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

AUDIO LABS

Beethoven.exe

How Machines Listen, Learn, and Remix Music

Meinard Müller

International Audio Laboratories Erlangen

meinard.mueller@audiolabs-erlangen.de

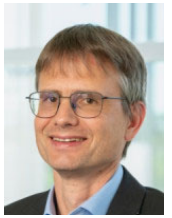
Weihnachtskolloquium der Fakultät für Mathematik und Informatik

Würzburg, December 16, 2025

FAU Friedrich-Alexander-Universität Erlangen-Nürnberg

Fraunhofer IIS

Meinard Müller



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

universitätbonn

- Senior Researcher (2007-2012)

max planck institut informatik

- Professor Semantic Audio Processing (since 2012)

FAU

- Former President of the International Society for Music Information Retrieval (MIR)

ISMIR

- IEEE Fellow for contributions to Music Signal Processing

IEEE

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

mp3

AUDIO LABS

FAU Friedrich-Alexander-Universität Erlangen-Nürnberg

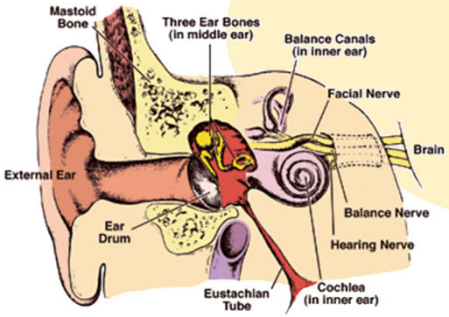
- Friedrich-Alexander Universität Erlangen-Nürnberg (FAU)
- One of Germany's largest universities with ≈ 40,000 students
- Strong Technical Faculty

International Audio Laboratories Erlangen

Audio Coding

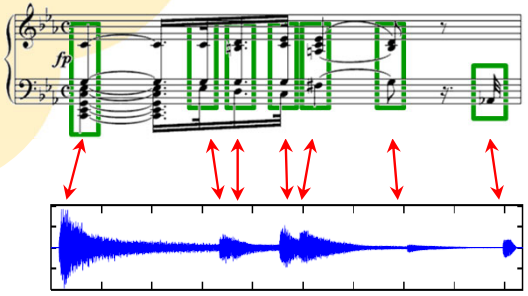
3D Audio

Audio



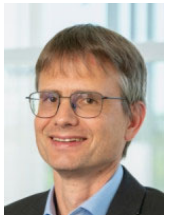
Psychoacoustics

Internet of Things



Music Processing

Meinard Müller: Research Group



- Ben Maman
- Simon Schwär
- Johannes Zeitler
- Peter Meier





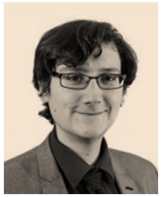


- Sebastian Strahl
- Uli Berendes
- Vlora Arifi-Müller
- Stefan Balke

- Ching-Yu Chiu (Sunny)
- Yigitcan Özer
- Michael Krause
- Christof Weiß
- Sebastian Rosenzweig
- Frank Zalkow





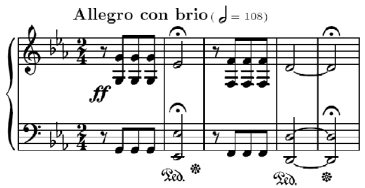




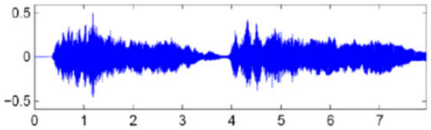
Music

Music Information Retrieval (MIR)

Sheet Music (Image)



CD / MP3 (Audio)



MusicXML (Text)

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<note>
  <pitch>
    <step>E</step>
    <alter>-1</alter>
    <octave>4</octave>
  </pitch>
  <duration>2</duration>
  <type>half</type>
</note>
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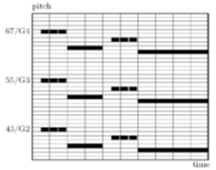
Dance / Motion (Mocap)

Music

MIDI

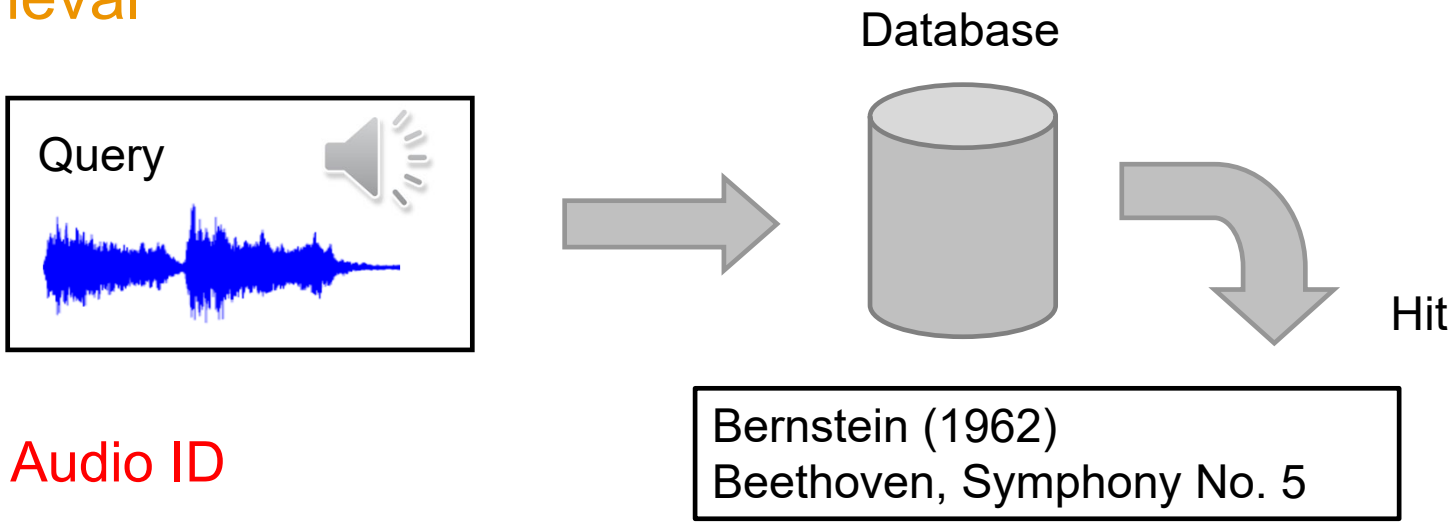


Singing / Voice (Audio)

Music Film (Video)

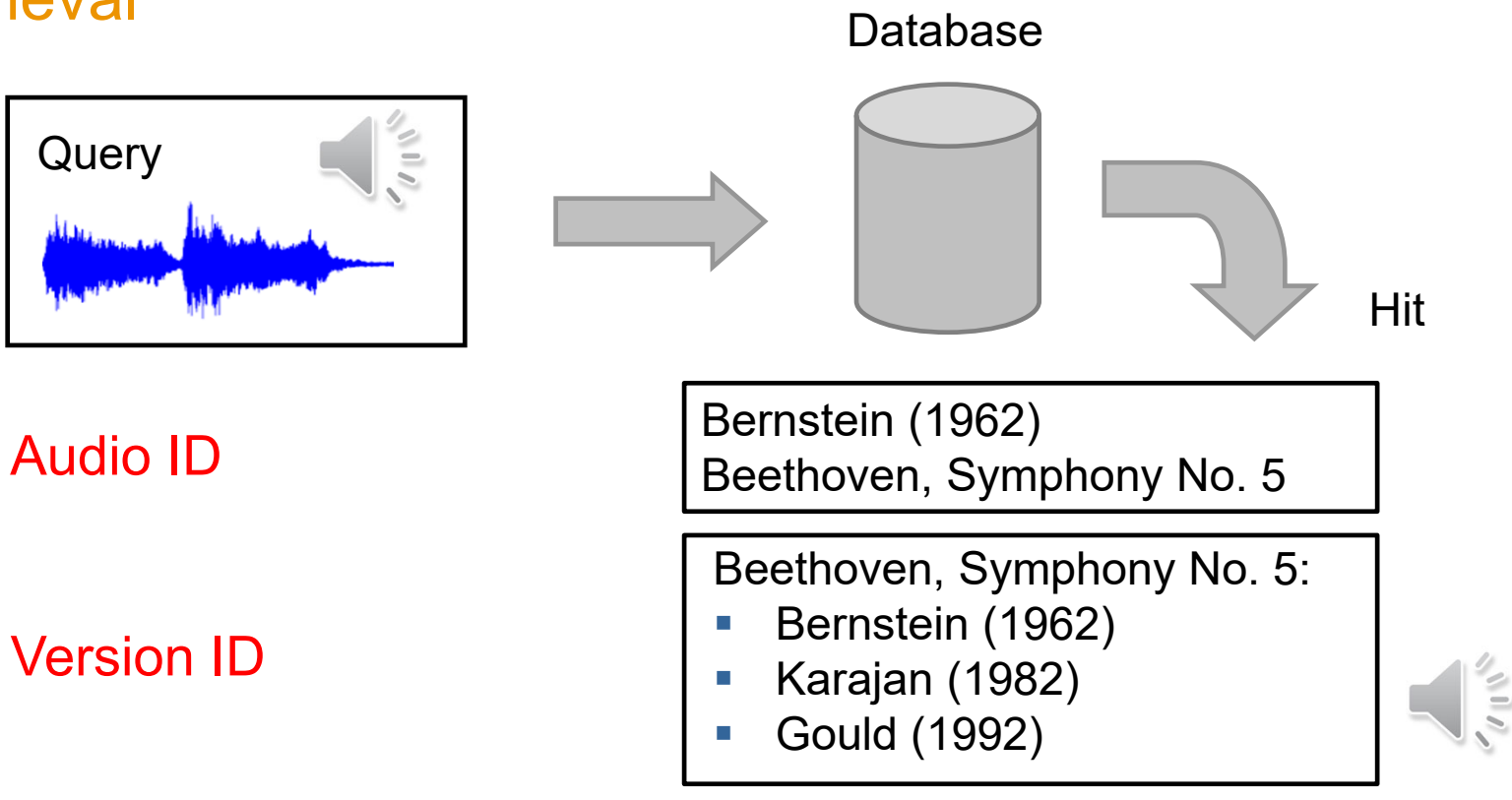
Music Literature (Text)

Music Retrieval



Audio ID

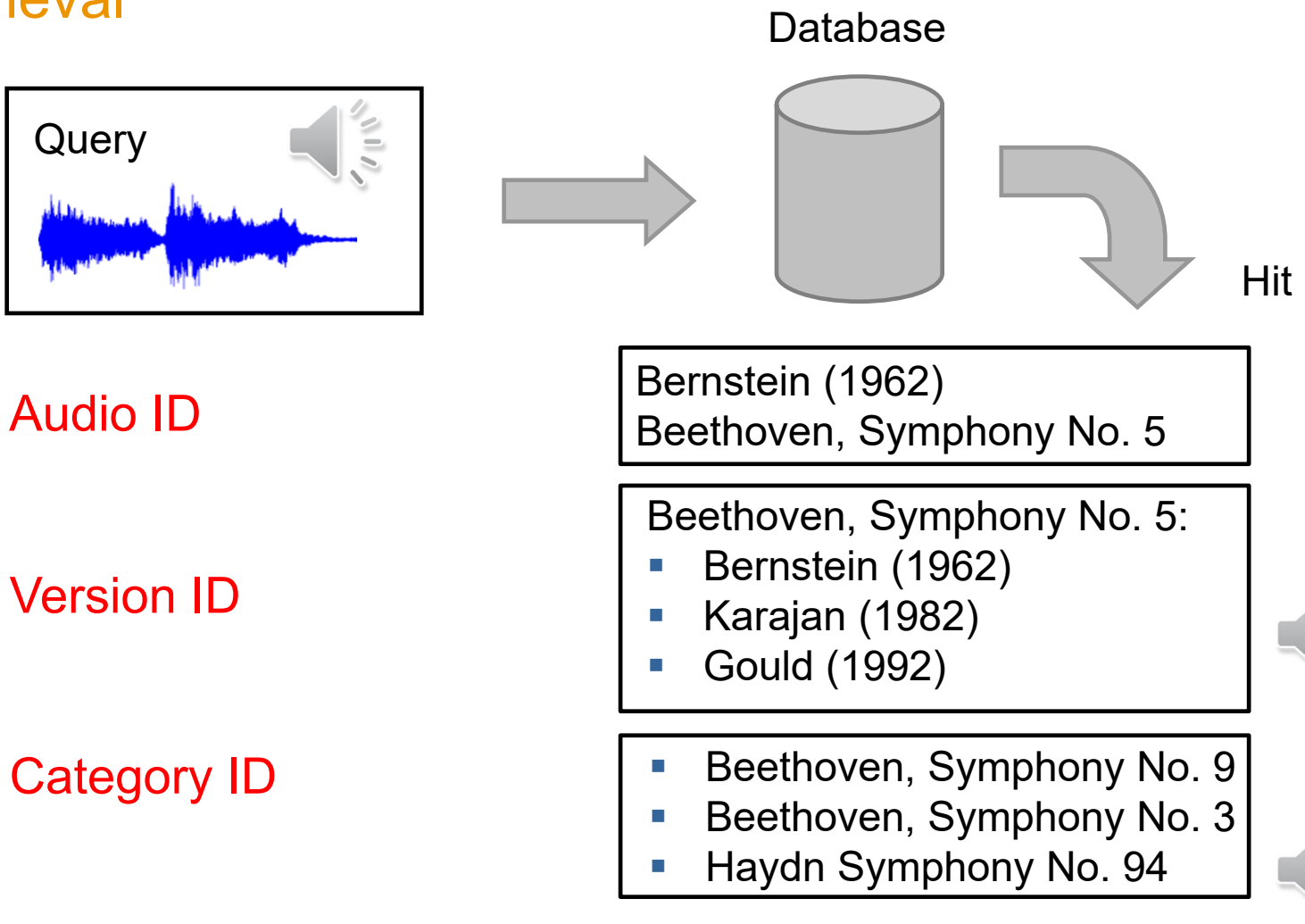
Music Retrieval



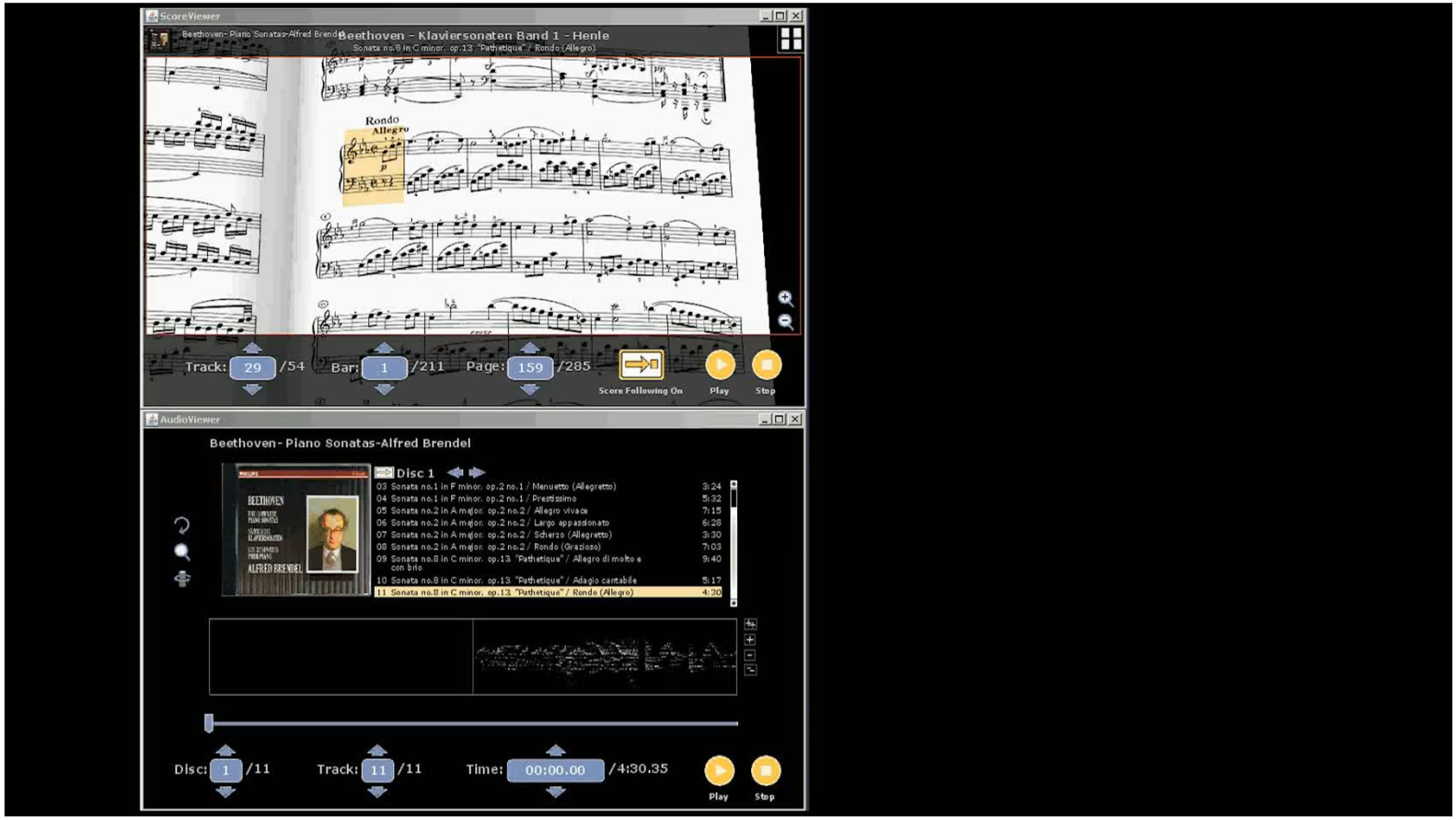
Audio ID

Version ID

Music Retrieval

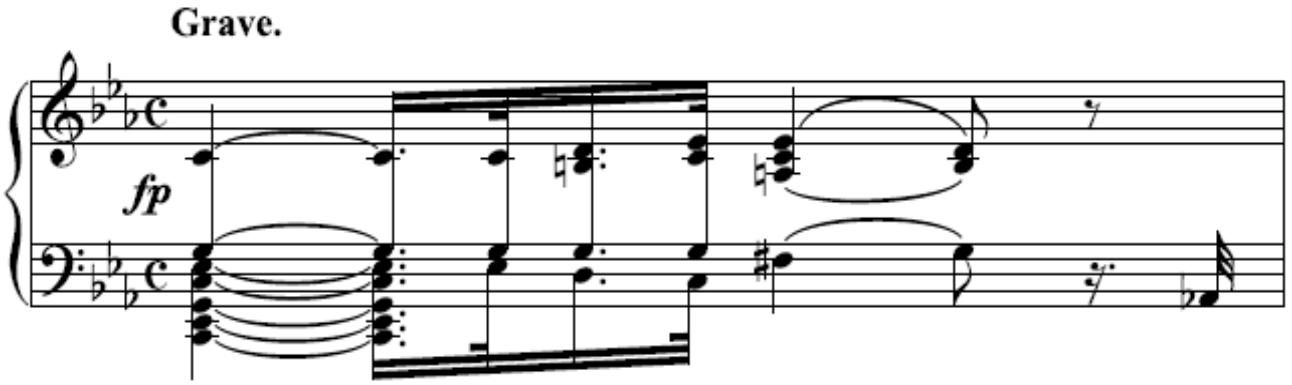


Music Synchronization

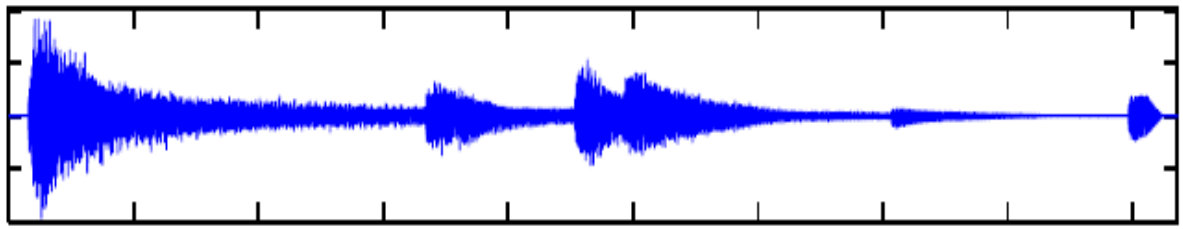


Music Synchronization: Image-Audio

Image



Audio

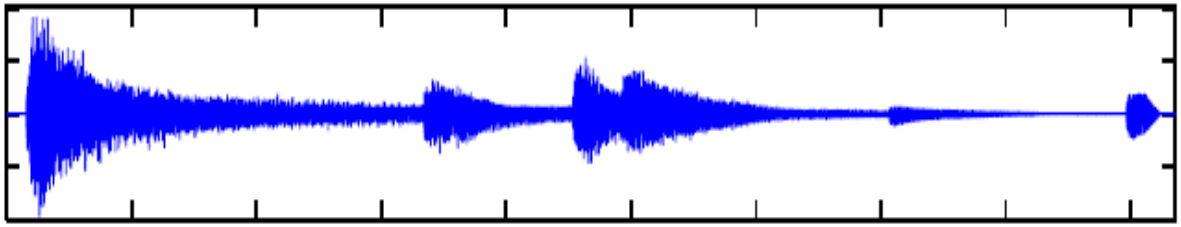


Music Synchronization: Image-Audio

Image Processing: Optical Music Recognition

Image

Audio



Music Synchronization: Image-Audio

Image Processing: Optical Music Recognition

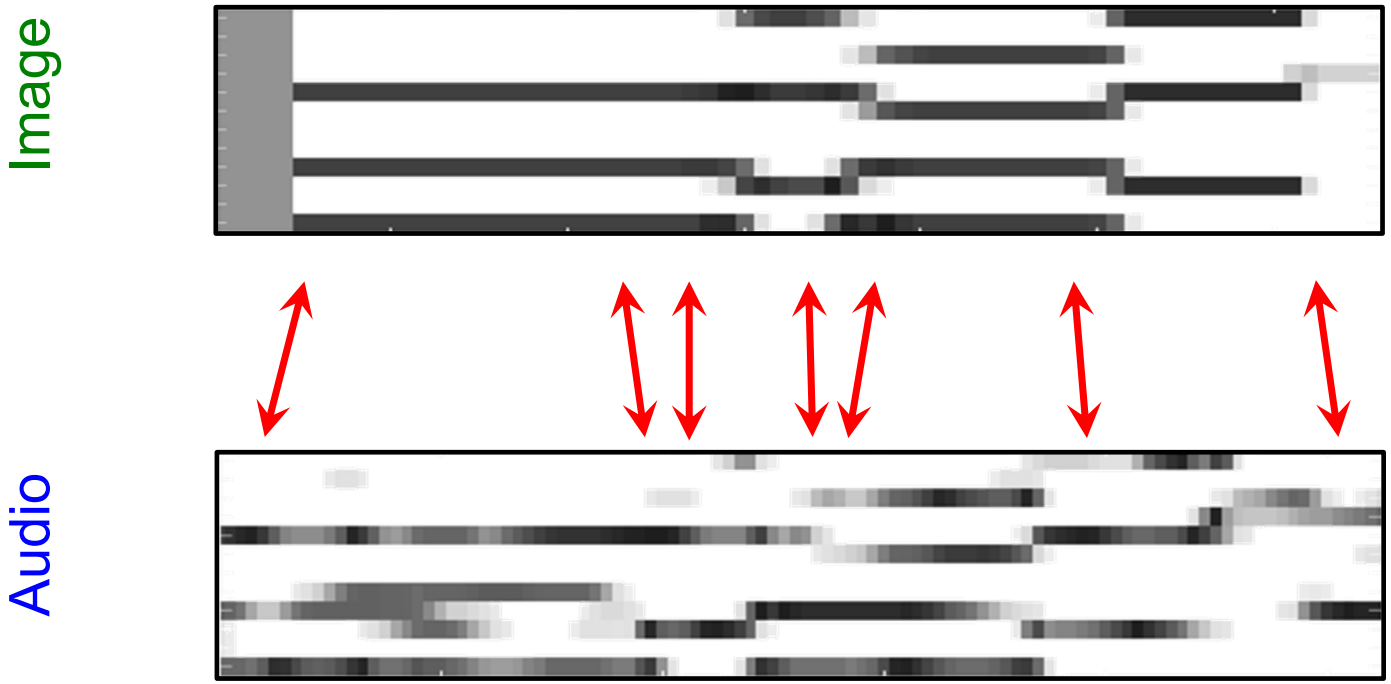
Image

Audio

Audio Processing: Fourier Analysis

Music Synchronization: Image-Audio

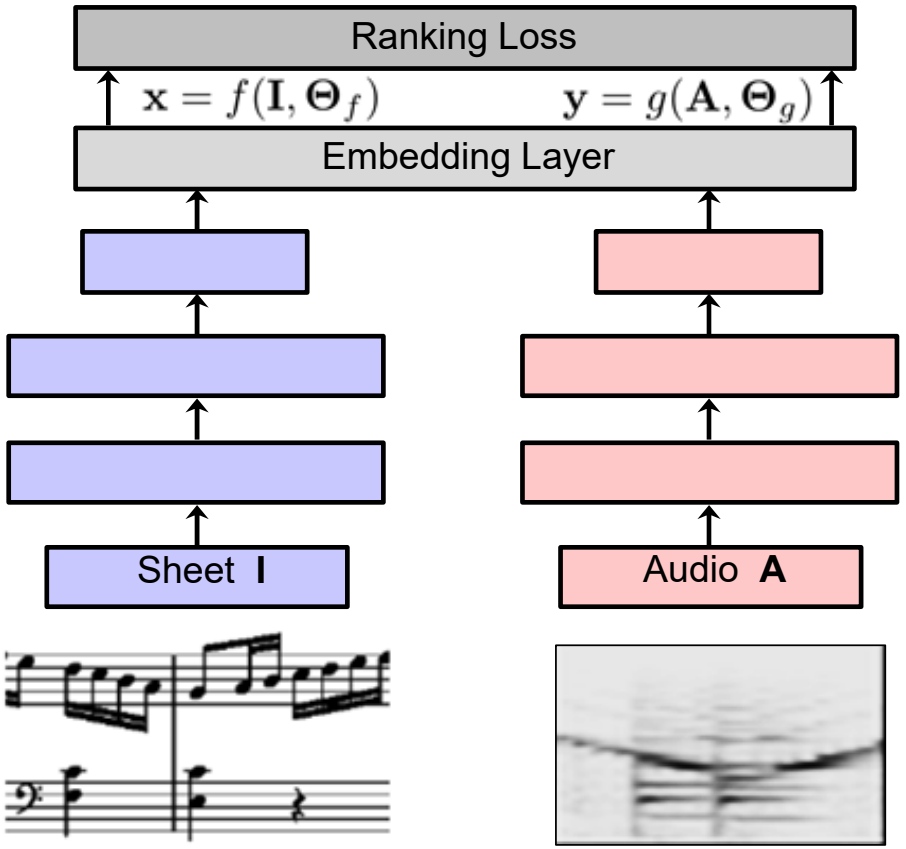
Image Processing: Optical Music Recognition



Audio Processing: Fourier Analysis

Music Synchronization: Image-Audio

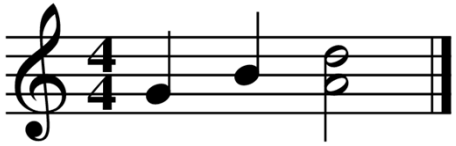
Müller, Arzt, Balke, Dorfer, Widmer: **Cross-Modal Music Retrieval and Applications.** IEEE Signal Process. Mag. 36(1): 52–62, 2019

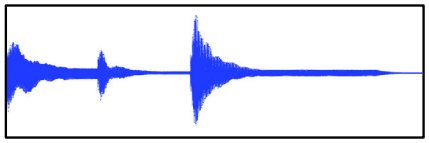


- Deep learning
- Embedding techniques
- Weak annotations
- Loss functions
- …

Score-Informed Audio Decomposition

Driedger, Grohganz, Prätzlich, Ewert, Müller: **Score-Informed Audio Decomposition and Applications**. Proc. ACM Multimedia: 541–544, 2013





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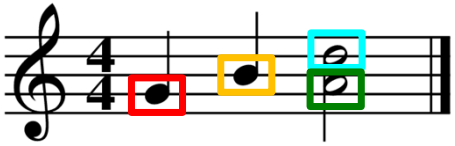

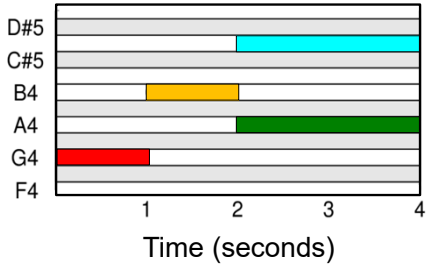

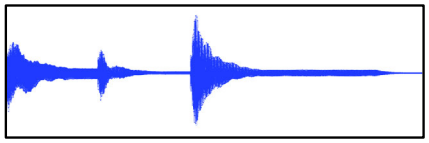

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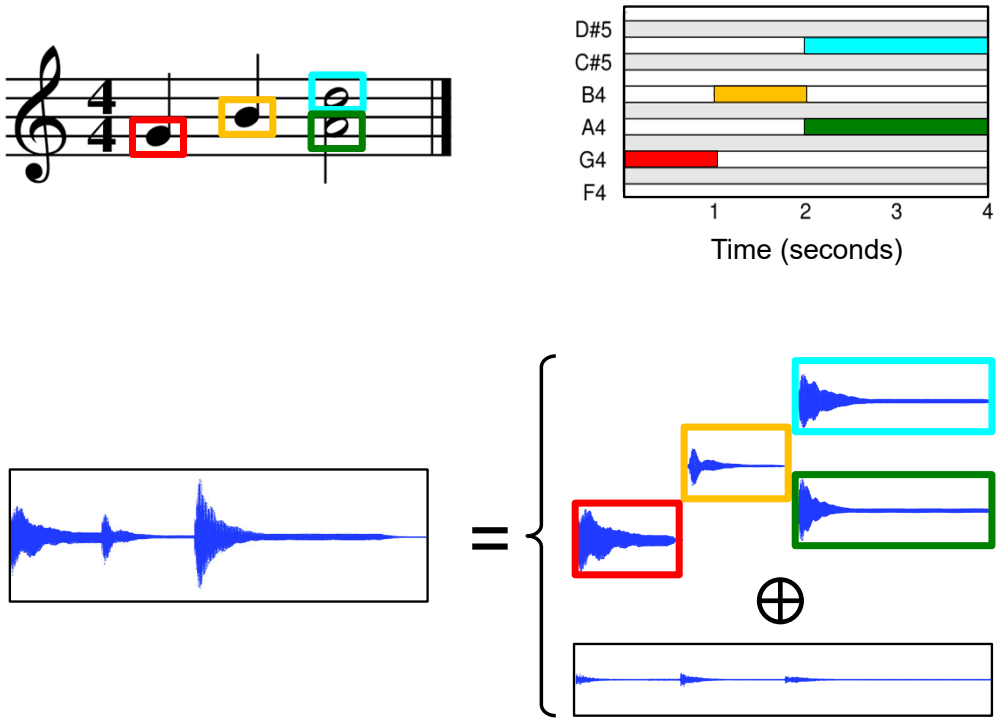

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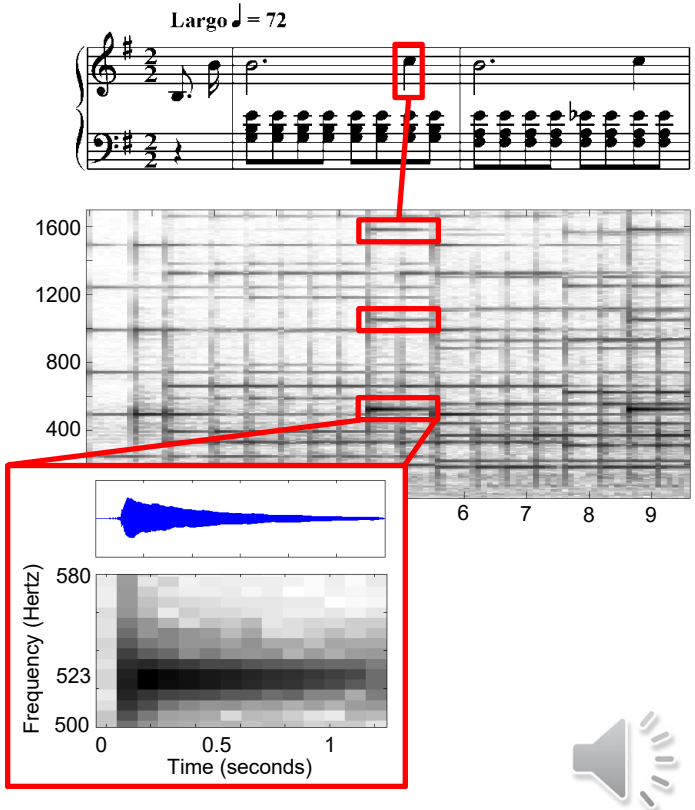

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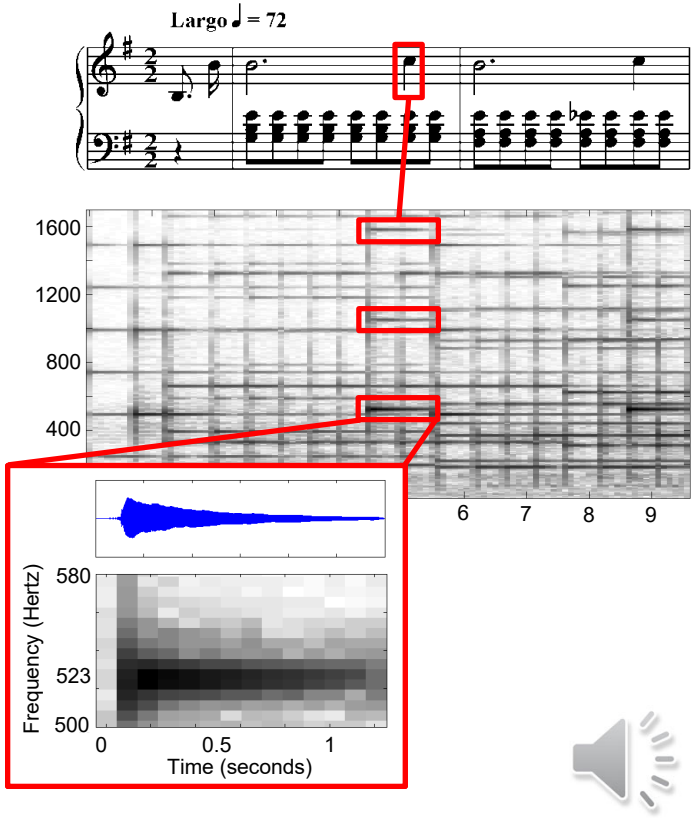
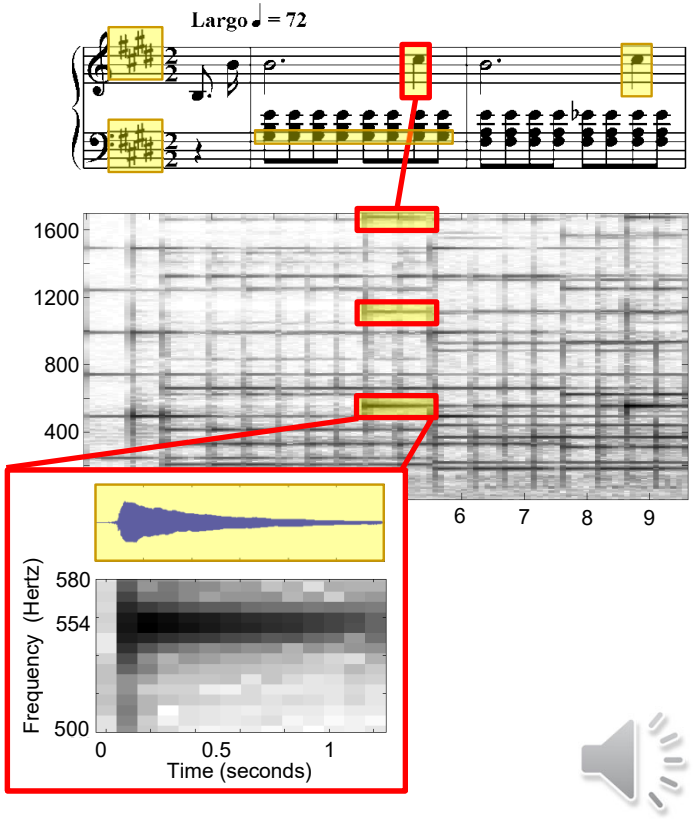
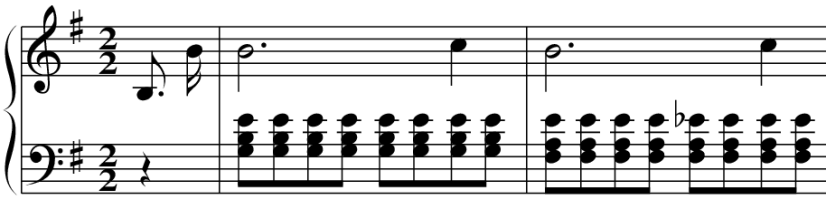




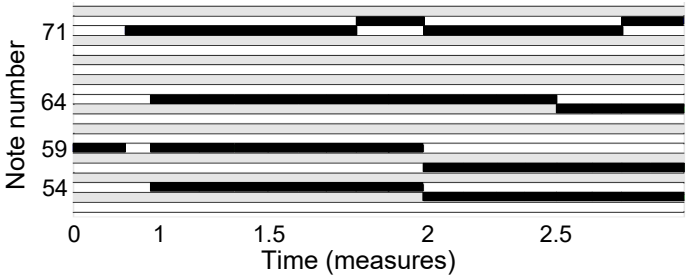
Score-Informed Audio Decomposition

Ewert, Pardo, Müller, Plumbley: **Score-Informed Source Separation for Musical Audio Recordings**. IEEE Signal Proc. Mag. 31(3): 116–124, 2014

Sheet music



Piano roll



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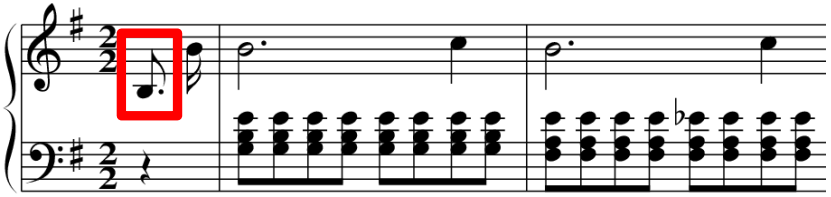
Sheet music



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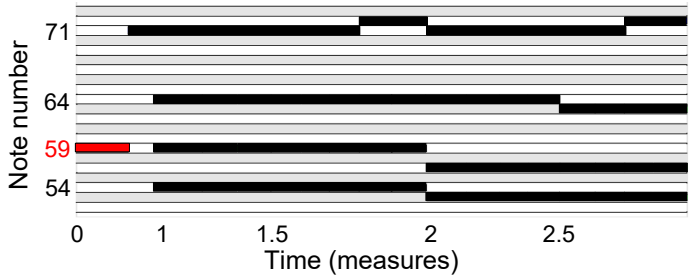
Piano roll



Score-Informed Audio Decomposition

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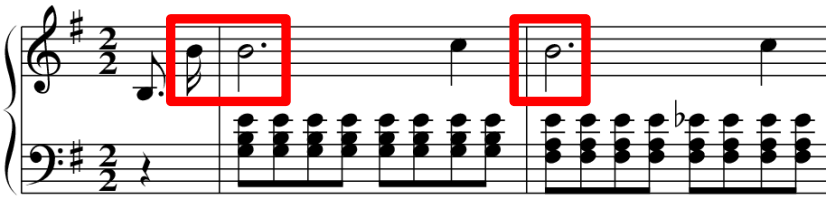
Sheet music



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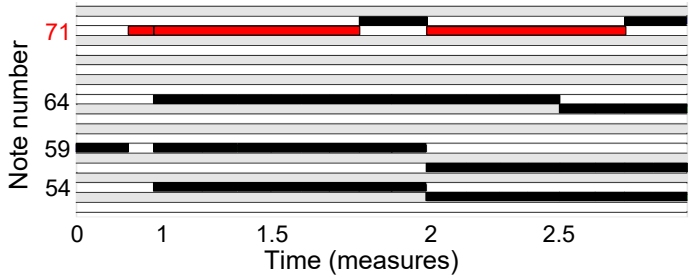
Piano roll



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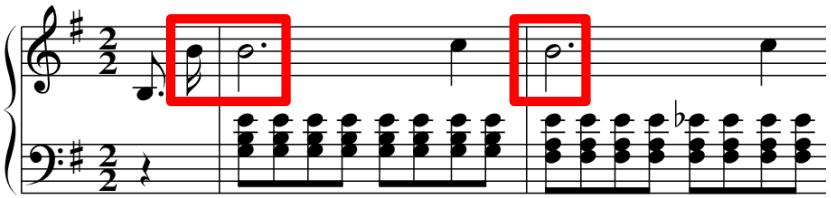
Sheet music



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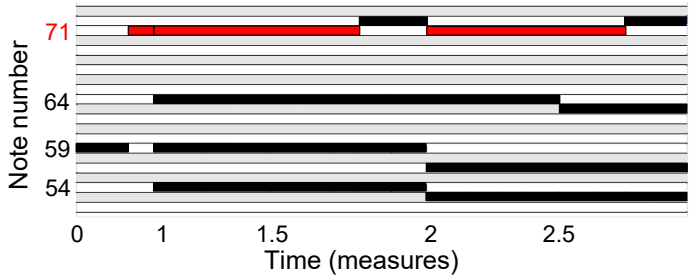
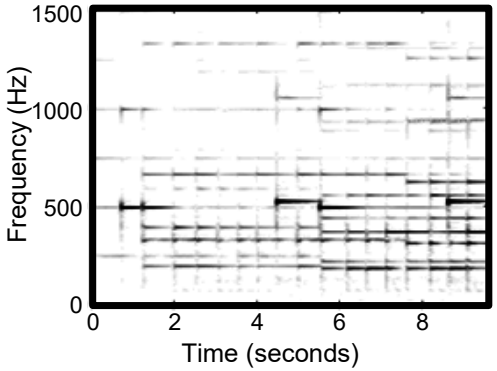
Piano roll



Spectrogram



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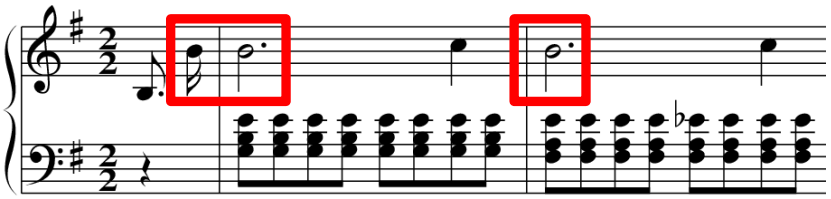
Sheet music



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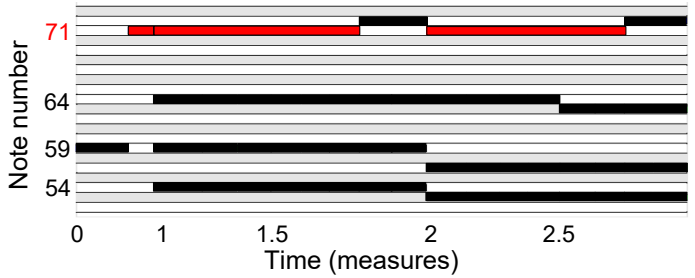
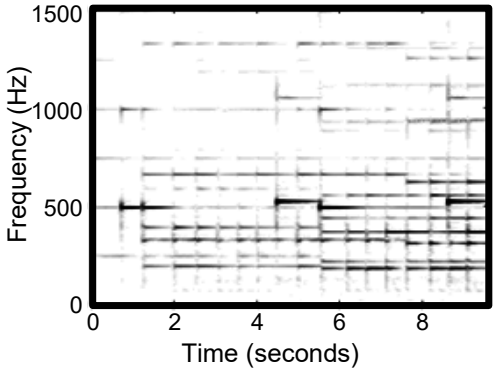
Piano roll



Spectrogram



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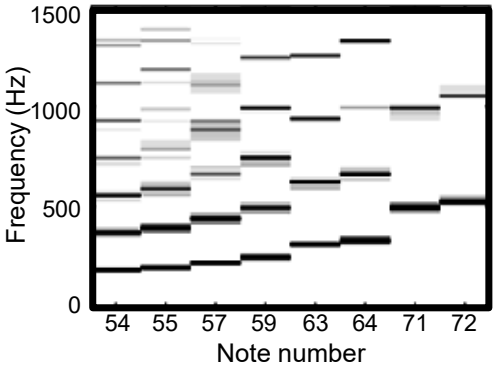
Spectral patterns



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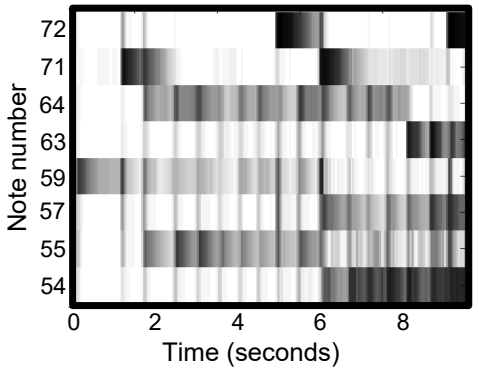
Activity patterns



Score-Informed Audio Decomposition

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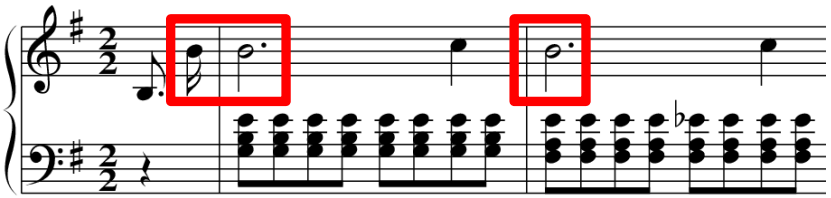
Sheet music



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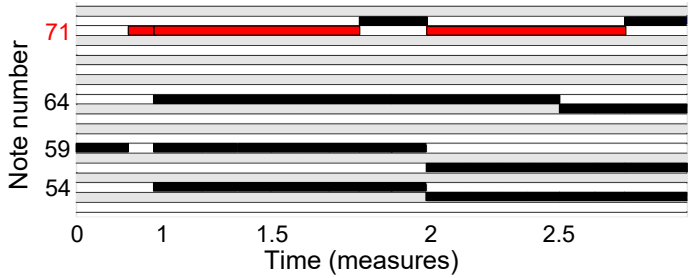
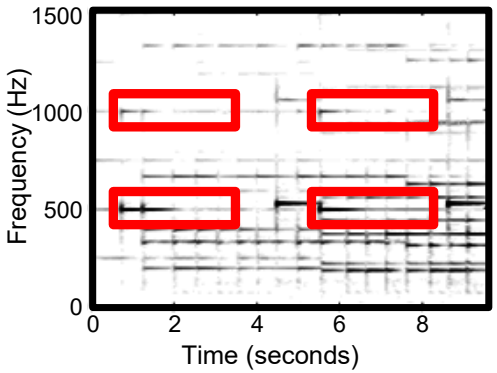
Piano roll



Spectrogram



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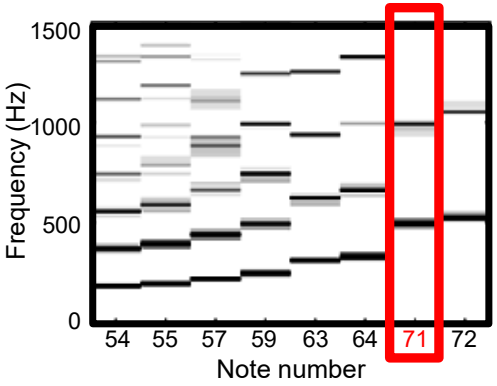
Spectral patterns



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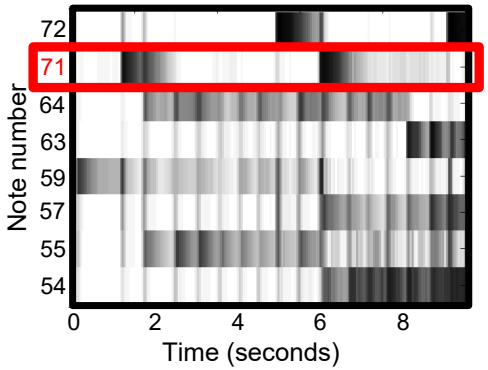
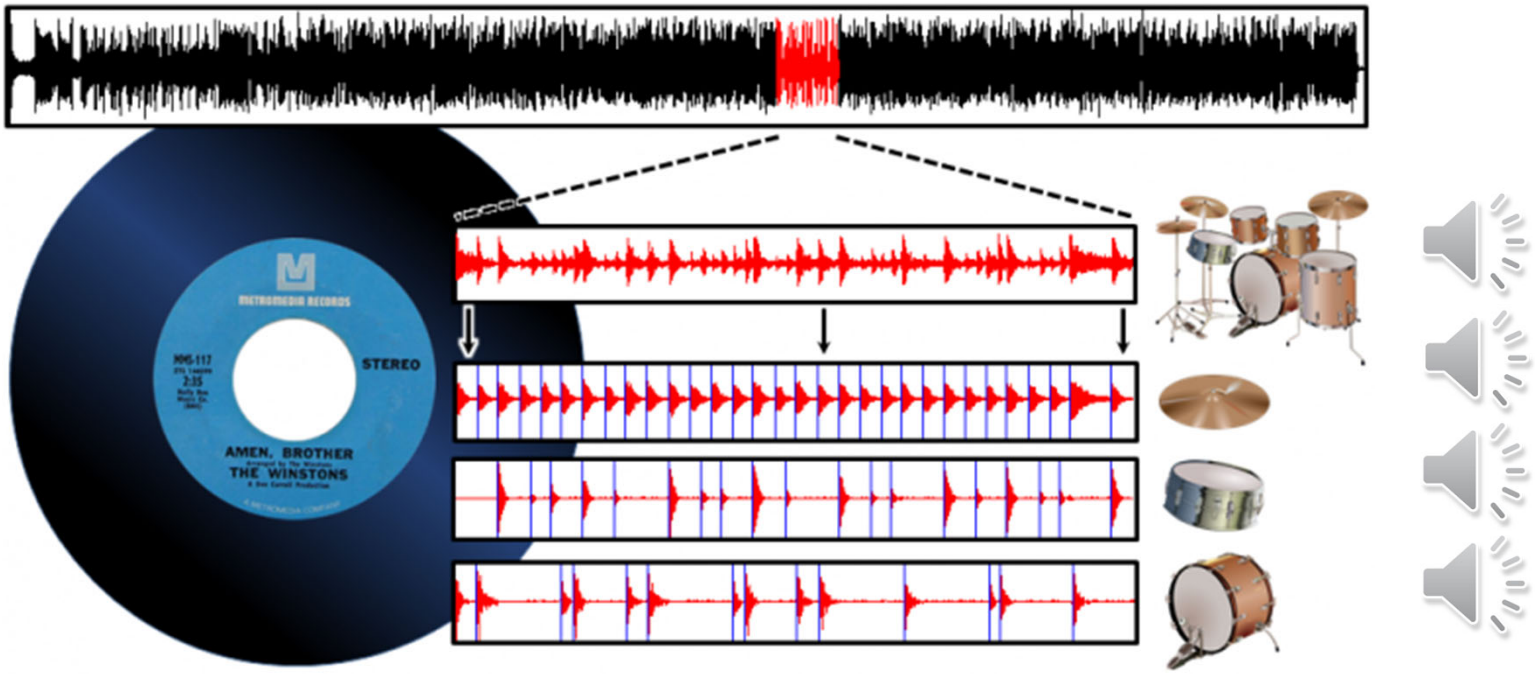
Activity patterns



Score-Informed Audio Decomposition

Informed Drum-Sound Decomposition

Dittmar, Müller: **Reverse Engineering the Amen Break — Score-Informed Separation and Restoration Applied to Drum Recording**. IEEE/ACM TASLP, 24(9): 1531–1543, 2016



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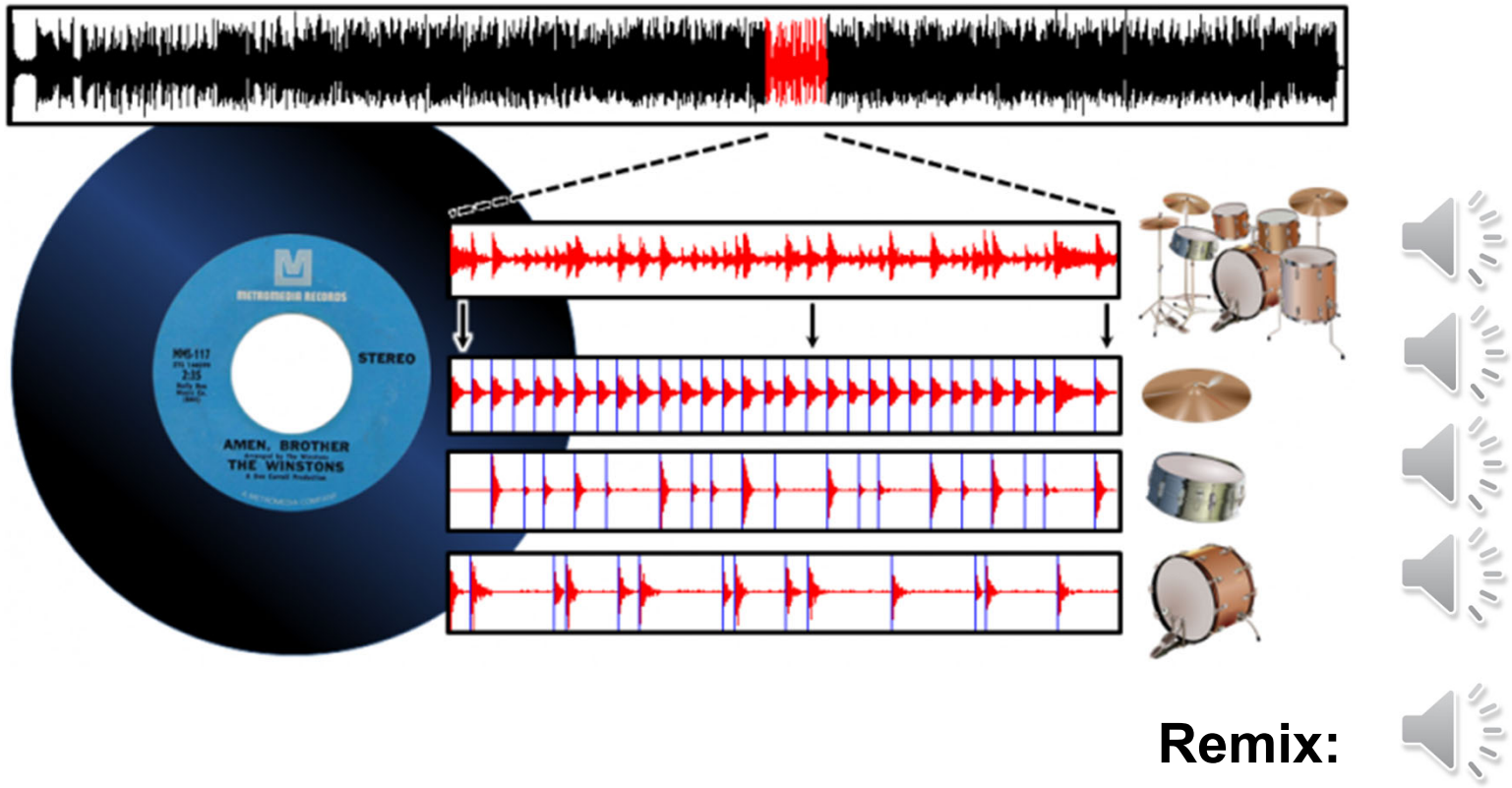
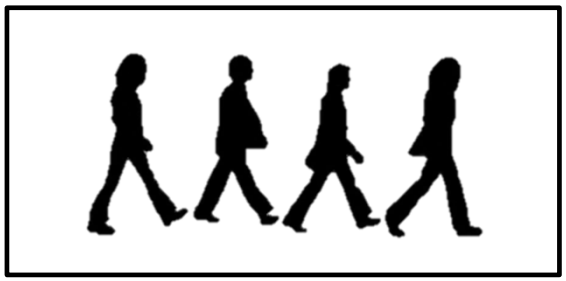


Score-Informed Audio Decomposition

Audio Mosaicing (Style Transfer)

Driedger, Prätzlich, Müller: **Let It Bee — Towards NMF-Inspired Audio Mosaicing**. ISMIR, 350–356, 2015

Target: Let it be



Score-Informed Audio Decomposition

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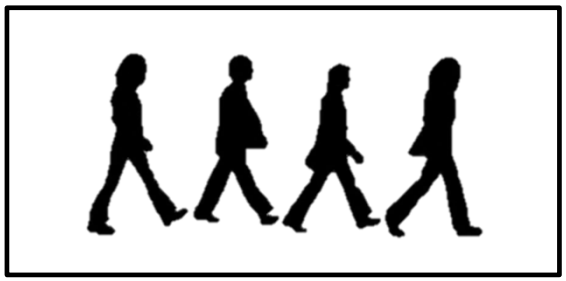
Driedger, Prätzlich, Müller: **Let It Bee — Towards NMF-Inspired Audio Mosaicing**. ISMIR, 350–356, 2015

Target: Let it be

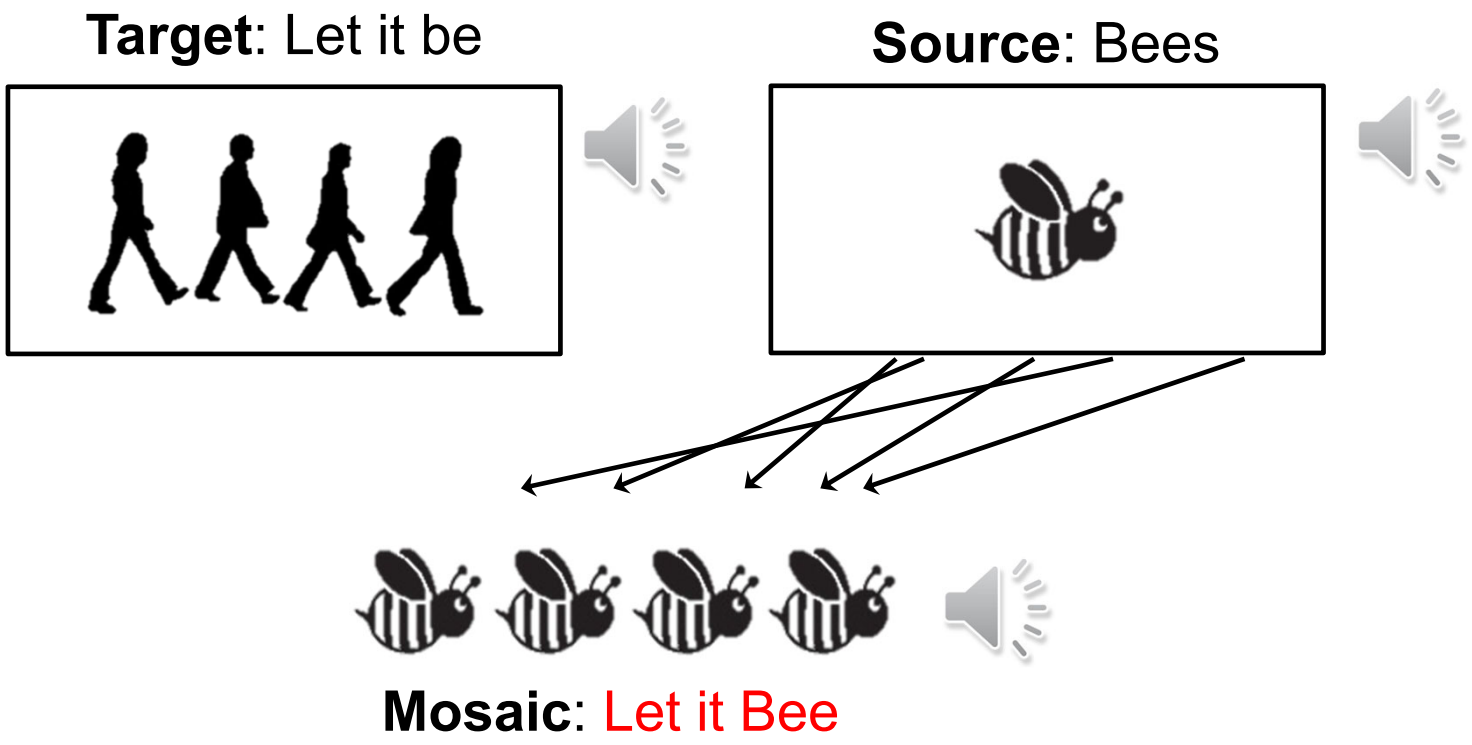


Source: Bees

Score-Informed Audio Decomposition

Audio Mosaicing (Style Transfer)

Driedger, Prätzlich, Müller: **Let It Bee — Towards NMF-Inspired Audio Mosaicing**. ISMIR, 350–356, 2015

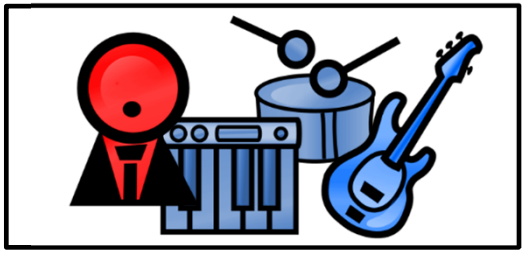


Source Separation

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

Source Separation
Singing Voice

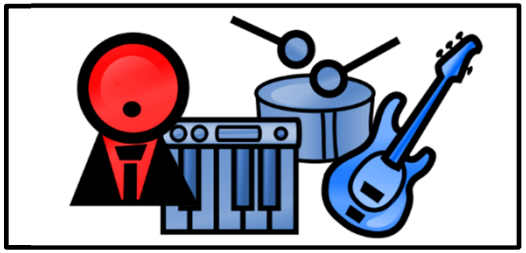
Original recording



Source Separation

Singing Voice

Original recording



Singing

Accompaniment

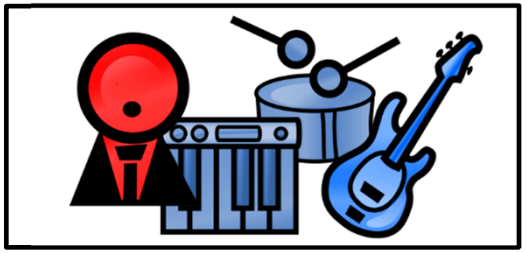
Reference

Reference

Source Separation

Singing Voice

Original recording



Singing

Accompaniment

Reference

Signal Processing

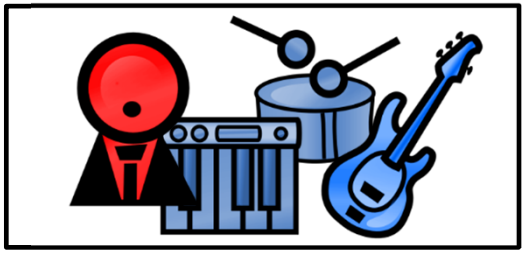
Reference

Signal Processing

Source Separation

Singing Voice

Original recording



Singing

Accompaniment

Reference

Signal Processing

AI

Reference

Signal Processing

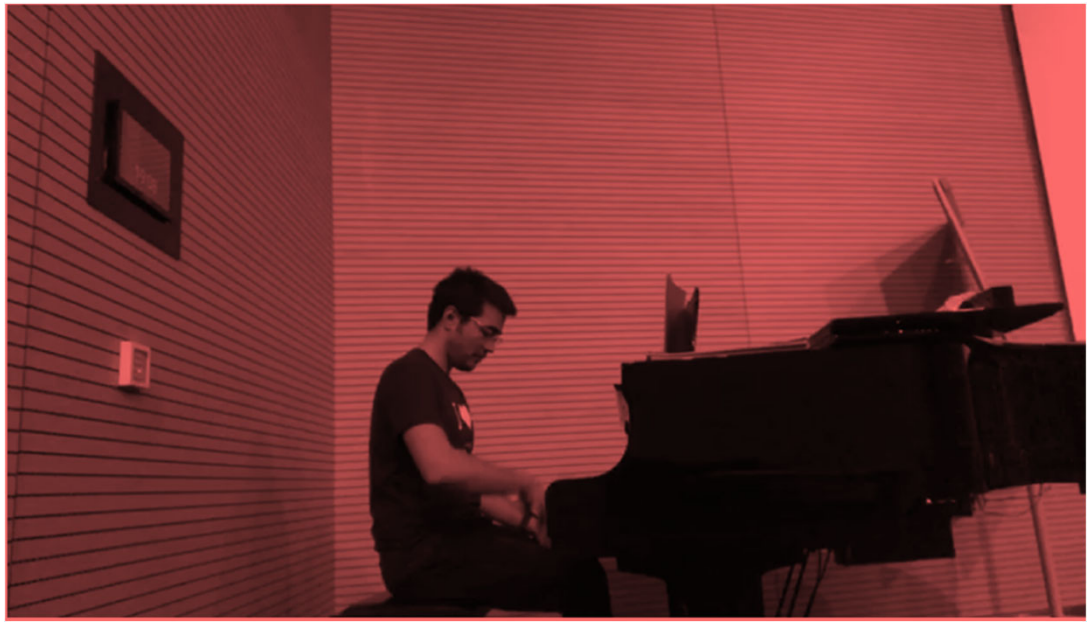
AI

Source Separation
Piano Concerto

- Yigitcan Özer
- PhD student in engineering
- Pianist

Source Separation
Piano Concerto

- Yigitcan Özer
- PhD student in engineering
- Pianist

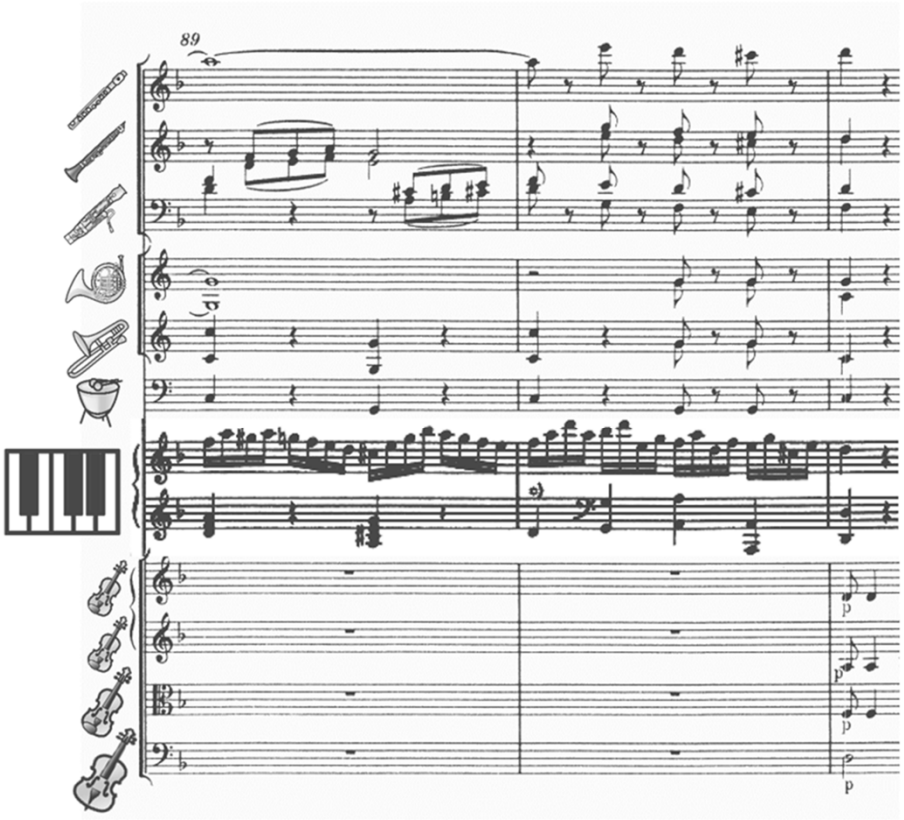


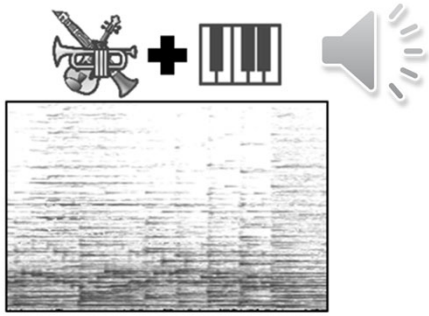
Only Piano!

Where is the orchestra?

Source Separation
Piano Concerto

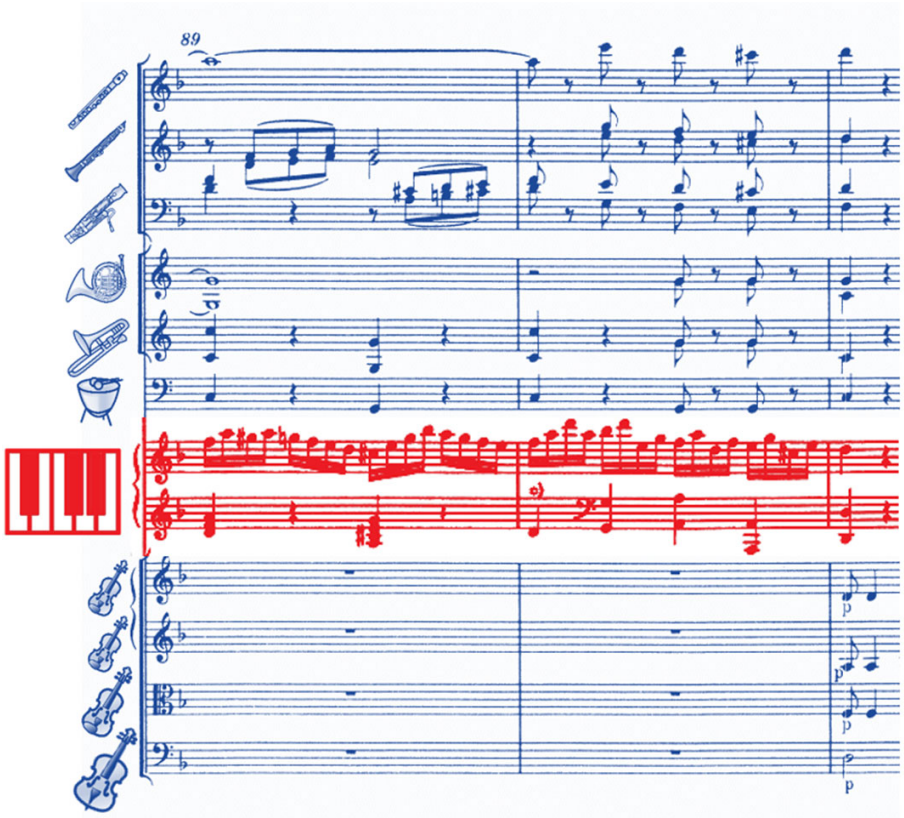
Özer, Müller: **Source Separation of Piano Concertos Using Musically Motivated Augmentation Techniques.** IEEE/ACM Trans. ASLP, 32: 1214–1225, 2024

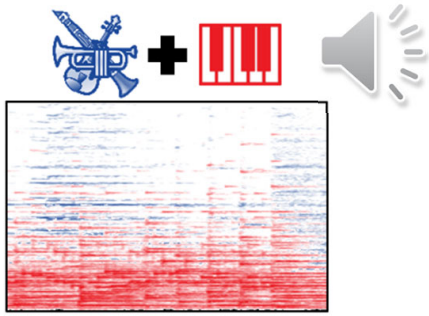




Source Separation
Piano Concerto

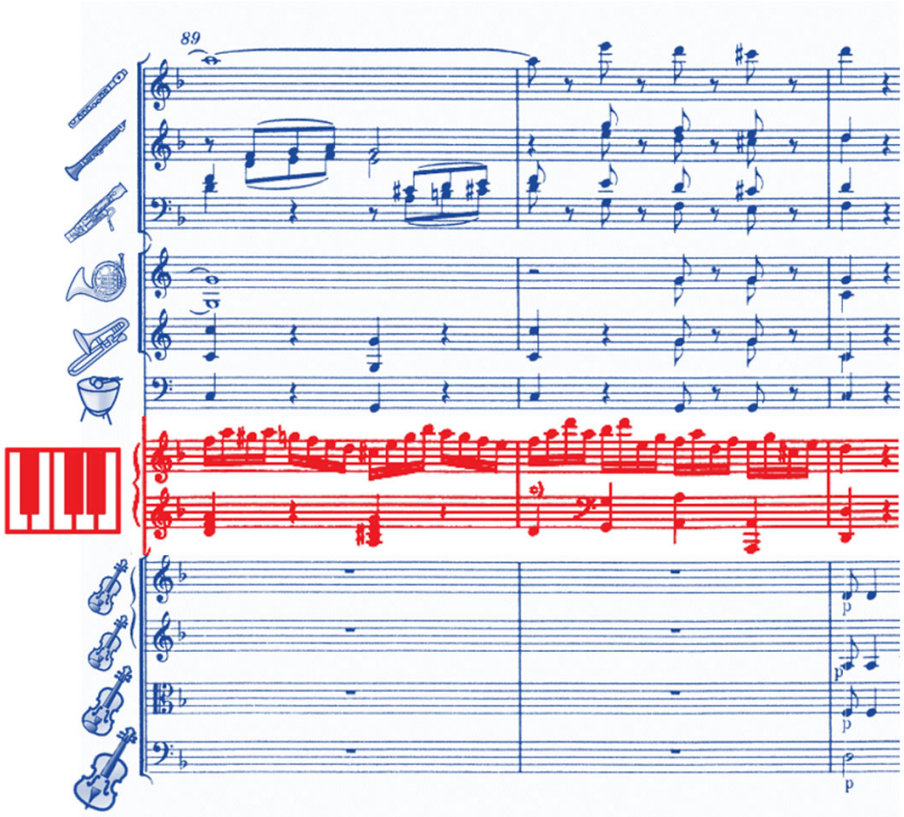
Özer, Müller: **Source Separation of Piano Concertos Using Musically Motivated Augmentation Techniques.** IEEE/ACM Trans. ASLP, 32: 1214–1225, 2024

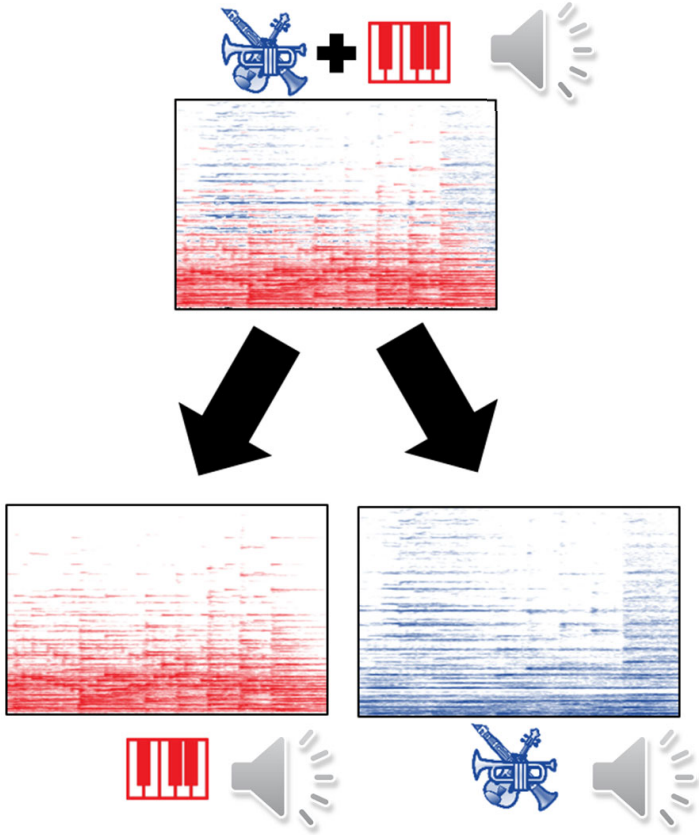




Source Separation
Piano Concerto

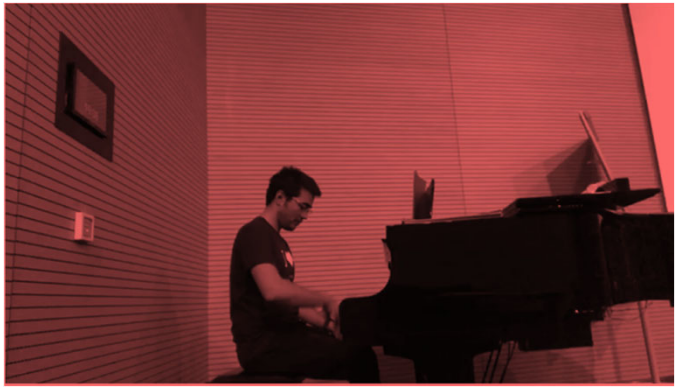
Özer, Müller: **Source Separation of Piano Concertos Using Musically Motivated Augmentation Techniques.** IEEE/ACM Trans. ASLP, 32: 1214–1225, 2024

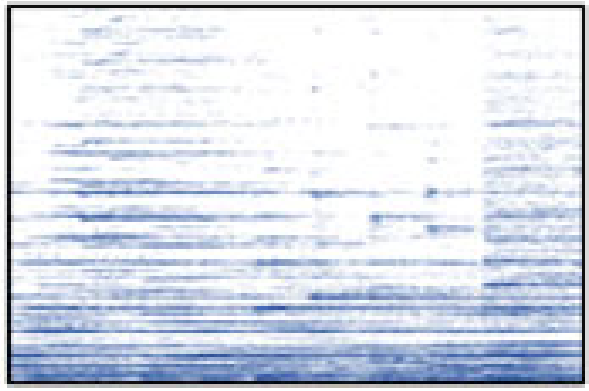




Source Separation
Piano Concerto

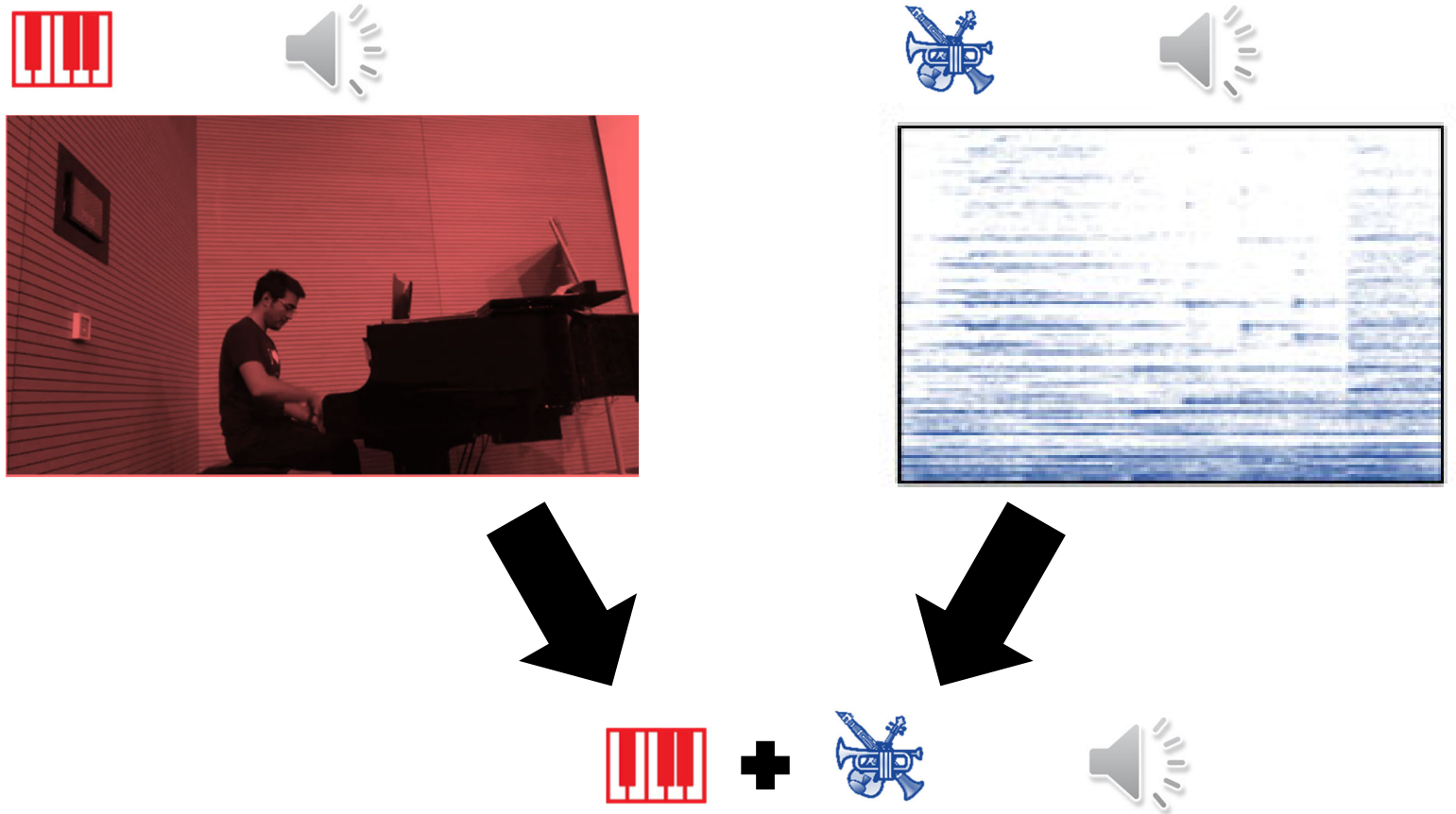
Özer, Müller: **Source Separation of Piano Concertos Using Musically Motivated Augmentation Techniques.** IEEE/ACM Trans. ASLP, 32: 1214–1225, 2024





Source Separation
Piano Concerto

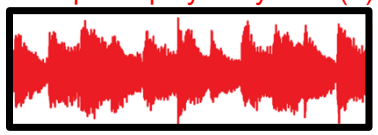
Özer, Müller: **Source Separation of Piano Concertos Using Musically Motivated Augmentation Techniques.** IEEE/ACM Trans. ASLP, 32: 1214–1225, 2024



Accompaniment Creation

- Lonely pianist plays solo piano part

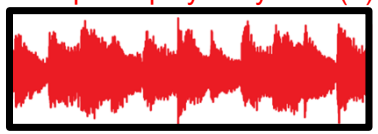
Solo piano played by user (**p**)



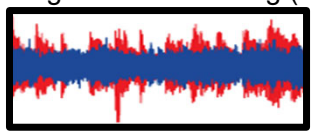
Accompaniment Creation

- Lonely pianist plays solo piano part
- Select full mix recording of concerto

Solo piano played by user (**P**)

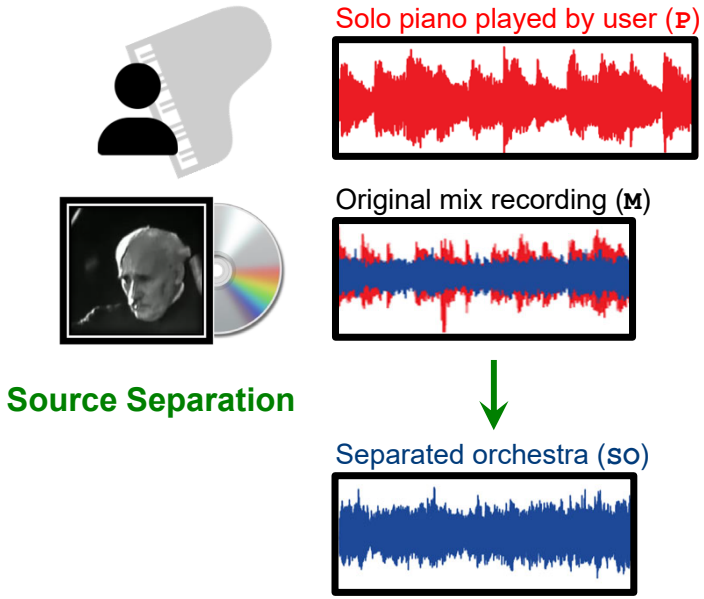


Original mix recording (**M**)



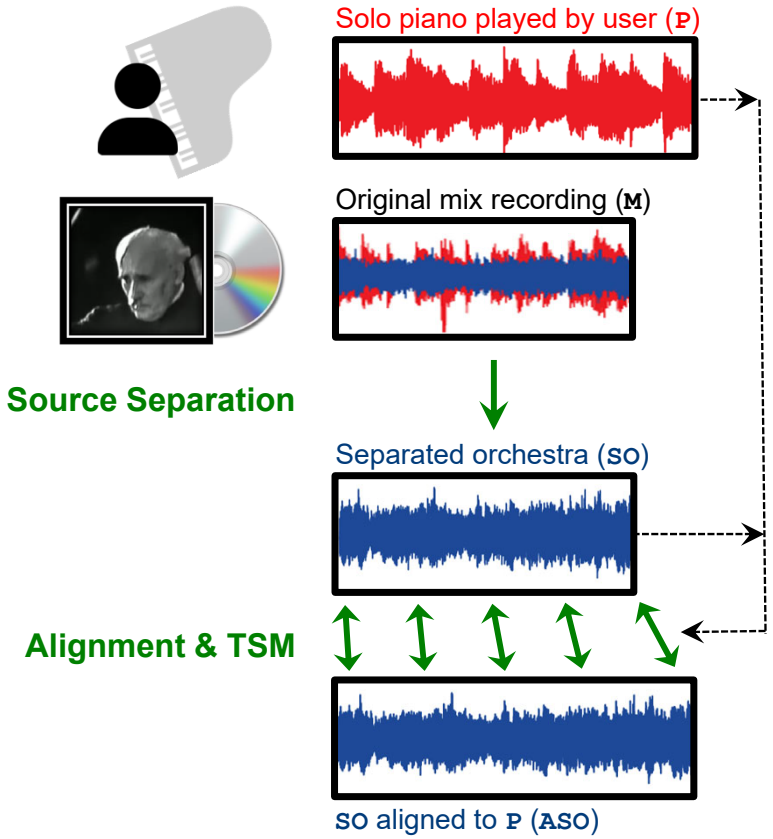
Accompaniment Creation

- Lonely pianist plays solo piano part
- Select full mix recording of concerto
- Isolate orchestra track



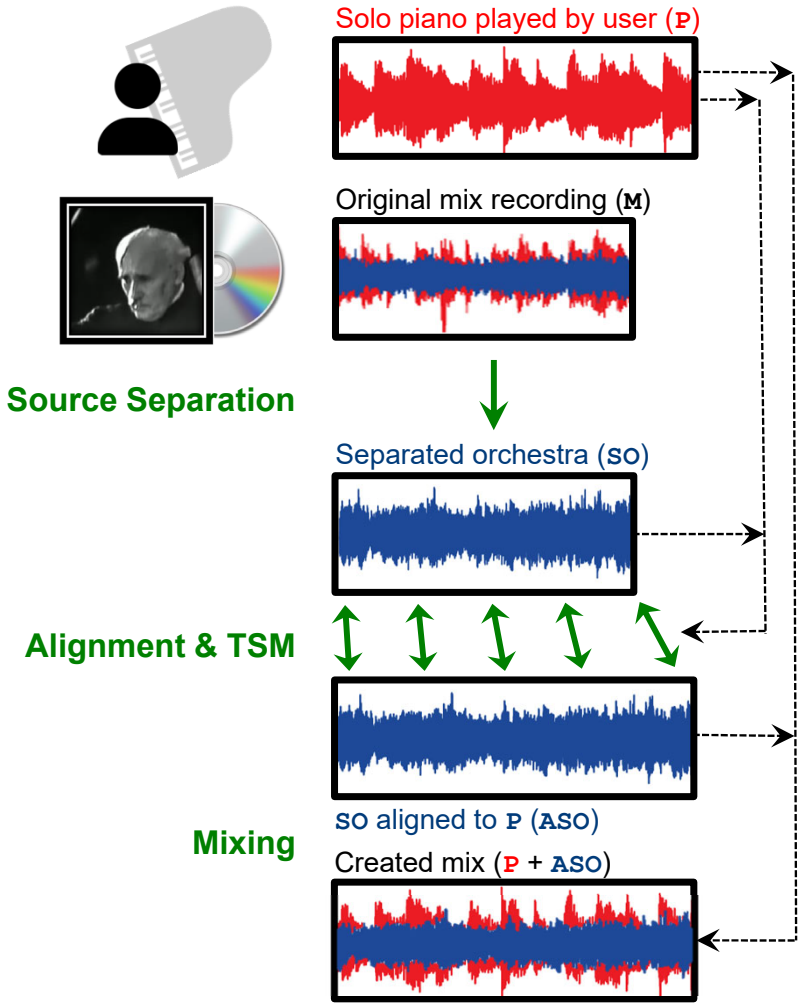
Accompaniment Creation

- Lonely pianist plays solo piano part
- Select full mix recording of concerto
- Isolate orchestra track
- Align to the solo performance



Accompaniment Creation

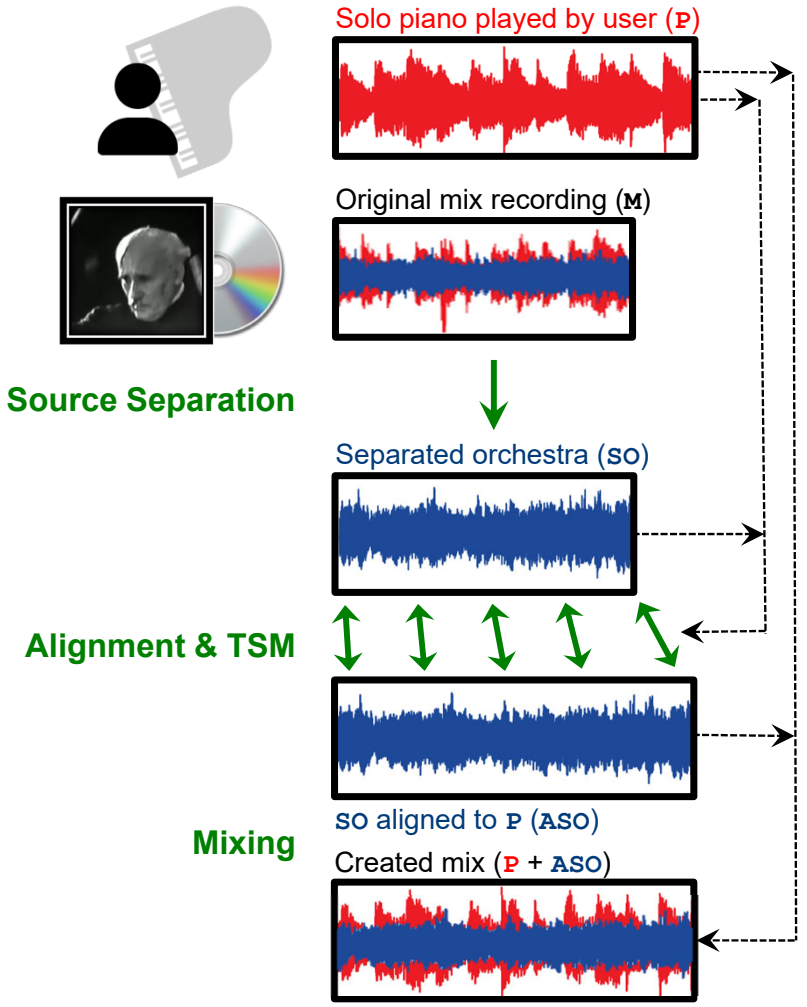
- Lonely pianist plays solo piano part
- Select full mix recording of concerto
- Isolate orchestra track
- Align to the solo performance
- Create own coherent mix



Accompaniment Creation

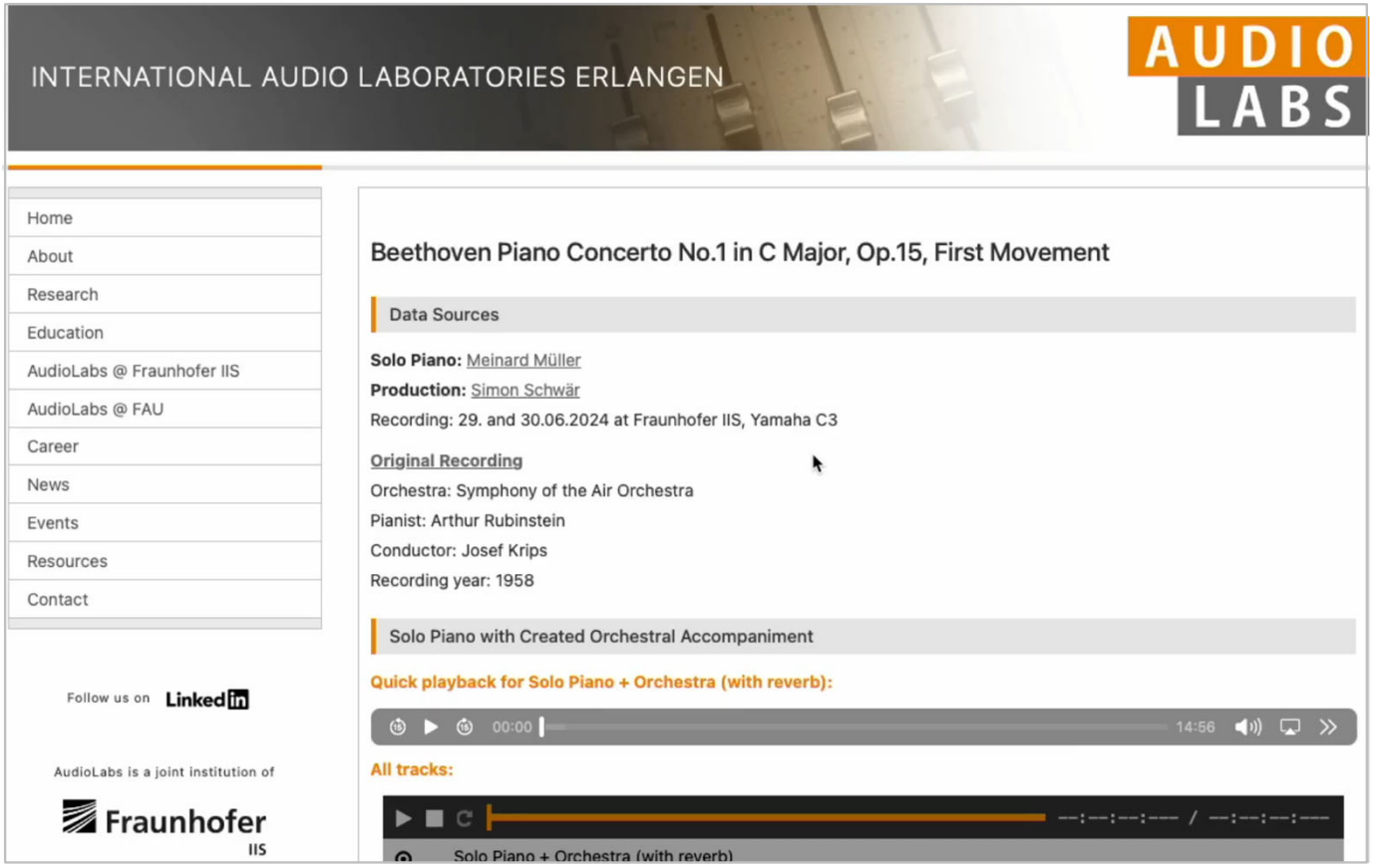
- Lonely pianist plays solo piano part
- Select full mix recording of concerto
- Isolate orchestra track
- Align to the solo performance
- Create own coherent mix

Make lonely pianist happy with “Berliner Philharmoniker”



Accompaniment Creation

Özer, Schwär, Müller: **Piano Concerto Accompaniment Creation.** LBD ISMIR, 2024



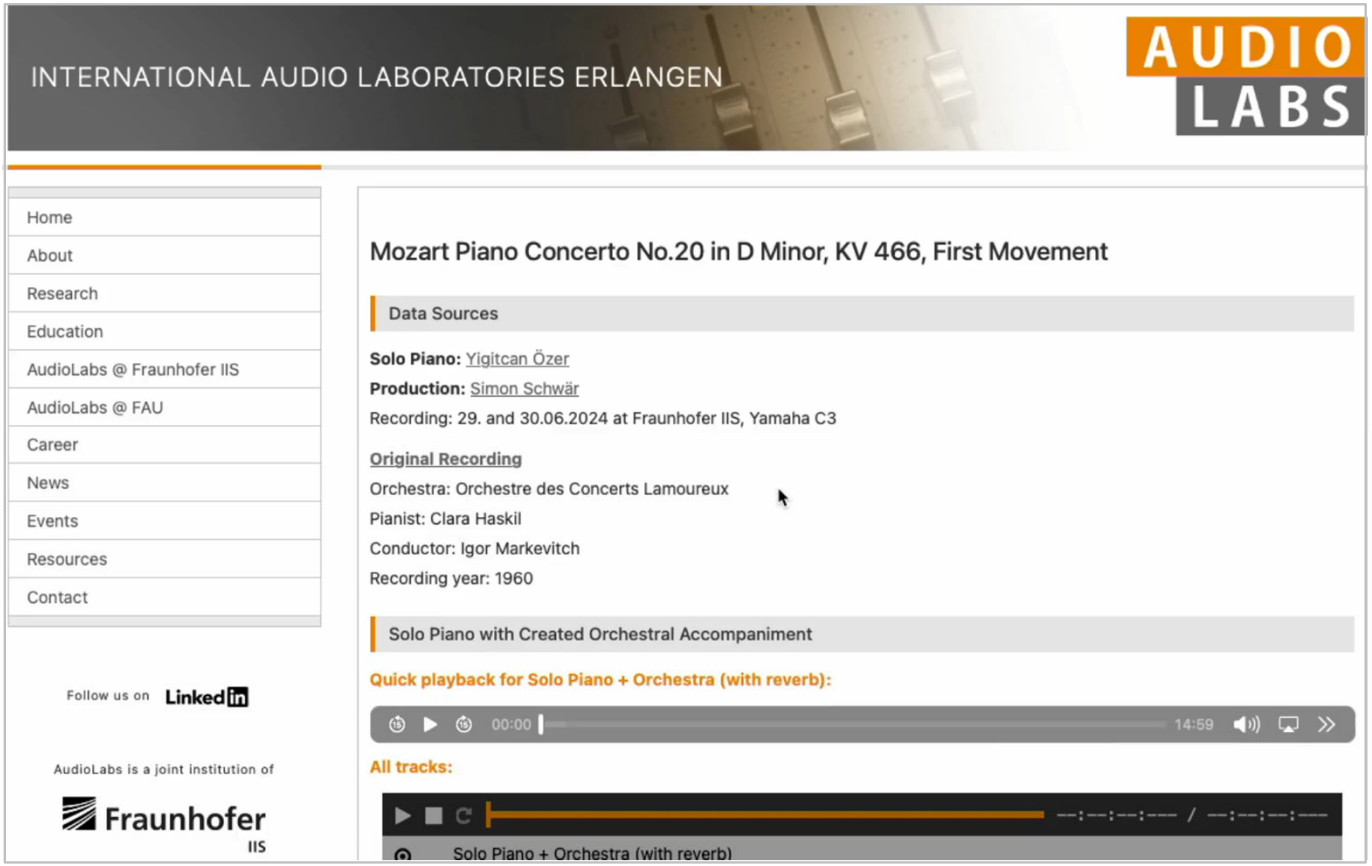
Beethoven: Piano Concerto No. 1

Lonely pianist: Meinard Müller

Recording (1958): Symphony of the Air Orchestra

Accompaniment Creation

Özer, Schwär, Müller: **Piano Concerto Accompaniment Creation.** LBD ISMIR, 2024



Mozart: Piano Concerto No. 20

Lonely pianist: Yiğitcan Özer

Recording (1960): Orchestre des Concerts Lamoureux

Concert Band

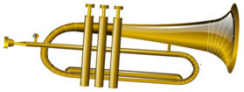
Concert Band

Four-Voice Choir (SATB)

Drese: Jesu geh voran

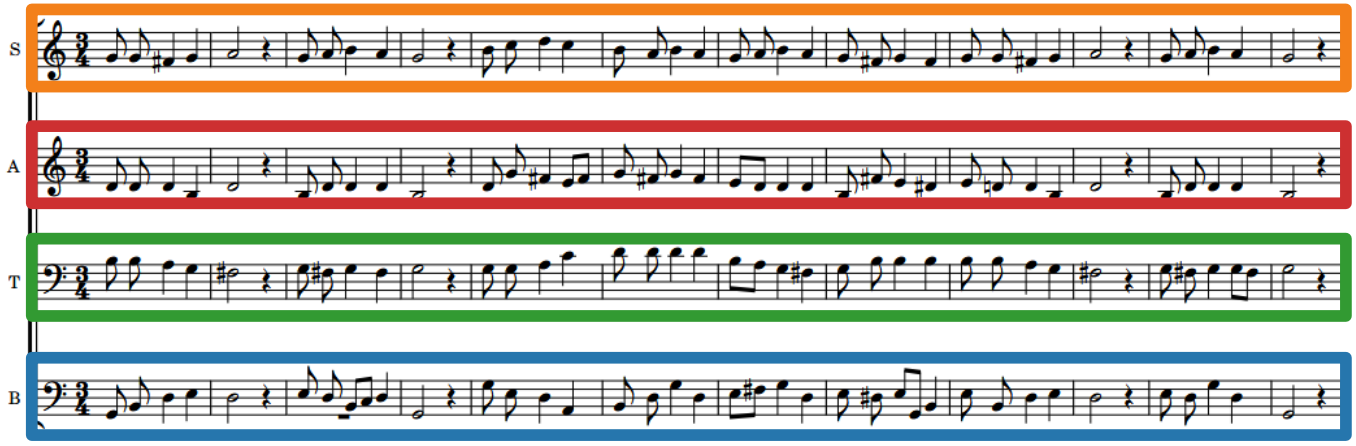
Soprano (S)

Alto (A)



Tenor (T)

Bass (B)

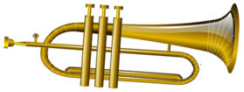


Four-Voice Choir (SATB)

Drese: Jesu geh voran

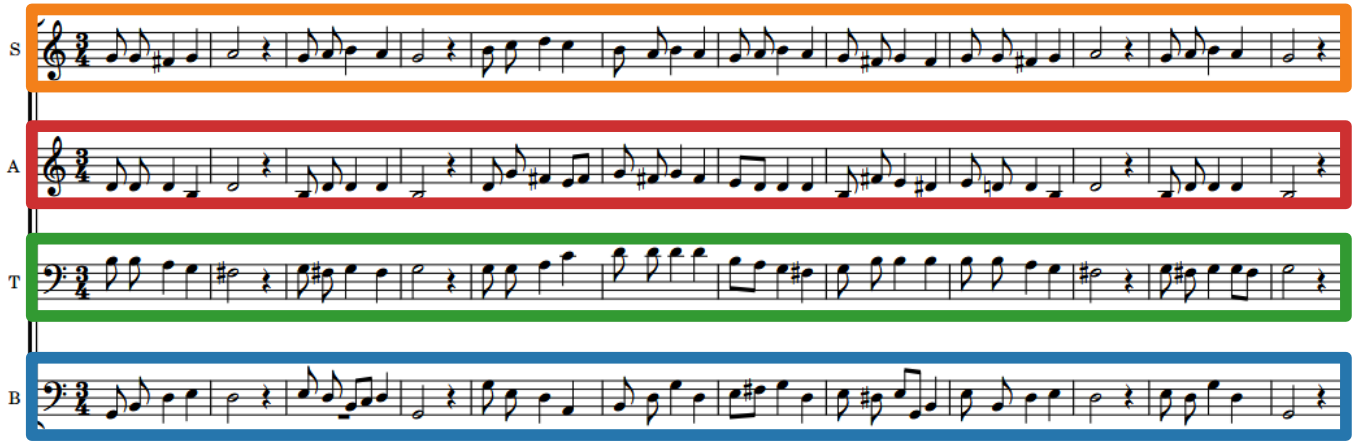
Soprano (S)

Alto (A)



Tenor (T)

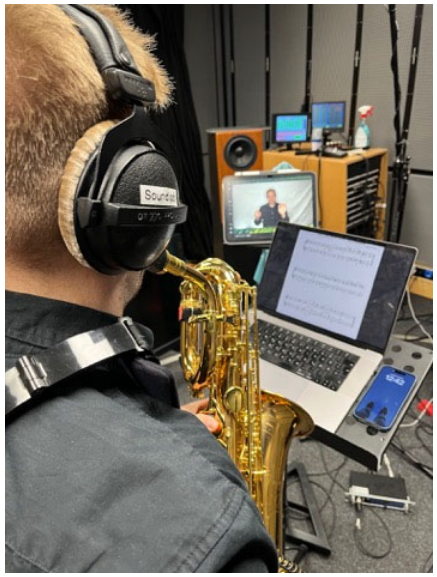
Bass (B)

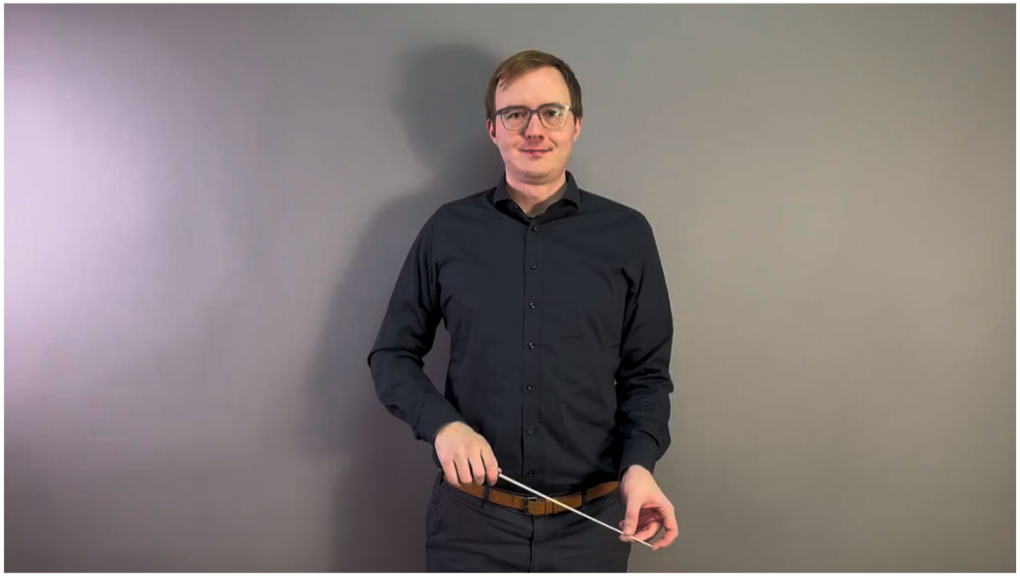


ChoraleBricks
Multitrack Dataset for Wind Music Research

Balke, Berndt, Müller: **ChoraleBricks: A Modular Multitrack Dataset for Wind Music Research**. TISMIR, 8(1): 39–54, 2025

- Dataset featuring 10 SATB chorales
- 193 isolated tracks with 13 instruments
- Recorded along conducting video for syncronization





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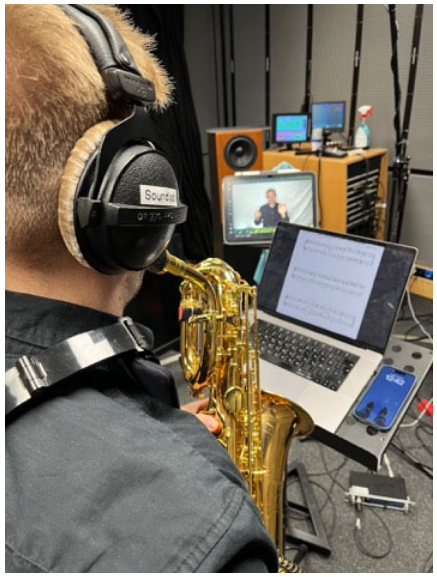
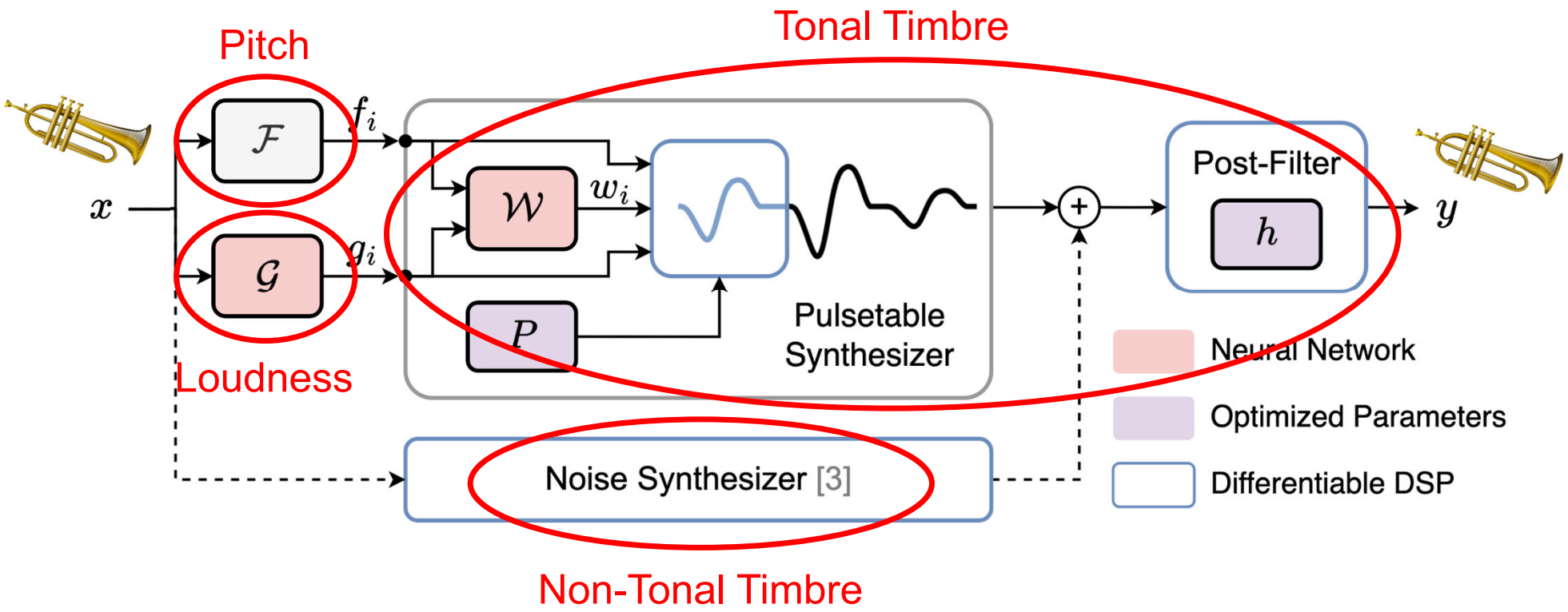


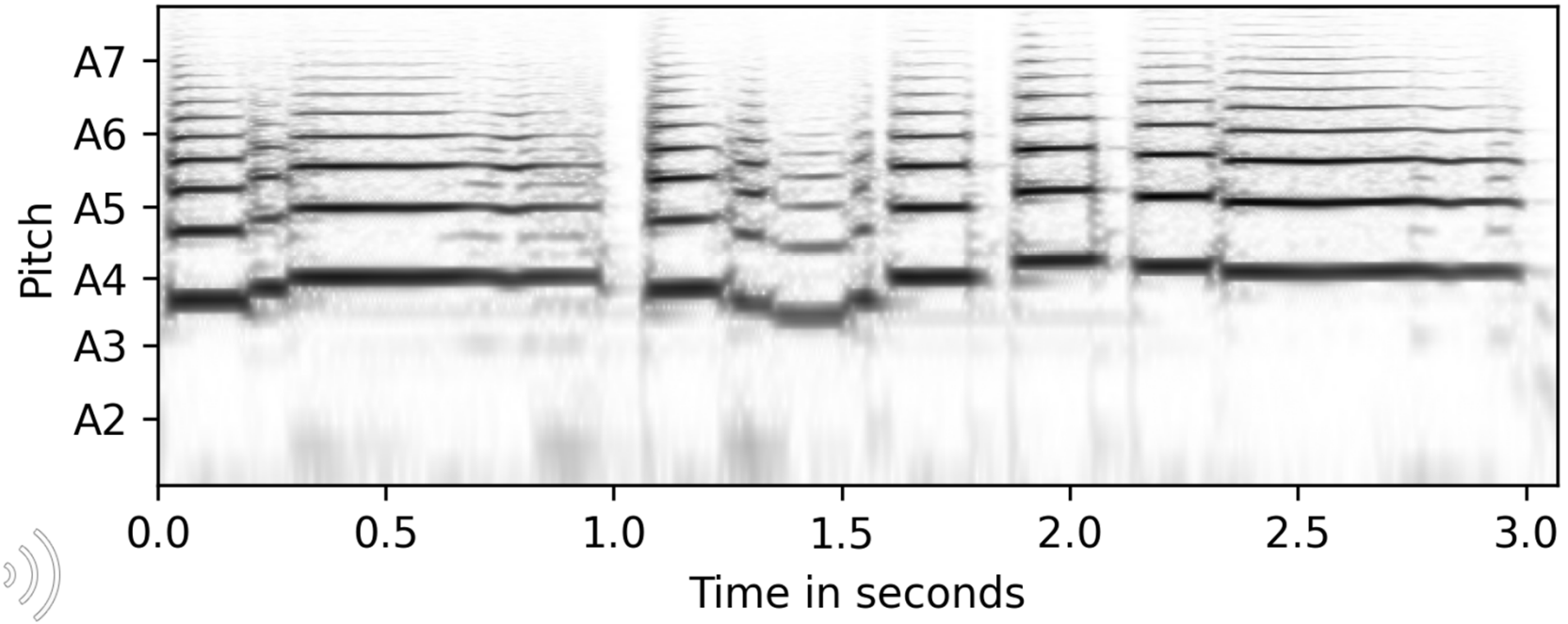
Differentiable Digital Signal Processing
Pulsetable Synthesis

Dittmar, Zeitler, Balke, Schwär, Müller: **PULSE-IT: Lightweight and Expressive Synthesis of Wind Instrument Playing**. LBD ISMIR, 2025



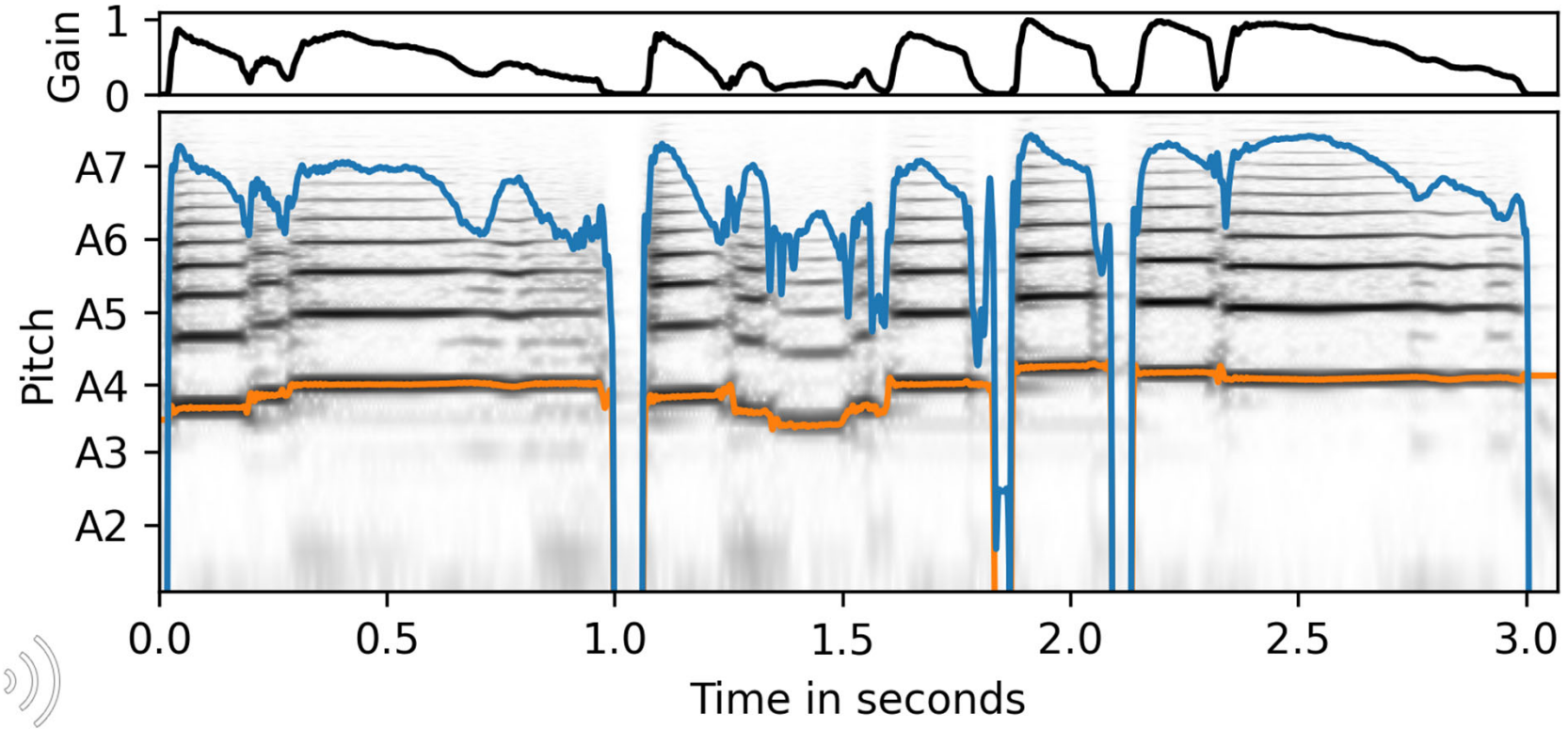
Wind Instrument Synthesis

Input Signal



Wind Instrument Synthesis

Extract Control Signals



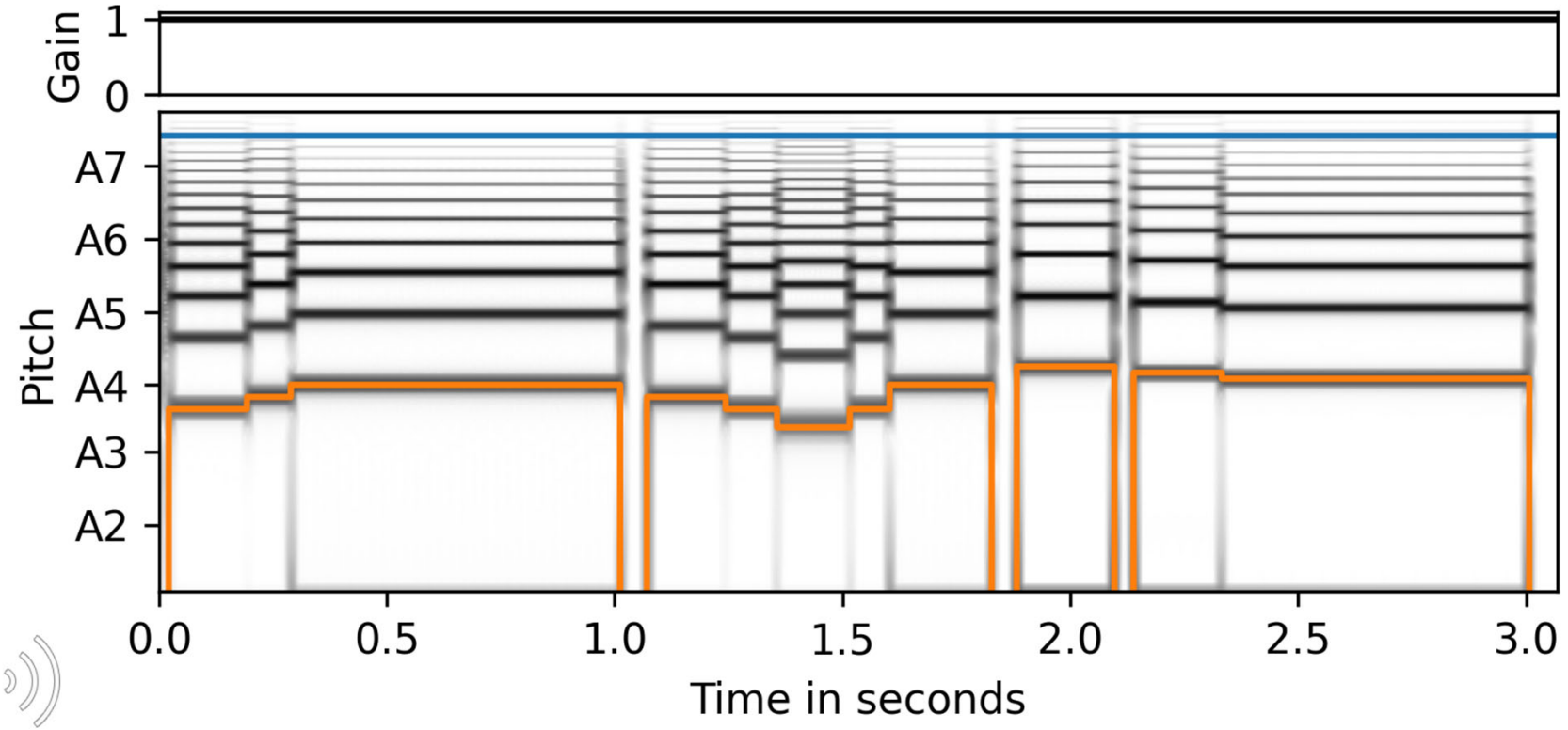
Loudness

Timbre

Pitch (F0)

Wind Instrument Synthesis

Generated Control Signals



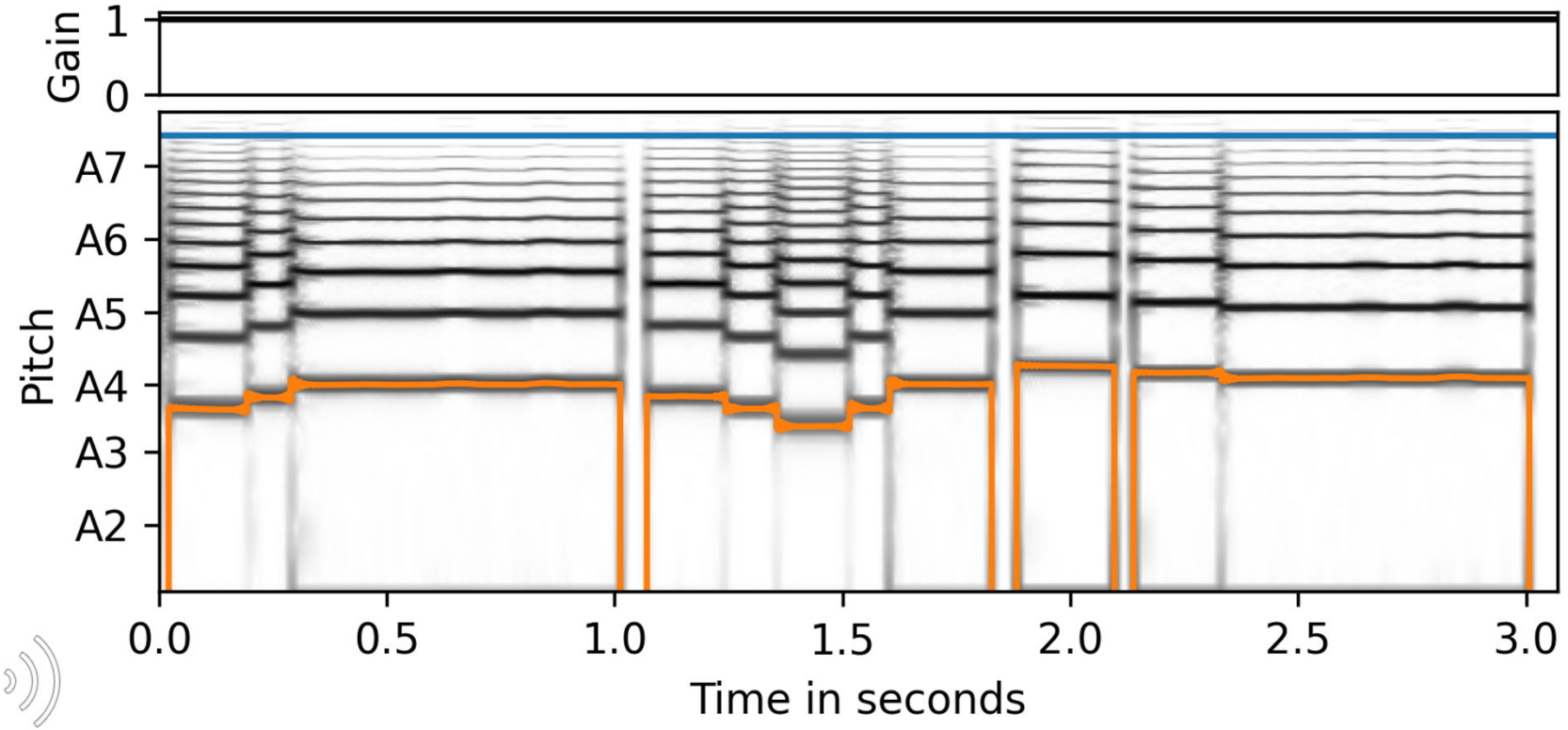
Loudness

Timbre

Pitch (F0)

Wind Instrument Synthesis

Generated Control Signals with Pitch Fluctuations



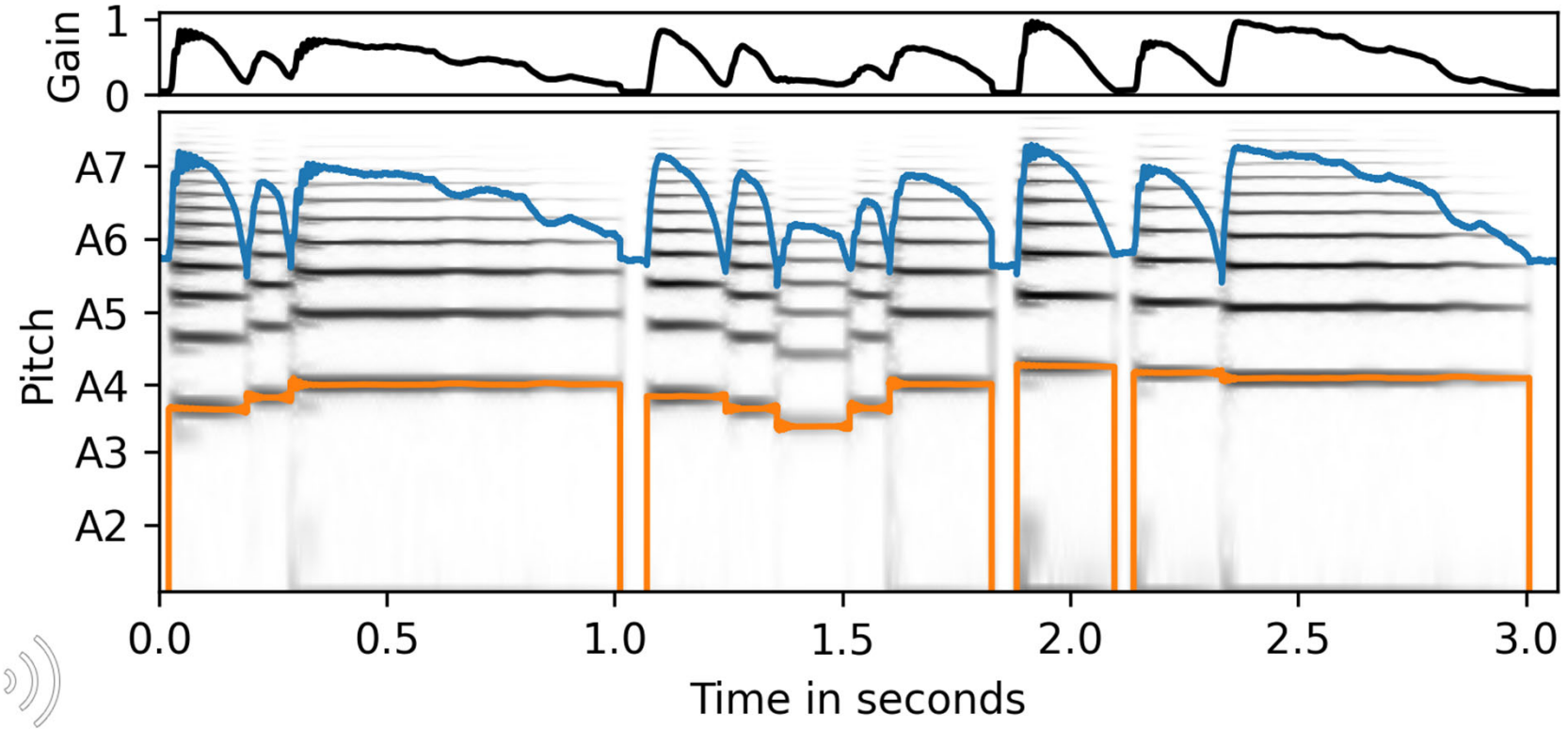
Loudness

Timbre

Pitch (F0)

Wind Instrument Synthesis

Generated Control Signals with Pitch & Loudness Fluctuations



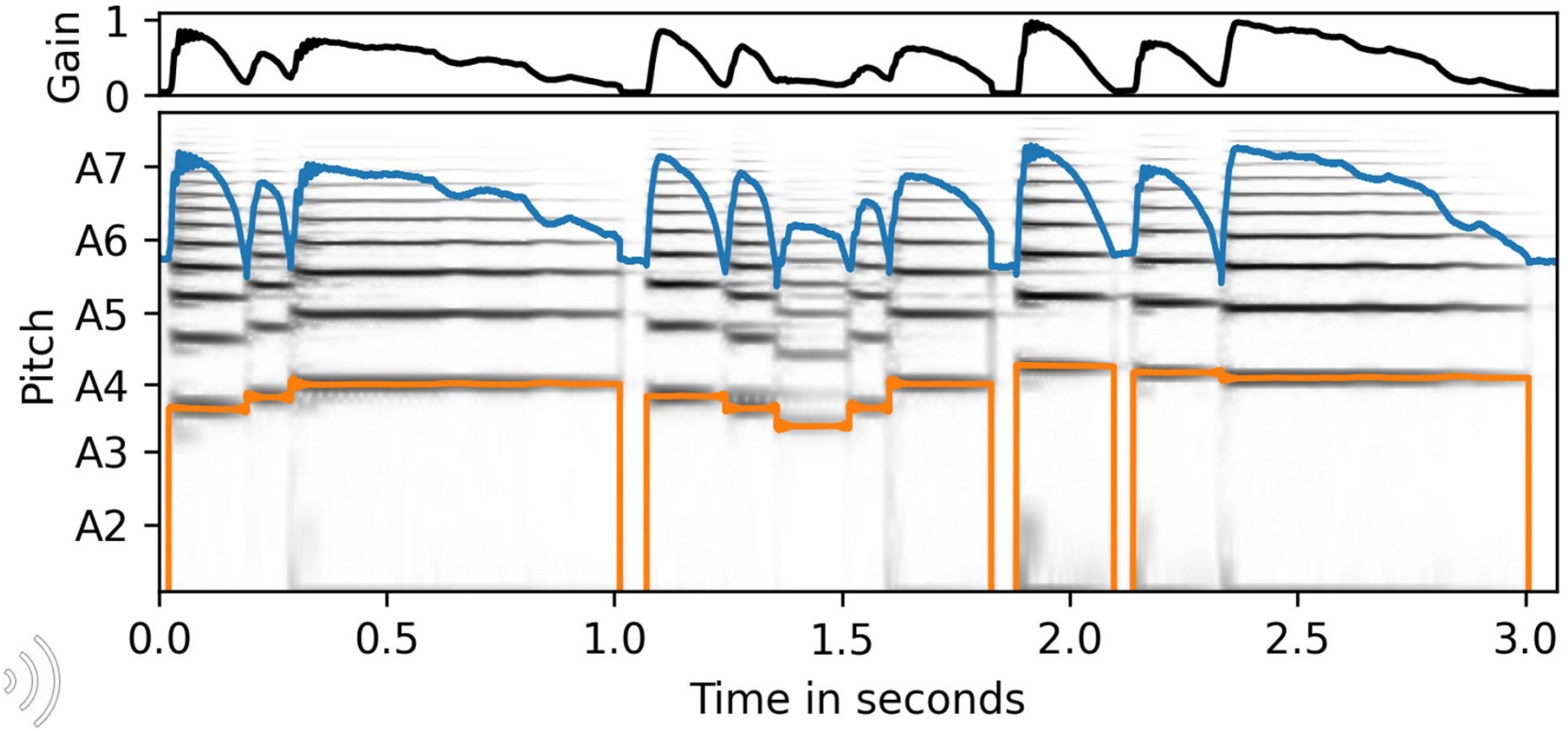
Loudness

Timbre

Pitch (F0)

Wind Instrument Synthesis

Generated Control Signals with Fluctuations and Room Acoustics



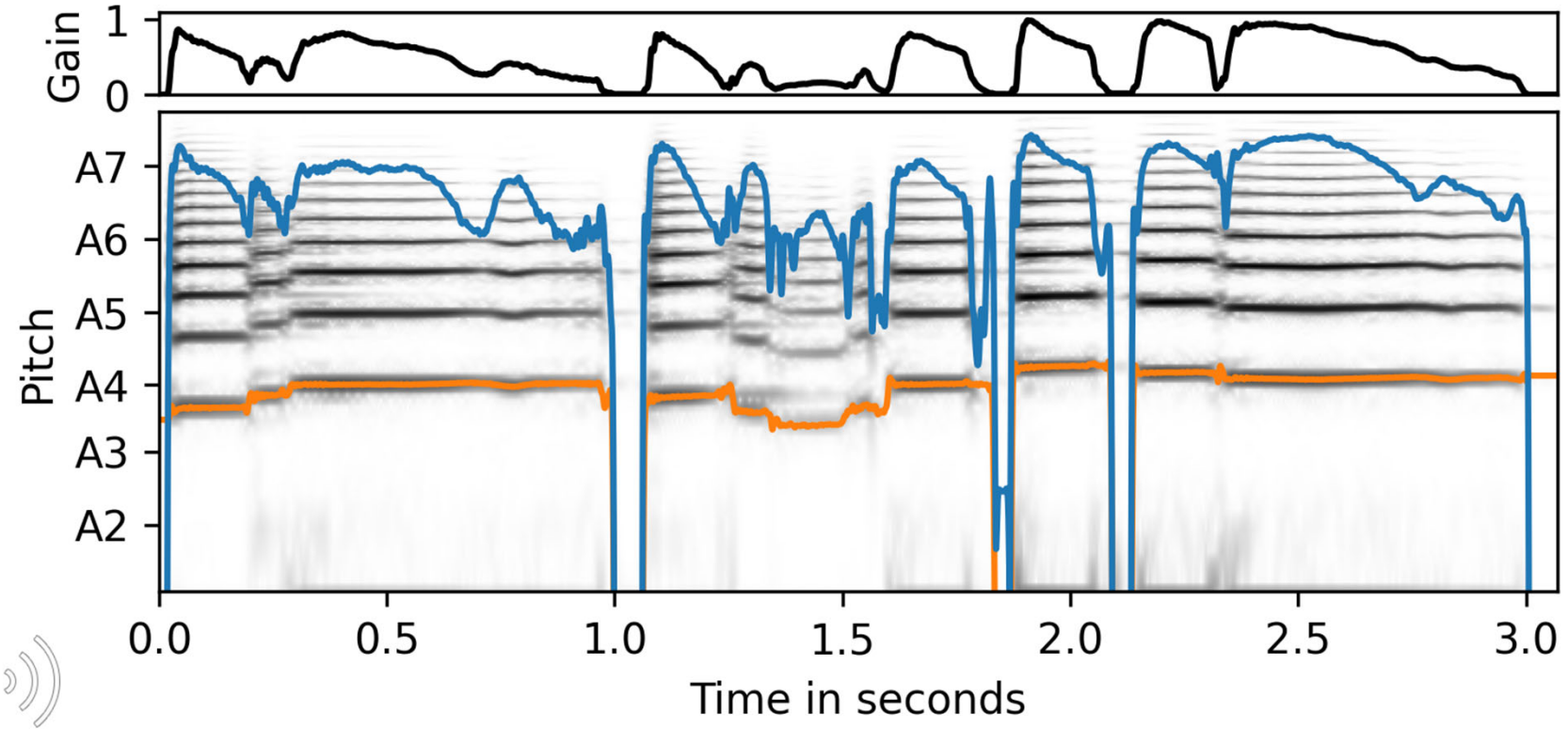
Loudness

Timbre

Pitch (F0)

Wind Instrument Synthesis

Resynthesized Trumpet



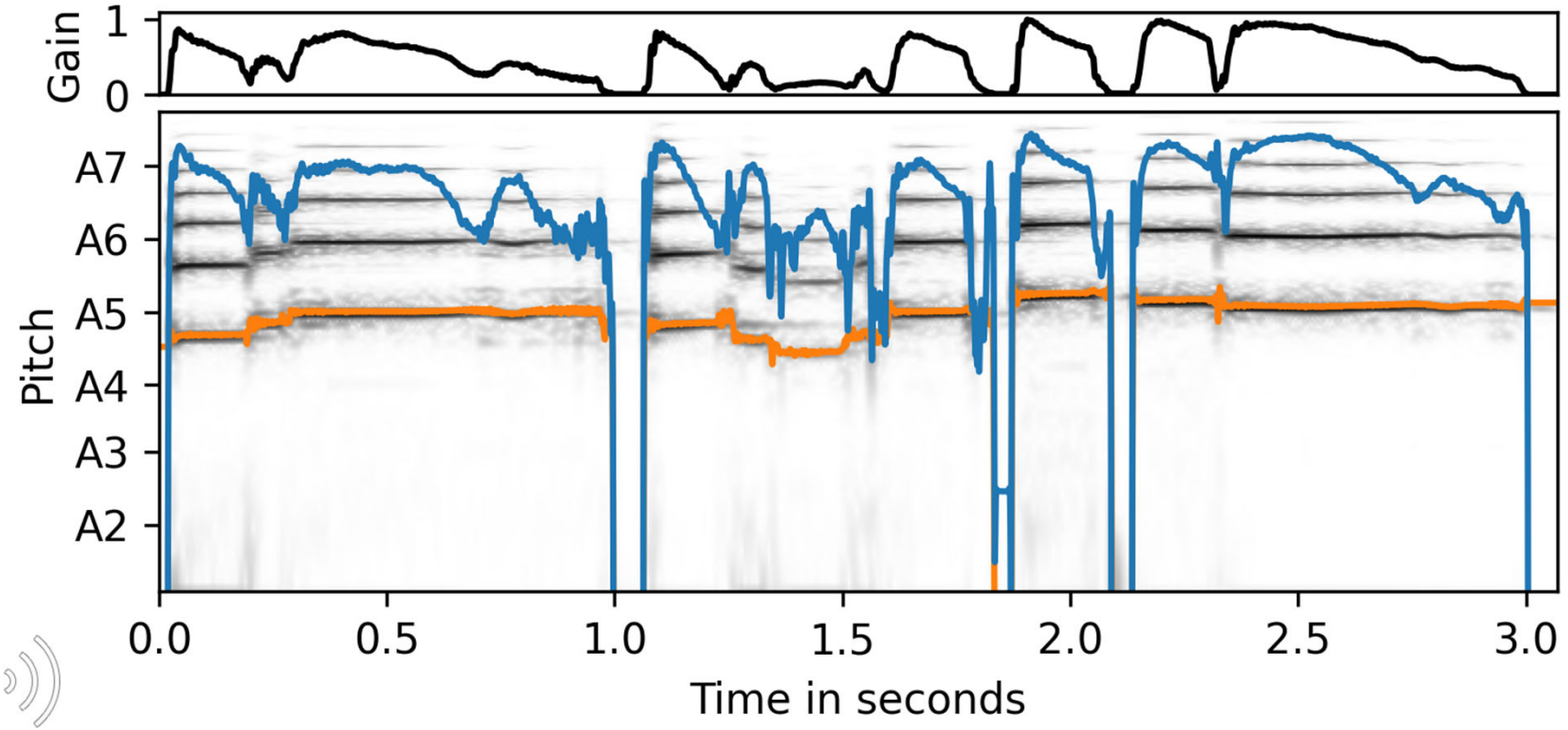
Loudness

Timbre

Pitch (F0)

Wind Instrument Synthesis

Resynthesized Trumpet (One Octave Higher)



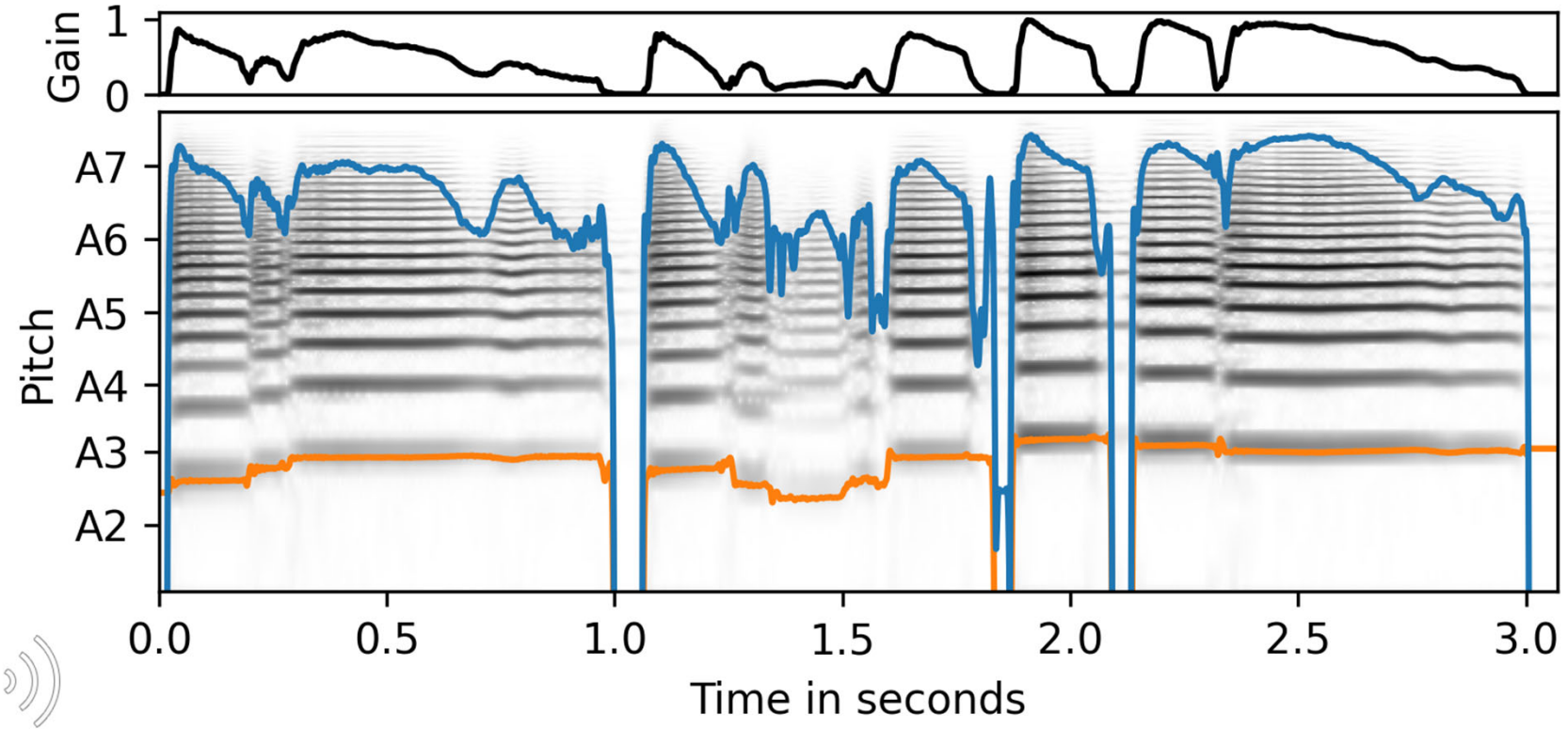
Loudness

Timbre

Pitch (F0)

Wind Instrument Synthesis

Resynthesized Trumpet (One Octave Lower)



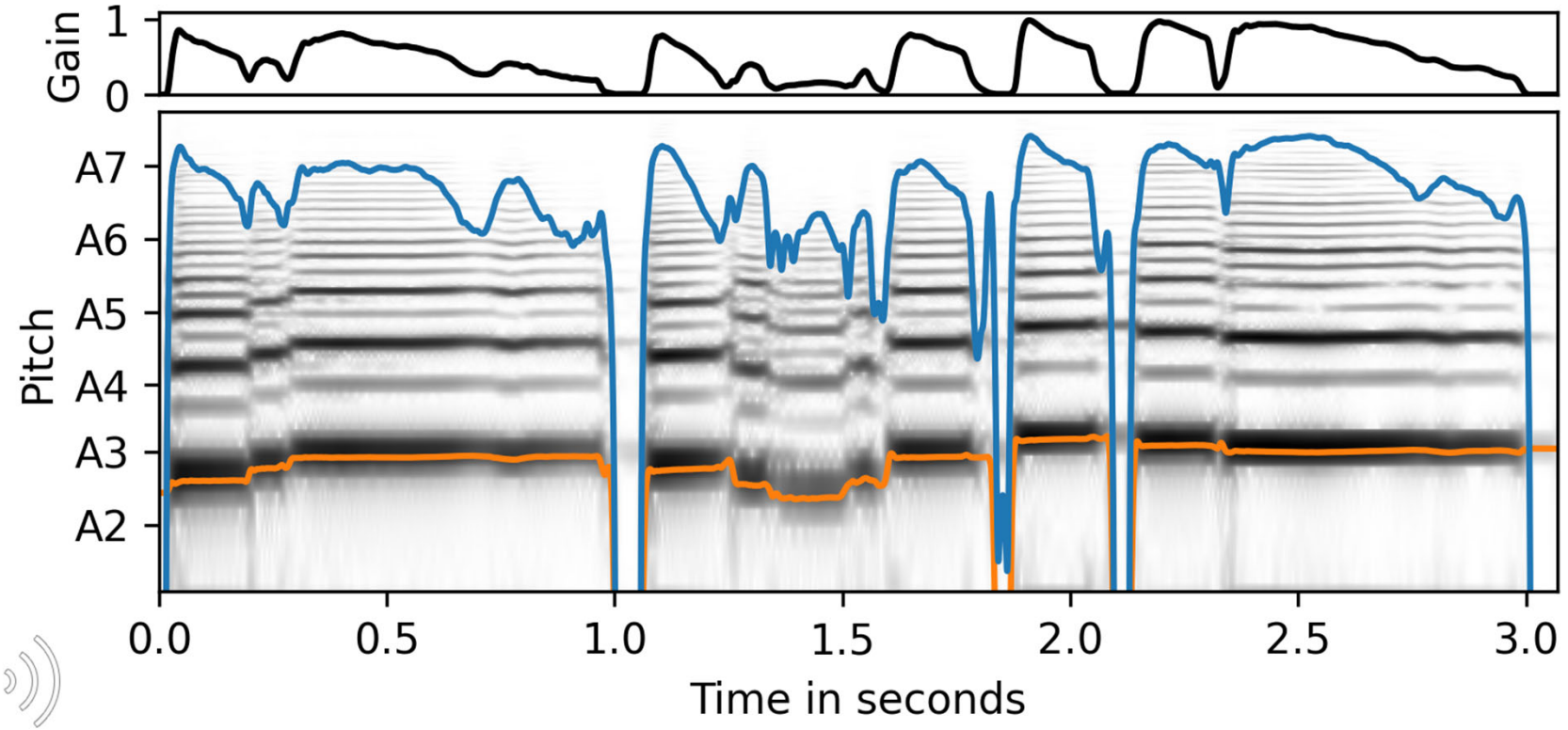
Loudness

Timbre

Pitch (F0)

Wind Instrument Synthesis

Resynthesized Clarinet (One Octave Lower)



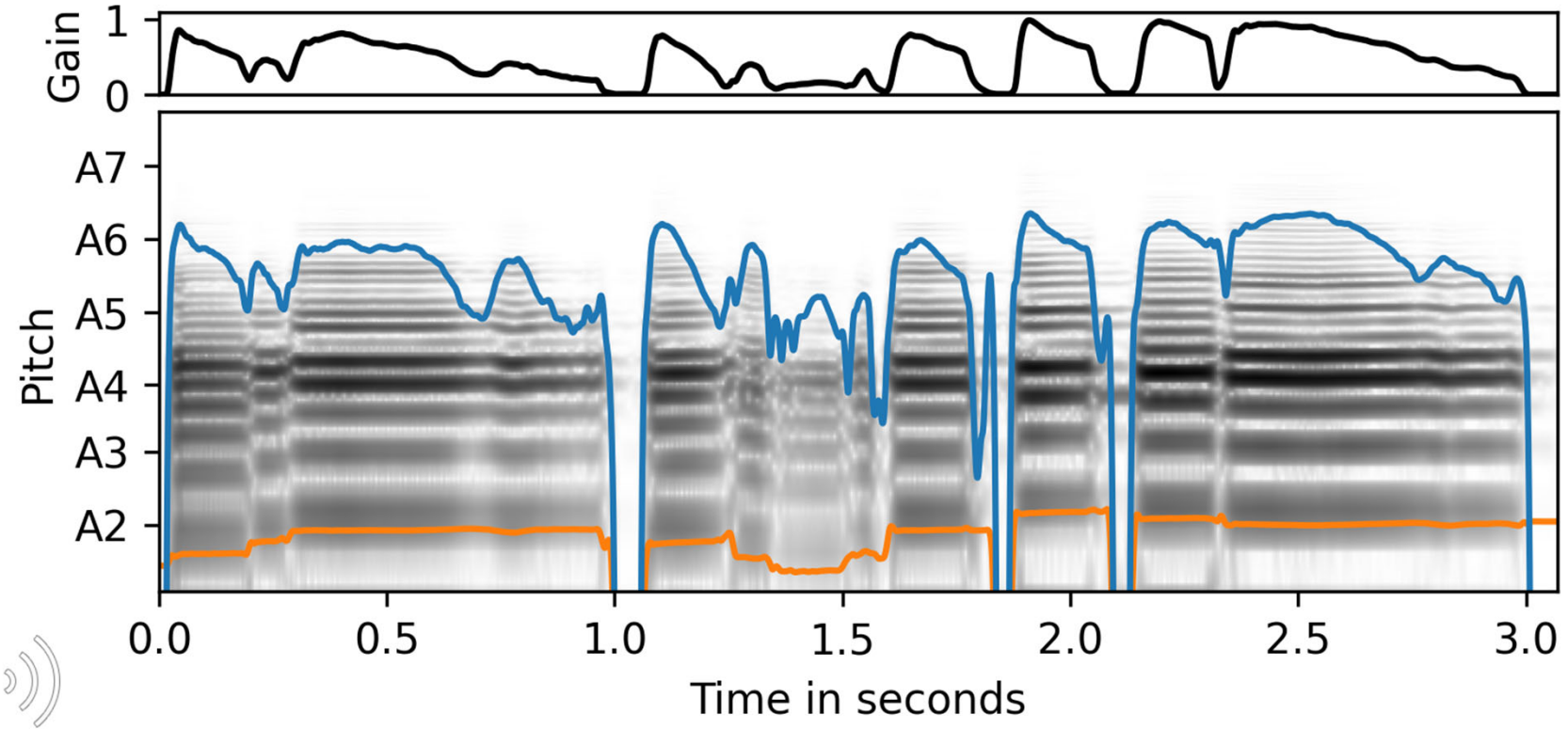
Loudness

Timbre

Pitch (F0)

Wind Instrument Synthesis

Resynthesized Bassoon (Two Octaves Lower)



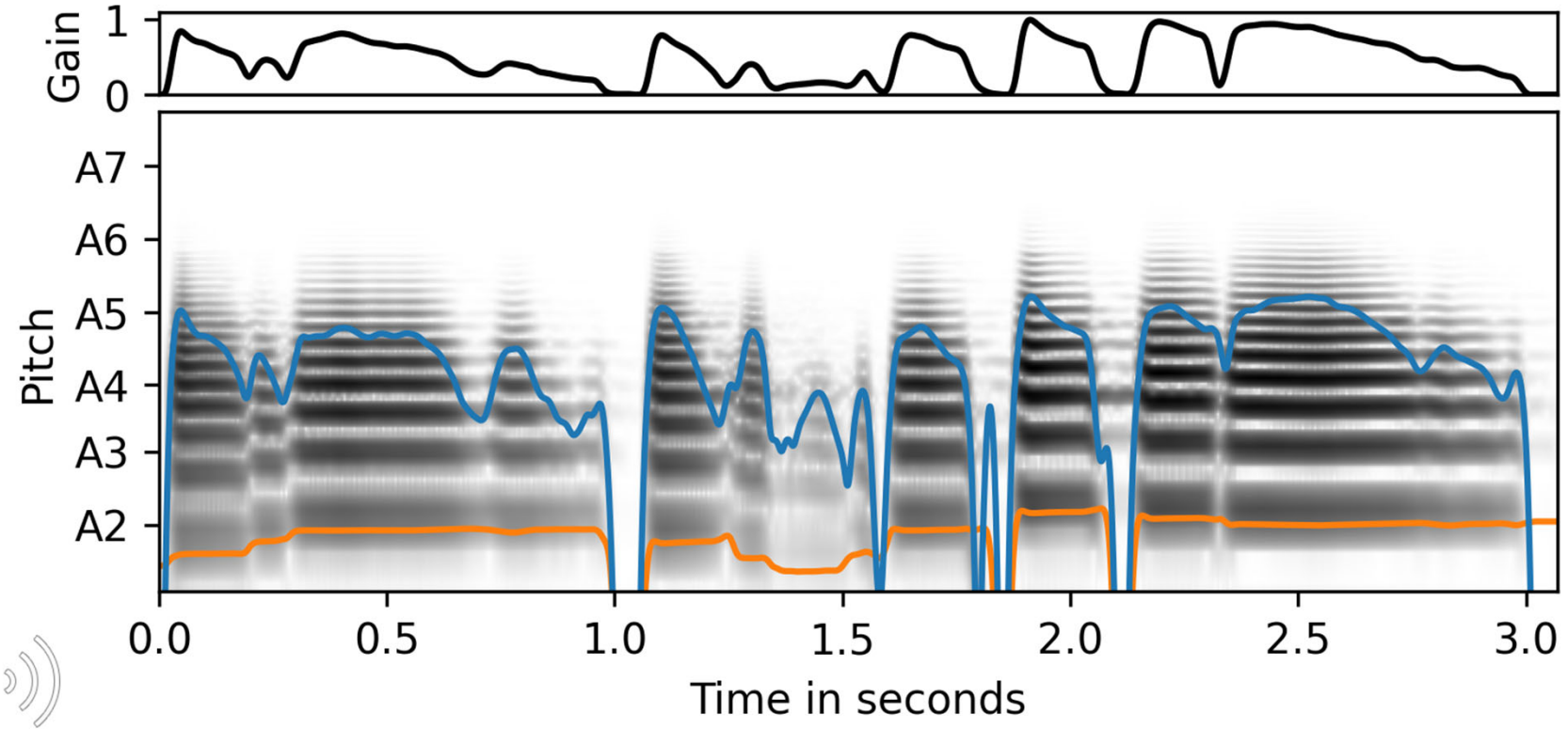
Loudness

Timbre

Pitch (F0)

Wind Instrument Synthesis

Resynthesized Tuba (Two Octaves Lower)

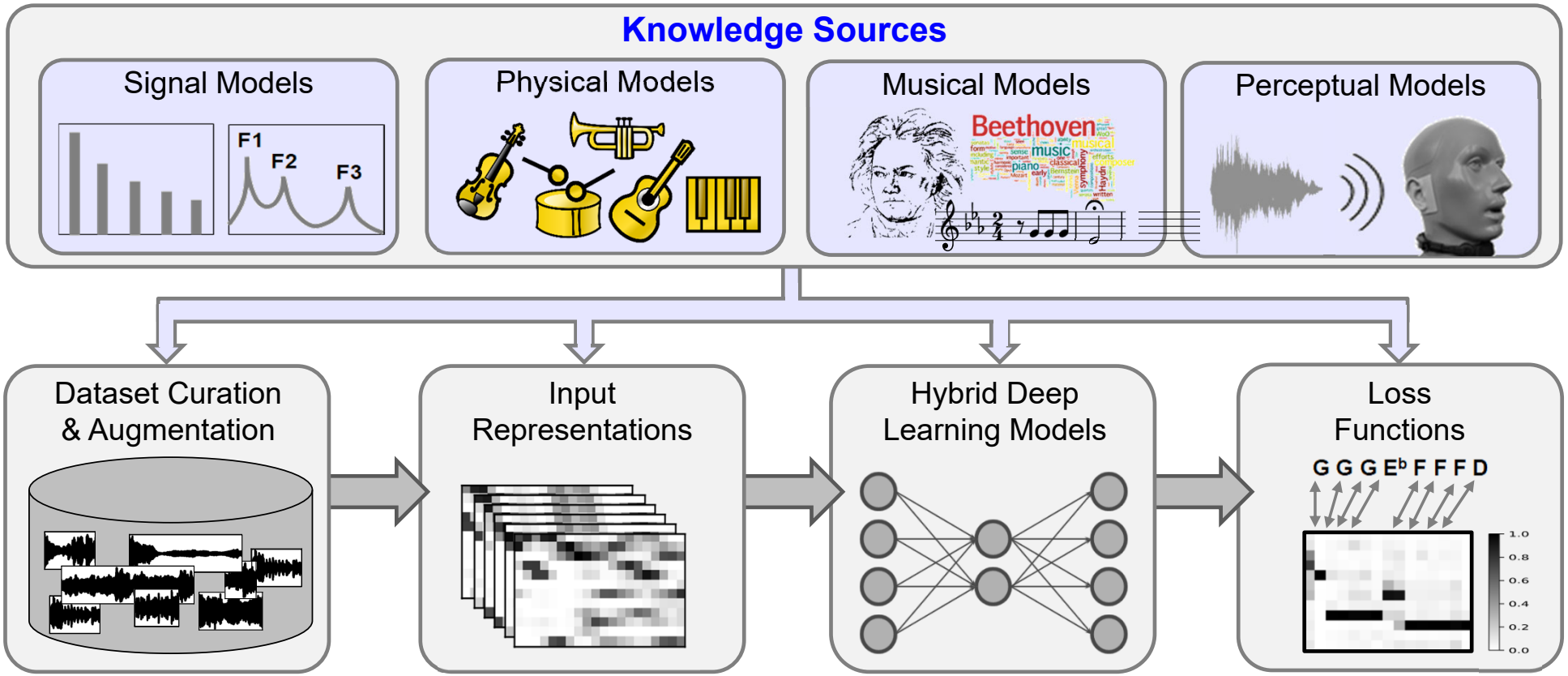


Loudness

Timbre

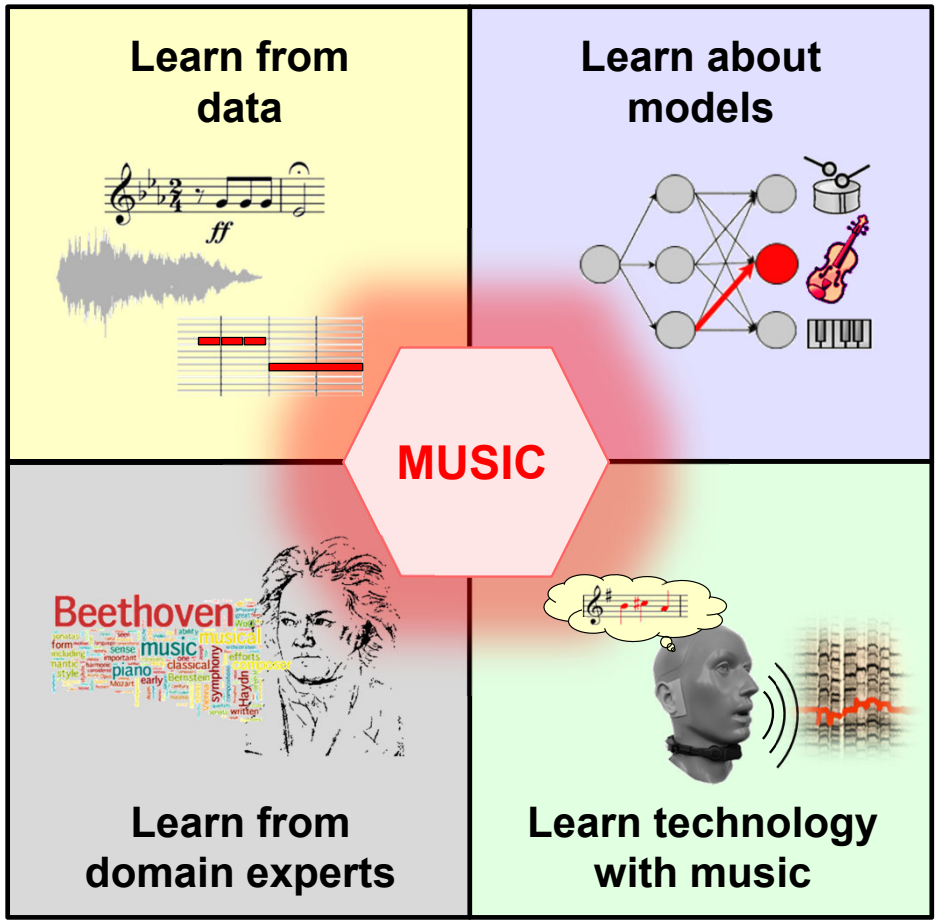
Pitch (F0)

Learning with Music Signals



Richard, Lostanlen, Yang, Müller: **Model-Based Deep Learning for Music Information Research**. IEEE Signal Processing Magazine, 41(6): 51–59, 2024

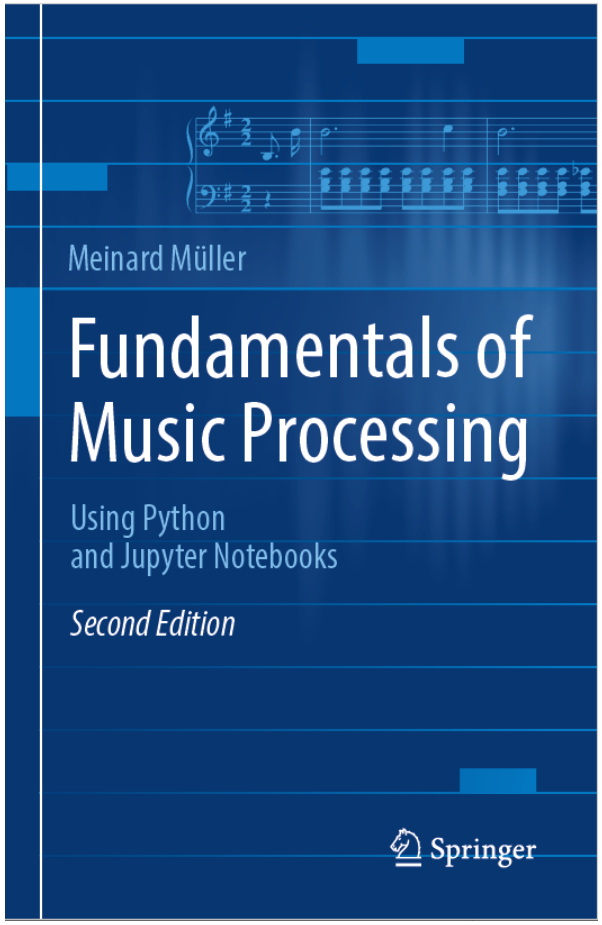
Learning with Music Signals: Technology Meets Education



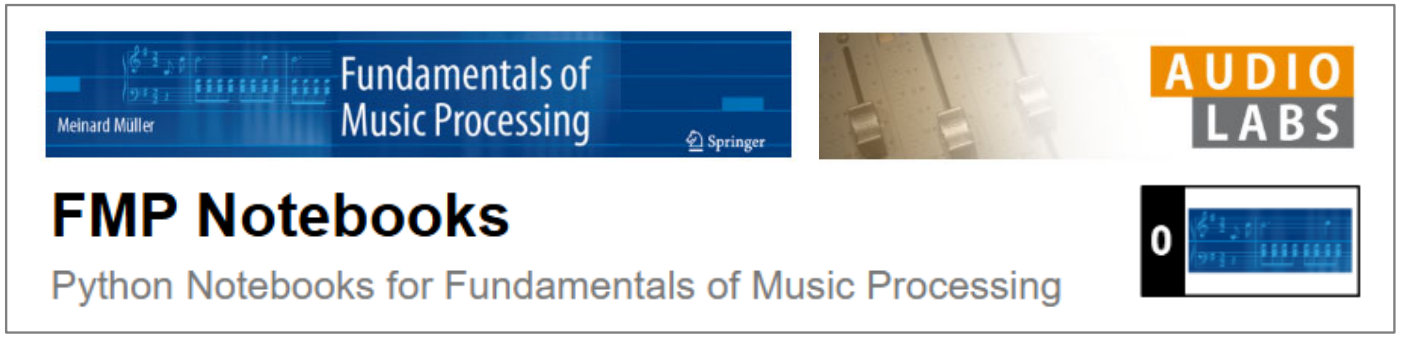
- Machine learning for music signal processing
- Interpretable models and knowledge integration
- Music understanding and applications
- Interactive learning in engineering through music

DFG Reinhart Koselleck-Projekt: LEARN
MU 2686/15-1; Grant No. 500643750
2023–2028

Fundamentals of Music Processing (FMP)



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



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