

# New Avenues for Music Research Using Digital Signal Processing

**Meinard Müller**

International Audio Laboratories Erlangen  
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Workshop

Understanding Beethoven – Musicology and Computer Science in Dialogue  
14. – 16. Juli 2022



Friedrich-Alexander-Universität  
Erlangen-Nürnberg



IIS

# Meinard Müller



- Mathematics (Diplom/Master, 1997)  
Computer Science (PhD, 2001)  
Information Retrieval (Habilitation, 2007)  
**Bonn University**



- Senior Researcher (2007-2012)  
**Max-Planck Institute, Saarland**



- Professor Semantic Audio Processing (since 2012)  
**Erlangen-Nürnberg University**



# Meinard Müller: Research Group

- Christof Weiß
- Vlora Arifi-Müller
- Sebastian Rosenzweig
- Michael Krause
- Yigitcan Özer
- Simon Schwär
- Peter Meier (external)



# International Audio Laboratories Erlangen



- Fraunhofer Institute for Integrated Circuits IIS
- Largest Fraunhofer institute with  $\approx 1000$  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

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# International Audio Laboratories Erlangen



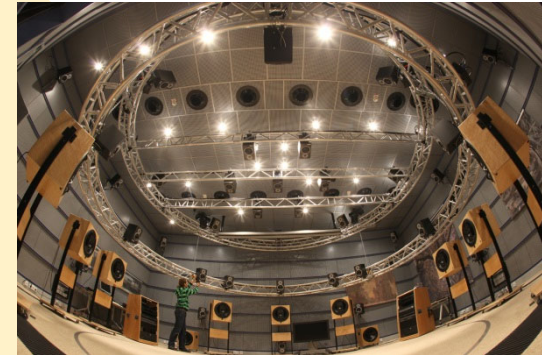
**Audio**

# International Audio Laboratories Erlangen

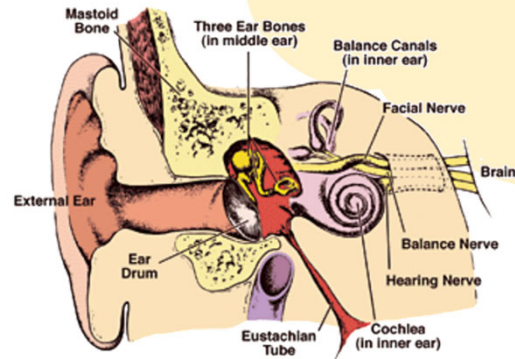
Audio Coding



3D Audio



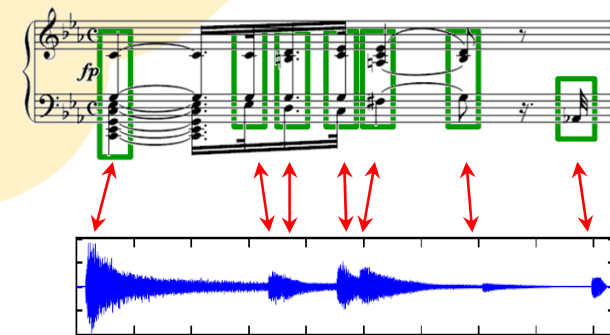
# Audio



Psychoacoustics



Internet of Things



Music Processing

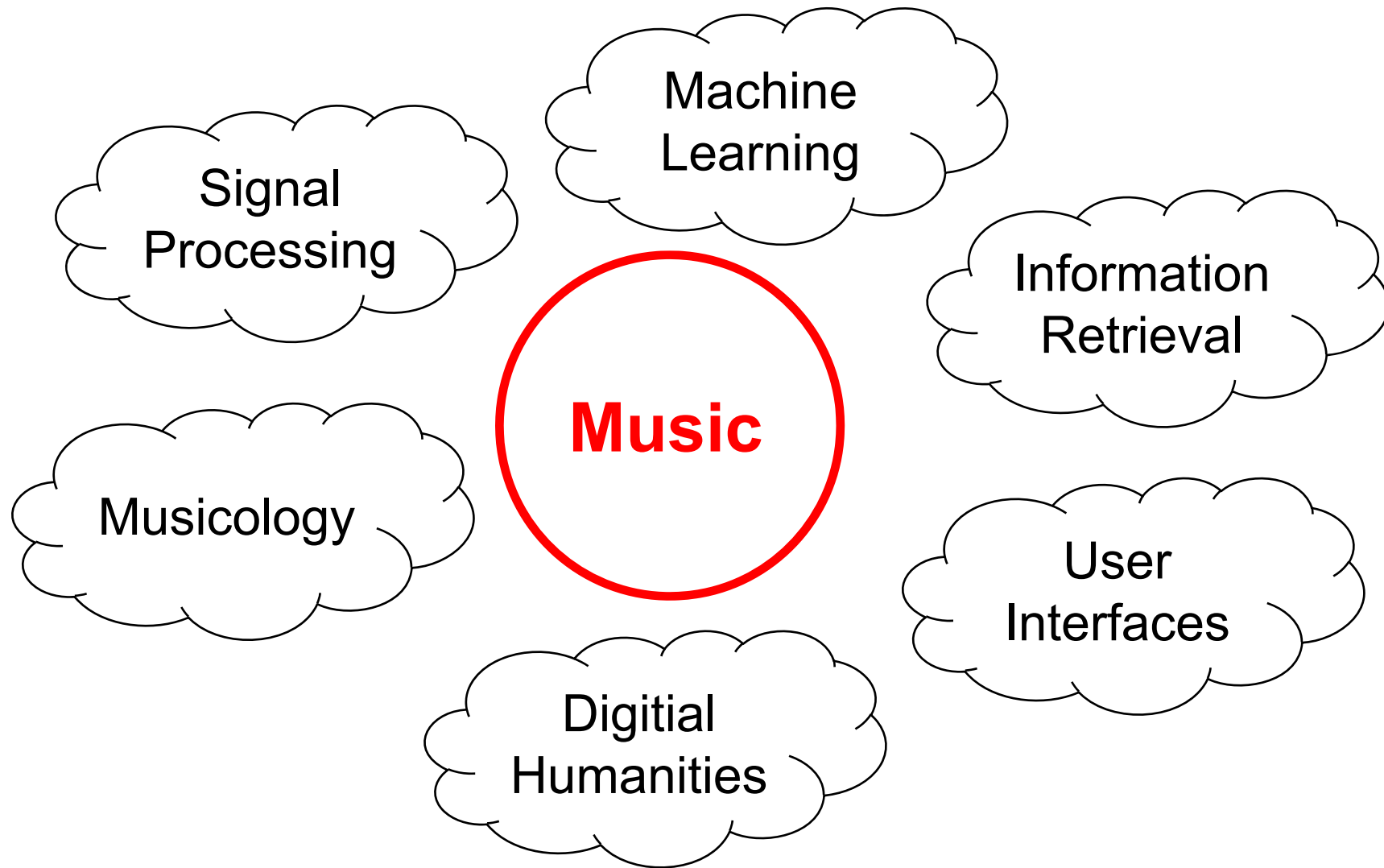
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**Music**



# Music Information Retrieval (MIR)



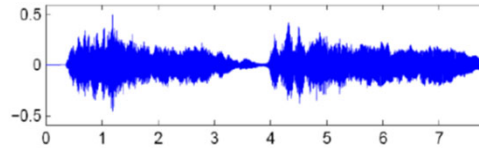


# Music Information Retrieval (MIR)

Sheet Music (Image)



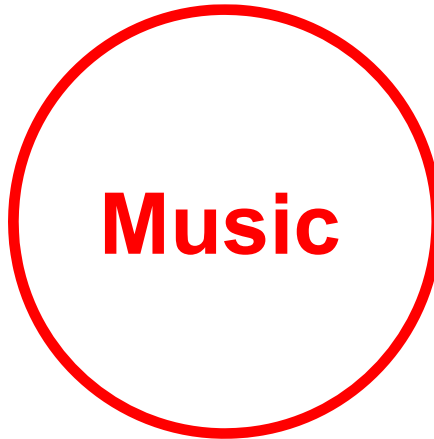
CD / MP3 (Audio)



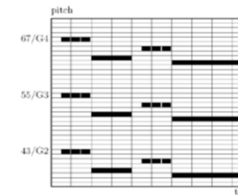
MusicXML (Text)

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

Dance / Motion (Mocap)



MIDI



Singing / Voice (Audio)



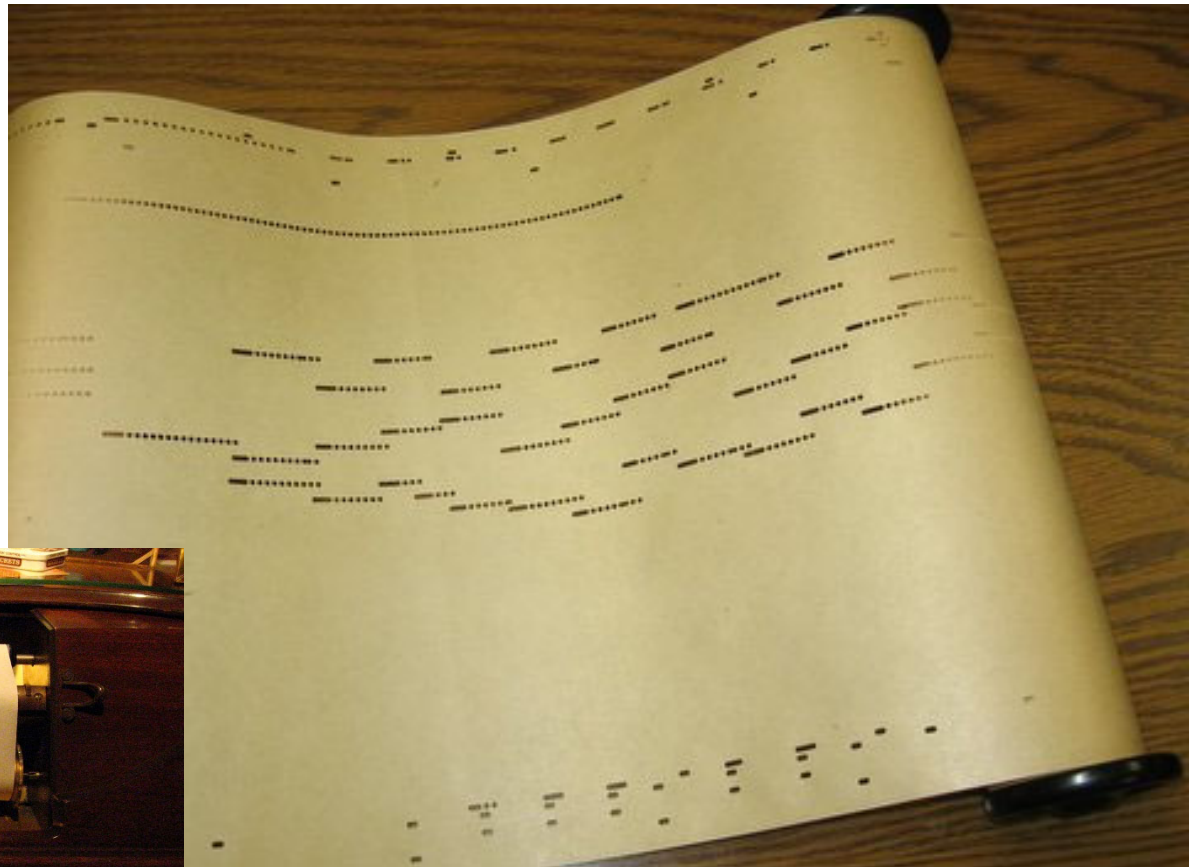
Music Film (Video)



Music Literature (Text)



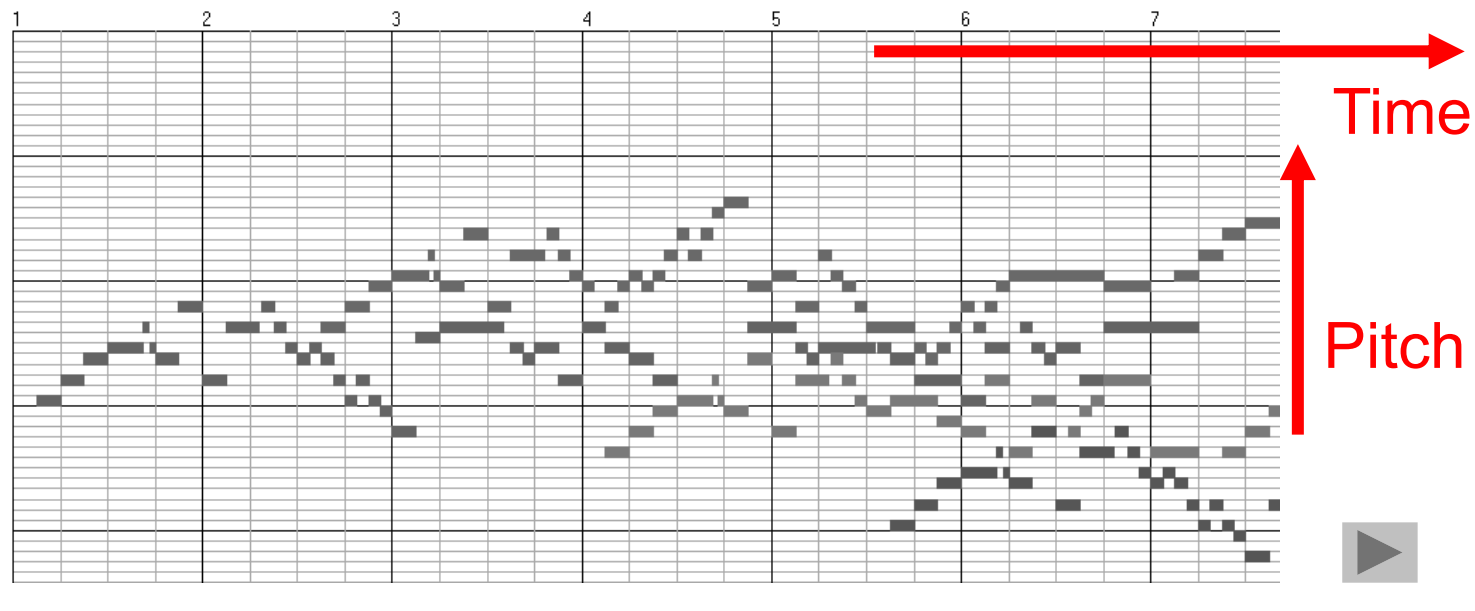
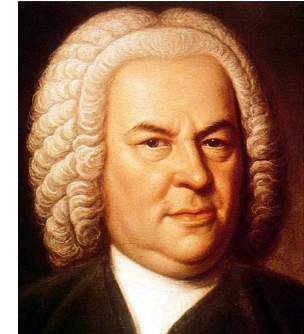
# Piano Roll Representation (1900)



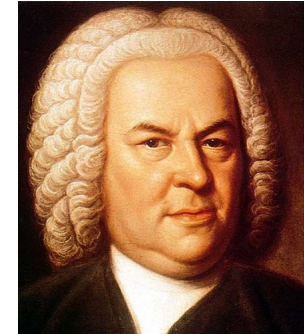
# Piano Roll Representation

J.S. Bach, C-Major Fuge

(Well Tempered Piano, BWV 846)



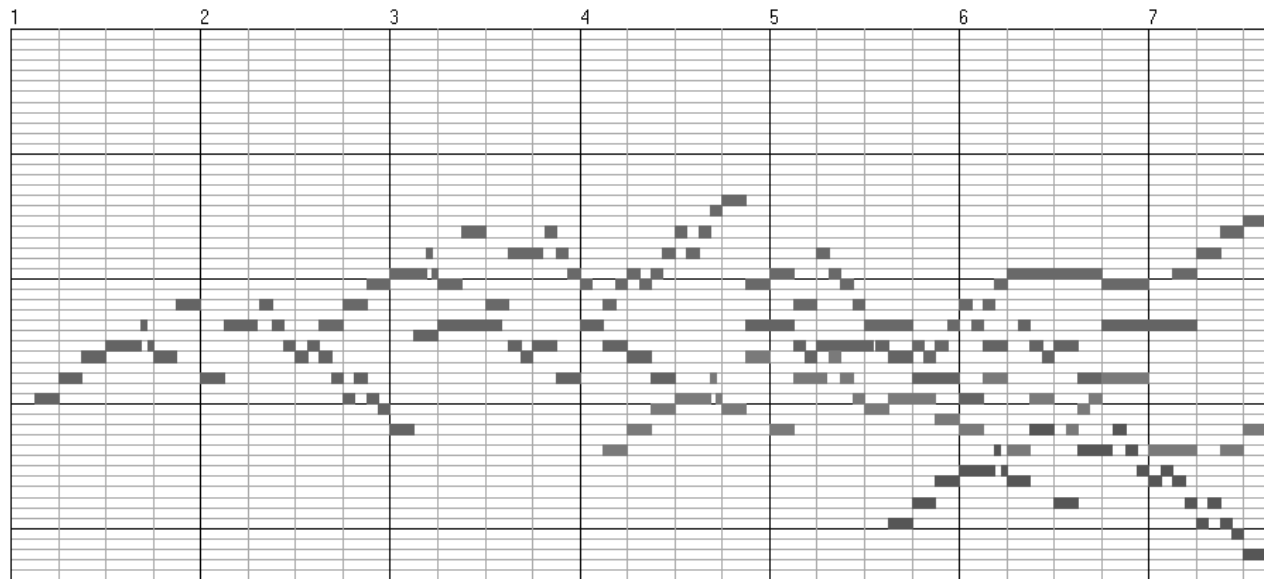
# Piano Roll Representation



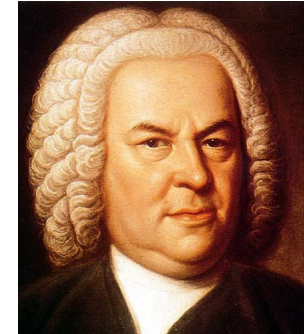
Query:



Goal: Find all occurrences of the query



# Piano Roll Representation

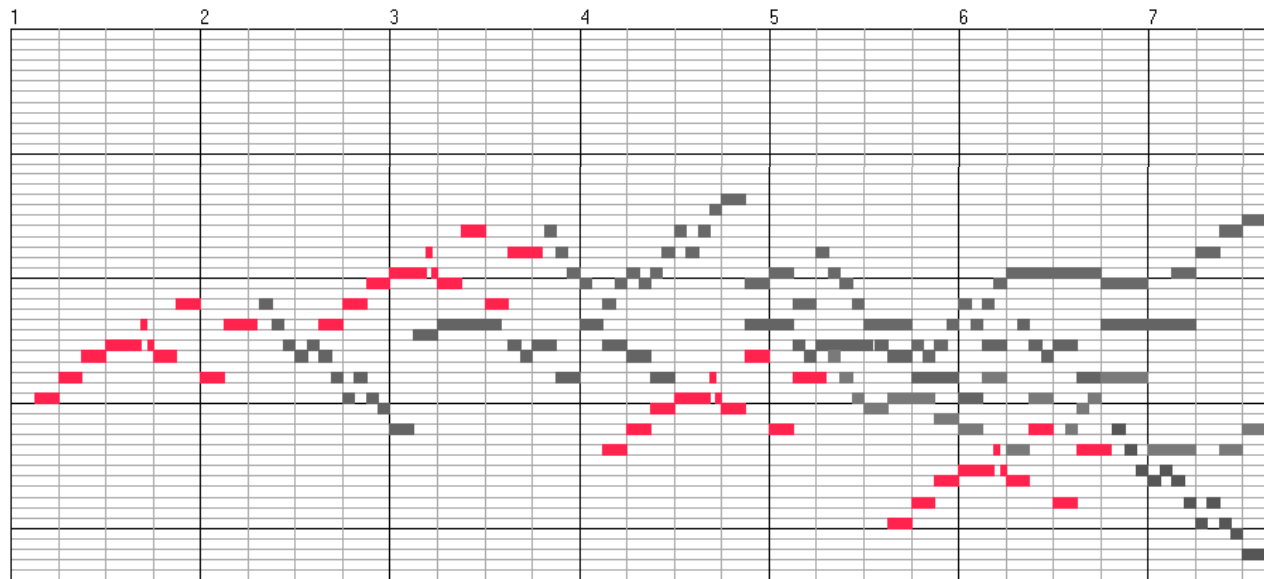


Query:

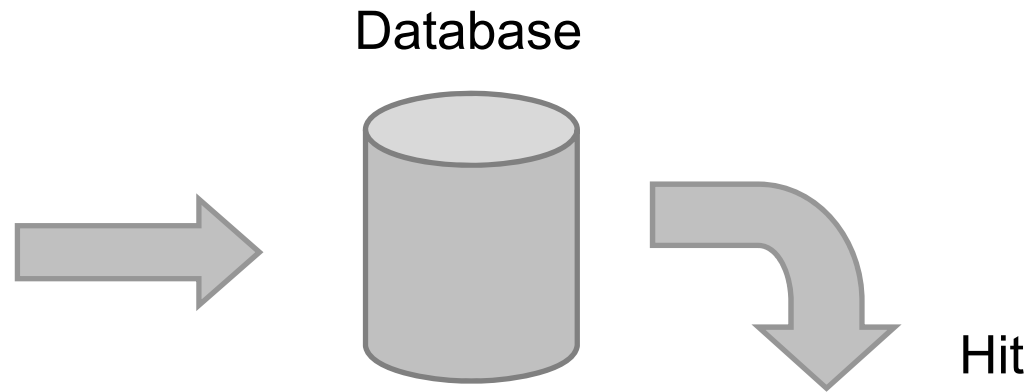


Goal: Find all occurrences of the query

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
- 

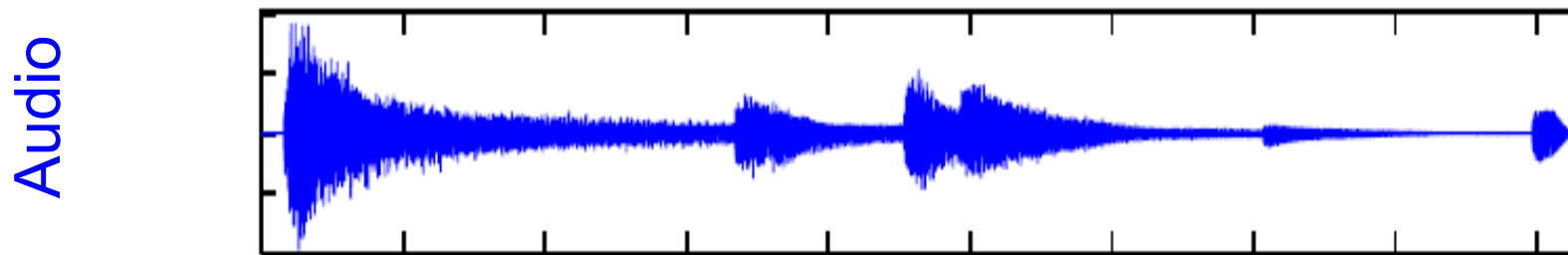
# Music Synchronization: Image-Audio

Image

Grave.



The image shows 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 a few melodic lines.



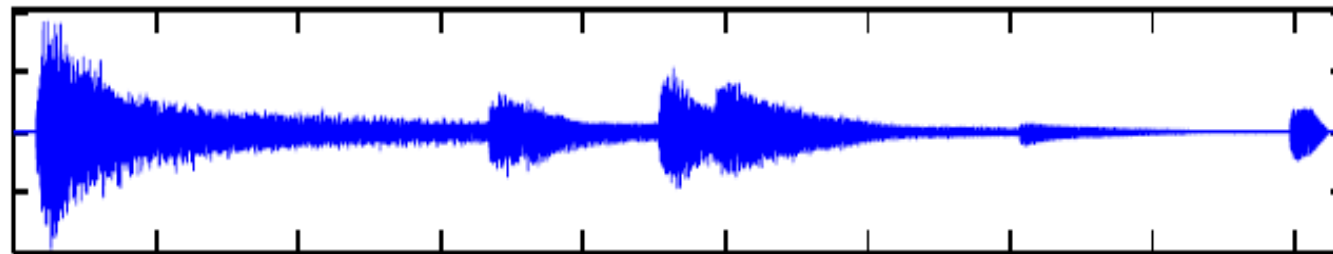
# Music Synchronization: Image-Audio

## Image Processing: Optical Music Recognition

Image



Audio





# Music Synchronization: Image-Audio

## Image Processing: Optical Music Recognition

Image



Audio



## Audio Processing: Fourier Analysis

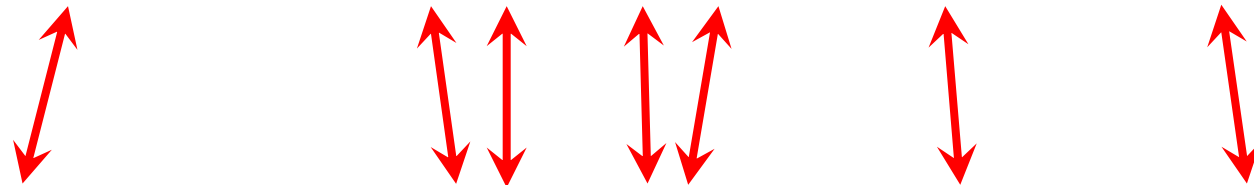
# Music Synchronization: Image-Audio

## Image Processing: Optical Music Recognition

Image



Audio



## Audio Processing: Fourier Analysis

# Music Synchronization

The screenshot displays two windows from a music synchronization application. The top window, titled "ScoreViewer", shows a musical score for "Beethoven - Klaviersonaten Band 1 - Henle". The score is for "Sonata no.8 in C minor, op.13 'Pathétique' / Rondo (Allegro)". The score is currently on track 29 of 54, bar 1 of 211, and page 159 of 285. The bottom window, titled "AudioViewer", shows a track list for "Beethoven - Piano Sonatas-Alfred Brendel". The track list includes 11 tracks, with track 11, "Sonata no.8 in C minor, op.13 'Pathétique' / Rondo (Allegro)", selected. The audio player shows a time of 00:00.00 out of 4:30.35. The interface includes navigation buttons for "Play" and "Stop" in both windows.

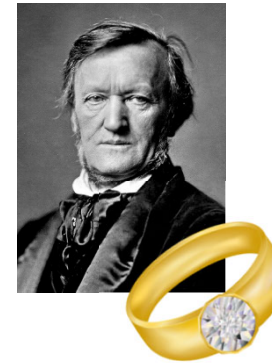


# Music Scenarios

- Freischütz Digital



- Wagner's Ring



- Georgian Music



- Schubert Winterreise



# Scenario: Freischütz Digital



- BMBF (2012 – 2016)
- Detmold/Paderborn  
(Prof. Veit, Digital Editions)
- Frankfurt  
(Prof. Betzwieser, Musicology)
- Erlangen  
(Prof. Müller, Computer Science)



# Scenario: Freischütz Digital



## Audio

- BMBF (2012 – 2016)
- Detmold/Paderborn  
(Prof. Veit, Digital Editions)
- Frankfurt  
(Prof. Betzwieser, Musicology)
- Erlangen  
(Prof. Müller, Computer Science)



# Scenario: Freischütz Digital



## Recordings

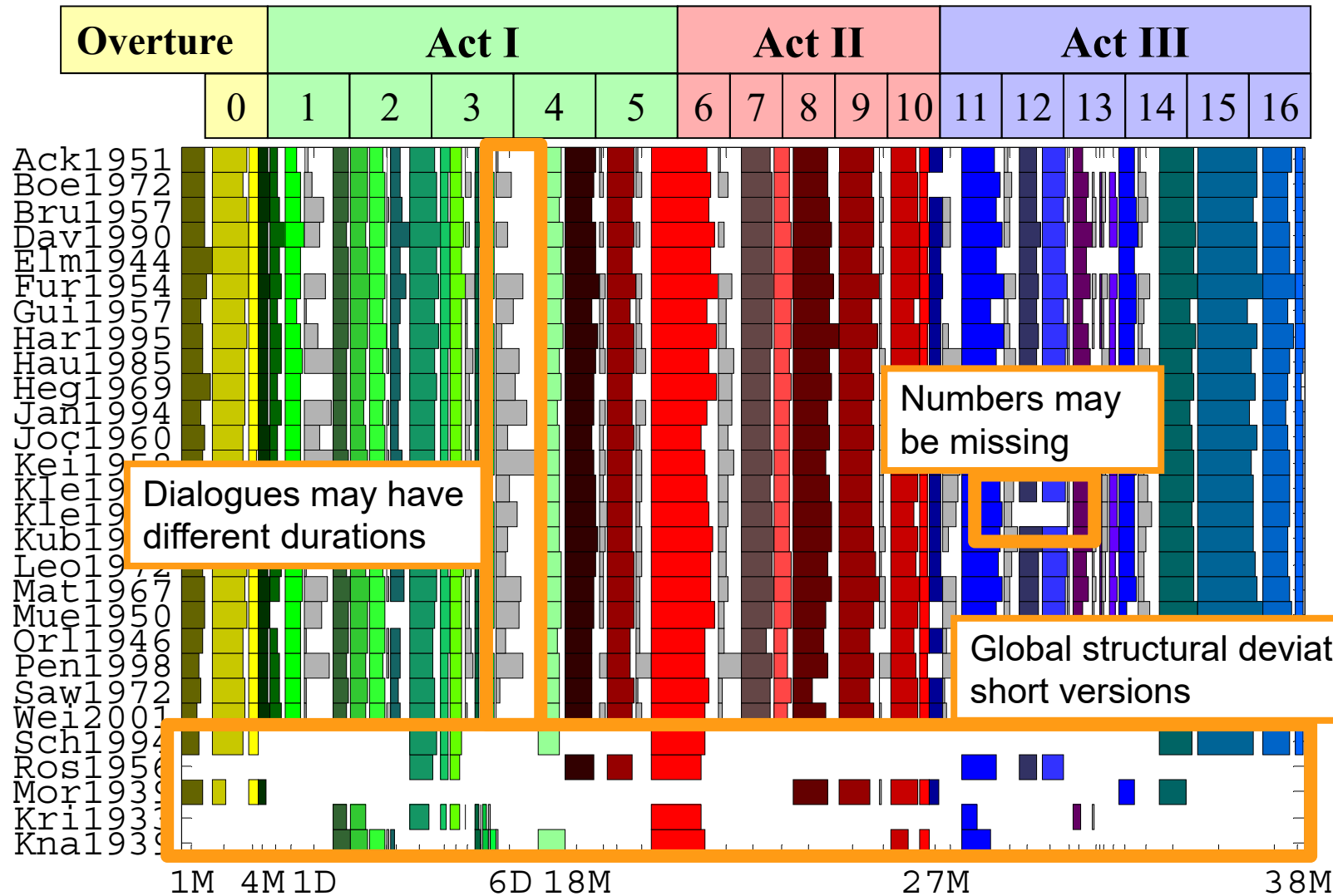
- 23 mostly complete recordings
- 10 abridged/short versions
- Recorded between 1933 and 2001

**Example:** Song (No. 4) from “Der Freischütz”

Variations	Performance	
	Kleiber C. , 1973	
Tempo	Elmendorff, 1944	
Language	Penin (fr.), 1998	
Key	Orlov (russ.), 1946	
Sound quality	Gui (it.), 1957	



# Scenario: Freischütz Digital





# Scenario: Freischütz Digital



## Example: Carl Maria von Weber: "Der Freischütz" (No. 4)

Introduction



Stanzas



Dialogues



Allegro feroce, ma non troppo presto.

Flauti piccoli.  
Oboi.  
Fagotti.  
Violino I.  
Violino II.  
Viola.  
Caspar.  
Violoncello e Basso.

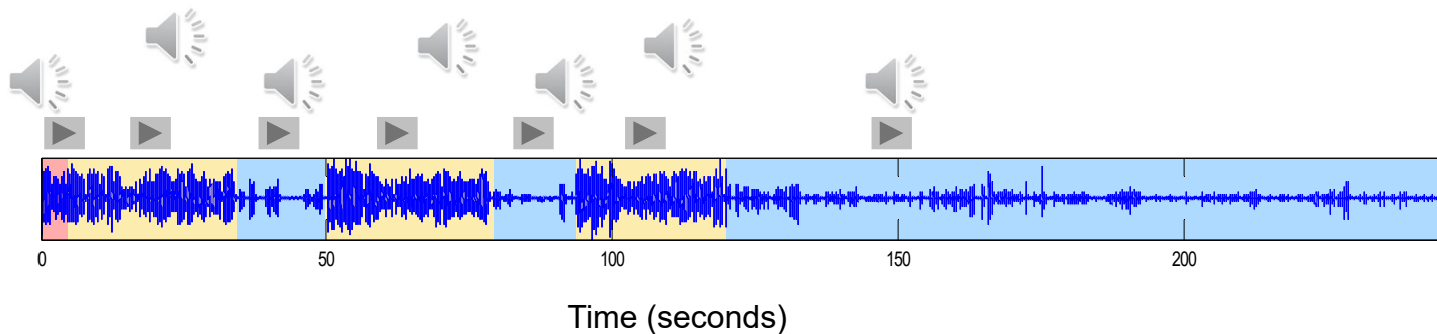
1. Hier im ird'schen Jammer - thal  
2. Eins ist Eins und Drei sind Drei!  
3. Oh - ne dies Tri - fo - li - um

(Nach der ersten Strophe wird gesprochen)  
Caspar. Ei, da mußt auch mit singen. (Trinkt)  
Max. Lach mich!  
Caspar. Jungfer Agathe soll leben! Wer die Gesundheit seiner Braut ausschüttet, wirft doch wahrlich ein Schöff!  
Max. Du wirst waverchäm. (Sie stossen an und trinken.)

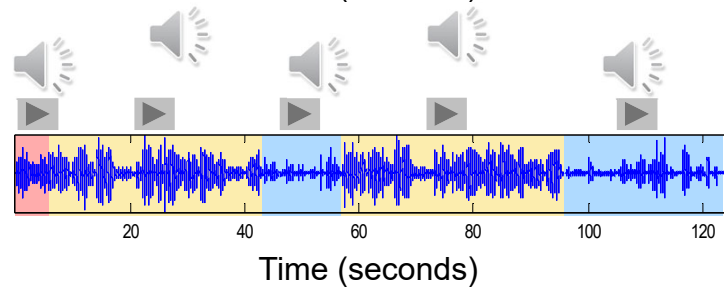
(Nach der zweiten Strophe)  
Caspar. Mir ist aber auch gar nichts anzufangen. (Trinkt)  
Max. Wie kannst du mir summen, in so etwas einzustimmen.  
Caspar. Unser Herr Fürst soll leben! Wer nicht dabei ist, wir' ein Jäcker!  
Max. Nun denn, aber dann auch keinen Tropfen mehr, ge - stossen an und trinken. Max wehrt sich mit dem Hute. (Lach und gibt sonst zu erkennen, dass ihm heiss sei.)

(Nach der dritten Strophe)  
Max. Aufspringend. Hühel! Agathe hat Recht, wenn sie mich immer vor dir warnt. (Will fort. Ist leicht besessen.)  
Caspar. Wie kannst du auch gleich so in Harnisch geraten, Bräutigam! Ich diene noch als Bube in der letzten Fabrik. Unsere Kriegsvolk lernt man solche Schmelmeliederlein. (Es schüttet seinen Hut Max' nach aus.) Willst du schon nach Hause?  
Max. Ja, es wird Zeit. Es schlug Sieben.  
Caspar. Zu Agathe! Das reißt ich doch nicht... du kümmerst sie erschrecken. Weinst du nicht, dass sie auf einem Gewin als gute Vorbedeutung für morgen hofft?  
Max. Ach, die Ärmer! und ich selbst! Morgen!  
Max. Was machst du, wirf mir doch ganz schauerlich. Was hast du geladen? Was war das für eine Kugel?  
Caspar. Gar keine Kugel, Narren. Eine trachtige Blindschliche, die trifft allemal.  
Max. Trauer! ich deut'... oder bin ich besessen? So etwas ist mir nie begegnet. Caspar! Ich bitte dich, ich beschwöre dich, lass ihn Caspar, ich bring' dich um! Sag, was war das für eine Kugel?  
Caspar. Hast du verwirrt vor Freude? Ich theile sie mit dir. (Warnt ihn.) Das war ein Schuss. Lass' mich los!  
Max. (lässt ihn los.) Wo hast du die Kugel her?

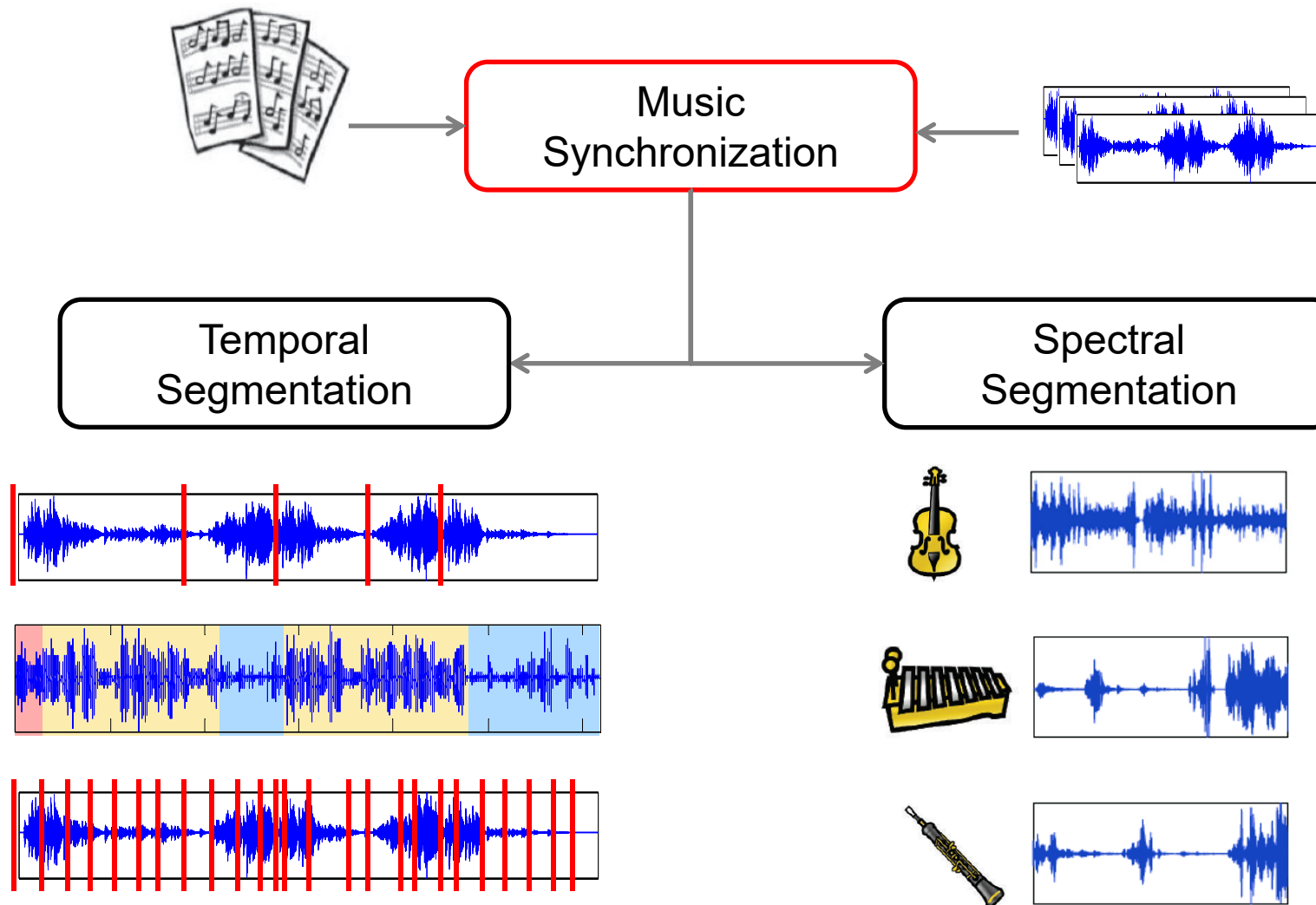
Kleiber



Ackermann



# Scenario: Freischütz Digital

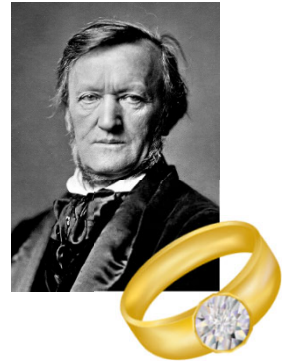


# Scenario: Freischütz Digital

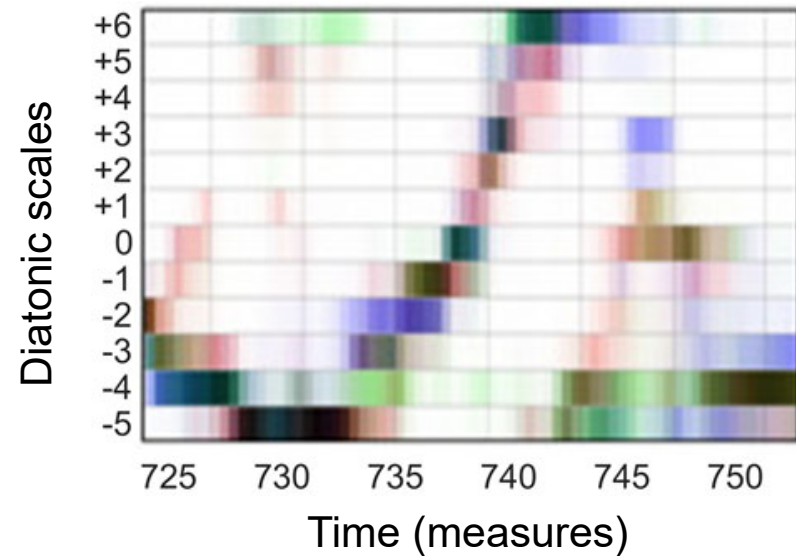


- Extraction of musical form
- Finding (nearly) repeating patterns
- Instrument detection and classification
- Language detection
- Detection of musical keys, chords, ...
- Detection of time signature, tempo, measures, beats, ...
- ...

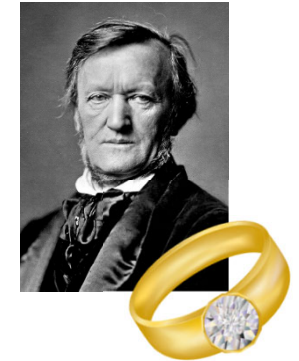
# Scenario: Wagner's Ring



- DFG (2014 – 2023)
- Saarbrücken  
(Prof. Kleinertz, Musicology)
- Erlangen  
(Prof. Müller, Computer Science)
- Objectives
  - Harmony-based structural analysis
  - Visualization techniques
  - Exploration of interdisciplinary research



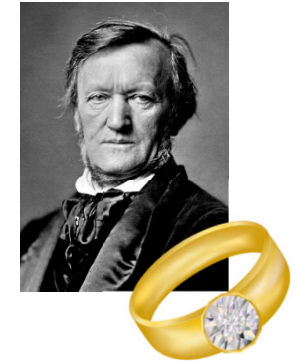
# Scenario: Wagner's Ring



No.	Conductor	Recording	hh:mm:ss
1	Barenboim	1991–92	14:54:55
2	Boulez	1980–81	13:44:38
3	Böhm	1967–71	13:39:28
4	Furtwängler	1953	15:04:22
5	Haitink	1988–91	14:27:10
6	Janowski	1980–83	14:08:34
7	Karajan	1967–70	14:58:08
8	Keilberth/Furtwängler	1952–54	14:19:56
9	Krauss	1953	14:12:27
10	Levine	1987–89	15:21:52
11	Neuhold	1993–95	14:04:35
12	Sawallisch	1989	14:06:50
13	Solti	1958–65	14:36:58
14	Swarowsky	1968	14:56:34
15	Thielemann	2011	14:31:13
16	Weigle	2010–12	14:48:46

- Large-scale work
- Four operas
  - ca. 15 hours
  - 21941 measures
- 16 performances

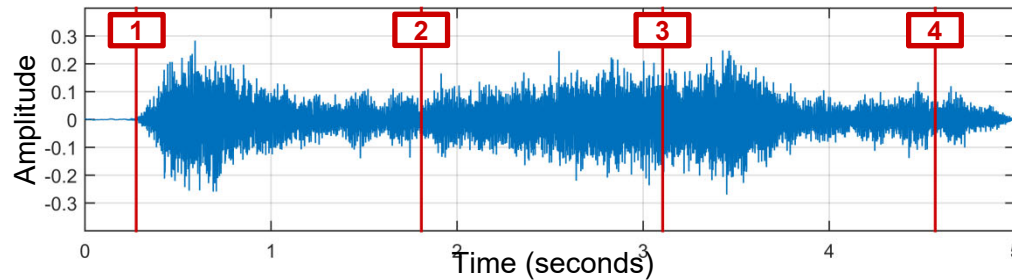
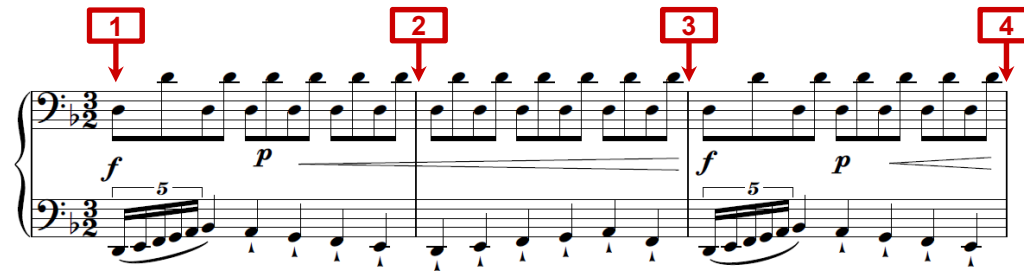
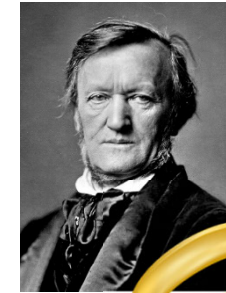
# Scenario: Wagner's Ring



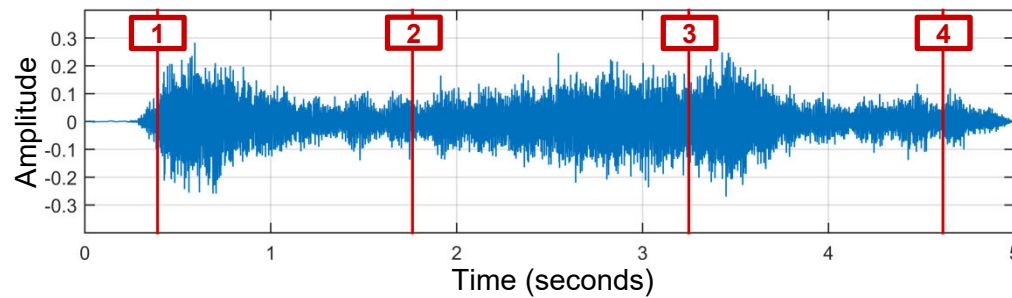
No.	Conductor	Recording	hh:mm:ss
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- Large-scale work
- Four operas
  - ca.15 hours
  - 21941 measures
- 16 performances
- Manual measure annotations

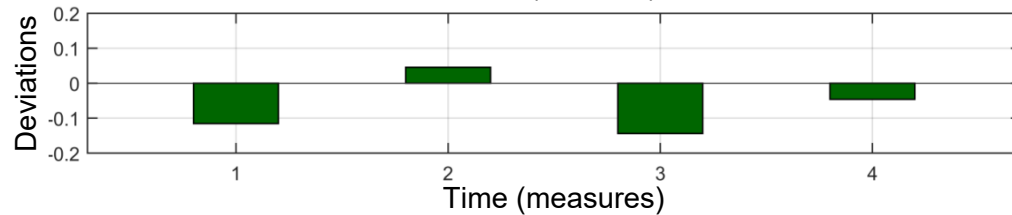
# Scenario: Wagner's Ring



Annotator 1

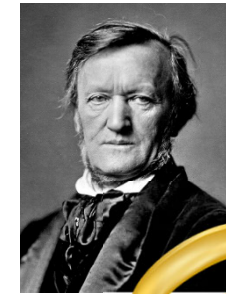


Annotator 2

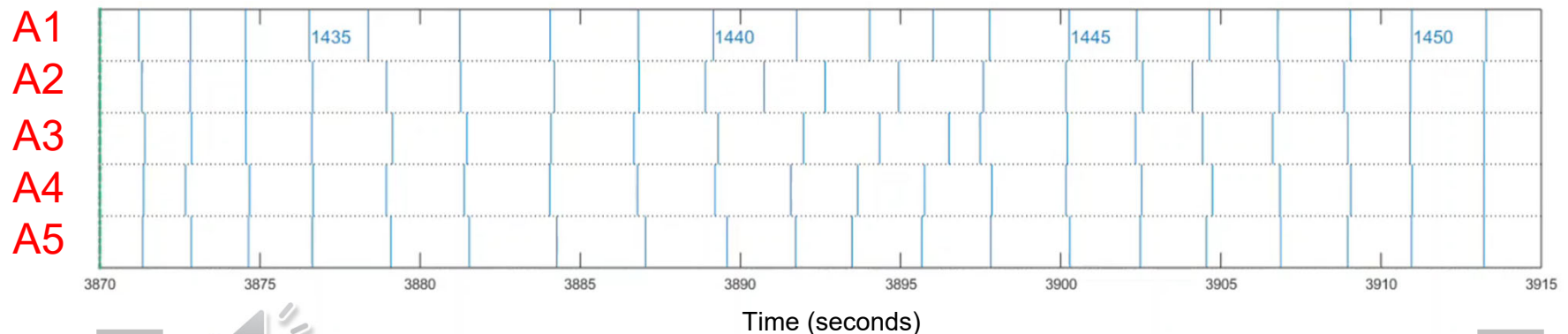
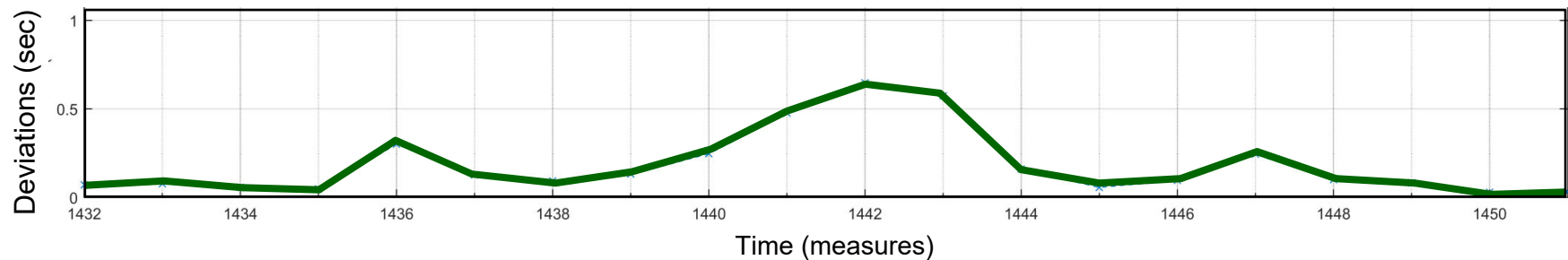


Deviations

# Scenario: Wagner's Ring

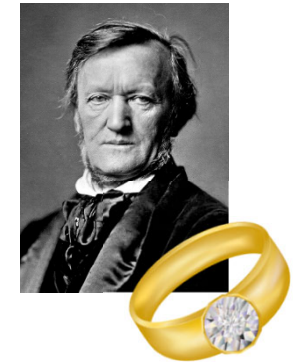


## Standard deviations among **annotators**





# Scenario: Wagner's Ring



- Measure position ambiguities
  - Rhythm or beat unclear
  - Vague note onset positions
  - Non-synchronous parts (e.g., singers and orchestra)
  - ...
- Introduce confidence measures
  - Cross-annotator agreement
  - Cost function based on novelty and homogeneity
  - ...

Christof Weiß, Vlora Arifi-Müller, Thomas Prätzlich, Rainer Kleinertz, Meinard Müller:  
**Analyzing Measure Annotations for Western Classical Music Recordings.**  
In Proceedings of the International Society for Music Information Retrieval Conference (ISMIR): 517–523, 2016.

# Scenario: Georgian Music



- DFG (2018 – 2022)
- Potsdam  
(Prof. Scherbaum, Ethnomusicology)
- Erlangen  
(Prof. Müller, Computer Science)
- Objectives
  - Harmonic and melodic singing analysis
  - New sensors (larynx microphones)
  - Digital humanities



# Scenario: Georgian Music

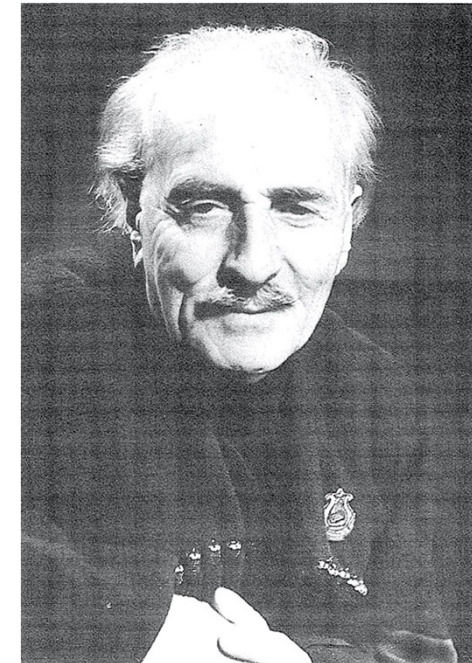


# Scenario: Georgian Music

Example: Erkomaishvili corpus

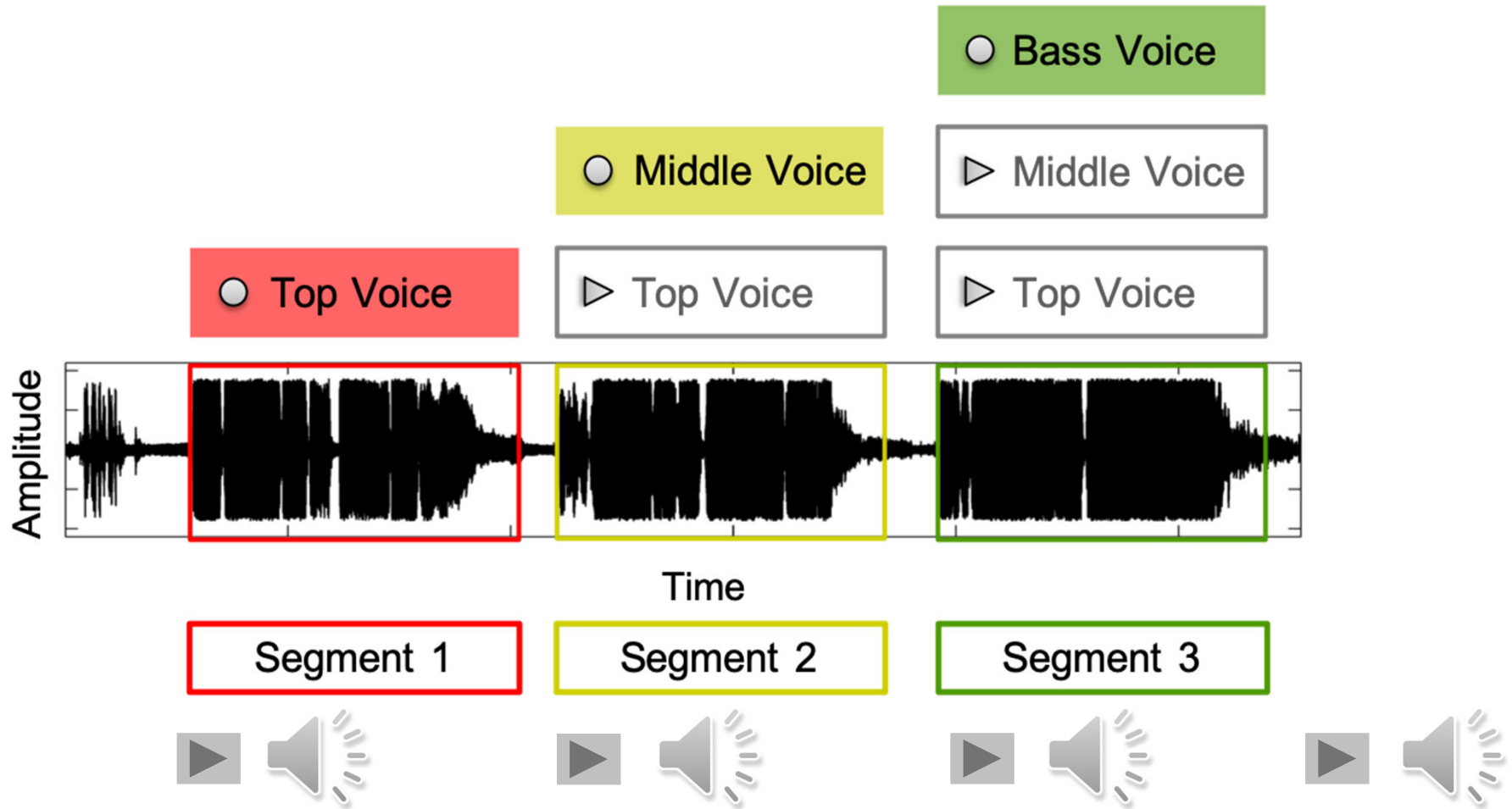
- Collection of traditional three-voice Georgian songs
- Performed by the former Georgian master chanter Artem Erkomaishvili (1887-1967)
- Recordings of 100 songs using tape recorders (1966)

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



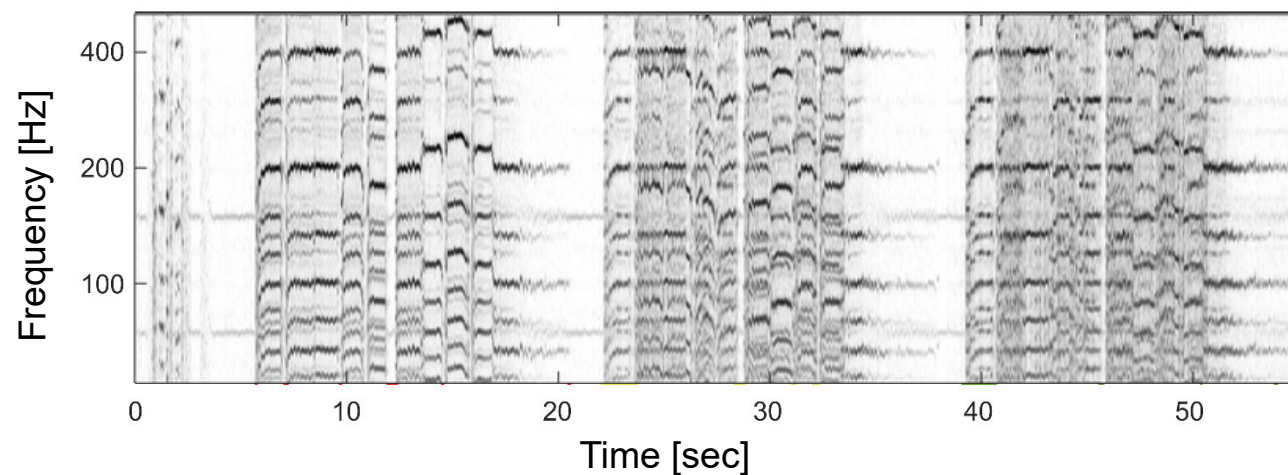
# Scenario: Georgian Music

Example: Erkomaishvili corpus



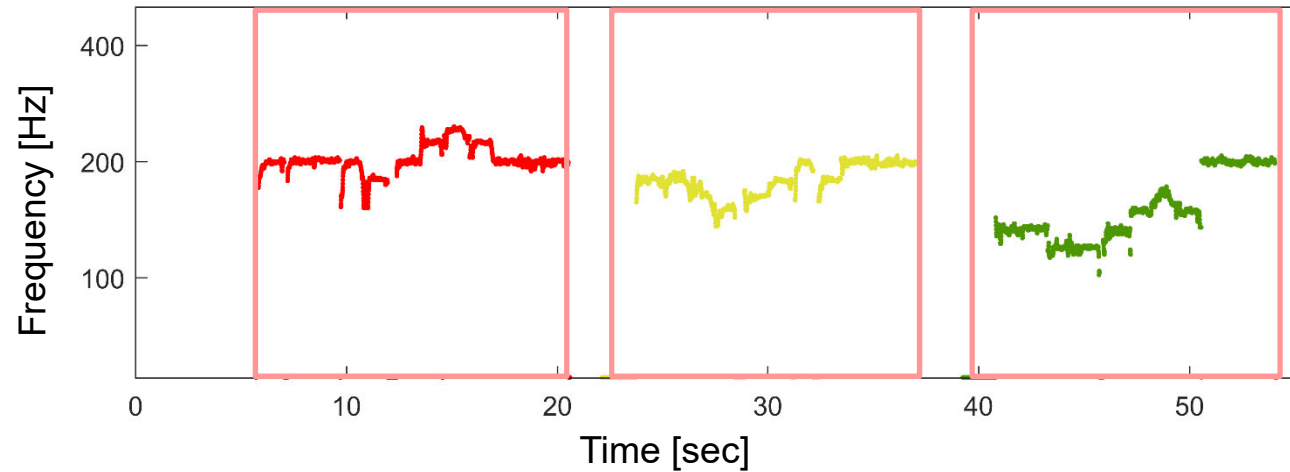
# Scenario: Georgian Music

Example: Erkomaishvili corpus



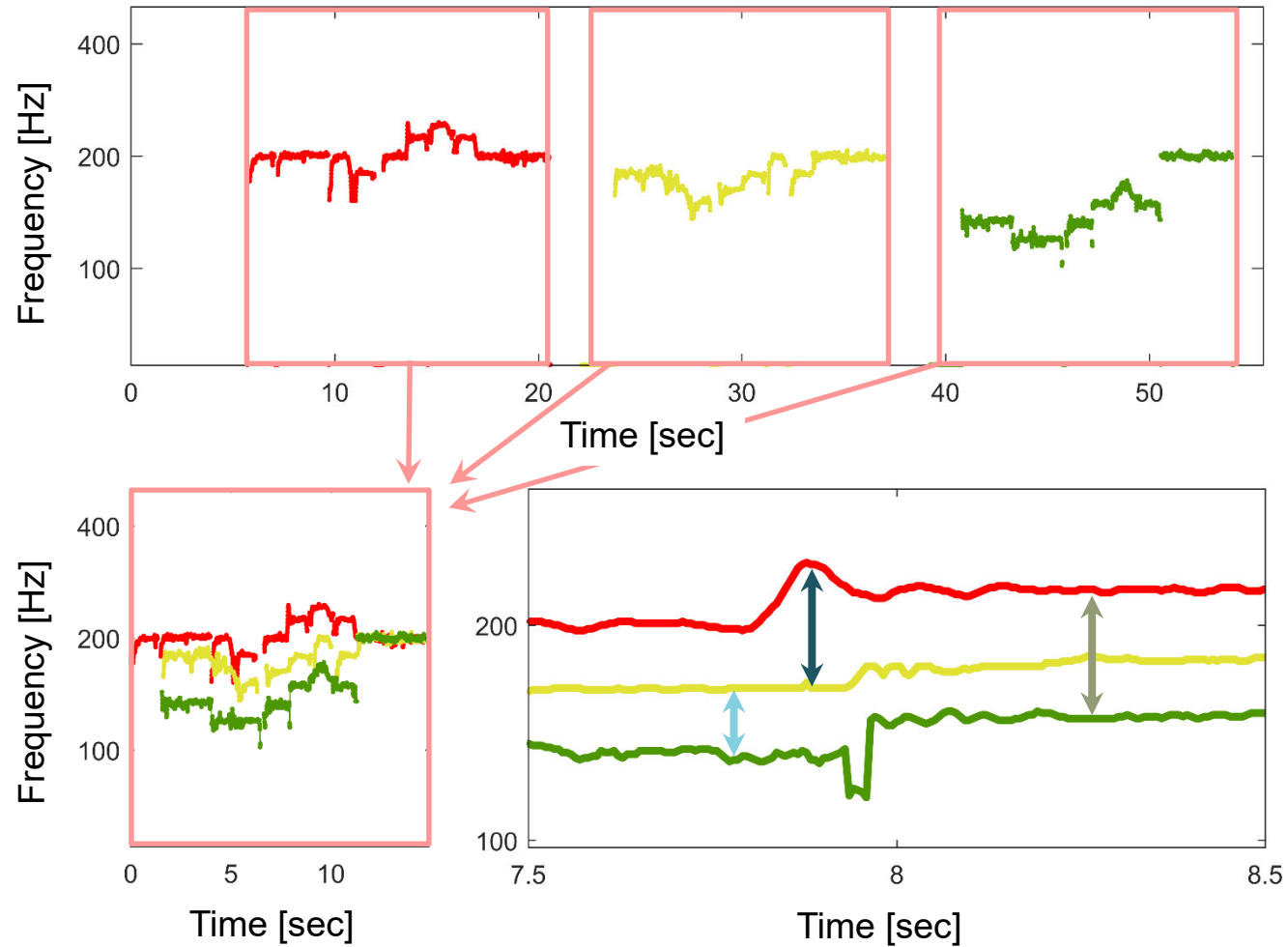
# Scenario: Georgian Music

Example: Erkomaishvili corpus



# Scenario: Georgian Music

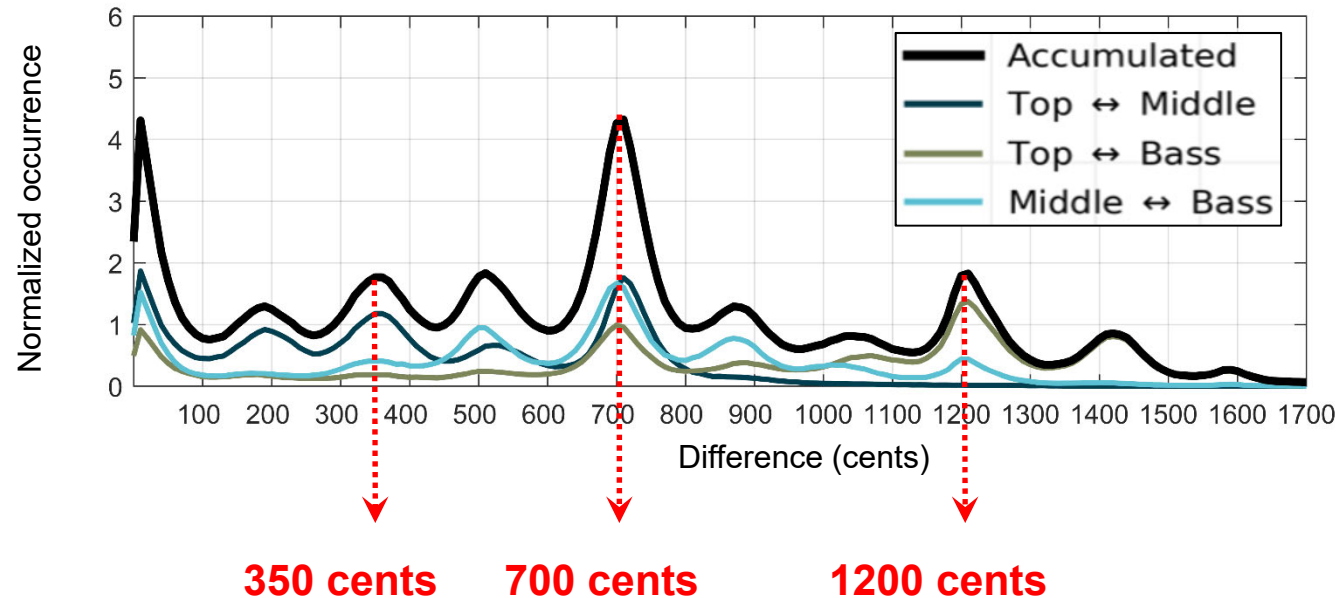
Example: Erkomaishvili corpus





# Scenario: Georgian Music

Example: Erkomaishvili corpus



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

# Scenario: Georgian Music

Example: Erkomaishvili corpus



The screenshot shows a web application interface. On the left, there is a table of recordings with columns for ID, English Title, Georgian Title, and Website. A red circle highlights the 'Link' column for the second recording, with a red arrow pointing to the right. On the right, there is a musical score player showing three staves of music with lyrics in Georgian and English. The lyrics are: 'agh-dgo-ma - sa she-n-sa, 1 2 3 6 7 9 10 11 12 13' and '[agh-dgo]-ma - sa she-n-sa 1 2 3 4 5 7 9 10 11 12 13'. Below the score, there is a playback control bar with a progress indicator and a list of segments: 'First Segment (Top Voice)', 'Second Segment (Top + Middle Voice)', 'Third Segment (Top + Middle + Bass Voice)', and 'Mix of all Segments'.

ID	English Title	Georgian Title	Website
001	Christ is risen from the dead	Qrist'e aghsdga	<a href="#">Link</a>
002	The Angels in the Heaven	Aghdgomasa shensa	<a href="#">Link</a>
003	Christ is risen from the dead	Qrist'e aghsdga	<a href="#">Link</a>
004	Christ is risen from the dead	Qrist'e aghsdga	<a href="#">Link</a>
005	The Day of Resurrection	Aghdgomisa dghe ars	<a href="#">Link</a>
006	Let us purify our senses	Ganvits'midnet satsnobelni	<a href="#">Link</a>
007	For meet is it that heavens	Tsani q'ovlad ghirsabit	<a href="#">Link</a>
008	O, come, let us quaff a beverage new	Movedit da vsvat	<a href="#">Link</a>
009	Now are filled with all the light	Ats' q'ovliturt aghivso	<a href="#">Link</a>
010	Yesterday, O Christ	Gushin shentana	<a href="#">Link</a>

<https://www.audiolabs-erlangen.de/resources/MIR/2019-GeorgianMusic-Erkomaishvili>

# Scenario: Georgian Music

Example: Erkomaishvili corpus



- Temporal organization
  - No notion of meter
  - Continuous note transitions (glissando)
  - Voices not synchronous
- Tonal organization
  - Non-western temperament
  - Harmonic vs. melodic intonation
  - Transcription problematic
- Poor recording conditions

Sebastian Rosenzweig, Frank Scherbaum, David Shugliashvili, Vlora Arifi-Müller, and Meinard Müller:  
**Erkomaishvili Dataset: A Curated Corpus of Traditional Georgian Vocal Music for Computational Musicology.**  
Transactions of the International Society for Music Information Retrieval (TISMIR), 3(1): 31–41, 2020.

# Scenario: Schubert Winterreise



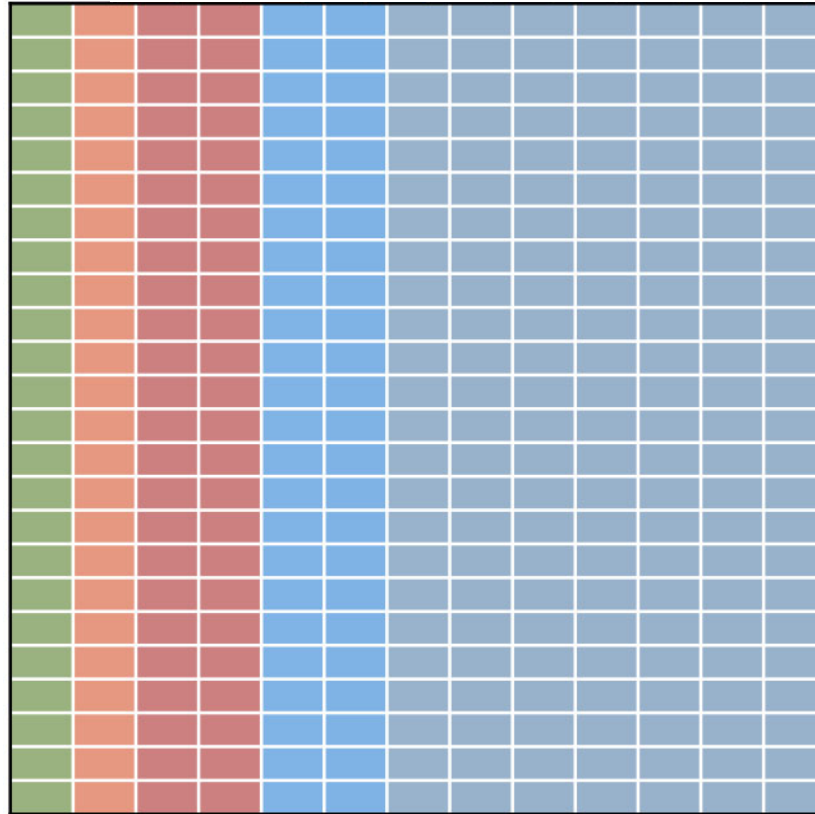
- Winterreise
  - Song cycle for voice and piano
  - Music: Franz Schubert (1828)
  - Poems: Wilhelm Müller
  
- MIR Objectives
  - Music synchronization
  - Structure analysis
  - Harmonic analysis
  - Activity detection (singing, lyrics, ...)
  - ...

# Scenario: Schubert Winterreise

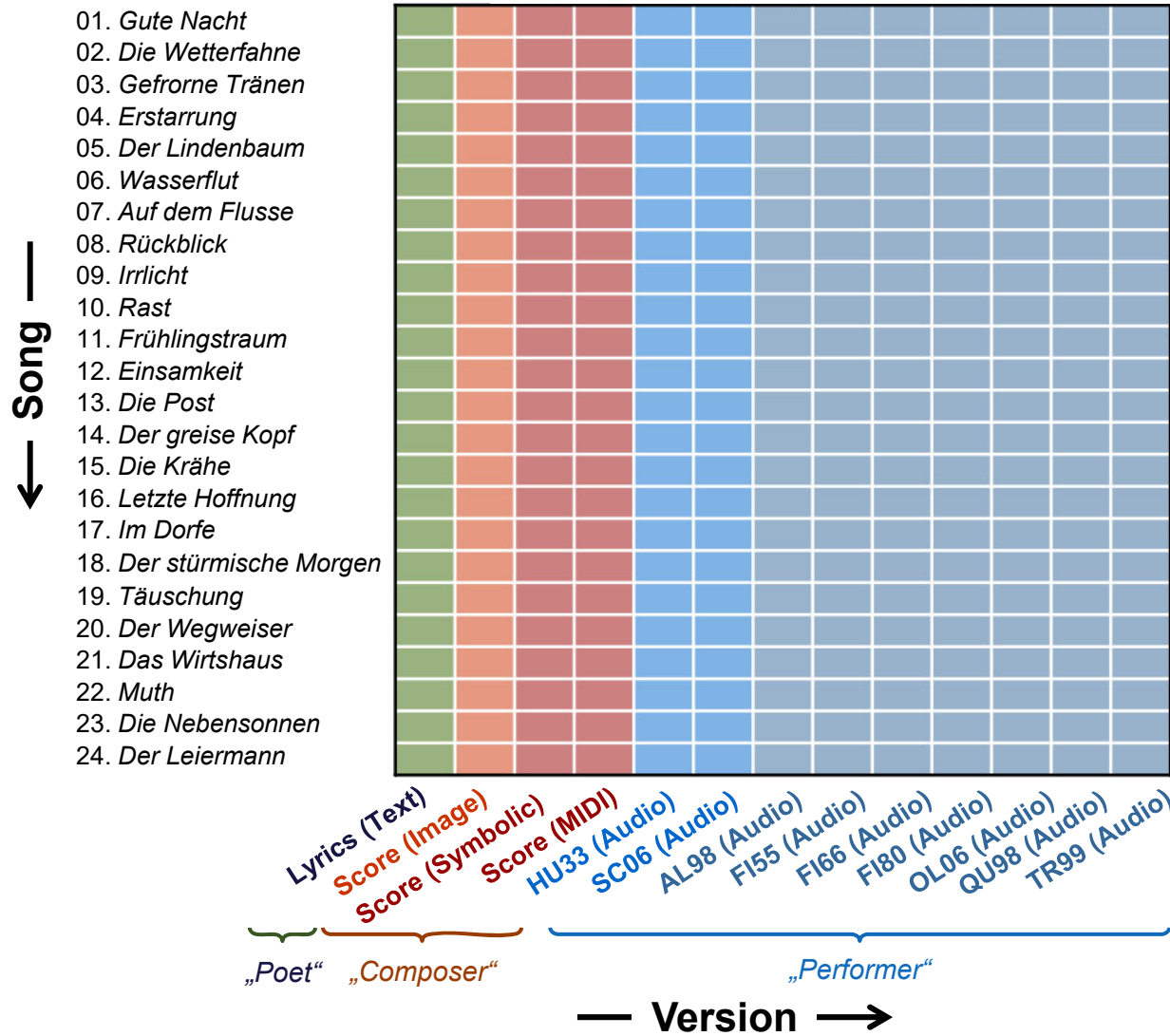


— Song —  
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— Song —

- 01. Gute Nacht
- 02. Die Wetterfahne
- 03. Gefrorene Tränen
- 04. Erstarrung
- 05. Der Lindenbaum
- 06. Wasserflut
- 07. Auf dem Flusse
- 08. Rückblick
- 09. Irrlicht
- 10. Rast
- 11. Frühlingstraum
- 12. Einsamkeit
- 13. Die Post
- 14. Der greise Kopf
- 15. Die Krähe
- 16. Letzte Hoffnung
- 17. Im Dorfe
- 18. Der stürmische Morgen
- 19. Täuschung
- 20. Der Wegweiser
- 21. Das Wirtshaus
- 22. Muth
- 23. Die Nebensonnen
- 24. Der Leiermann



# Scenario: Schubert Winterreise



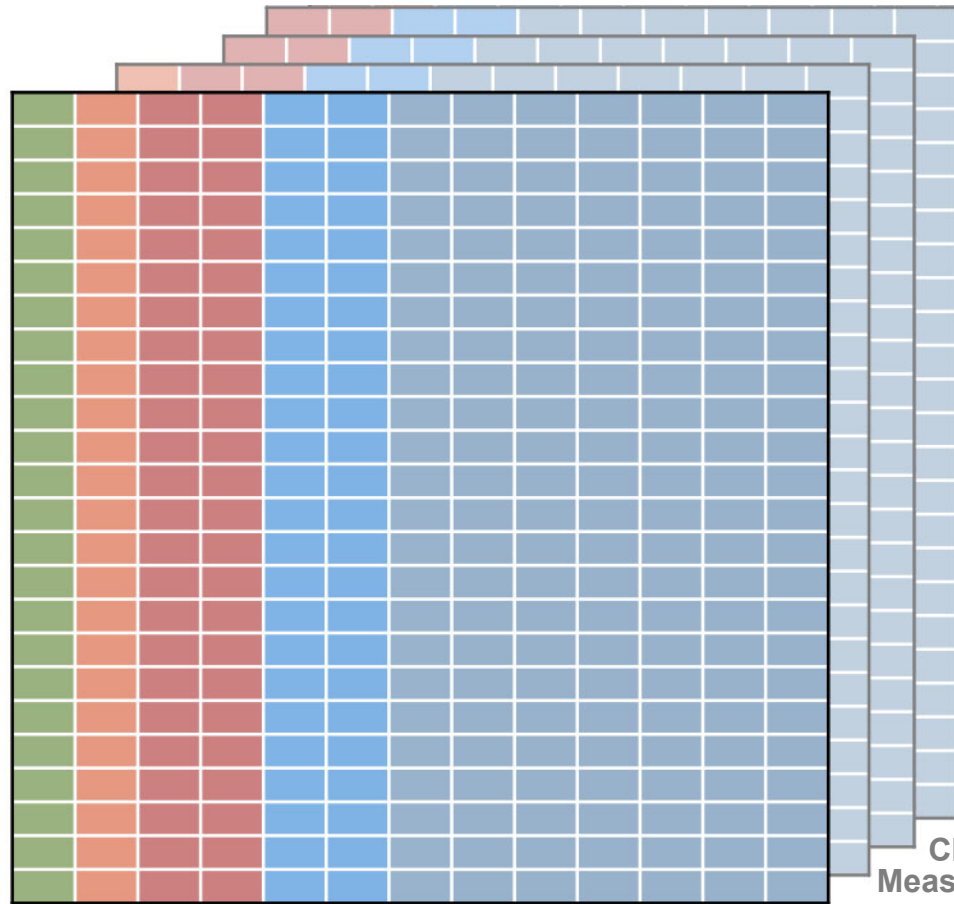
— Song —  
↓

- 01. Gute Nacht
- 02. Die Wetterfahne
- 03. Gefrorne Tränen
- 04. Erstarrung
- 05. Der Lindenbaum
- 06. Wasserflut
- 07. Auf dem Flusse
- 08. Rückblick
- 09. Irrlicht
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- 12. Einsamkeit
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- 18. Der stürmische Morgen
- 19. Täuschung
- 20. Der Wegweiser
- 21. Das Wirtshaus
- 22. Muth
- 23. Die Nebensonnen
- 24. Der Leiermann

Lyrics (Text)  
 Score (Image)  
 Score (Symbolic)  
 Score (MIDI)  
 HU33 (Audio)  
 SC06 (Audio)  
 AL98 (Audio)  
 FI55 (Audio)  
 FI66 (Audio)  
 FI80 (Audio)  
 OL06 (Audio)  
 QU98 (Audio)  
 TR99 (Audio)

„Poet“    „Composer“    „Performer“

— Version —→



Local Keys  
 Chords  
 Measures  
 Raw data  
 — Annotations —→

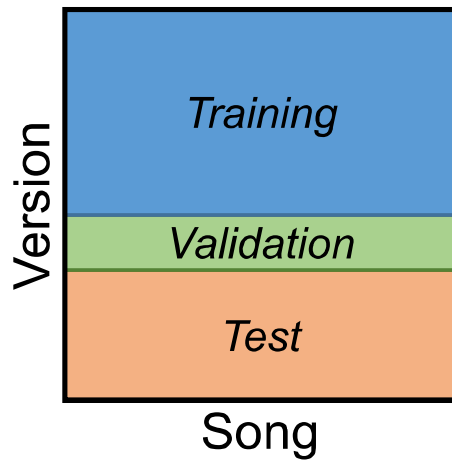


# Scenario: Schubert Winterreise

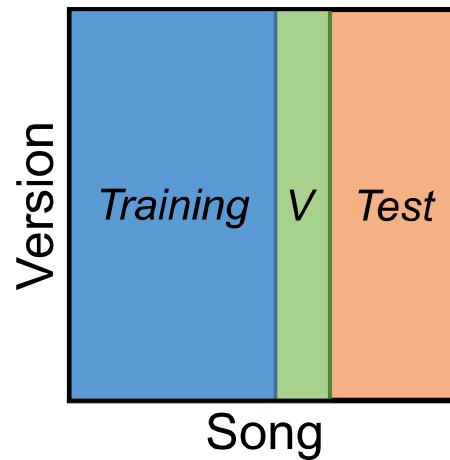
## Cross-Version Evaluation



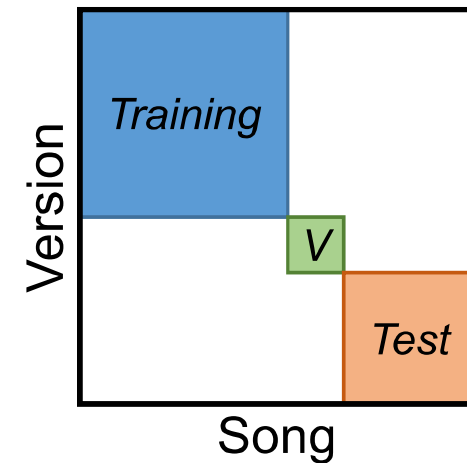
**Version split**



**Song split**



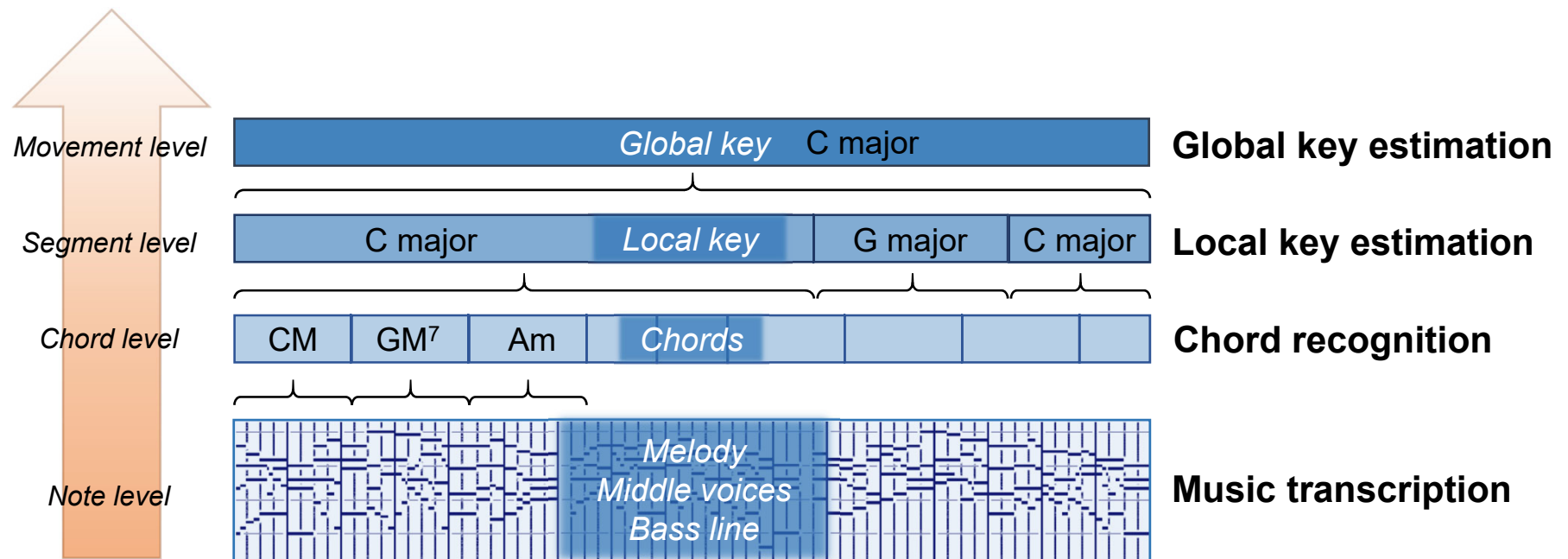
**Neither split**





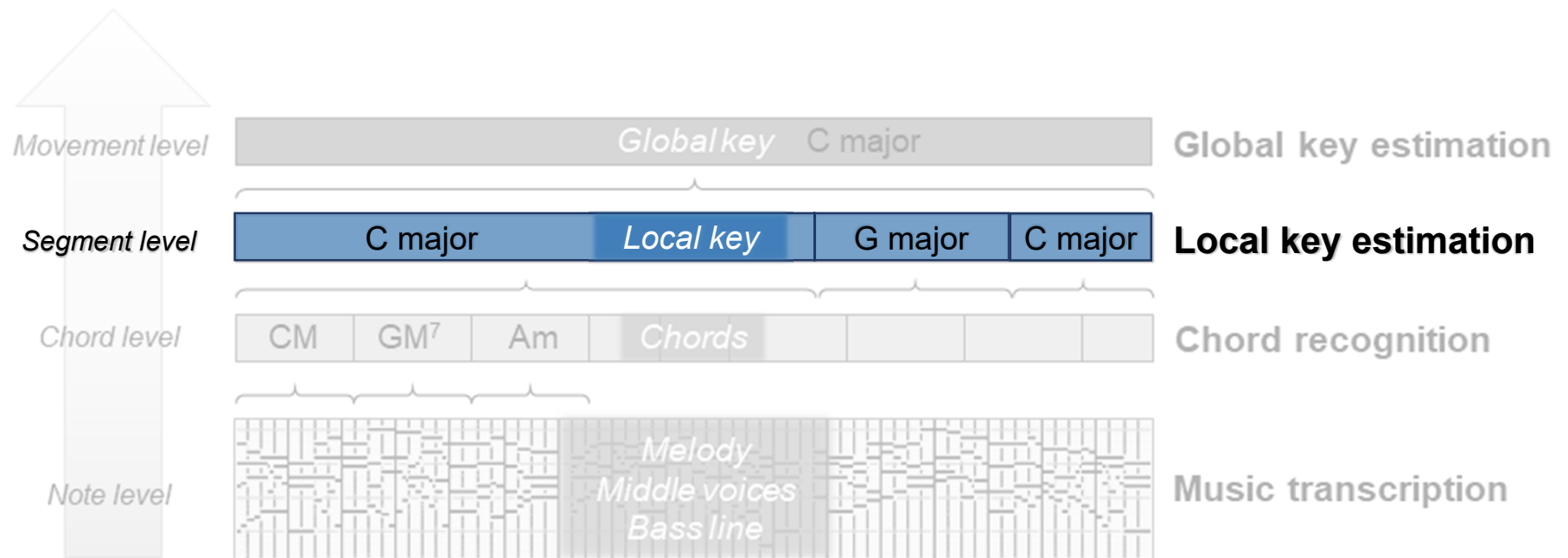
# Scenario: Schubert Winterreise

## Harmony Analysis



# Scenario: Schubert Winterreise

## Harmony Analysis



# Scenario: Schubert Winterreise

## Harmony Analysis



21 22 23 24 25 26 27 28 29 30 31

Voice

Ach! wer wie ich so e-lend ist, gibt gern sich hin der bun-ten List, die hin-ter Eis und Nacht und Graus ihm weist ein

Piano

*cresc.* *p*



## Annotations

A1

A major	A minor	E major	A major
---------	---------	---------	---------

A2

A major
---------

A3

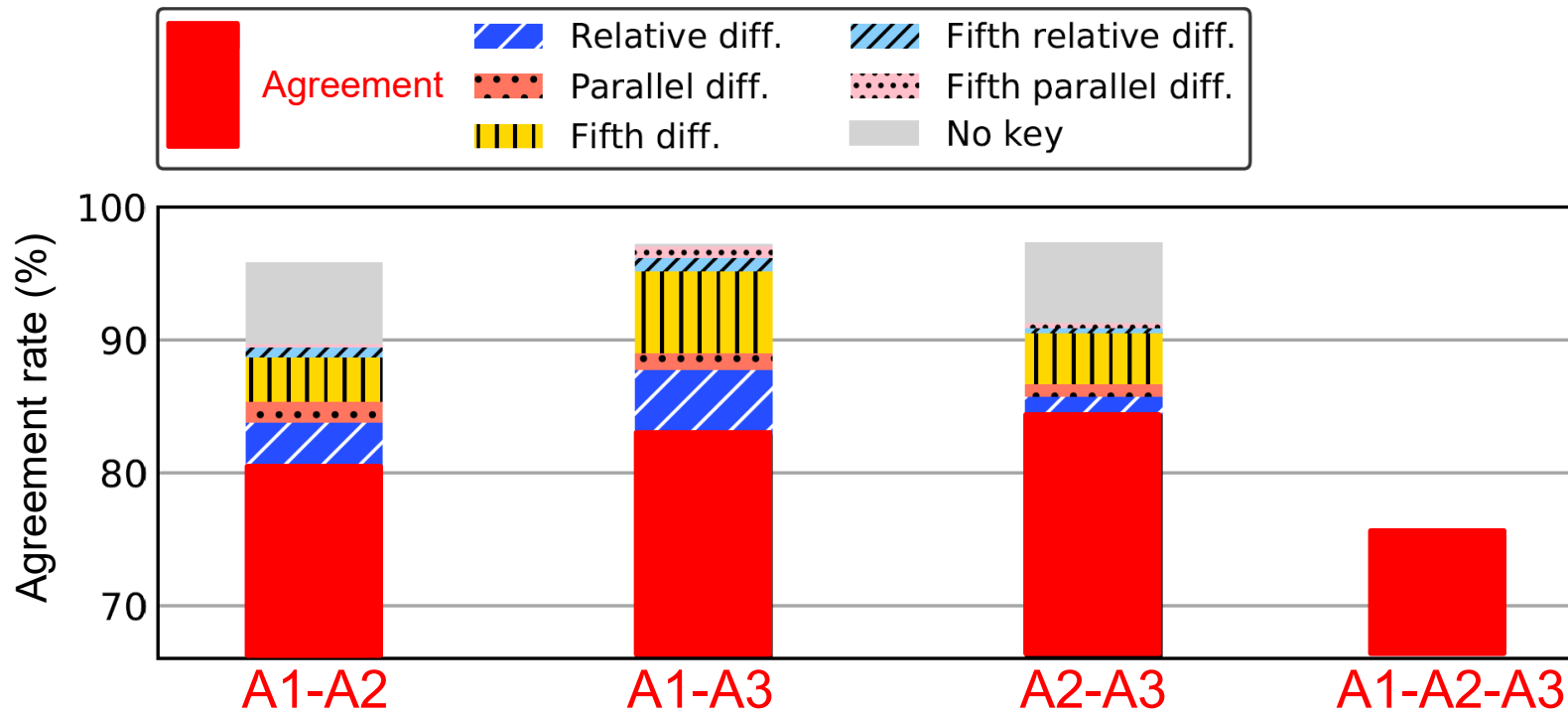
A major	A minor	A major
---------	---------	---------

# Scenario: Schubert Winterreise

## Harmony Analysis



Annotator **agreements** and differences



# Scenario: Schubert Winterreise



- Harmony-related annotations
  - Hierarchical nature of musical structures
  - High degree of subjectivity
  - Dependence on user needs and applications
- ...

Christof Weiß, Frank Zalkow, Vlora Arifi-Müller, Meinard Müller, Hendrik Vincent Koops, Anja Volk, Harald Grohgan: **Schubert Winterreise Dataset: A Multimodal Scenario for Music Analysis.** ACM Journal on Computing and Cultural Heritage (JOCCH), 15(2): 1–18, 2021.

# Conclusions (Annotations)

- Annotating music data is a challenge
  - Data inconsistencies
  - Underlying model assumptions often violated
  - High degree of subjectivity
  - Dependency on user needs and applications
  - **Never trust your annotations!**
- Annotations and analyses cannot be separated
  - Needs to be an interactive process
  - Requires a dialogue between domain experts and computer scientists
  - Requires an understanding and adaption of tools
- Opportunities
  - Annotation process becomes subject of research
  - Increasing appreciation of datasets
  - Great potential for interdisciplinary research

# Why is Music Processing Challenging?

**Example:** Chopin, Mazurka Op. 63 No. 3



Mazurka.

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

Allegretto.

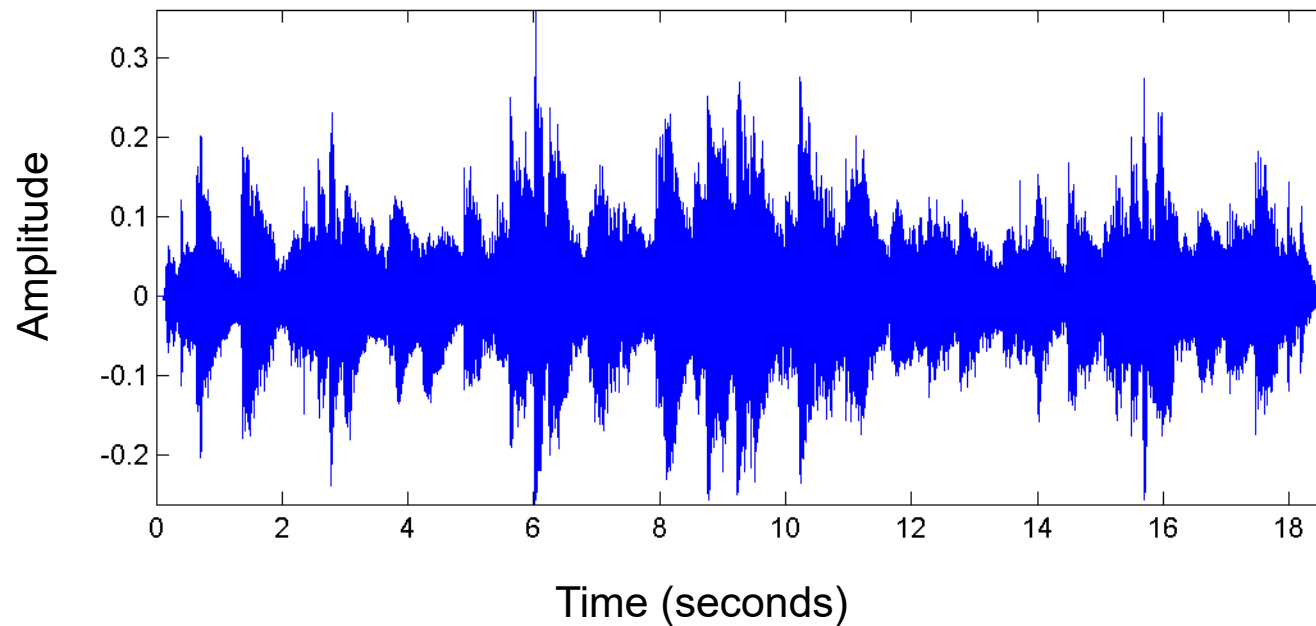
41. *p*

The image shows a musical score for Chopin's Mazurka Op. 63 No. 3, measures 41-50. The score is in 3/4 time, key of D major, and marked 'Allegretto'. It features a piano (*p*) dynamic. The notation includes a treble and bass staff with various musical symbols such as triplets, slurs, and fingerings. The bass staff has 'Ped.' markings with asterisks indicating pedaling points.

# Why is Music Processing Challenging?

**Example:** Chopin, Mazurka Op. 63 No. 3

- Waveform

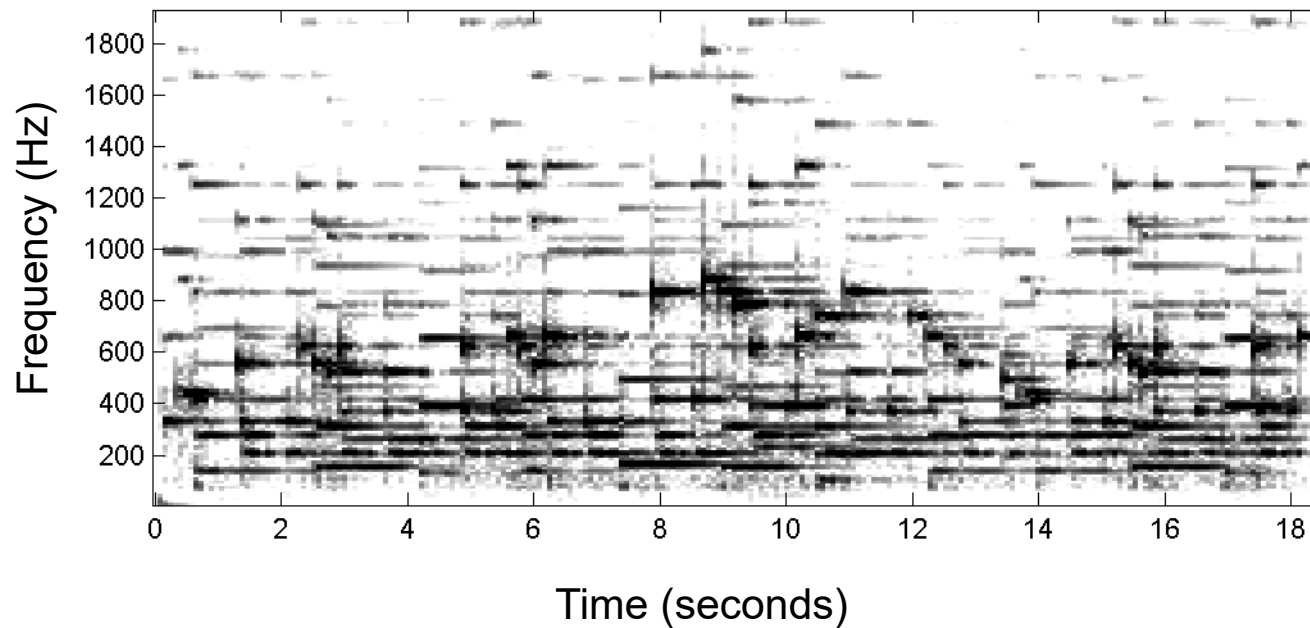




# Why is Music Processing Challenging?

**Example:** Chopin, Mazurka Op. 63 No. 3

- Waveform / Spectrogram



# Why is Music Processing Challenging?

**Example:** Chopin, Mazurka Op. 63 No. 3



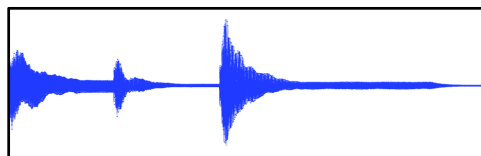
- Waveform / Spectrogram
- Performance
  - Tempo
  - Dynamics
  - Note deviations
  - Sustain pedal
- Polyphony

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

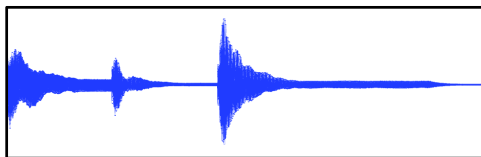
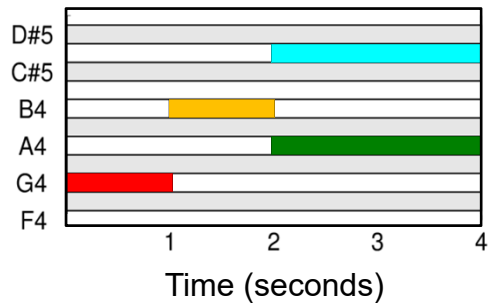
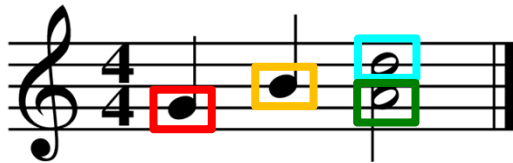
-  **Main Melody**
-  **Additional melody line**
-  **Accompaniment**

---

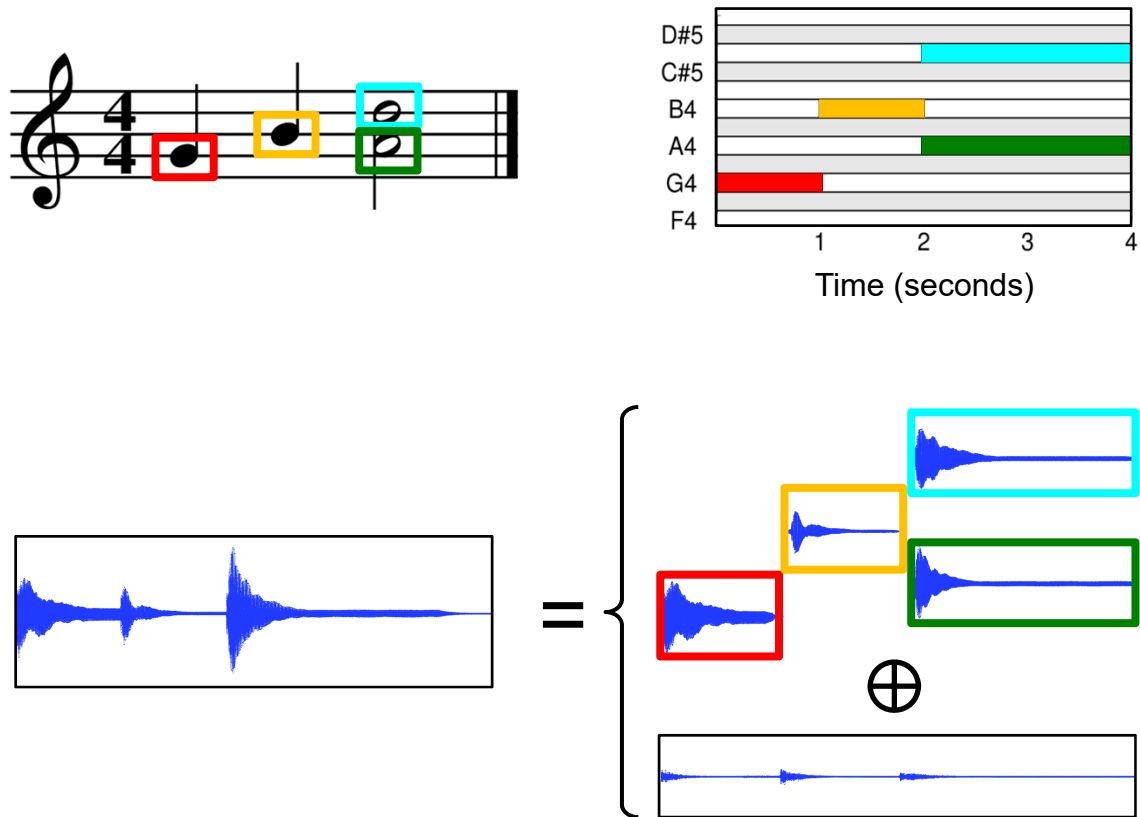
# Score-Informed Audio Decomposition



# Score-Informed Audio Decomposition

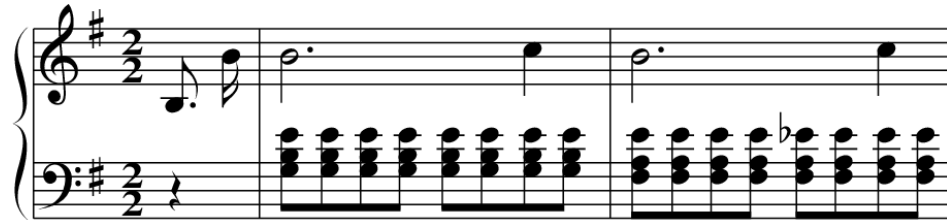


# Score-Informed Audio Decomposition

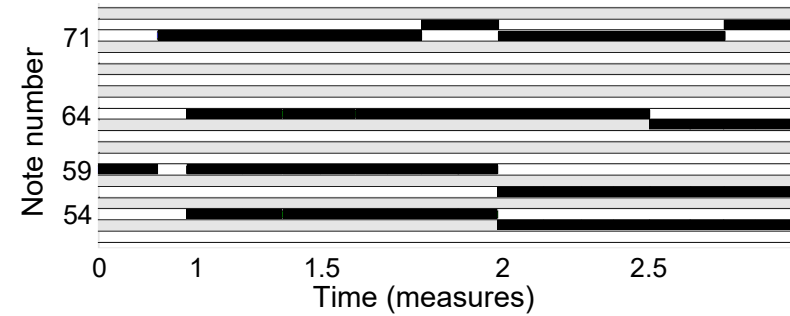


# Score-Informed Audio Decomposition

Sheet music

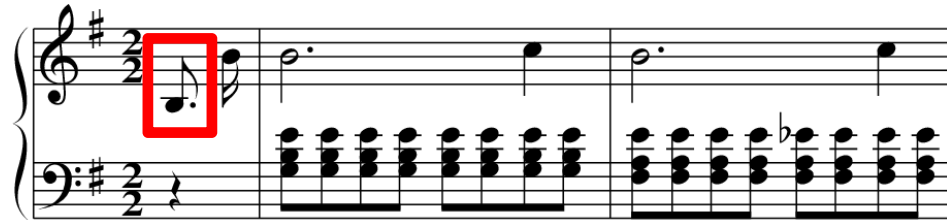


Piano roll



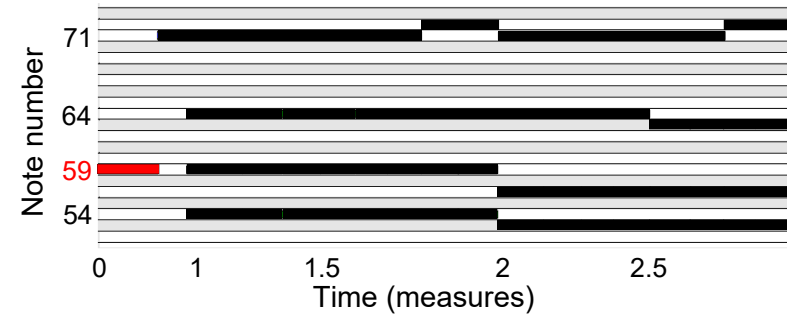
# Score-Informed Audio Decomposition

Sheet music



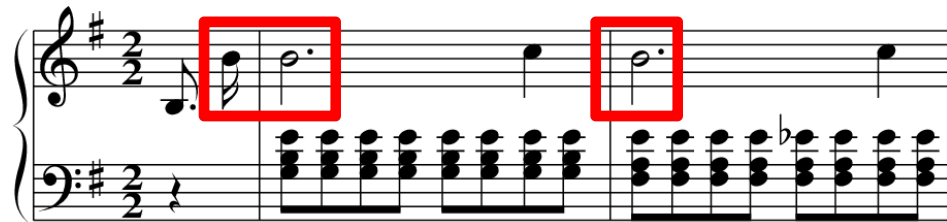
$p = 59$

Piano roll



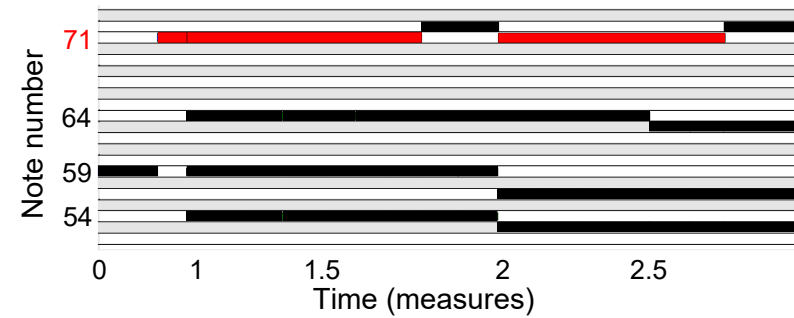
# Score-Informed Audio Decomposition

Sheet music



$p = 71$

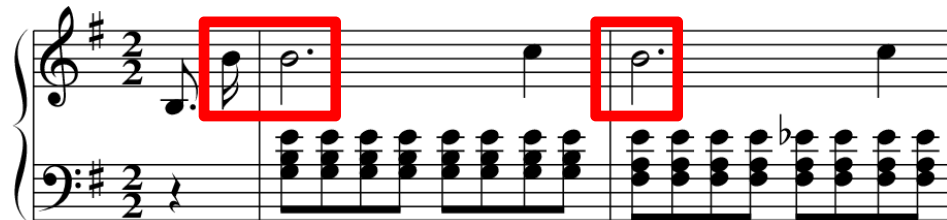
Piano roll





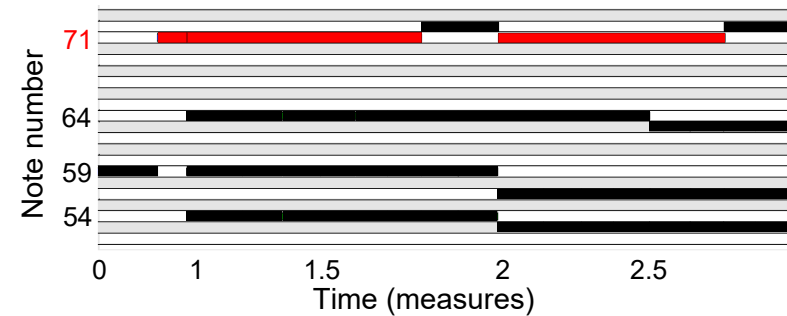
# Score-Informed Audio Decomposition

Sheet music

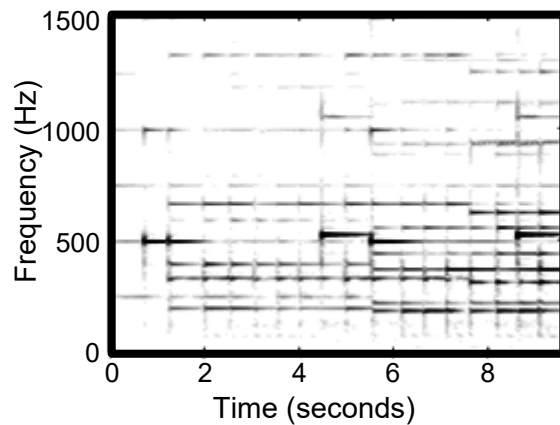


$p = 71$

Piano roll

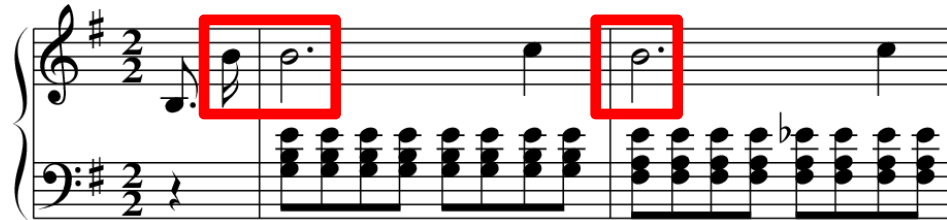


Spectrogram



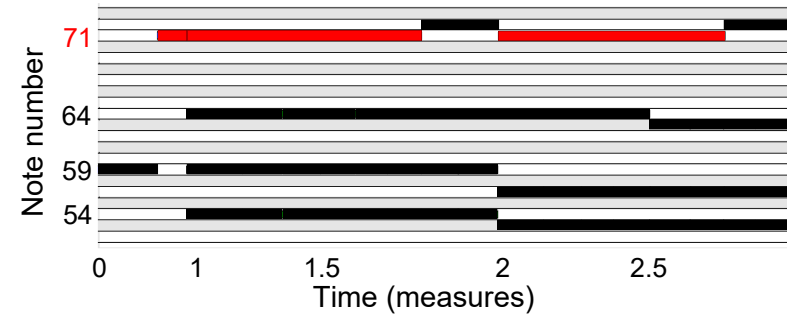
# Score-Informed Audio Decomposition

Sheet music

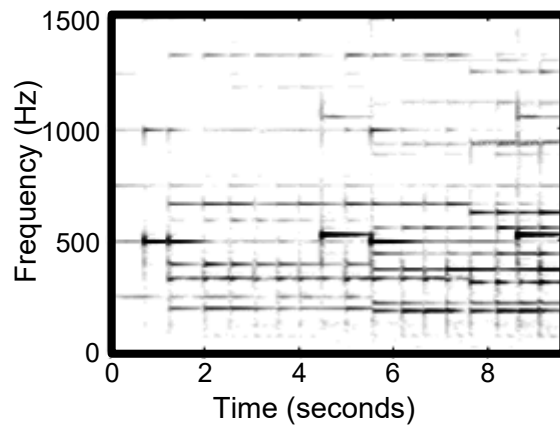


$p = 71$

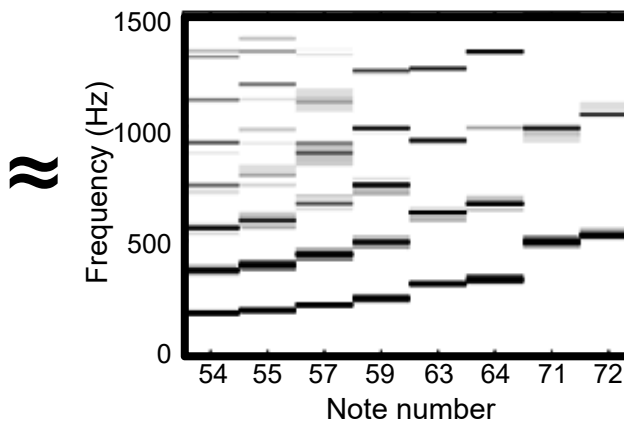
Piano roll



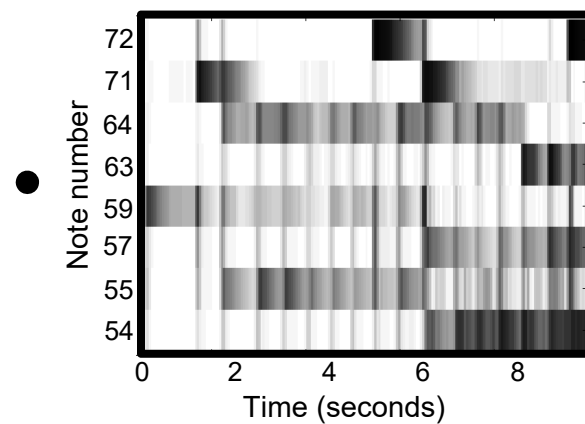
Spectrogram



Spectral patterns

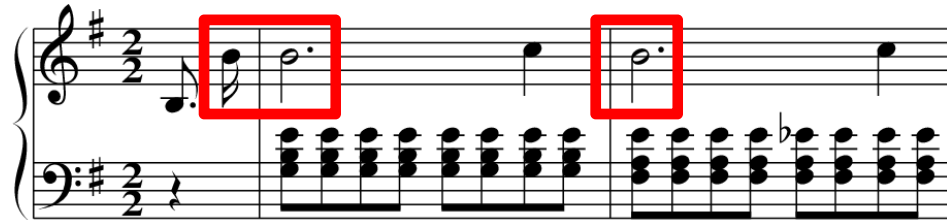


Activity patterns



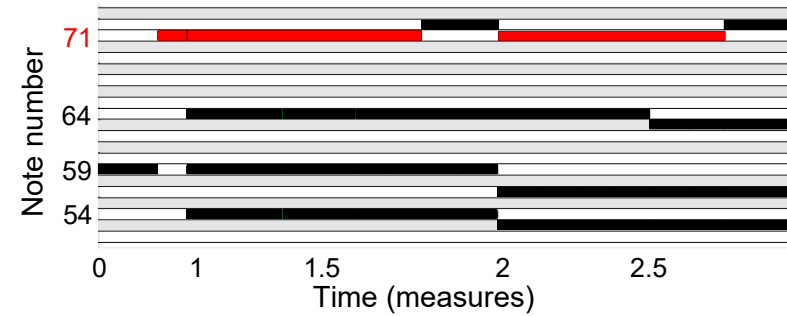
# Score-Informed Audio Decomposition

Sheet music

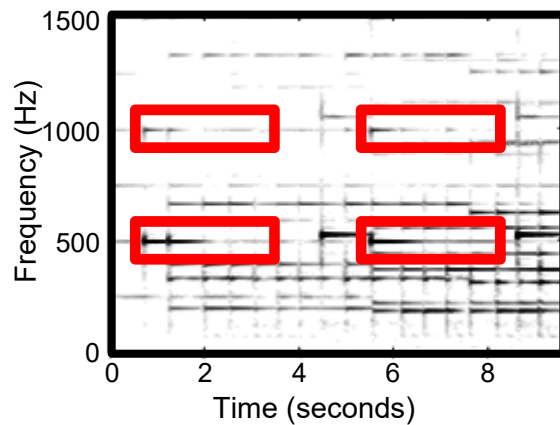


$p = 71$

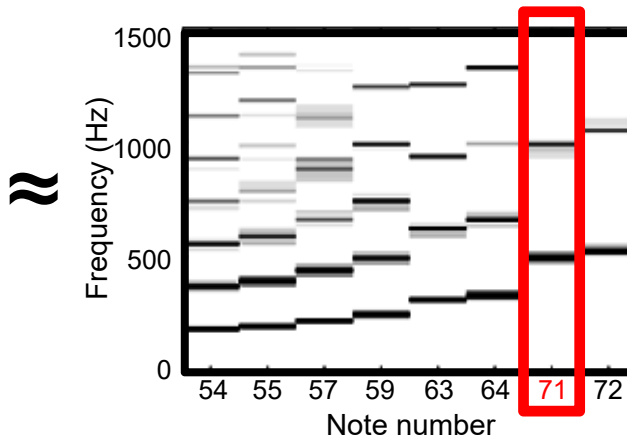
Piano roll



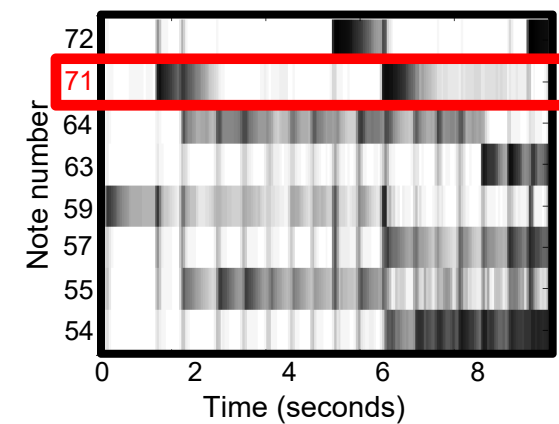
Spectrogram



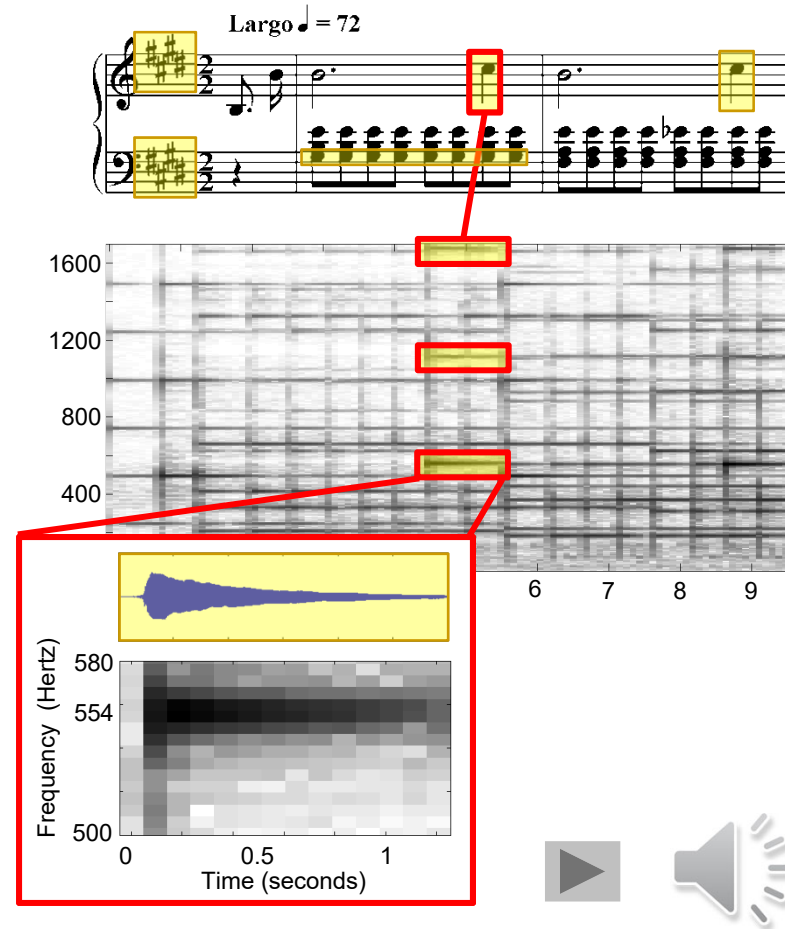
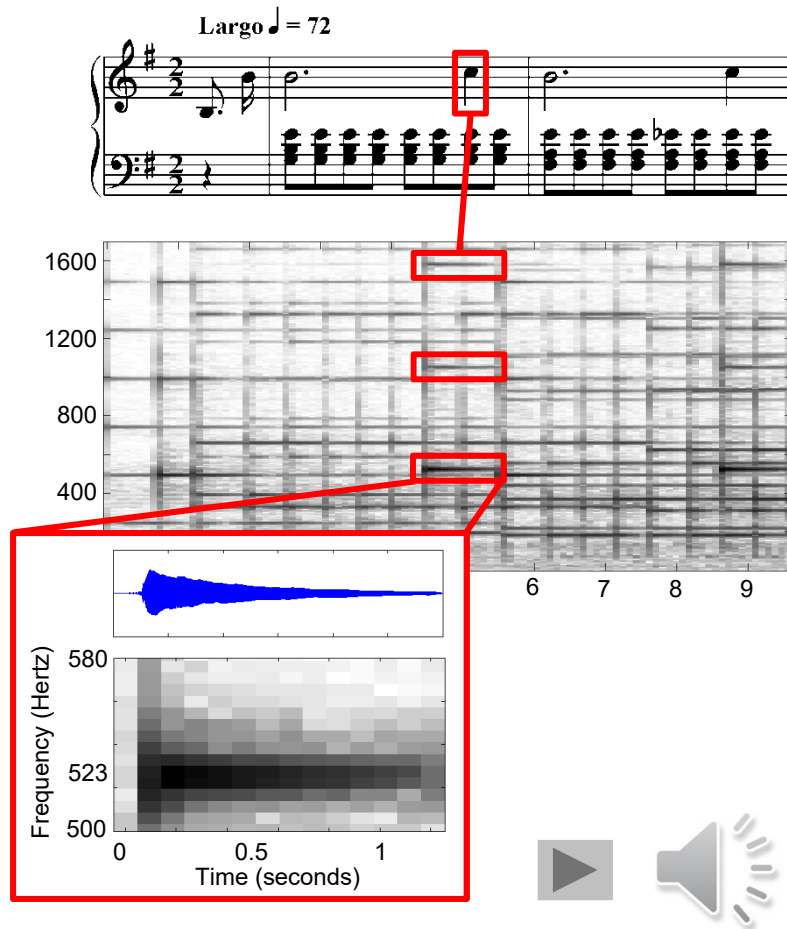
Spectral patterns



Activity patterns

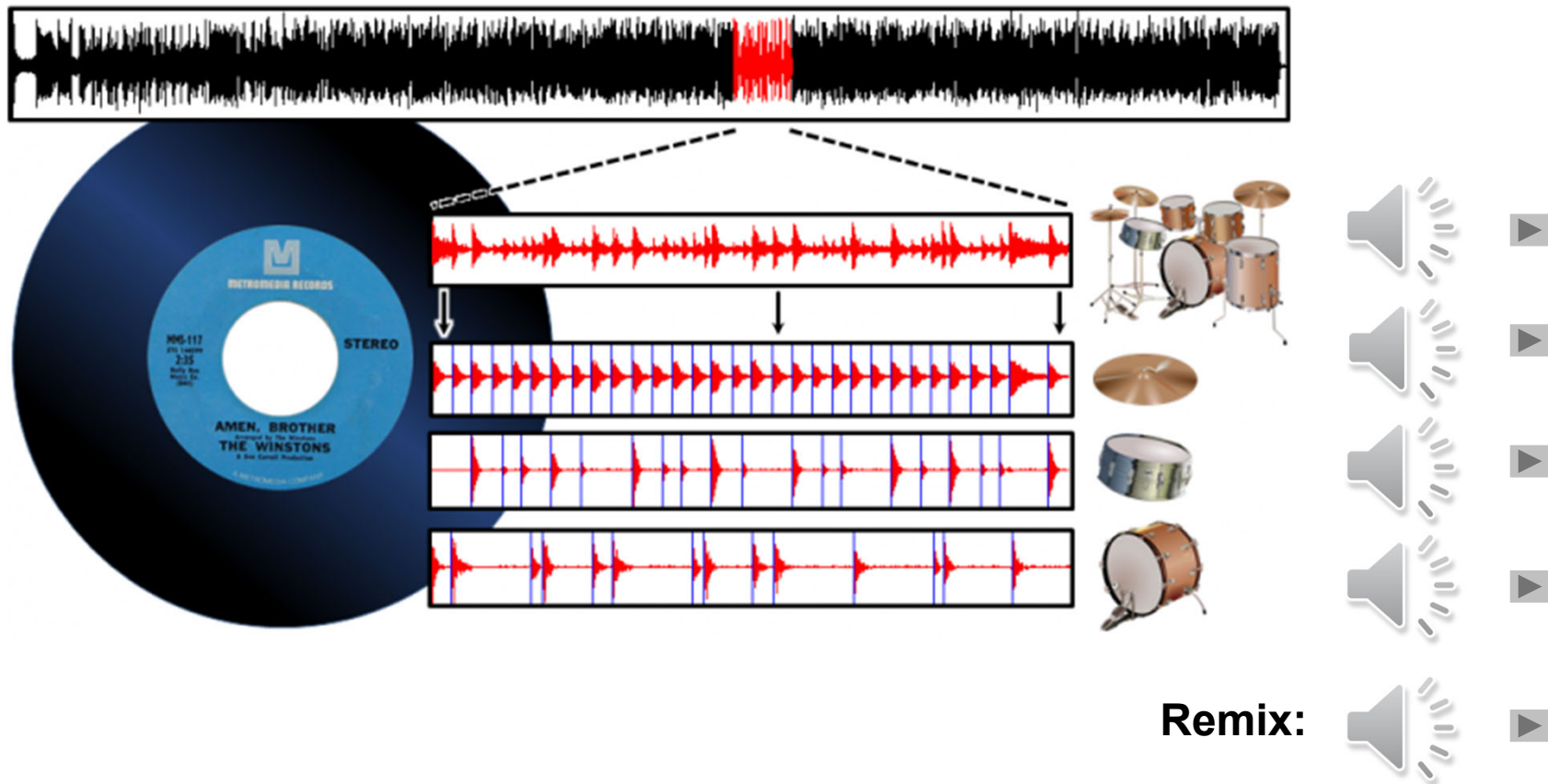


# Score-Informed Audio Decomposition



# Score-Informed Audio Decomposition

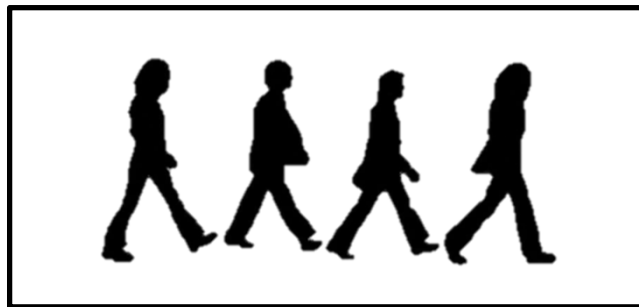
## Informed Drum-Sound Decomposition



# Score-Informed Audio Decomposition

Audio mosaicing (style transfer)

**Target** signal: Beatles—Let it be



**Source** signal: Bees



**Mosaic** signal: **Let it Bee**

# Singing Voice Processing



# Singing Voice Processing



Room  
Microphone

*Allegro moderato*

Soprano *p* Lo - cus i - ste a De - o fa - ctus est, *mf* lo - cus i - ste a De - o *f*

Alto *p* Lo - cus i - ste a De - o fa - ctus est, *mf* lo - cus i - ste a De - o *f*

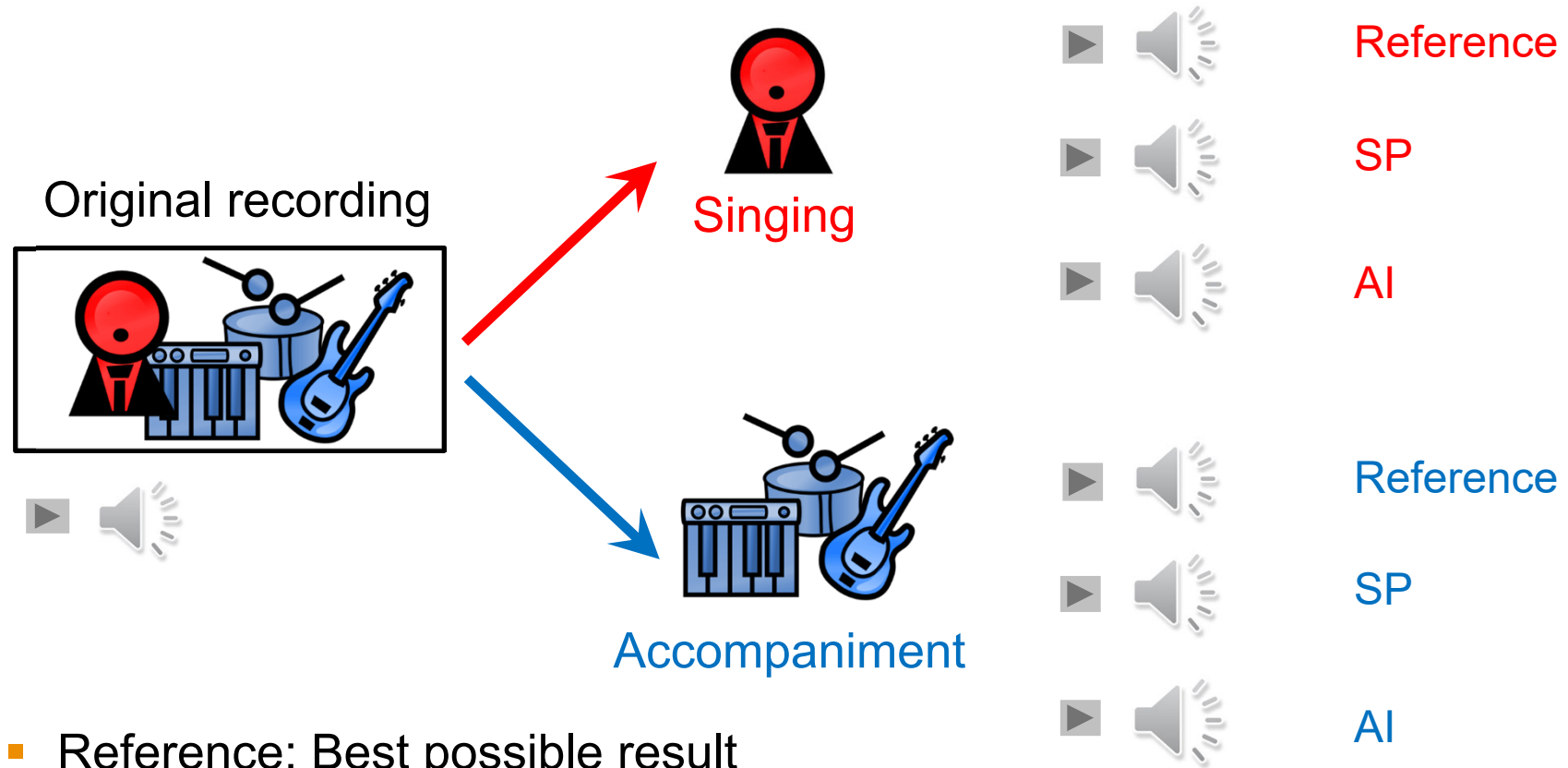
Tenor *p* Lo - cus i - ste a De - o fa - ctus est, *mf* lo - cus i - ste a De - o *f*

Bass *p* Lo - cus i - ste a De - o fa - ctus est, *mf* lo - cus i - ste a De - o *f*





# AI-Based Source Separation



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

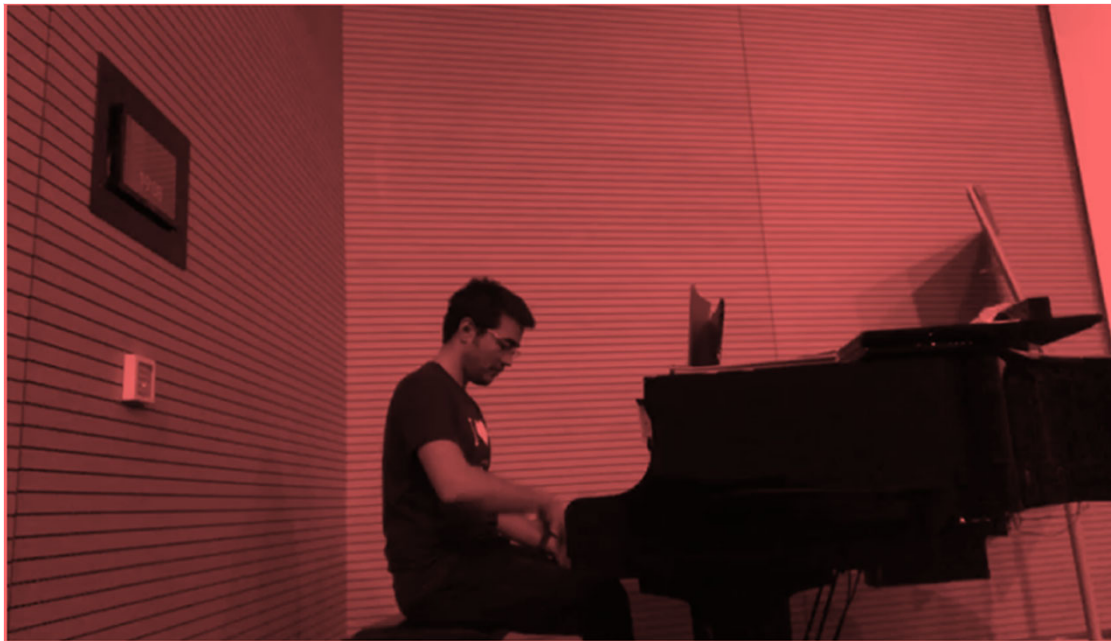
# AI-Based Source Separation

- Yigitcan Özer
- PhD student in engineering
- Pianist



# AI-Based Source Separation

- Yigitcan Özer
- PhD student in engineering
- Pianist



**Only Piano!**



**Where is the  
orchestra?**



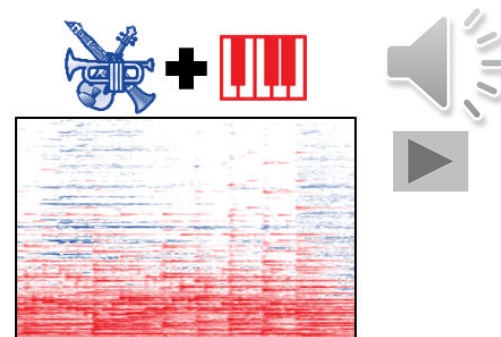
# AI-Based Source Separation

A musical score for Beethoven's Piano Concerto No. 5, starting at measure 89. The score is arranged in a grand staff with multiple staves. On the left side, there are icons for various instruments: two flutes, a clarinet, a horn, a trumpet, a trombone, a piano, two violins, and a viola. The piano part is the most prominent, showing a complex melodic line. The other instruments have more sparse parts, often playing chords or single notes.

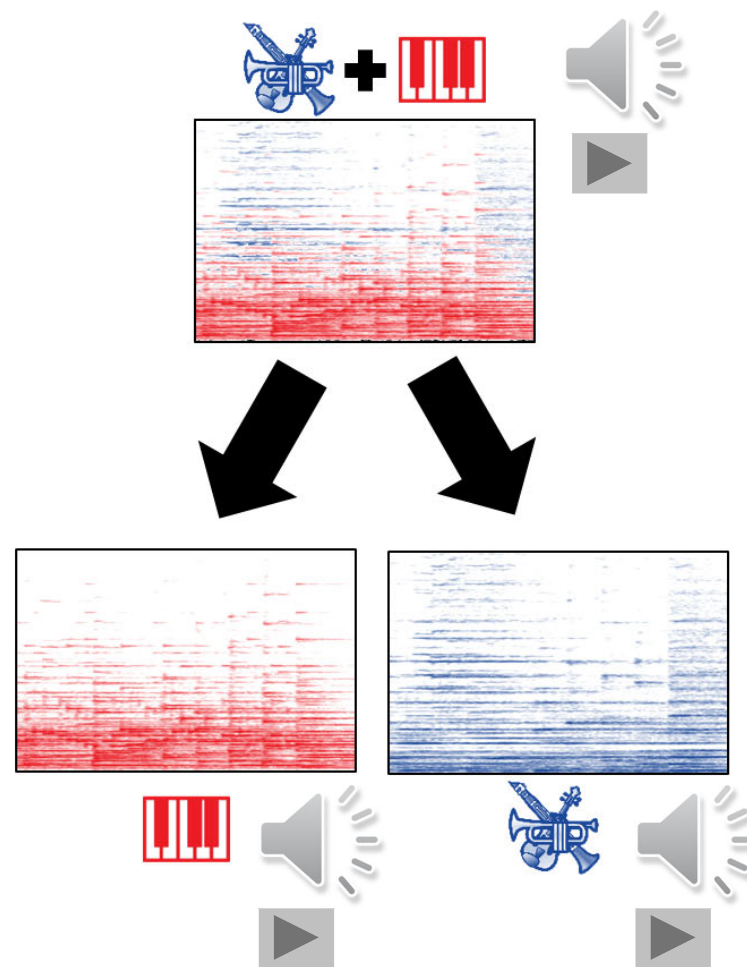


# AI-Based Source Separation

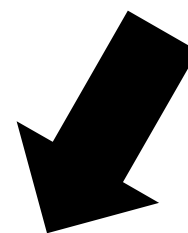
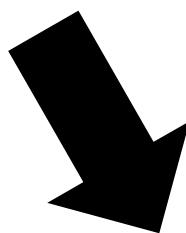
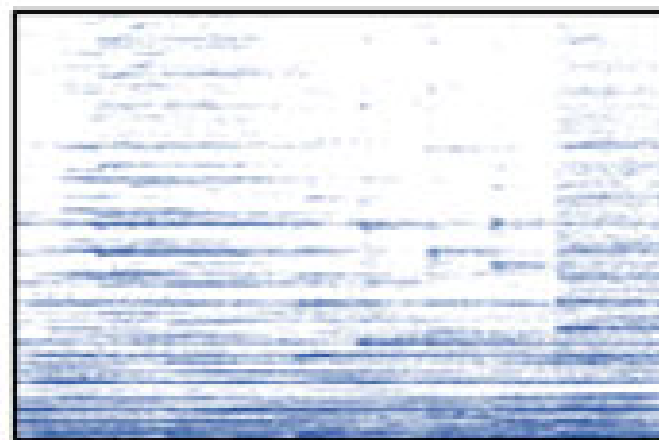
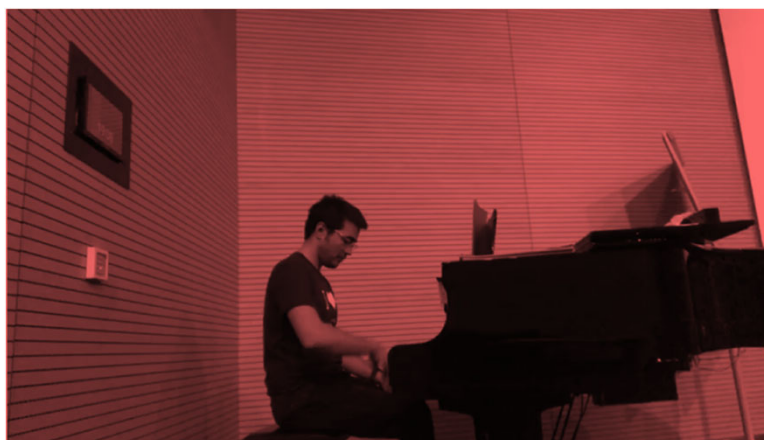
A musical score for Beethoven's Piano Sonata No. 29, Op. 106, starting at measure 89. The score is divided into two main sections. The upper section, in blue, contains staves for various instruments: flute, oboe, clarinet, horn, trumpet, trombone, and cymbal. The lower section, in red, contains staves for the piano. A red piano keyboard icon is positioned to the left of the piano staves, indicating that the piano part has been isolated from the full orchestral score.



# AI-Based Source Separation



# AI-Based Source Separation



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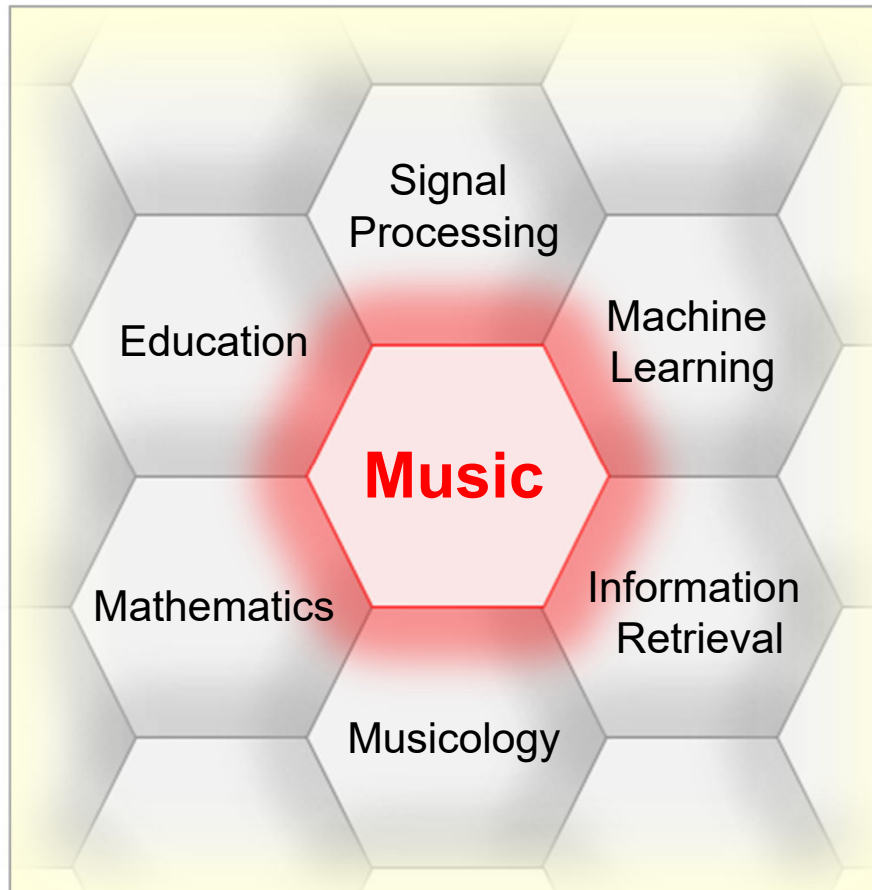
# AI-Based Source Separation

## Conclusions

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

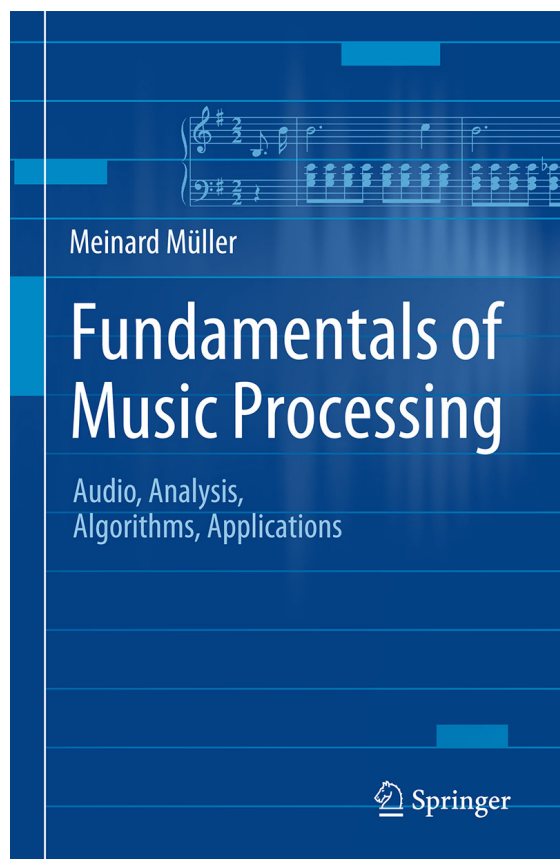


# Computational Music Research



- Music is a ubiquitous and vital part of our lives
- Digital music services: Spotify, Pandora, iTunes, ...
- Music yields intuitive entry point to support and motivate education in technical disciplines
- Music bridges the gap between engineering, computer science, mathematics, and the humanities

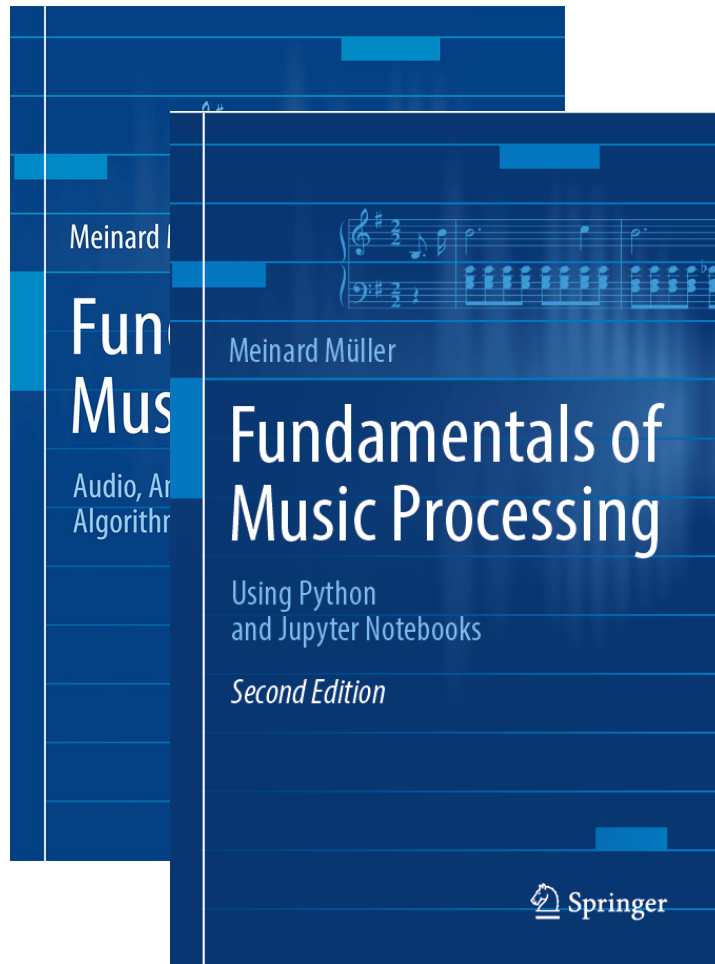
# Fundamentals of Music Processing (FMP)



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

Accompanying website:  
[www.music-processing.de](http://www.music-processing.de)

# Fundamentals of Music Processing (FMP)

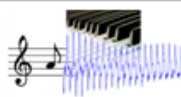

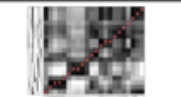
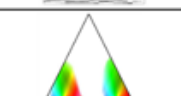

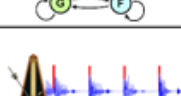




Meinard Müller  
Fundamentals of Music Processing  
Audio, Analysis, Algorithms, Applications  
Springer, 2015

Accompanying website:  
[www.music-processing.de](http://www.music-processing.de)

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

# Fundamentals of Music Processing (FMP)

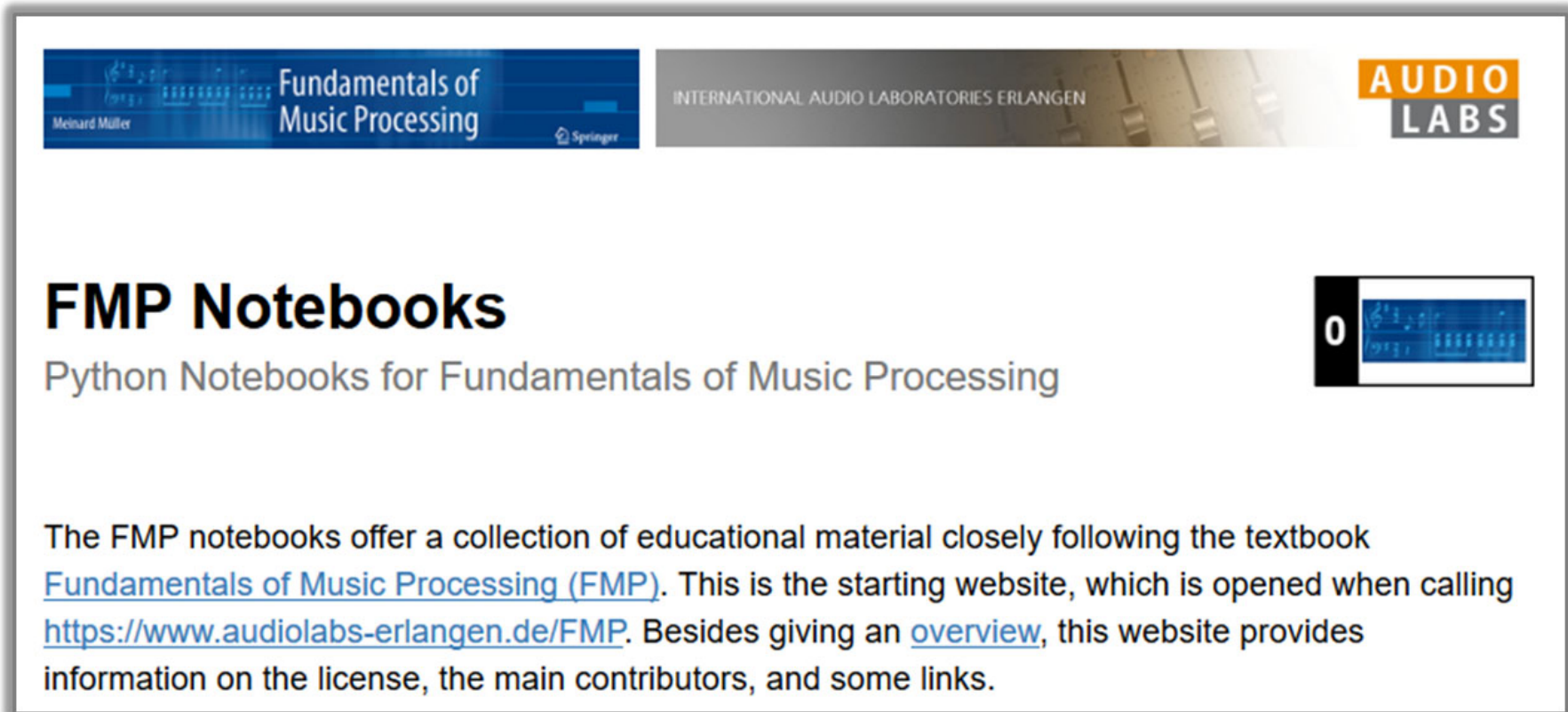
Chapter	Music Processing Scenario
1	 <b>Music Representations</b>
2	 <b>Fourier Analysis of Signals</b>
3	 <b>Music Synchronization</b>
4	 <b>Music Structure Analysis</b>
5	 <b>Chord Recognition</b>
6	 <b>Tempo and Beat Tracking</b>
7	 <b>Content-Based Audio Retrieval</b>
8	 <b>Musically Informed Audio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

Meinard Müller  
Fundamentals of Music Processing  
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Springer, 2015

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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 the text 'INTERNATIONAL AUDIO LABORATORIES ERLANGEN' and the 'AUDIO LABS' logo. Below the banner, 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. Below the 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>

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# References (FMP Notebooks)

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<https://ieeexplore.ieee.org/document/9418542>

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# 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>