AUDIO LABS

Learning with Music Signals: Technology Meets Education

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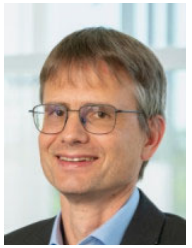
03. April 2023

FAU Friedrich-Alexander-Universität Erlangen-Nürnberg

Fraunhofer IIS

Meinard Müller



- Mathematics (Diplom/Master, 1997)
  Computer Science (PhD, 2001)
  Information Retrieval (Habilitation, 2007)
- Senior Researcher (2007-2012)
- Professor Semantic Audio Processing (since 2012)
- Former President of the International Society for Music Information Retrieval (MIR)
- IEEE Fellow for contributions to Music Signal Processing

Meinard Müller: Research Group

Semantic Audio Processing

- Michael Krause
- Yigitcan Özer
- Simon Schwär
- Johannes Zeitler
- Peter Meier (external)





- Christof Weiß
- Sebastian Rosenzweig
- Frank Zalkow
- Christian Dittmar
- Stefan Balke
- Jonathan Driedger
- Thomas Prätzlich
- …

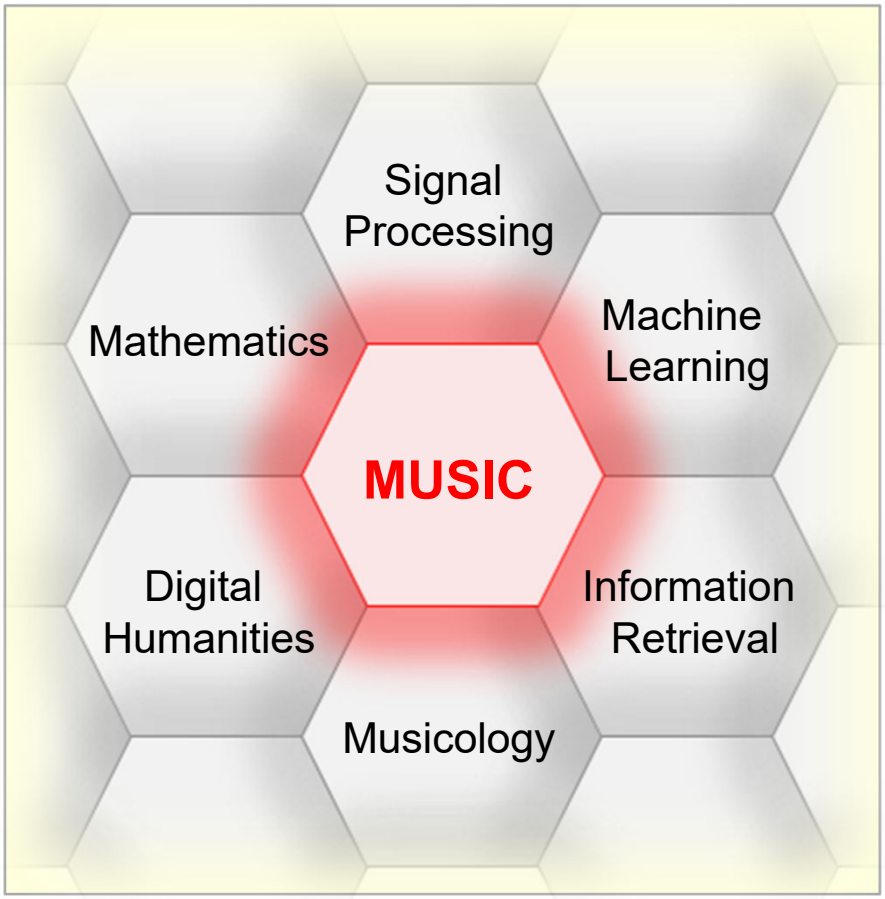






Music Processing

Music Processing: A Multifaceted Research Area

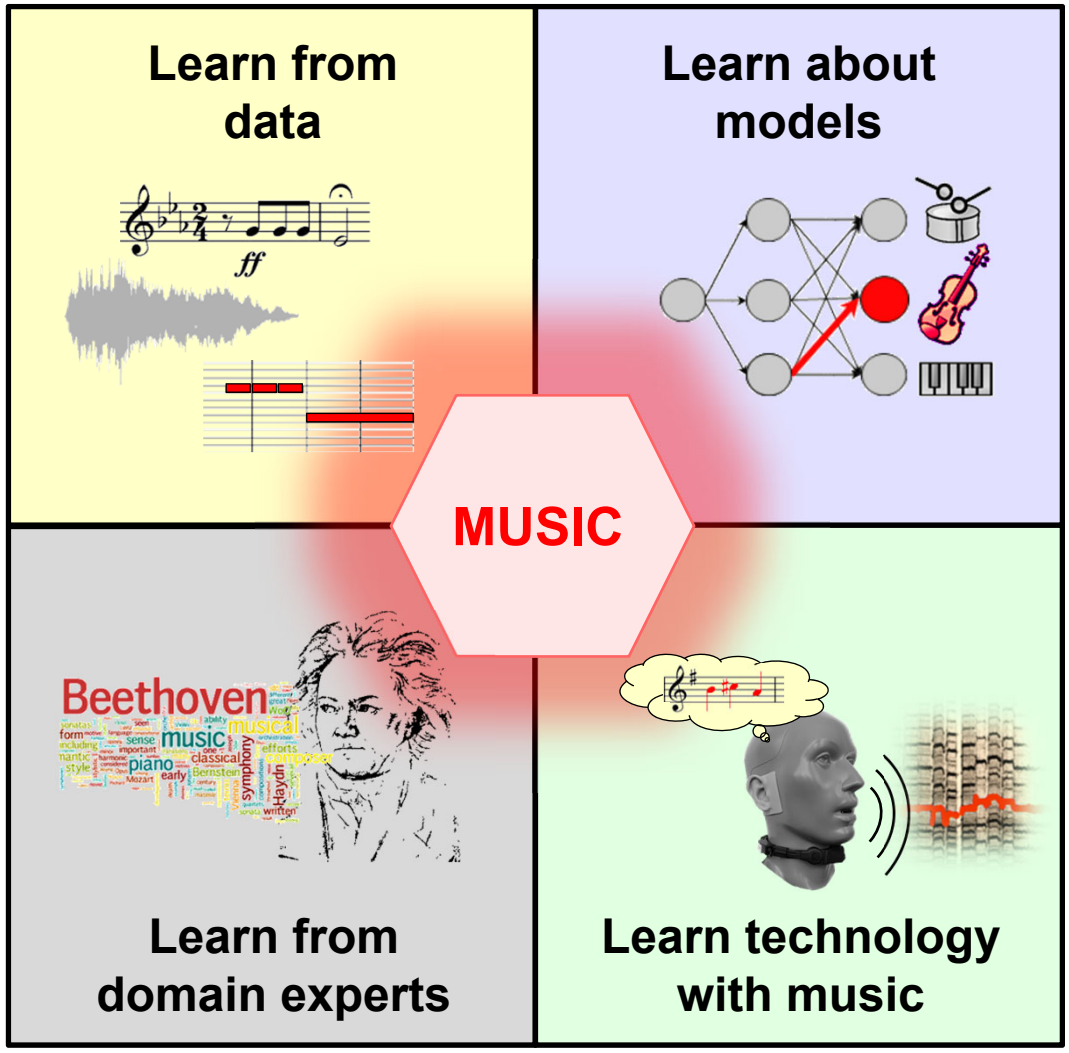


Music …

- important part of our lives …
- … Spotify, Pandora, iTunes, …
- interdisciplinary research
- intuitive entry point to education

Reinhart Koselleck-Projekt: LEARN

Learning with Music Signals: Technology Meets Education



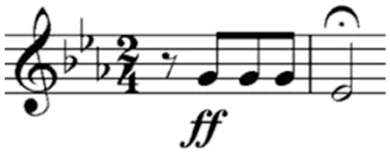
- Machine learning for music signal processing
- Interpretable models and knowledge integration
- Music understanding and applications
- Interactive learning in engineering through music

Multimodal Music Processing

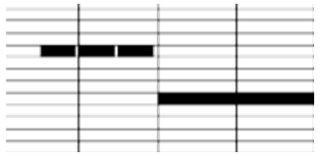
Multimodal Music Processing

Recording (Audio)

Sheet Music (Image)



Piano Roll (MIDI)



Singing (Audio)

MUSIC

Literature (Text)

Dance (Mocap)

Film (Video)

MusicXML (Symbolic)

```
<pitch>
  <step>E</step>
  <alter>-1</alt
```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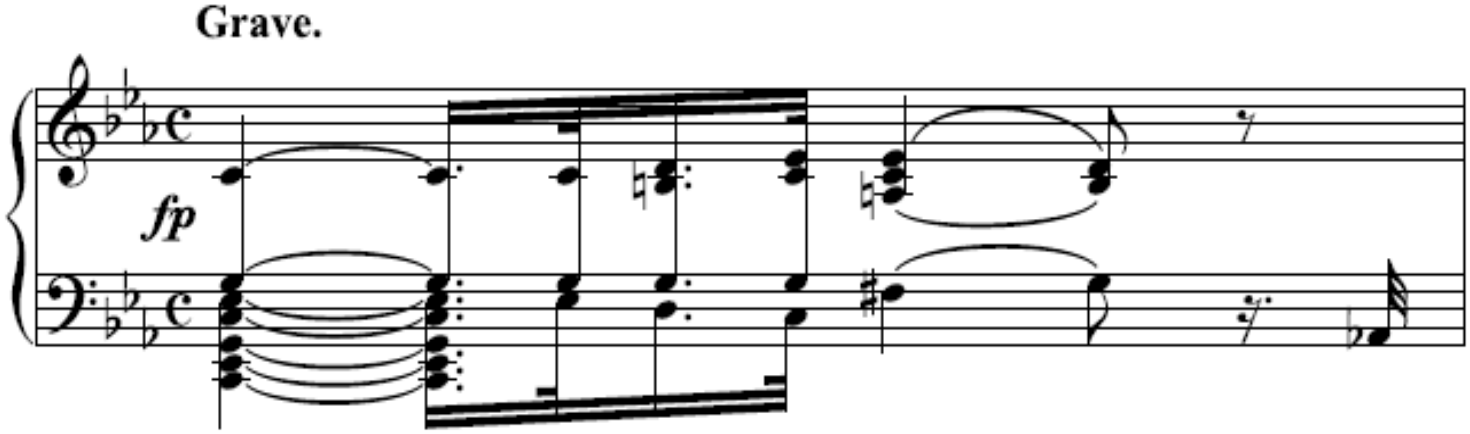
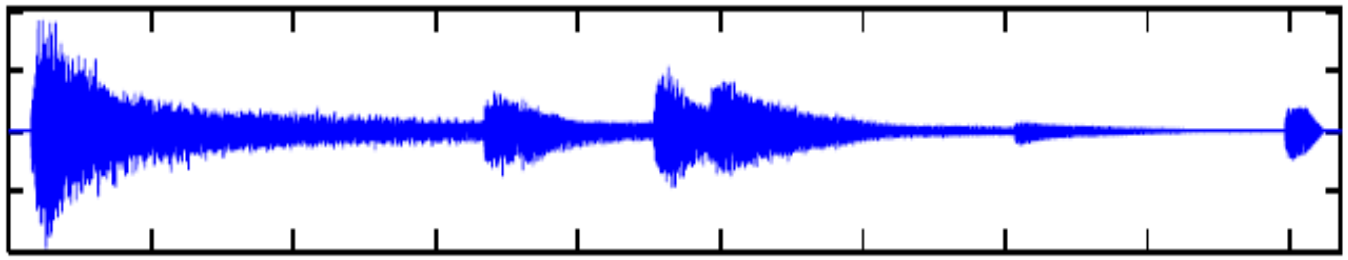
Multimodal Music Processing

Image



Audio

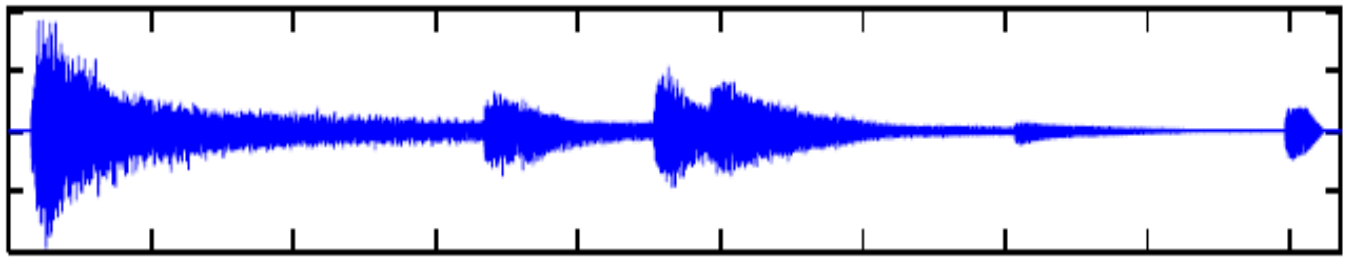


Multimodal Music Processing

Image Processing: Optical Music Recognition

Image

Audio



Multimodal Music Processing

Image Processing: Optical Music Recognition

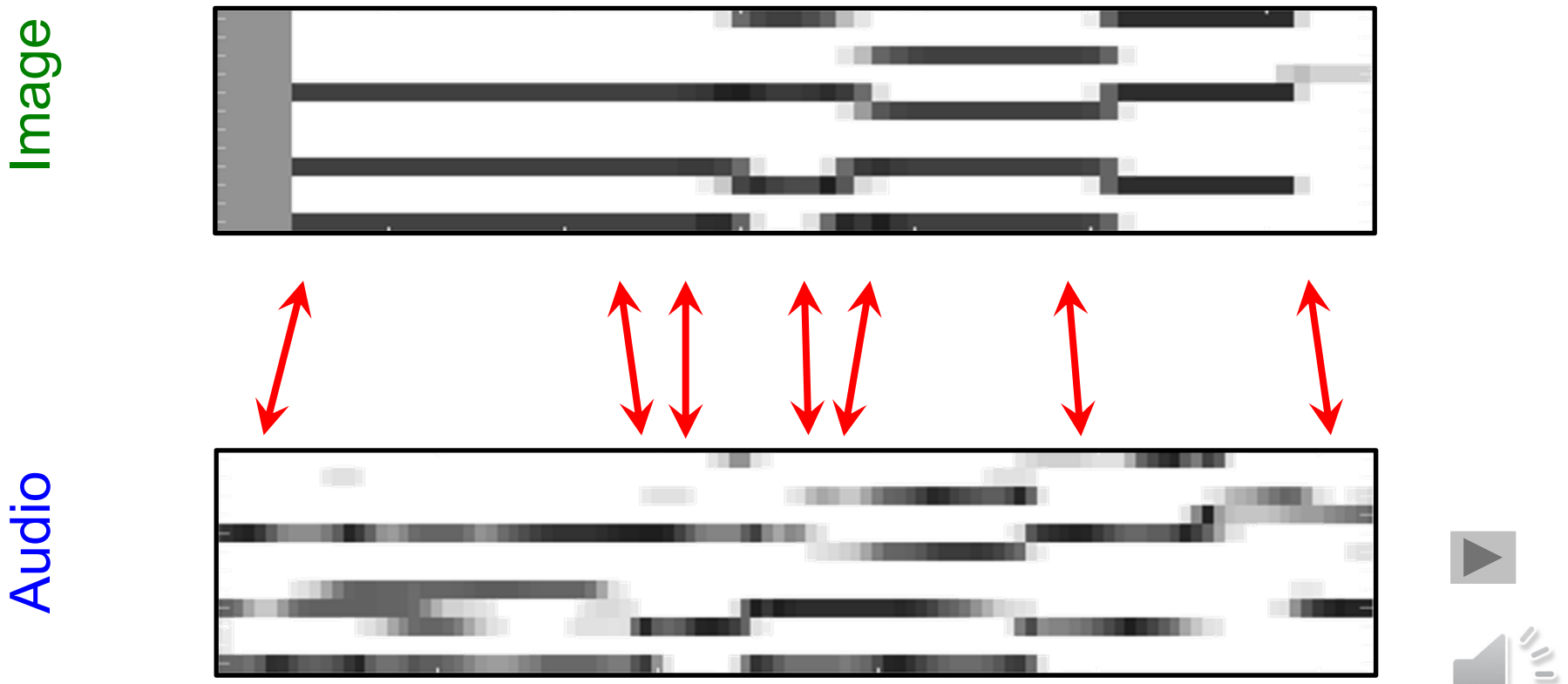
Image

Audio

Audio Processing: Fourier Analysis

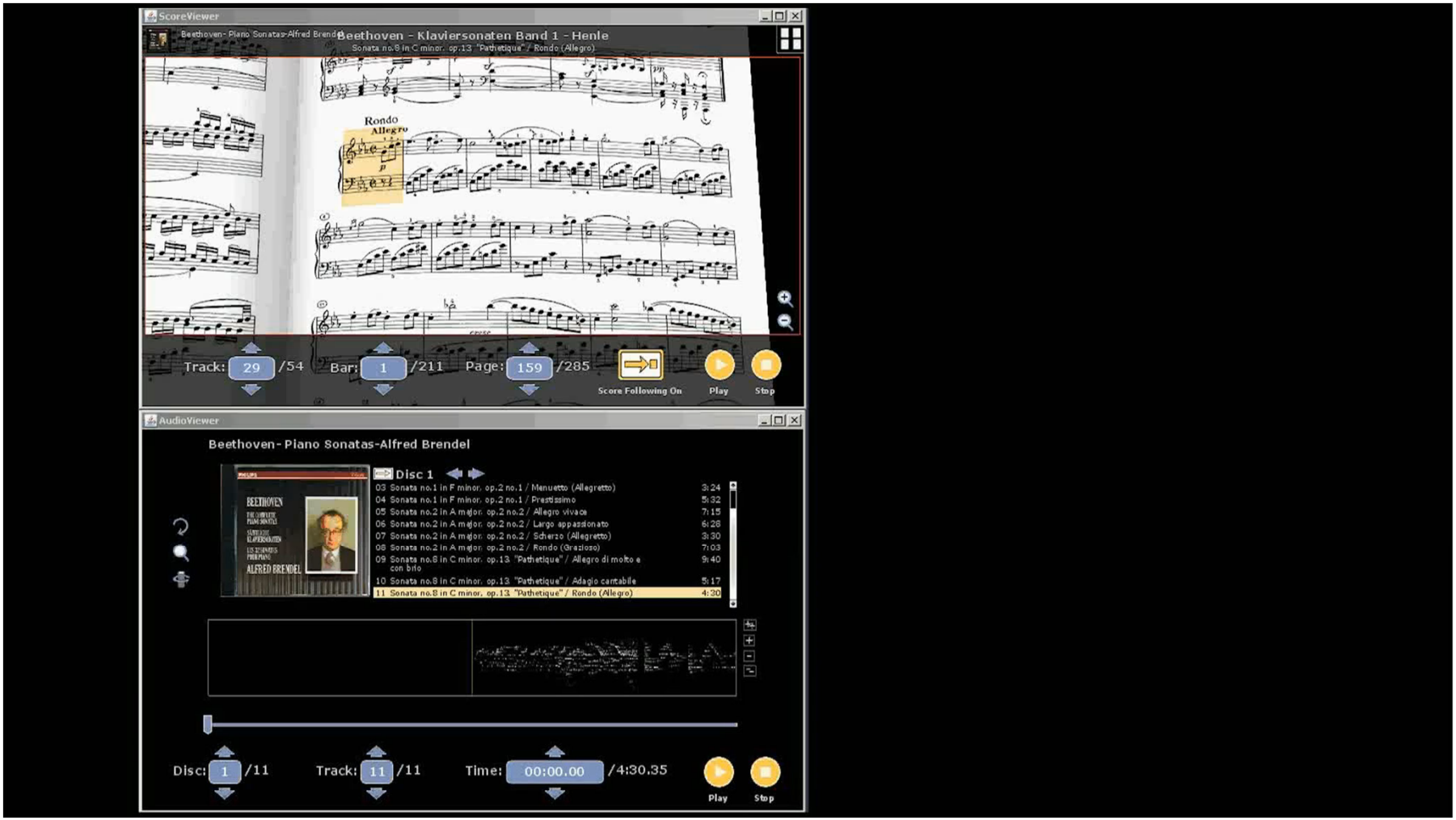
Multimodal Music Processing

Image Processing: Optical Music Recognition

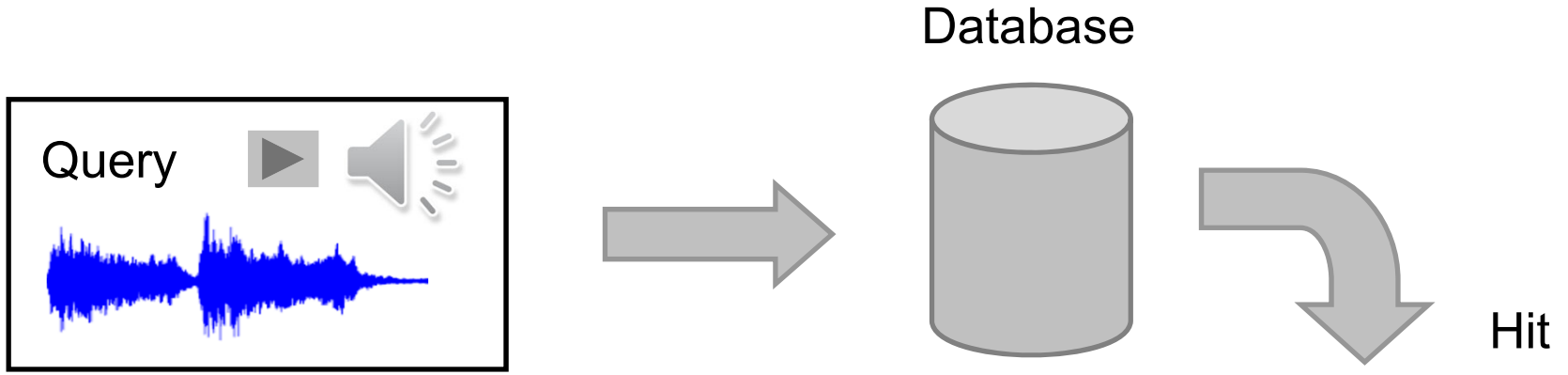


Audio Processing: Fourier Analysis

Multimodal Music Processing



Multimodal Music Processing



Audio ID

Bernstein (1962)
Beethoven, Symphony No. 5

Version ID

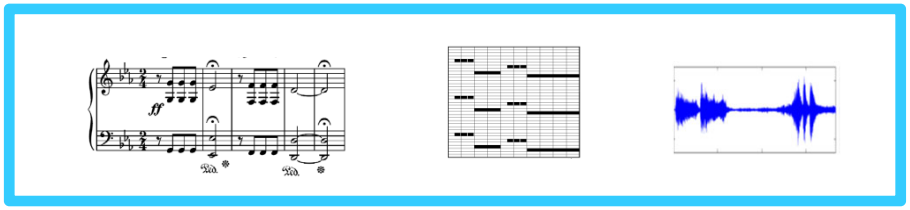
Beethoven, Symphony No. 5:
- Bernstein (1962)
- Karajan (1982)
- Gould (1992)

Category ID

- Beethoven, Symphony No. 9
- Beethoven, Symphony No. 3
- Haydn Symphony No. 94

Multimodal Music Processing

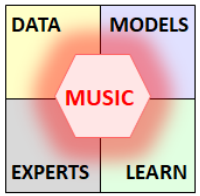
Modalities



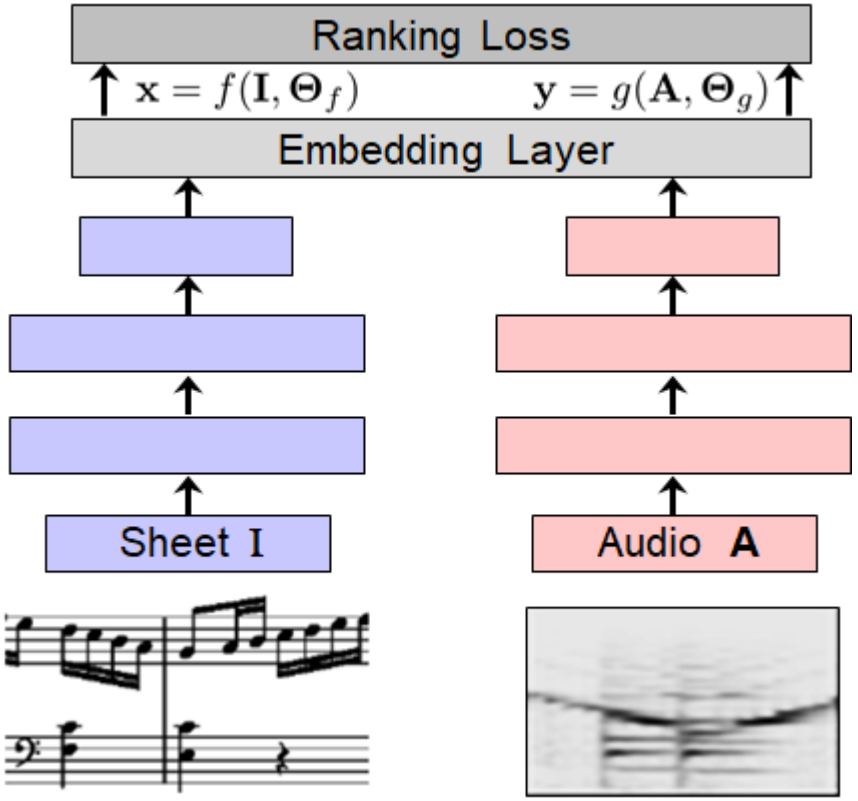
Retrieval tasks:

	Specificity	Granularity
Audio ID	High specificity	Fragment-based retrieval
Version ID		
Category ID	Low specificity	Document-based retrieval

Reinhart Koselleck-Projekt: LEARN

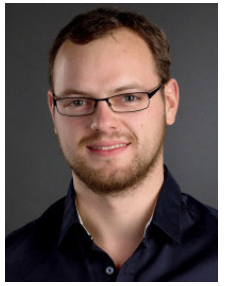


- Representation learning
- Embedding techniques
- Weak annotations
- Loss functions
- …



Computational Musicology

- Cooperation:
  - Rainer Kleinertz (Saarbrücken)
  - Stephanie Klauk (Saarbrücken)
  - Christof Weiß (Würzburg)
- Objectives
  - Harmony-based structural analysis
  - Beethoven Sonatas & Wagner's Ring
  - Interdisciplinary dialogue
- Since 2014: DFG-funded project



Julius-Maximilians-
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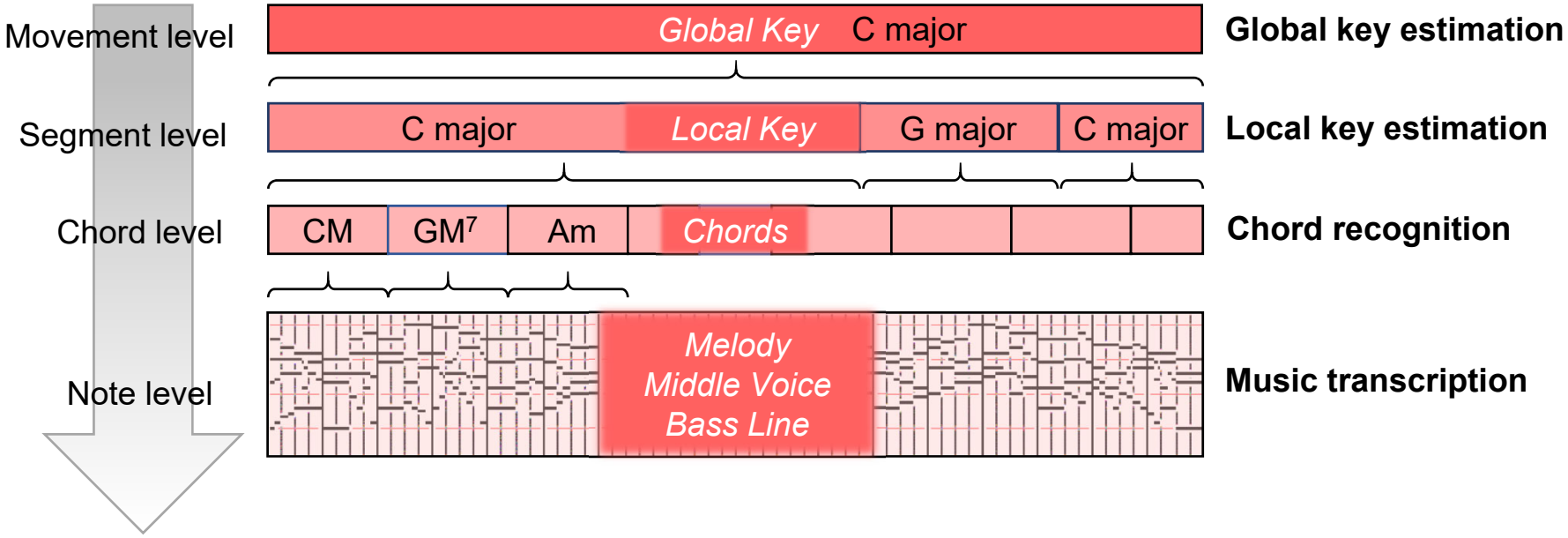
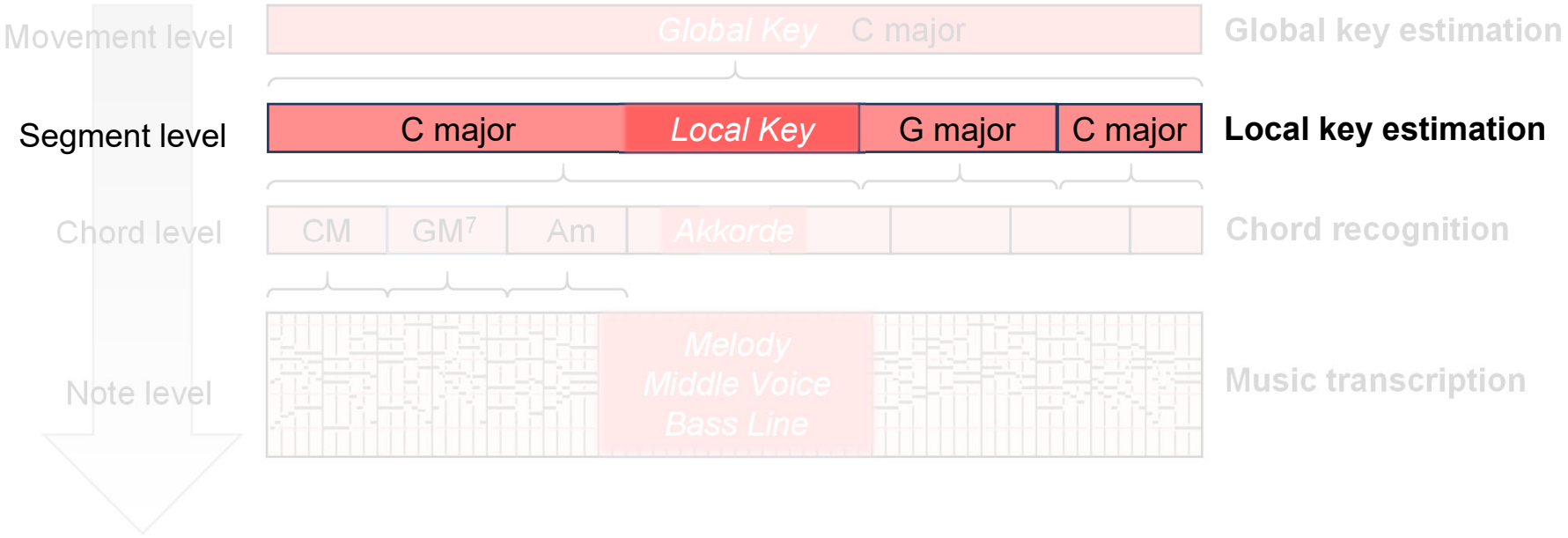
Computational Musicology: Harmony Analysis

- Different concepts
- Different temporal levels



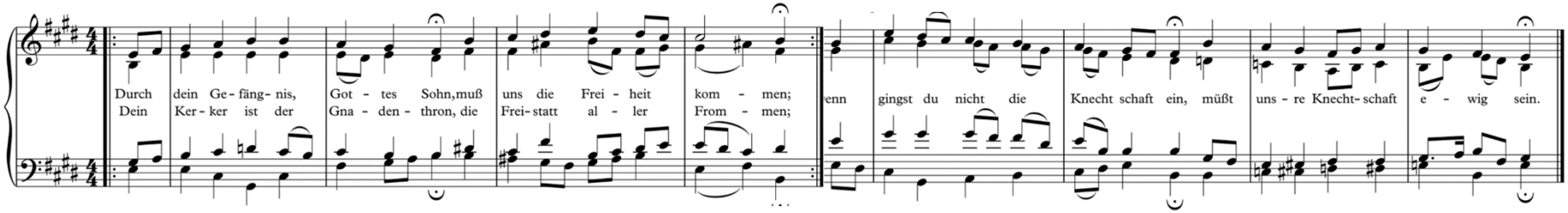
Computational Musicology: Harmony Analysis

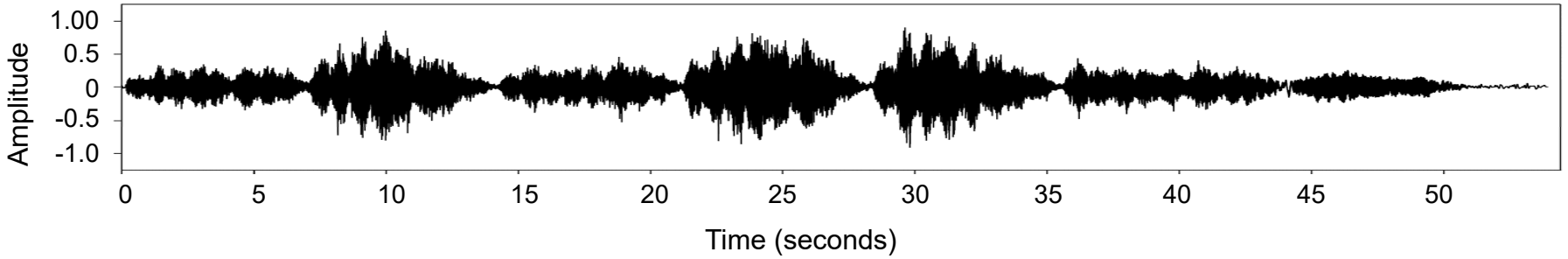
- Different concepts
- Different temporal levels



Local Key Estimation

Example: J.S. Bach, Choral "Durch Dein Gefängnis" (*Johannespassion*)





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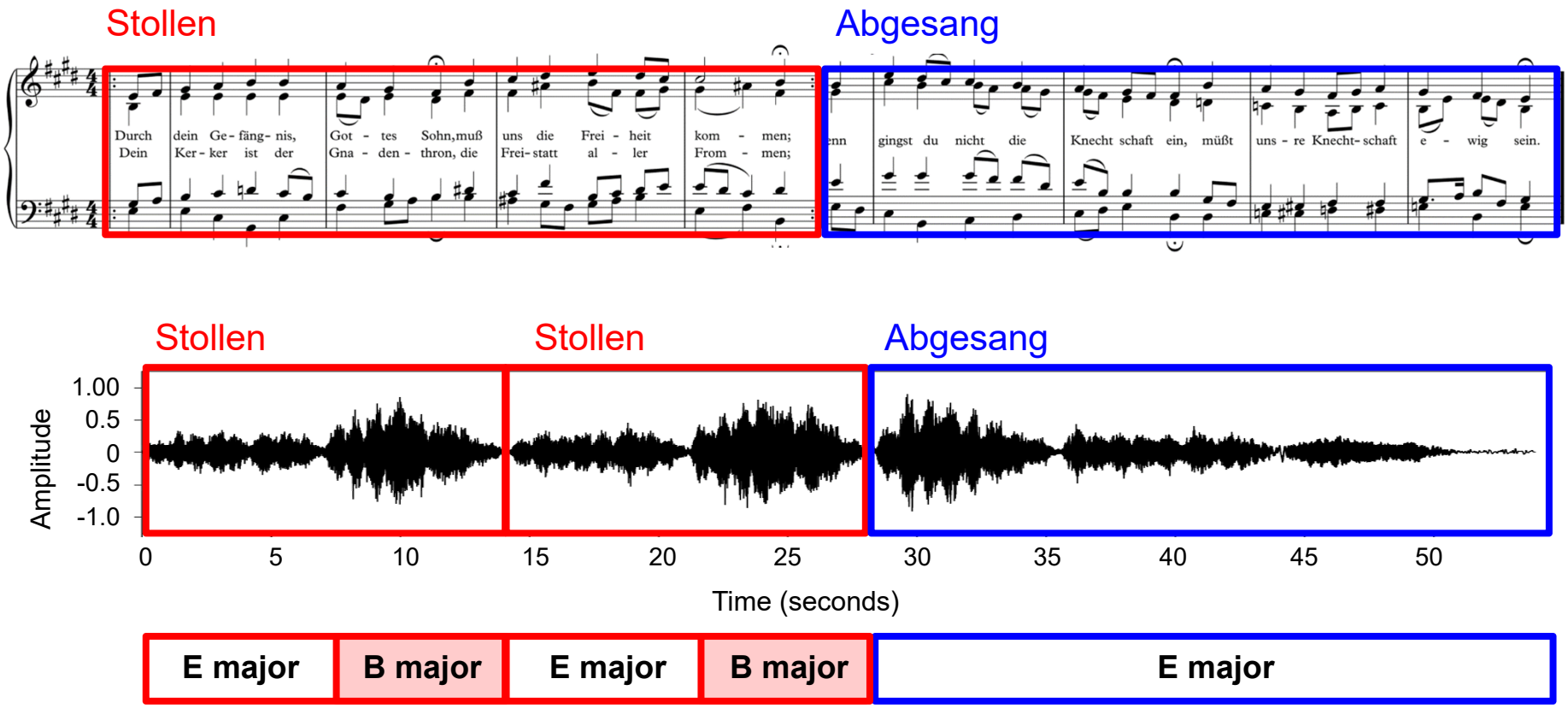
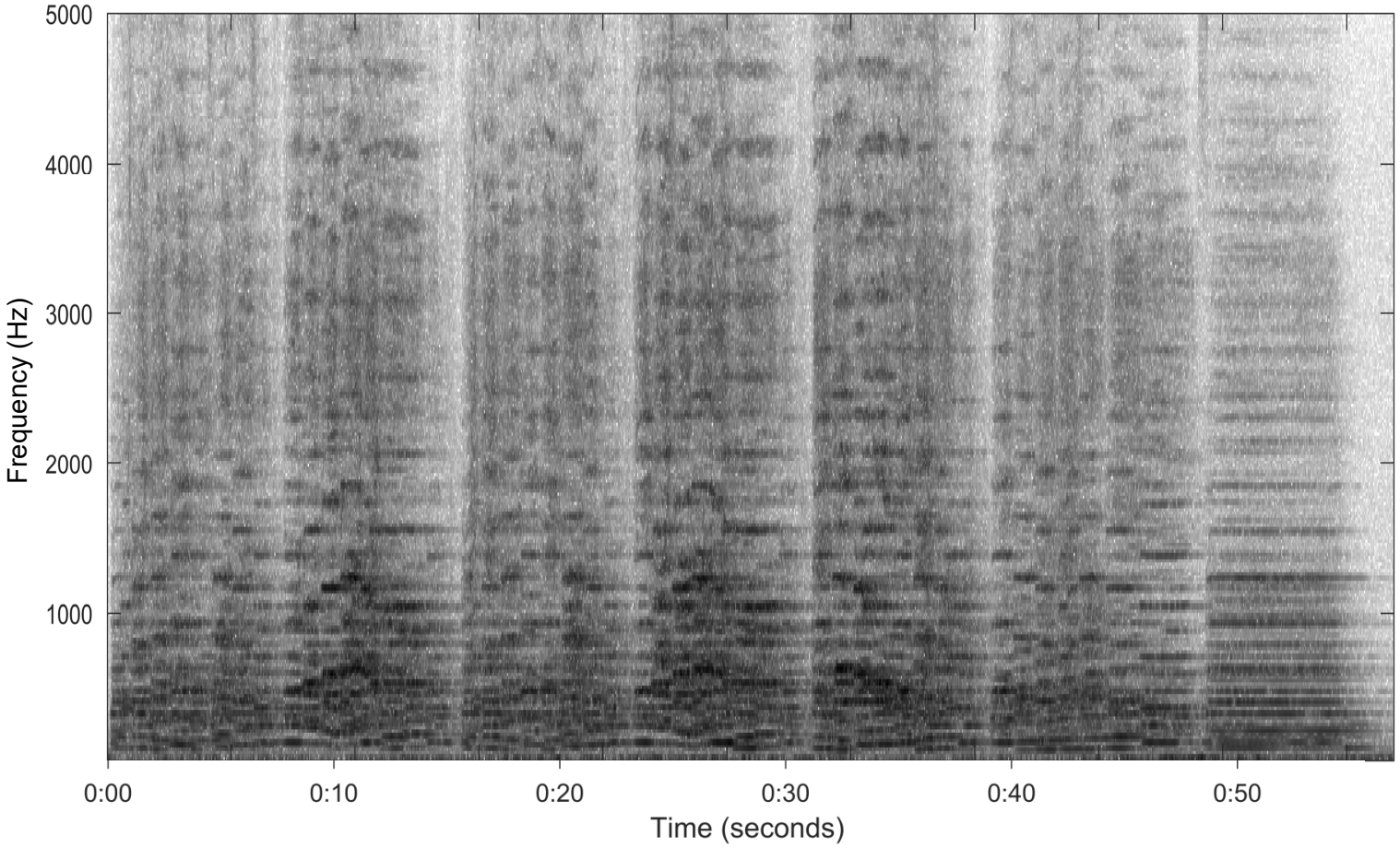


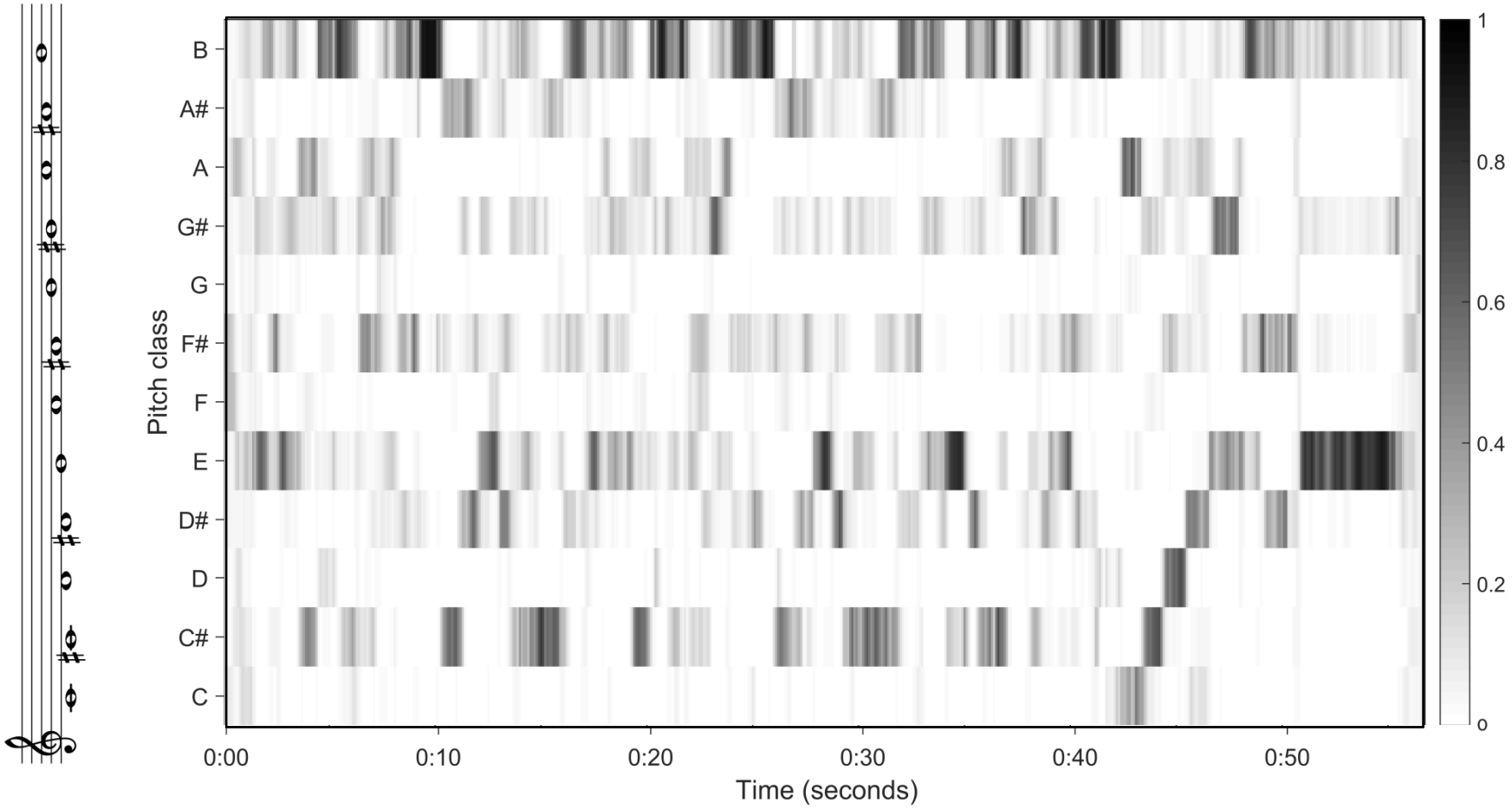
Local Key Estimation

Spectrogram



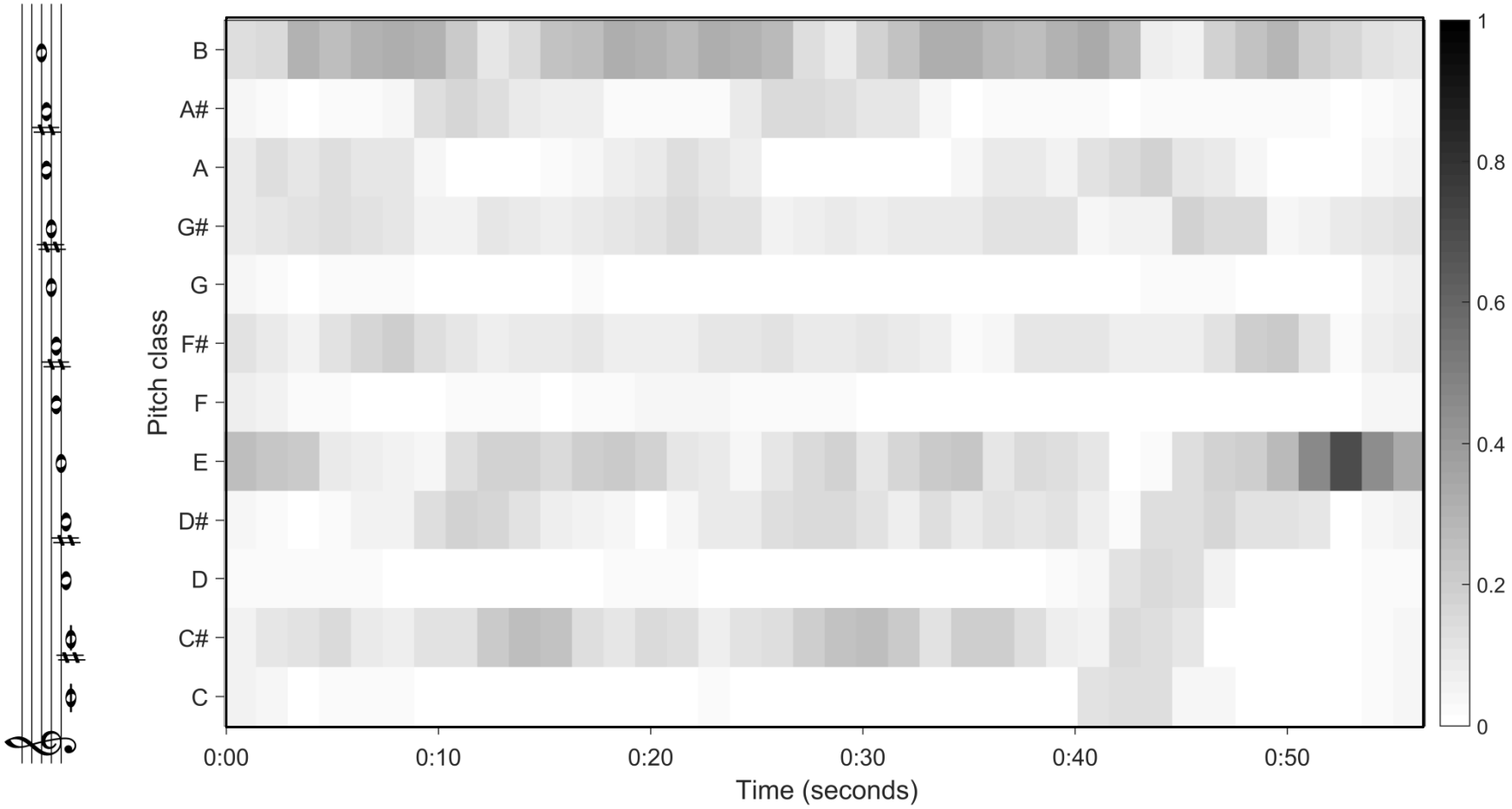
Local Key Estimation

Chromagram



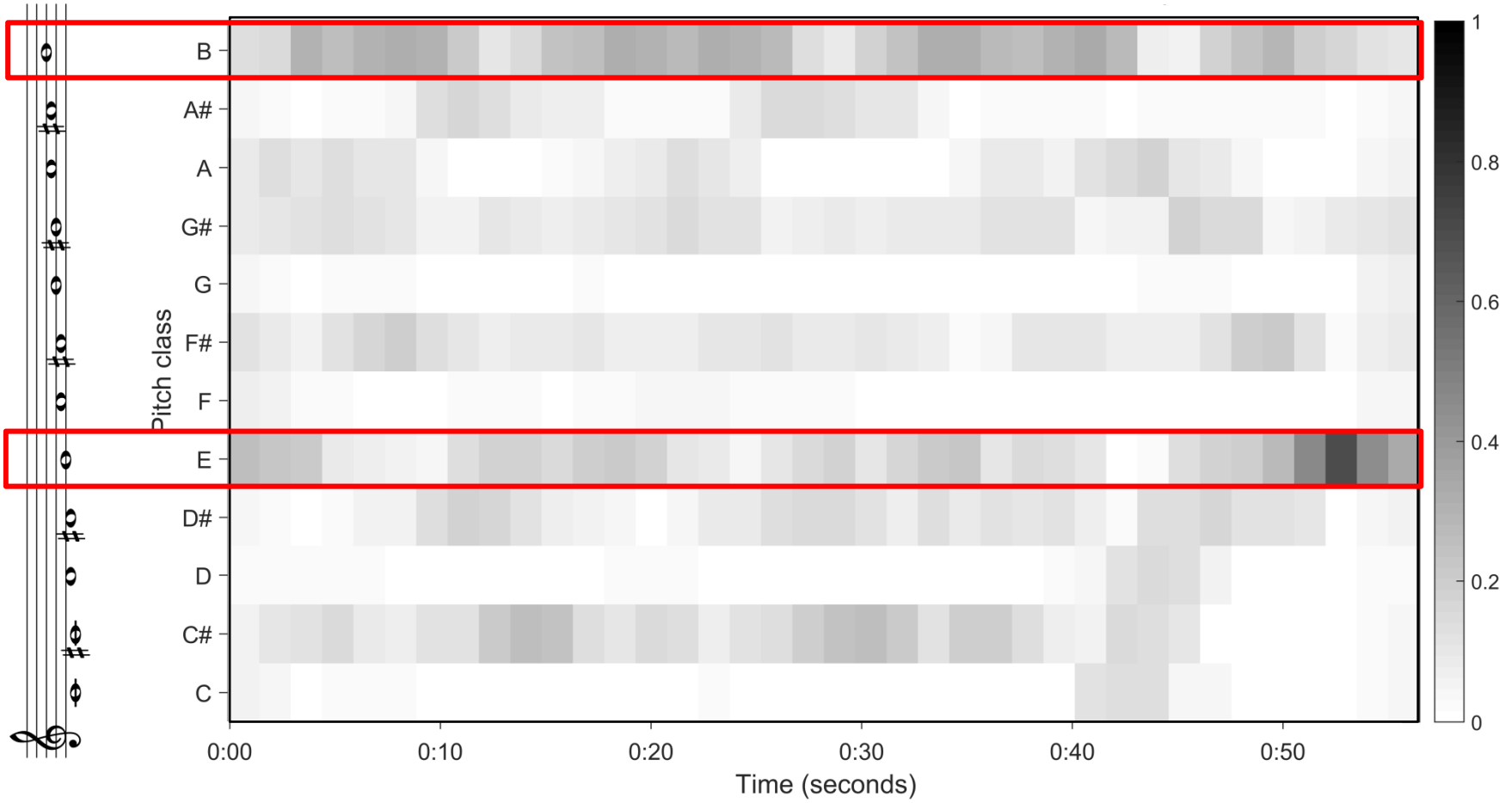
Local Key Estimation

Chromagram after smoothing



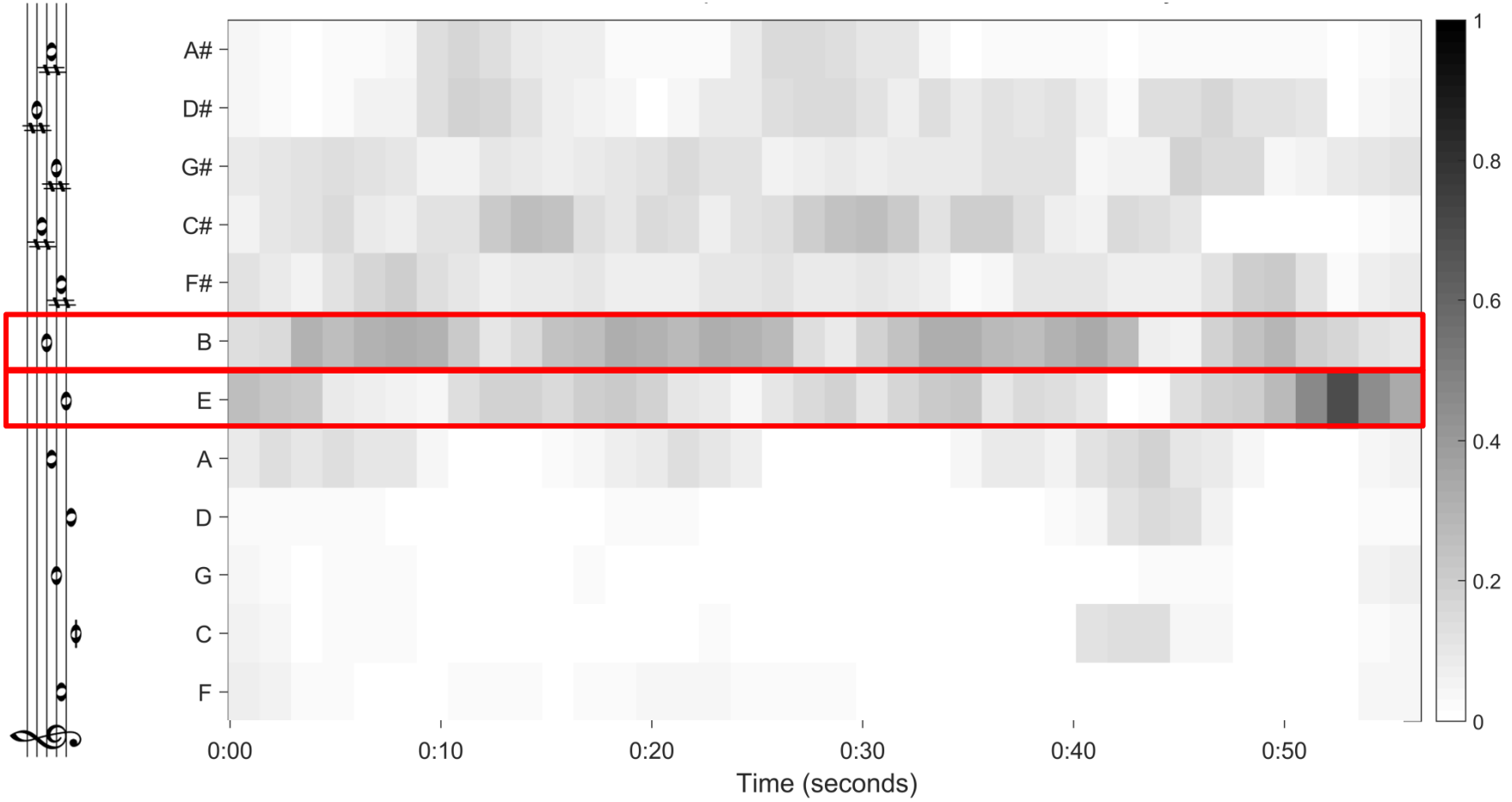
Local Key Estimation

Arrange pitch classes according to **perfect fifth** series



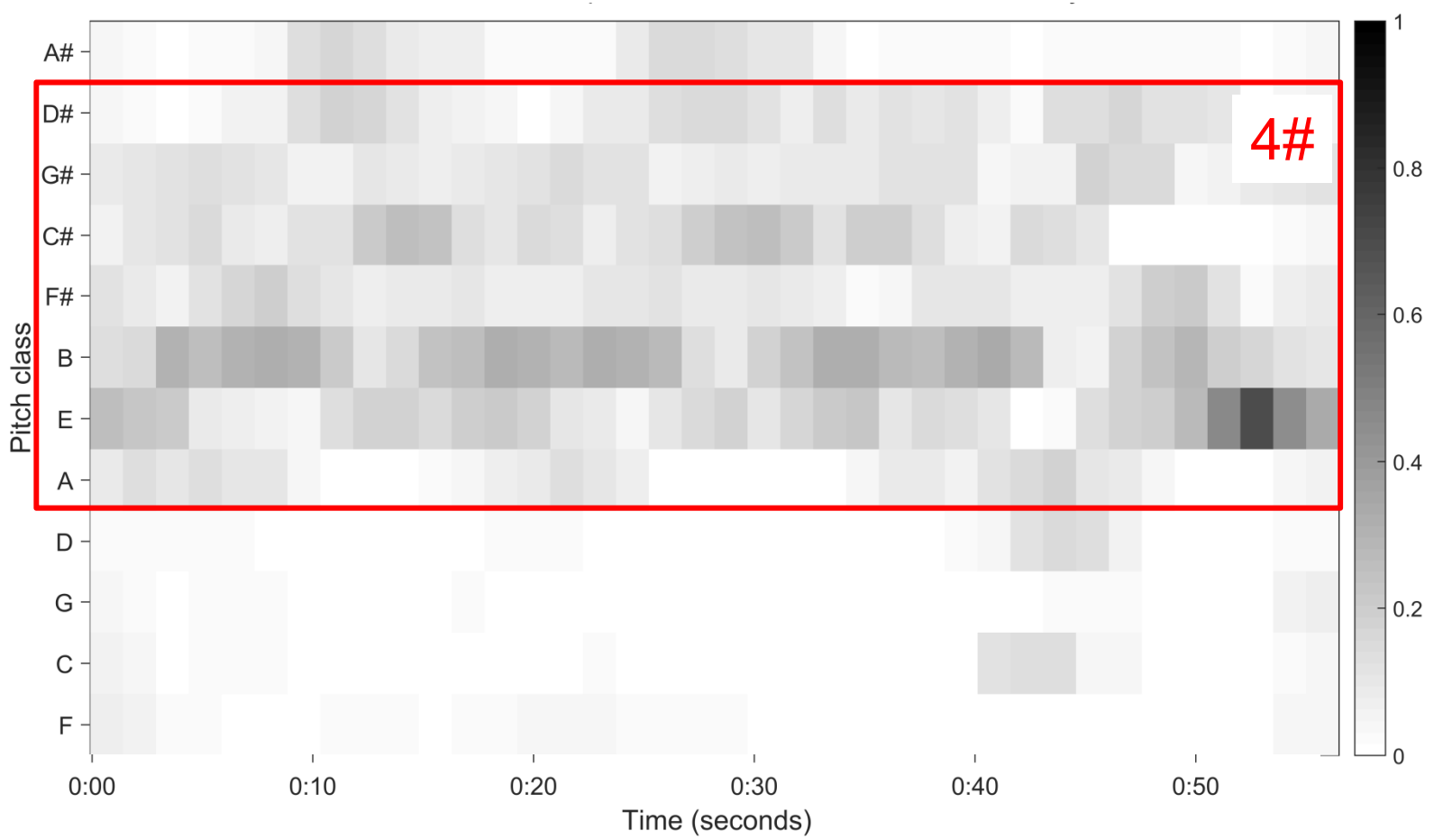
Local Key Estimation

Arrange pitch classes according to **perfect fifth** series



Local Key Estimation

Summarize pitch class content according to **diatonic scales**



Local Key Estimation

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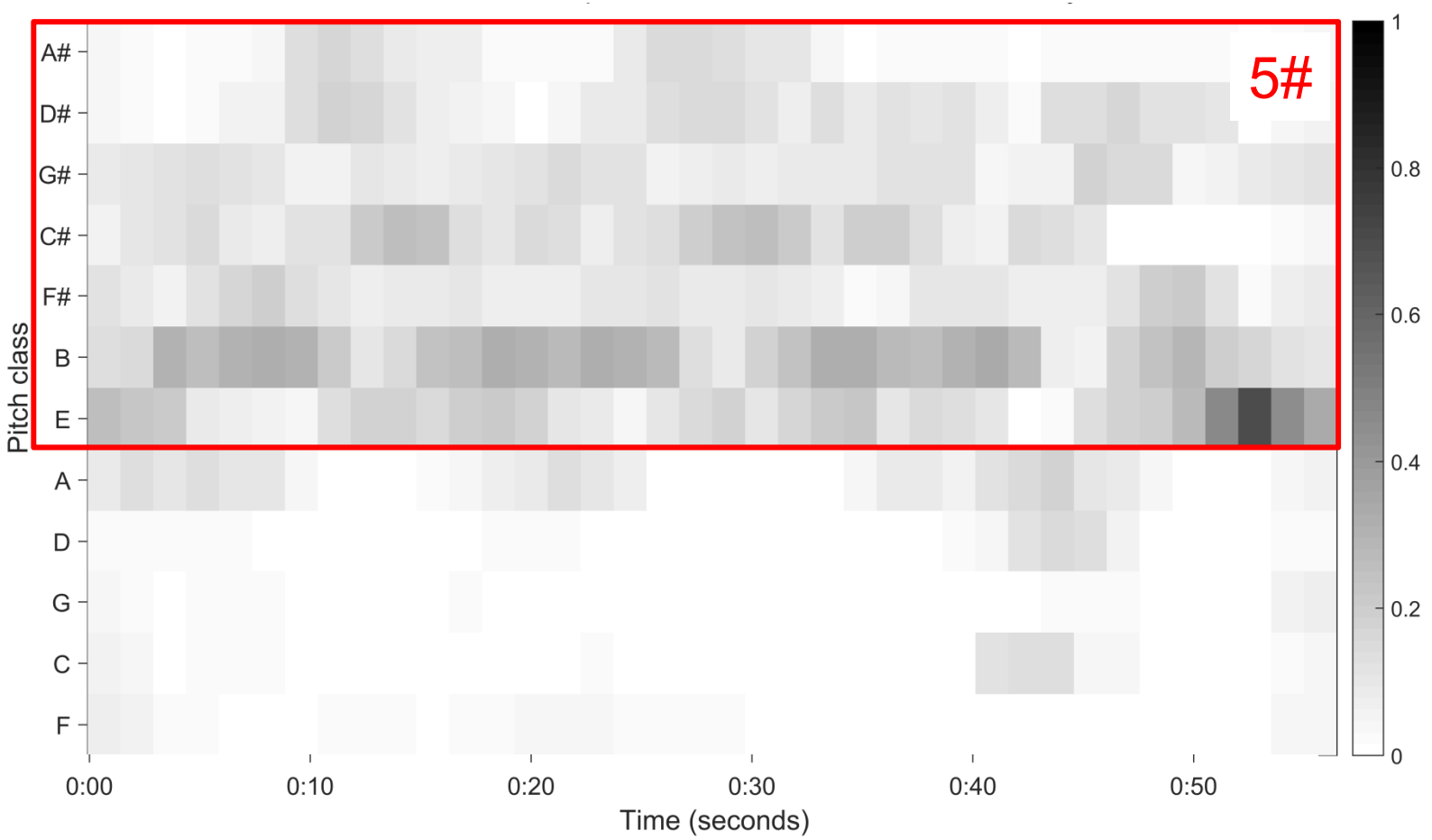
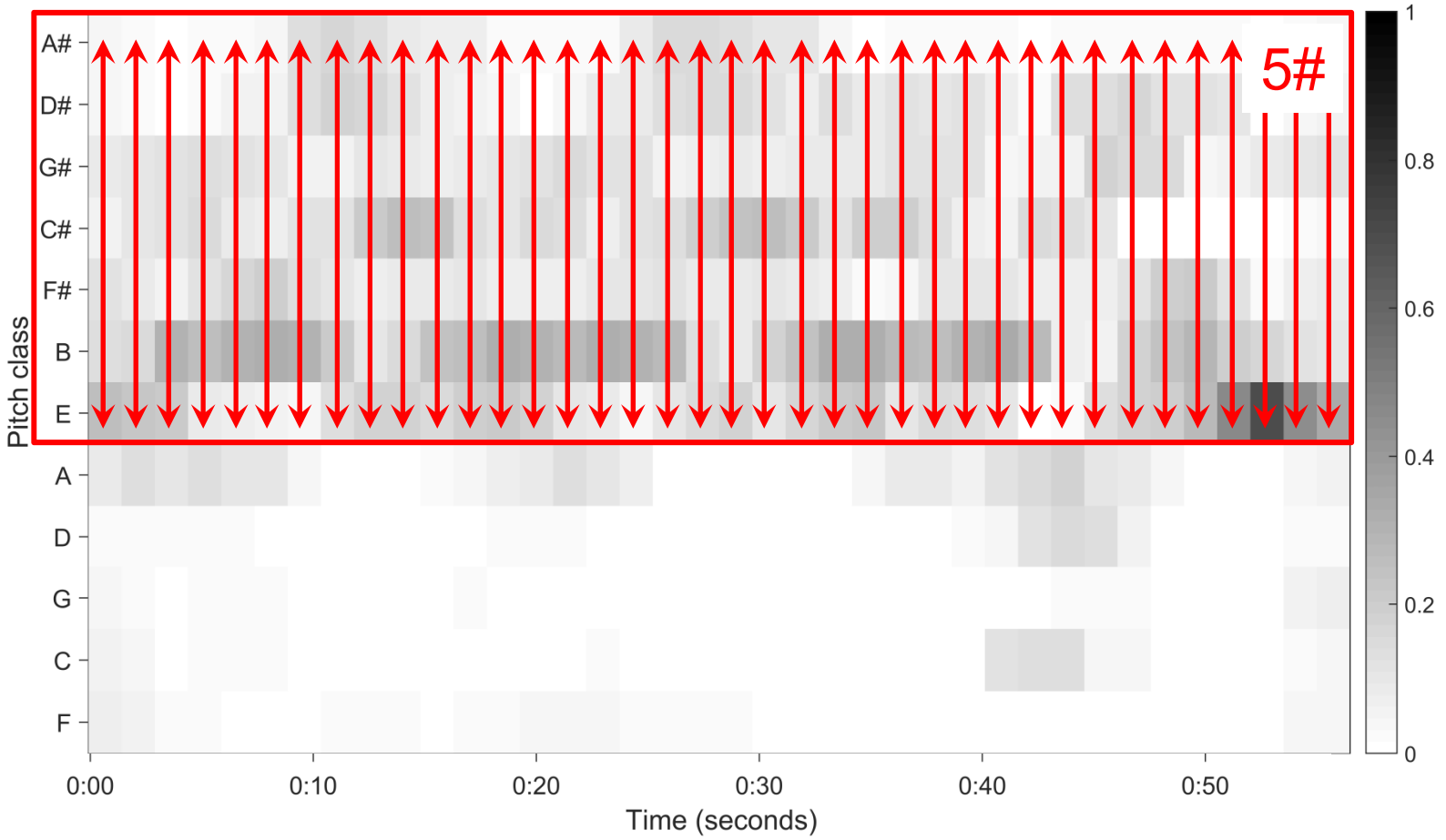


Local Key Estimation

Summarize pitch class content according to **diatonic scales**

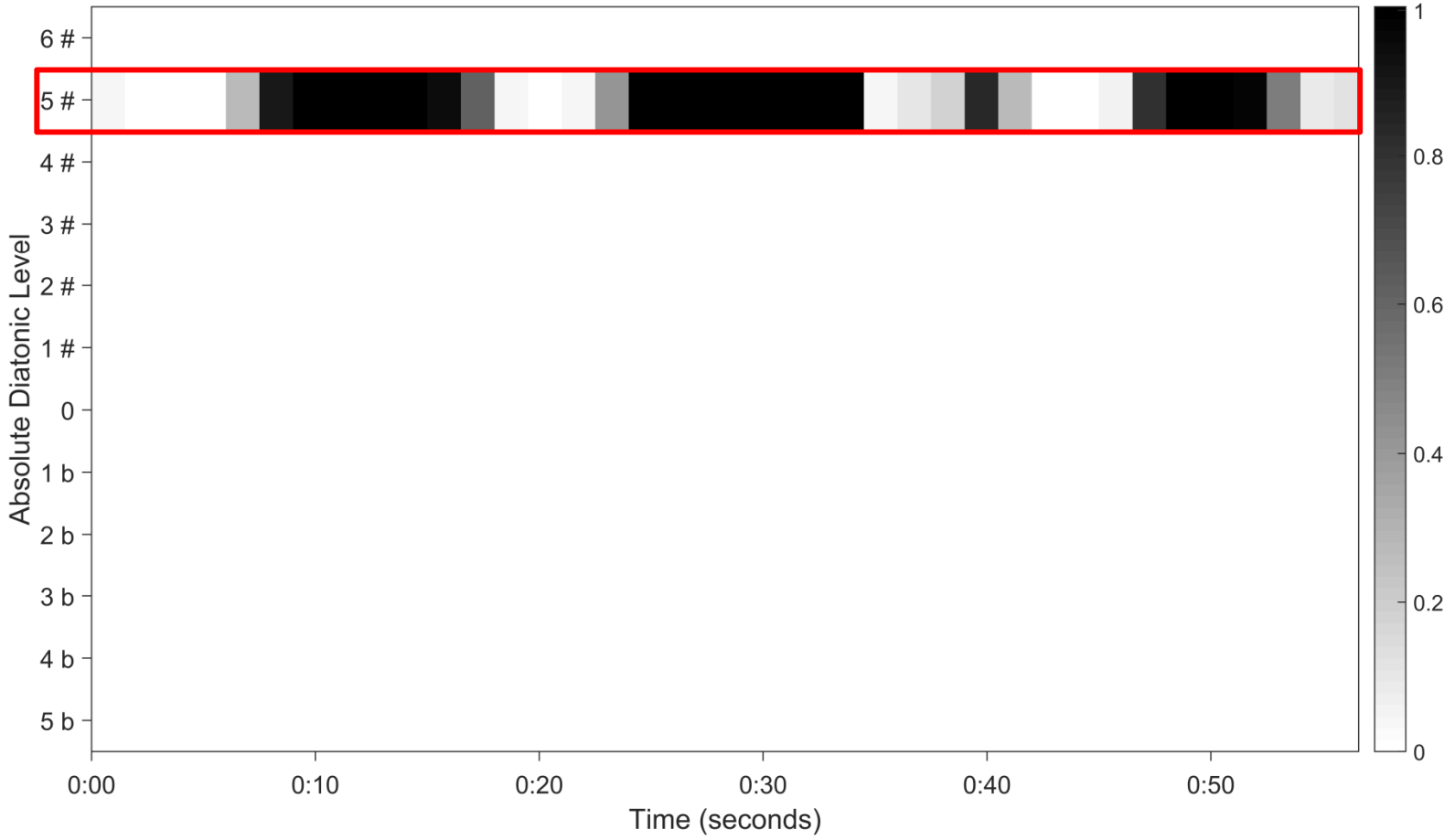
Multiply chroma values (in each column)



Local Key Estimation

Summarize pitch class content according to **diatonic scales**

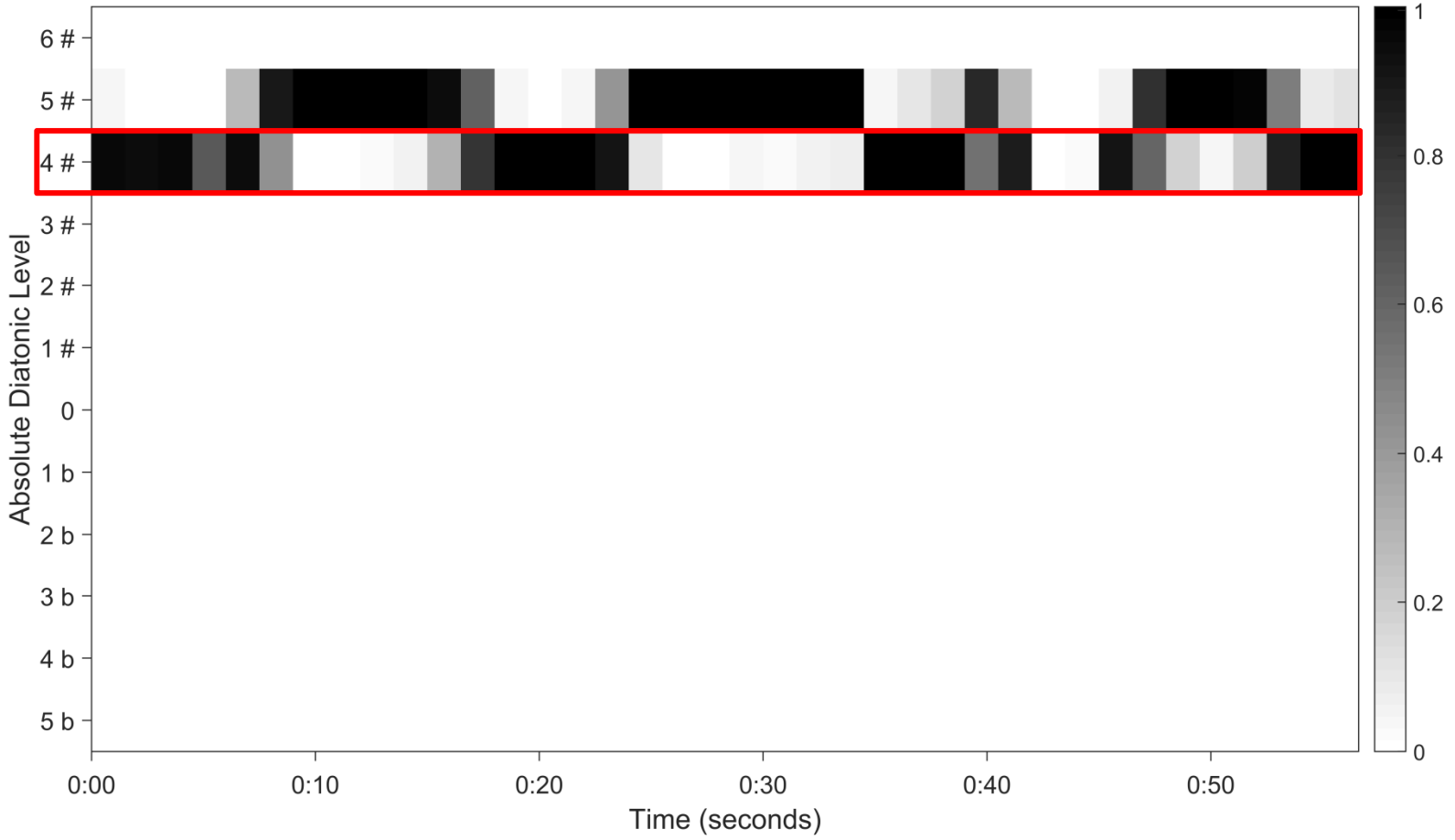
Multiply chroma values



Local Key Estimation

Summarize pitch class content according to **diatonic scales**

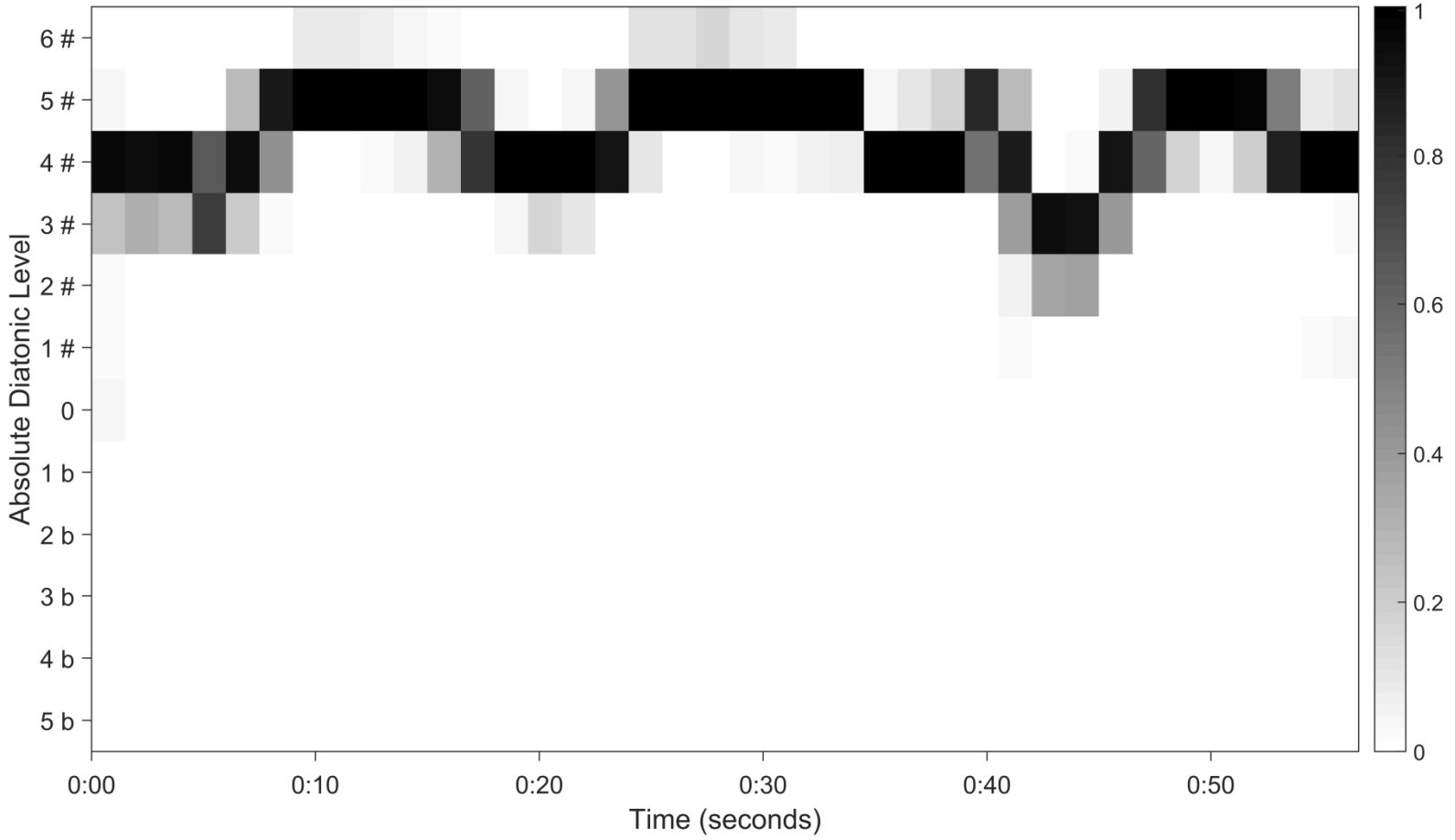
Multiply chroma values



Local Key Estimation

Summarize pitch class content according to **diatonic scales**

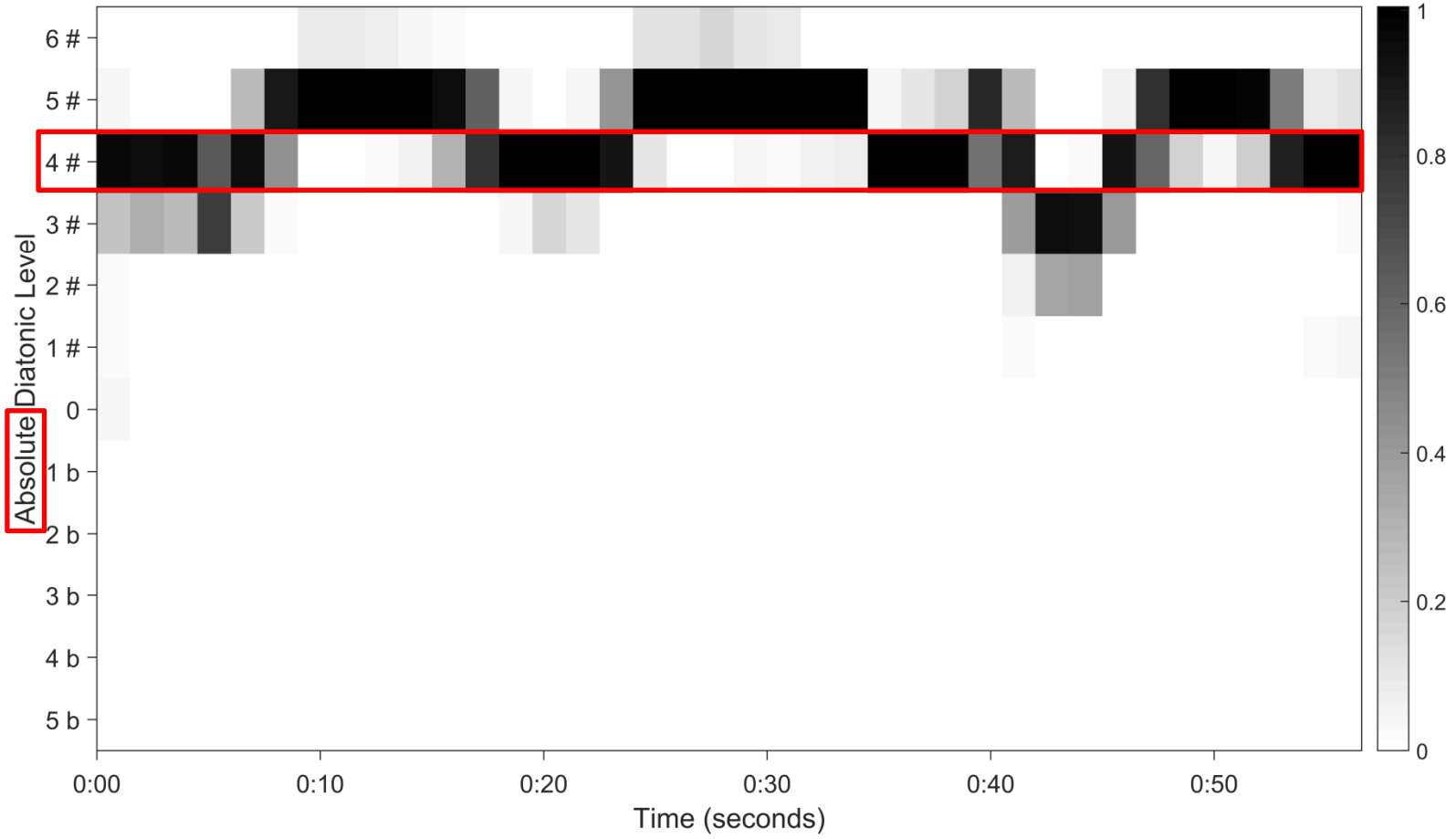
Multiply chroma values



Local Key Estimation

Normalize representation relative to global key

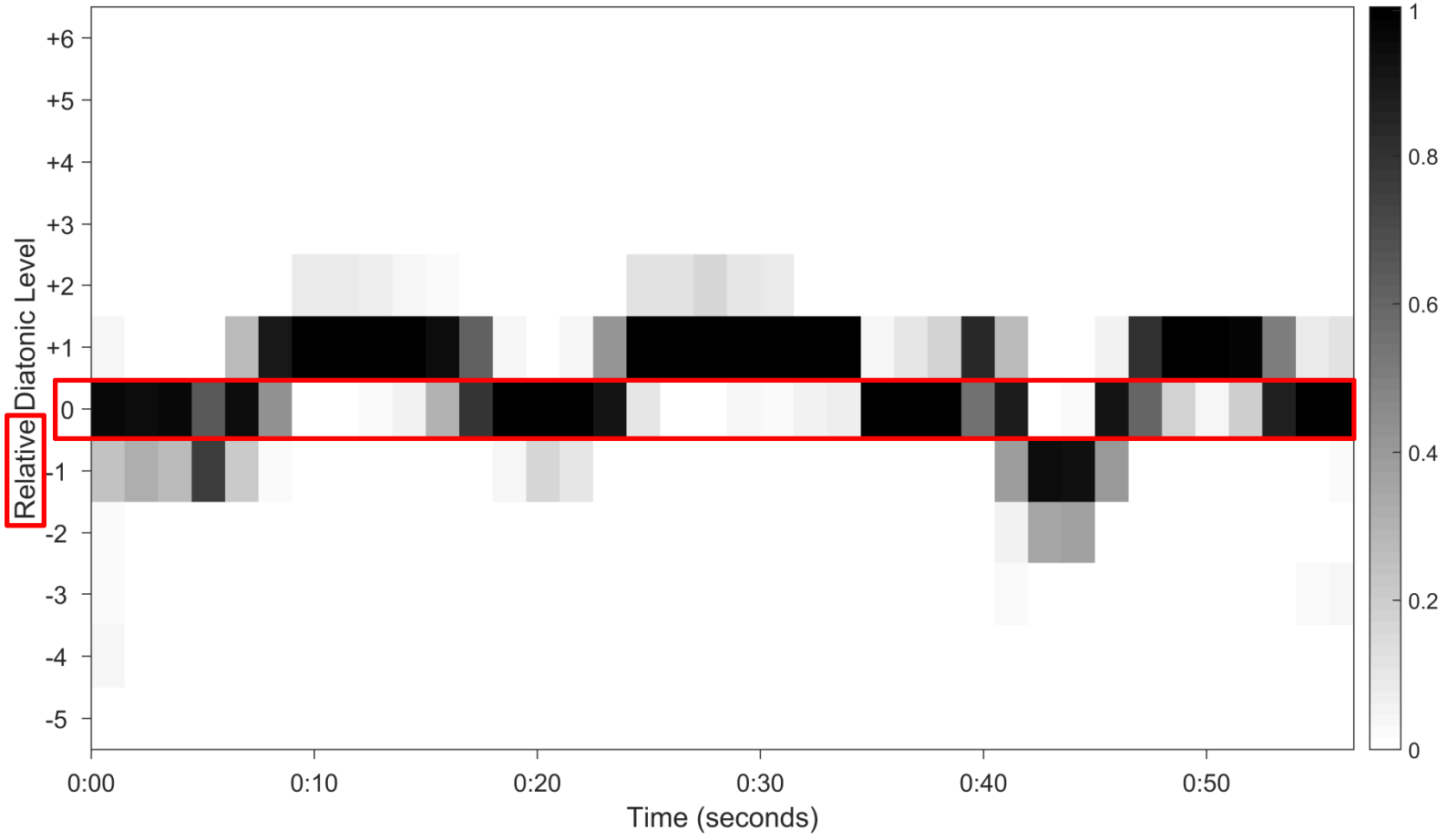
4 #
(E major)



Local Key Estimation

Normalize representation relative to global key

4 #
(E major)

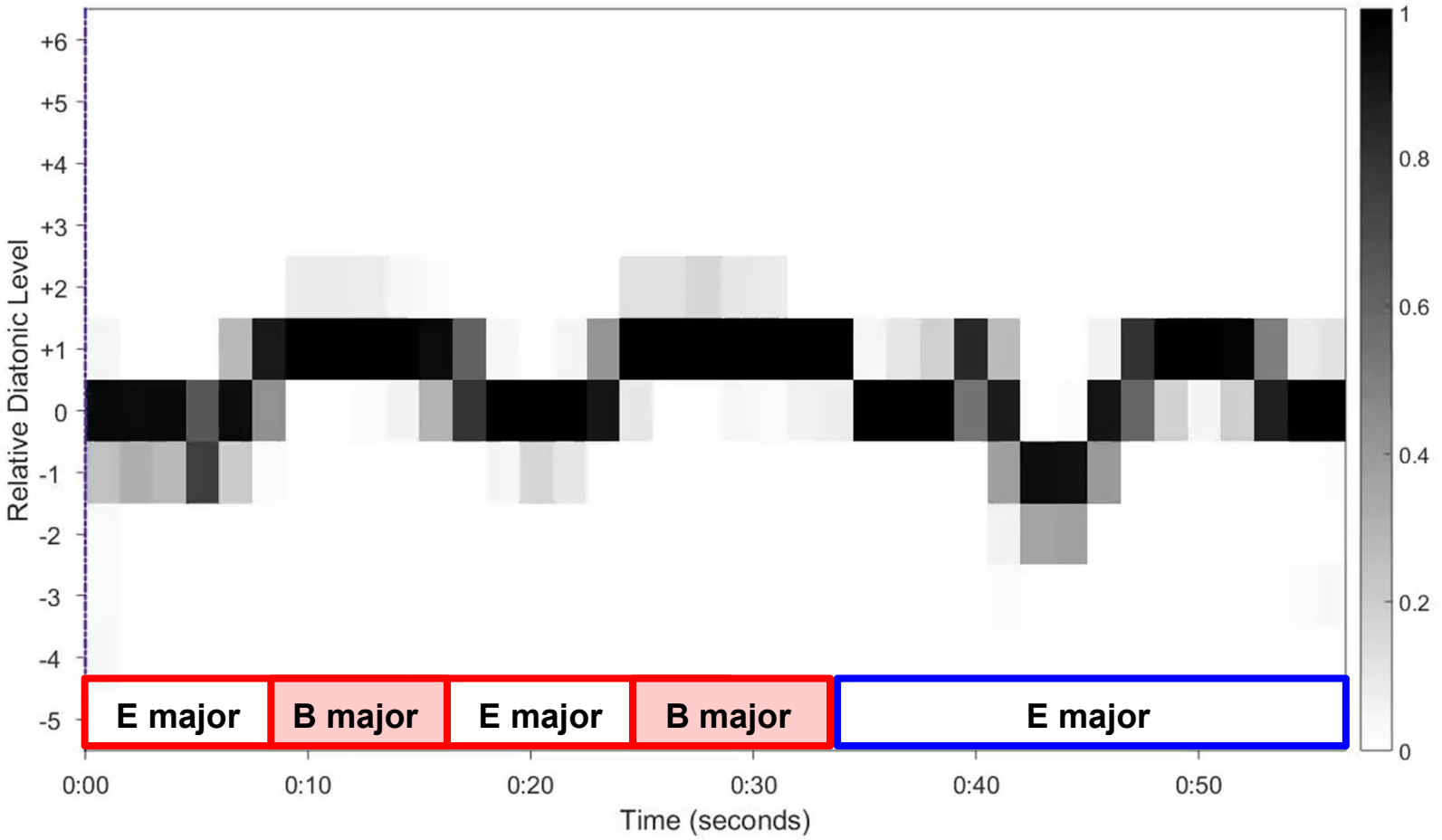


Local Key Estimation

J.S. Bach: Choral "Durch Dein Gefängnis" (*Johannespassion*)

Recording: Scholars Baroque Ensemble, Naxos 1994

4 #
(E major)

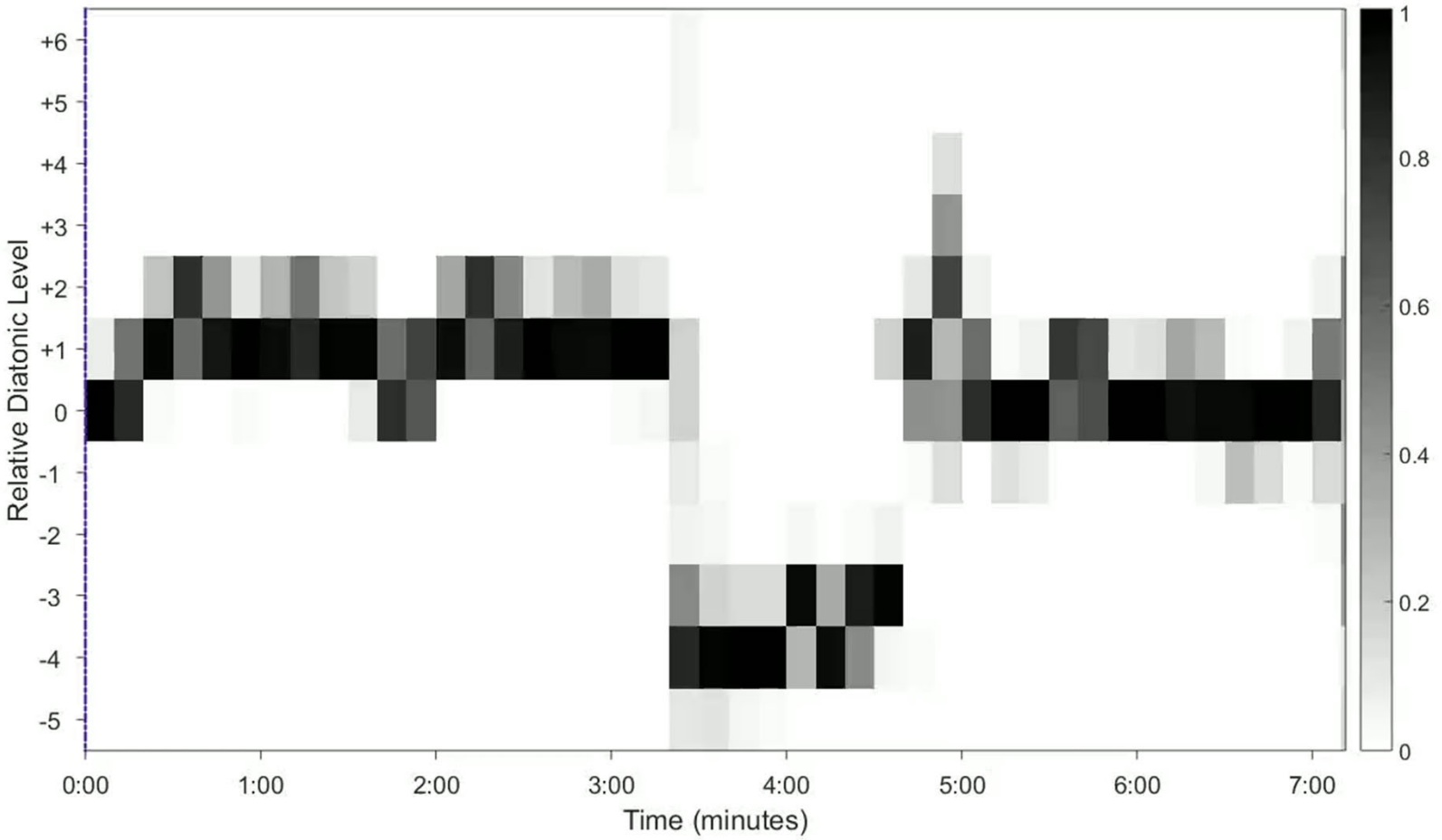


Local Key Estimation

L. v. Beethoven: Piano Sonata No. 10 (Op. 14 Nr. 2), 1. Allegro

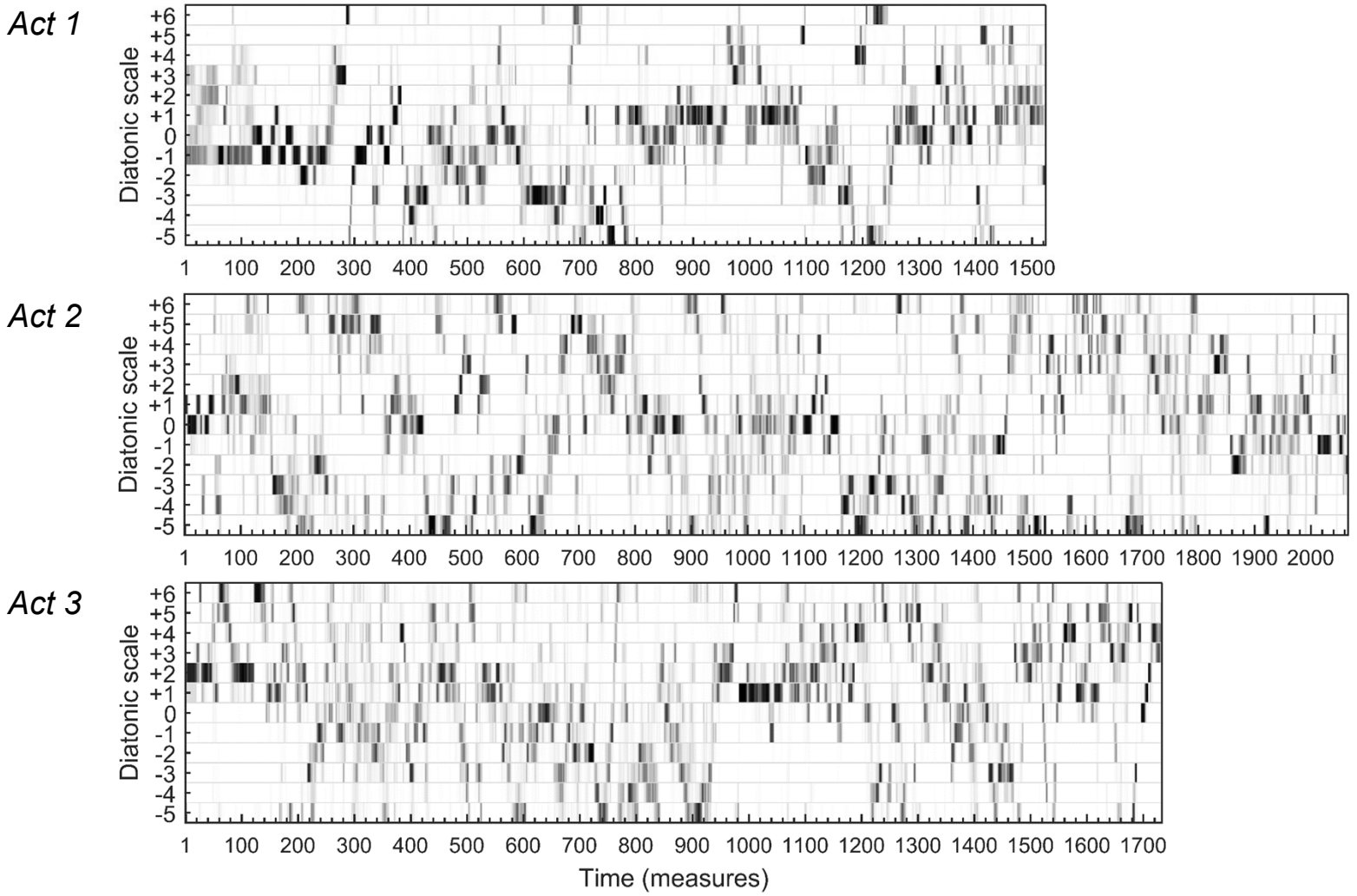
Recording: Barenboim, EMI 1998

1 #
(G major)



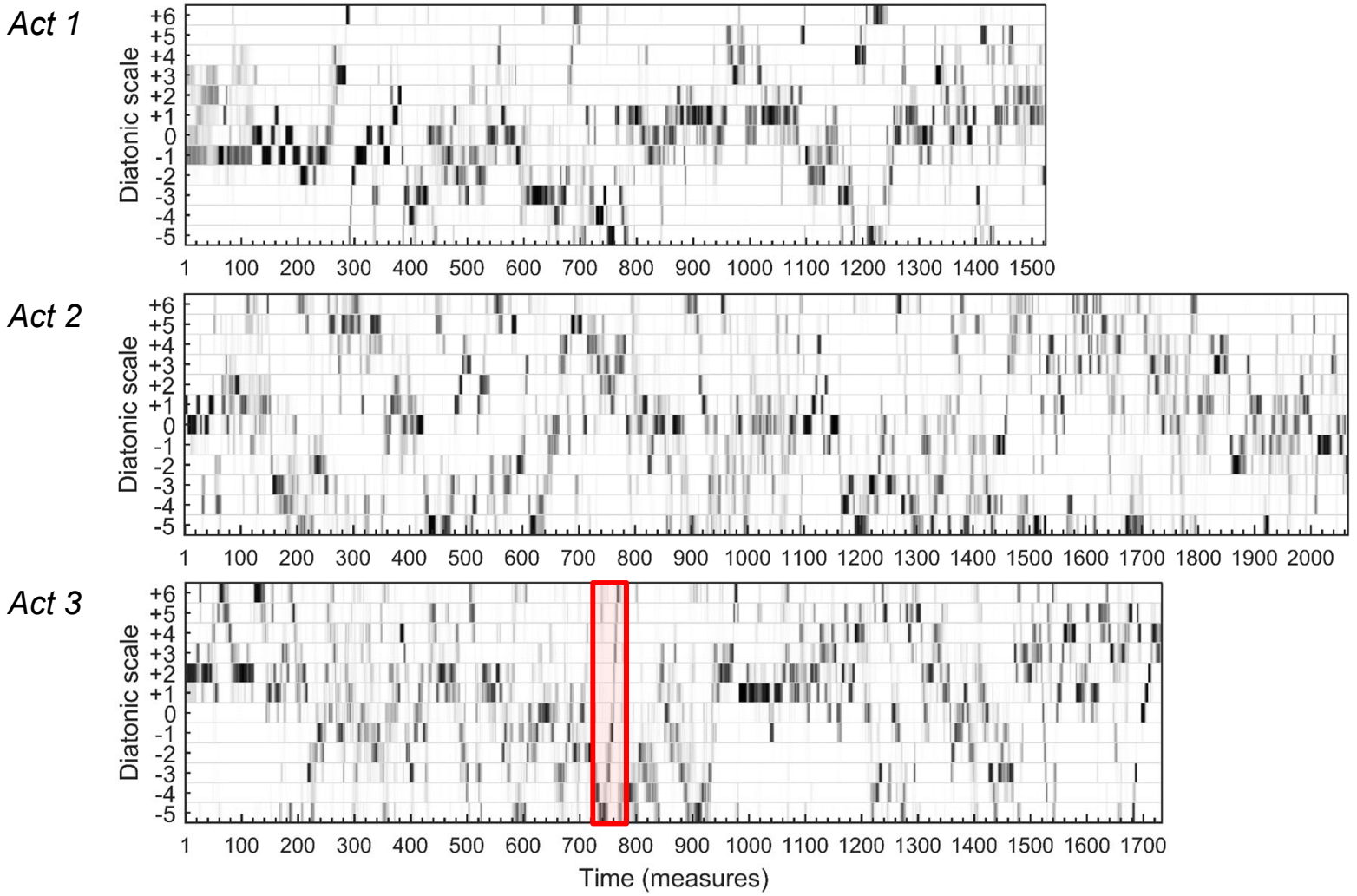
Local Key Estimation

R. Wagner: WWV 86 B (*Die Walküre*)



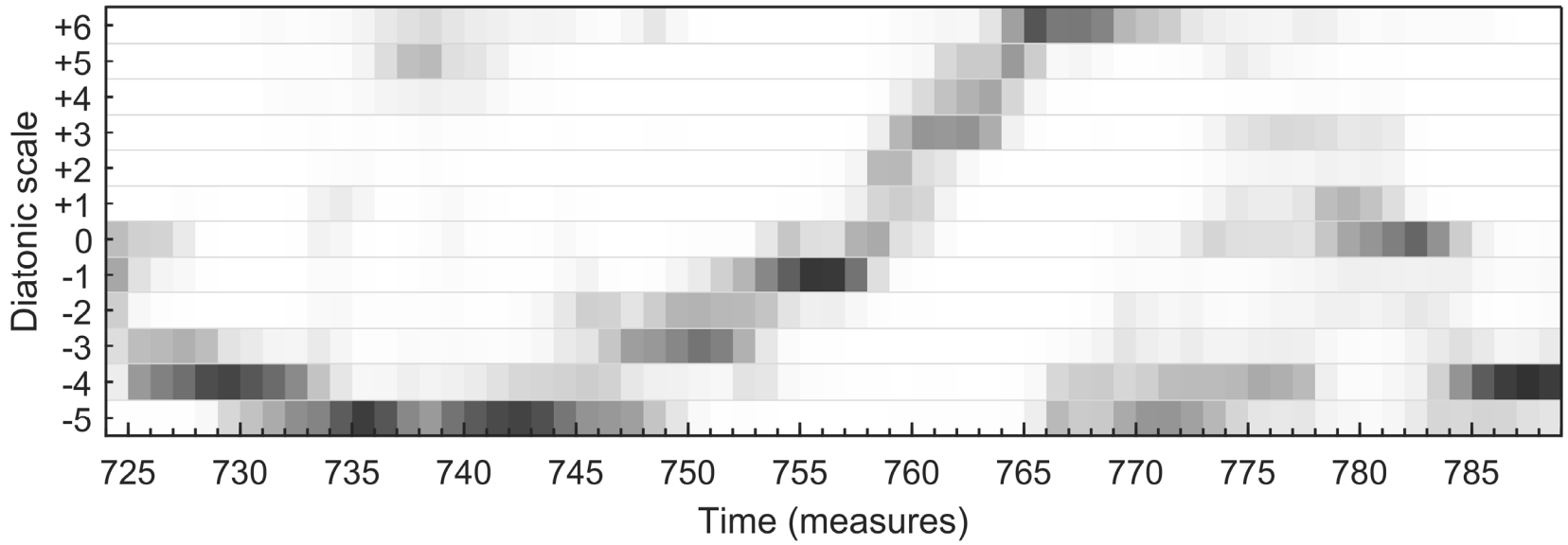
Local Key Estimation

R. Wagner: WWV 86 B (*Die Walküre*)



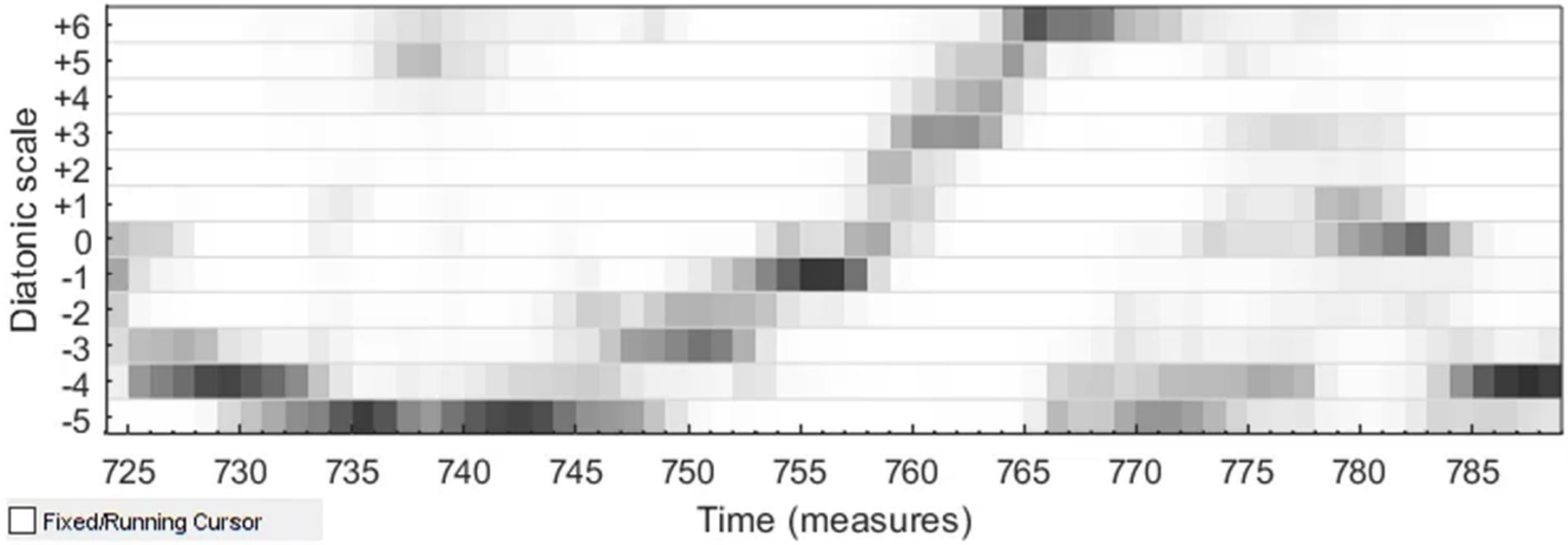
Local Key Estimation

R. Wagner: WWV 86 B (*Die Walküre*)
Act 3, measure 724–789 (*Wotan's punishment*)

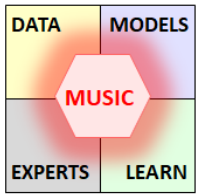


Local Key Estimation

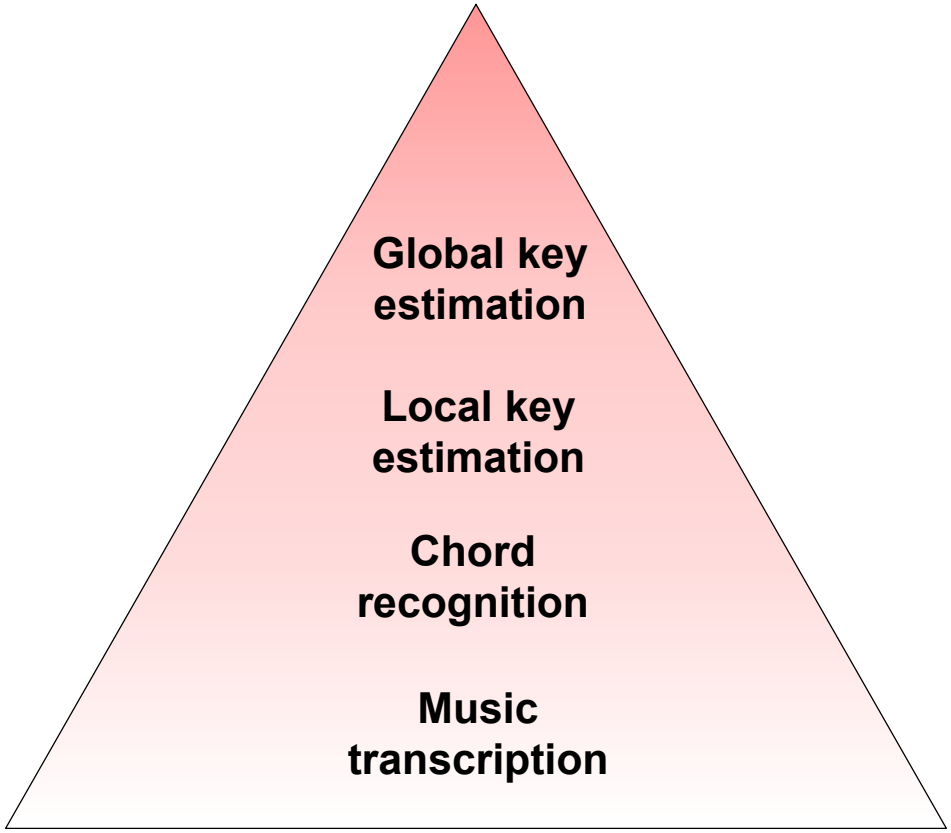
R. Wagner: WWV 86 B (*Die Walküre*)
Act 3, measure 724–789 (*Wotan's punishment*)



Reinhart Koselleck-Projekt: LEARN

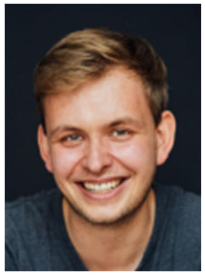


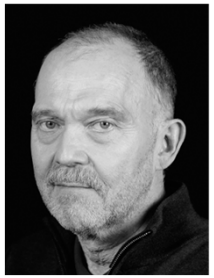
- Interpretability & explainability
- Knowledge integration
- Hybrid models
- Multitask learning
- Hierarchical approaches
- …



Computational Ethnomusicology: Traditional Georgian Vocal Music

- Interdisciplinary research project
  - Prof. Dr. Frank Scherbaum (Potsdam)
  - Dr. Nana Mzhavanadze (Tbilisi)
  - Sebastian Rosenzweig (FAU)





Universität Potsdam

FAU
Friedrich-Alexander-Universität Erlangen-Nürnberg

- Objective: Tonal analysis

- 2018 – 2022: DFG-funded project

DFG

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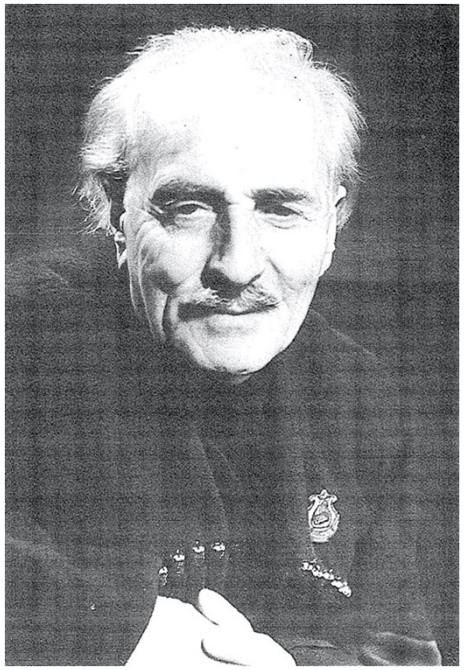
Traditional Georgian Vocal Music

Example: Erkomaishvili corpus

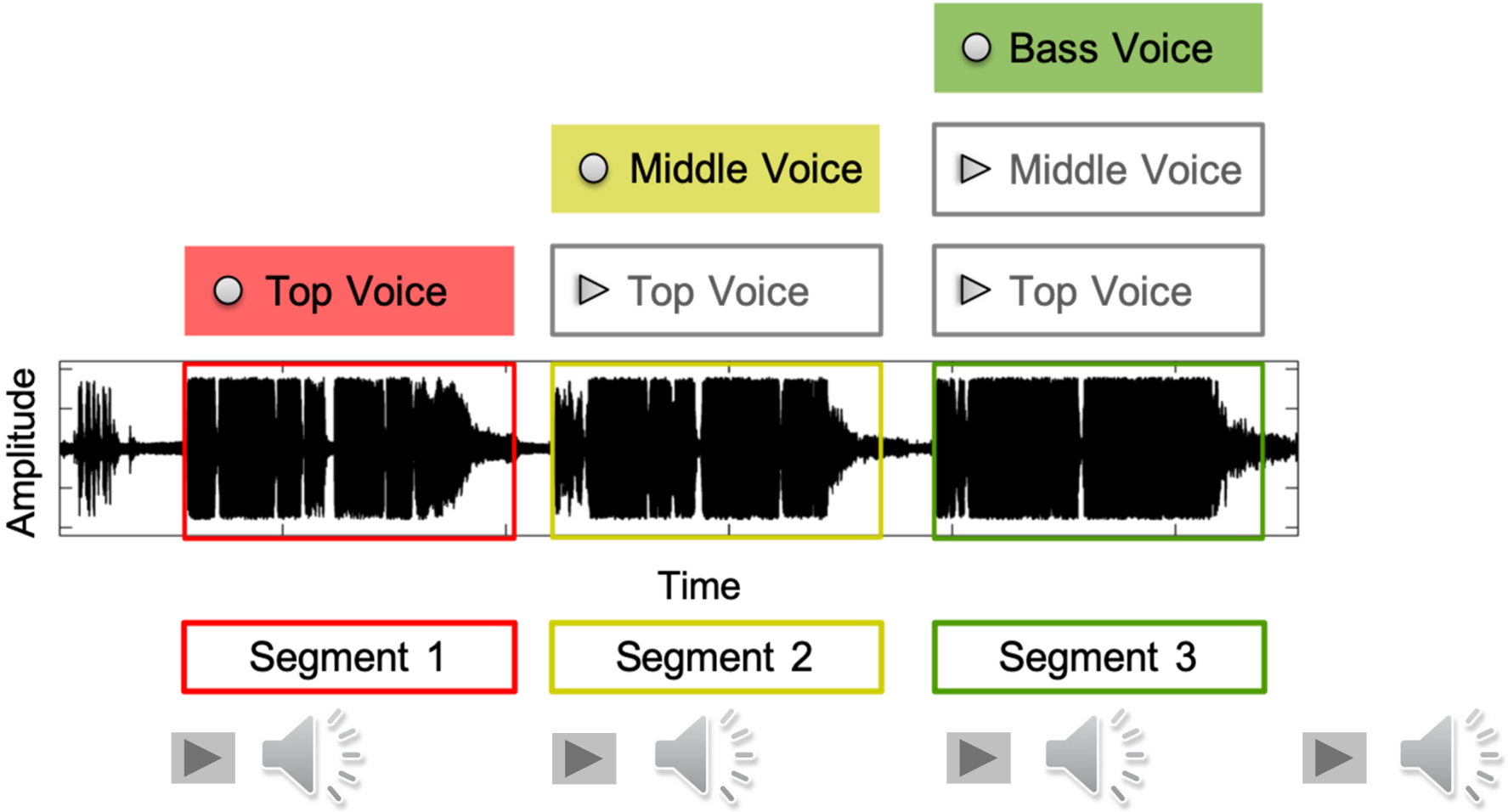


- Collection of traditional three-voice Georgian songs
- Performed by the former Georgian master chanter Artem Erkomaishvili (1887-1967)
- Recordings of 100 songs using tape recorders (1966)

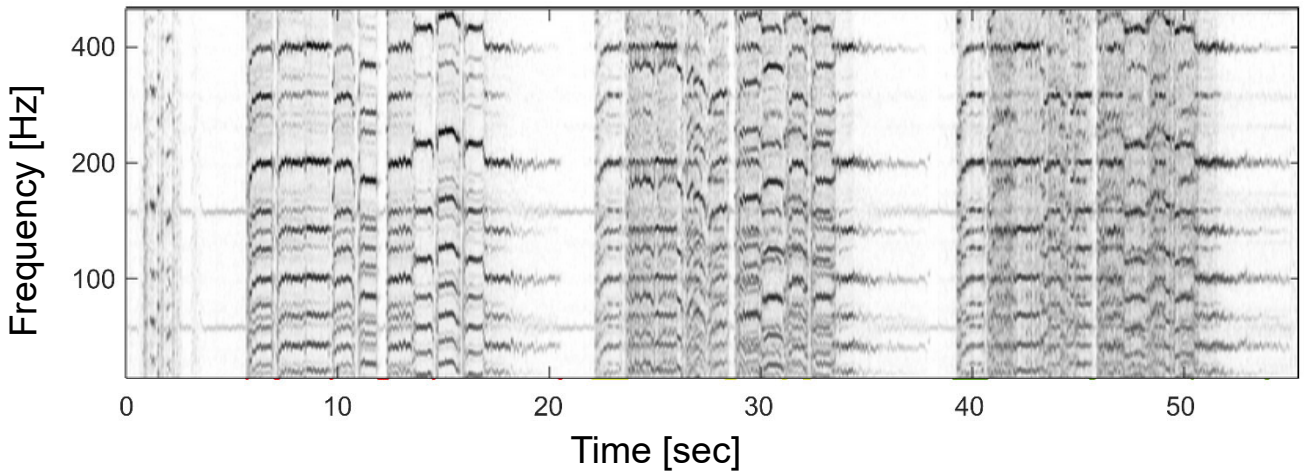
"*Original masterpieces of Georgian musical thinking.*" (Shugliashvili, 2014)

Traditional Georgian Vocal Music

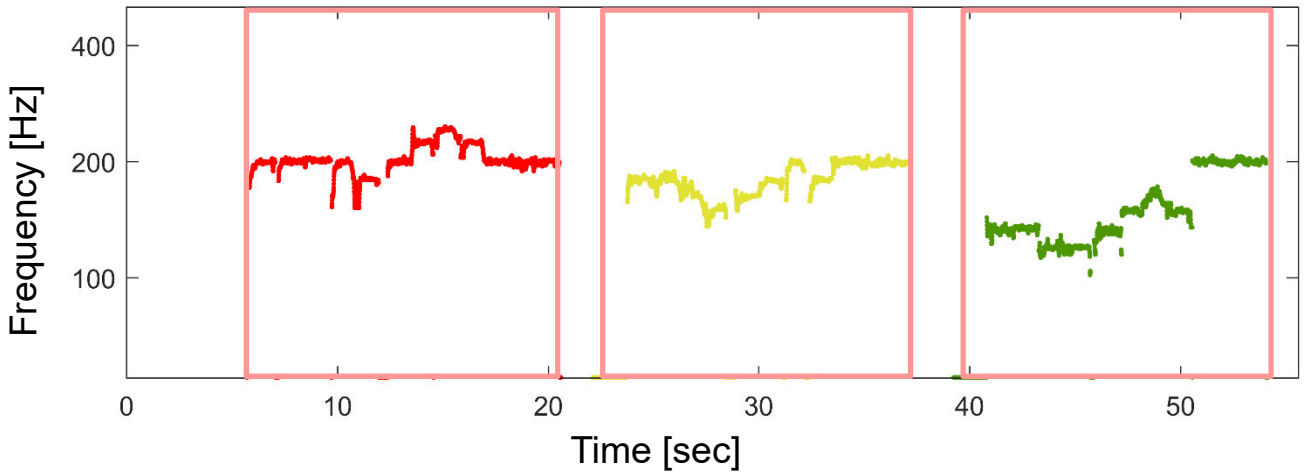
Example: Erkomaishvili corpus



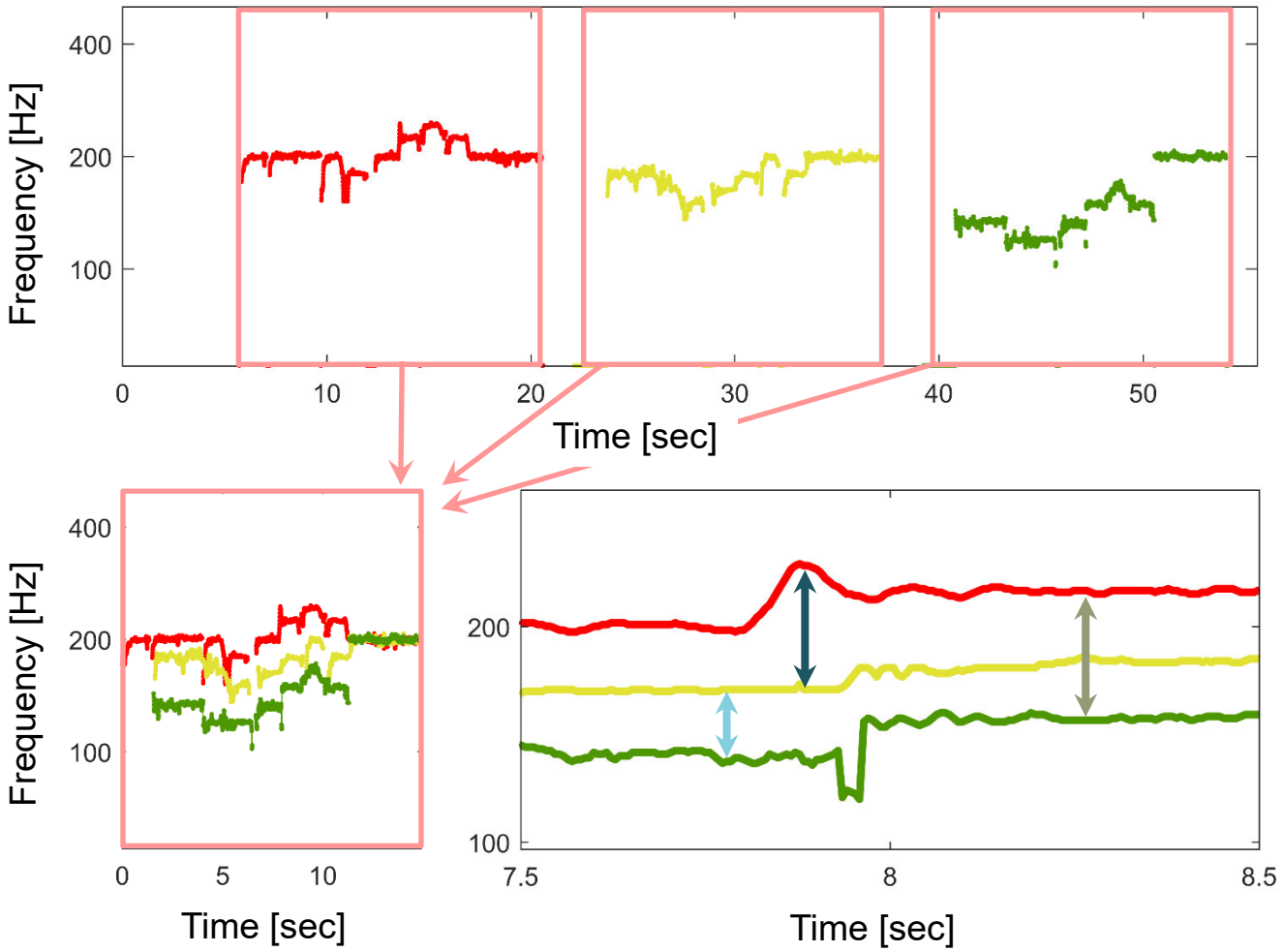
Traditional Georgian Vocal Music



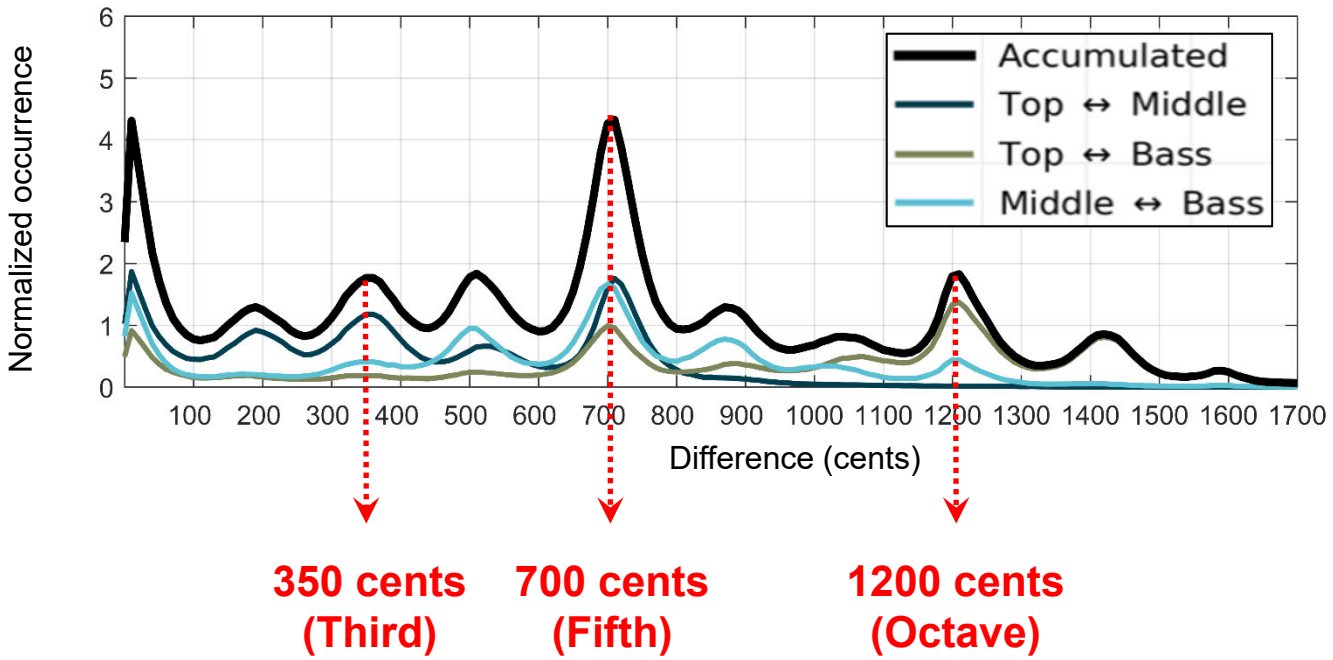
Traditional Georgian Vocal Music



Traditional Georgian Vocal Music



Traditional Georgian Vocal Music



- Peak at 350 cents (between minor and major third)
- **Non-western temperament**

Traditional Georgian Vocal Music

- Recordings from field expedition in 2016
- 216 performances
- Multitrack audio + video
  - Room, HSM, LRX
- Total duration: 6 h

Room Microphone

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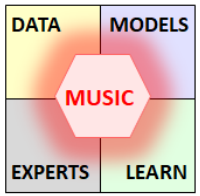
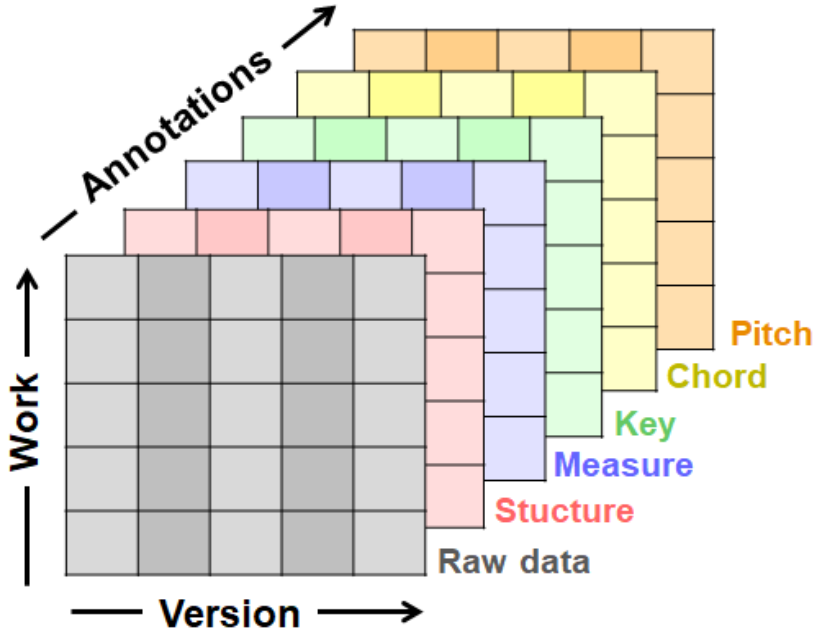
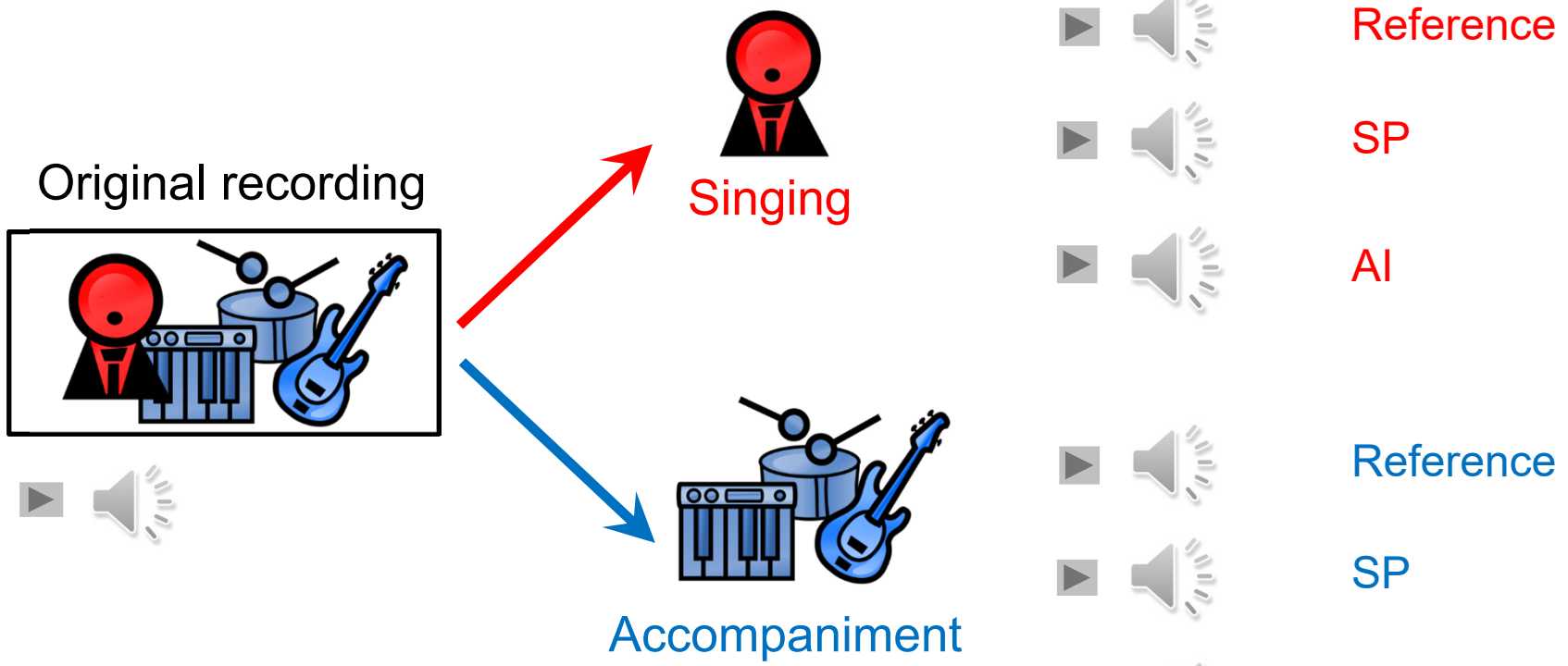


- Non-standard datasets
  - Variety of music
  - Poor audio quality
  - Various sensor types
- Exploring DL models
  - Generalization
  - Overfitting
  - Data scarceness



Source Separation (Singing)



- Reference: Best possible result
- SP: Using traditional signal processing
- AI: Using data-driven approach

Source Separation (Piano Concerto)

- Yigitcan Özer
- PhD student in engineering
- Pianist

Source Separation (Piano Concerto)

- Yigitcan Özer
- PhD student in engineering
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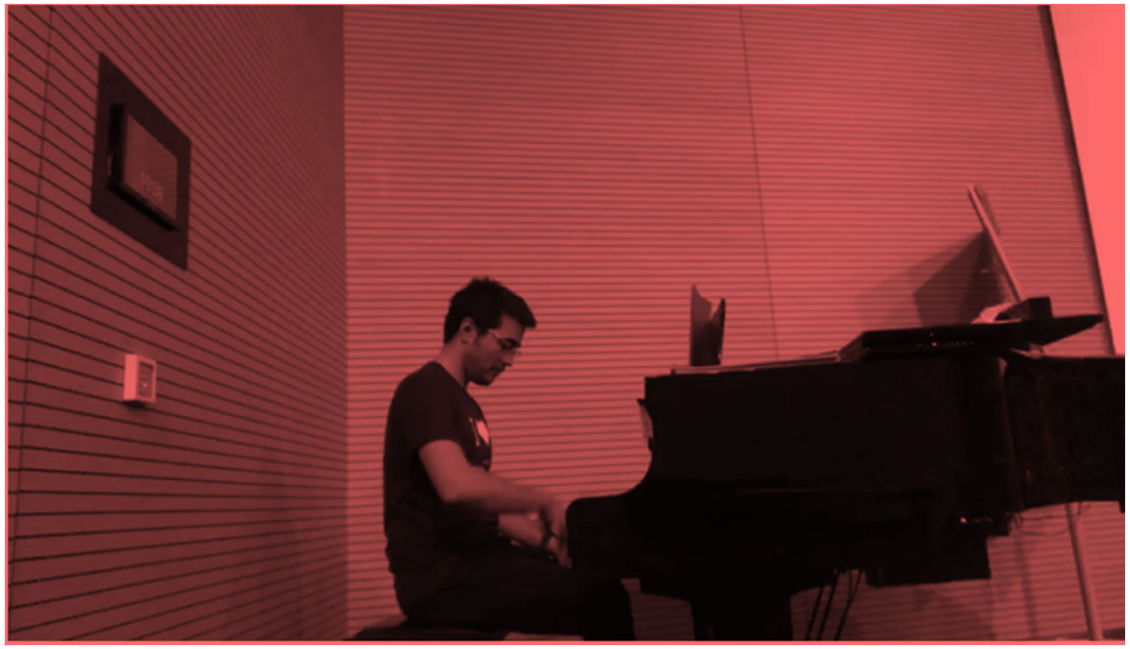
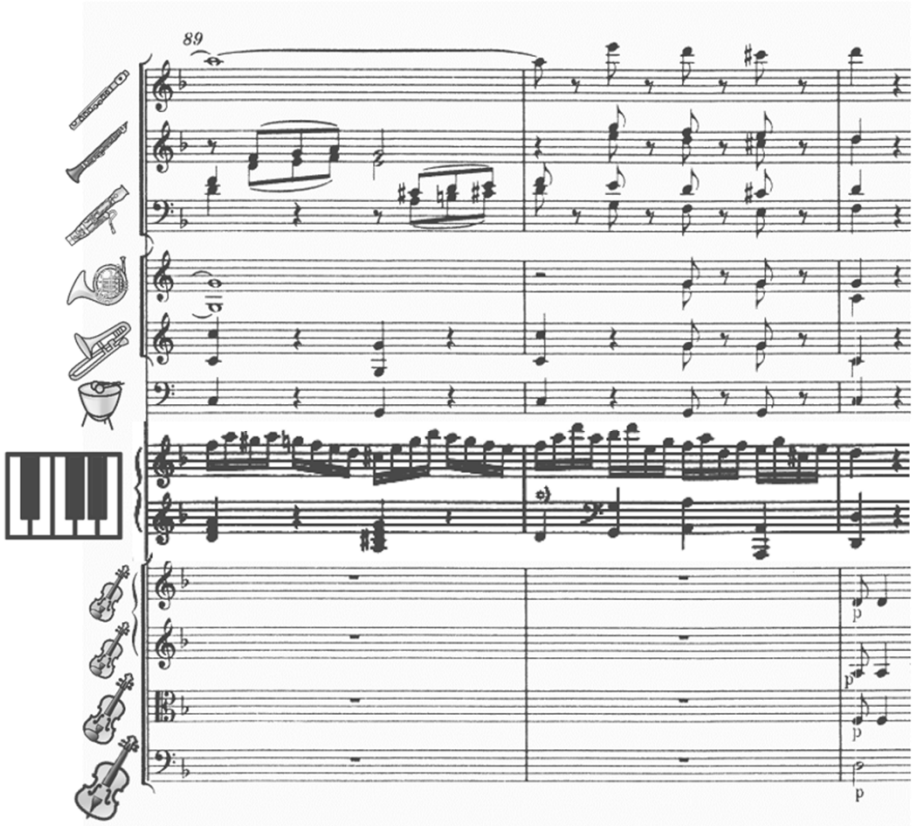
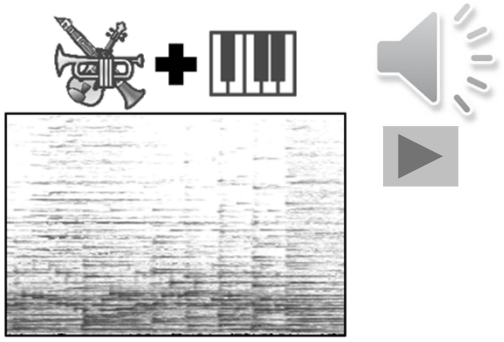


Only Piano!

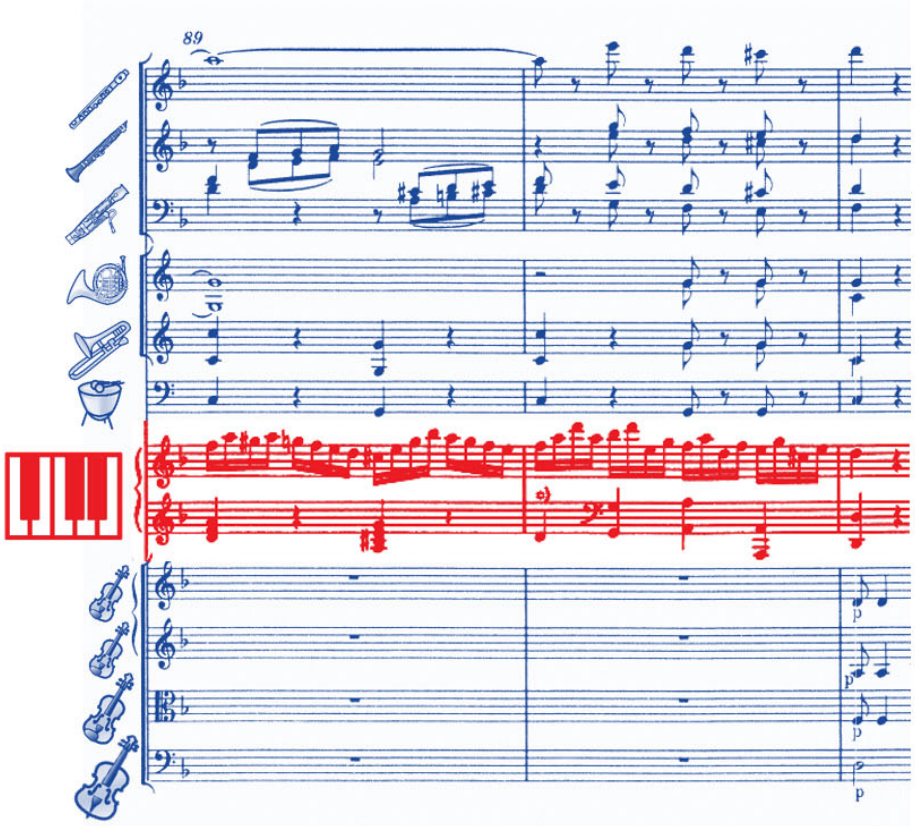
Where is the orchestra?

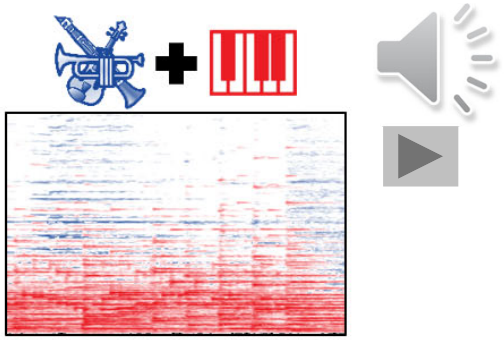
Source Separation (Piano Concerto)



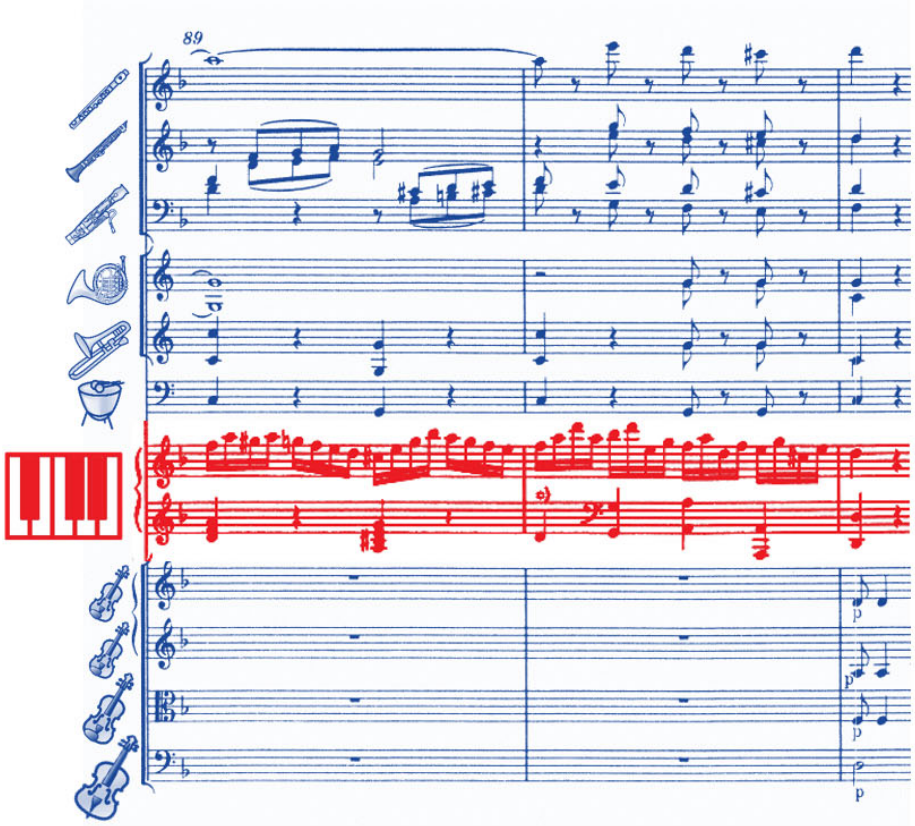


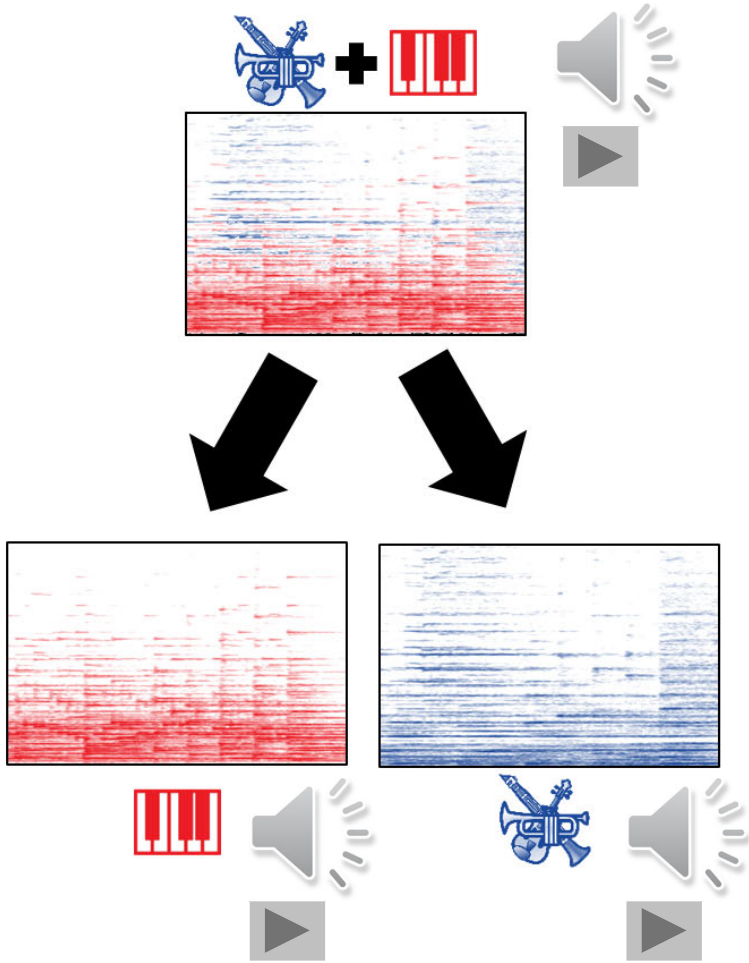
Source Separation (Piano Concerto)



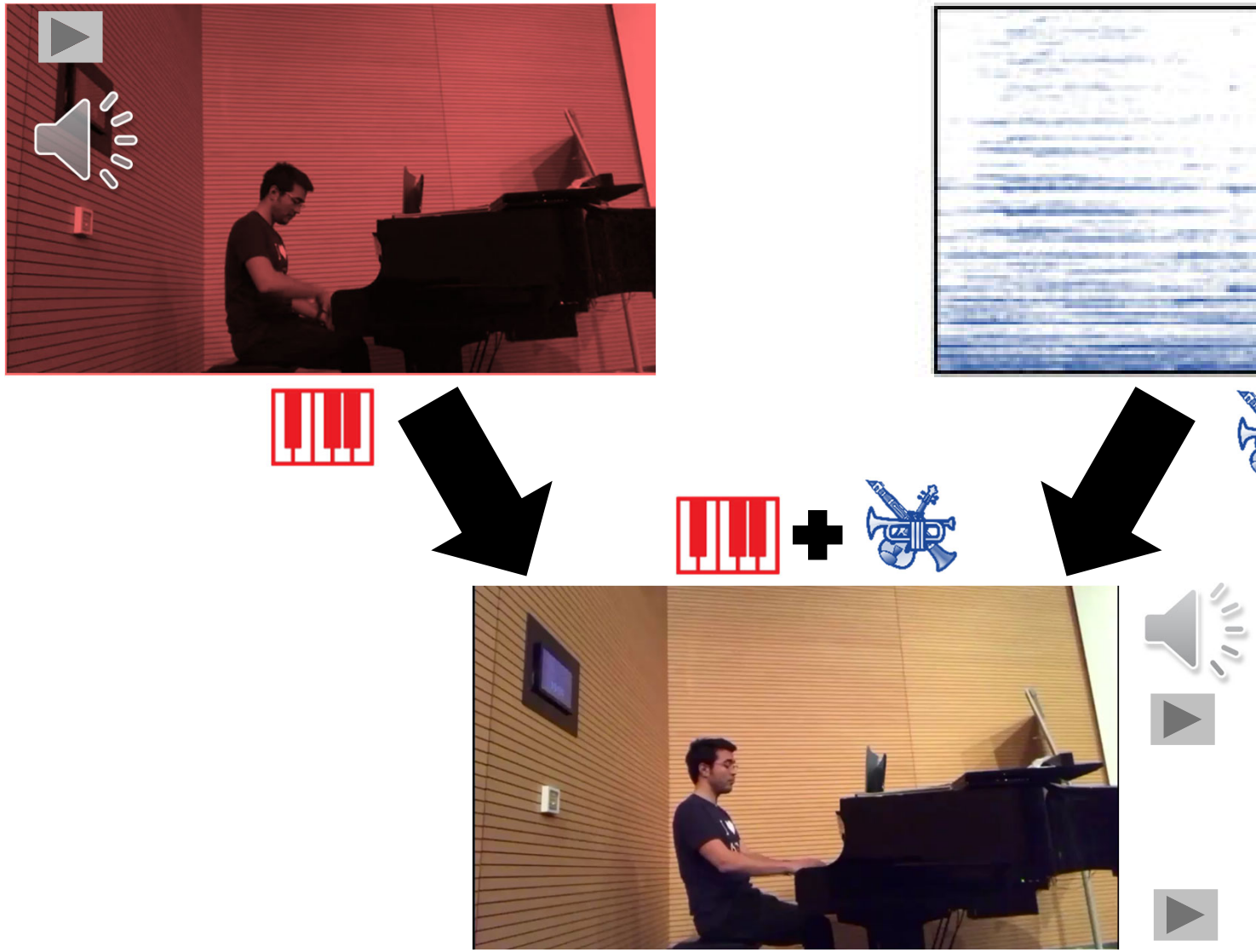


Source Separation (Piano Concerto)



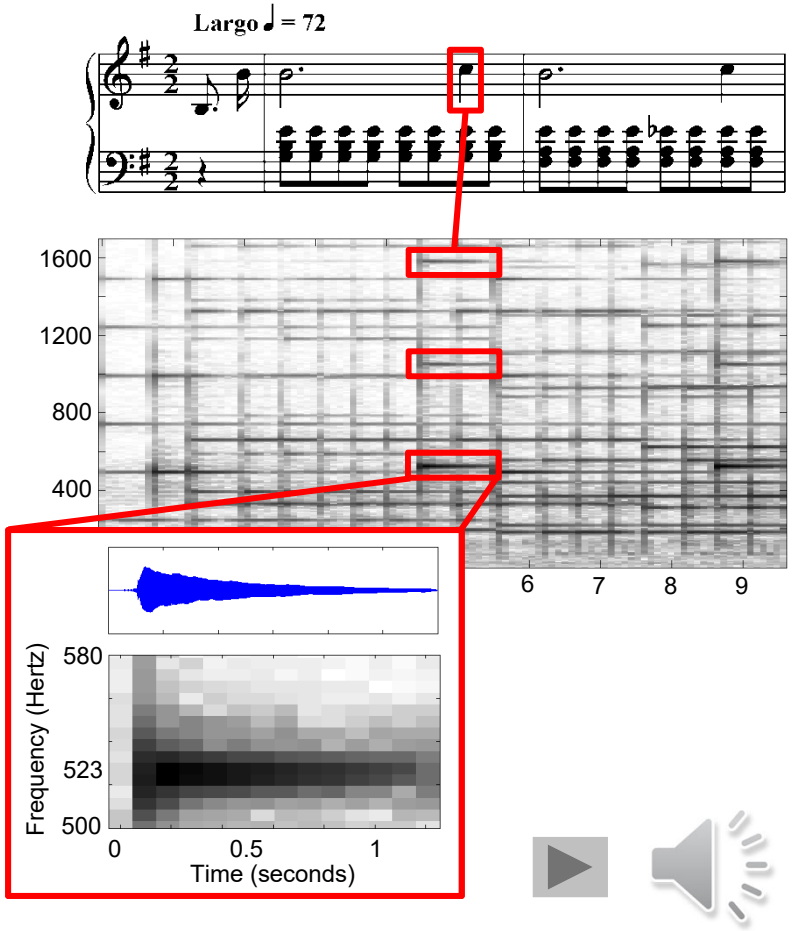


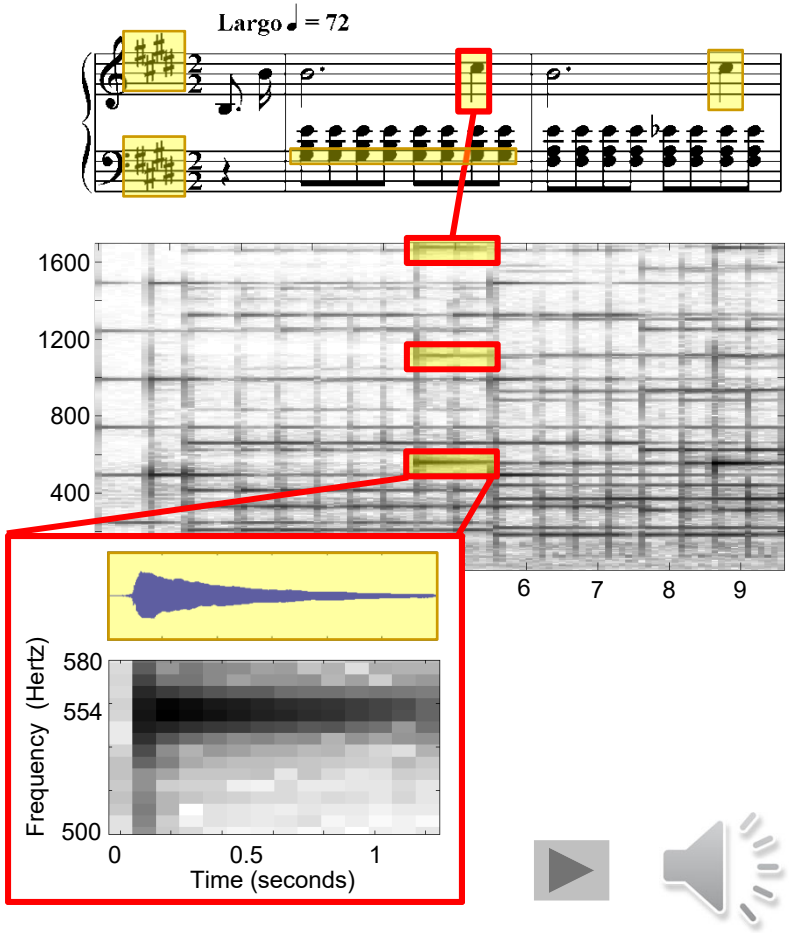
Source Separation (Piano Concerto)



Source Separation

Score-informed audio editing



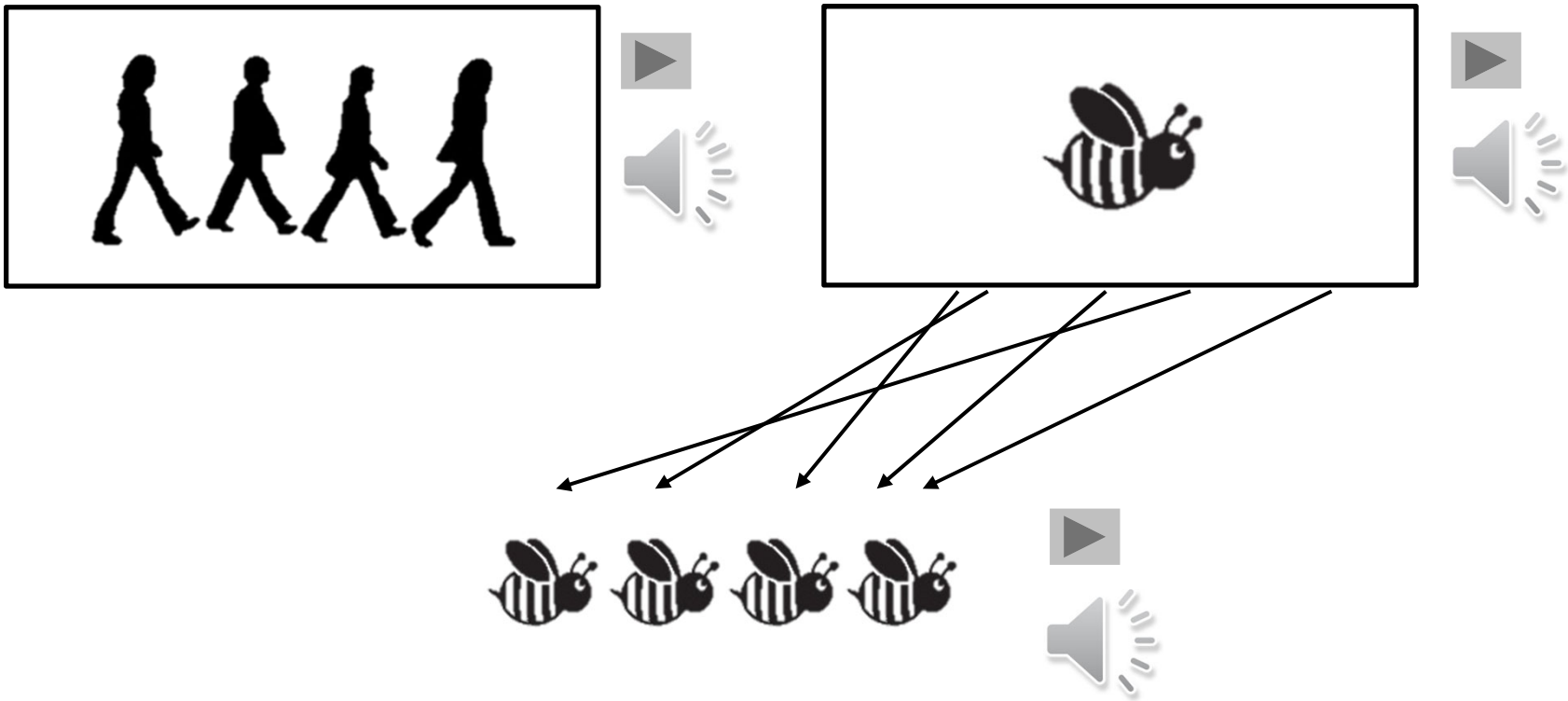


Source Separation

Audio mosaicing (style transfer)

Target signal: Beatles–Let it be

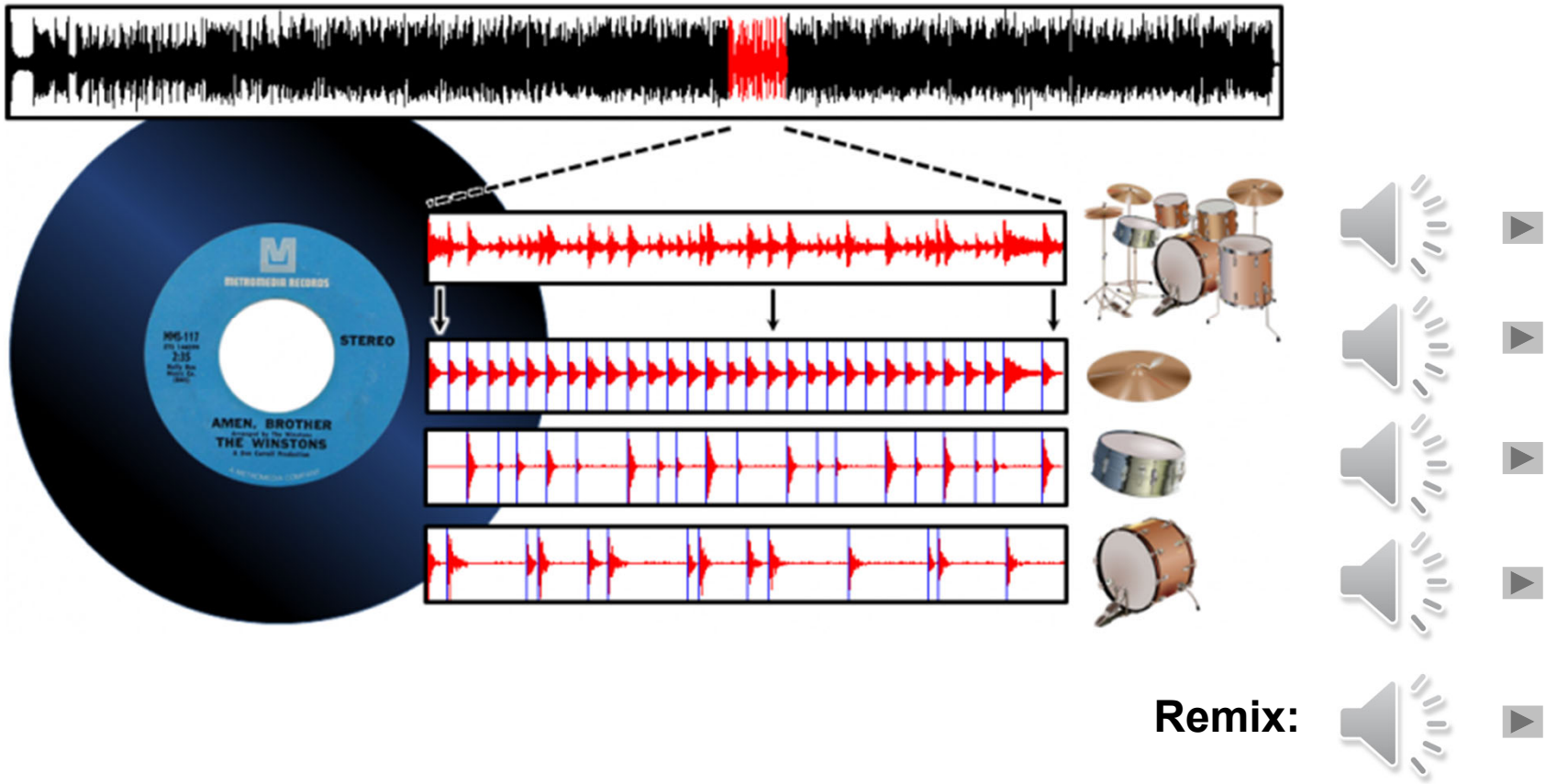
Source signal: Bees



Mosaic signal: Let it Bee

Source Separation

Informed Drum-Sound Decomposition



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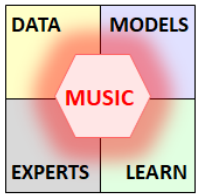
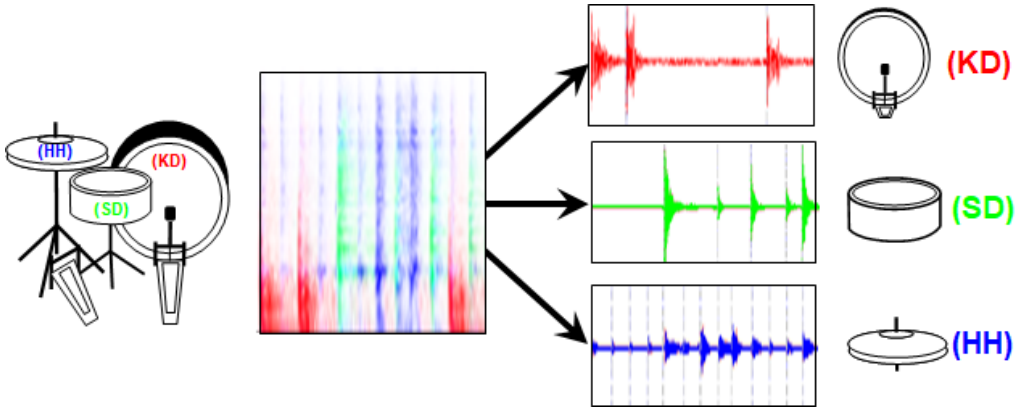
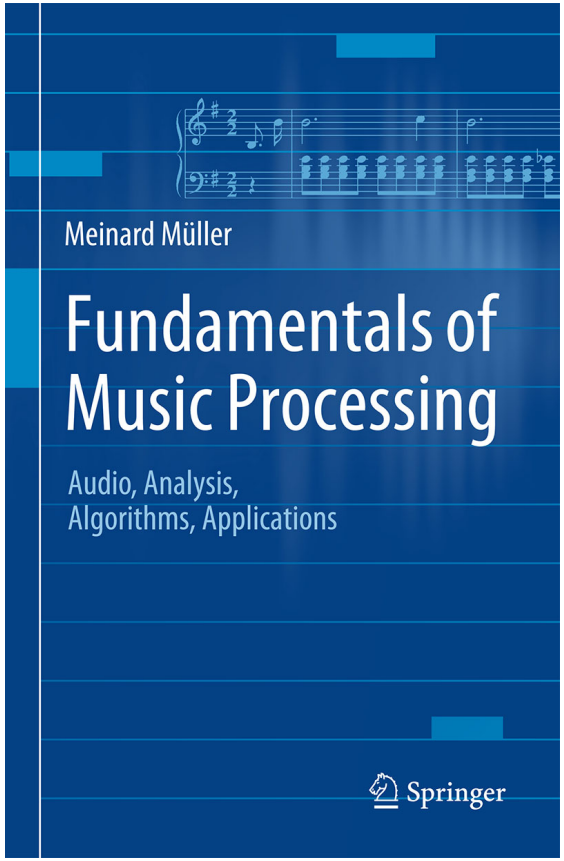


- Reconstruction of sources
- Generative models
- Differentiable DSP
- Analysis by synthesis
- …



Fundamentals of Music Processing (FMP)

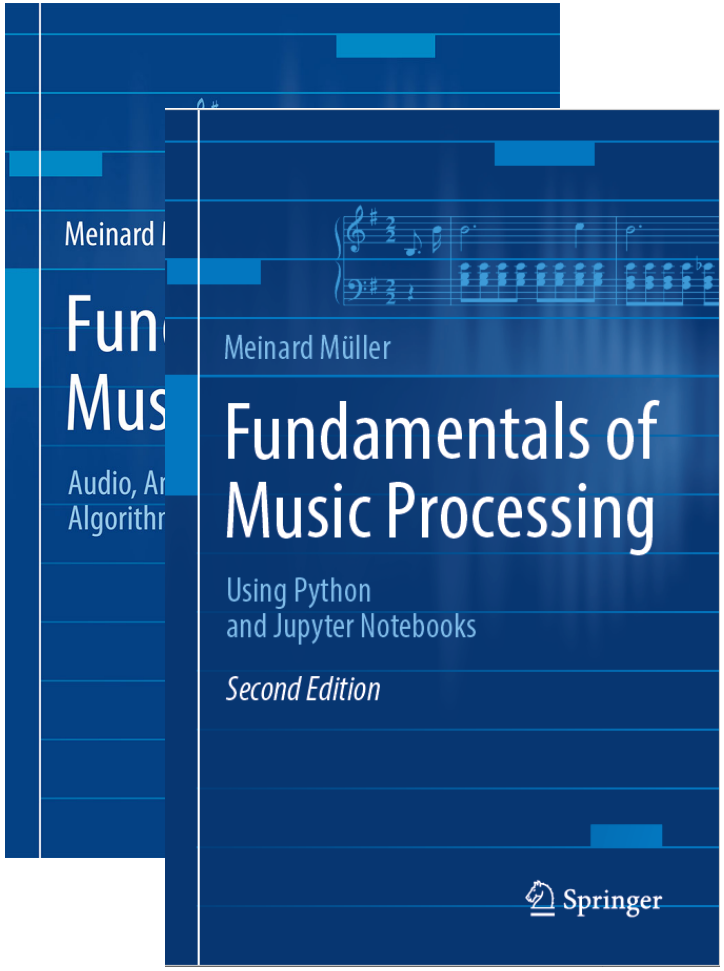


Meinard Müller
Fundamentals of Music Processing
Audio, Analysis, Algorithms, Applications
Springer, 2015

Accompanying website:
www.music-processing.de

AUDIO LABS

Fundamentals of Music Processing (FMP)



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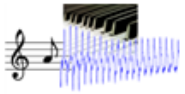
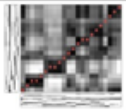
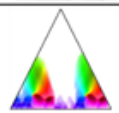
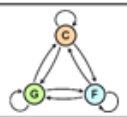
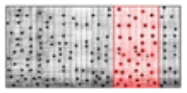
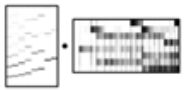
2nd edition
Meinard Müller
Fundamentals of Music Processing
Using Python and Jupyter Notebooks
Springer, 2021

Fundamentals of Music Processing (FMP)

Chapter		Music Processing Scenario
1		Music Represenations
2		Fourier Analysis of Signals
3		Music Synchronization
4		Music Structure Analysis
5		Chord Recognition
6		Tempo and Beat Tracking
7		Content-Based Audio Retrieval
8		Musically Informed Audio Decomposition

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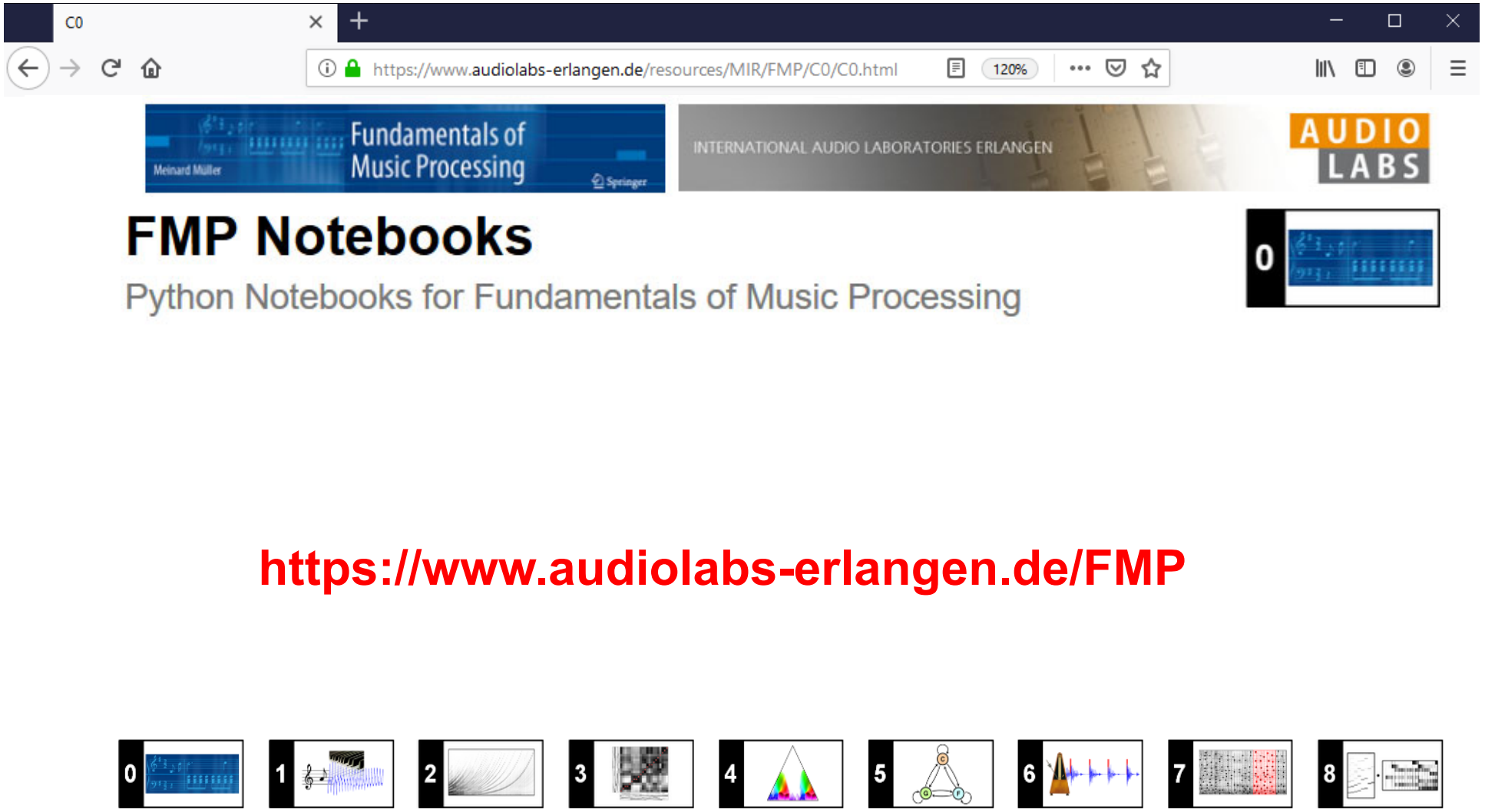
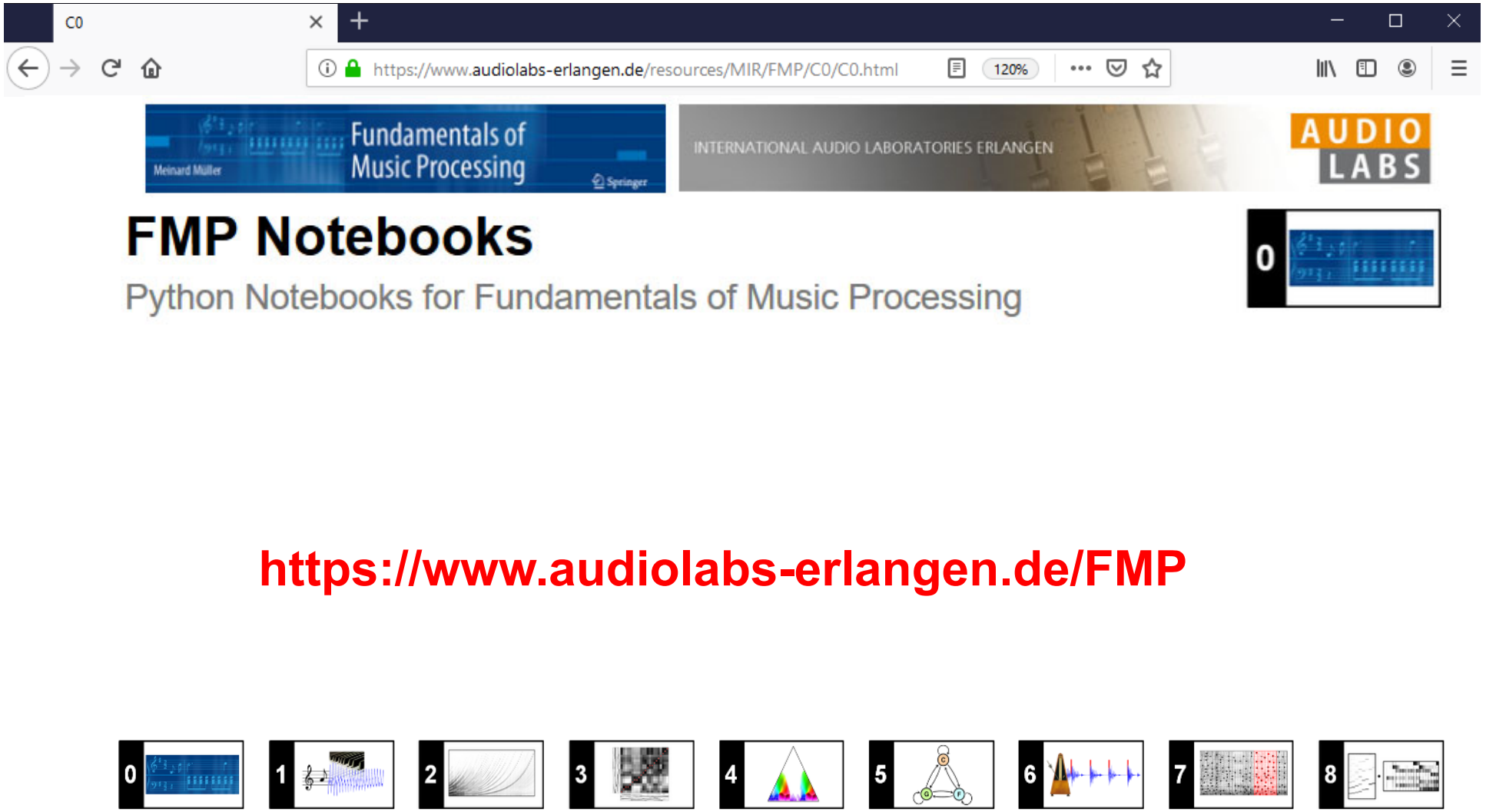
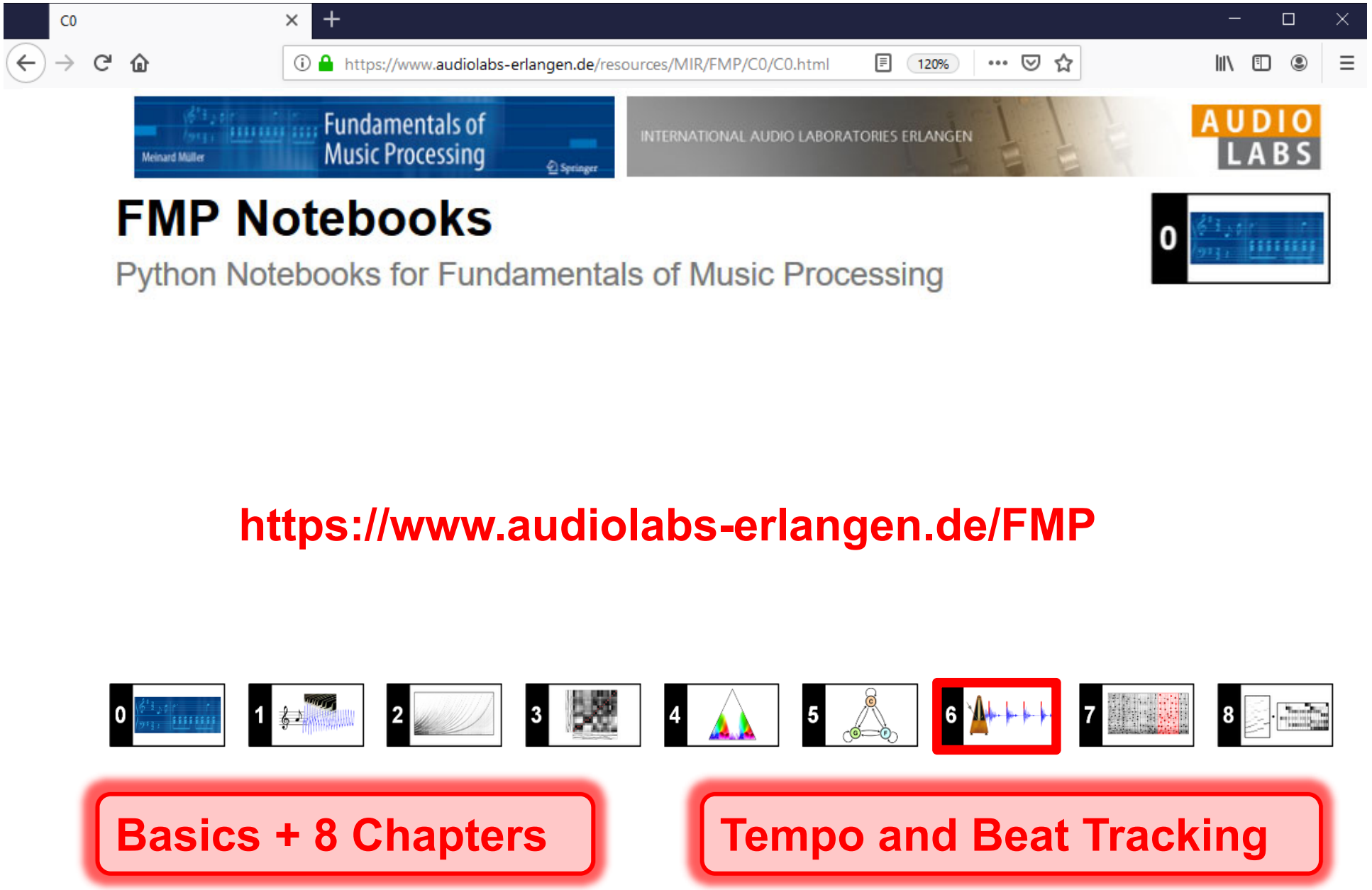
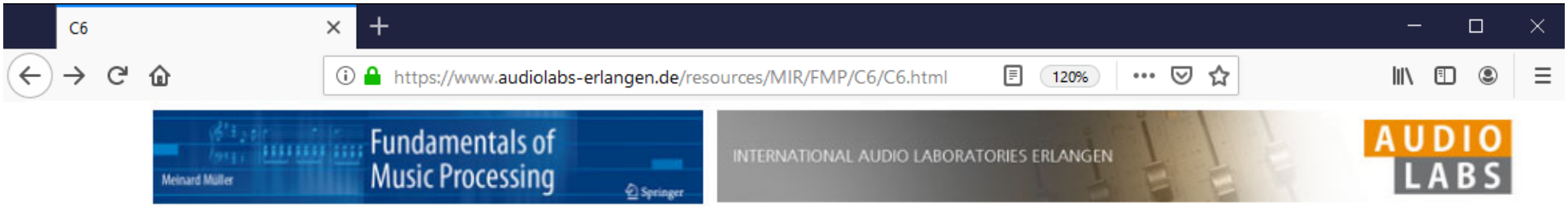
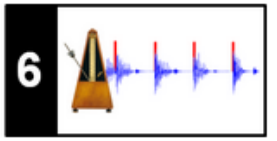




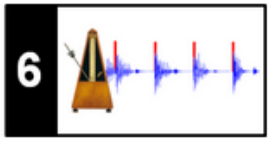




Tempo and Beat Tracking



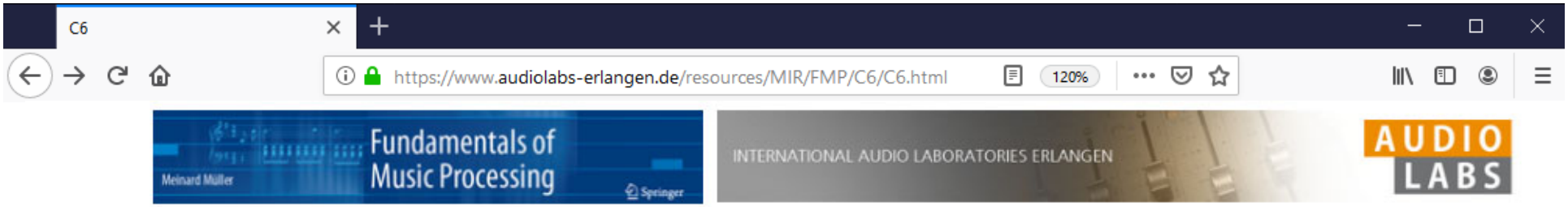
Tempo and Beat Tracking



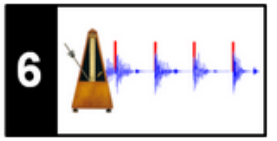
Definition

We assume that we are given a discrete-time novelty function $\Delta : \mathbb{Z} \to \mathbb{R}$ *indicate note onset candidates. The idea of Fourier analysis is to detect lo in novelty curve by comparing it with windowed sinusoids. A high correlati section of* Δ *with a windowed sinusoid indicates a periodicity of the sinus (given a suitable phase). This correlation (along with the phase) can be cc short-time Fourier transform. To this end, we fix a window function* $w : \mathbb{Z}$ *length centered at* $n = 0$ *(e.g., a sampled Hann window). Then, for a frec parameter* $\omega \in \mathbb{R}_{\geq 0}$ *and time parameter* $n \in \mathbb{Z}$*, the complex Fourier coe is defined by*

$$\mathcal{F}(n, \omega) := \sum_{m \in \mathbb{Z}} \Delta(m) \overline{w}(m - n) \exp(-2\pi i \omega m).$$



Tempo and Beat Tracking



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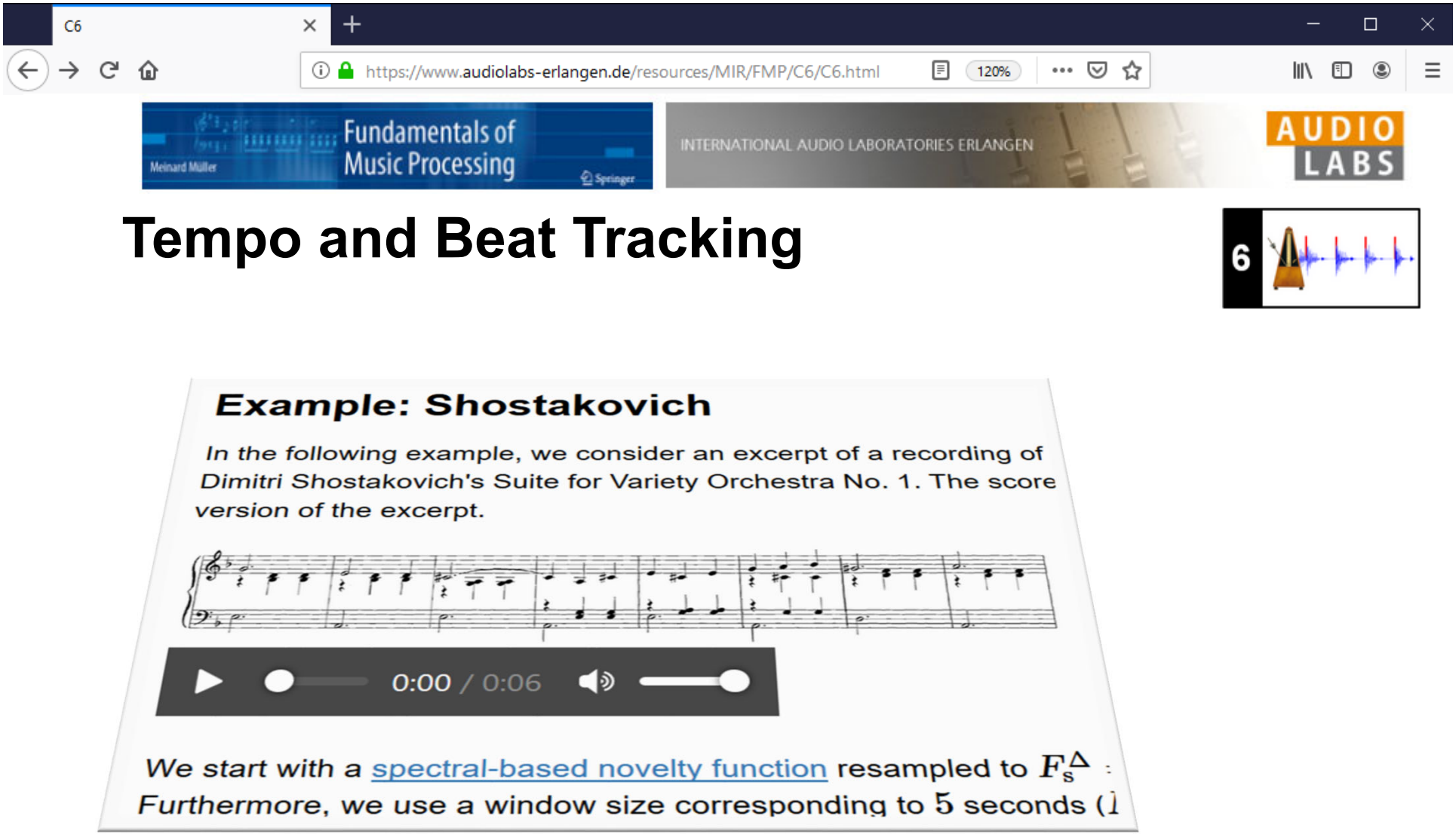
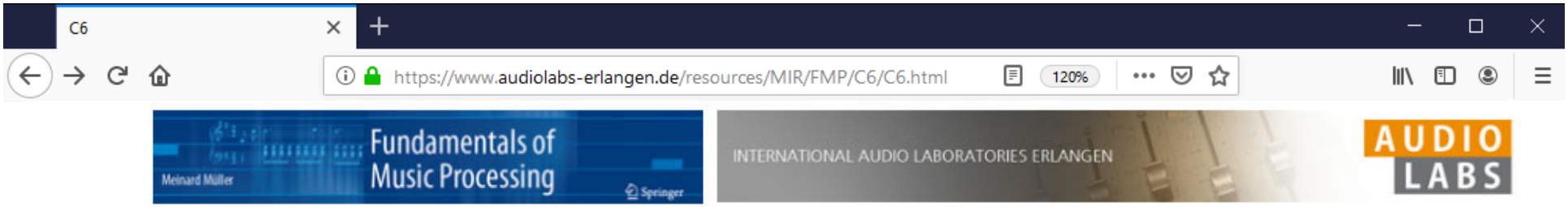
Explanations

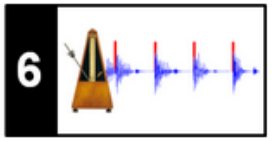
Theory

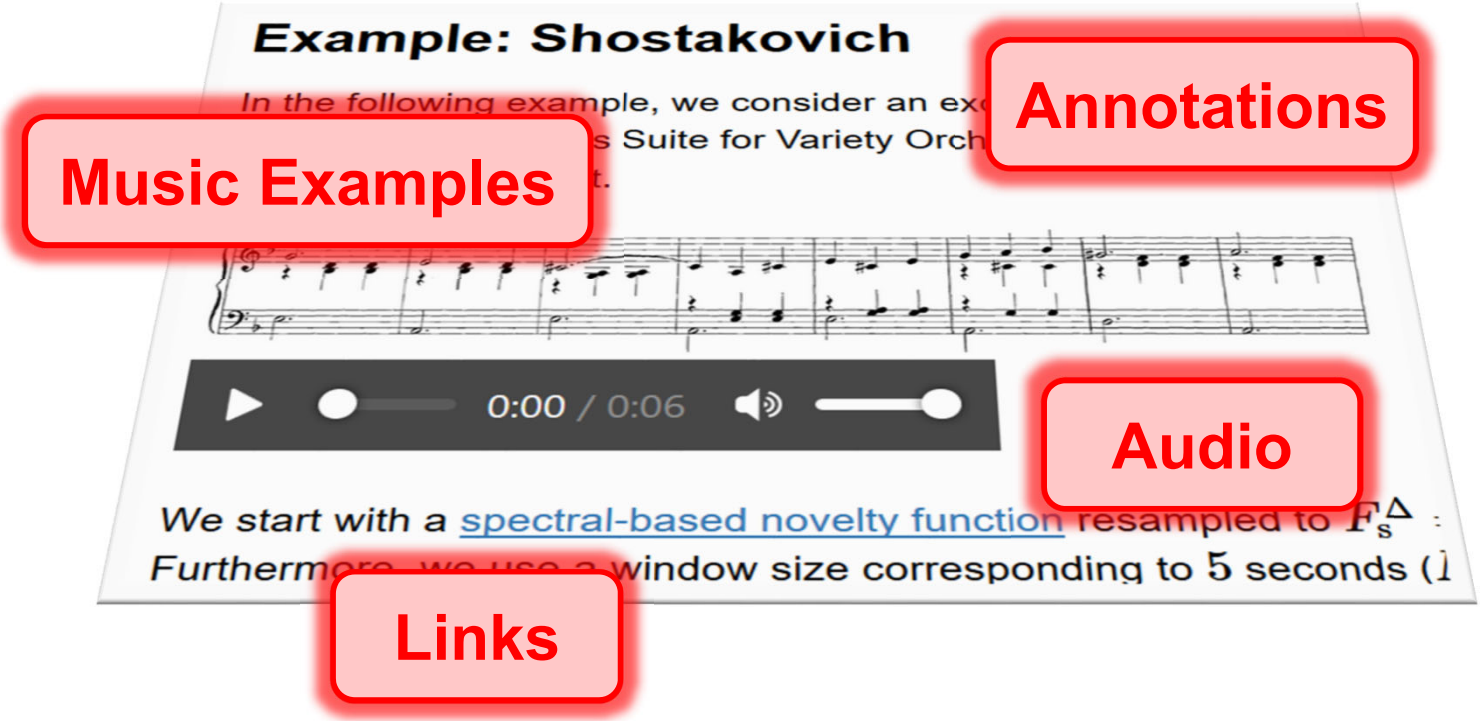
Mathematics

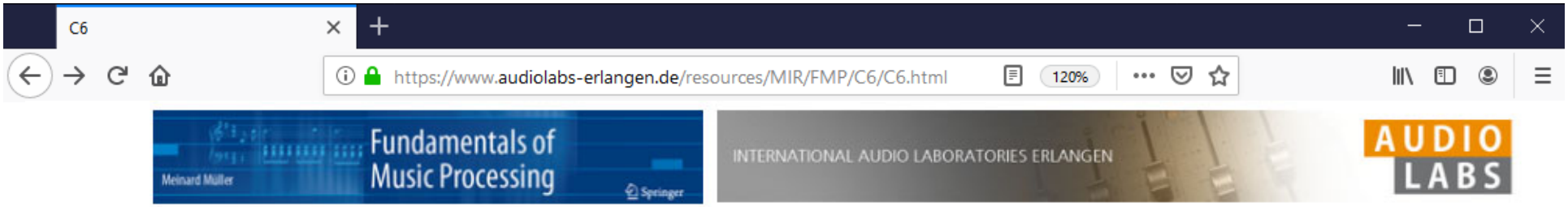




Tempo and Beat Tracking







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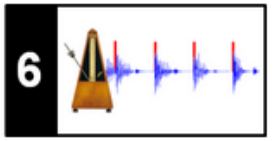
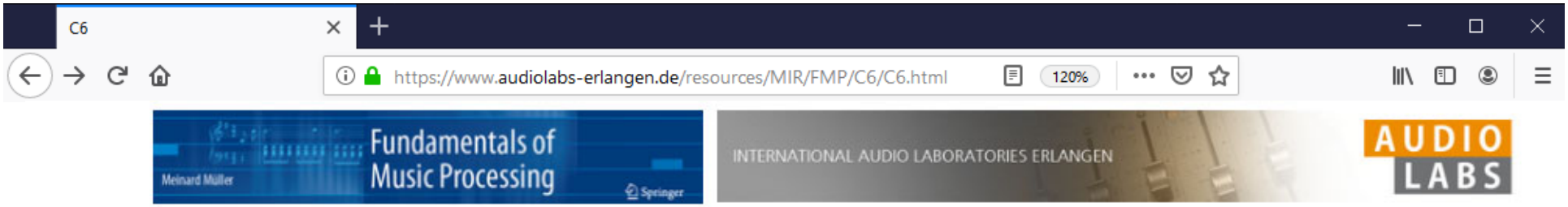
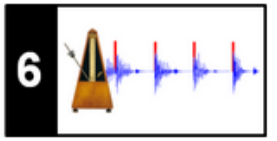
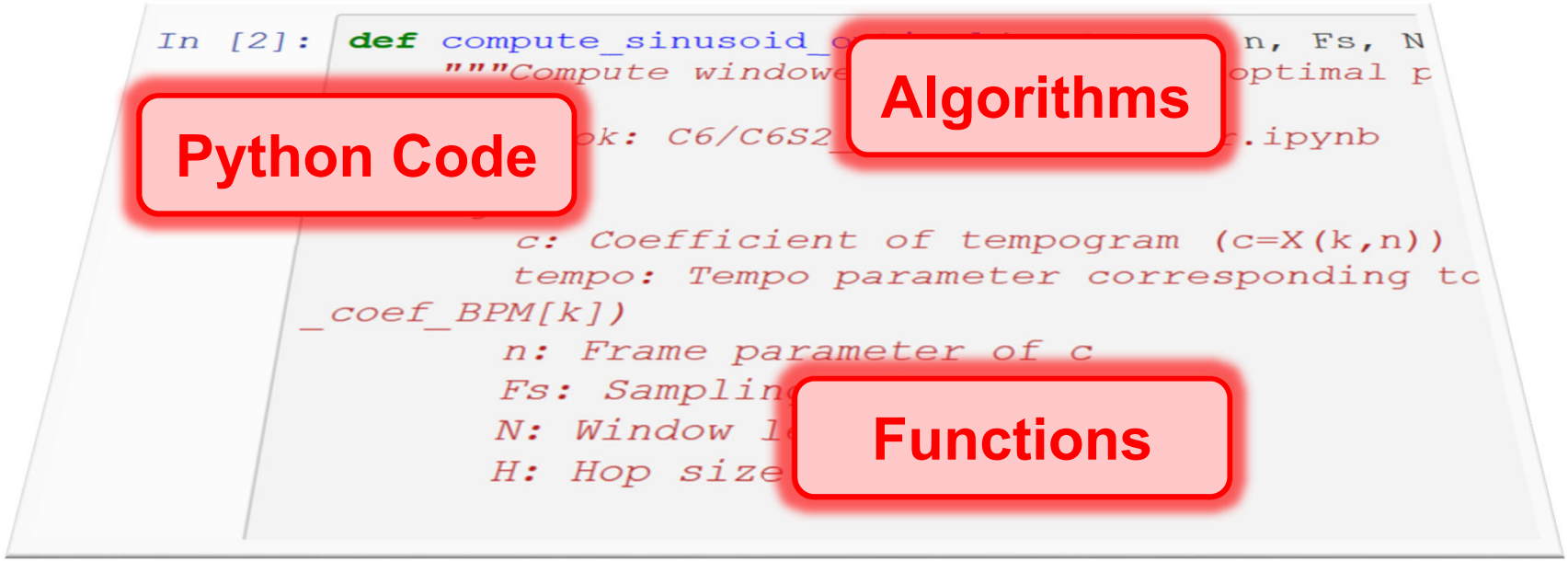


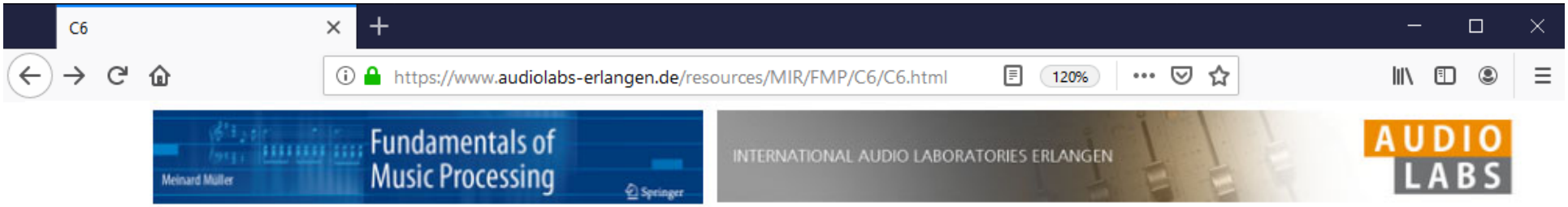

```
In [2]: def compute_sinusoid_optimal(c, tempo, n, Fs, N
            """Compute windowed sinusoid with optimal p

            Notebook: C6/C6S2_TempogramFourier.ipynb

            Args:
                c: Coefficient of tempogram (c=X(k,n))
                tempo: Tempo parameter corresponding tc
        _coef_BPM[k])
                n: Frame parameter of c
                Fs: Sampling rate
                N: Window length
                H: Hop size
```



Tempo and Beat Tracking







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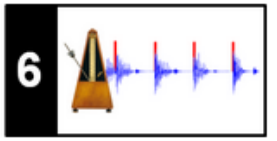
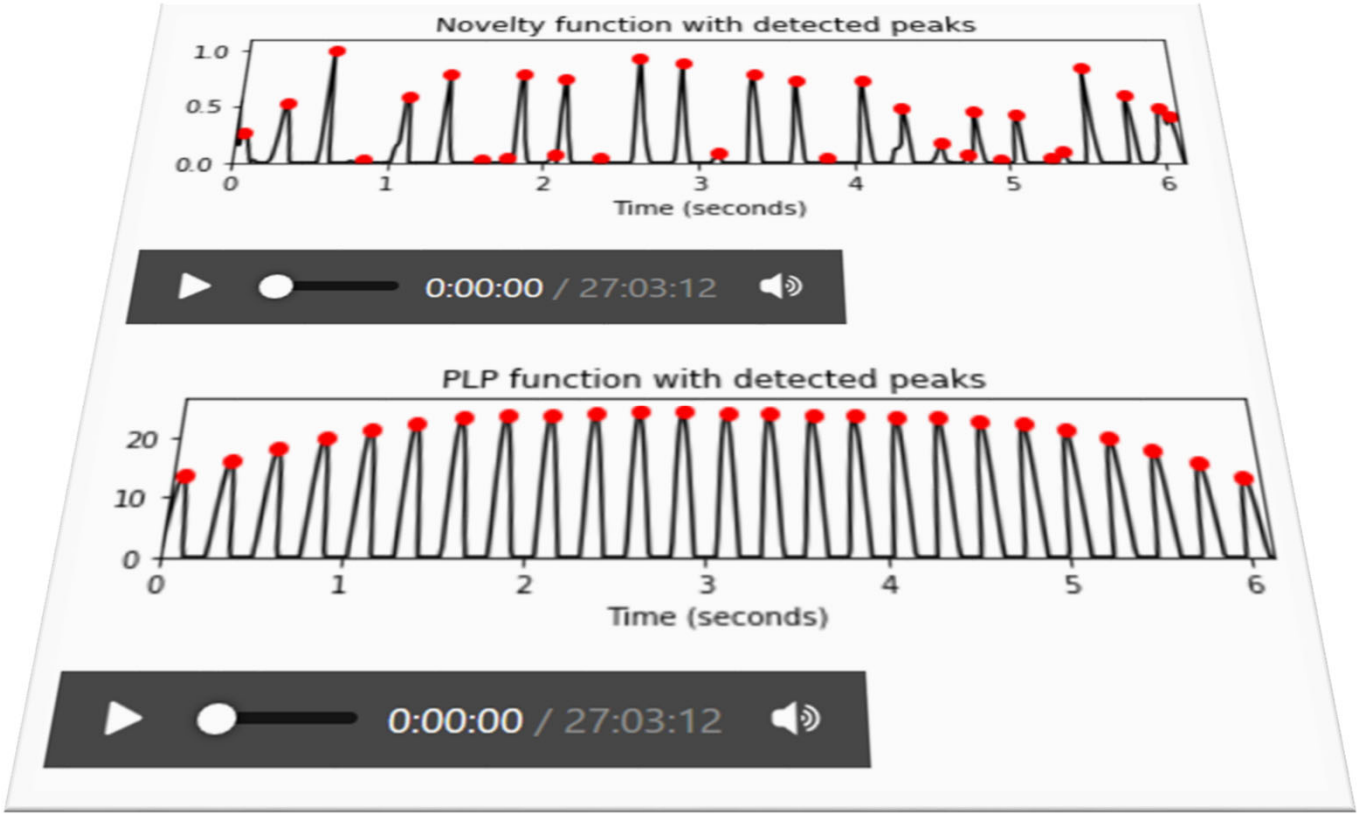
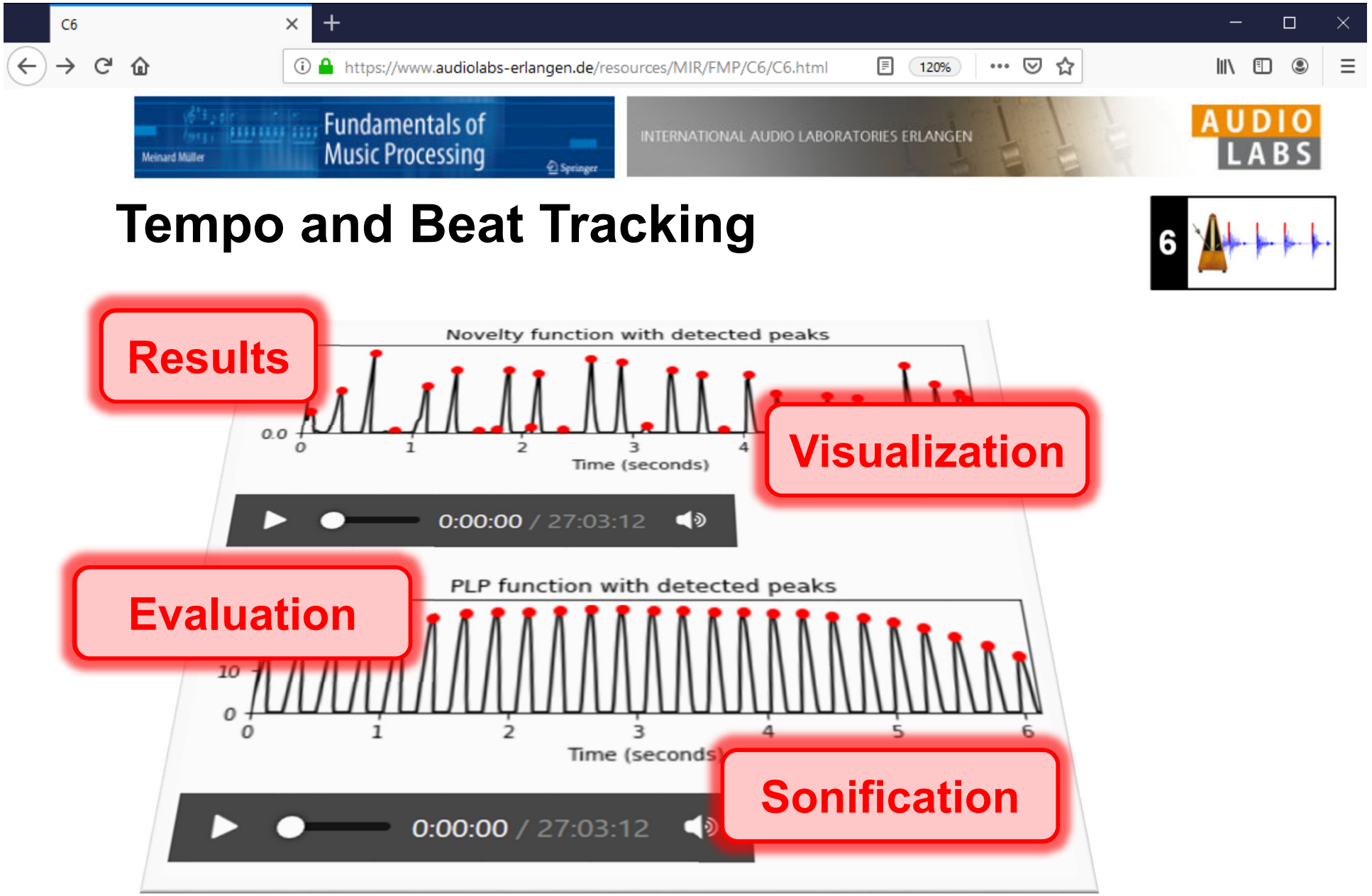
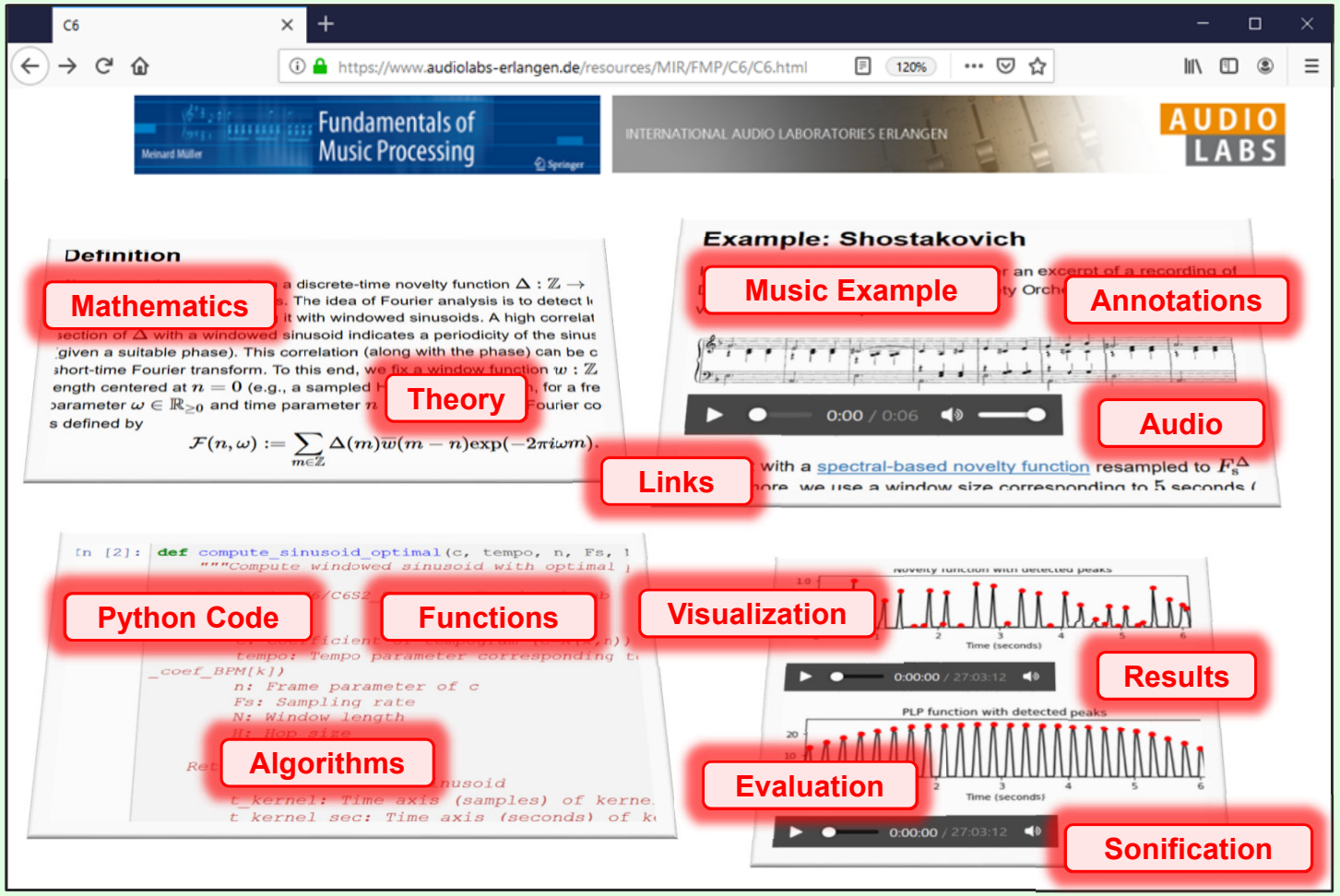






FMP Notebooks

- Teaching
- Understanding
- Programming
- Baselines
- Research
- Multimedia



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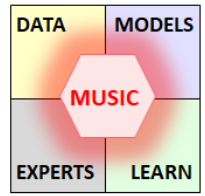
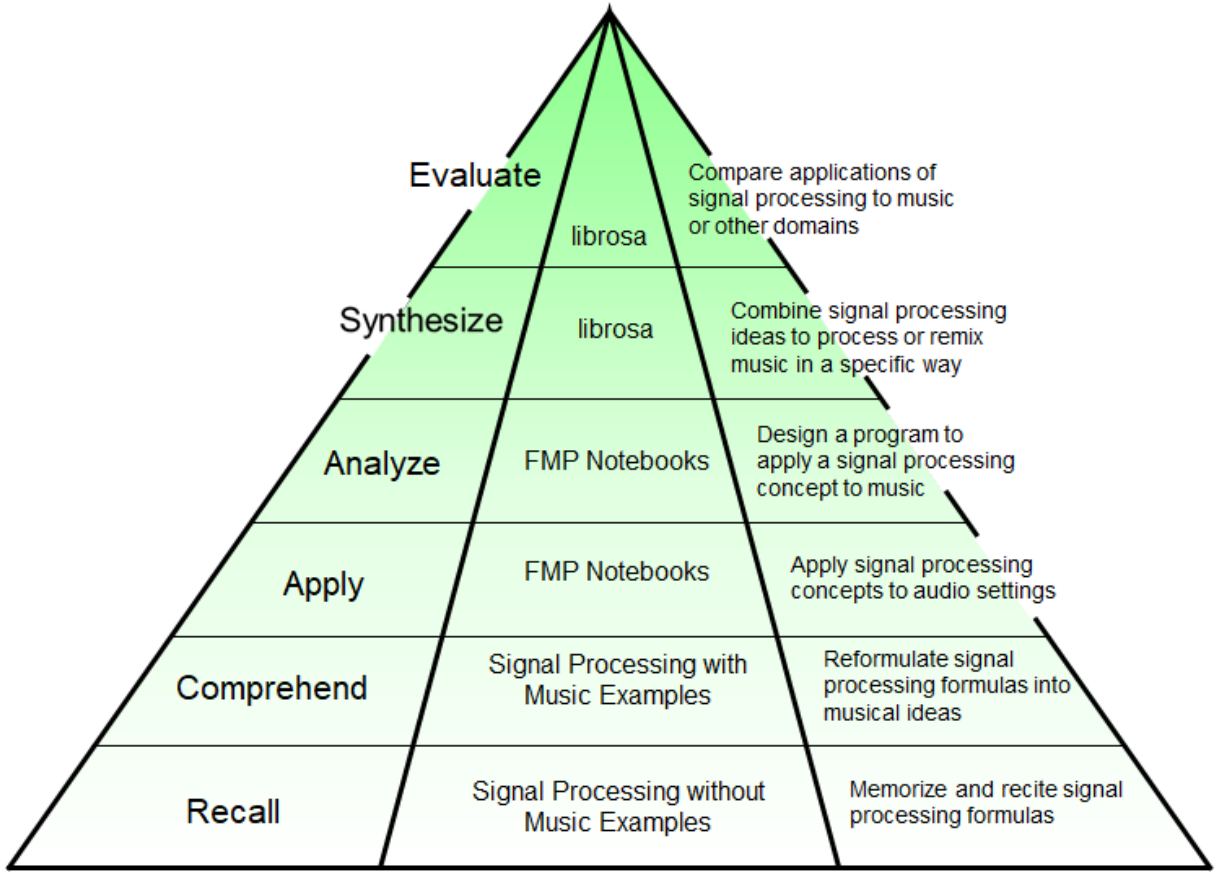


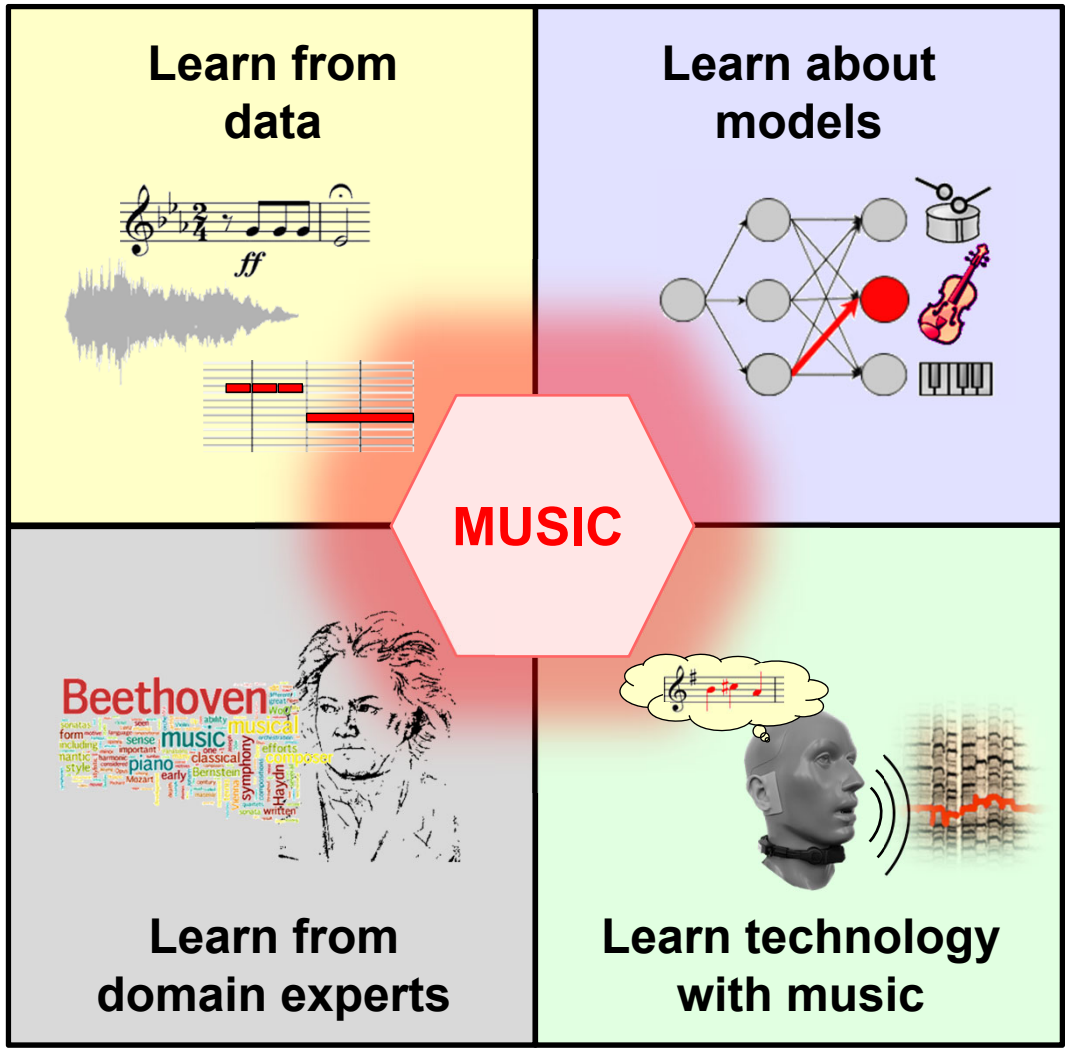
- Motivating examples
- Challenging domain
- Interdisciplinarity
- Structured learning
- …



Bloom's taxonomy

Reinhart Koselleck-Projekt: LEARN

Learning with Music Signals: Technology Meets Education



- Machine learning for music signal processing
- Interpretable models and knowledge integration
- Music understanding and applications
- Interactive learning in engineering through music

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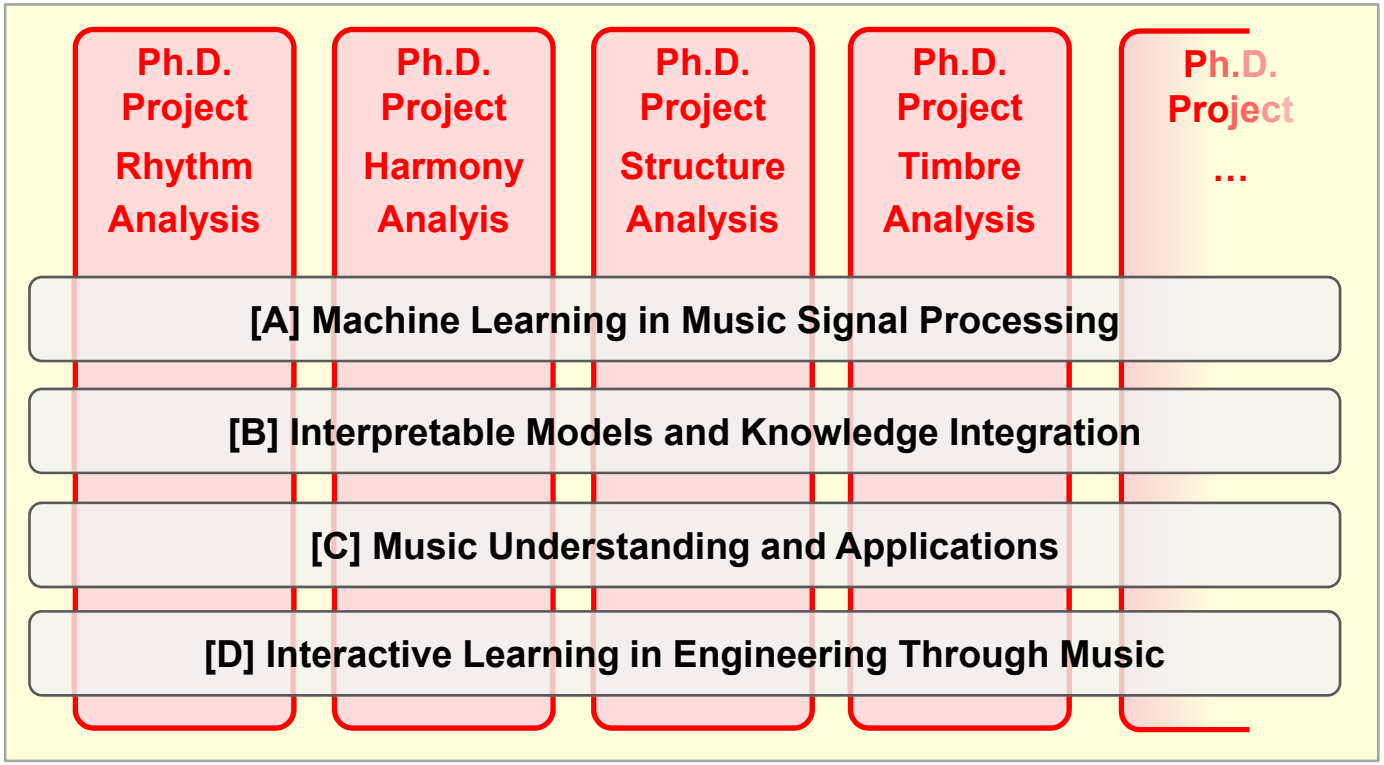

References

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  https://joss.theoj.org/papers/10.21105/joss.03326

- Meinard Müller: An Educational Guide Through the FMP Notebooks for Teaching and Learning Fundamentals of Music Processing. Signals, 2(2): 245–285, 2021.
  https://www.mdpi.com/2624-6120/2/2/18

- Meinard Müller and Frank Zalkow: FMP Notebooks: Educational Material for Teaching and Learning Fundamentals of Music Processing. Proc. International Society for Music Information Retrieval Conference (ISMIR): 573–580, 2019.
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- Meinard Müller, Brian McFee, and Katherine Kinnaird: Interactive Learning of Signal Processing Through Music: Making Fourier Analysis Concrete for Students. IEEE Signal Processing Magazine, 38(3): 73–84, 2021.
  https://ieeexplore.ieee.org/document/9418542

Resources (Group Meinard Müller)

- FMP Notebooks:
  https://www.audiolabs-erlangen.de/FMP
- libfmp:
  https://github.com/meinardmueller/libfmp
- synctoolbox:
  https://github.com/meinardmueller/synctoolbox
- libtsm:
  https://github.com/meinardmueller/libtsm
- Preparation Course Python (PCP) Notebooks:
  https://www.audiolabs-erlangen.de/resources/MIR/PCP/PCP.html
  https://github.com/meinardmueller/PCP