

Beethoven.exe

How Machines Listen, Learn, and Remix Music

Meinard Müller

International Audio Laboratories Erlangen
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Weihnachtskolloquium der Fakultät für Mathematik und Informatik

Würzburg, December 16, 2025

Meinard Müller

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



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 ≈ 40,000 students
- Strong Technical Faculty



Audio

International Audio Laboratories Erlangen

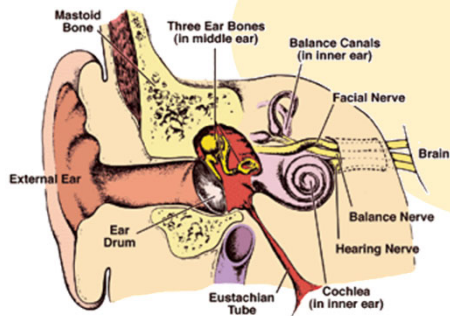
Audio Coding



3D Audio



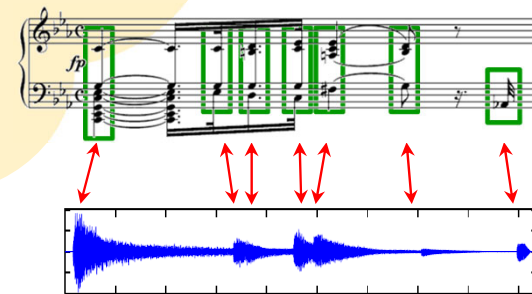
Audio



Psychoacoustics



Internet of Things

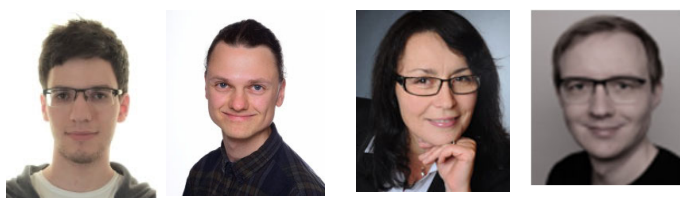


Music Processing

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
- Hendrik Schreiber
- Christian Dittmar
- Stefan Balke
- Jonathan Driedger
- Thomas Prätzlich
- ...



Music

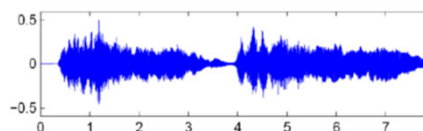


Music Information Retrieval (MIR)

Sheet Music (Image)



CD / MP3 (Audio)



MusicXML (Text)

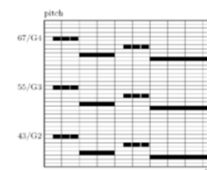
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Dance / Motion (Mocap)



Music

MIDI



Singing / Voice (Audio)



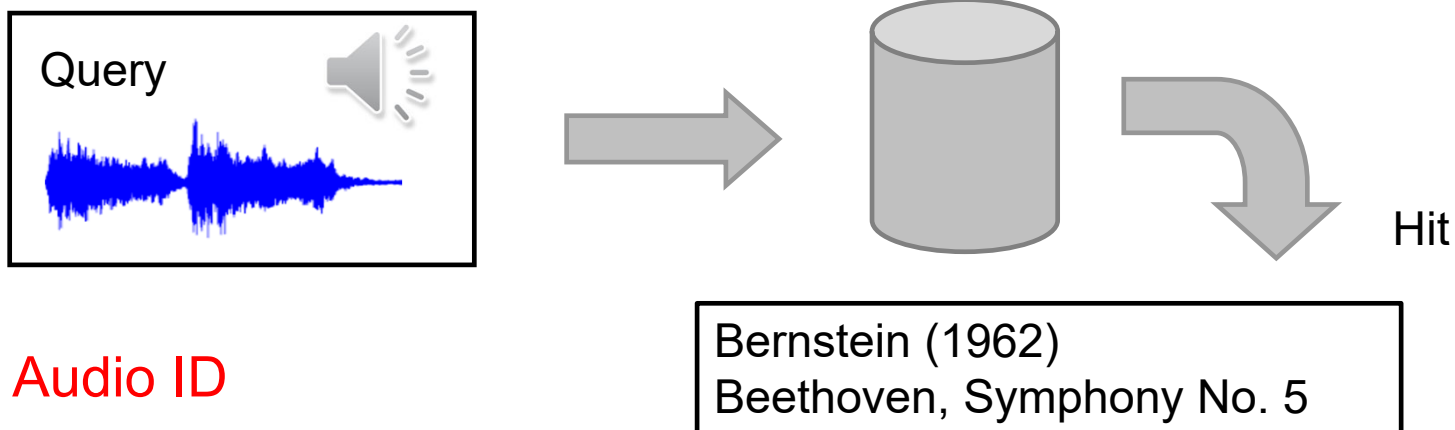
Music Film (Video)



Music Literature (Text)

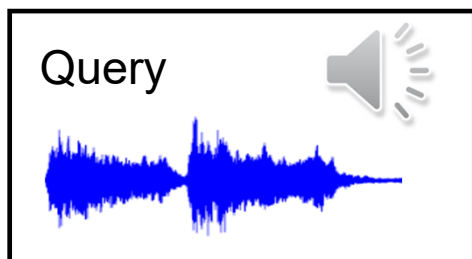


Music Retrieval



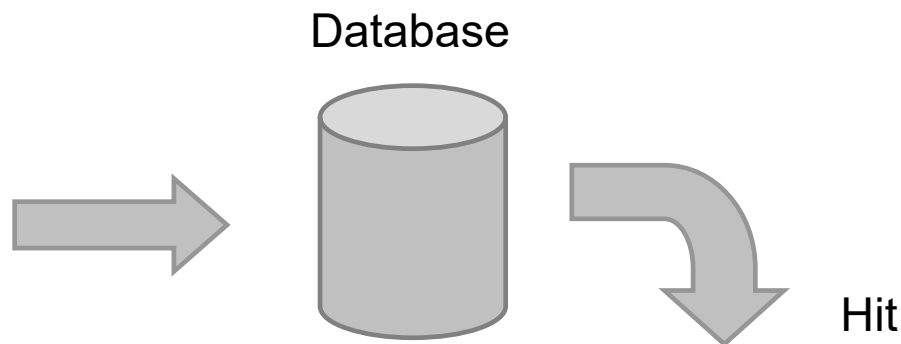
Audio ID

Music Retrieval



Audio ID

Version ID



Bernstein (1962)
Beethoven, Symphony No. 5

Beethoven, Symphony No. 5:

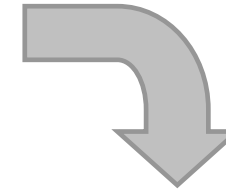
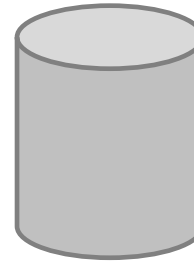
- Bernstein (1962)
- Karajan (1982)
- Gould (1992)



Music Retrieval



Database



Hit

Audio ID

Bernstein (1962)
Beethoven, Symphony No. 5

Version ID

Beethoven, Symphony No. 5:

- Bernstein (1962)
- Karajan (1982)
- Gould (1992)

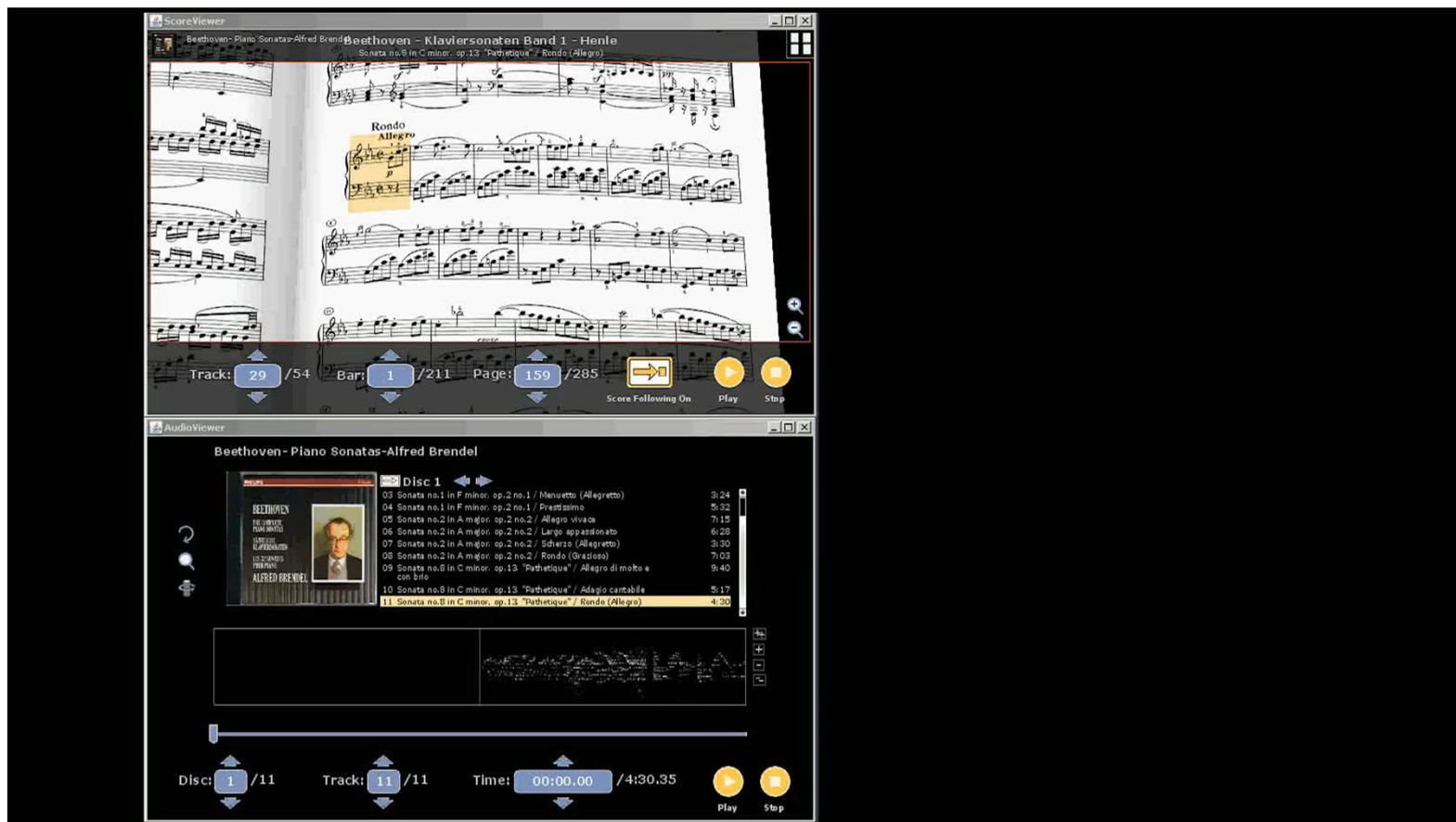


Category ID

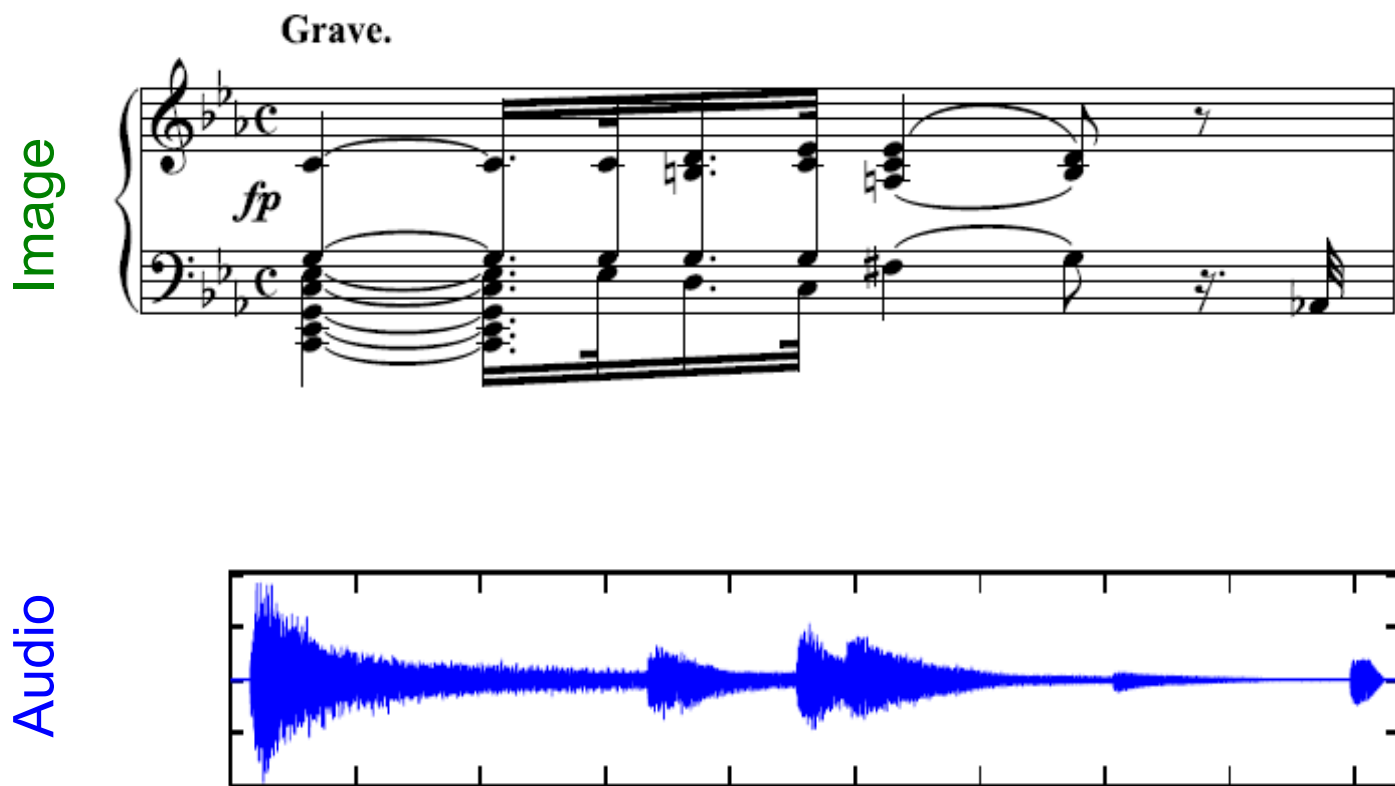
- Beethoven, Symphony No. 9
- Beethoven, Symphony No. 3
- Haydn Symphony No. 94



Music Synchronization



Music Synchronization: Image-Audio



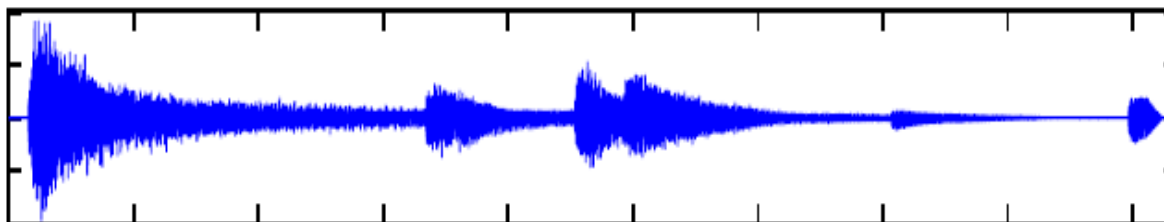
Music Synchronization: Image-Audio

Image Processing: Optical Music Recognition

Image



Audio



Music Synchronization: Image-Audio

Image Processing: Optical Music Recognition

Image



Audio



Audio Processing: Fourier Analysis

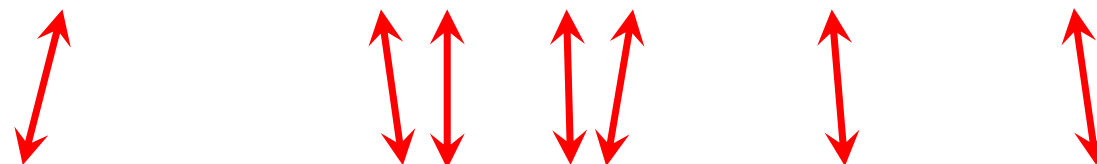
Music Synchronization: Image-Audio

Image Processing: Optical Music Recognition

Image



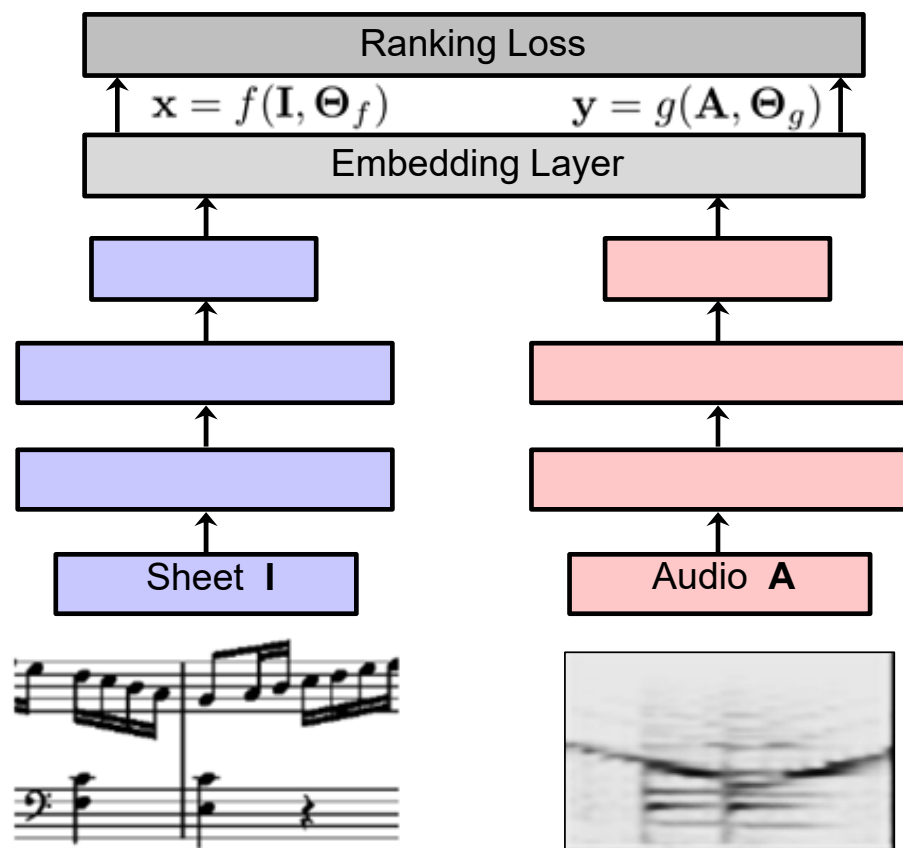
Audio



Audio Processing: Fourier Analysis

Music Synchronization: Image-Audio

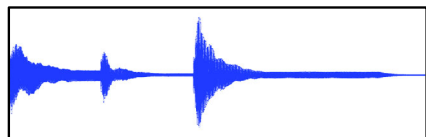
Müller, Arzt, Balke, Dorfer, Widmer: **Cross-Modal Music Retrieval and Applications.**
IEEE Signal Process. Mag. 36(1): 52–62, 2019



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

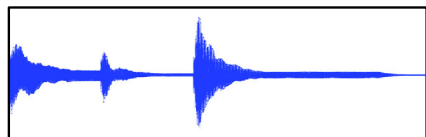
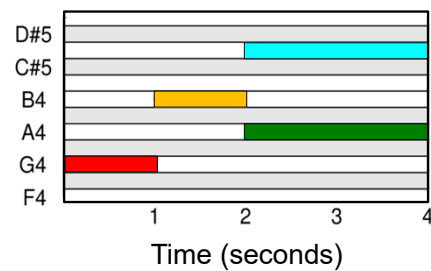
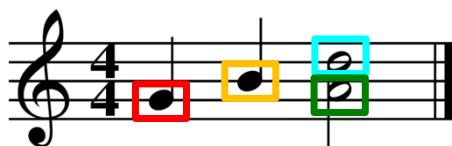
Score-Informed Audio Decomposition

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



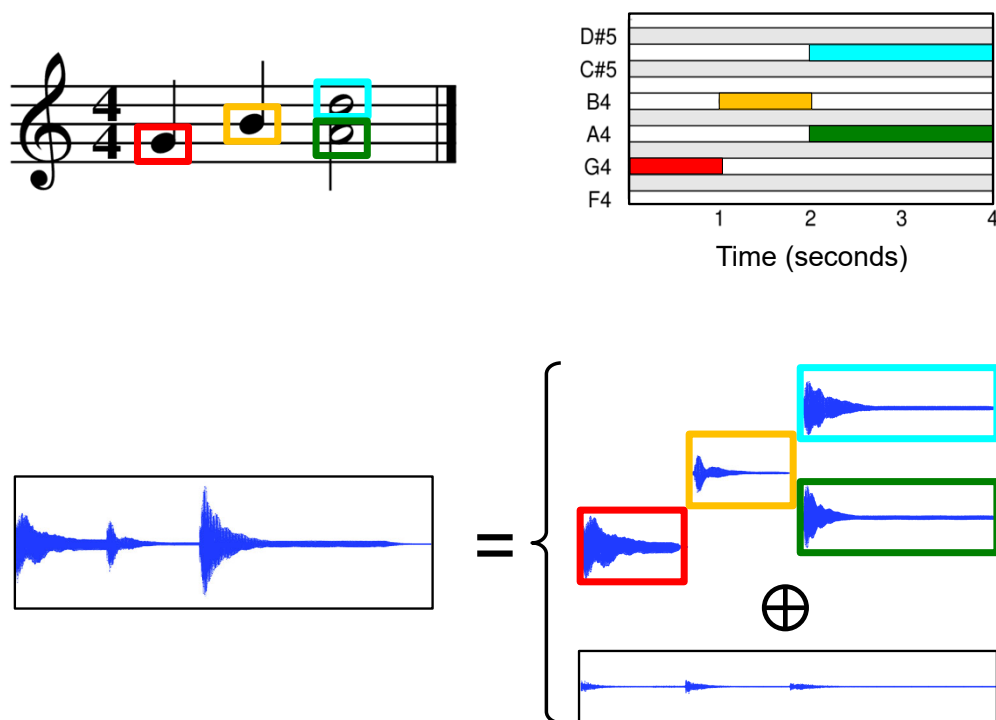
Score-Informed Audio Decomposition

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



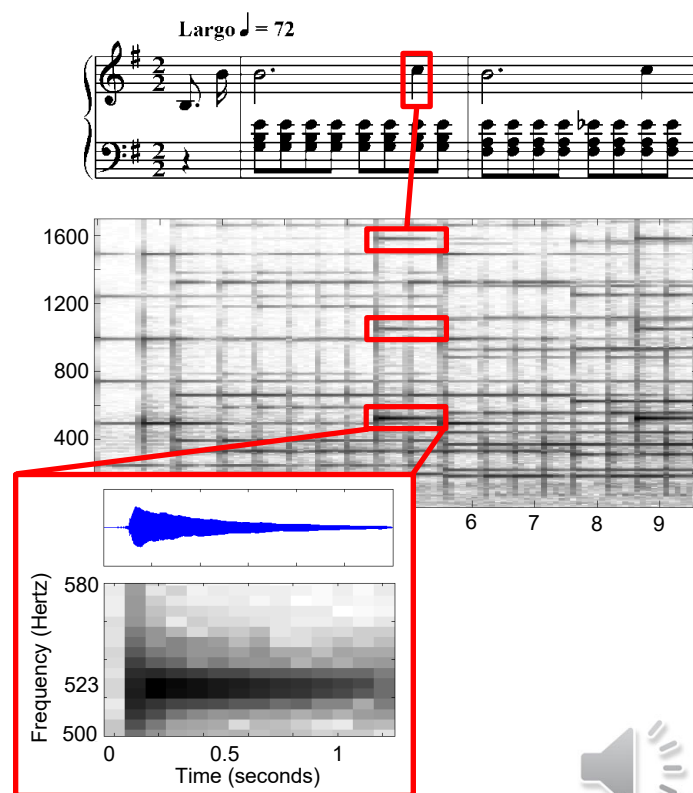
Score-Informed Audio Decomposition

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



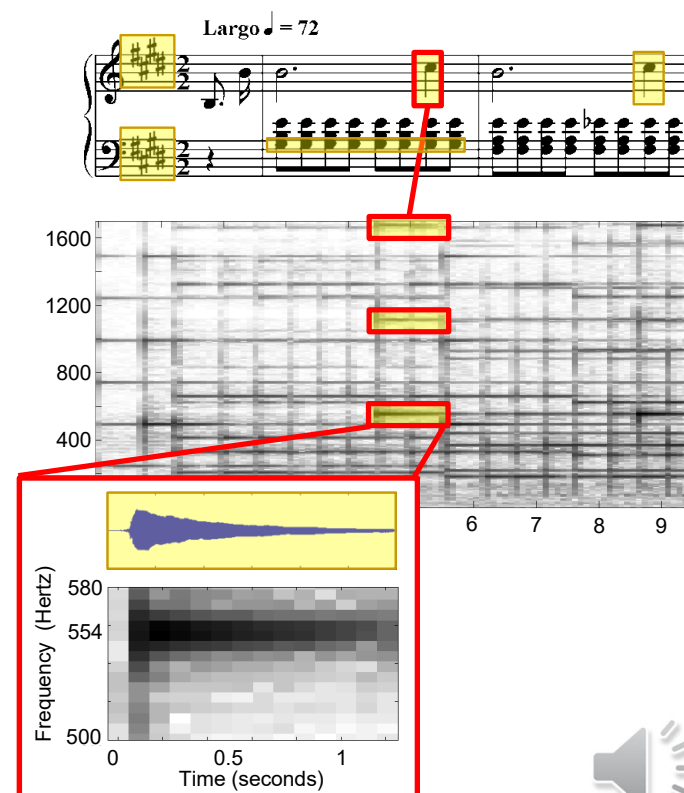
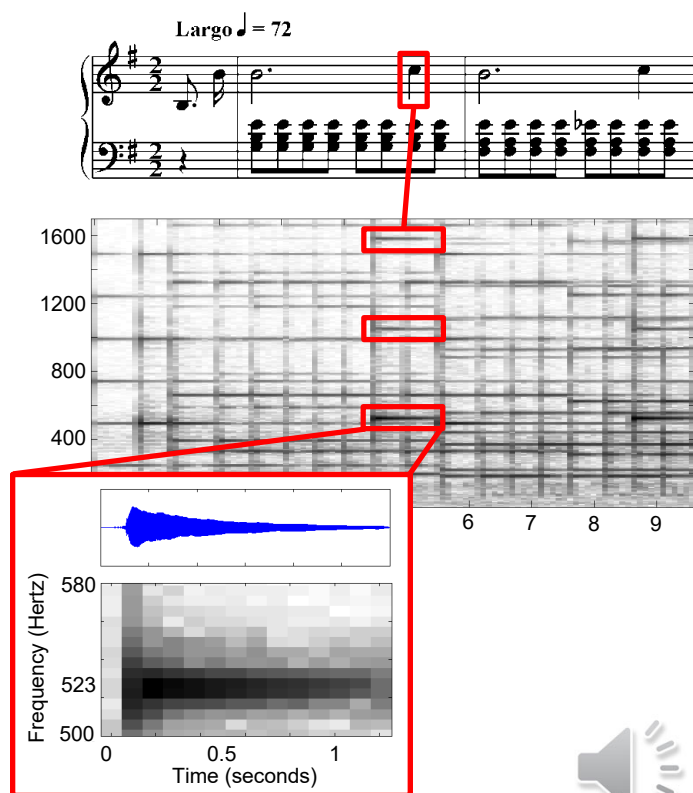
Score-Informed Audio Decomposition

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



Score-Informed Audio Decomposition

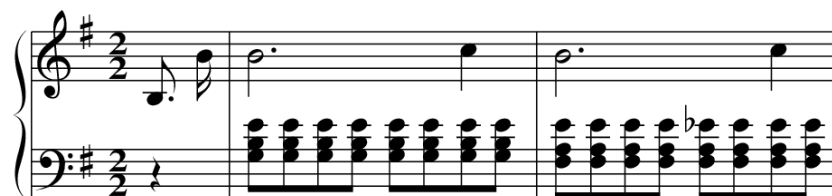
Driedger, Grohgan, Prätzlich, Ewert, Müller: **Score-Informed Audio Decomposition and Applications**.
Proc. ACM Multimedia: 541–544, 2013



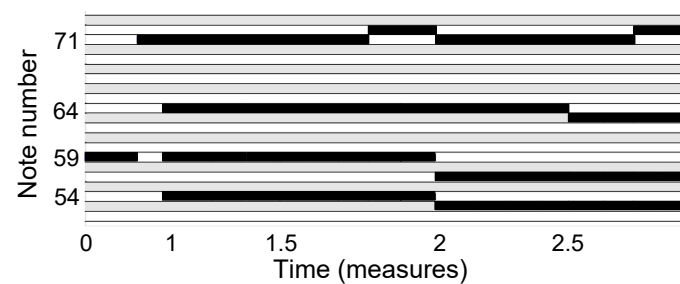
Score-Informed Audio Decomposition

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

Sheet music



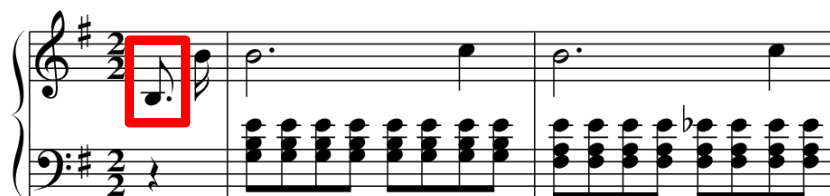
Piano roll



Score-Informed Audio Decomposition

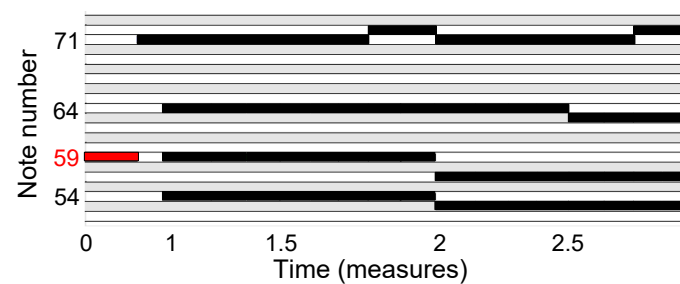
Ewert, Pardo, Müller, Plumbley: **Score-Informed Source Separation for Musical Audio Recordings**.
IEEE Signal Proc. Mag. 31(3): 116–124, 2014

Sheet music



$p = 59$

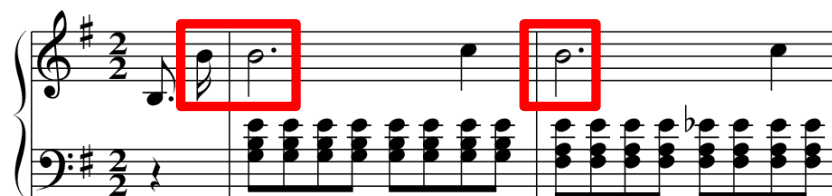
Piano roll



Score-Informed Audio Decomposition

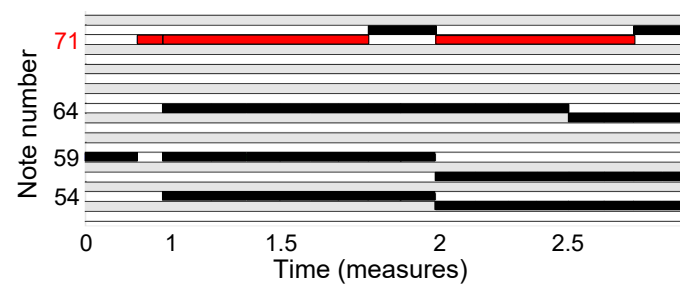
Ewert, Pardo, Müller, Plumbly: **Score-Informed Source Separation for Musical Audio Recordings**.
IEEE Signal Proc. Mag. 31(3): 116–124, 2014

Sheet music



$p = 71$

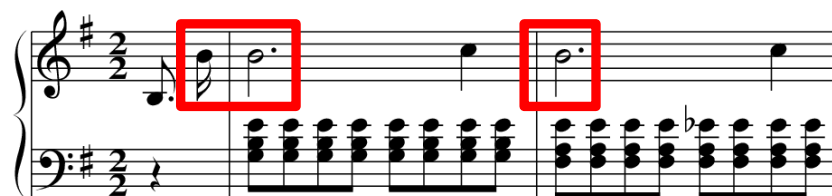
Piano roll



Score-Informed Audio Decomposition

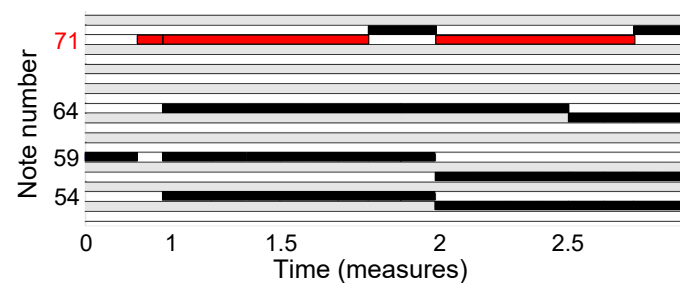
Ewert, Pardo, Müller, Plumbley: **Score-Informed Source Separation for Musical Audio Recordings**.
IEEE Signal Proc. Mag. 31(3): 116–124, 2014

Sheet music

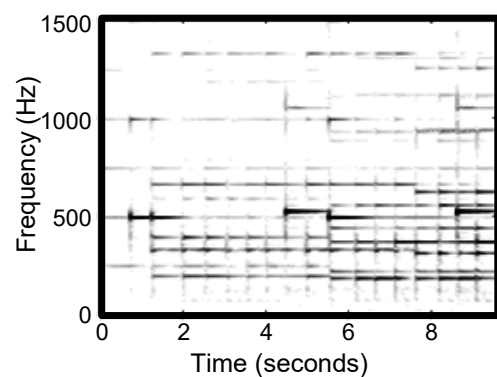


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Piano roll



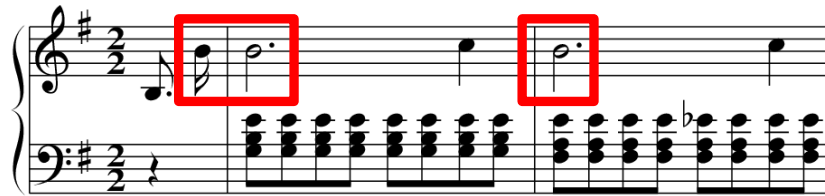
Spectrogram



Score-Informed Audio Decomposition

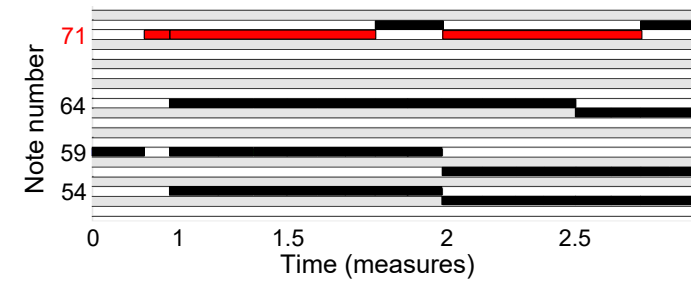
Ewert, Pardo, Müller, Plumbly: **Score-Informed Source Separation for Musical Audio Recordings**.
IEEE Signal Proc. Mag. 31(3): 116–124, 2014

Sheet music

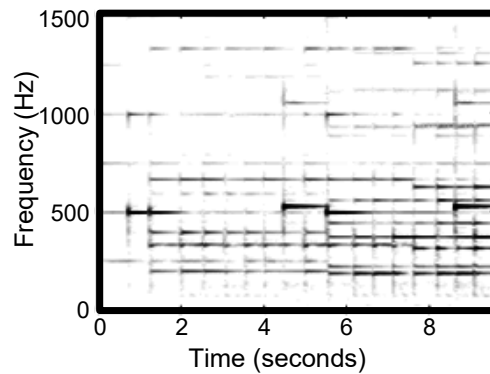


$p = 71$

Piano roll

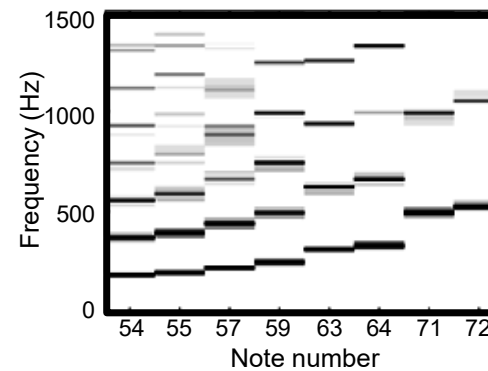


Spectrogram



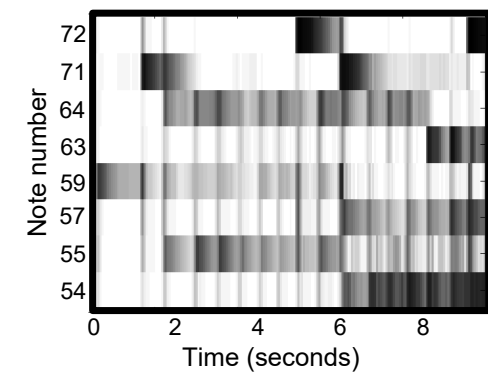
$\approx$

Spectral patterns



$\cdot$

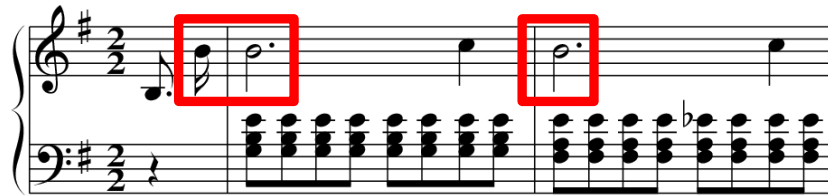
Activity patterns



Score-Informed Audio Decomposition

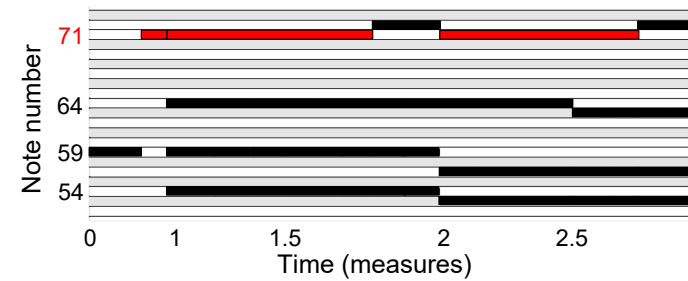
Ewert, Pardo, Müller, Plumbly: **Score-Informed Source Separation for Musical Audio Recordings**.
IEEE Signal Proc. Mag. 31(3): 116–124, 2014

Sheet music

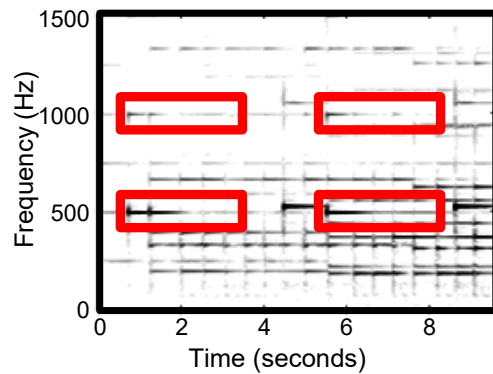


$p = 71$

Piano roll

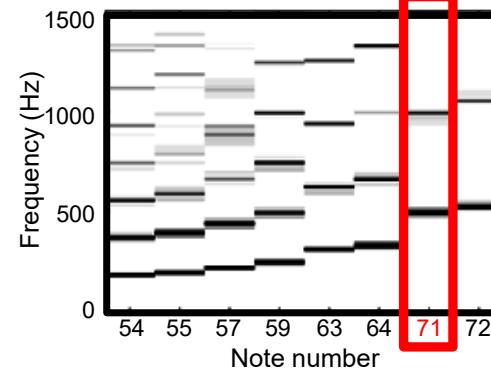


Spectrogram



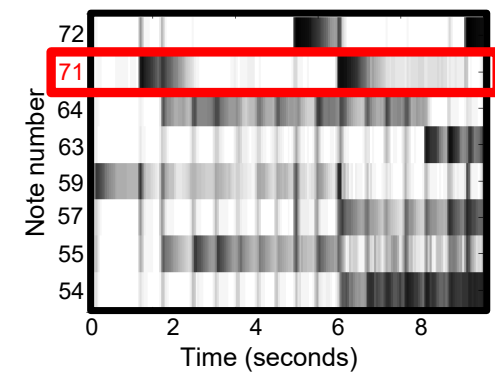
$\approx$

Spectral patterns



$\cdot$

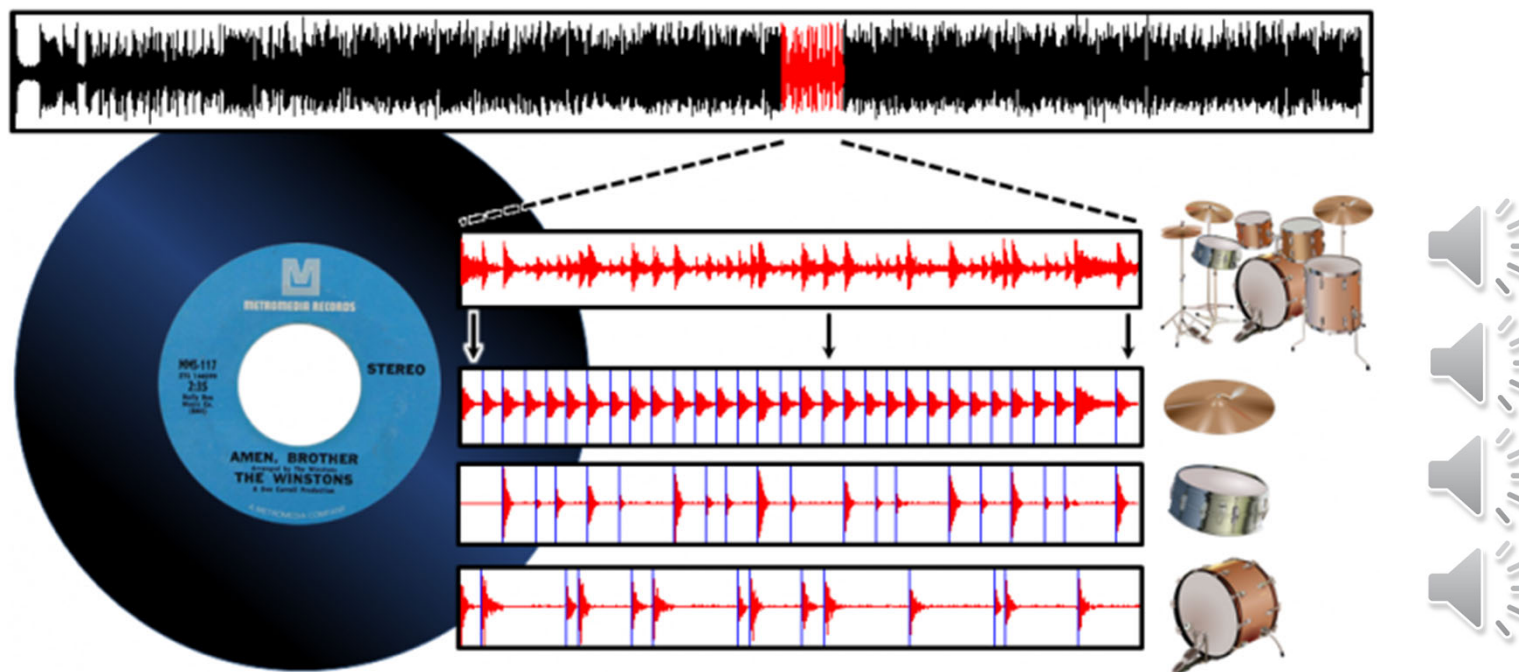
Activity patterns



Score-Informed Audio Decomposition

Informed Drum-Sound Decomposition

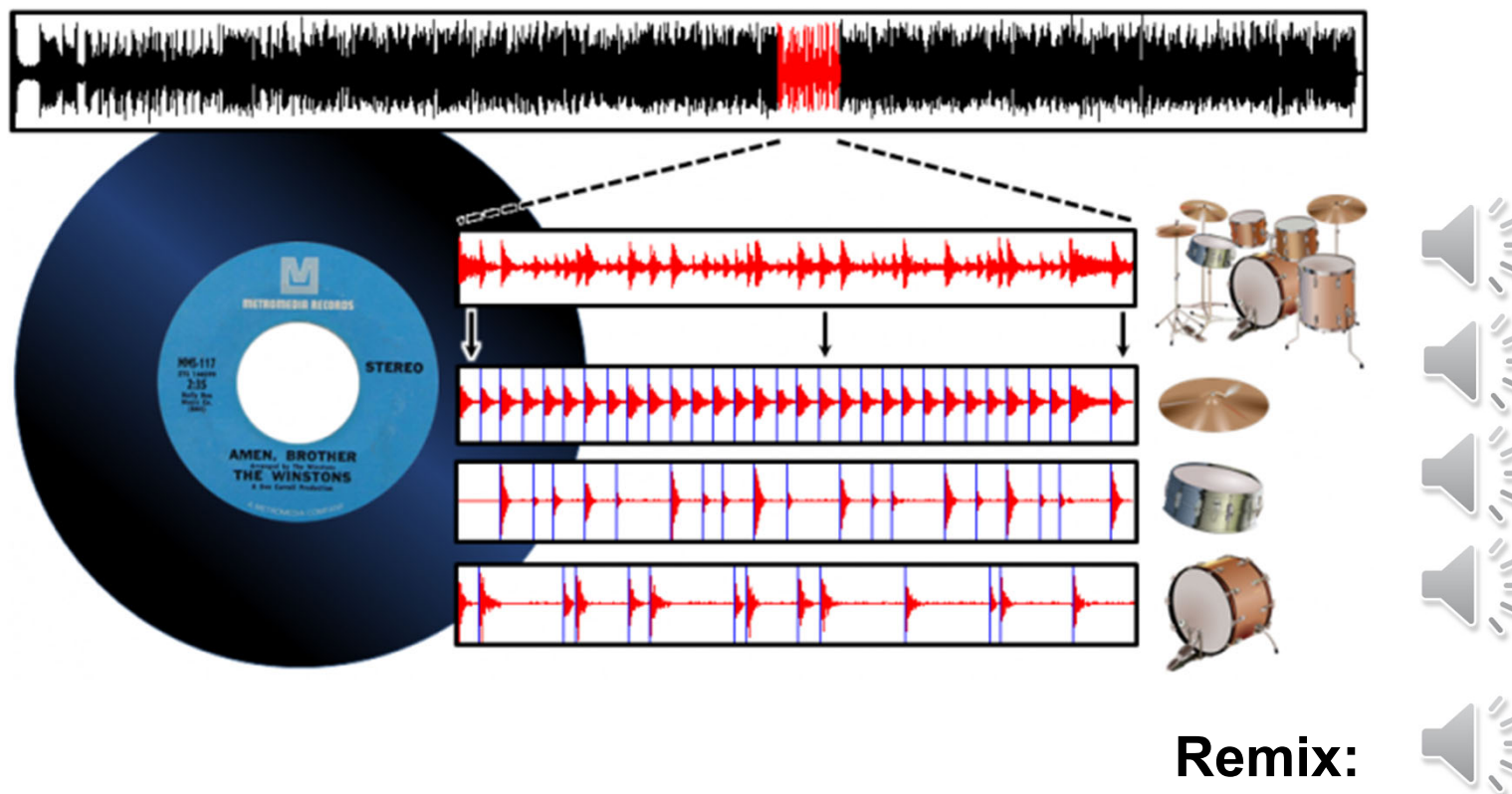
Dittmar, Müller: **Reverse Engineering the Amen Break — Score-Informed Separation and Restoration Applied to Drum Recording.**
IEEE/ACM TASLP, 24(9): 1531–1543, 2016



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



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

Audio Mosaicing (Style Transfer)

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

Target: Let it be



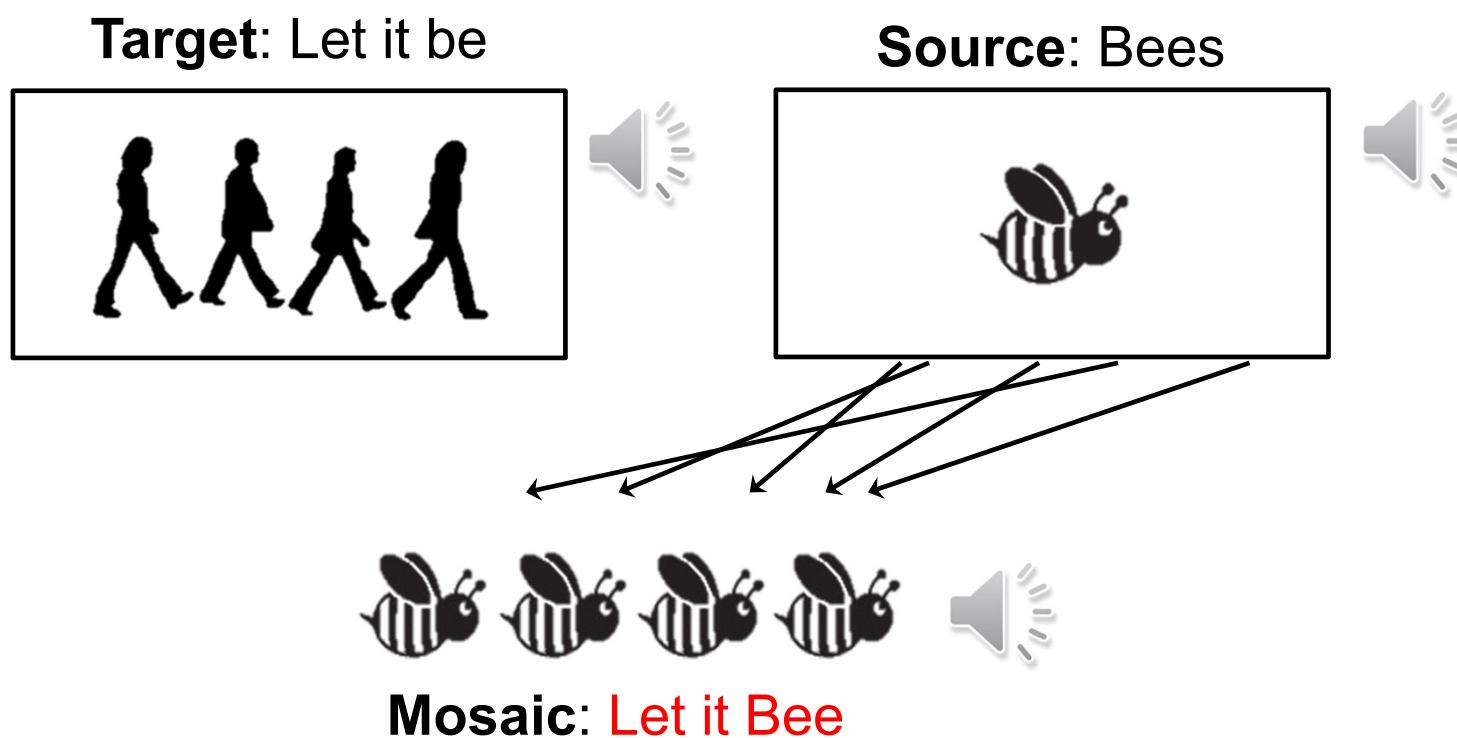
Source: Bees



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

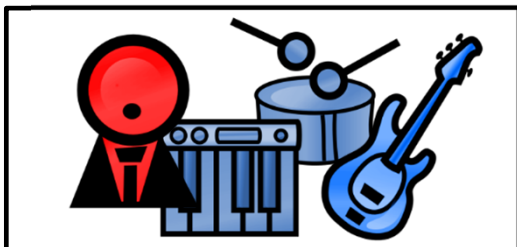
- Decomposition of audio stream into different sound sources
- Central task in digital signal processing
- “Cocktail party effect”



Source Separation

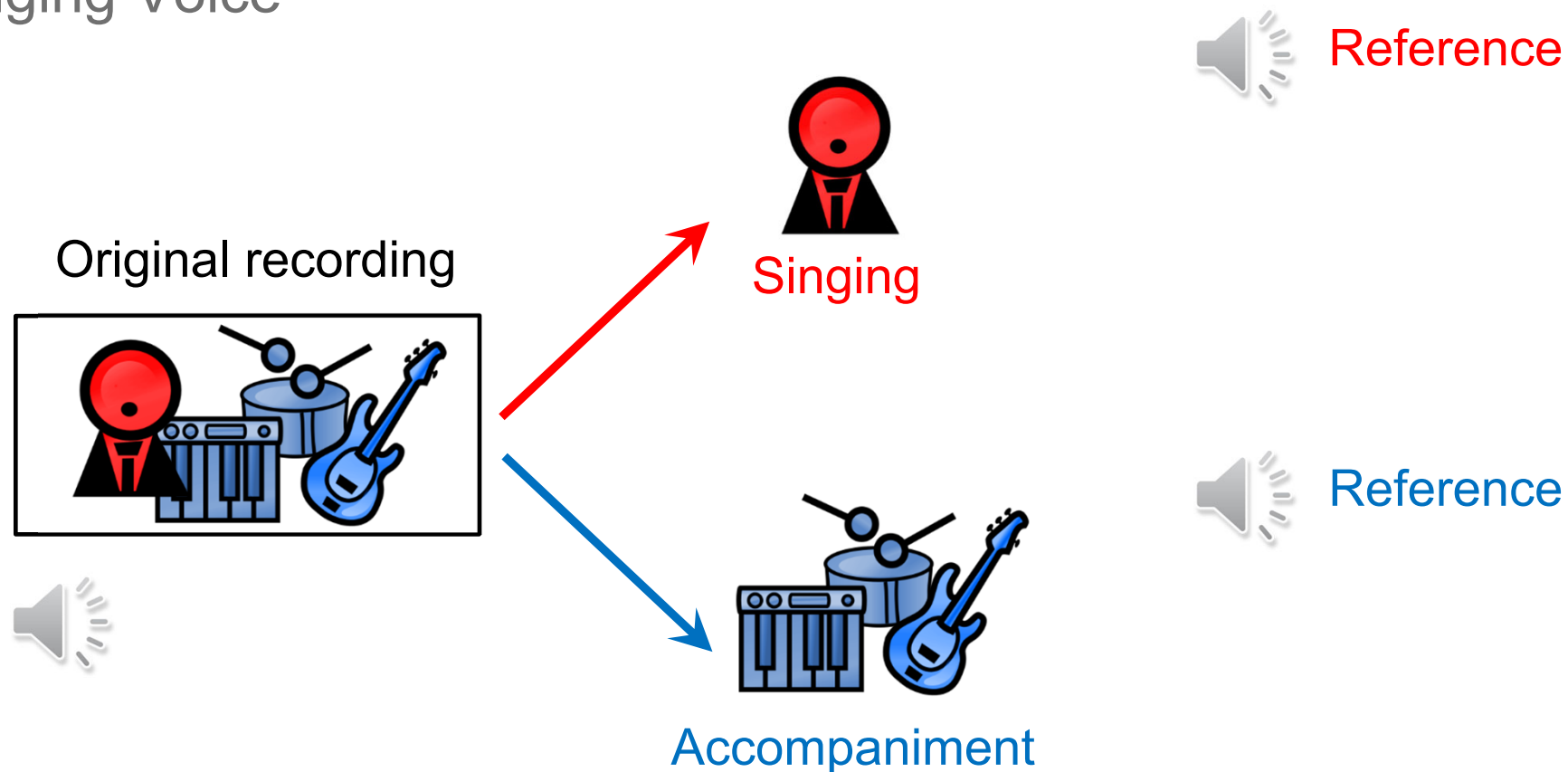
Singing Voice

Original recording



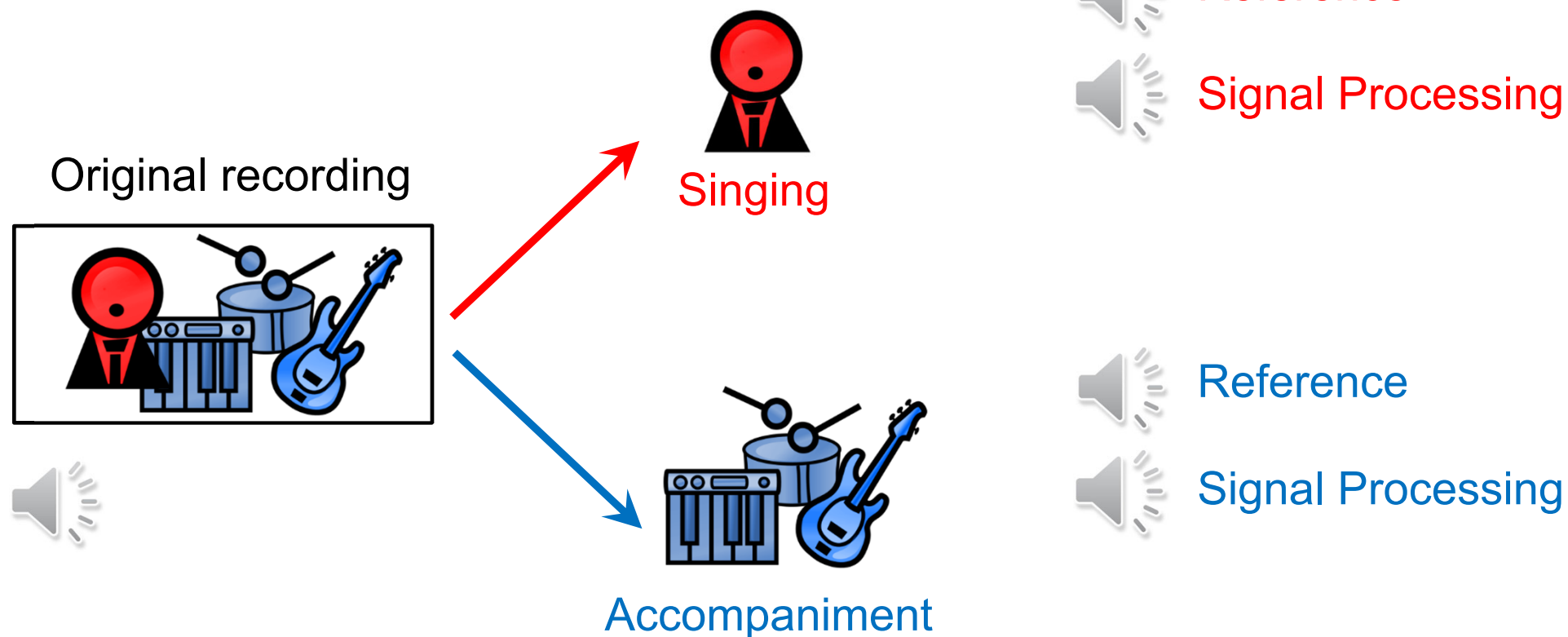
Source Separation

Singing Voice



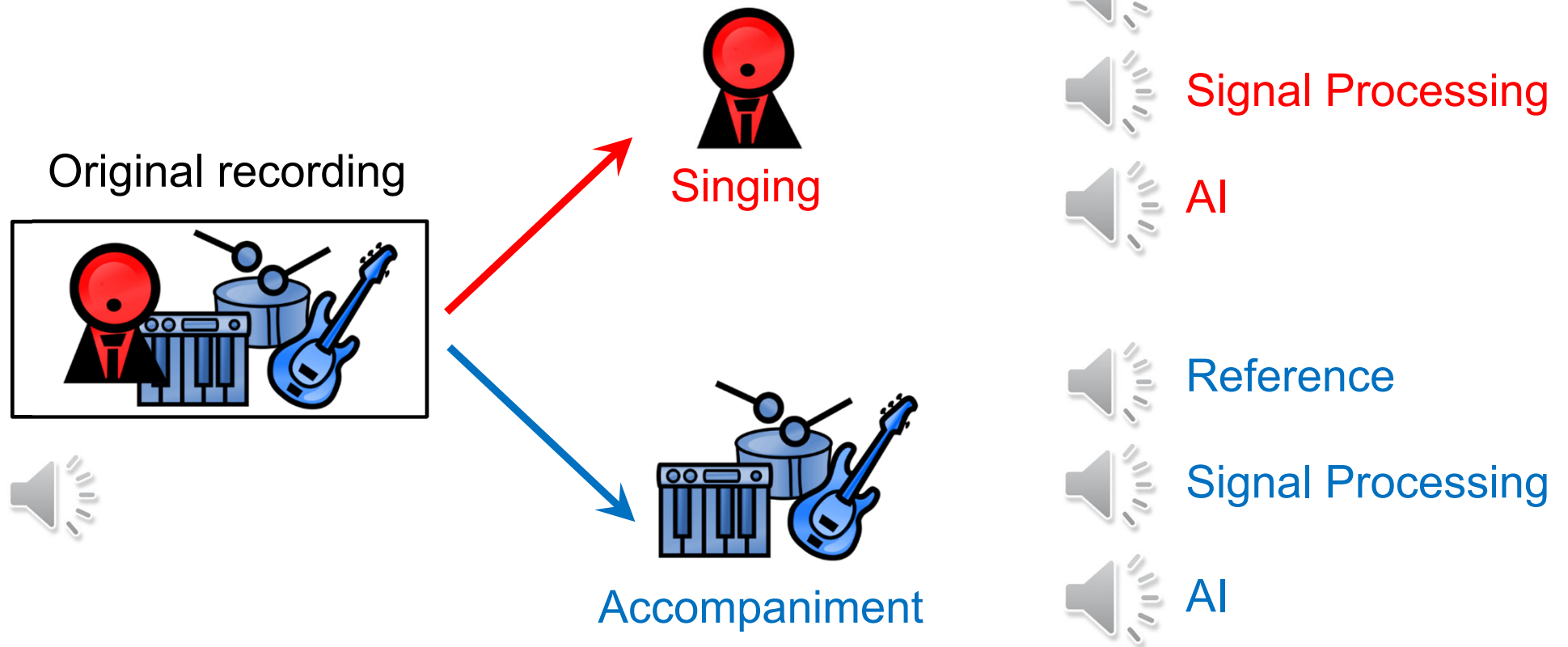
Source Separation

Singing Voice



Source Separation

Singing Voice



Source Separation

Piano Concerto

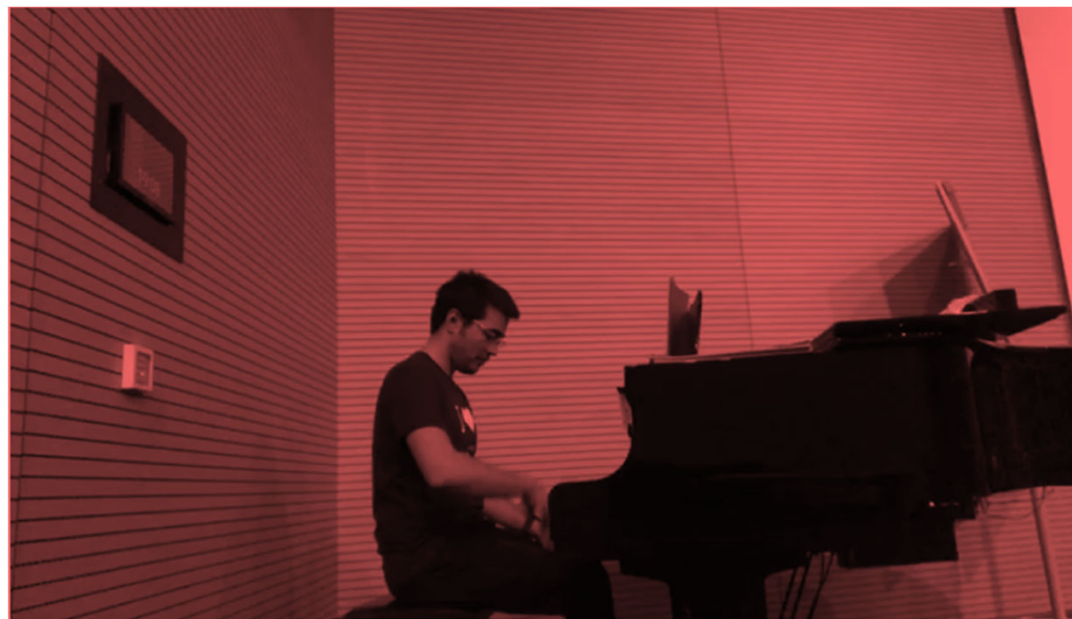
- Yigitcan Özer
- PhD student in engineering
- Pianist



Source Separation

Piano Concerto

- Yigitcan Özer
- PhD student in engineering
- Pianist



Only Piano!



Where is the orchestra?



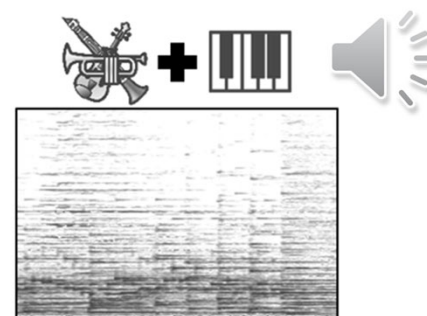
Source Separation

Piano Concerto

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



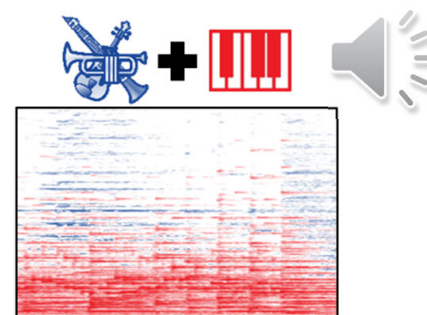
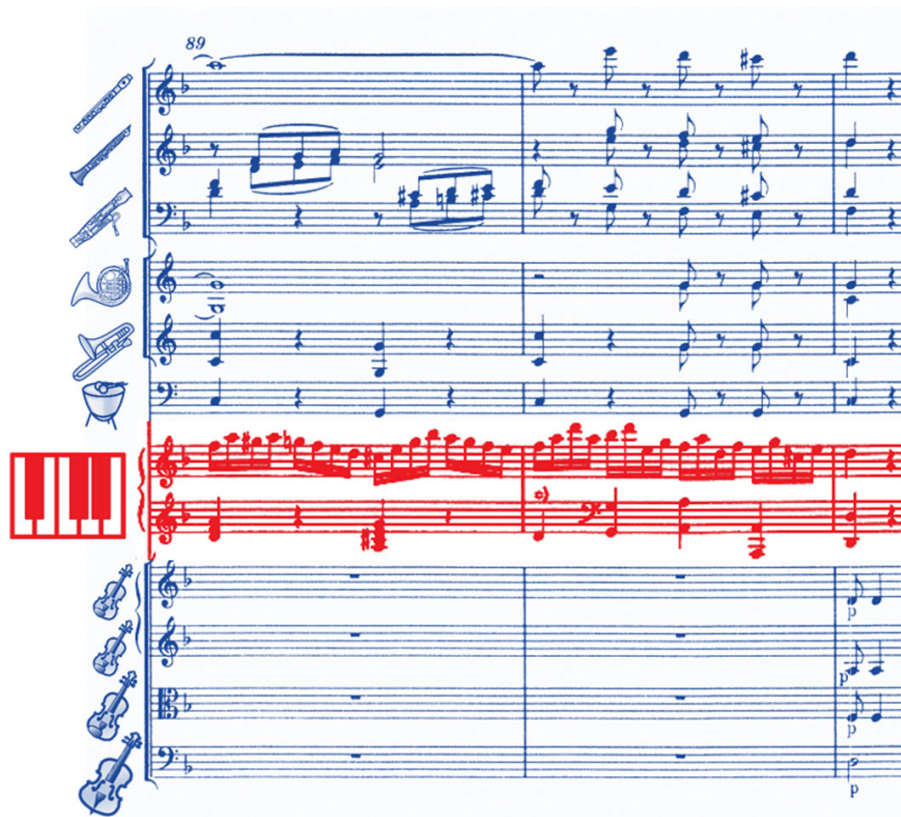
A musical score snippet for measures 89-91 of a piano concerto. The score is arranged in a grand staff with piano (piano) and orchestral parts. The piano part is on the left, and the orchestral parts are on the right. The piano part features a complex, fast-moving melody in the right hand and a more rhythmic accompaniment in the left hand. The orchestral parts include woodwinds (flute, oboe, clarinet, bassoon), brass (trumpet, trombone, tuba), and strings (violin, viola, cello, double bass). The score is written in a key with one flat (B-flat) and a 2/4 time signature. The piano part is marked with a 'p' for piano.



Source Separation

Piano Concerto

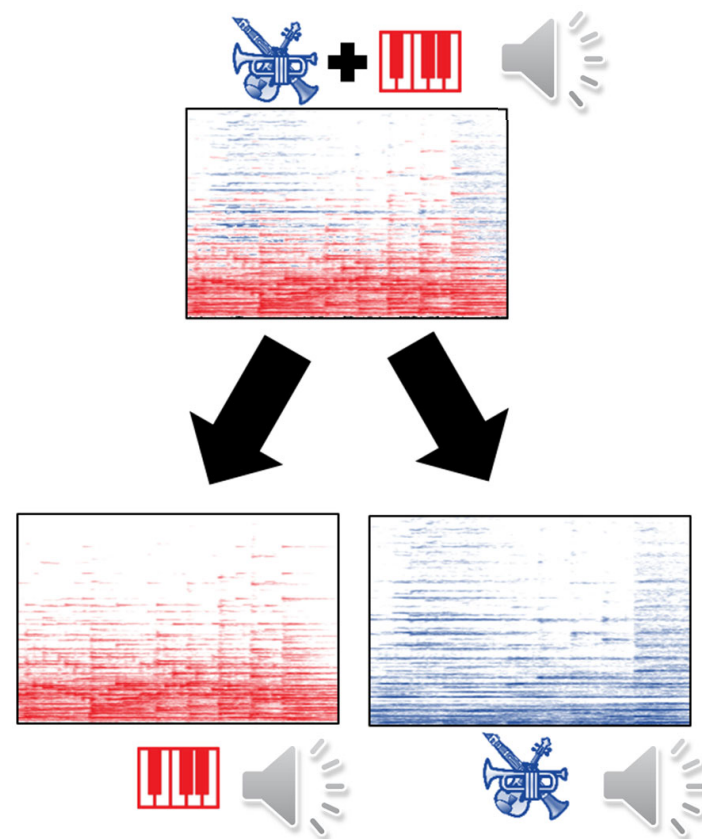
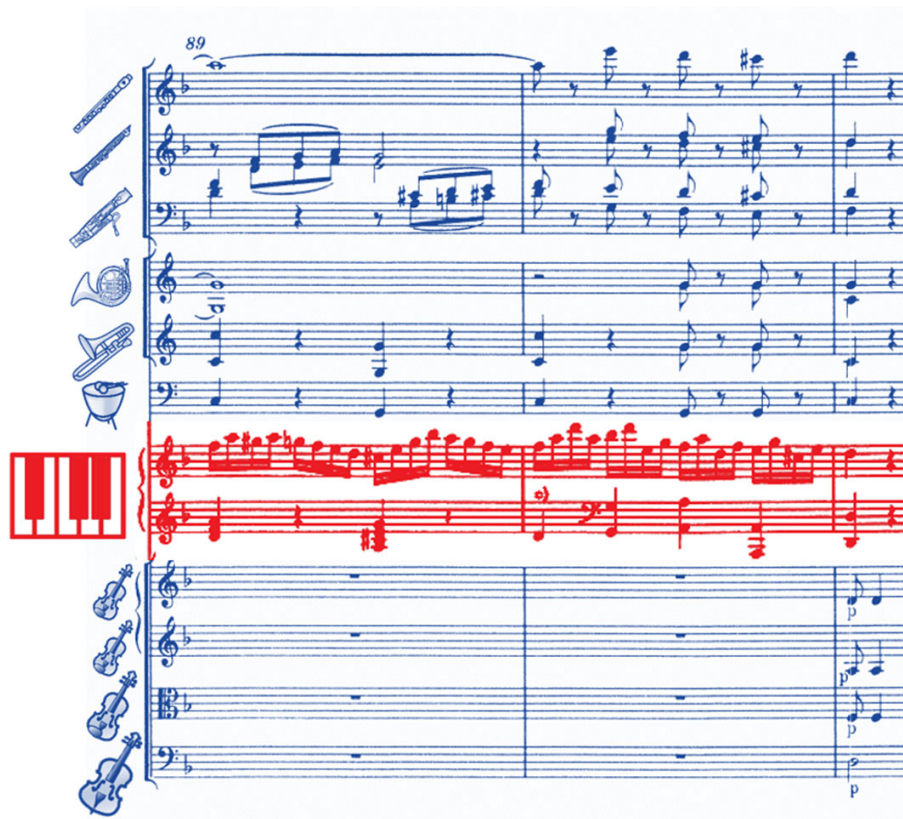
Özer, Müller: **Source Separation of Piano Concertos Using Musically Motivated Augmentation Techniques.**
IEEE/ACM Trans. ASLP, 32: 1214–1225, 2024



Source Separation

Piano Concerto

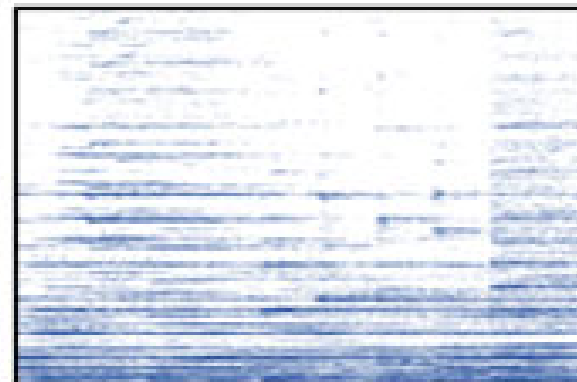
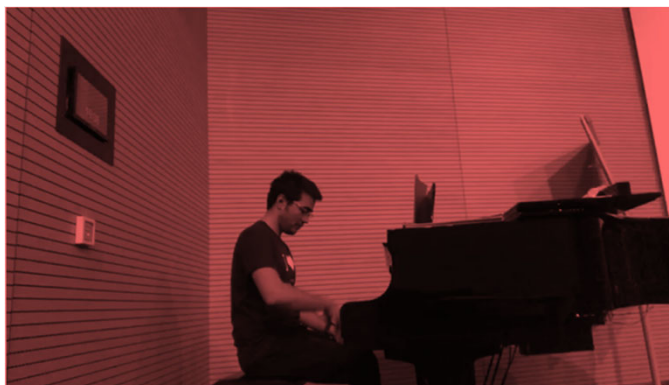
Özer, Müller: **Source Separation of Piano Concertos Using Musically Motivated Augmentation Techniques.**
IEEE/ACM Trans. ASLP, 32: 1214–1225, 2024



Source Separation

Piano Concerto

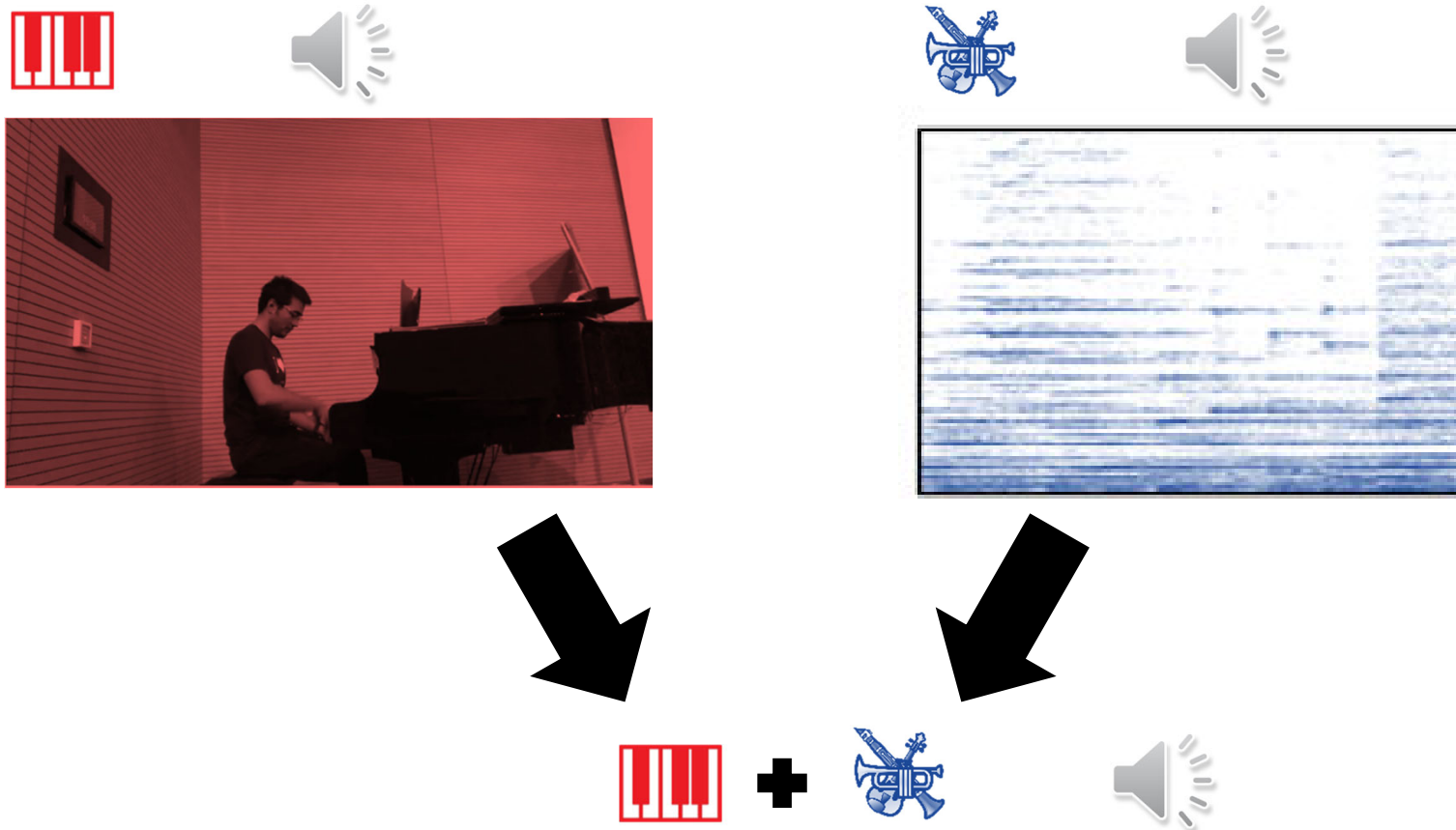
Özer, Müller: **Source Separation of Piano Concertos Using Musically Motivated Augmentation Techniques.**
IEEE/ACM Trans. ASLP, 32: 1214–1225, 2024



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

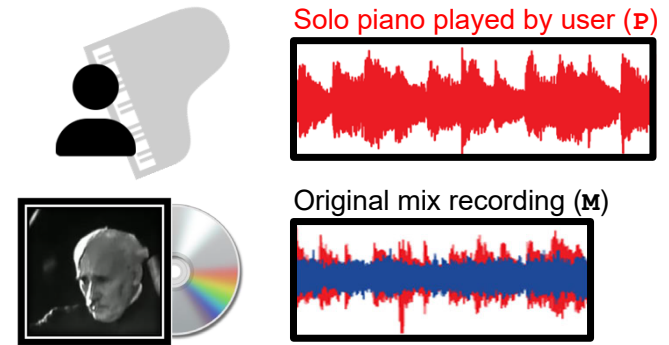


Solo piano played by user (P)



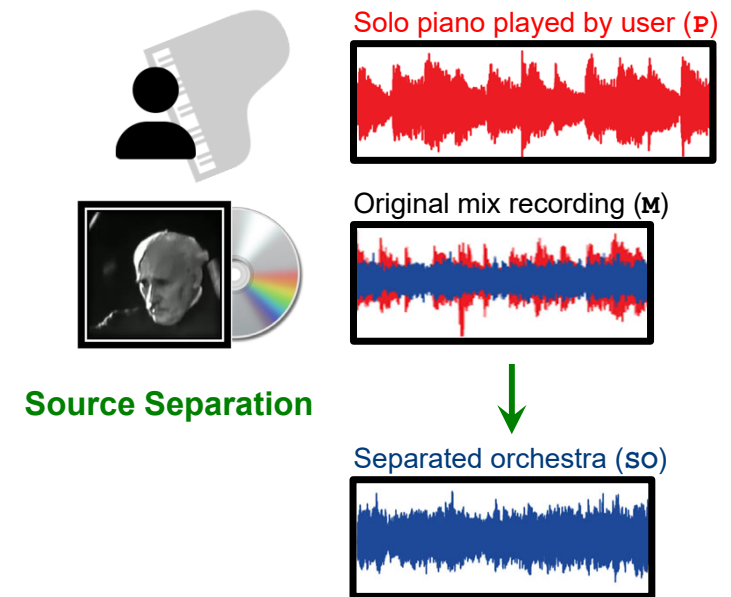
Accompaniment Creation

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



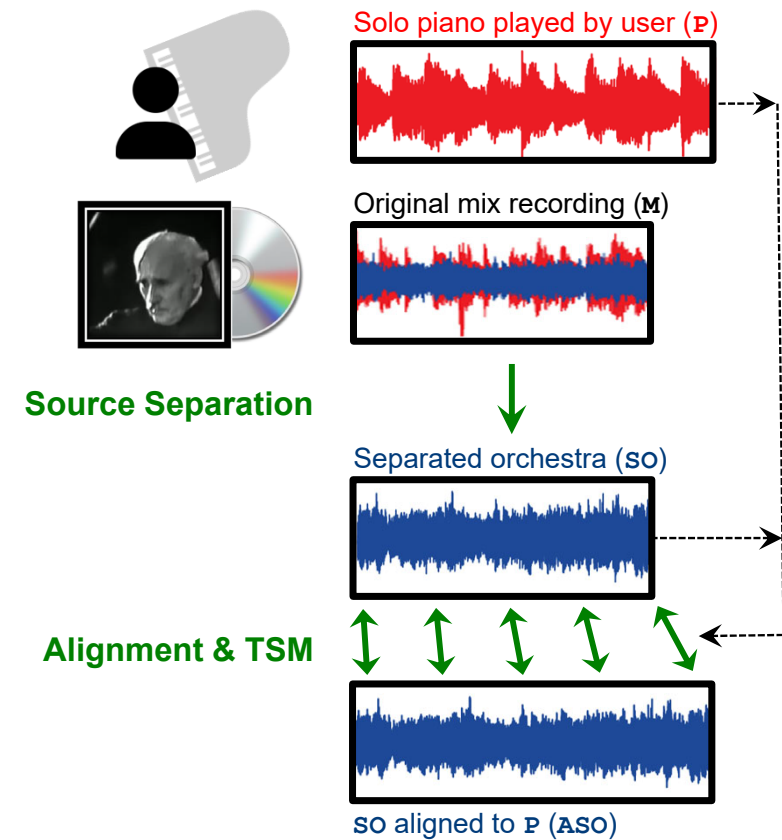
Accompaniment Creation

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



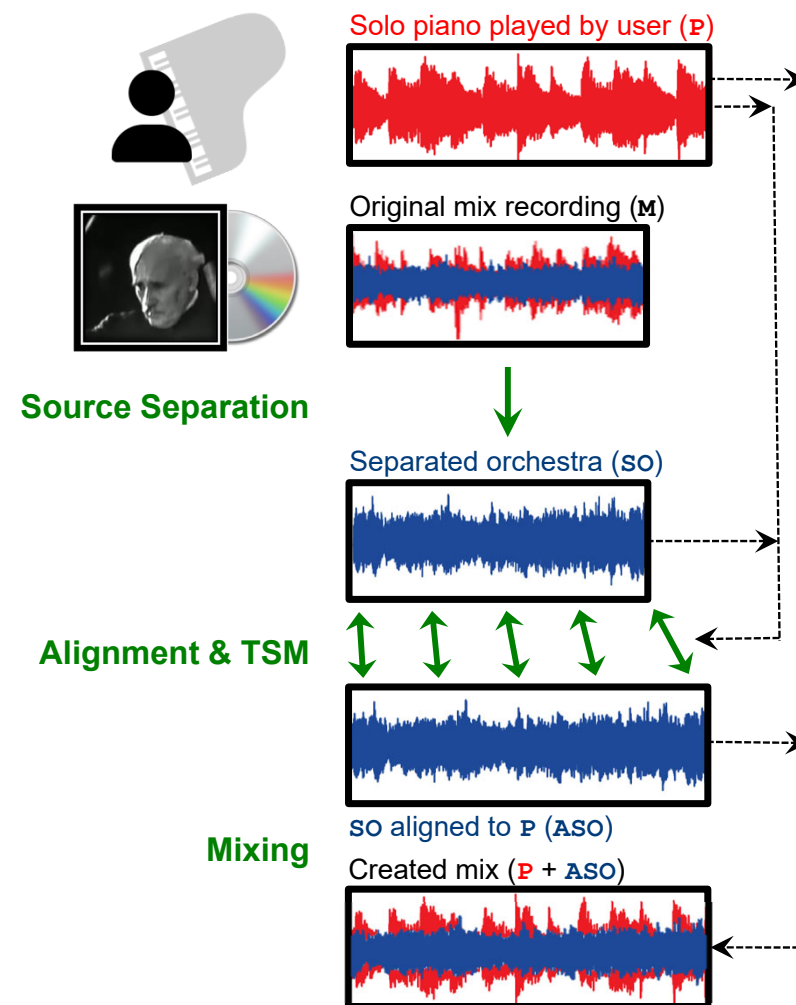
Accompaniment Creation

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



Accompaniment Creation

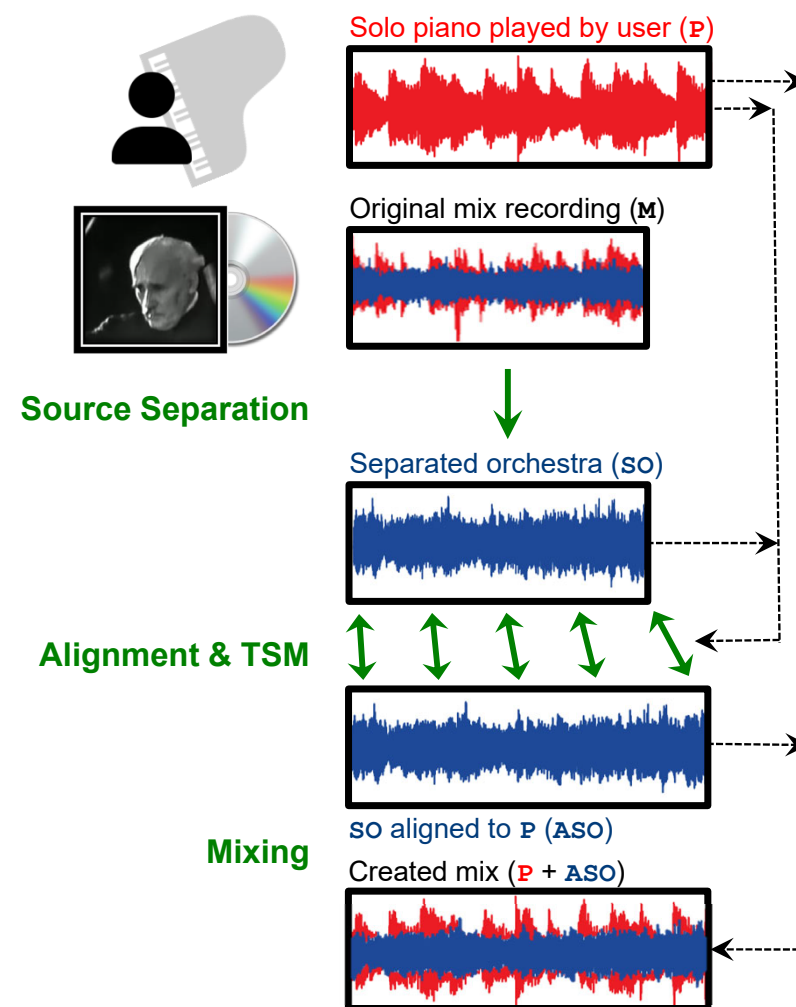
- Lonely pianist plays solo piano part
- Select full mix recording of concerto
- Isolate orchestra track
- Align to the solo performance
- Create own coherent mix



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



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Beethoven Piano Concerto No.1 in C Major, Op.15, First Movement

Data Sources

Solo Piano: [Meinard Müller](#)
Production: [Simon Schwär](#)
Recording: 29. and 30.06.2024 at Fraunhofer IIS, Yamaha C3

Original Recording
Orchestra: Symphony of the Air Orchestra
Pianist: Arthur Rubinstein
Conductor: Josef Krips
Recording year: 1958

Solo Piano with Created Orchestral Accompaniment

Quick playback for Solo Piano + Orchestra (with reverb):

00:00 | 14:58

All tracks:

Solo Piano + Orchestra (with reverb)

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



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- Career
- News
- Events
- Resources
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Mozart Piano Concerto No.20 in D Minor, KV 466, First Movement

Data Sources

Solo Piano: [Yigitcan Özer](#)

Production: [Simon Schwär](#)

Recording: 29. and 30.06.2024 at Fraunhofer IIS, Yamaha C3

Original Recording

Orchestra: Orchestre des Concerts Lamoureux

Pianist: Clara Haskil

Conductor: Igor Markevitch

Recording year: 1960

Solo Piano with Created Orchestral Accompaniment

Quick playback for Solo Piano + Orchestra (with reverb):

00:00

14:59

All tracks:

Solo Piano + Orchestra (with reverb)

Mozart: Piano
Concerto No. 20

Lonely pianist:
Yiğitcan Özer

Recording (1960):
Orchestre des
Concerts Lamoureux

Concert Band



Concert Band



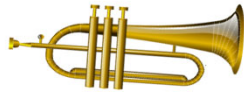
Four-Voice Choir (SATB)

Drese: Jesu geh voran

Soprano (S)



Alto (A)



Tenor (T)



Bass (B)



Sheet music for the Four-Voice Choir (SATB) of 'Drese: Jesu geh voran'. The music is written for Soprano (S), Alto (A), Tenor (T), and Bass (B) voices. The Soprano part is highlighted in orange, the Alto part in red, the Tenor part in green, and the Bass part in blue. The music is in 3/4 time and features a mix of eighth and quarter notes.

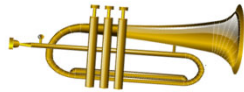
Four-Voice Choir (SATB)

Drese: Jesu geh voran

Soprano (S)



Alto (A)



Tenor (T)



Bass (B)



Sheet music for the Four-Voice Choir (SATB) of 'Jesu geh voran' by Drese. The music is written in 3/4 time and features four staves: Soprano (S), Alto (A), Tenor (T), and Bass (B). Each staff is color-coded: Soprano (orange), Alto (red), Tenor (green), and Bass (blue). The music is written in treble and bass clefs, with various musical notations including notes, rests, and accidentals.



ChoraleBricks

Multitrack Dataset for Wind Music Research

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

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



ChoraleBricks

Multitrack Dataset for Wind Music Research

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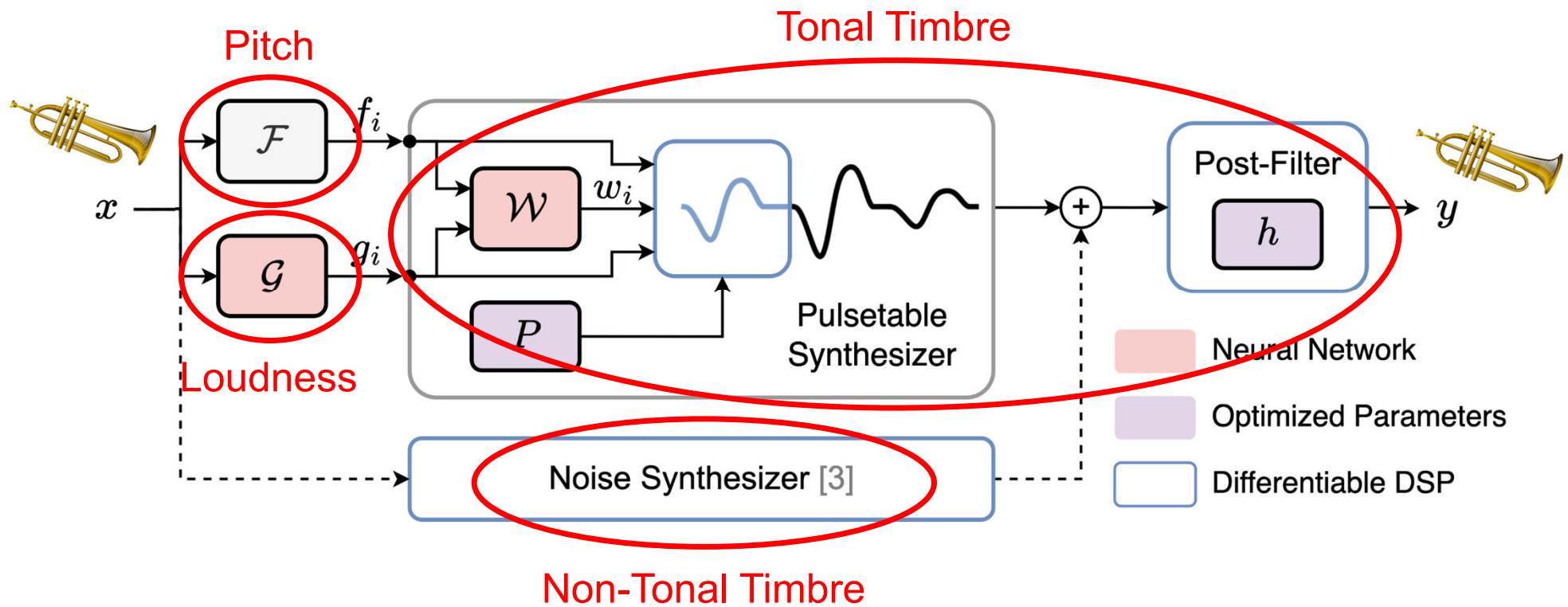
Balke, Berndt, Müller: **ChoraleBricks: A Modular Multitrack Dataset for Wind Music Research**. TISMIR, 8(1): 39–54, 2025



Differentiable Digital Signal Processing

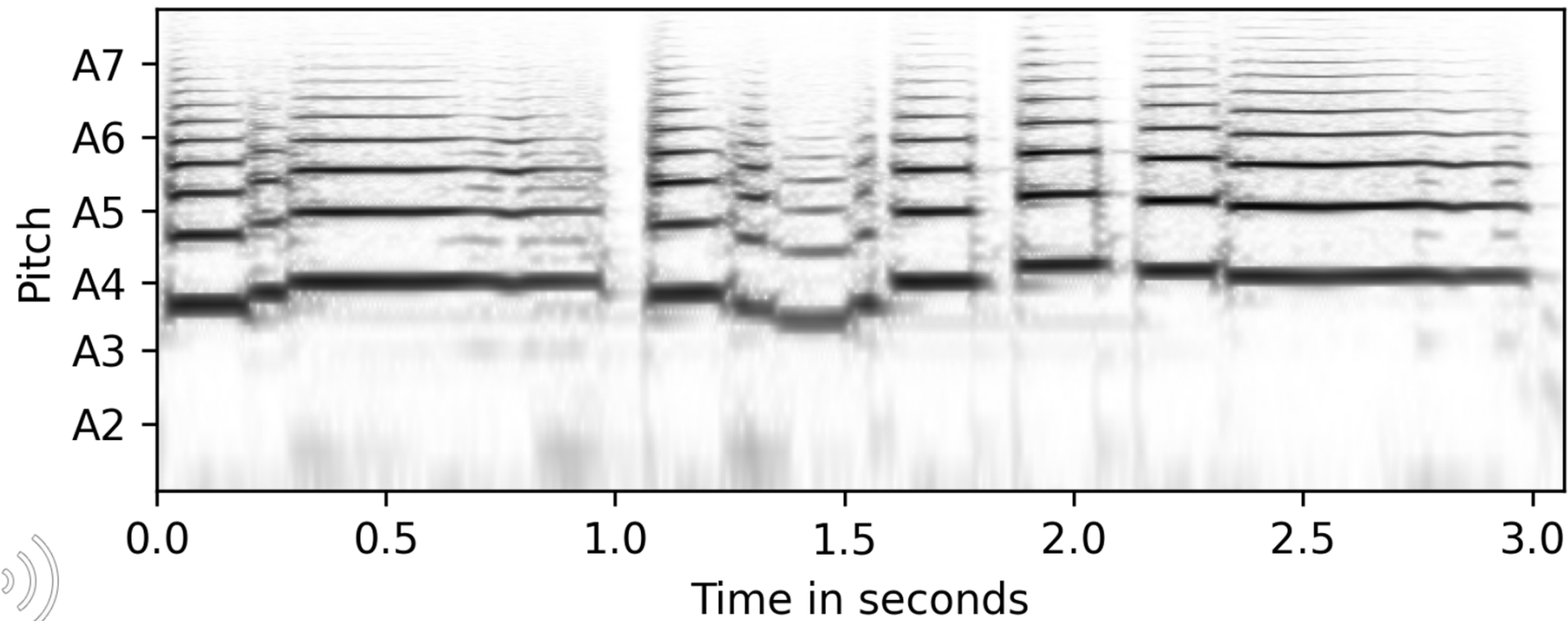
Pulsetable Synthesis

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



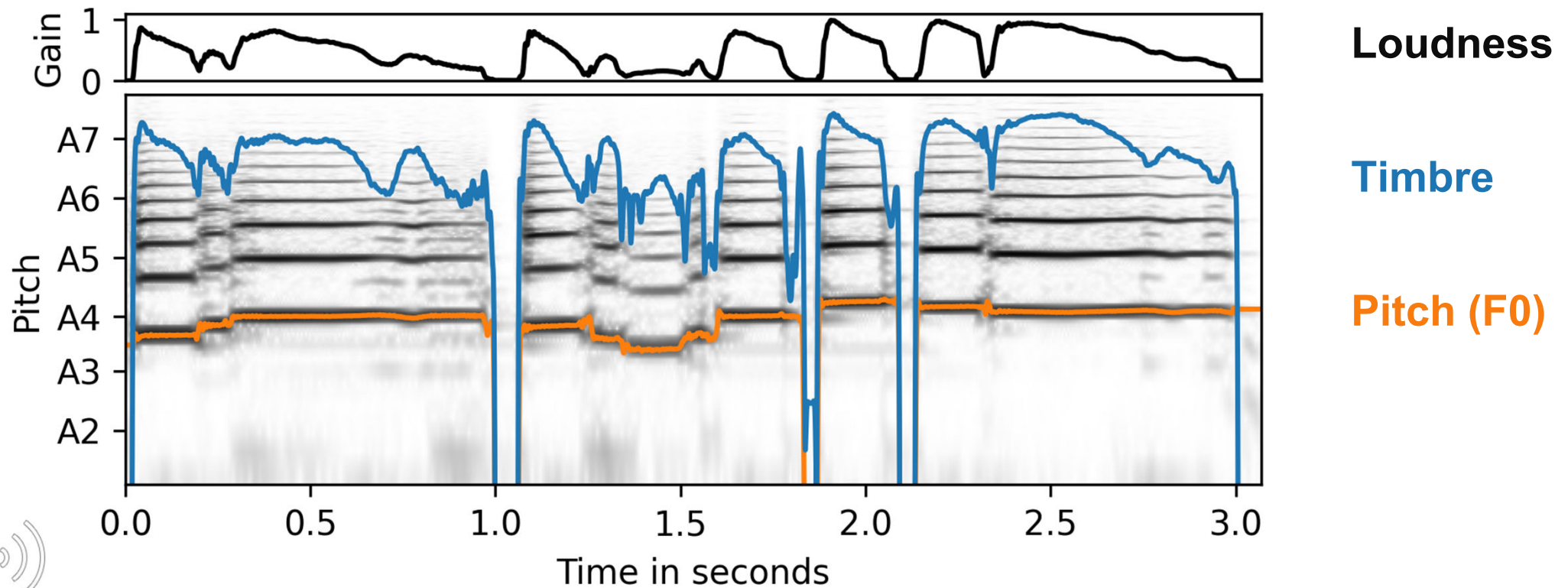
Wind Instrument Synthesis

Input Signal



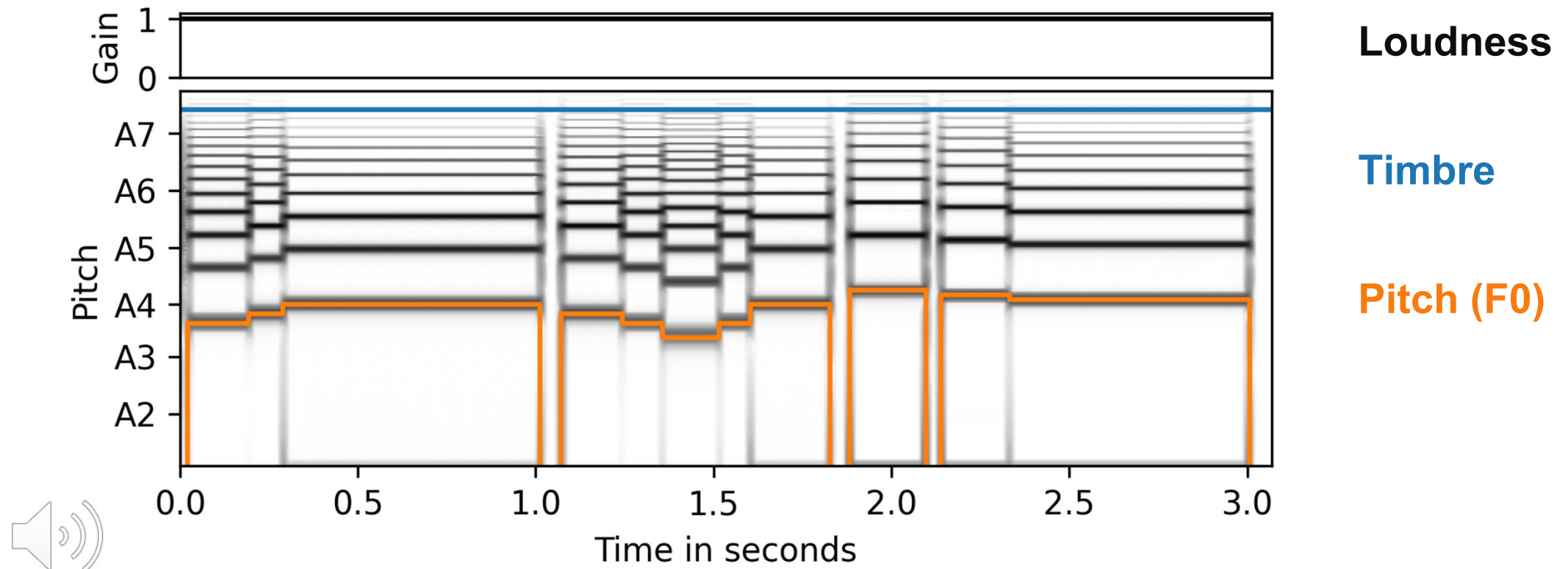
Wind Instrument Synthesis

Extract Control Signals



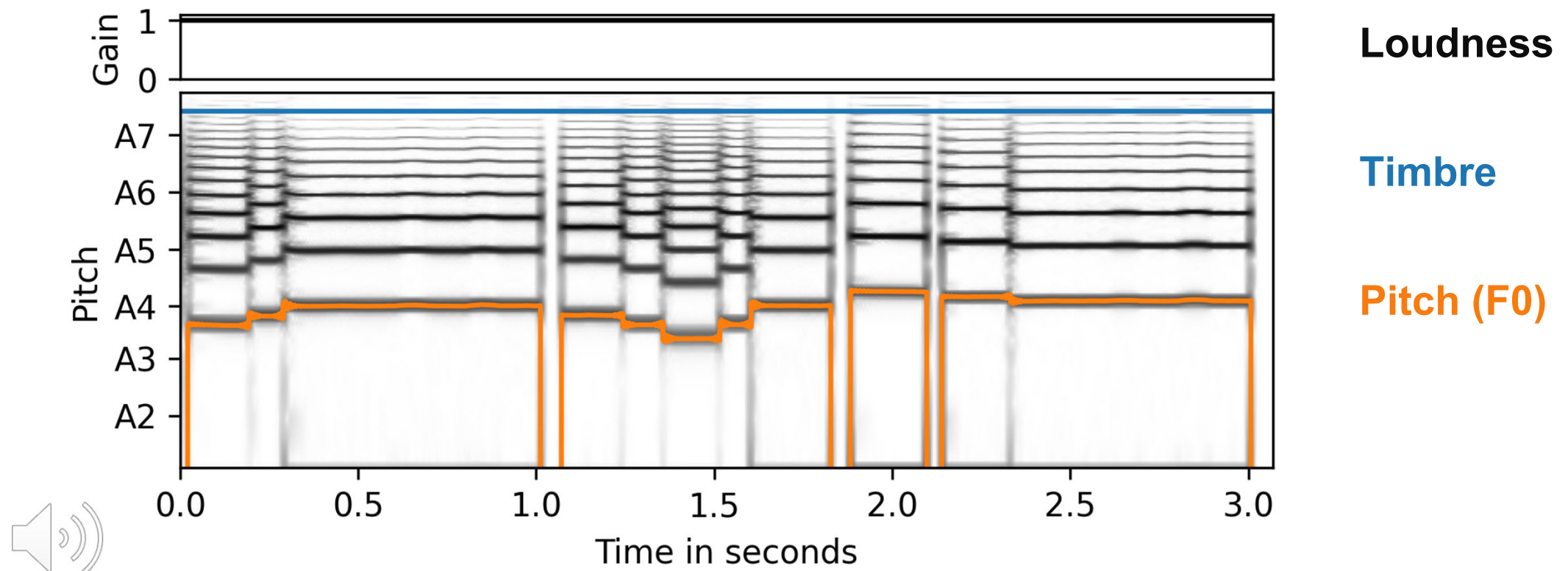
Wind Instrument Synthesis

Generated Control Signals



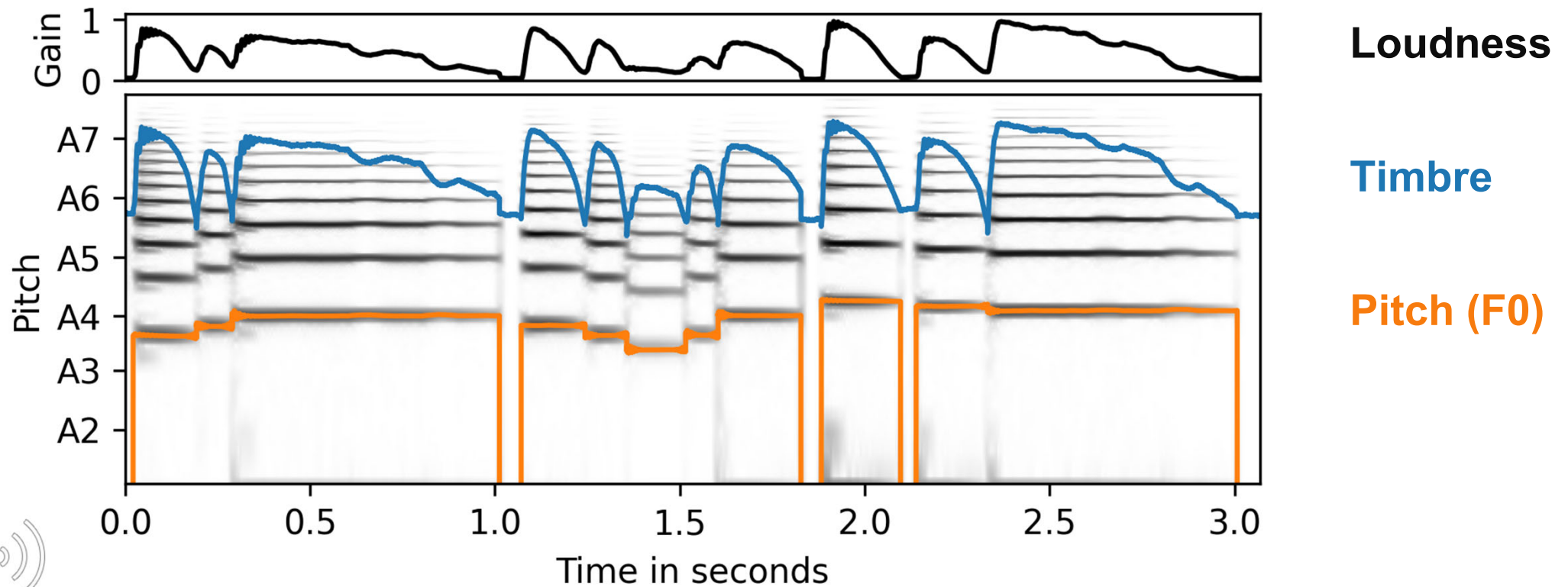
Wind Instrument Synthesis

Generated Control Signals with Pitch Fluctuations



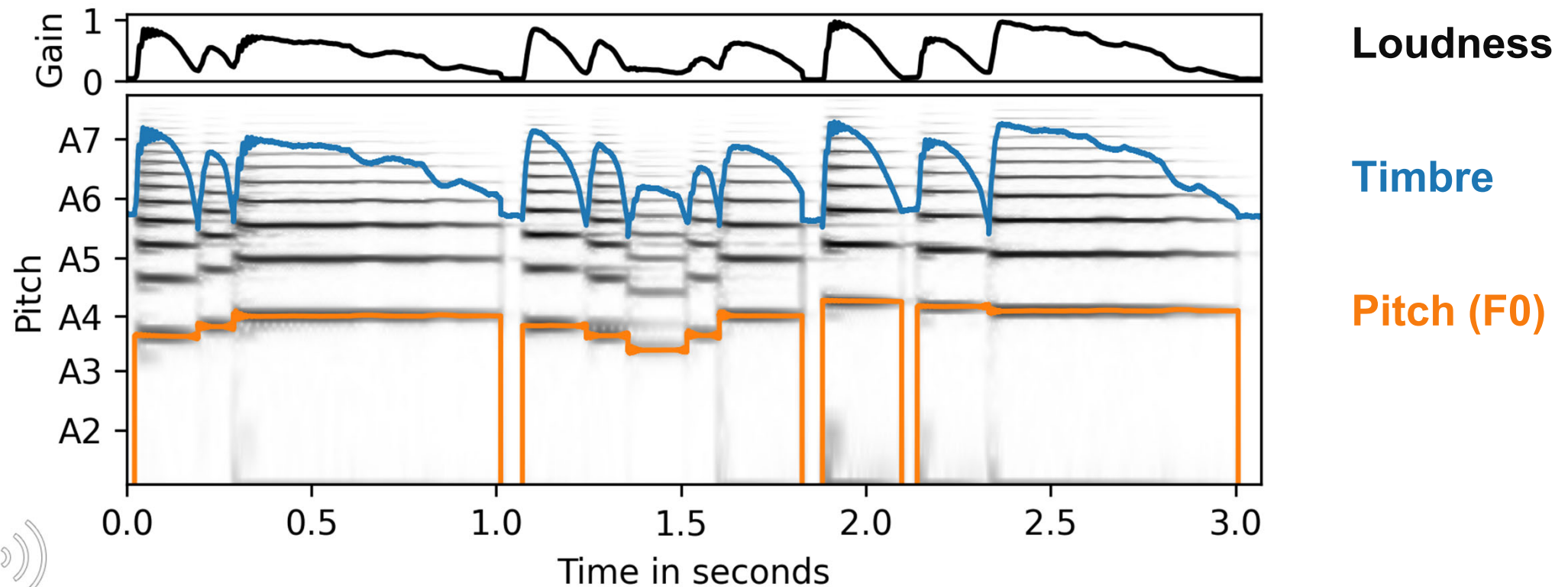
Wind Instrument Synthesis

Generated Control Signals with Pitch & Loudness Fluctuations



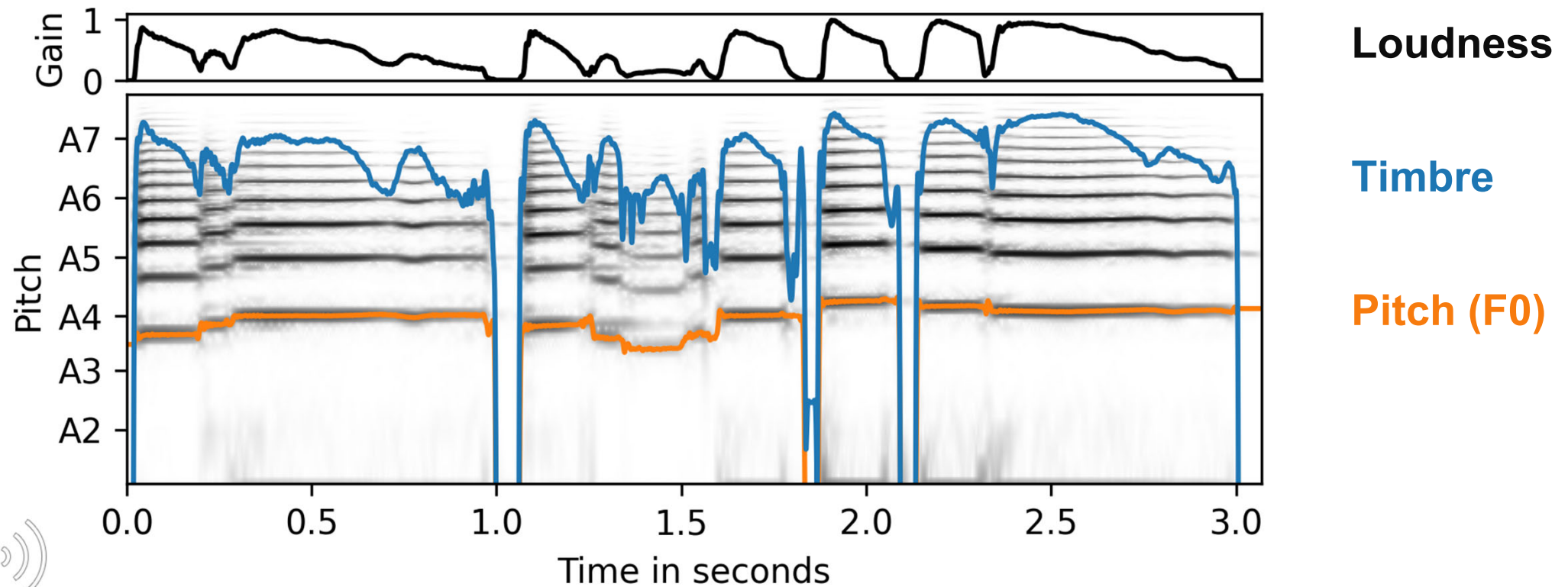
Wind Instrument Synthesis

Generated Control Signals with Fluctuations and Room Acoustics



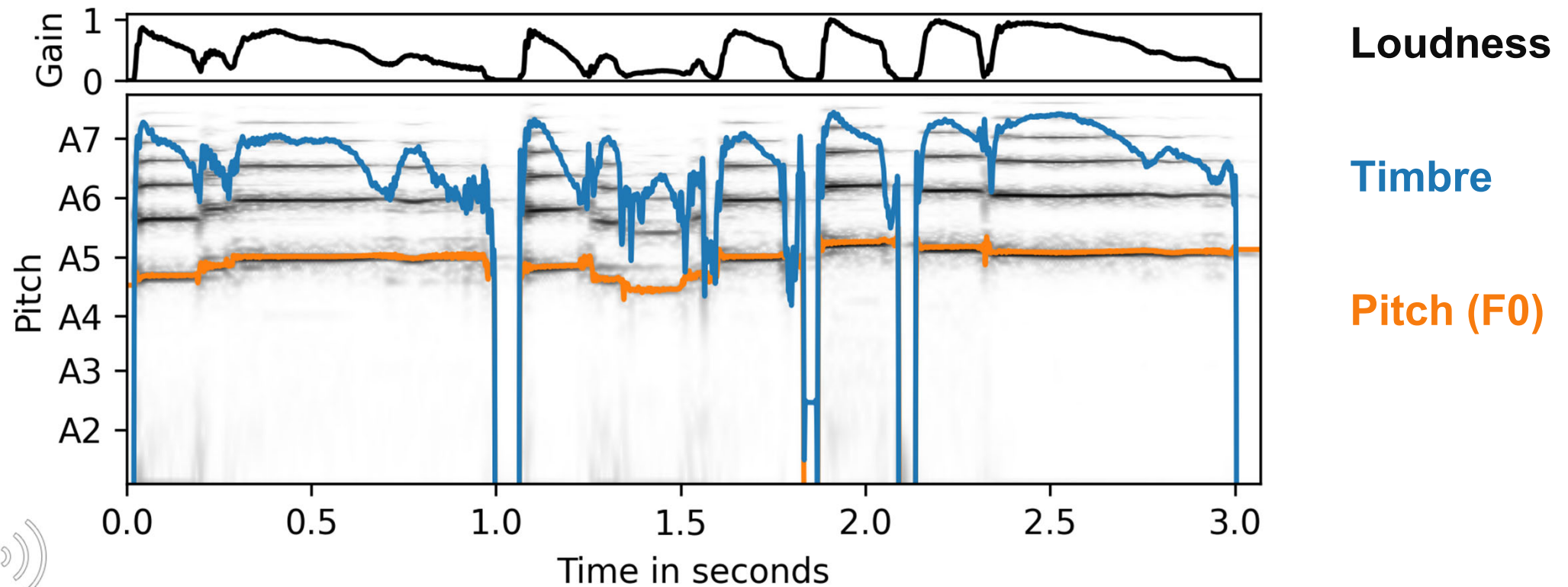
Wind Instrument Synthesis

Resynthesized Trumpet



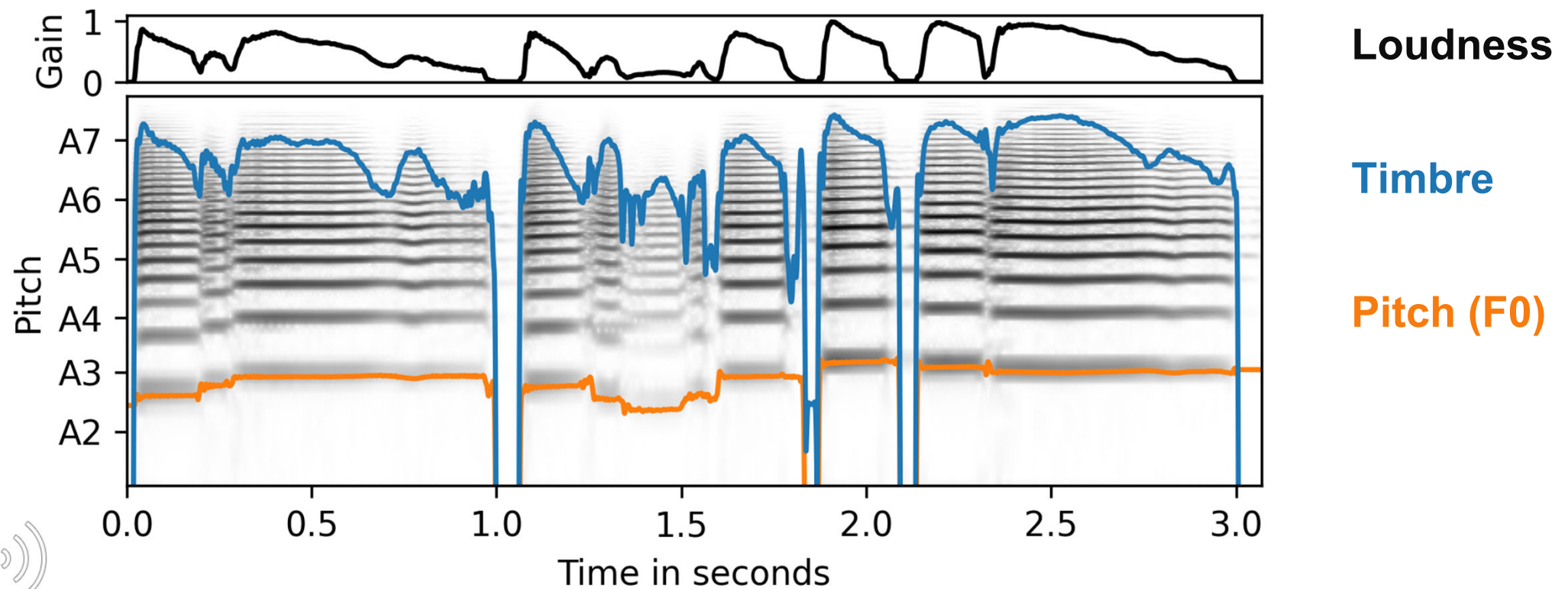
Wind Instrument Synthesis

Resynthesized Trumpet (One Octave Higher)



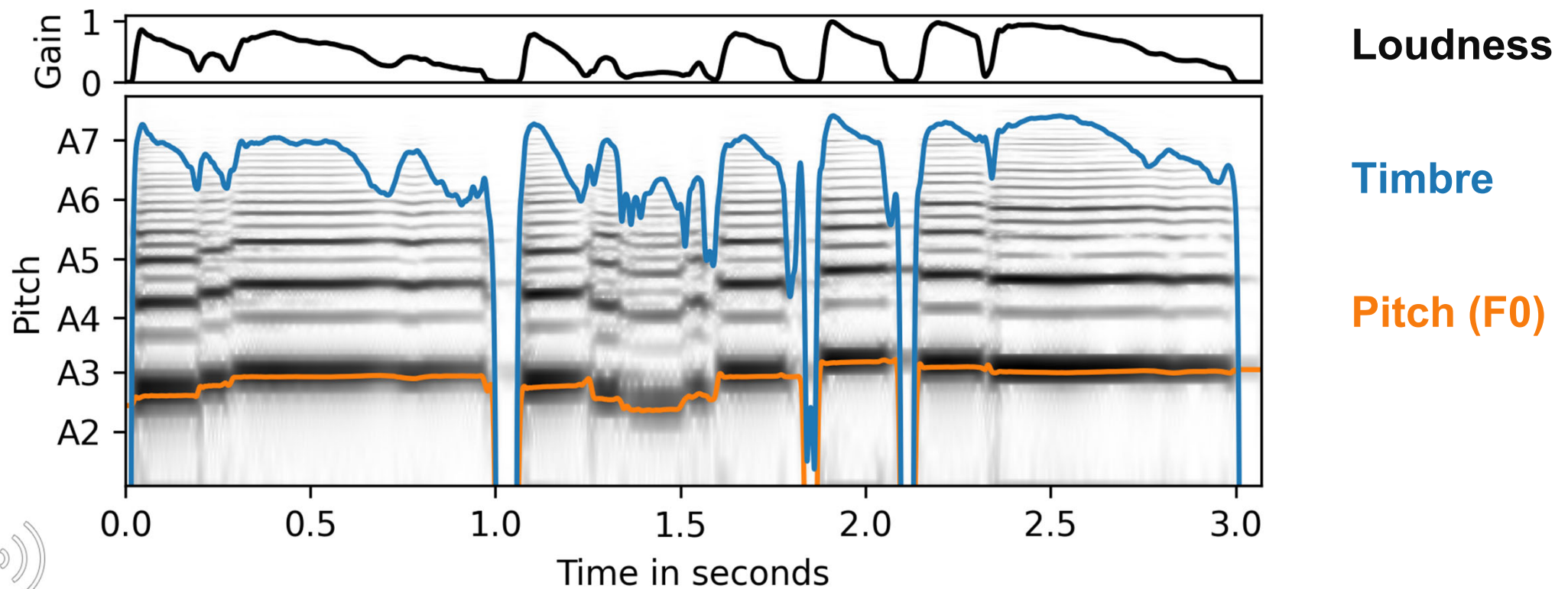
Wind Instrument Synthesis

Resynthesized Trumpet (One Octave Lower)



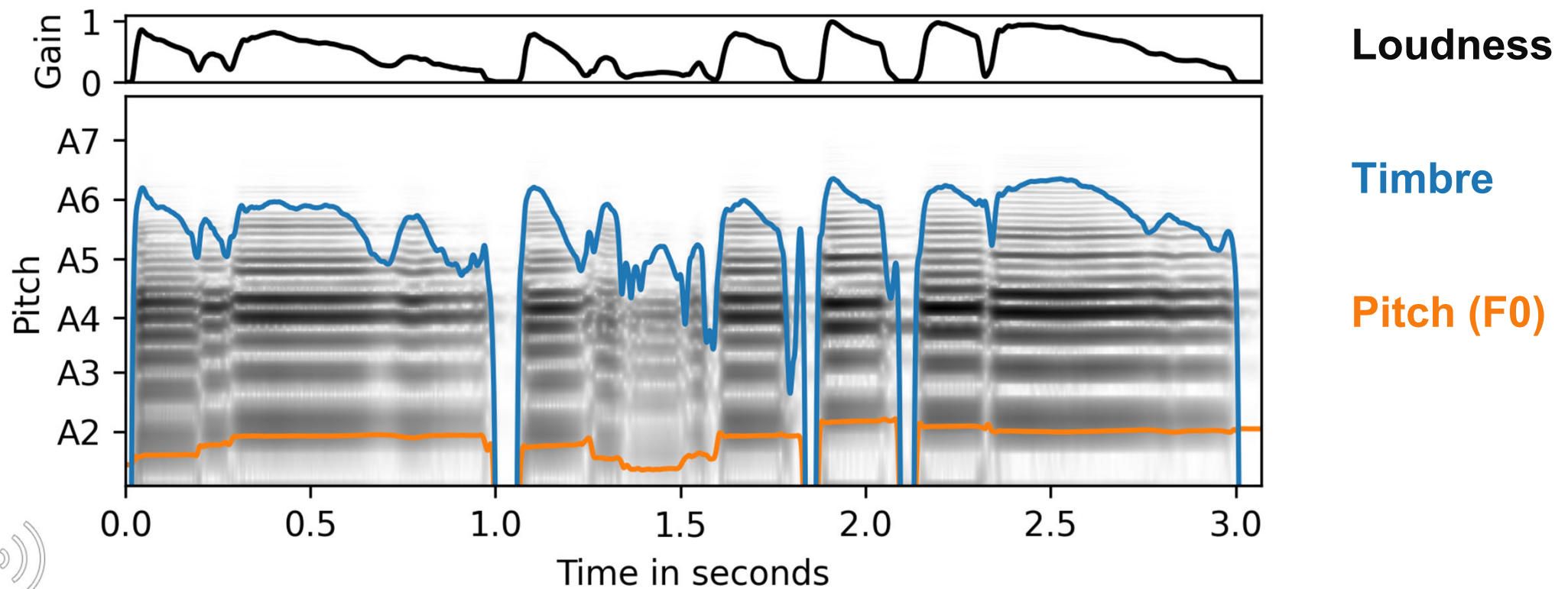
Wind Instrument Synthesis

Resynthesized Clarinet (One Octave Lower)



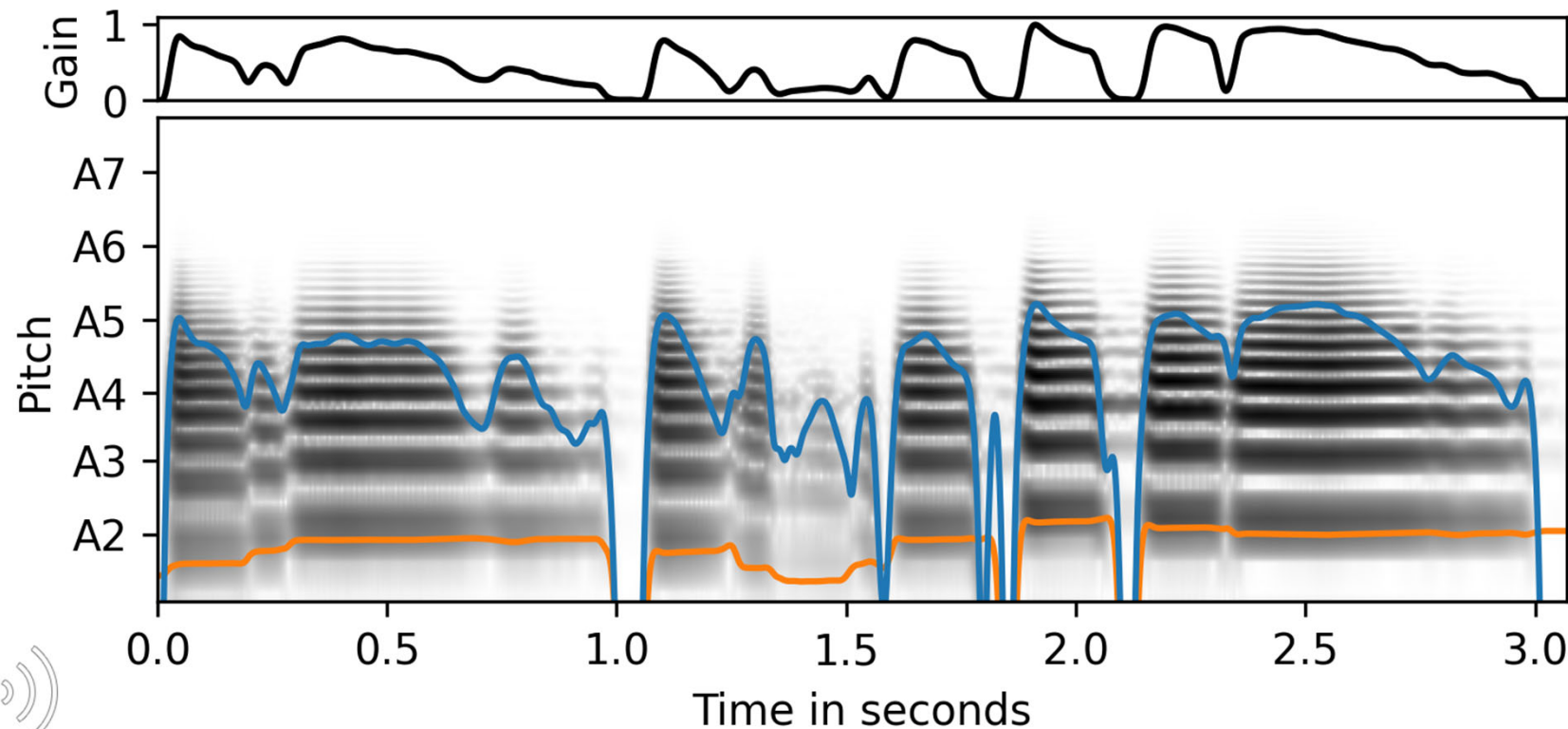
Wind Instrument Synthesis

Resynthesized Bassoon (Two Octaves Lower)



Wind Instrument Synthesis

Resynthesized Tuba (Two Octaves Lower)



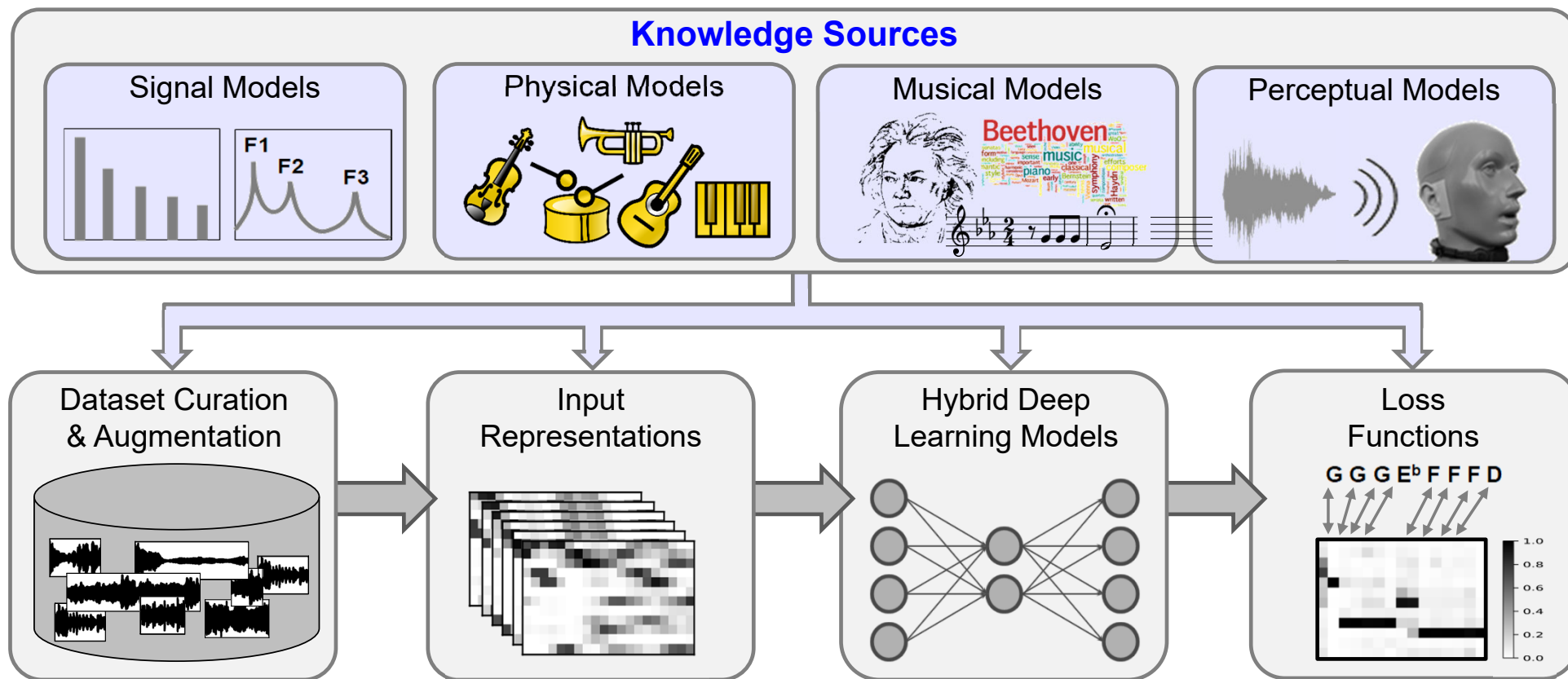
Loudness

Timbre

Pitch (F0)

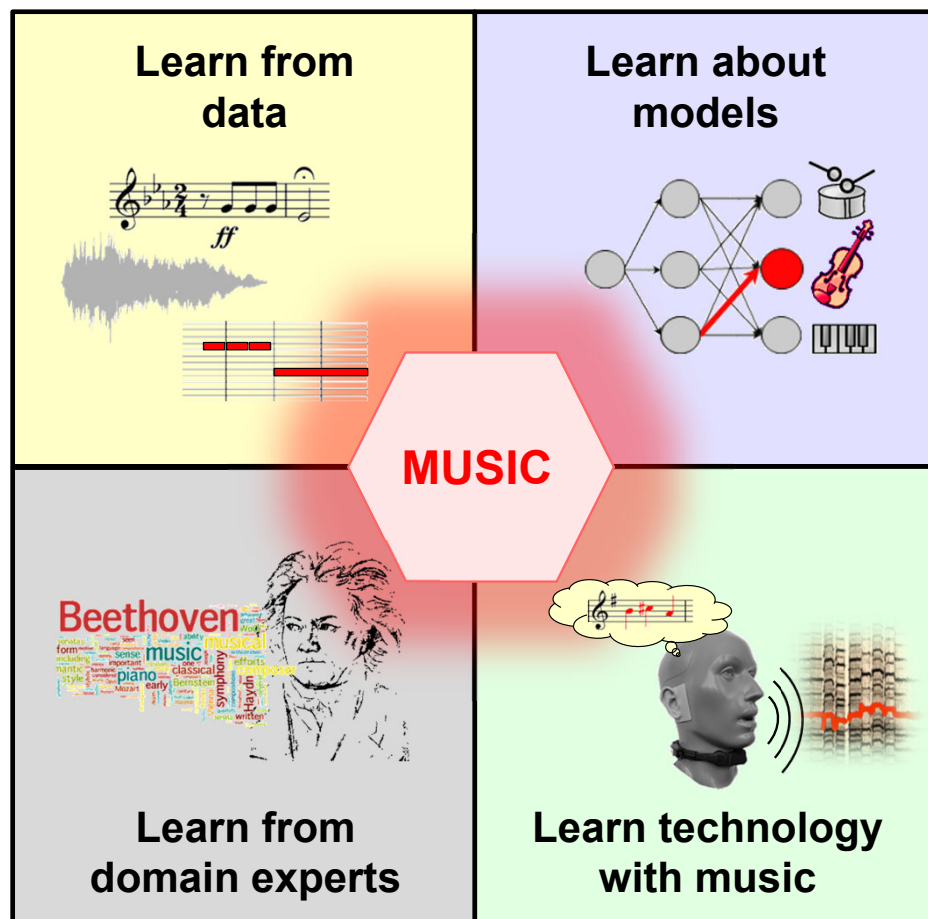


Learning with Music Signals



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

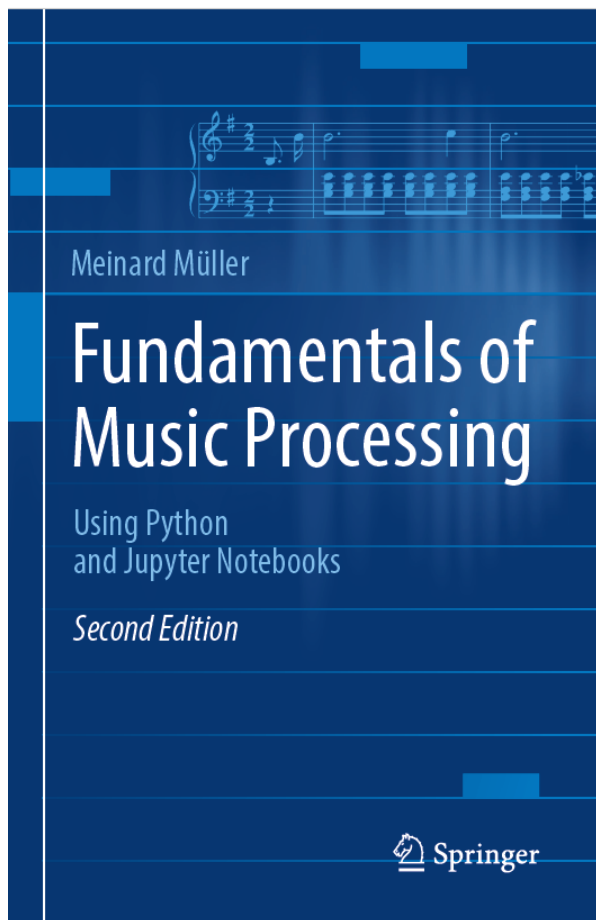


- Machine learning for music signal processing
- Interpretable models and knowledge integration
- Music understanding and applications
- Interactive learning in engineering through music

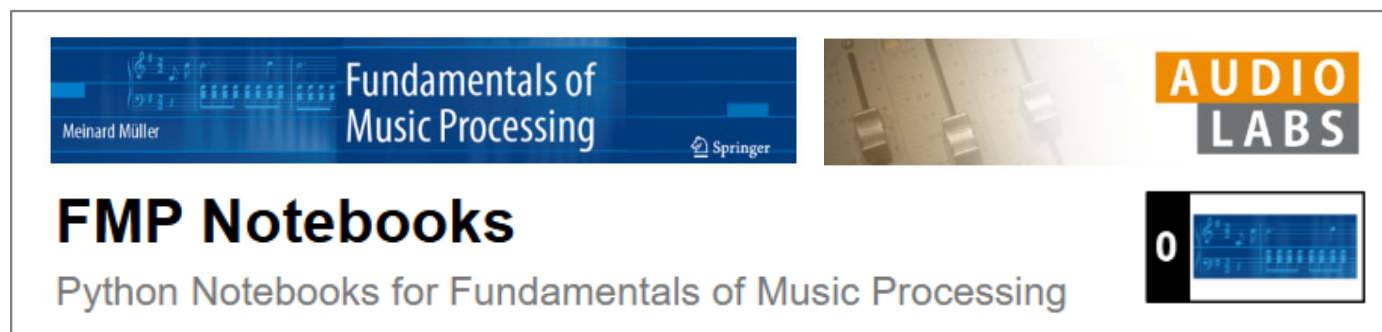
DFG Reinhart Koselleck-Projekt: LEARN
MU 2686/15-1; Grant No. 500643750
2023–2028



Fundamentals of Music Processing (FMP)



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



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