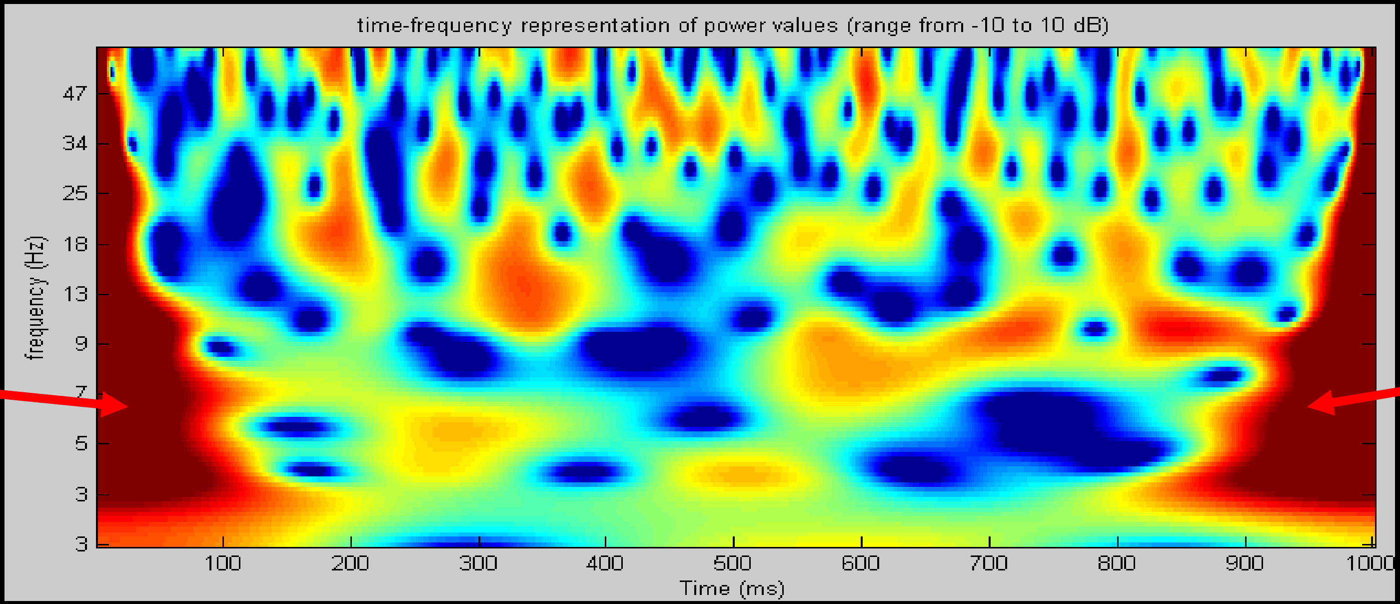
You must sample at least twice the highest frequency you want to analyze!

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



Practical issues: Life on the fringe…

Edge artifacts!!!

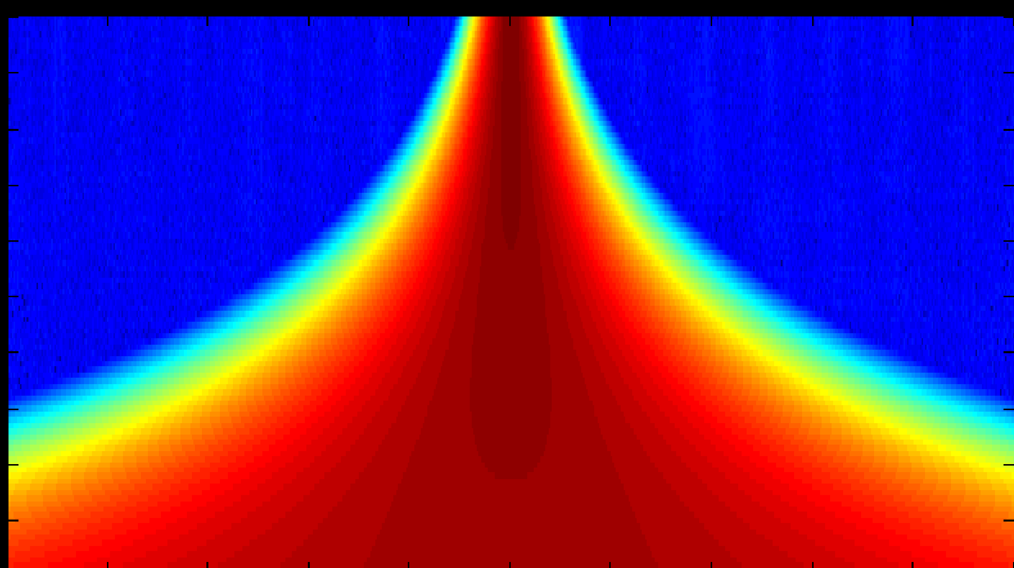


Edge artifacts!!!

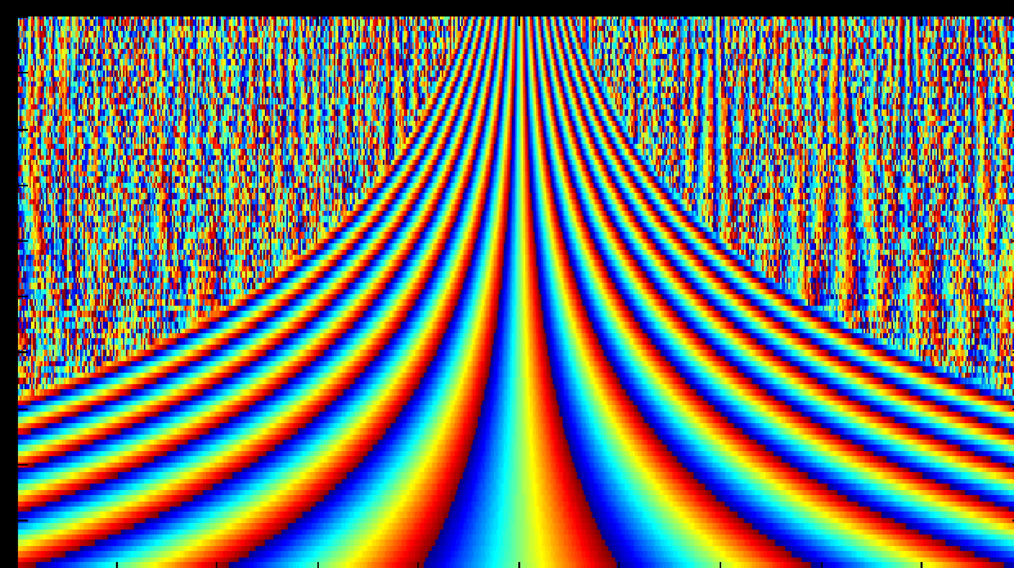
Practical issues: Life on the fringe…

Time course with sharp edge

Power



Phase

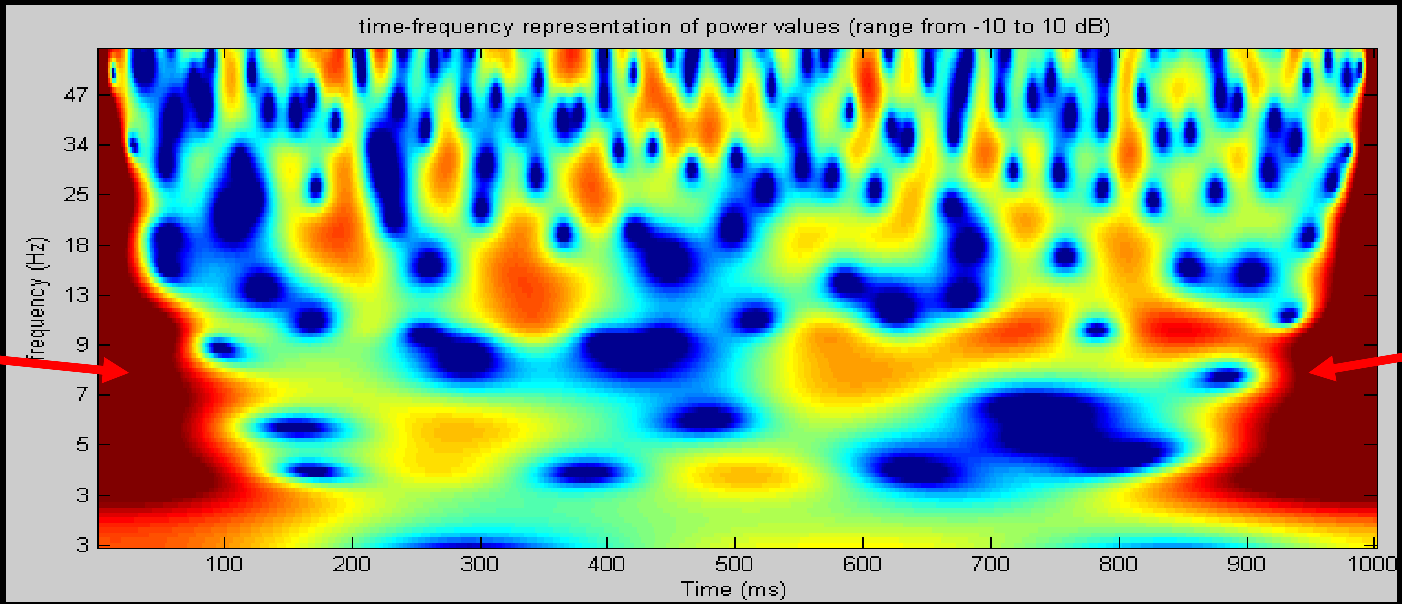


Practical issues: Life on the fringe…

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.

Edge artifacts!!!



Edge artifacts!!!