INTERNATIONAL AUDIO LABORATORIES ERLANGEN
A joint institution of Fraunhofer IIS and Universität Erlangen-Nürnberg

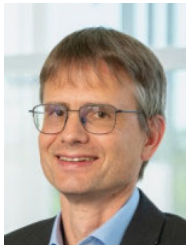
Automatische Erschließung von Musikdaten

Meinard Müller

International Audio Laboratories Erlangen

meinard.mueller@audiolabs-erlangen.de

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

universitätbonn

max planck institut informatik

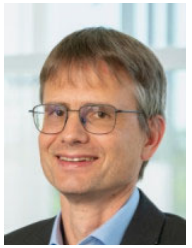
FAU

ISMIR

IEEE

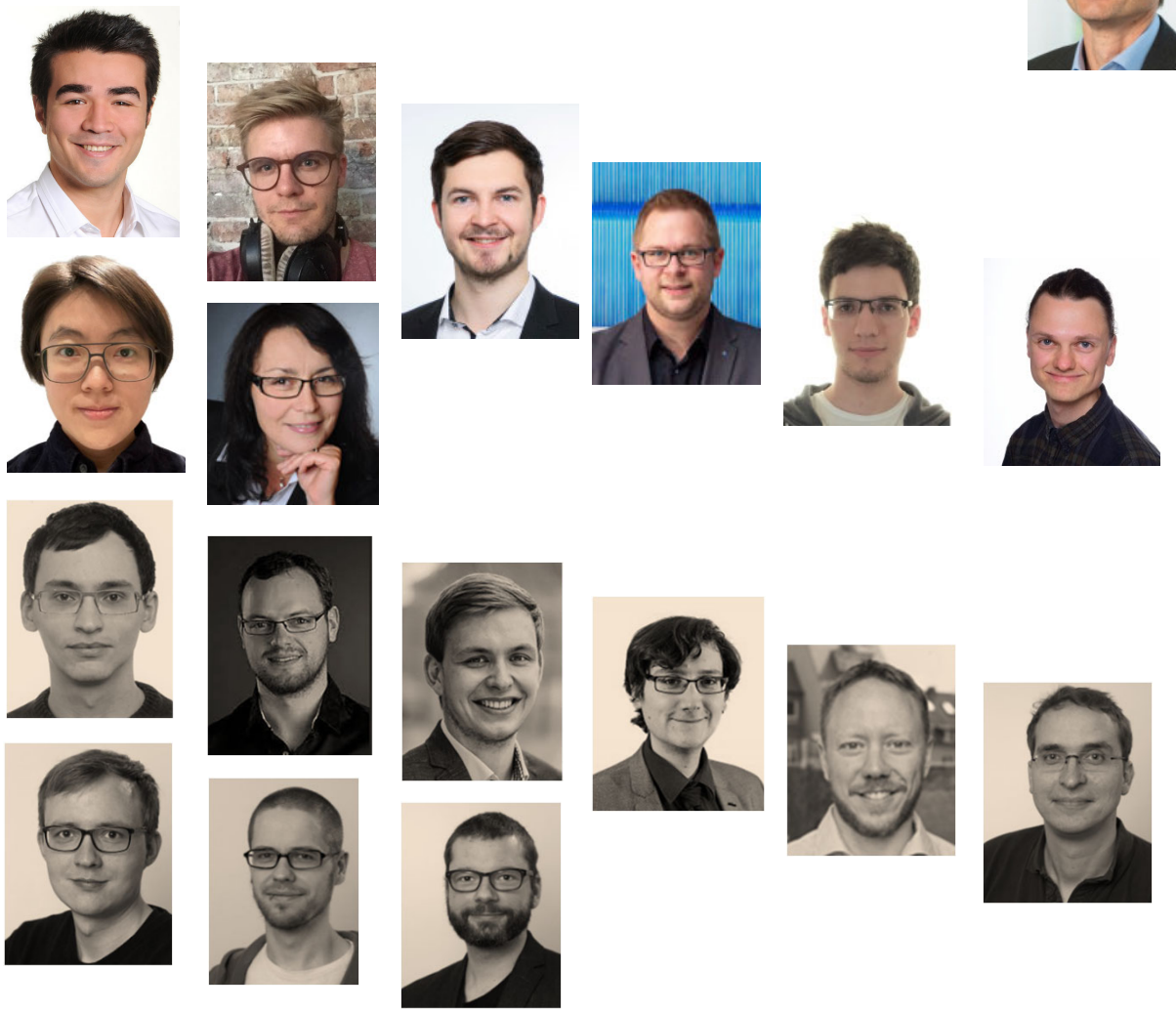
AUDIO LABS

Meinard Müller: Research Group
Semantic Audio Processing



- Yigitcan Özer
- Simon Schwär
- Johannes Zeitler
- Peter Meier
- Sebastian Strahl
- Uli Berendes
- Chiu Ching/Sunny
- Vlora Arifi-Müller

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



International Audio Laboratories Erlangen

Fraunhofer IIS

- Fraunhofer Institute for Integrated Circuits IIS
- Largest Fraunhofer institute with ≈ 1000 members
- Applied research for sensor, audio, and media technology

AUDIO LABS

Friedrich-Alexander-Universität Erlangen-Nürnberg

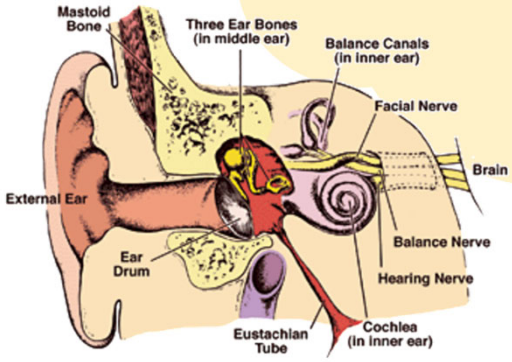
- Friedrich-Alexander Universität Erlangen-Nürnberg (FAU)
- One of Germany's largest universities with ≈ 40,000 students
- Strong Technical Faculty

International Audio Laboratories Erlangen

Audio Coding

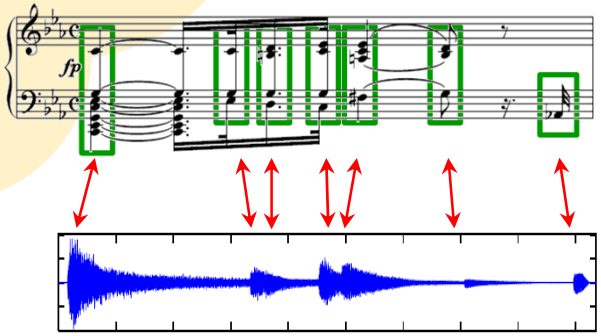
3D Audio

Audio



Psychoacoustics

Internet of Things

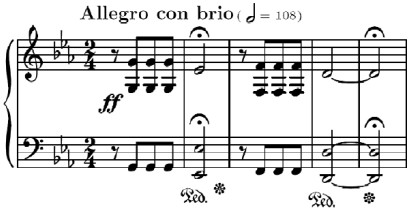


Music Processing

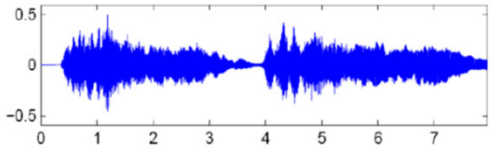
Music

Music Information Retrieval (MIR)

Sheet Music (Image)



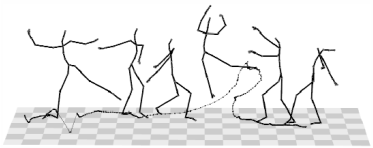
CD / MP3 (Audio)



MusicXML (Text)

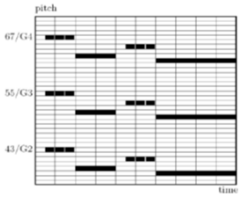
```
<note>
  <pitch>
    <step>E</step>
    <alter>-1</alter>
    <octave>4</octave>
  </pitch>
  <duration>2</duration>
  <type>half</type>
</note>
```

Dance / Motion (Mocap)



Music

MIDI

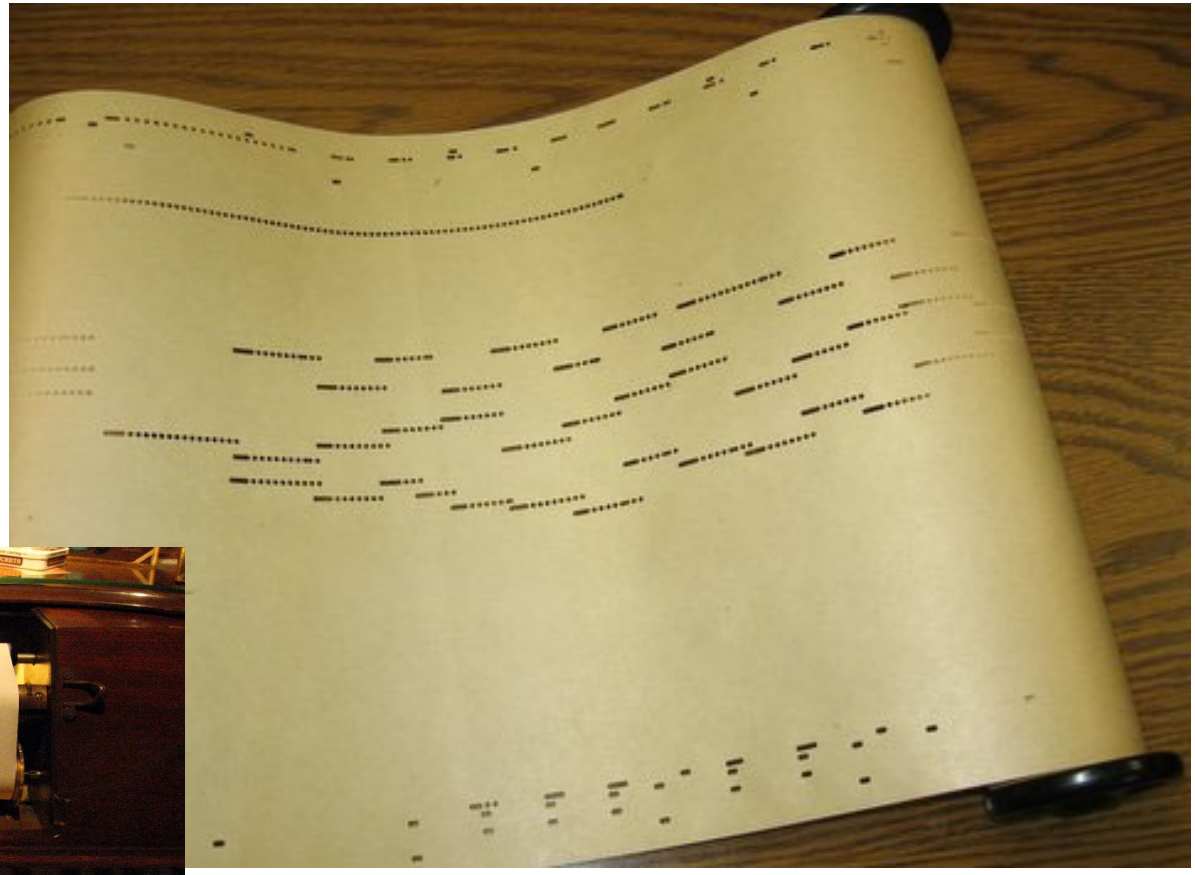


Singing / Voice (Audio)

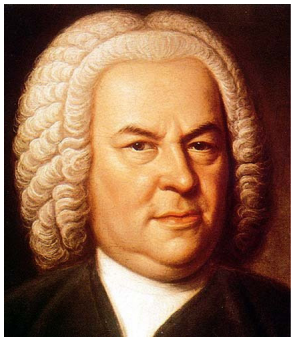
Music Film (Video)

Music Literature (Text)

Piano Roll Representation (1900)

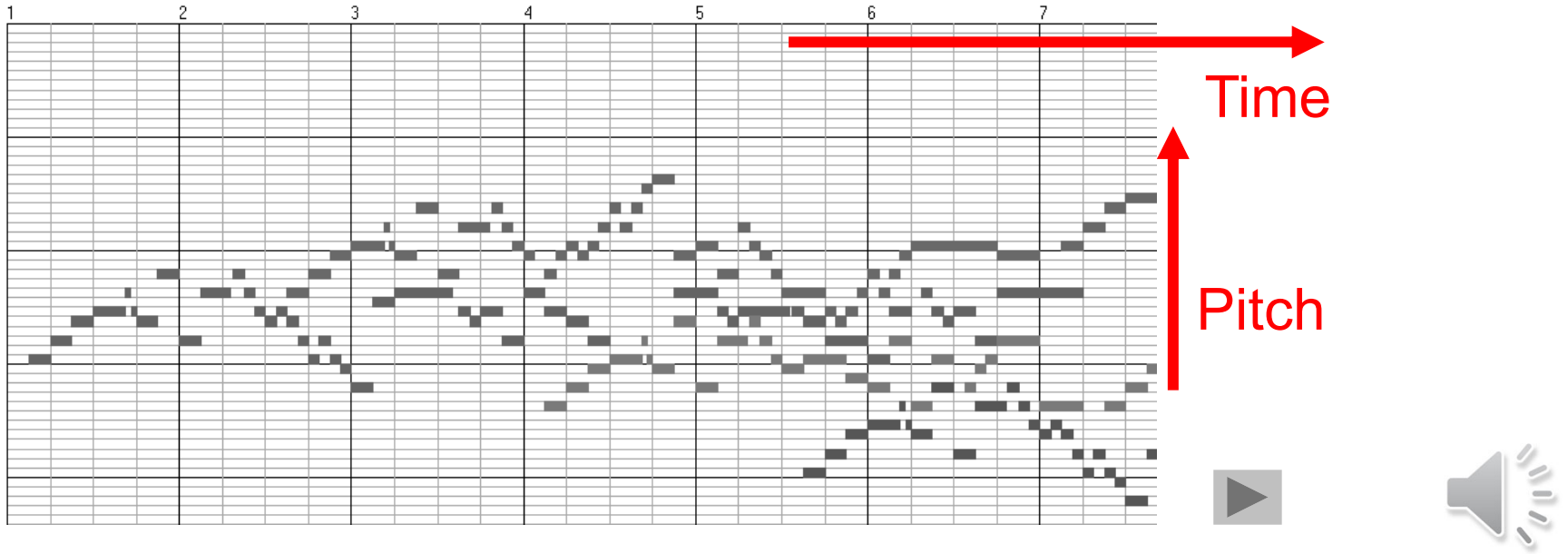


Piano Roll Representation

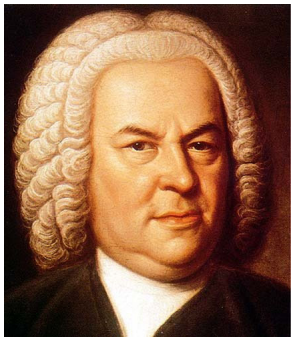


J.S. Bach, C-Major Fuge

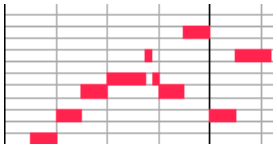
(Well Tempered Piano, BWV 846)



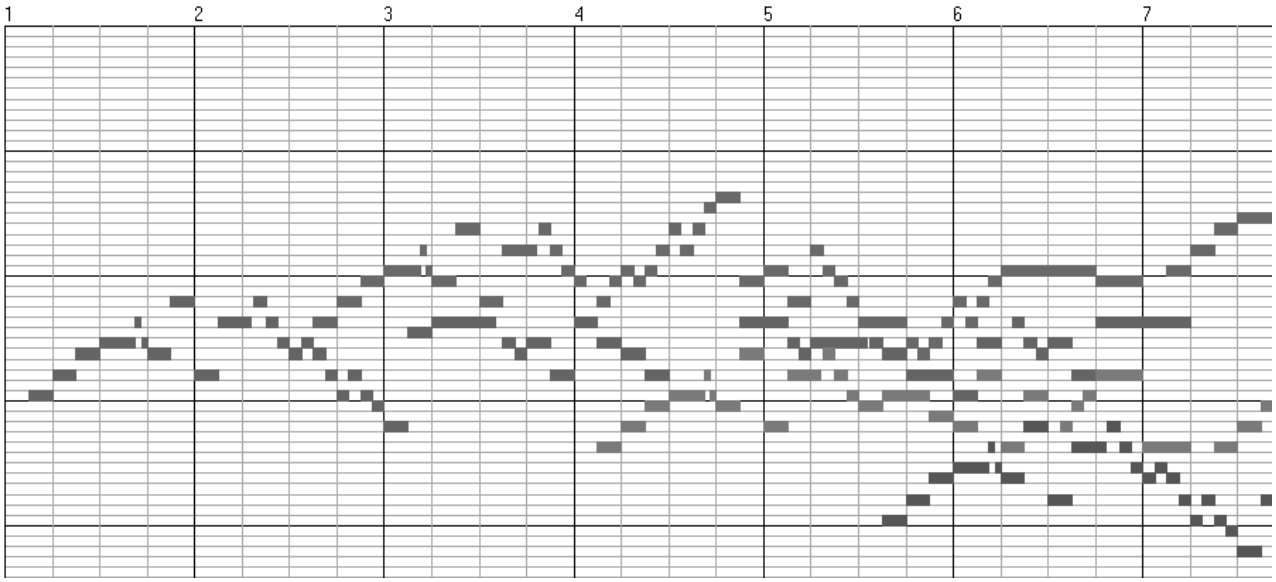
Piano Roll Representation



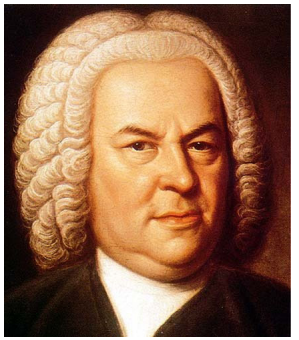
Query:



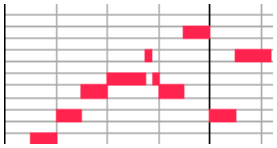
Goal: Find all occurrences of the query



Piano Roll Representation

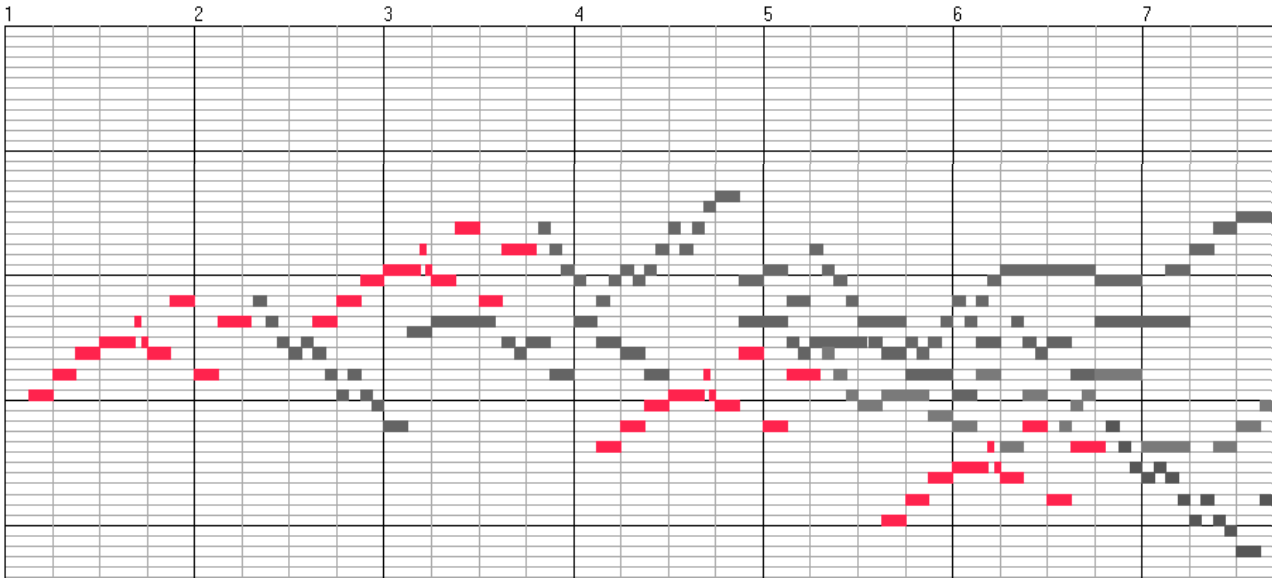


Query:

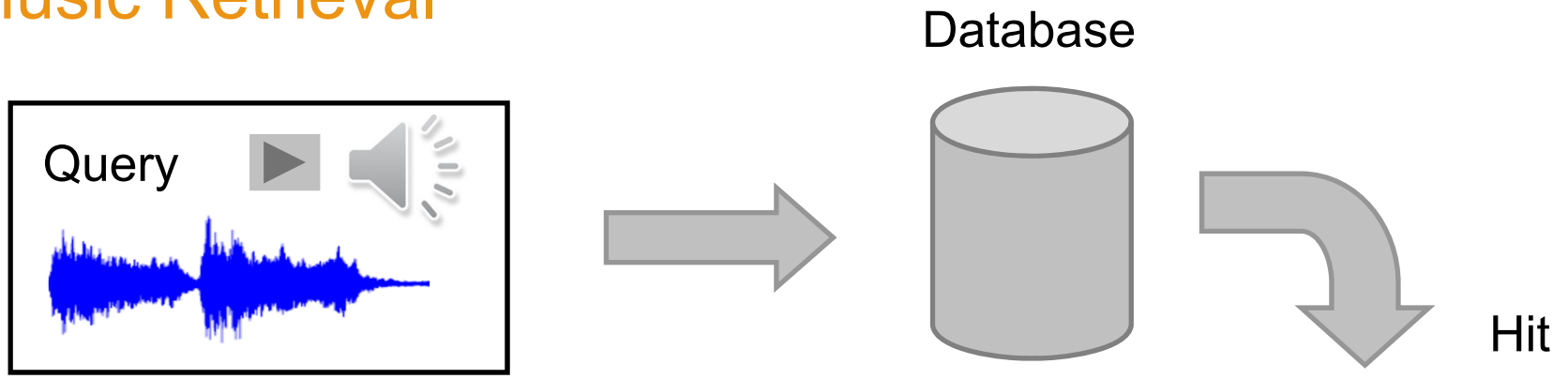


Goal: Find all occurrences of the query

Matches:



Music Retrieval



Audio ID

Bernstein (1962)
Beethoven, Symphony No. 5

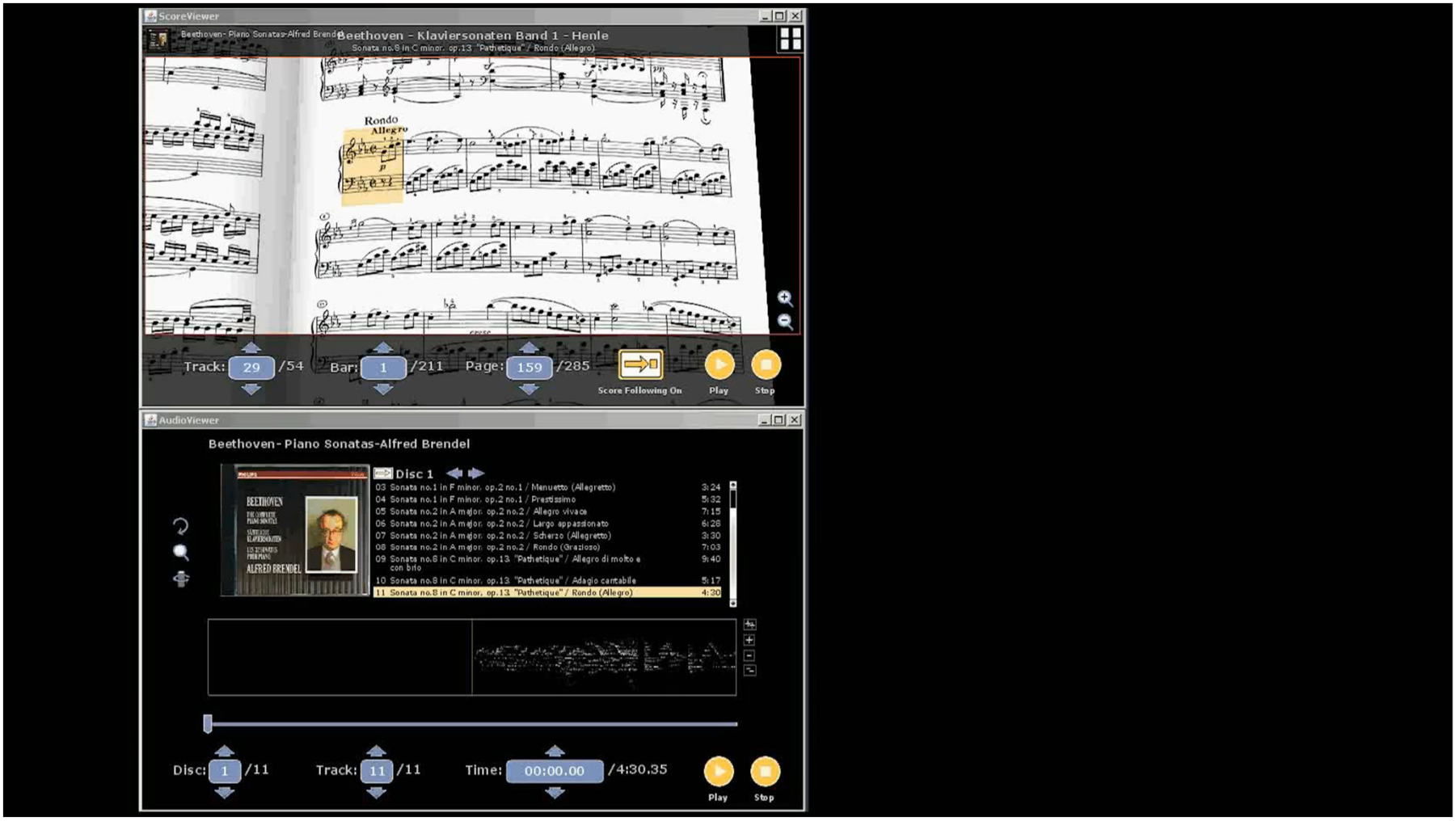
Version ID

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

Category ID

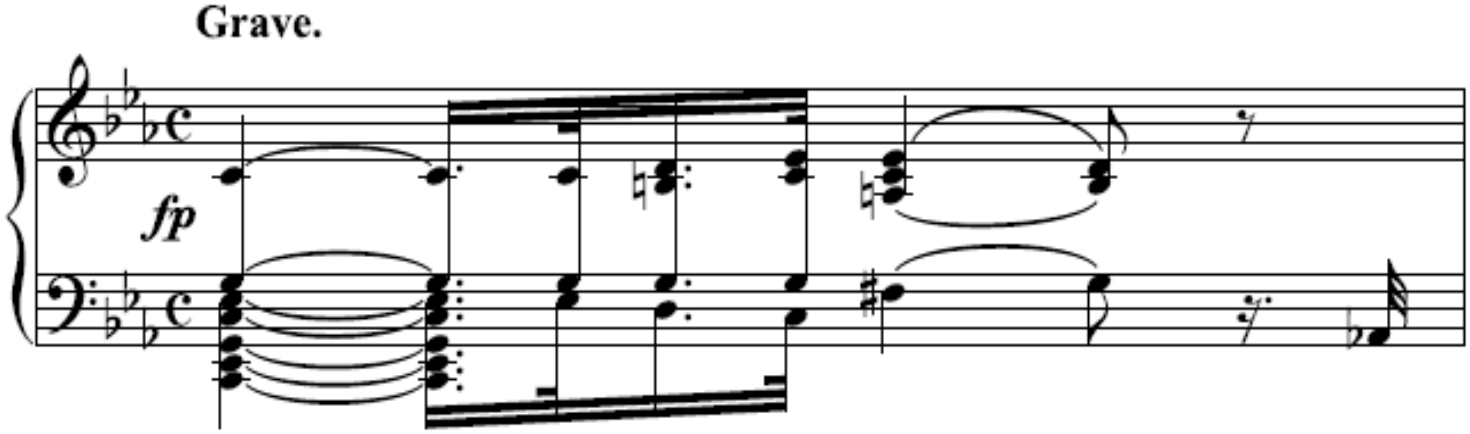
- Beethoven, Symphony No. 9
- Beethoven, Symphony No. 3
- Haydn Symphony No. 94

Music Synchronization

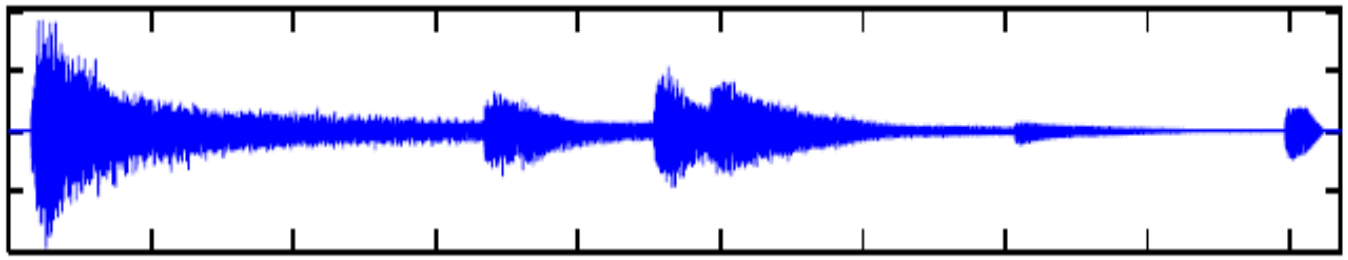


Music Synchronization: Image-Audio

Image



Audio

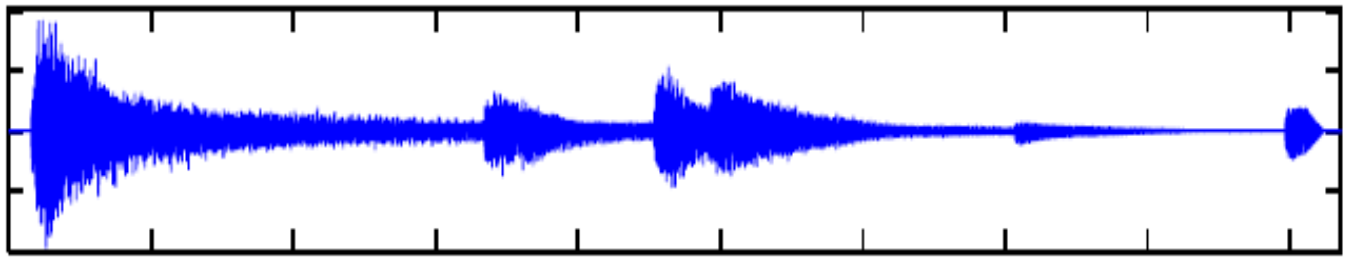


Music Synchronization: Image-Audio

Image Processing: Optical Music Recognition

Image

Audio



Music Synchronization: Image-Audio

Image Processing: Optical Music Recognition

Image

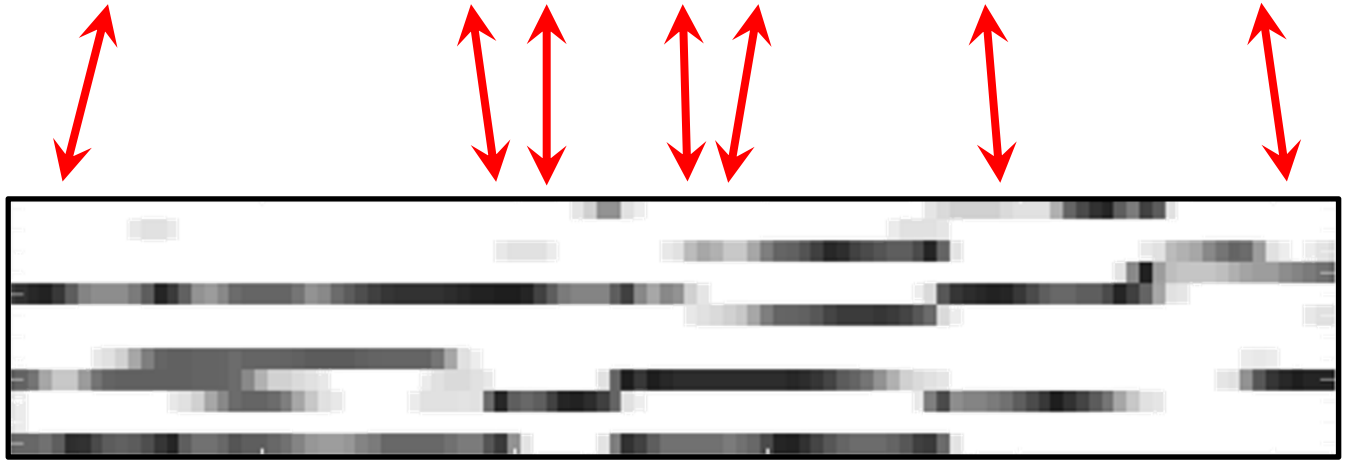
Audio

Audio Processing: Fourier Analysis

Music Synchronization: Image-Audio

Image Processing: Optical Music Recognition

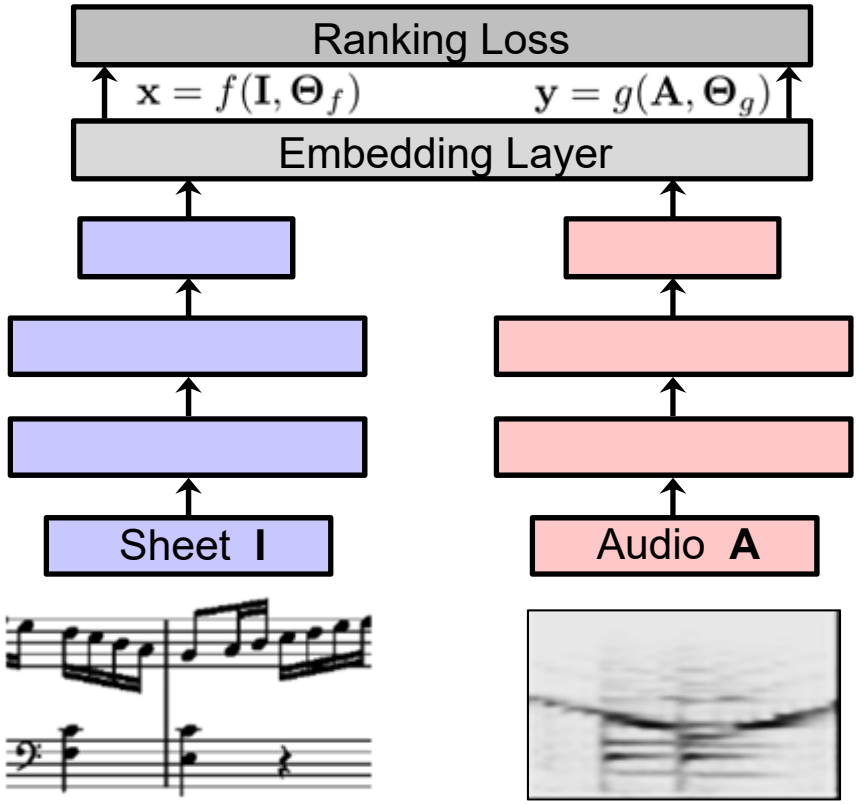
Image



Audio

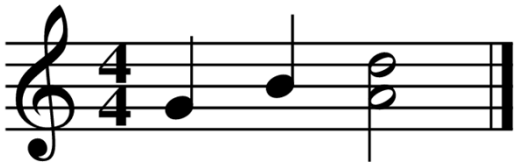
Audio Processing: Fourier Analysis

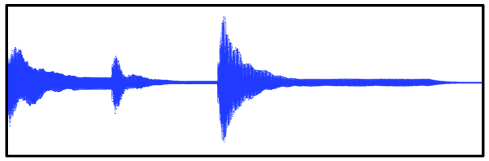
Music Synchronization: Image-Audio



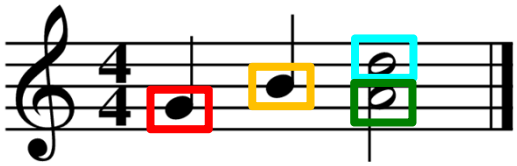
- Deep learning
- Embedding techniques
- Weak annotations
- Loss functions
- …

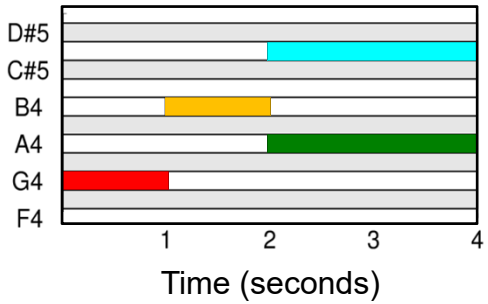
Score-Informed Audio Decomposition

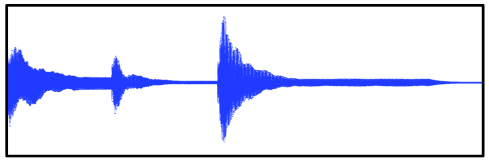




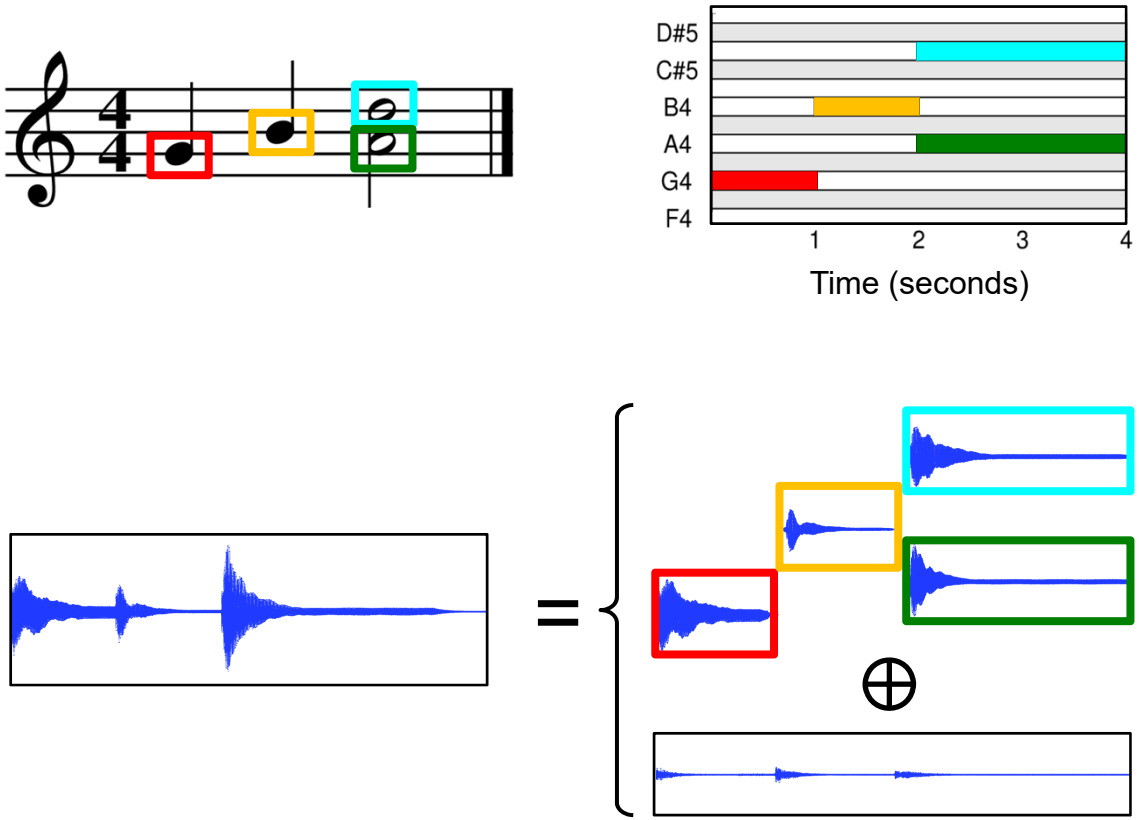
Score-Informed Audio Decomposition



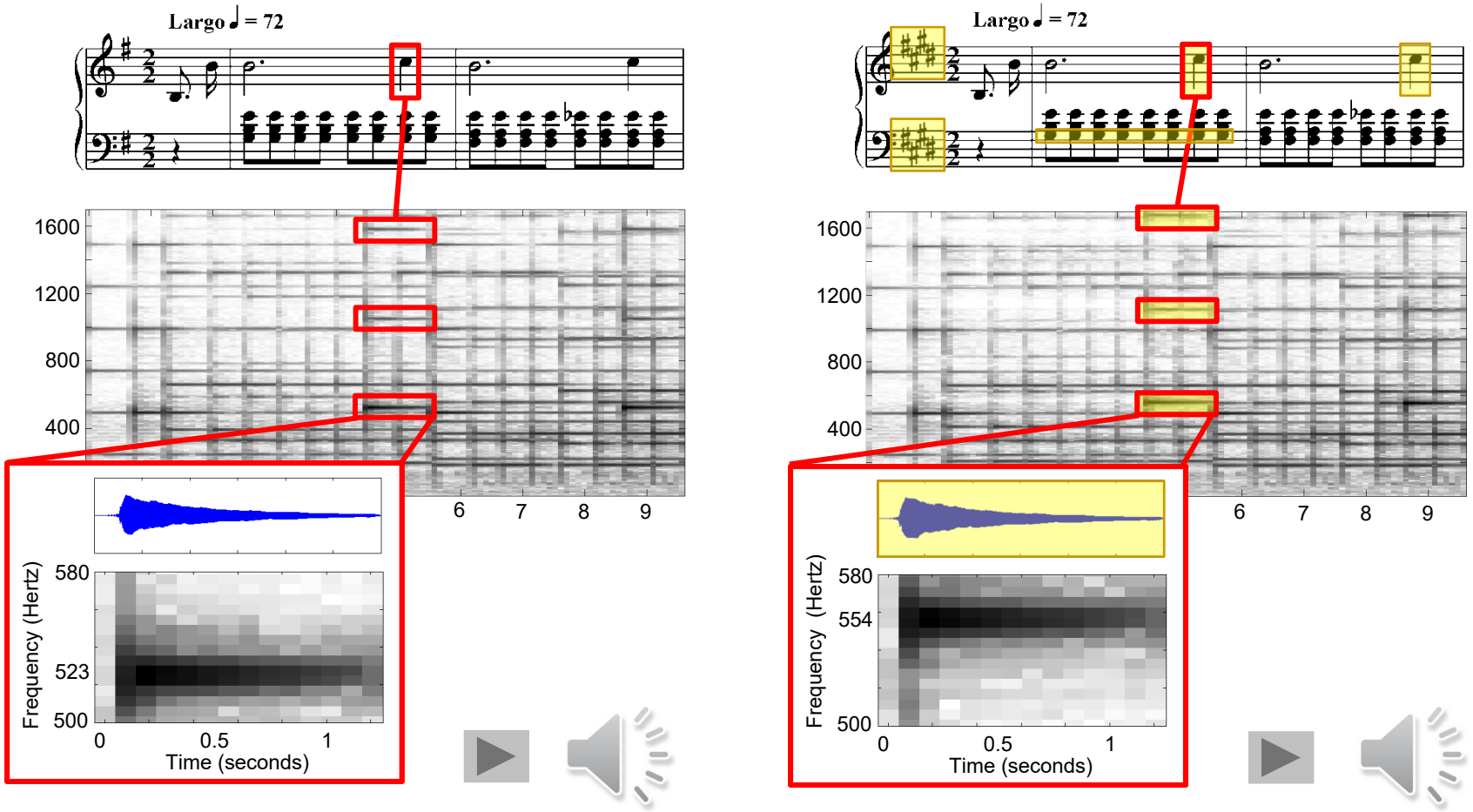




Score-Informed Audio Decomposition

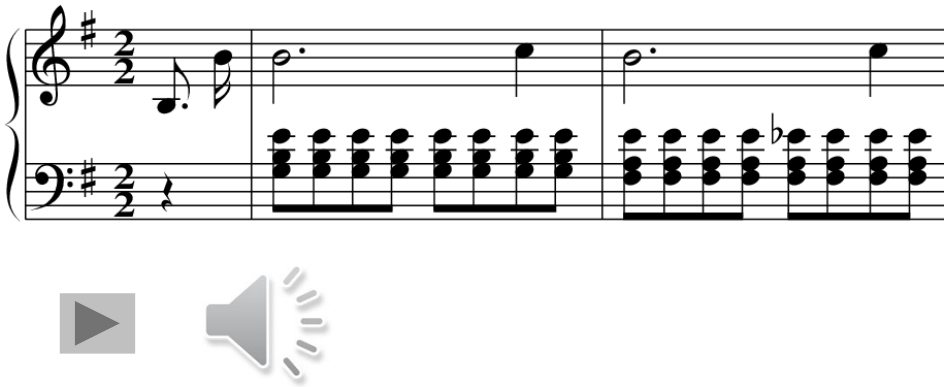


Score-Informed Audio Decomposition

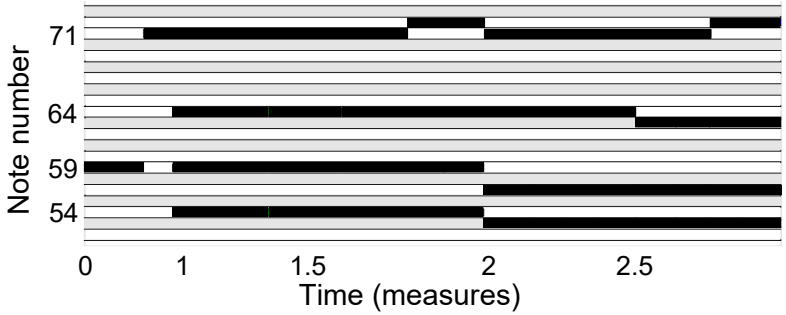


Score-Informed Audio Decomposition

Sheet music



Piano roll

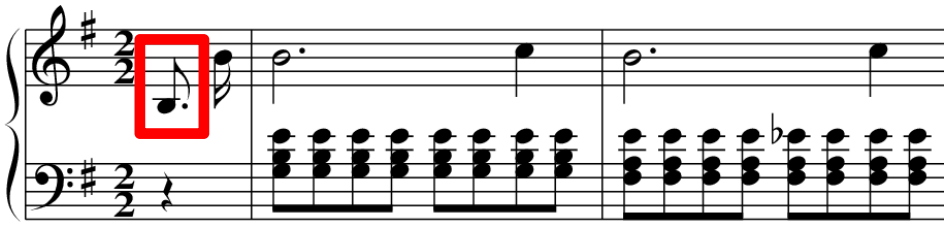


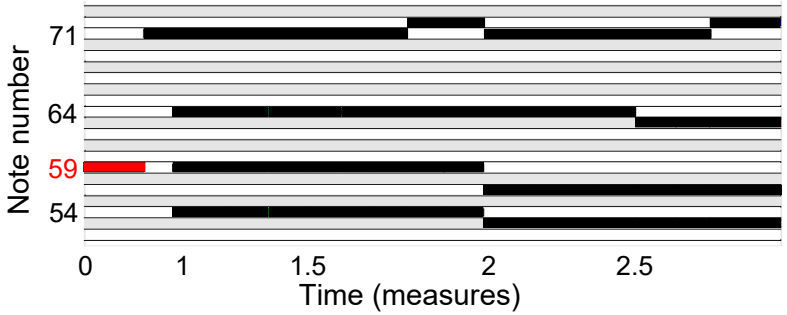
Score-Informed Audio Decomposition

Sheet music

$p = 59$

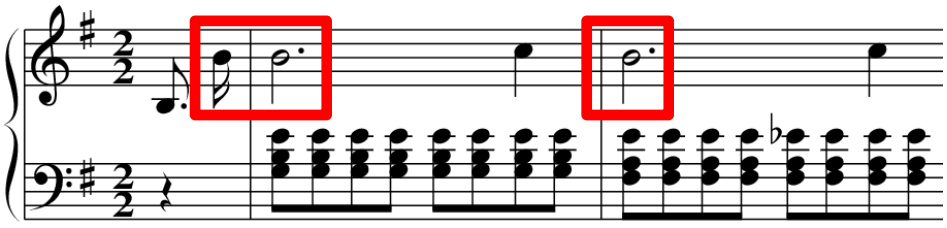
Piano roll





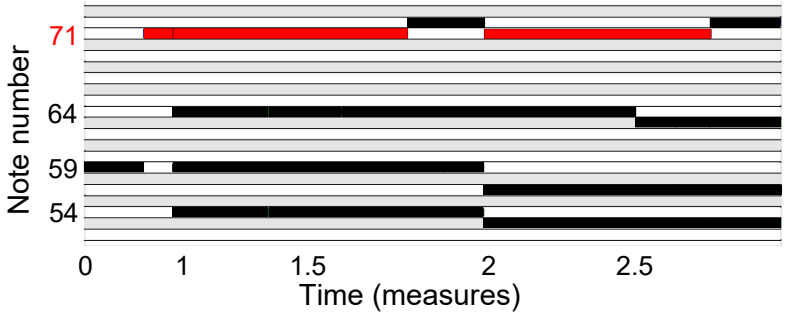
Score-Informed Audio Decomposition

Sheet music



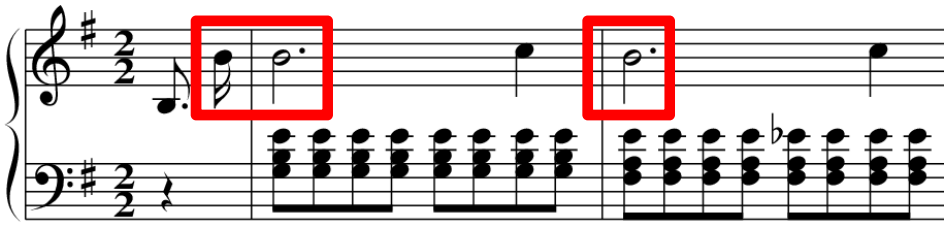
p = 71

Piano roll



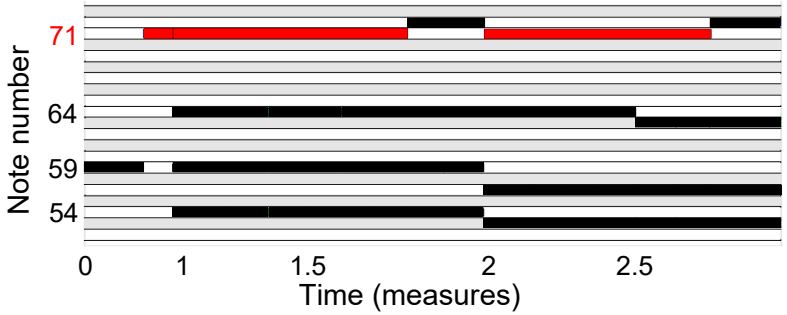
Score-Informed Audio Decomposition

Sheet music

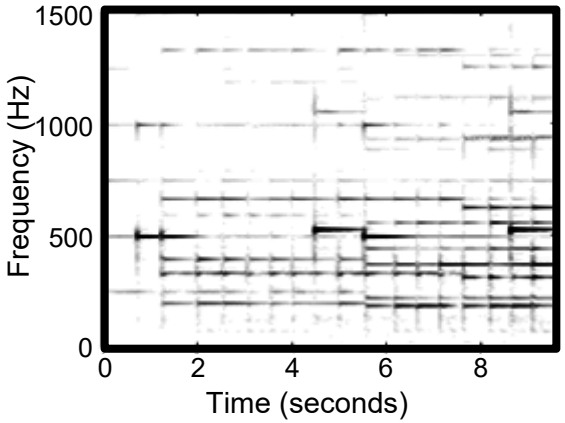


p = 71

Piano roll

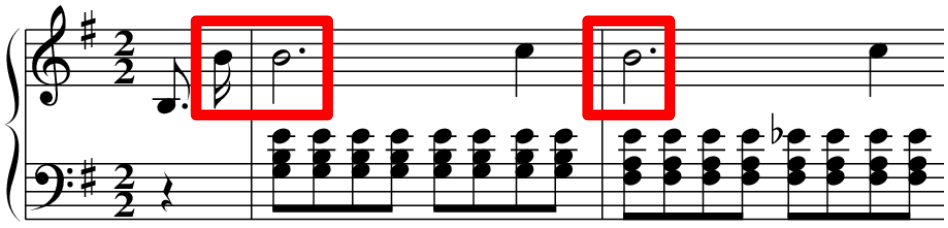


Spectrogram



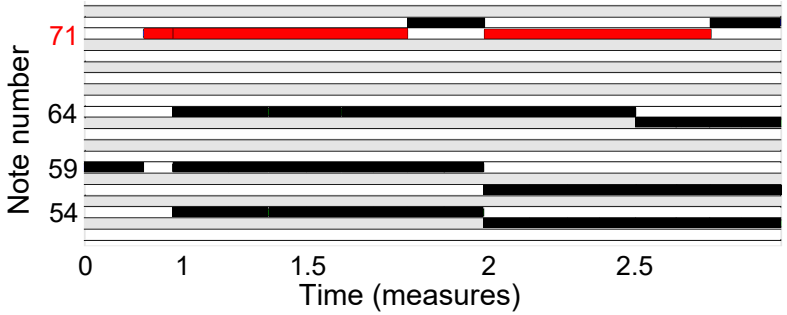
Score-Informed Audio Decomposition

Sheet music

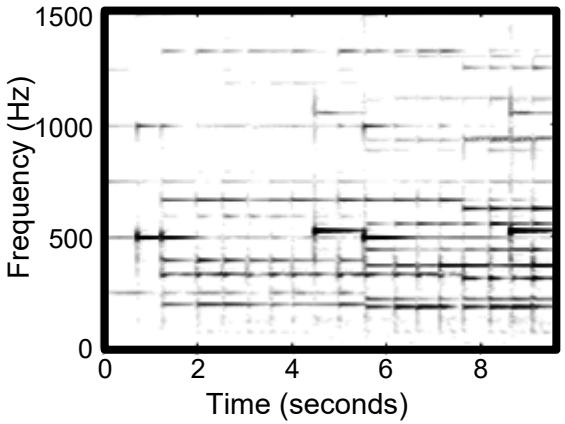


$p = 71$

Piano roll

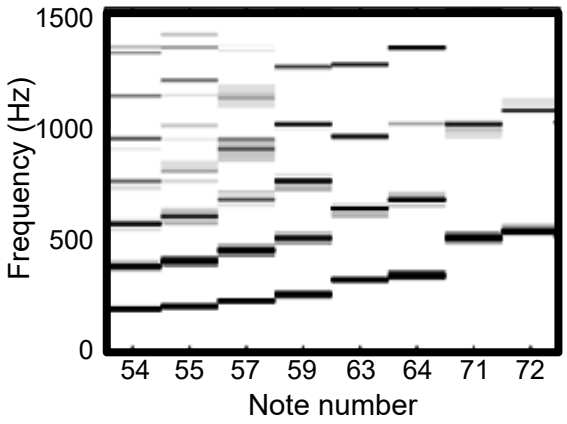


Spectrogram



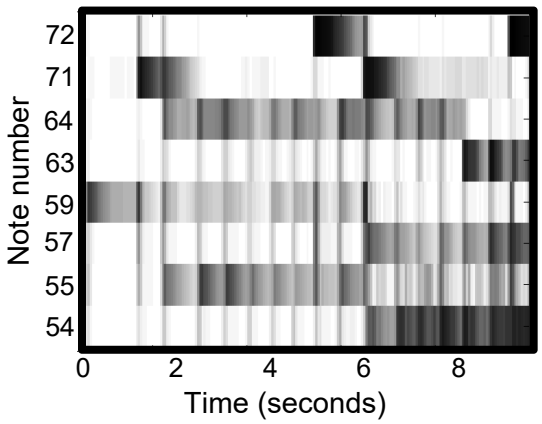
≈

Spectral patterns



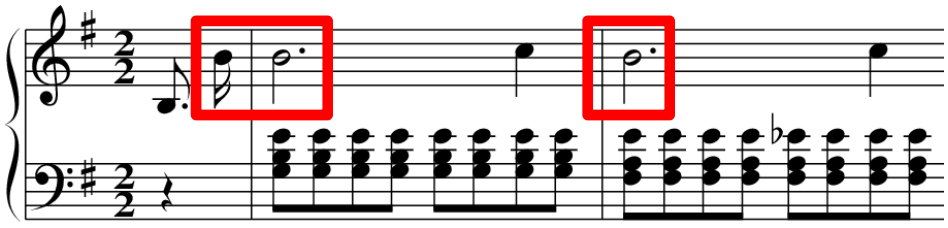
•

Activity patterns



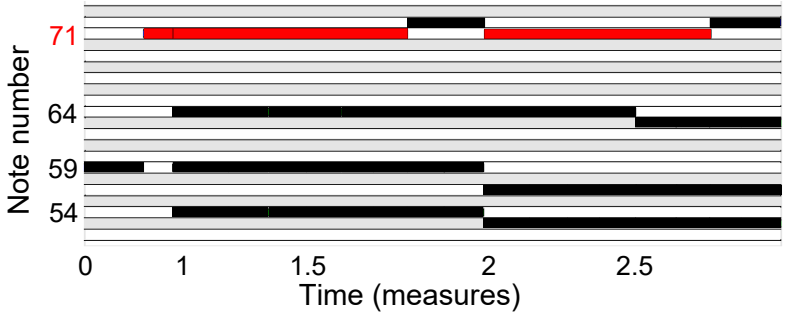
Score-Informed Audio Decomposition

Sheet music

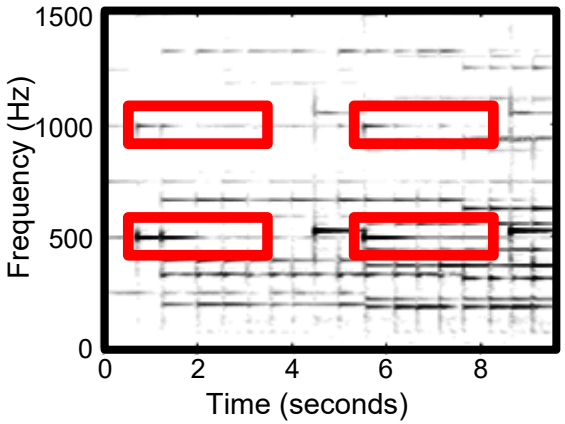


$p = 71$

Piano roll

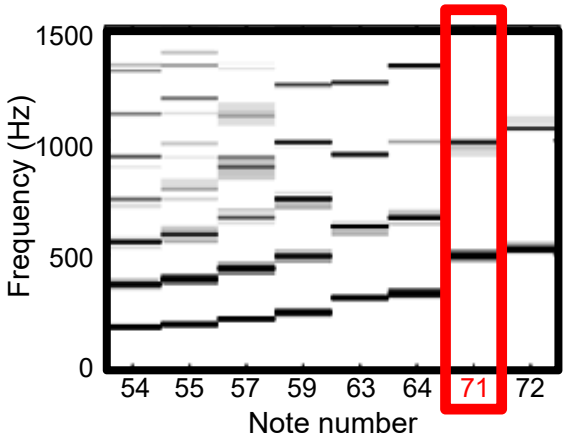


Spectrogram



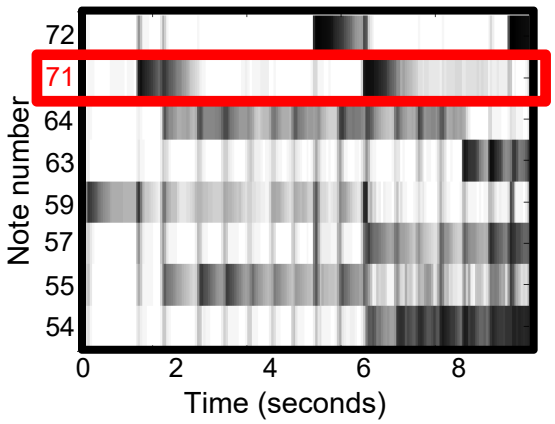
≈

Spectral patterns



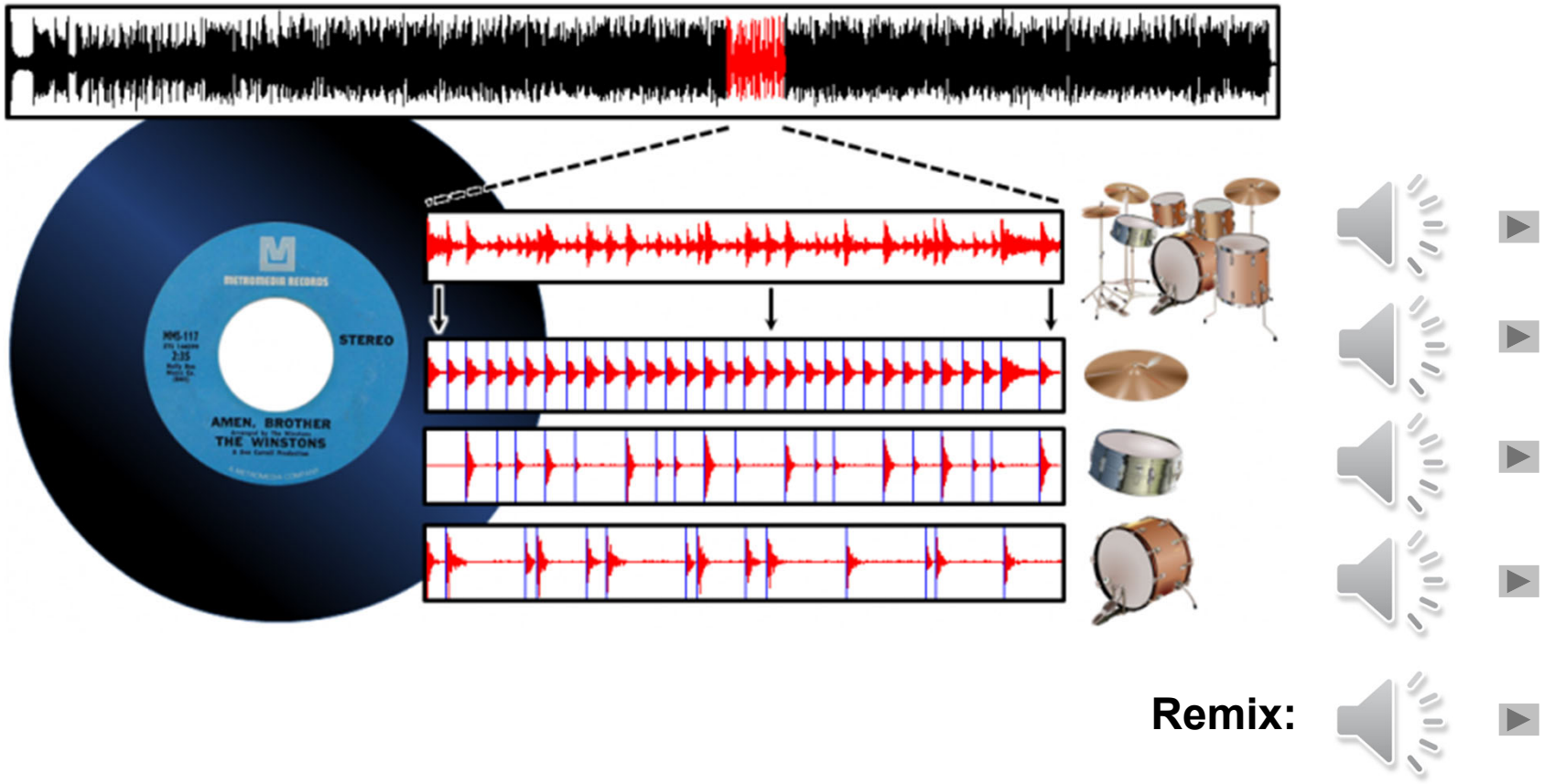
•

Activity patterns



Score-Informed Audio Decomposition

Informed Drum-Sound Decomposition

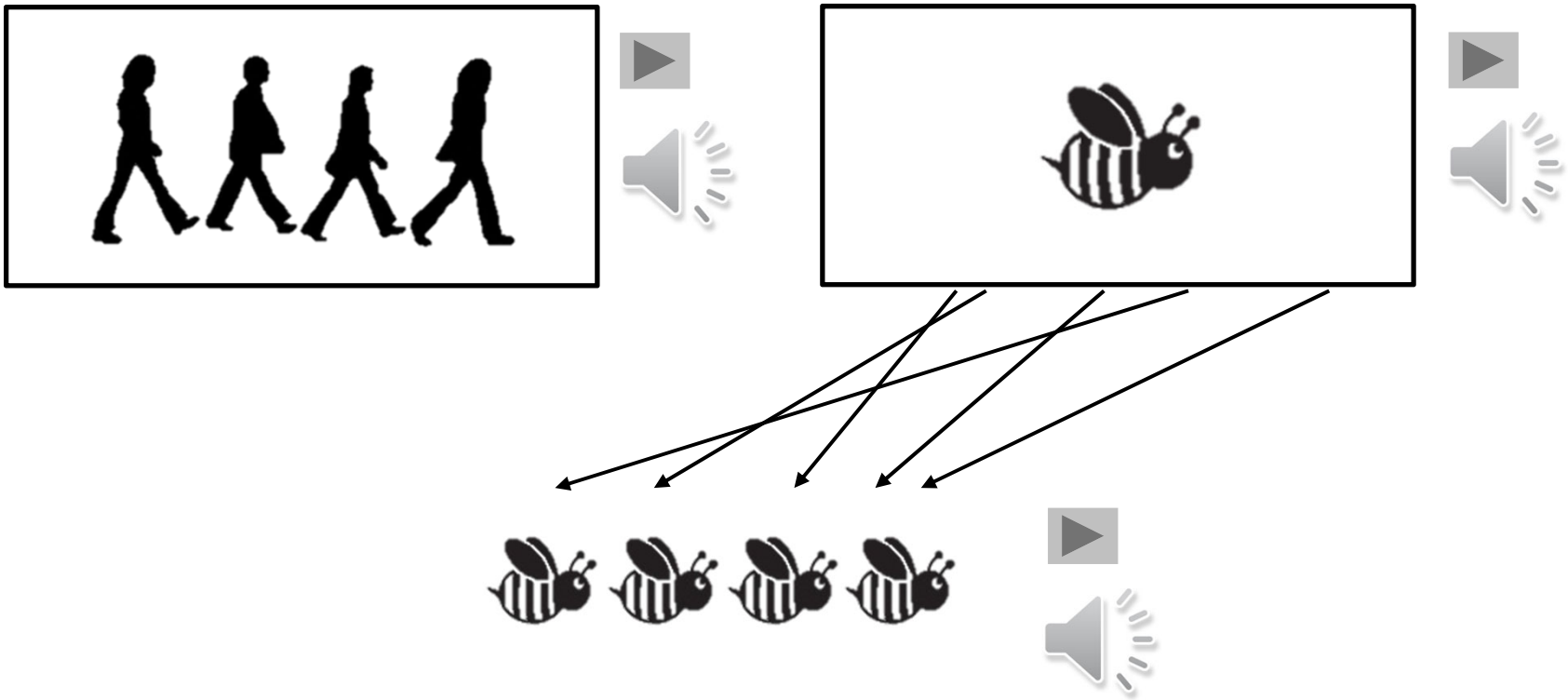


Score-Informed Audio Decomposition

Audio mosaicing (style transfer)

Target signal: Beatles–Let it be

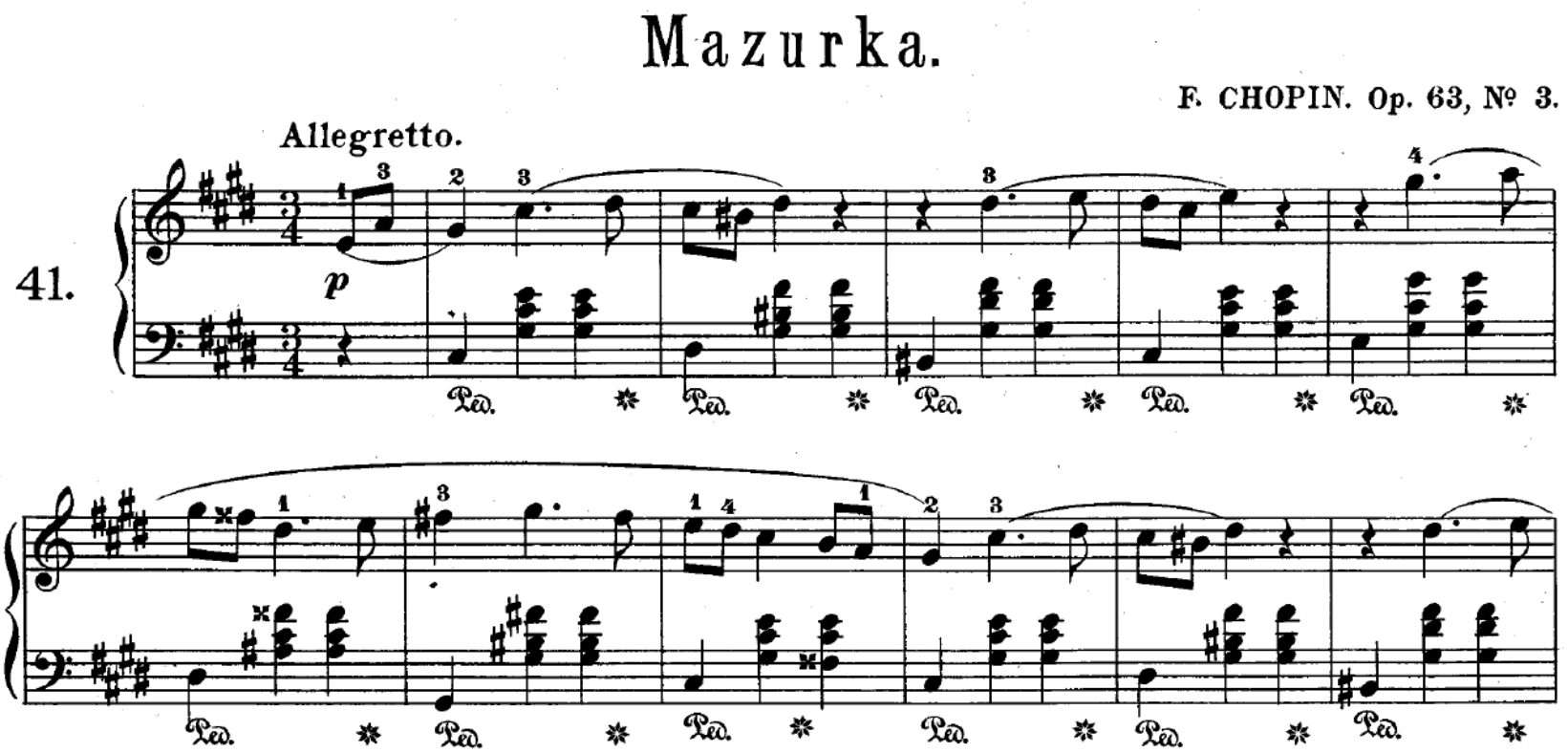
Source signal: Bees



Mosaic signal: Let it Bee

Why is Music Processing Challenging?

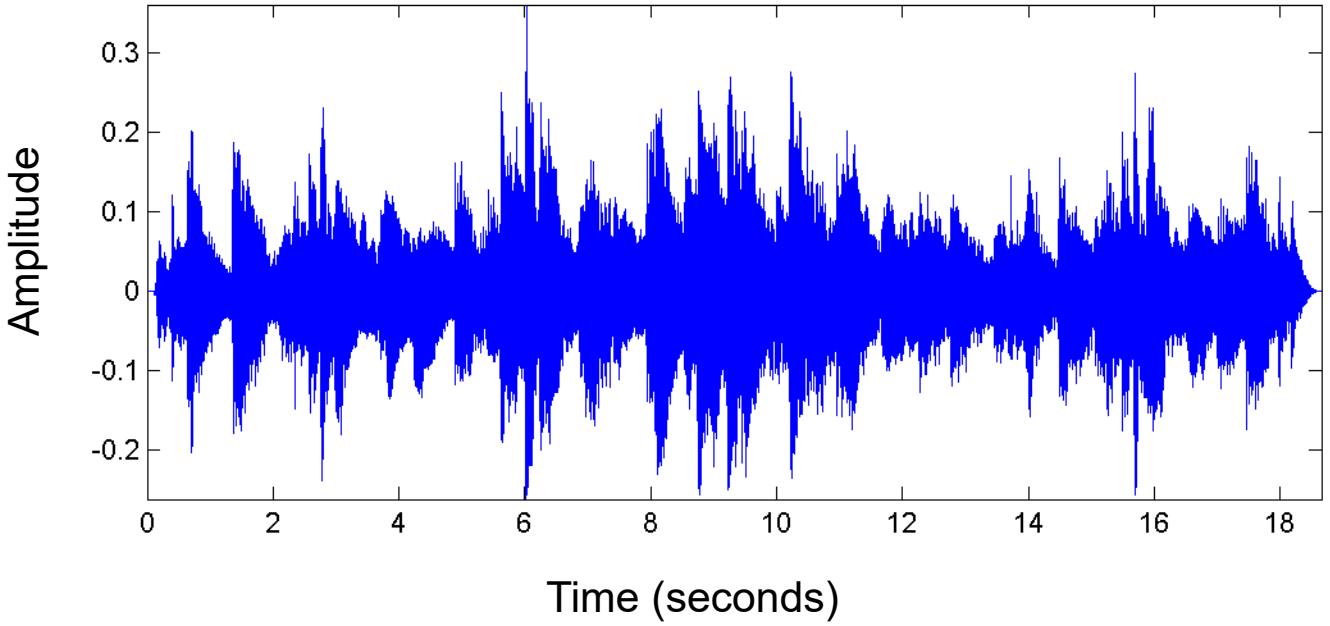
Example: Chopin, Mazurka Op. 63 No. 3



Why is Music Processing Challenging?

Example: Chopin, Mazurka Op. 63 No. 3

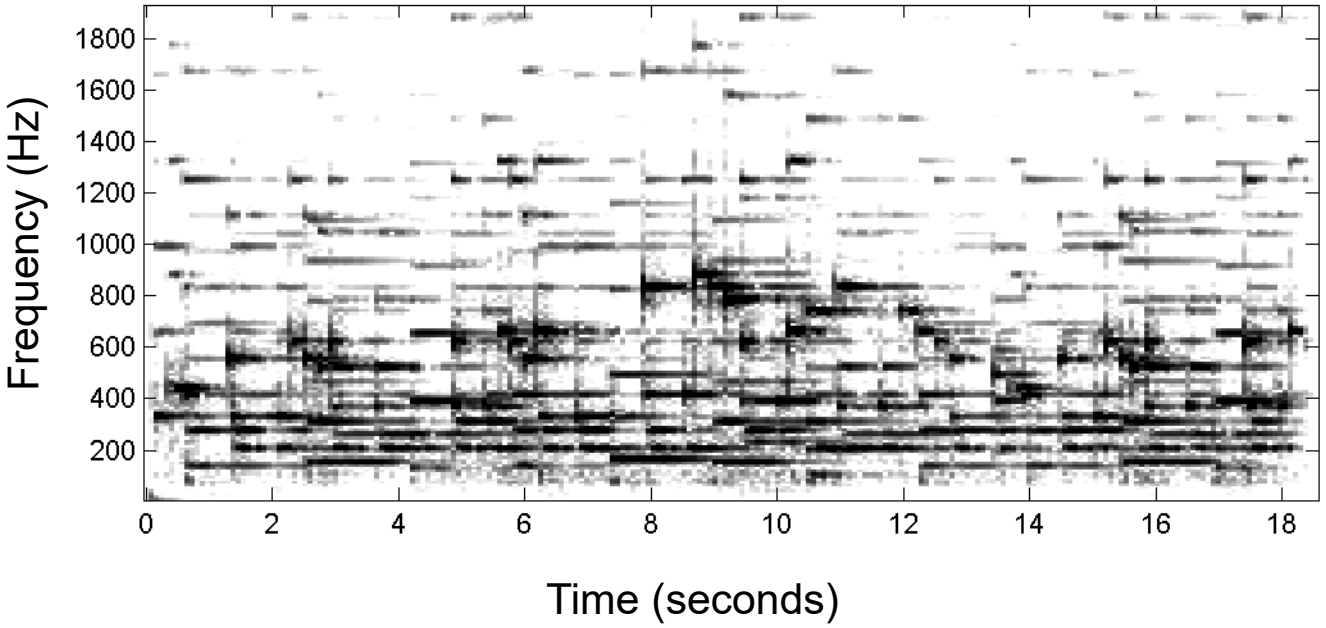
- Waveform



Why is Music Processing Challenging?

Example: Chopin, Mazurka Op. 63 No. 3

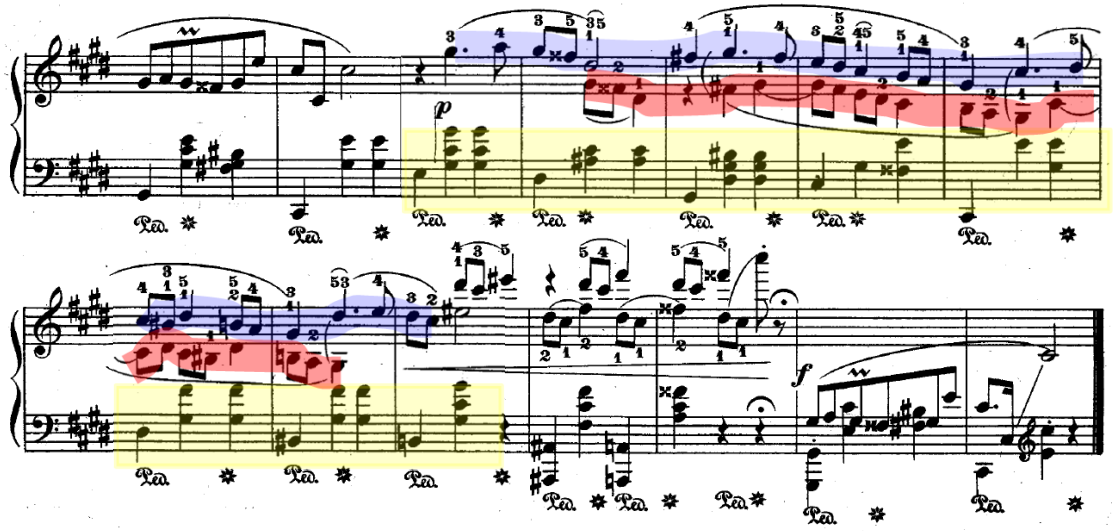
- Waveform / Spectrogram



Why is Music Processing Challenging?

Example: Chopin, Mazurka Op. 63 No. 3

- Waveform / Spectrogram
- Performance
  - Tempo
  - Dynamics
  - Note deviations
  - Sustain pedal
- Polyphony



Main Melody

Additional melody line

Accompaniment

Source Separation

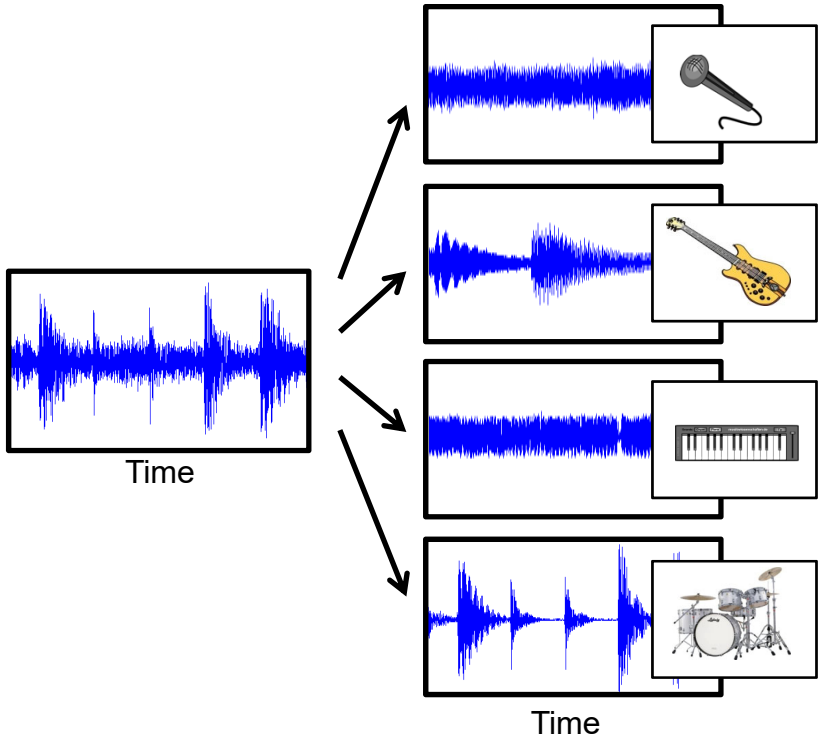
- Decomposition of audio stream into different sound sources
- Central task in digital signal processing
- “Cocktail party effect”

Source Separation

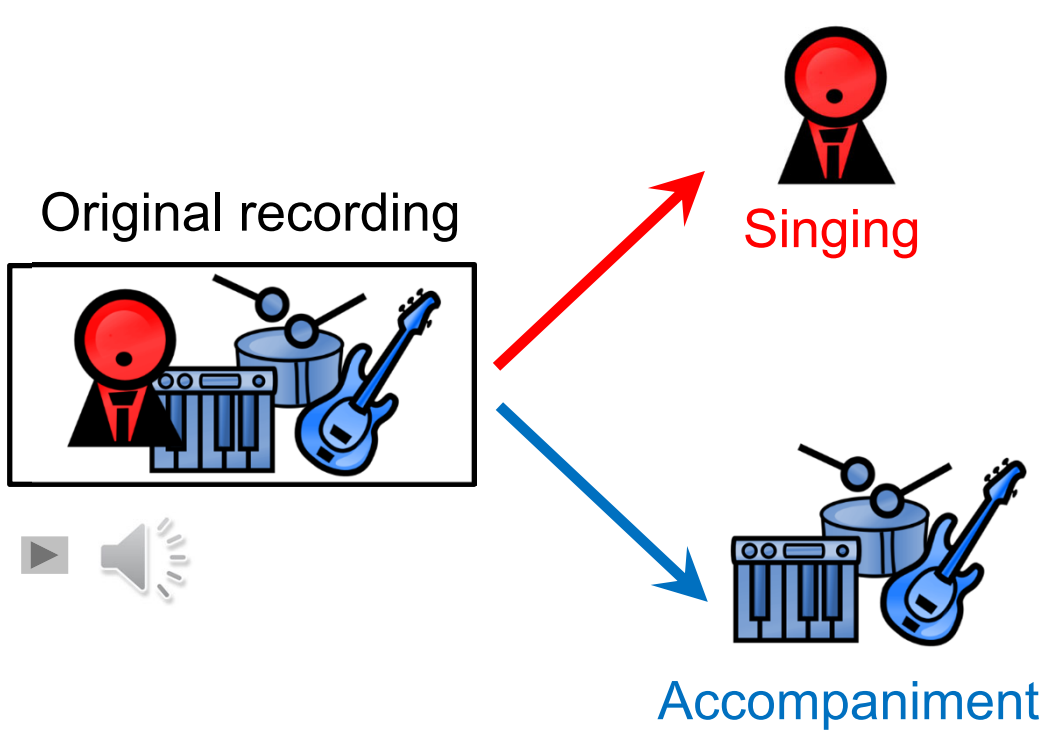
- Decomposition of audio stream into different sound sources
- Central task in digital signal processing
- “Cocktail party effect”
- Several input signals
- Sources are assumed to be statistically independent

Source Separation (Music)

- Main melody, accompaniment, drum track
- Instrumental voices
- Individual note events
- Only mono or stereo
- Sources are often highly dependent



AI-Based Source Separation



Reference
SP
AI

Reference
SP
AI

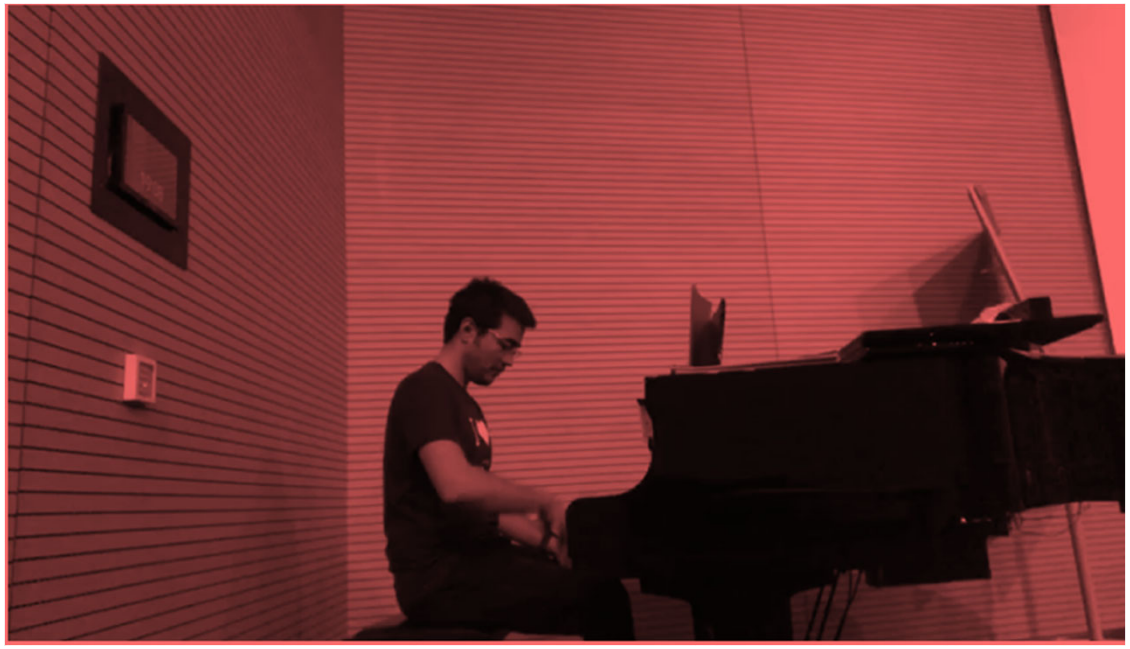
- Reference: Best possible result
- SP: Using traditional signal processing
- AI: Using data-driven approach

AI-Based Source Separation

- Yigitcan Özer
- PhD student in engineering
- Pianist

AI-Based Source Separation

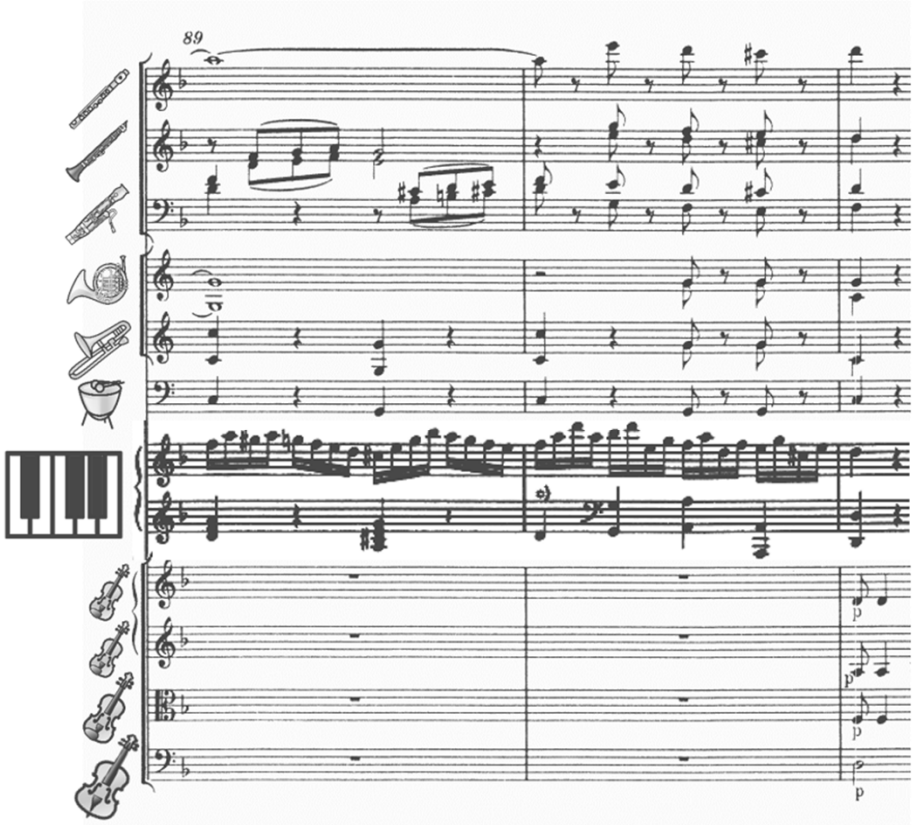
- Yigitcan Özer
- PhD student in engineering
- Pianist

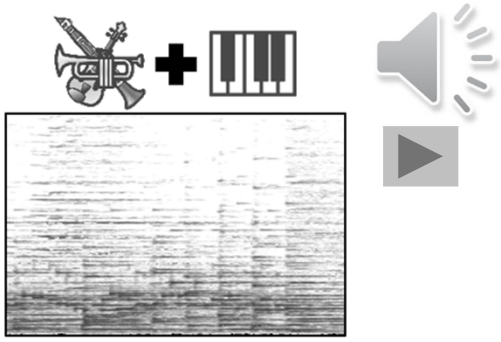


Only Piano!

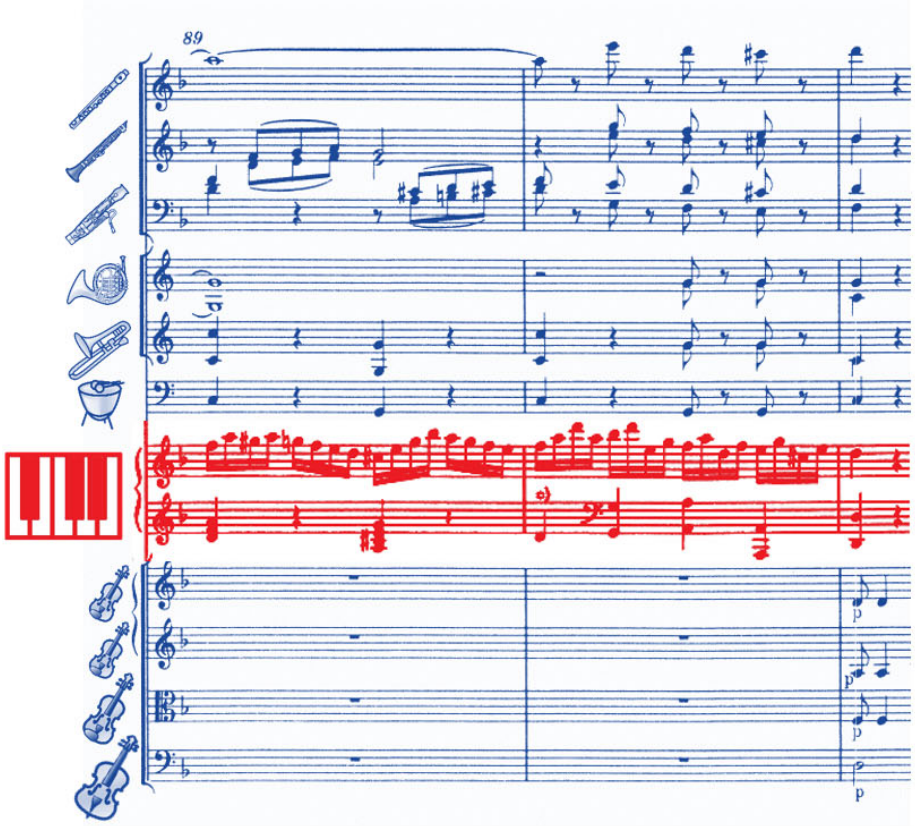
Where is the orchestra?

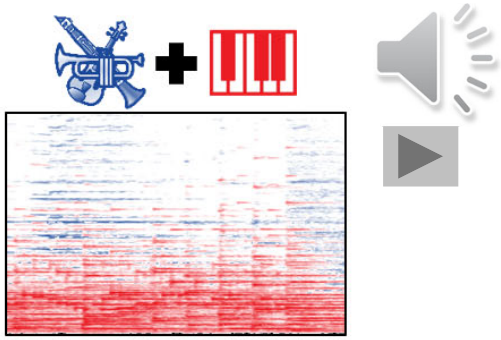
AI-Based Source Separation



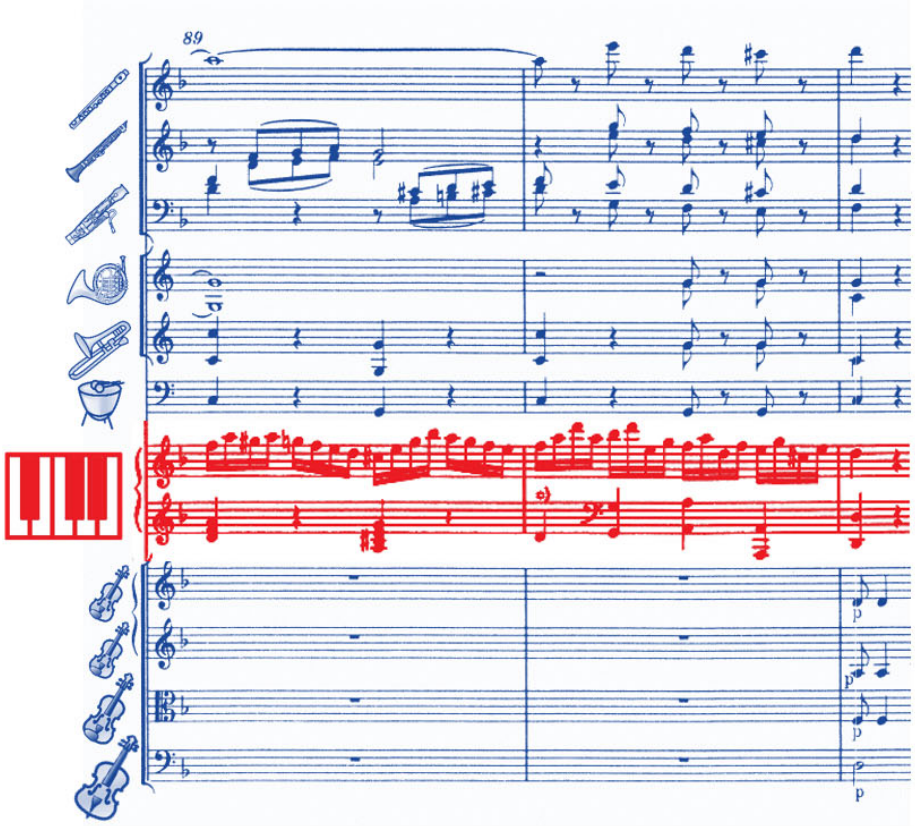


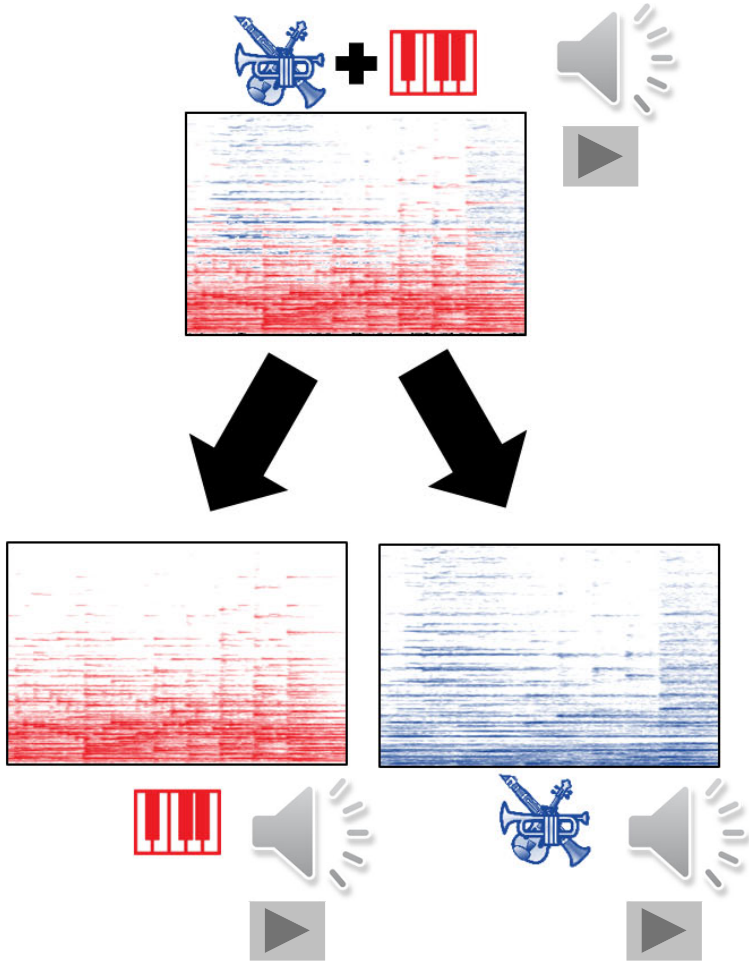
AI-Based Source Separation



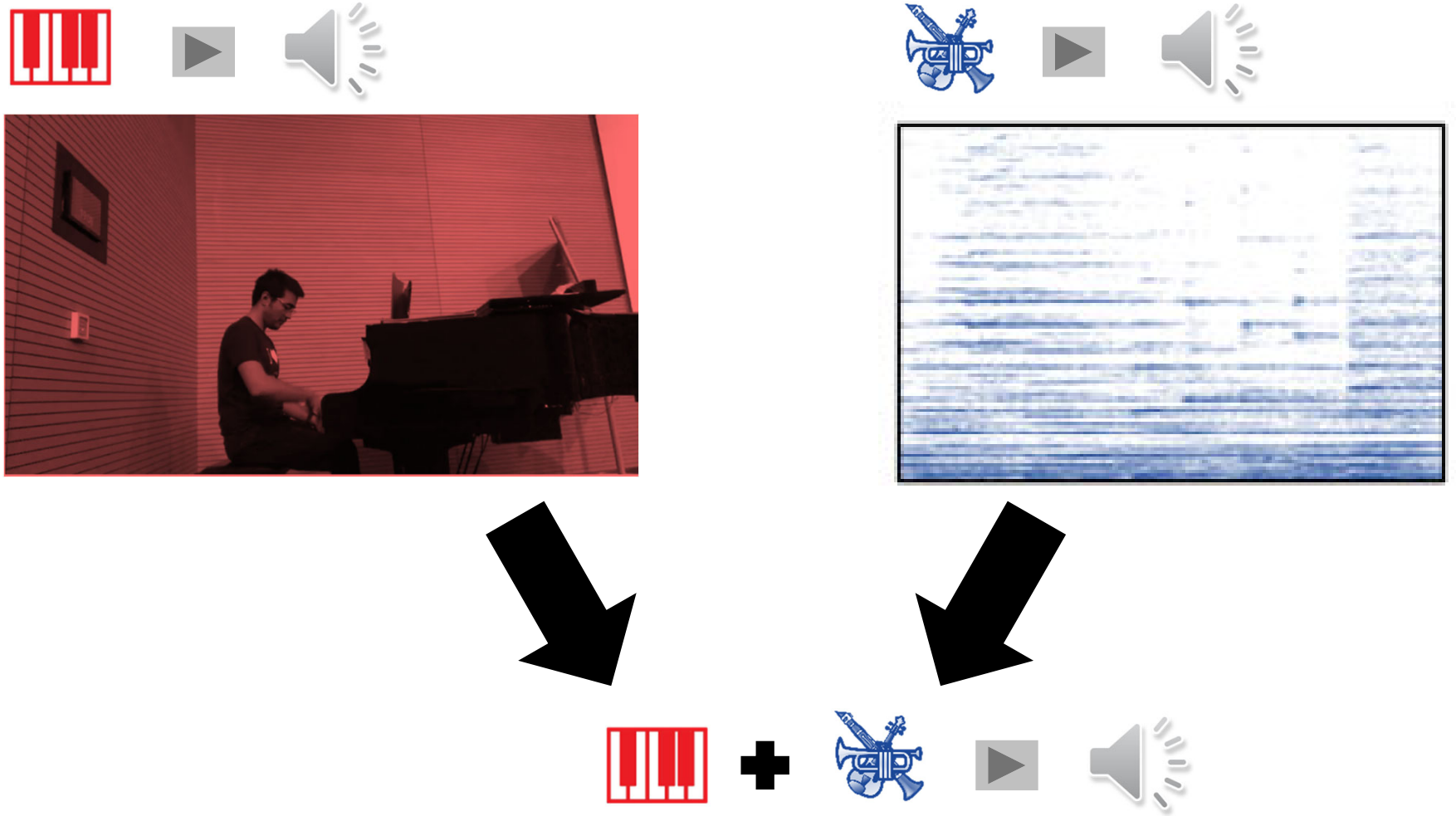


AI-Based Source Separation





AI-Based Source Separation



AI-Based Source Separation

- Understanding modern machine learning techniques
- Critical questioning of artificial intelligence (AI) concepts
- Developing explainable AI models
- Educating next generation of scientists
- …

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-
UNIVERSITÄT
WÜRZBURG

UNIVERSITÄT
DES
SAARLANDES

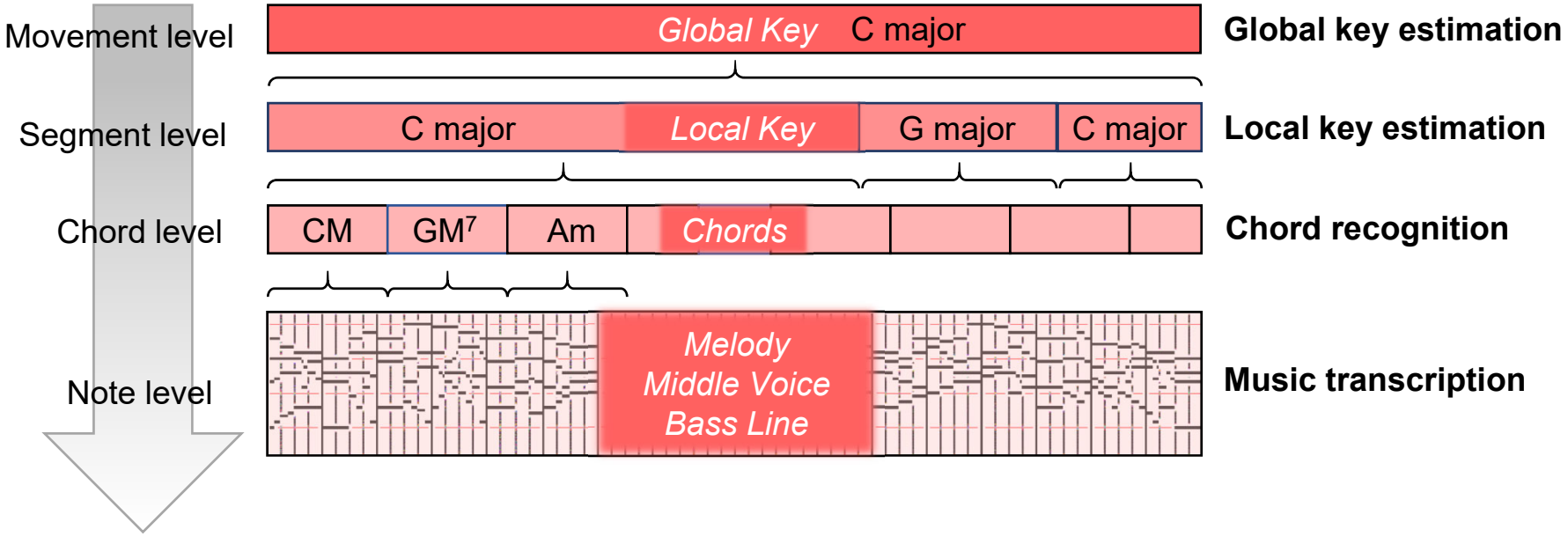
FAU
Friedrich-Alexander-Universität
Erlangen-Nürnberg

DFG

AUDIO
LABS

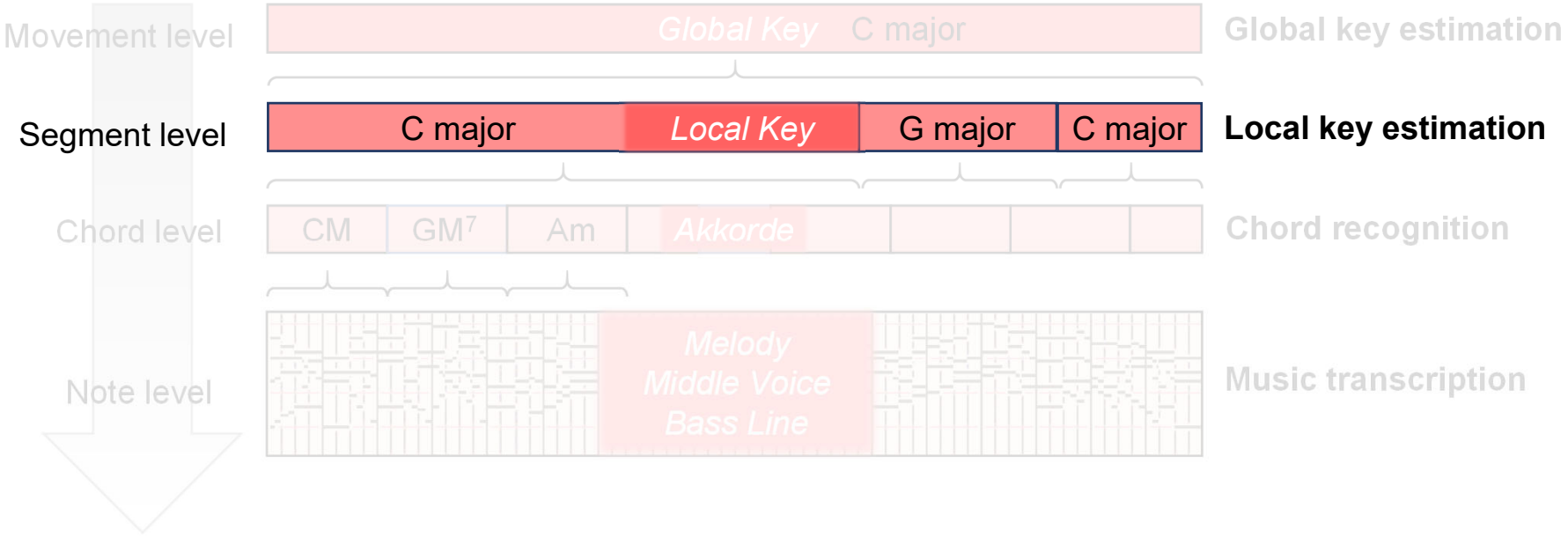
Computational Musicology: Harmony Analysis

- Different concepts
- Different temporal levels



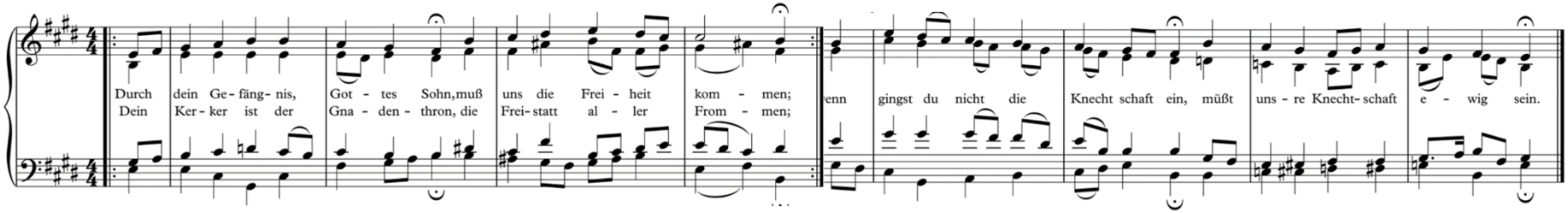
Computational Musicology: Harmony Analysis

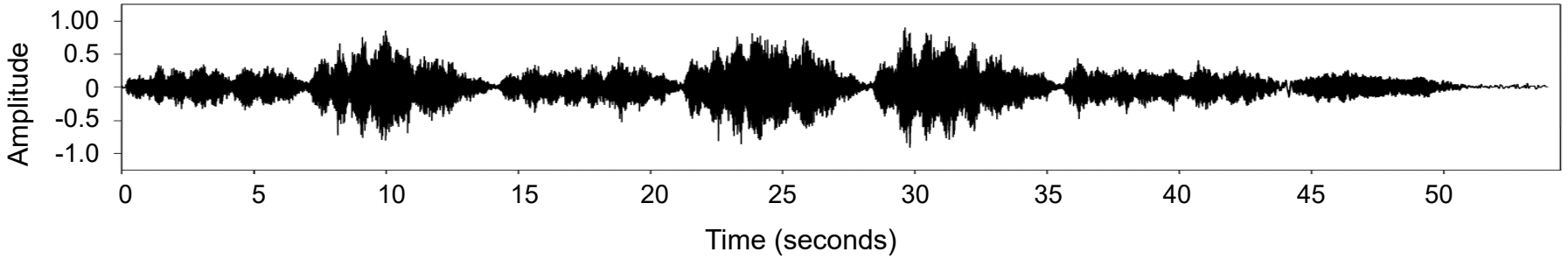
- Different concepts
- Different temporal levels



Local Key Estimation

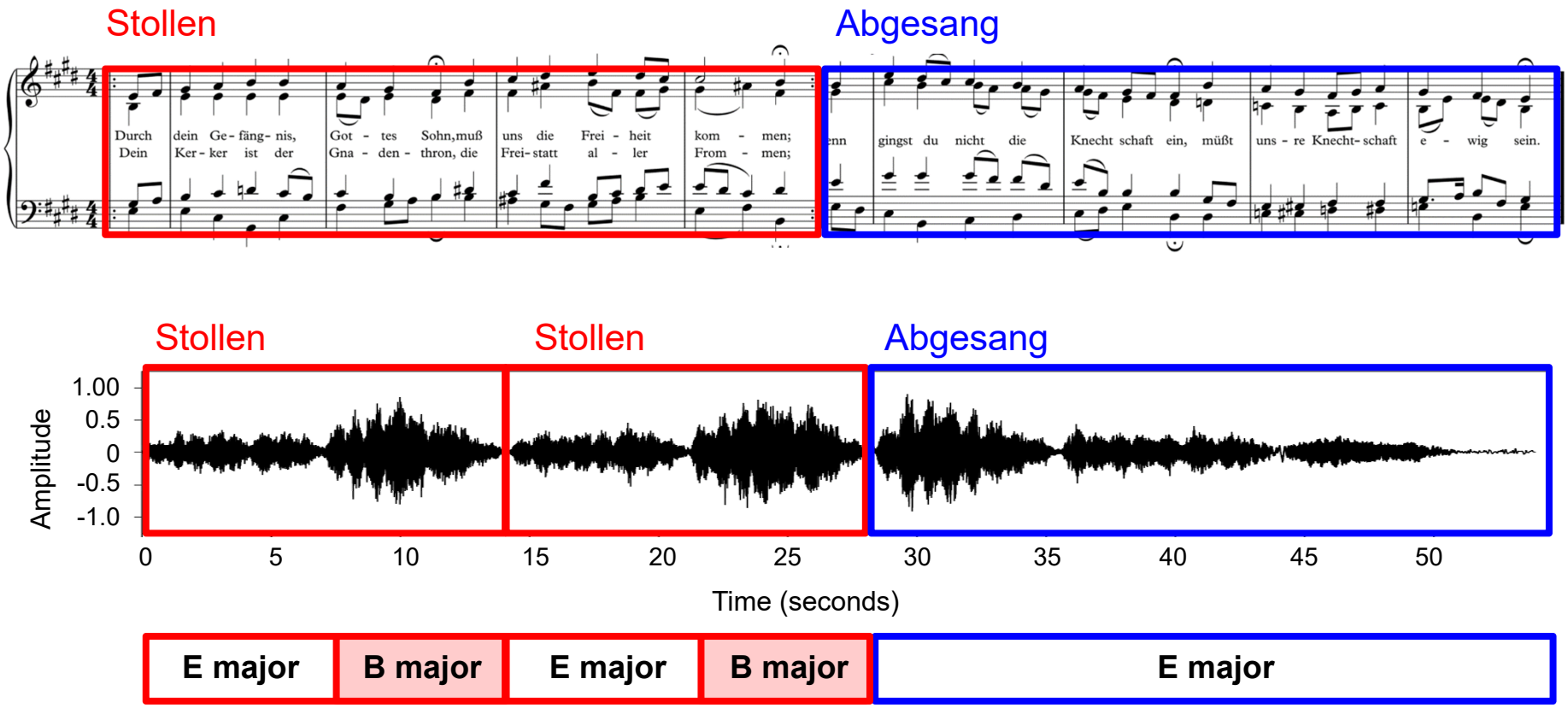
Example: J.S. Bach, Choral "Durch Dein Gefängnis" (*Johannespassion*)





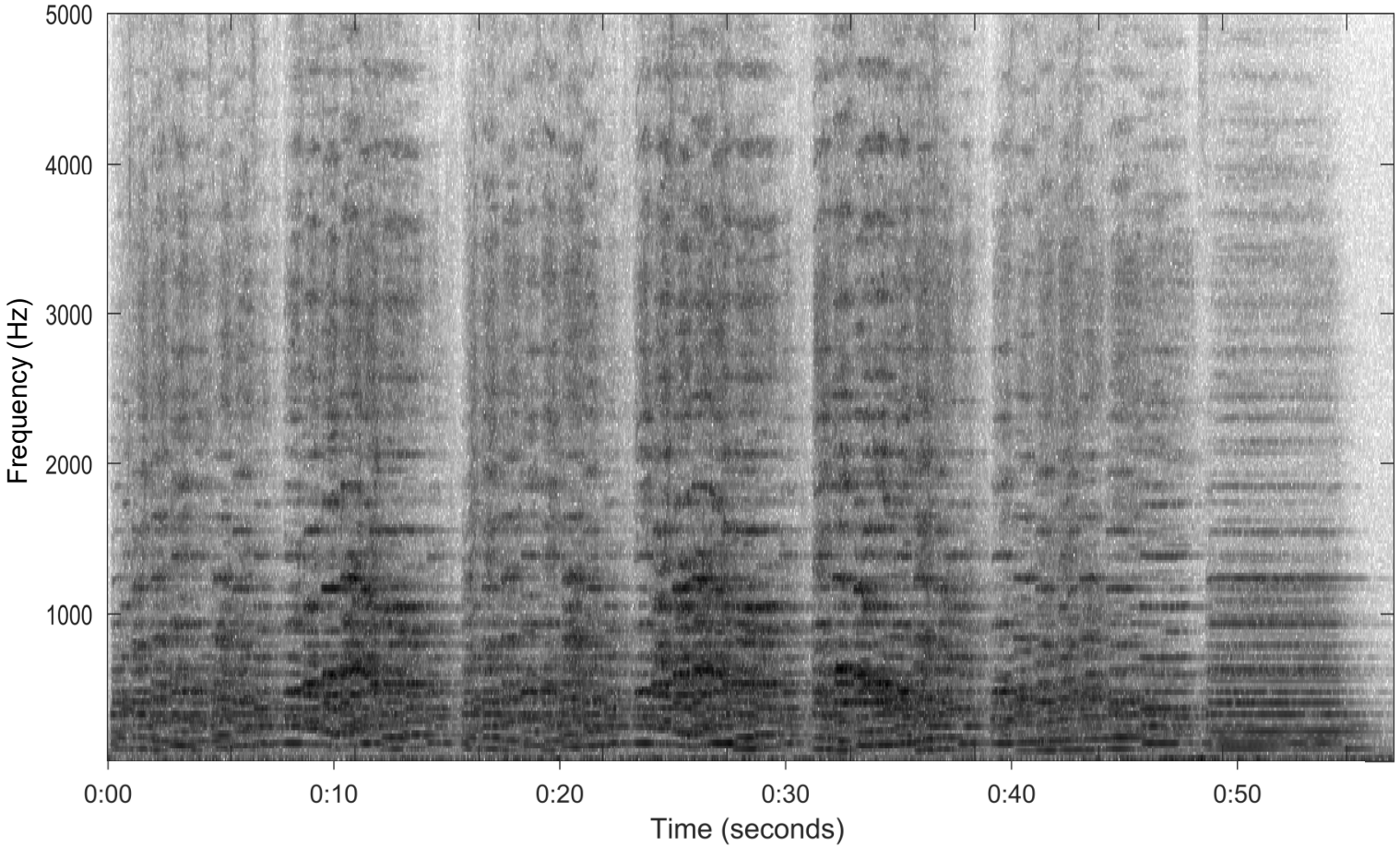
Local Key Estimation

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



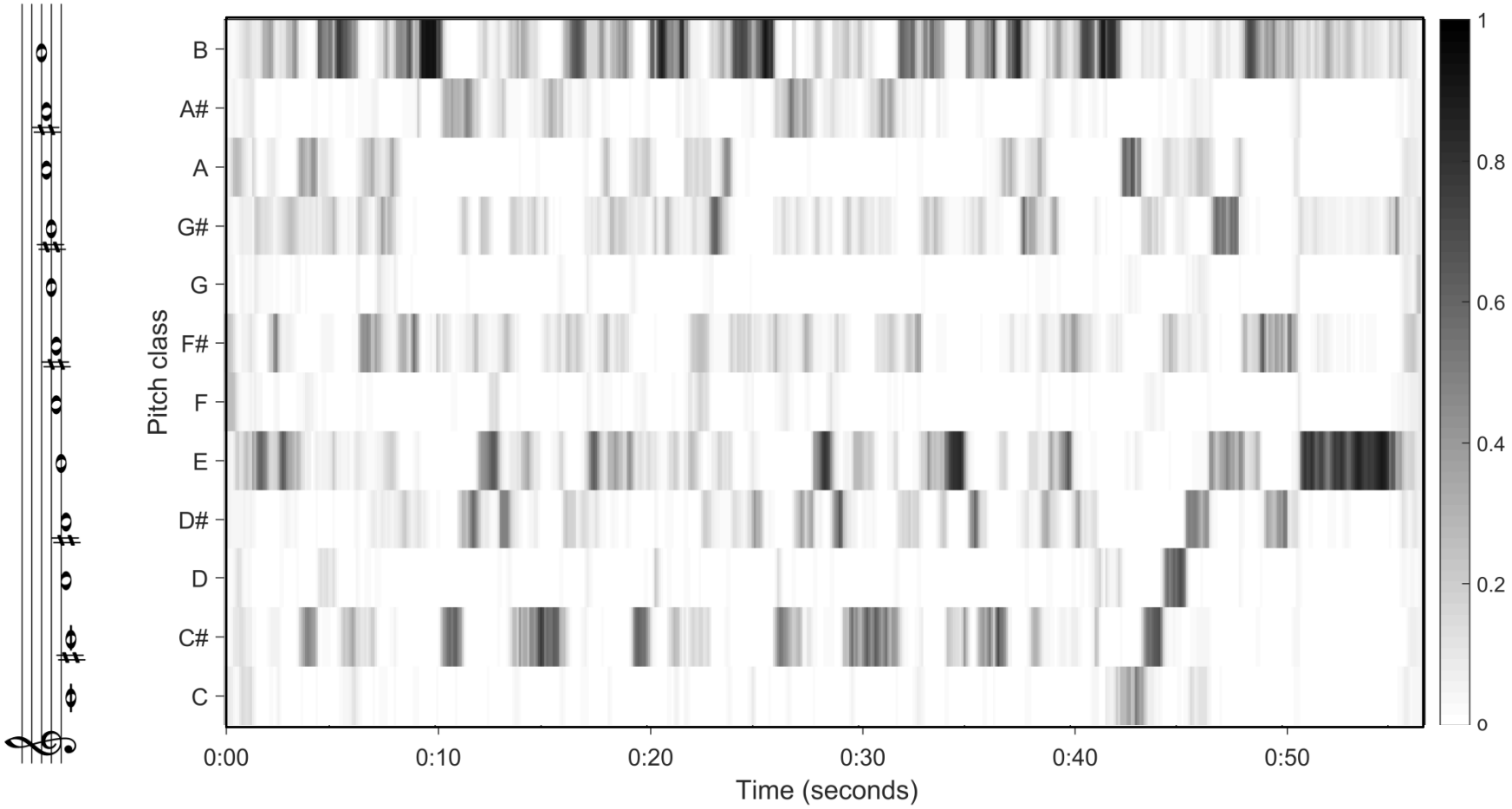
Local Key Estimation

Spectrogram



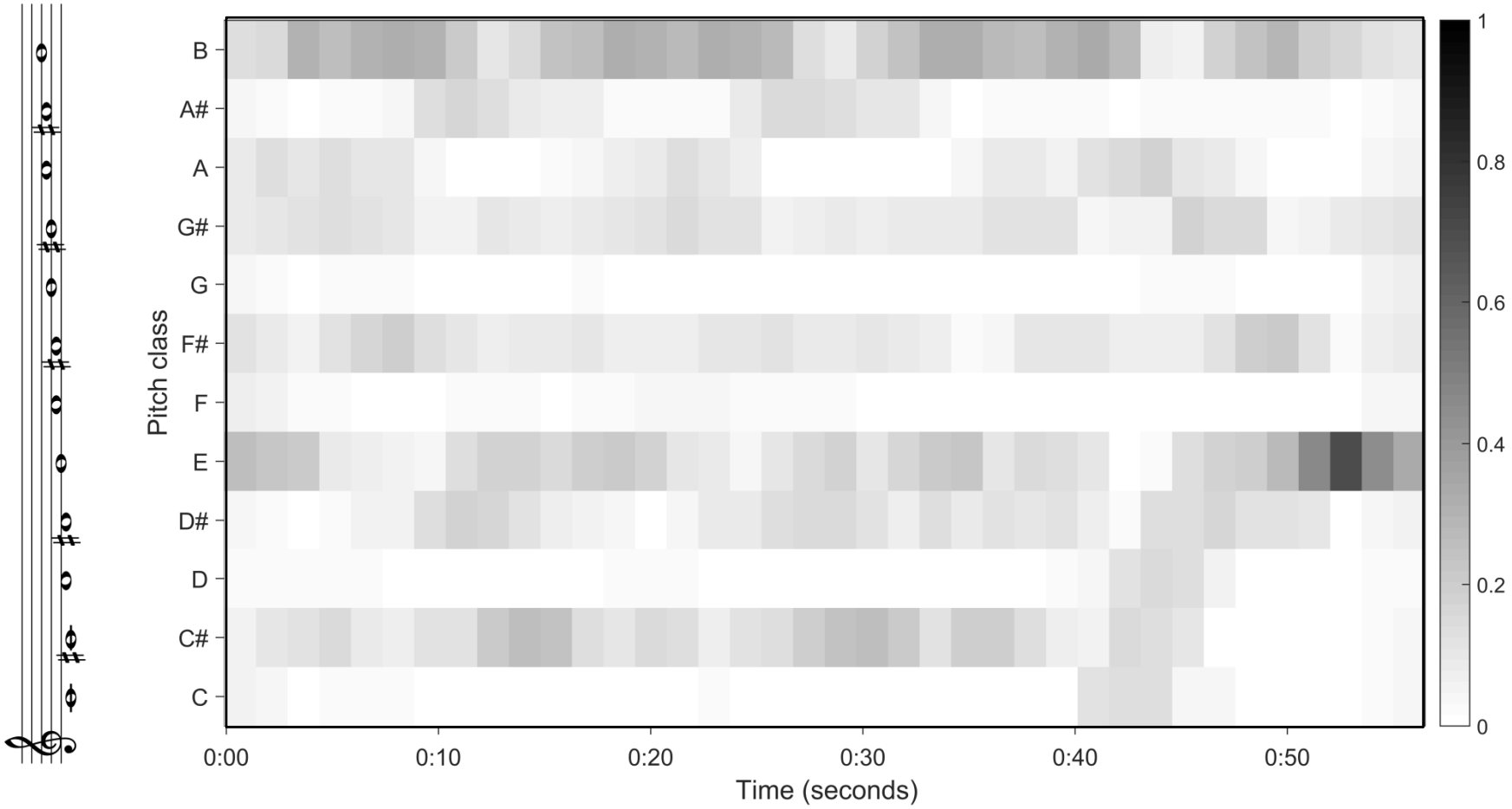
Local Key Estimation

Chromagram



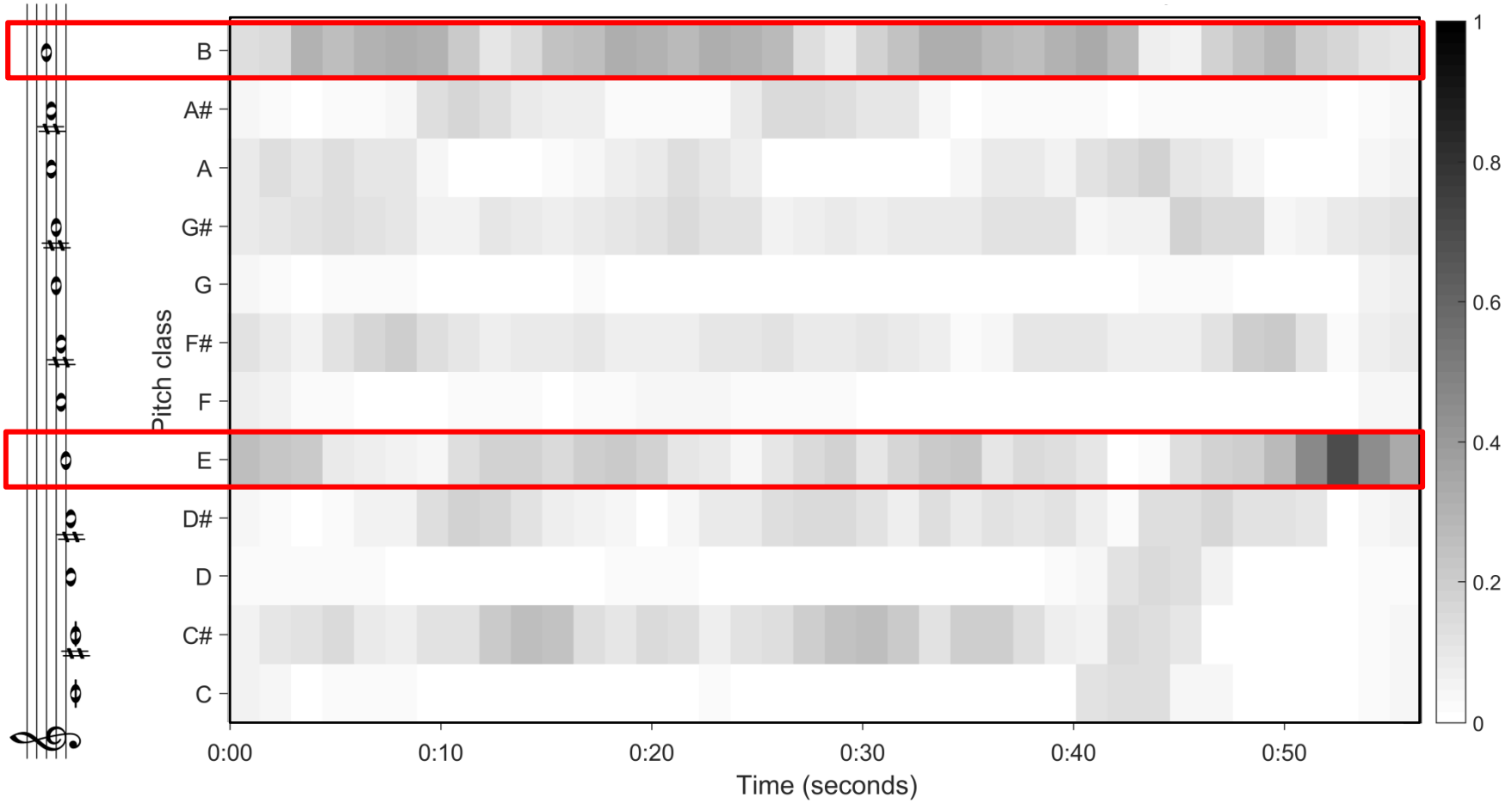
Local Key Estimation

Chromagram after smoothing



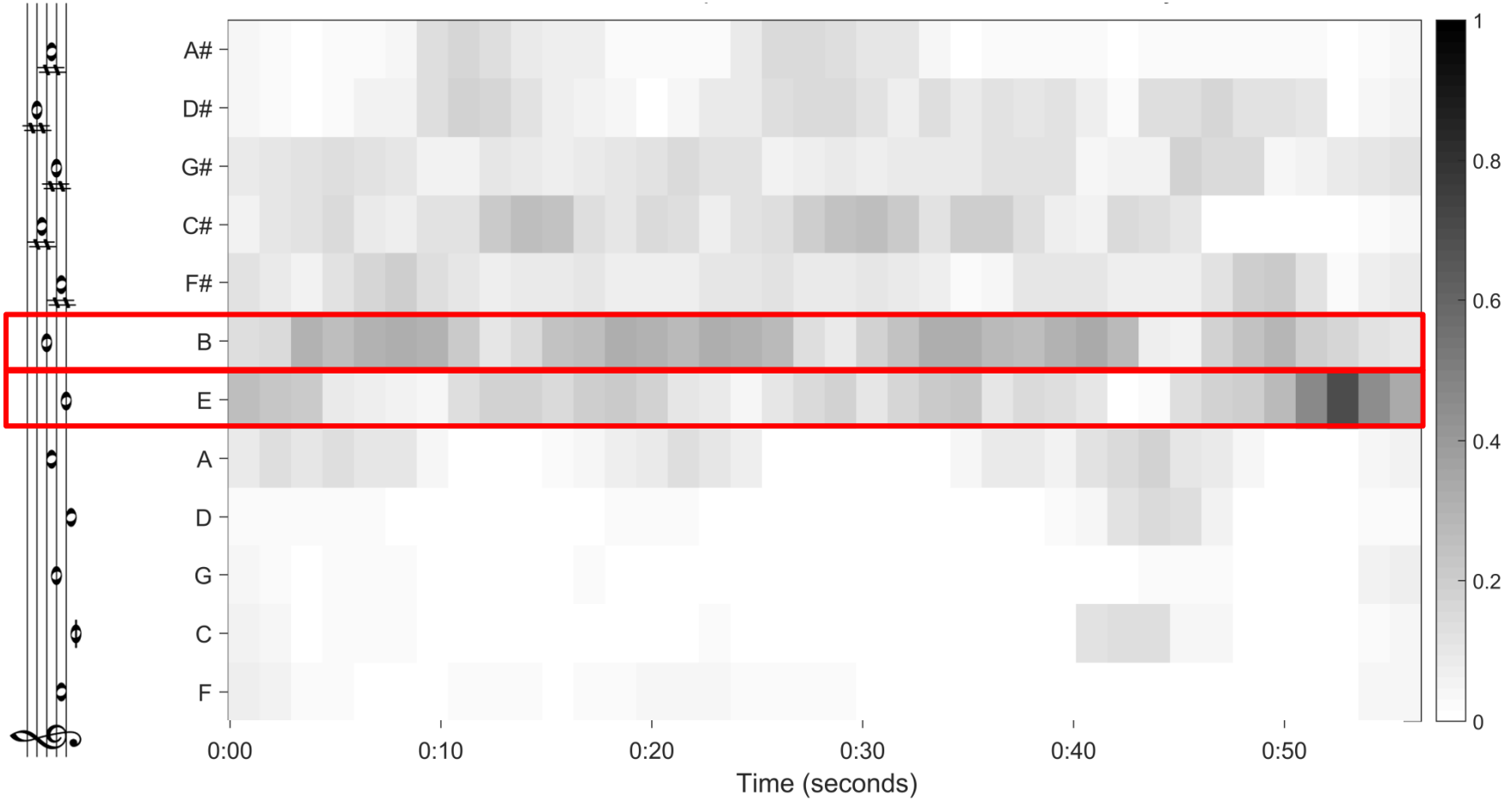
Local Key Estimation

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



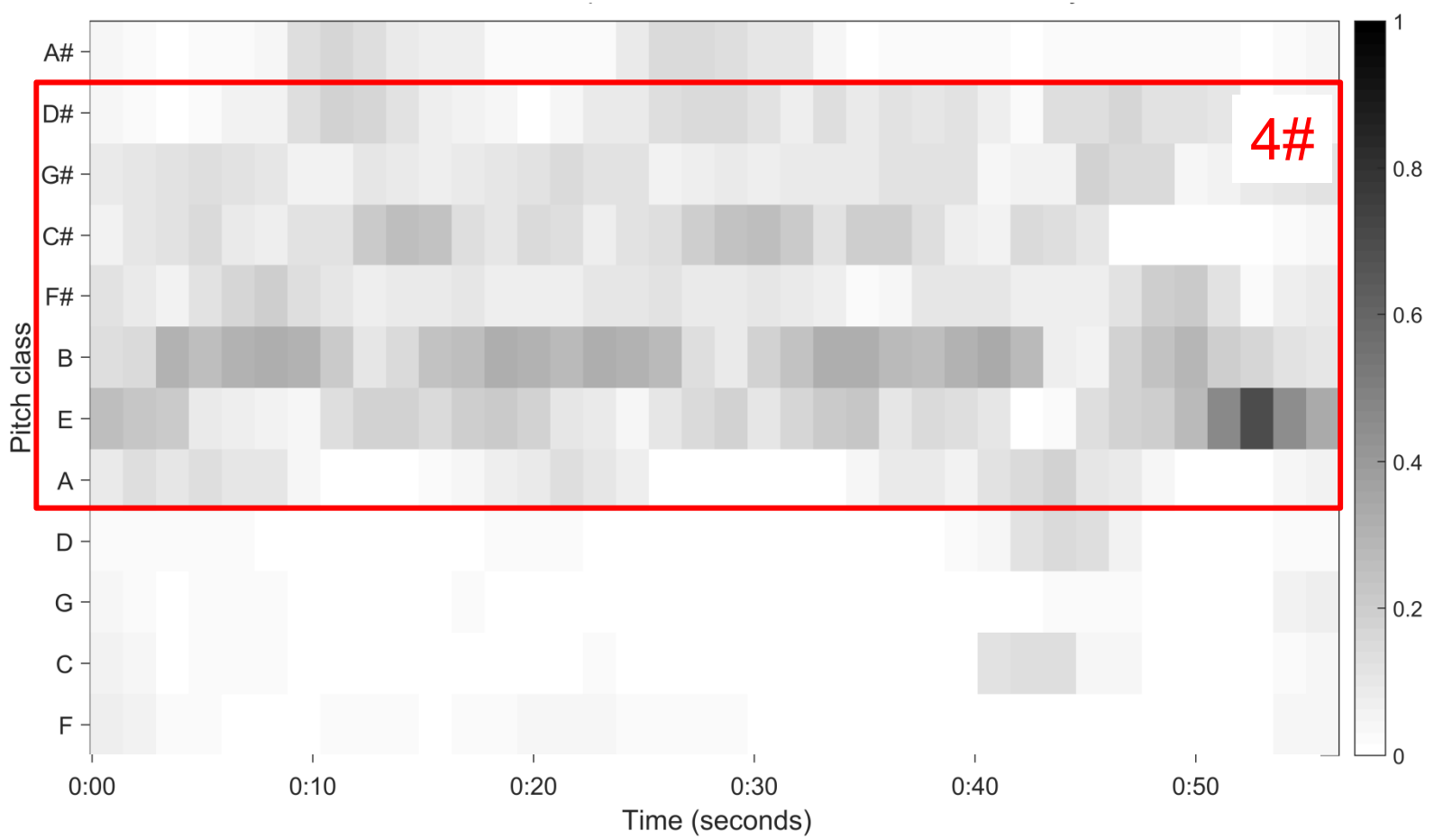
Local Key Estimation

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



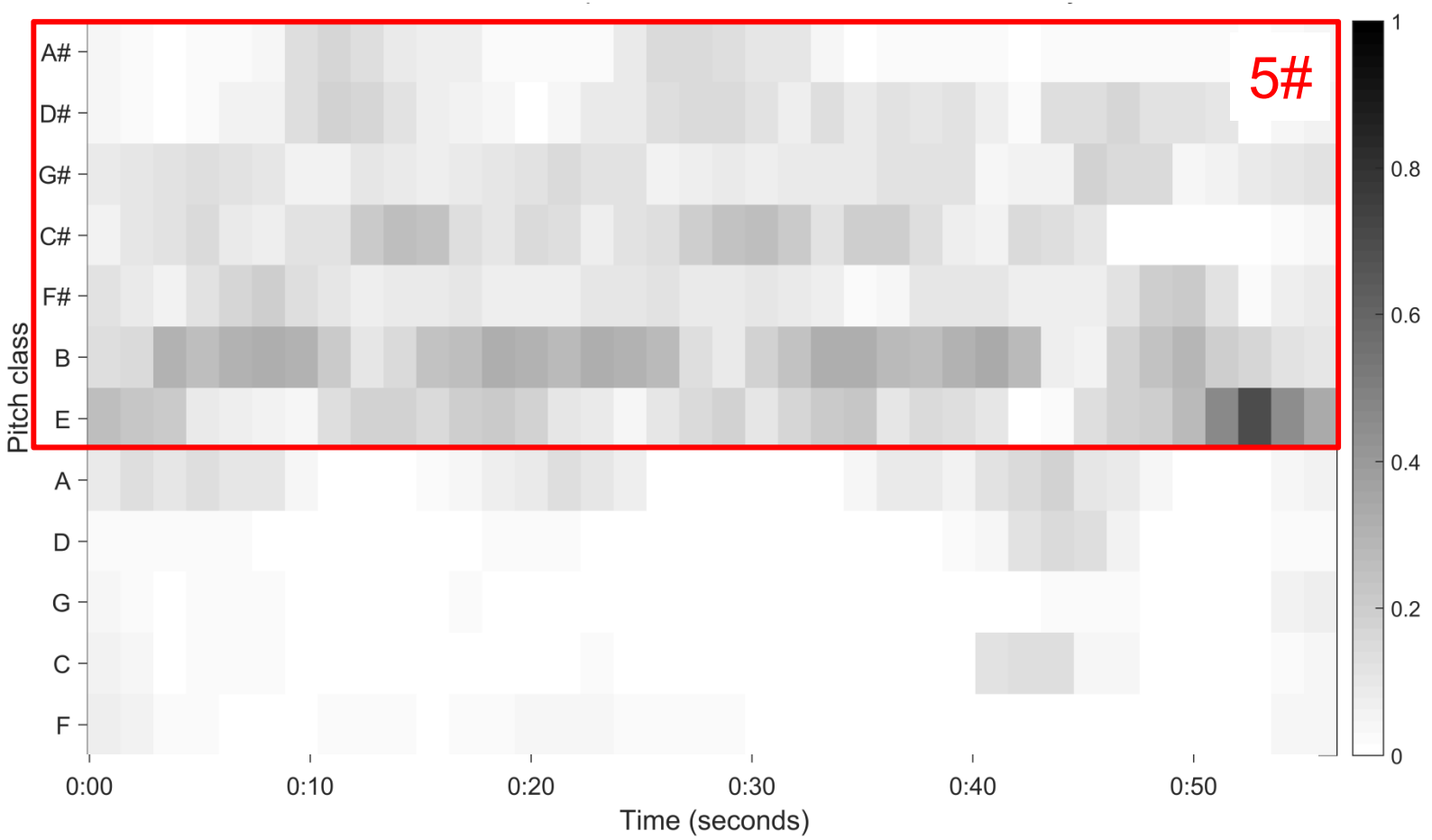
Local Key Estimation

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



Local Key Estimation

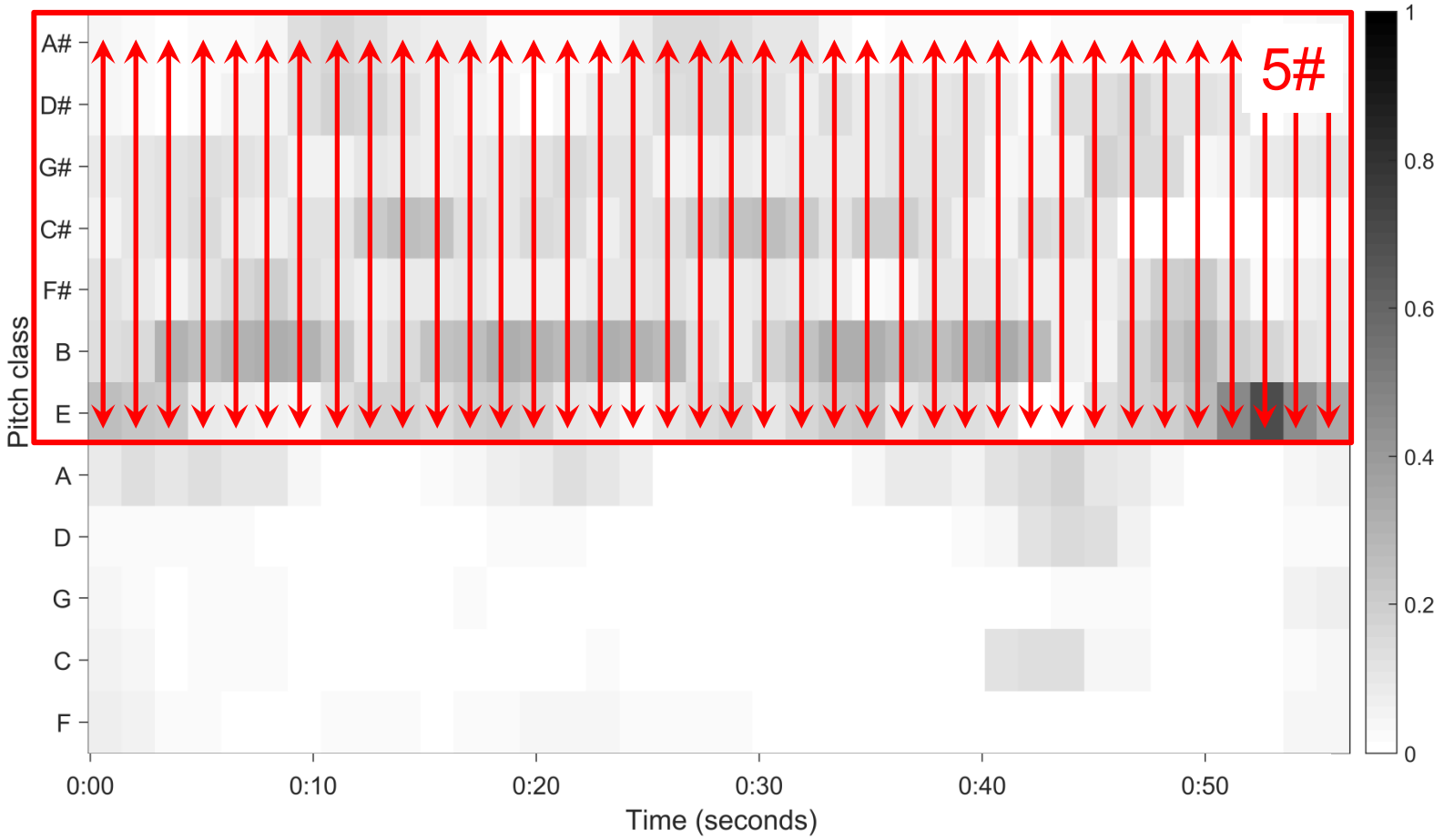
Summarize pitch class content according to **diatonic scales**



Local Key Estimation

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

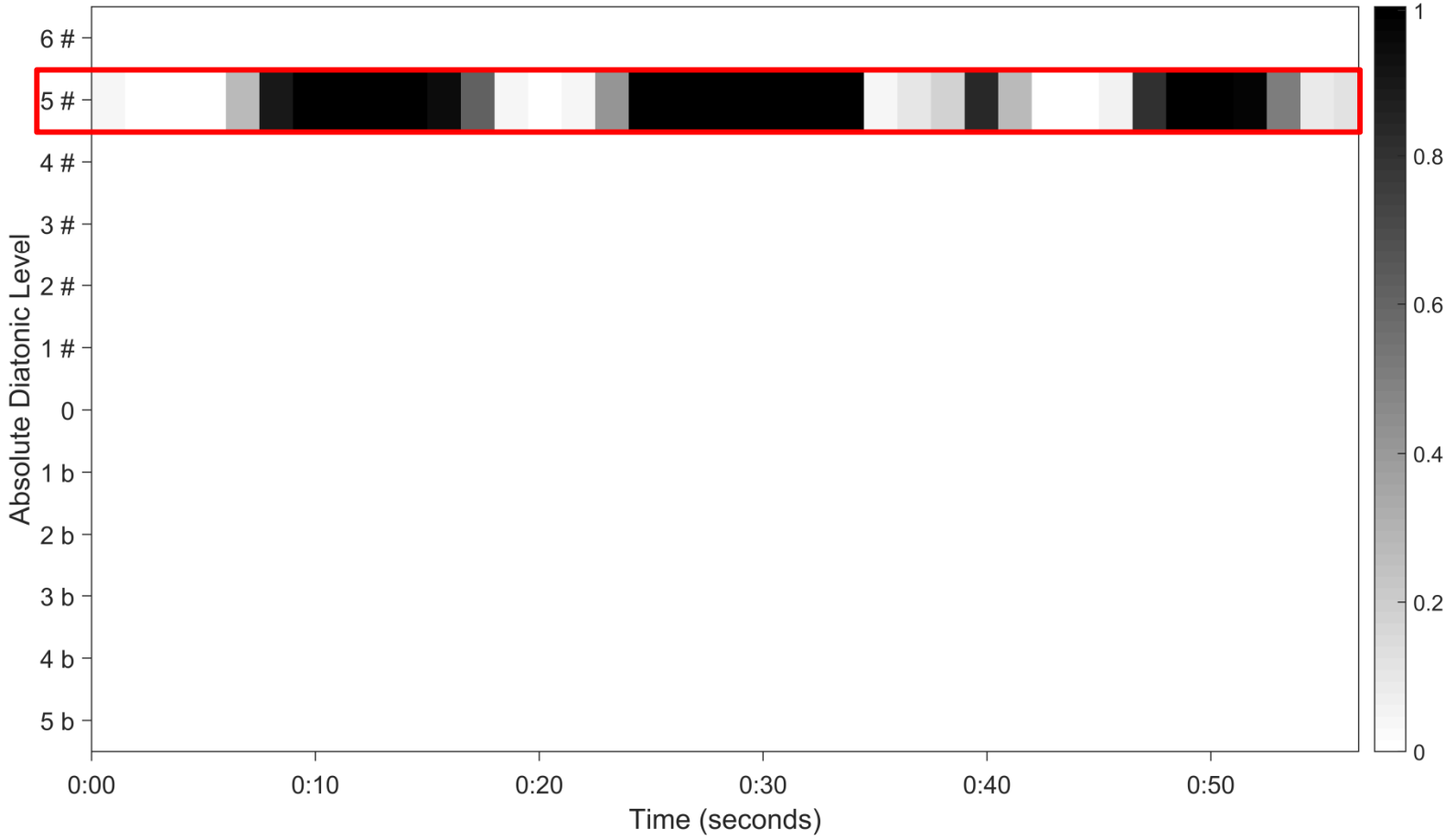
Multiply chroma values (in each column)



Local Key Estimation

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

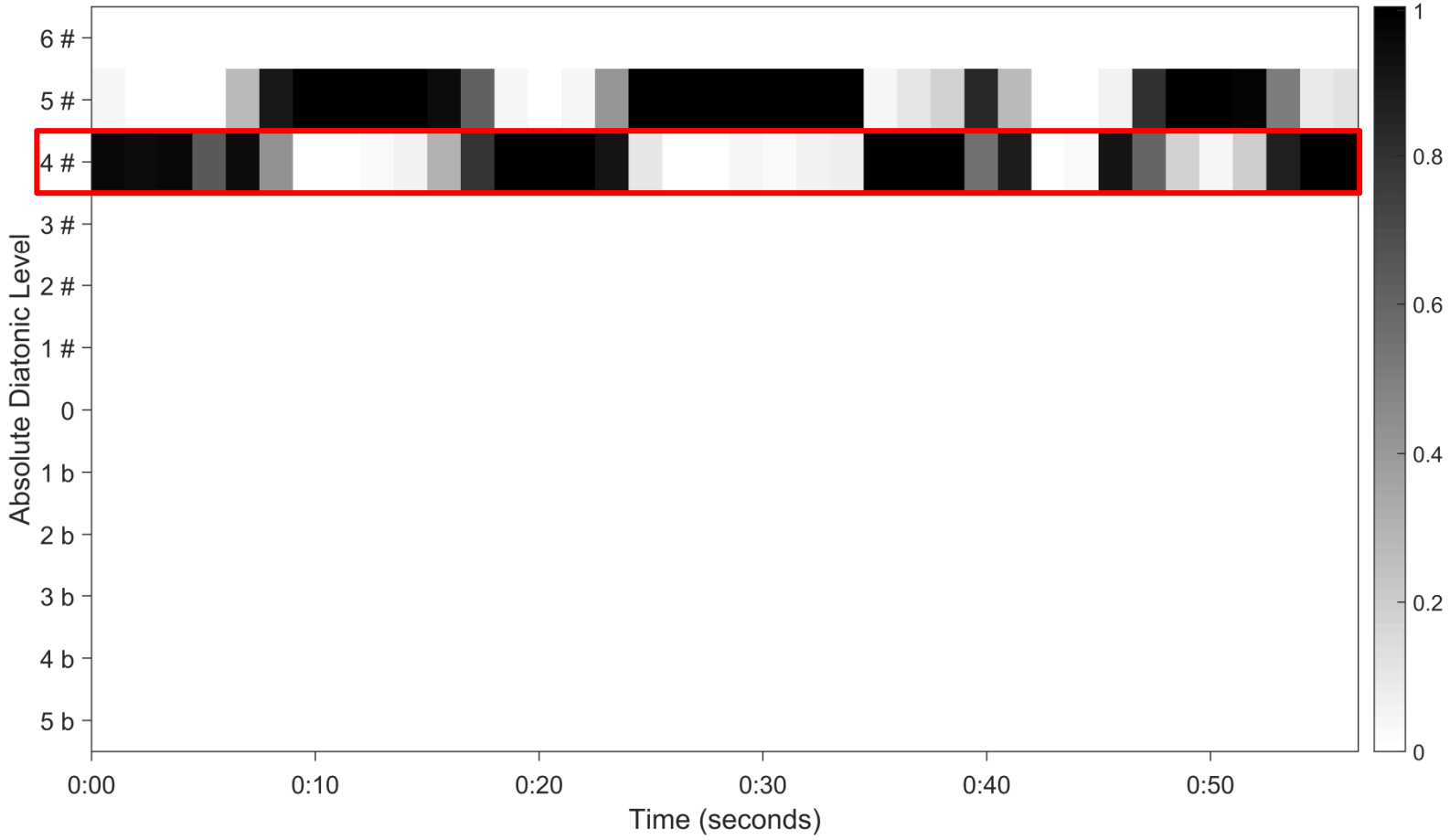
Multiply chroma values



Local Key Estimation

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

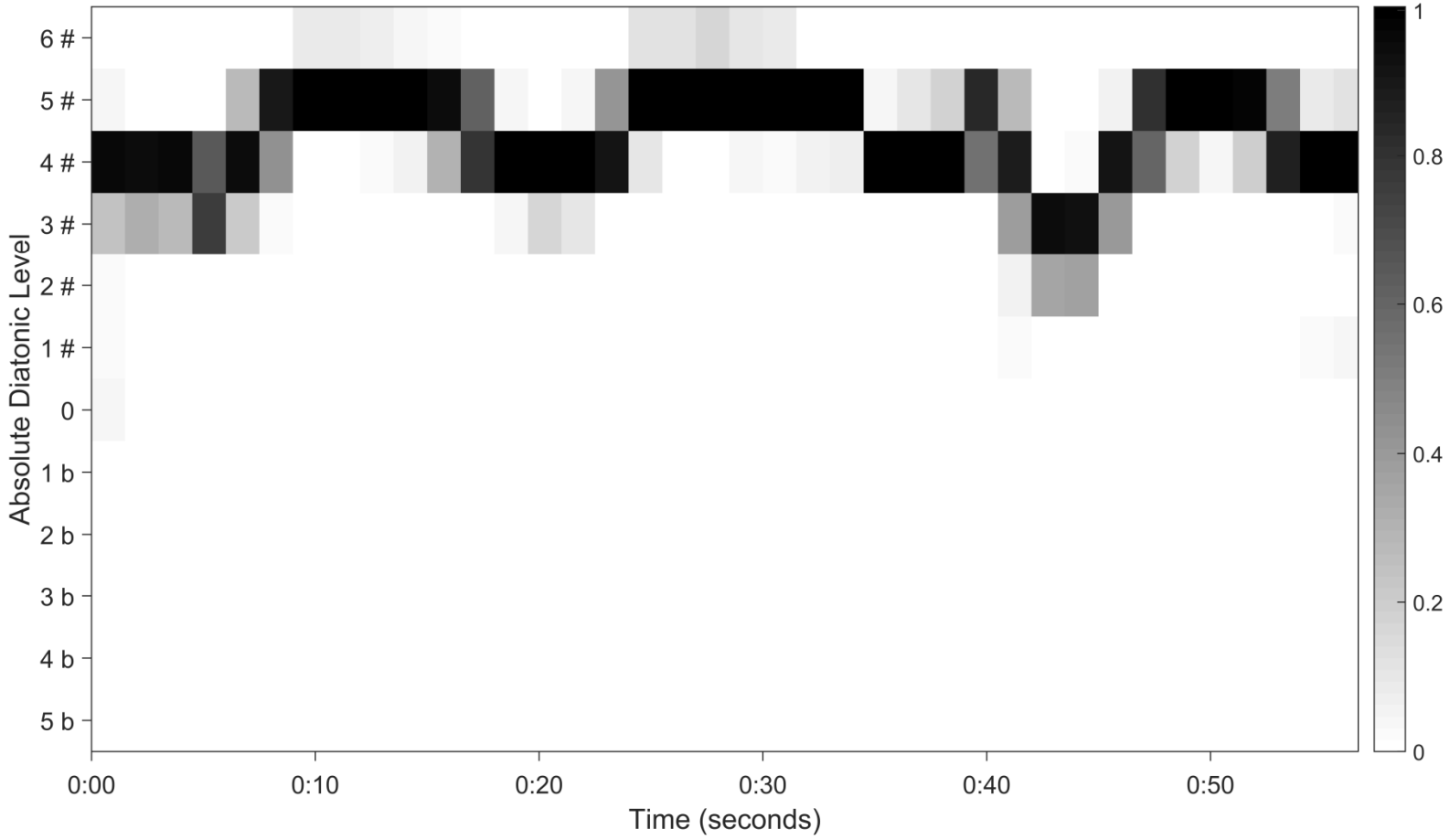
Multiply chroma values



Local Key Estimation

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

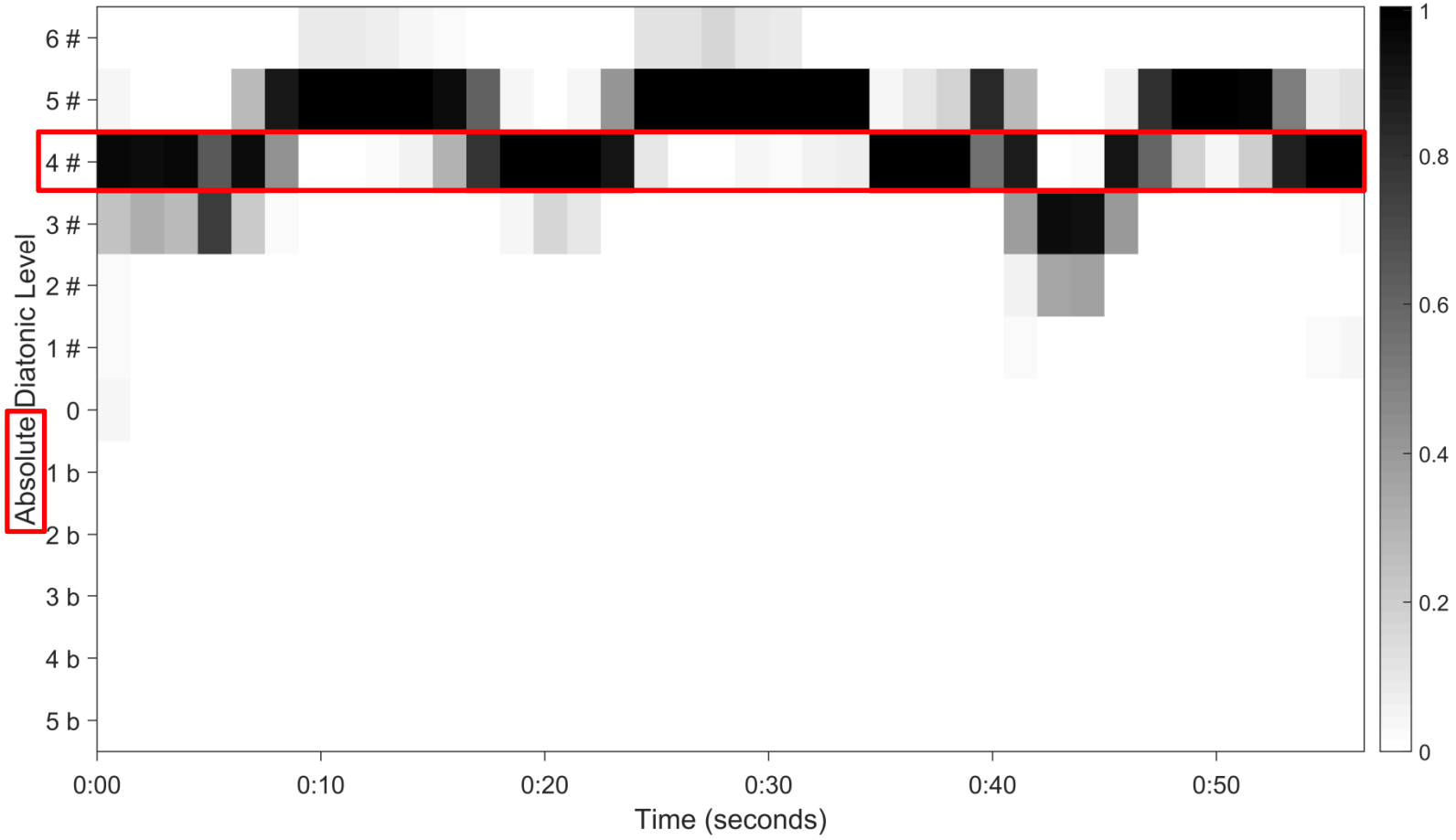
Multiply chroma values



Local Key Estimation

Normalize representation relative to global key

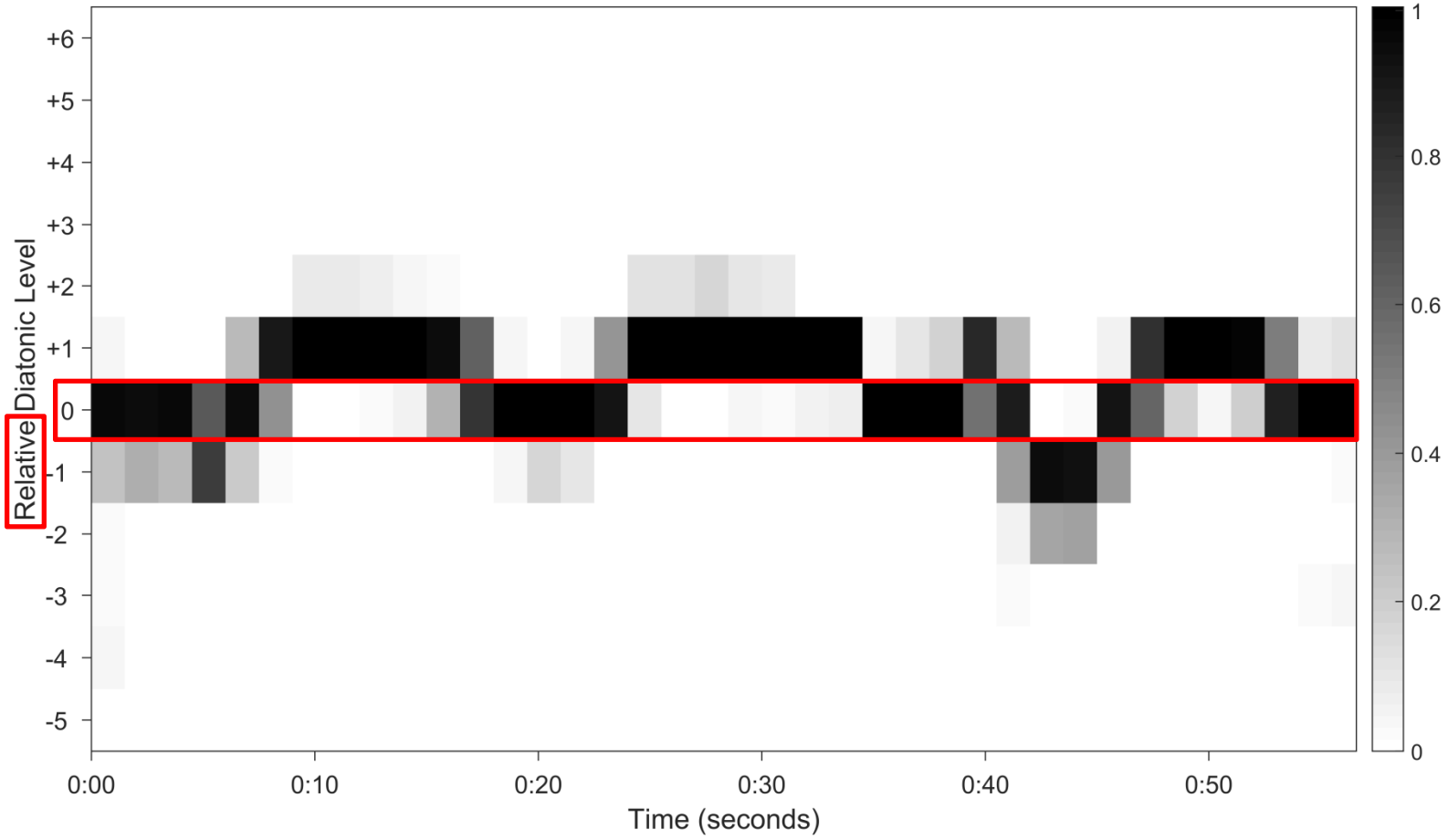
4 #
(E major)



Local Key Estimation

Normalize representation relative to global key

4 #
(E major)

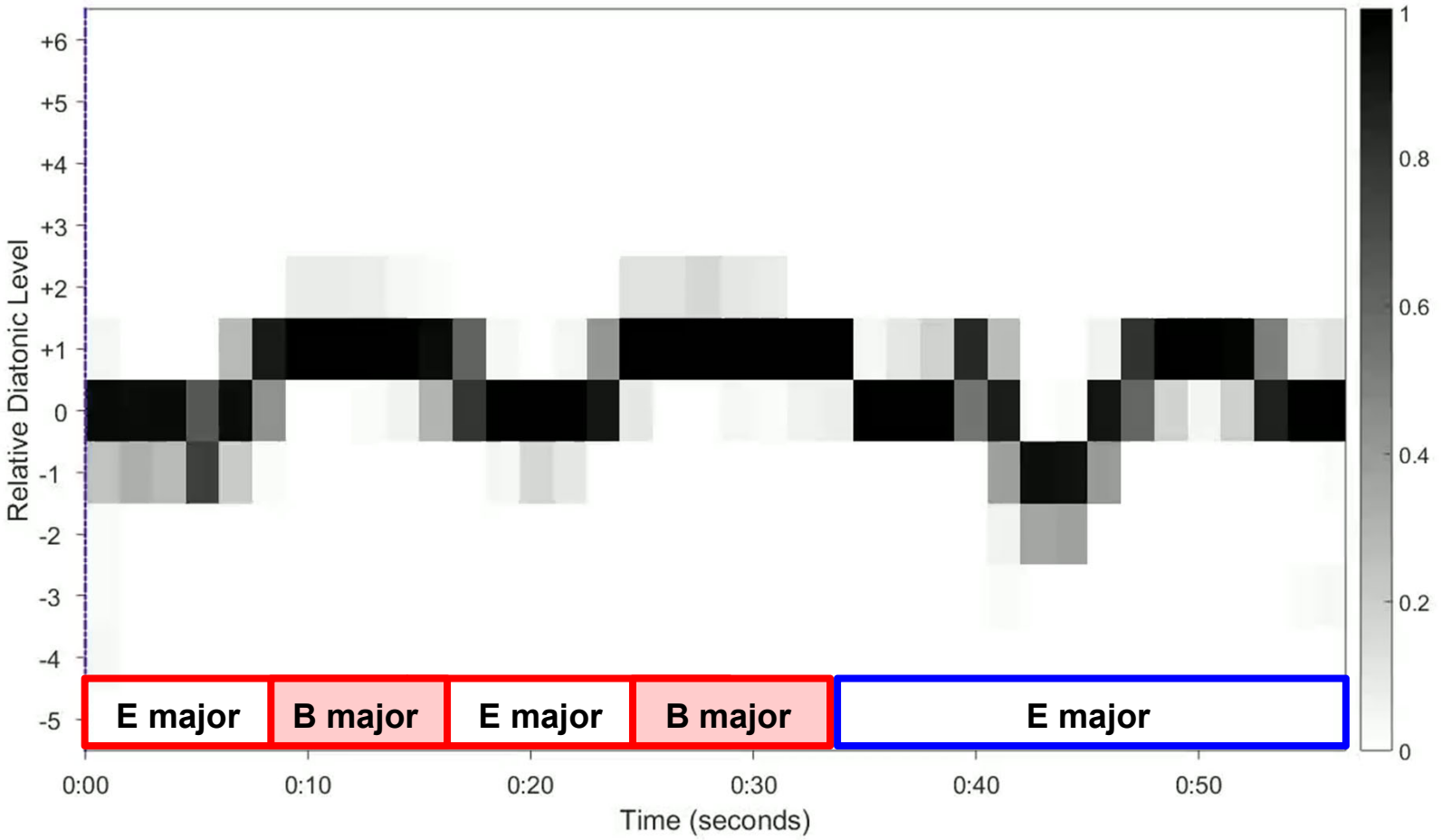


Local Key Estimation

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

Recording: Scholars Baroque Ensemble, Naxos 1994

4 #
(E major)

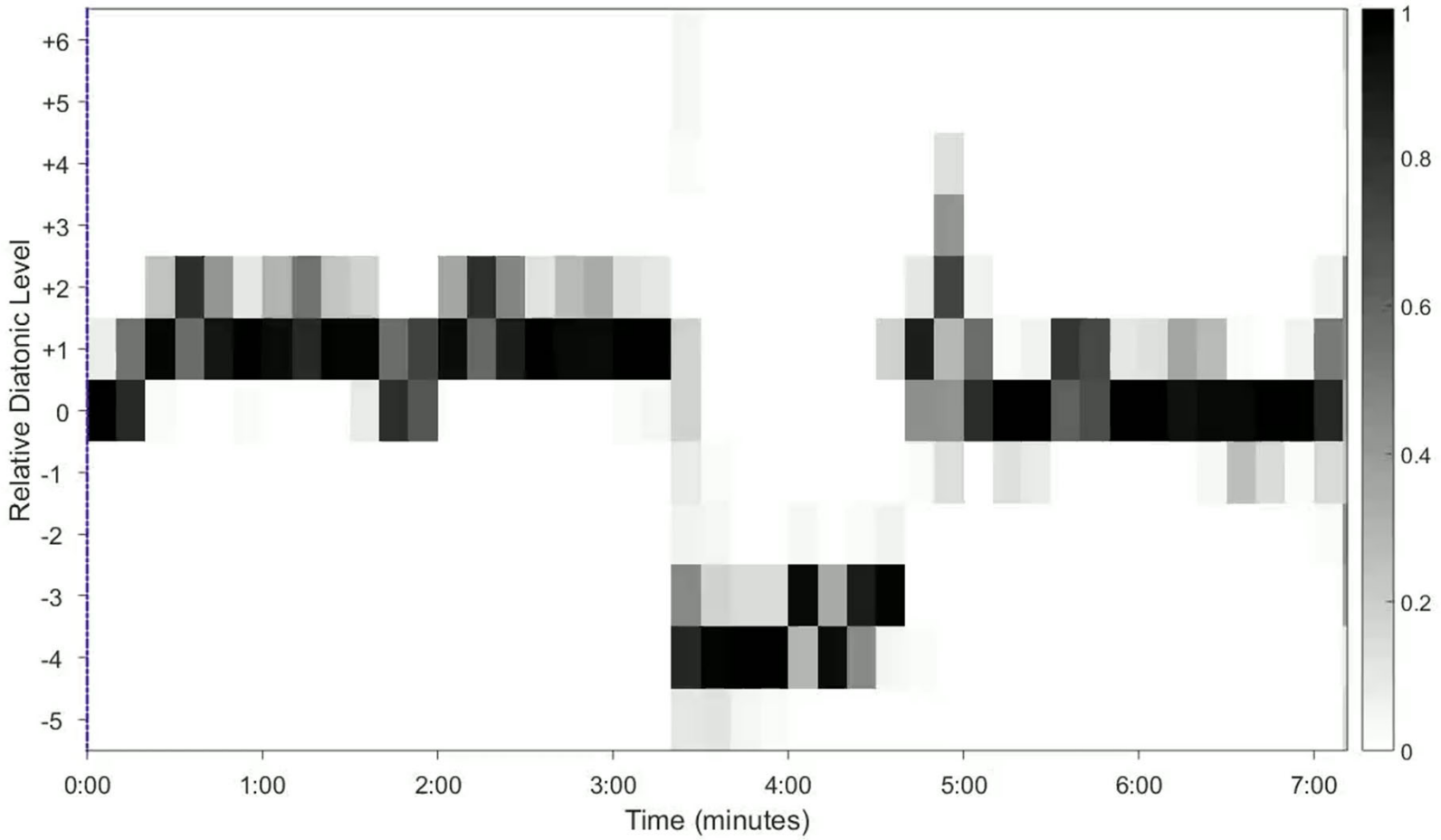


Local Key Estimation

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

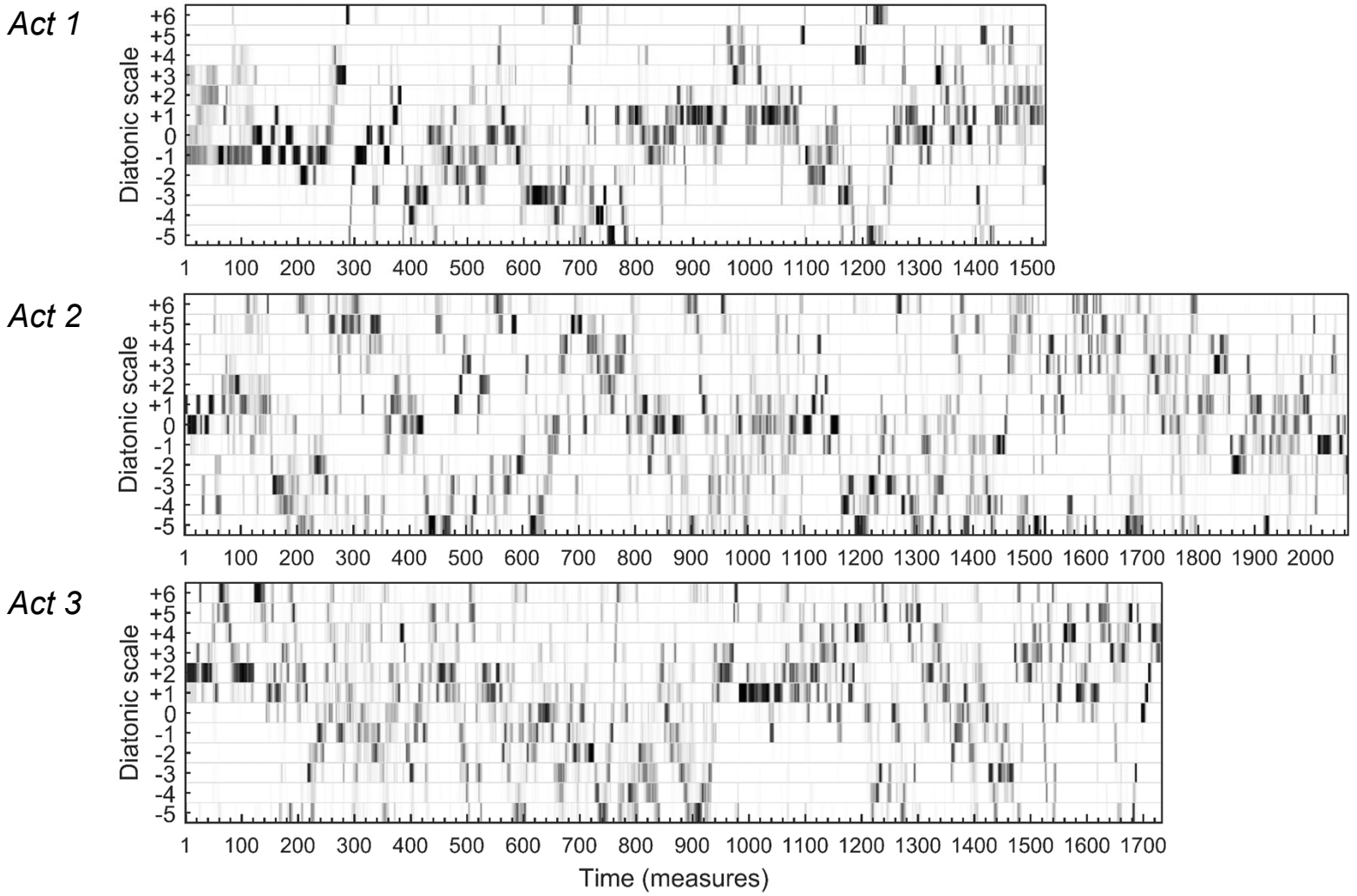
Recording: Barenboim, EMI 1998

1 #
(G major)



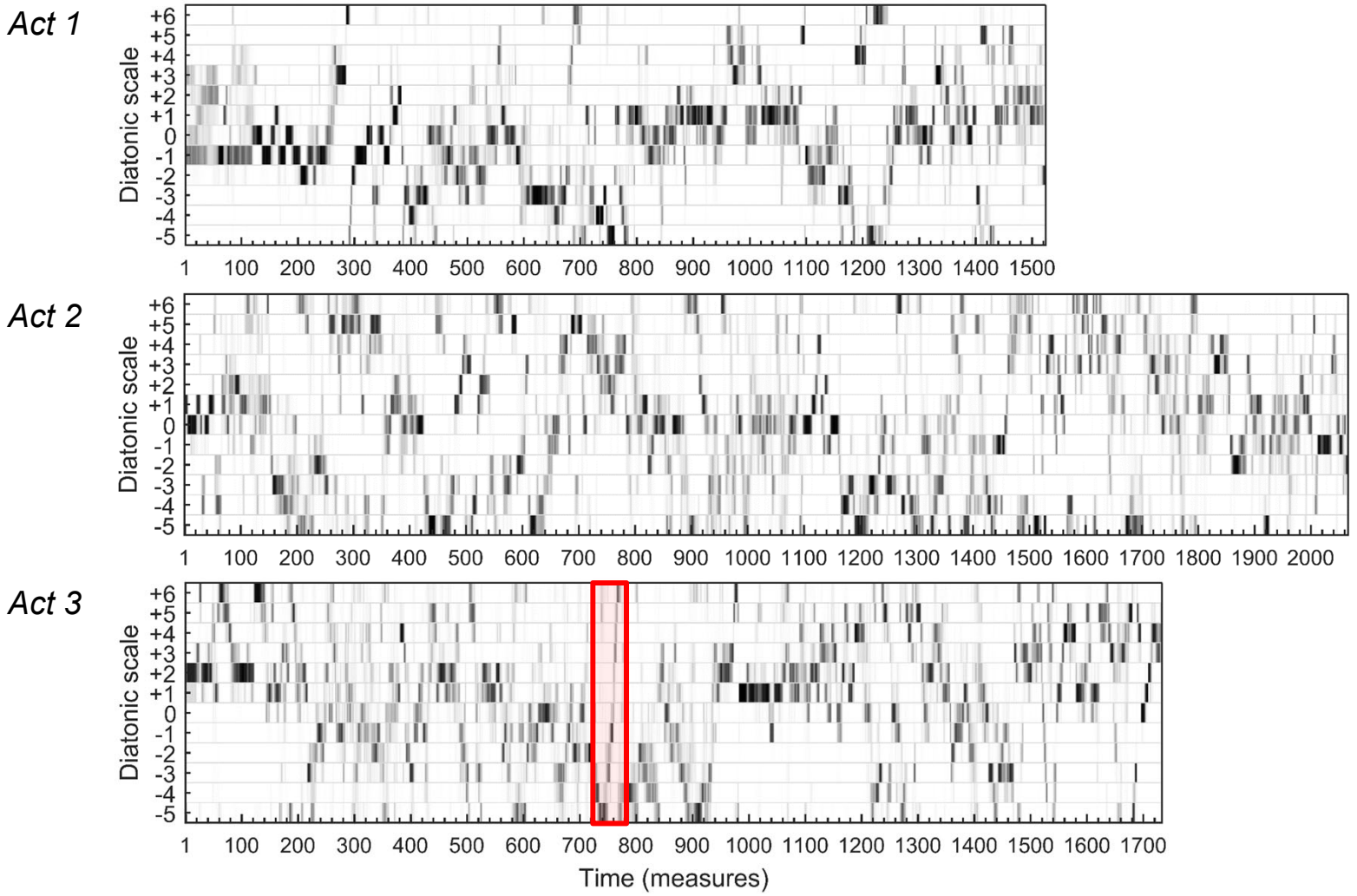
Local Key Estimation

R. Wagner: WWV 86 B (*Die Walküre*)



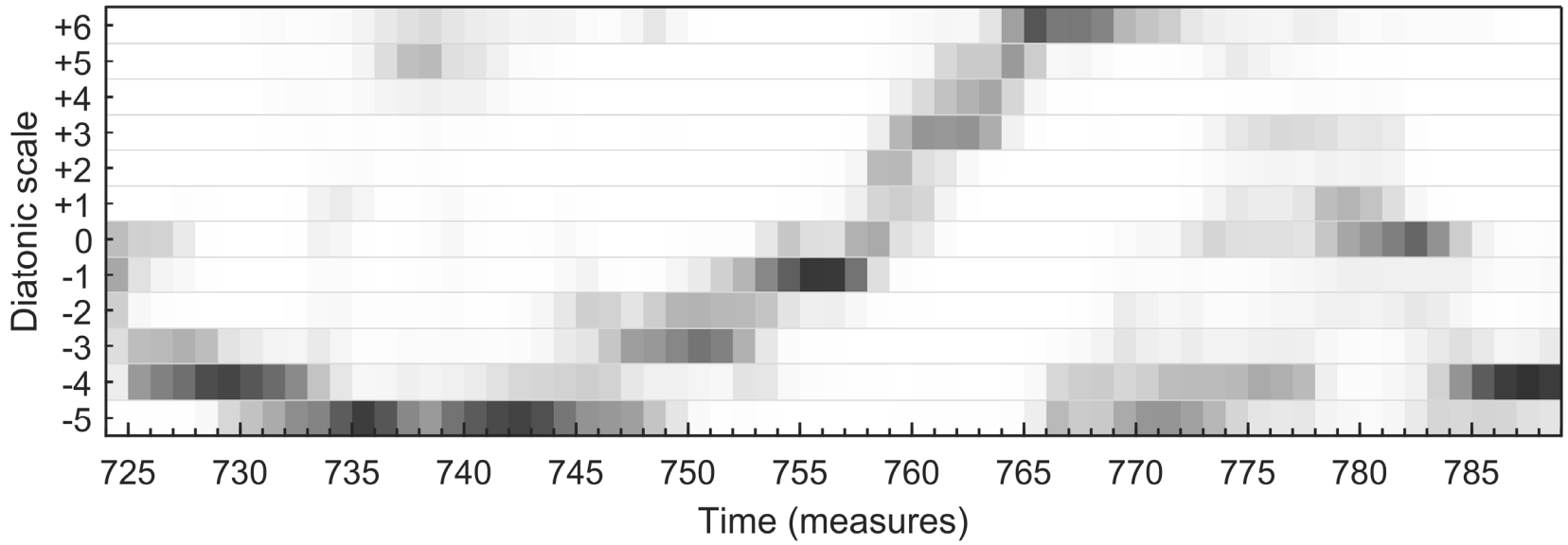
Local Key Estimation

R. Wagner: WWV 86 B (*Die Walküre*)



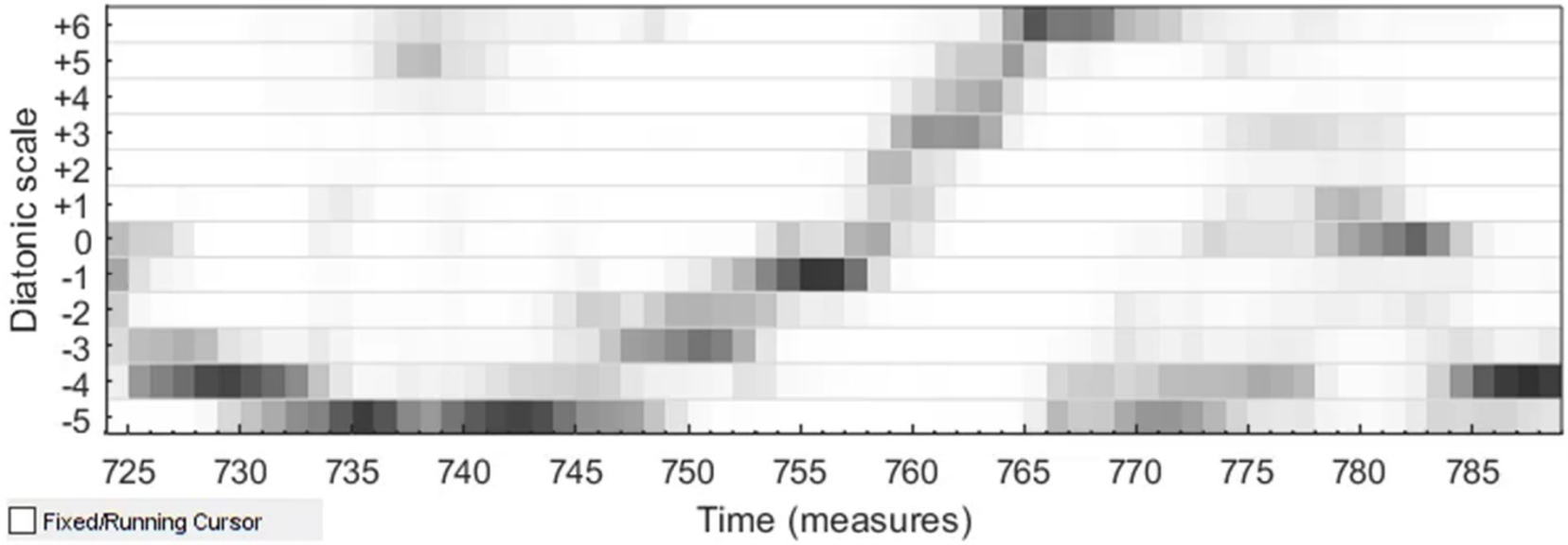
Local Key Estimation

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



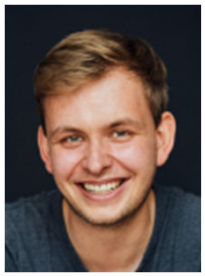
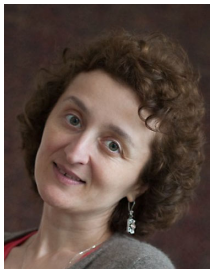
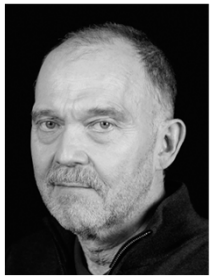
Local Key Estimation

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



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

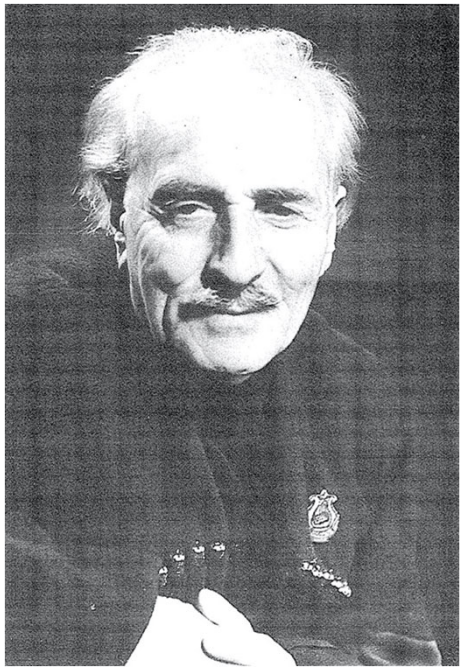
- 2018 – 2022: DFG-funded project

DFG

AUDIO LABS

Traditional Georgian Vocal Music

Example: Erkomaishvili corpus

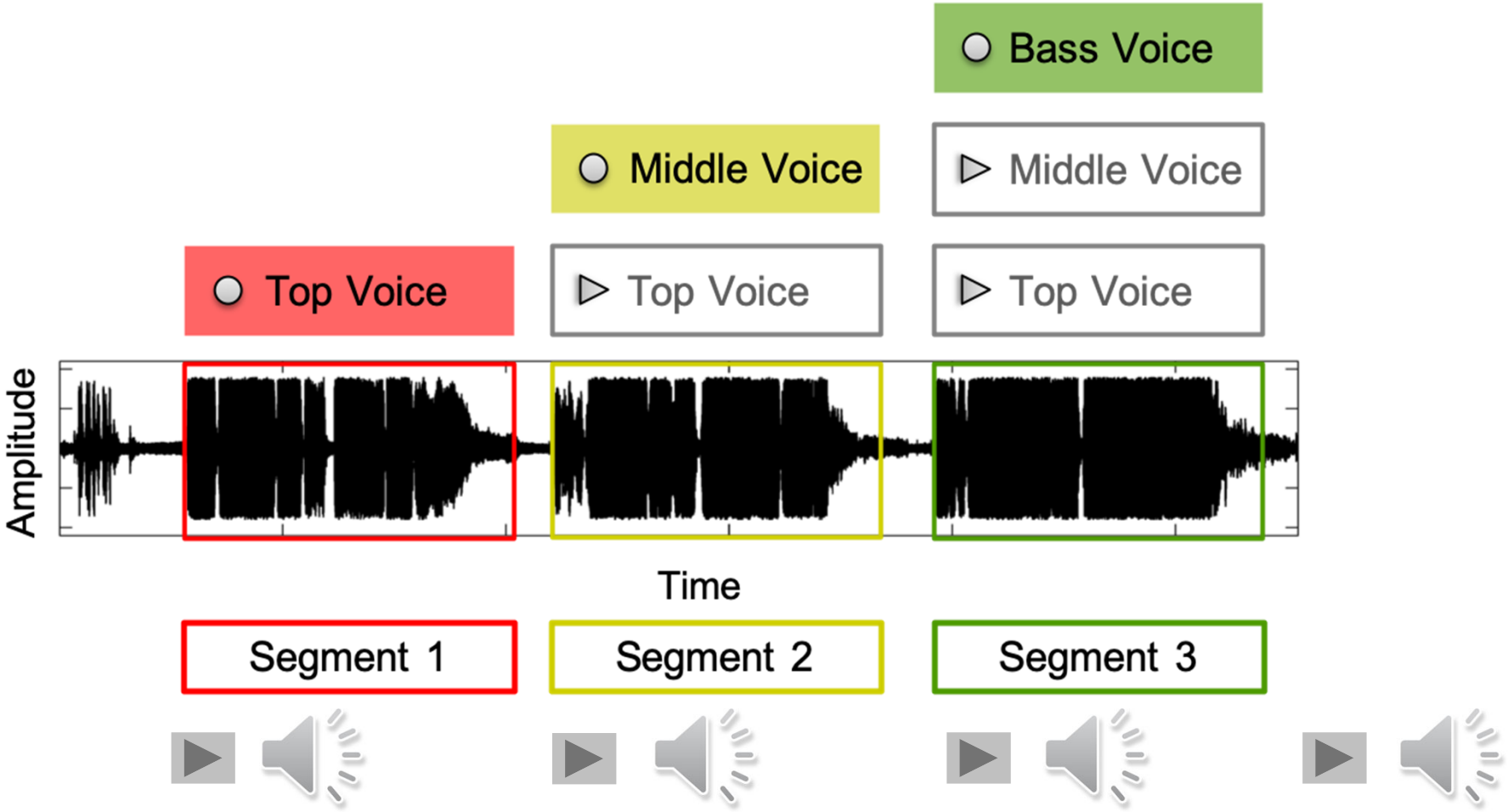


- Collection of traditional three-voice Georgian songs
- Performed by the former Georgian master chanter Artem Erkomaishvili (1887-1967)
- Recordings of 100 songs using tape recorders (1966)

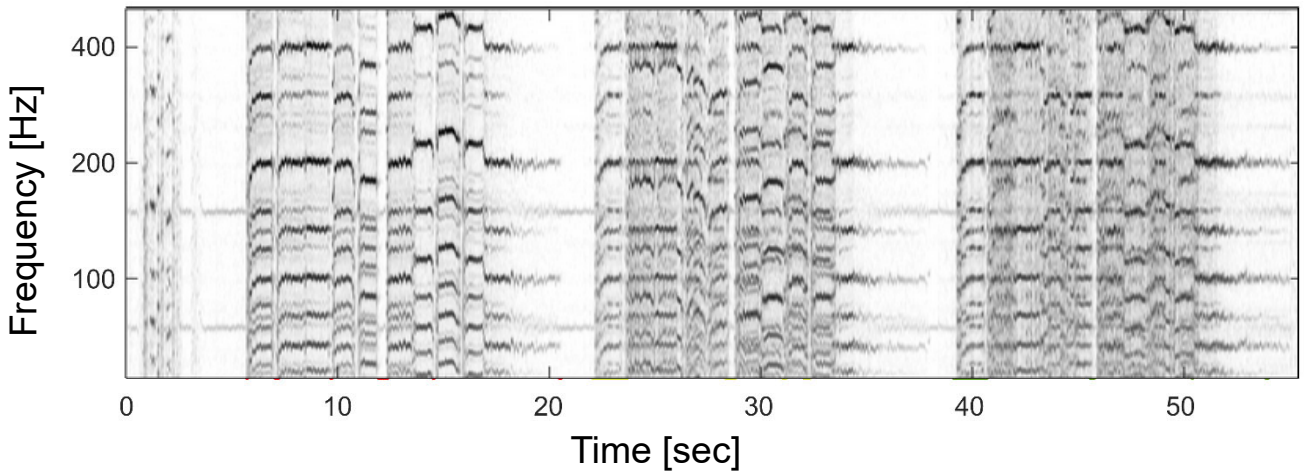
> "*Original masterpieces of Georgian musical thinking.*" (Shugliashvili, 2014)

Traditional Georgian Vocal Music

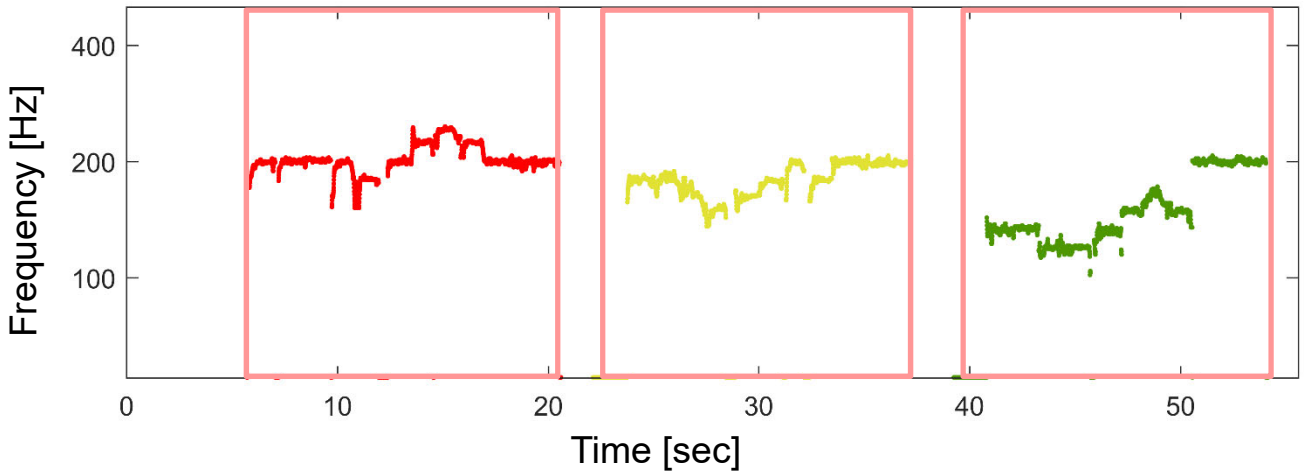
Example: Erkomaishvili corpus



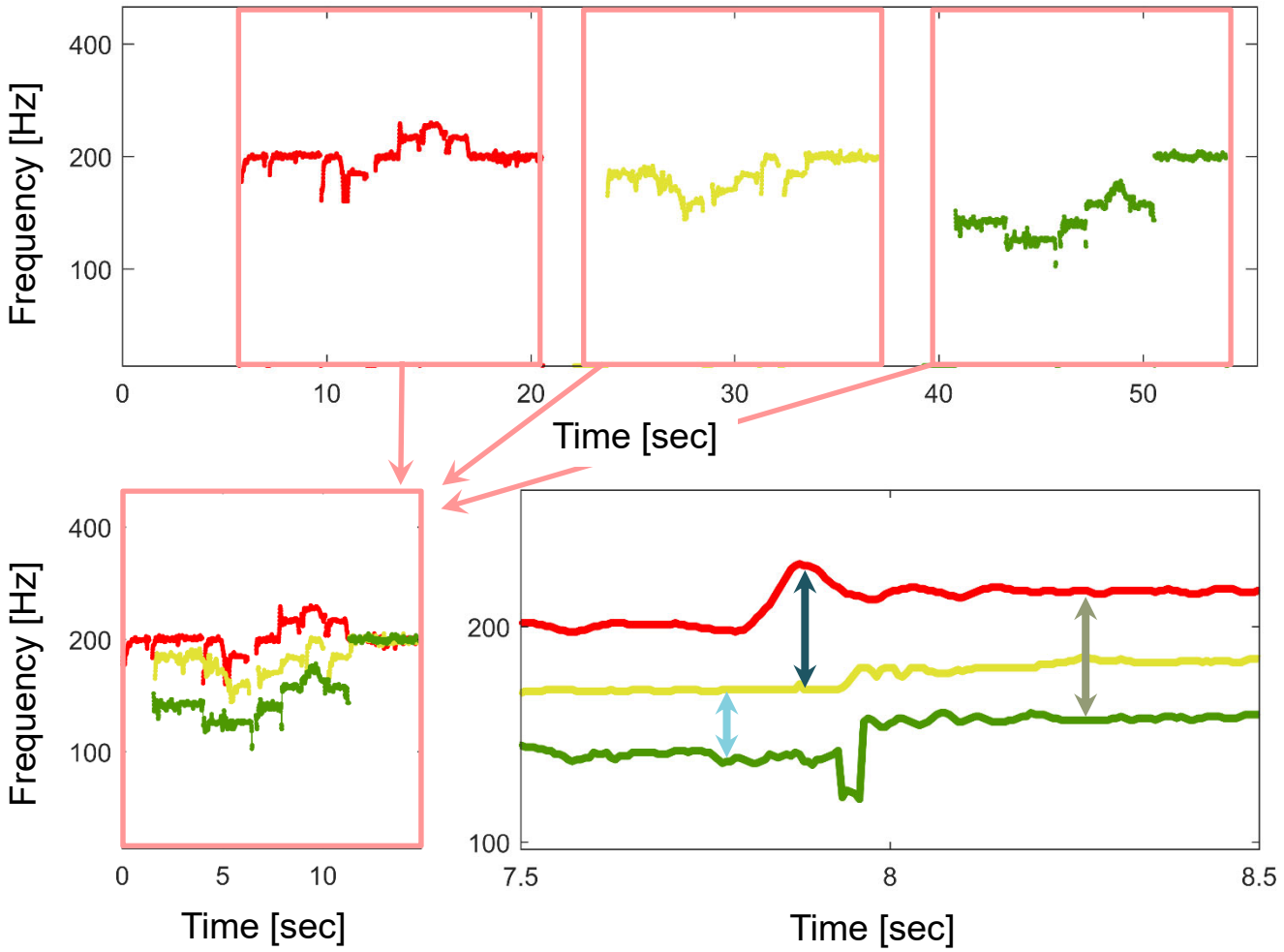
Traditional Georgian Vocal Music



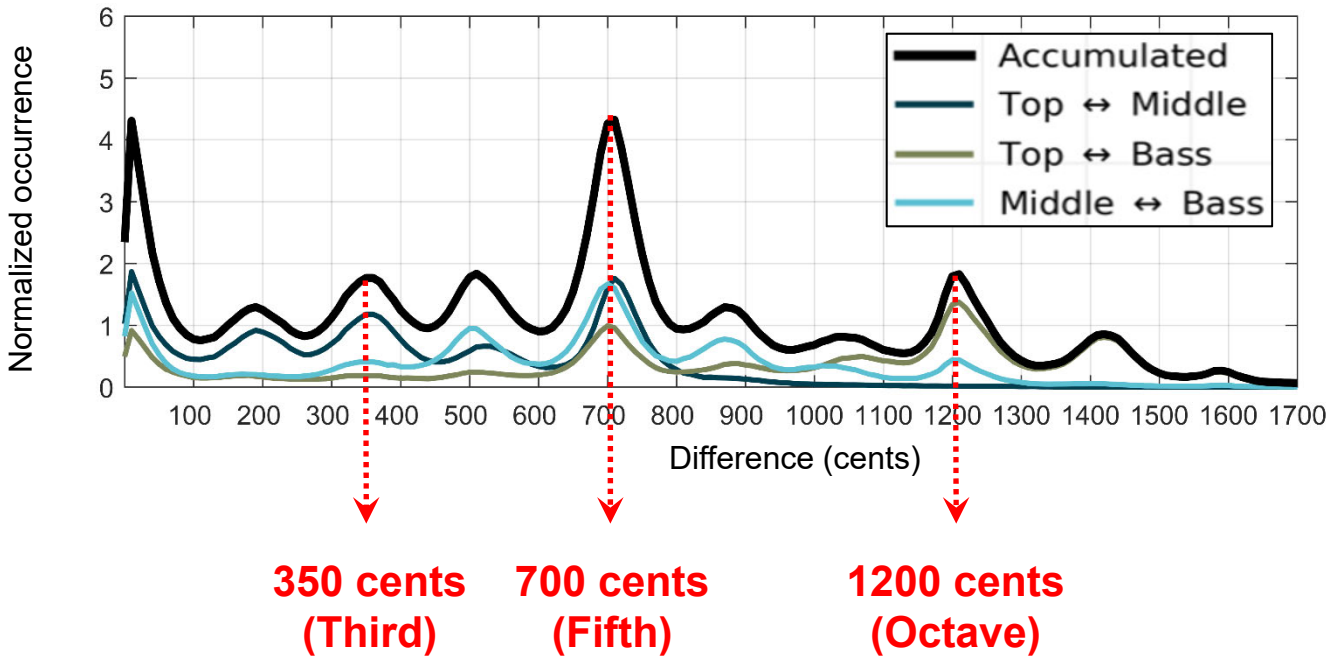
Traditional Georgian Vocal Music



Traditional Georgian Vocal Music



Traditional Georgian Vocal Music



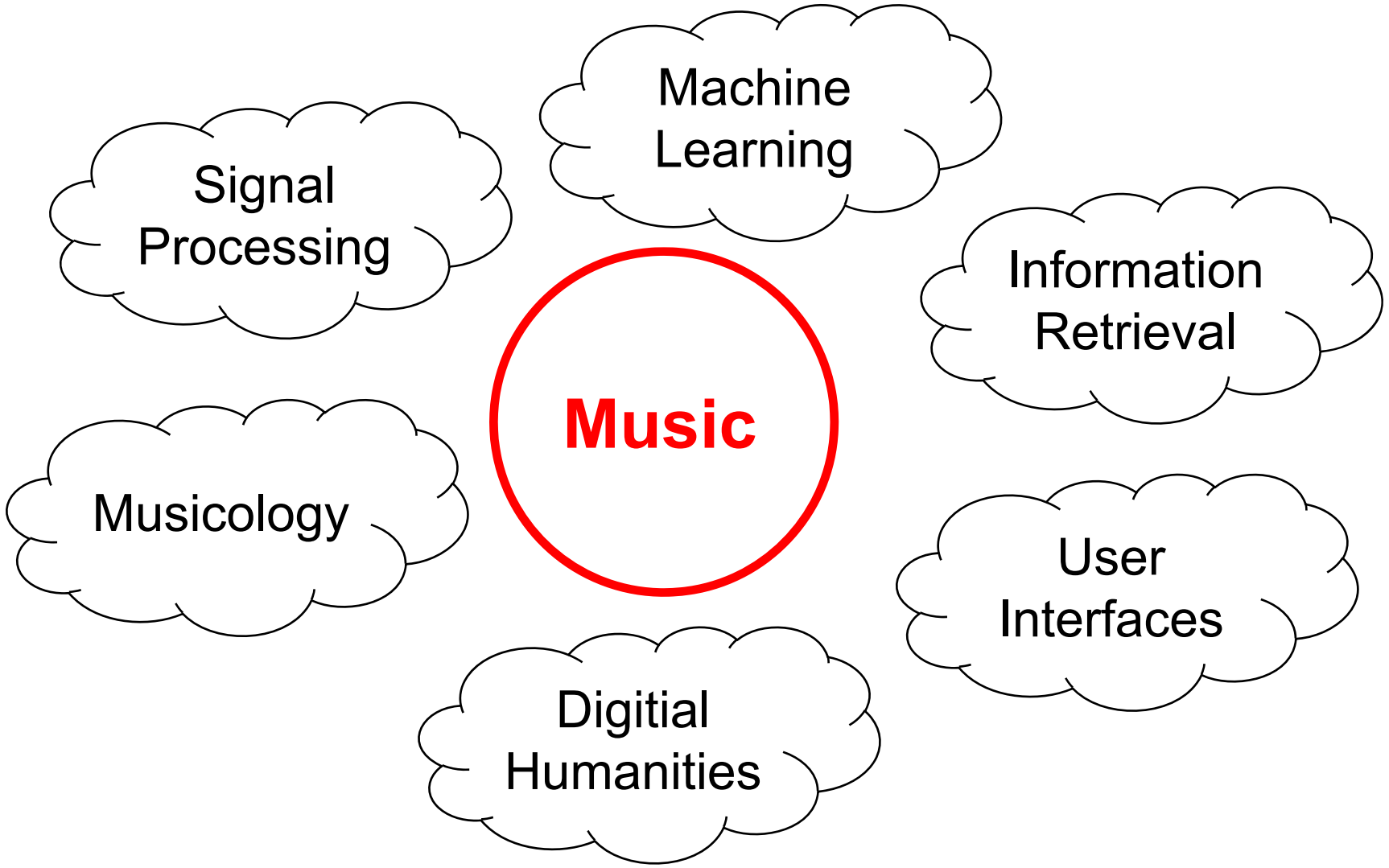
- Peak at 350 cents (between minor and major third)
- **Non-western temperament**

Traditional Georgian Vocal Music

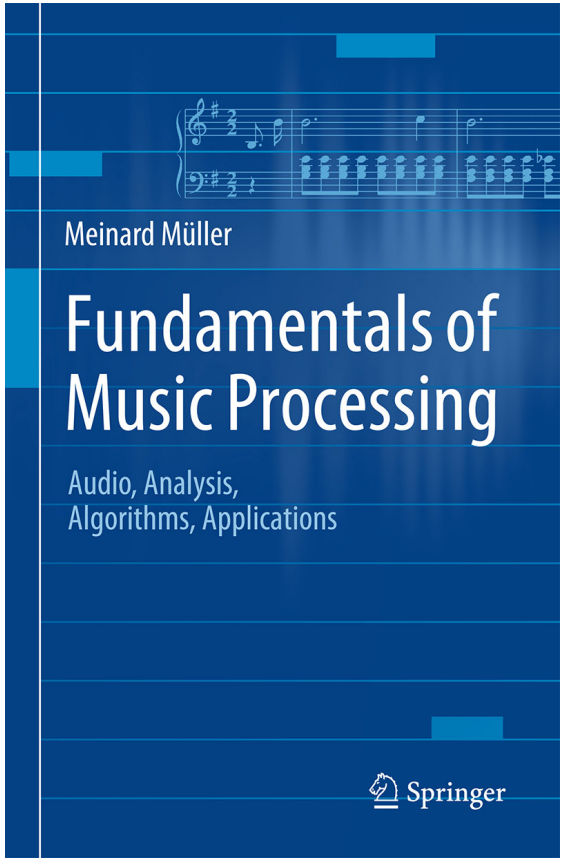
- Recordings from field expedition in 2016
- 216 performances
- Multitrack audio + video
  - Room, HSM, LRX
- Total duration: 6 h

Room Microphone

Music Information Retrieval (MIR)



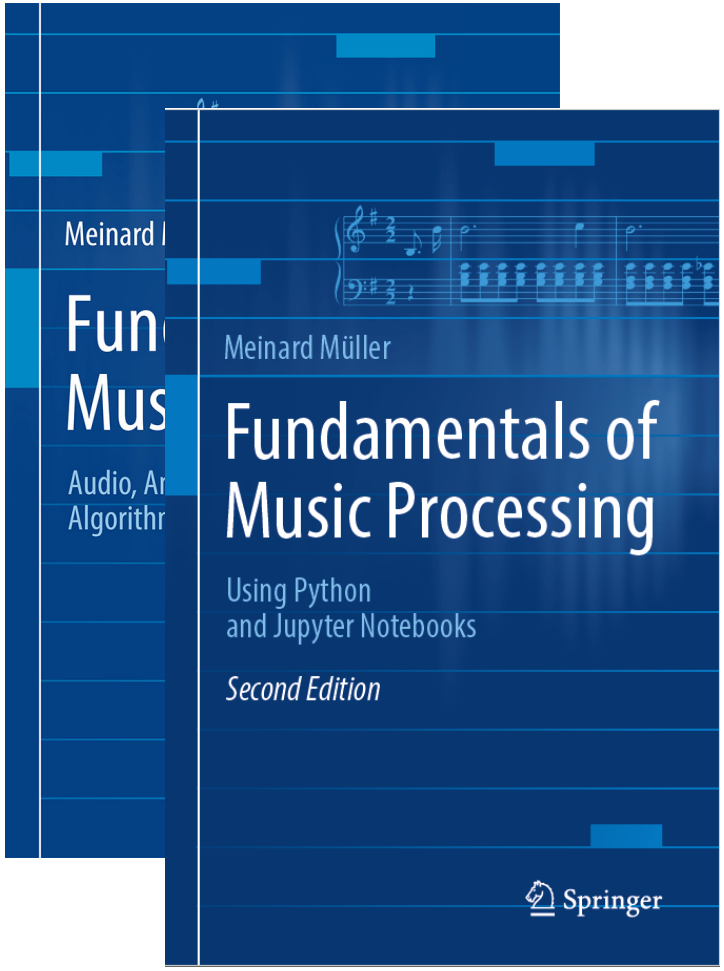
Fundamentals of Music Processing (FMP)



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

Accompanying website:
www.music-processing.de

Fundamentals of Music Processing (FMP)

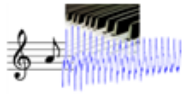
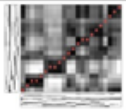
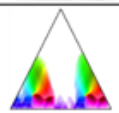
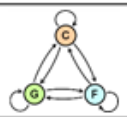
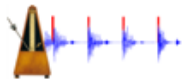
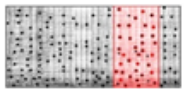
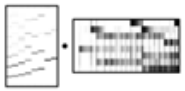


Meinard Müller
Fundamentals of Music Processing
Audio, Analysis, Algorithms, Applications
Springer, 2015

Accompanying website:
www.music-processing.de

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

Fundamentals of Music Processing (FMP)

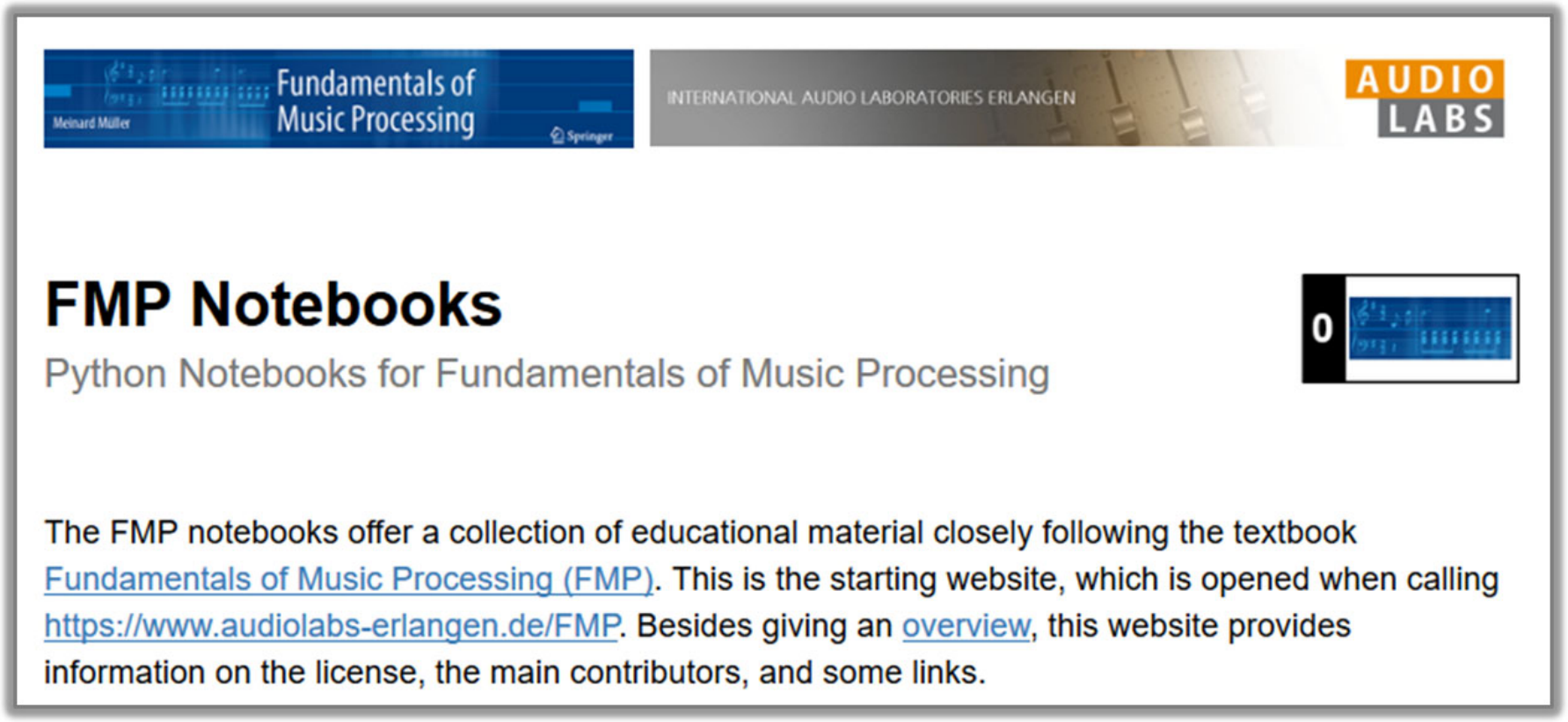
Chapter		Music Processing Scenario
1		Music Represenations
2		Fourier Analysis of Signals
3		Music Synchronization
4		Music Structure Analysis
5		Chord Recognition
6		Tempo and Beat Tracking
7		Content-Based Audio Retrieval
8		Musically Informed Audio Decomposition

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

Accompanying website:
www.music-processing.de

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

FMP Notebooks: Education & Research



https://www.audiolabs-erlangen.de/FMP

References (FMP Notebooks)

- Meinard Müller: Fundamentals of Music Processing – Using Python and Jupyter Notebooks. 2nd Edition, Springer, 2021.
  https://www.springer.com/gp/book/9783030698072

- Meinard Müller and Frank Zalkow: libfmp: A Python Package for Fundamentals of Music Processing. Journal of Open Source Software (JOSS), 6(63): 1–5, 2021.
  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.
  https://zenodo.org/record/3527872#.YOhEQOgzaUk

- 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