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

AUDIO LABS

Wie gut können Computer hören? – Über die Anwendung musiktheoretischer Konzepte auf Audiodaten

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Hochschule für Musik Würzburg

12.12.2018

FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG

Fraunhofer IIS

Christof Weiß

- 2006: Abitur, Max-Reger-Gymnasium Amberg
- 2006-2012: Studium **Physik** Diplom, Universität Würzburg
- 2006-2011: Studium **Komposition**, HfM Würzburg
  (Prof. Heinz Winbeck)
- 2011-2012: Fortbildungsklasse Komposition (Tobias Schneid)
- 2012-2015: **Promotion** Fraunhofer Institut für Digitale Medientechnologie (IDMT), Ilmenau, Thüringen, gefördert von Stiftung der Dt. Wirtschaft (sdw)

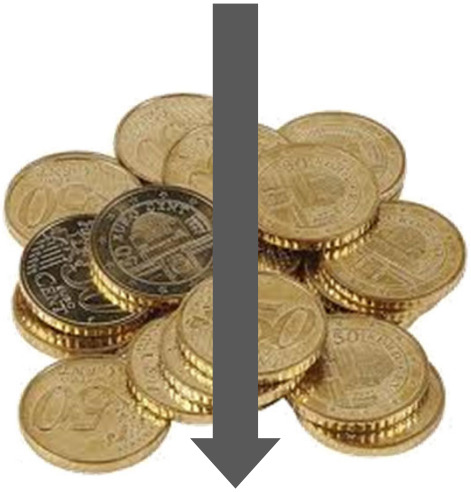
Computational Methods for Tonality-Based Style Analysis of Classical Music Audio Recordings

- Seit 09/2015: AudioLabs Erlangen / freischaffender Komponist
- 2018: KlarText-Preis für Wissenschaftskommunikation

International Audio Laboratories Erlangen

Fraunhofer IIS

mp3



FAU FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG

AUDIO LABS

AUDIO LABS

AudioLabs - FAU

- Prof. Dr. Jürgen Herre
  Audio Coding
- Prof. Dr. Bernd Edler
  Audio Signal Analysis
- Prof. Dr. Meinard Müller
  Semantic Audio Processing
- Prof. Dr. Emanuël Habets
  Spatial Audio Signal Processing
- Prof. Dr. Frank Wefers
  Virtual Reality
- Dr. Stefan Turowski
  Coordinator AudioLabs-FAU

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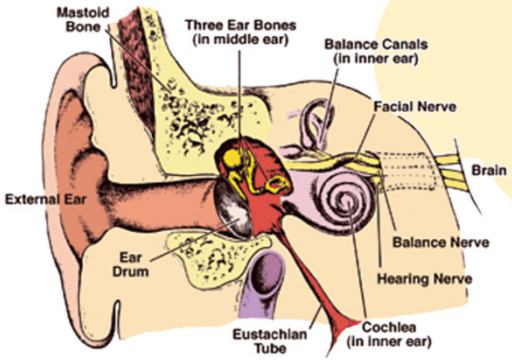
International Audio Laboratories Erlangen

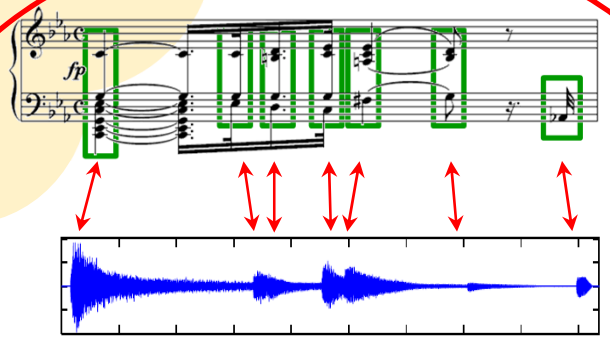
3D Audio

Audio Coding

Audio



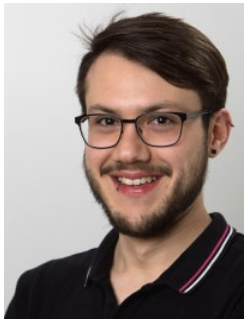
Psychoacoustics

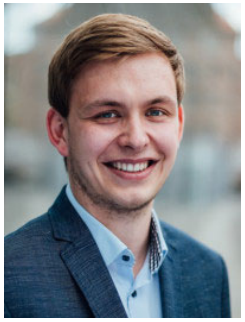


Music Processing

Group Prof. Meinard Müller

- Patricio López-Serrano
- Frank Zalkow
- Sebastian Rosenzweig
- Christof Weiß





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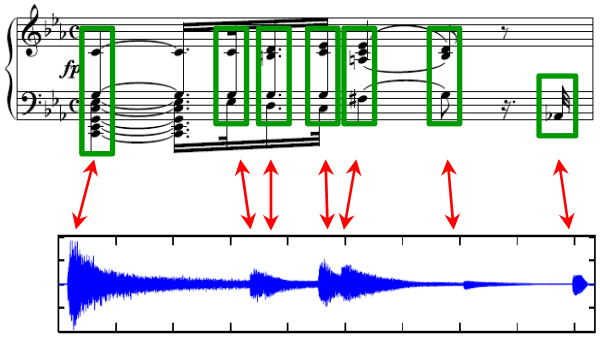
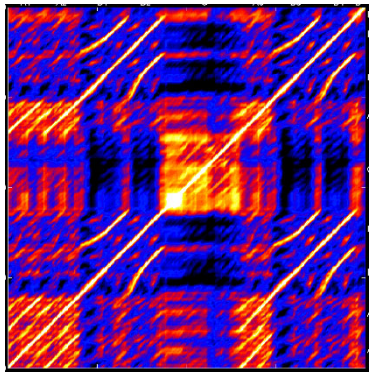
Music Processing / Music Information Retrieval (MIR)

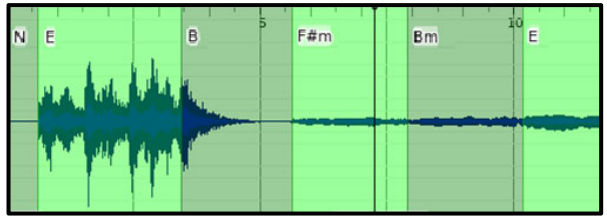
Music Synchronization



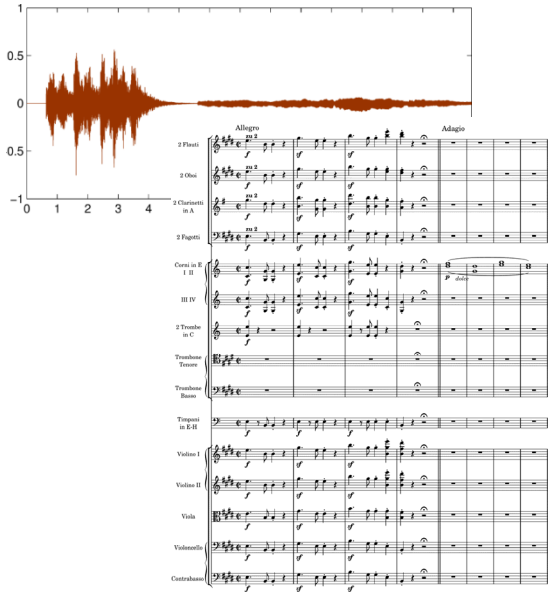
Structure Analysis



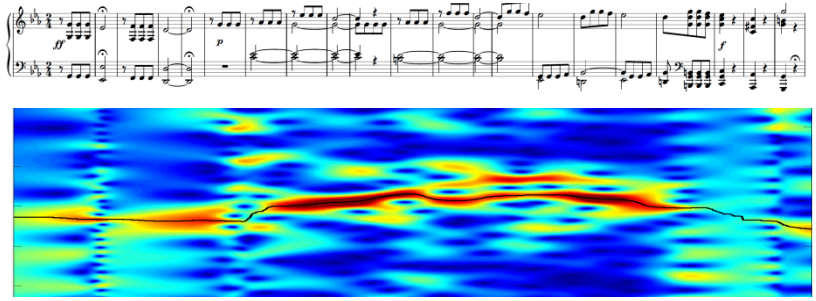
Harmony Analysis



Automatic Music Transcription



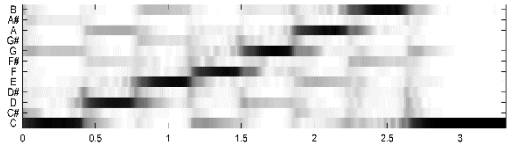
Tempo Estimation and Beat Tracking



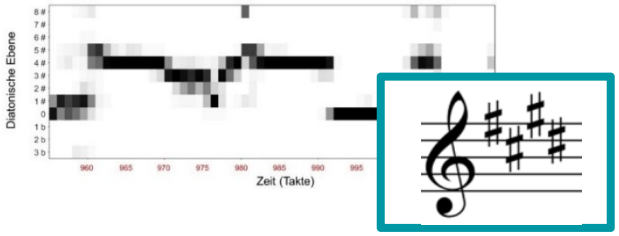
AUDIO LABS

Outline

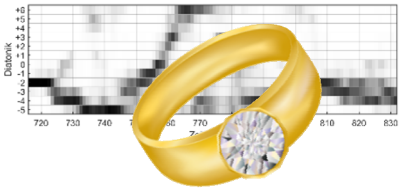
1. Spectral Analysis and Chroma Features



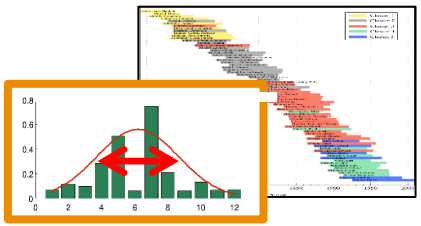
2. Local Tonality Analysis



3. Cross-Version Analysis of Wagner‘s *Ring*

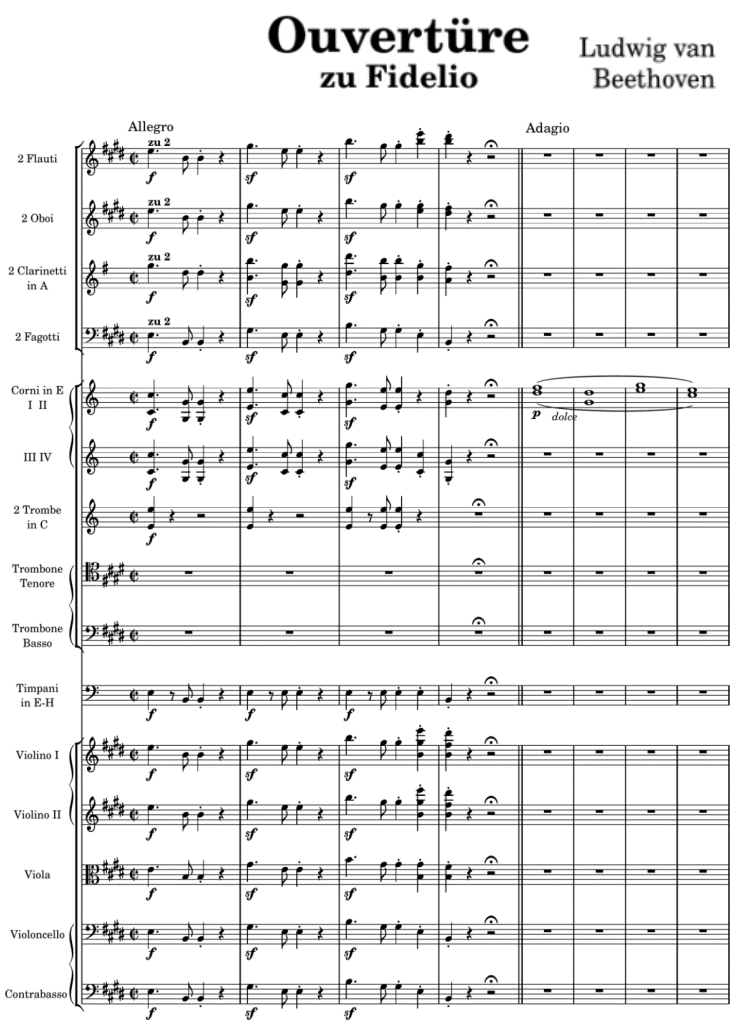


4. Analyzing and Classifying Composer Styles

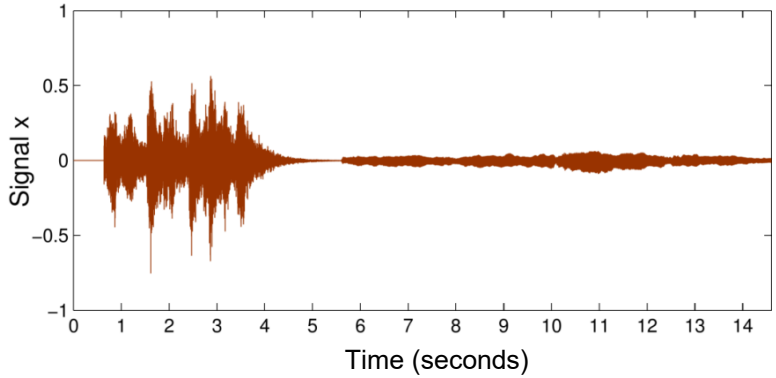


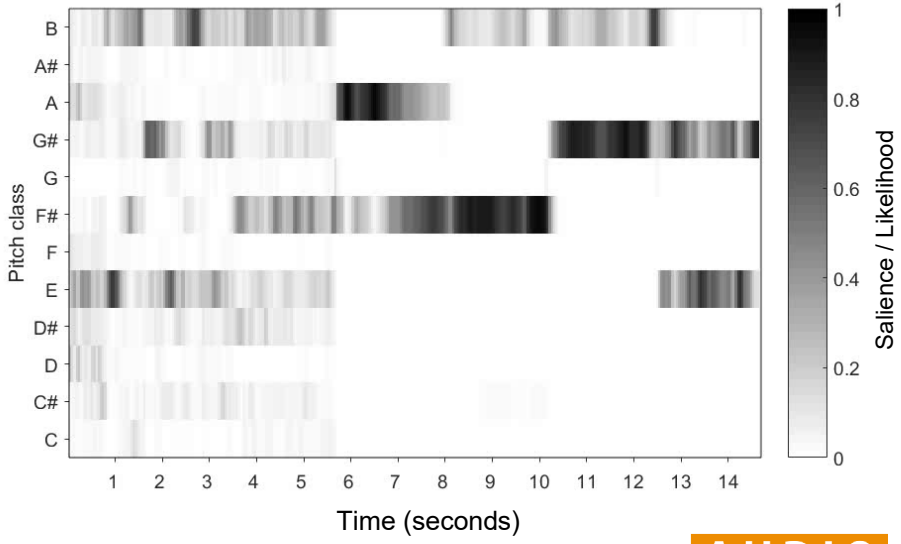
AUDIO LABS

Chroma Representations



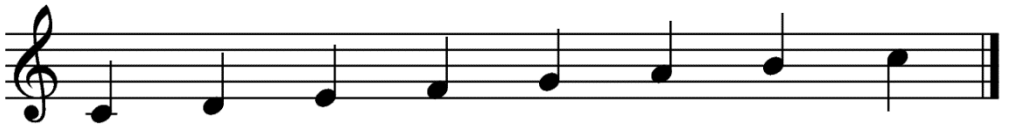
L. van Beethoven,
Fidelio, Overture,
Slovak Philharmonic



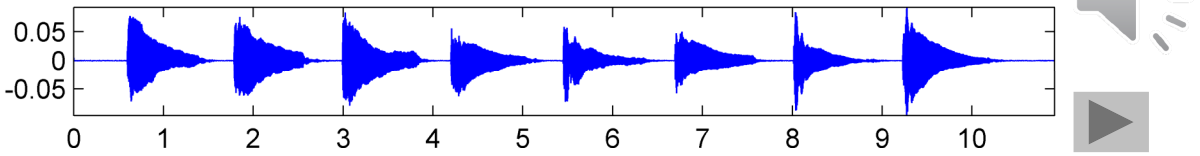


Chroma Representations

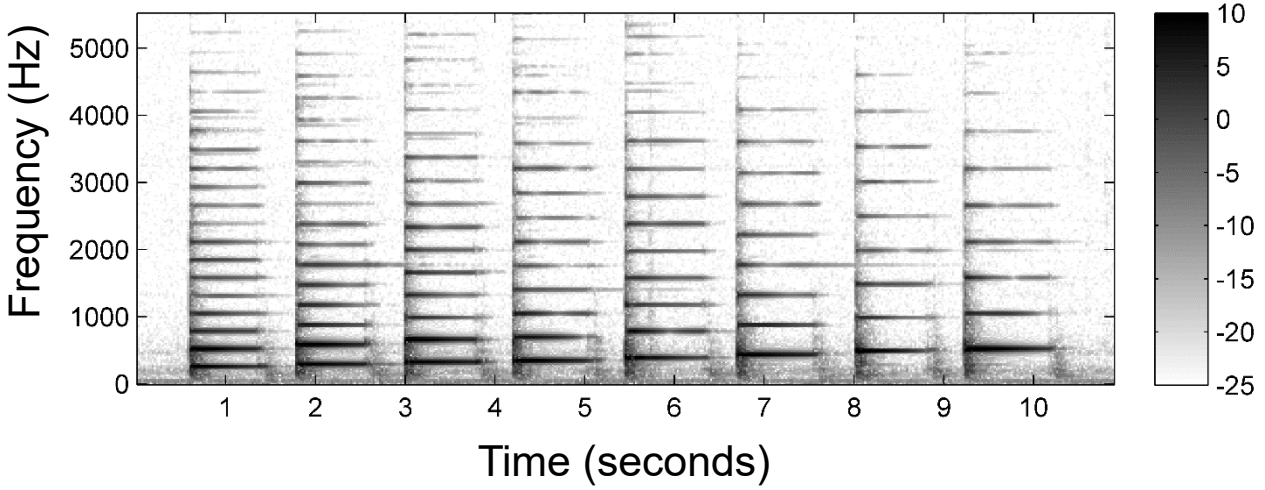
- Example: C-major scale (piano)
  - Score



  - Audio – **Waveform**

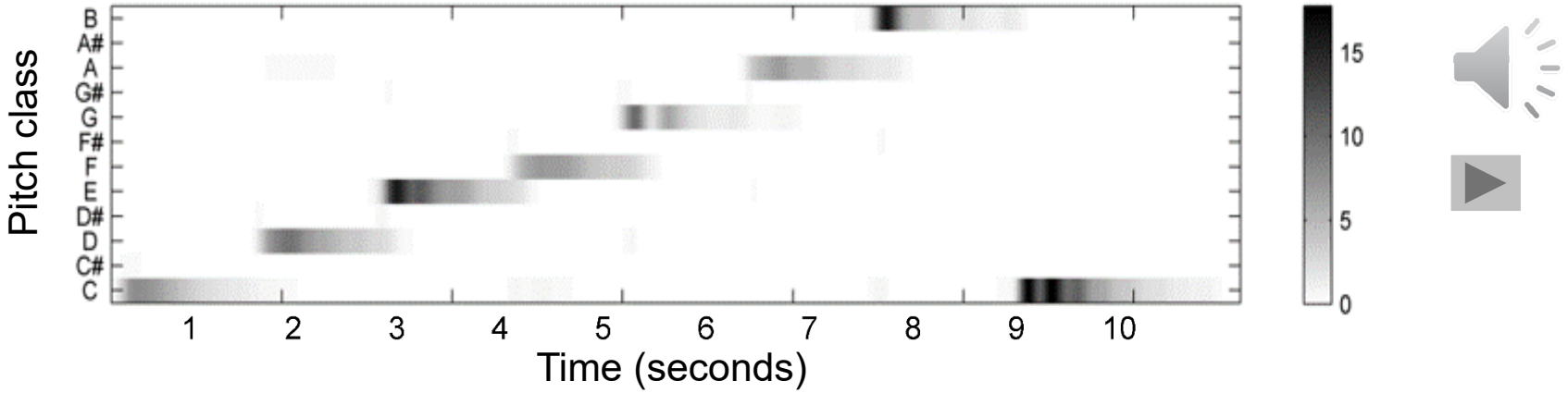


  - Audio - **Spectrogram**

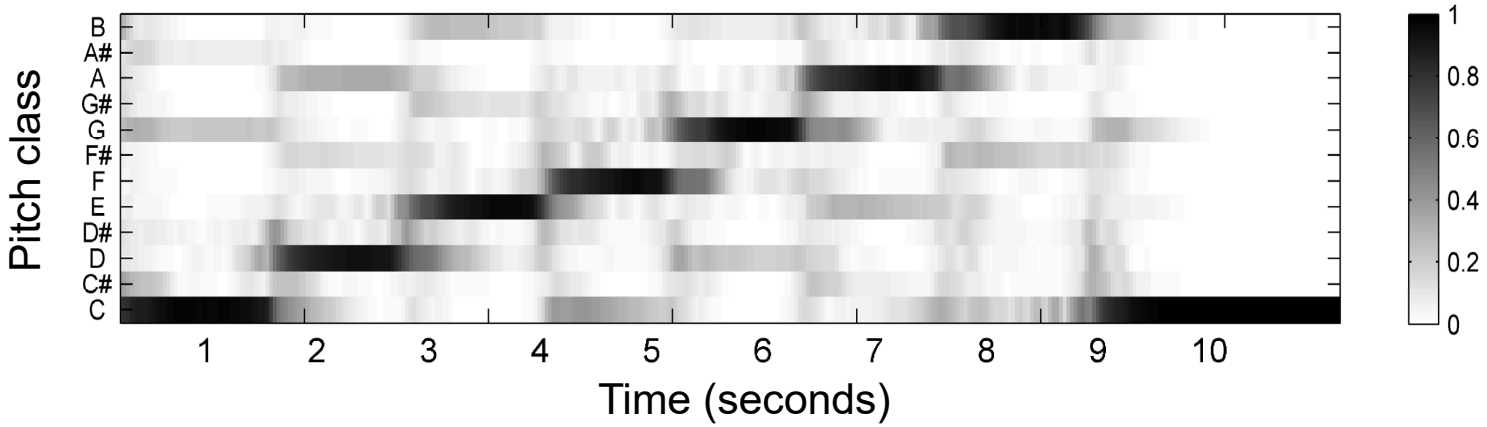


Chroma Representations

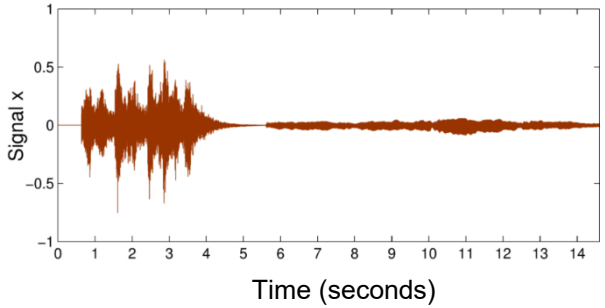
- Example: C-major scale (piano)
  - Audio – **Chromagram**

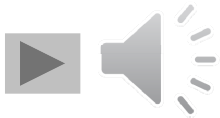


  - Audio – **Chromagram (normalized)**



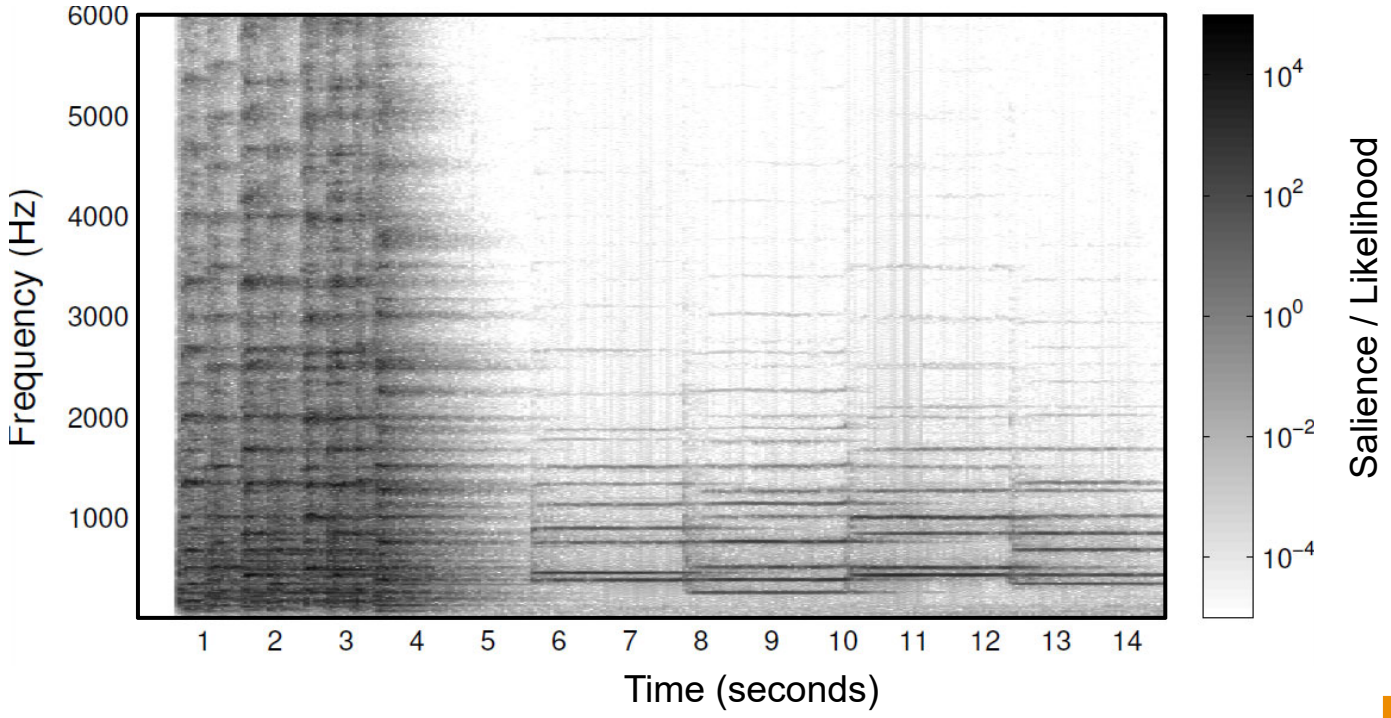
Chroma Representations



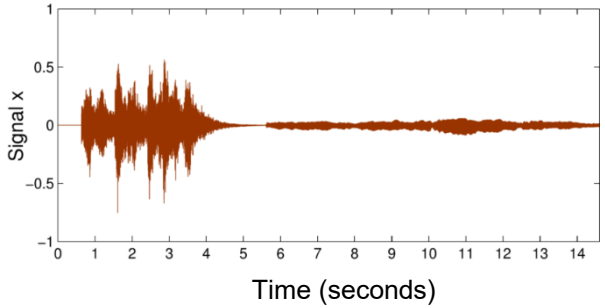


L. van Beethoven,
Fidelio, Overture,
Slovak Philharmonic

Spectrogram: Time – Frequency

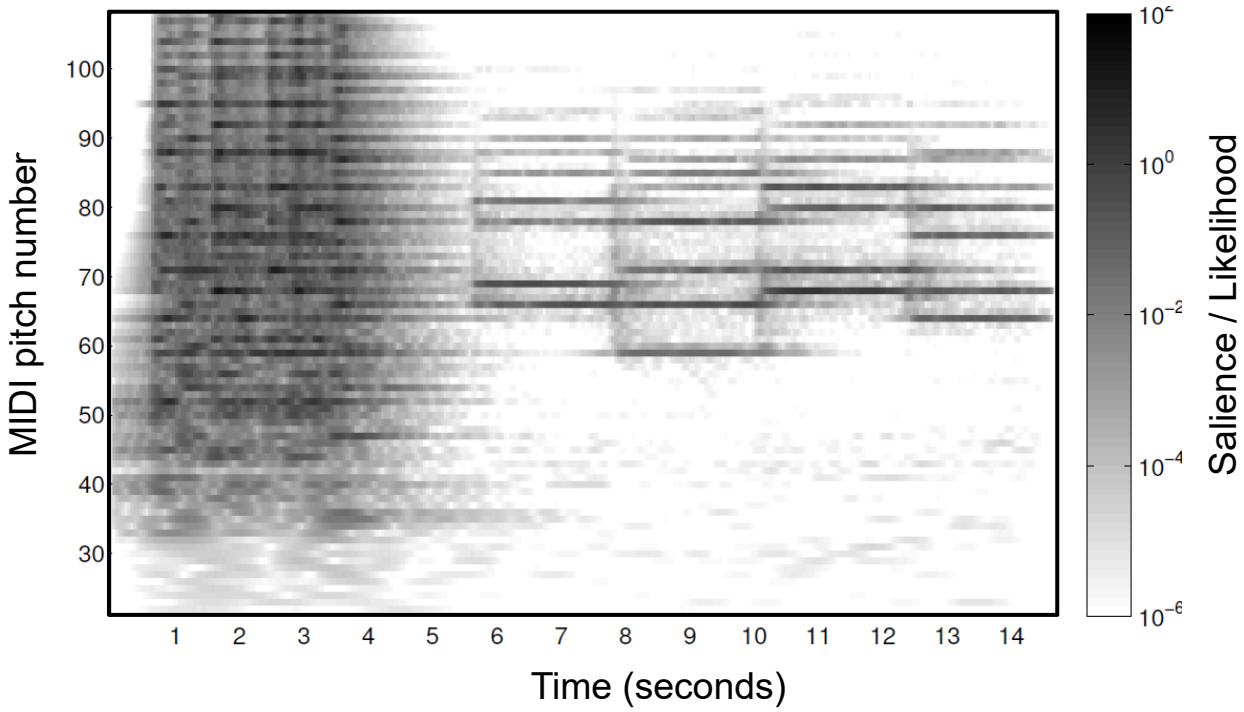


Chroma Representations

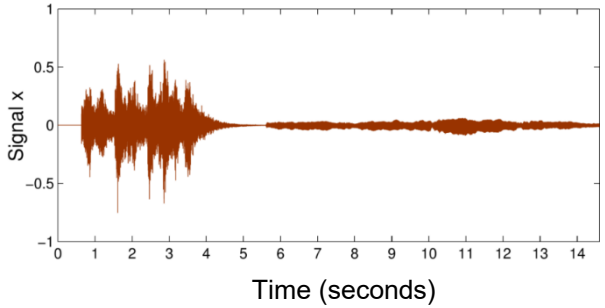


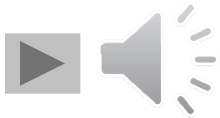
L. van Beethoven,
Fidelio, Overture,
Slovak Philharmonic

Log-Frequency-Spectrogram: Time – Pitch



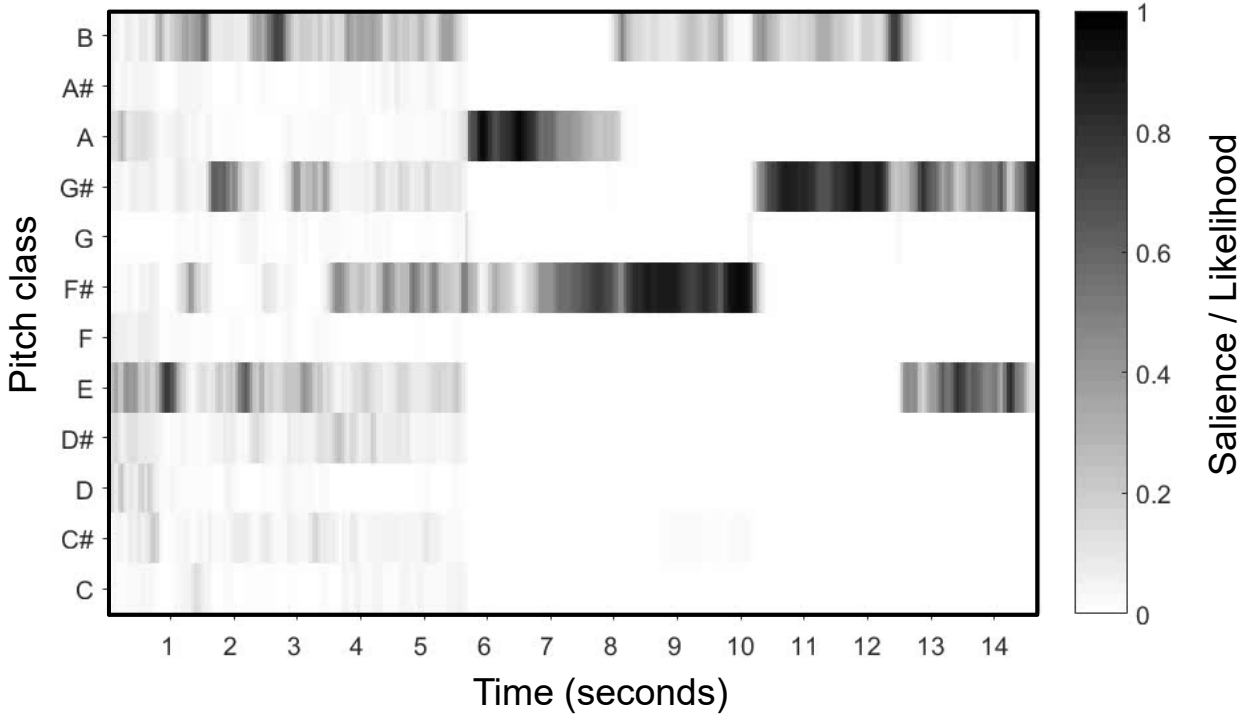
Chroma Representations





L. van Beethoven,
Fidelio, Overture,
Slovak Philharmonic

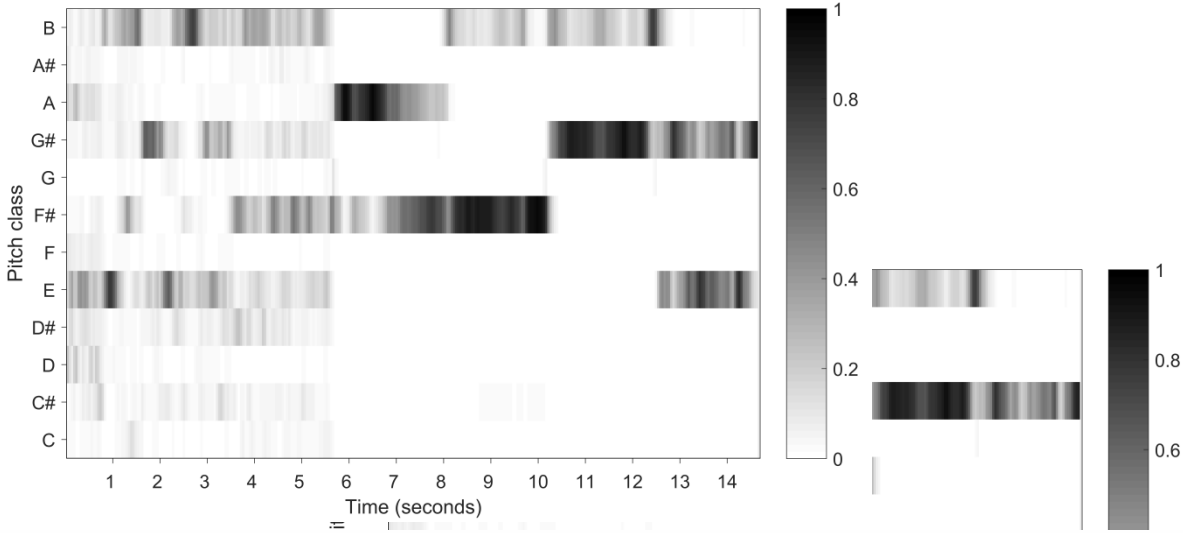
Chromagram: Time – Pitch class



Chroma Representations

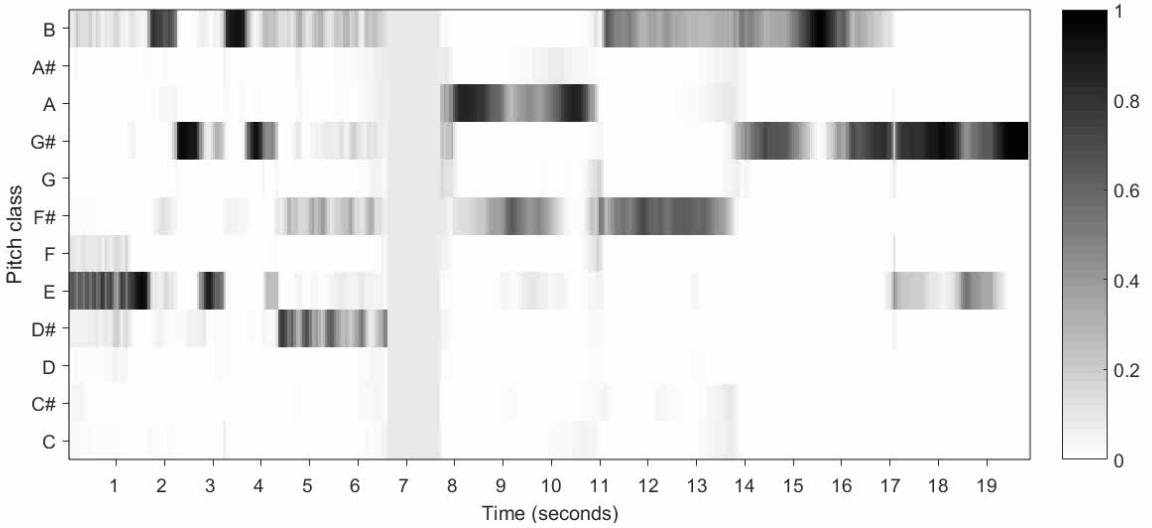
- Orchestra

L. van Beethoven,
Fidelio, Overture,
Slovak Philharmonic

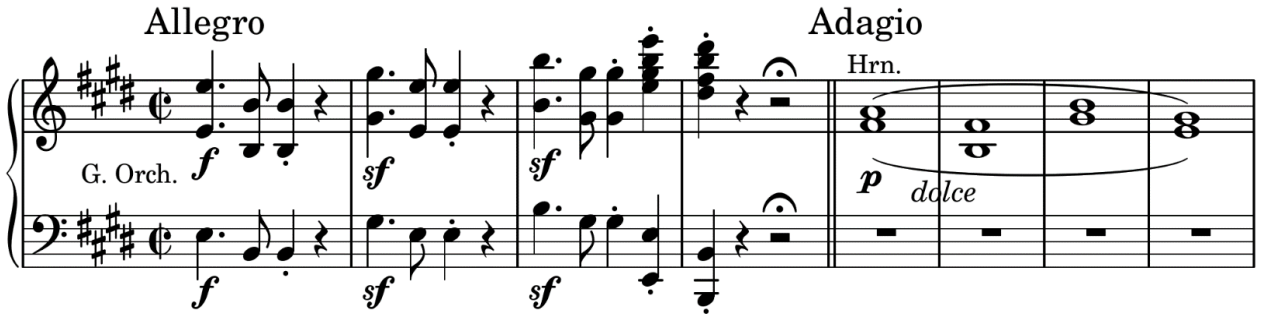


- Piano

Fidelio, Overture,
arr. Alexander Zemlinsky
M. Namekawa, D.R. Davies,
piano four hands

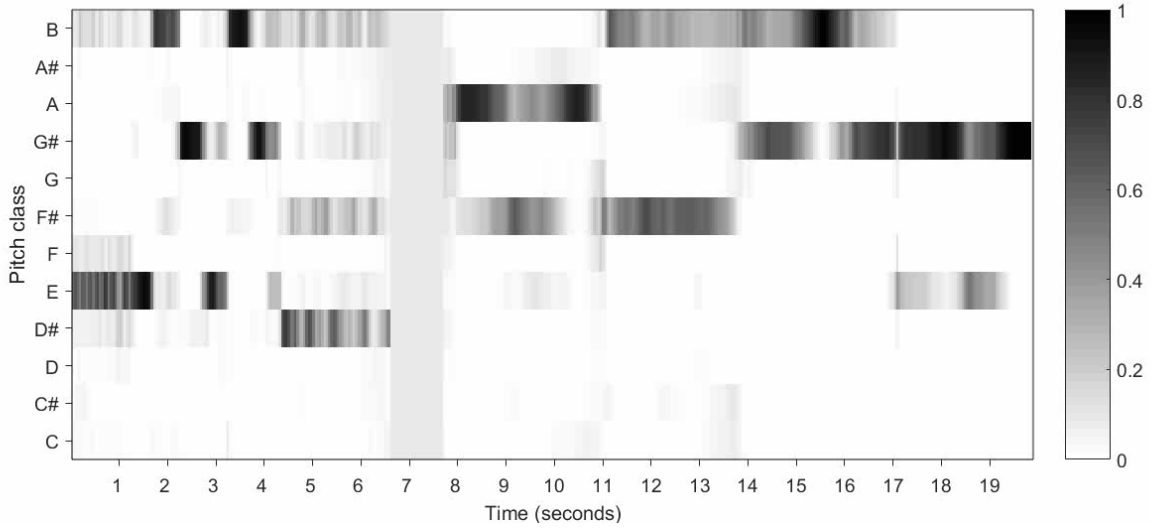


Chroma Representations



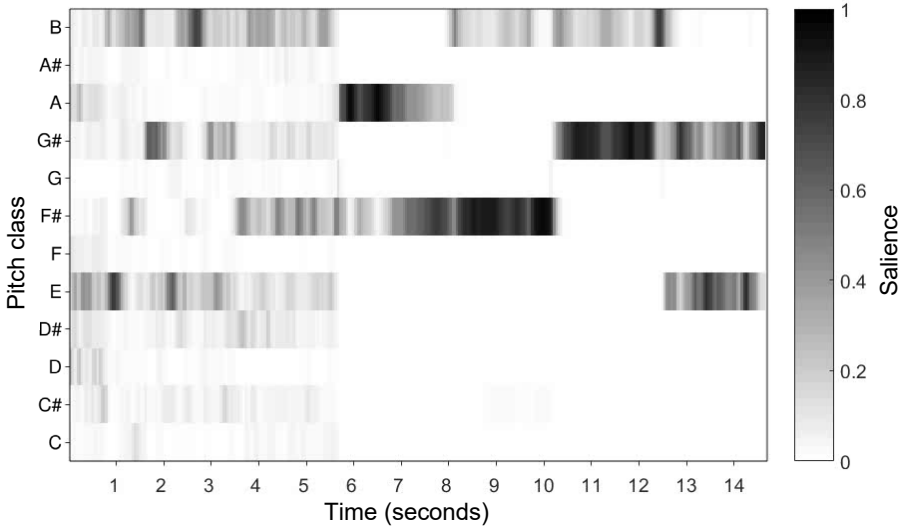
- Piano

Fidelio, Overture,
arr. Alexander Zemlinsky
M. Namekawa, D.R. Davies,
piano four hands

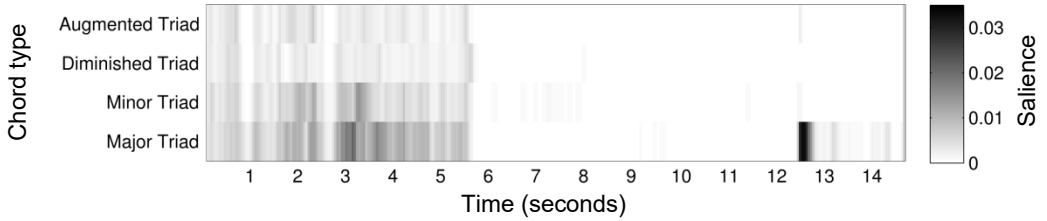


Chroma Representations

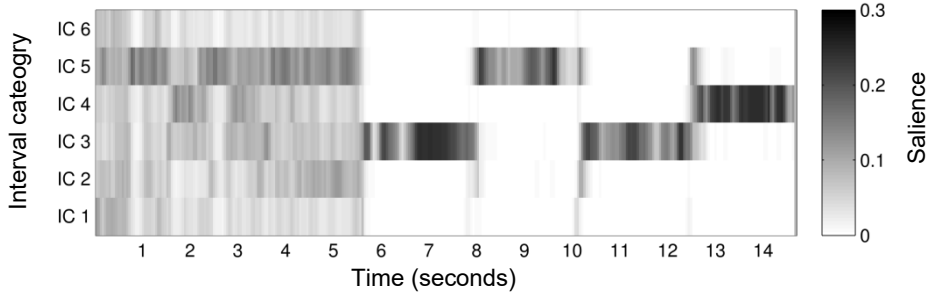
- Chromagram



- Chord types



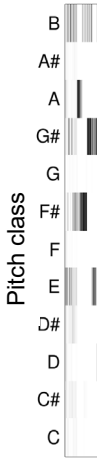
- Interval categories



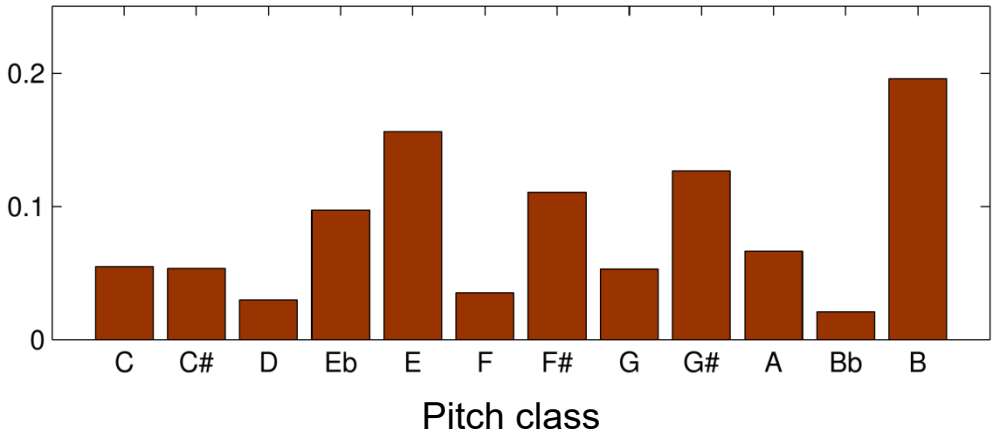
→ transposition-invariant descriptors!

Chroma Representations

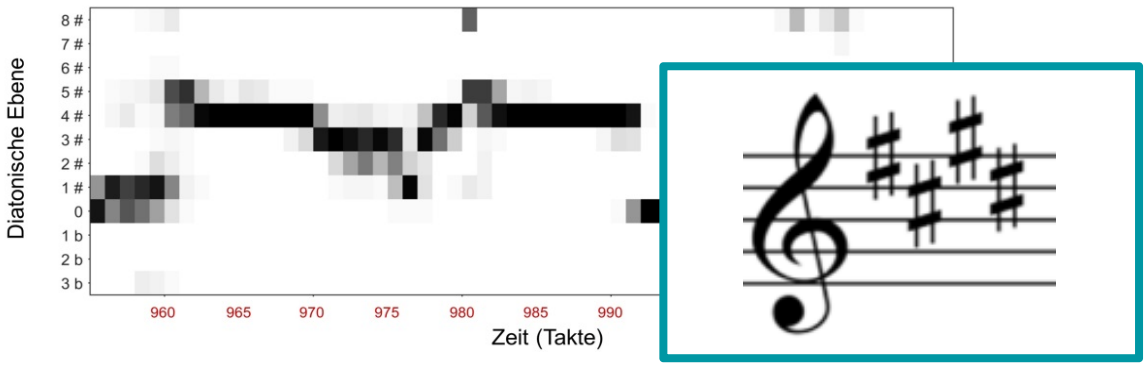
- Chromagram: Full piece



- Chroma statistics:



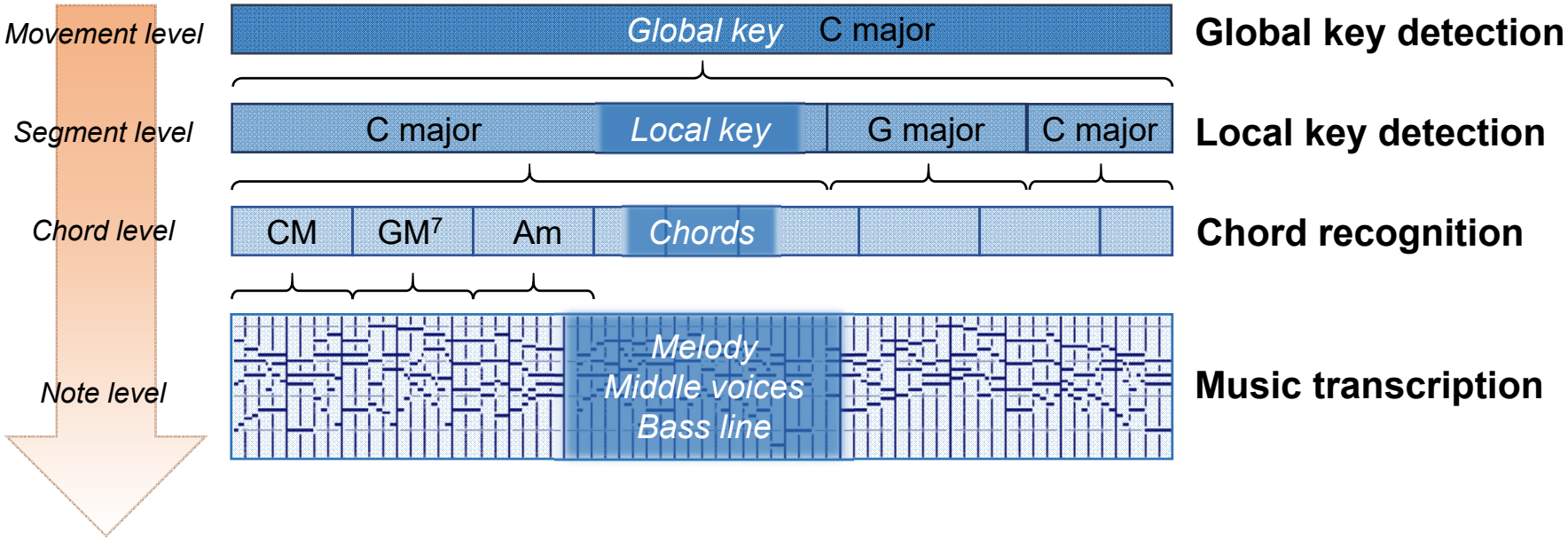
2. Local Tonality Analysis Based on Diatonic Scales



AUDIO LABS

Motivation

- **Harmony analysis** of music:
  - Different concepts
  - Concepts relate to different **temporal granularity**



AUDIO LABS

Motivation

- **Harmony analysis** of music:
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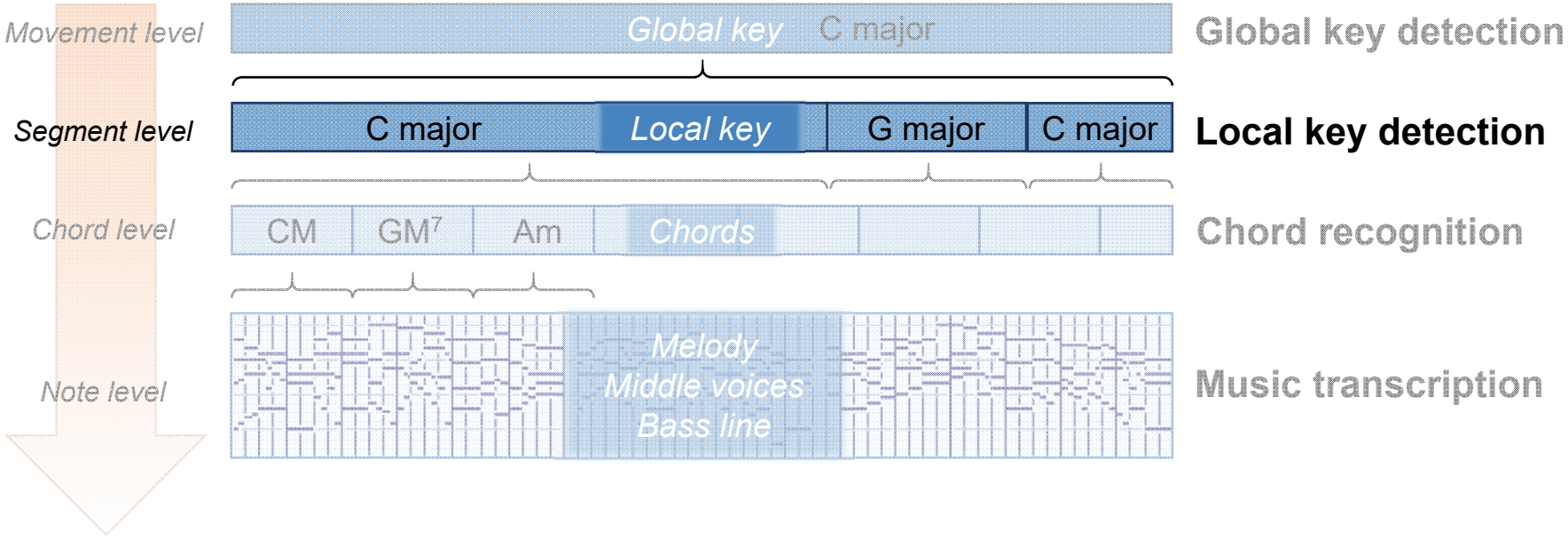
  - Concepts relate to different **temporal granularity**

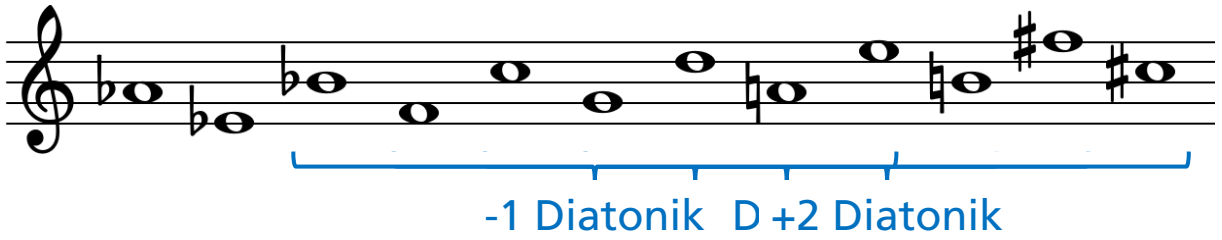


AUDIO LABS

Musicological Foundations

- Method: estimate **diatonic scales – 7** fifth-related pitches

- Relationship of diatonic scales:
  - Fifth-neighbouring scales share 6 of 7 notes
  - Ordering of scales according to the **circle of fifths:**



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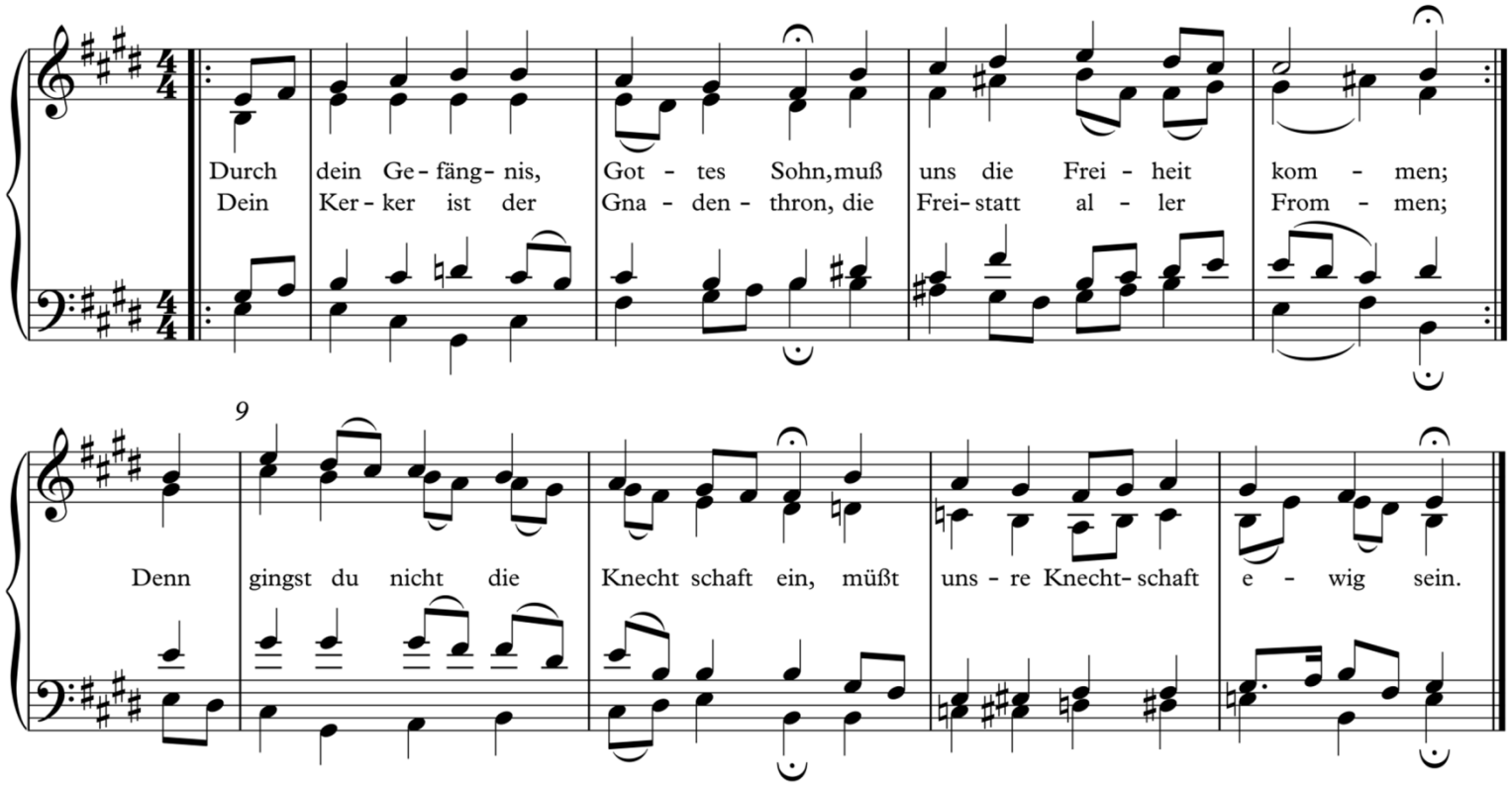
Visualization of Diatonic Scales

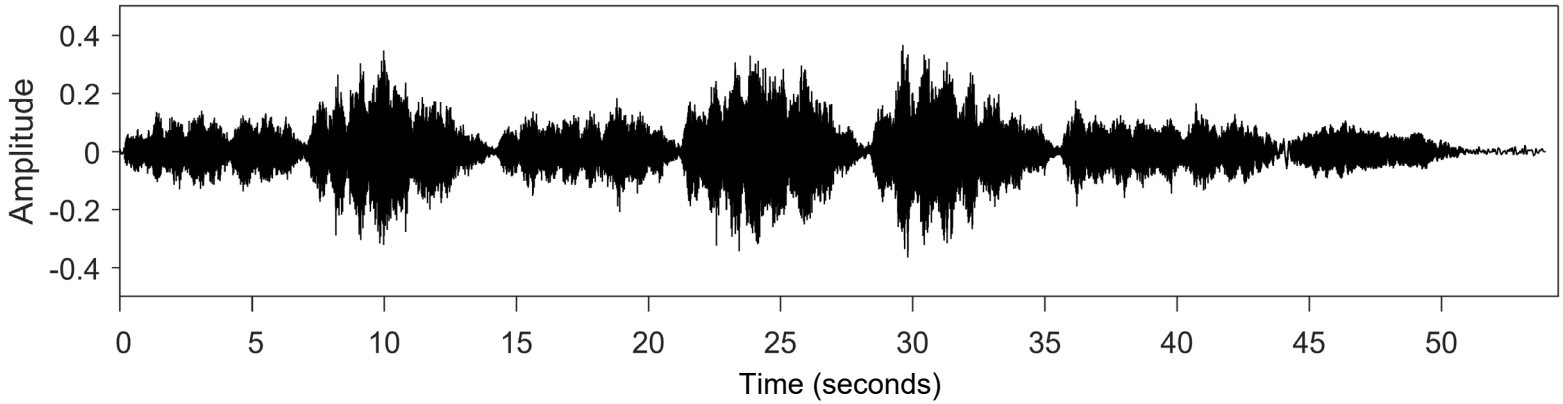
- Example: J.S. Bach, Choral "Durch Dein Gefängnis" (*Johannespassion*)
- **Score** – Piano reduction



AUDIO LABS

Visualization of Diatonic Scales

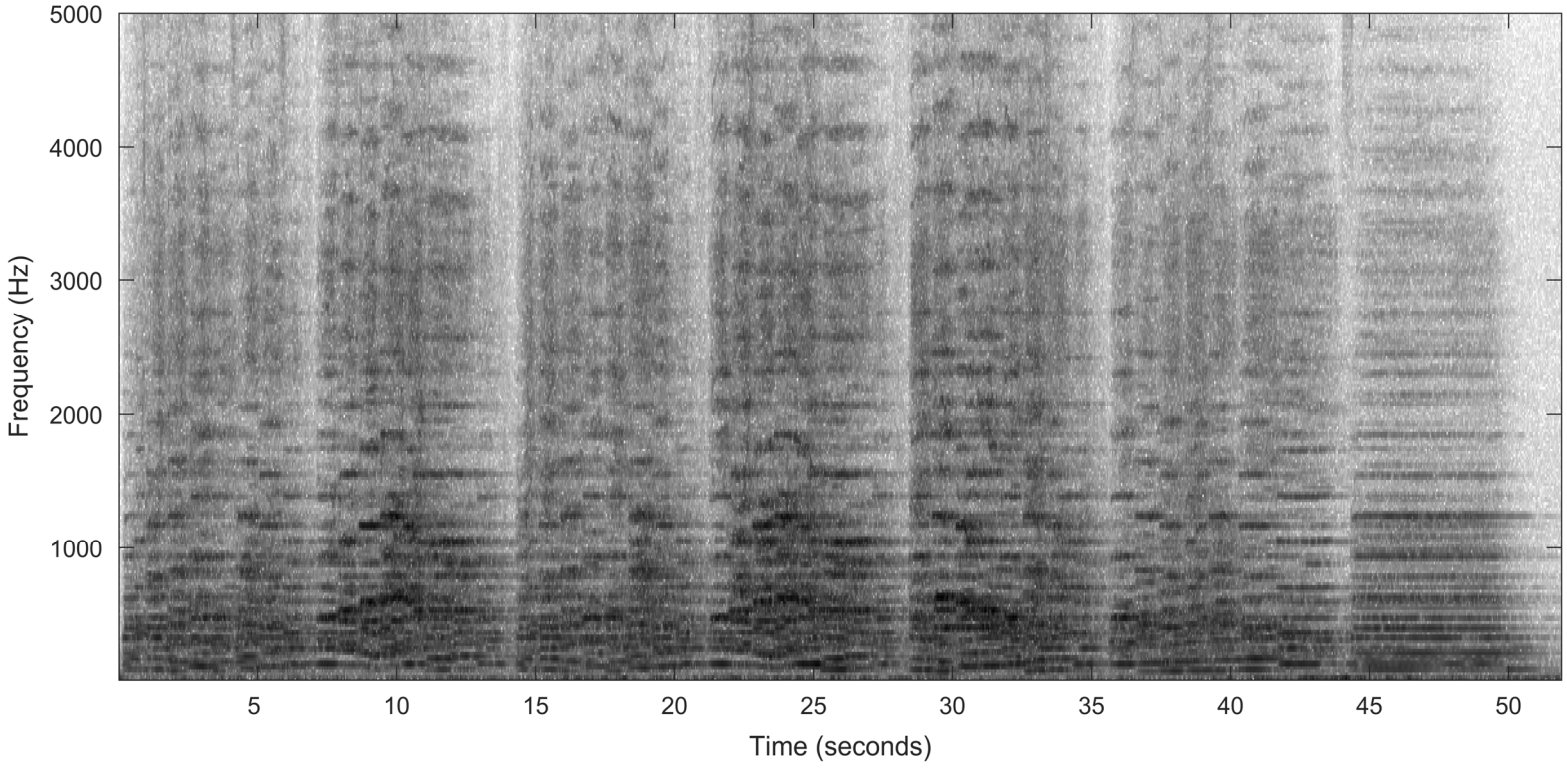
- Example: J.S. Bach, Choral "Durch Dein Gefängnis" (*Johannespassion*)
- **Audio** – Waveform (Scholars Baroque Ensemble, Naxos 1994)



AUDIO LABS

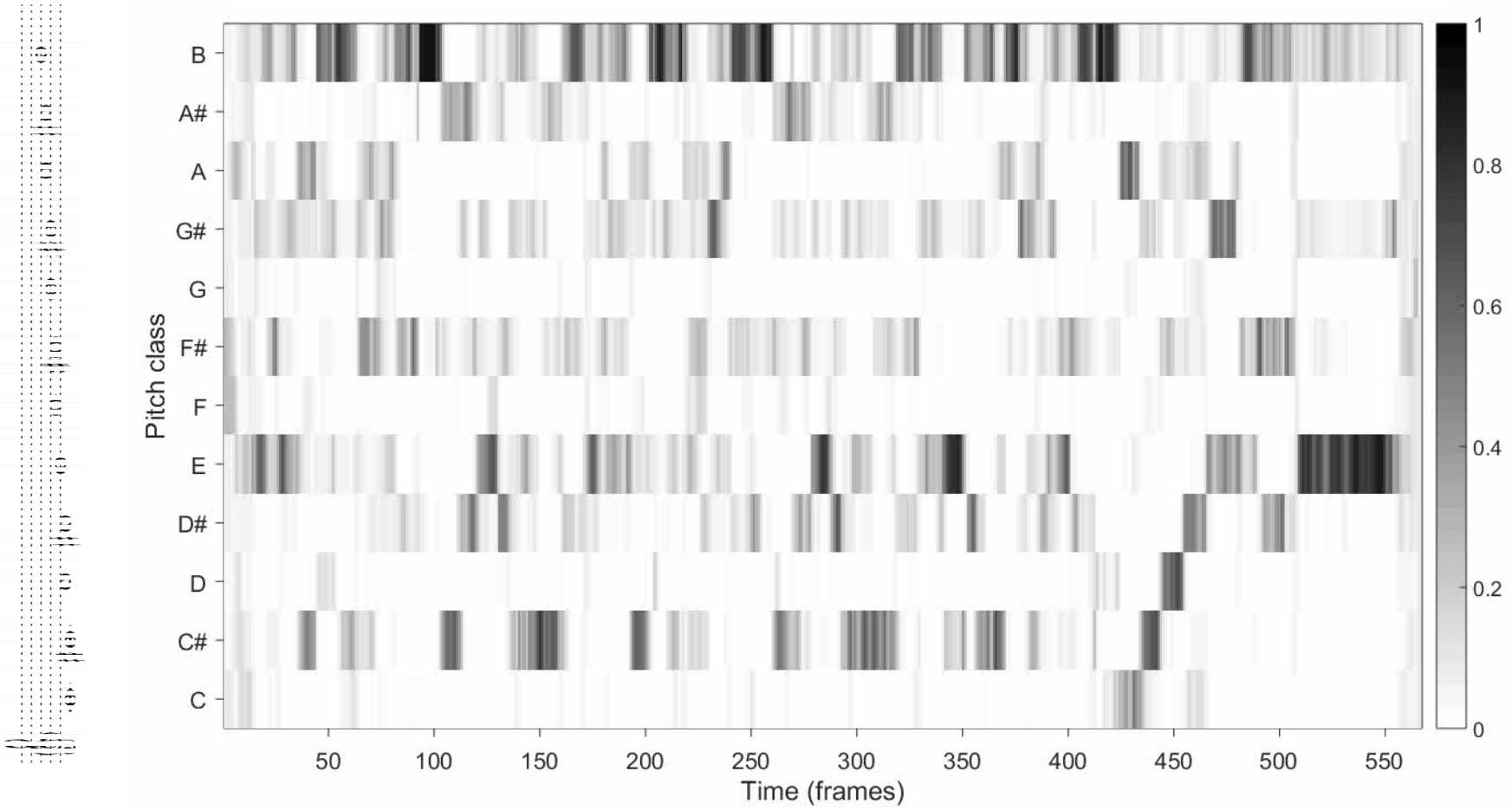
Visualization of Diatonic Scales

- Example: J.S. Bach, Choral "Durch Dein Gefängnis" (*Johannespassion*)
- **Audio** – Spectrogram (Scholars Baroque Ensemble, Naxos 1994)



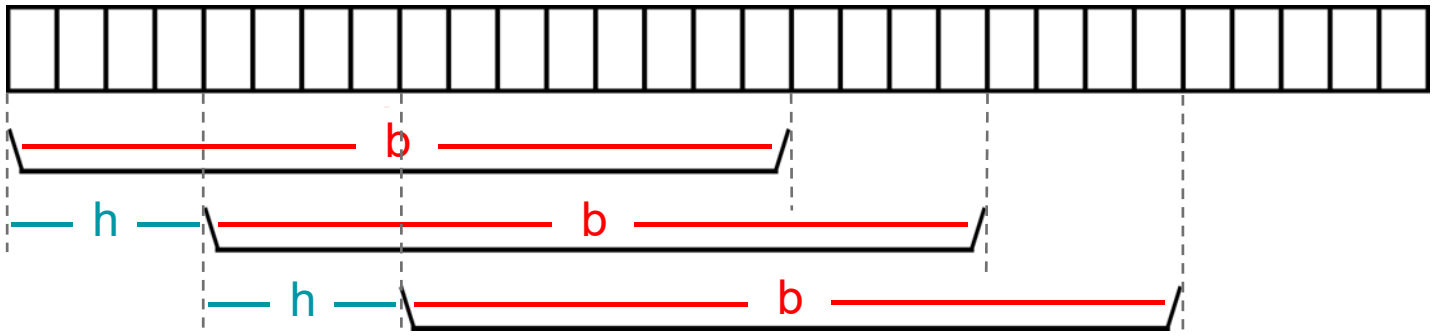
Visualization of Diatonic Scales

- Example: J.S. Bach, Choral "Durch Dein Gefängnis" (*Johannespassion*)
- **Audio** – Chroma features (Scholars Baroque Ensemble, Naxos 1994)



Visualization of Diatonic Scales

- Summarize pitch classes over a certain time
  - **Chroma smoothing**
  - Parameters: blocksize b and hopsize h



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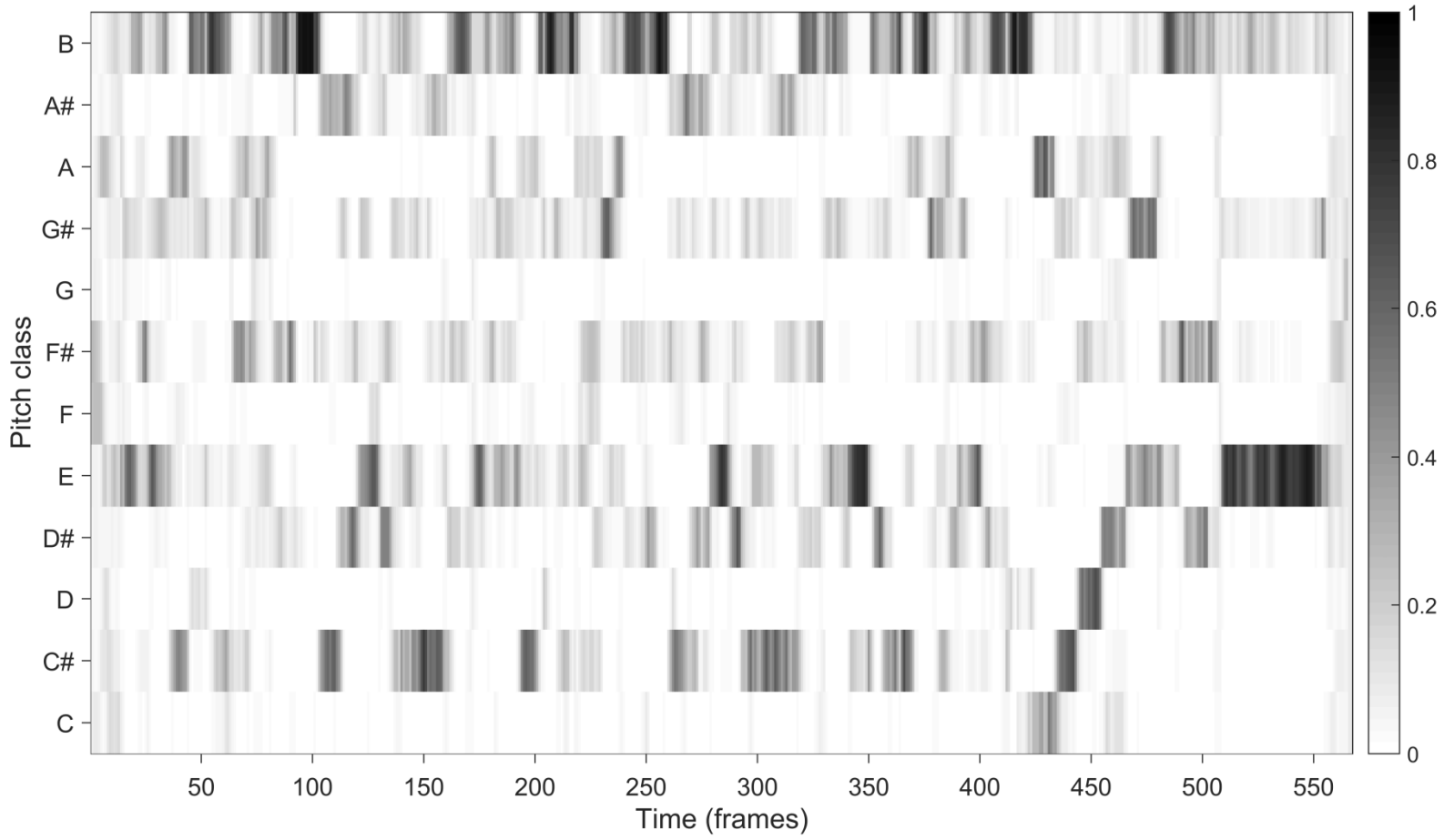
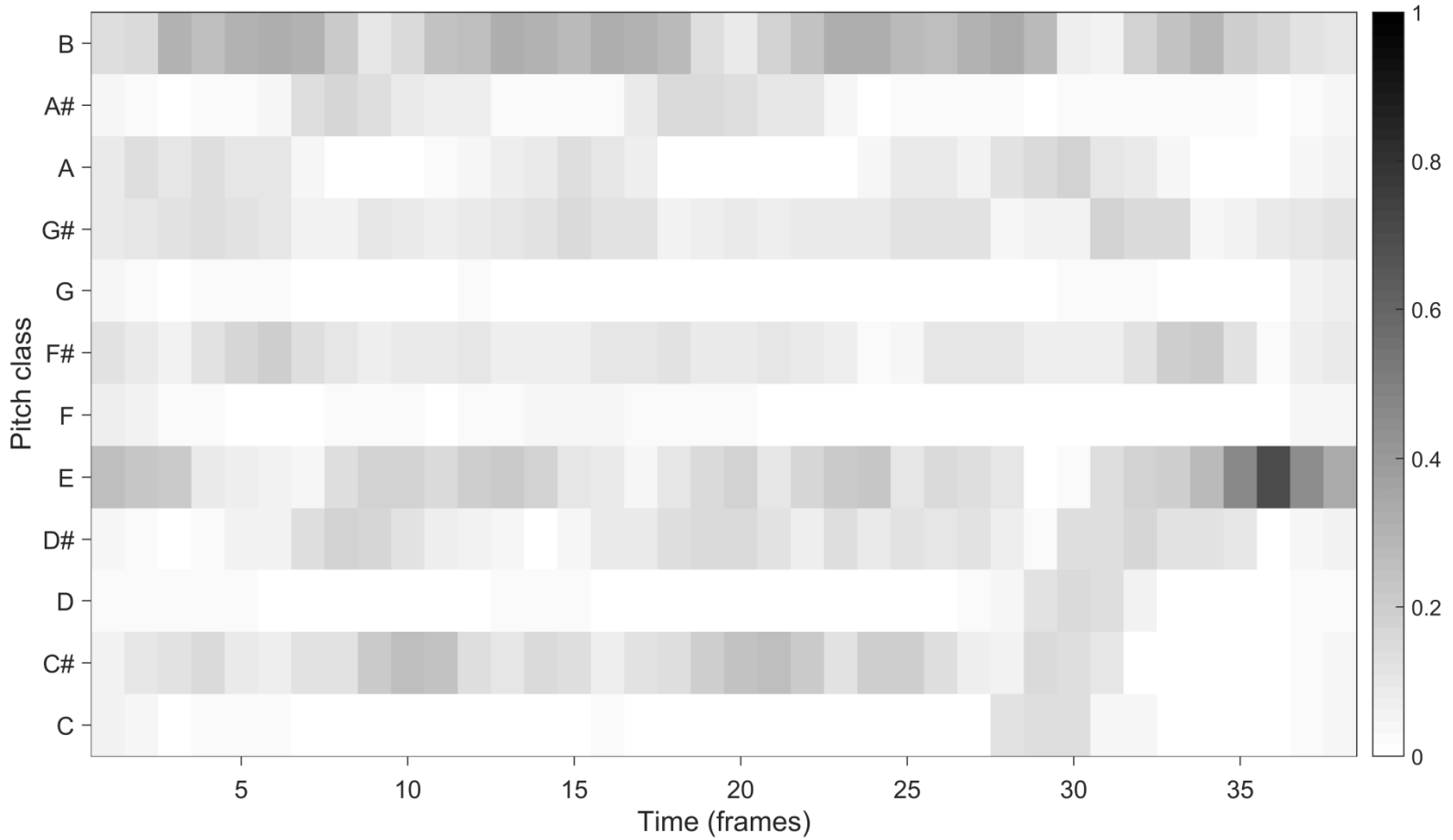
Visualization of Diatonic Scales

- Choral (Bach)



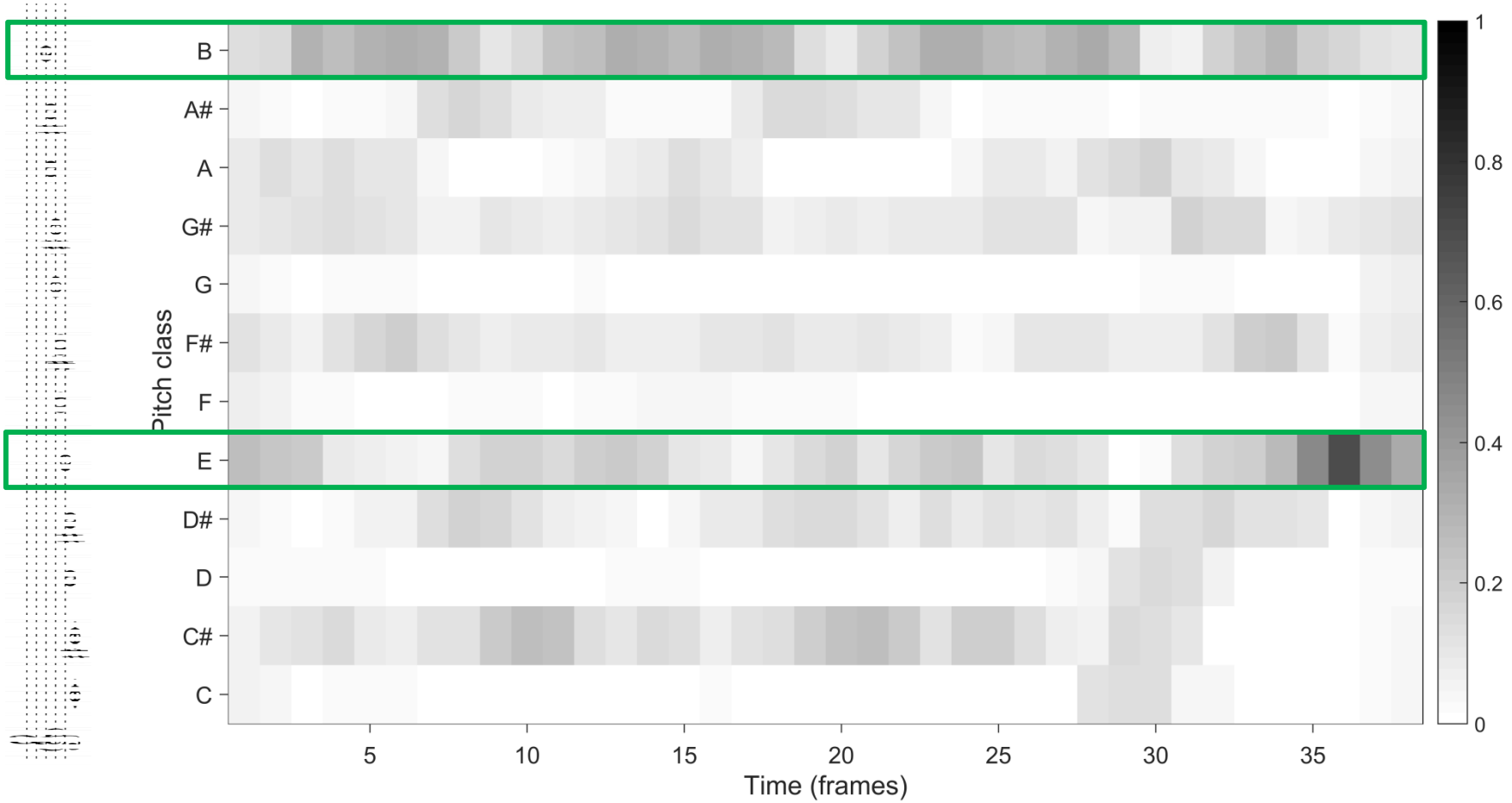
Visualization of Diatonic Scales

- Choral (Bach) — smoothed with b = 42 and h = 15



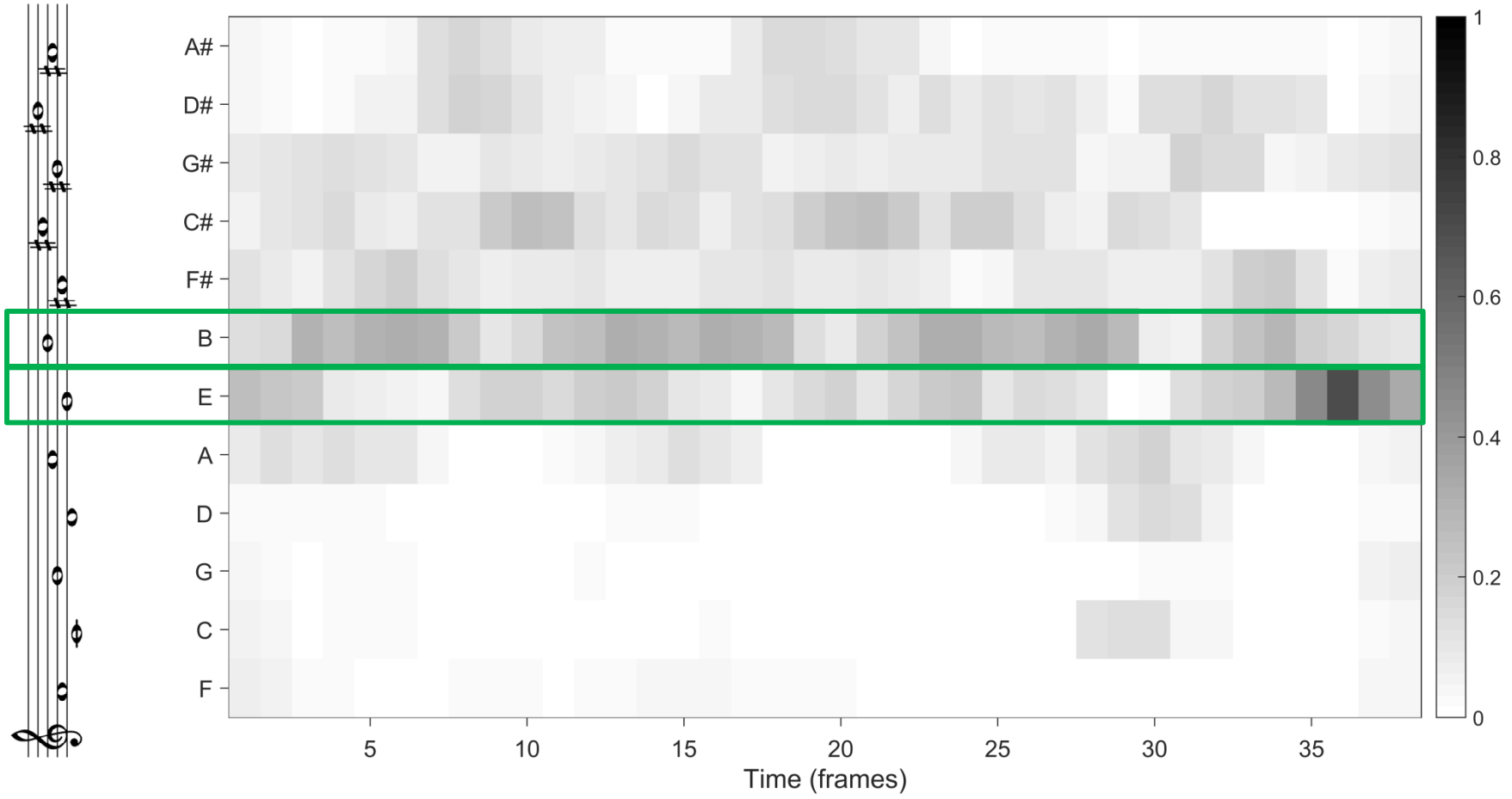
Visualization of Diatonic Scales

- Choral (Bach) — Re-ordering to **perfect fifth** series



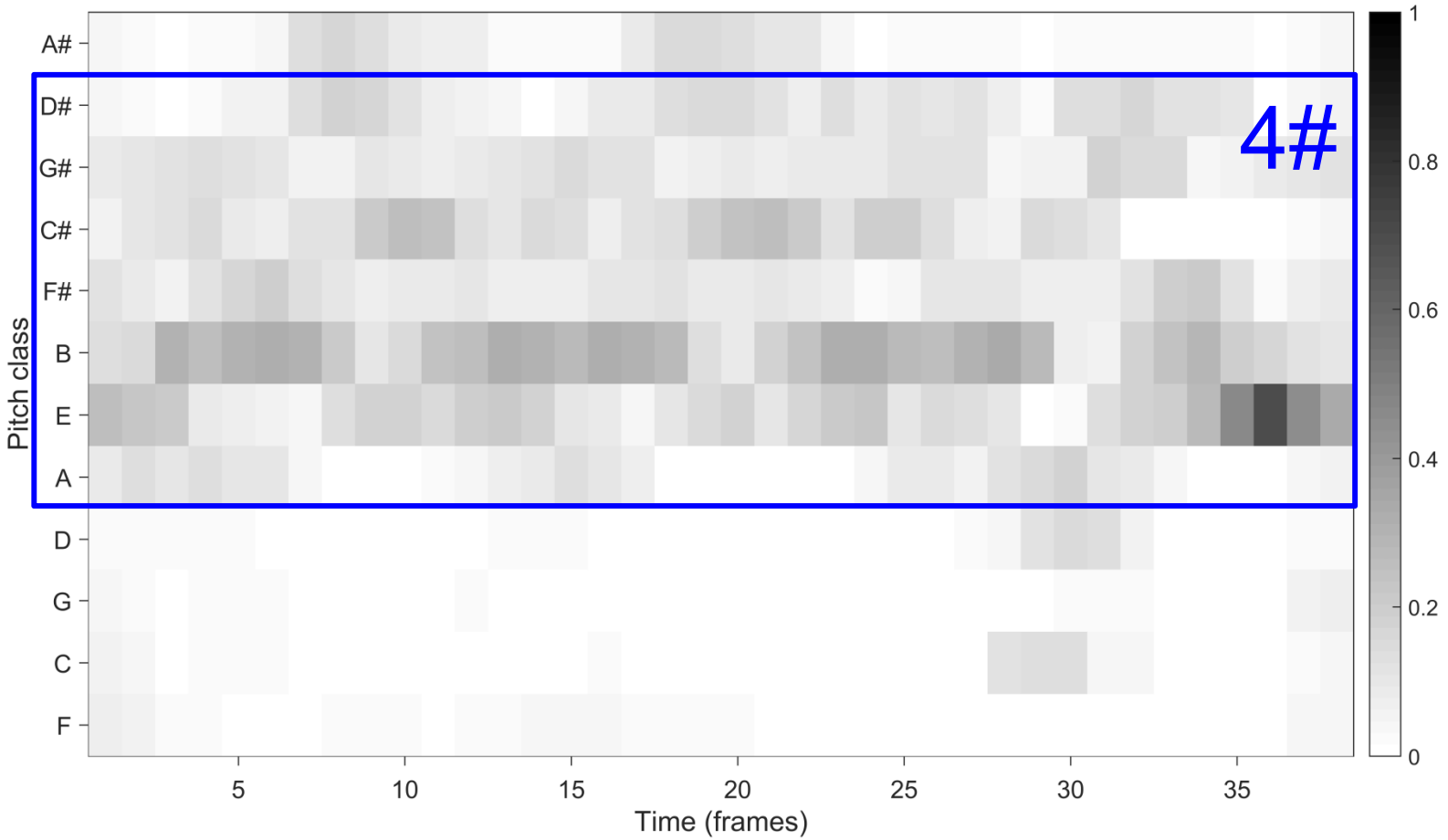
Visualization of Diatonic Scales

- Choral (Bach) — Re-ordering to **perfect fifth** series



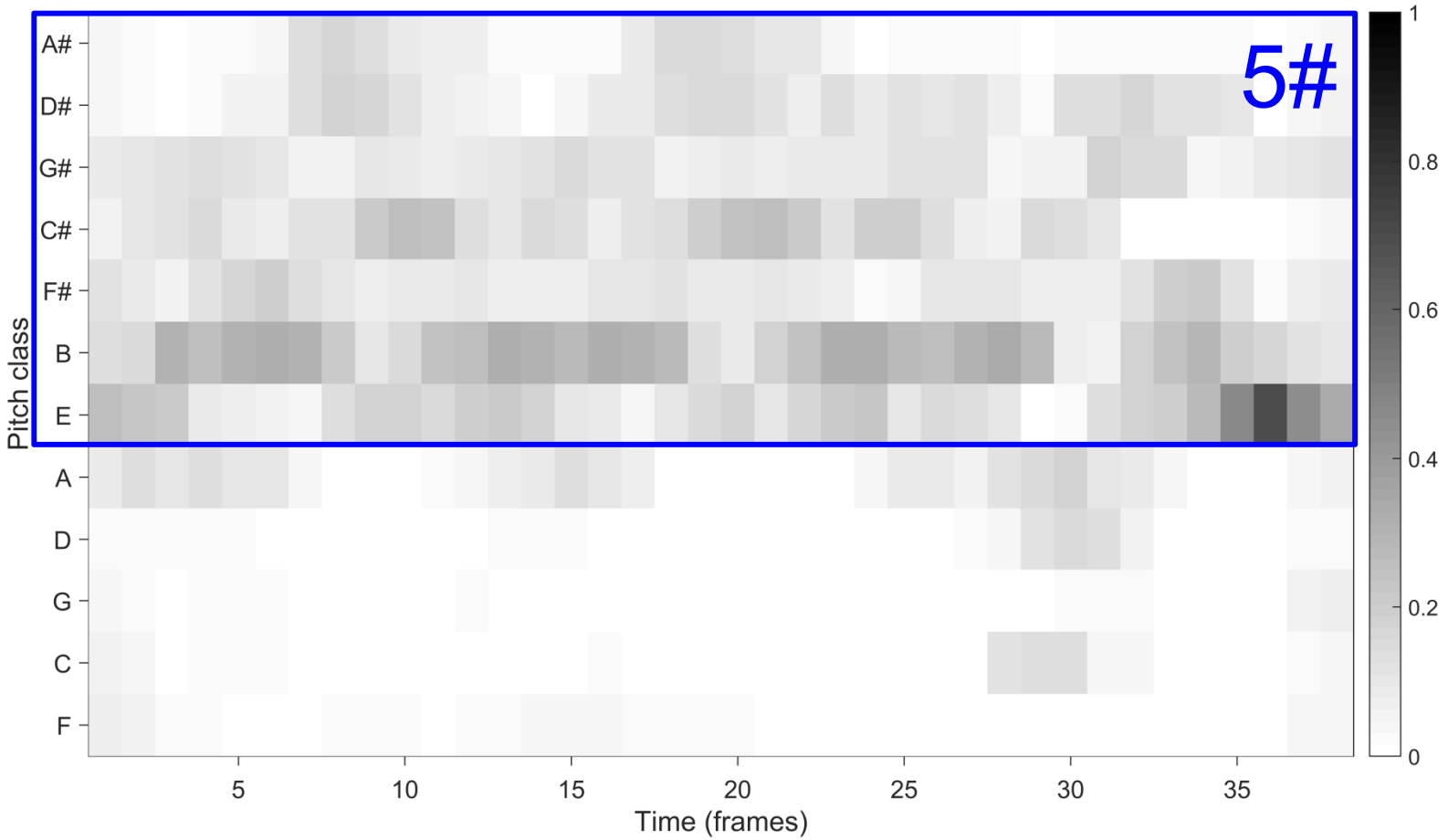
Visualization of Diatonic Scales

- Choral (Bach) — Diatonic Scale Estimation (7 fifths)



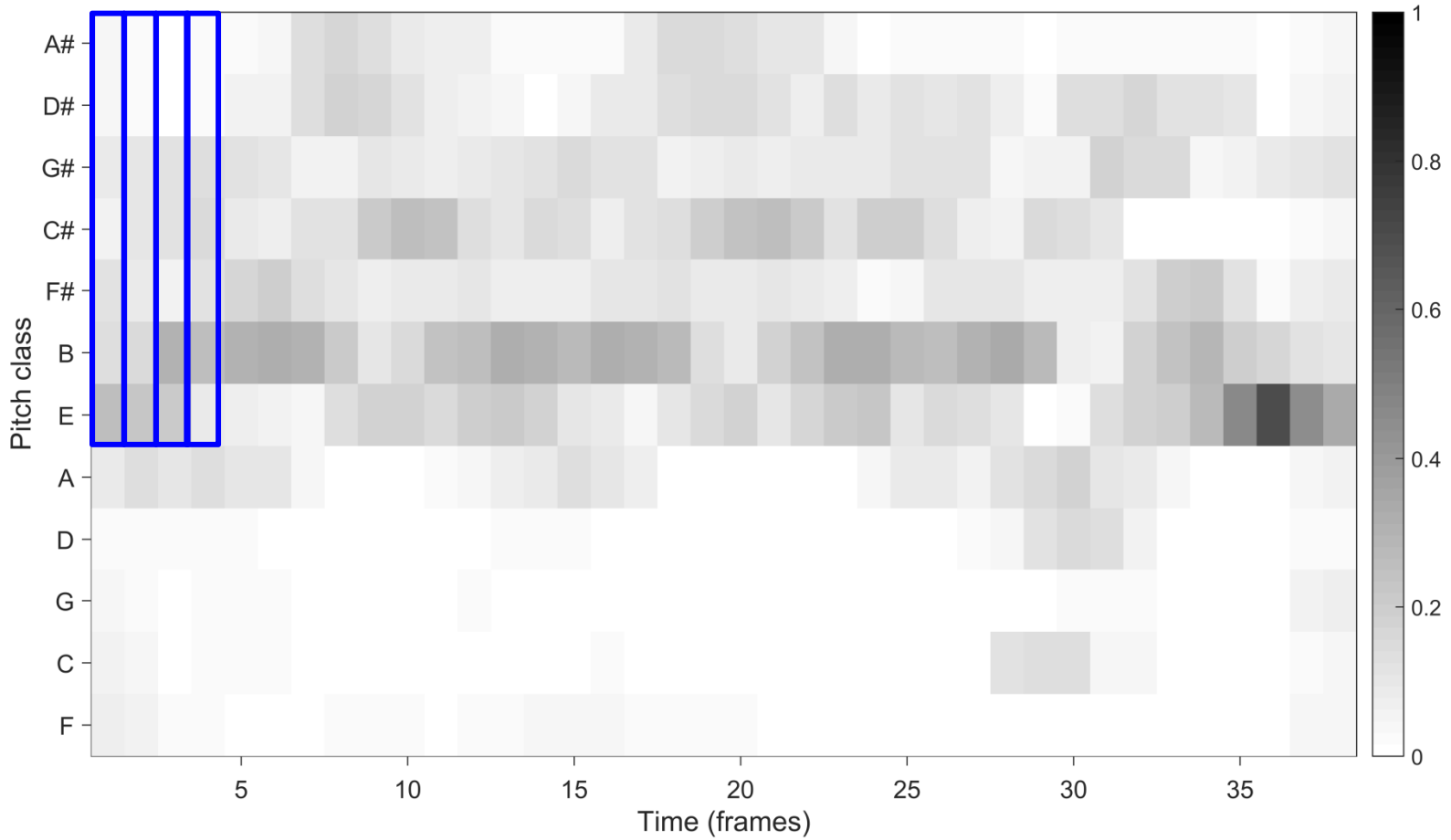
Visualization of Diatonic Scales

- Choral (Bach) — Diatonic Scale Estimation (7 fifths)



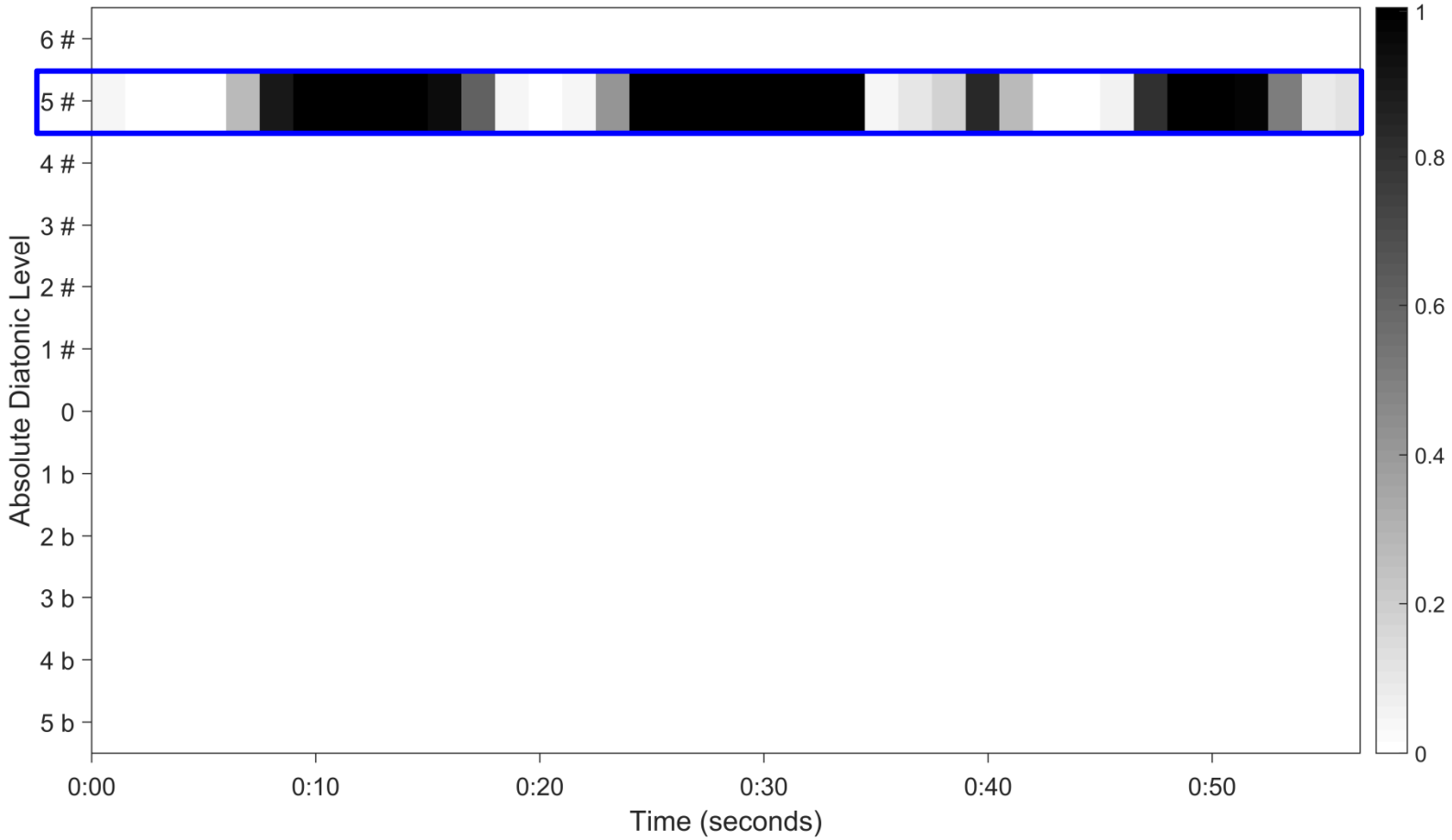
Visualization of Diatonic Scales

- Choral (Bach) — Diatonic Scale Estimation: Multiply chroma values



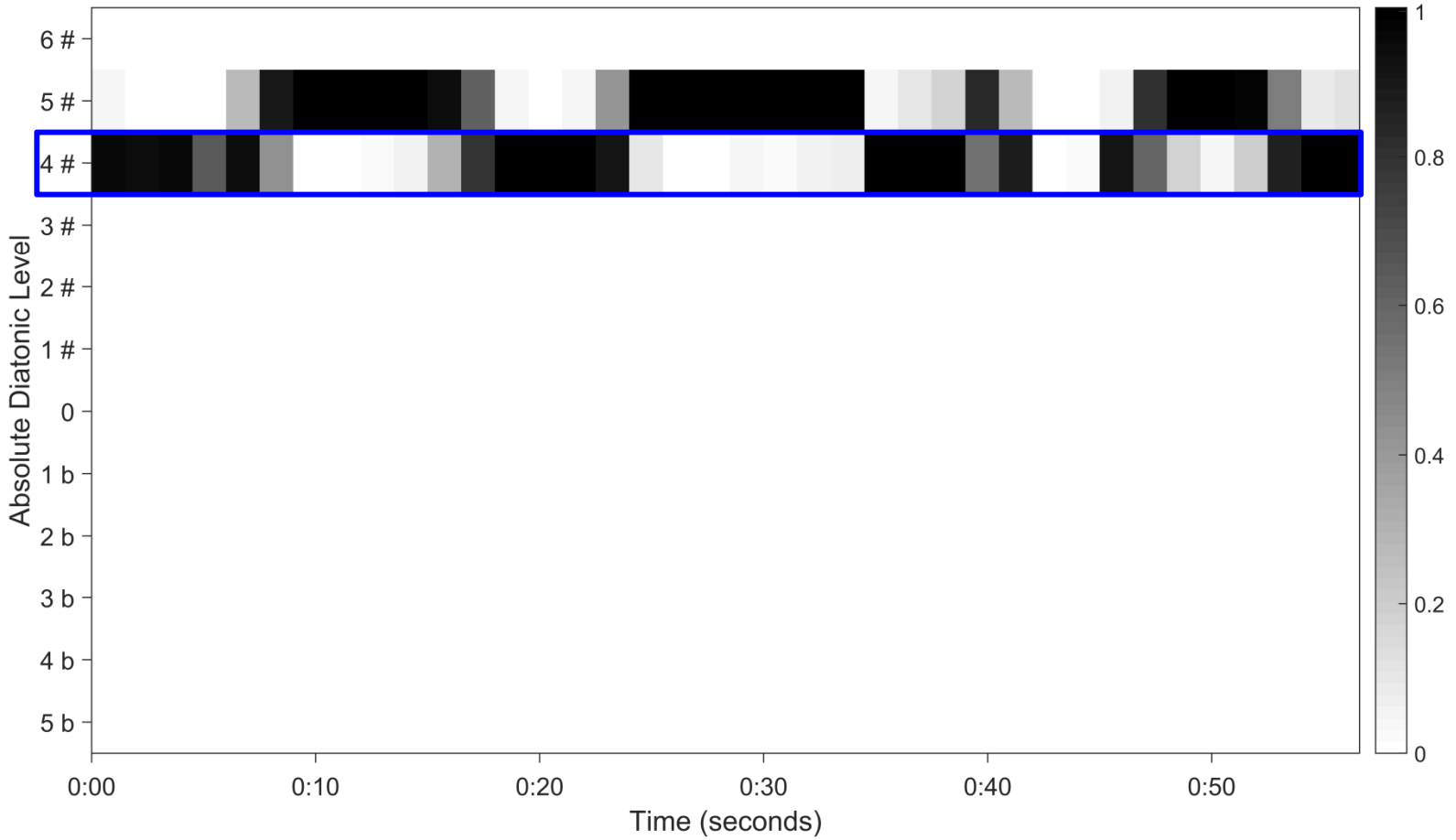
Visualization of Diatonic Scales

- Choral (Bach) — Diatonic Scale Estimation: Multiply chroma values



Visualization of Diatonic Scales

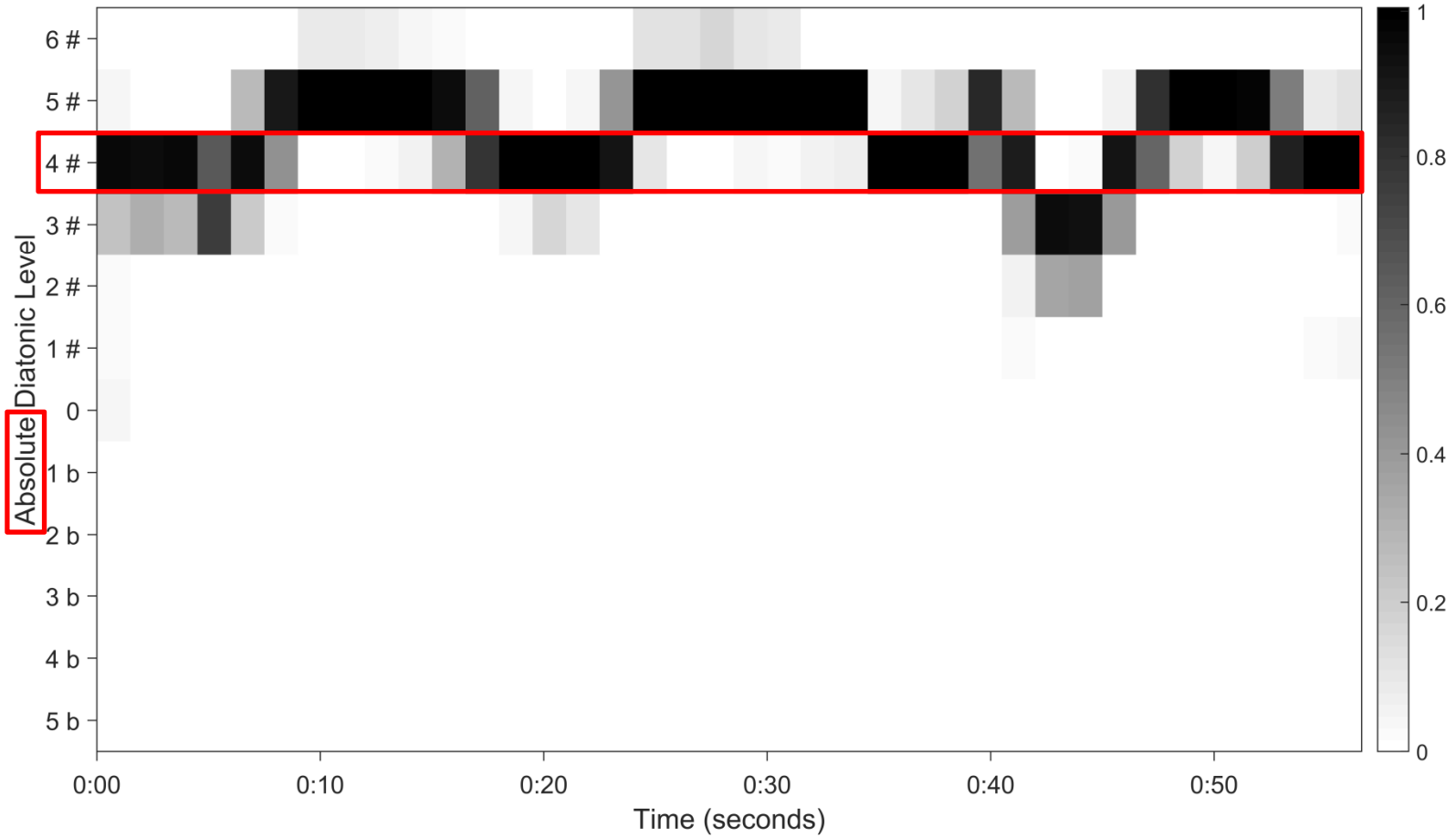
- Choral (Bach) — Diatonic Scale Estimation



Visualization of Diatonic Scales

- Choral (Bach) — Diatonic Scale Estimation

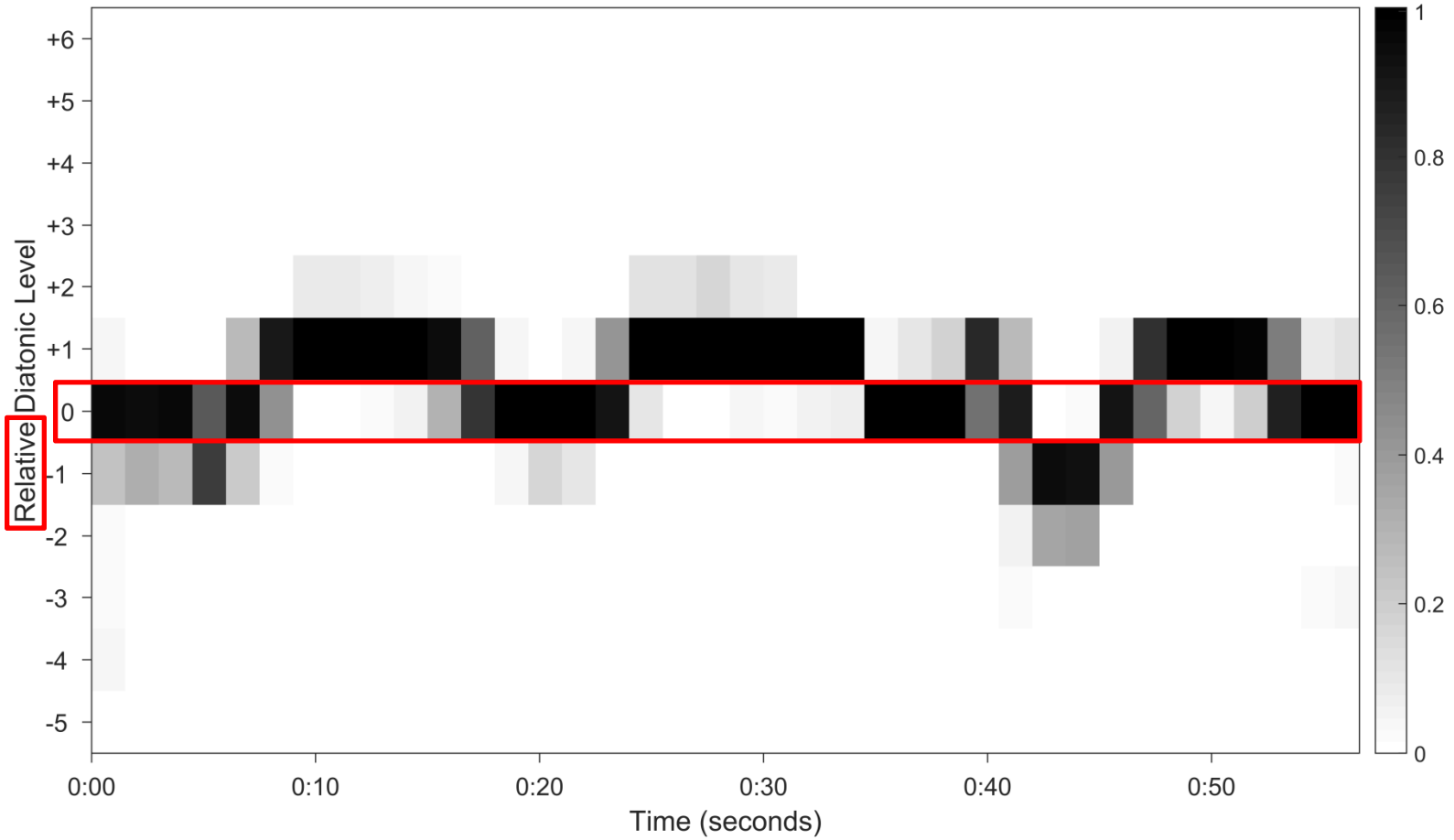
4 #
(E major)



Visualization of Diatonic Scales

- Choral (Bach) — Diatonic Scale Estimation: Shift to **global key**

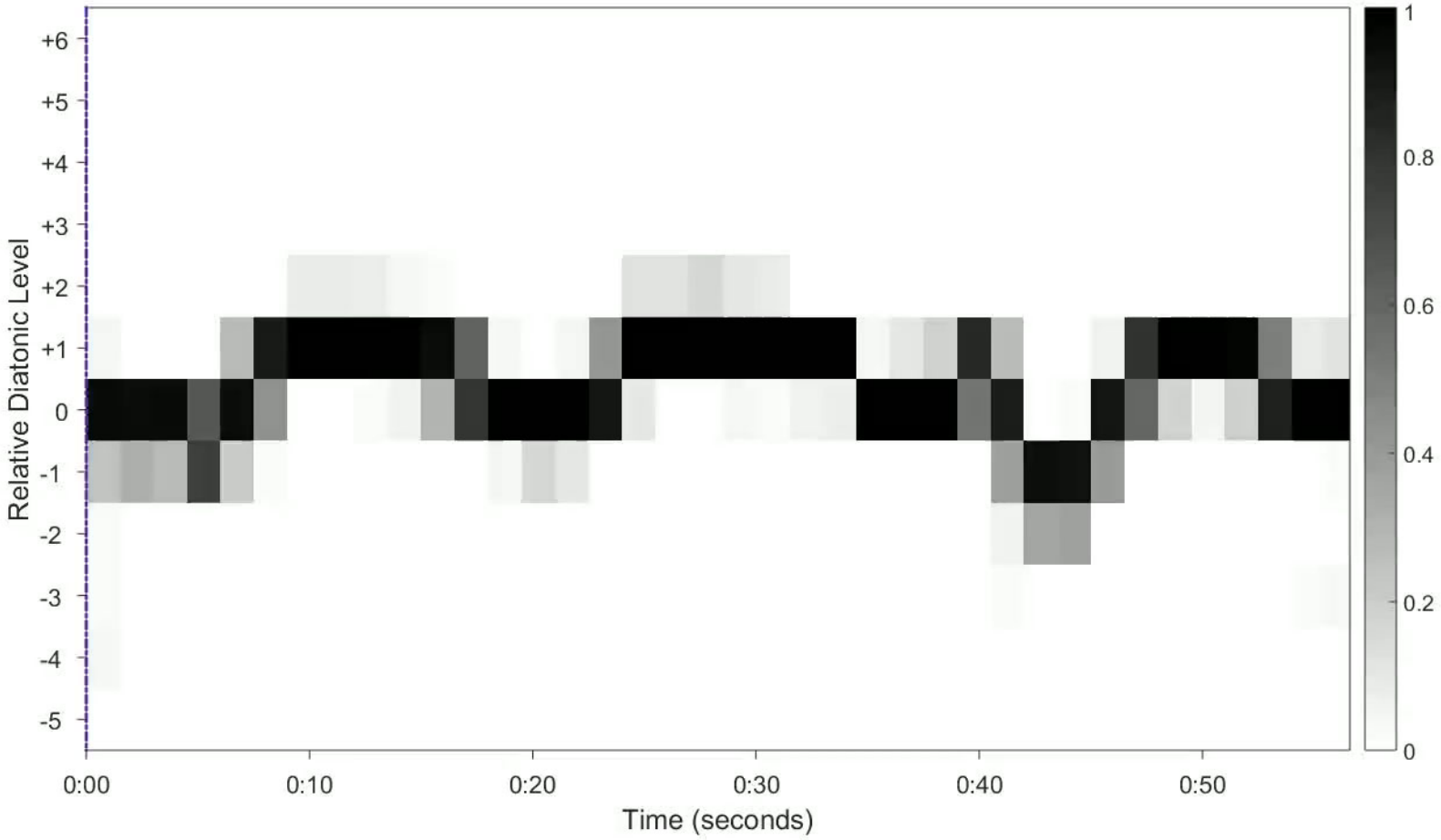
4 #
(E major)



Visualization of Diatonic Scales

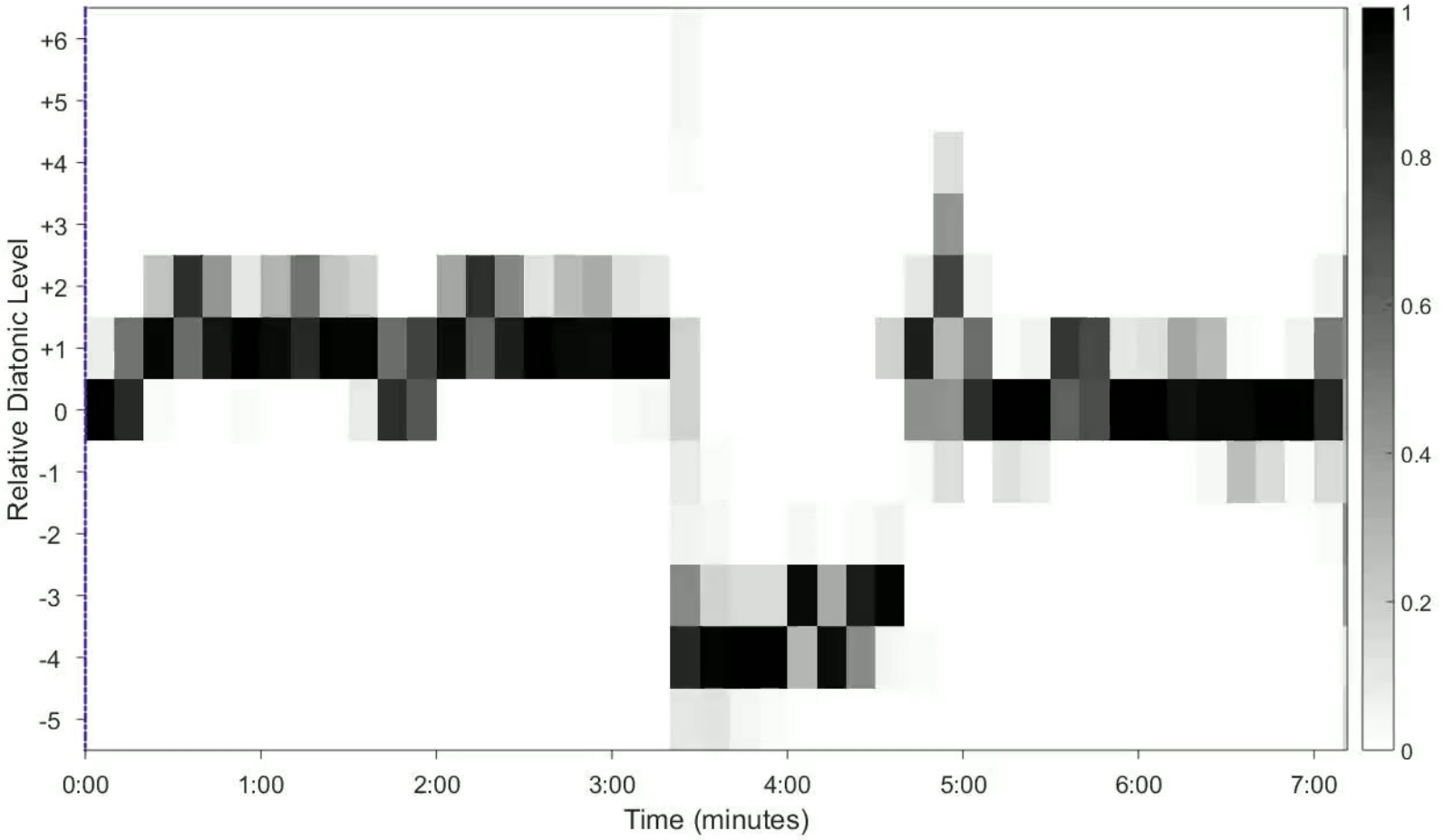
- Choral (Bach) — 0 ≙ 4#

C. Weiß, J. Habryka, “Chroma-Based Scale Matching for Audio Tonality Analysis” In: *Proceedings of the 9th Conference on Interdisciplinary Musicology*, Berlin 2014.



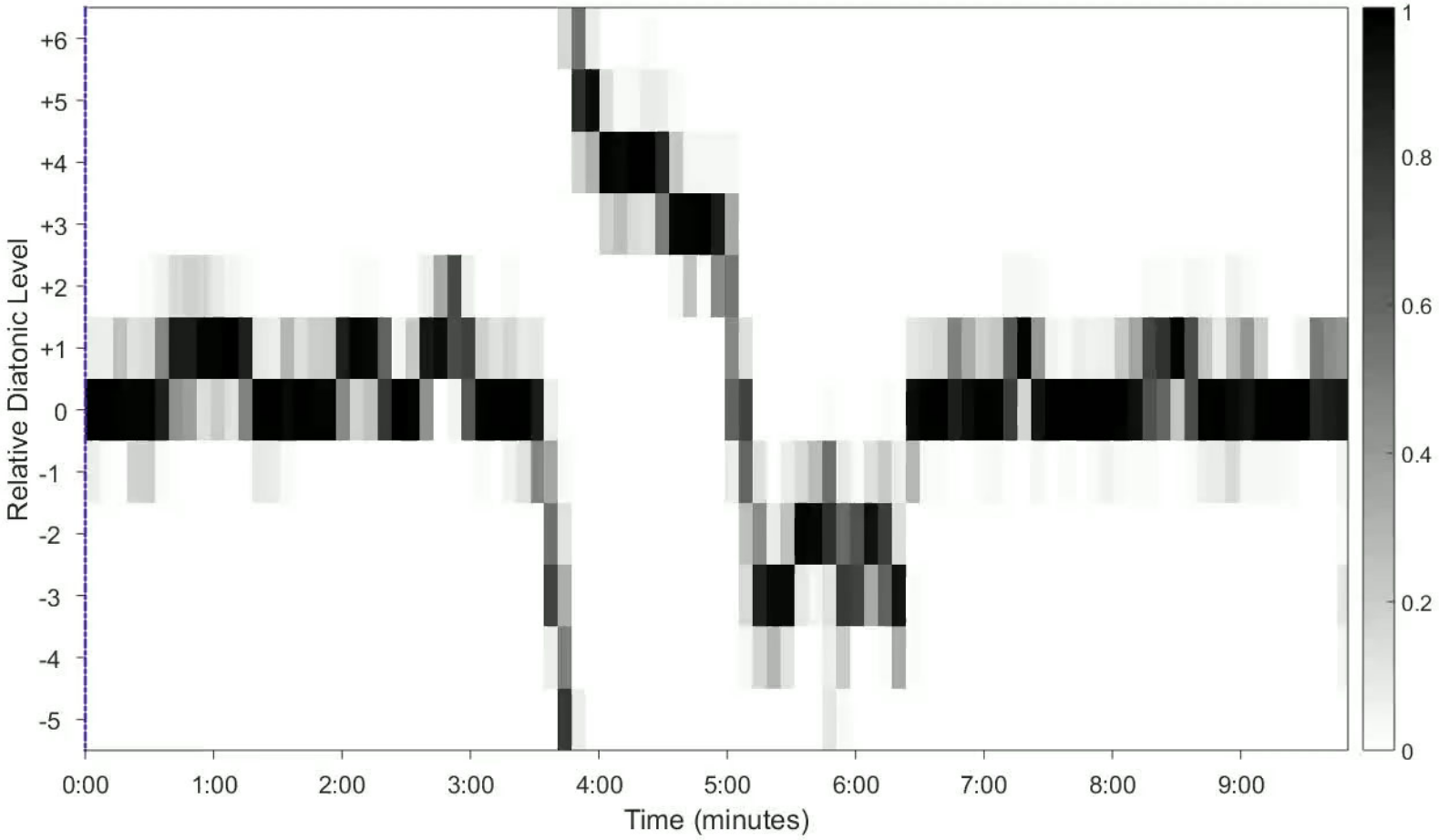
Visualization of Diatonic Scales

- L. v. Beethoven – Sonata No. 10 op. 14 Nr. 2, 1. Allegro — 0 ≙ 1
  (Barenboim, EMI 1998)

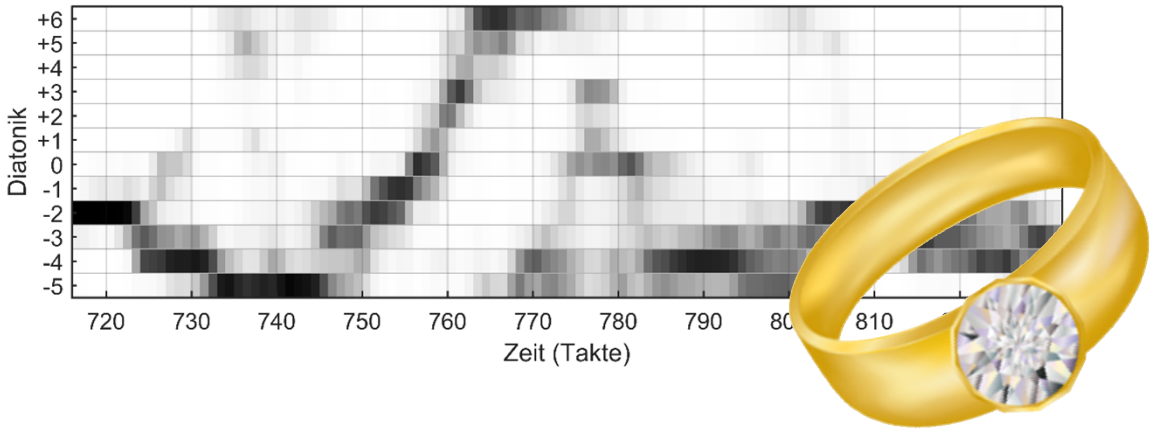


Visualization of Diatonic Scales

- R. Wagner, *Die Meistersinger von Nürnberg*, Vorspiel — 0 ≙ 0
  (Polish National Radio Symphony Orchestra, J. Wildner, Naxos 1993)



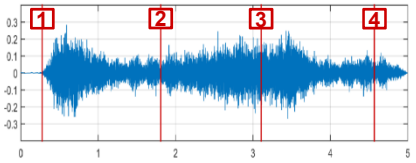
3. Cross-Version Tonality Analysis of the *Ring*



AUDIO LABS

Cross-Version Analysis

- Up to 18 versions
- 3 versions manually annotated



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

AUDIO LABS

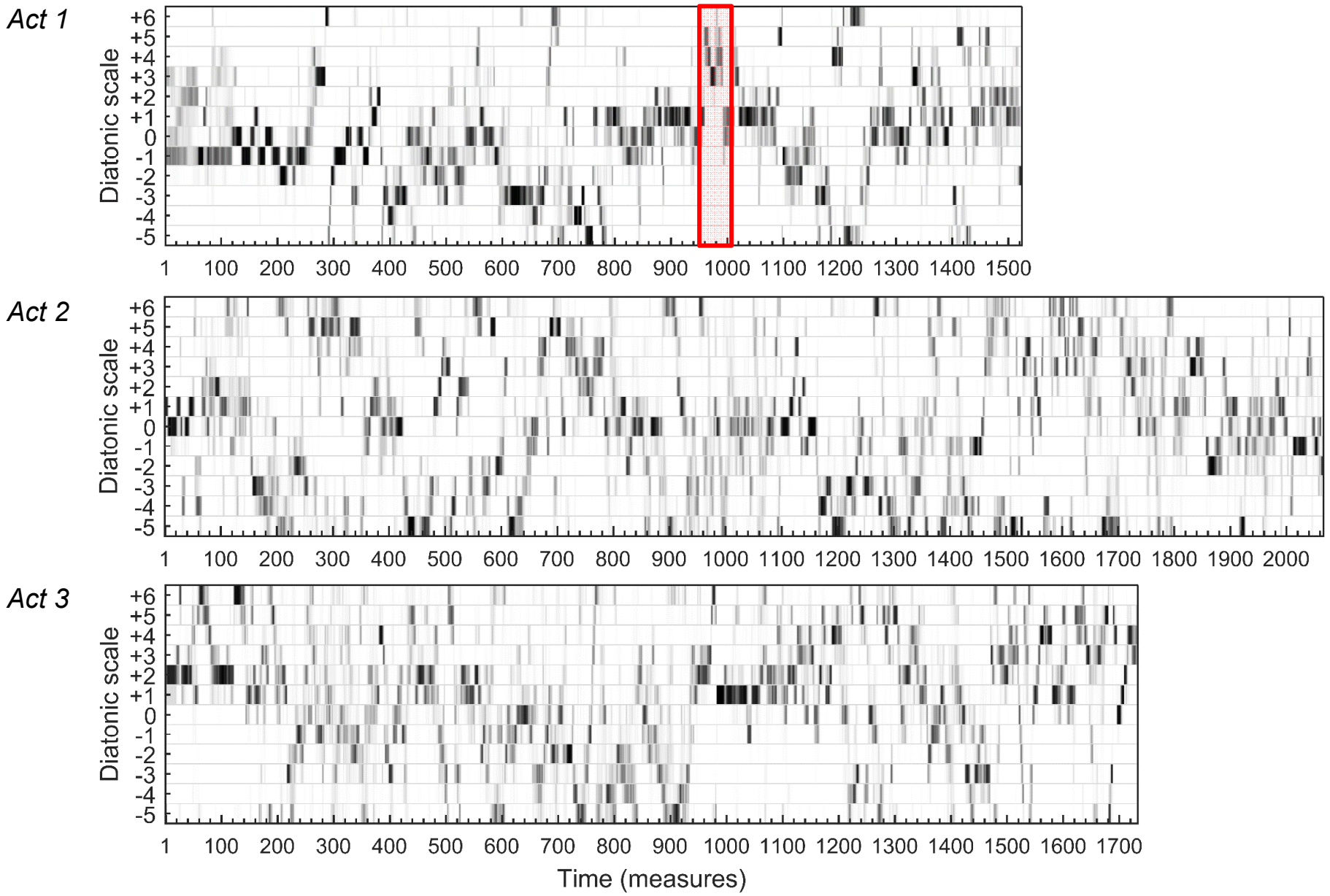
Cross-Version Analysis

- Idea: Use analysis results based on different interpretations (versions)
- Tonal characteristics should not depend on interpretation

→ Test reliability of the method

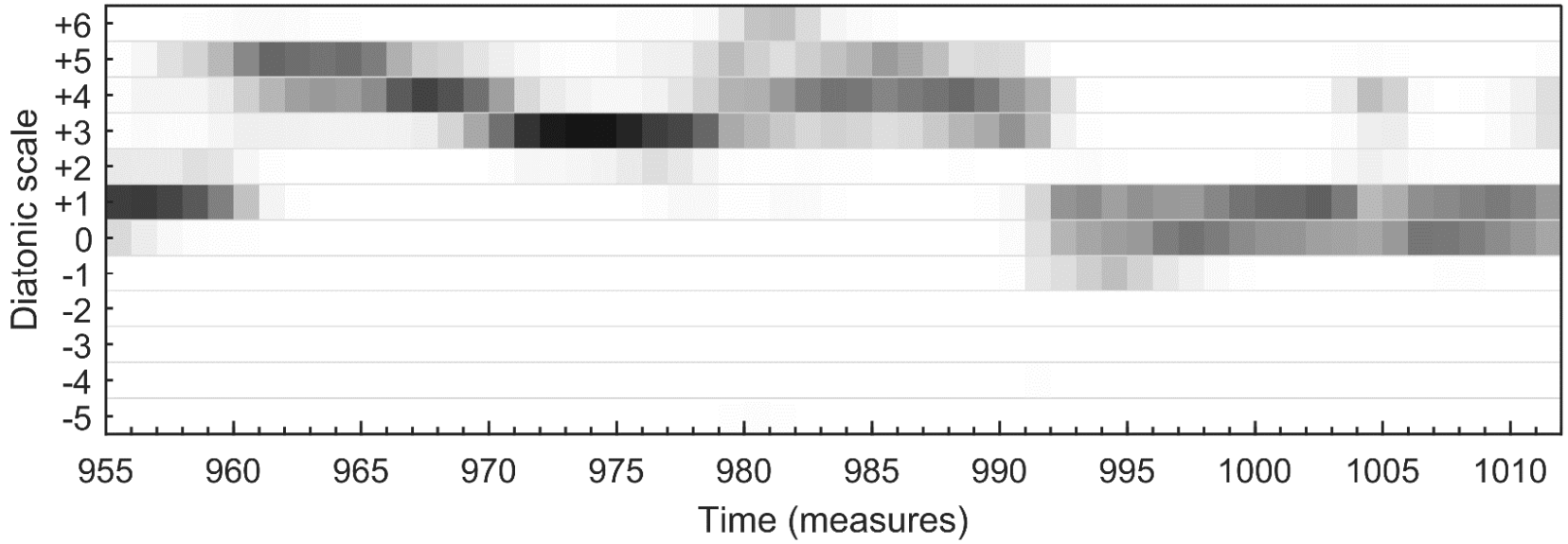
- Visualize consistency with gray scheme

Die Walküre WWV 86 B



Die Walküre WWV 86 B

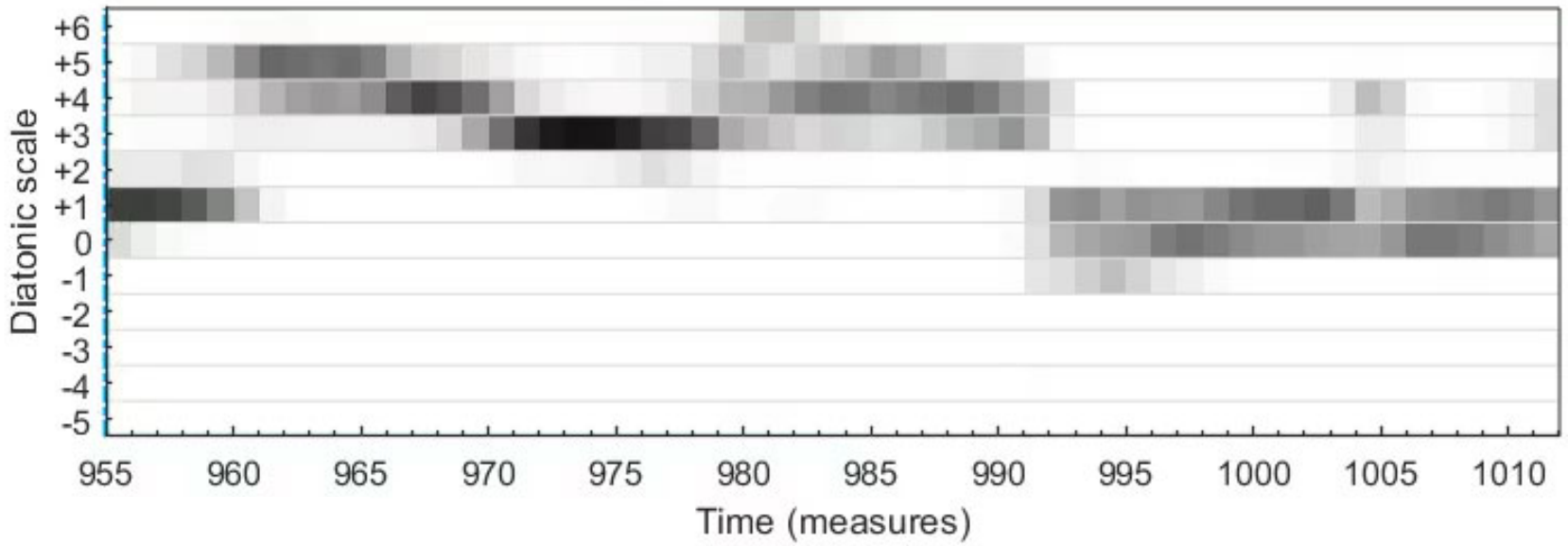
- Act 1, measures 955–1012
- Sieglinde´s narration



AUDIO LABS

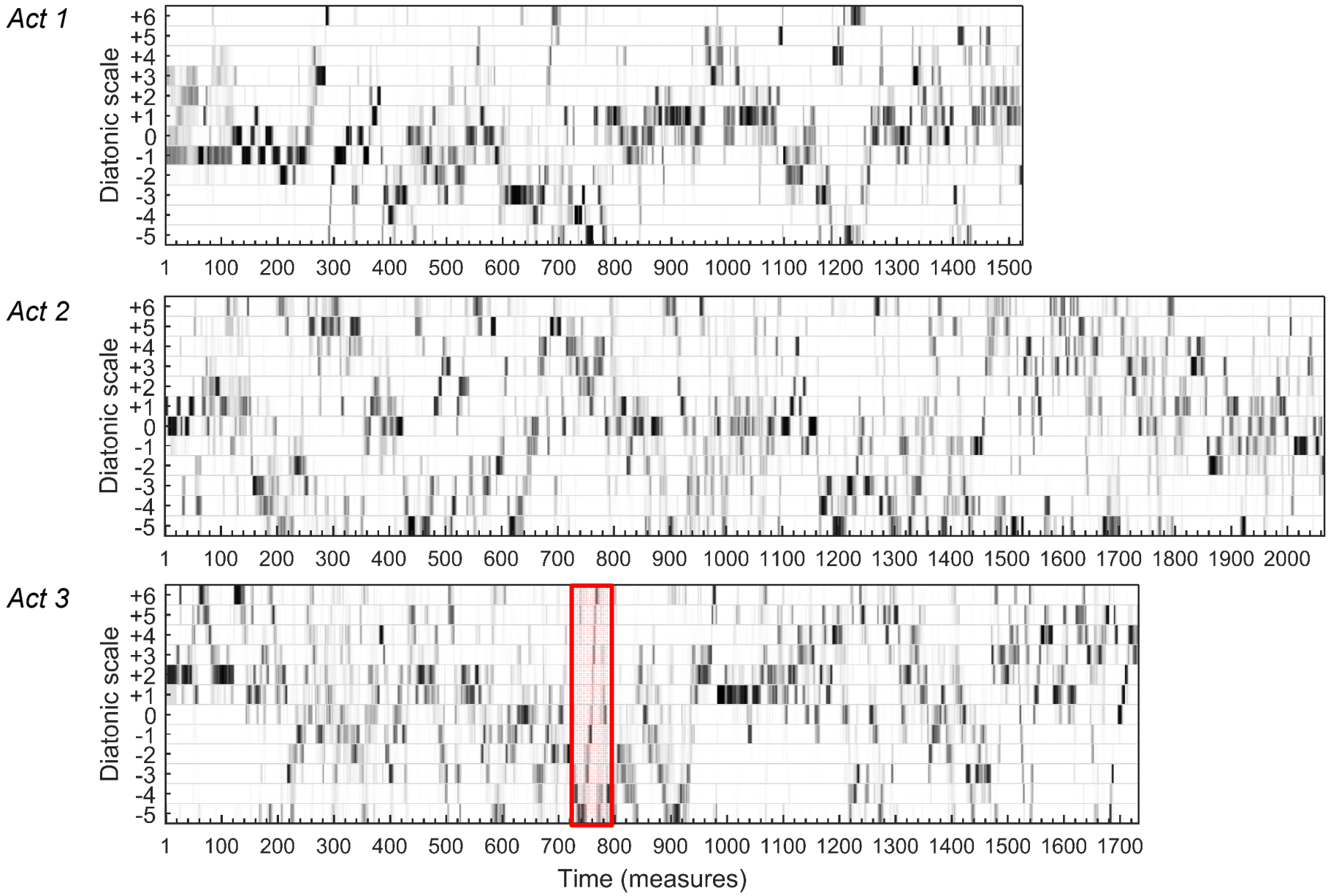
Die Walküre WWV 86 B

- Act 1, measures 955–1012
- Sieglinde´s narration



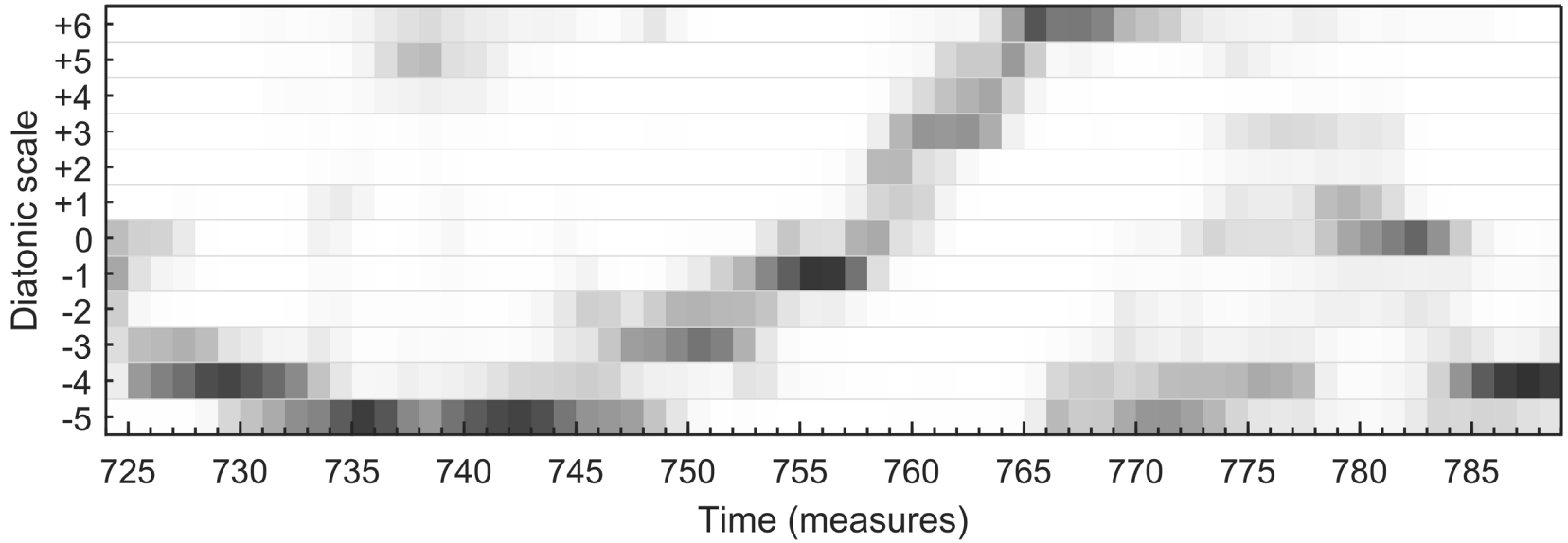
AUDIO LABS

Die Walküre WWV 86 B



Die Walküre WWV 86 B

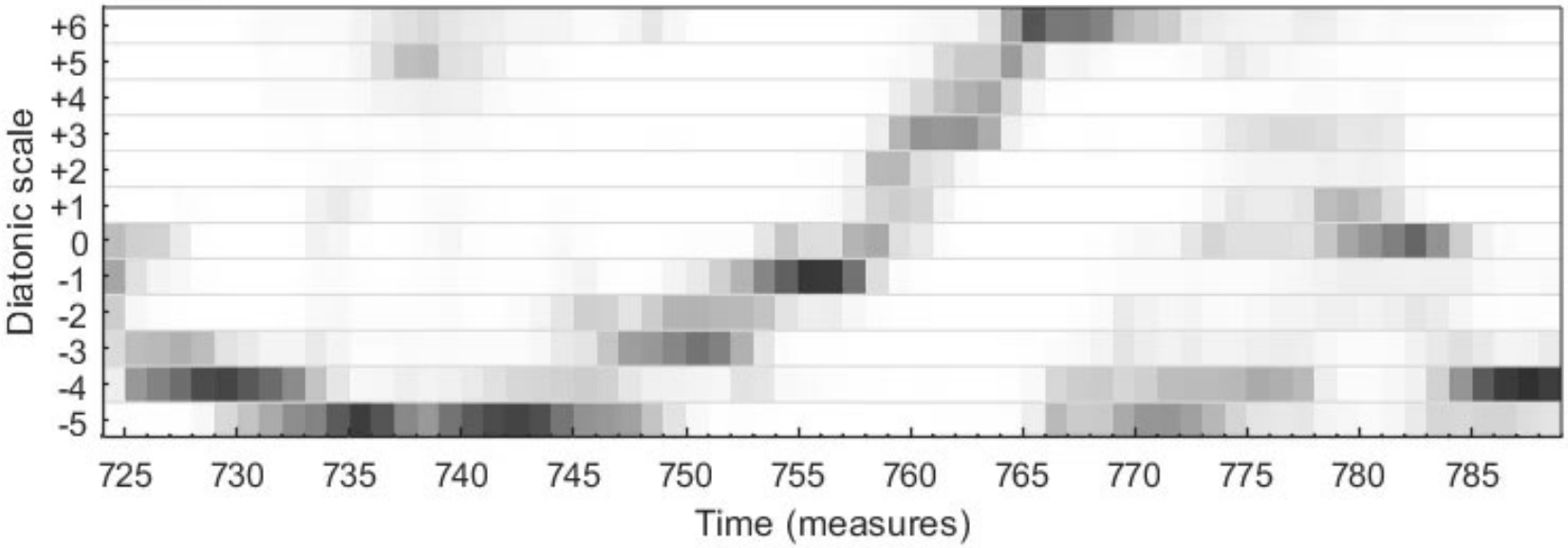
- Act 3, measures 724–789
- Wotan´s punishment



AUDIO LABS

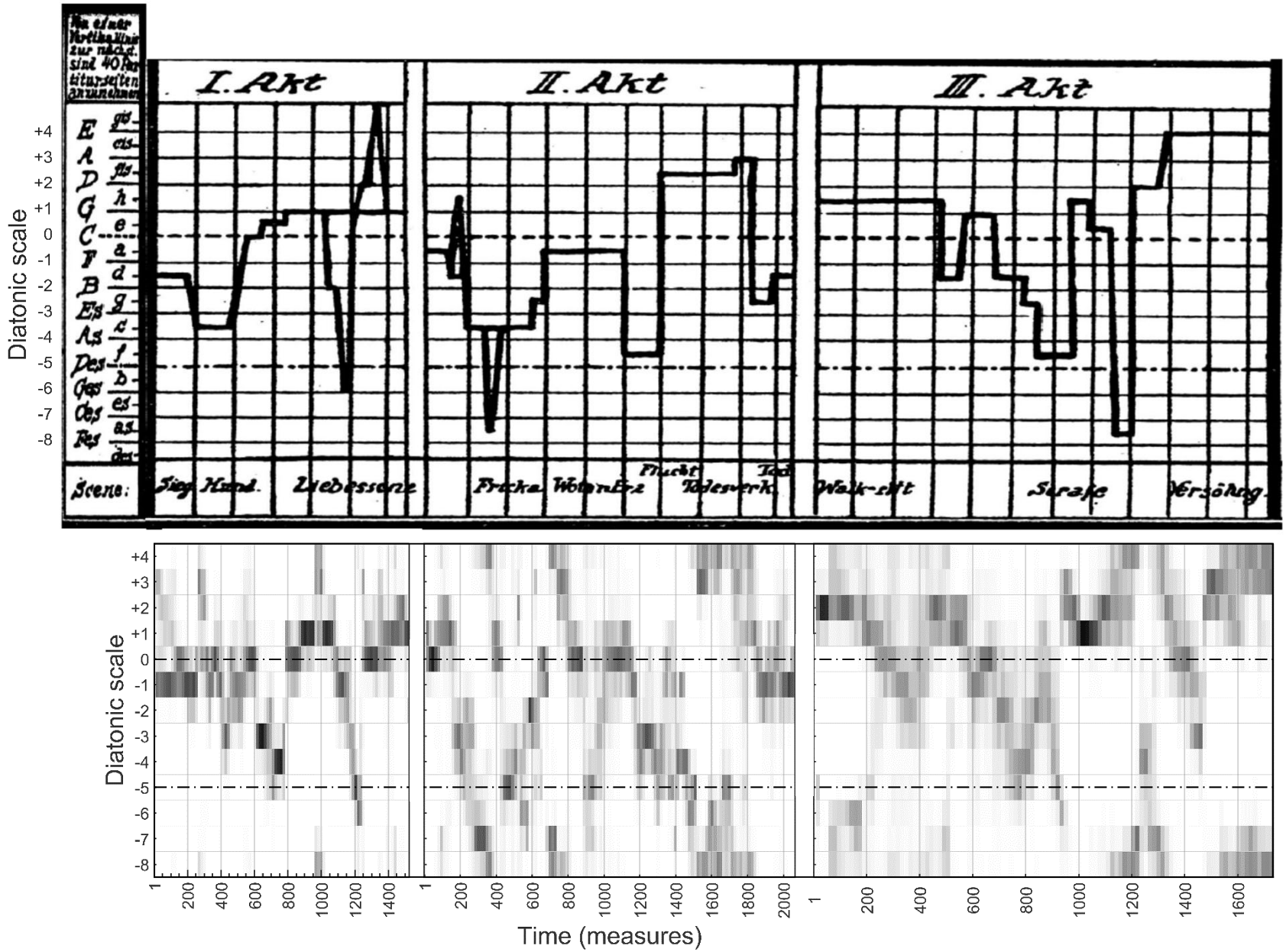
Die Walküre WWV 86 B

- Act 3, measures 724–789
- Wotan´s punishment



AUDIO LABS

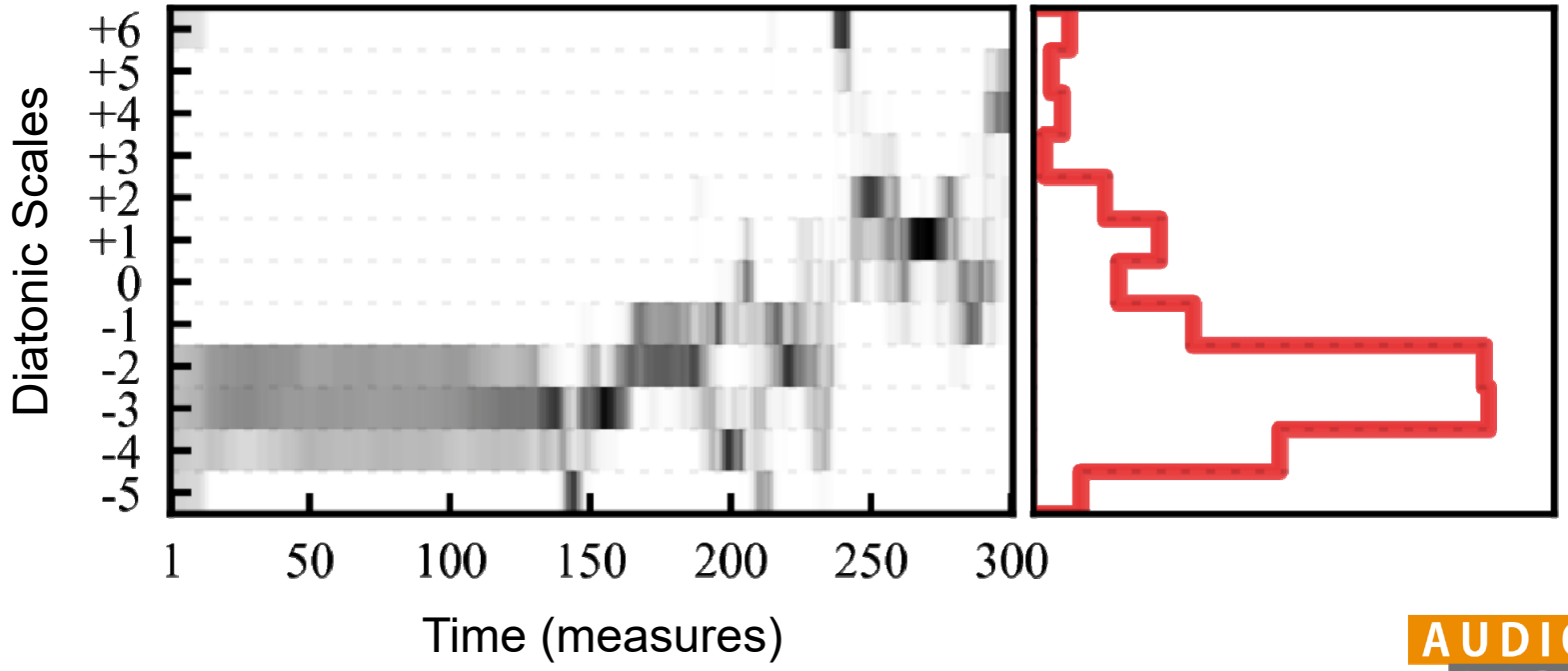
Die Walküre WWV 86 B



Exploring Tonal-Dramatic Relationships

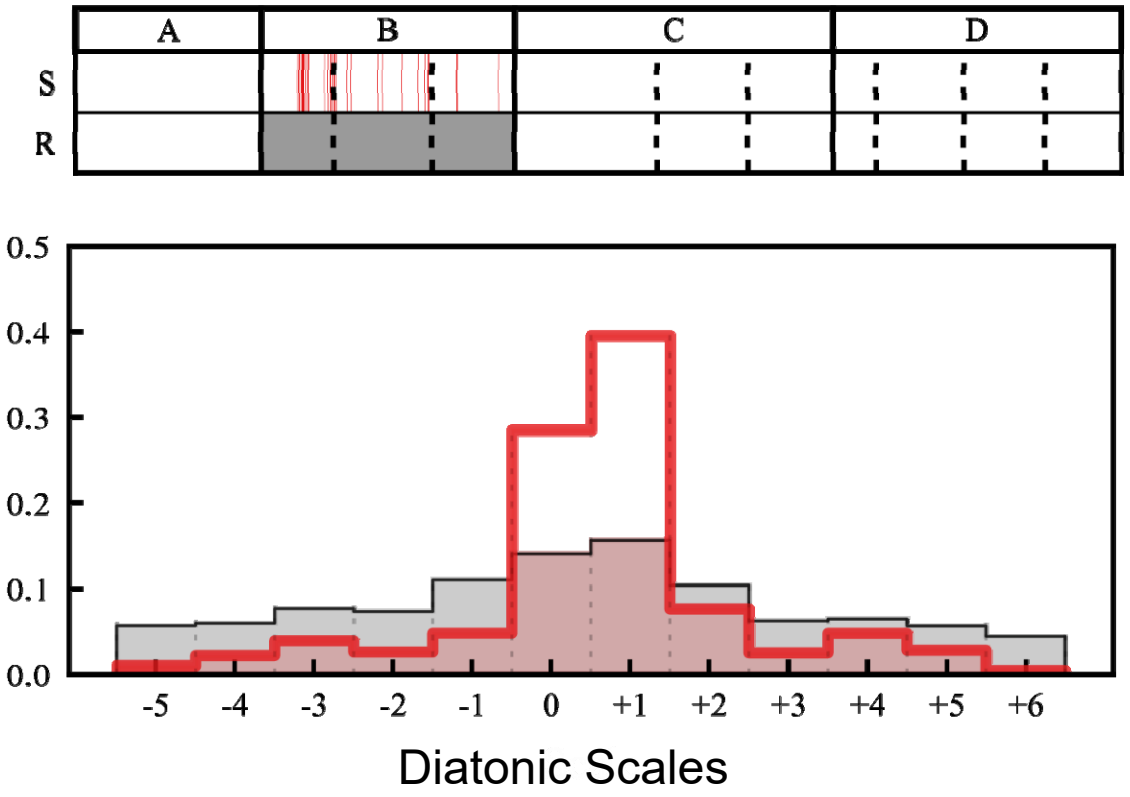
- Histograms of Analysis over time

Das Rheingold WWV 86 A 3897 measures	Die Walküre WWV 86 B 5322 measures	Siegfried WWV 86 C 6682 measures	Götterdämmerung WWV 86 D 6040 measures



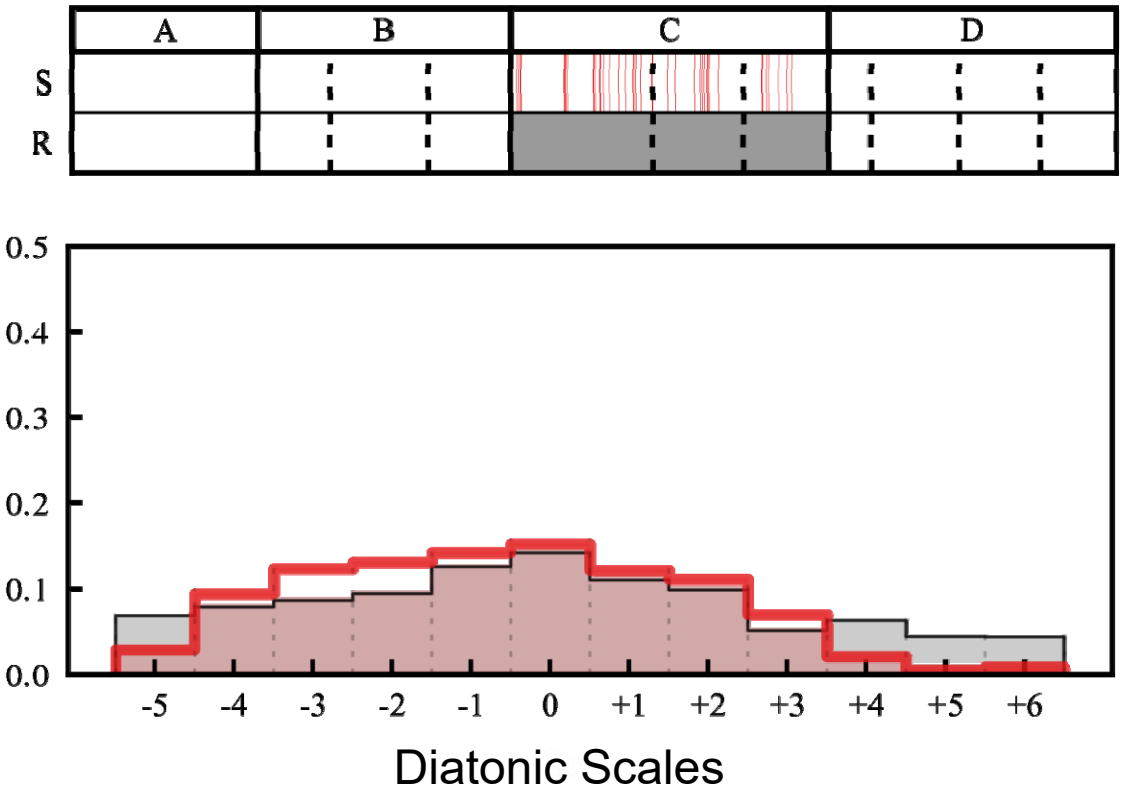
Exploring Tonal-Dramatic Relationships

Sword motif – *Die Walküre*



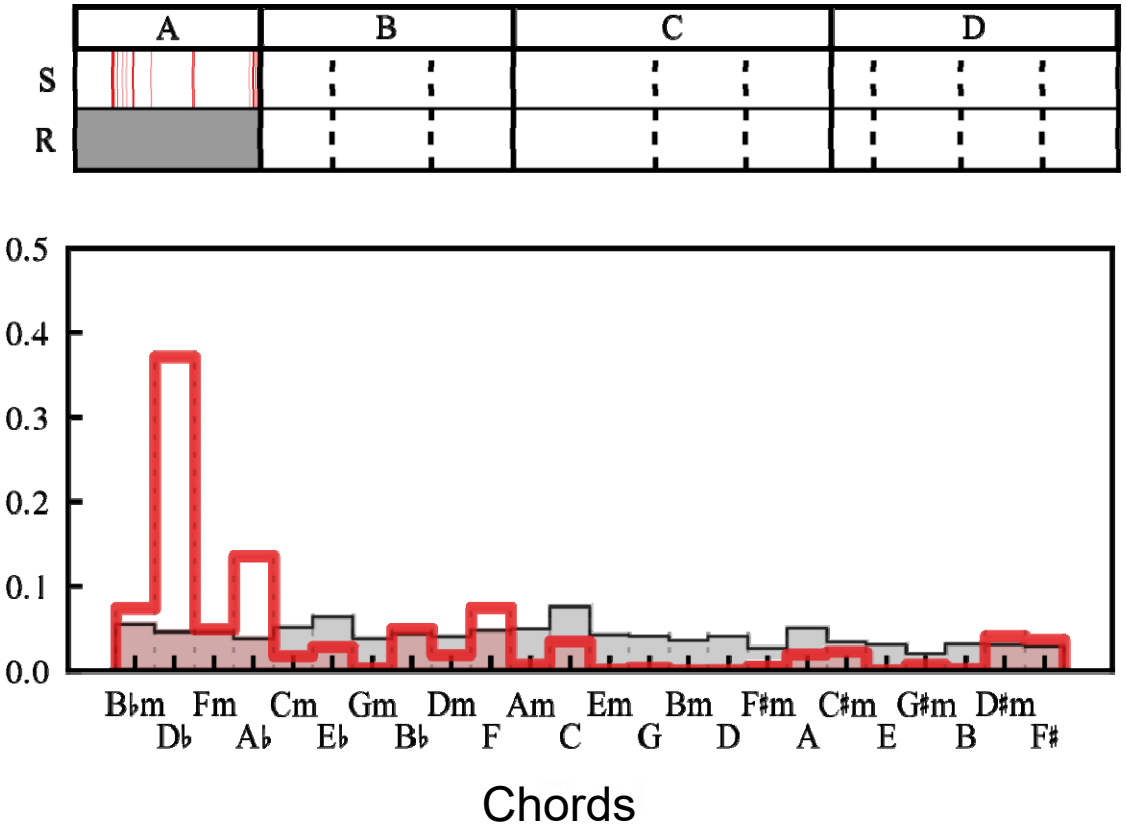
Exploring Tonal-Dramatic Relationships

Sword motif – *Siegfried*



Exploring Tonal-Dramatic Relationships

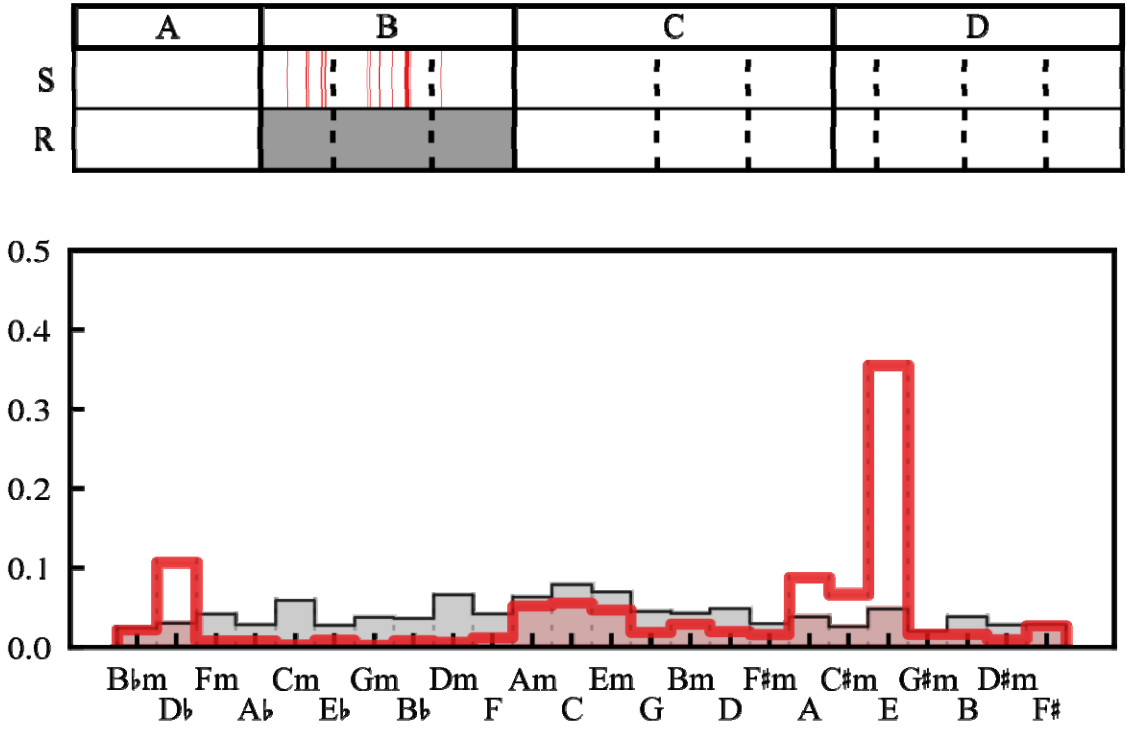
Valhalla motif – *Das Rheingold*



AUDIO LABS

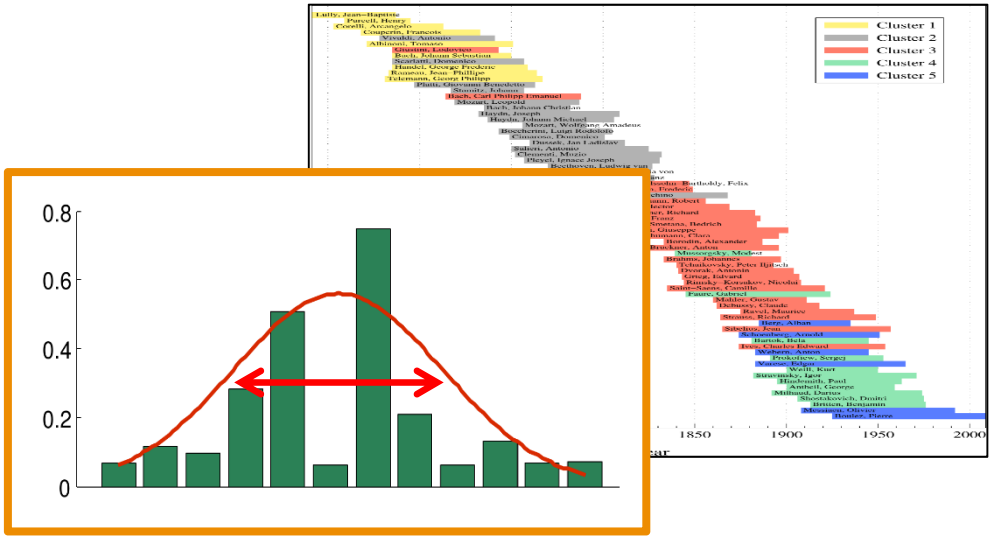
Exploring Tonal-Dramatic Relationships

Valhalla motif – *Die Walküre*



AUDIO LABS

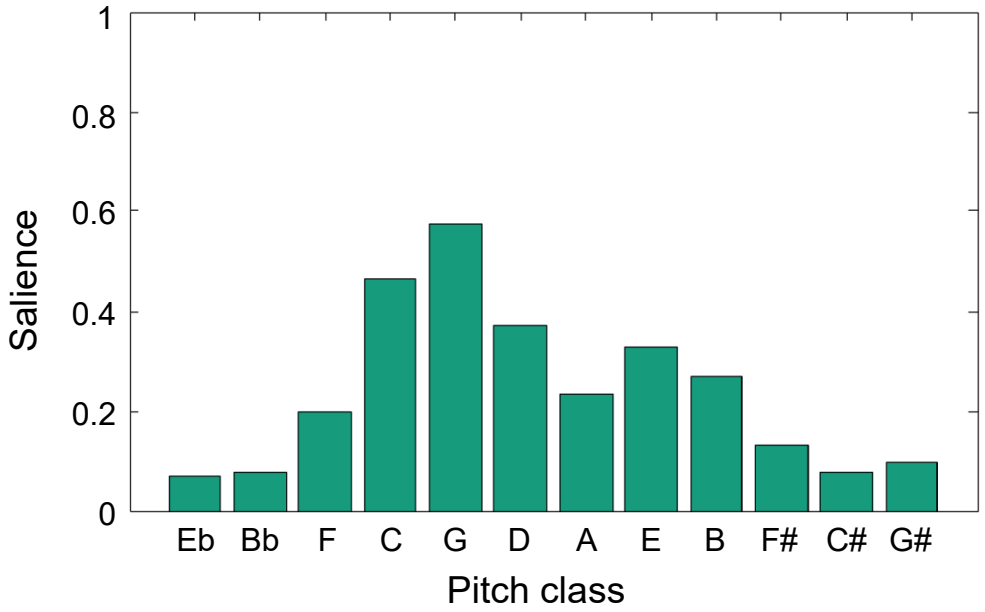
4. Computational Methods for Analyzing Composer Styles



AUDIO LABS

Tonal Complexity

- Global chroma statistics (audio)
- **1783** – W. A. Mozart, „Linz“ symphony KV 425, 1. Adagio / Allegro (C major)

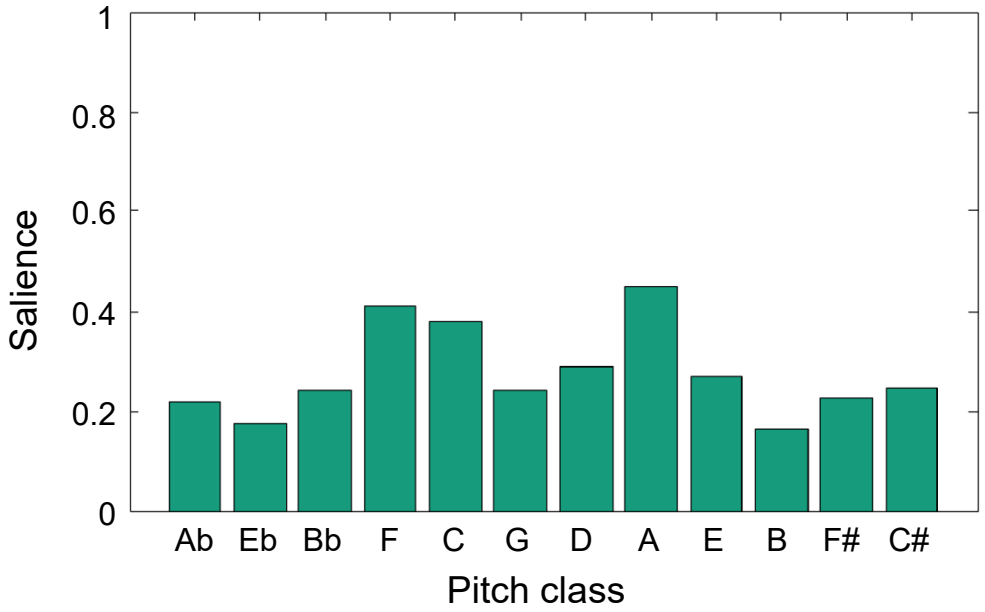


Circle of fifths →

AUDIO LABS

Tonal Complexity

- Global chroma statistics (audio)
- **1883** – J. Brahms, Symphony No. 3, 1. Allegro con brio (F major)

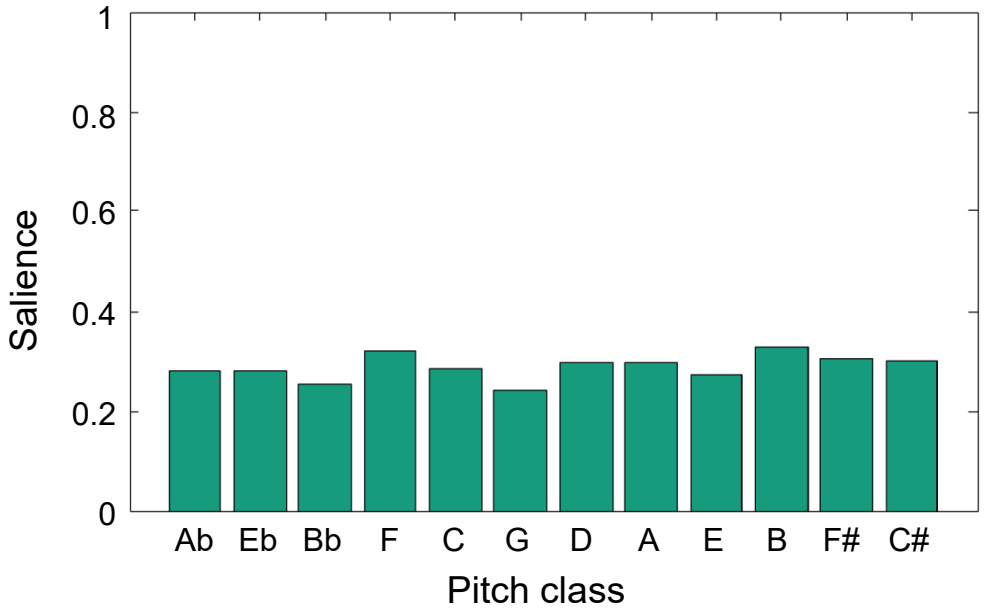


Circle of fifths →

AUDIO LABS

Tonal Complexity

- Global chroma statistics (audio)
- **1940** – A. Webern, Variations for Orchestra op. 30



Circle of fifths →

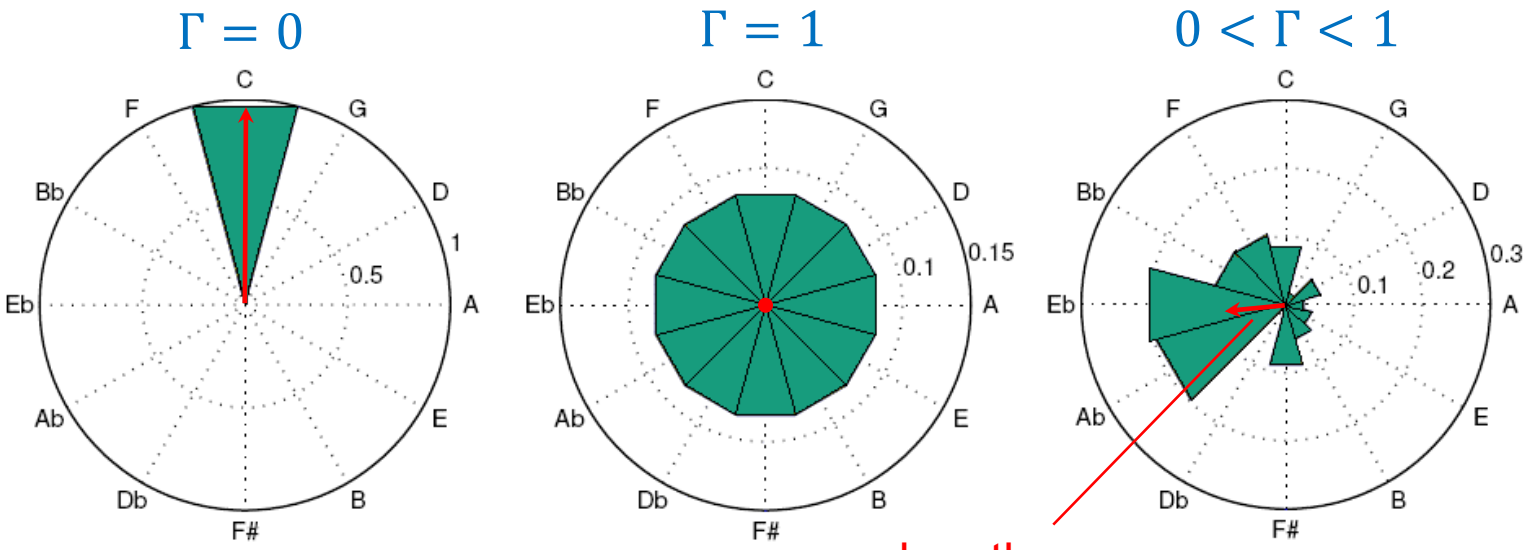
AUDIO LABS

Tonal Complexity

- Realization of complexity measure Γ

  Entropy / Flatness measures

  Distribution over *Circle of Fifths*

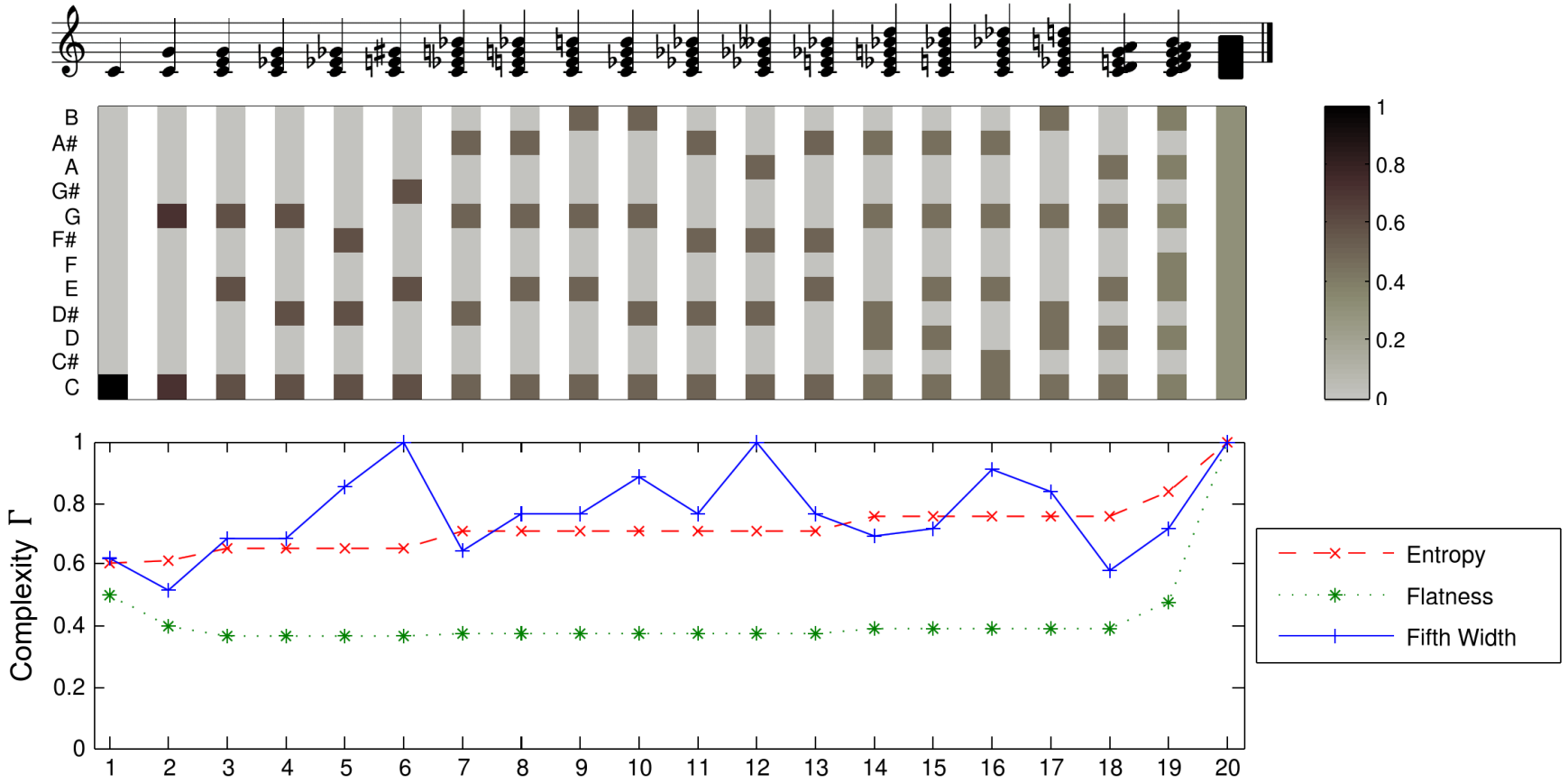


$$\Gamma = \sqrt{1 - r}$$

- Relating to different time scales!

AUDIO LABS

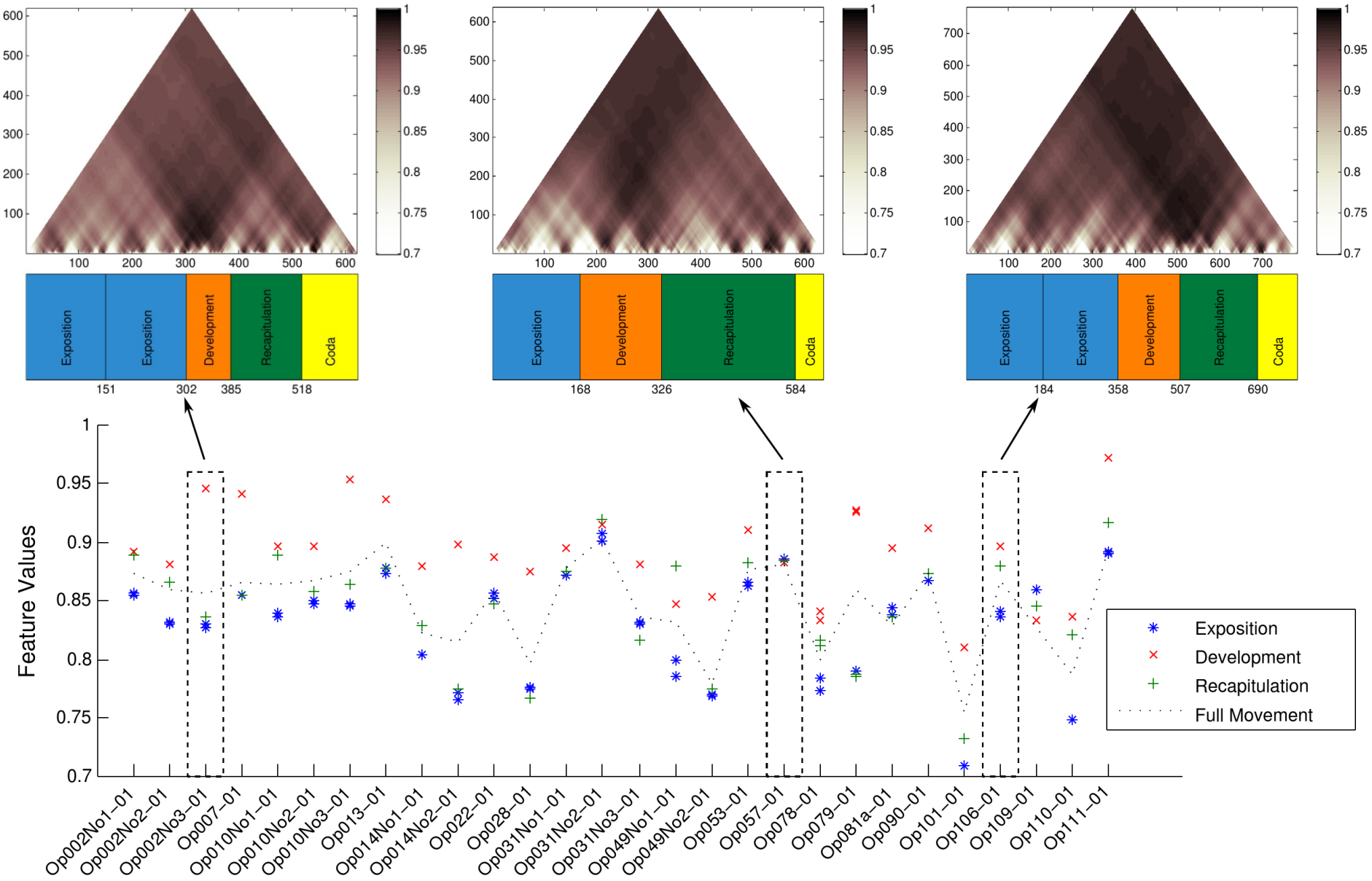
Tonal Complexity – Chords



[8] Weiss / Müller, *Quantifying and Visualizing Tonal Complexity*, CIM 2014

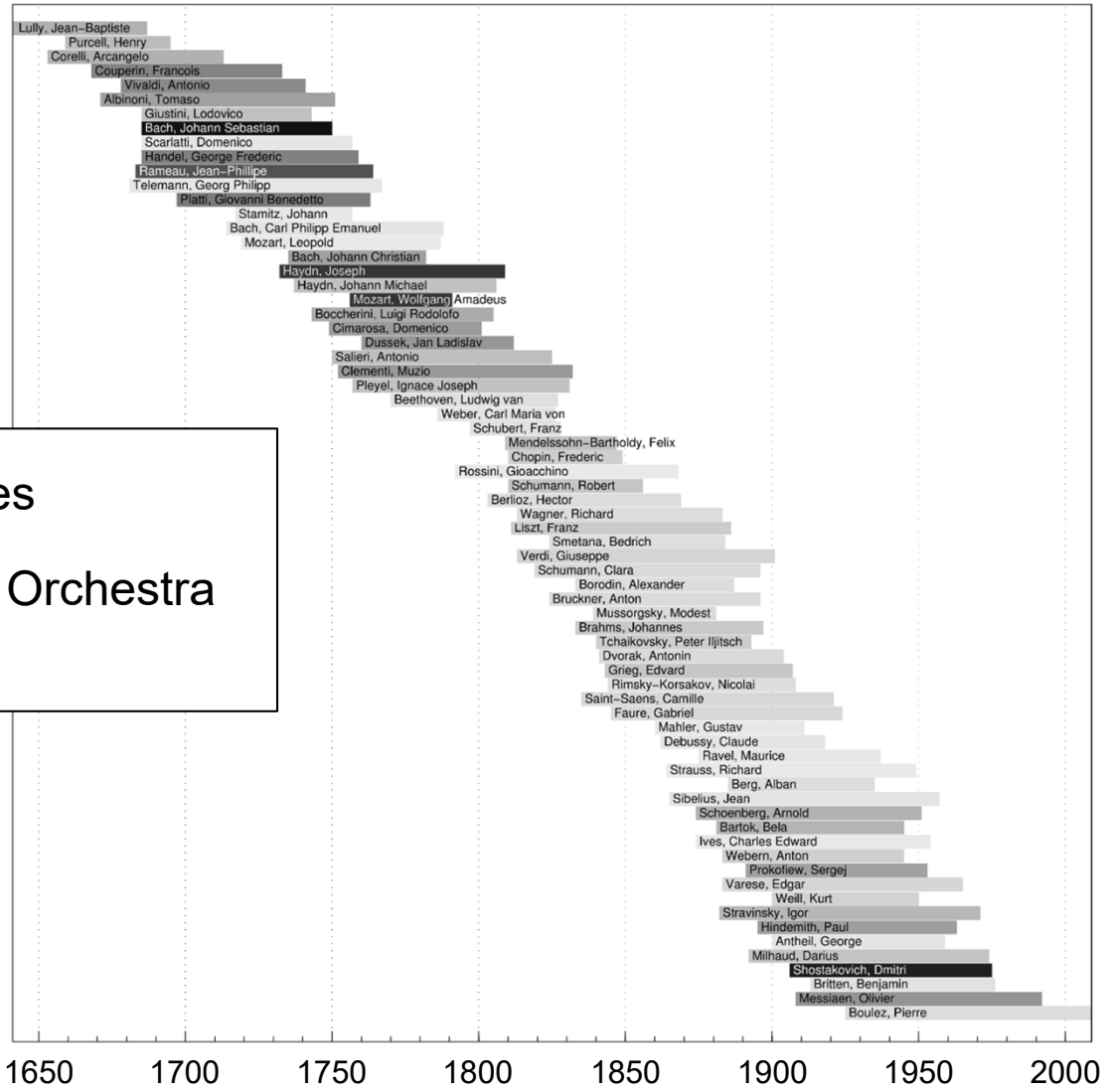
AUDIO LABS

Tonal Complexity – Beethoven's Sonatas



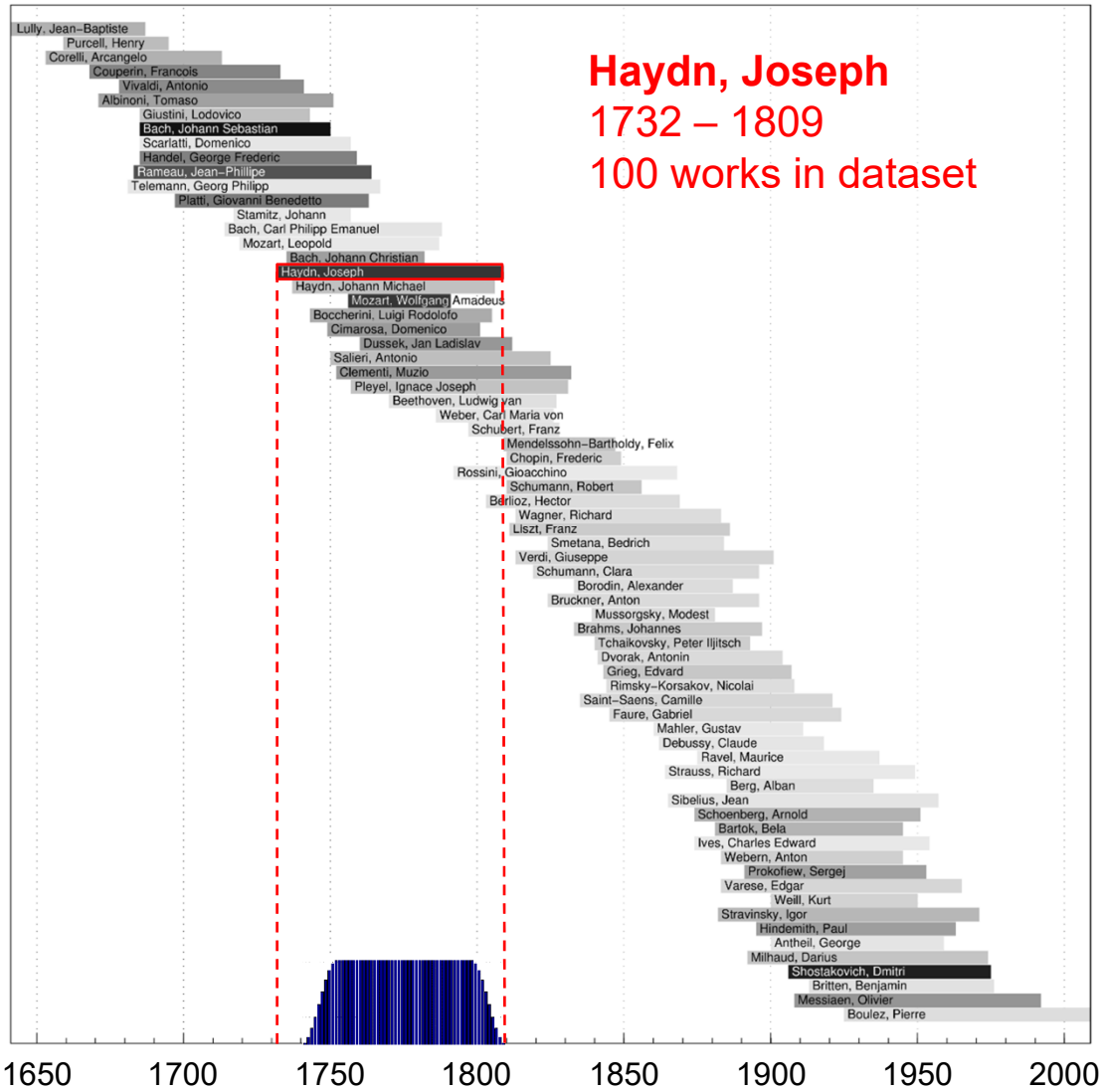
Analyzing Composer Styles

- 2000 pieces
- Piano and Orchestra music

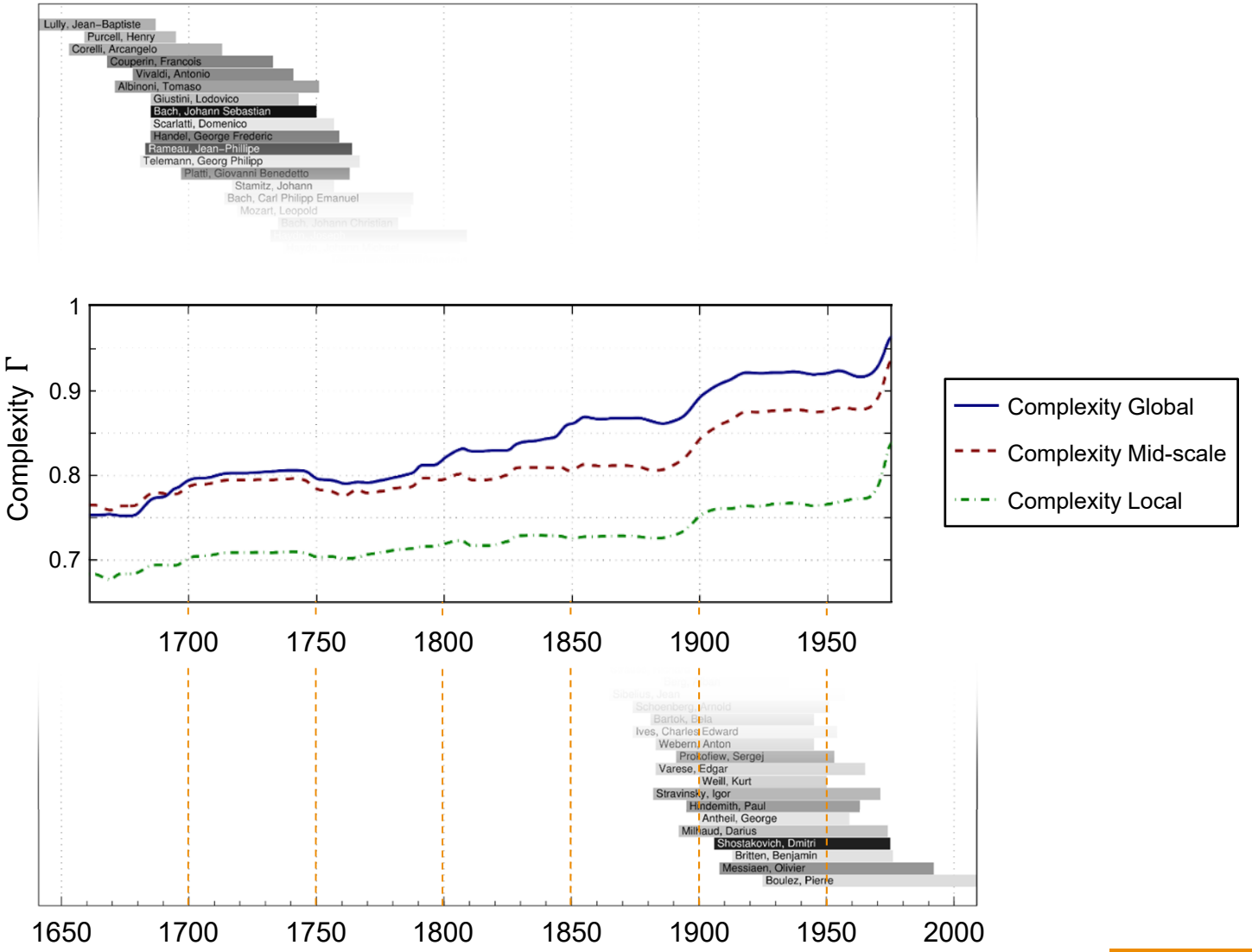


AUDIO LABS

Analyzing Composer Styles

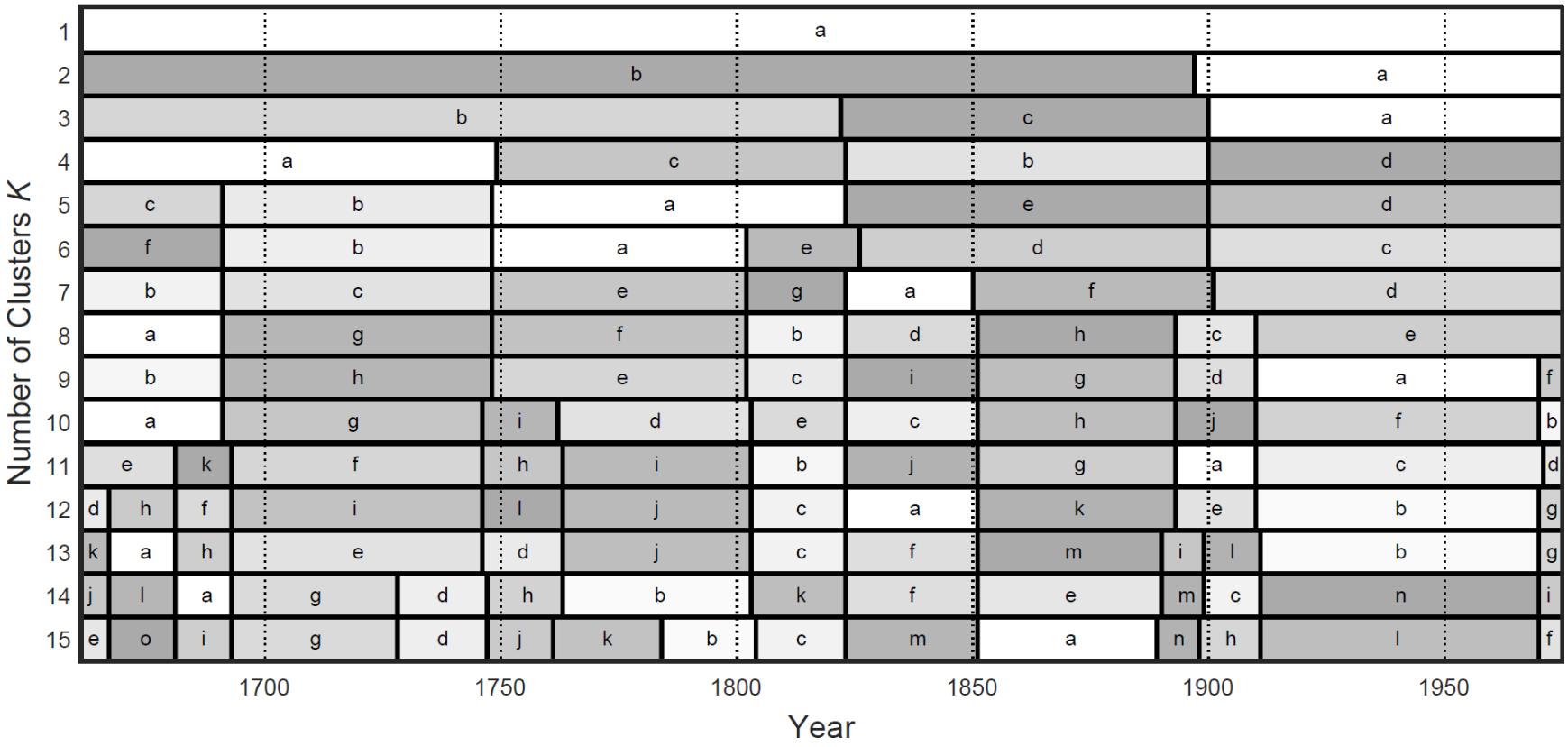


Analyzing Composer Styles

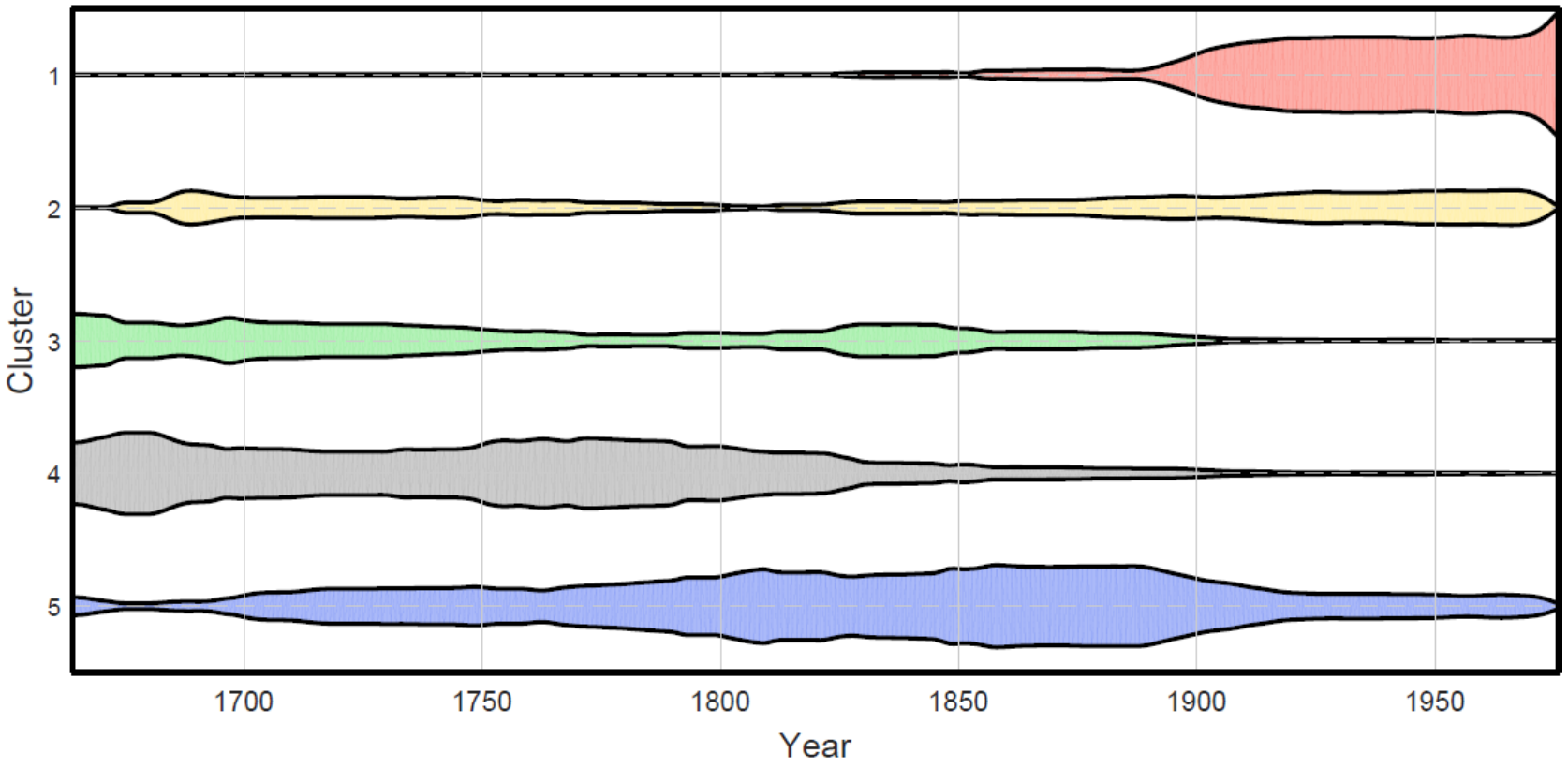


AUDIO LABS

Clustering Composition Years

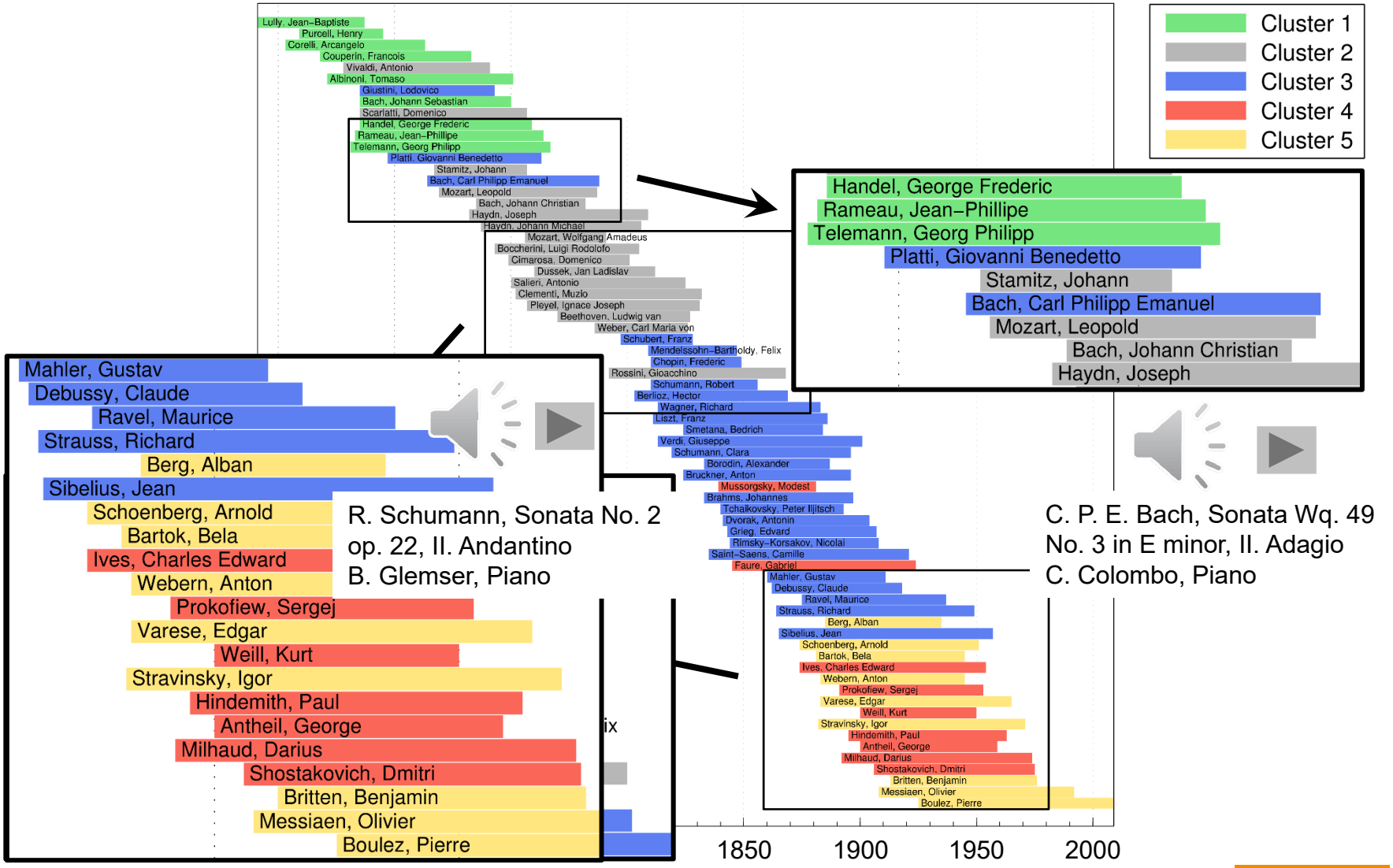


Clustering Individual Pieces



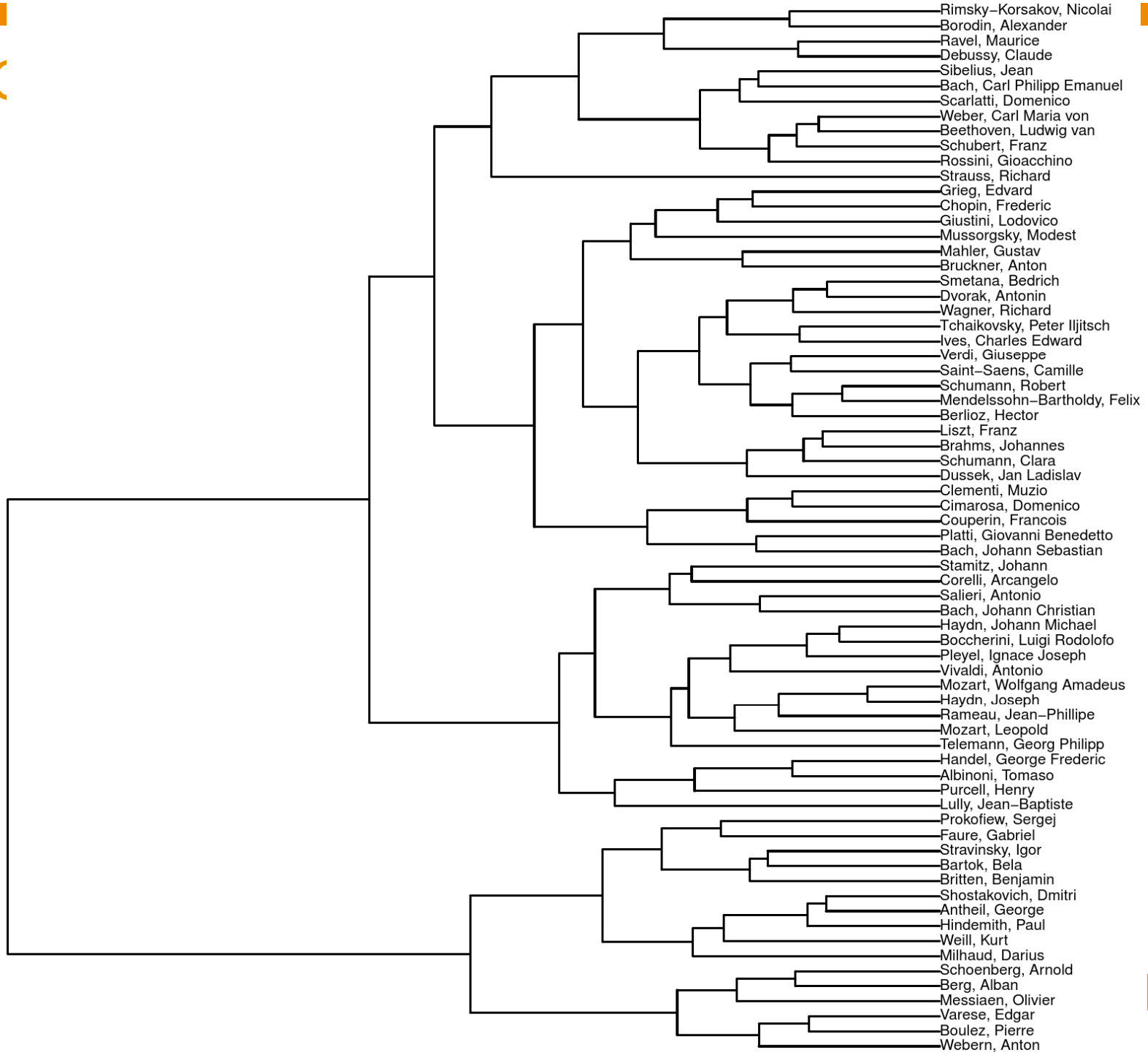
AUDIO LABS

Clustering Composers



R. Schumann, Sonata No. 2
op. 22, II. Andantino
B. Glemser, Piano

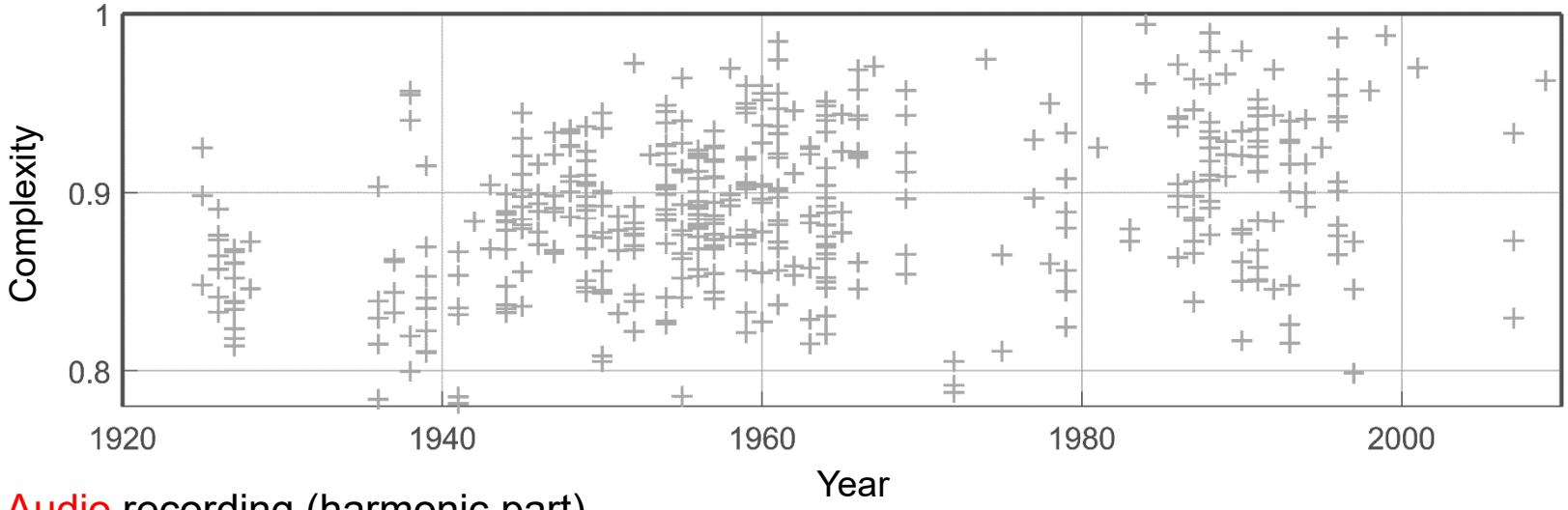
C. P. E. Bach, Sonata Wq. 49
No. 3 in E minor, II. Adagio
C. Colombo, Piano


Rimsky–Korsakov, Nicolai
Borodin, Alexander
Ravel, Maurice
Debussy, Claude
Sibelius, Jean
Bach, Carl Philipp Emanuel
Scarlatti, Domenico
Weber, Carl Maria von
Beethoven, Ludwig van
Schubert, Franz
Rossini, Gioacchino
Strauss, Richard
Grieg, Edvard
Chopin, Frederic
Giustini, Lodovico
Mussorgsky, Modest
Mahler, Gustav
Bruckner, Anton
Smetana, Bedrich
Dvorak, Antonin
Wagner, Richard
Tchaikovsky, Peter Iljitsch
Ives, Charles Edward
Verdi, Giuseppe
Saint–Saens, Camille
Schumann, Robert
Mendelssohn–Bartholdy, Felix
Berlioz, Hector
Liszt, Franz
Brahms, Johannes
Schumann, Clara
Dussek, Jan Ladislav
Clementi, Muzio
Cimarosa, Domenico
Couperin, Francois
Platti, Giovanni Benedetto
Bach, Johann Sebastian
Stamitz, Johann
Corelli, Arcangelo
Salieri, Antonio
Bach, Johann Christian
Haydn, Johann Michael
Boccherini, Luigi Rodolofo
Pleyel, Ignace Joseph
Vivaldi, Antonio
Mozart, Wolfgang Amadeus
Haydn, Joseph
Rameau, Jean–Phillipe
Mozart, Leopold
Telemann, Georg Philipp
Handel, George Frederic
Albinoni, Tomaso
Purcell, Henry
Lully, Jean–Baptiste
Prokofiew, Sergej
Faure, Gabriel
Stravinsky, Igor
Bartok, Bela
Britten, Benjamin
Shostakovich, Dmitri
Antheil, George
Hindemith, Paul
Weill, Kurt
Milhaud, Darius
Schoenberg, Arnold
Berg, Alban
Messiaen, Olivier
Varese, Edgar
Boulez, Pierre
Webern, Anton

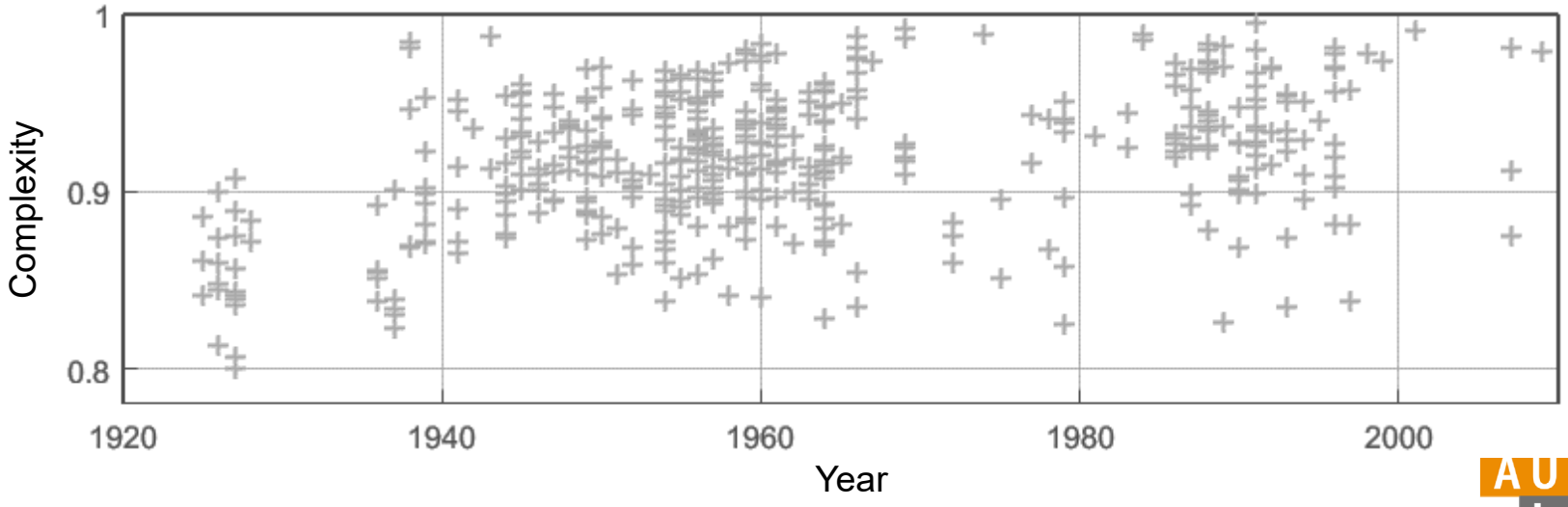
AUDIO LABS

Tonal Complexity: Jazz Solos

- Symbolic transcription

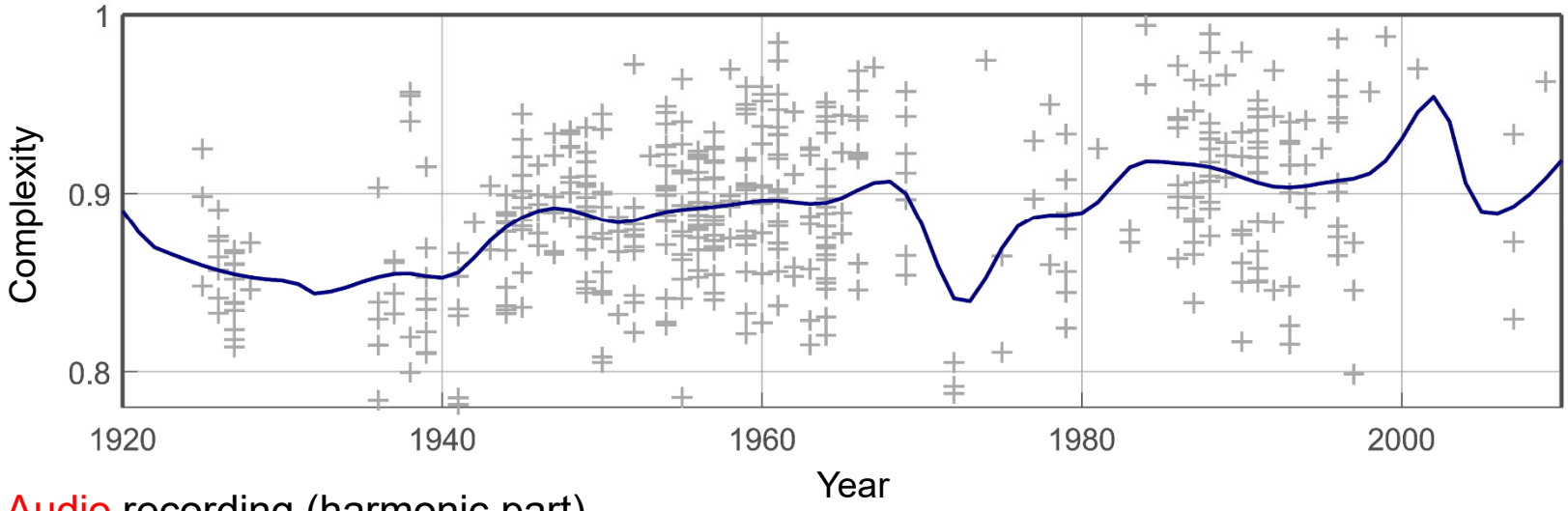


- Audio recording (harmonic part)

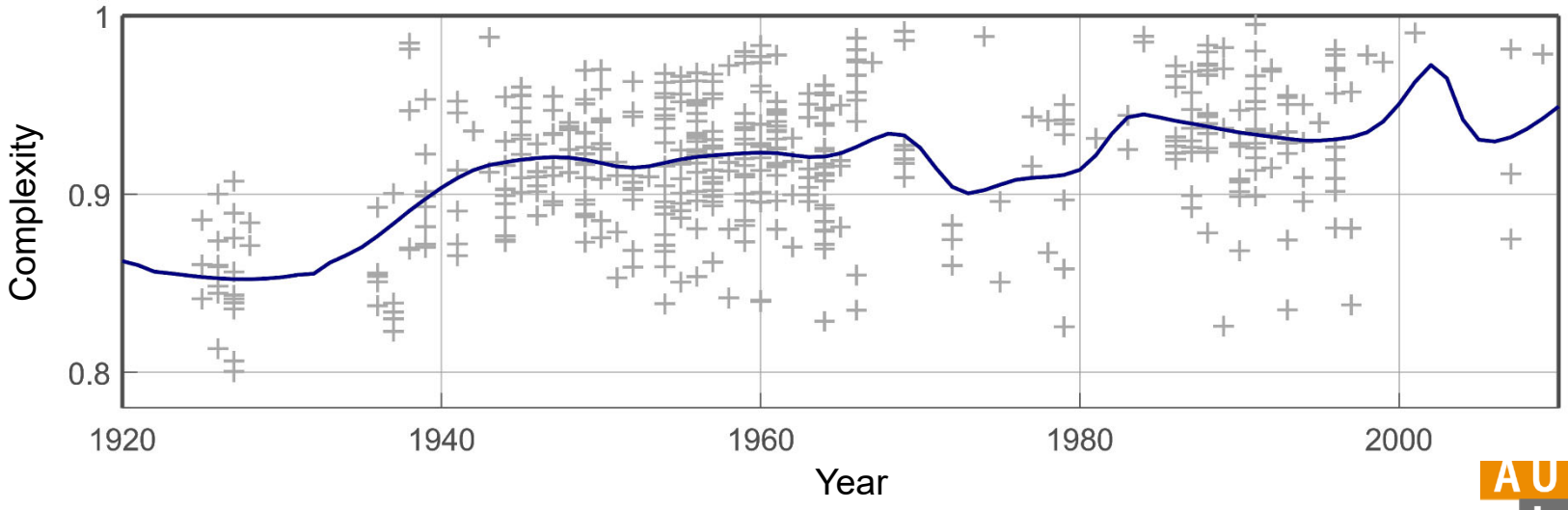


Tonal Complexity: Jazz Solos

- Symbolic transcription



- Audio recording (harmonic part)



Music Genre Classification

J. S. Bach,
Brandenburg Concerto
No. 2 in F major, I. Allegro,
Cologne Chamber Orch.

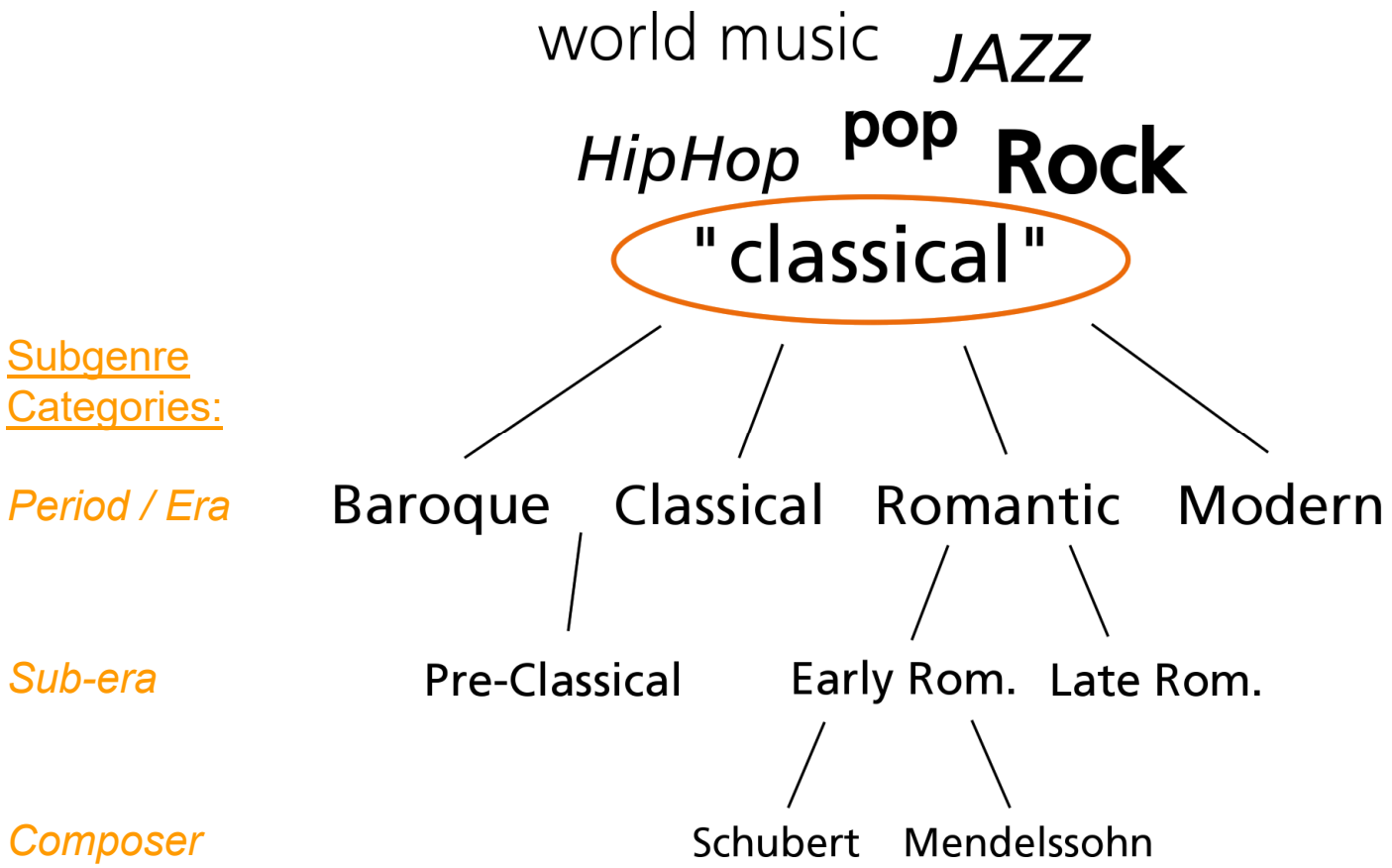
L. van Beethoven,
Fidelio, Overture,
Slovak Philharm.

R. Schumann,
Sonata No. 2 op. 22,
II. Andantino
B. Glemser, Piano

A. Webern,
Variations for Orchestra op. 30
Ulster Orchestra

AUDIO LABS

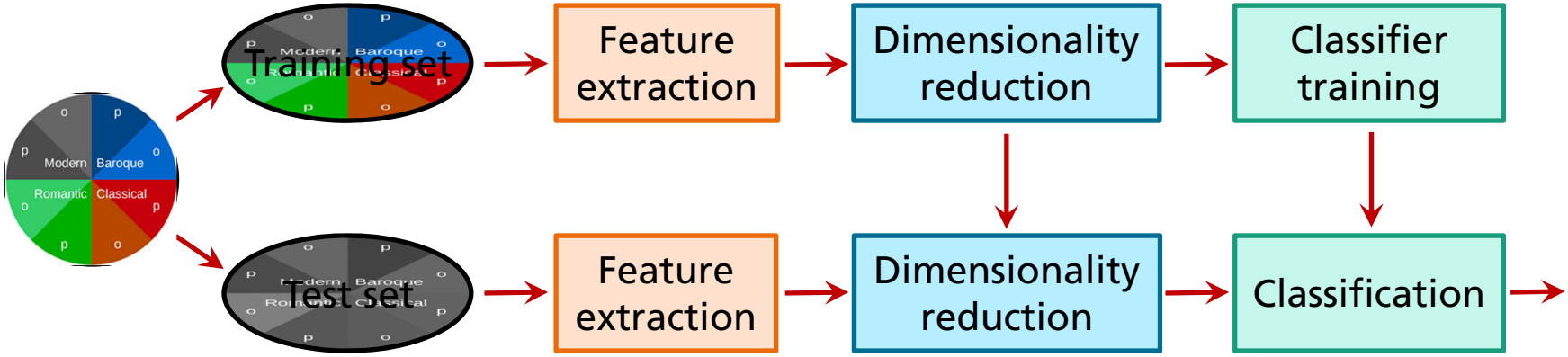
Music Genre Classification



AUDIO LABS

Music Genre Classification

- Typical approach: Supervised machine learning



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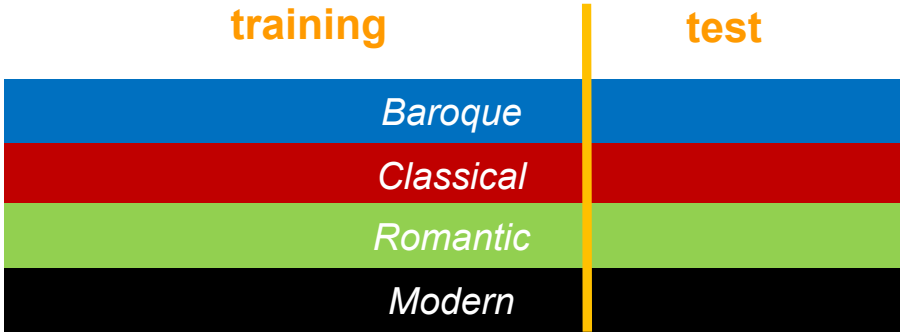
Music Genre Classification

- Experimental design: Evaluation with Cross Validation (CV)
- Separate data into different parts (*folds*)

	Fold 1	*Fold 2*	*Fold 3*
Round 1	Training fold	Training fold	Test fold
Round 2	Training fold	Test fold	Training fold
Round 3	Test fold	Training fold	Training fold

- Distribution of classes balanced for all folds



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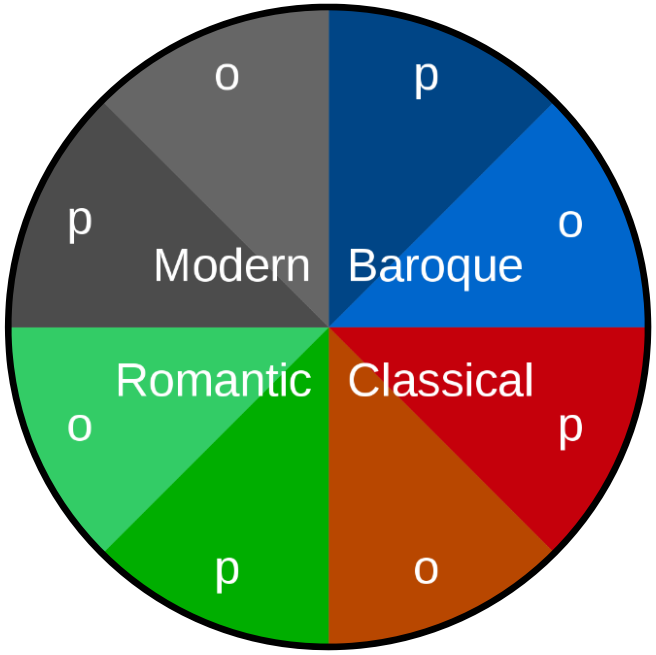
Classification Scenario

- Dataset: *CrossEraDB* (Historical Periods)
  - Balanced Piano (p) – Orchestra (o)
  - Each 200 pieces → 1600 in total



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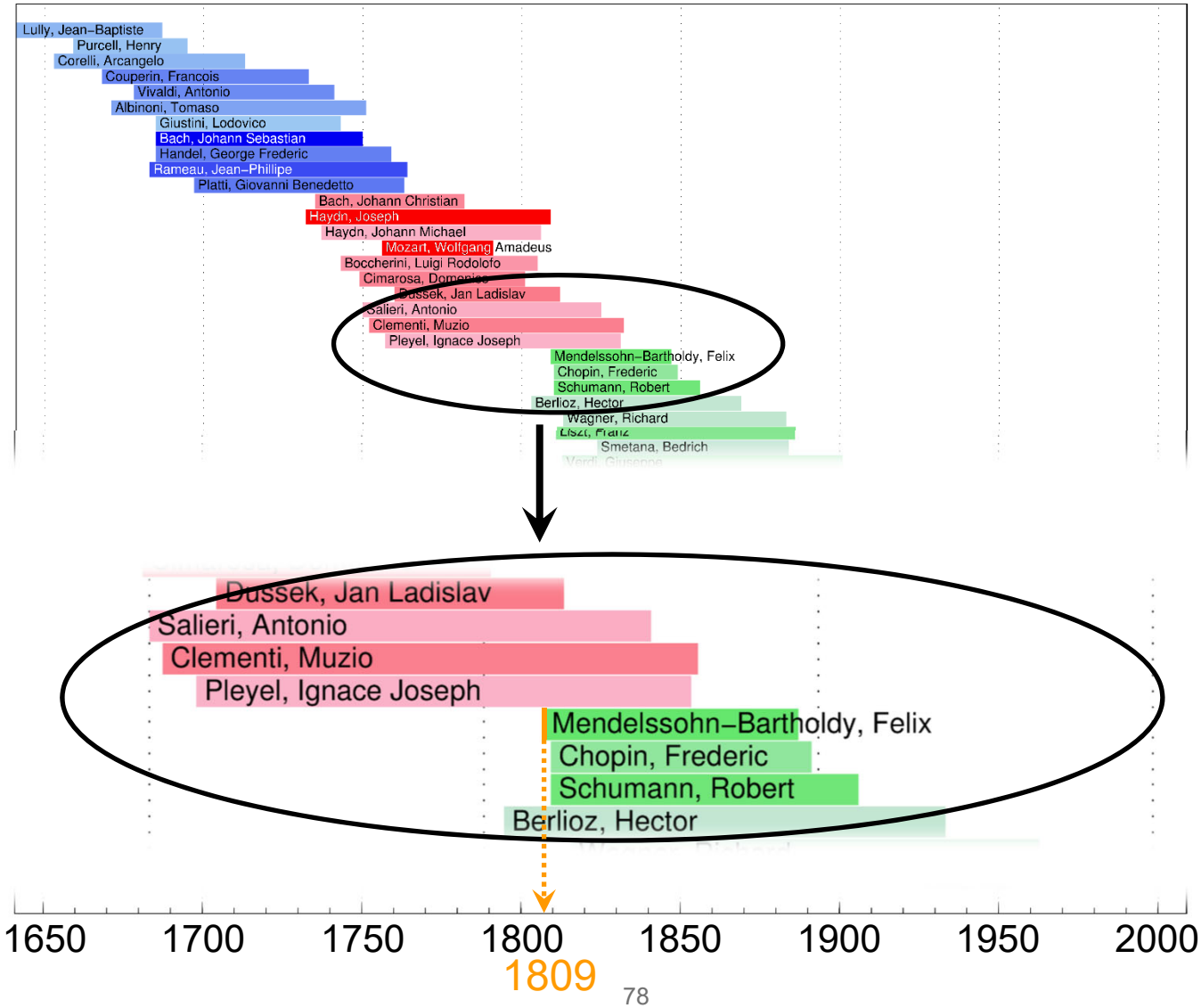
Classification Scenario

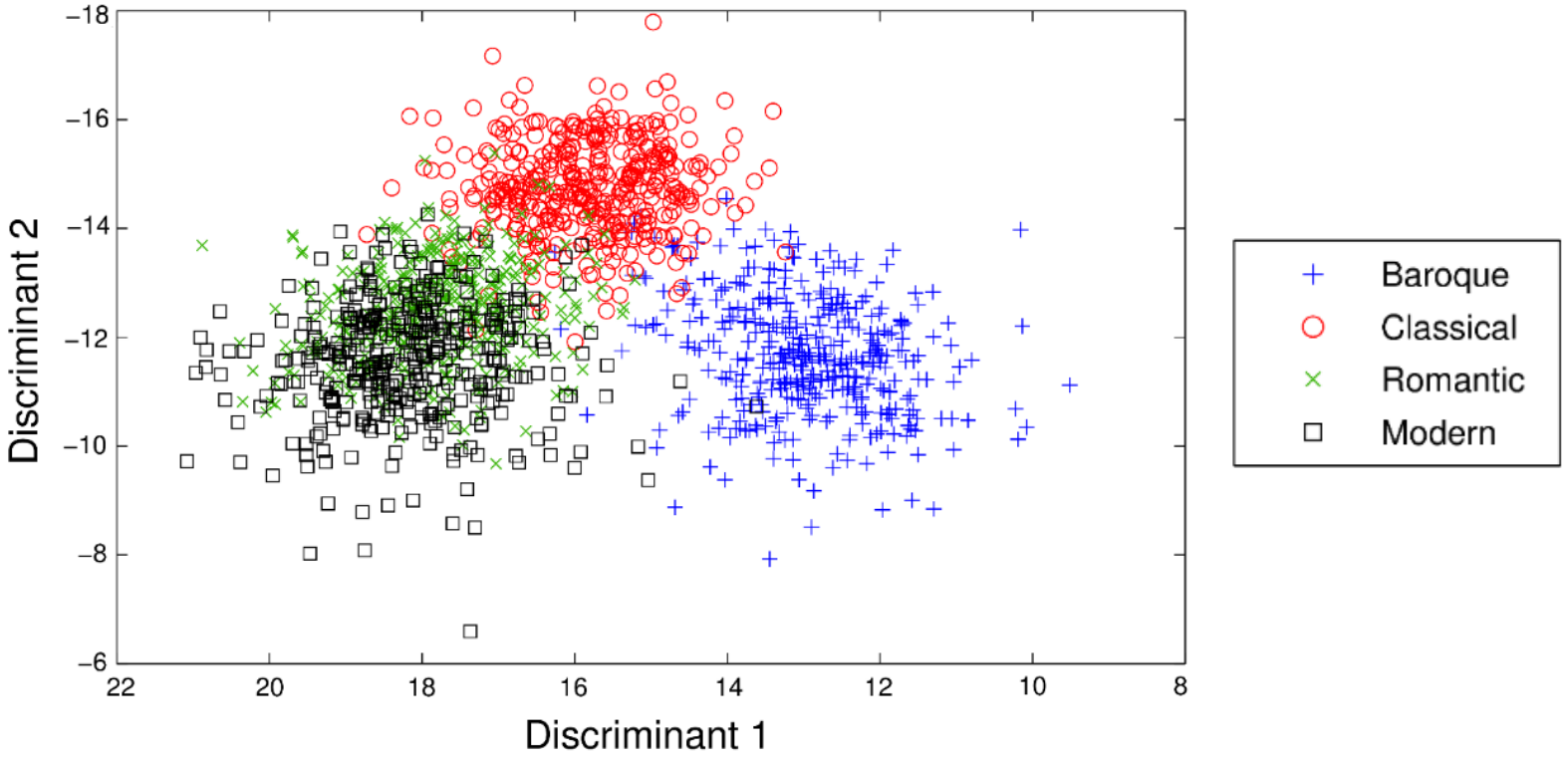


Classification Features

Standard	Dim.	Tonal	Dim.
MFCC	16	Interval cat.	6 x 4
OSC	14	Triad types	4 x 4
ZCR	1	Complexity	7 x 4
ASE	16	Chord progr.	11 x 5
SFM	16		
SCF	16		
SC	16		
LogLoud	12		
NormLoud	12		
Sum	119	Sum	123
Mean & Std	x 2	Mean & Std	x 2
Total	**238**	**Total**	**246**

Dimensionality Reduction

- Reduce feature space to few dimensions (prevent **curse of dimensionality**)
- Maximize separation of classes with **Linear Discriminant Analysis (LDA)**
- Using **standard features** (MFCC, spectral envelope, …)



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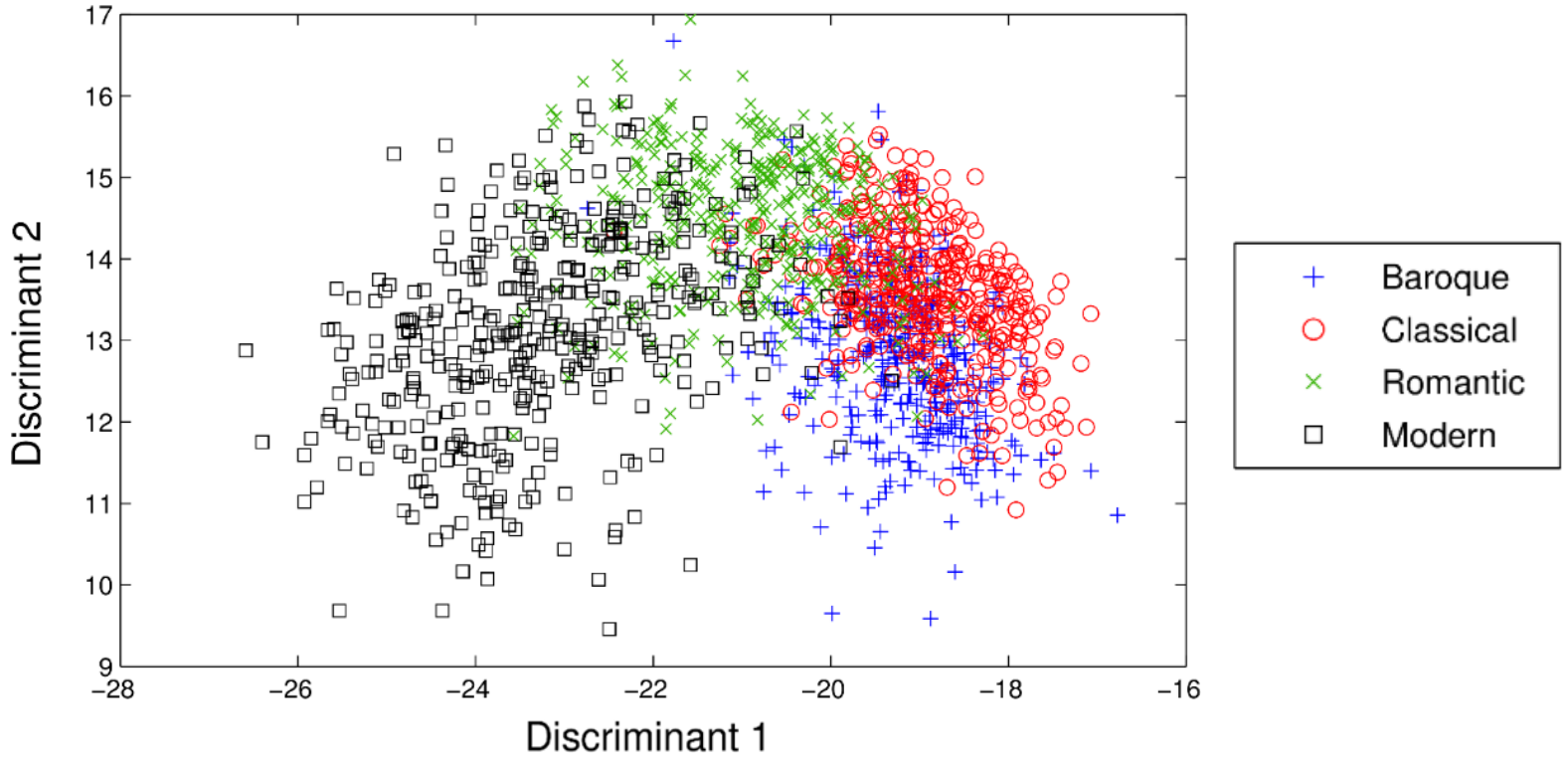
Dimensionality Reduction

- Reduce feature space to few dimensions
- Maximize separation of classes with **Linear Discriminant Analysis (LDA)**
- Using **tonal features** (interval, triad types, tonal complexity, … 4 time scales)



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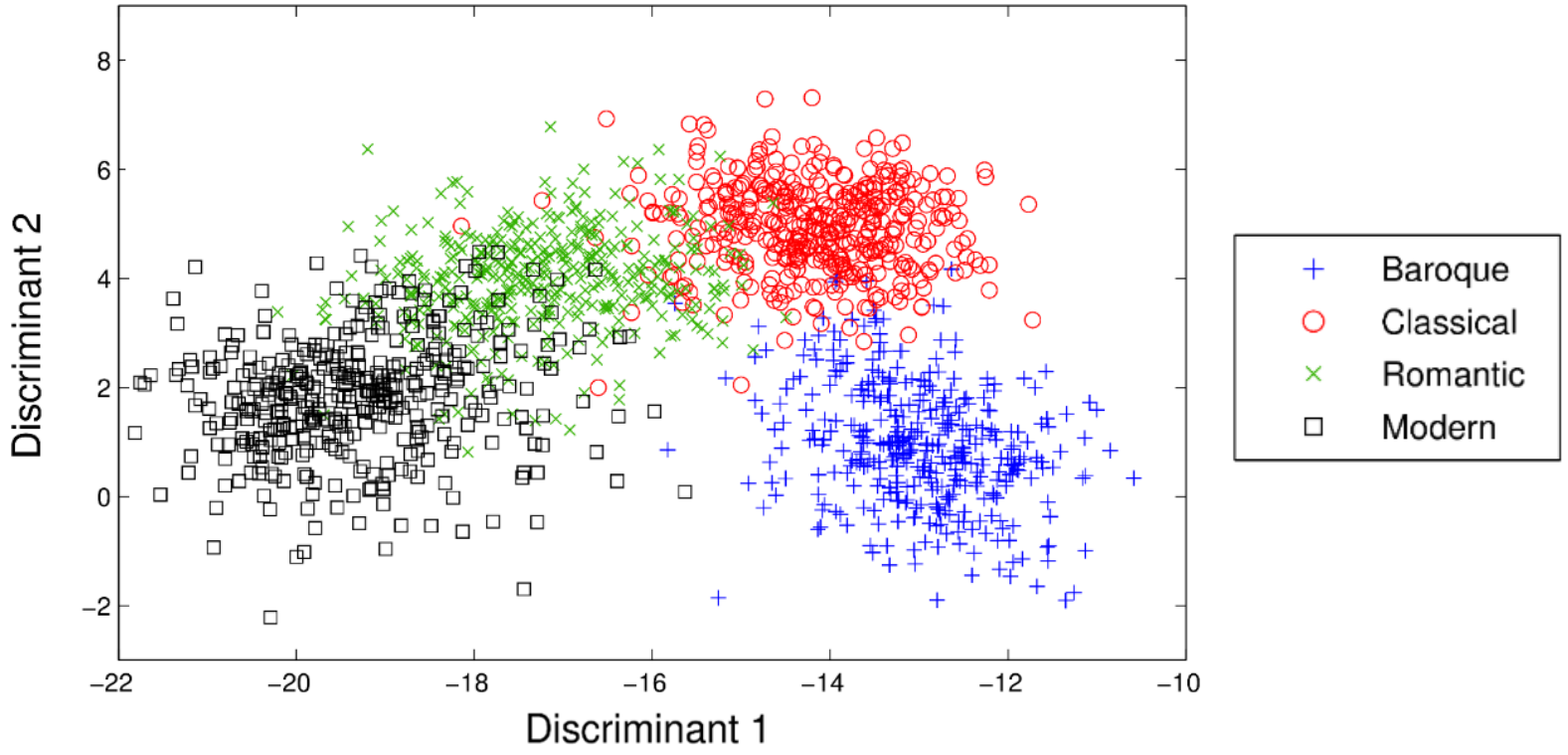
Dimensionality Reduction

- Reduce feature space to few dimensions
- Maximize separation of classes with **Linear Discriminant Analysis (LDA)**
- Using **tonal & standard features**



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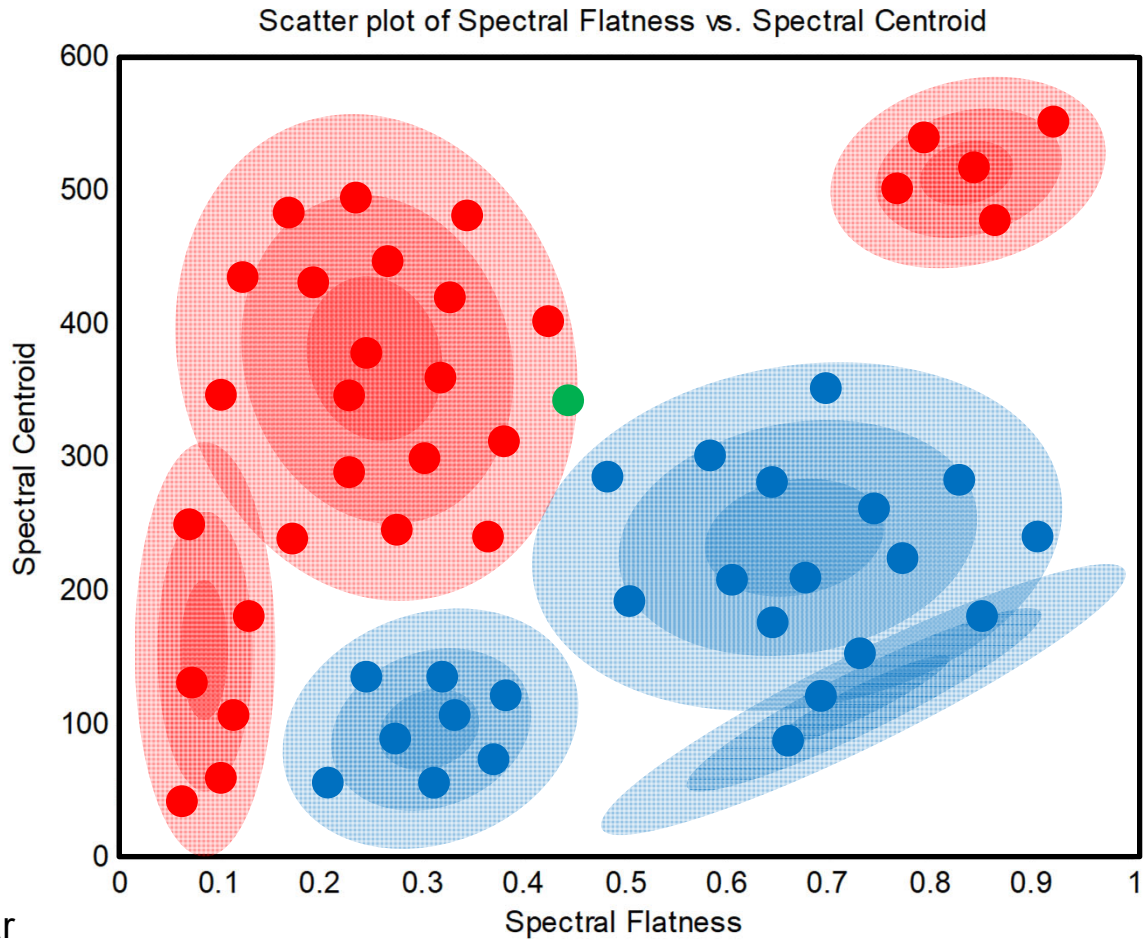
Classification methods

- Gaussian Mixture Models (GMM)



$$f(\mathbf{x}) = \sum_{g=1}^{G} w_g \cdot p\left(\mathbf{x}\middle|\mu_g \Sigma_g\right)$$

Slides:
Christian Dittmar

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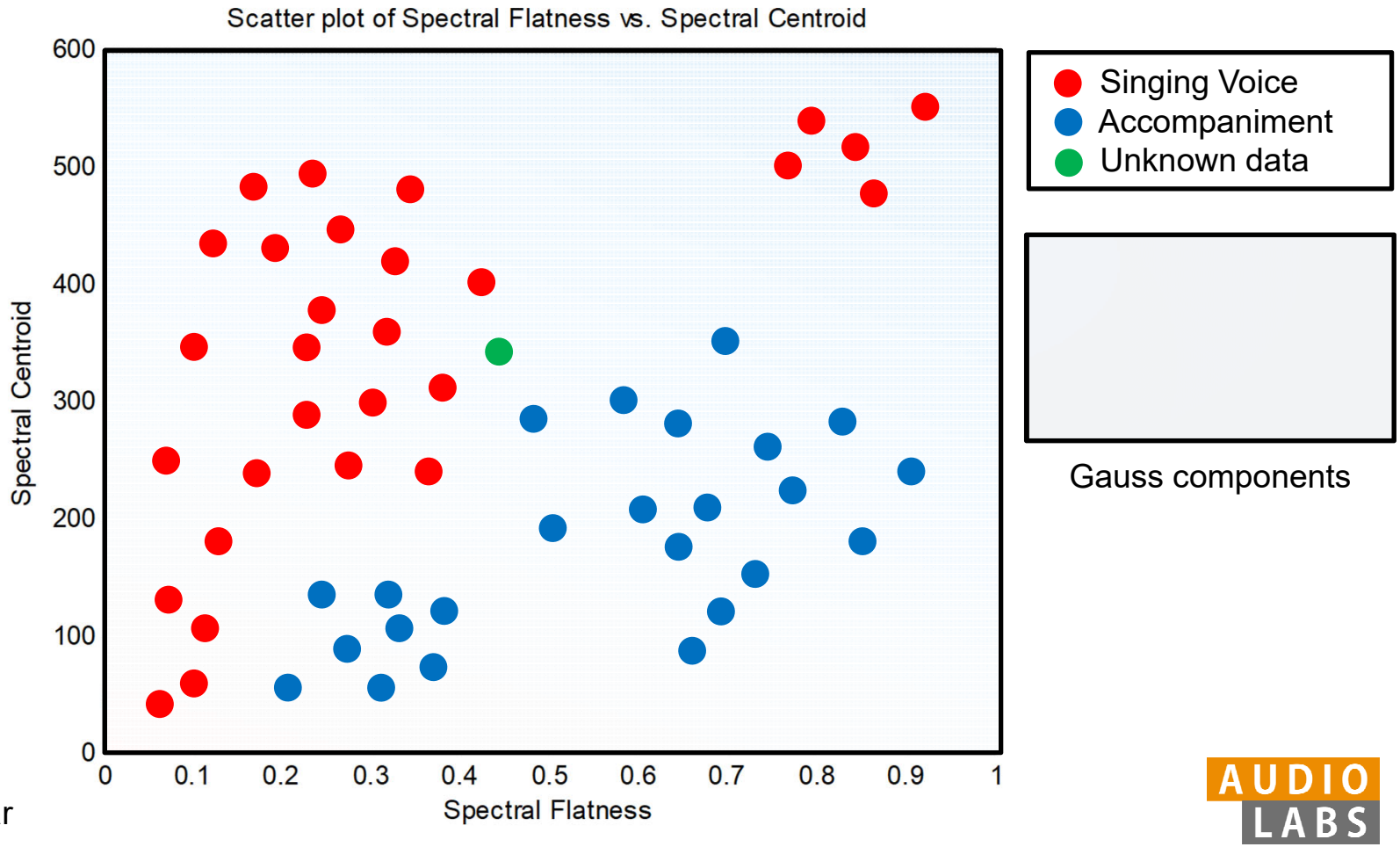
Classification methods

- Gaussian Mixture Models (GMM)



Slides:
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Classification Results

- Gaussian Mixture Model (GMM) classifier, LDA reduction, 3-fold cross validation

	Full Dataset	Piano	Orchestra
Standard features	87 %	88 %	85 %
Tonal features	84 %	84 %	86 %
Combined	**92 %**	**86 %**	**80 %**

Weiss / Mauch / Dixon, *Timbre-Invariant Audio Features for Style Analysis of Classical Music*, ICMC / SMC 2014

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Overfitting???

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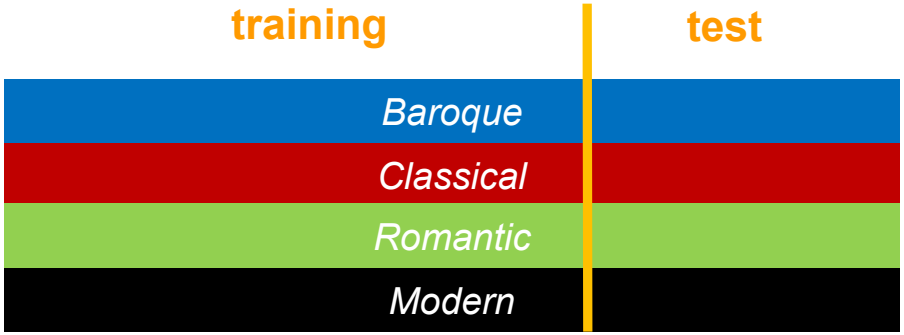

Flexer, *A Closer Look on Artist Filters for Musical Genre Classification*, ISMIR 2007

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Classification Results

- GMM classifier, LDA reduction, 3-fold cross validation
- **No composer filter**

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- **Using composer filter**

	Full Dataset	Piano	Orchestra
Standard features	54 %	36 %	70 %
Tonal features	73 %	70 %	78 %
Combined	**68 %**	**44 %**	**68 %**

Weiss / Müller, *Tonal Complexity Features for Style Classification of Classical Music*, ICASSP 2015

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Classification Results

- What is actually learned?
- Pay attention to:
  - Overfitting
  - „Curse of dimensionality“ – use dimensionality reduction techniques
  - Artist / album effects
- Evaluation: „Figures of merit“:
  - Confusion matrix
  - Error examples: Consistently misclassified items
  - Listening tests
- Evaluation on unseen data (no cross validation)

Bob Sturm, *Classification Accuracy is not enough*,
Journal of Intelligent Information Systems, 2013

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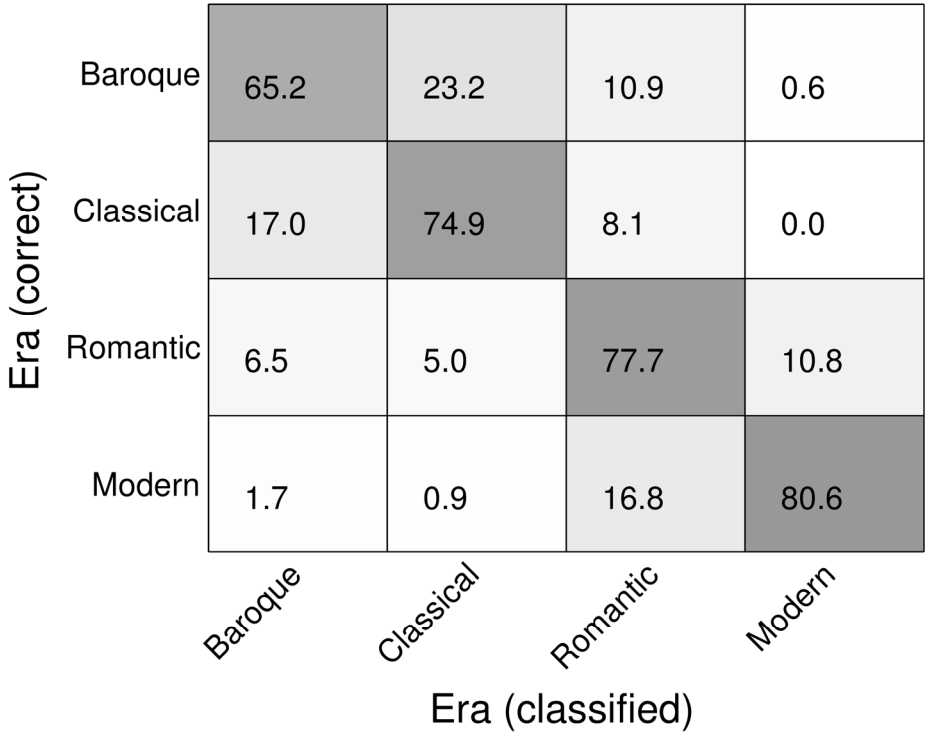
Classification Results – Confusion Matrix

- 80 tonal features, GMM with 1 Gaussian, LDA, composer filtering
- **Full** dataset
- Mean accuracy: **75 %**
- Inter-class standard deviation: **6.7 %**



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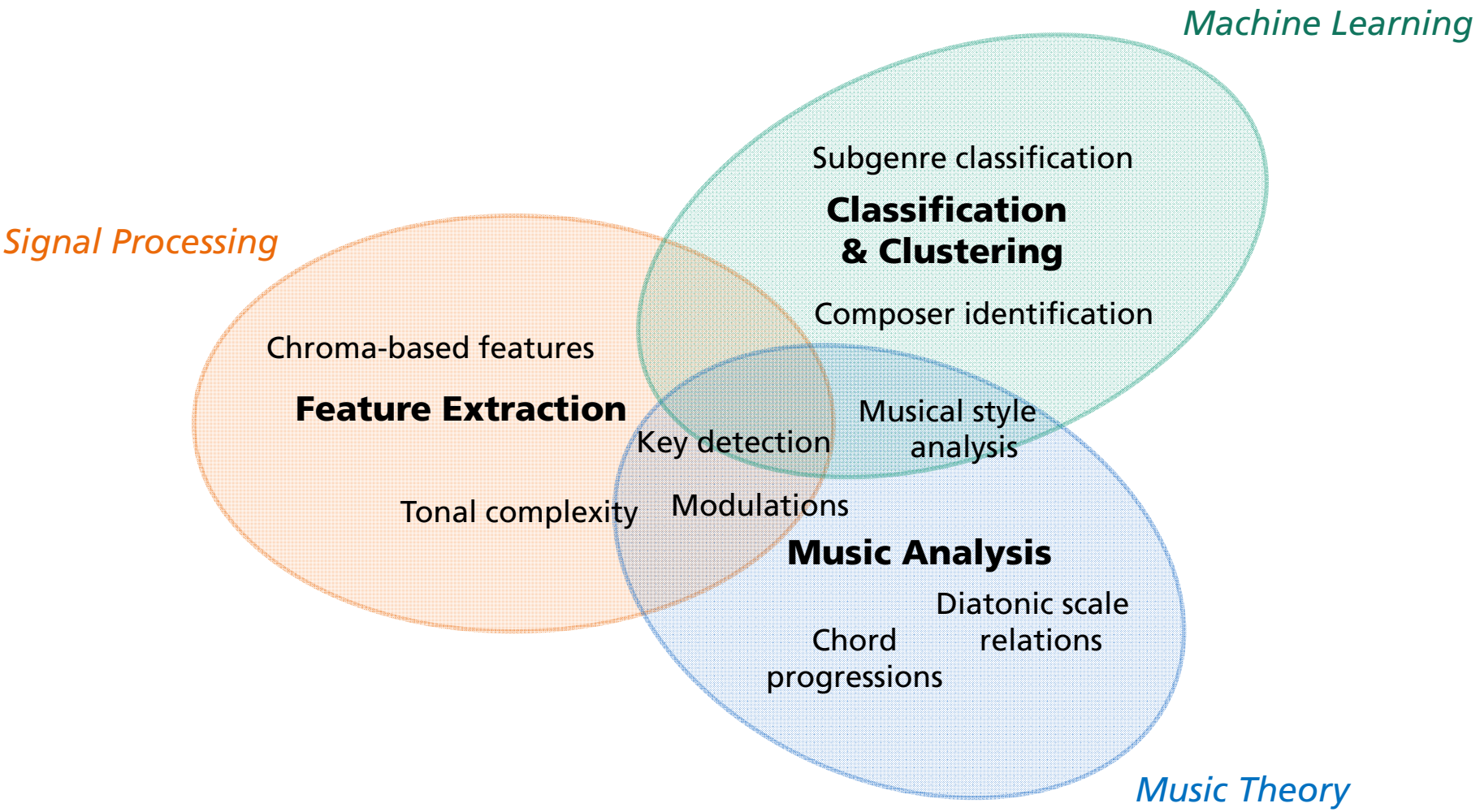
Classification Results: Error Examples

- 80 tonal features, GMM with 1 Gaussian, LDA
- Look at **consistently** and **persistently** misclassified items

Class	*Composer*	*Piece*	*Classified*
Baroque	Bach, J. S.	Well-Tempered Piano 1, Prelude in E♭ minor BWV 853	Romantic
Baroque	Bach, J. S.	Well-Tempered Piano 1, Prelude in F major BWV 856	Romantic
Baroque	Bach, J. S.	Well-Tempered Piano 1, Prelude in A minor BWV 865	Romantic
Baroque	Bach, J. S.	Well-Tempered Piano 1, Prelude in B♭ major BWV 866	Romantic
Baroque	Bach, J. S.	Well-Tempered Piano 1, Prelude in B♭ minor BWV 867	Romantic
Baroque	Bach, J. S.	English Suite No. 3 in G minor BWV 808, Sarabande	Romantic
Baroque	Bach, J. S.	Brandenburg Conc. No. 1 in F major BWV 1046, Adagio	Romantic
Baroque	Bach, J. S.	Overture No. 2 in B minor BWV 1067, Badinerie	Romantic
Baroque	Bach, J. S.	Overture No. 3 in D major BWV 1068, Gigue	Romantic
Baroque	Couperin, F.	27 Ordres, Huitième ordre, IX. Rondeau passacaille	Romantic
Baroque	Corelli, A.	Concerto grosso op. 6 No. 2, III. Grave – Andante largo	Romantic
Baroque	Lully, J.-B.	Ballet de Xerces LWV 12, Gavotte en rondeau	Romantic
Baroque	Purcell, H.	Opera "Dido and Aeneas" Z. 626, Overture	Romantic
Baroque	Vivaldi, A.	"The Four Seasons," RV 293 "Autumn," Adagio molto	Romantic
Romantic	Schumann, R.	Kinderszenen op. 15, "Haschemann"	Baroque
Romantic	Grieg, E.	Holberg suite op. 40, Gavotte	Baroque
Romantic	Mendelssohn, F.	Symphony No. 4 in A major, IV. Saltarello, presto	Baroque
Modern	Shostakovich, D.	Preludes & Fugues op. 87 Fugue No. 1 in C major	Baroque
Modern	Shostakovich, D.	Preludes & Fugues op. 87 Fugue No. 5 in D major	Baroque

Conclusions



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