

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 (ISMIR)
- IEEE Fellow for contributions to Music Signal Processing



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



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

International Audio Laboratories Erlangen



Audio

International Audio Laboratories Erlangen

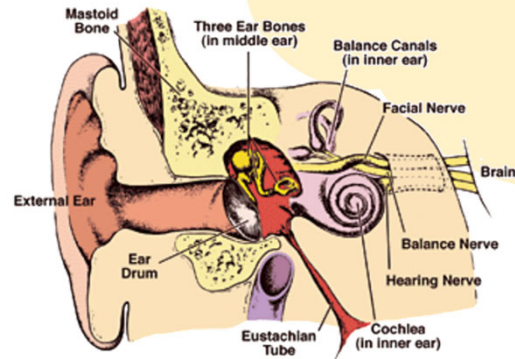
Audio Coding



3D Audio



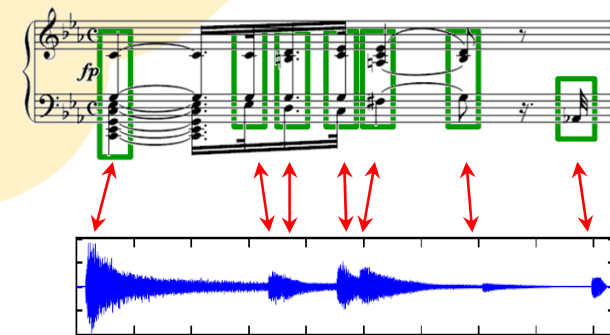
Audio



Psychoacoustics



Internet of Things



Music Processing



Music

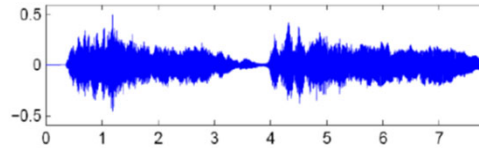


Music Information Retrieval (MIR)

Sheet Music (Image)



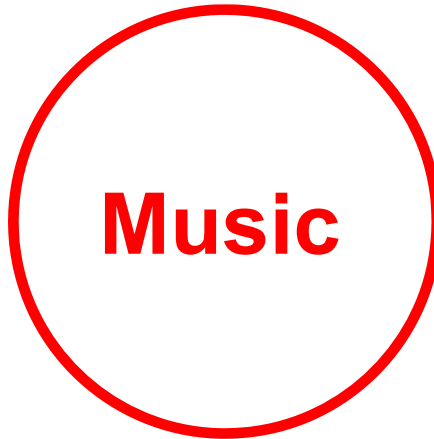
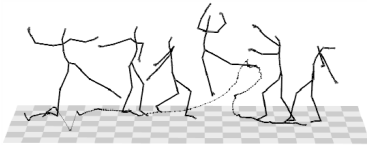
CD / MP3 (Audio)



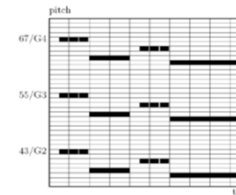
MusicXML (Text)

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

Dance / Motion (Mocap)



MIDI



Singing / Voice (Audio)



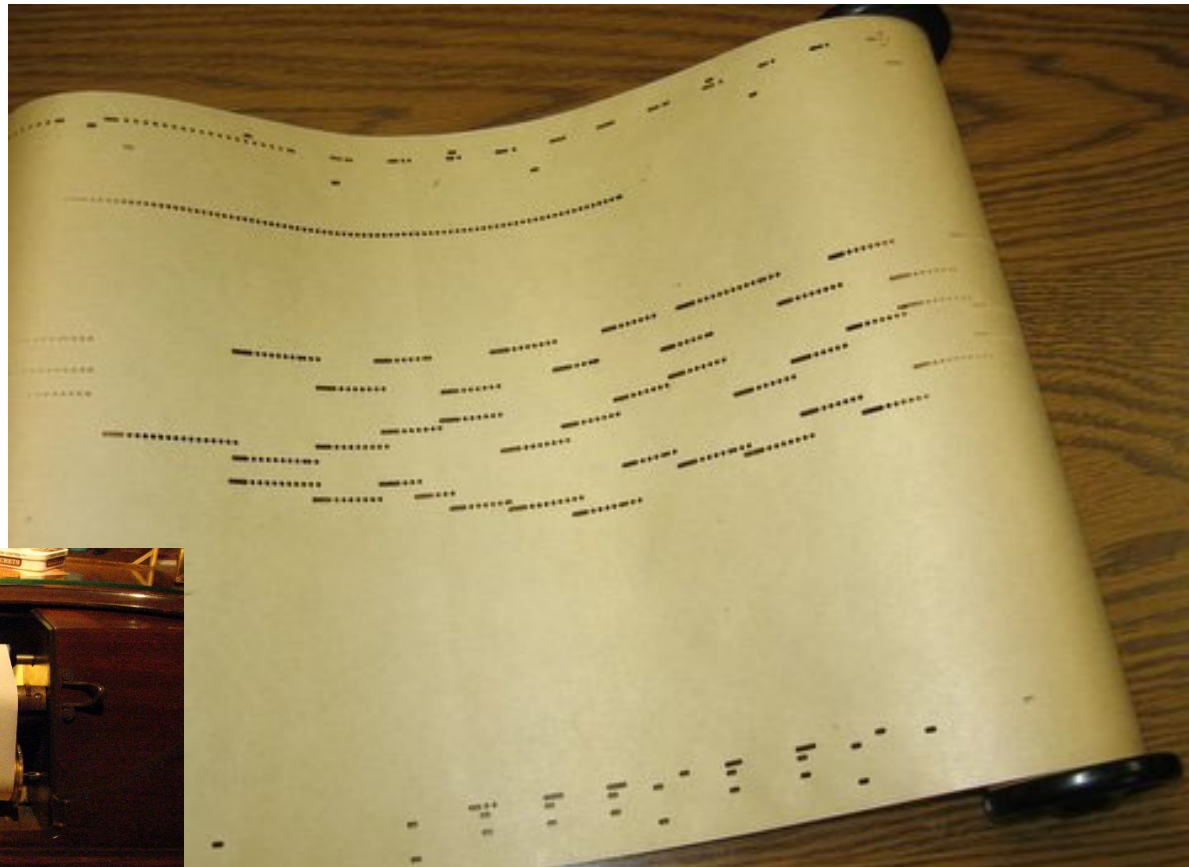
Music Film (Video)



Music Literature (Text)



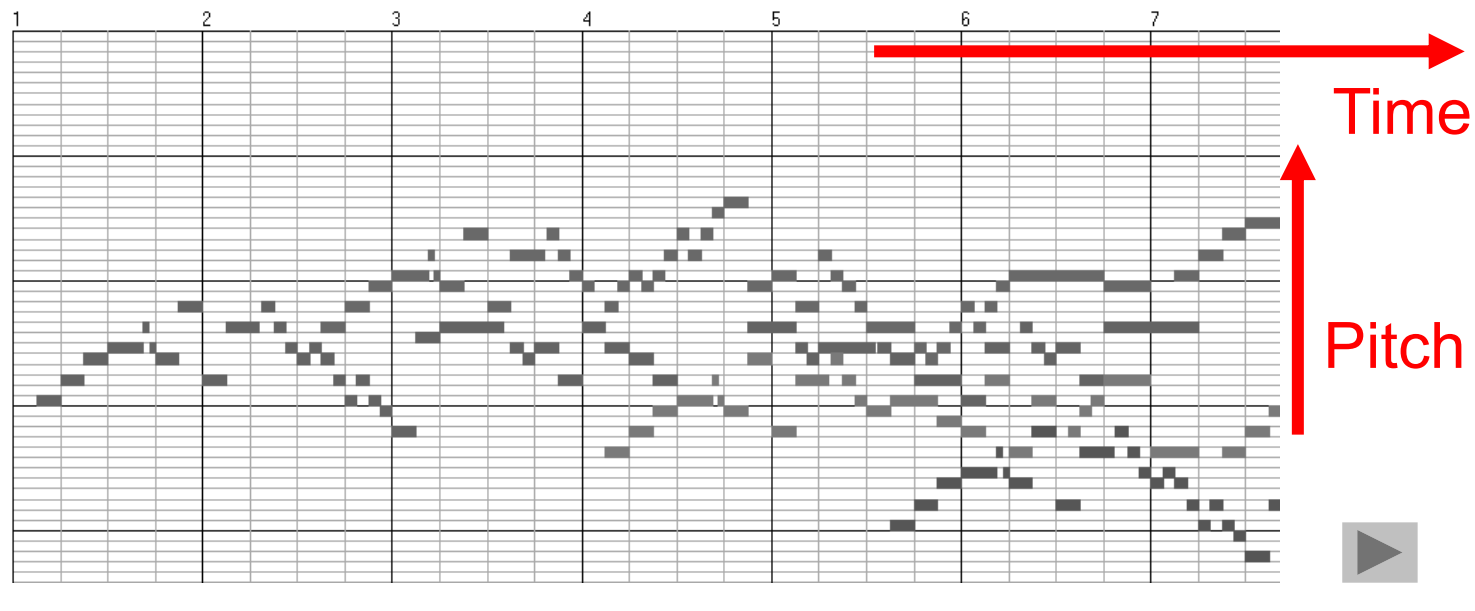
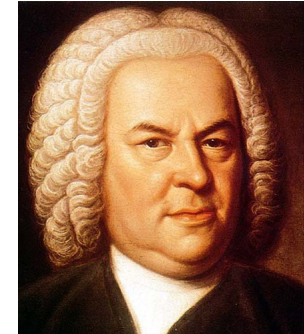
Piano Roll Representation (1900)



Piano Roll Representation

J.S. Bach, C-Major Fuge

(Well Tempered Piano, BWV 846)

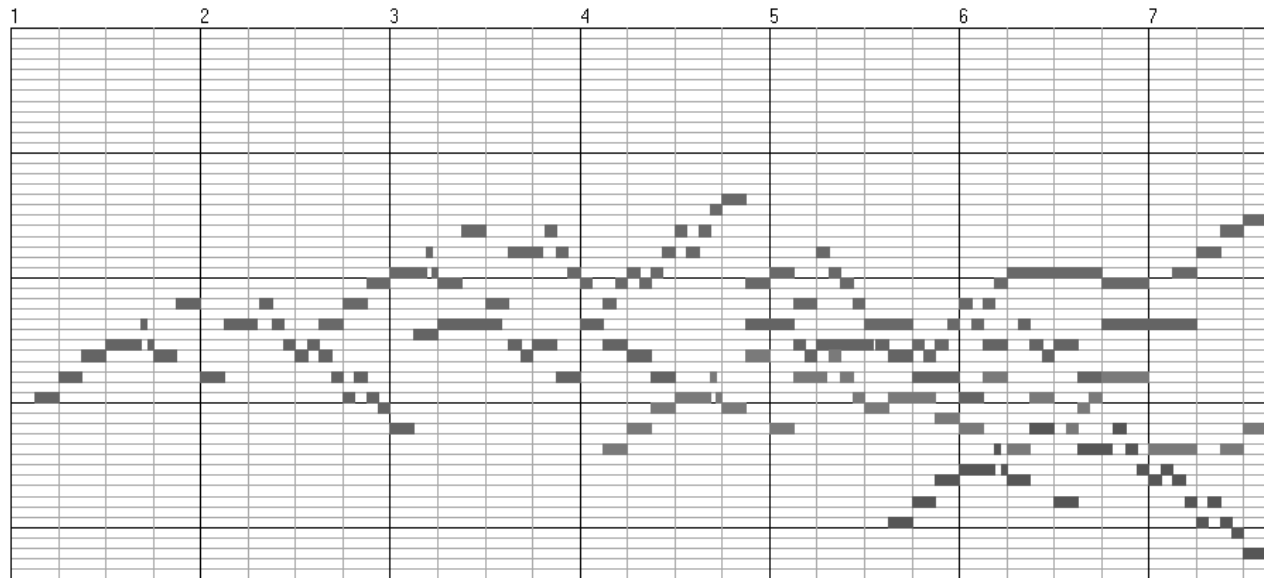
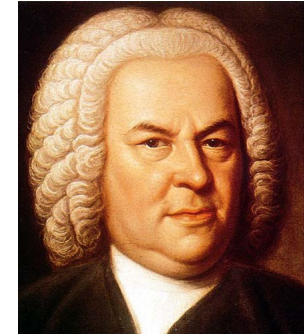


Piano Roll Representation

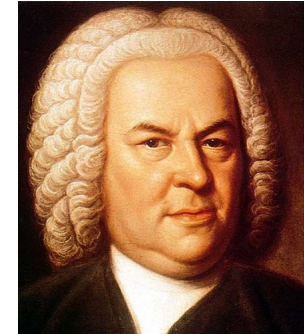
Query:



Goal: Find all occurrences of the query



Piano Roll Representation

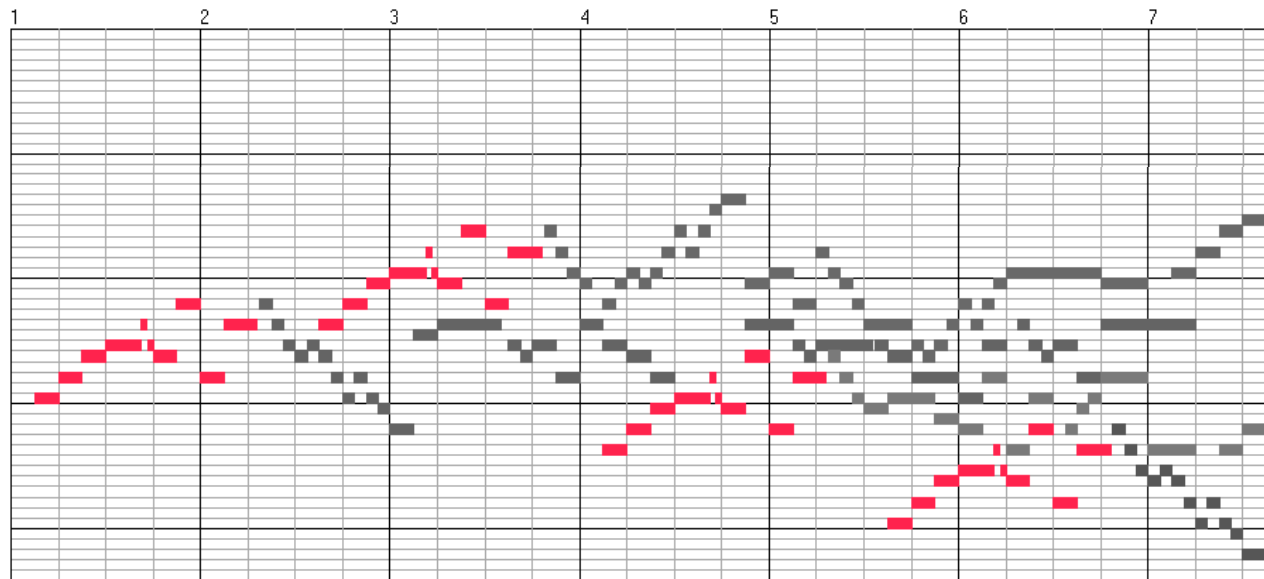


Query:

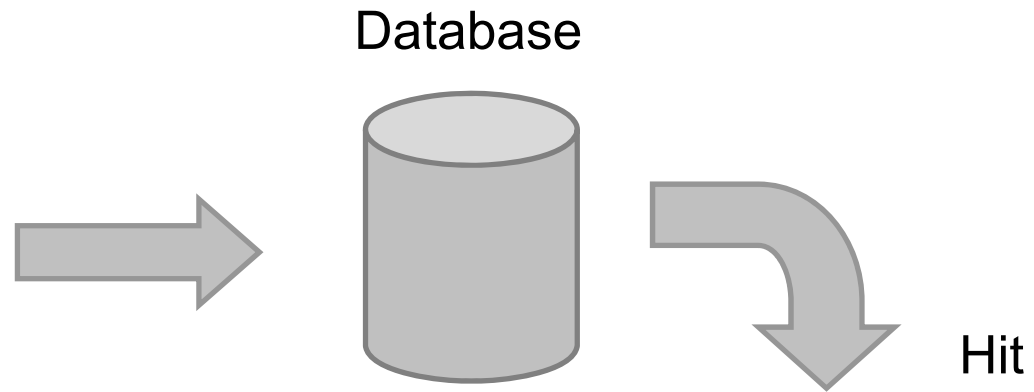


Goal: Find all occurrences of the query

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

The screenshot displays two windows from a music synchronization application:

- ScoreViewer:** Shows the musical score for "Beethoven - Klaviersonaten Band 1 - Henle". The current track is "Sonata no.8 in C minor, op.13 'Pathétique' / Rondo (Allegro)". The score is displayed in a multi-staff format. The interface includes navigation controls for Track (29 / 54), Bar (1 / 211), and Page (159 / 285). A "Score Following On" indicator and "Play" / "Stop" buttons are visible.
- AudioViewer:** Shows a playlist for "Beethoven - Piano Sonatas-Alfred Brendel". The current track is "11 Sonata no.8 in C minor, op.13 'Pathétique' / Rondo (Allegro)" with a duration of 4:20. The interface includes navigation controls for Disc (1 / 11), Track (11 / 11), and Time (00:00.00 / 4:30.35). A "Play" / "Stop" button is visible.

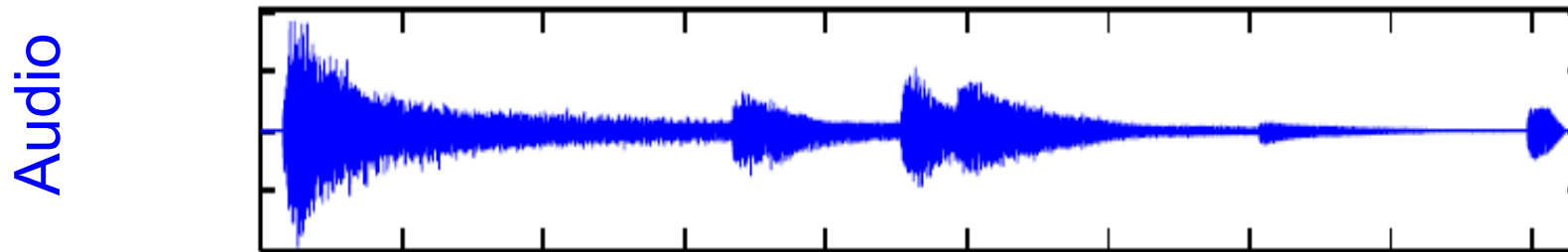
Music Synchronization: Image-Audio

Image

Grave.



A musical score for piano, marked 'Grave.' and 'fp'. The score is written for a grand piano, with a treble clef on the upper staff and a bass clef on the lower staff. The key signature is three flats (B-flat, E-flat, A-flat) and the time signature is common time (C). The music features a slow, somber mood with a focus on sustained chords and melodic lines.



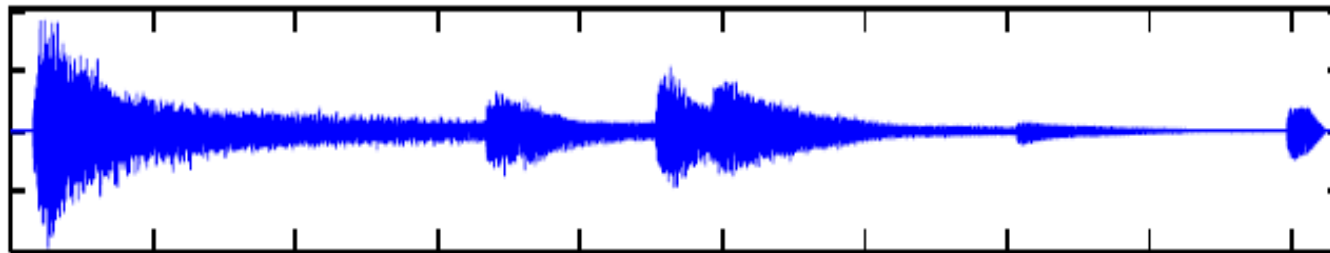
Music Synchronization: Image-Audio

Image Processing: Optical Music Recognition

Image



Audio



Music Synchronization: Image-Audio

Image Processing: Optical Music Recognition

Image



Audio



Audio Processing: Fourier Analysis

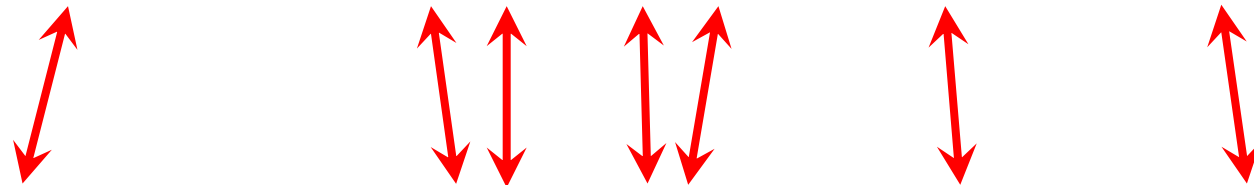
Music Synchronization: Image-Audio

Image Processing: Optical Music Recognition

Image

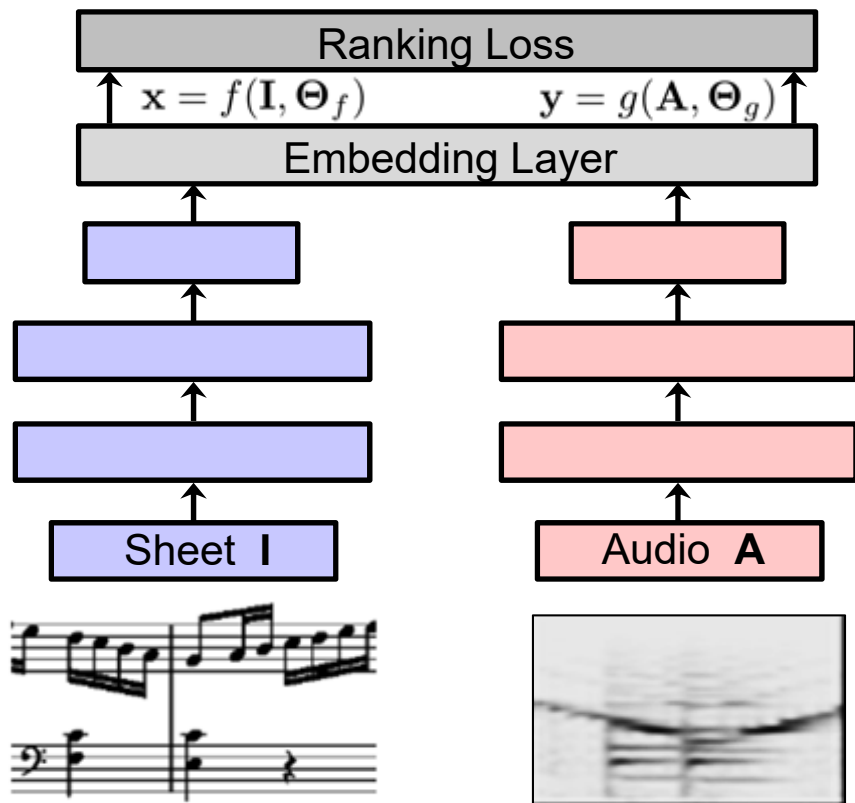


Audio



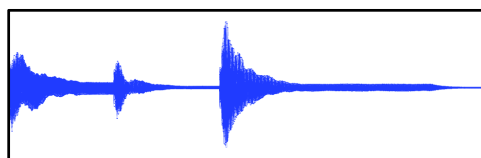
Audio Processing: Fourier Analysis

Music Synchronization: Image-Audio

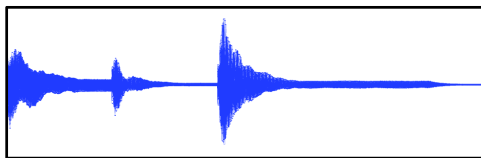
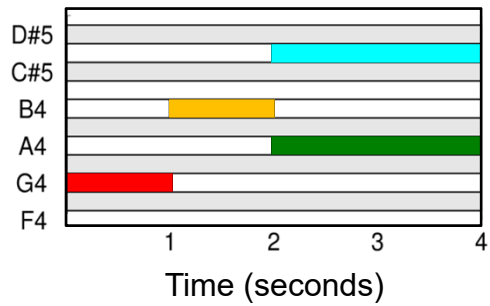
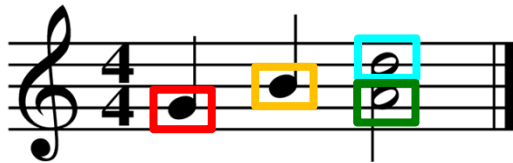


- Deep learning
- Embedding techniques
- Weak annotations
- Loss functions
- ...

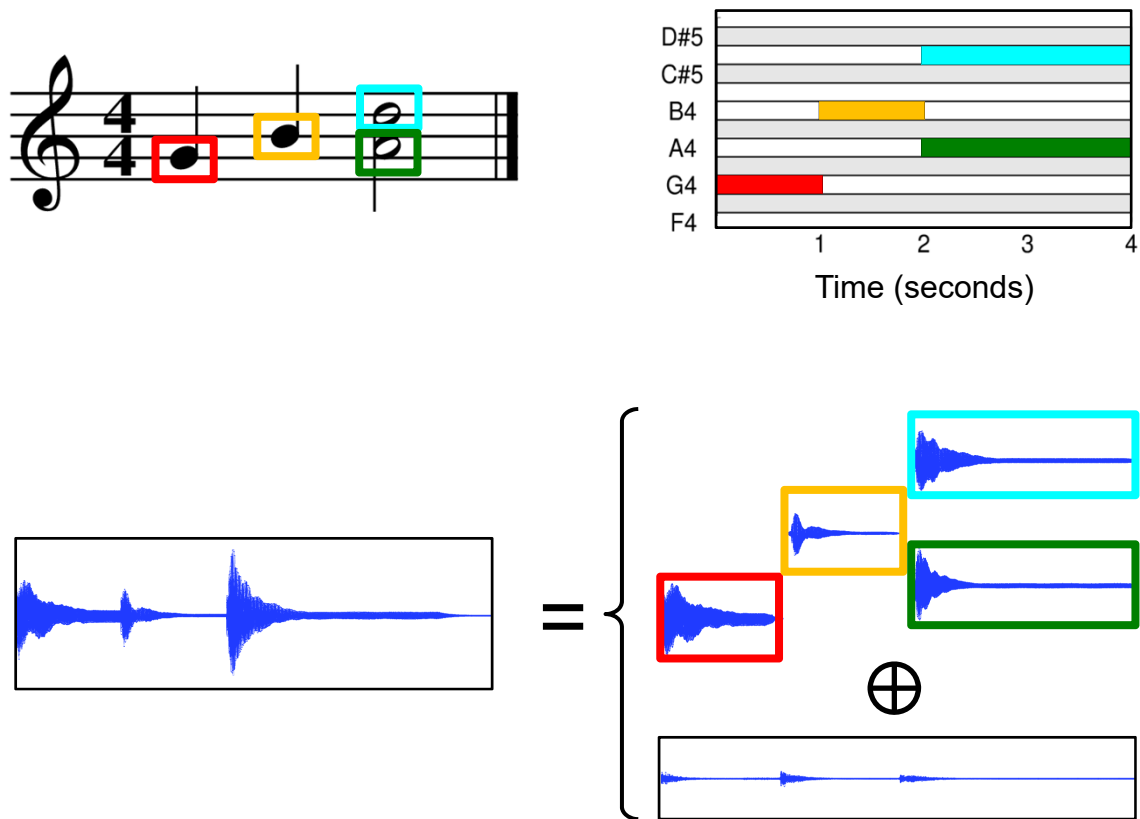
Score-Informed Audio Decomposition



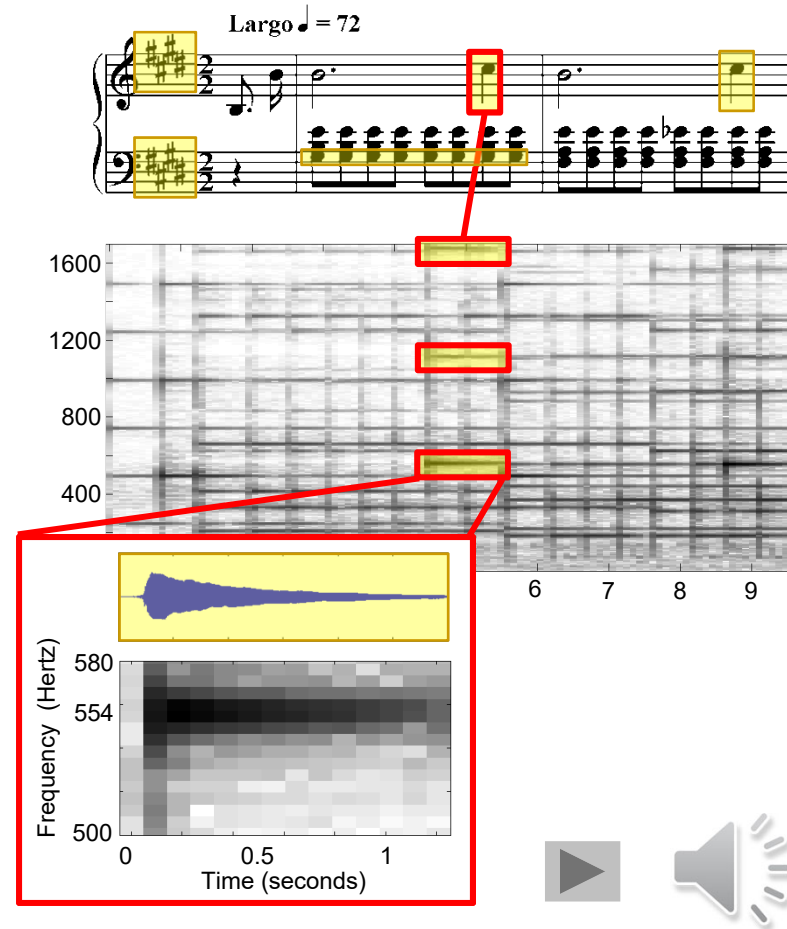
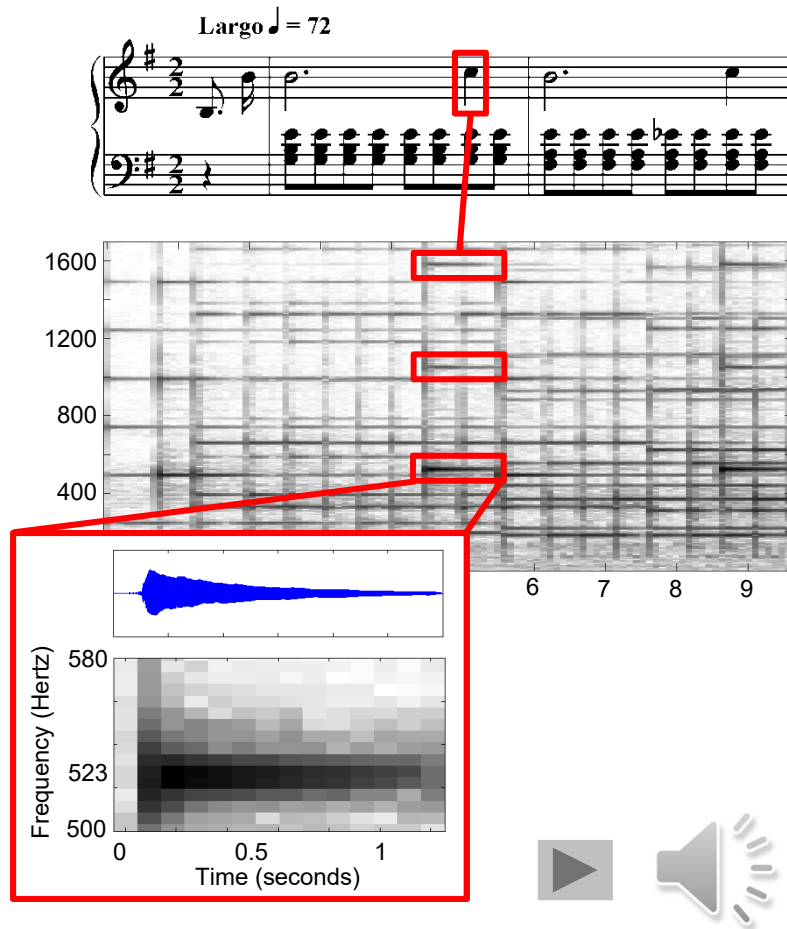
Score-Informed Audio Decomposition



Score-Informed Audio Decomposition

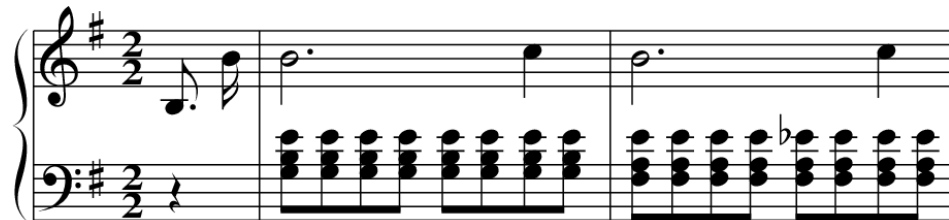


Score-Informed Audio Decomposition

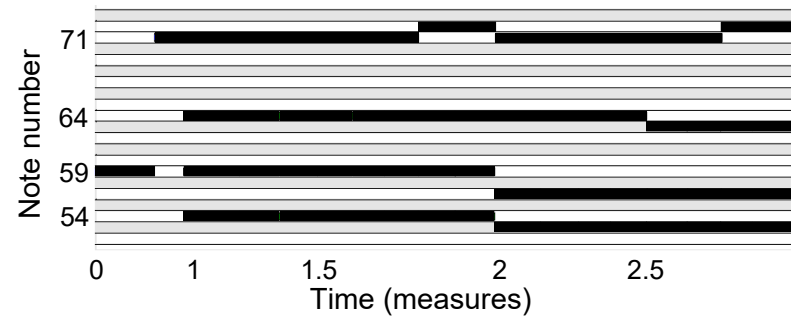


Score-Informed Audio Decomposition

Sheet music

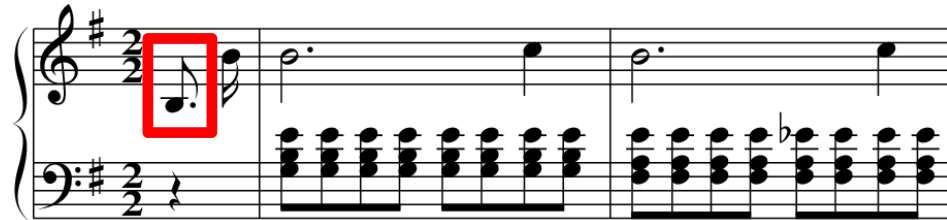


Piano roll



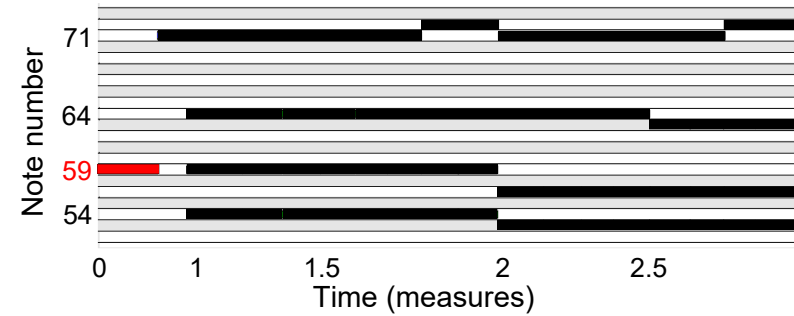
Score-Informed Audio Decomposition

Sheet music



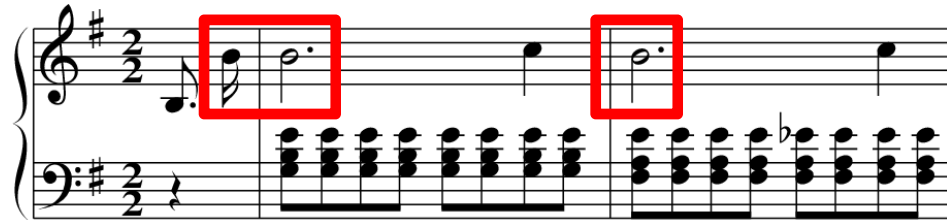
$p = 59$

Piano roll



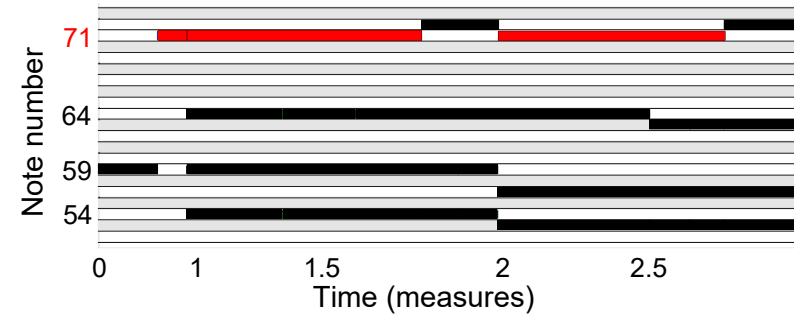
Score-Informed Audio Decomposition

Sheet music



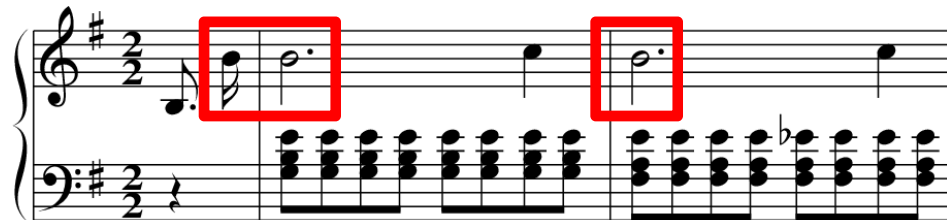
$p = 71$

Piano roll



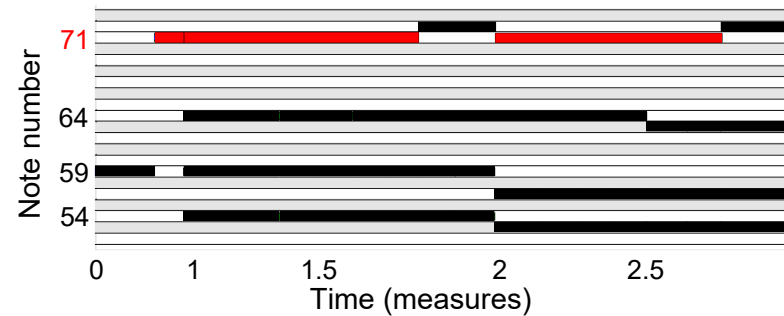
Score-Informed Audio Decomposition

Sheet music

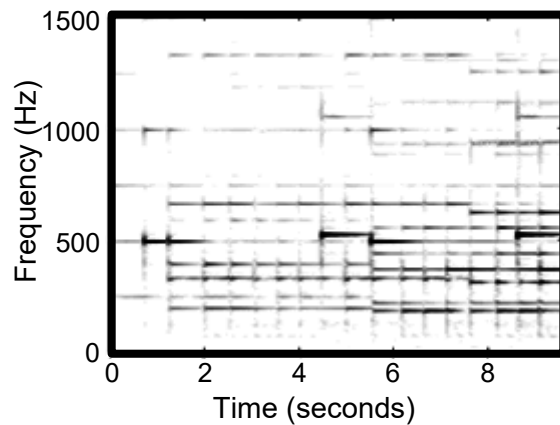


$p = 71$

Piano roll

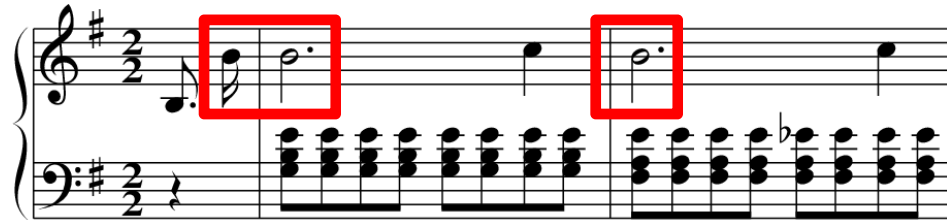


Spectrogram



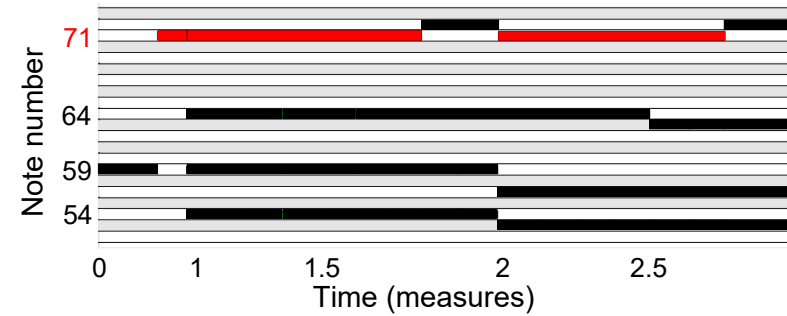
Score-Informed Audio Decomposition

Sheet music

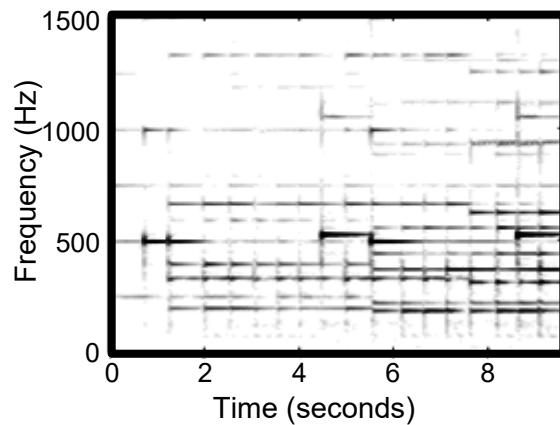


$p = 71$

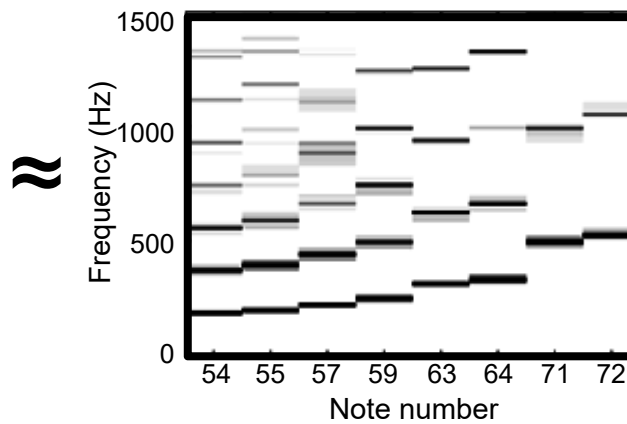
Piano roll



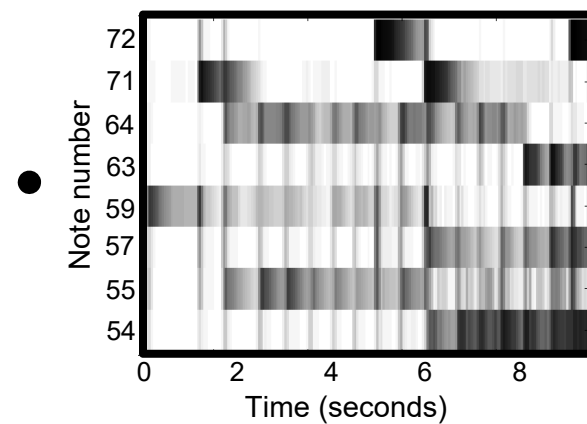
Spectrogram



Spectral patterns

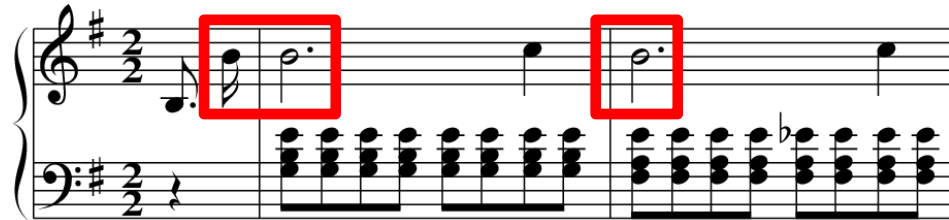


Activity patterns



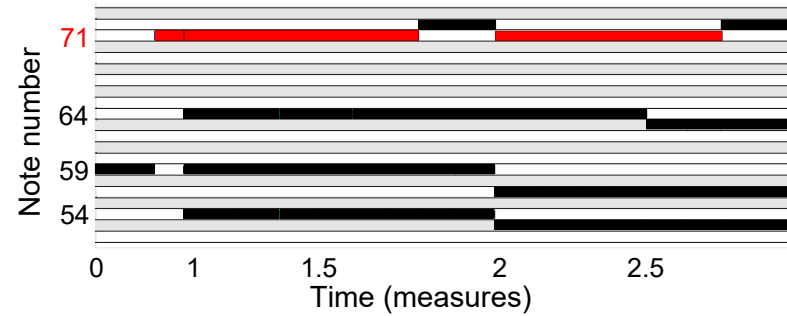
Score-Informed Audio Decomposition

Sheet music

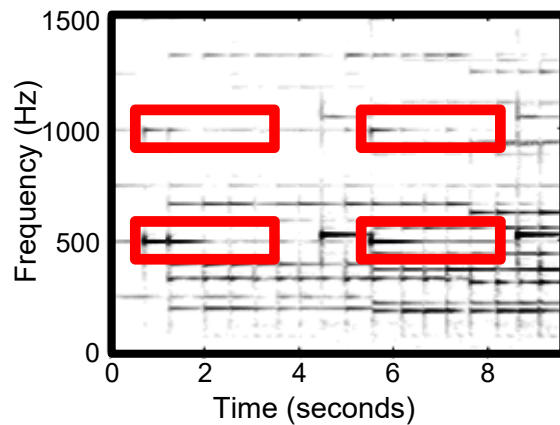


$p = 71$

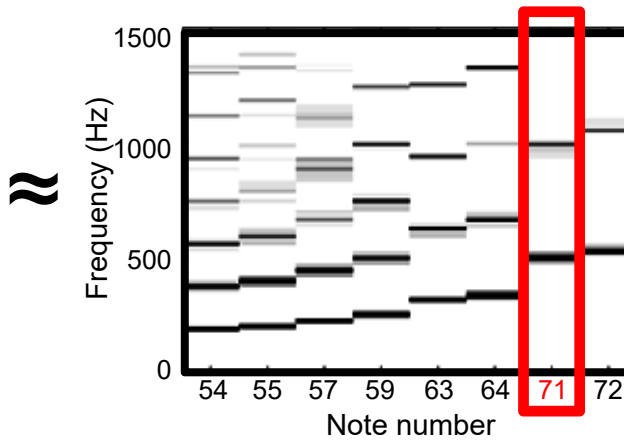
Piano roll



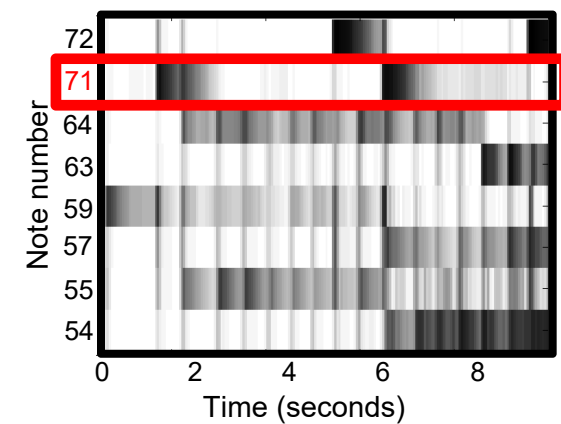
Spectrogram



Spectral patterns

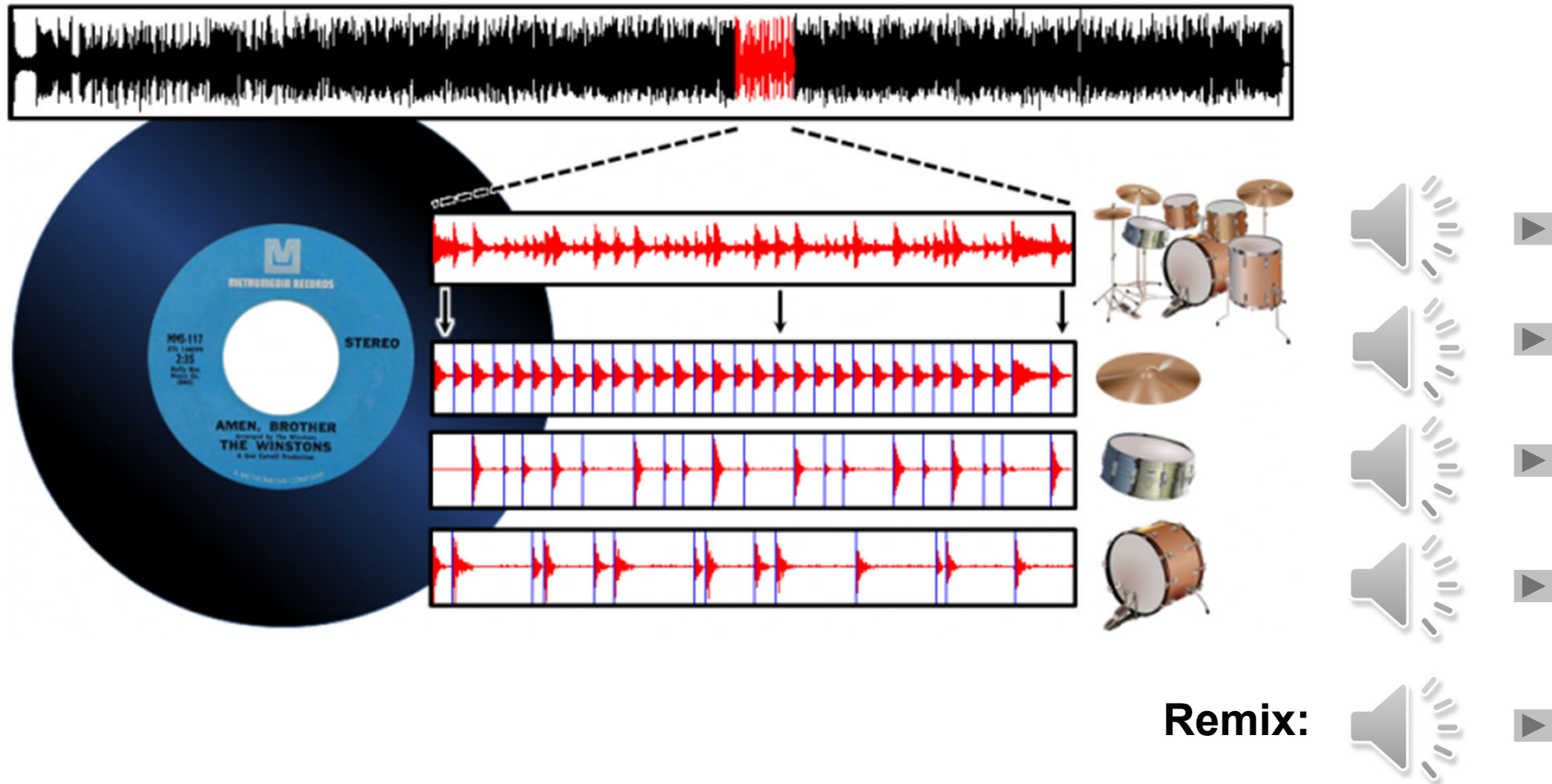


Activity patterns



Score-Informed Audio Decomposition

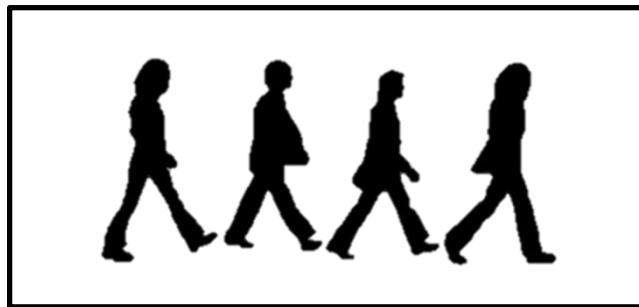
Informed Drum-Sound Decomposition



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



Mazurka.

F. CHOPIN. Op. 63, No. 3.

Allegretto.

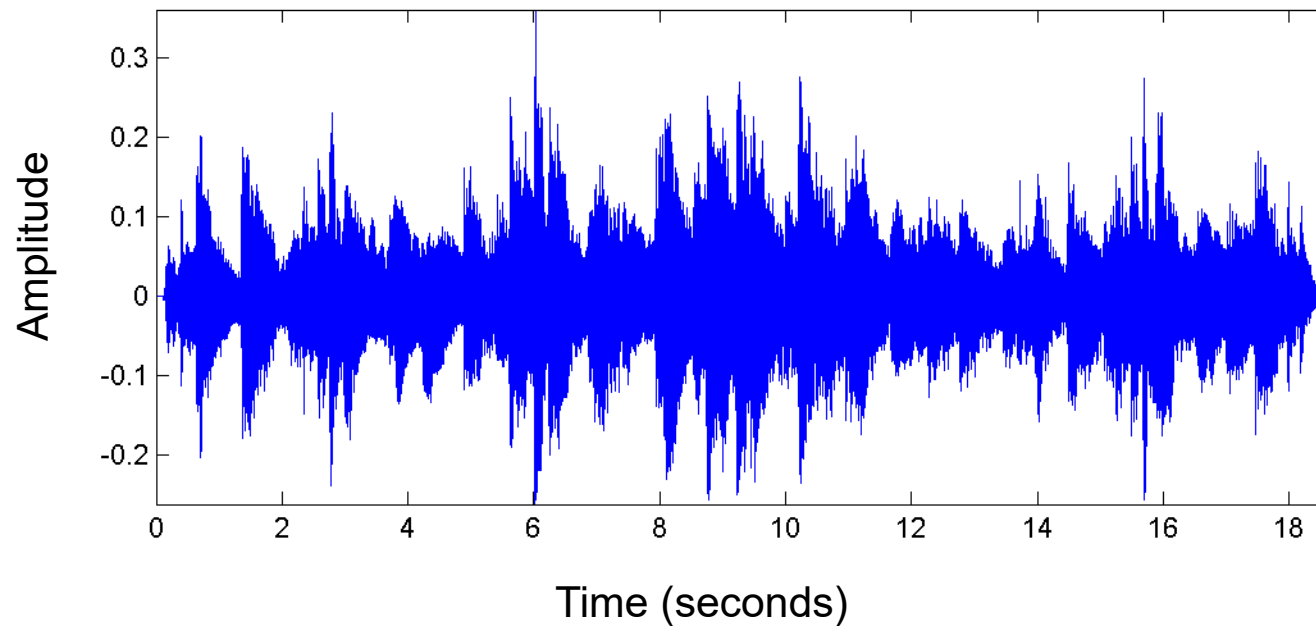
41. *p*

The image shows a musical score for Chopin's Mazurka Op. 63 No. 3, measures 41-50. It is in 3/4 time, D major, and marked 'Allegretto'. The score consists of two systems of piano music. Each system has a treble and bass clef staff. The first system starts with a piano (*p*) dynamic. The music features characteristic Mazurka rhythms, including triplets and a 'Pea' (pedal point) in the bass line. The second system continues the piece with similar rhythmic patterns and dynamics.

Why is Music Processing Challenging?

Example: Chopin, Mazurka Op. 63 No. 3

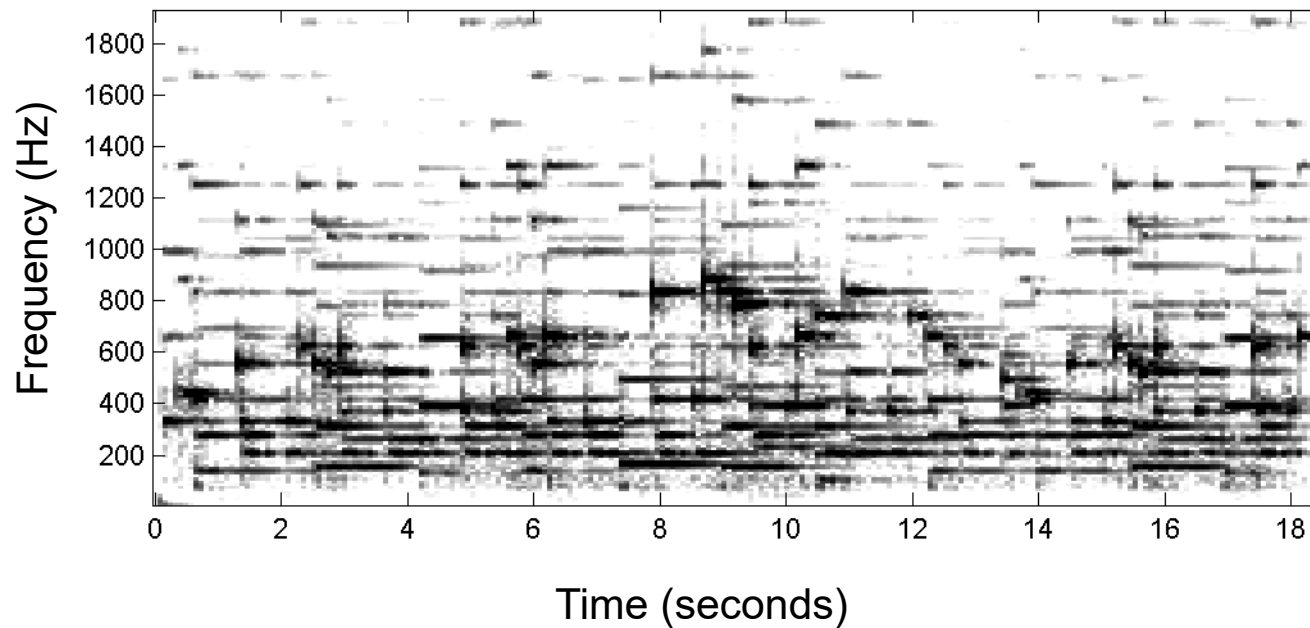
- Waveform



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

A musical score for Chopin's Mazurka Op. 63 No. 3, showing two systems of piano music. The score is annotated with performance information: blue highlights on the upper staff indicate the main melody, red highlights on the lower staff indicate an additional melody line, and yellow highlights on the lower staff indicate the accompaniment. Fingerings and dynamics like 'p' and 'f' are also visible.



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”

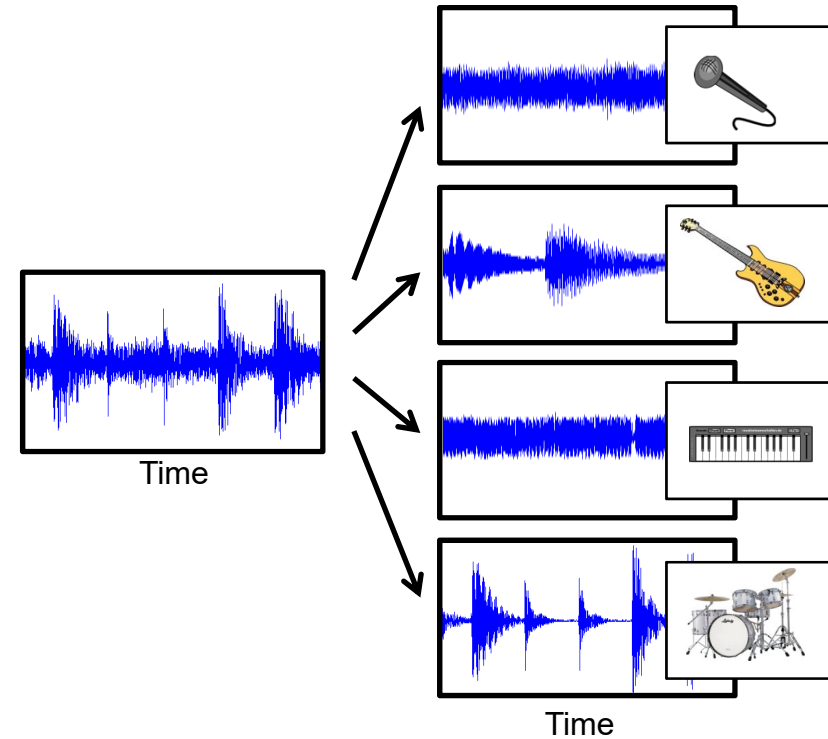


Source Separation

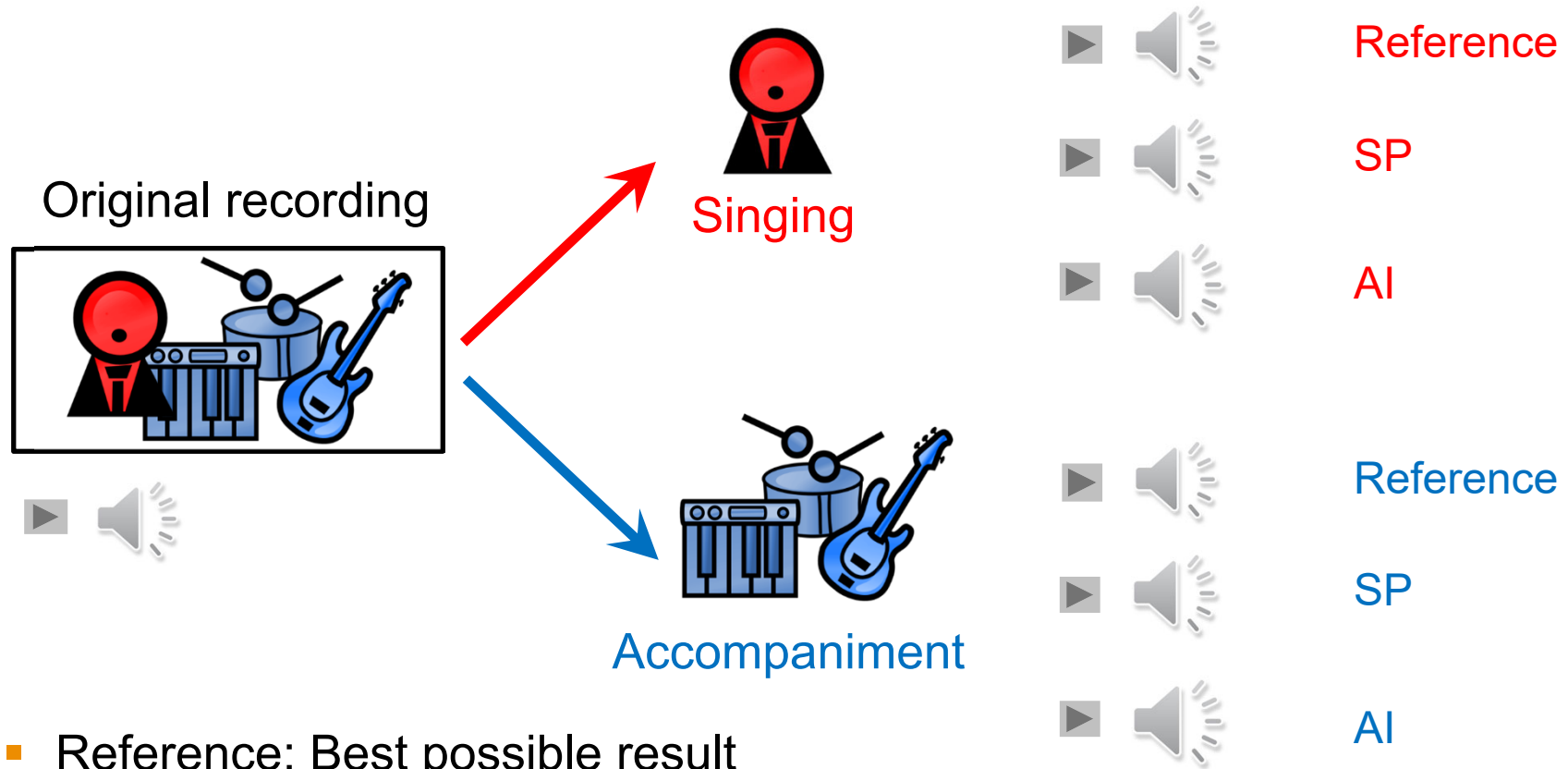
- Decomposition of audio stream into different sound sources
- Central task in digital signal processing
- “Cocktail party effect”
- Several input signals
- Sources are assumed to be statistically independent

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

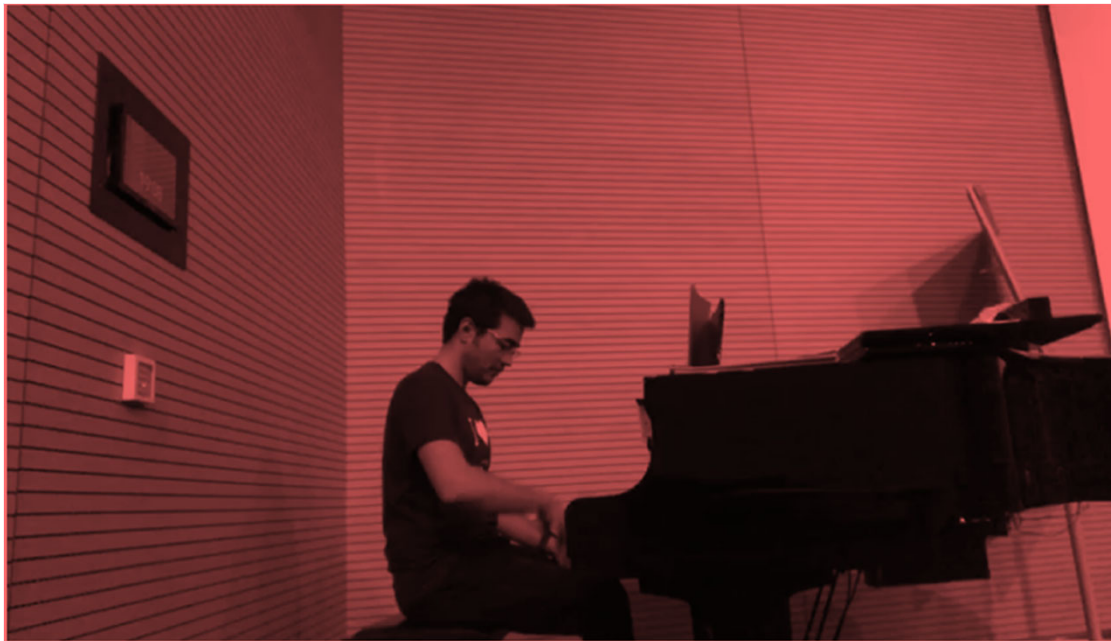
AI-Based Source Separation

- Yigitcan Özer
- PhD student in engineering
- Pianist



AI-Based Source Separation

- Yigitcan Özer
- PhD student in engineering
- Pianist



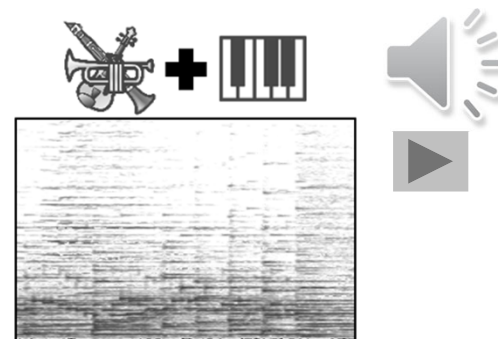
Only Piano!



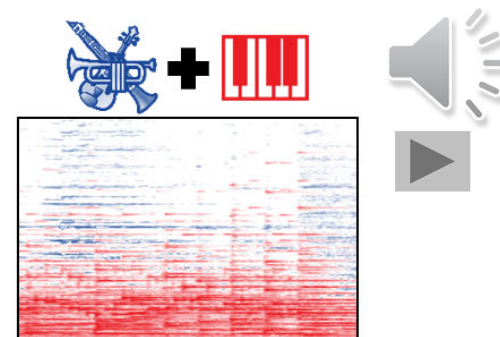
**Where is the
orchestra?**



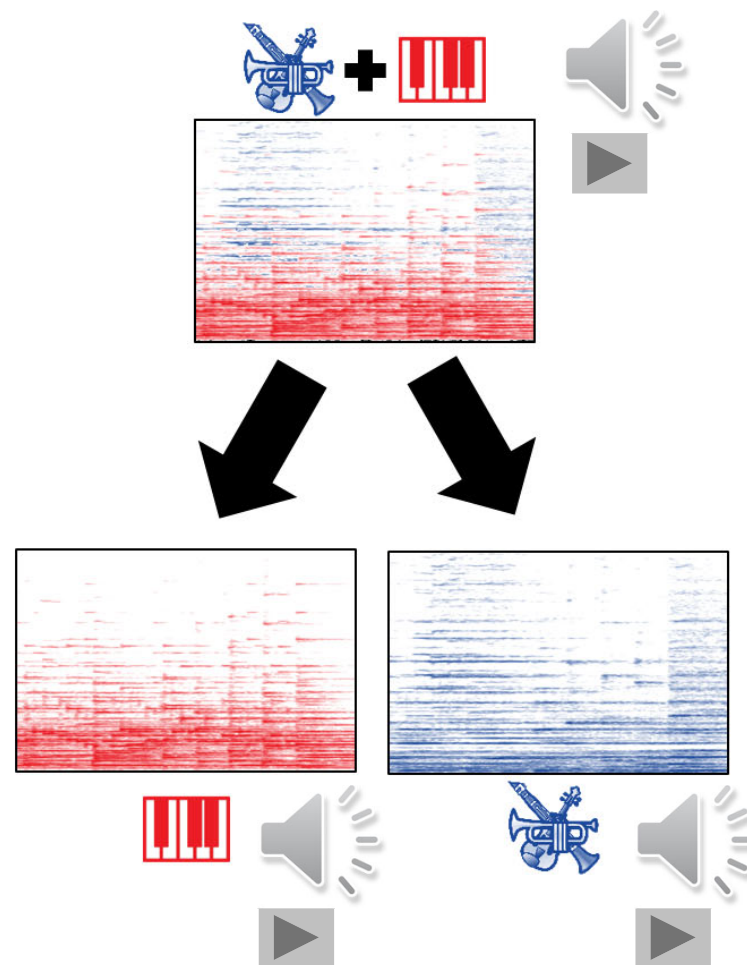
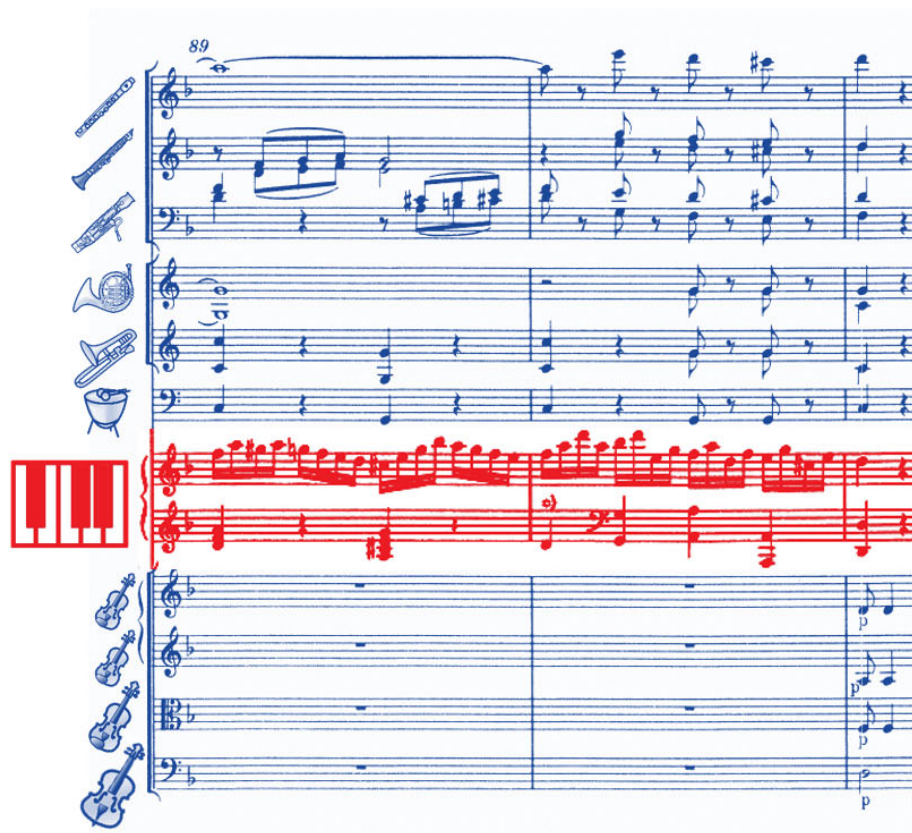
AI-Based Source Separation



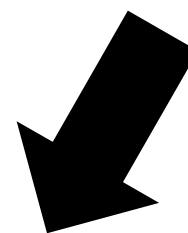
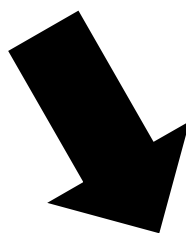
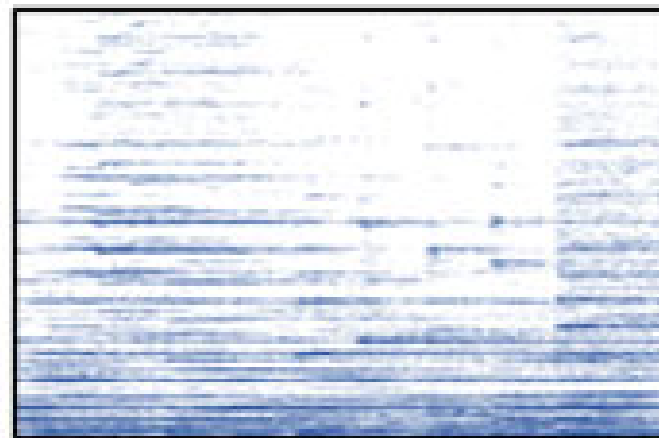
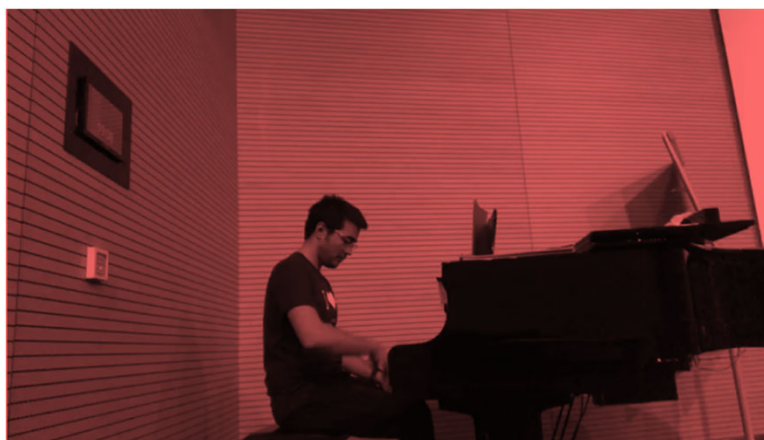
AI-Based Source Separation



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
- ...

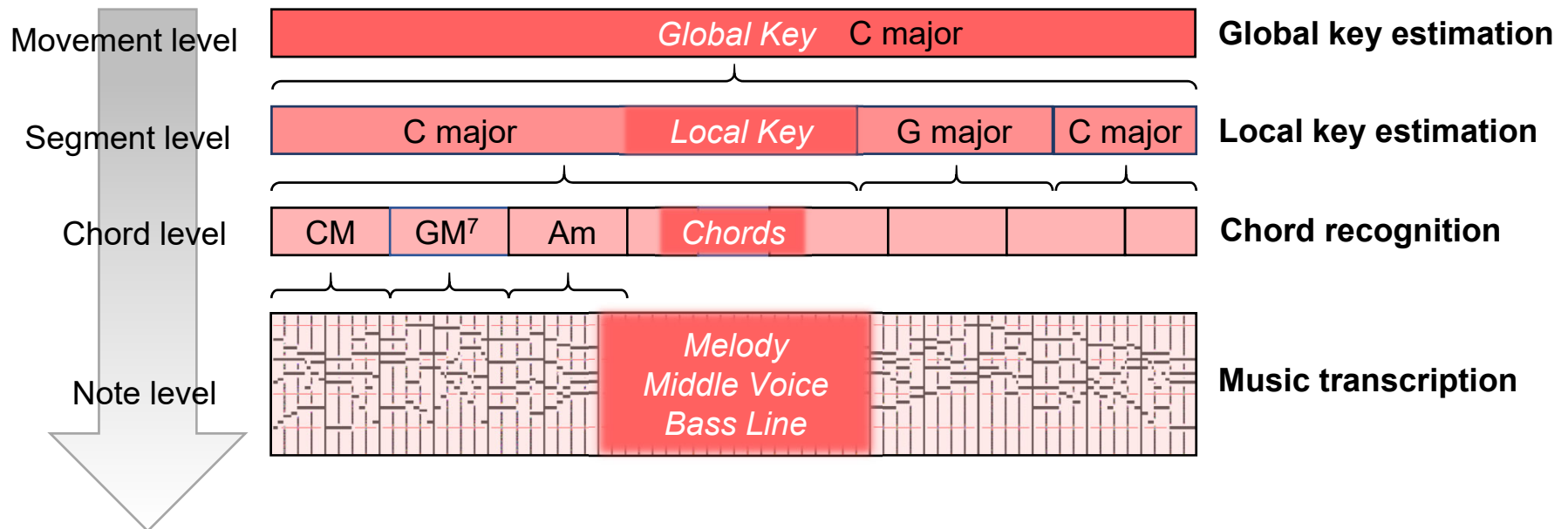
Computational Musicology

- 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



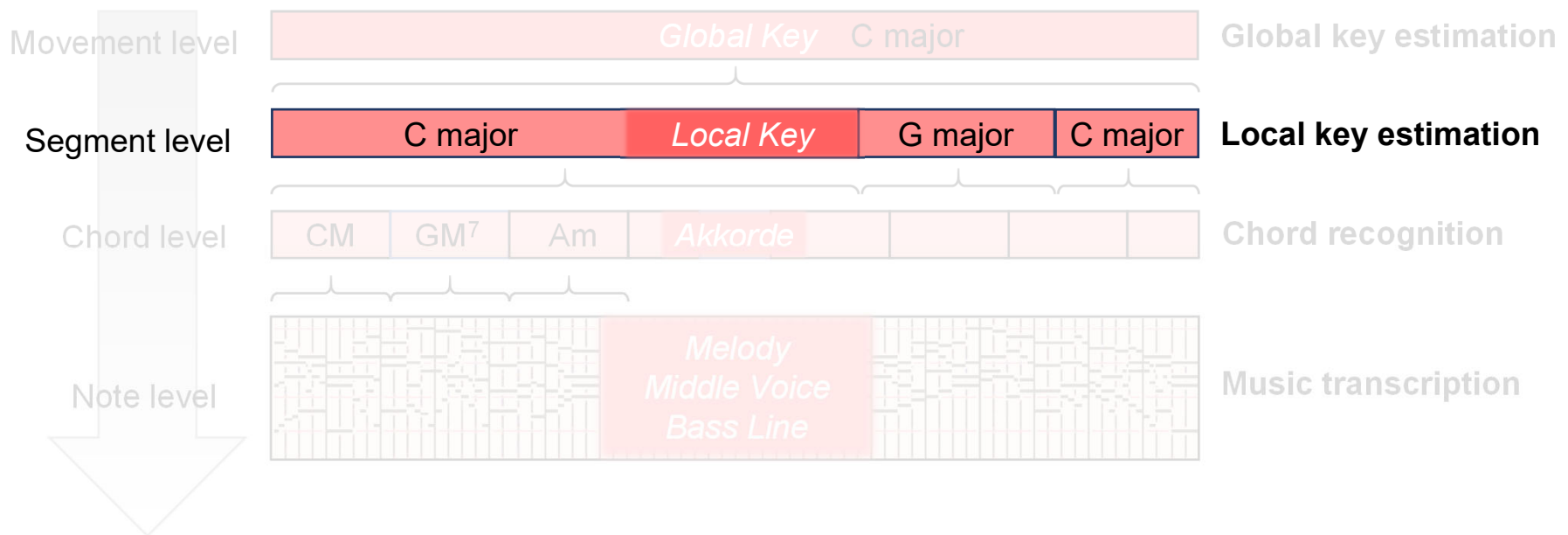
Computational Musicology: Harmony Analysis

- Different concepts
- Different temporal levels



Computational Musicology: Harmony Analysis

- Different concepts
- Different temporal levels

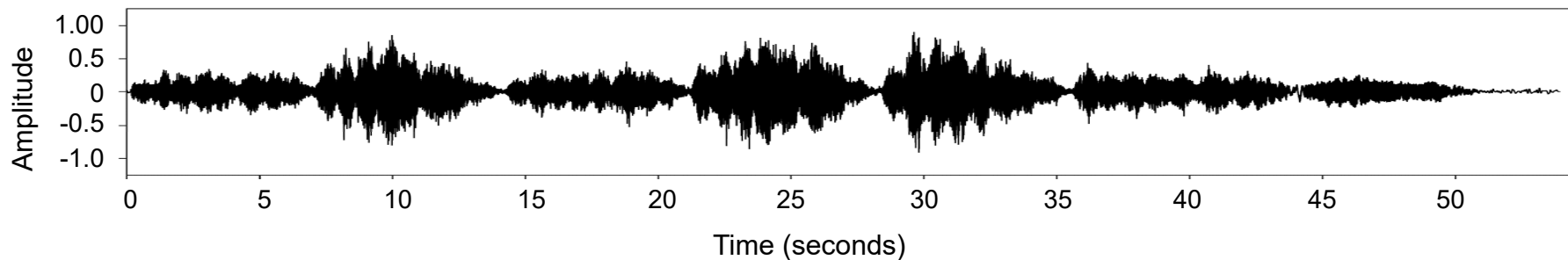


Local Key Estimation

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



Musical score for the choral piece "Durch Dein Gefängnis" by J.S. Bach. The score is in G major (one sharp) and 4/4 time. It features a vocal line with lyrics and a piano accompaniment. The lyrics are: "Durch dein Ge-fäng-nis, Got-tes Sohn, muß uns die Frei-heit kom-men; enn gingst du nicht die Knecht-schaft ein, müßt uns-re Knecht-schaft e-wig sein. Dein Ker-ker ist der Gna-den-thron, die Frei-statt al-ler From-men;".

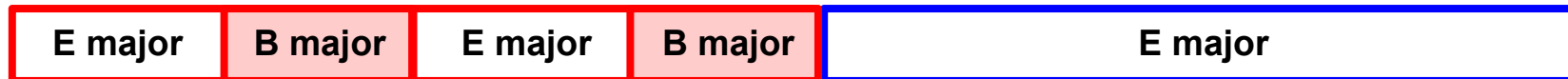
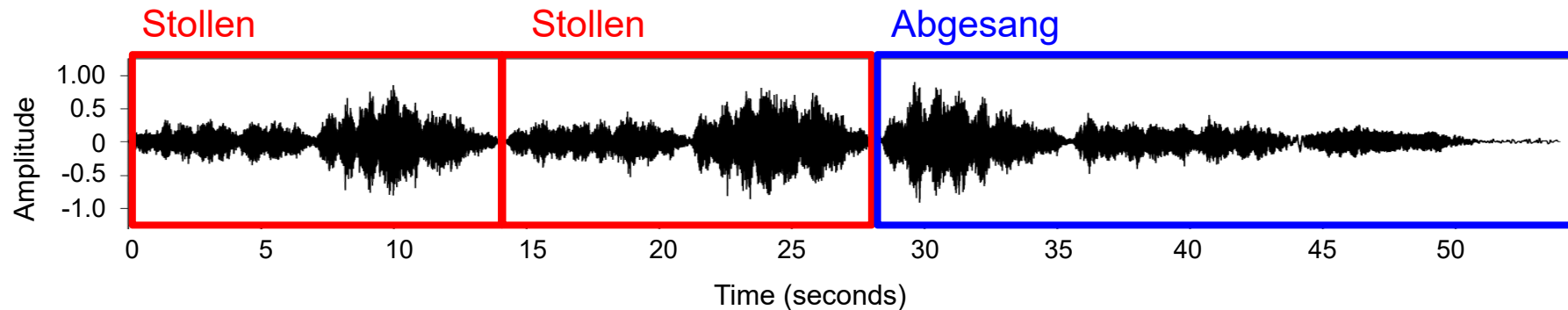


Local Key Estimation

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

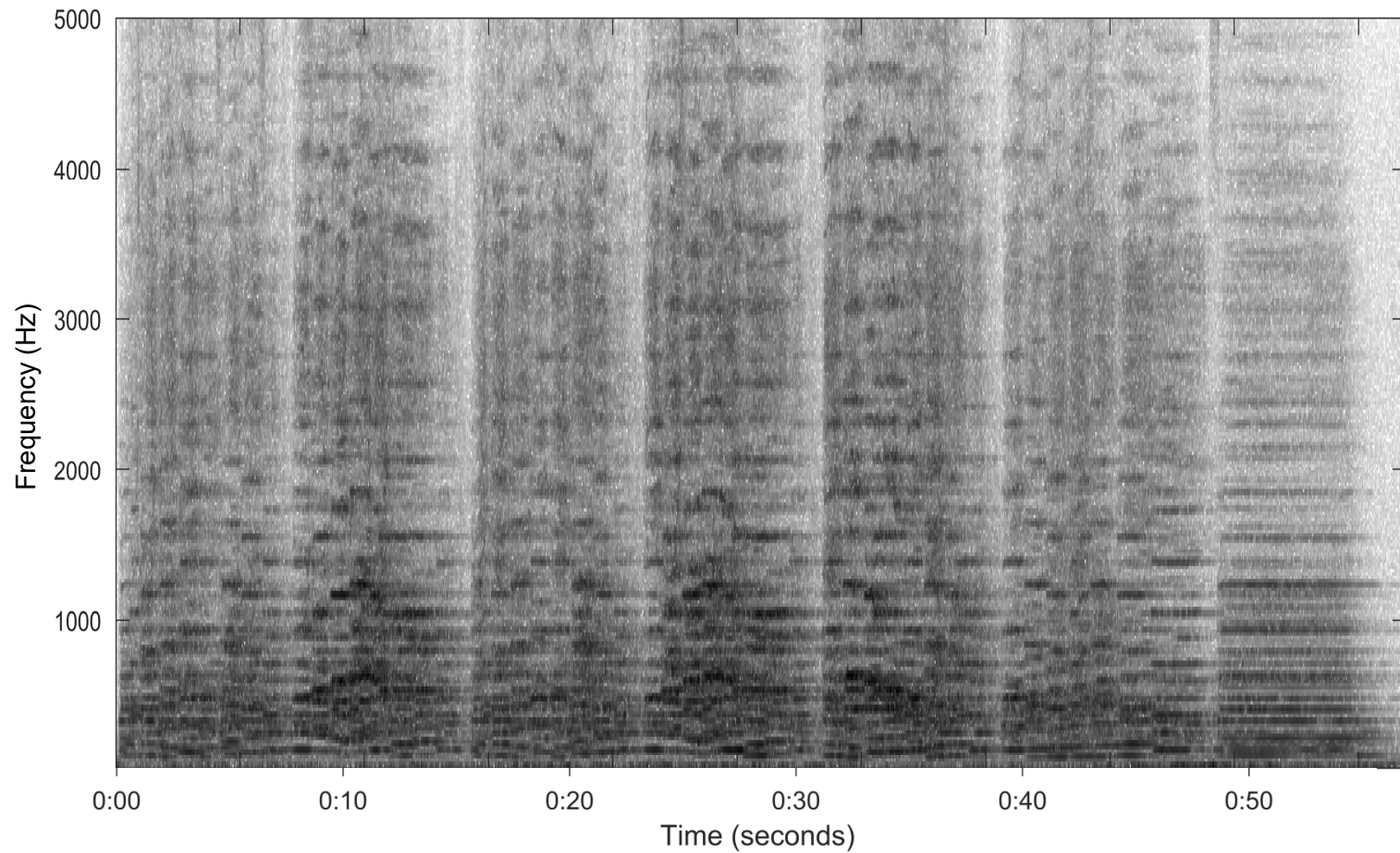
Stollen **Abgesang**

Durch dein Ge-fäng-nis, Got-tes Sohn,muß uns die Frei-heit kom-men; enn gingst du nicht die Knecht-schaft ein, müßt uns-re Knecht-schaft e-wig sein.
Dein Ker-ker ist der Gna-den-thron, die Frei-statt al-ler From-men;



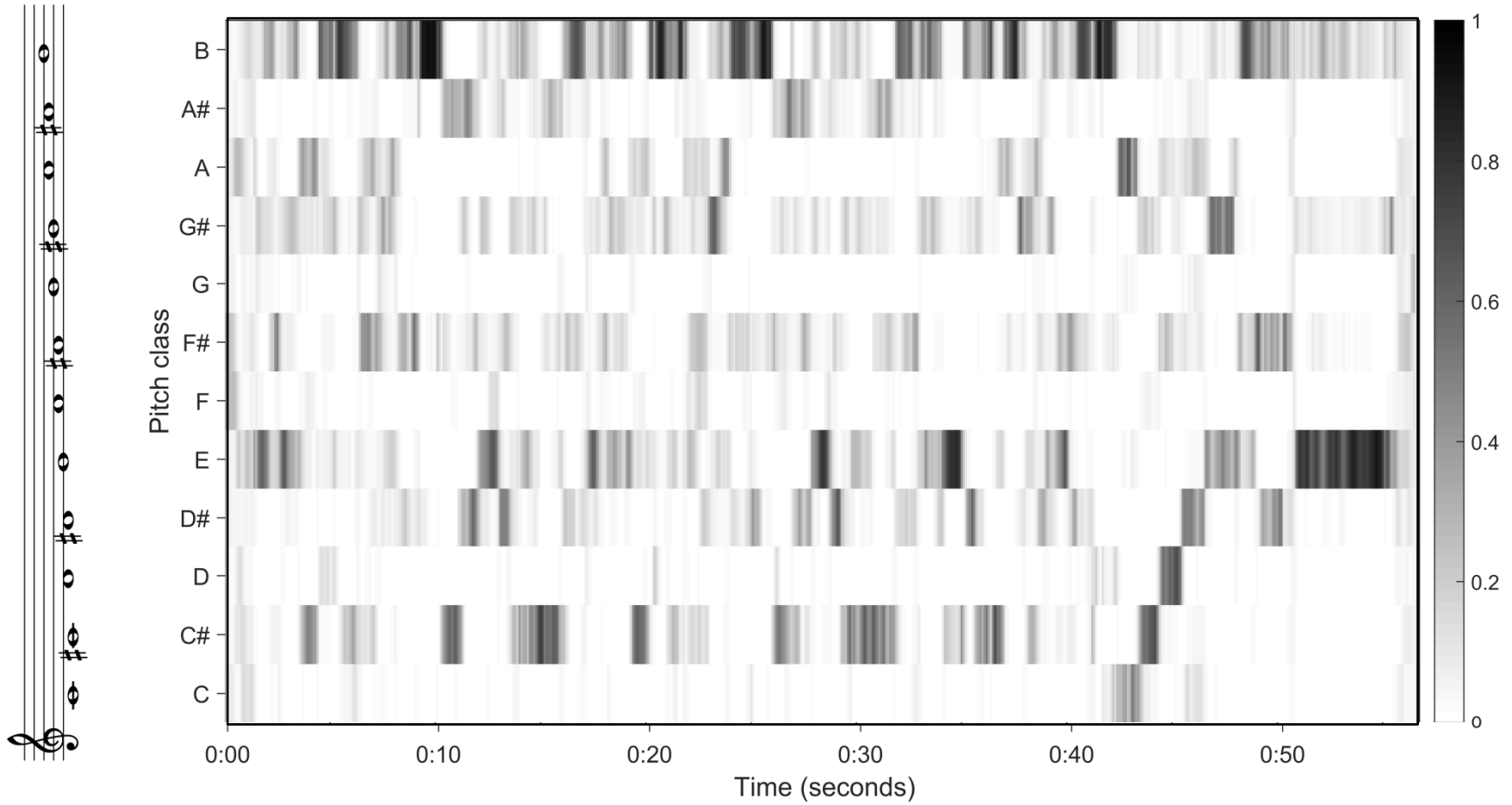
Local Key Estimation

Spectrogram



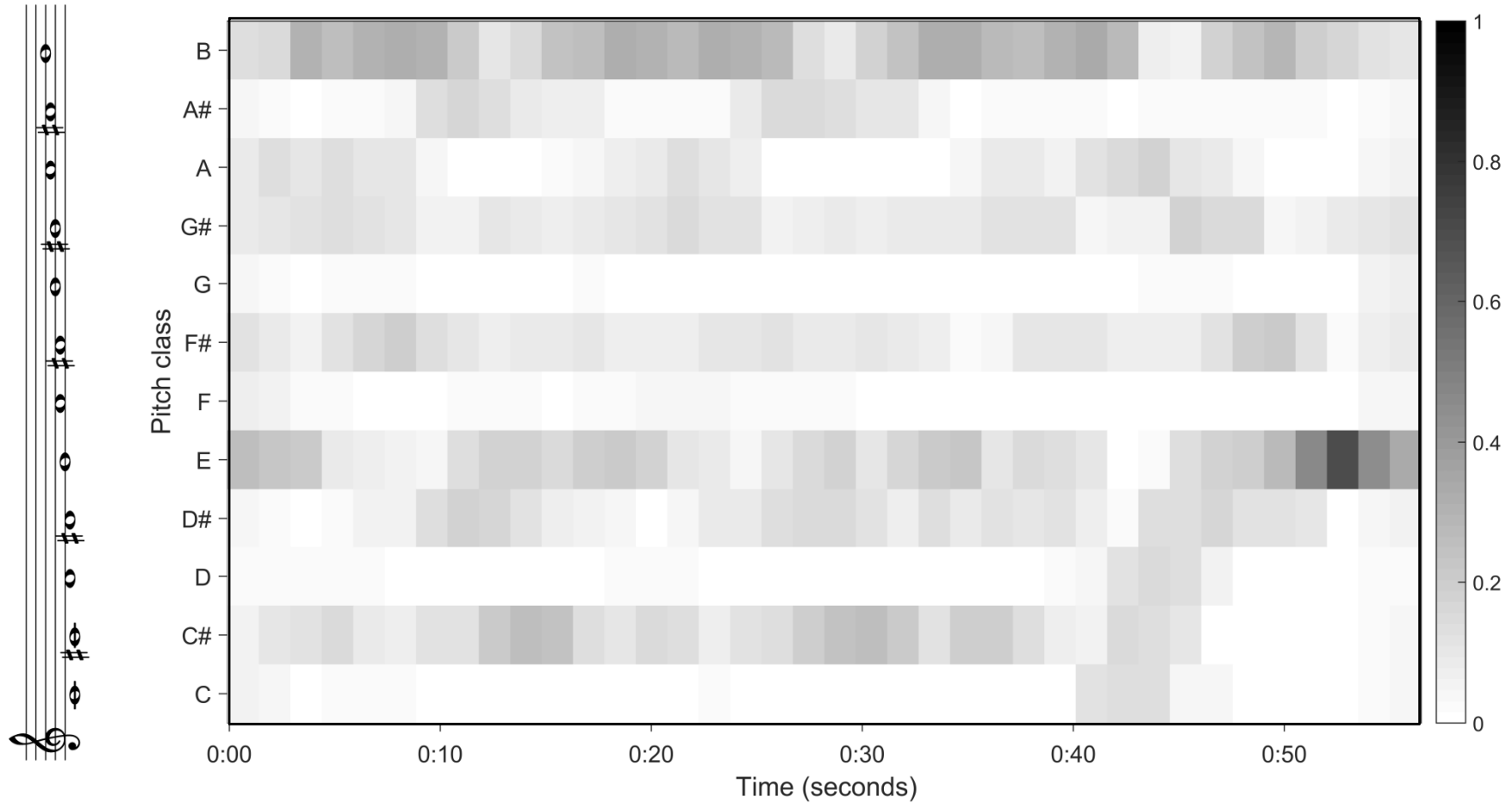
Local Key Estimation

Chromagram



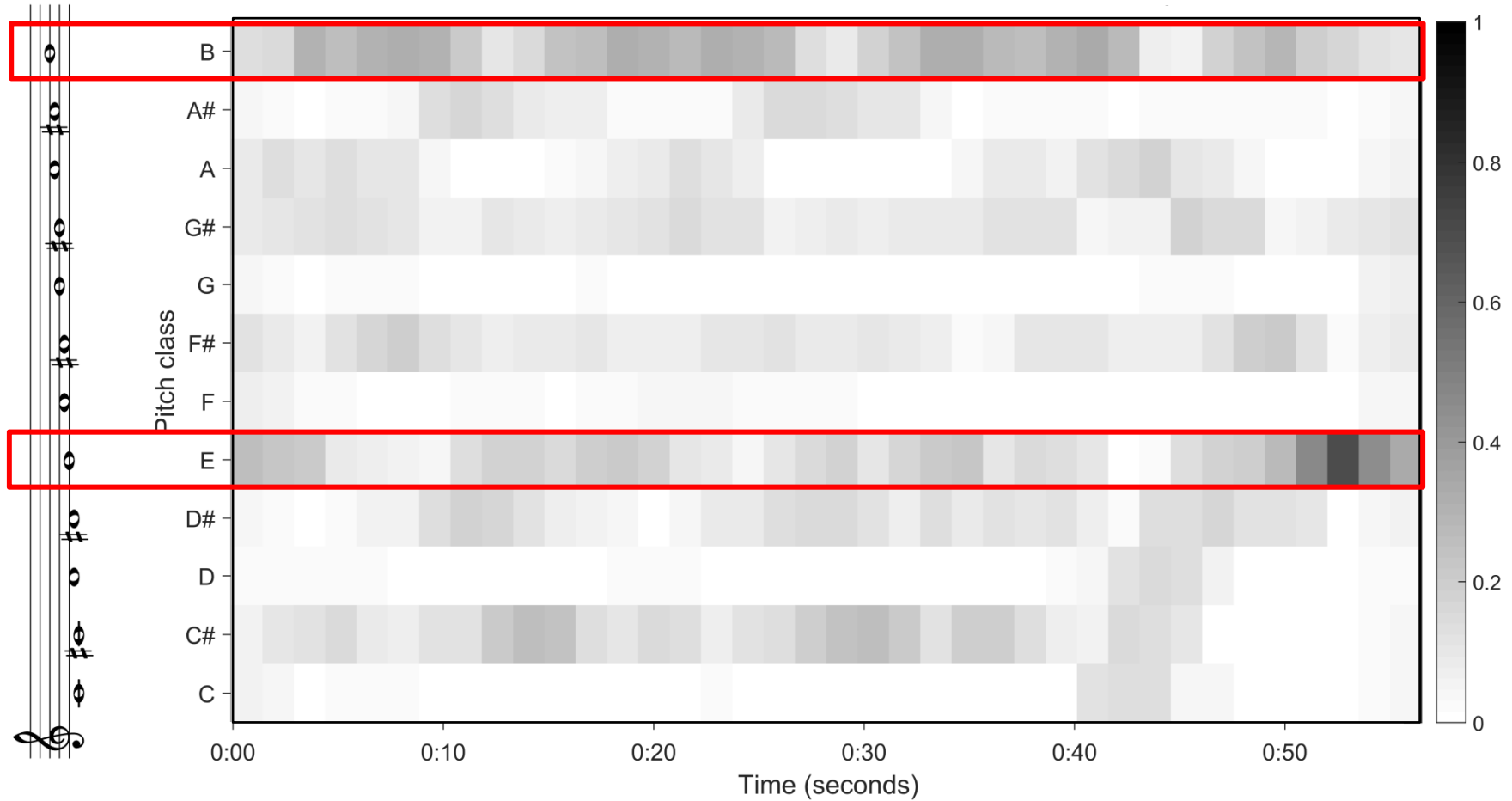
Local Key Estimation

Chromagram after smoothing



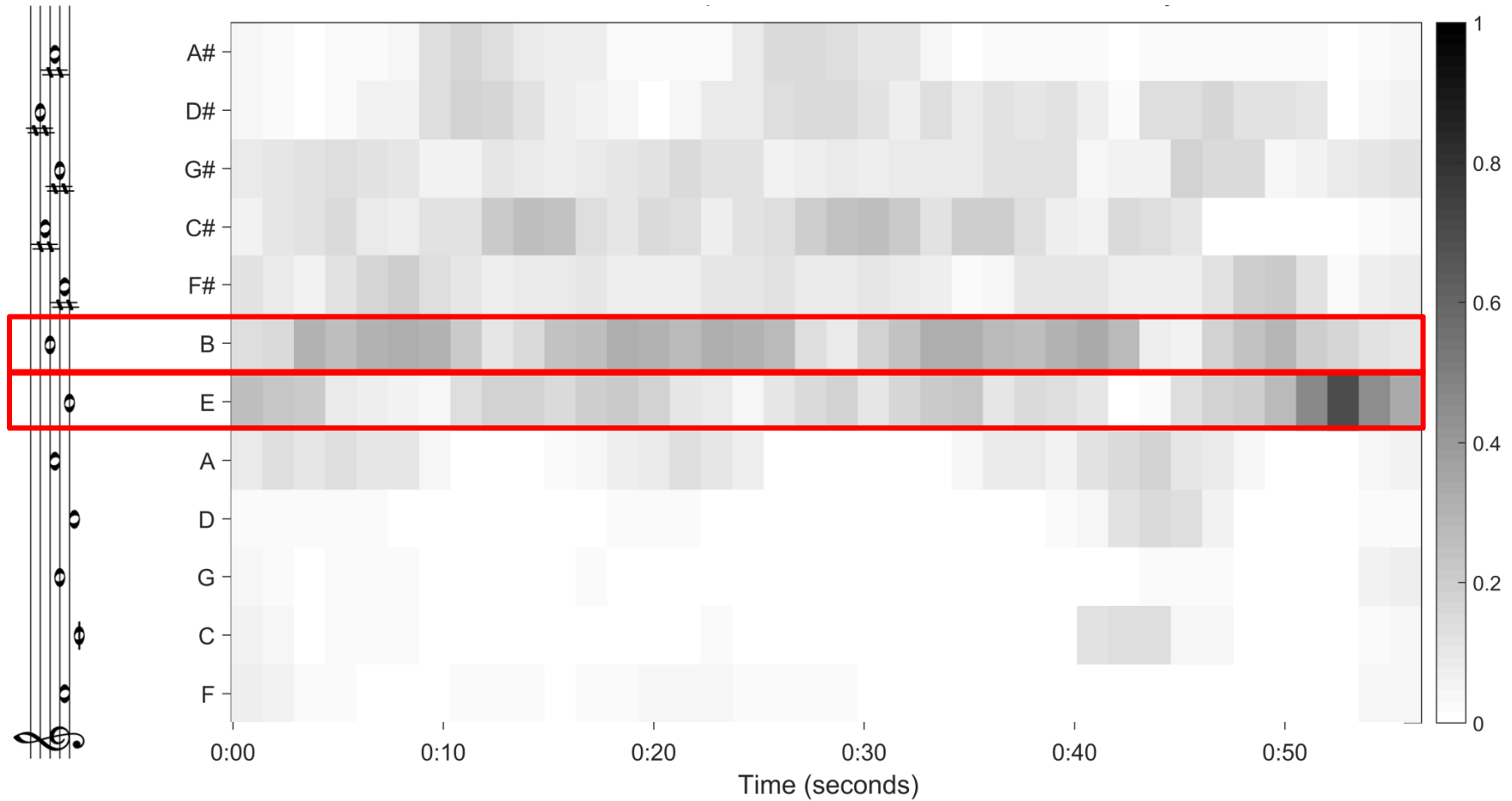
Local Key Estimation

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



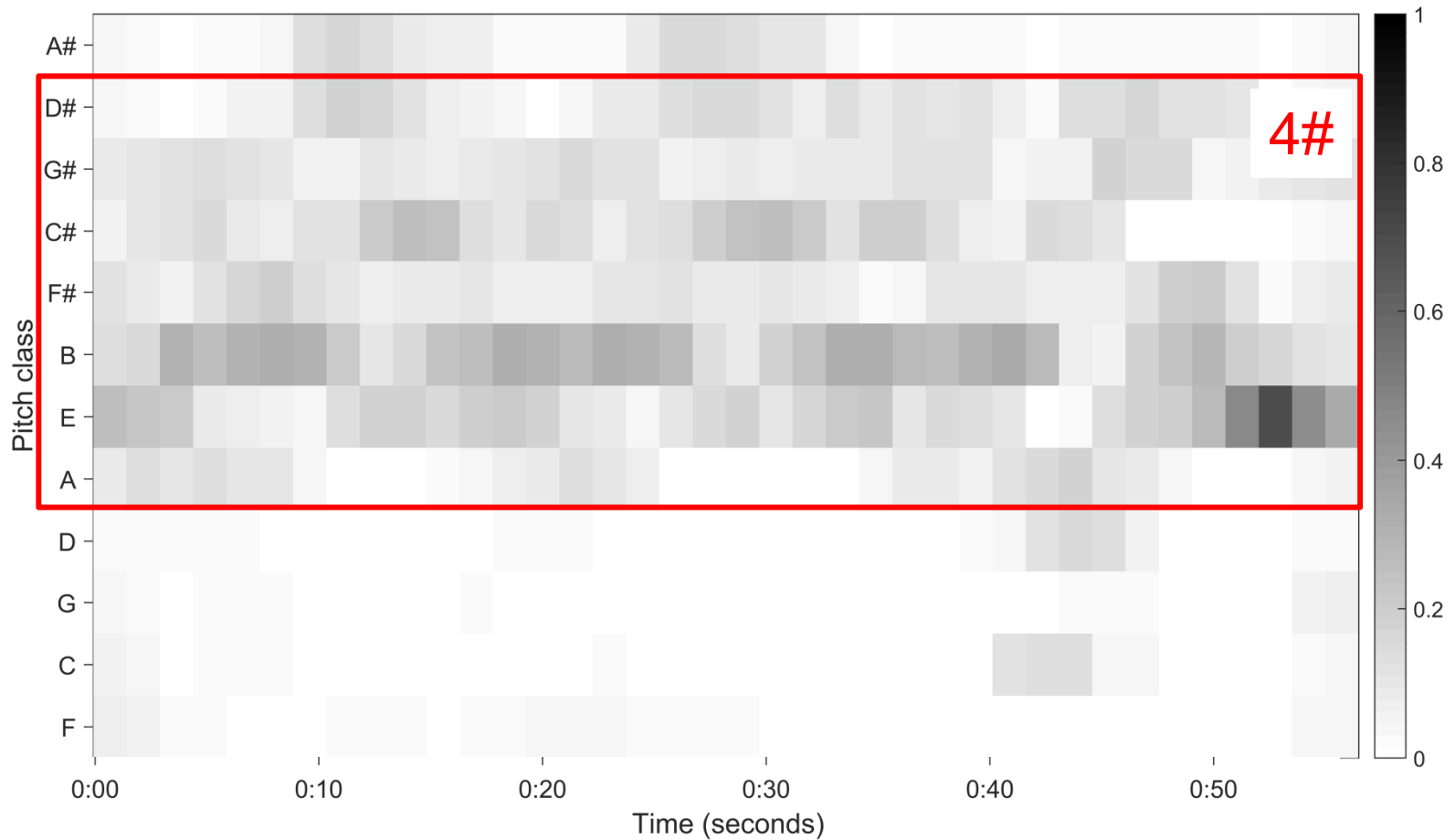
Local Key Estimation

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



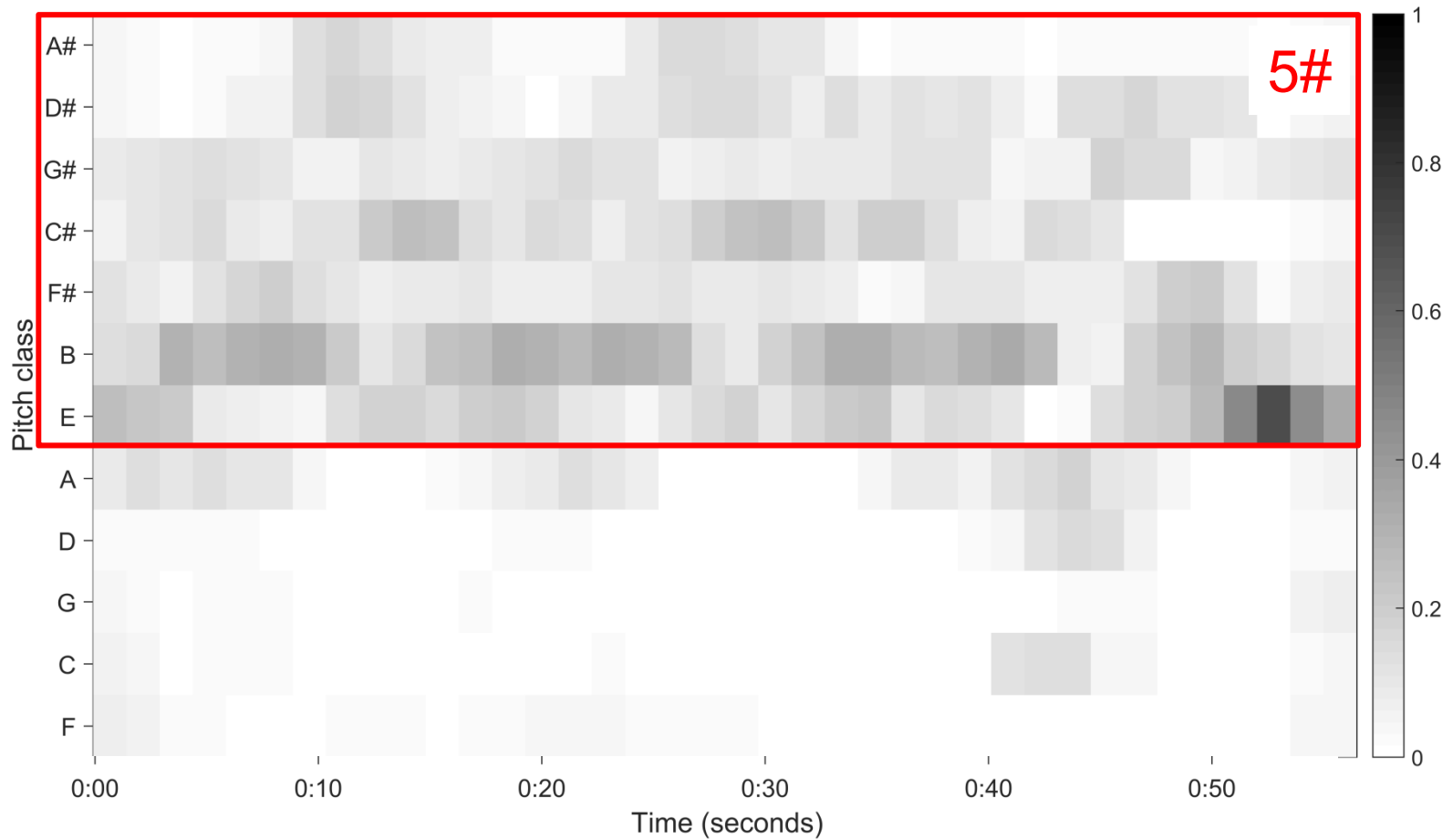
Local Key Estimation

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



Local Key Estimation

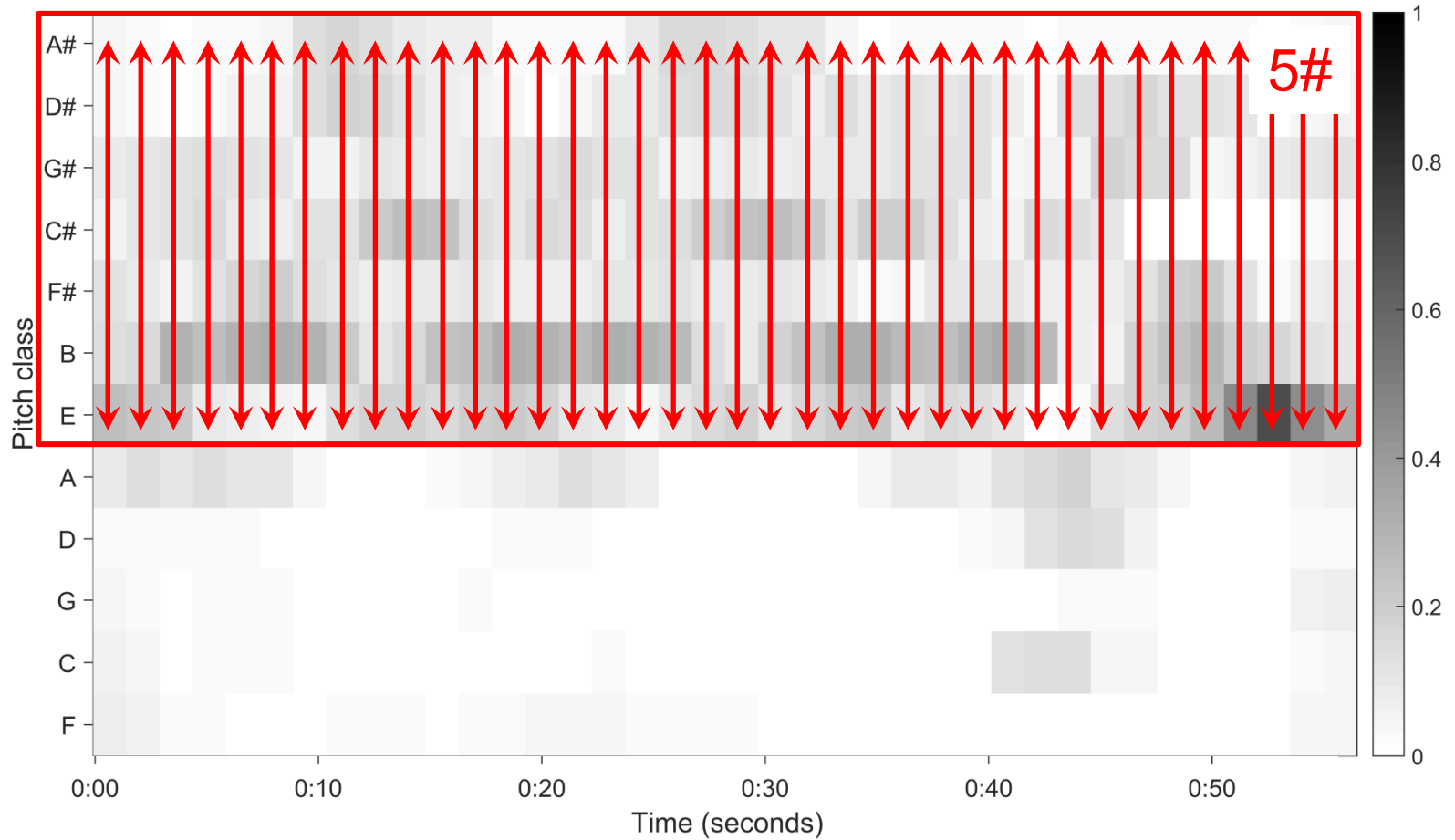
Summarize pitch class content according to **diatonic scales**



Local Key Estimation

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

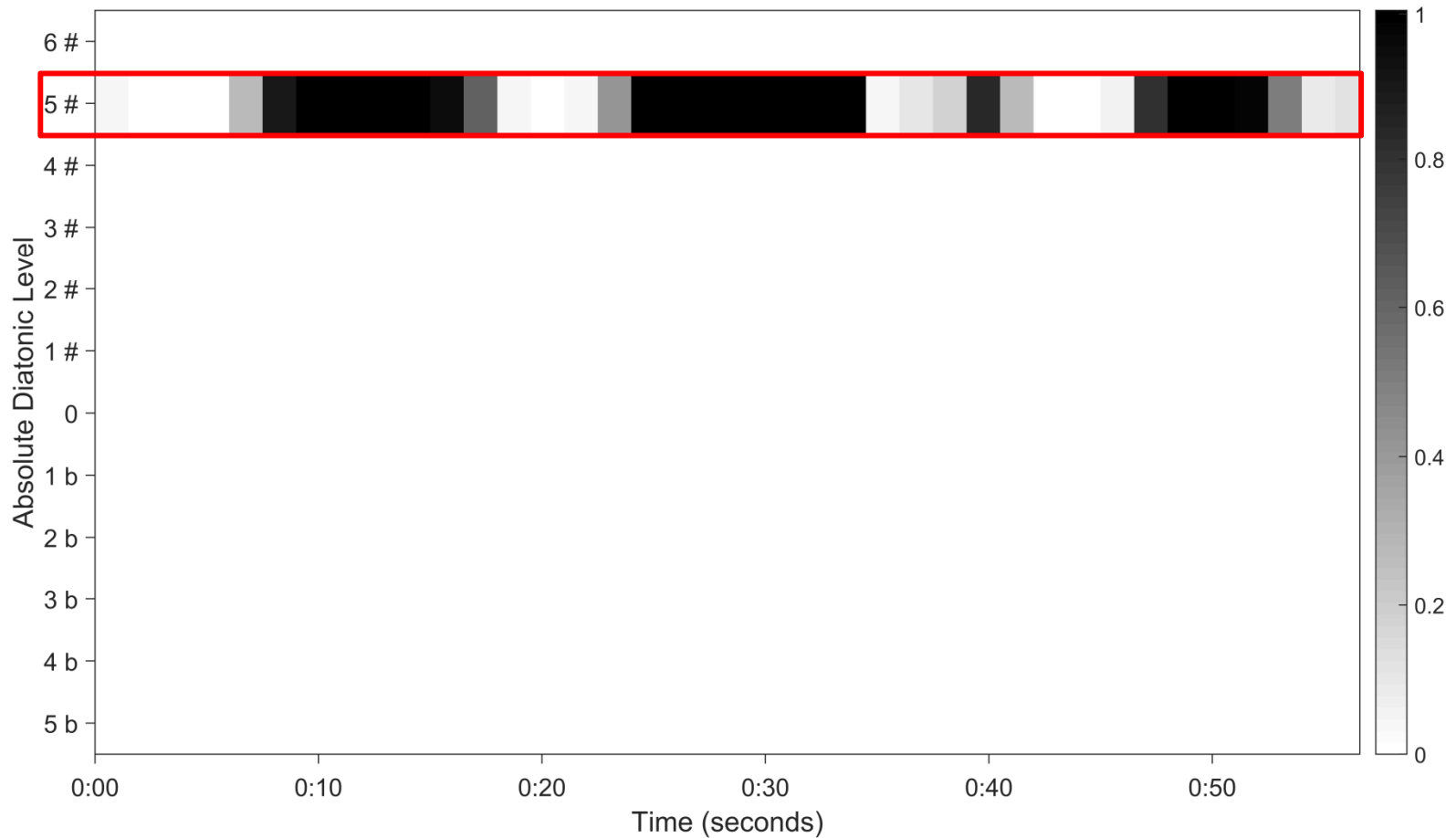
Multiply chroma values (in each column)



Local Key Estimation

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

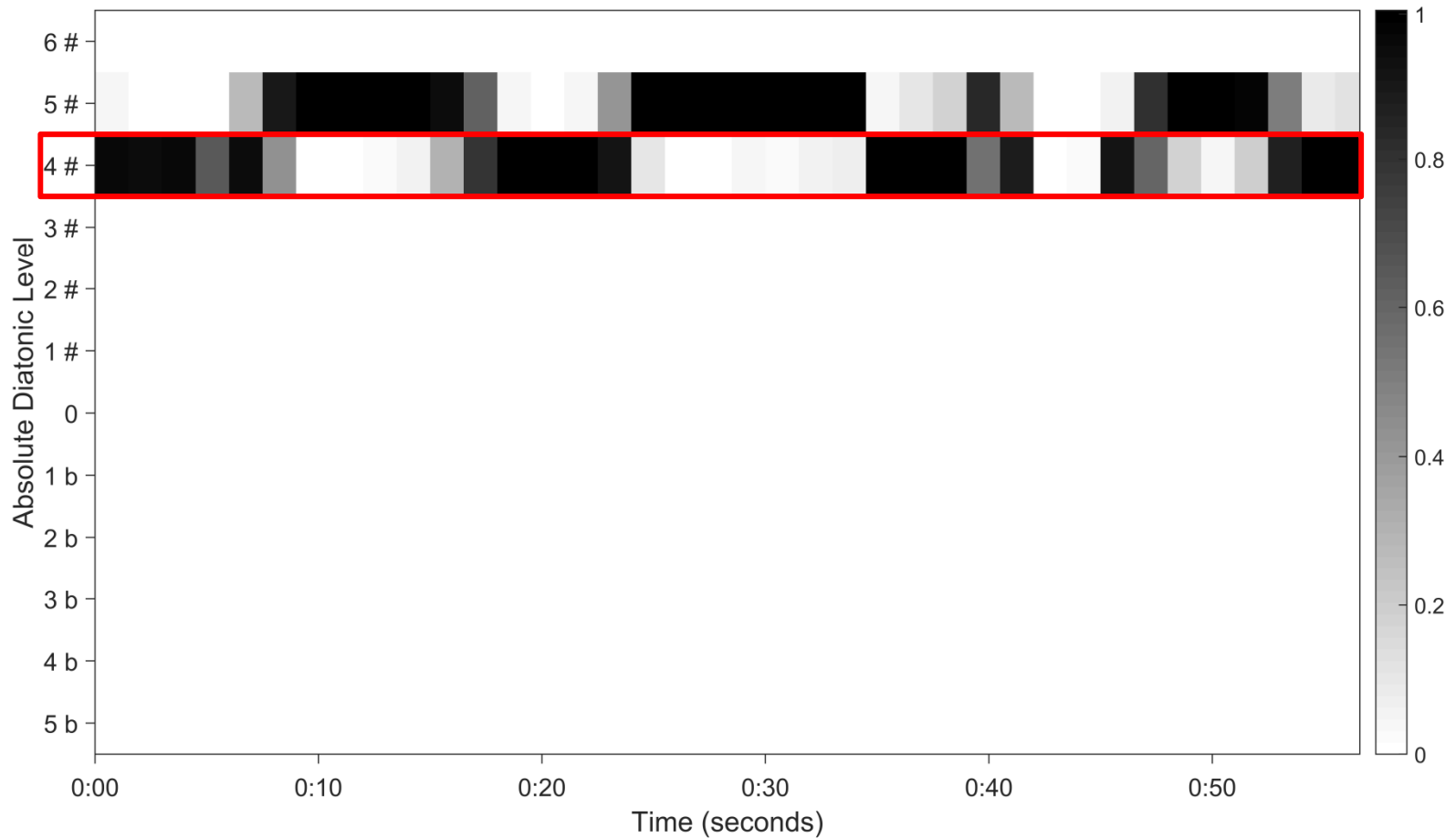
Multiply chroma values



Local Key Estimation

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

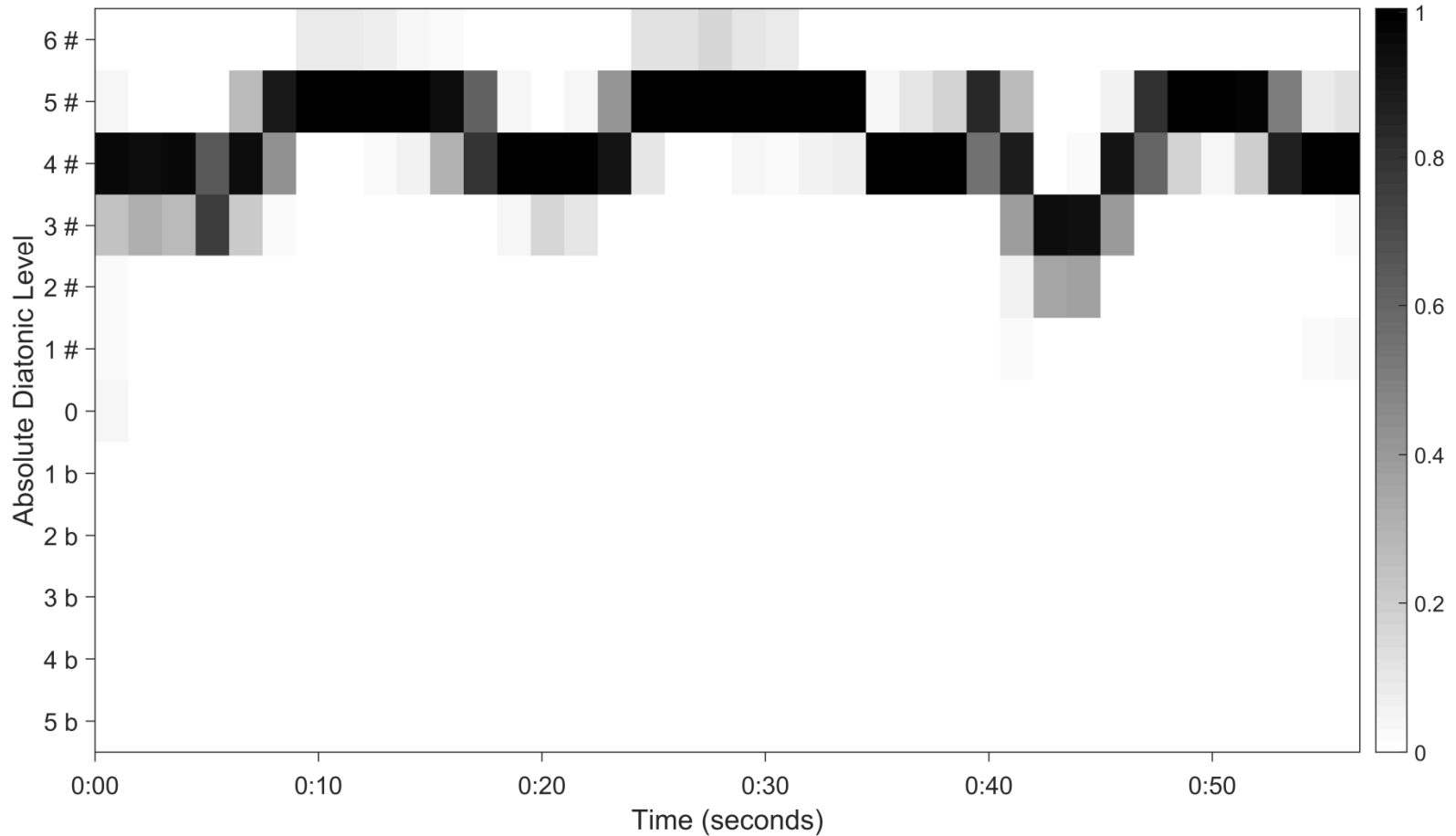
Multiply chroma values



Local Key Estimation

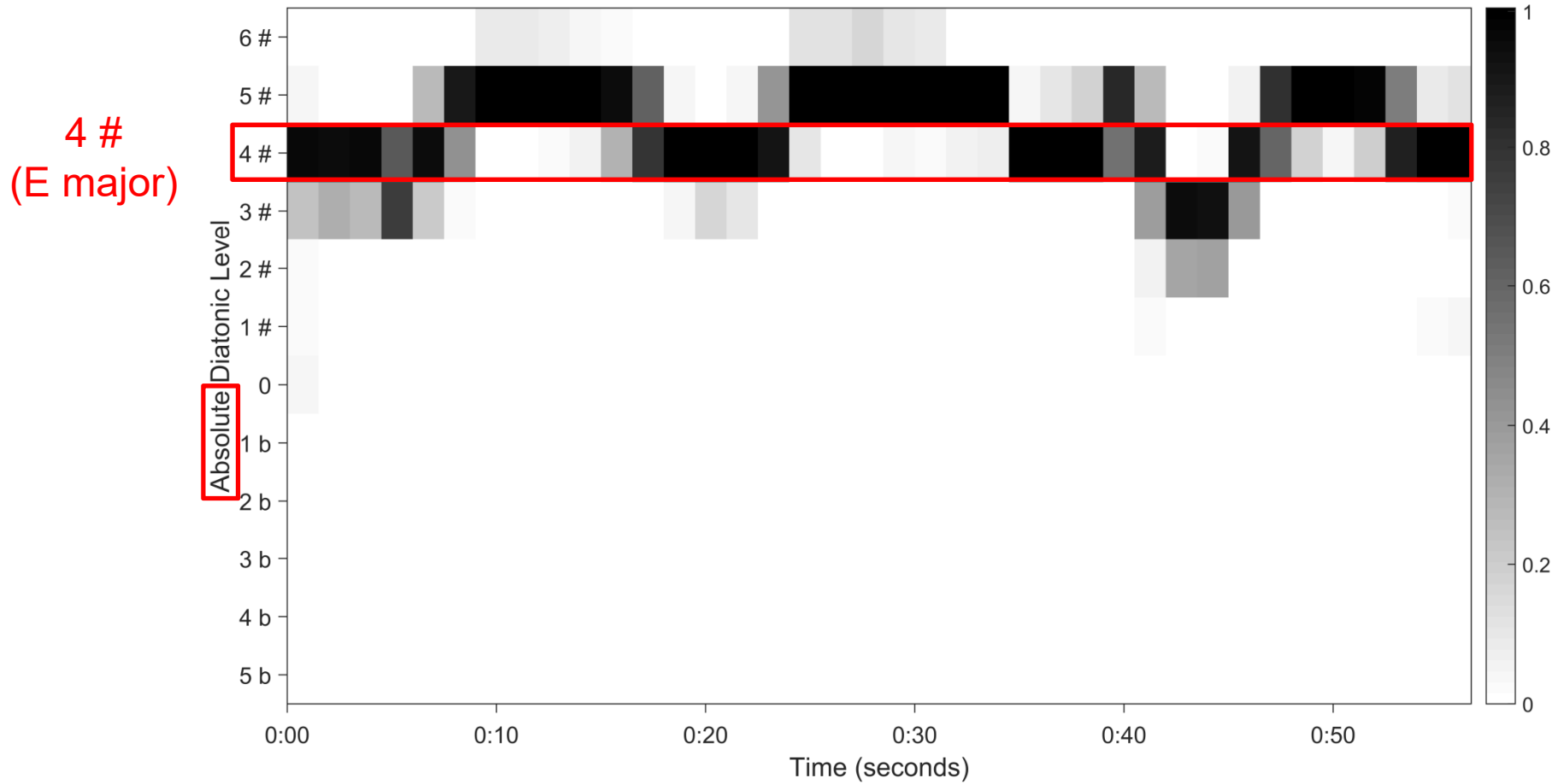
Summarize pitch class content according to **diatonic scales**

Multiply chroma values



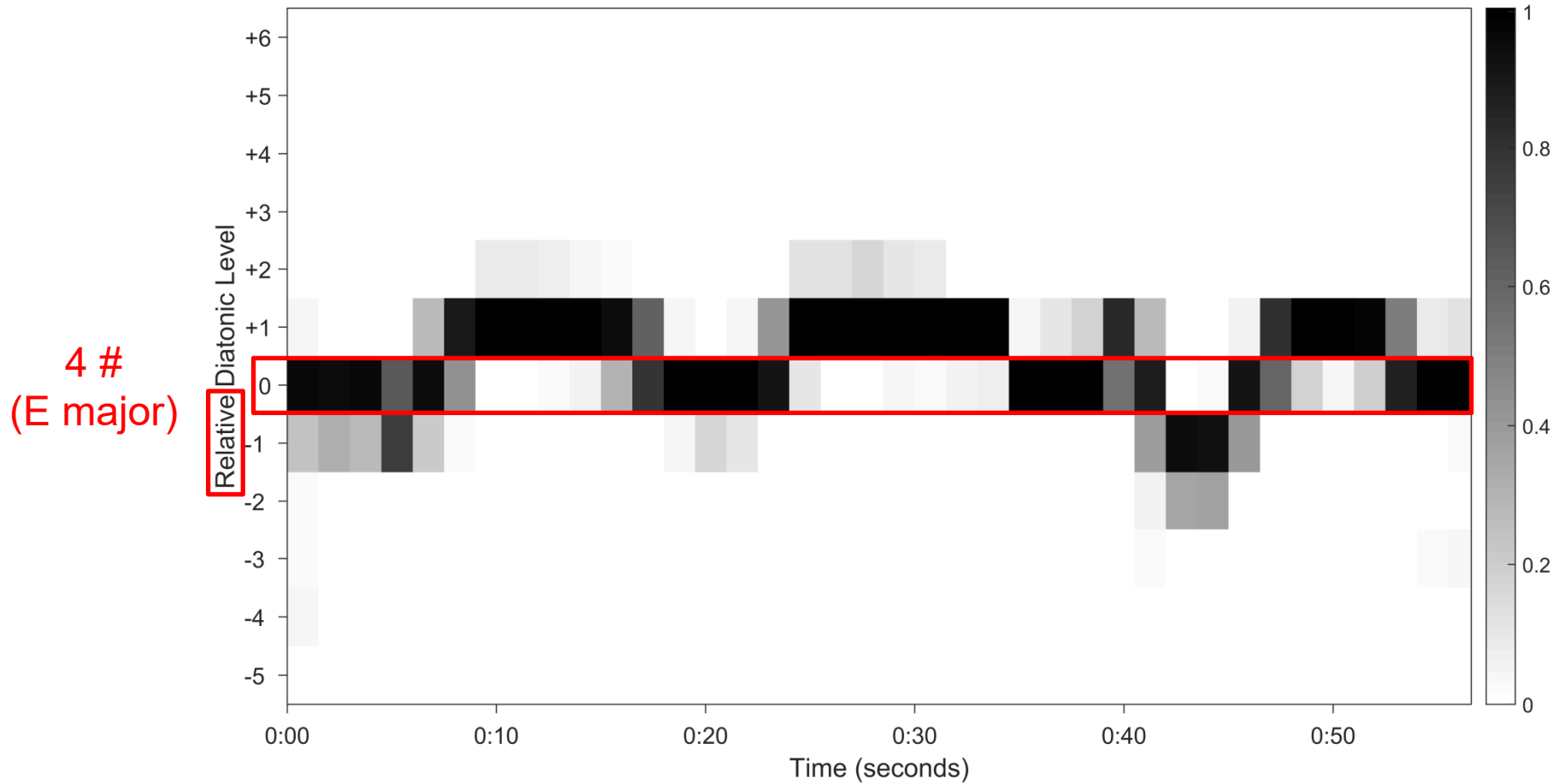
Local Key Estimation

Normalize representation relative to **global key**



Local Key Estimation

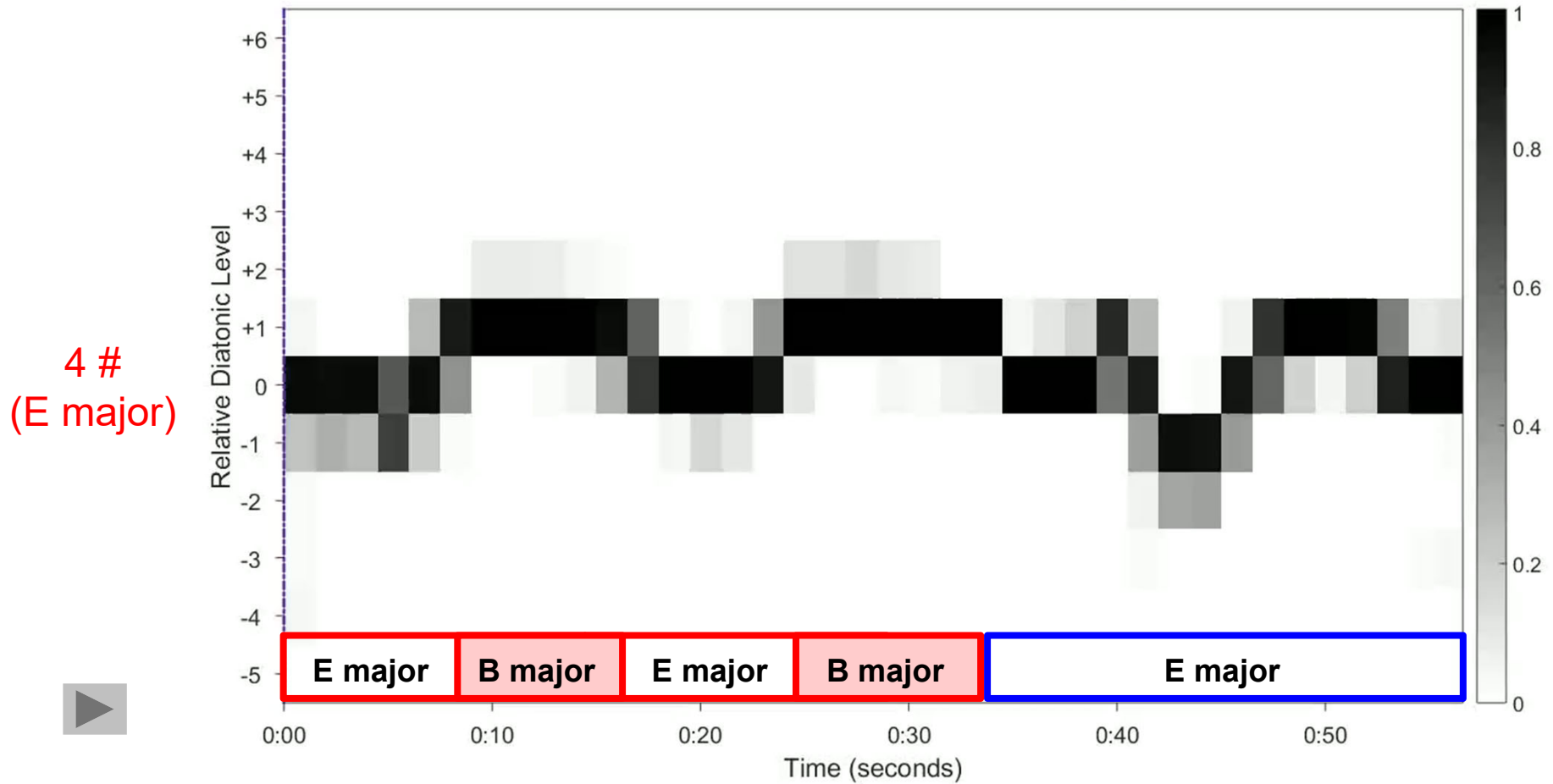
Normalize representation relative to **global key**



Local Key Estimation

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

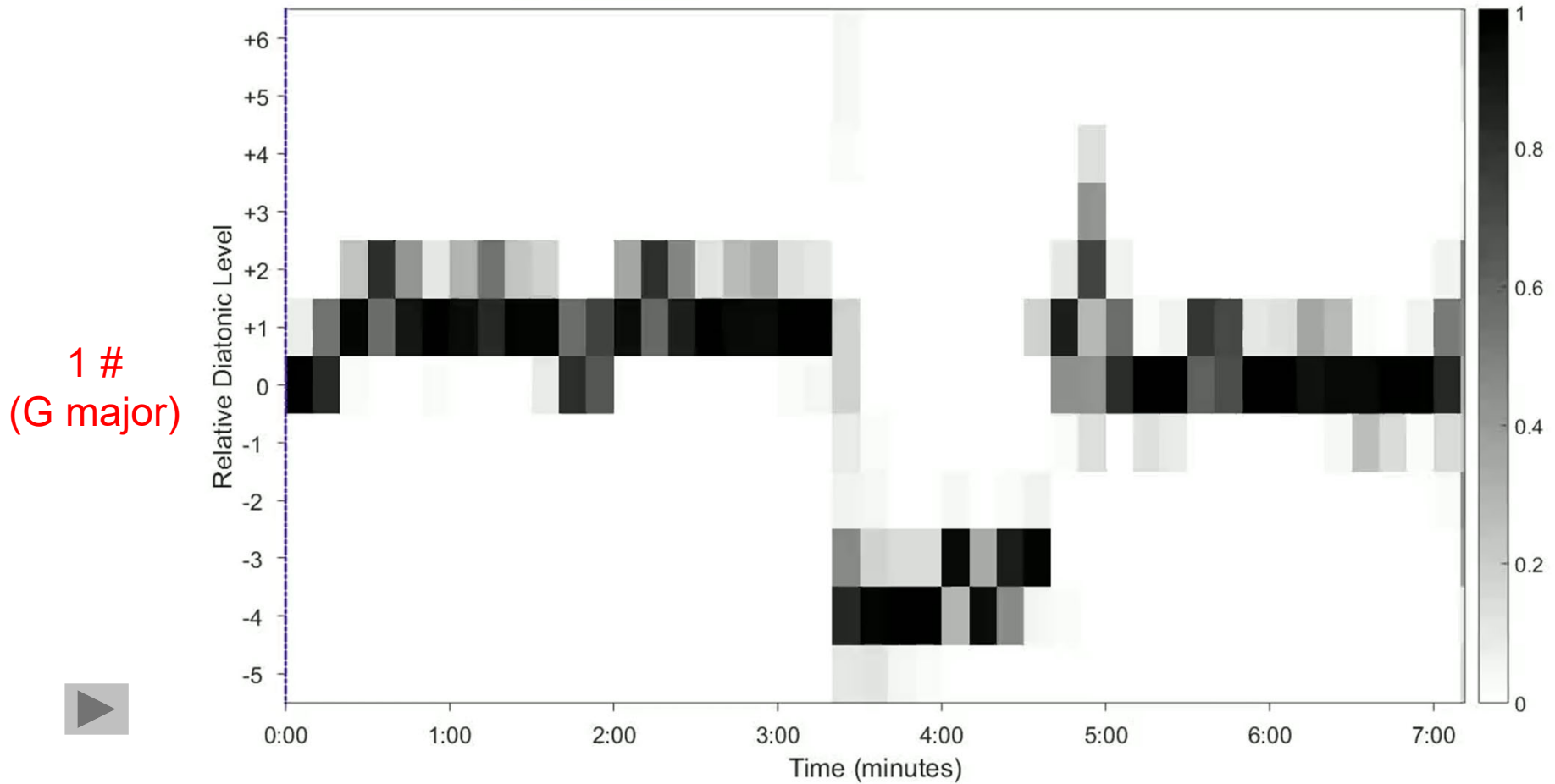
Recording: Scholars Baroque Ensemble, Naxos 1994



Local Key Estimation

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

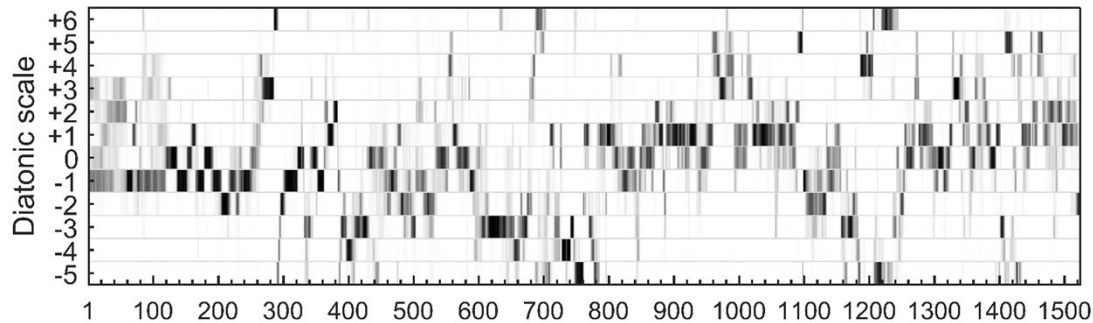
Recording: Barenboim, EMI 1998



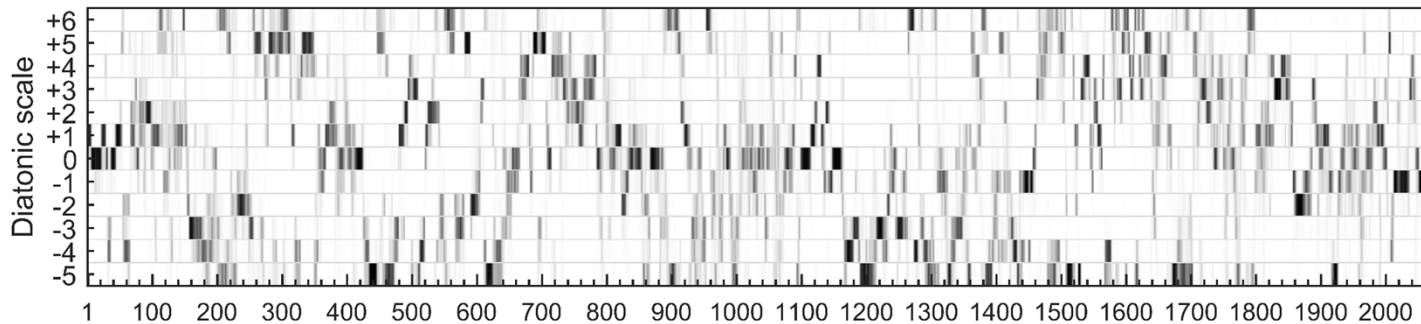
Local Key Estimation

R. Wagner: WWV 86 B (*Die Walküre*)

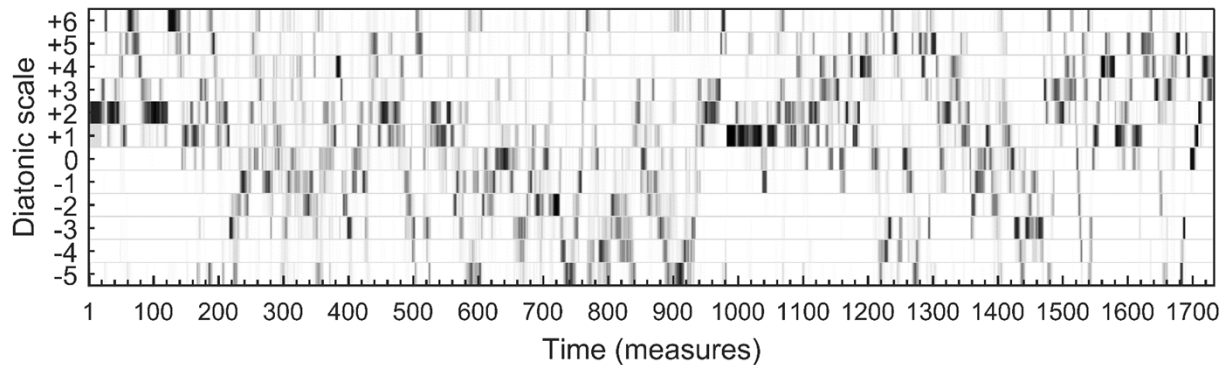
Act 1



Act 2



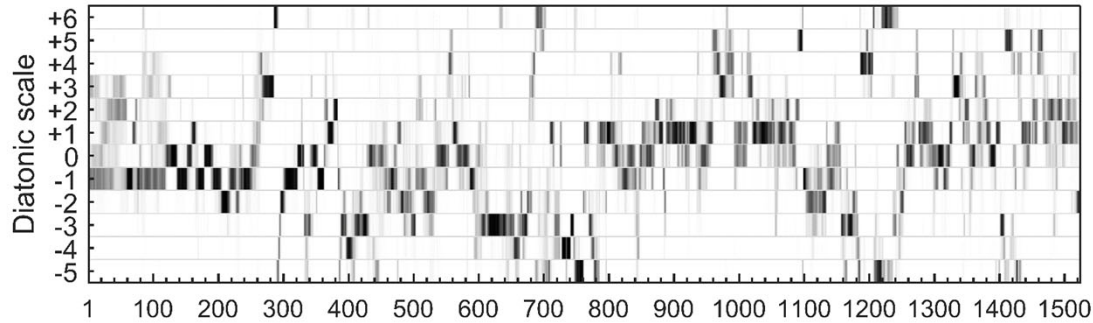
Act 3



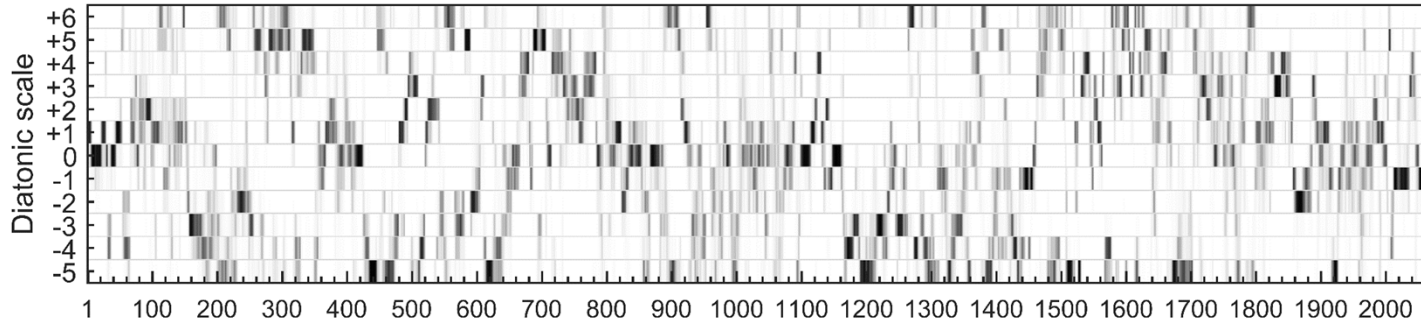
Local Key Estimation

R. Wagner: WWV 86 B (*Die Walküre*)

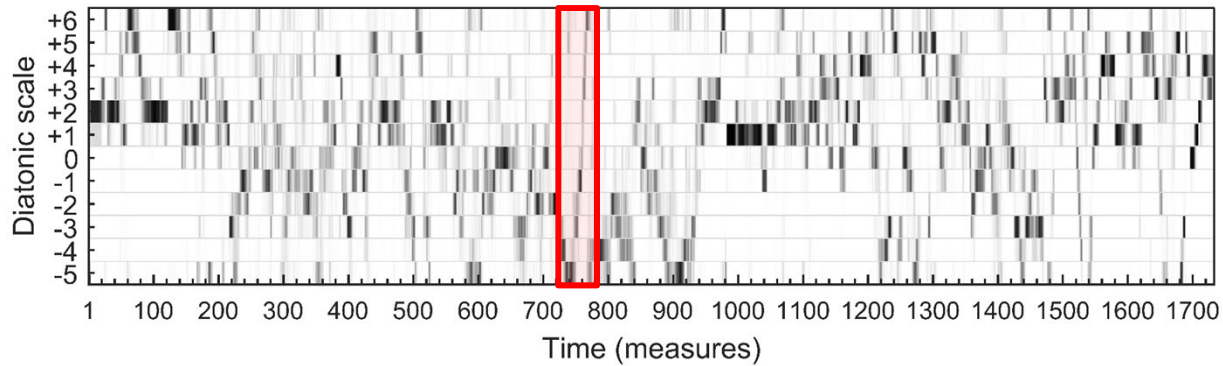
Act 1



Act 2



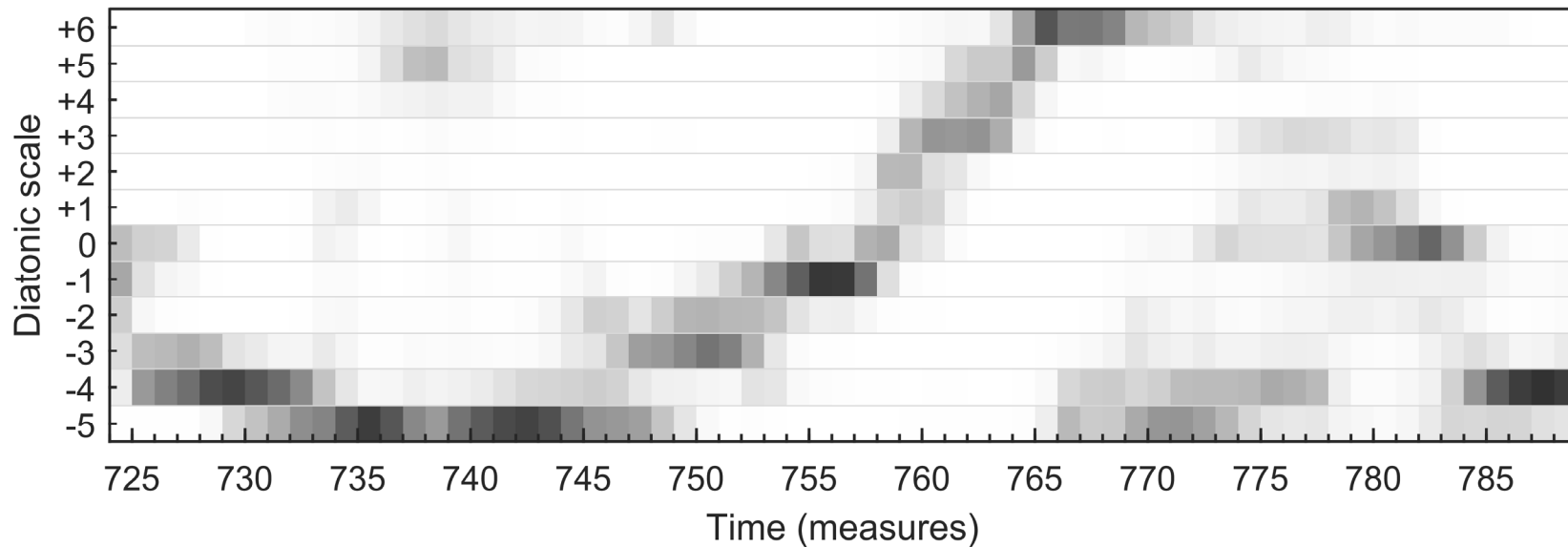
Act 3



Local Key Estimation

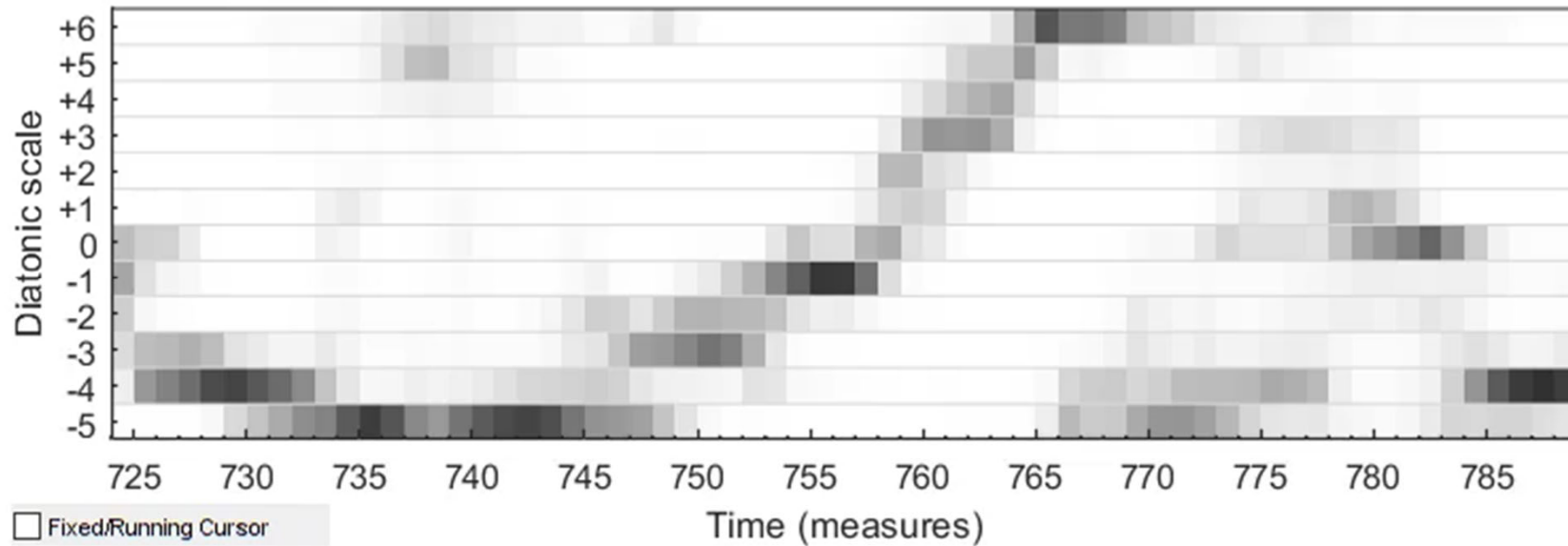
R. Wagner: WWV 86 B (*Die Walküre*)

Act 3, measure 724–789 (*Wotan's punishment*)



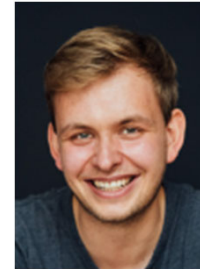
Local Key Estimation

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



Computational Ethnomusicology: Traditional Georgian Vocal Music

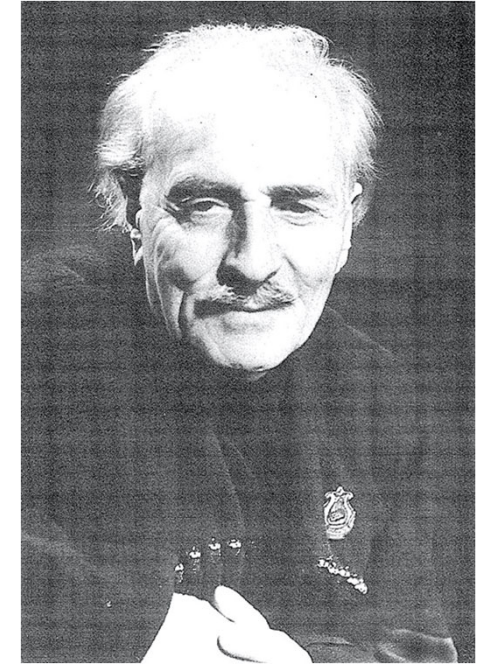
- Interdisciplinary research project
 - Prof. Dr. Frank Scherbaum (Potsdam)
 - Dr. Nana Mzhavanadze (Tbilisi)
 - Sebastian Rosenzweig (FAU)
- Objective: Tonal analysis
- 2018 – 2022: DFG-funded project



Traditional Georgian Vocal Music

Example: Erkomaishvili corpus

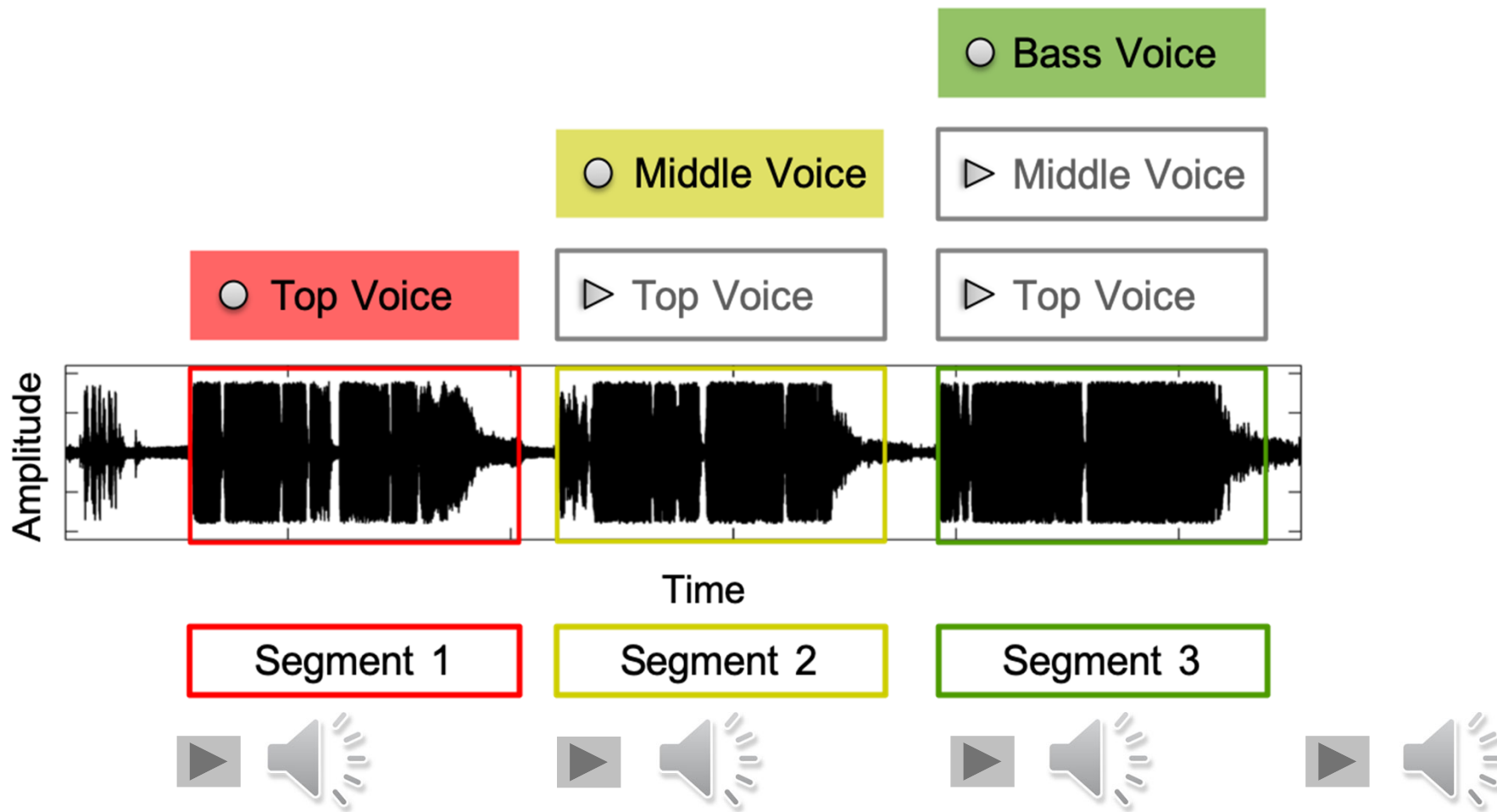
- Collection of traditional three-voice Georgian songs
- Performed by the former Georgian master chanter Artem Erkomaishvili (1887-1967)
- Recordings of 100 songs using tape recorders (1966)



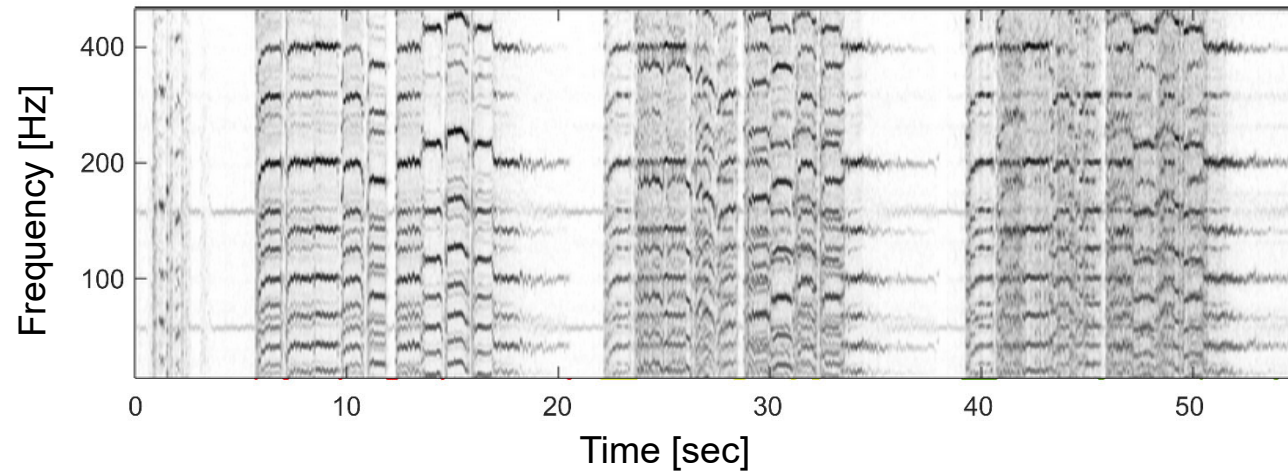
“Original masterpieces of Georgian musical thinking.” (Shugliashvili, 2014)

Traditional Georgian Vocal Music

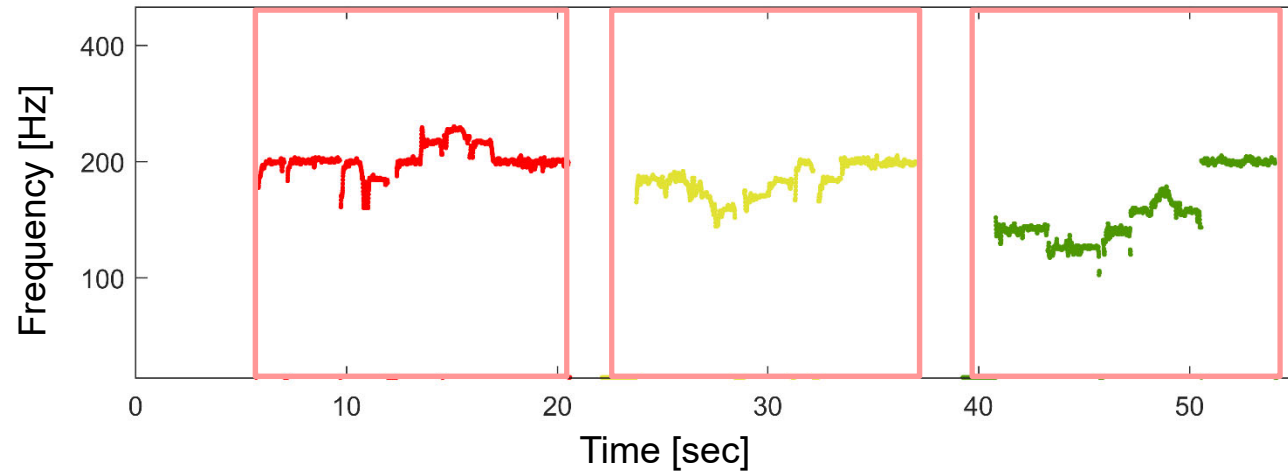
Example: Erkomaishvili corpus



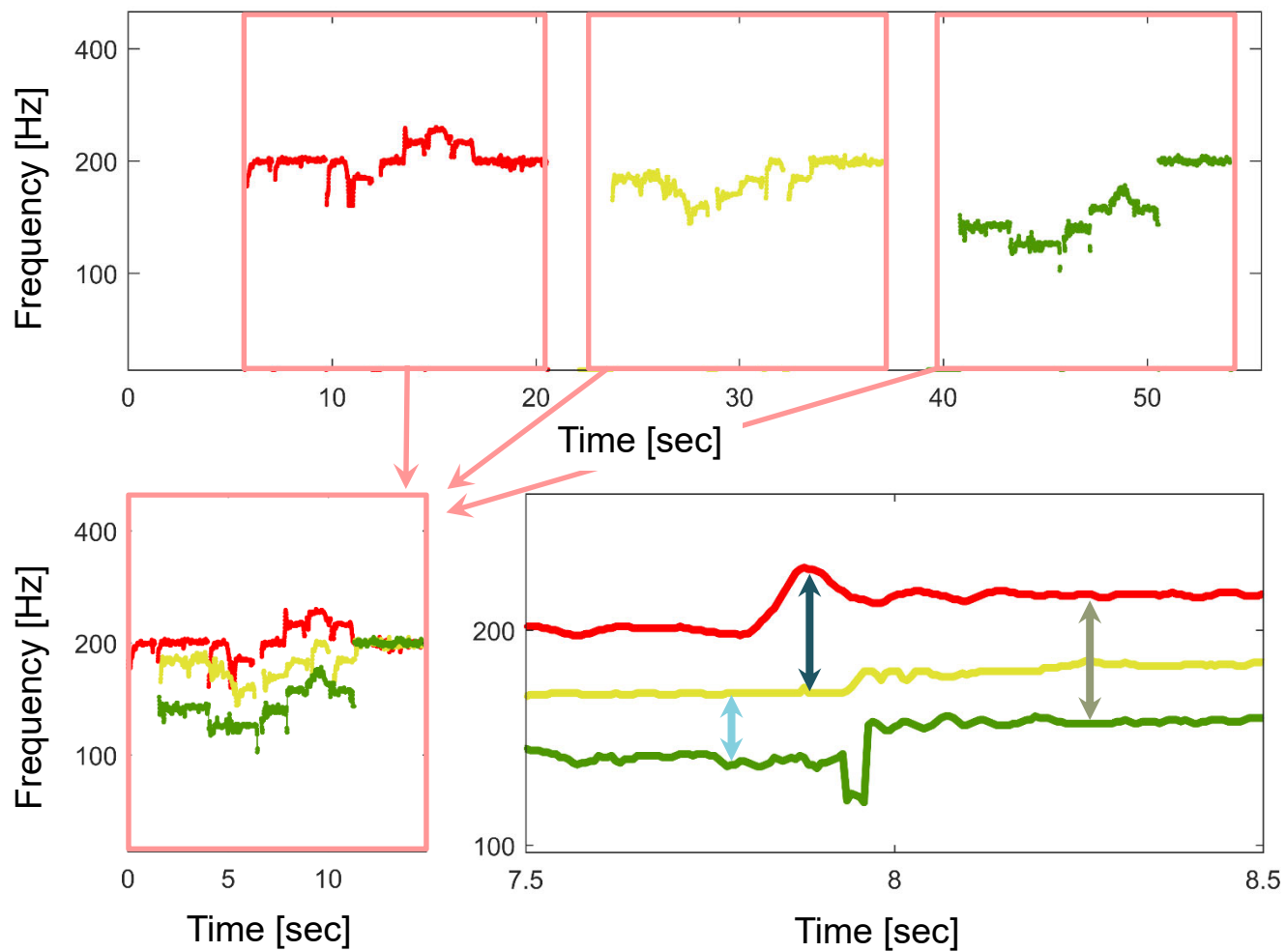
Traditional Georgian Vocal Music



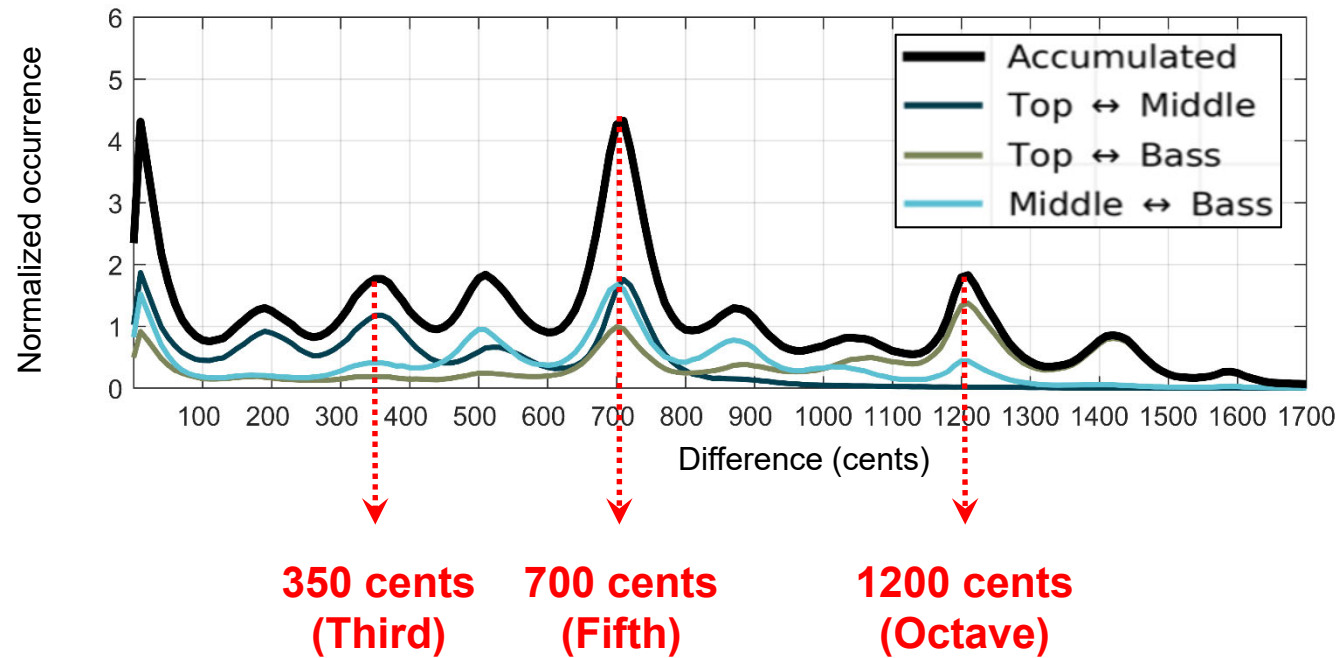
Traditional Georgian Vocal Music



Traditional Georgian Vocal Music



Traditional Georgian Vocal Music



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

Traditional Georgian Vocal Music

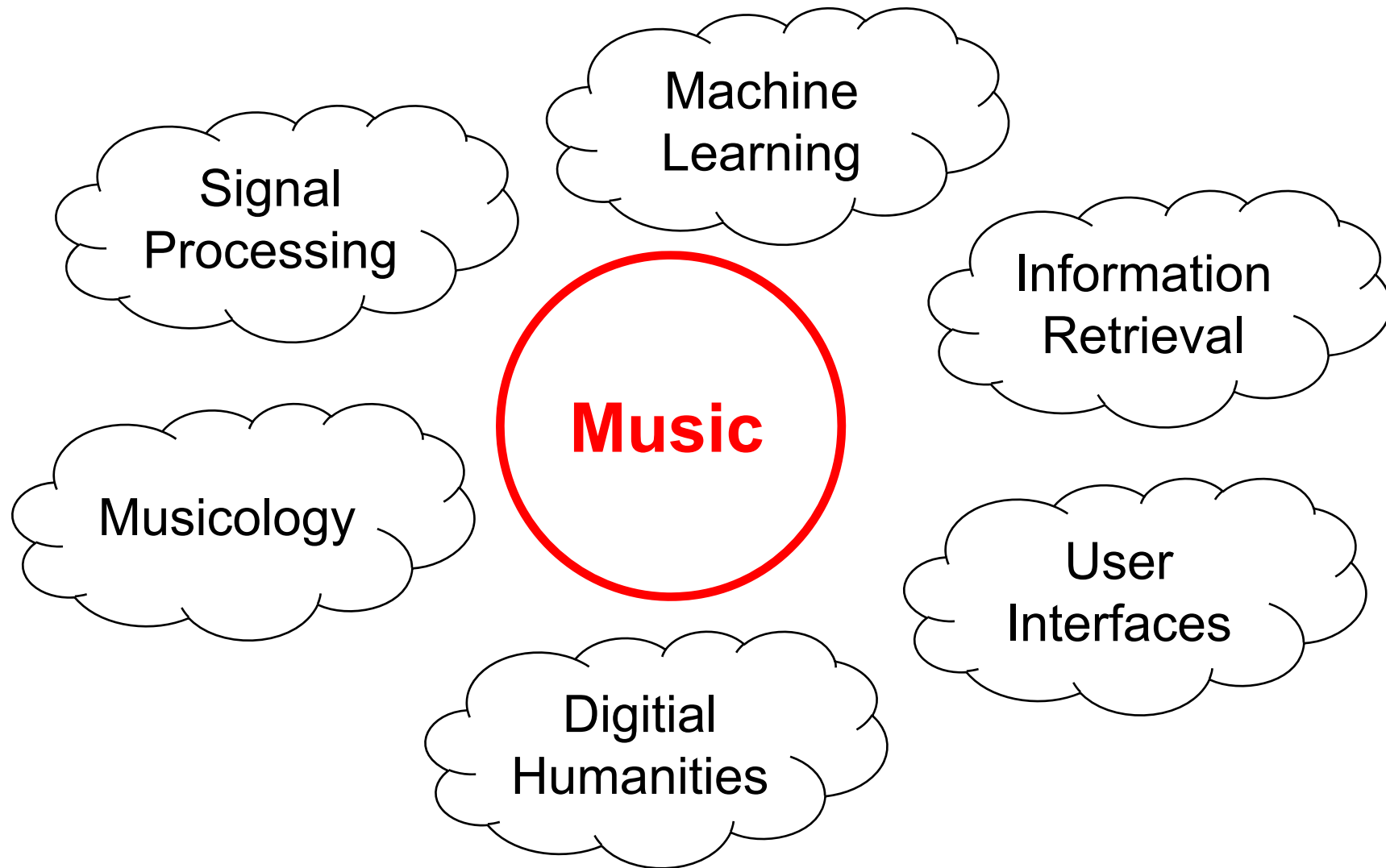


- Recordings from field expedition in 2016
- 216 performances
- Multitrack audio + video
 - Room, **HSM**, **LRX**
- Total duration: 6 h

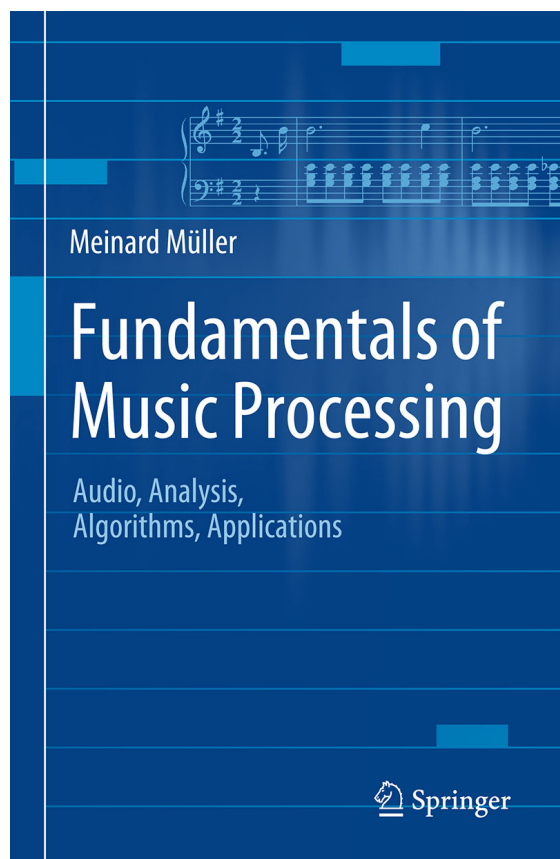


Room
Microphone

Music Information Retrieval (MIR)



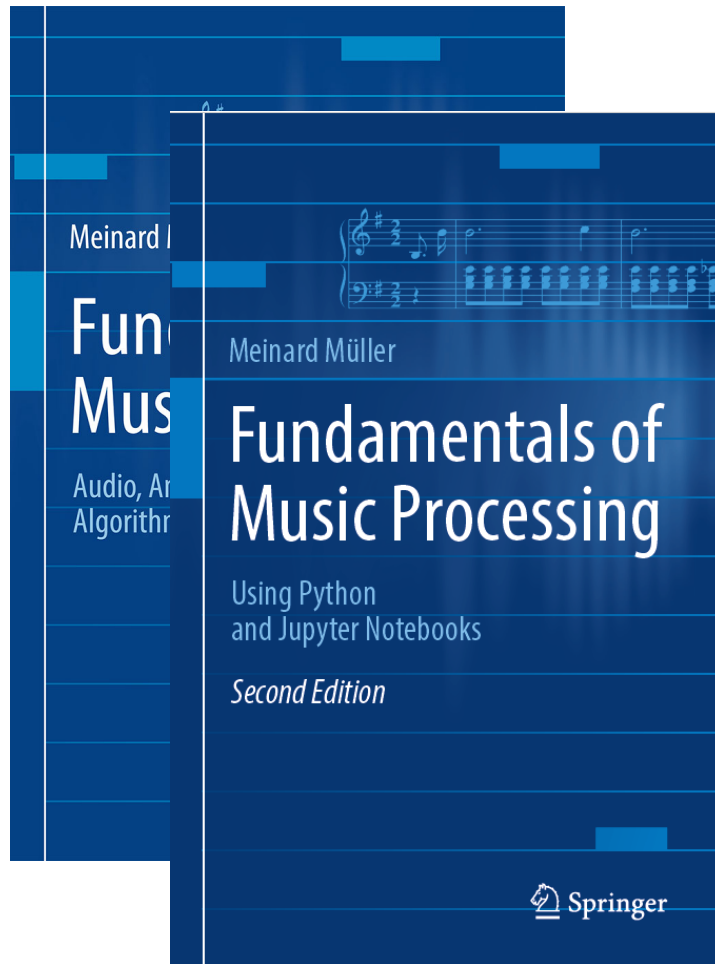
Fundamentals of Music Processing (FMP)



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

Accompanying website:
www.music-processing.de

Fundamentals of Music Processing (FMP)

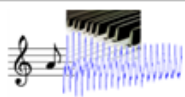

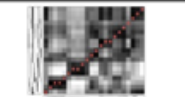
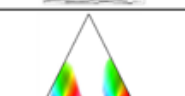

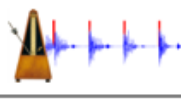




Meinard Müller
Fundamentals of Music Processing
Audio, Analysis, Algorithms, Applications
Springer, 2015

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)

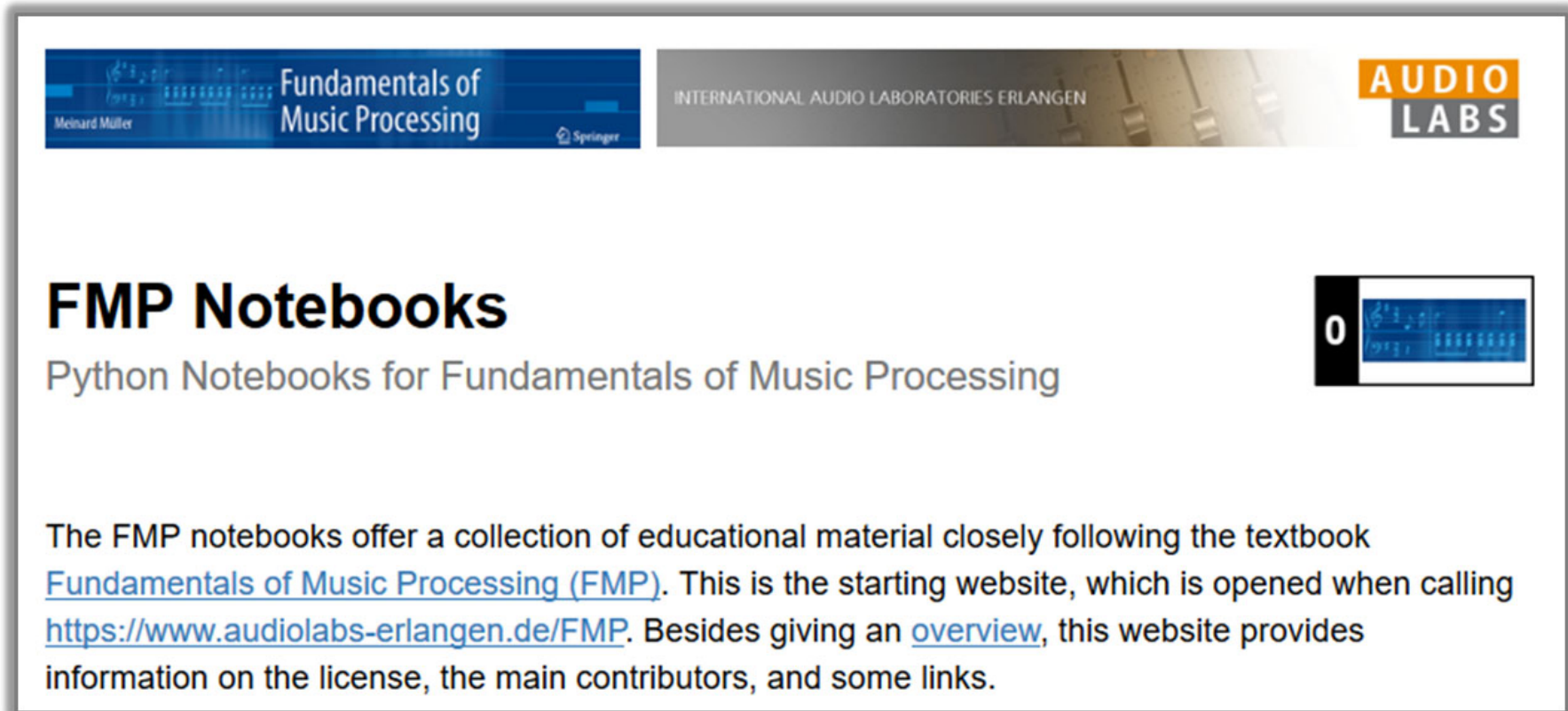
Chapter	Music Processing Scenario
1	 Music Representations
2	 Fourier Analysis of Signals
3	 Music Synchronization
4	 Music Structure Analysis
5	 Chord Recognition
6	 Tempo and Beat Tracking
7	 Content-Based Audio Retrieval
8	 Musically Informed Audio Decomposition

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



The screenshot shows the header of the FMP Notebooks website. On the left, there is a blue banner for the book 'Fundamentals of Music Processing' by Meinard Müller, published by Springer. To the right of this banner is a grey banner for 'INTERNATIONAL AUDIO LABORATORIES ERLANGEN' with the 'AUDIO LABS' logo. Below the banners, the main heading reads 'FMP Notebooks' in a large, bold, black font, followed by the subtitle 'Python Notebooks for Fundamentals of Music Processing' in a smaller, grey font. To the right of the subtitle is a small icon of a notebook with a blue cover and a white page, with a black circle containing the number '0' to its left. Below the heading and subtitle, a paragraph of text describes the notebooks: 'The FMP notebooks offer a collection of educational material closely following the textbook [Fundamentals of Music Processing \(FMP\)](#). This is the starting website, which is opened when calling <https://www.audiolabs-erlangen.de/FMP>. Besides giving an [overview](#), this website provides information on the license, the main contributors, and some links.'

<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>