OSHER LIFELONG LEARNING INSTITUTE

Тон Шепарда (Shepard's Tone)
Rabbit Killer (2019)

Mandelbrot Fractals from "Fire & Ice", *Maths Town* (2017)

An Ear for Music

Session 3
Hearing and the Ear

OLLI at Illinois

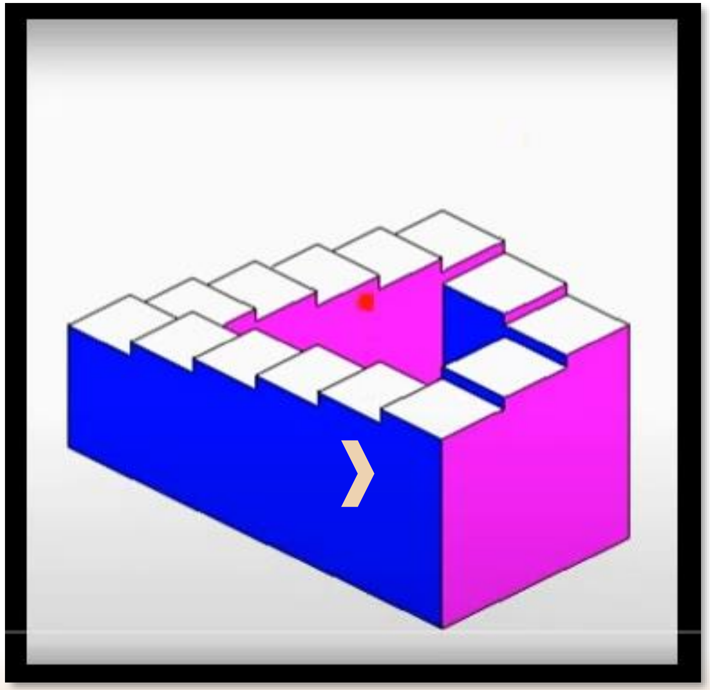
Spring 2024

D. H. Tracy

OSHER LIFELONG LEARNING INSTITUTE

An Ear for Music

Shepard/Penrose Mix-2
JHFreeland (2009)



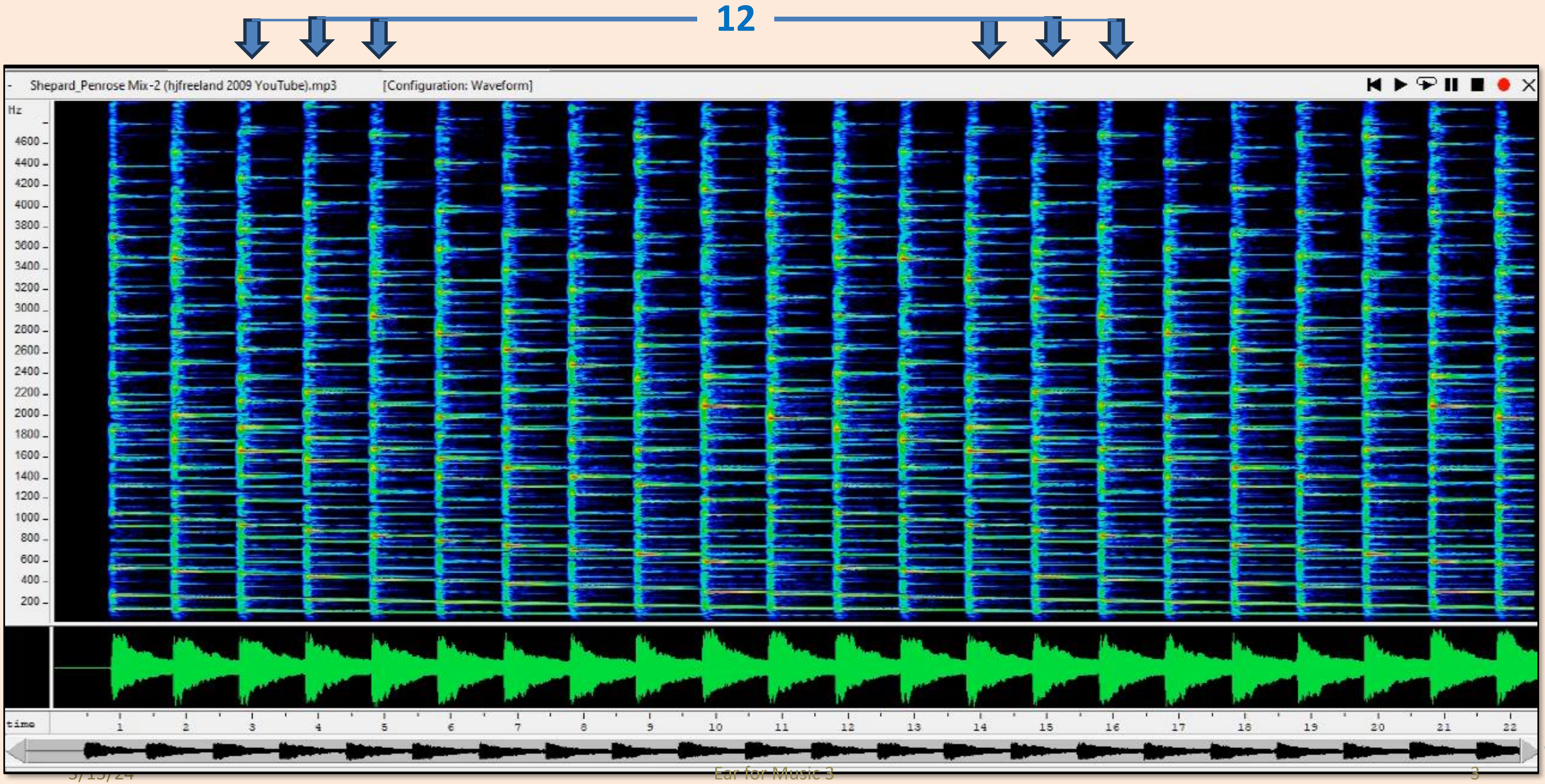
Session 3
Hearing and the Ear

OLLI at Illinois

Spring 2024

D. H. Tracy

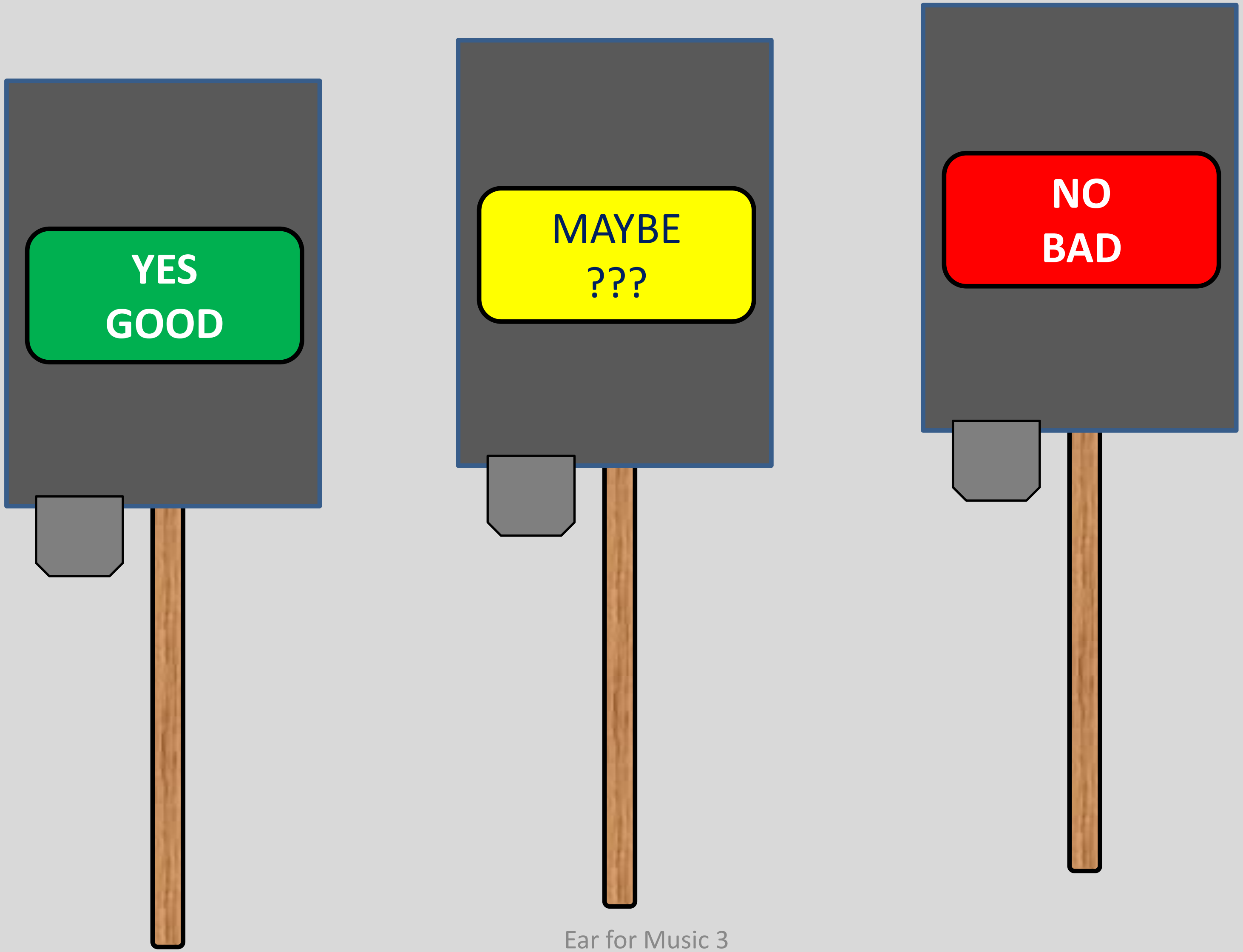
Spectrogram of Shepard/Penrose Mix-2

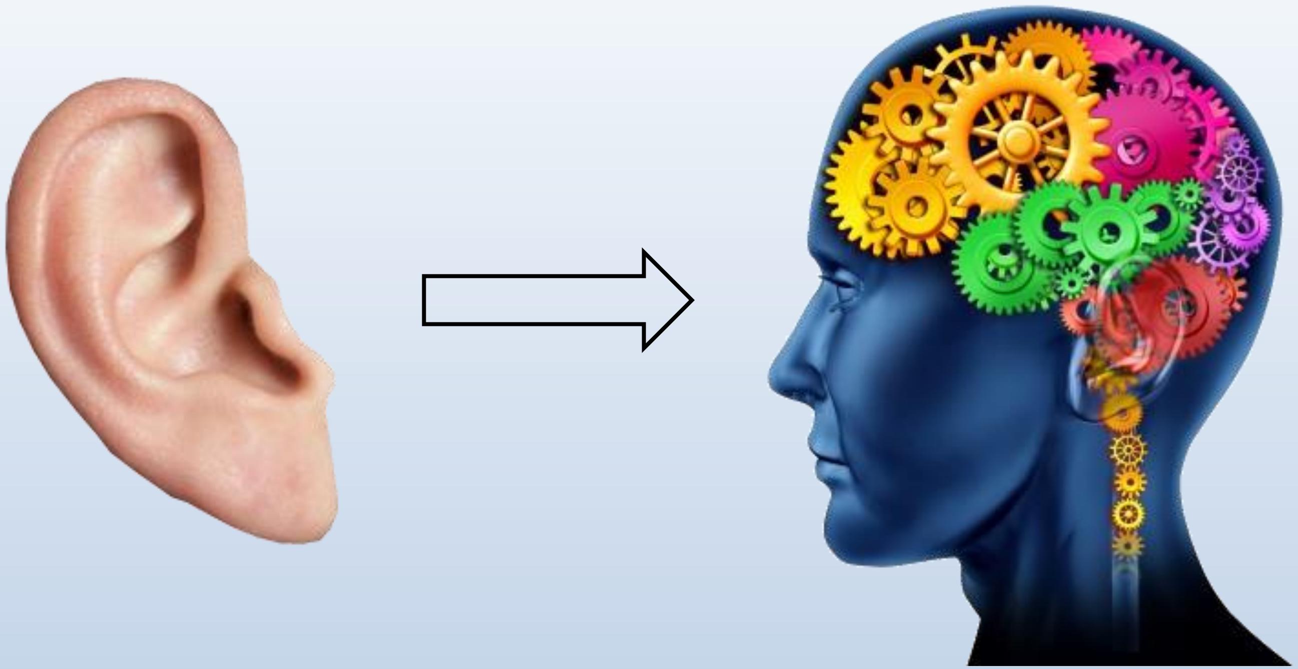


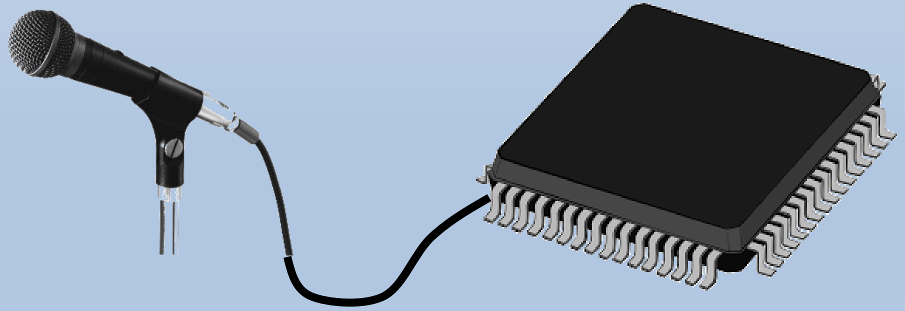
Course Outline

1. Building Blocks: Some basic concepts
2. Resonance: Building Complex Sounds
3. **Hearing and the Ear**
4. Musical Scales
5. Musical Notation; String Instruments
6. Timbre and Pipe Instruments
7. Human Voice and Singing
8. Harmony and Dissonance; Chords

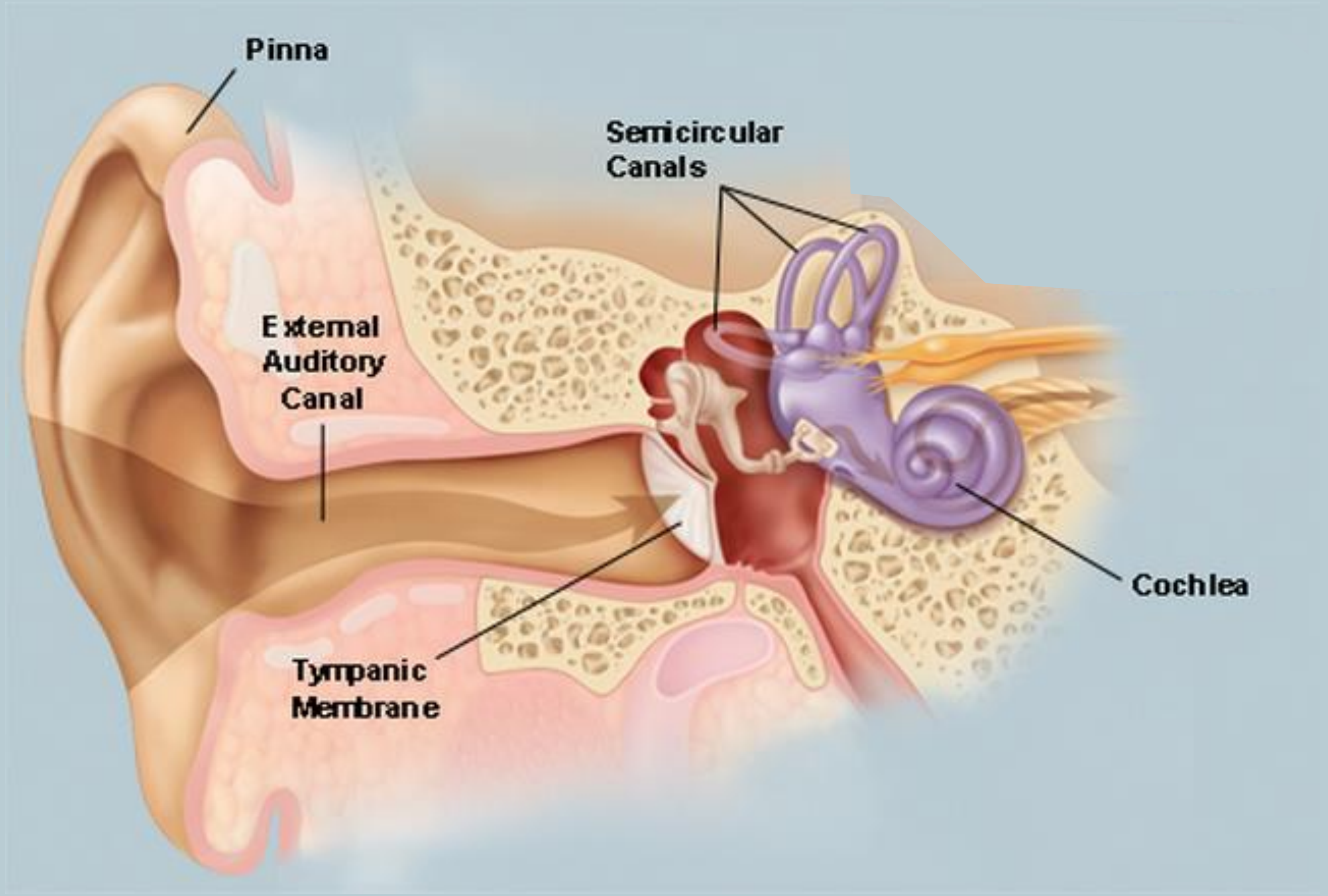
OLLI-Vote Wands





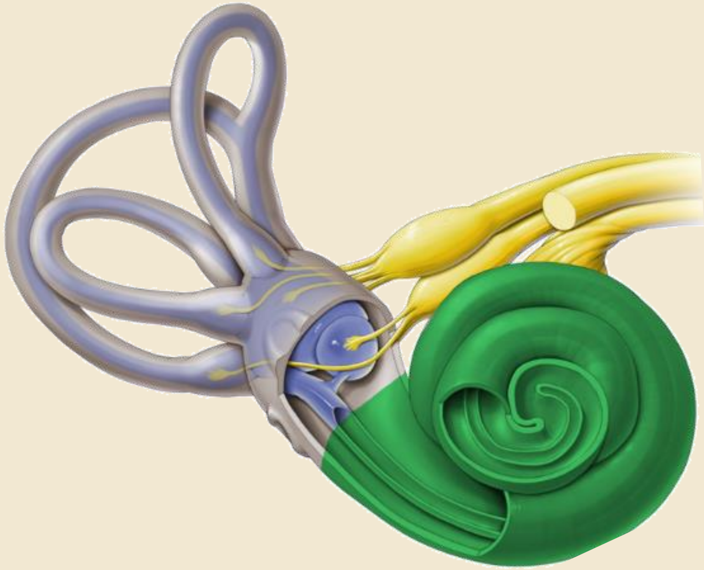


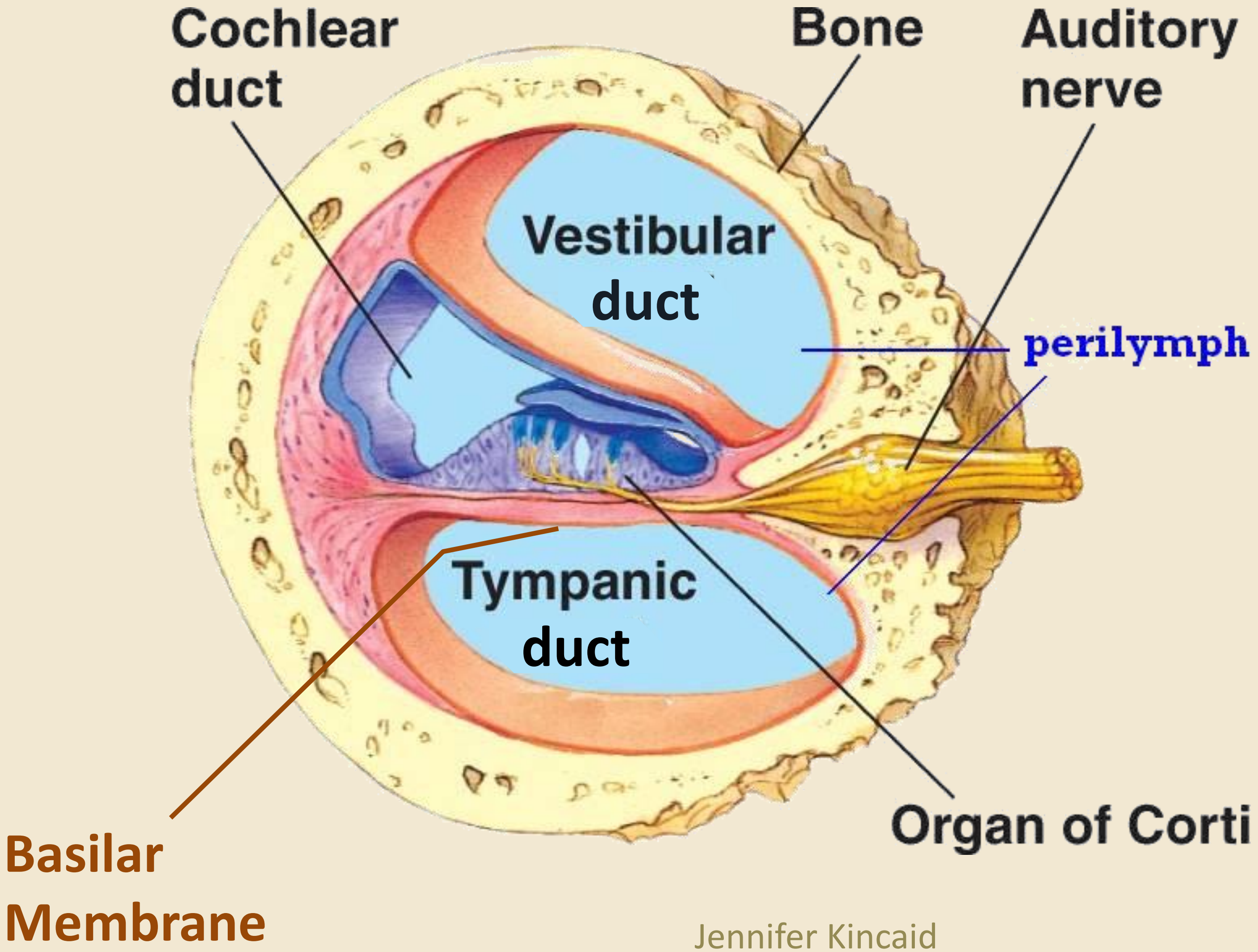
Human Ear


Pinna
Semicircular Canals
External Auditory Canal
Cochlea
Tympanic Membrane

Brandon Pletsch (2002) Medical College of Georgia

Detailed Look at the Cochlea





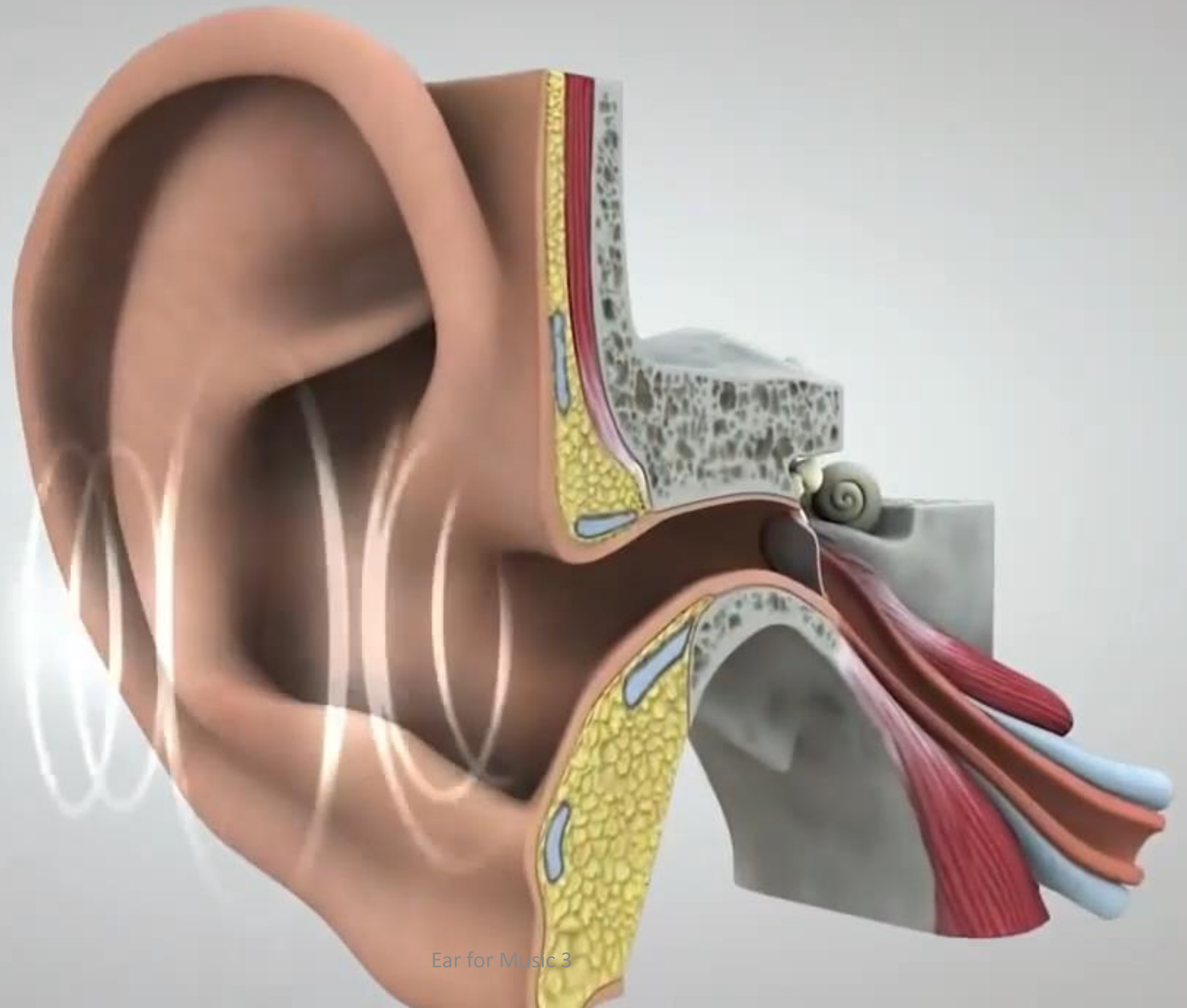
Jennifer Kincaid

Another Cartoonish look at ear….

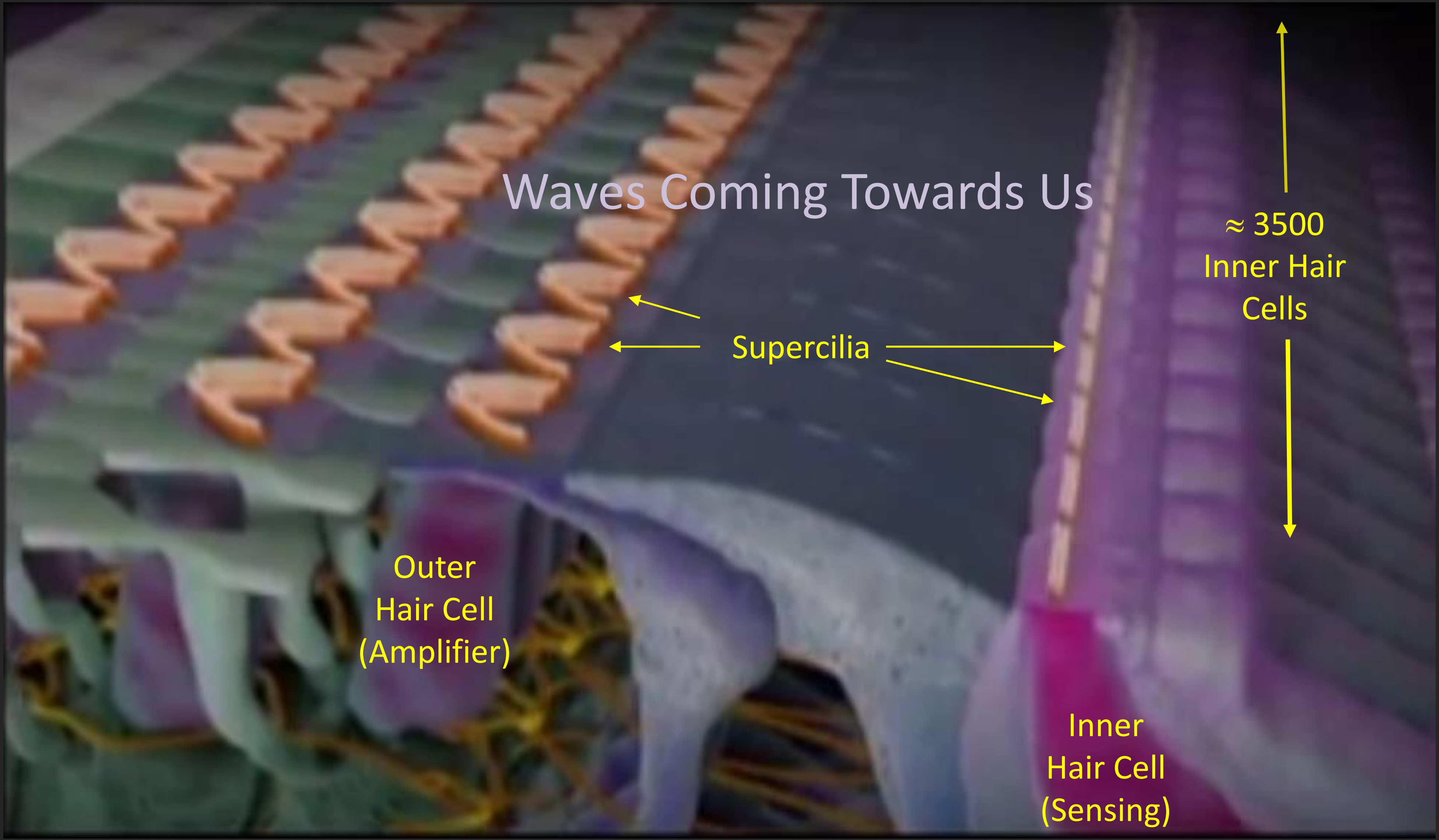
“Journey of Sound to the Brain”

NIH - 2017

[Wikimedia|Cochlea]



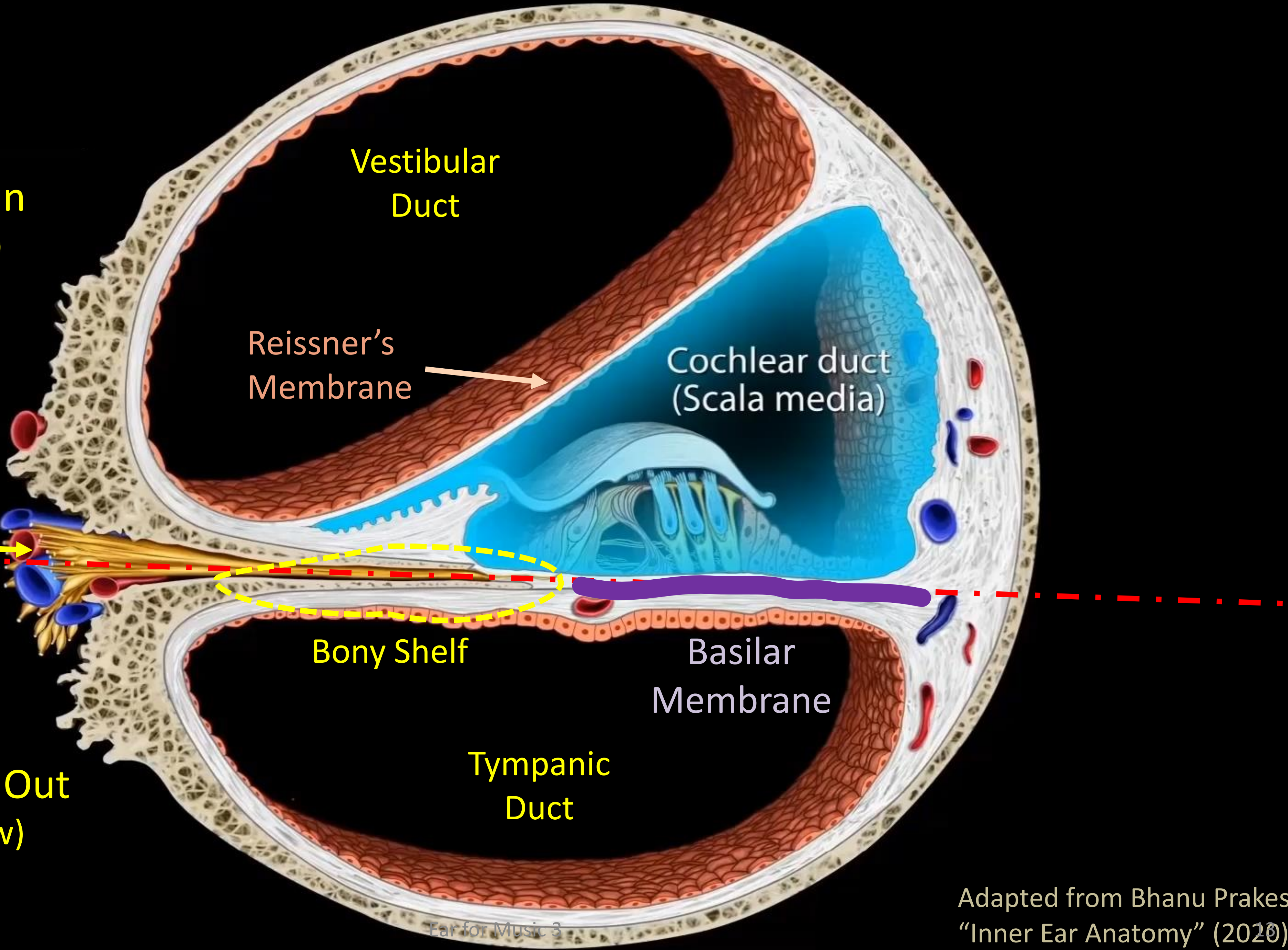
Detailed Look at the Organ of Corti



INTERNAL EAR

Sound Vibrations In
(*from* Oval Window)

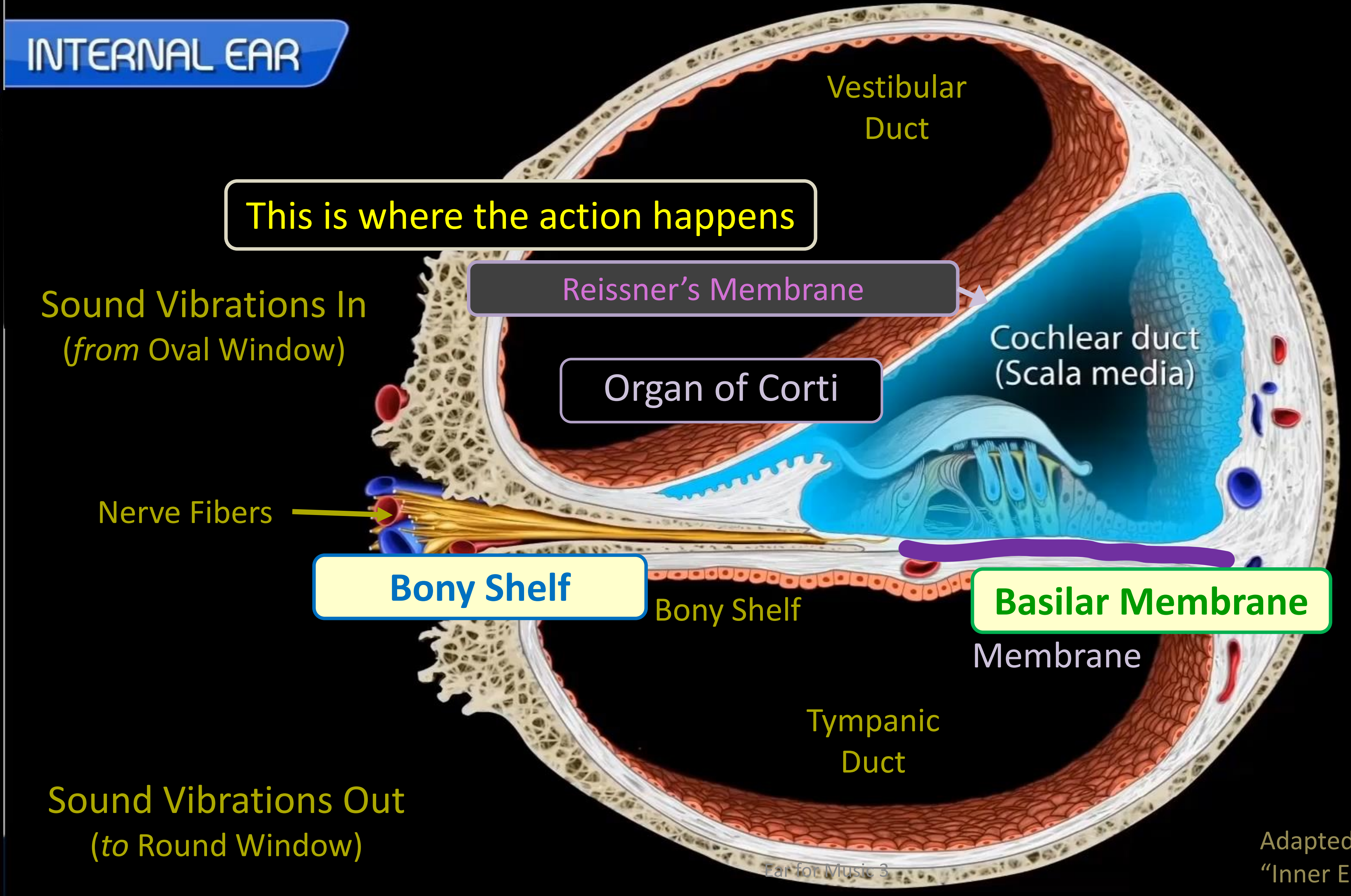
Nerve Fibers



Sound Vibrations Out
(*to* Round Window)

Adapted from Bhanu Prakesh, "Inner Ear Anatomy" (2020)

INTERNAL EAR



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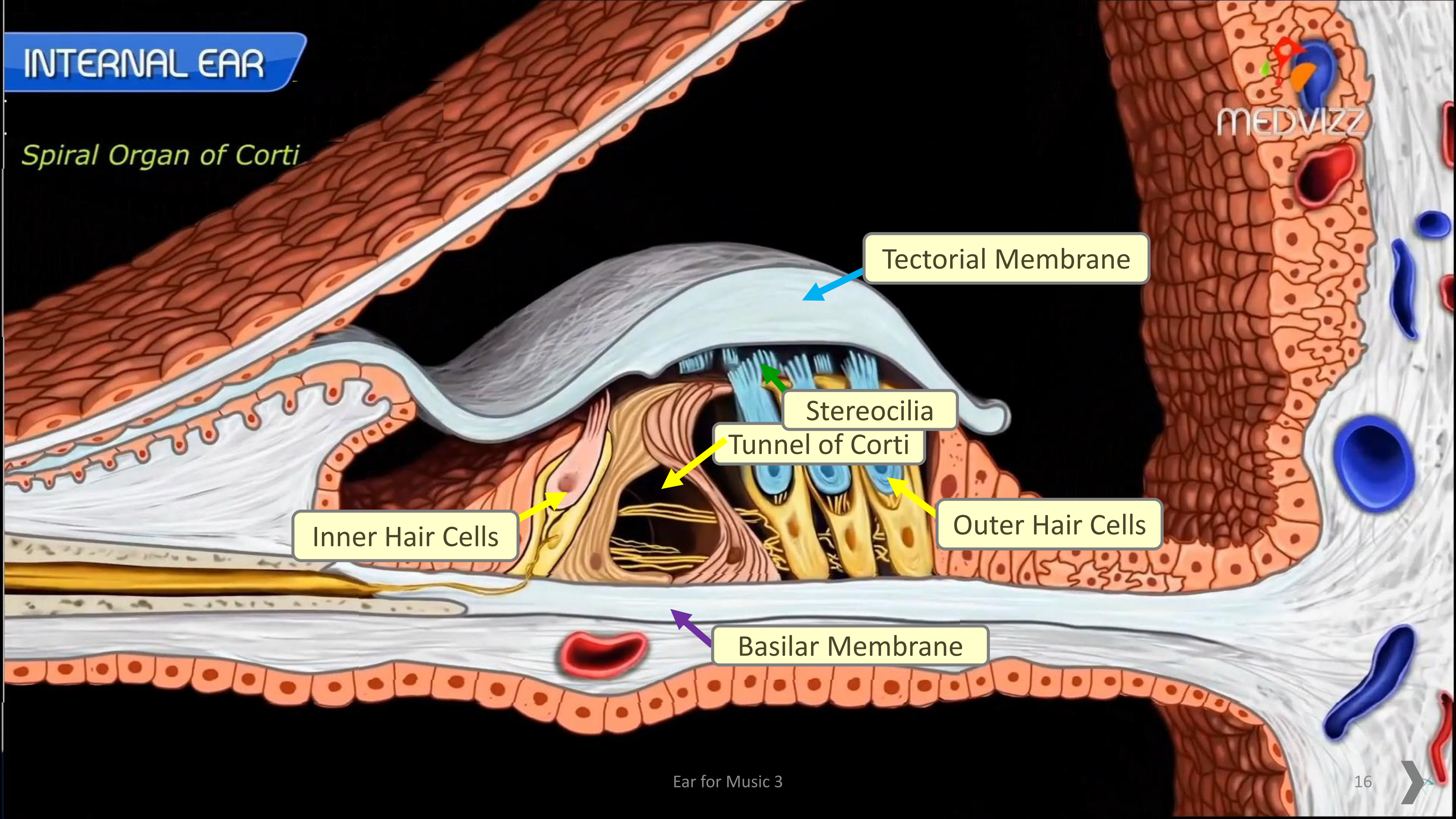
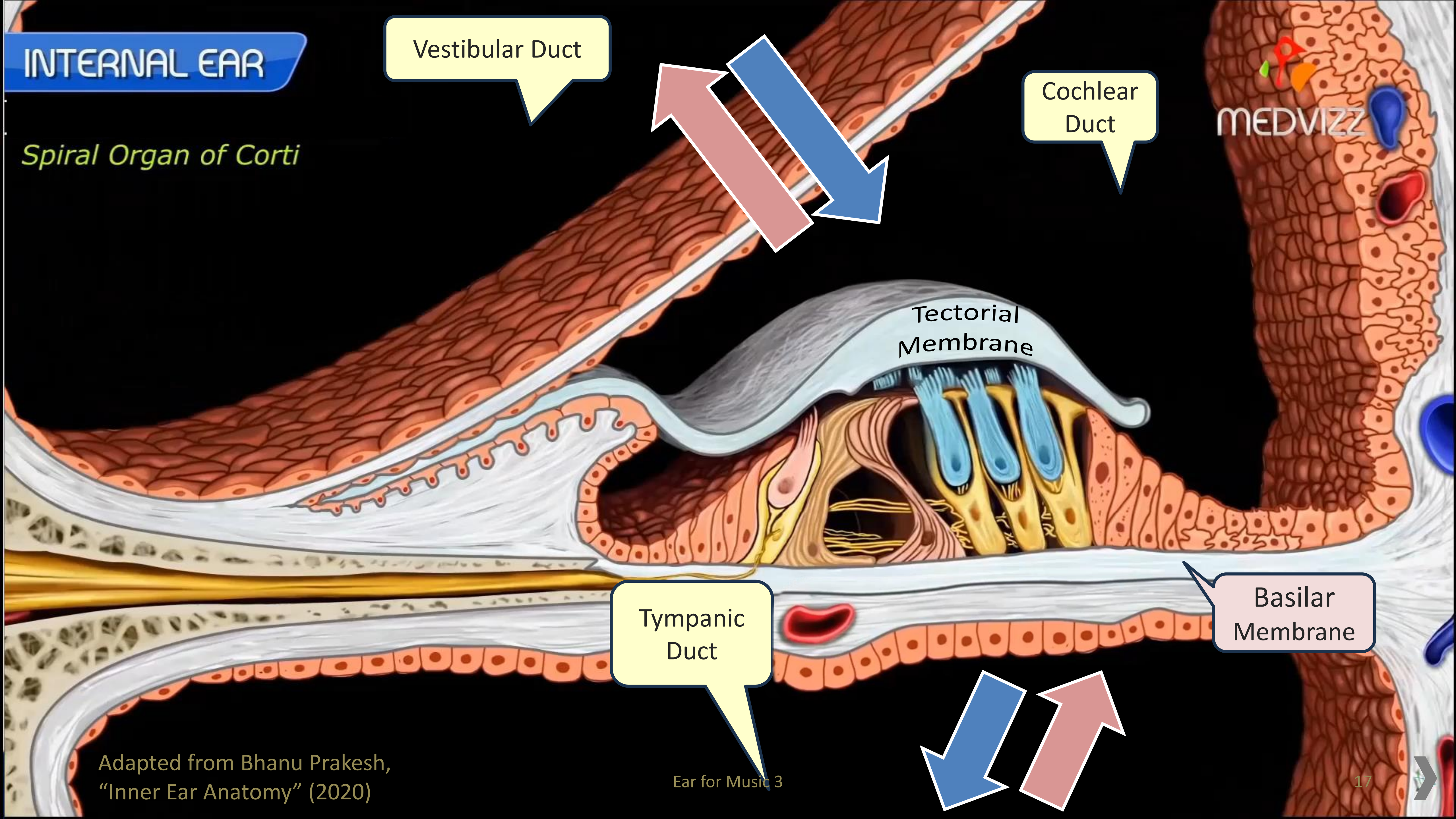

INTERNAL EAR
Spiral Organ of Corti
MEDVIZZ
Tectorial Membrane
Stereocilia
Tunnel of Corti
Inner Hair Cells
Outer Hair Cells
Basilar Membrane



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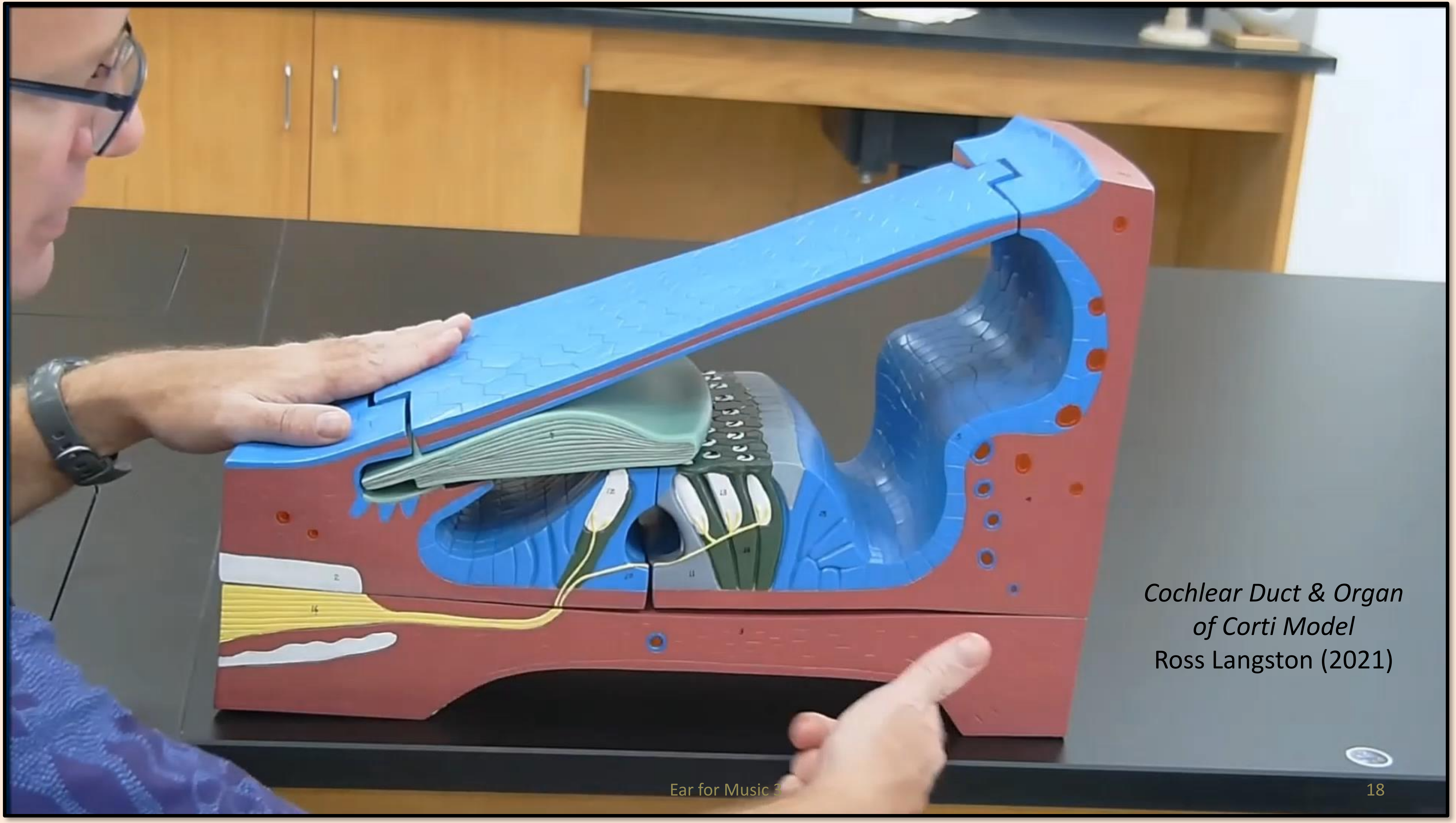


Cochlear Duct & Organ of Corti Model
Ross Langston (2021)

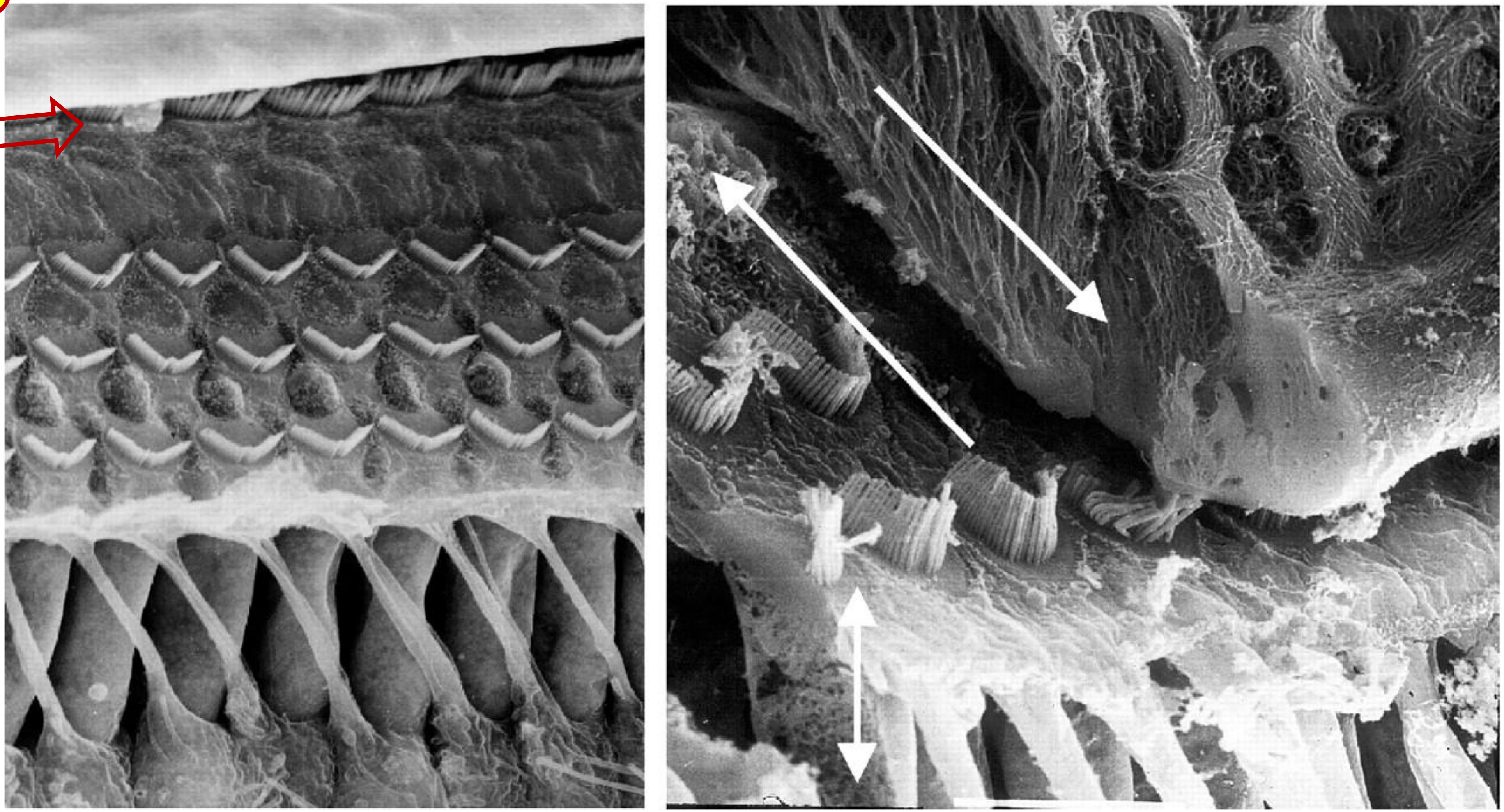
Tectorial Membrane Peeled Back

Not touching Tectorial Membrane

Inner Hair Cells

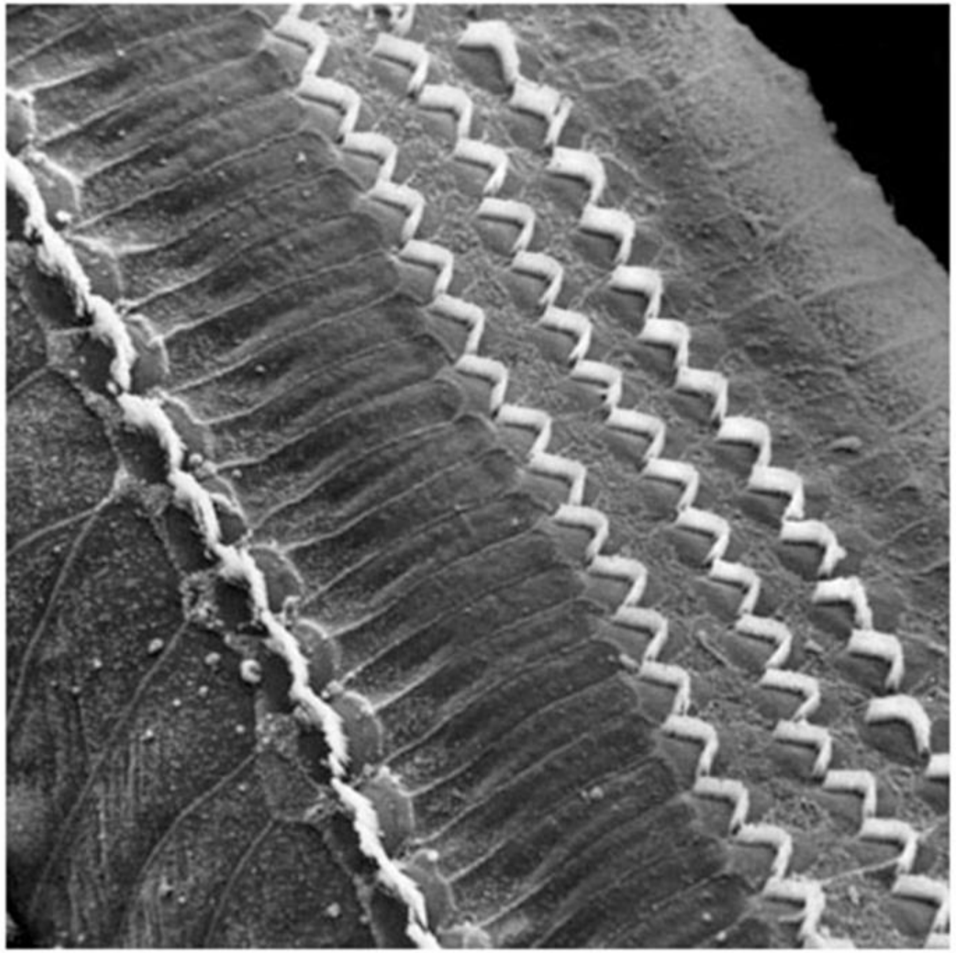
Outer Hair Cells

Attached to Tectorial Membrane

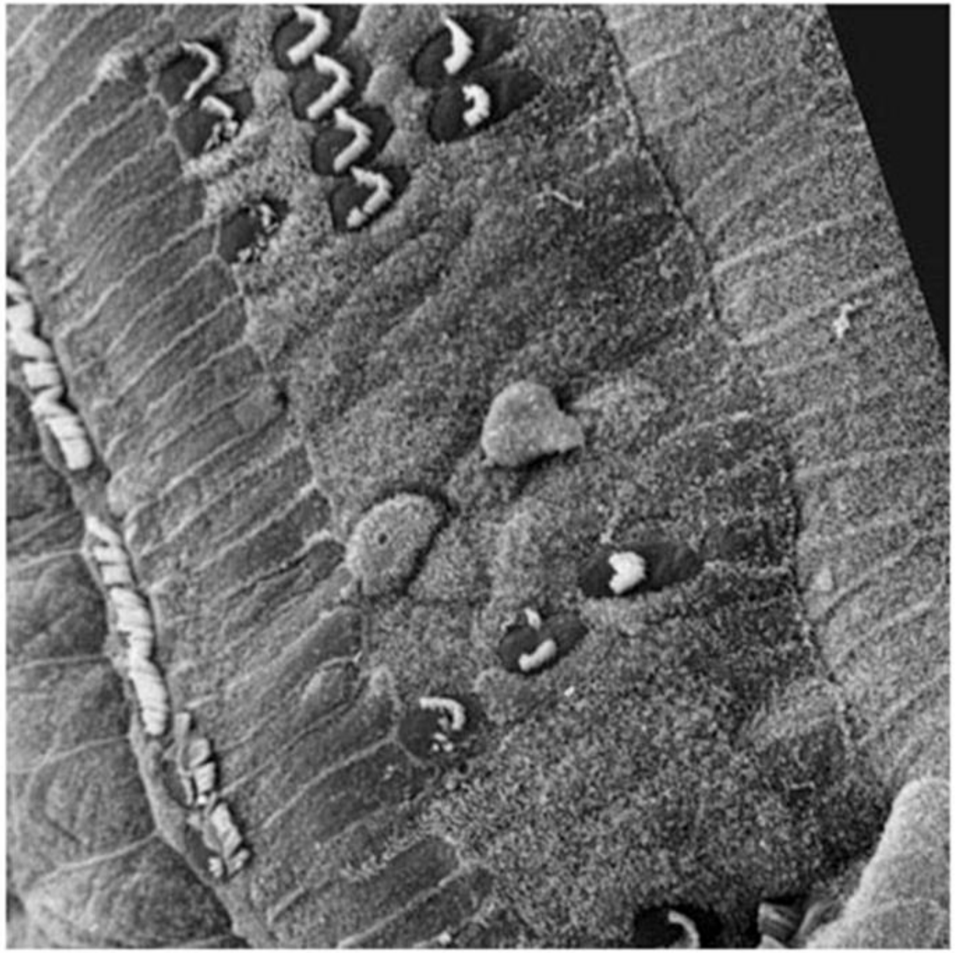


SEM Images by Andrew Forge
Univ. College London

Severe Damage

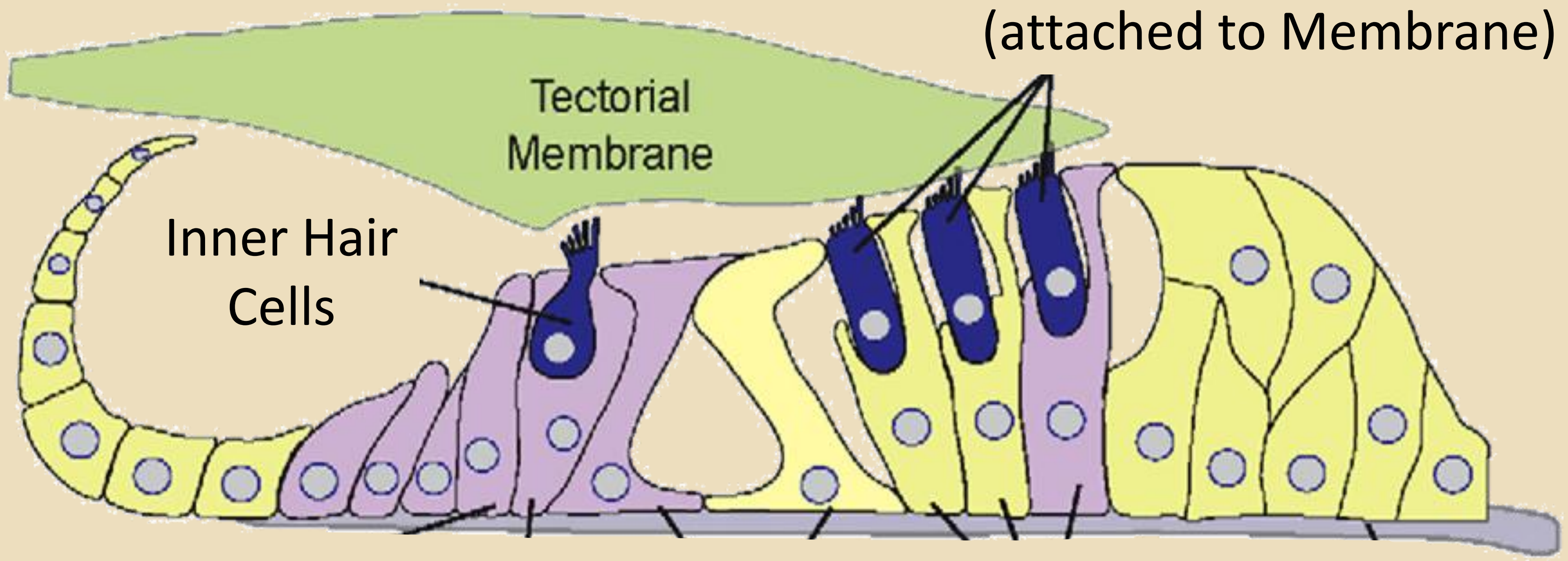


Intact cochlea

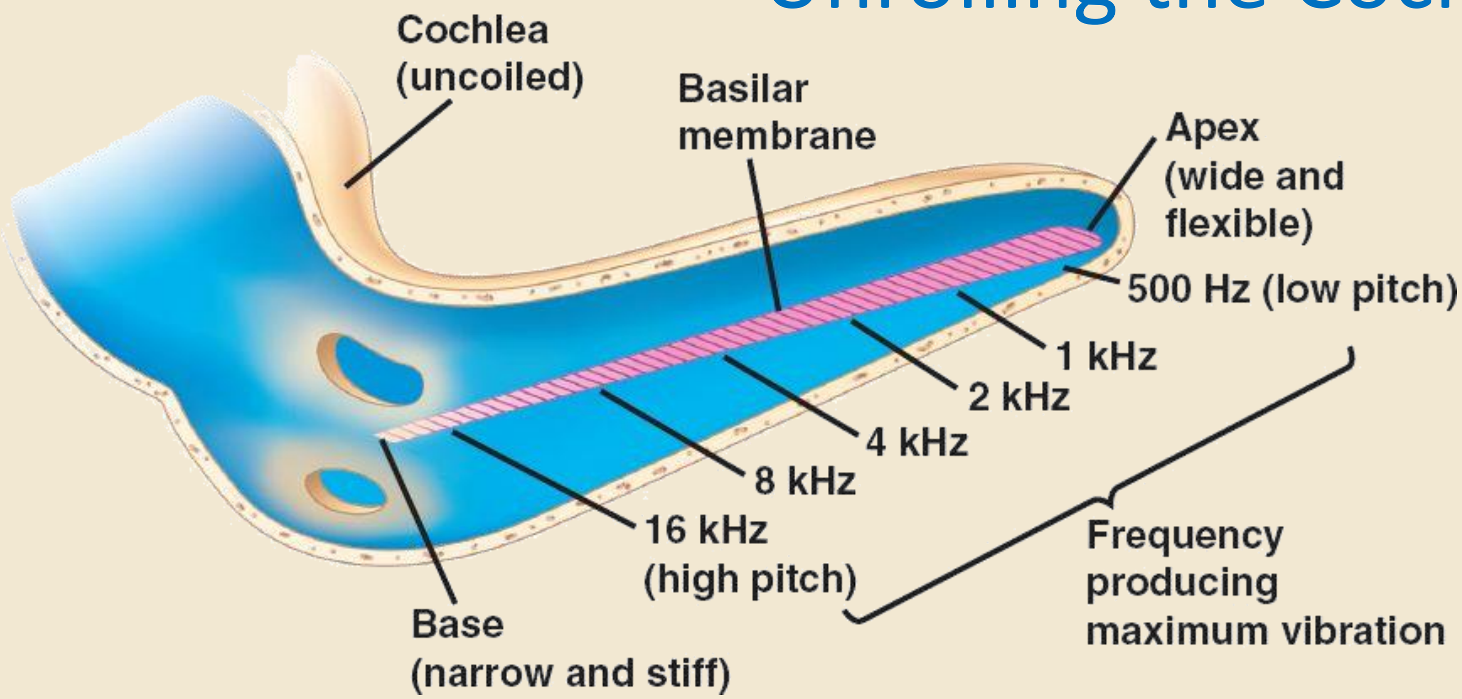


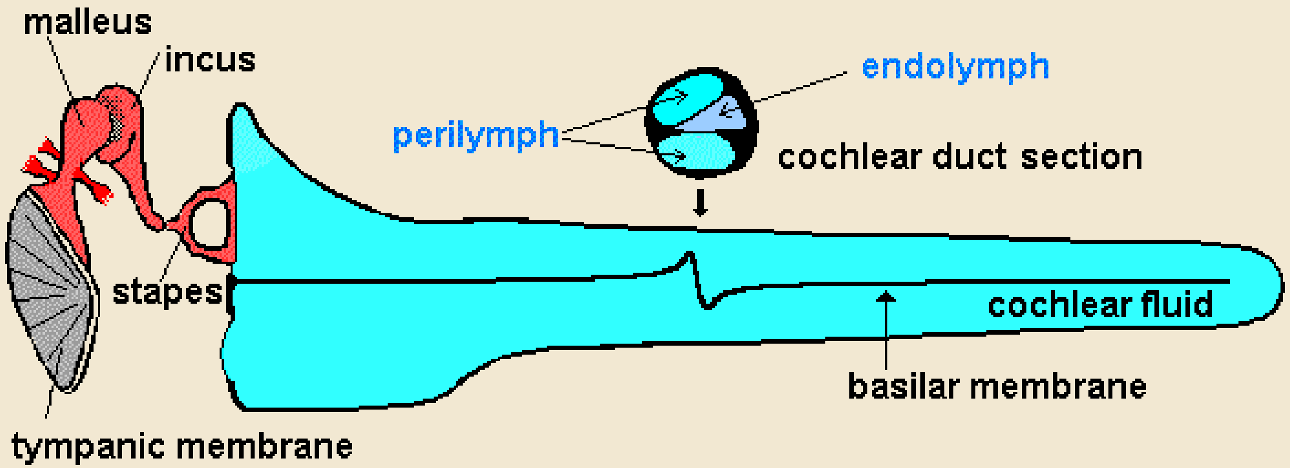
Damaged cochlea

Outer Hair Cells Shake the Tectorial Membrane



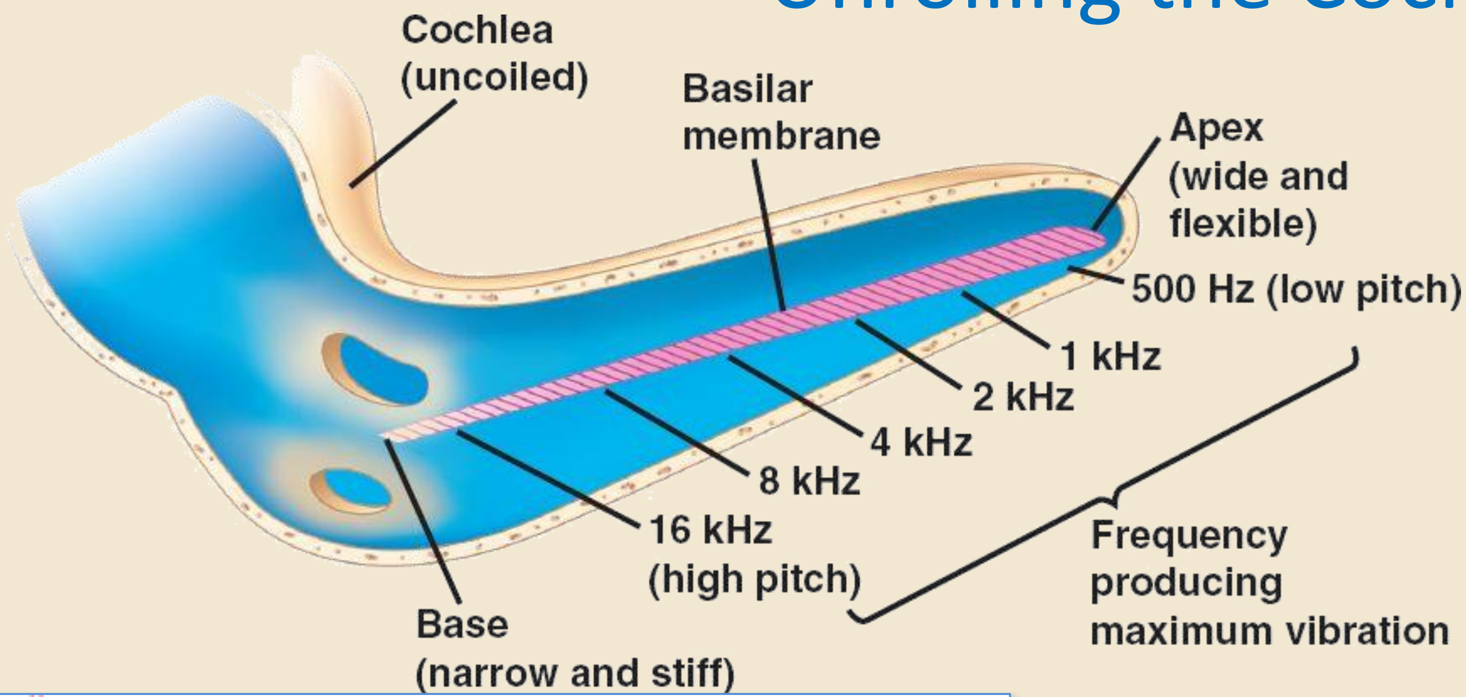
Unrolling the Cochlea



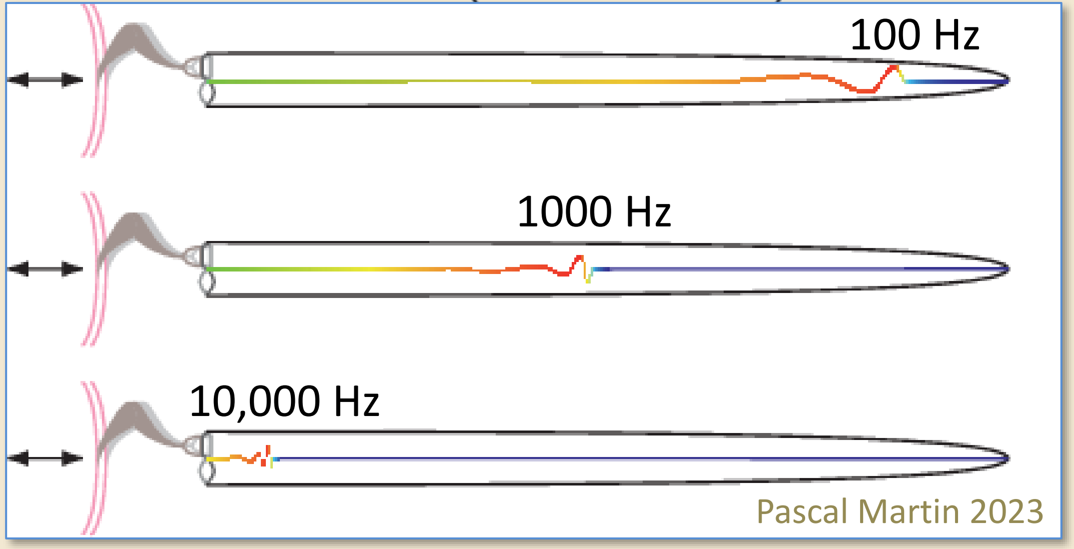


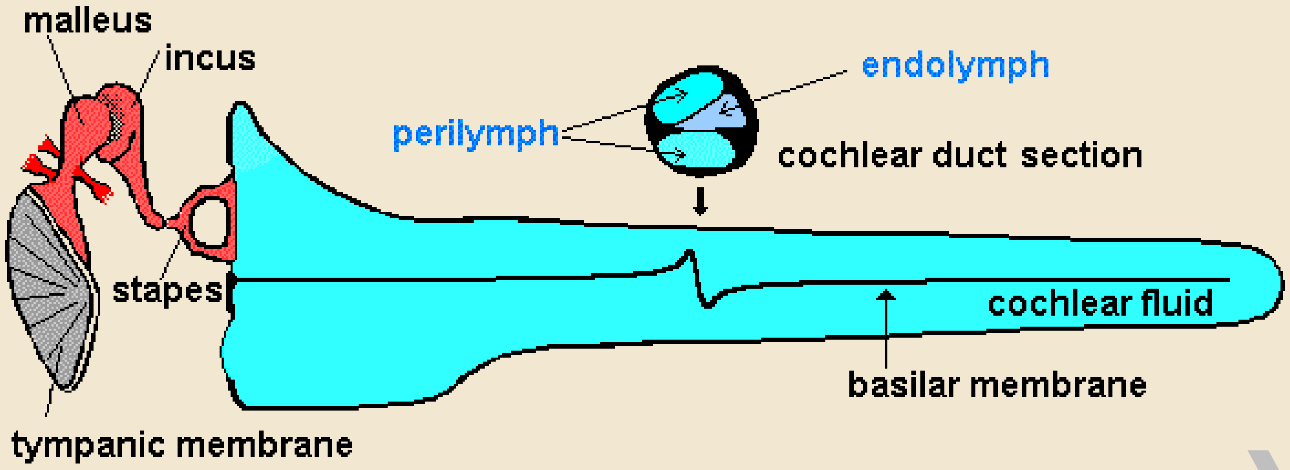
Unrolling the Cochlea

This physical behavior is not obvious!



Herman von Helmholtz
ca. 1863





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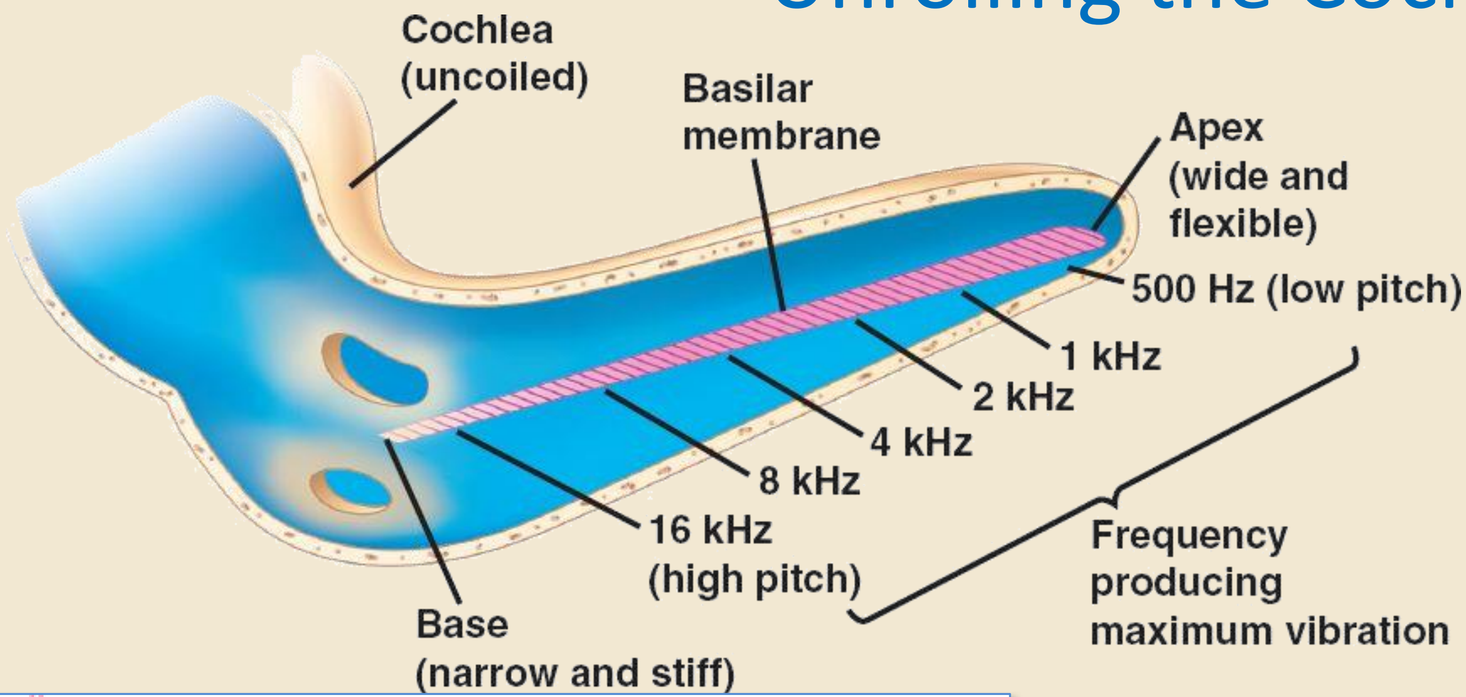
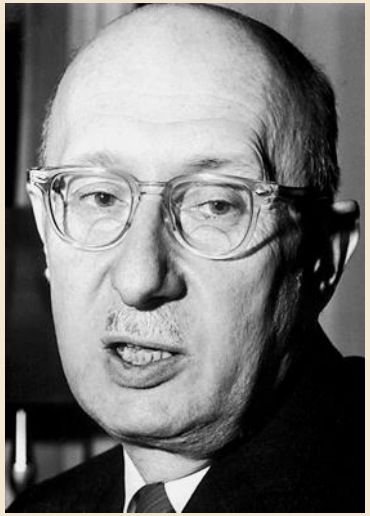
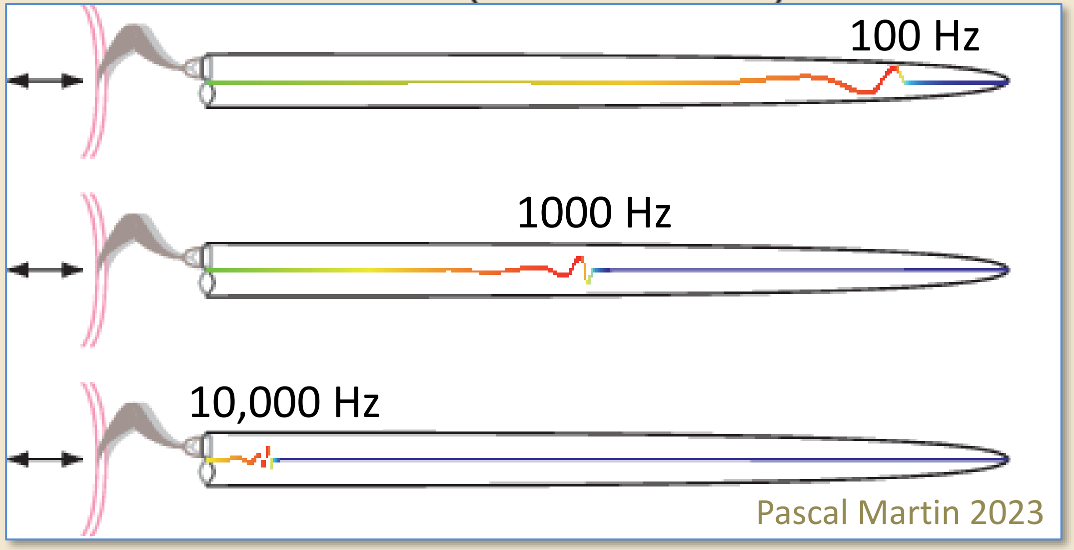
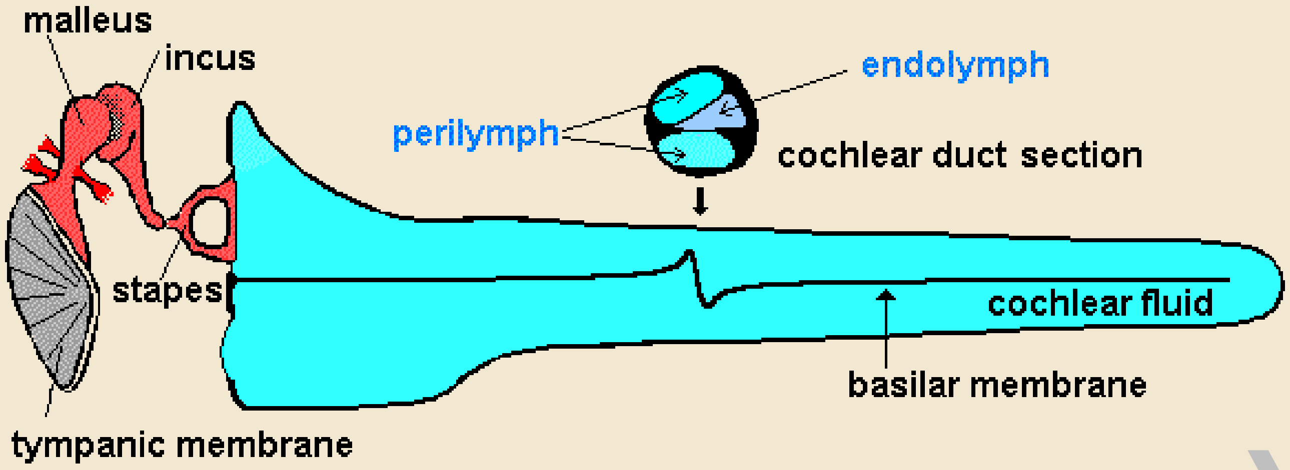


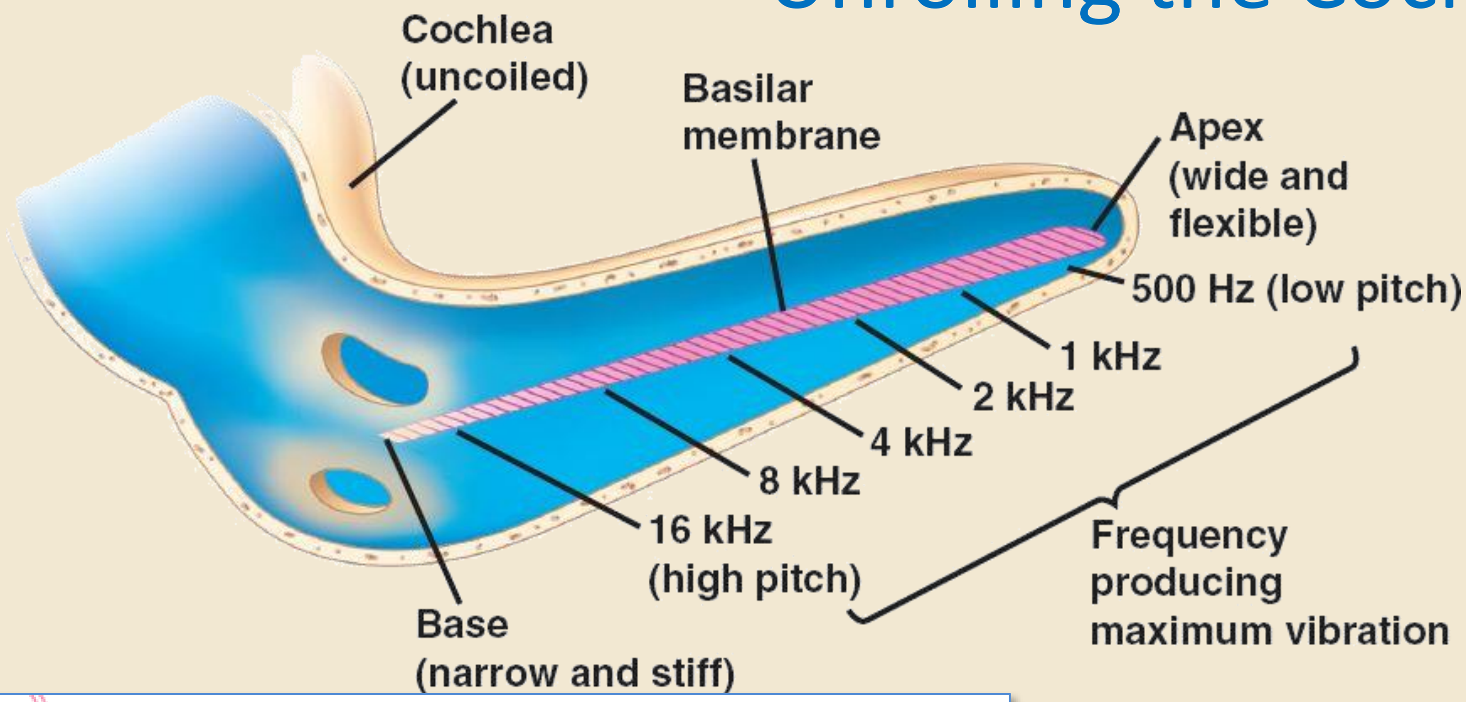


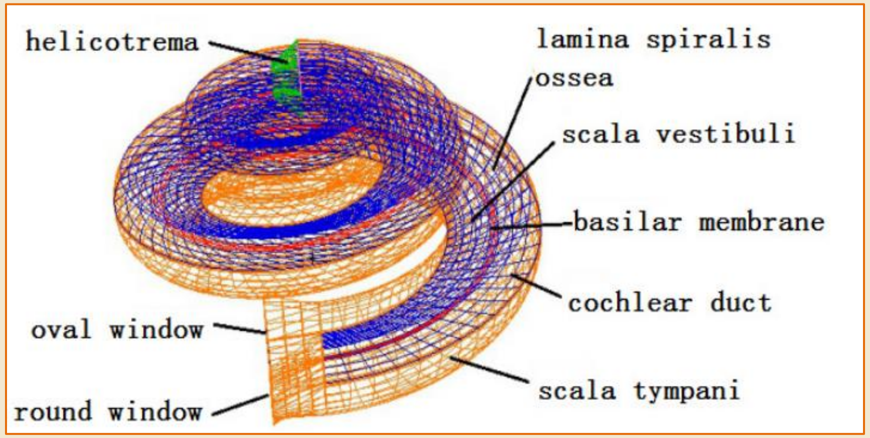
Georg von Békésy
Nobelist Physiology
1961



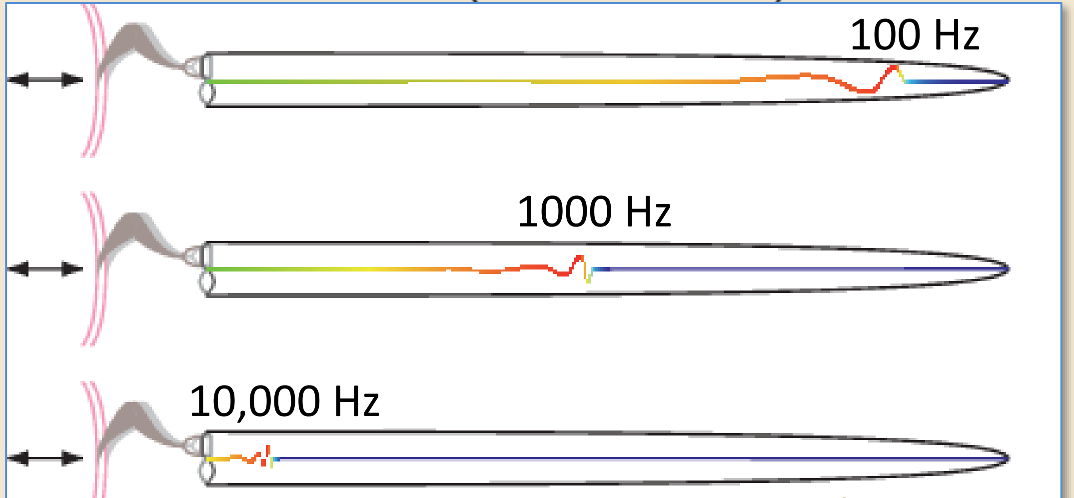


Unrolling the Cochlea

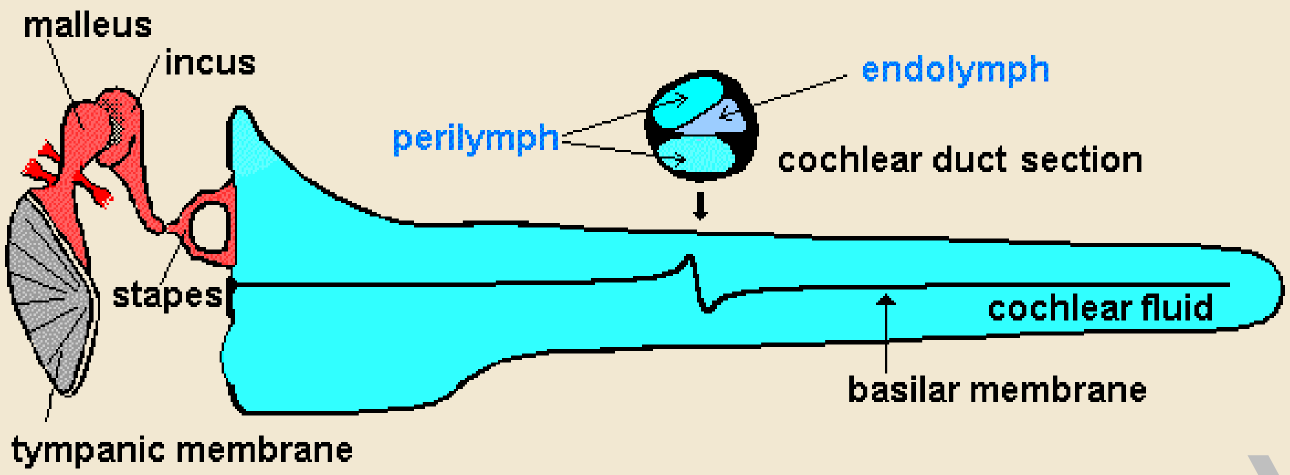




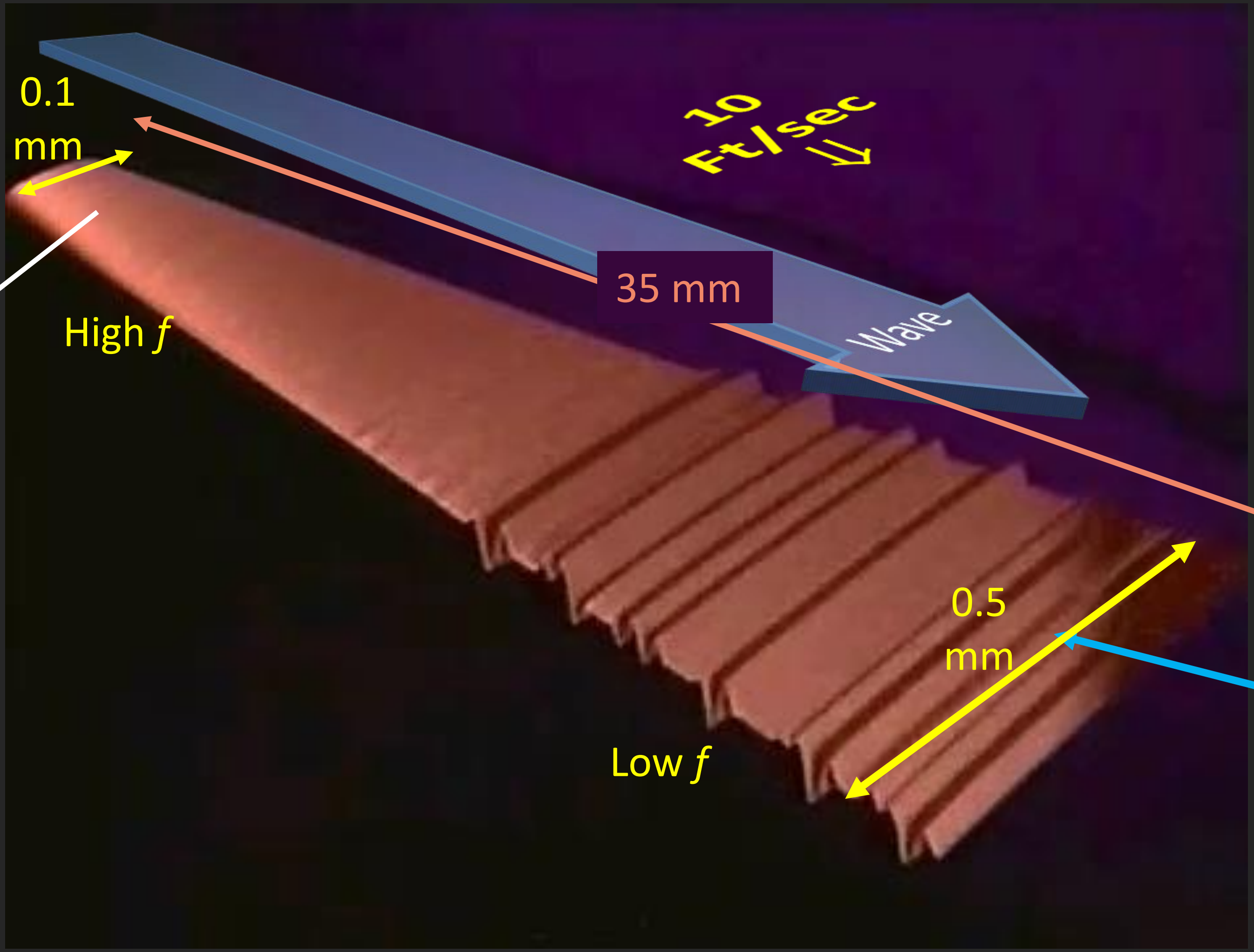
Tang, Shen et al 2017



Pascal Martin 2023



Unrolling the Cochlea

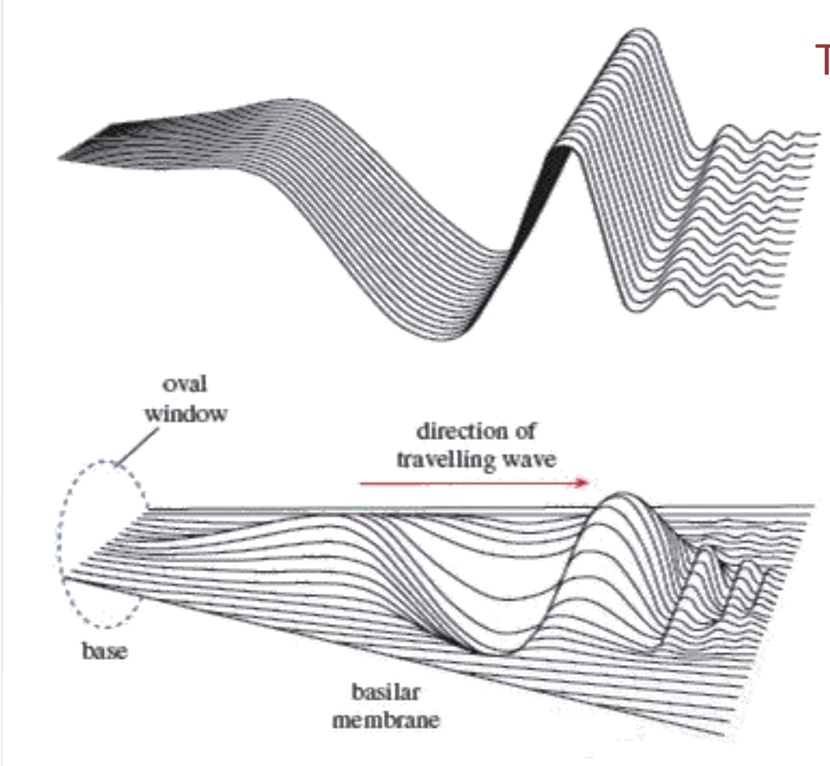


10,000 x
Stiffer!

Basilar
Membrane

Howard Hughes Medical Institute

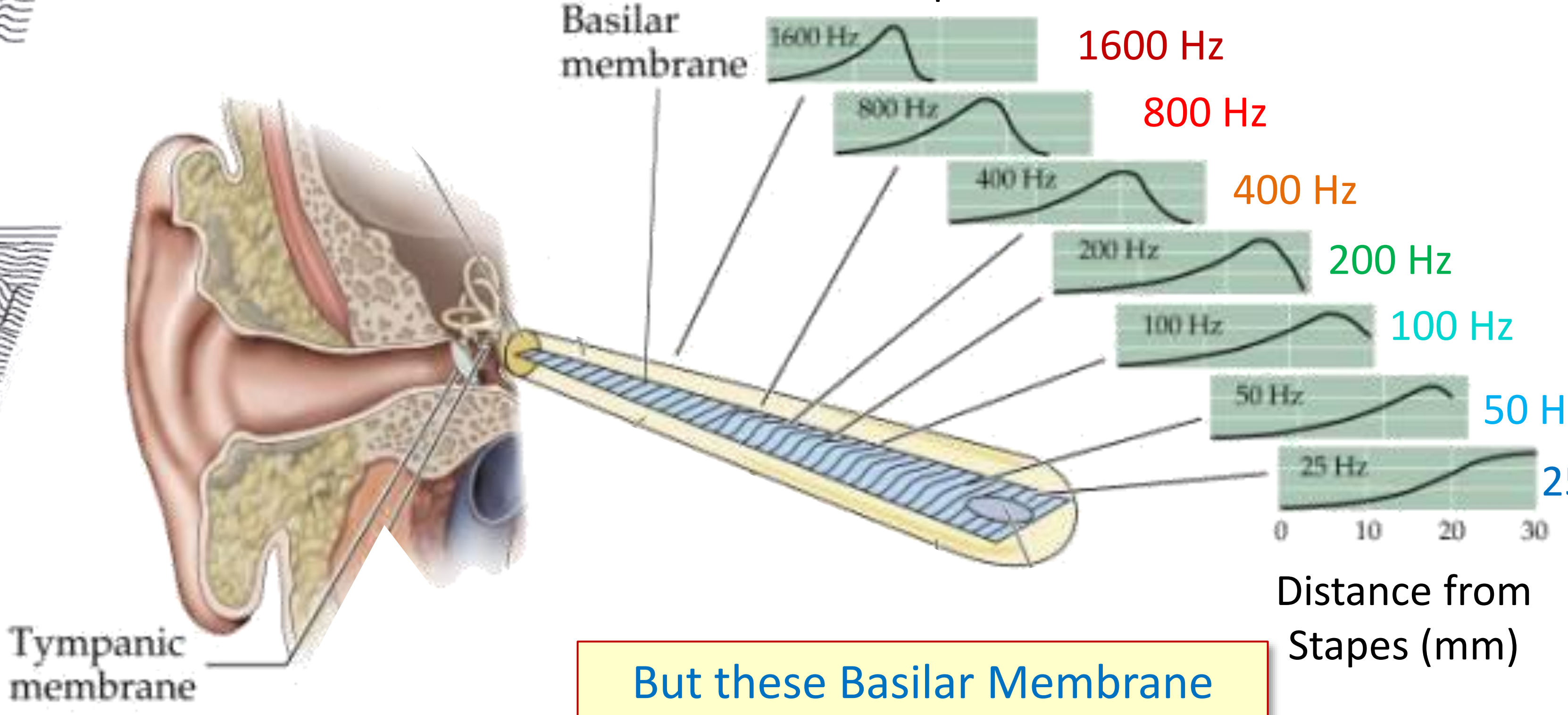
"Traveling Wave" on Basilar Membrane



Traveling wave moves slowly – ~1% of speed of sound in air

Very poor frequency discrimination!

Relative Amplitudes



1600 Hz

800 Hz

400 Hz

200 Hz

100 Hz

50 Hz

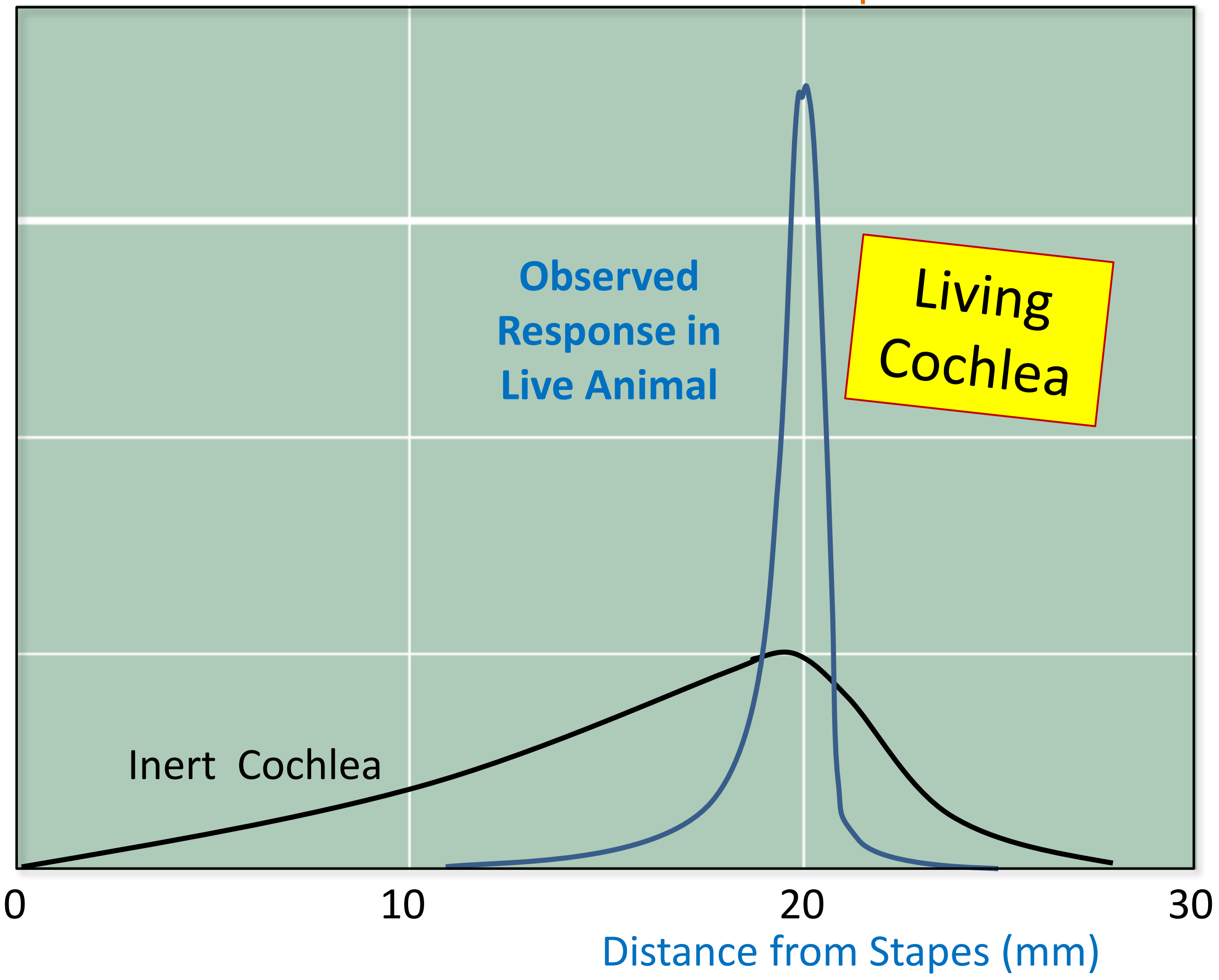
25 Hz

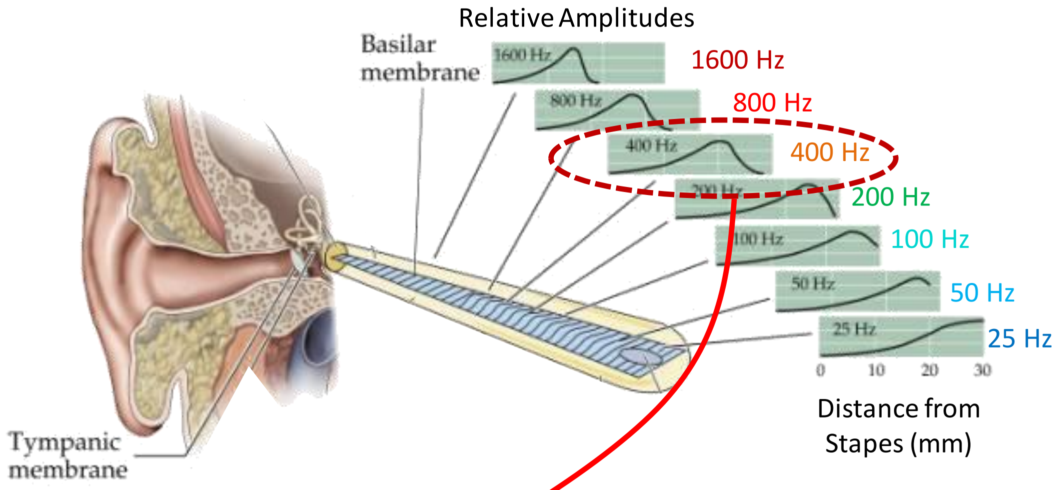
Distance from Stapes (mm)

But these Basilar Membrane responses were measured on "dead" Cochleas…

But Something Magic Happens in Live Cochlea…

400 Hz Basilar Membrane Response





Why?

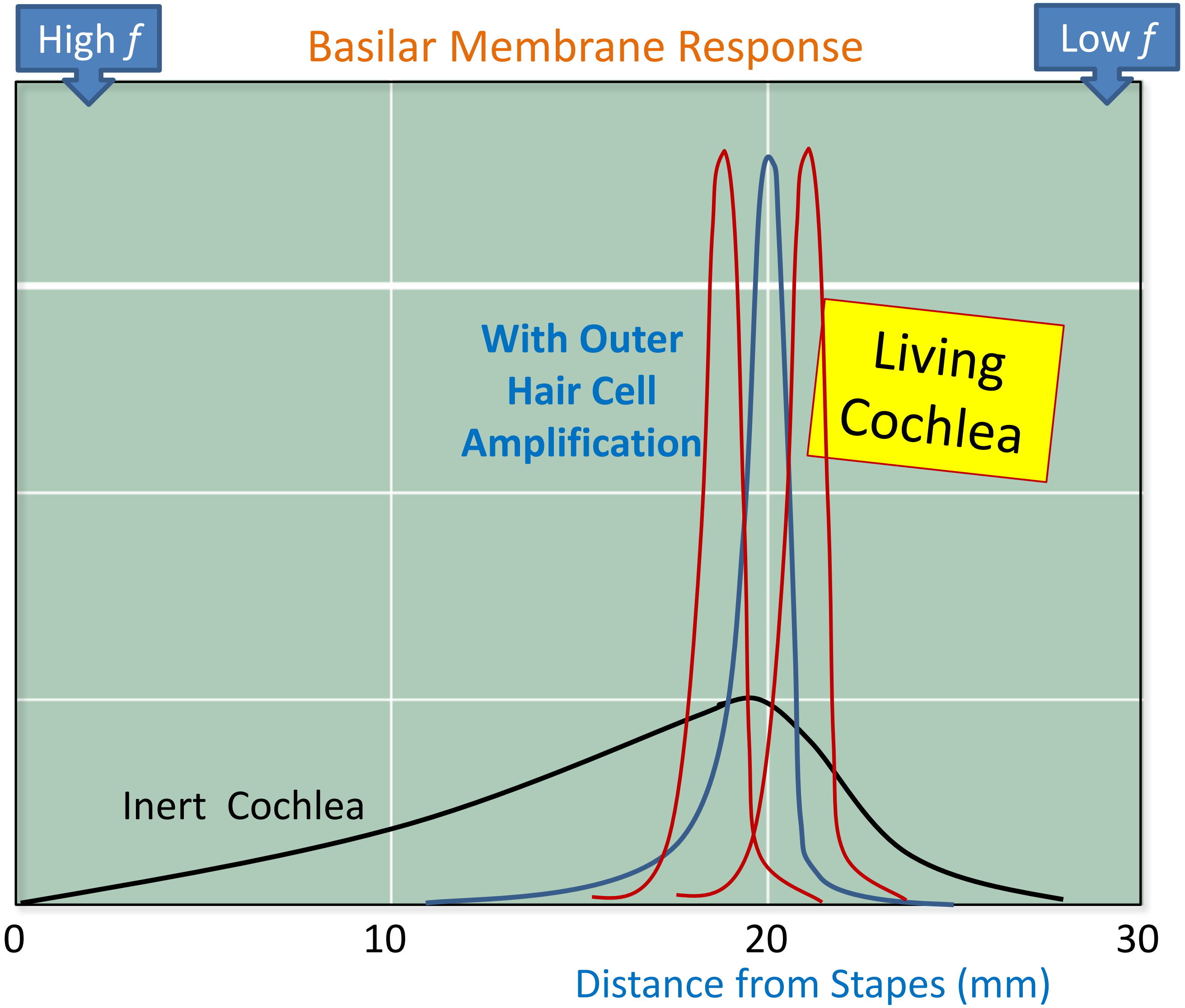
Probably due to active intervention by motile outer hair cells

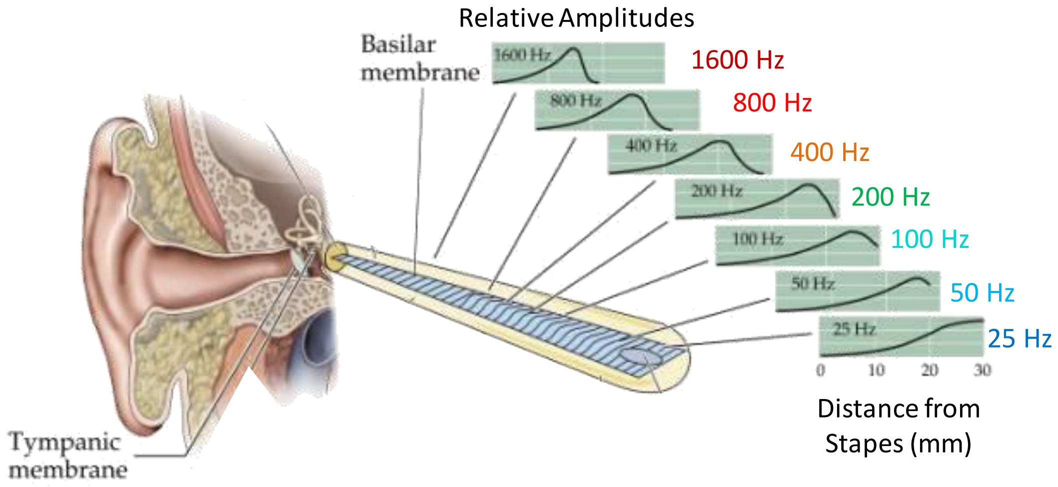
Dancing Outer Hair Cell with Stereocilia

Isolated Guinea Pig Outer Hair Cell with Patch Clamp

J. Santos-Sacchi
Yale University

Dancing Outer Hair Cells to the Rescue



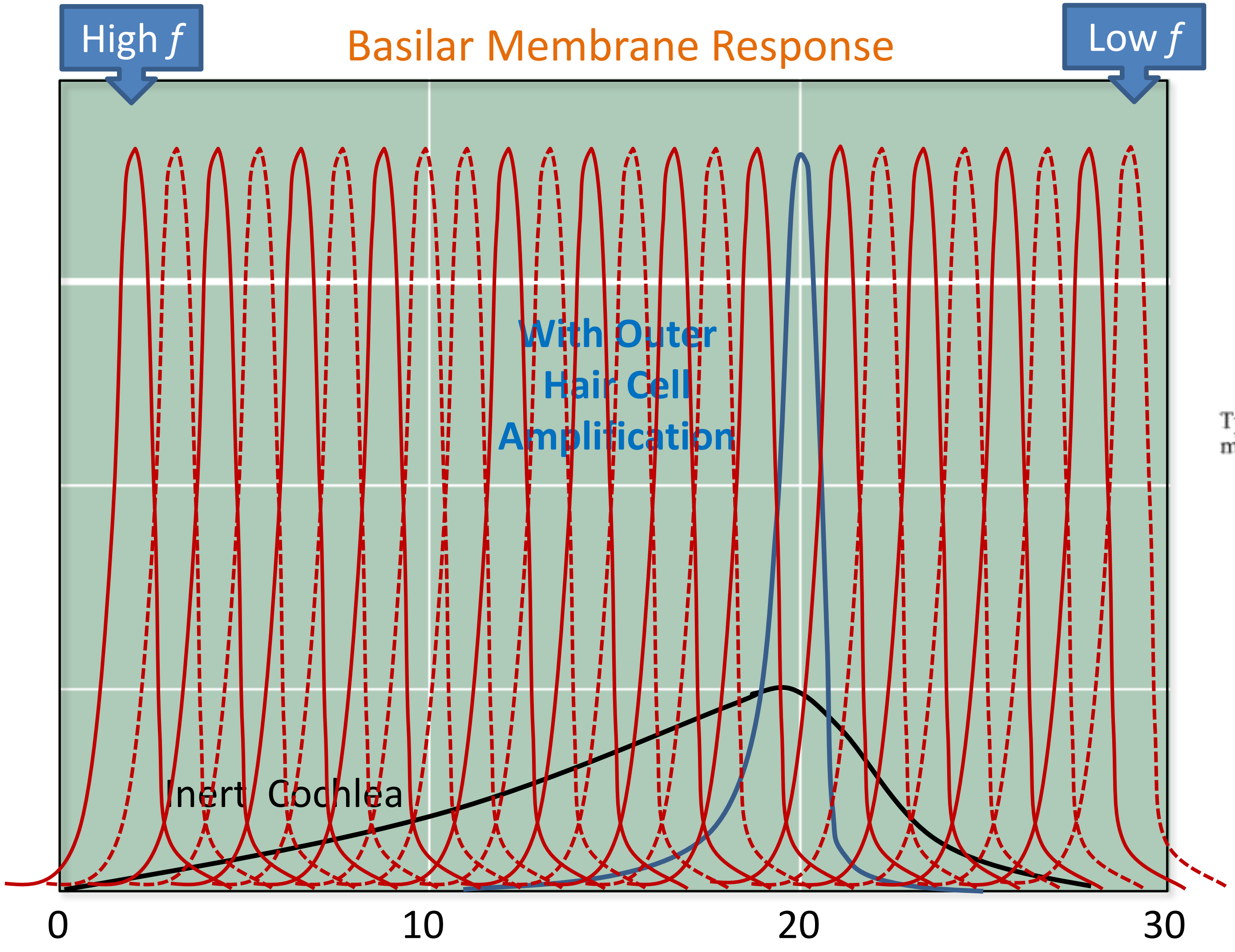


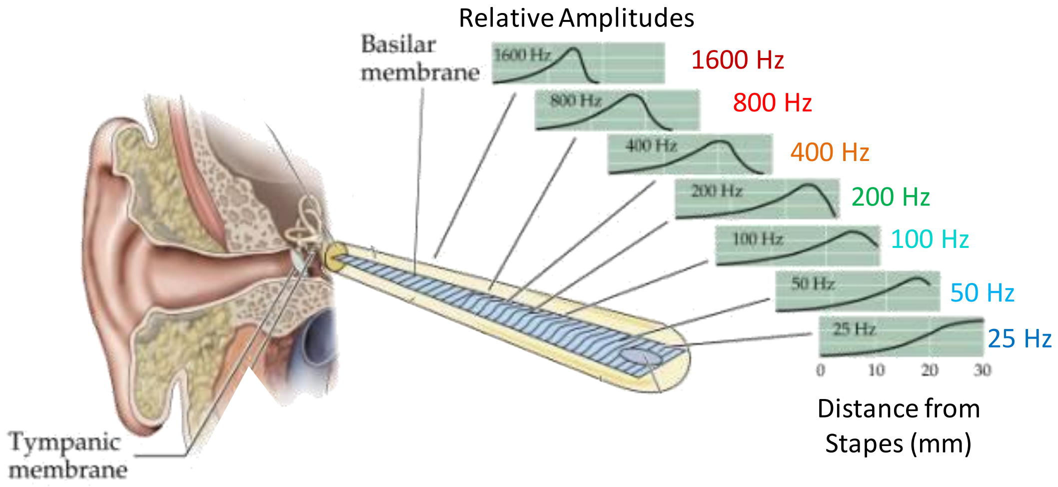
Critical Bands

- ≈ **25** bands across audible spectrum
- ≈ 1.3 mm wide along Basilar Membrane
- ≈ 150 Inner Hair Cells within a band
- Each Inner Hair Cell belongs to a Critical Band
- Frequency range of bands varies:
  - ≈ 100 Hz at low frequencies
  - ≈ 3000 Hz at high end

- Important for understanding Harmony

Dancing Outer Hair Cells to the Rescue





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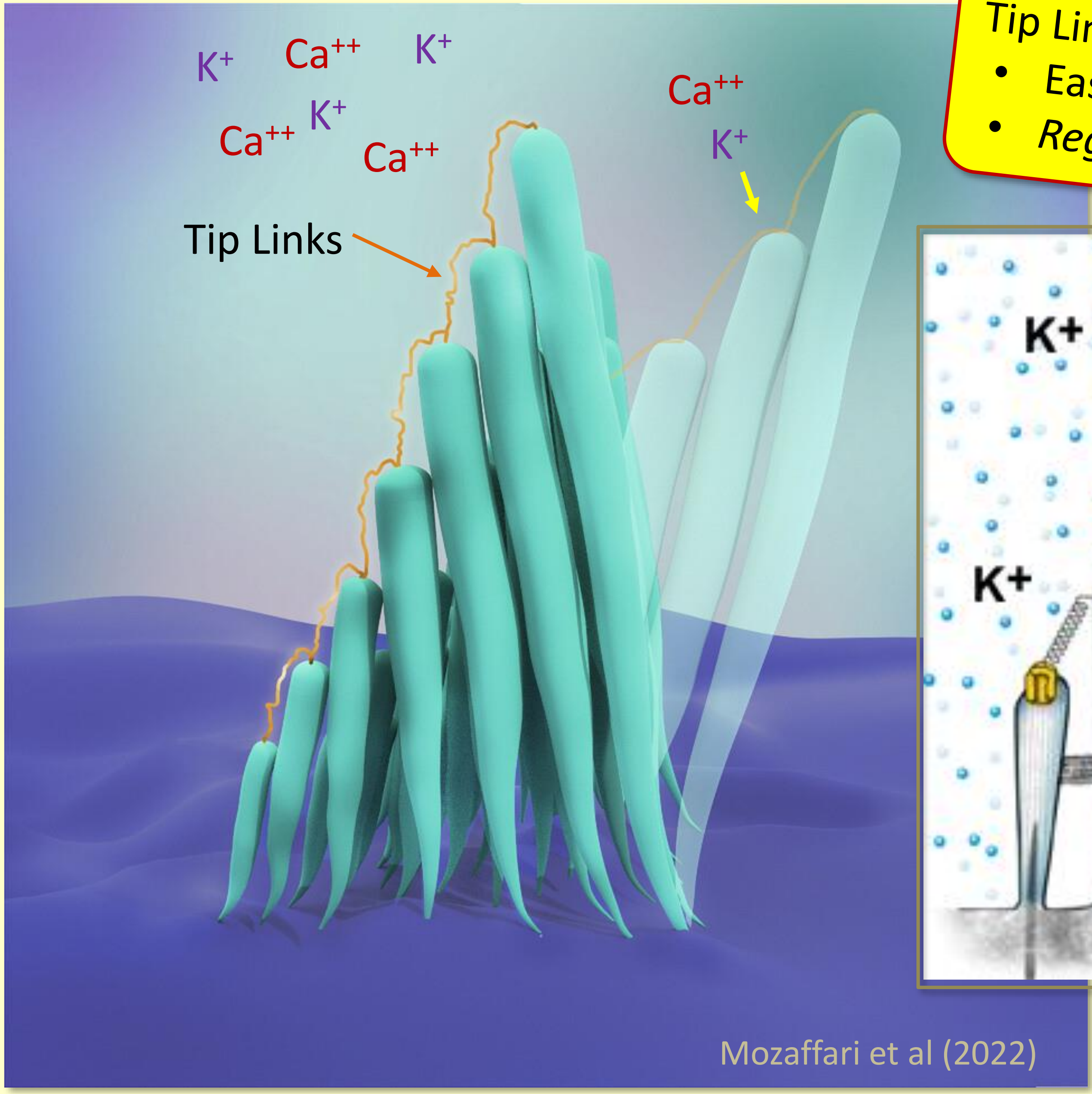
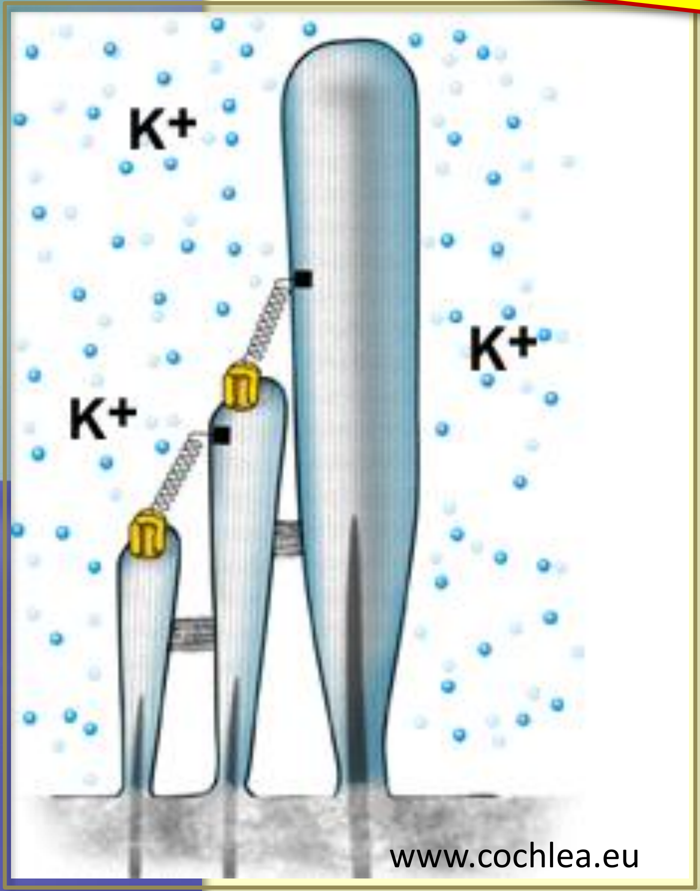
Pushing **Stereocilia** over opens <u>mechanical</u> valves, letting ions enter

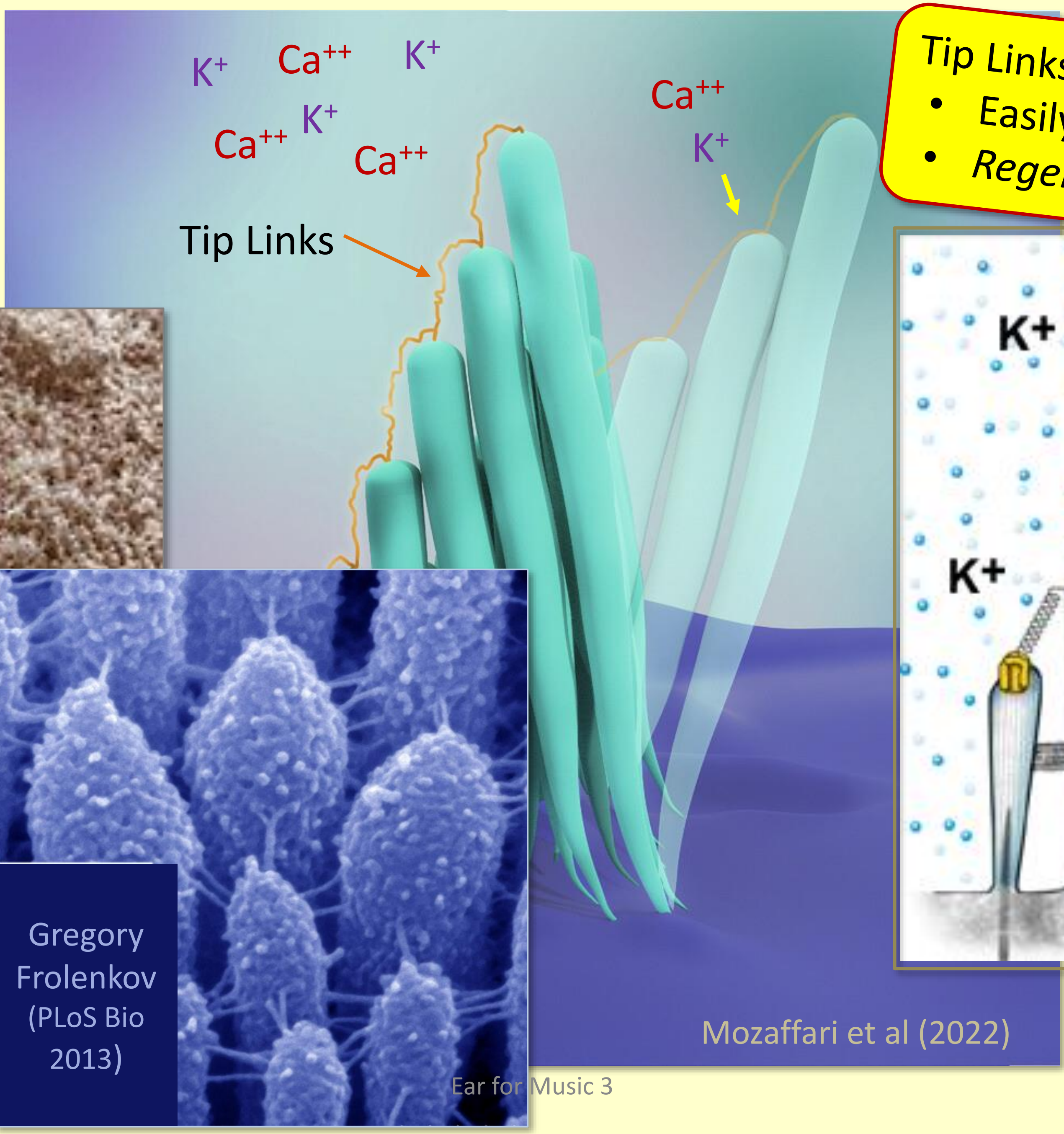




Tip Links are delicate:

- Easily broken -> Deafness
- *Regenerate* in hours

Pushing **Stereocilia** over opens <u>mechanical</u> valves, letting ions enter



Mozaffari et al (2022)

Tip Links are delicate:

- Easily broken -> Deafness
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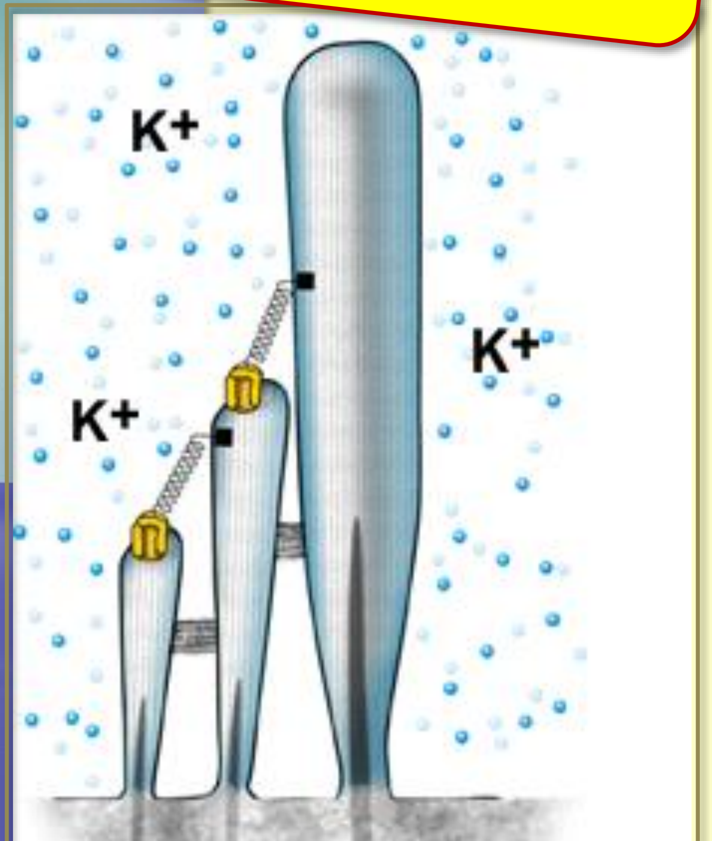


www.cochlea.eu

Frog Stereocilia (Wikipedia)

Gregory Frolenkov (PLoS Bio 2013)

Aside:

NSAIDs can produce permanent or temporary hearing loss

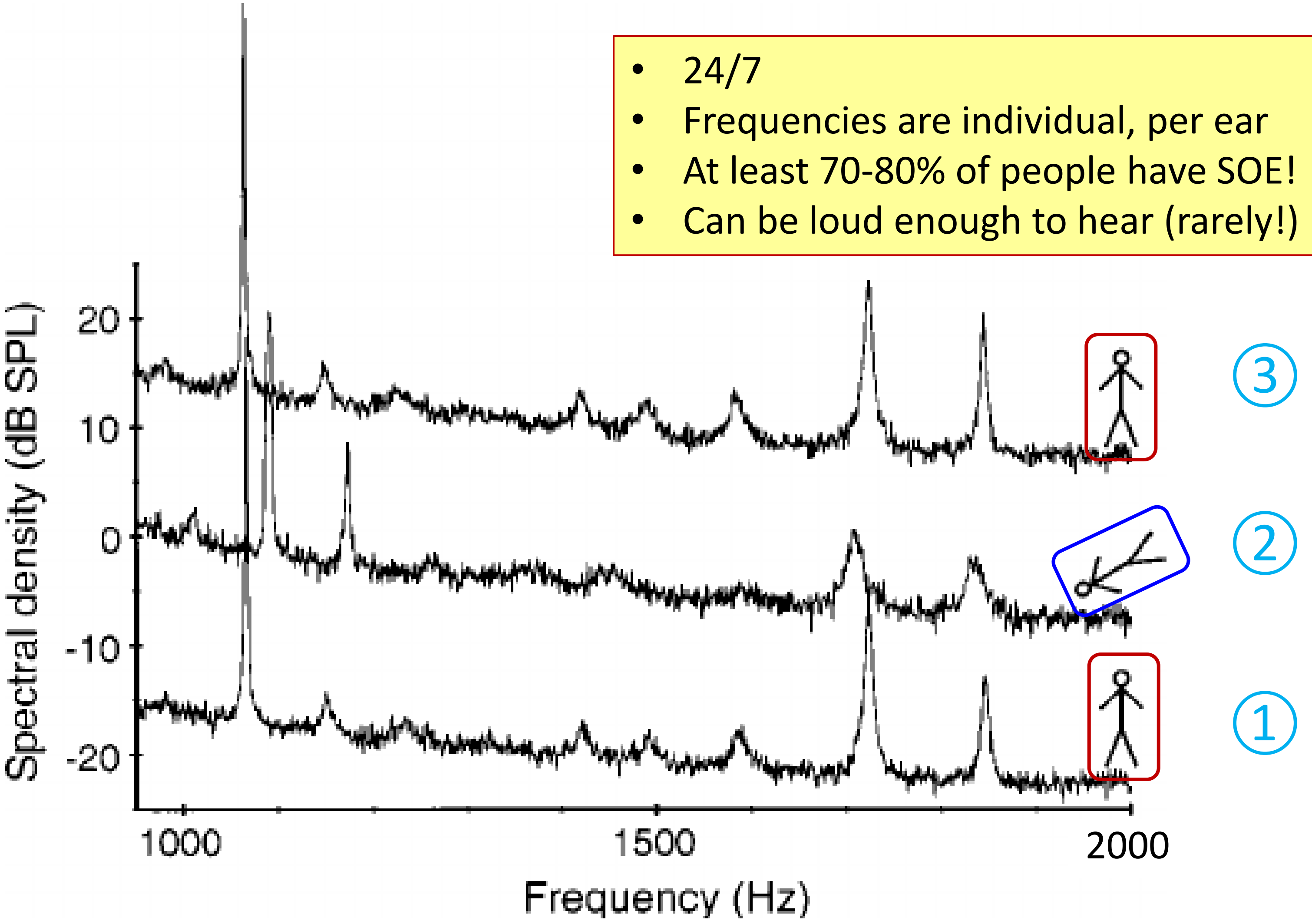
[How Hearing Happens - Cornell Video]

1 hour Lecture

James Hudspeth (2010)

Spontaneous OtoAcoustic Emission (SOAE)

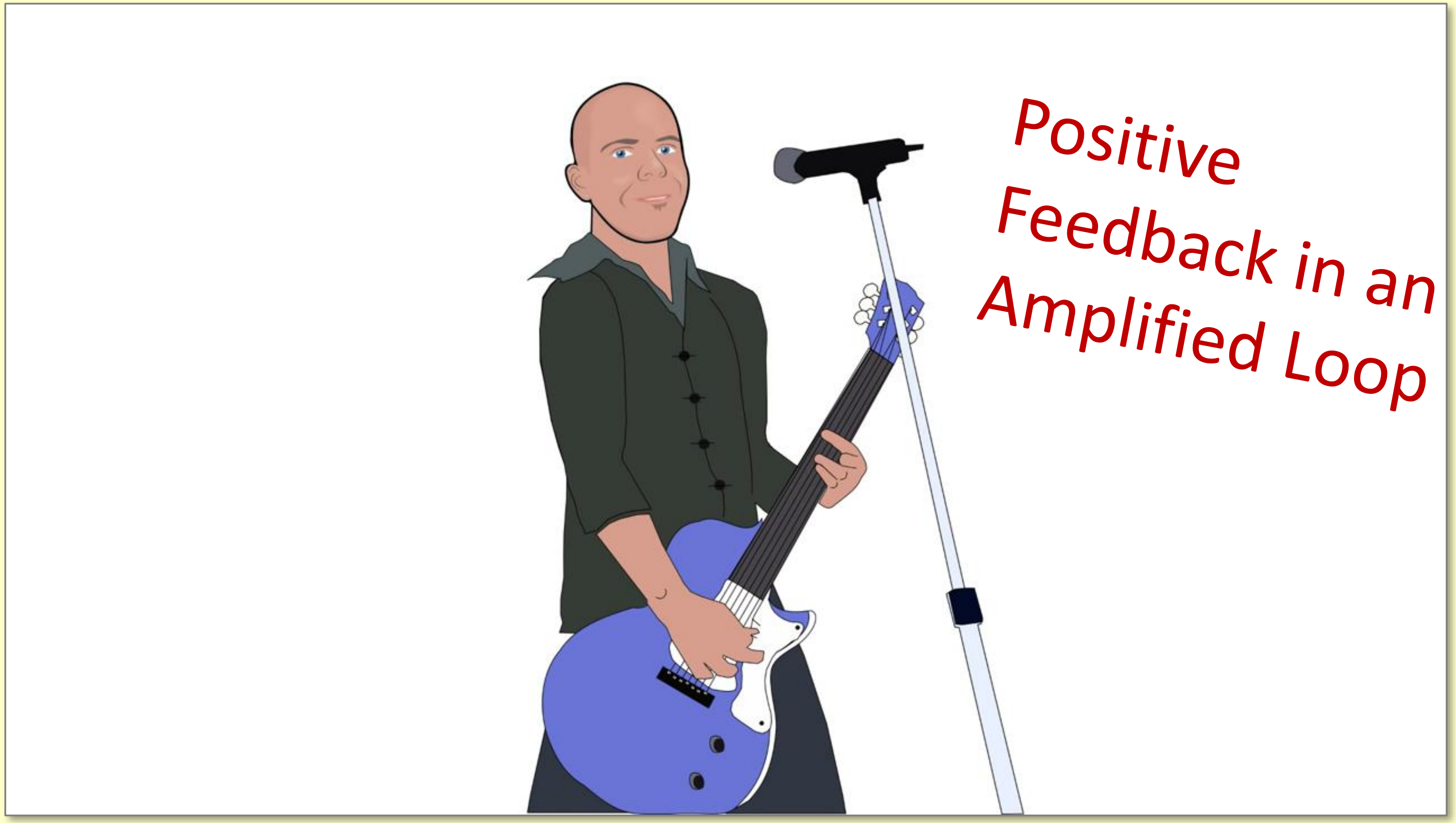
- 24/7
- Frequencies are individual, per ear
- At least 70-80% of people have SOE!
- Can be loud enough to hear (rarely!)



de Kleine et al JASA (2000)

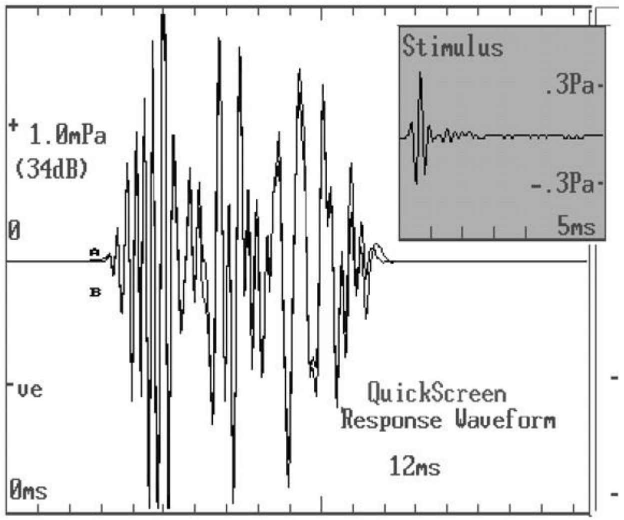
SOAE is Similar to PA System Squeal…

A Curious Aside

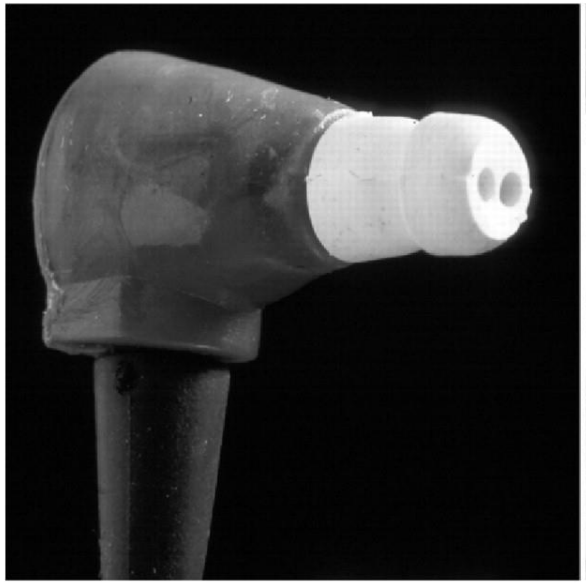


A Curious Aside

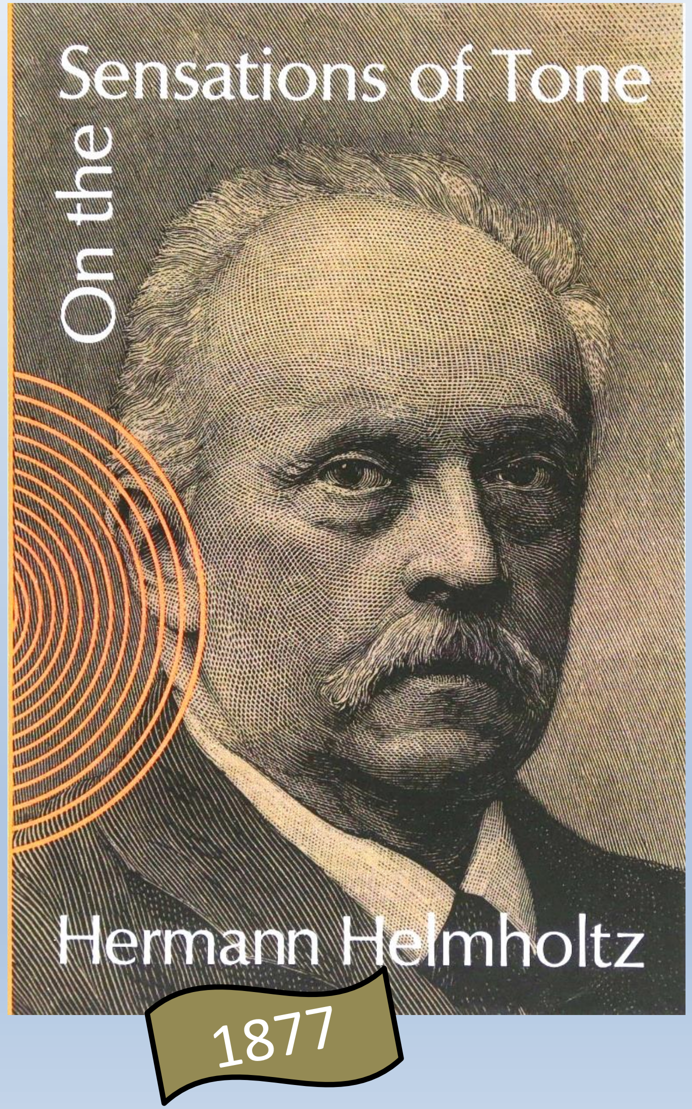
Transient Evoked OtoAcoustic Emission (TEOAE)

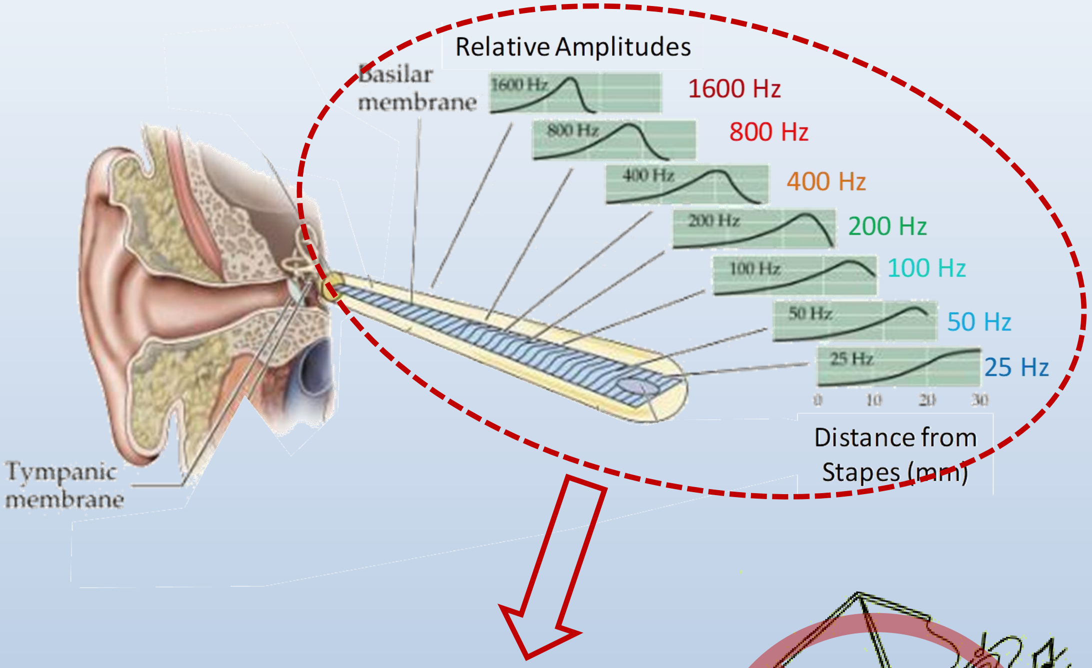


- "Click" Stimulus evokes delayed emission
- Works on everyone
- Routine baby screen for ear function
- High signal – no need for quiet booth



Hermann Helmholtz had it ~~mostly~~ partly right

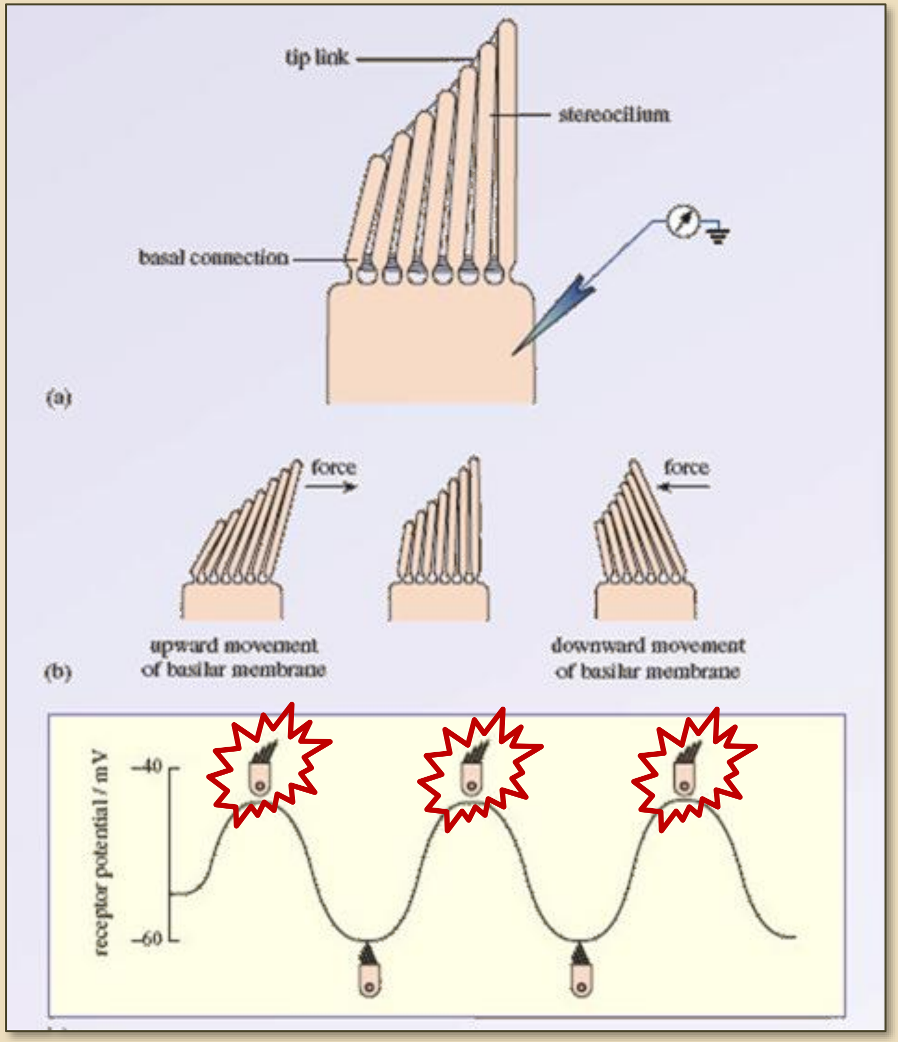


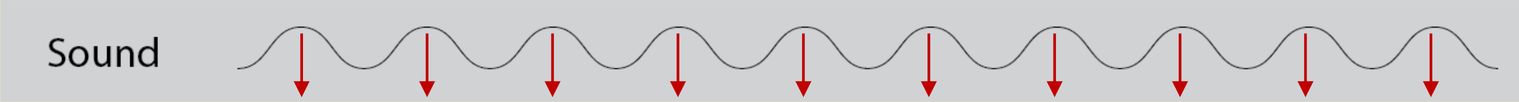


Place Theory:
Frequency perception is determined by distance along the Basilar Membrane

Hair Cells Fire Near Sound Wave Peak

For Low frequencies (50-300 Hz):





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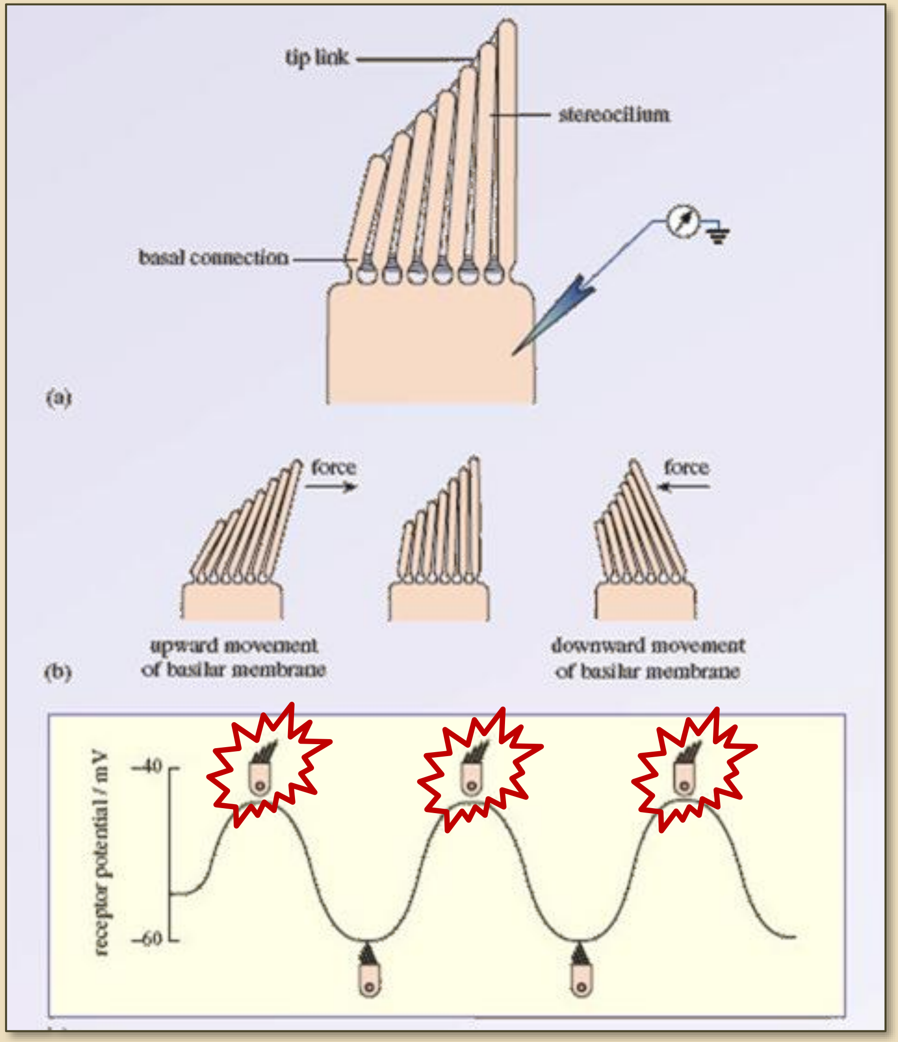
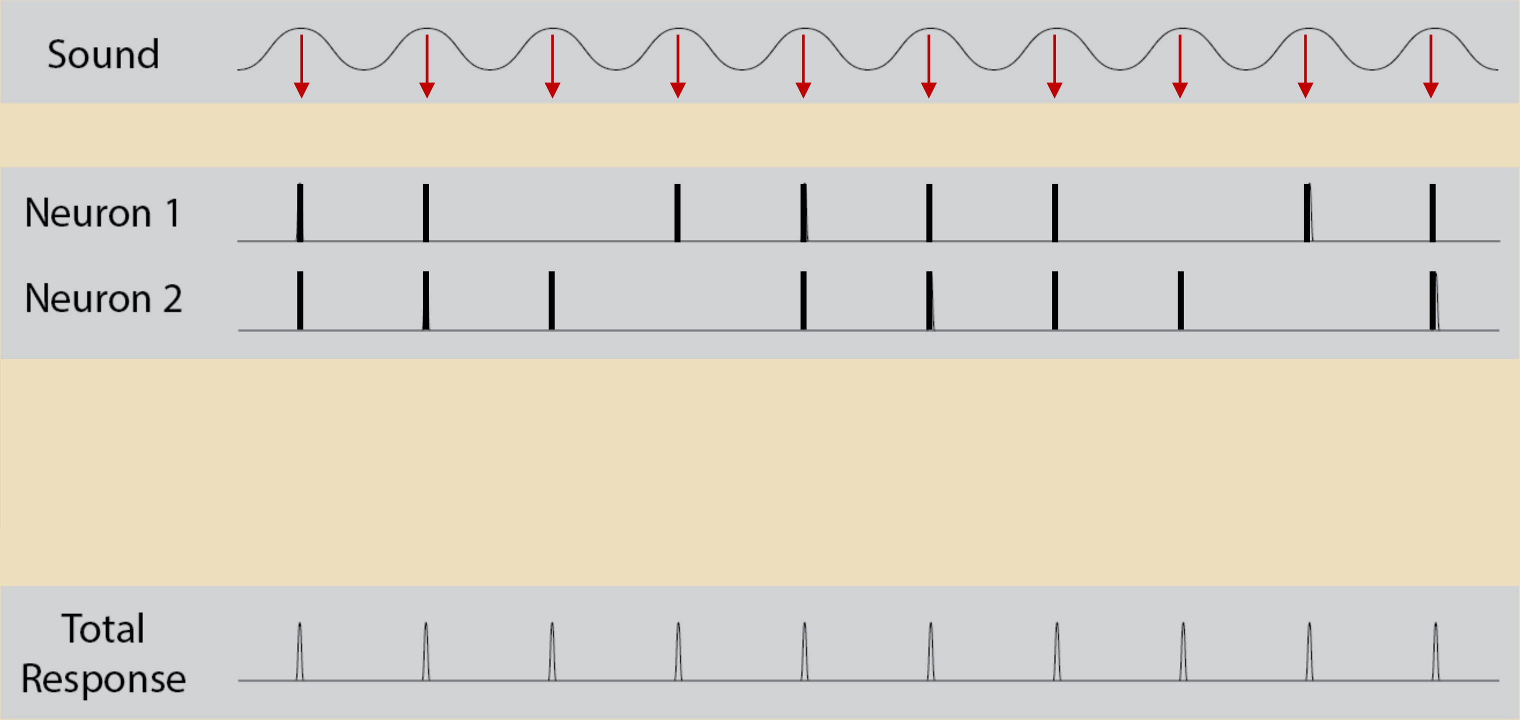
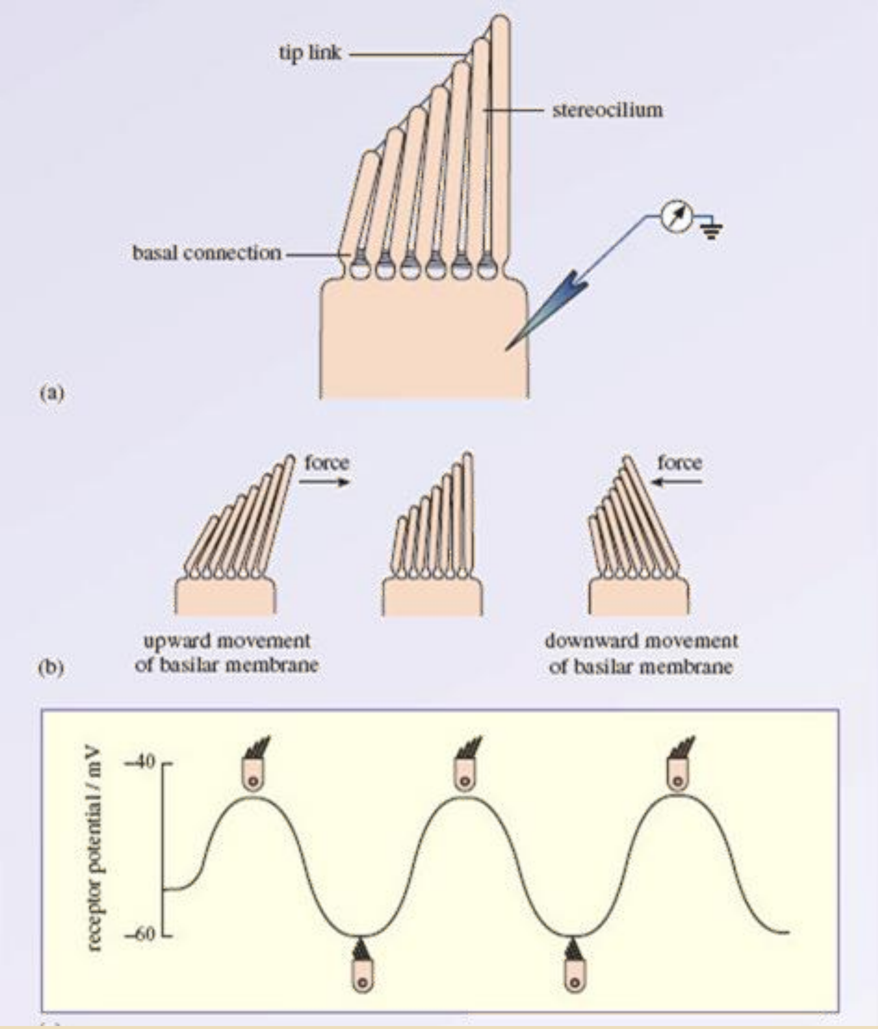
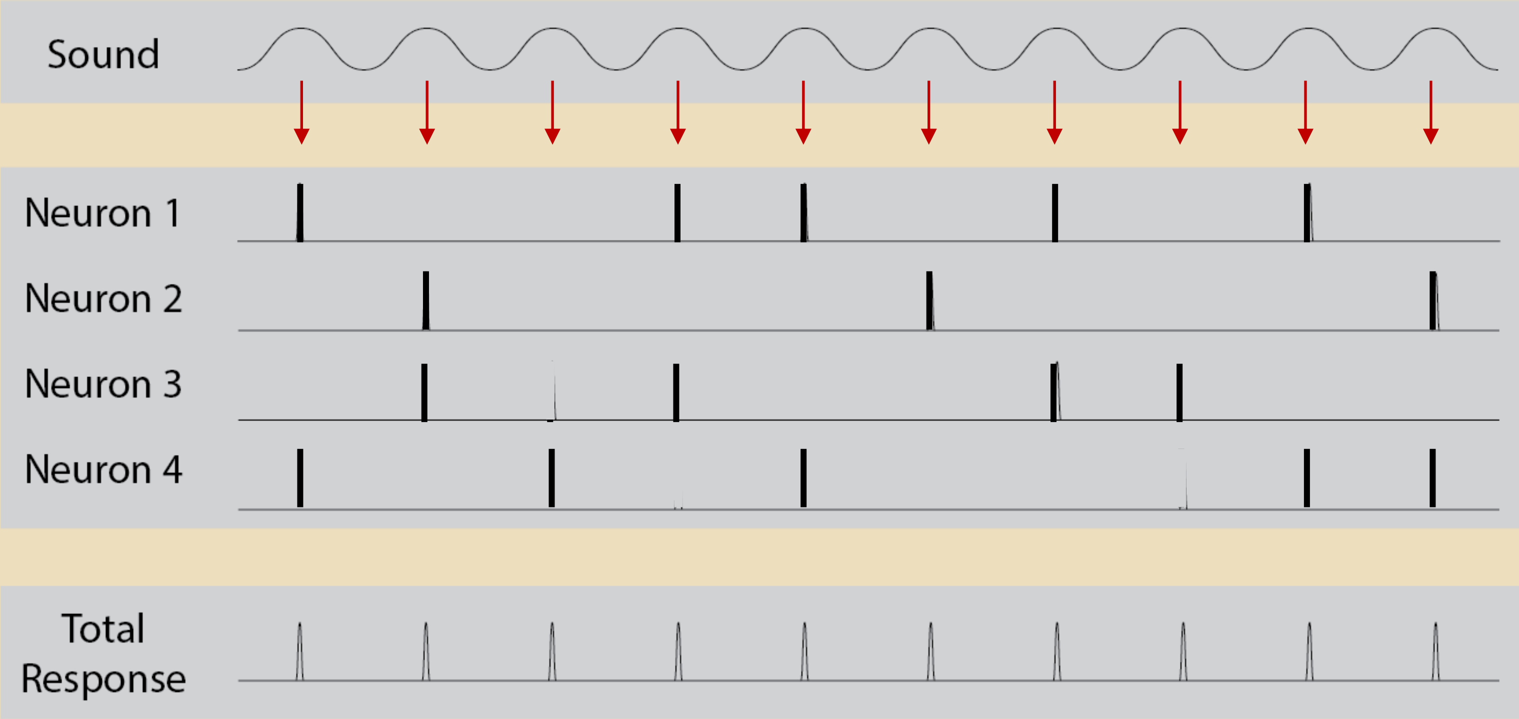




Hair Cells Fire Near Sound Wave Peak

For Medium Frequencies (500-5000 Hz):





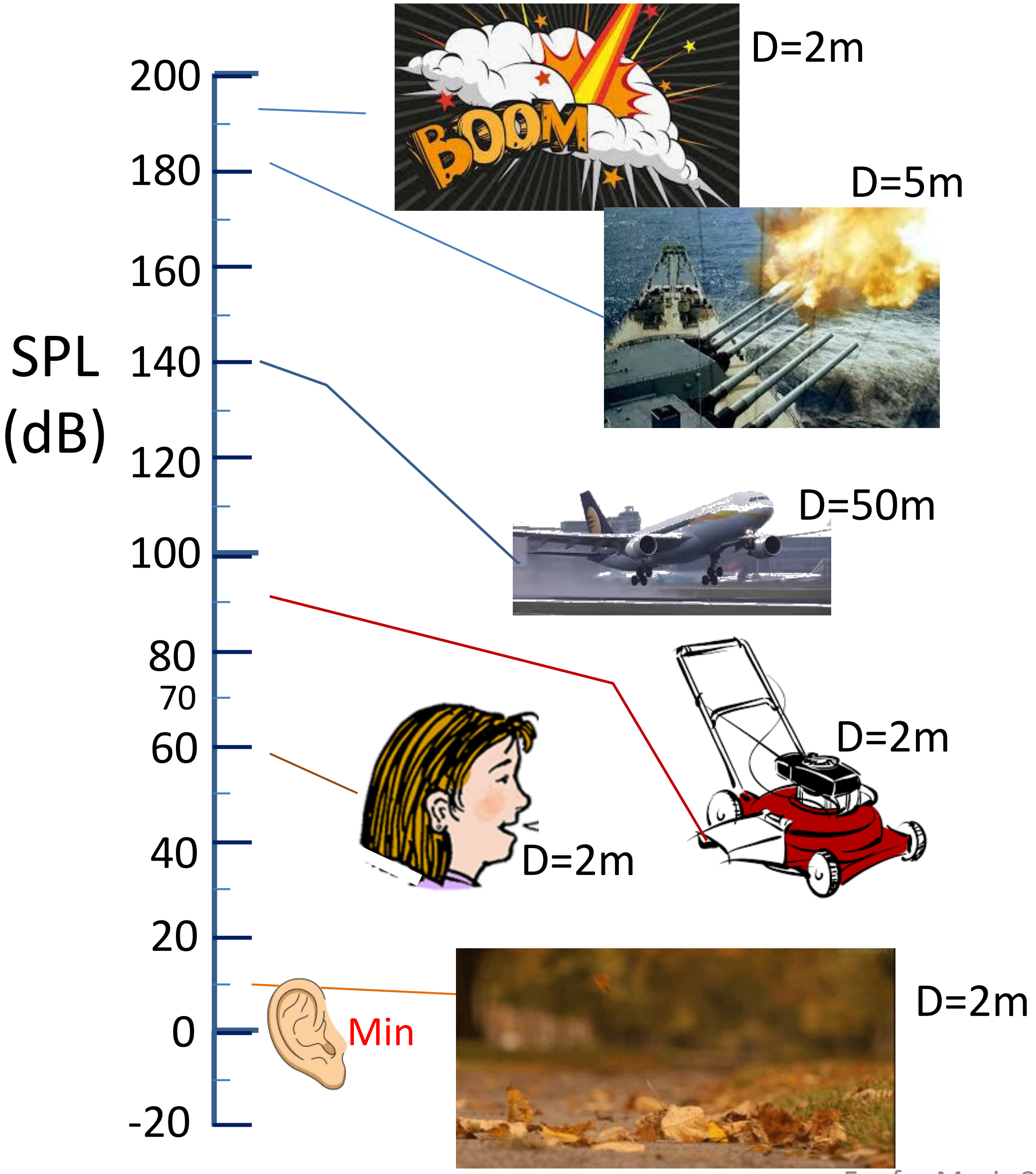
Volley Theory: (Ernest Wever 1939)
Multiple nearby hair cells taken together
can send a spike on every cycle

Question Time

- How the Ear Works
- Hair Cells
- Basilar Membrane

?

The Decibel Scale of Sound Pressure Level



Units are **Decibels** **(dB)**

Each **20 dB → 10x Pressure**

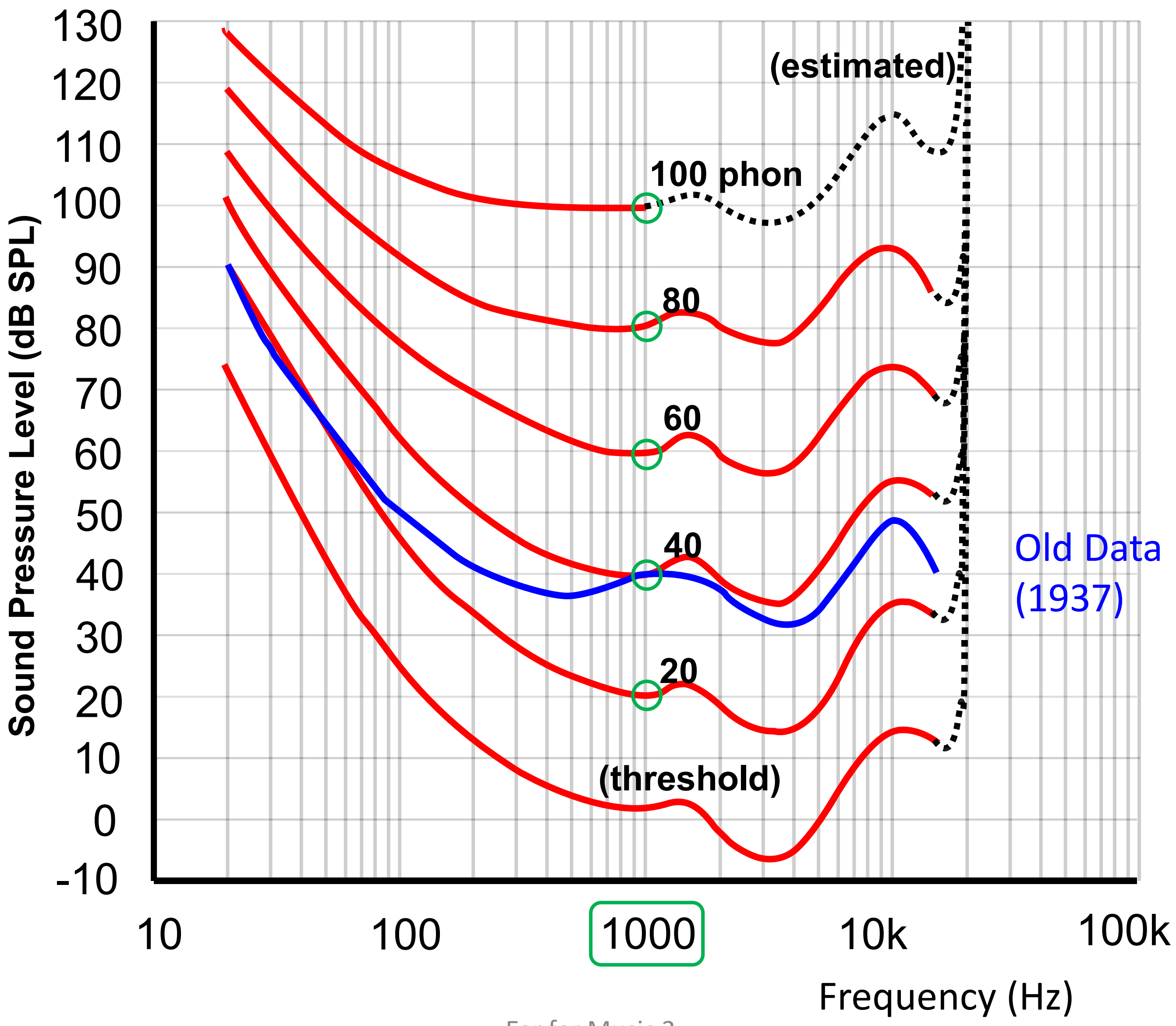
Each **10 dB → 10x Power**

Each **10 dB → ~2x "Loudness"**

Each 1 dB → Min Change (JND)

Physical Scale –
Nothing to do with
human perception

Equal Loudness Contours (ISO 226:2003)

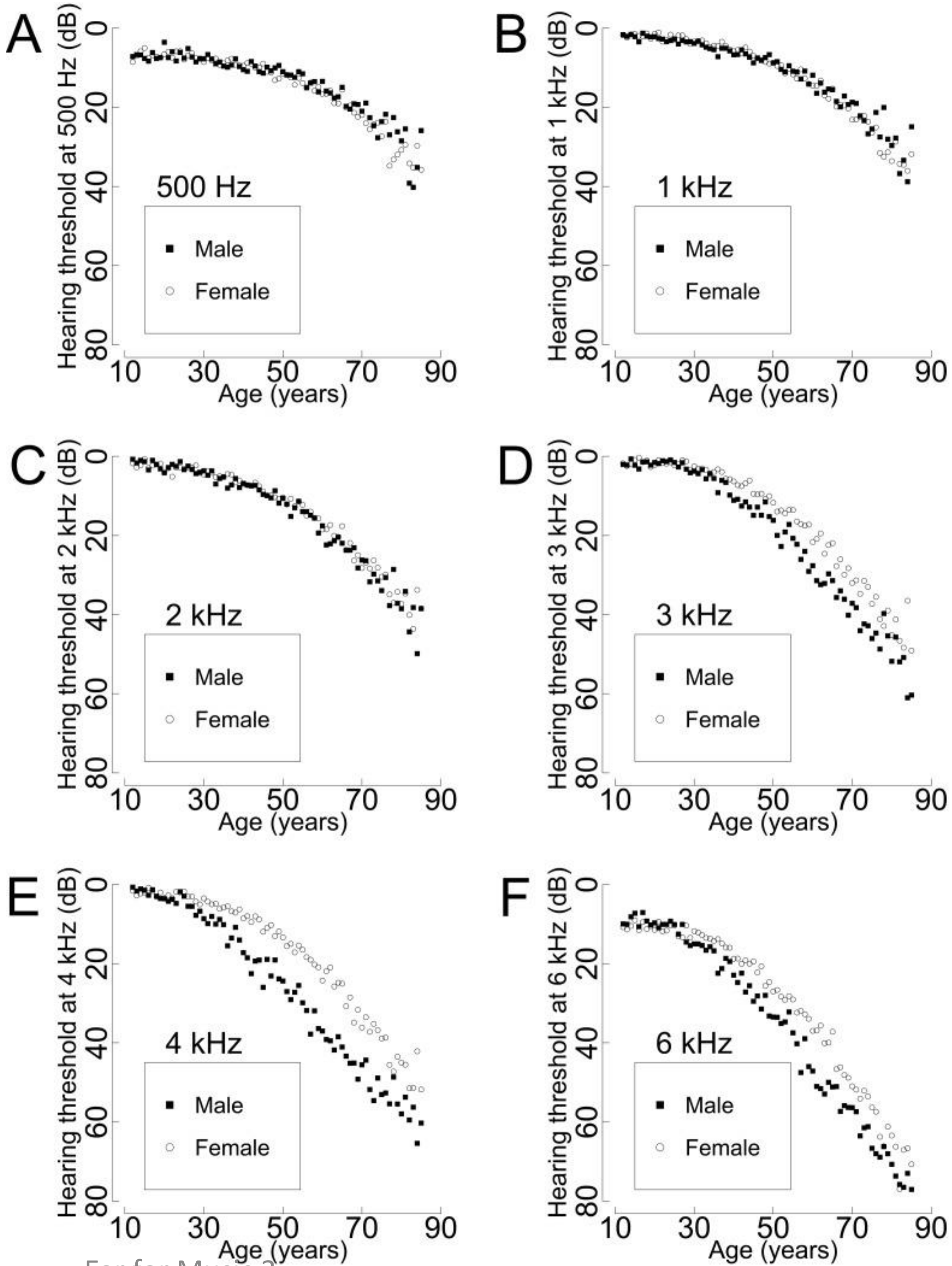


Units of Subjective Loudness are Phons
[Phons = dB @ 1kHz]

For 20-year olds!

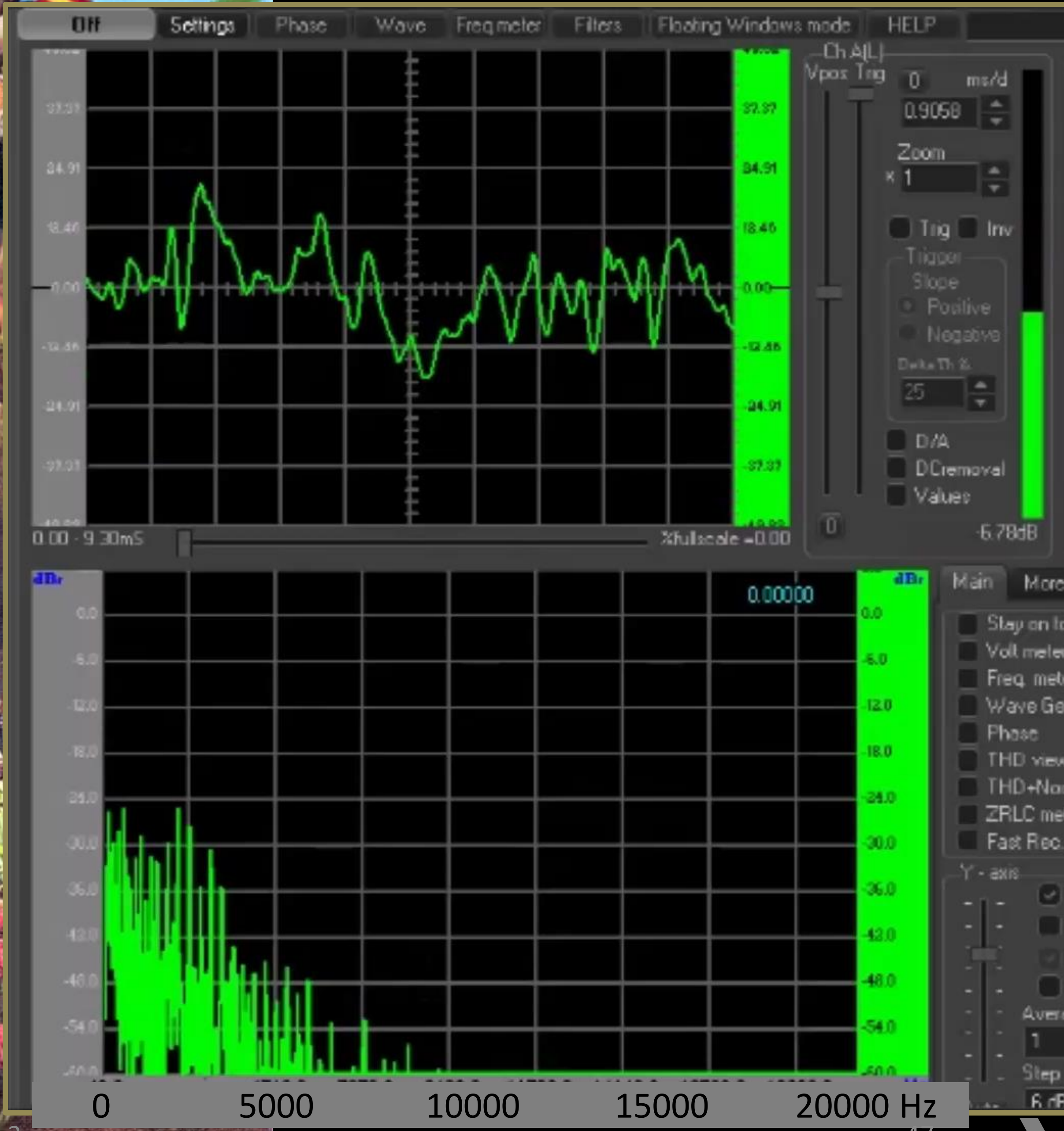
We're 15-30dB worse off

Hearing Threshold Drops with Age



(Edited)

St PEPPERS
LONELY HEARTS
CLUB BAND



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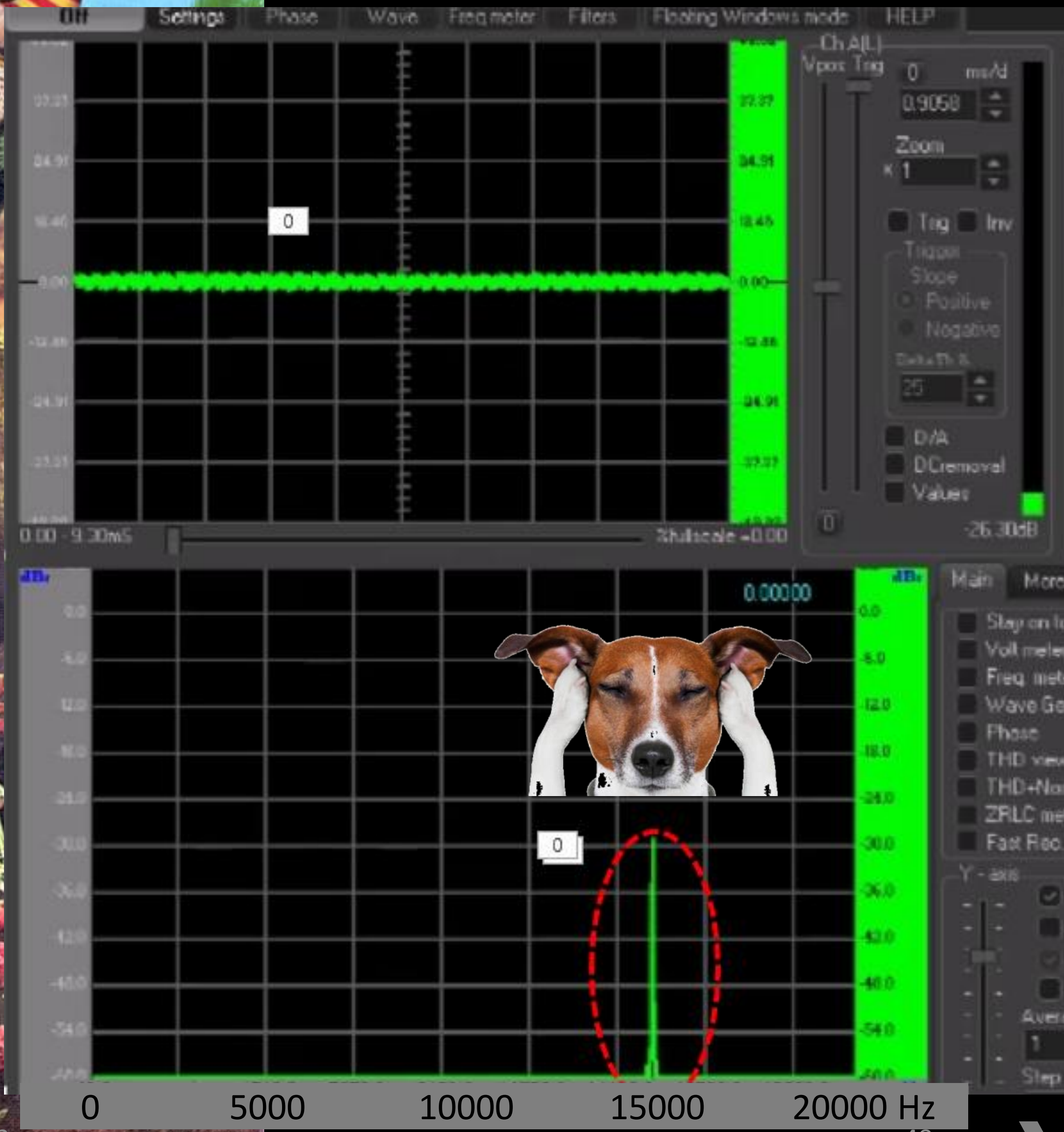
Settings
Phase
Wave
Freq meter
Filters
Floating Windows mode
HELP
Zoom
Trigger
Slope
Positive
Negative
D/A
DCremoval
Values
0.00 - 9.30mS
Main
0.00000
0
5000
10000
15000
20000 Hz


LONELY HEARTS
CLUB BAND
BEATLES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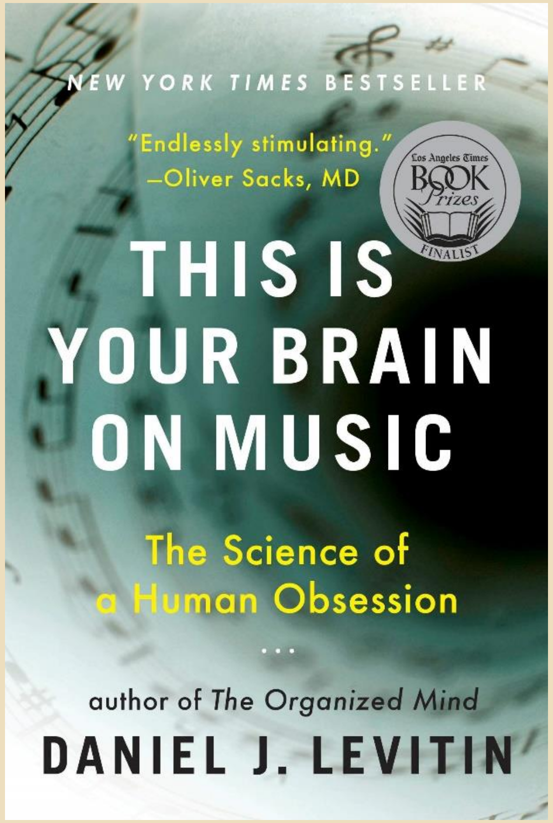
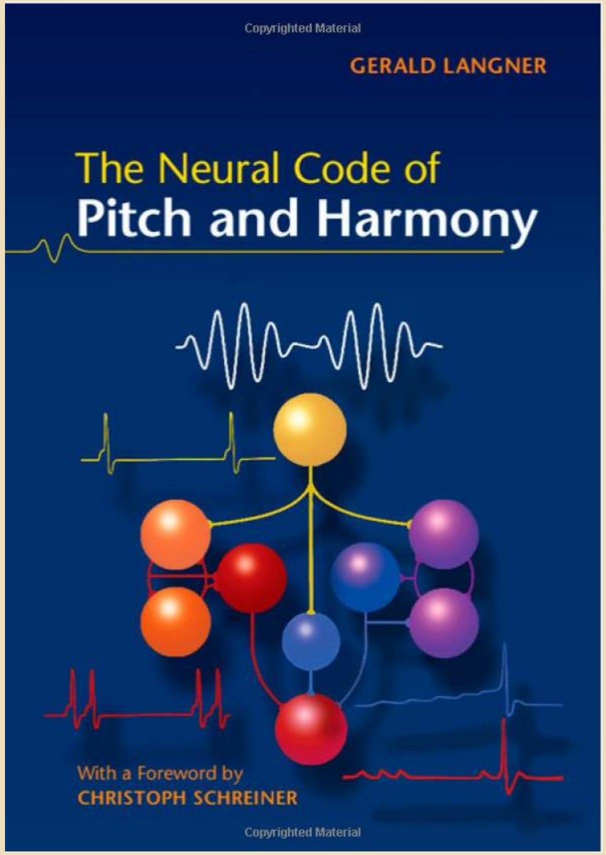
Wave
Freq meter
Filters
Floating Windows mode
HELP
Zoom
0
0
0 5000 10000 15000 20000 Hz

Two Approaches to Understanding Musical Sound Perception



1. Follow the neurons from the ears onward
   - Bottom up

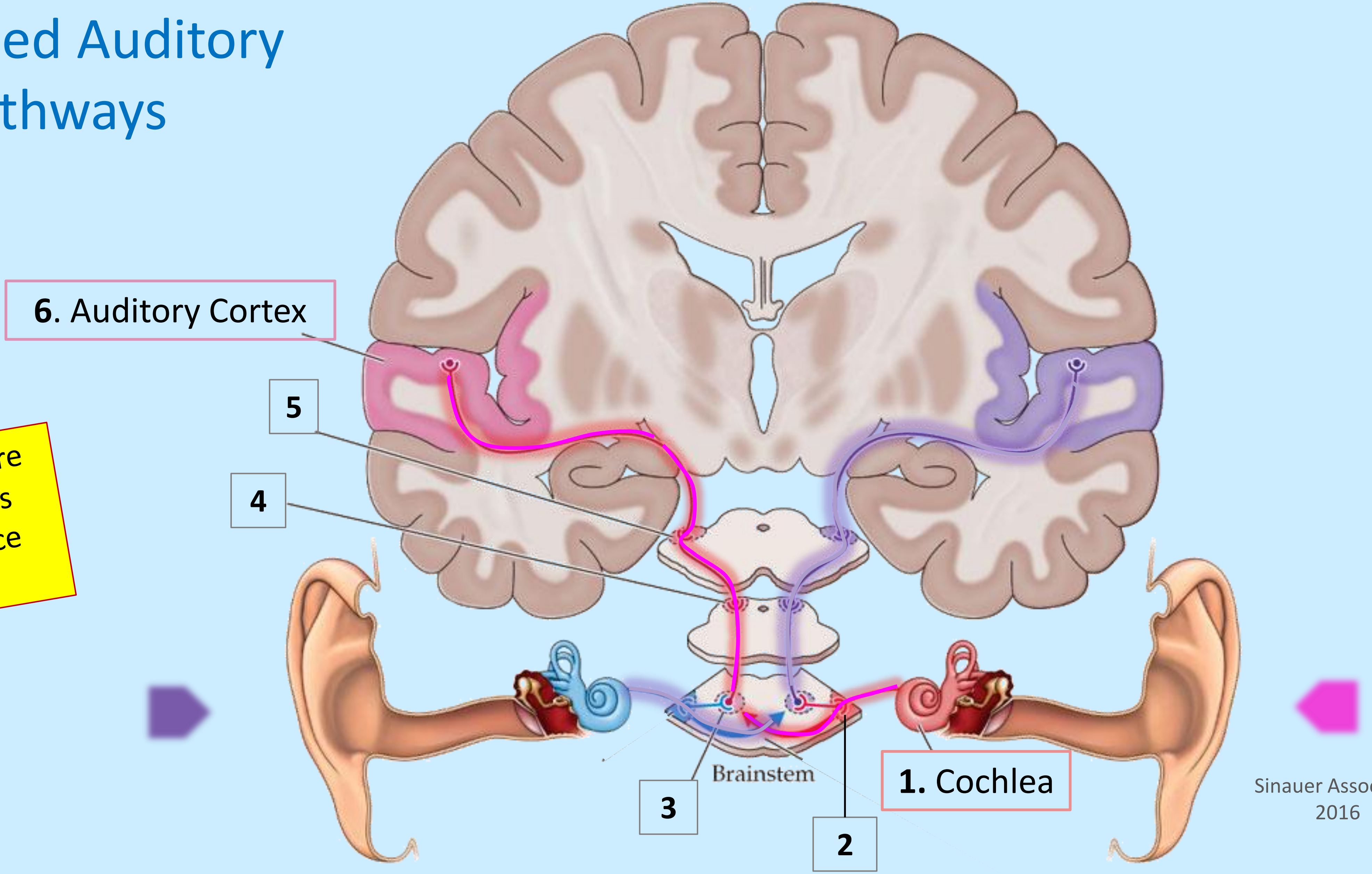
2. Look at the final perceptions of sound
   - Top down



Spoiler Alert:
These approaches have yet to meet!

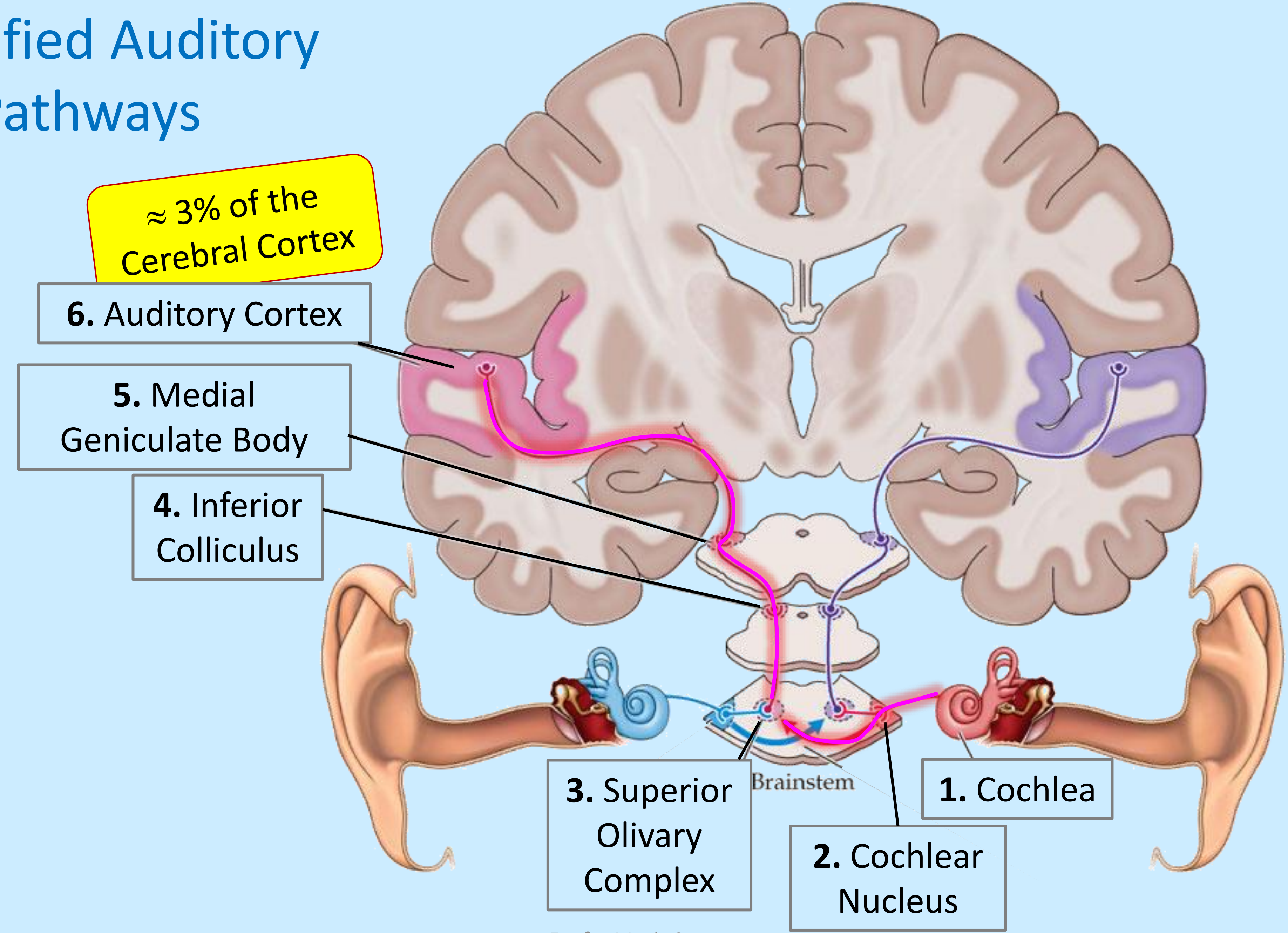
Simplified Auditory Pathways

Right Hemisphere (mostly) handles Left Ear, and vice versa….



Sinauer Associates 2016

Simplified Auditory Pathways

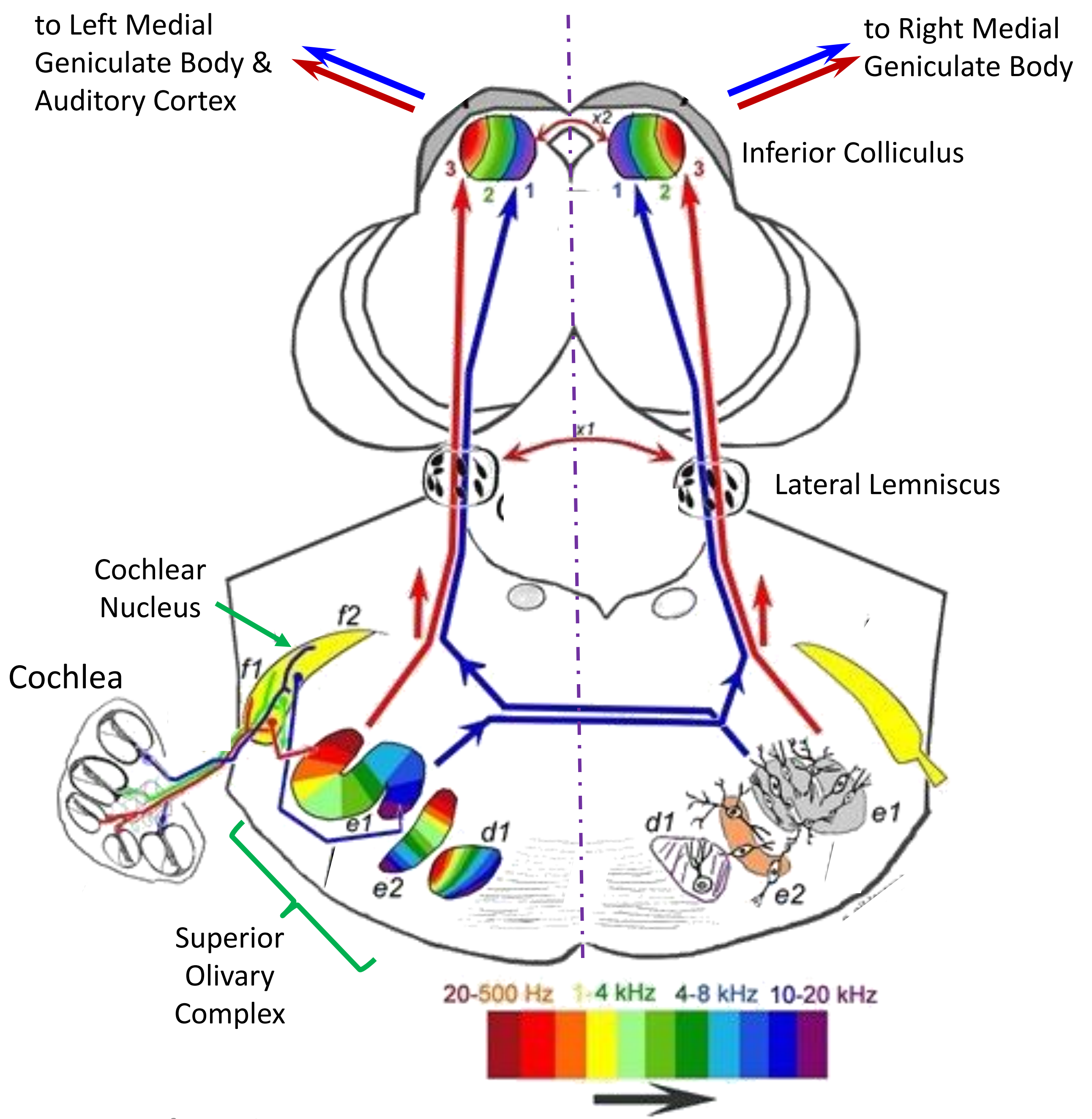


Sinauer Associates
2016

Most Auditory Brain Regions are <u>Tonotopic</u>

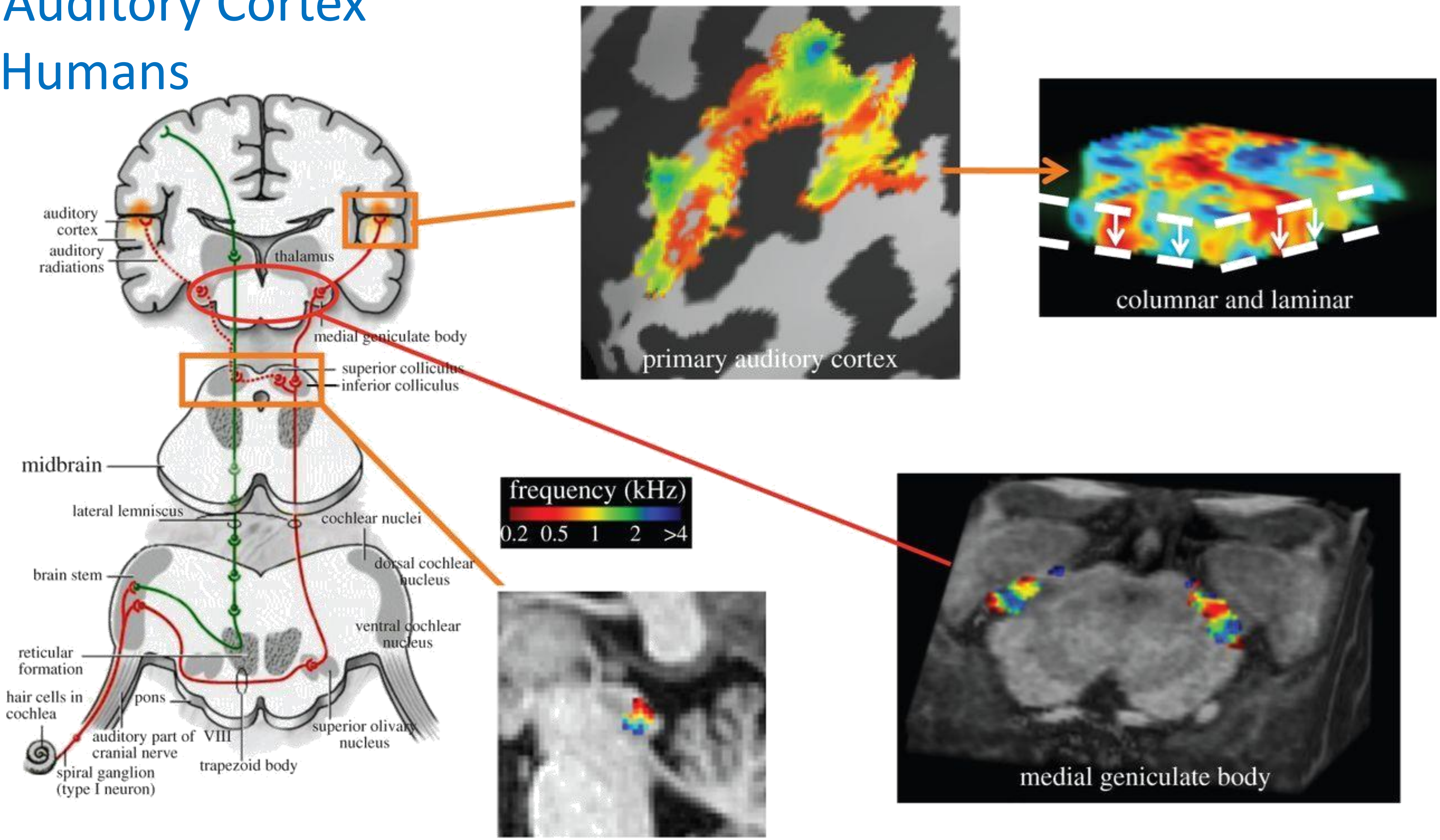
(at least partially)

Frequencies are spatially mapped in each Processing Region



Including Auditory Cortex In Humans

fMRI:
High Resolution Functional MRI on Human Subjects

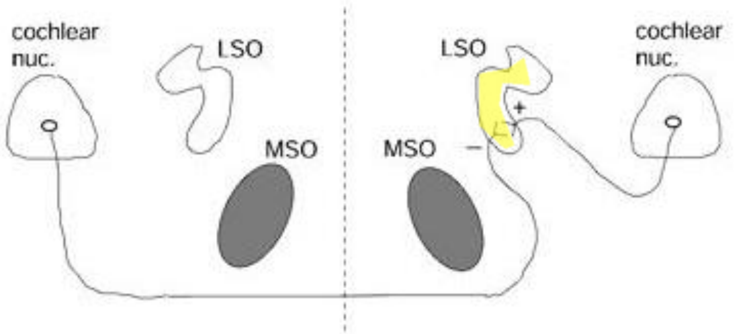


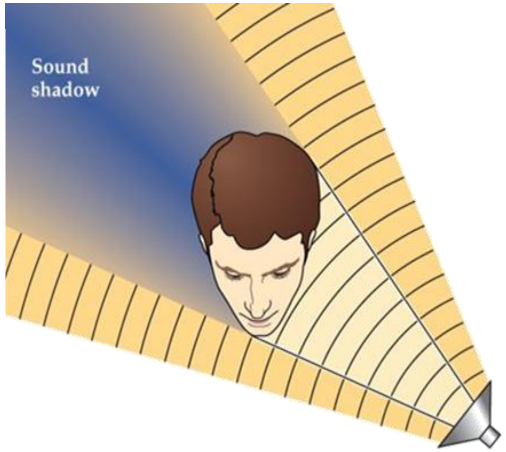
Kamil Ugurbil et al (2015-2016)

Using 2 Ears: Sound Localization in Superior Olive

Lateral Superior Olive (LSO) Neurons Compute Left-Right **Intensity** Difference

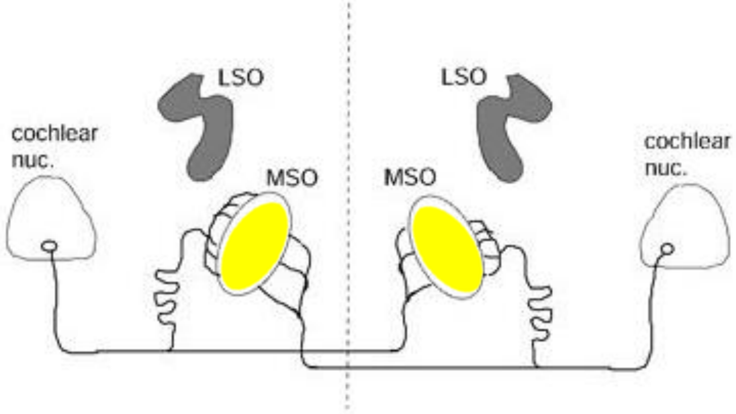
(High *f*)

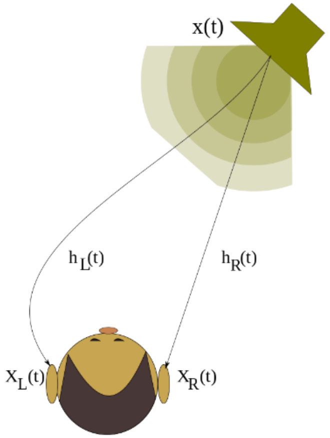




Medial Superior Olive (MSO) Neurons Compute Left-Right **Arrival Time** Difference

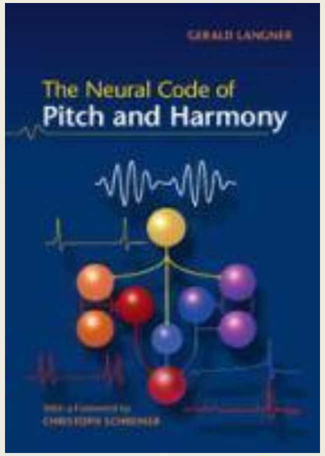
(Low - Medium *f*)



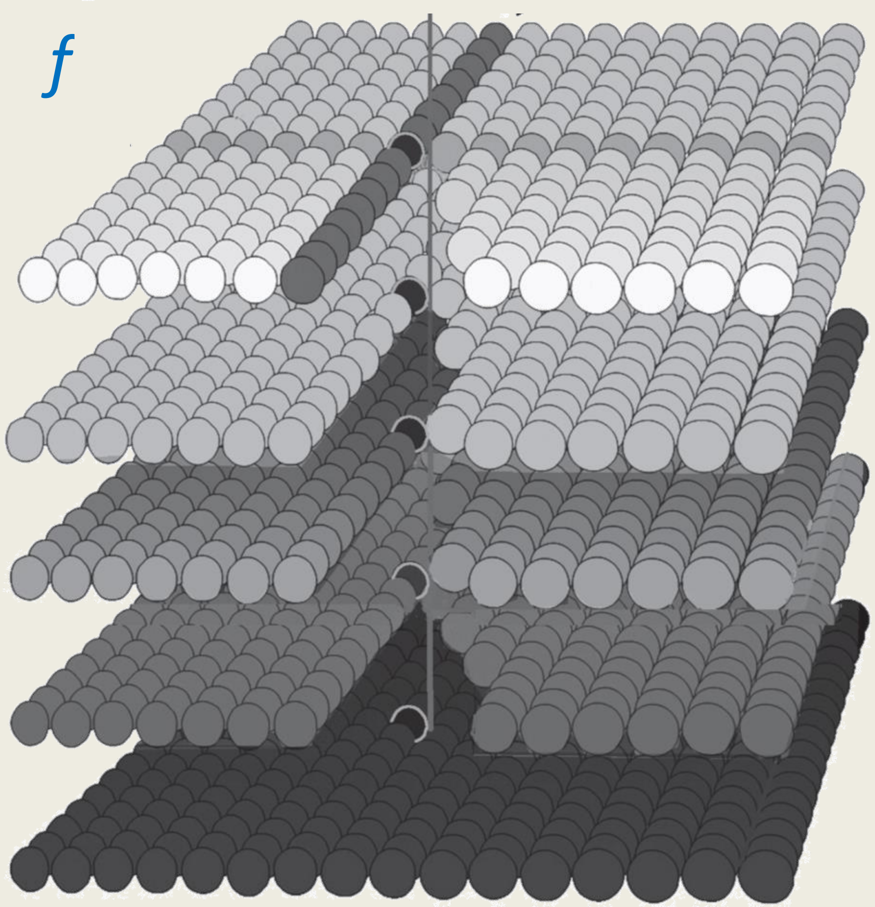


Example of 3D Auditory Neural Spatial Organization:

Small region in Cat Inferior Colliculus



Gerald Langner,
The Neural Code of Pitch and Harmony
(2015)

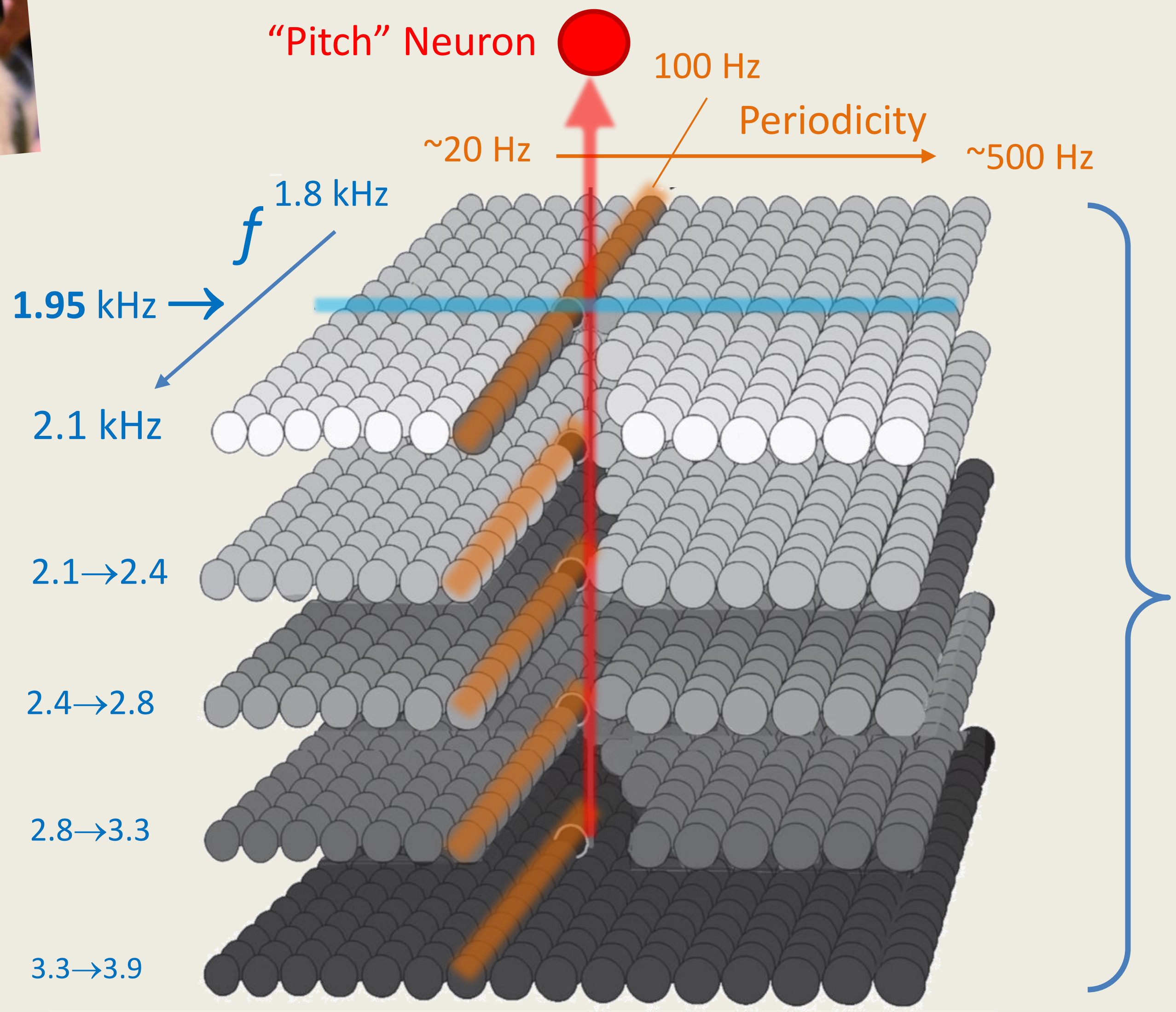


≈ **30** Planar Layers, each receiving input from a narrow section of the Basilar Membrane

i.e., small frequency ranges à la ~25 Critical Bands!

Example of 3D Auditory Neural Spatial Organization:

Small region in Cat Inferior Colliculus



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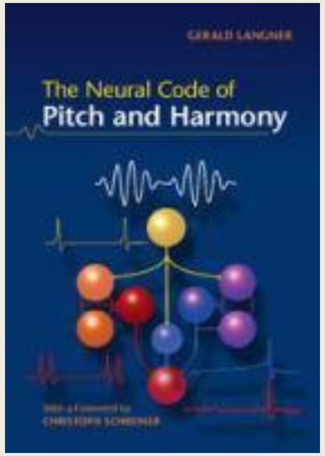
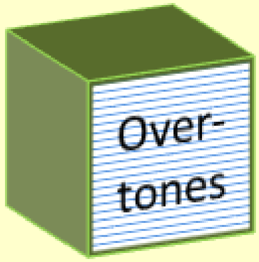


Gerald Langner, *The Neural Code of Pitch and Harmony* (2015)



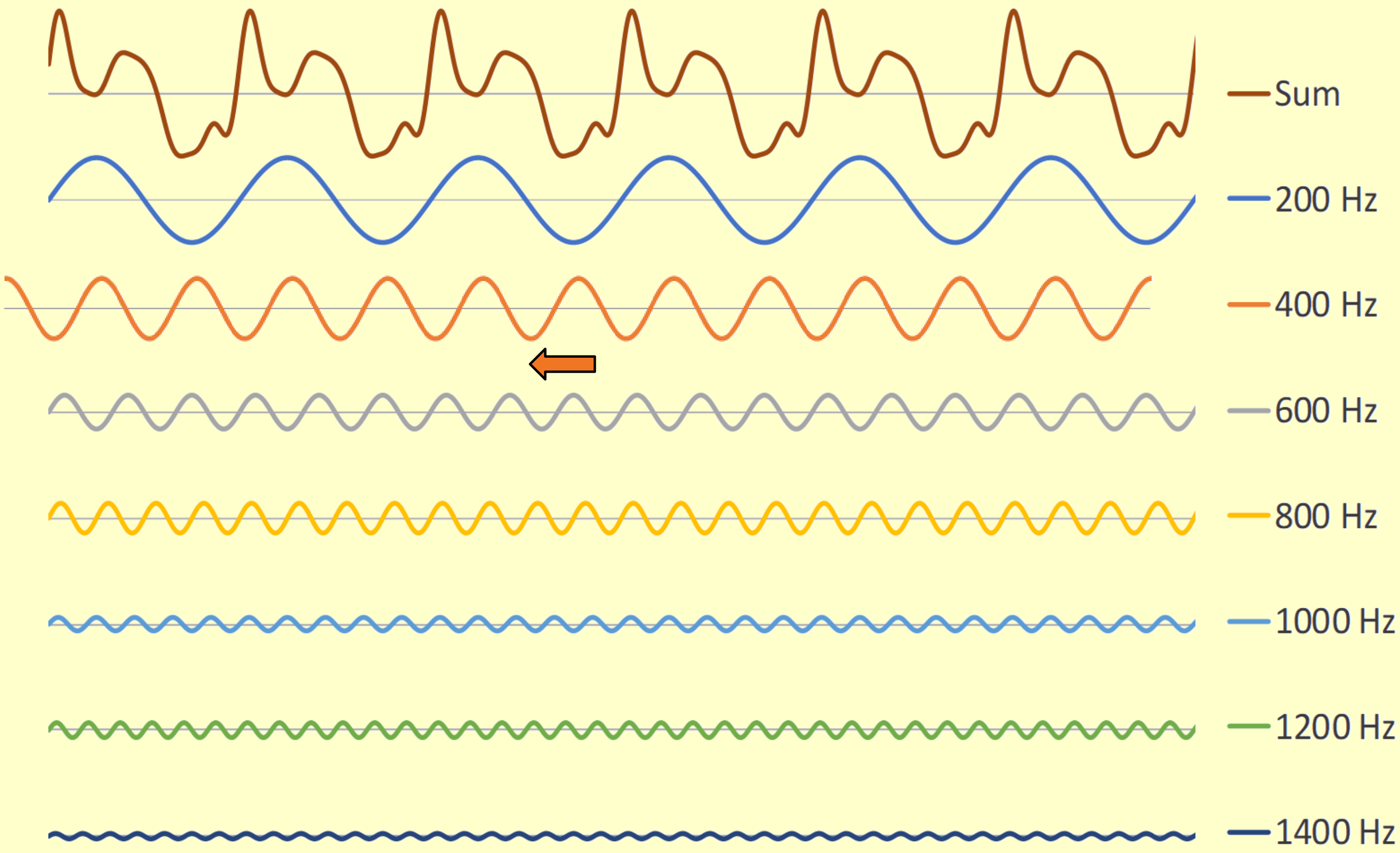
Remember: Real Musical Notes are *not* Pure Sine Waves

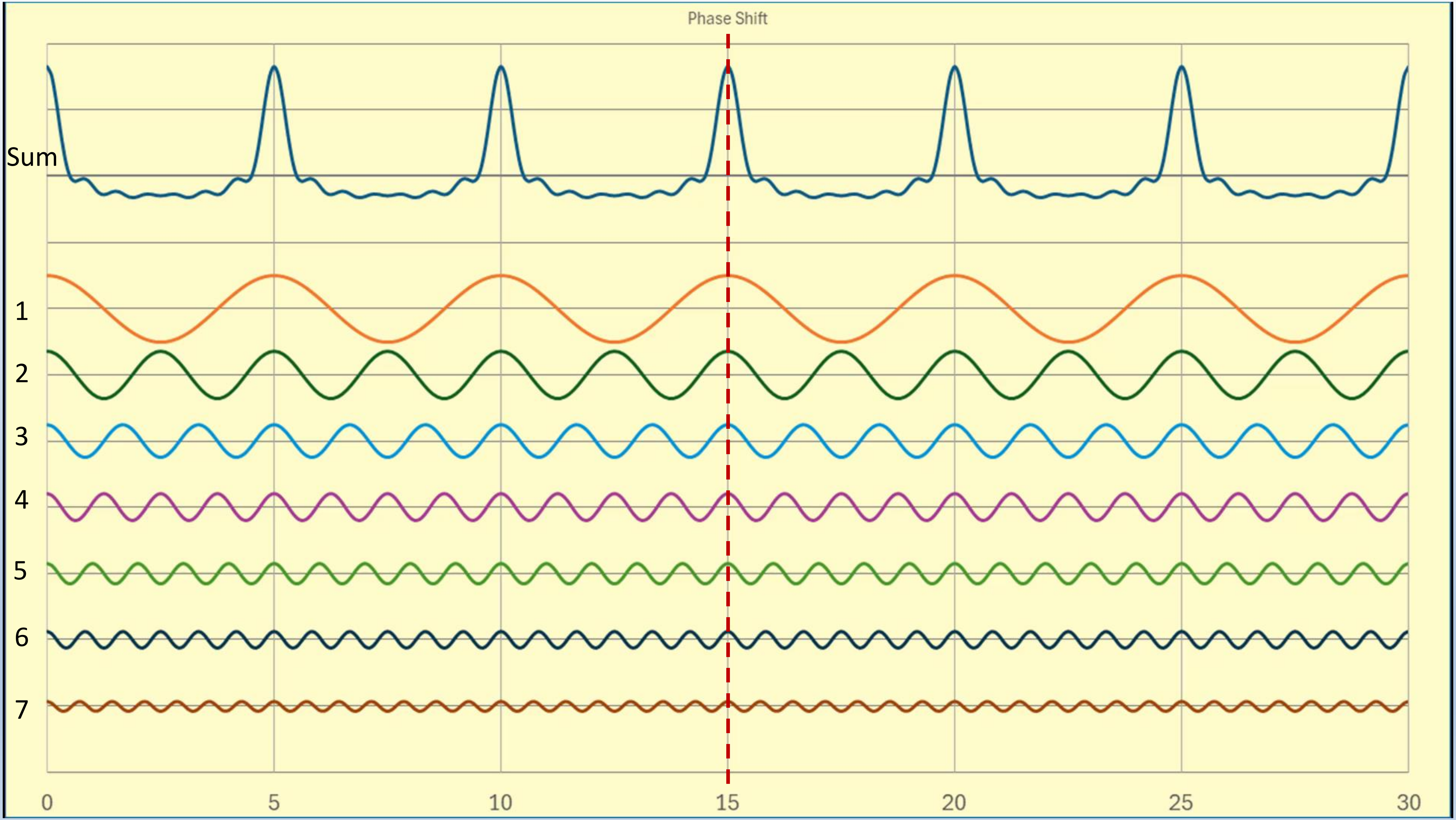
- Complex tones
  - Fundamental frequency f_0

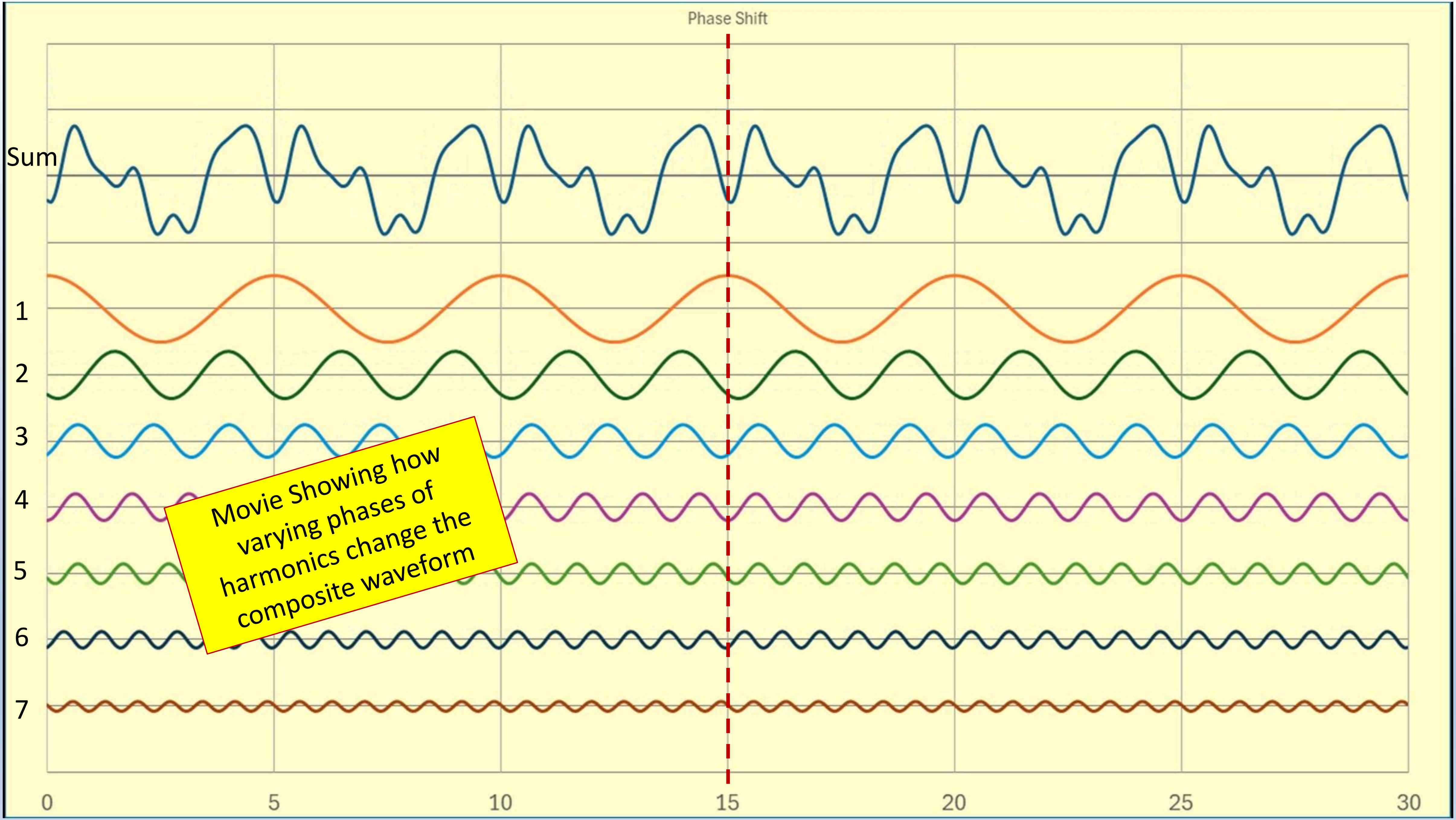
+

Phase Shift

  - Several Overtones



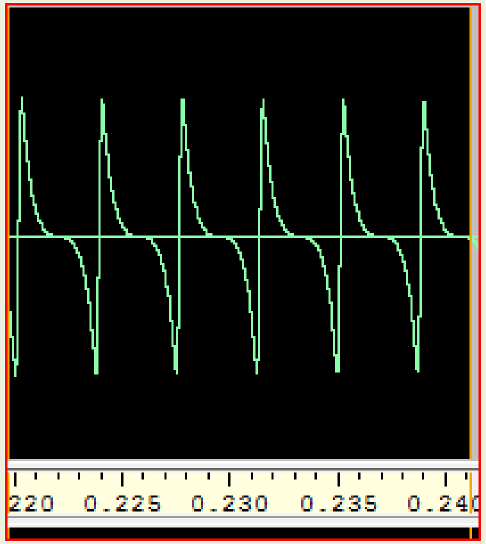

Phase Shift
Sum
1
2
3
4
5
6
7
0
5
10
15
20
25
30


Phase Shift
Sum
1
2
3
4
5
6
7
Movie Showing how varying phases of harmonics change the composite waveform
0
5
10
15
20
25
30

Can We Hear Phases?

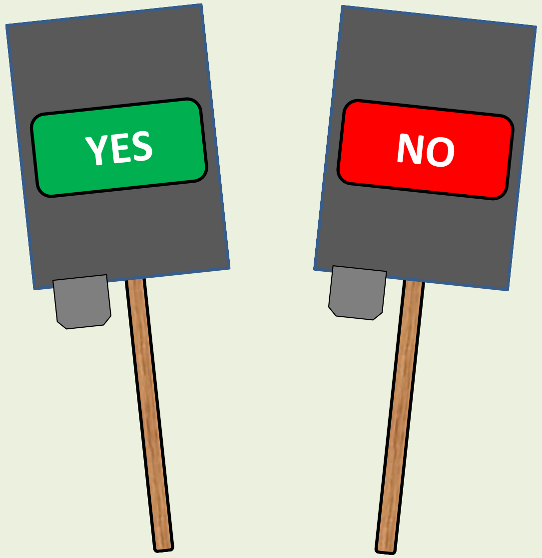
WaveGen

Fixed
Harmonic
Phases

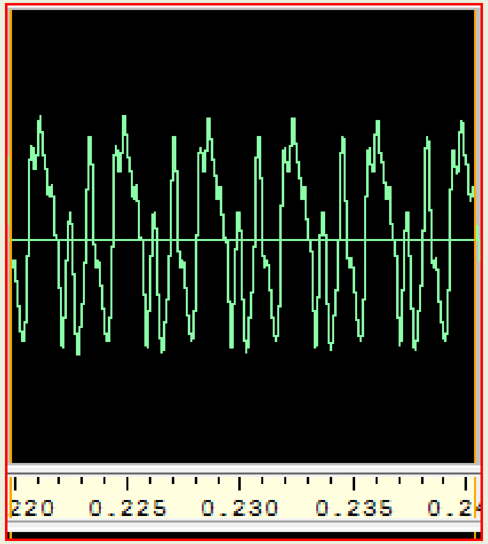


Hear the Difference?

C4
[262 Hz]

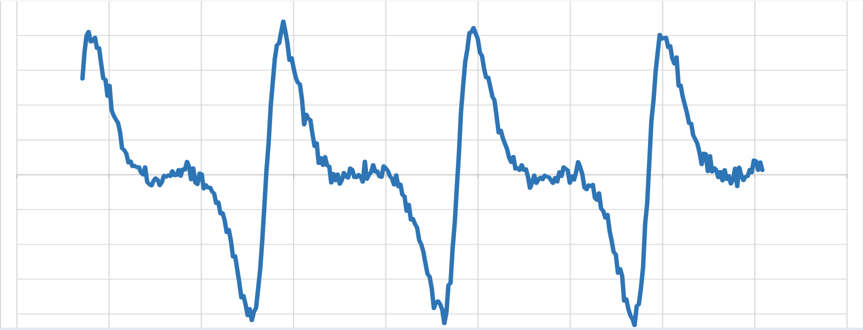


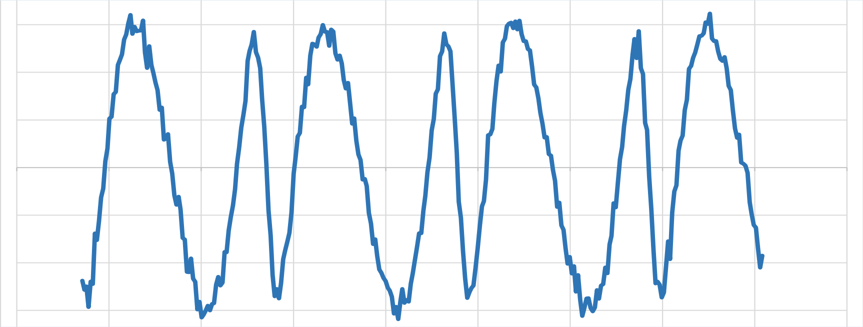
Random
Harmonic
Phases

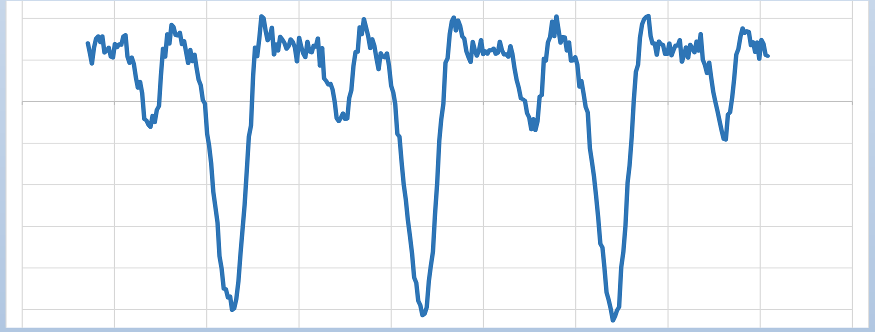


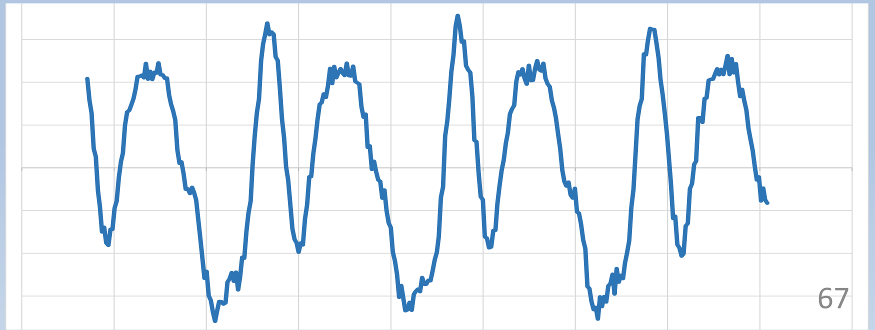
What *Alien* Sounds *Can* We Distinguish?

Hear the Differences?







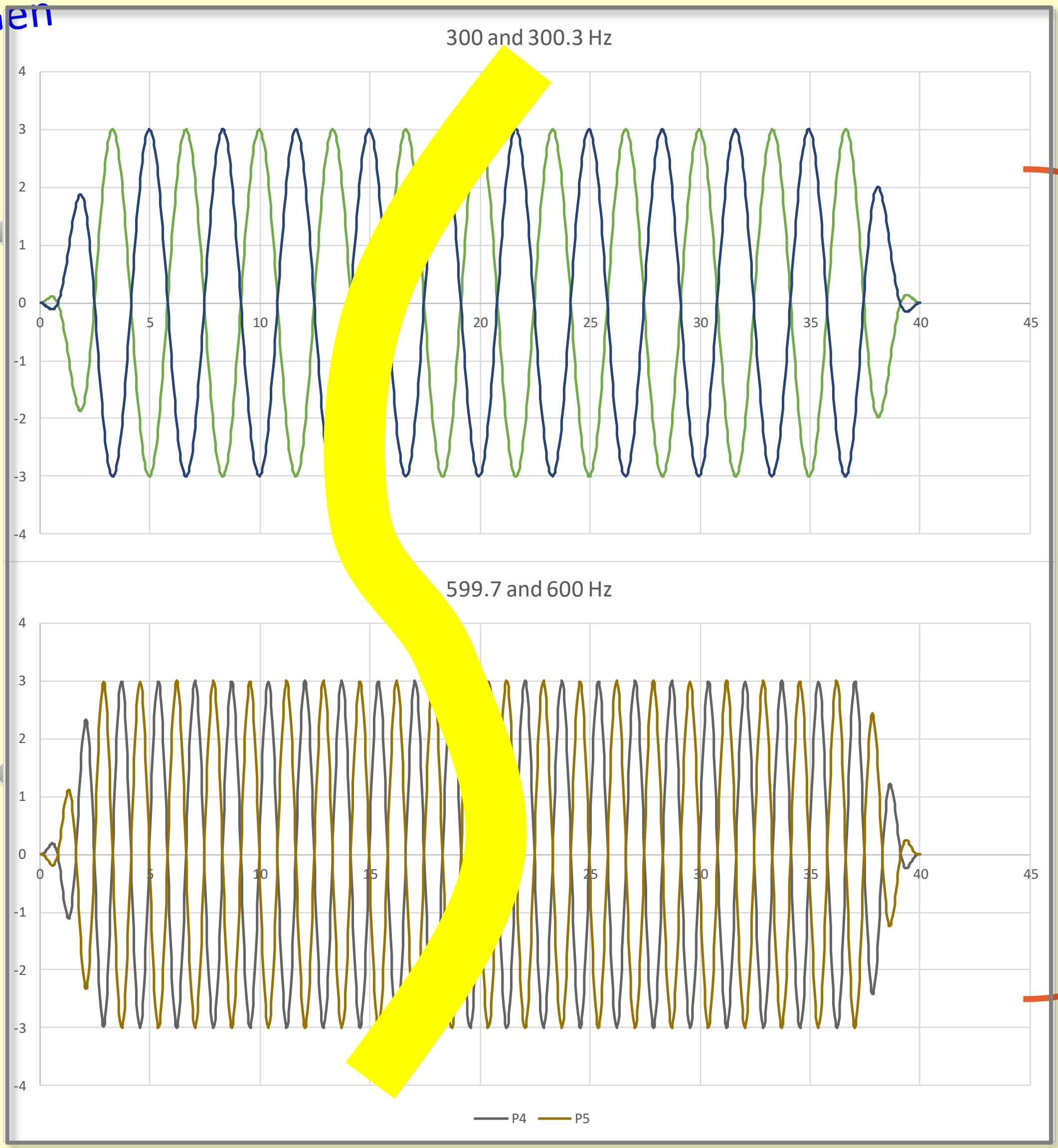


What If We Combined Lots of Pure Tones?

WaveGen

300 Hz

600 Hz



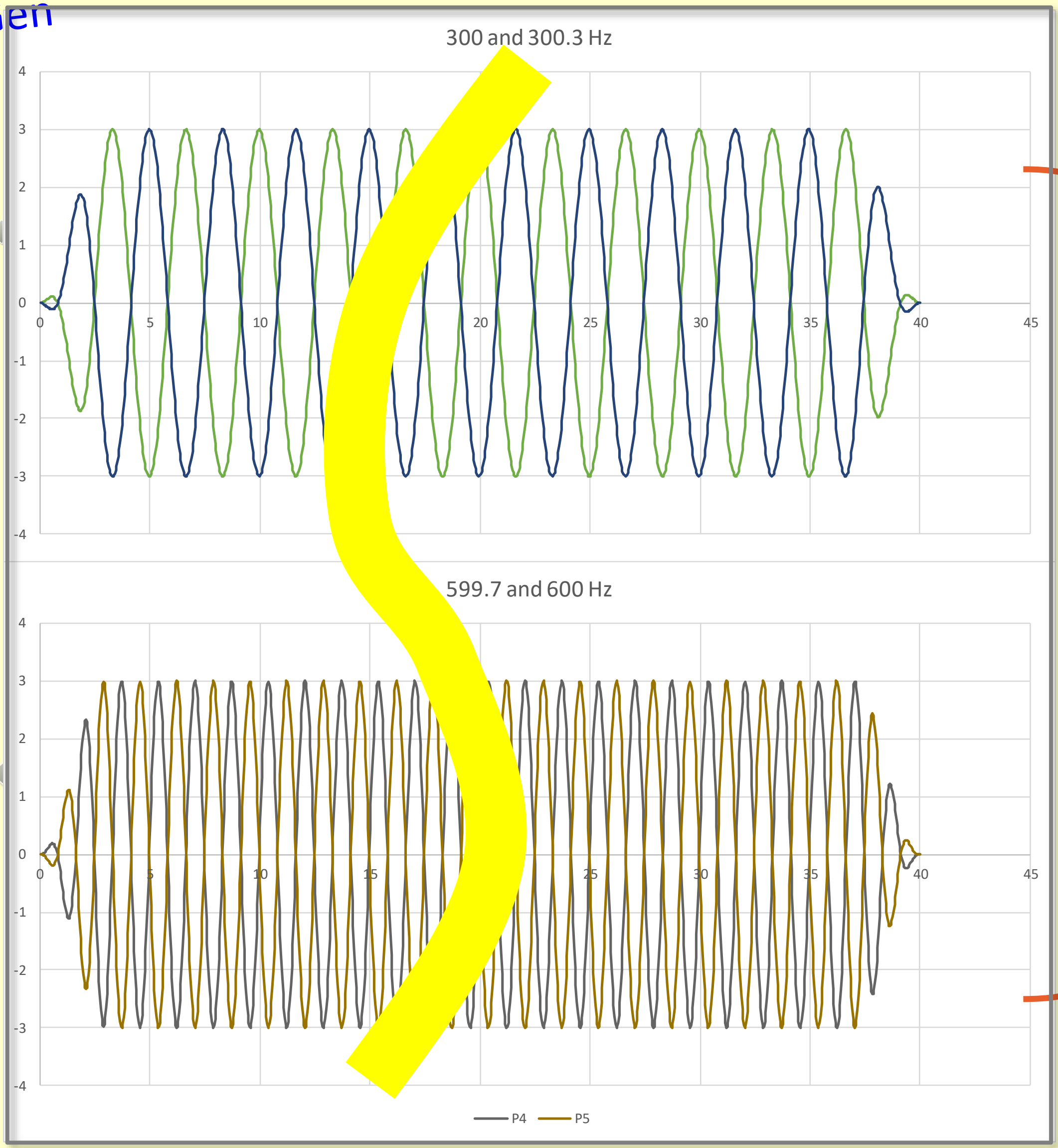
1001 Tones:
300 to 600 Hz
3 sec long

What If We Combined Lots of Pure Tones?

WaveGen

300 Hz

600 Hz



All at once:

① Phases: Random

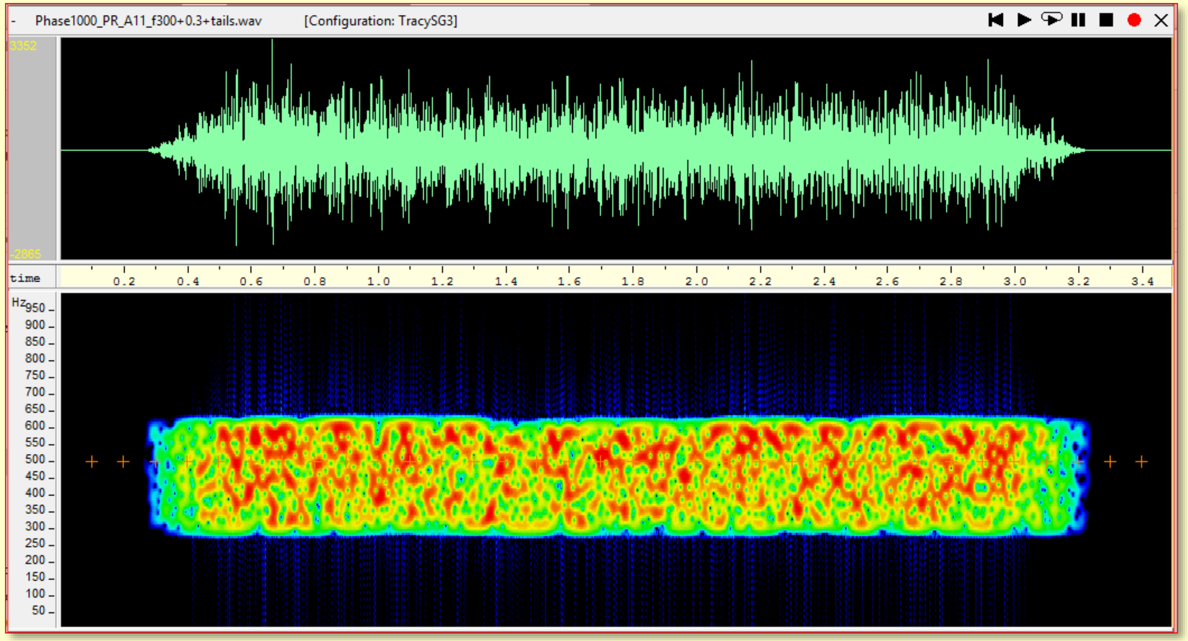
② Phases:
In Phase at Center

1001 Tones:
300 to 600 Hz
3 sec long

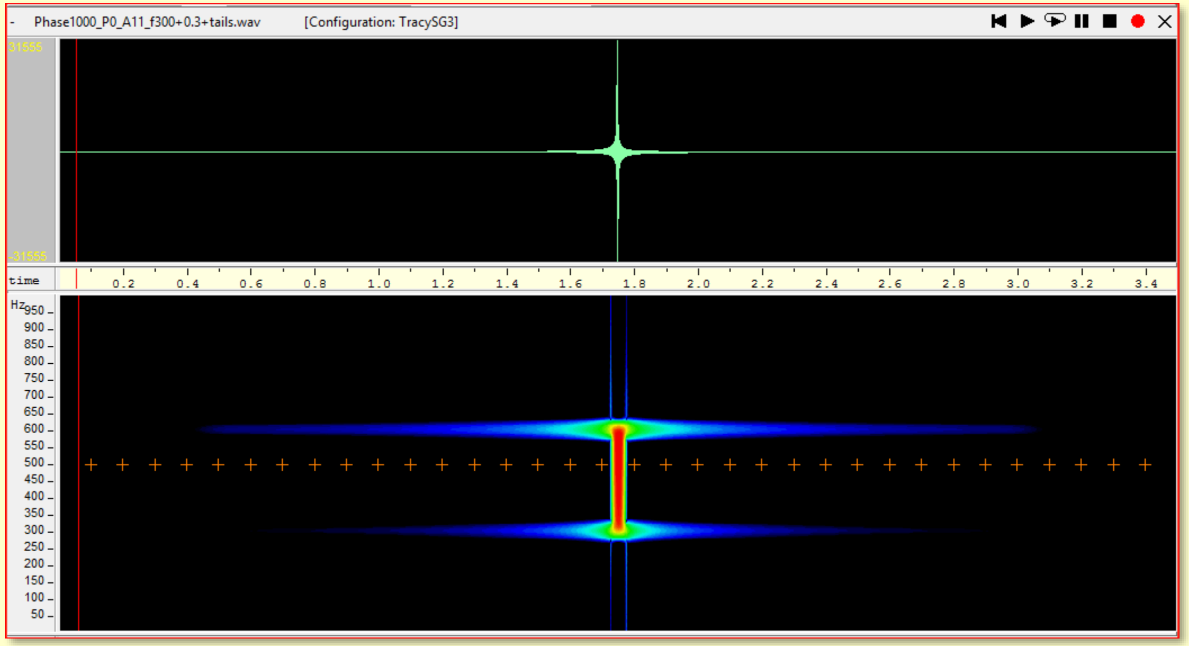
③ Phases: Varying Systematically

Spectrograms for 1001 Tones

① Phases: Random

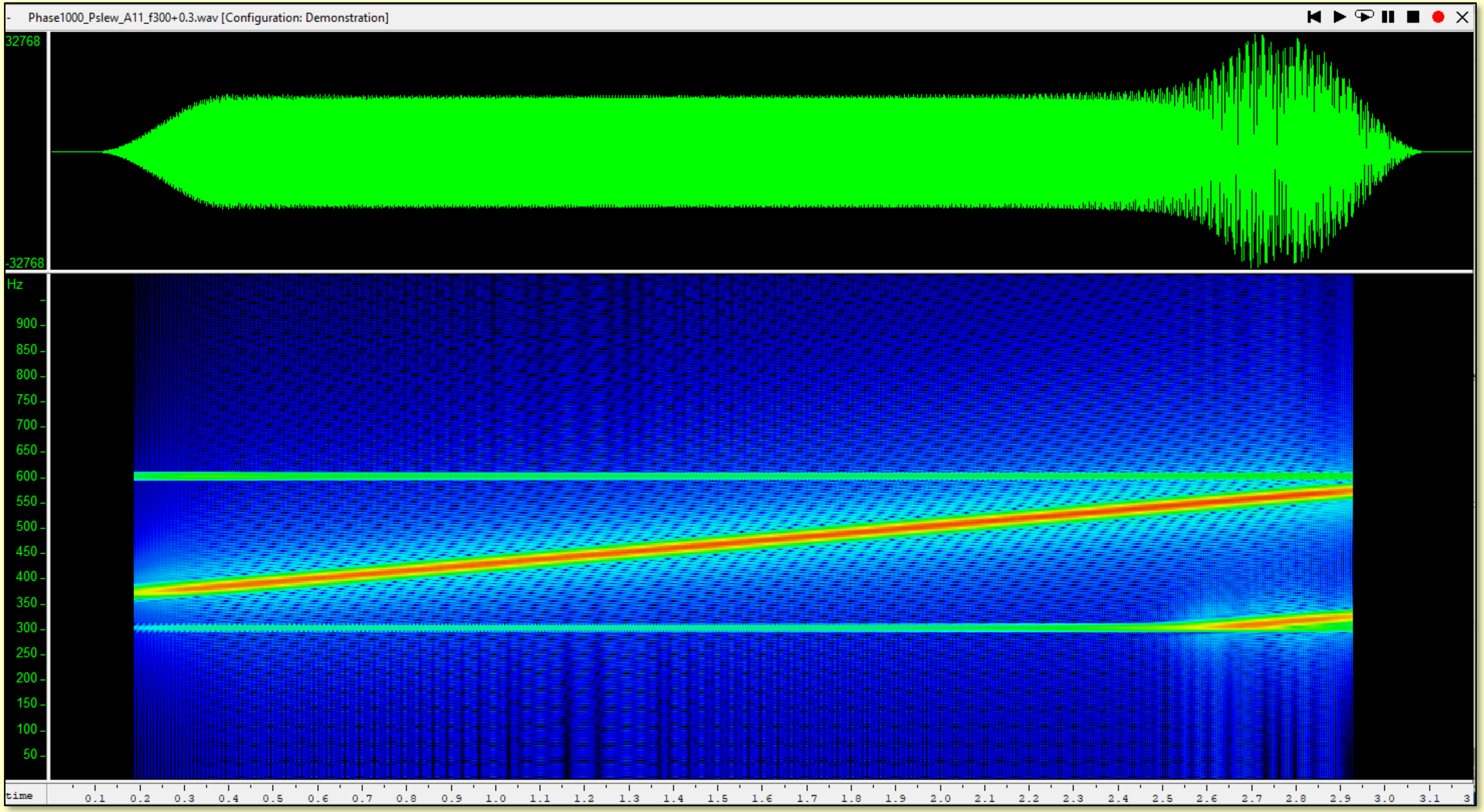


② Phases: In Phase at Center



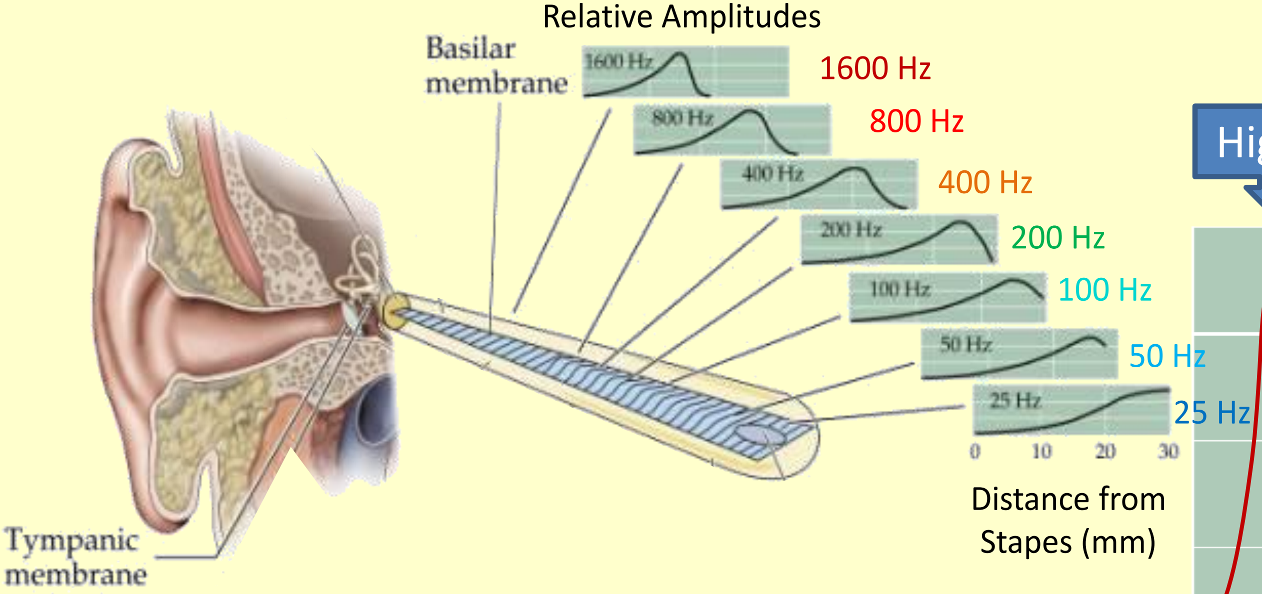
Spectrograms for 1001 Tones

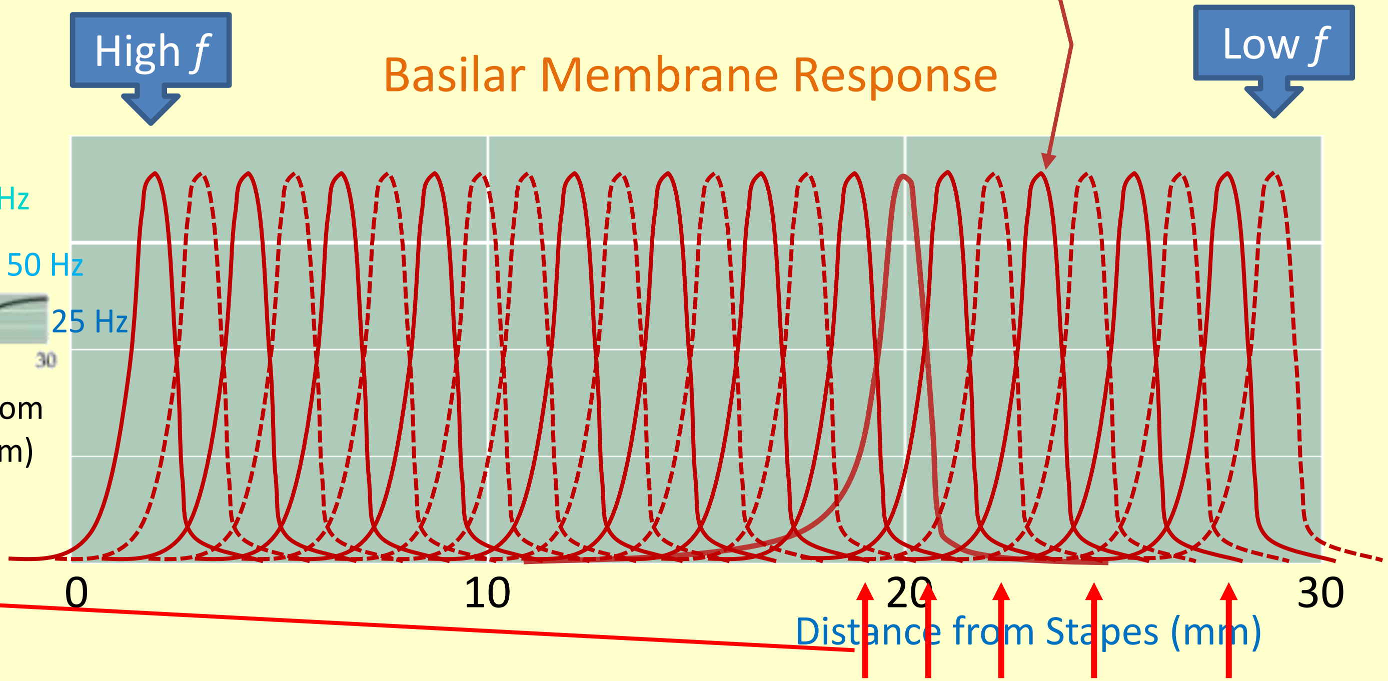
③ Phases: Varying Systematically



So Why Can We Detect Phase in One Case … and Not the Other?

It’s the Basilar Membrane, Stupid

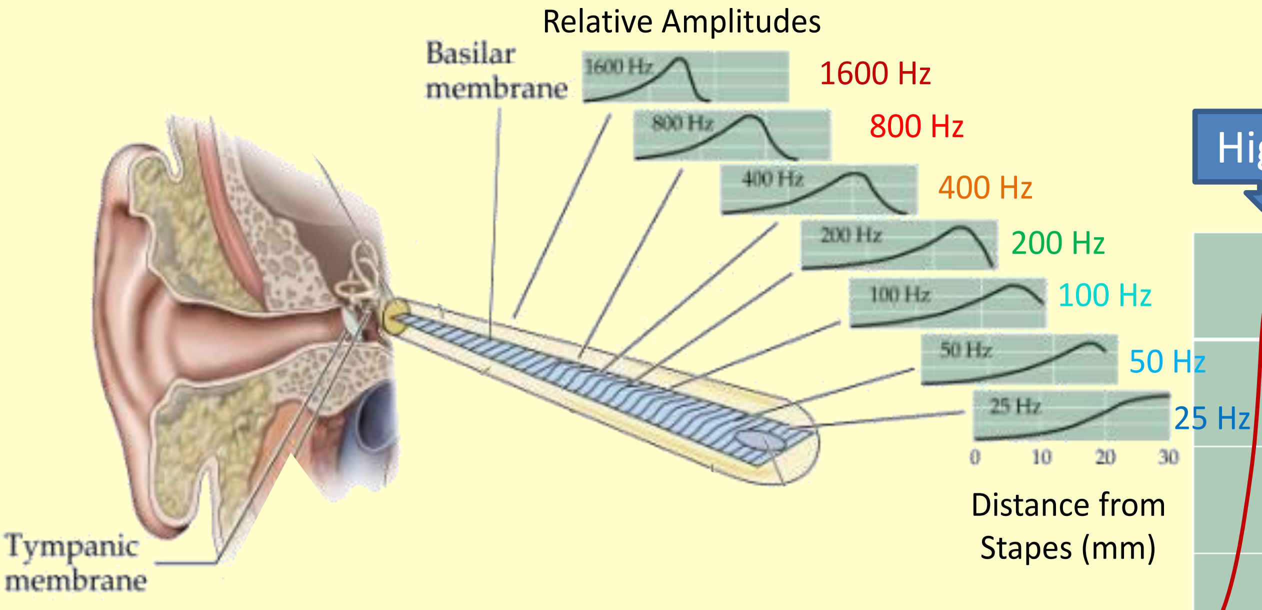


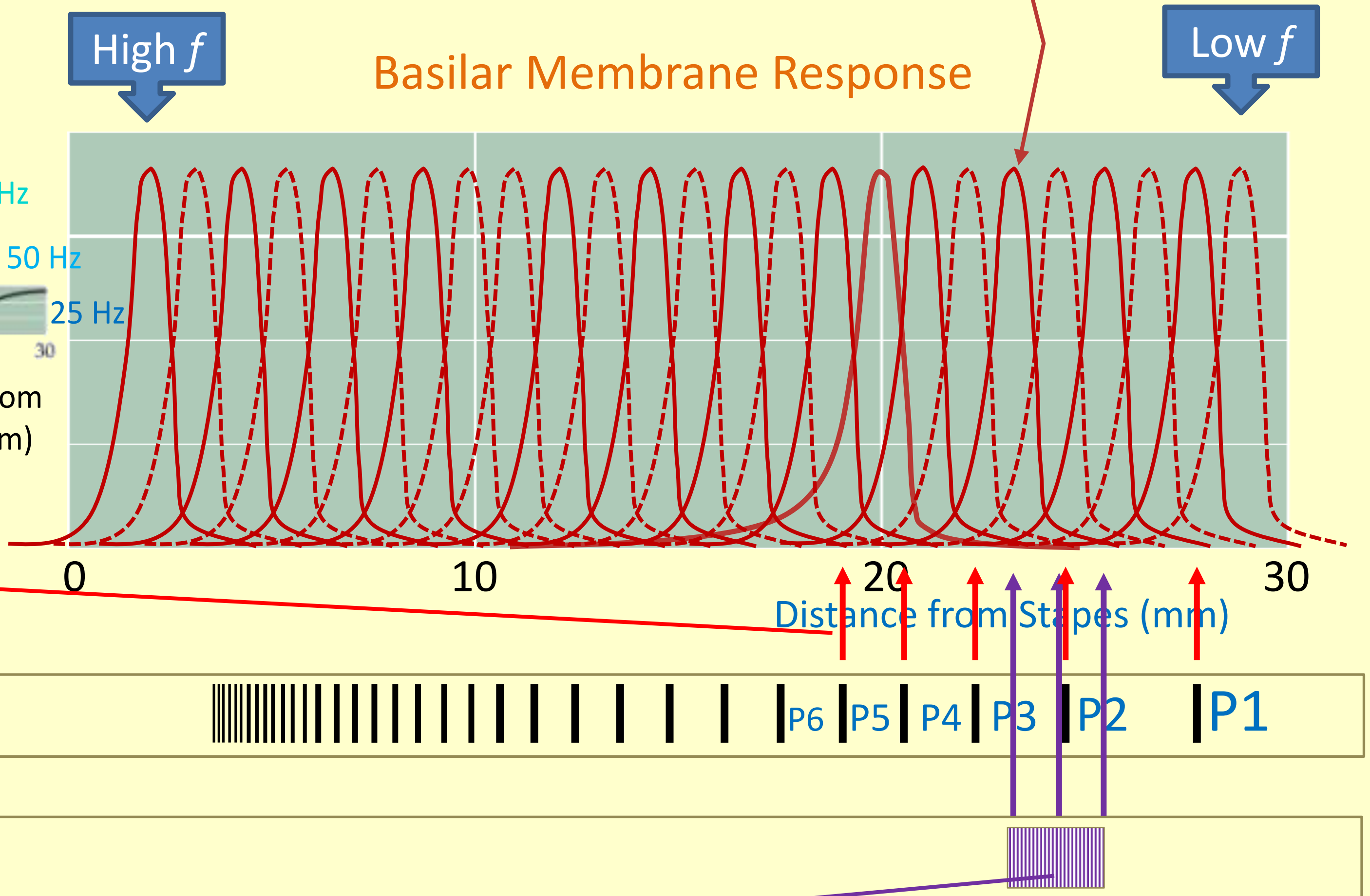


Lower Harmonics Fall on *Different* Critical Bands

1. Musical Note with Harmonics P6 P5 P4 P3 P2 P1

It’s the Basilar Membrane, Stupid





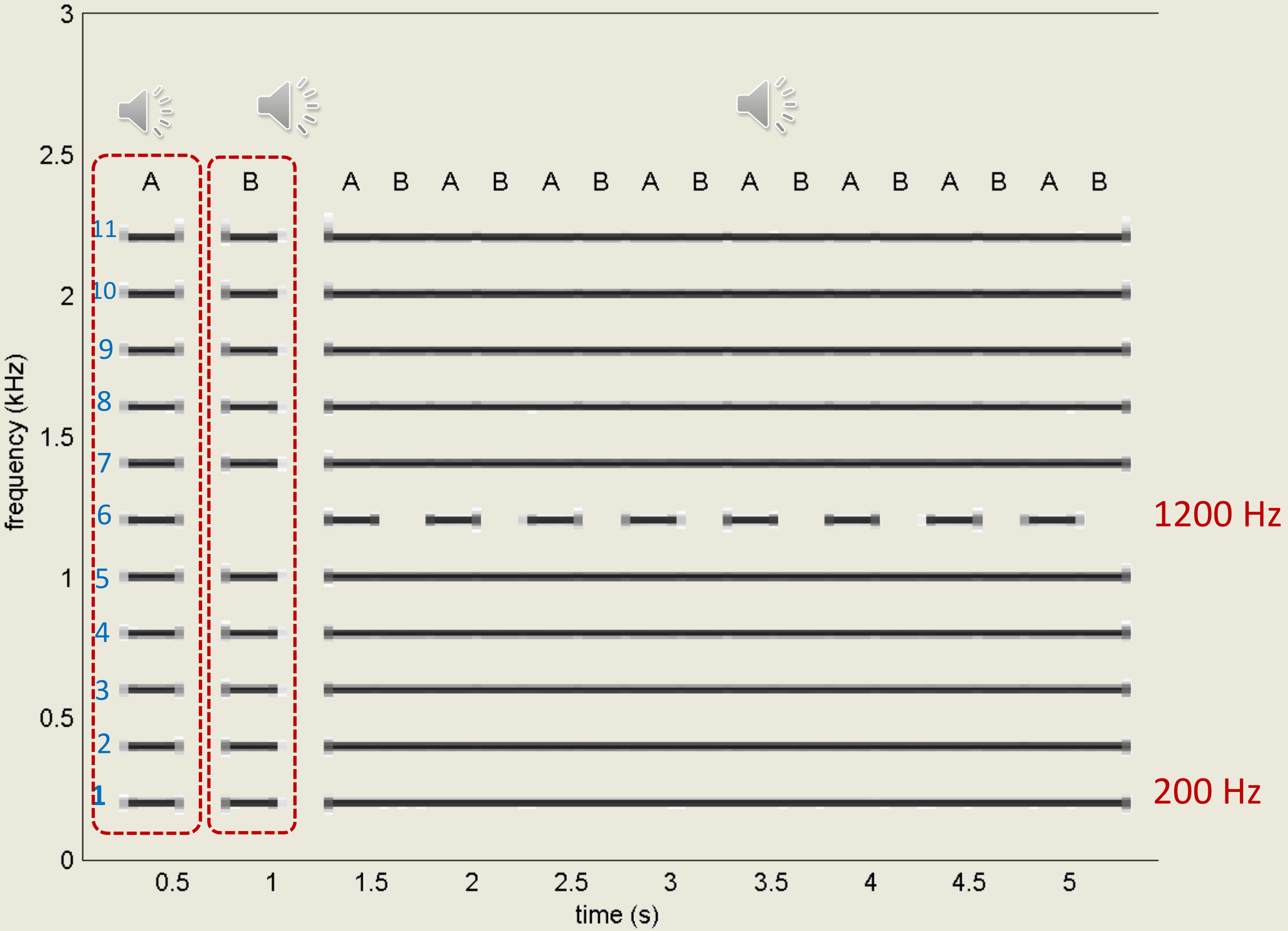
Lower Harmonics Fall on *Different* Critical Bands

1. Musical Note with Harmonics

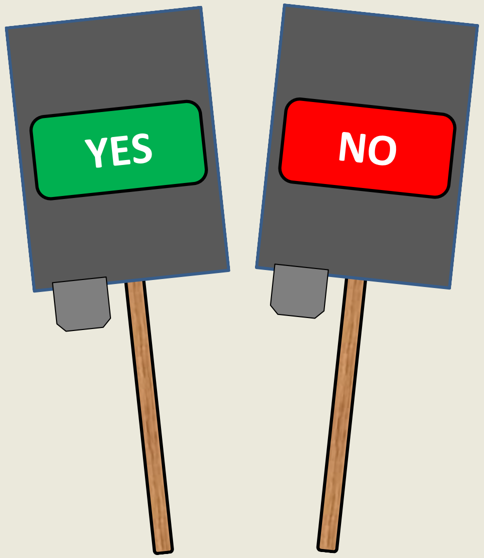
2. “Thousand Partial” Case

All 1001 Closely Spaced Partials Fall on 1 or 2 Critical Bands

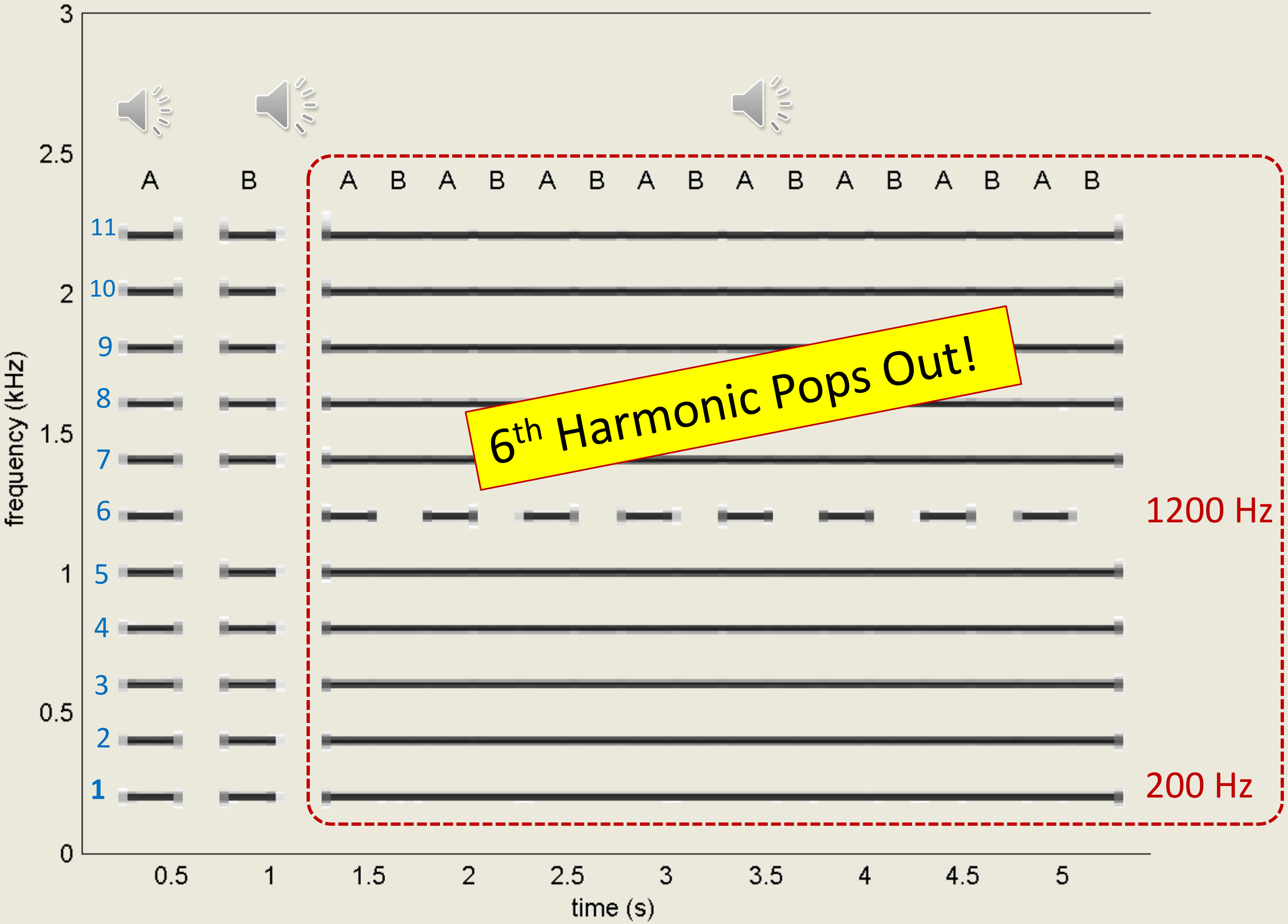
Missing Harmonic Hardly Noticed…



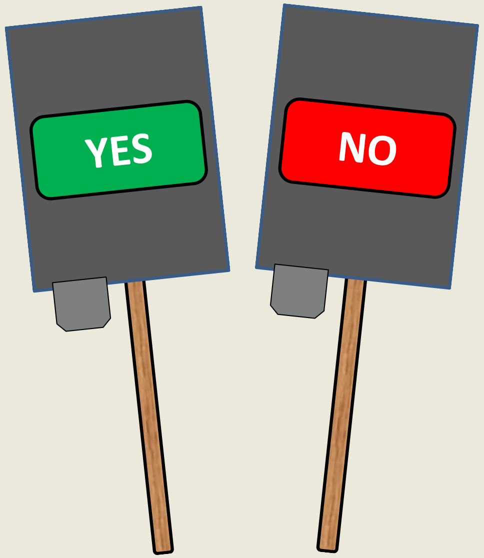
Hear the Difference?



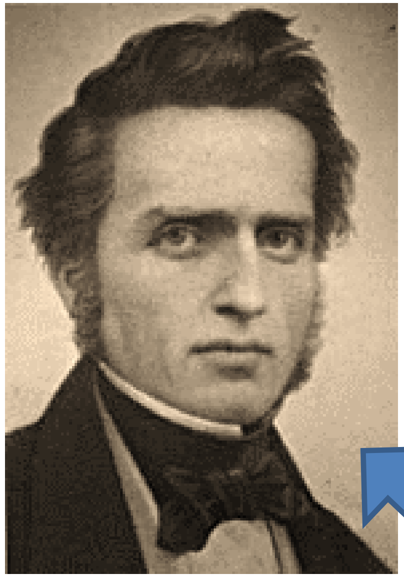
Missing Harmonic Hardly Noticed…



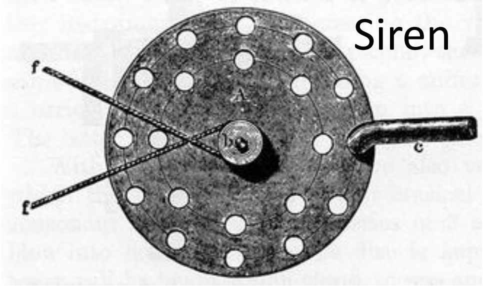
NOW can you hear it?
Hear the Difference?



Pitch *vs.* Frequency in Complex Tones



August Seebeck
(1805-1849)
Technische Universität Dresden



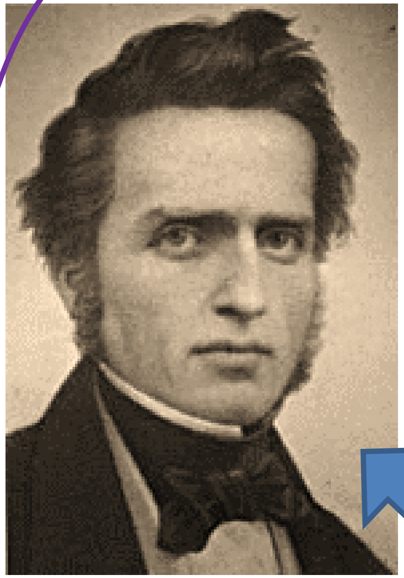
For Simple sine wave tones,
Pitch *is* directly determined by Frequency

Question:
For Complex Tones, is Perceived musical Pitch determined simply by the **Fundamental**
.. or Lowest Frequency Component?

or, is Pitch something quite different?

Georg Simon Ohm
(1789-1854)
Polytechnic School of Nuremburg

Pitch *vs.* Frequency in Complex Tones



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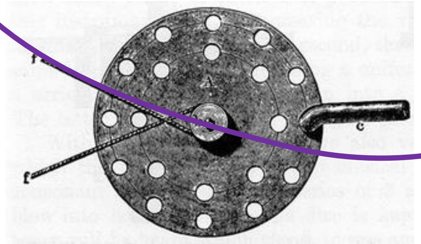

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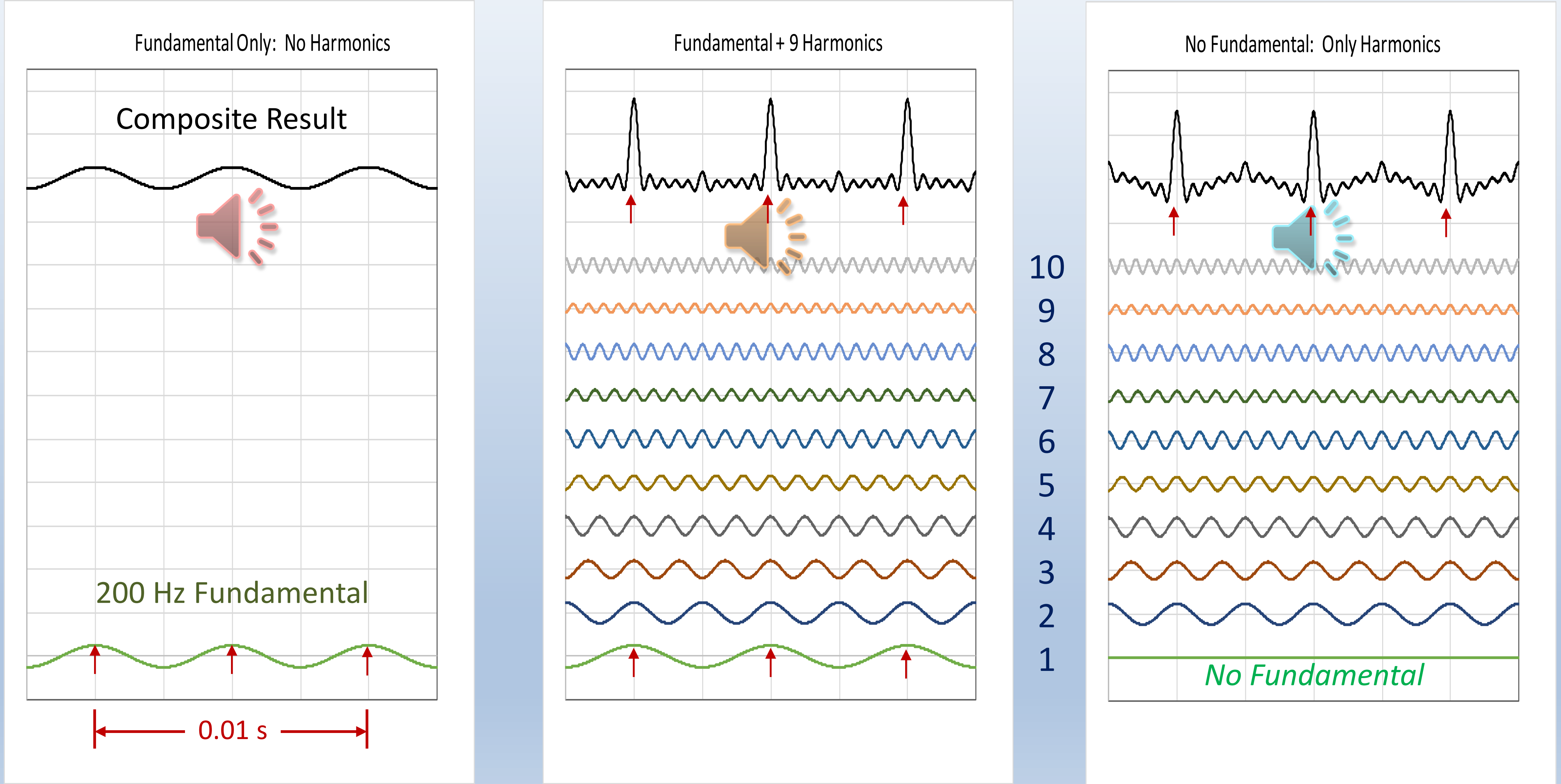
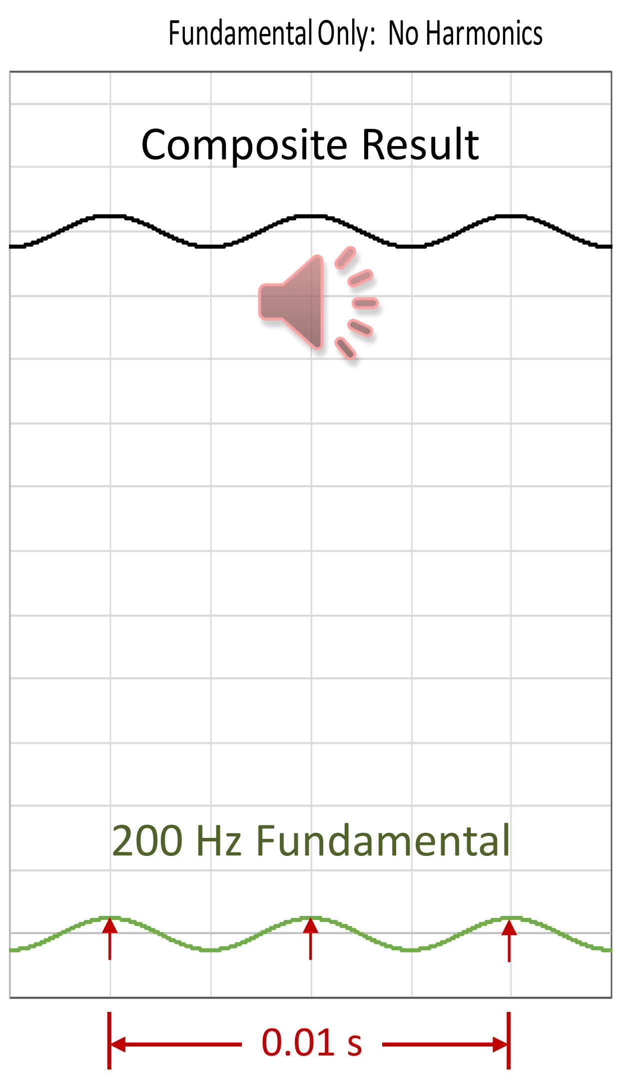
Polytechnic School of Nuremburg

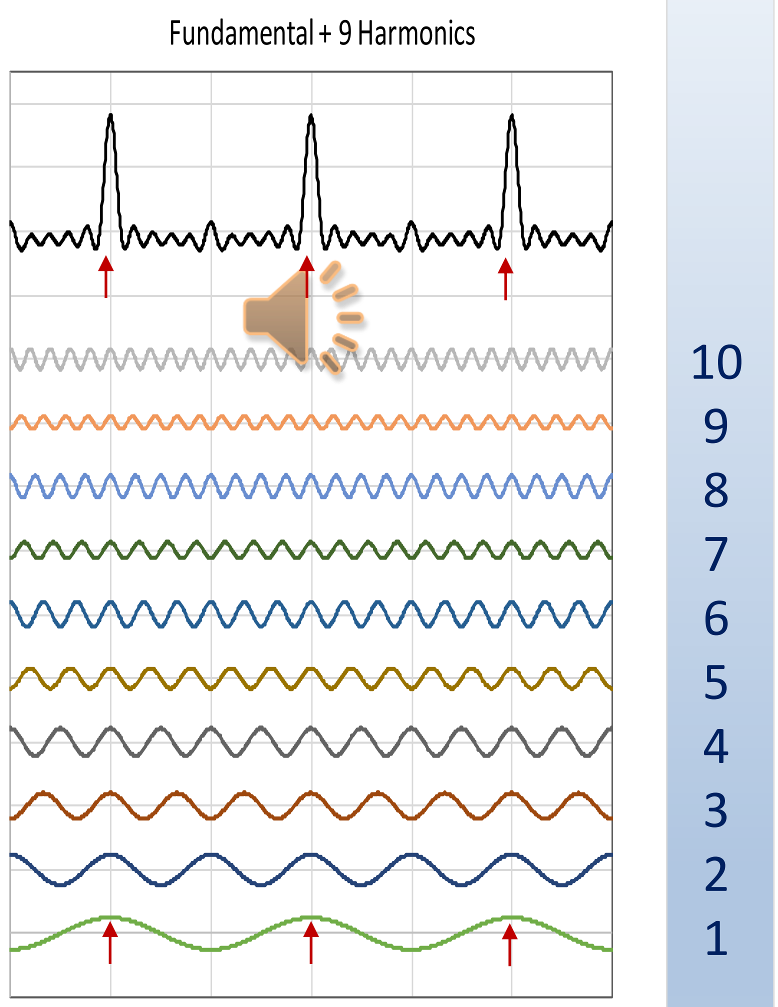
Herman von Helmholtz
(1821-1894)

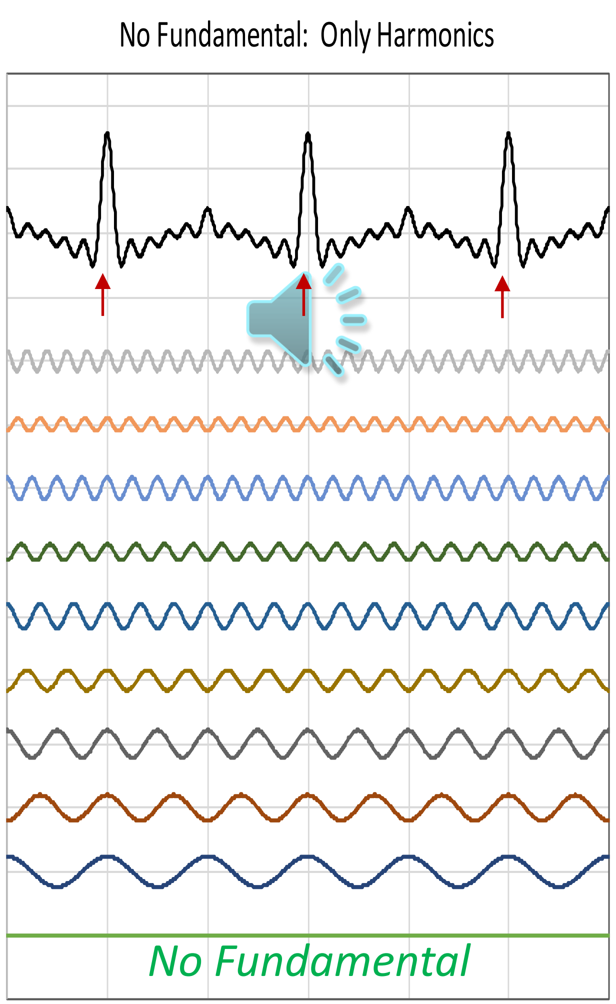
The Strange Case of the Missing Fundamental



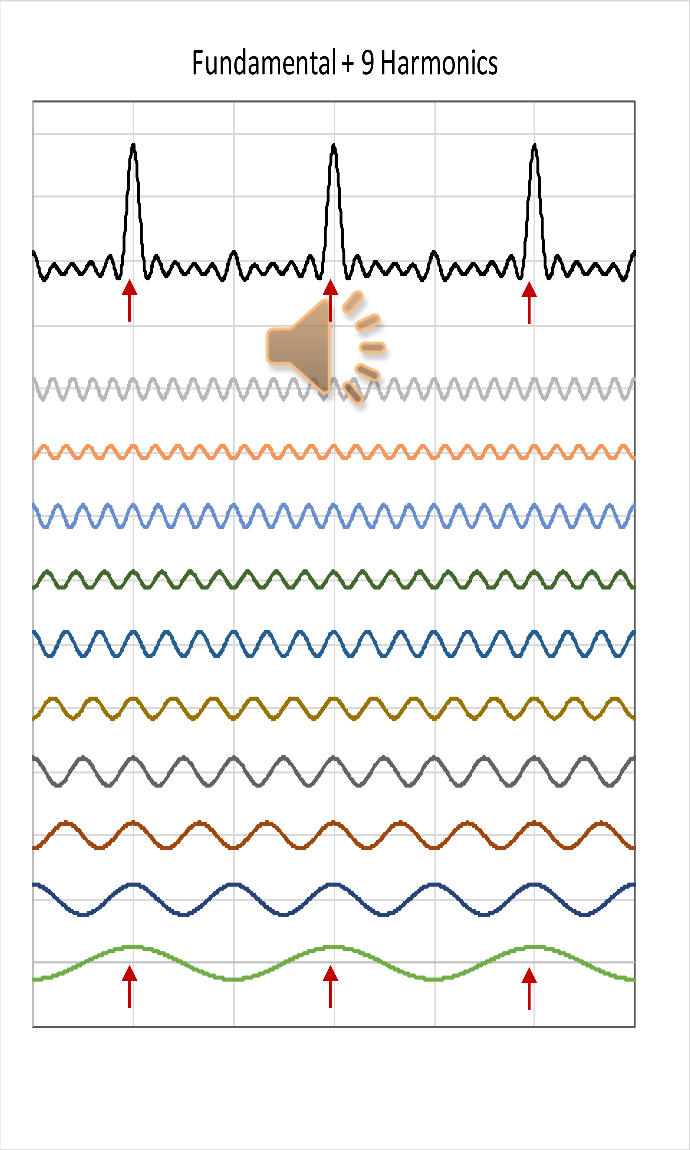
The Strange Case of the Missing Fundamental

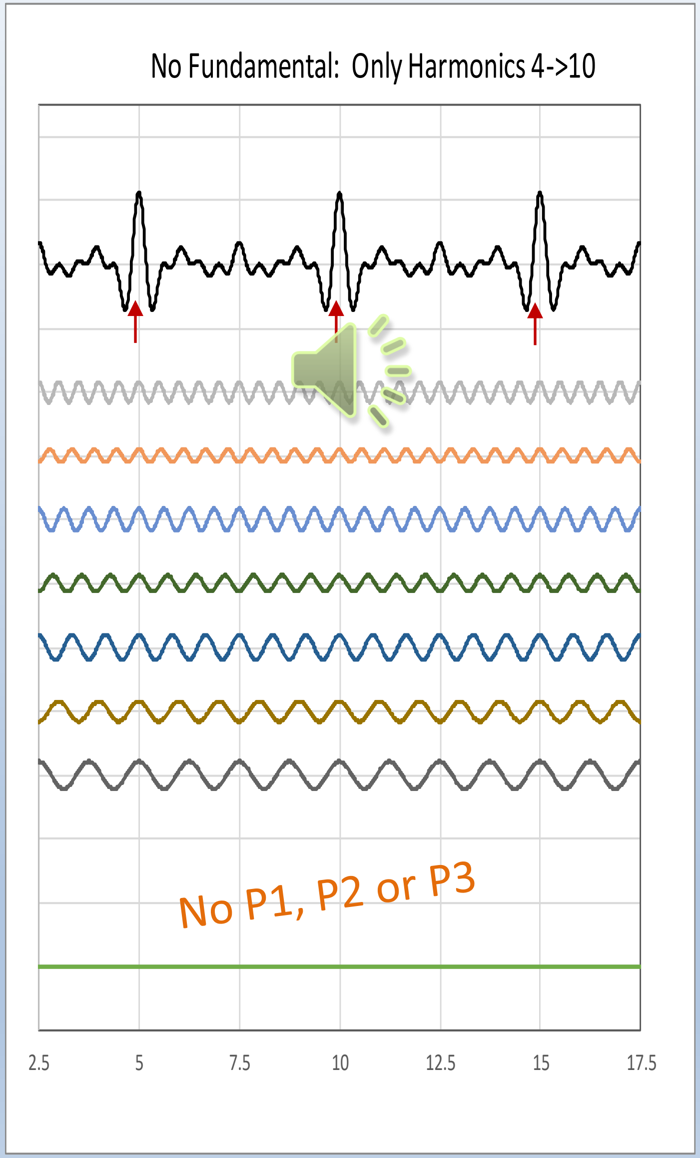




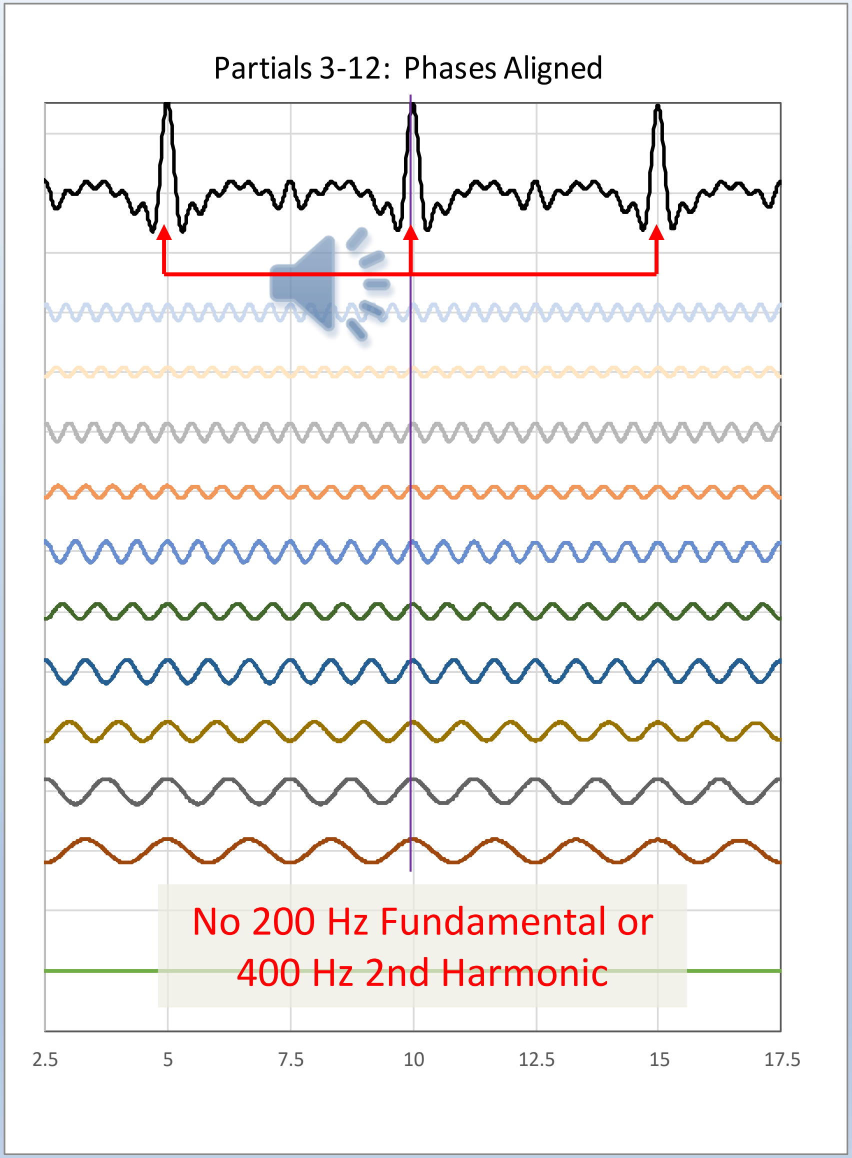


The Strange Case of the Missing Fundamental

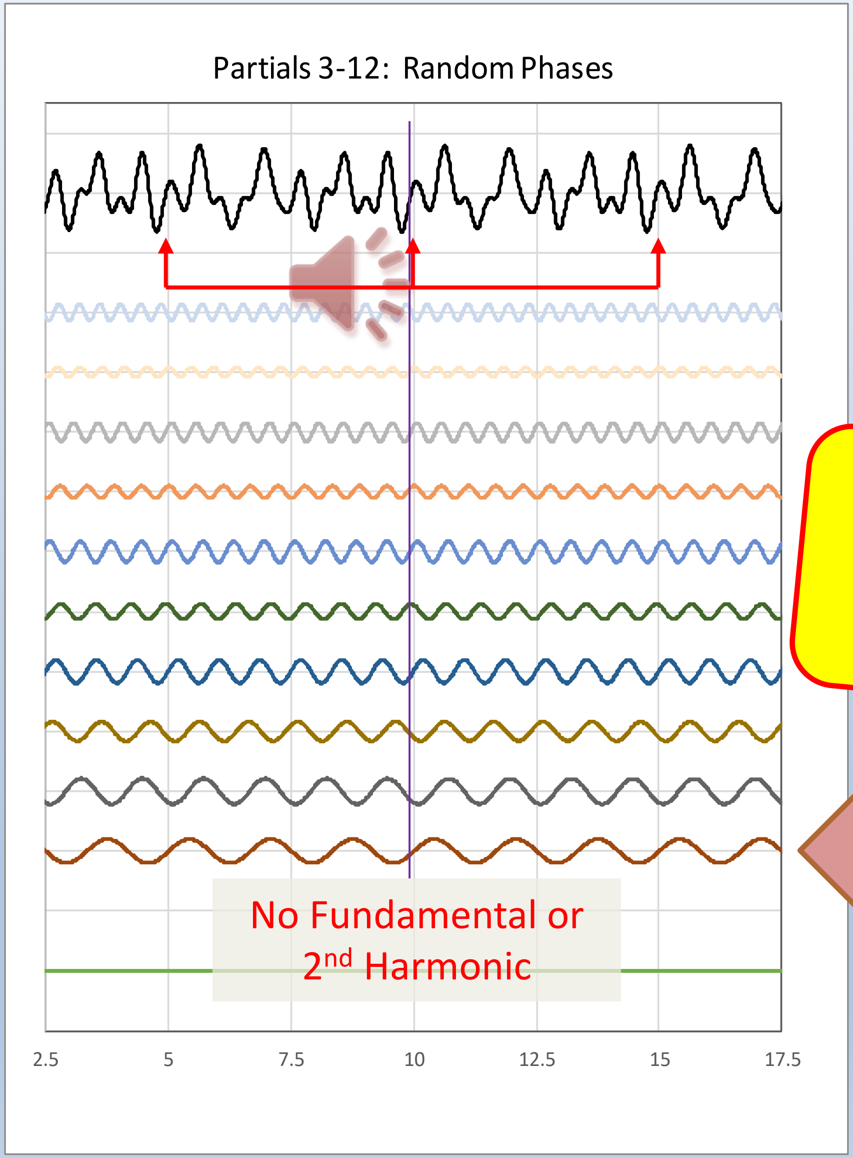




Phase Scrambled + Missing Fundamental



12
11
10
9
8
7
6
5
4
3
2
1



We still perceive a clear 200 Hz Pitch! How????

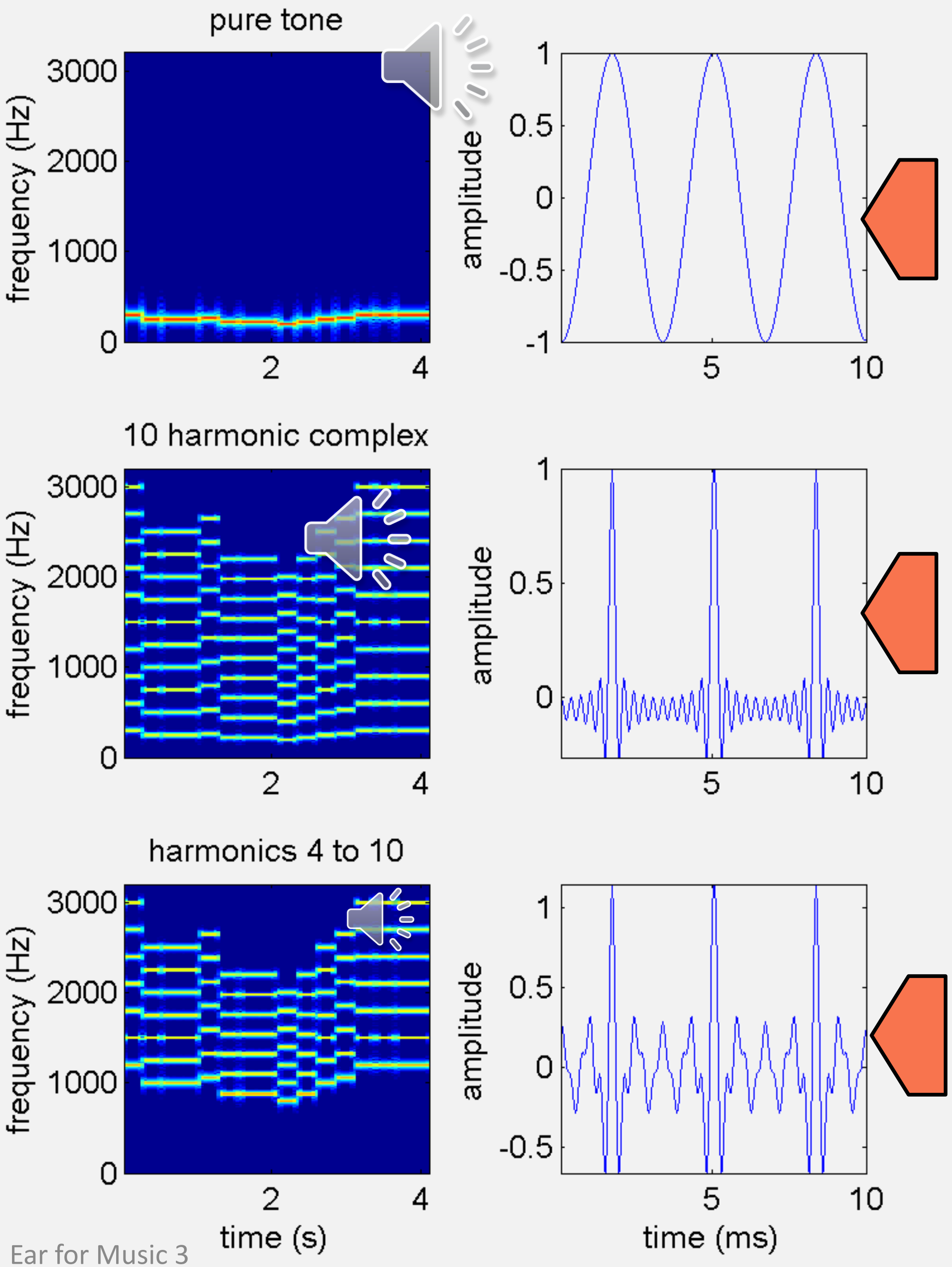
600 Hz

Missing Fundamental in a Complete Melody

Fundamental Only

Fundamental + 9 Harmonics

Higher Harmonics Only

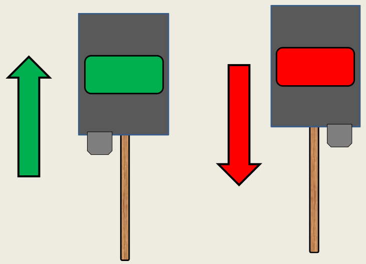


Absolute Pitch

Ability to quickly and accurately *name* the Pitch of a complex tone

- Fairly rare – 1 in 10,000 estimate in general population
- Not to be confused with Relative Pitch
- Odds go up if you
  - are musically trained (up to 4%)
  - were exposed to intensive musical training as a young child
  - have a tonal first language (e.g. Chinese, Vietnamese)
  - are on the autism spectrum
  - are named Mozart or John Phillip Sousa
  - are Synesthetic
- Many non-musicians have good pitch *recall*

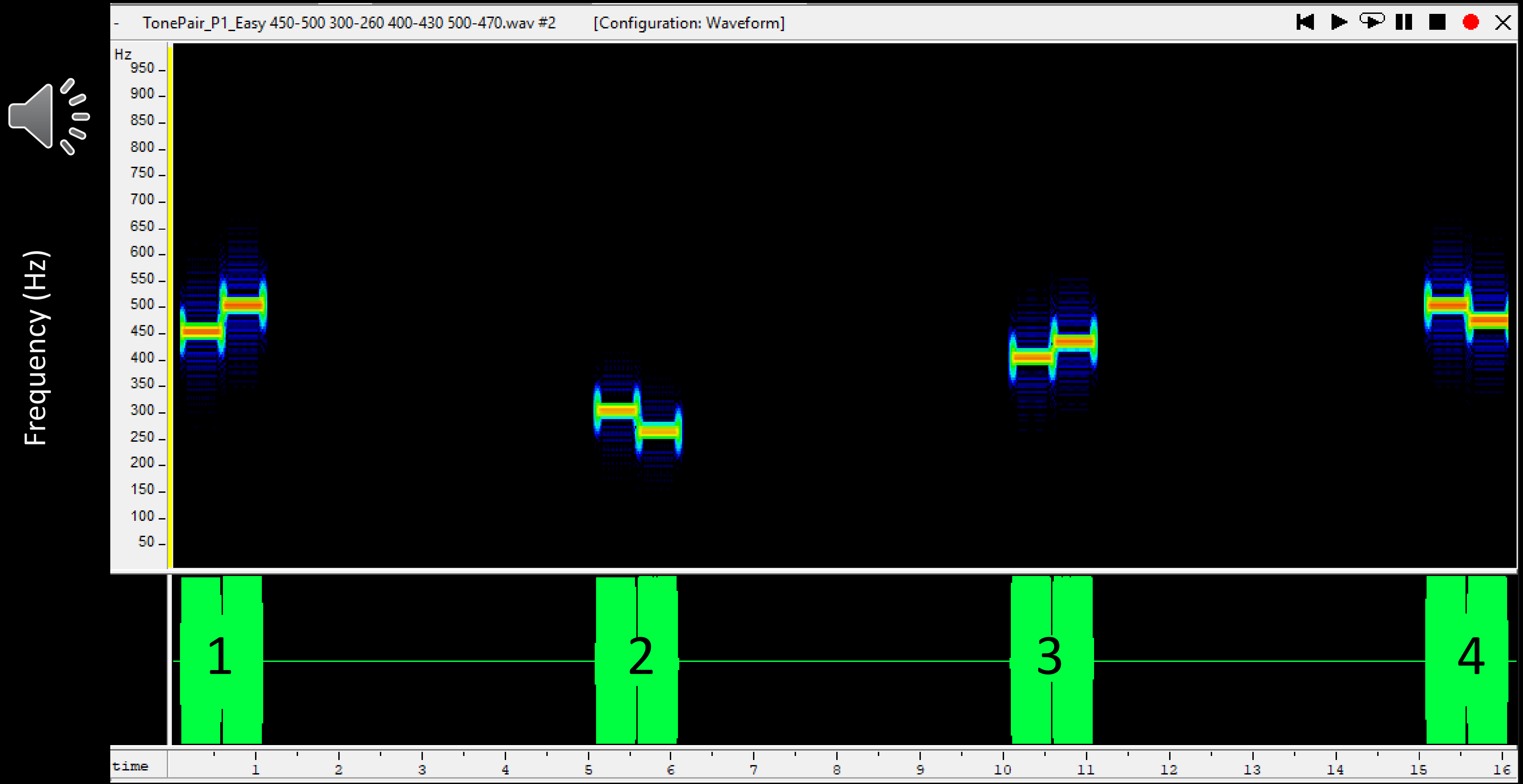
Pitch Rising ↑
or Falling ↓



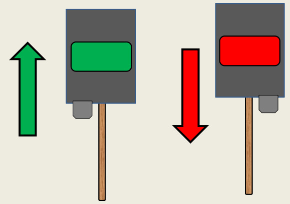
Pitch Perception Test

Tone Pairs		Pair **1**	Pair **2**	Pair **3**	Pair **4**
Test **A** (pure tones)		↑	↓	↑	↓
Test **B** (pure tones)					
Test **C** (complex tones)					
Test **D** (complex tones)					

Spectrogram of Test A



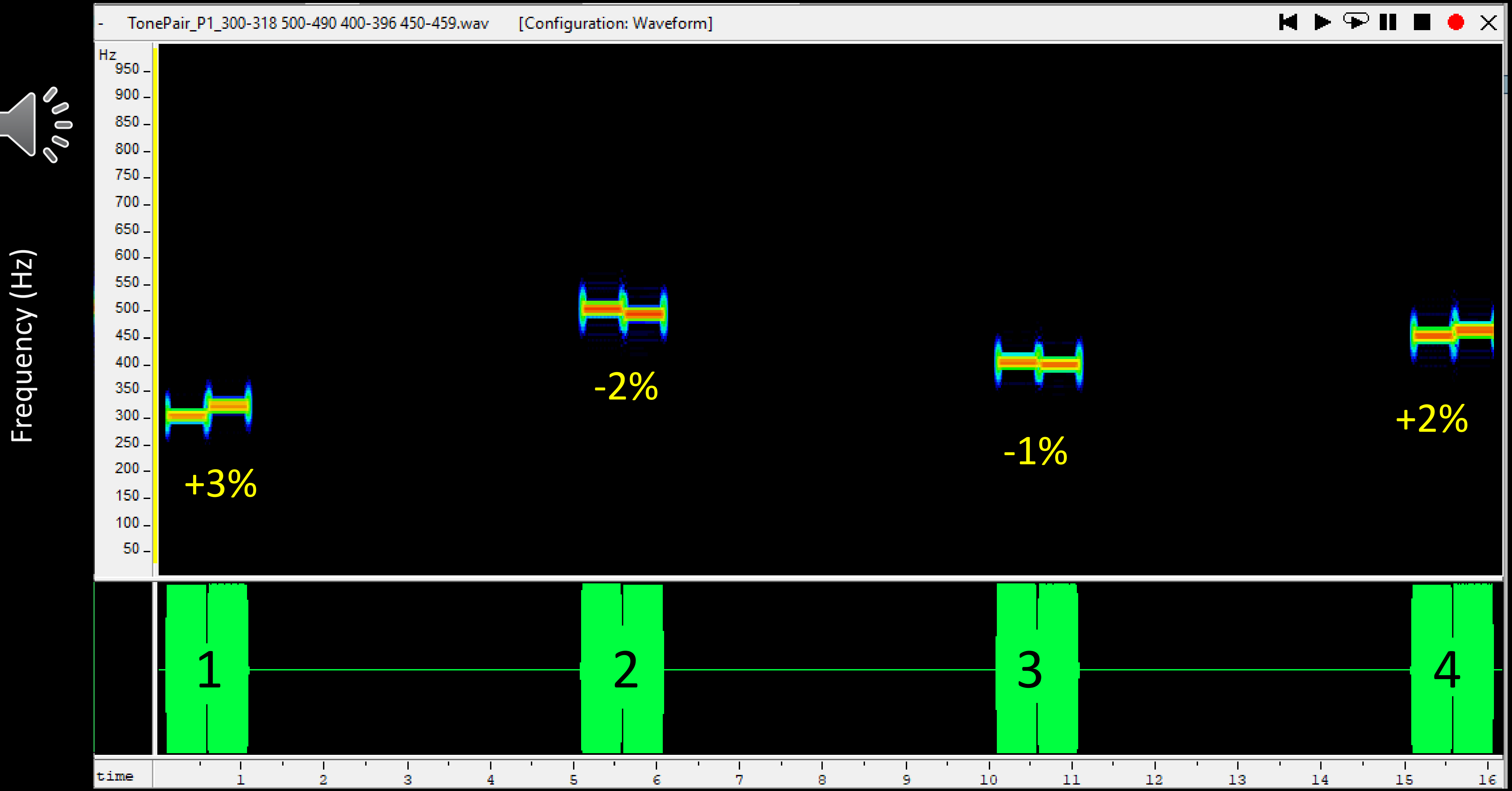
Pitch Rising ↑
or Falling ↓



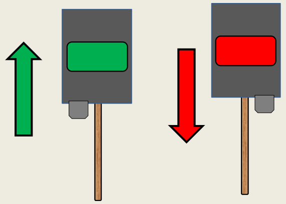
Pitch Perception Test

Tone Pairs		Pair **1**	Pair **2**	Pair **3**	Pair **4**
Test **A** (pure tones)		↑	↓	↑	↓
Test **B** (pure tones)					
Test **C** (complex tones)					
Test **D** (complex tones)					

Spectrogram of Test B



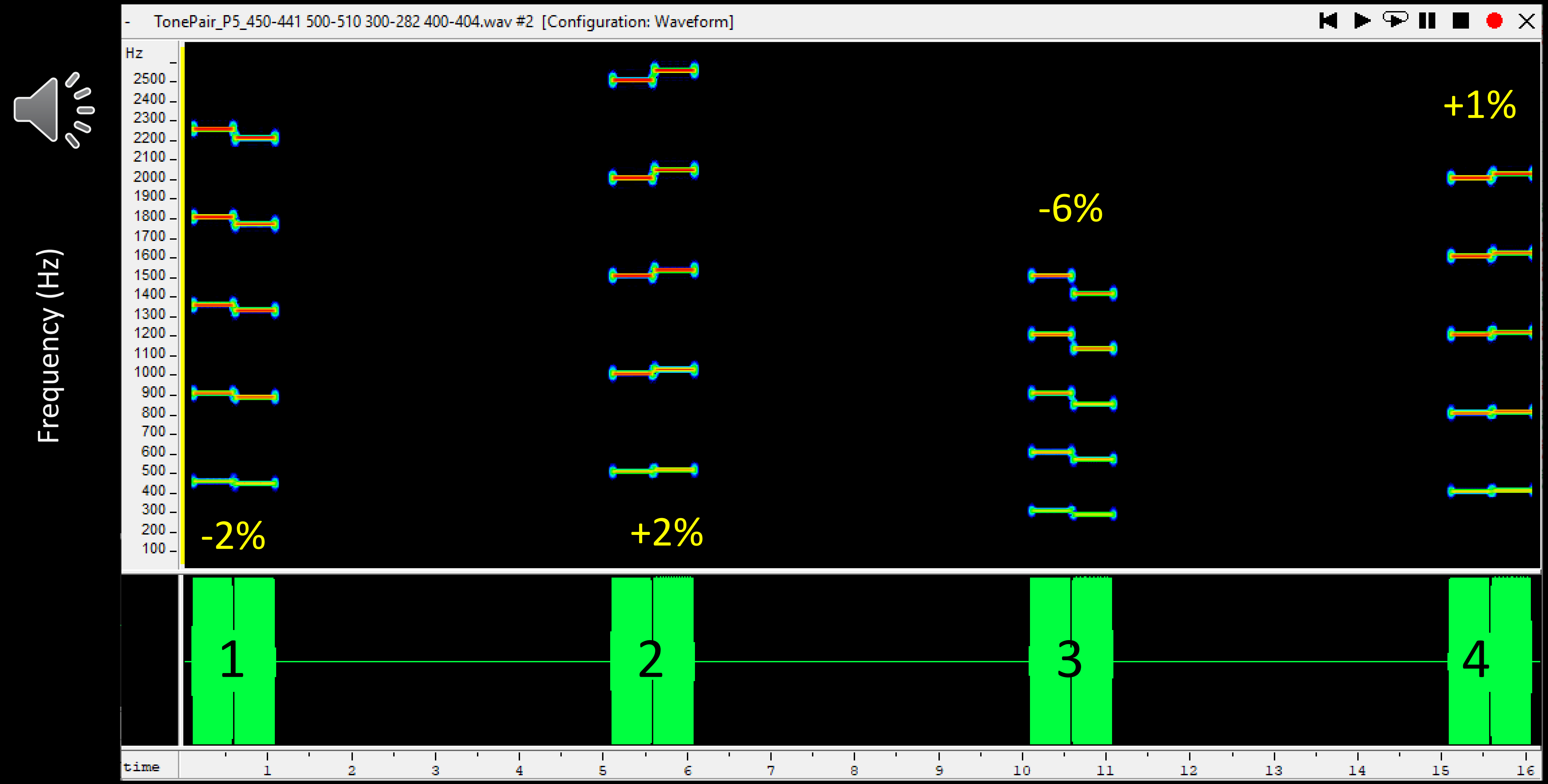
Pitch Rising ↑
or Falling ↓



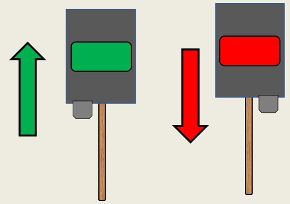
Pitch Perception Test

Tone Pairs		Pair **1**	Pair **2**	Pair **3**	Pair **4**
Test **A** (pure tones)		↑	↓	↑	↓
Test **B** (pure tones)		↑	↓	↓	↑
Test **C** (complex tones)					
Test **D** (complex tones)					

Spectrogram of Test C



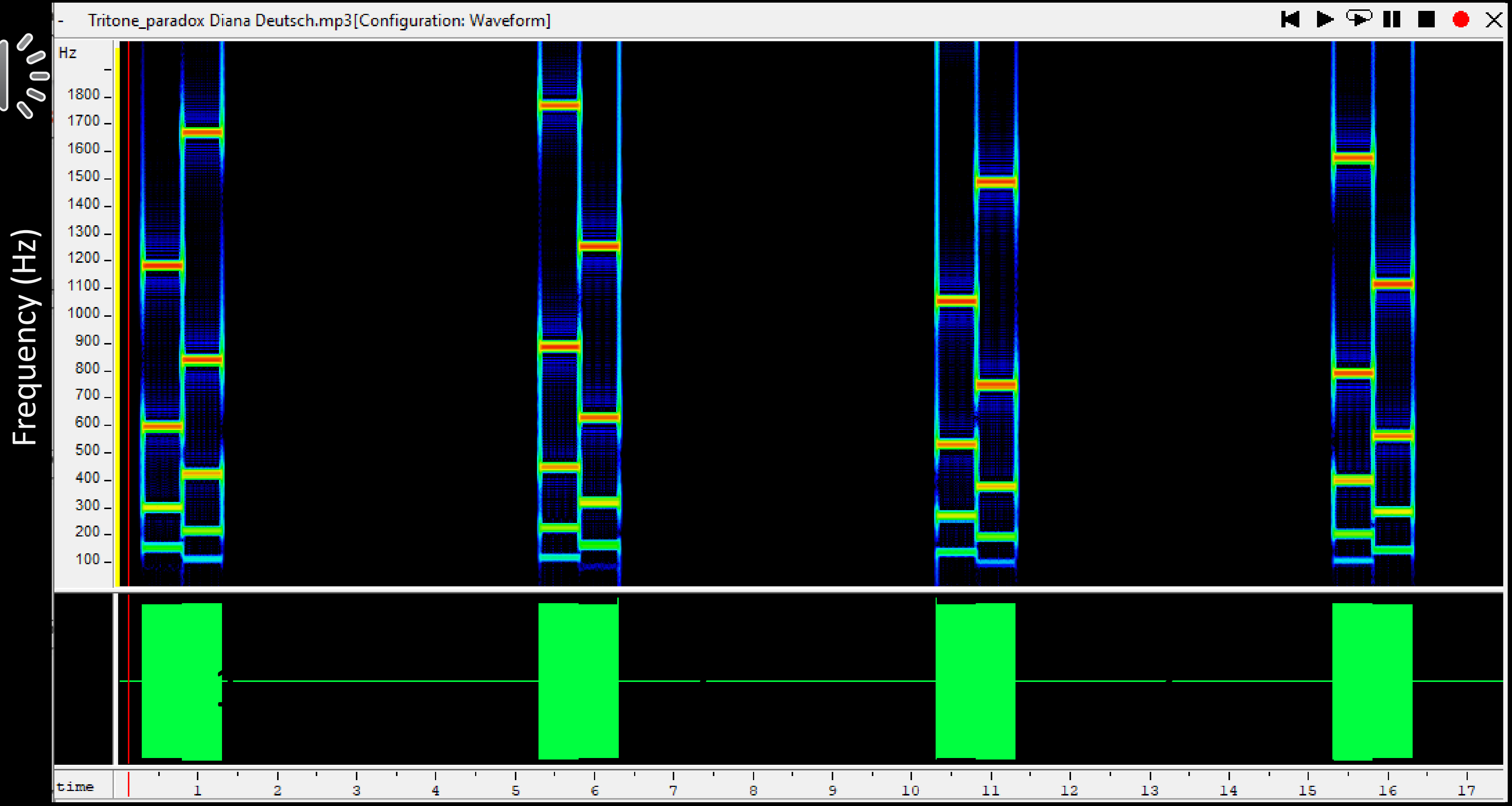
Pitch Rising ↑
or Falling ↓

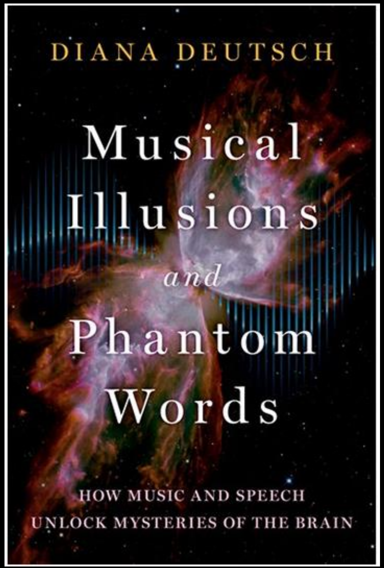


Pitch Perception Test

Tone Pairs		Pair **1**	Pair **2**	Pair **3**	Pair **4**
Test **A** (pure tones)		↑	↓	↑	↓
Test **B** (pure tones)		↑	↓	↓	↑
Test **C** (complex tones)		↓	↑	↓	↑
Test **D** (complex tones)					

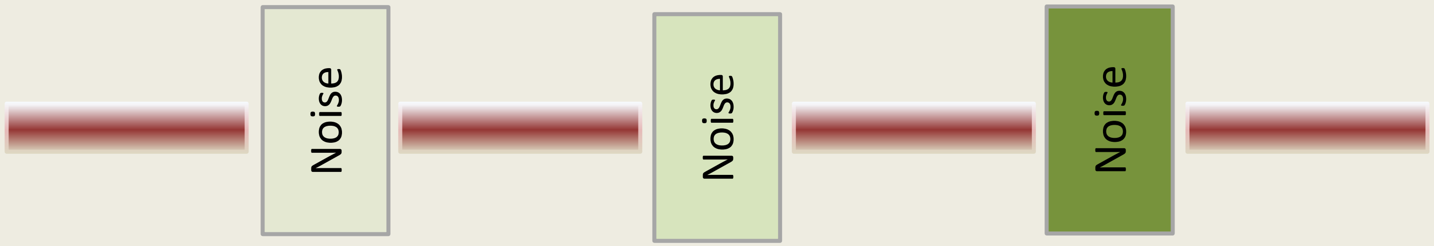
Diana Deutsch's Tritone Paradox *(Test D)*





Continuity Illusion

Series of beeps…

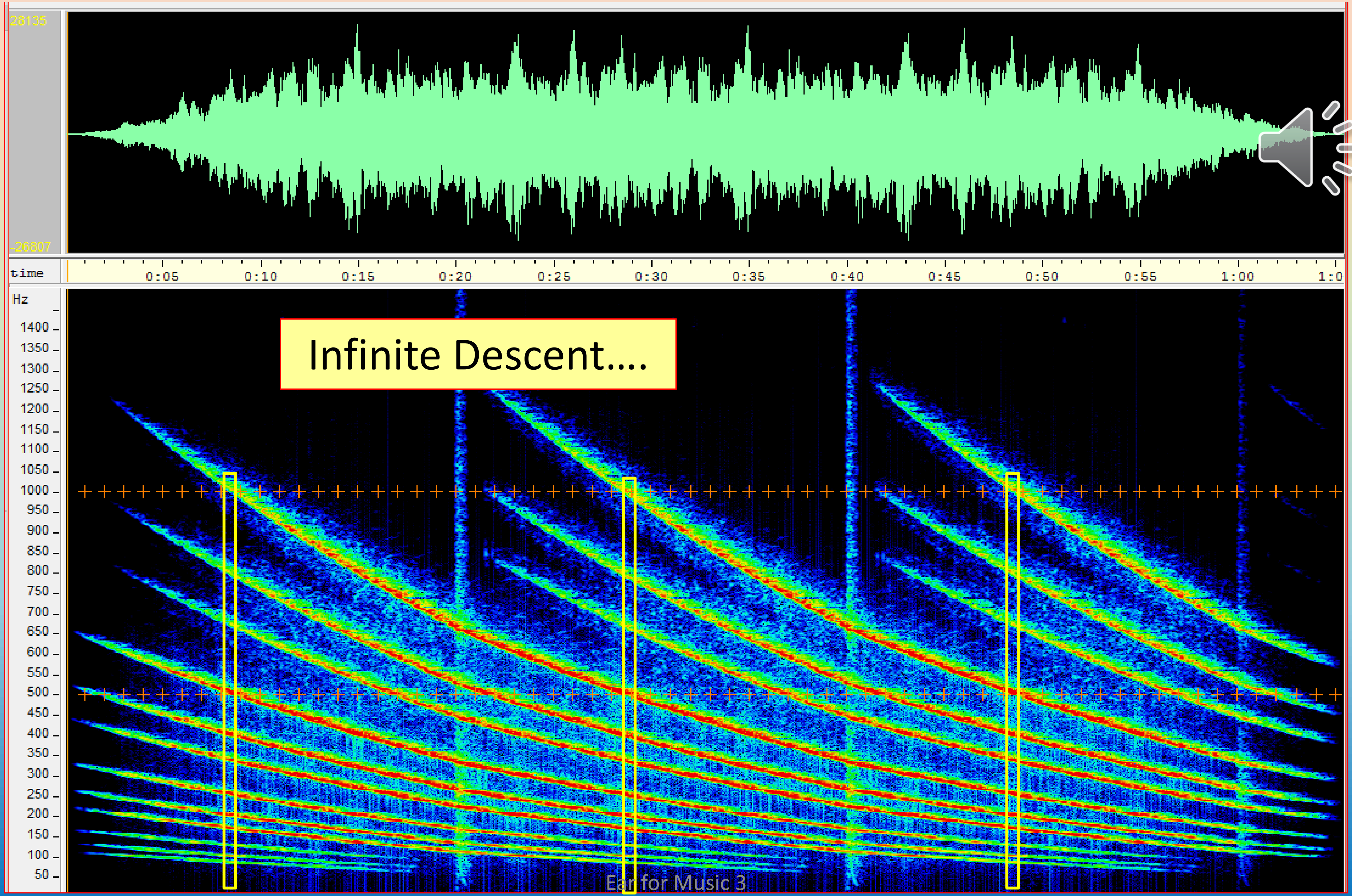


Now concentrate on the beeps…

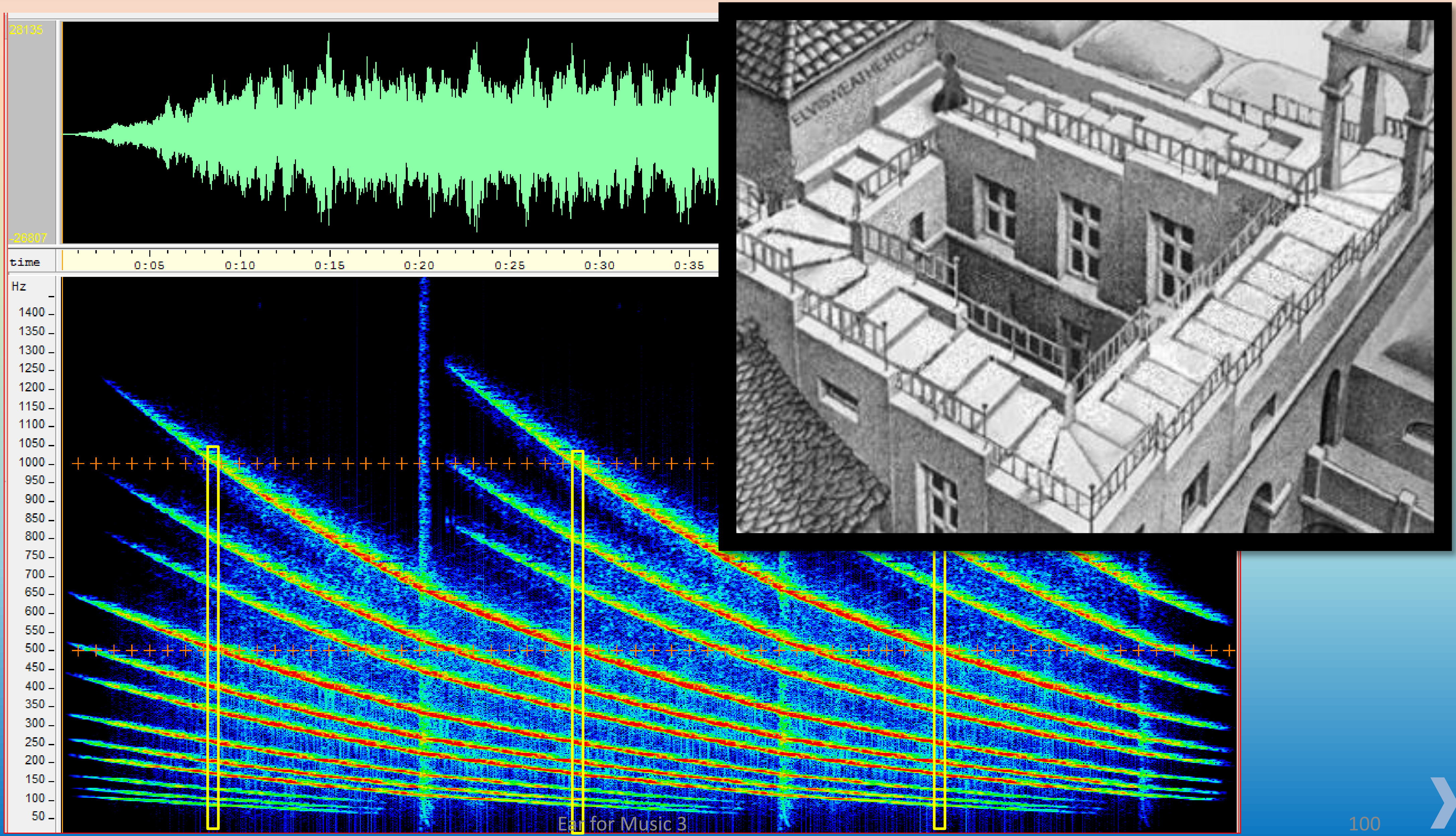
Ignore the noise

The beeps merge into one continuous tone when masked by noise

Shepard-Risset Glissando



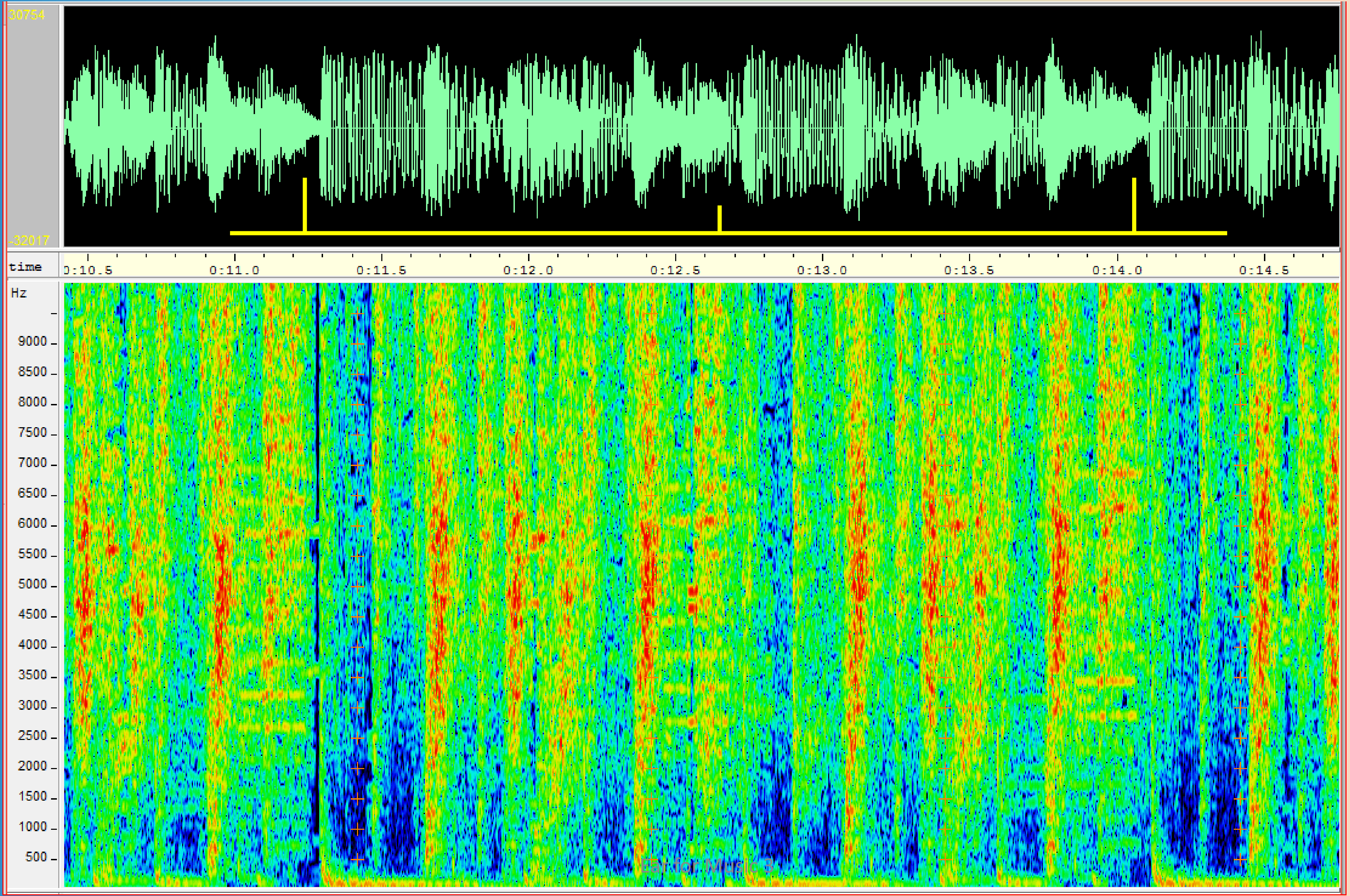
Shepard-Risset Glissando



Risset's Accelerando

Jean-Clause Risset (1938-2016)
Composer, Bell Labs

Risset's Accelerando



Question Time

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Course Outline

1. Building Blocks: Some basic concepts
2. Resonance: Building Complex Sounds
3. **Hearing and the Ear**
4. Musical Scales
5. Musical Notation; String Instruments
6. Timbre and Pipe Instruments
7. Human Voice and Singing
8. Harmony and Dissonance; Chords