**Tutorial**
**Automatisierte Methoden der Musikverarbeitung**
**47. Jahrestagung der Gesellschaft für Informatik**

# Harmony Analysis

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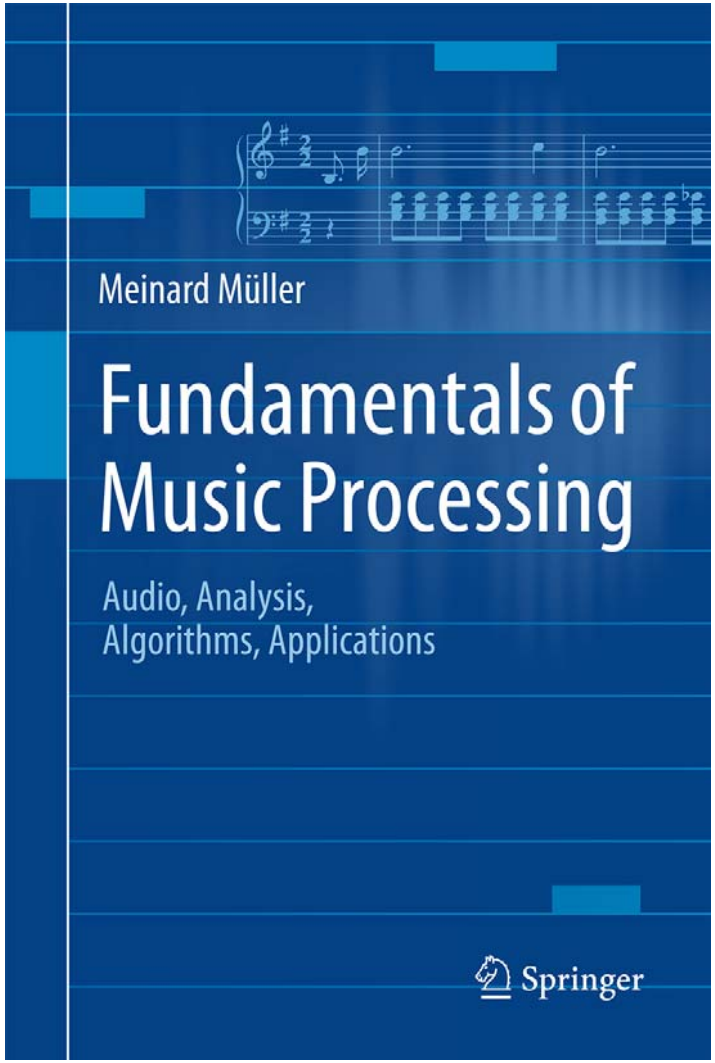
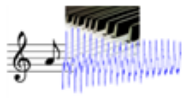
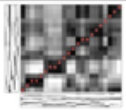
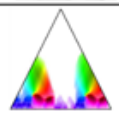
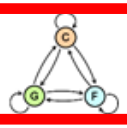
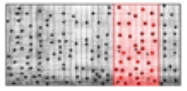
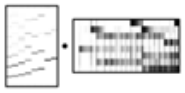
# Book: Fundamentals of Music Processing




Meinard Müller
Fundamentals of Music Processing
Audio, Analysis, Algorithms, Applications
483 p., 249 illus., hardcover
ISBN: 978-3-319-21944-8
Springer, 2015

Accompanying website:
www.music-processing.de

# Book: Fundamentals of Music Processing

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

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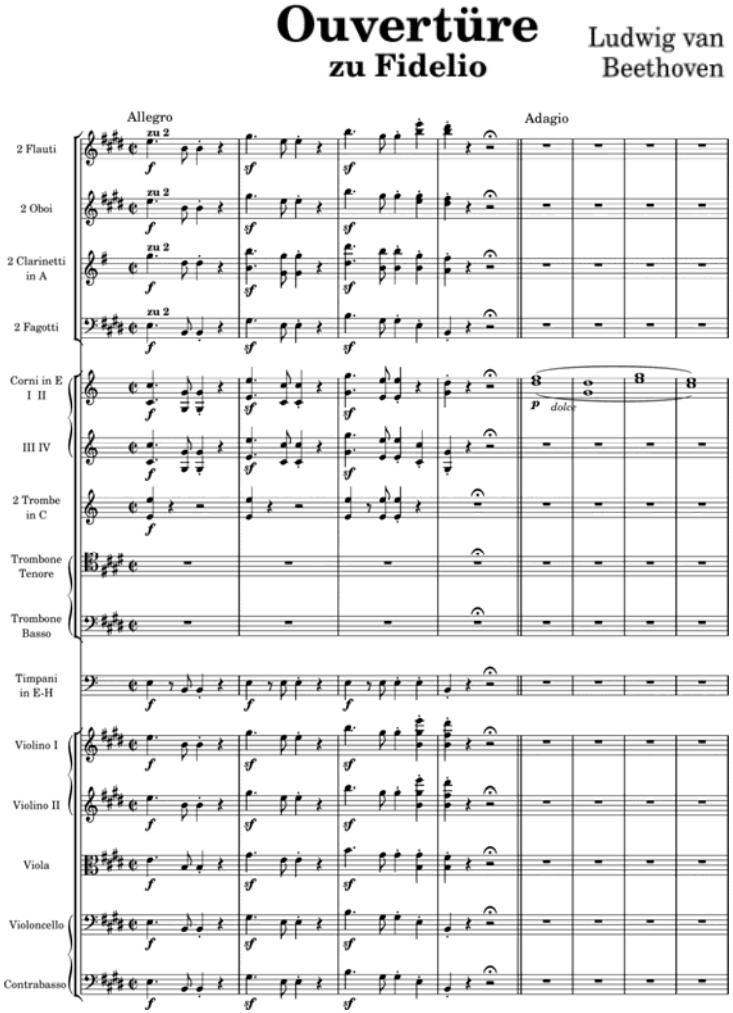
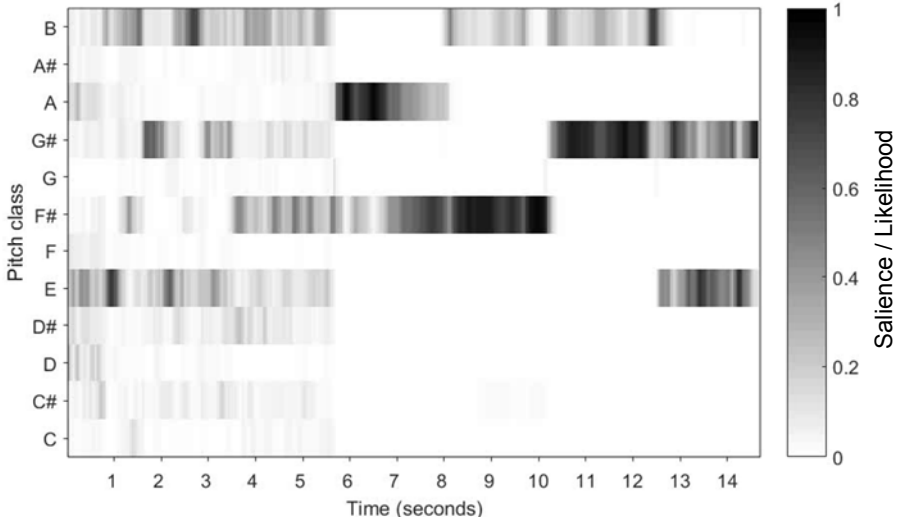
# Dissertation: Tonality-Based Style Analysis

Christof Weiß
*Computational Methods for Tonality-Based Style Analysis of Classical Music Audio Recordings*
PhD thesis, Technical University of Ilmenau, 2017

Chapter 5: Analysis Methods for Key and Scale Structures
Chapter 6: Design of Tonal Features

# Recall: Chroma Representations



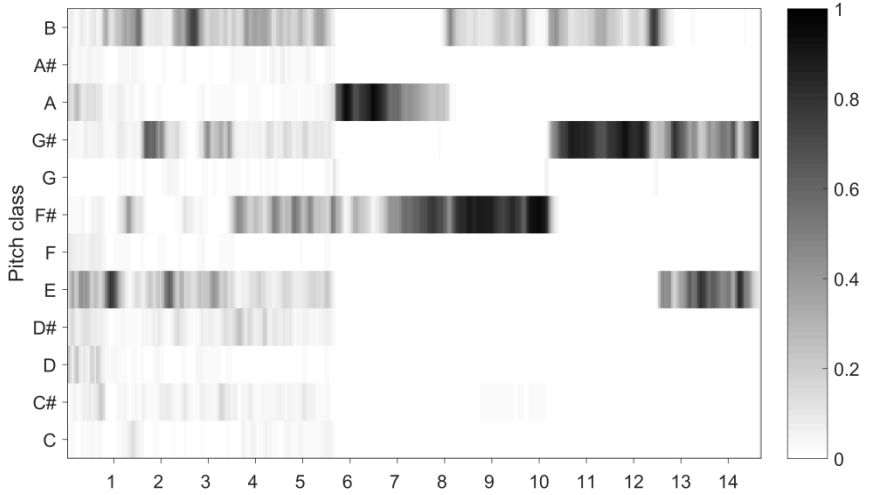




L. van Beethoven,
*Fidelio*, Overture,
Slovak Philharmonic

# Recall: Chroma Representations

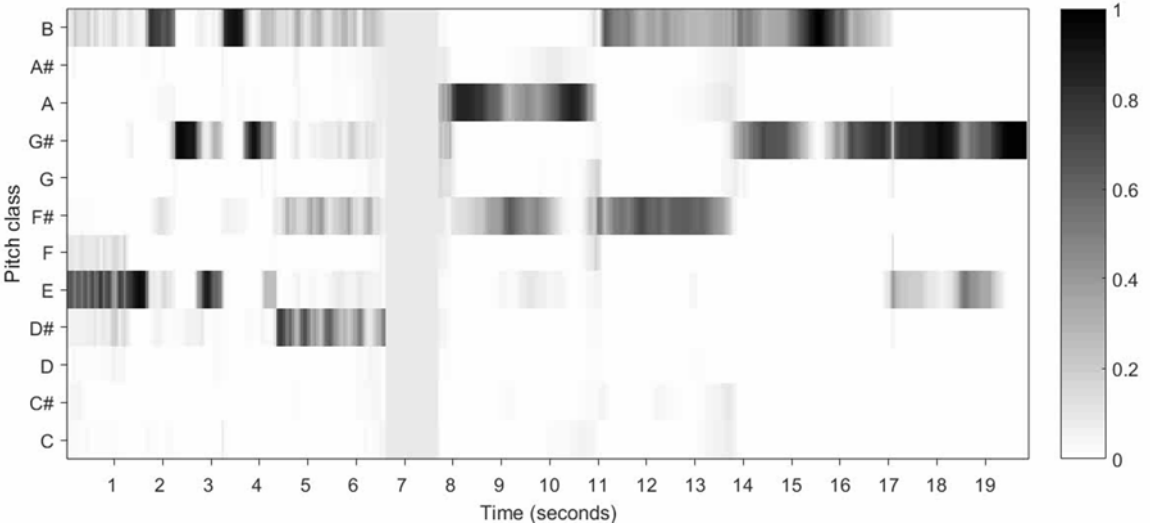
- Orchestra

L. van Beethoven,
*Fidelio*, Overture,
Slovak Philharmonic




- Piano

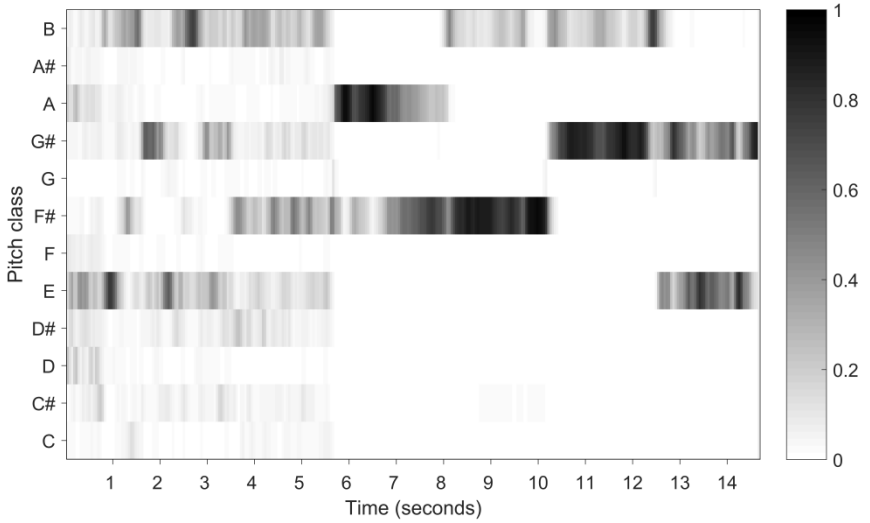
*Fidelio*, Overture,
arr. Alexander Zemlinsky
M. Namekawa, D.R. Davies,
piano four hands



# Recall: Chroma Representations

- Orchestra

L. van Beethoven,
*Fidelio*, Overture,
Slovak Philharmonic

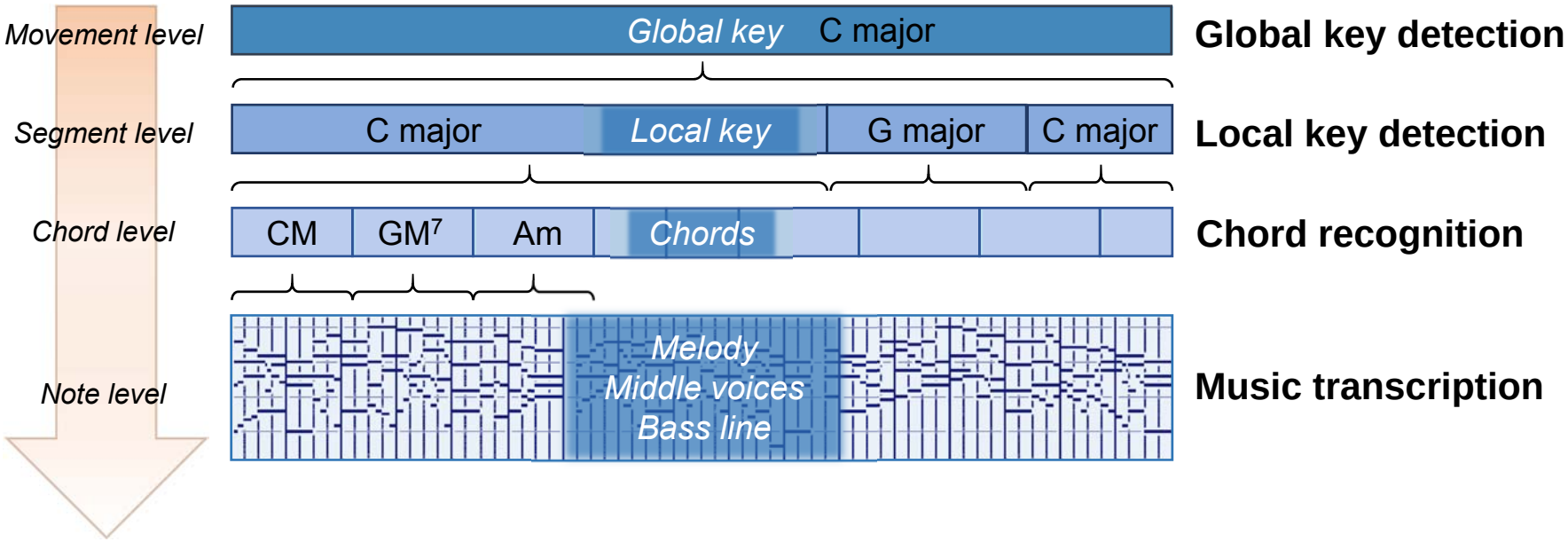



Gómez, *Tonal Description of Polyphonic Audio*, PhD thesis, Barcelona 2006

Müller / Ewert, *Towards Timbre-Invariant Audio Features for Harmony-Based Music*, IEEE TASLP, 2010

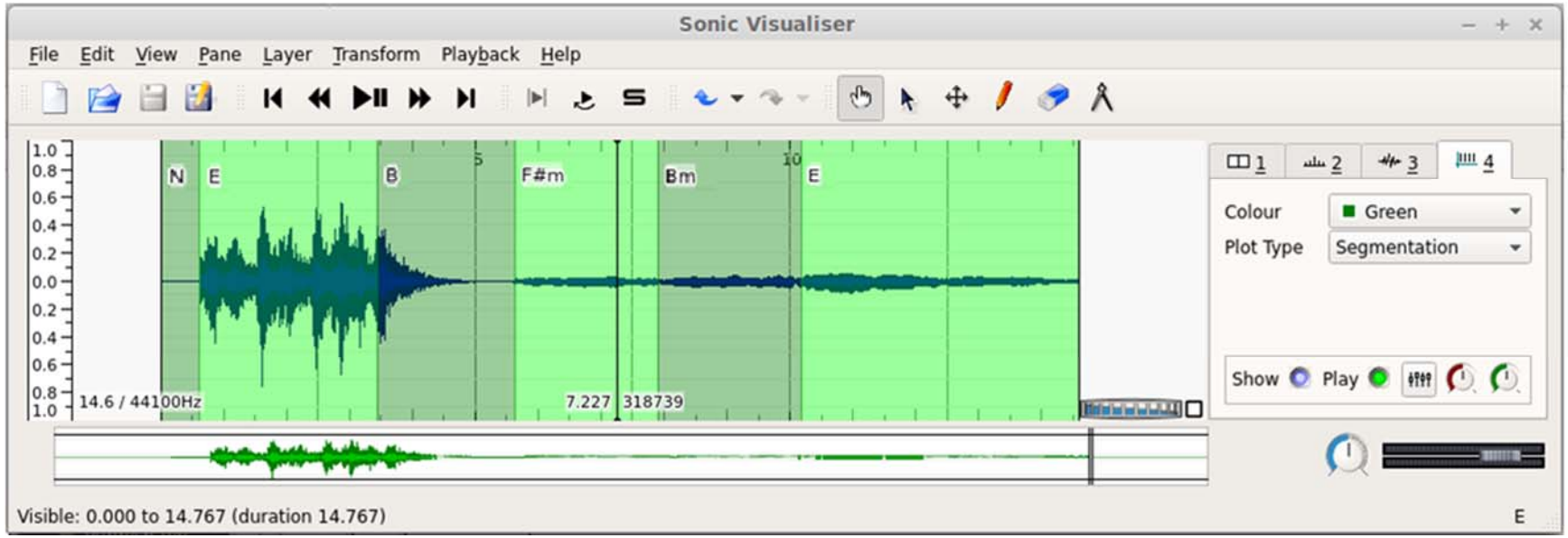
Mauch / Dixon, *Approximate Note Transcription for the Improved Identification of Difficult Chords*, ISMIR 2010

# Tonal Structures



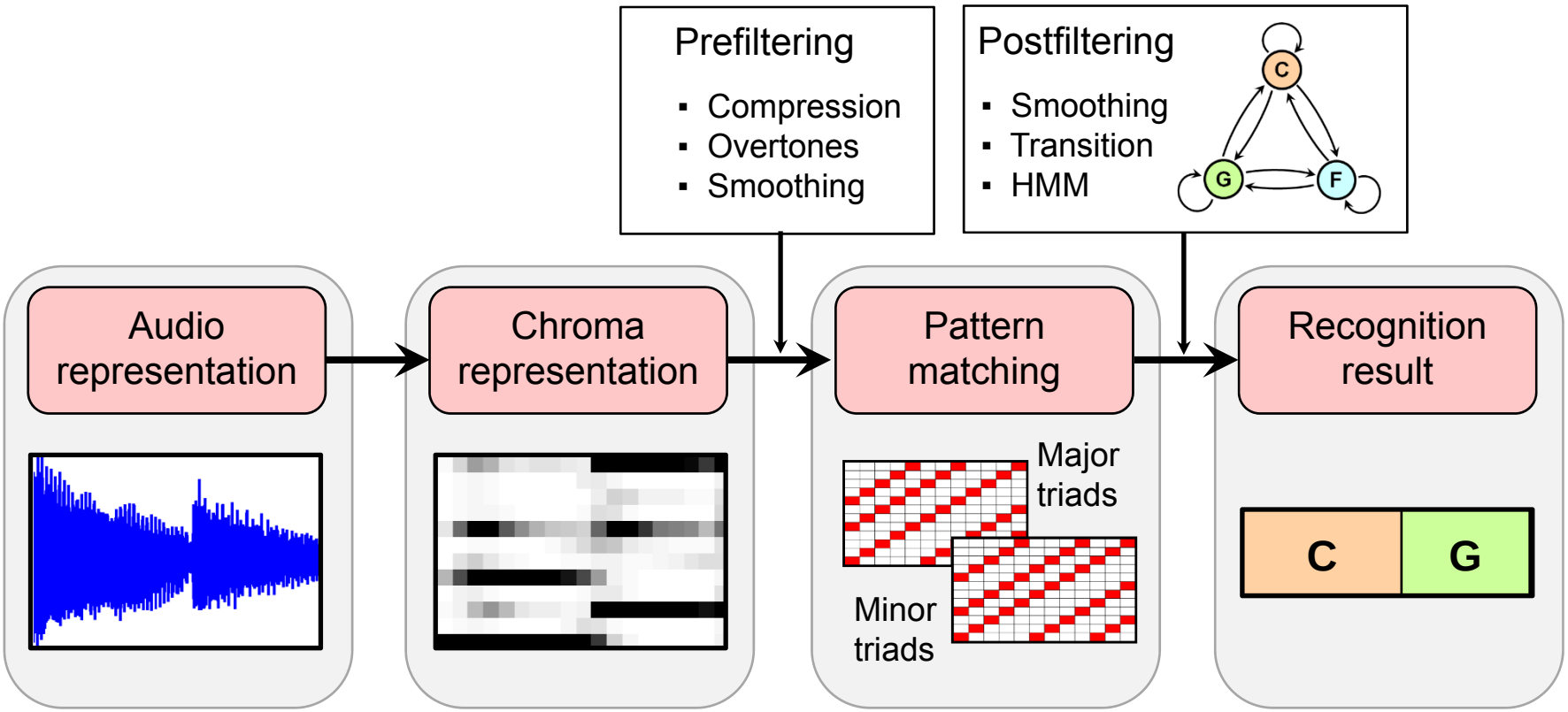
# Chord Recognition

- Chord recognition
  - Typically: Feature extraction, pattern matching, filtering
  - “Out-of-the-box” solutions

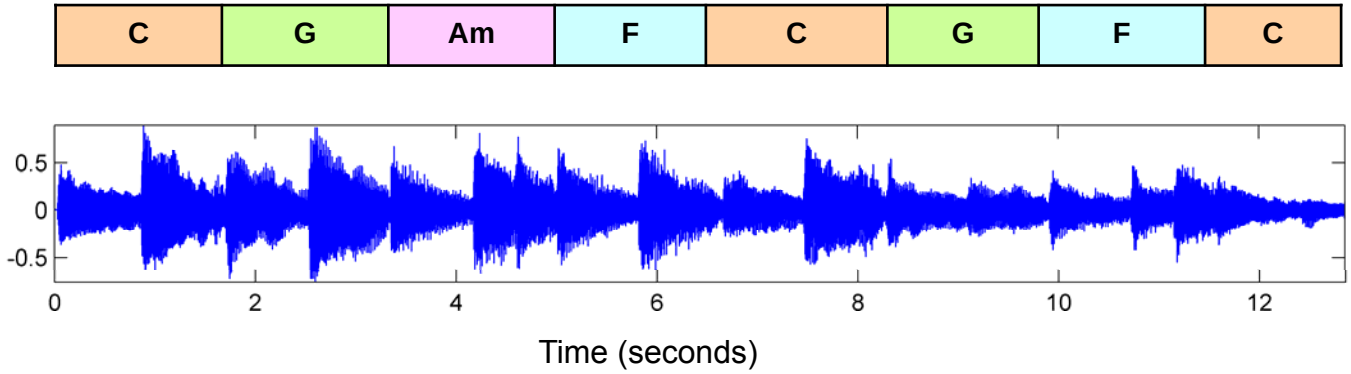



*Sonic Visualizer, Chordino Vamp Plugin*
*(Queen Mary University of London)*

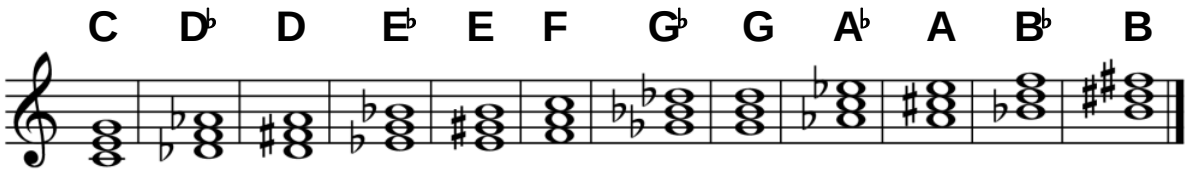
# Chord Recognition

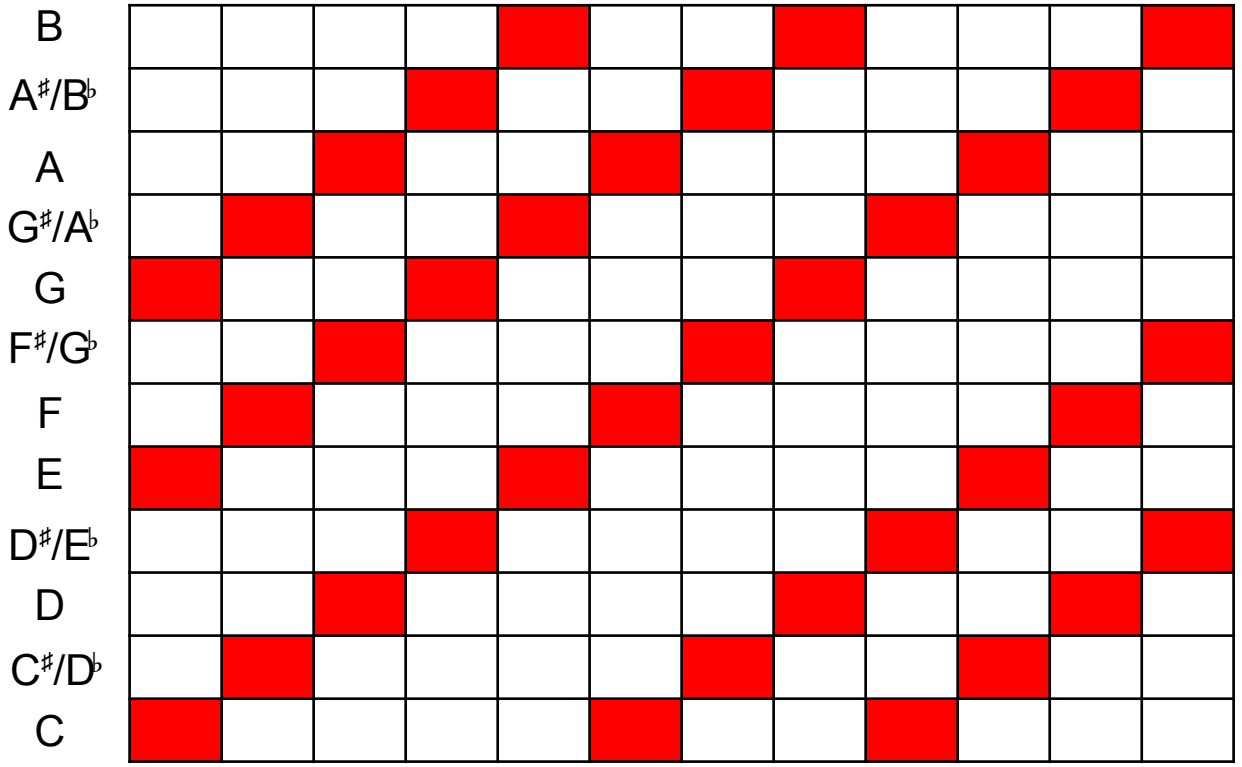


# Chord Recognition




# Chord Recognition: Basics



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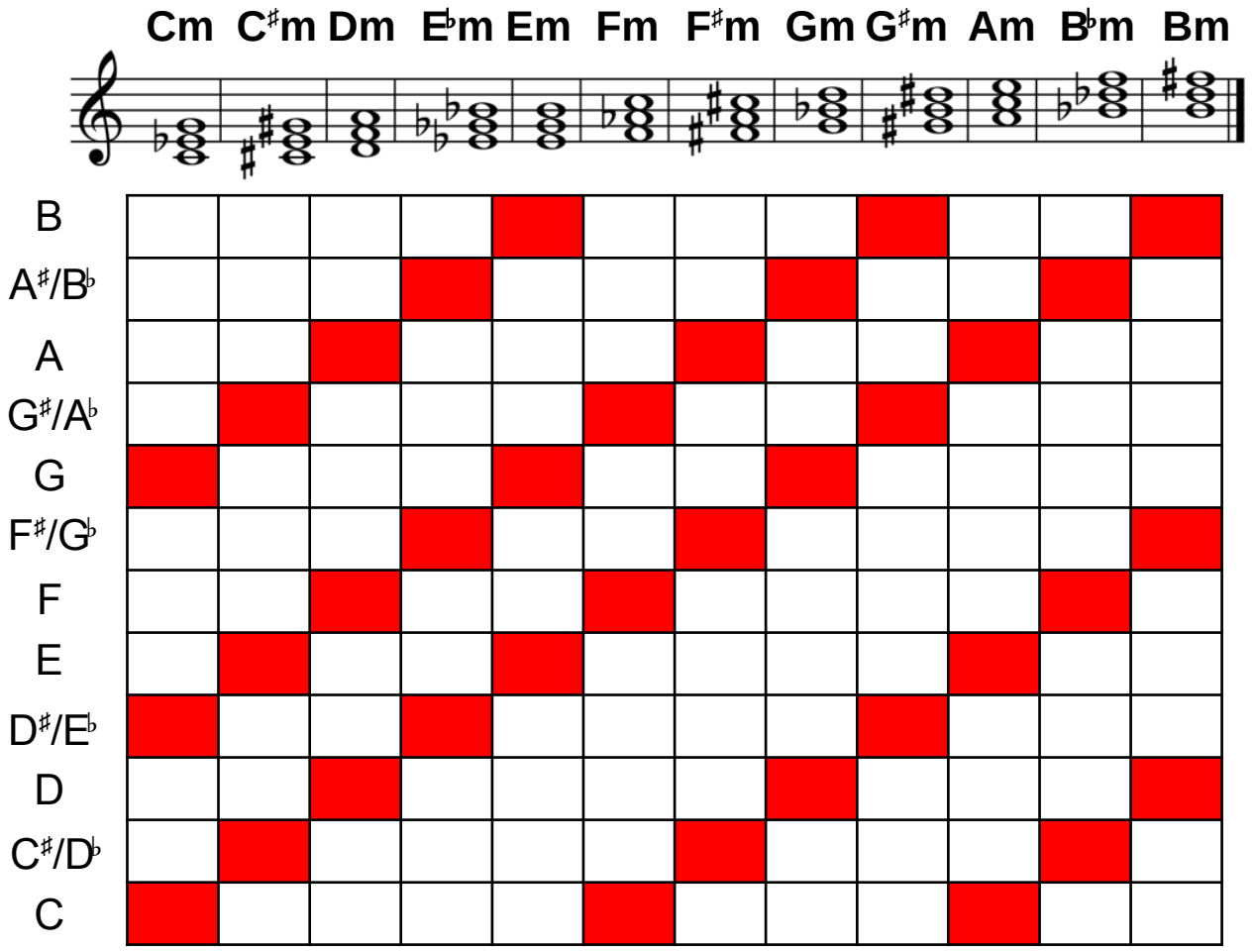
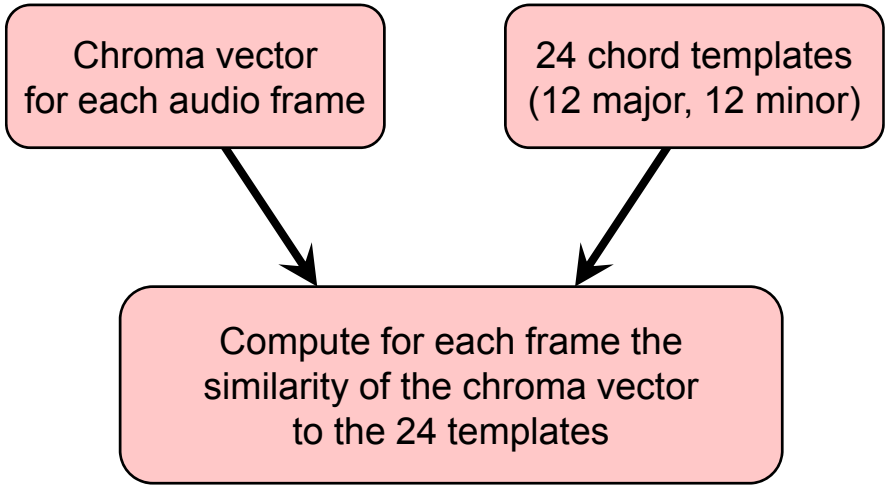
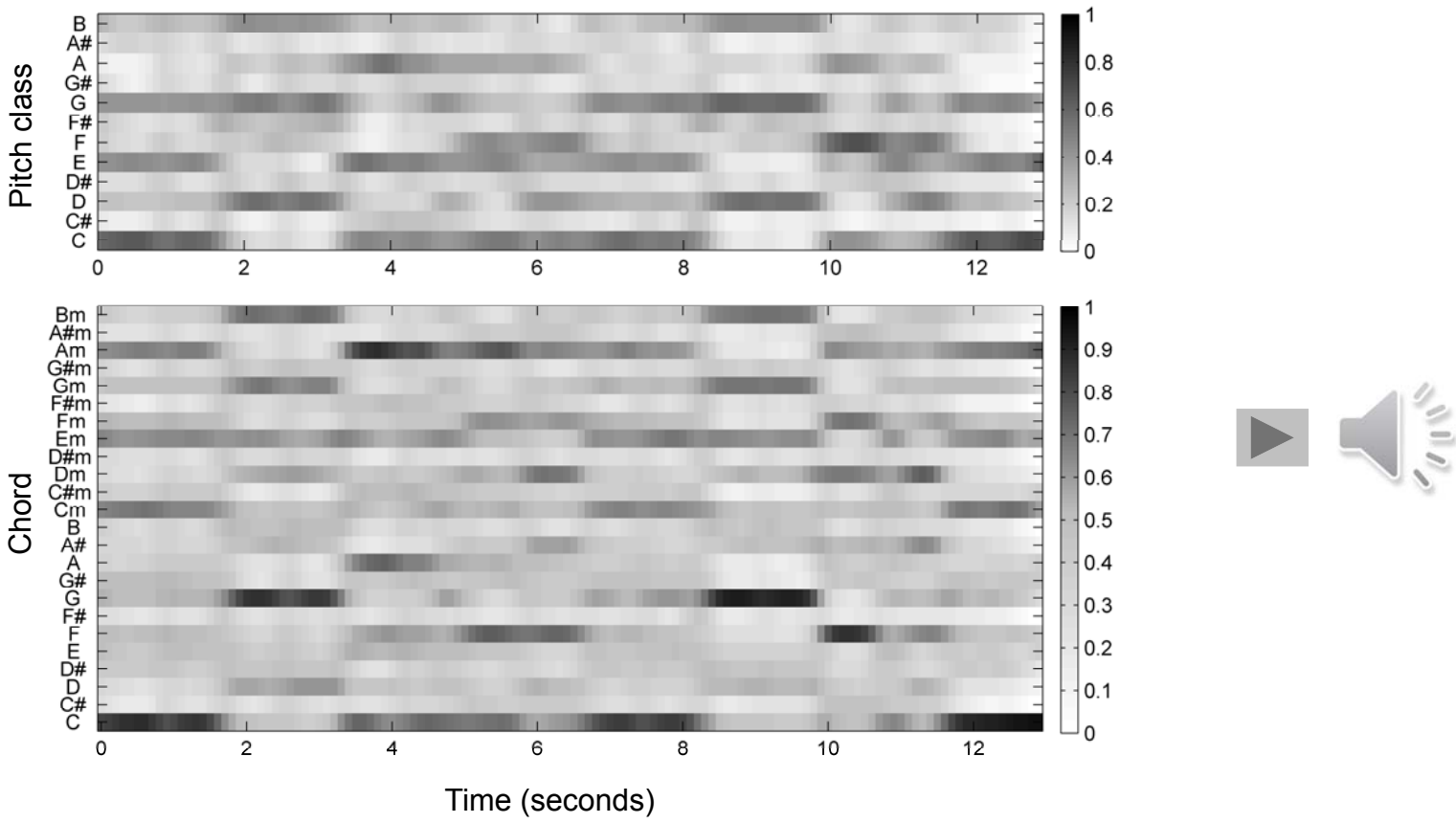


# Chord Recognition: Template Matching

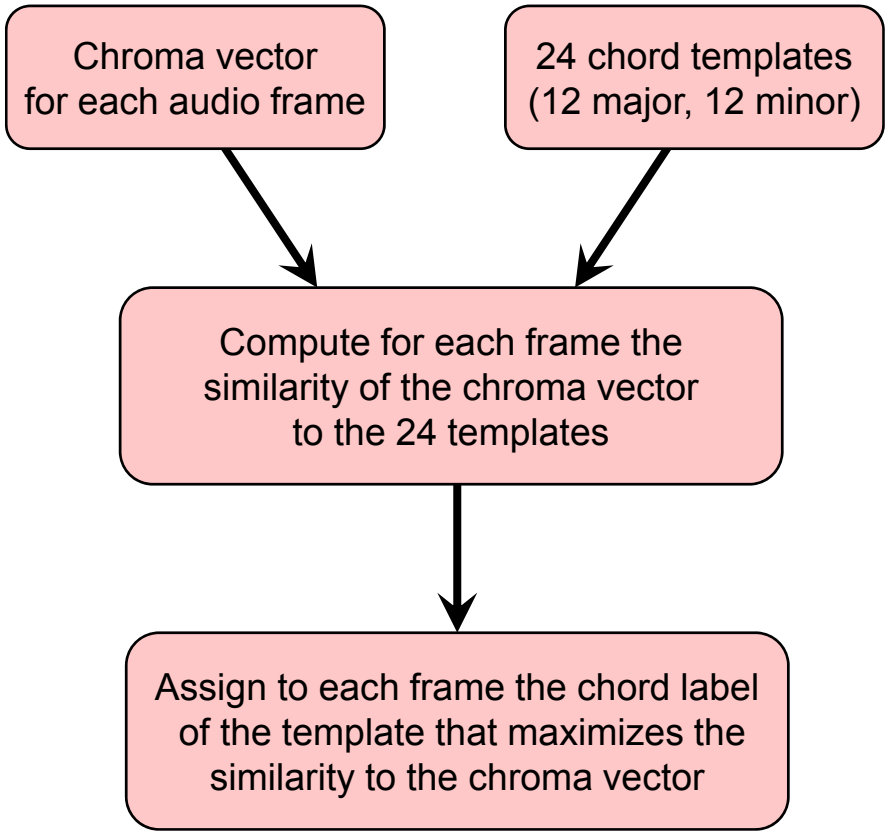



| | C | C♯ | D | … | Cm | C♯m | Dm | … |
|---|---|---|---|---|---|---|---|---|
| B | 0 | 0 | 0 | … | 0 | 0 | 0 | … |
| A♯ | 0 | 0 | 0 | … | 0 | 0 | 0 | … |
| A | 0 | 0 | 1 | … | 0 | 0 | 1 | … |
| G♯ | 0 | 1 | 0 | … | 0 | 1 | 0 | … |
| G | 1 | 0 | 0 | … | 1 | 0 | 0 | … |
| F♯ | 0 | 0 | 1 | … | 0 | 0 | 0 | … |
| F | 0 | 1 | 0 | … | 0 | 0 | 1 | … |
| E | 1 | 0 | 0 | … | 0 | 1 | 0 | … |
| D♯ | 0 | 0 | 0 | … | 1 | 0 | 0 | … |
| D | 0 | 0 | 1 | … | 0 | 0 | 1 | … |
| C♯ | 0 | 1 | 0 | … | 0 | 1 | 0 | … |
| C | 1 | 0 | 0 | … | 1 | 0 | 0 | … |

# Chord Recognition: Template Matching

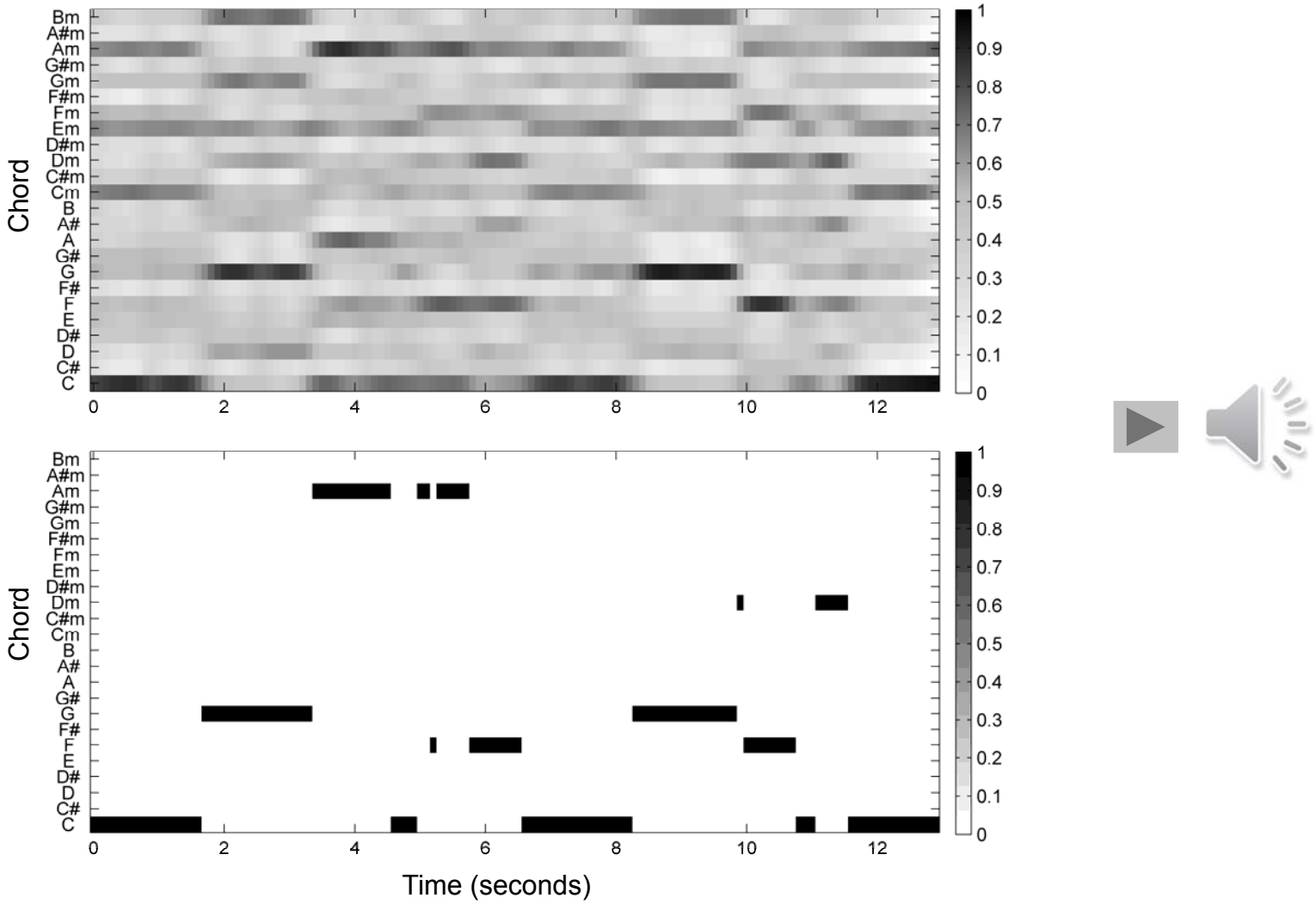


# Chord Recognition: Label Assignment

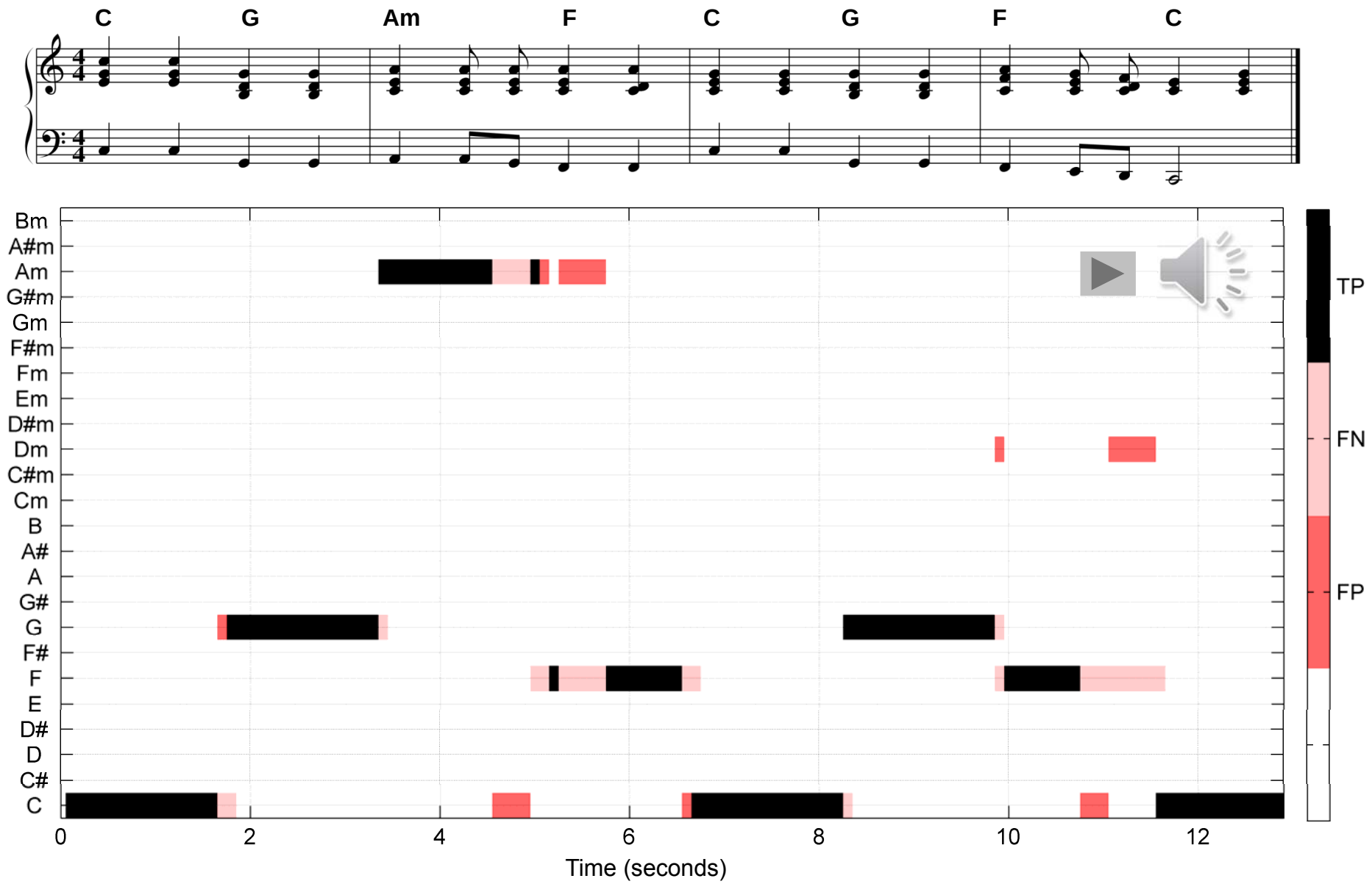



| | C | C♯ | D | … | Cm | C♯m | Dm | … |
|---|---|---|---|---|---|---|---|---|
| B | 0 | 0 | 0 | … | 0 | 0 | 0 | … |
| A♯ | 0 | 0 | 0 | … | 0 | 0 | 0 | … |
| A | 0 | 0 | 1 | … | 0 | 0 | 1 | … |
| G♯ | 0 | 1 | 0 | … | 0 | 1 | 0 | … |
| G | 1 | 0 | 0 | … | 1 | 0 | 0 | … |
| F♯ | 0 | 0 | 1 | … | 0 | 0 | 0 | … |
| F | 0 | 1 | 0 | … | 0 | 0 | 1 | … |
| E | 1 | 0 | 0 | … | 0 | 1 | 0 | … |
| D♯ | 0 | 0 | 0 | … | 1 | 0 | 0 | … |
| D | 0 | 0 | 1 | … | 0 | 0 | 1 | … |
| C♯ | 0 | 1 | 0 | … | 0 | 1 | 0 | … |
| C | 1 | 0 | 0 | … | 1 | 0 | 0 | … |

# Chord Recognition: Label Assignment

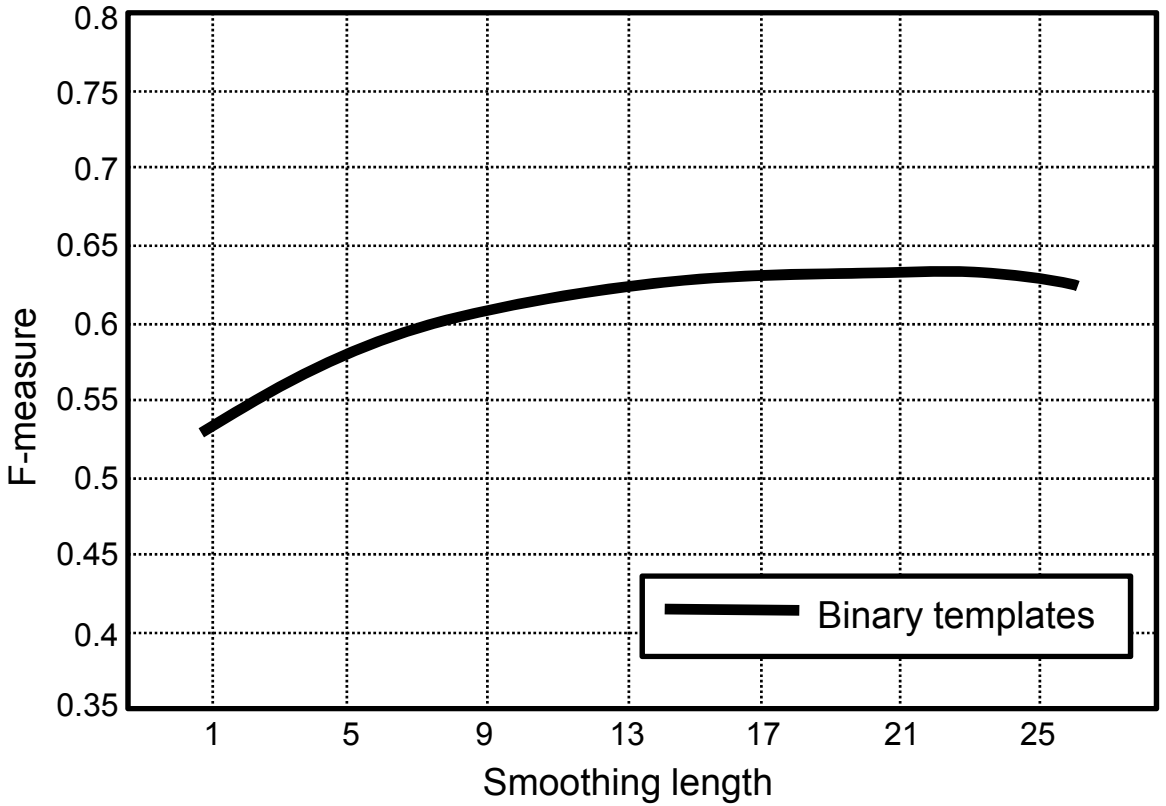


# Chord Recognition: Evaluation



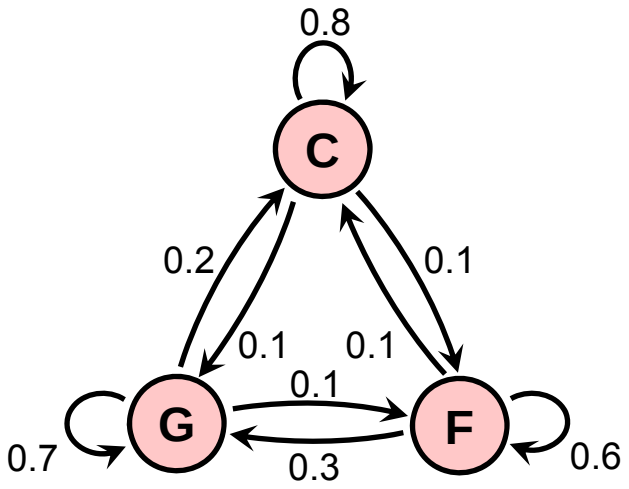
# Chord Recognition: Evaluation

- Frame-wise approach: Too many / too rapid changes of output label
- Improvement strategies:
  - Pre-filtering: Average chroma features over several frames (**smoothing**)
  - Evaluation on all Beatles songs



# Chord Recognition: Markov Chains

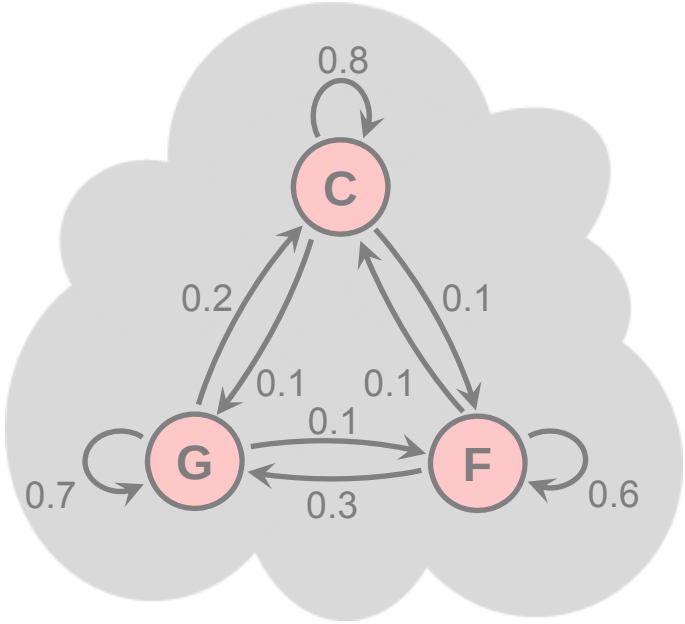
- Probabilistic model for sequential data
- Markov property: Next state depends only on current state (no “memory”)
- Consist of:
  - Set of states
  - State transition probabilities
  - *Initial state probabilities*



# Chord Recognition: Hidden Markov Models

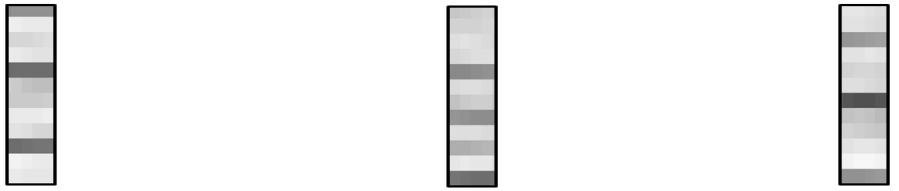
- States as **hidden** variables

- Consist of:
  - Set of states (hidden)
  - State transition probabilities
  - *Initial state probabilities*

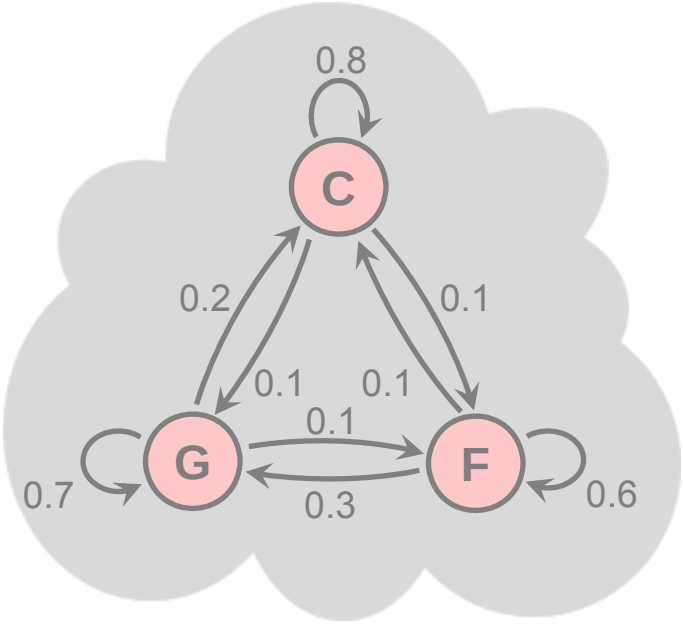


# Chord Recognition: Hidden Markov Models

- States as **hidden** variables

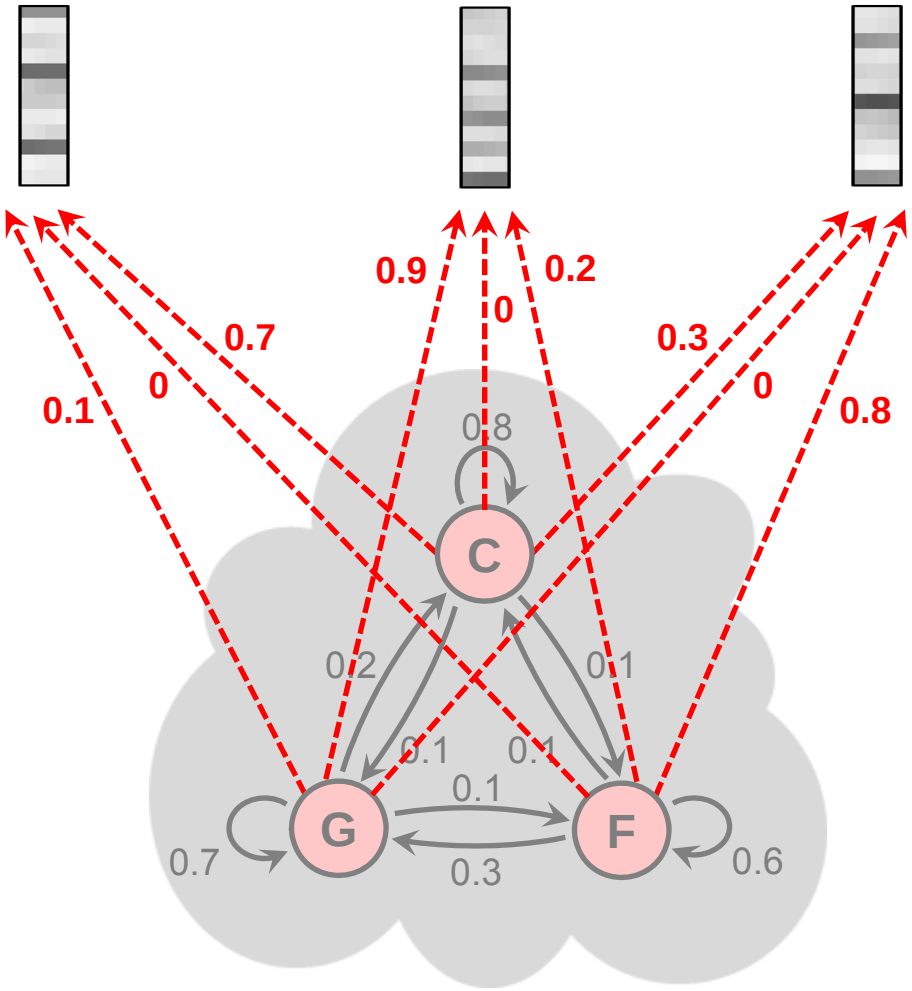


- Consist of:
  - Set of states (hidden)
  - State transition probabilities
  - *Initial state probabilities*
  - Observations (visible)



# Chord Recognition: Hidden Markov Models

- States as **hidden** variables
- Consist of:
  - Set of states (hidden)
  - State transition probabilities
  - *Initial state probabilities*
  - Observations (visible)
  - Emission probabilities



# Chord Recognition: Hidden Markov Models

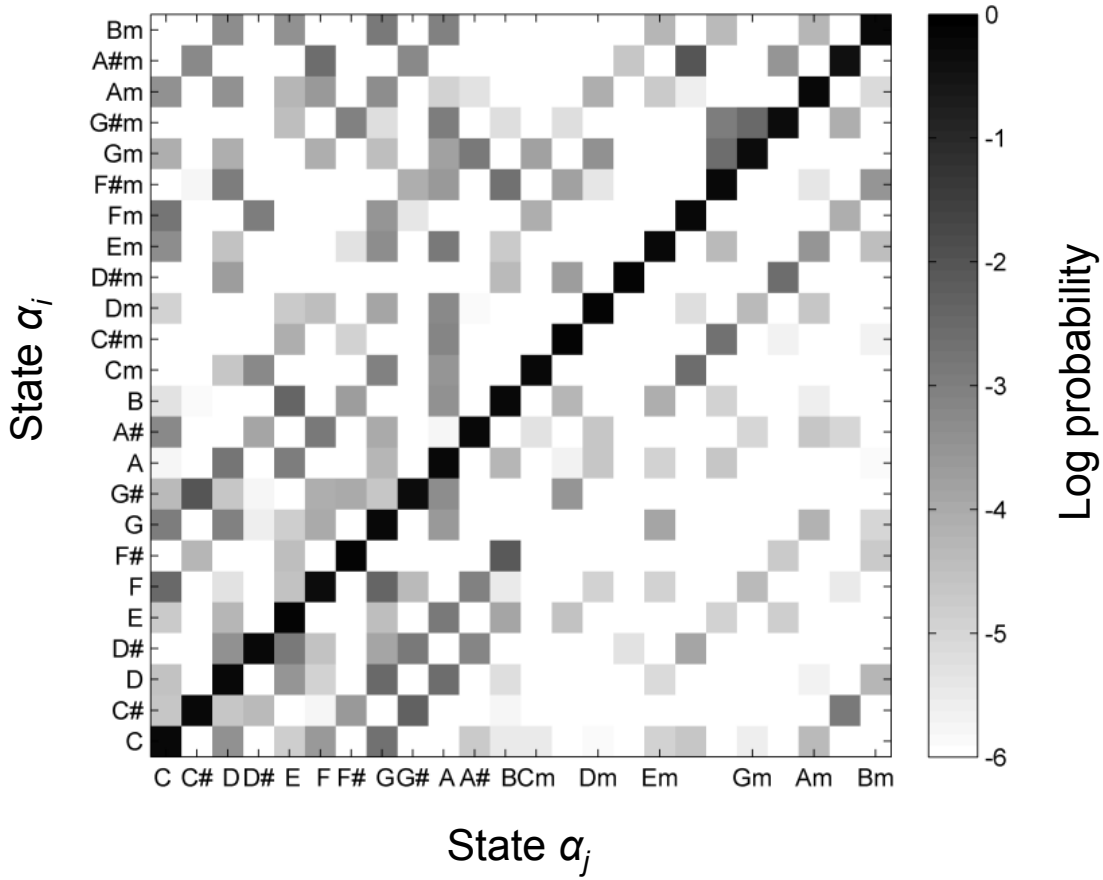
- Different algorithmic problems

- **Estimation problem:**
  - Given an observation sequence, determine the *model parameters*
  - „Training“ the HMM on given data
  - Baum-Welch algorithm (Expectation-Maximization)

- **Uncovering problem:**
  - Given the model, find the optimal *hidden state sequence*
  - Use Viterbi algorithm based on dynamic programming
  - Corresponds to chord estimation task!

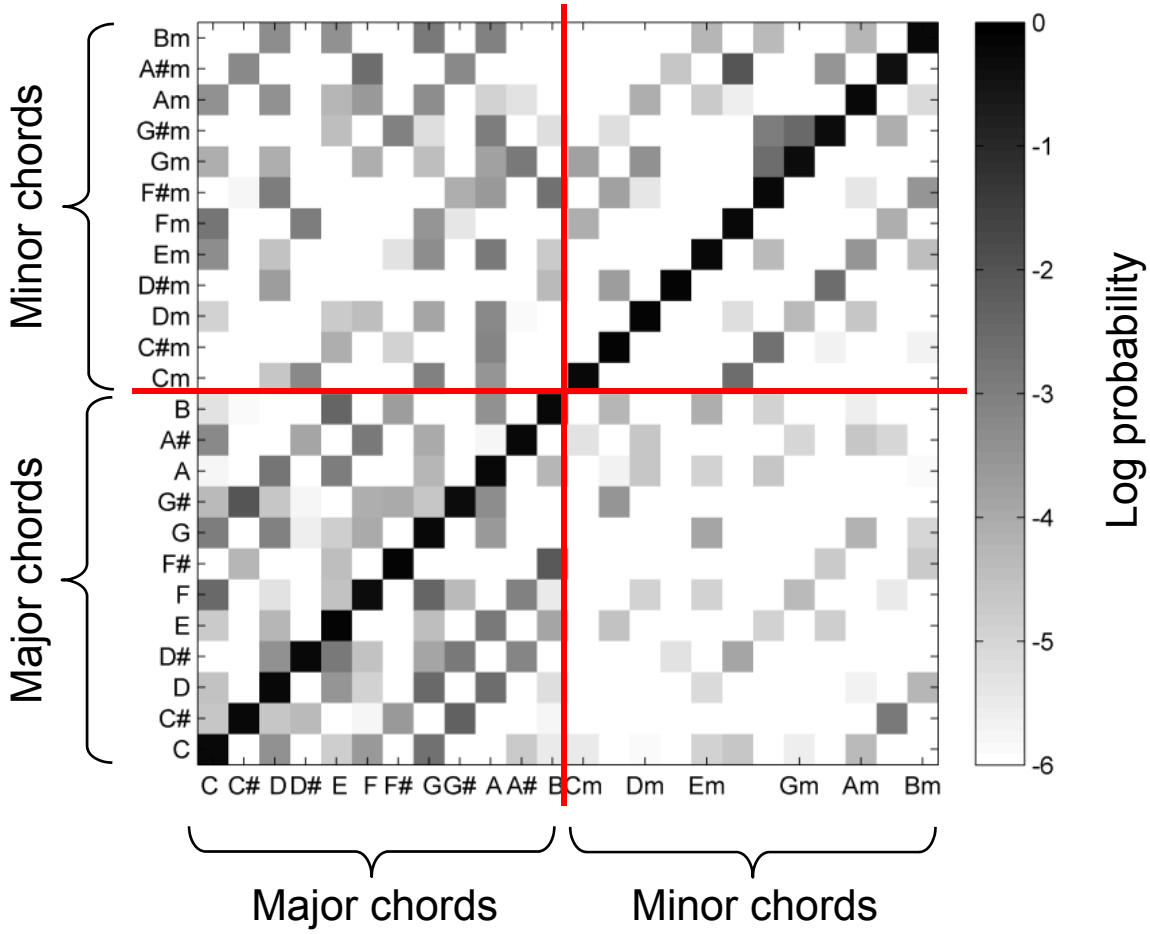
# Chord Recognition: Hidden Markov Models

- Parameters: **Transition probabilities**
- Estimated from data



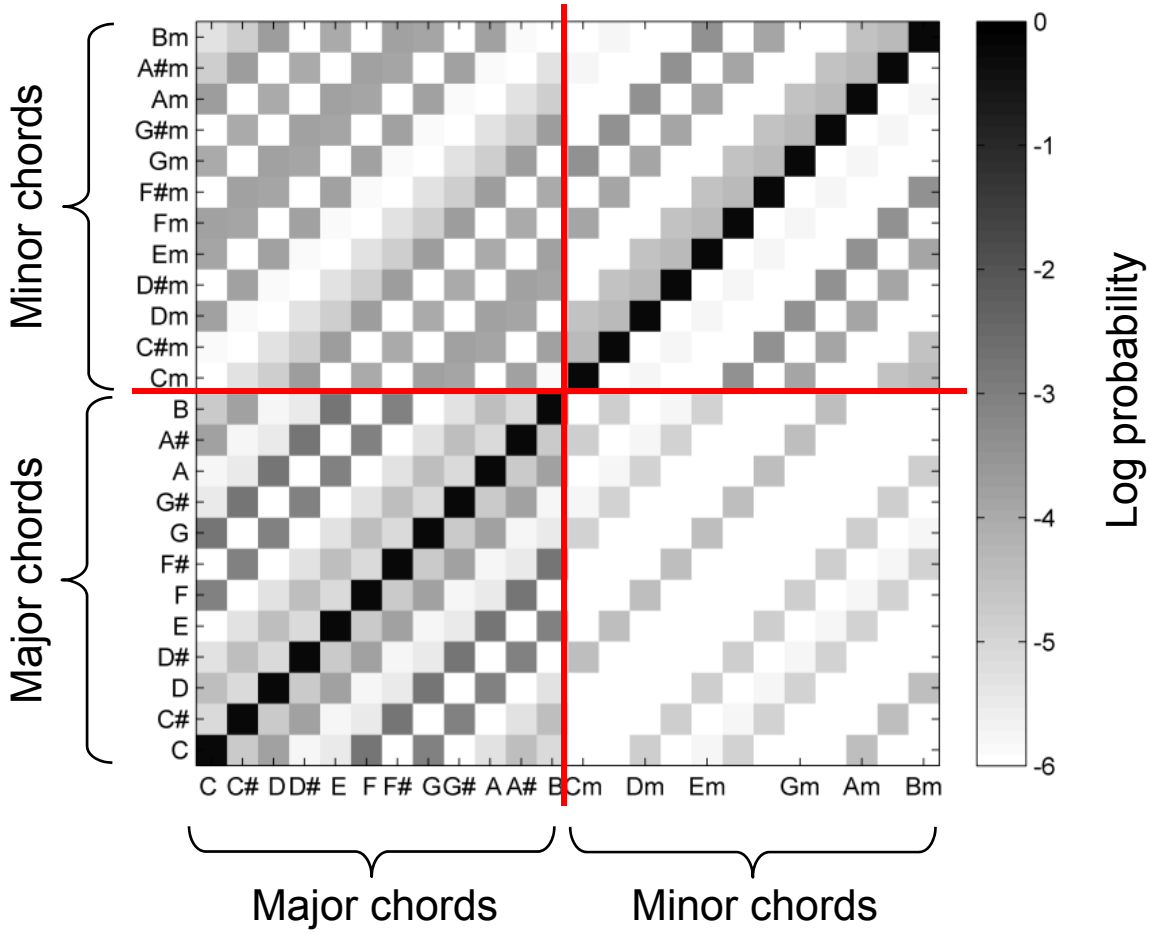
# Chord Recognition: Hidden Markov Models

- Parameters: **Transition probabilities**
- Estimated from data



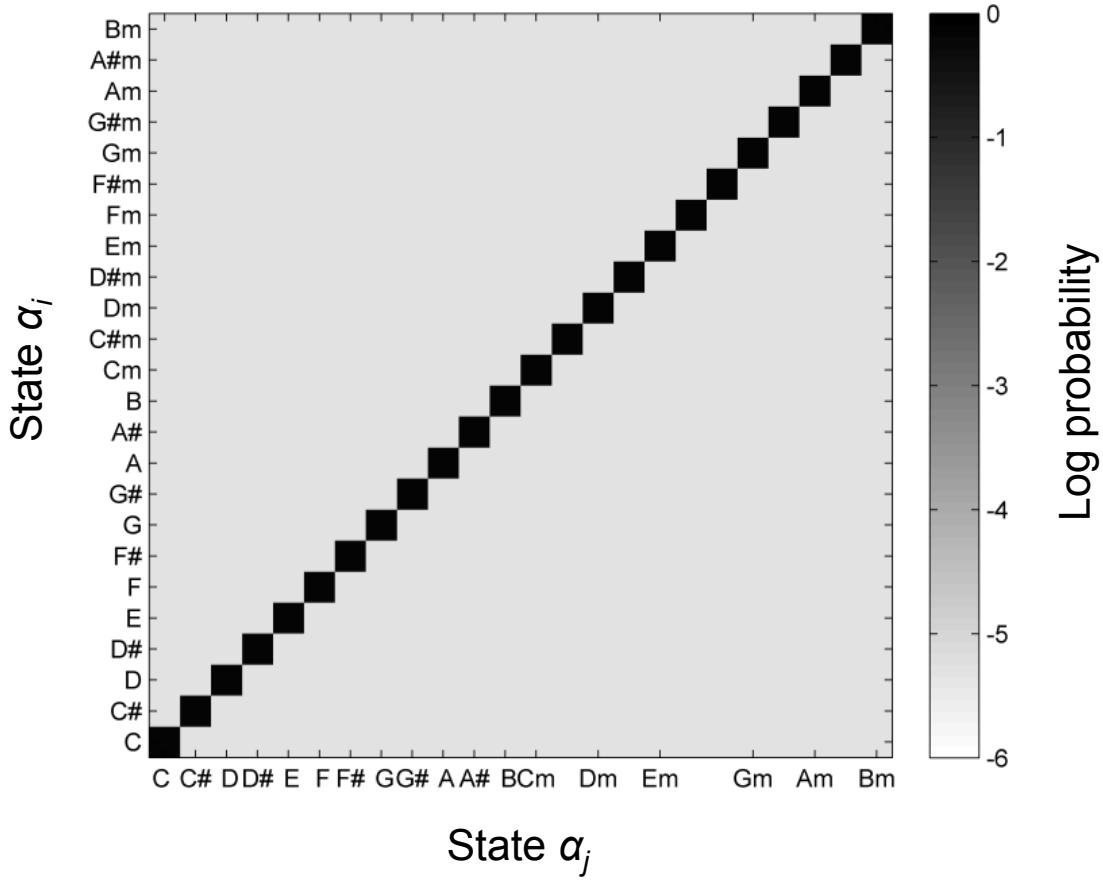
# Chord Recognition: Hidden Markov Models

- Parameters: **Transition probabilities**
- Transposition-invariant



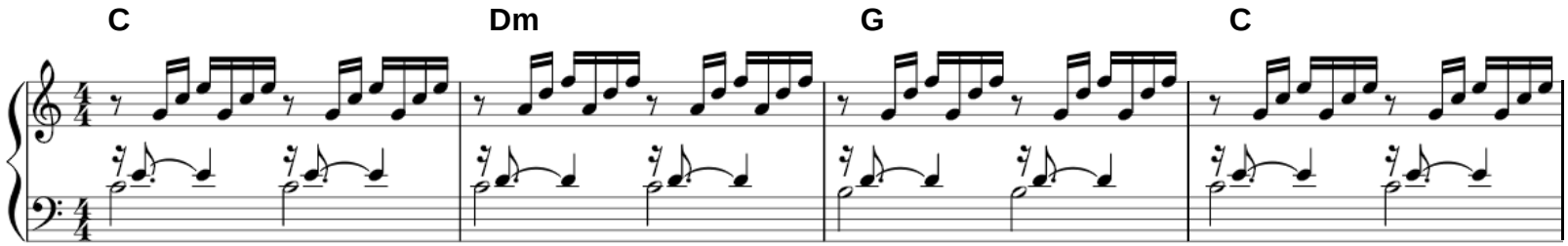
# Chord Recognition: Hidden Markov Models

- Parameters: **Transition probabilities**
- Uniform transition matrix (only smoothing)

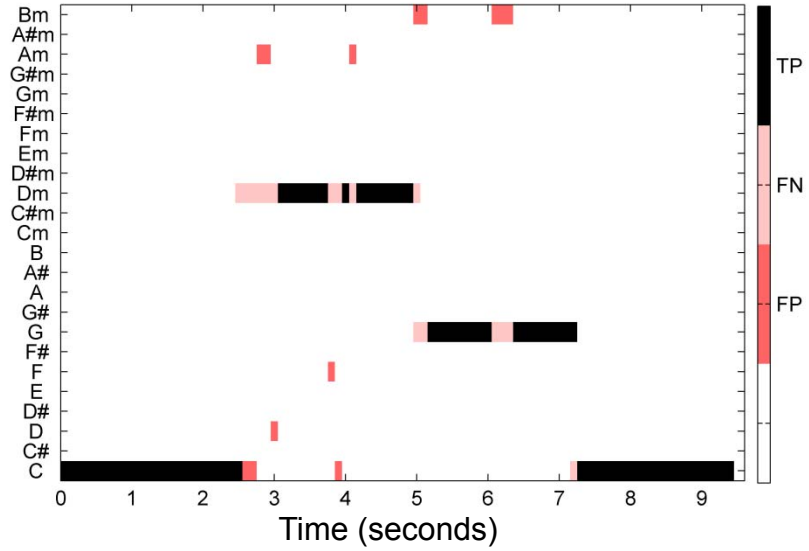


# Chord Recognition: Evaluation

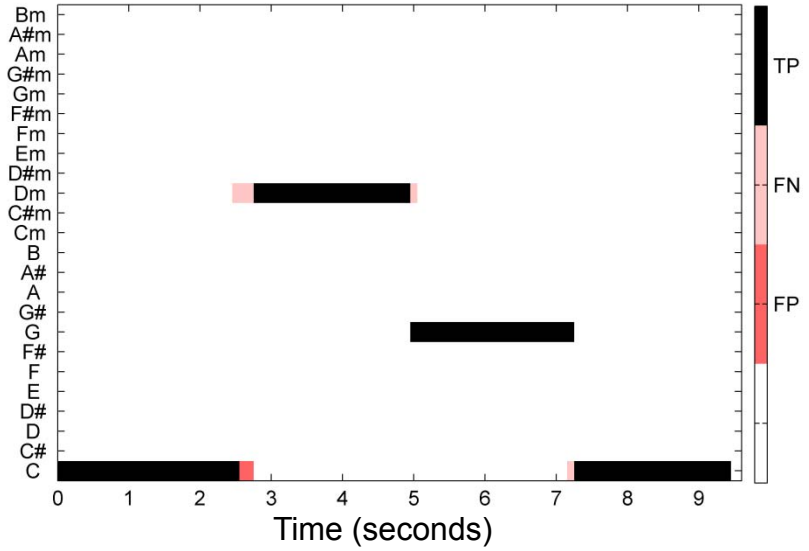
- Effect of HMM-based chord estimation and smoothing:




(a) Template Matching (frame-wise)

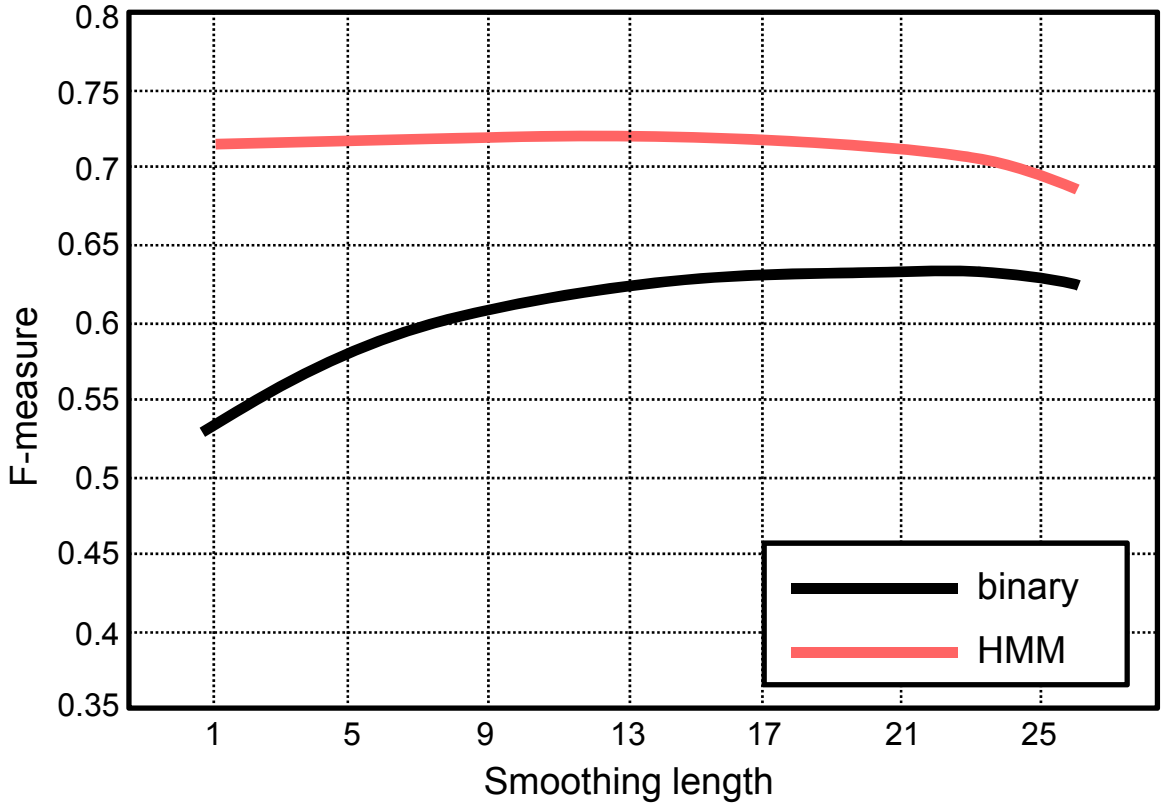



(b) HMM

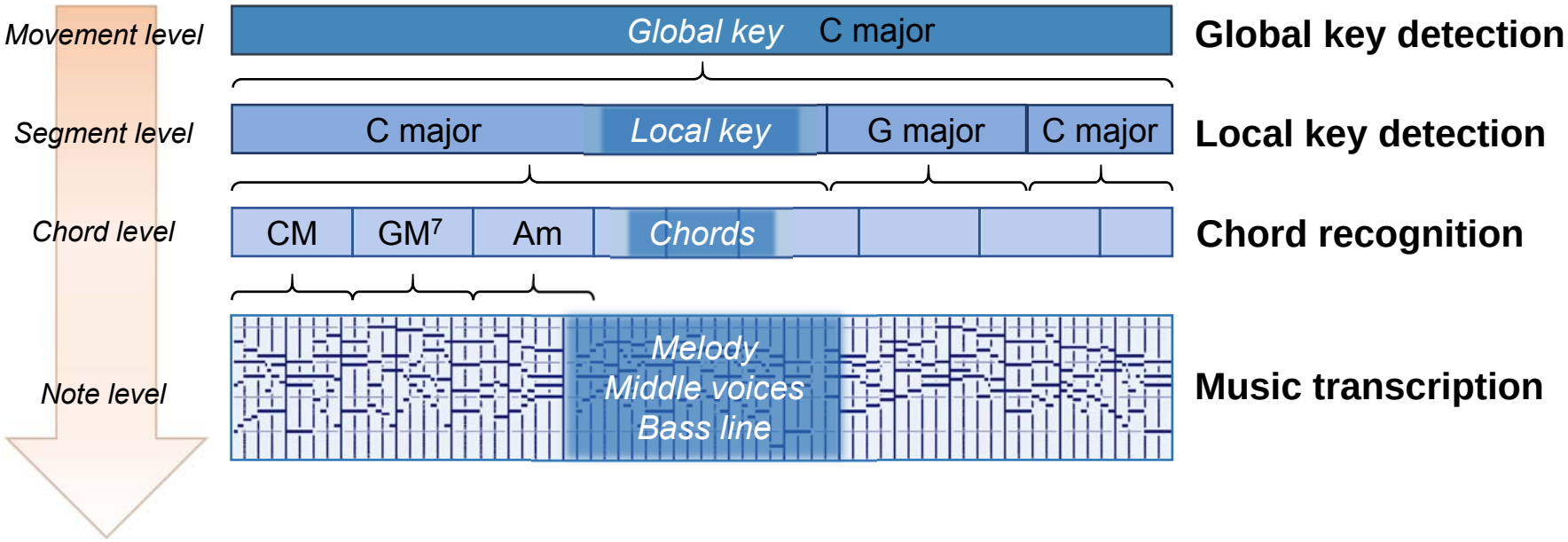


# Chord Recognition: Evaluation

- Evaluation on all Beatles songs

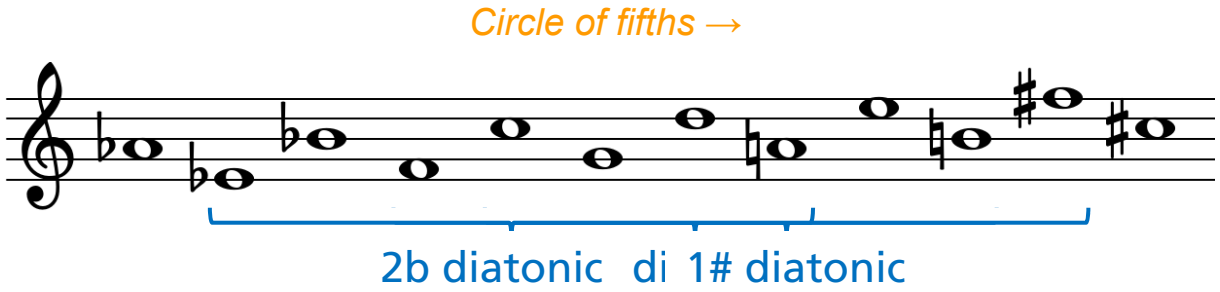


# Tonal Structures



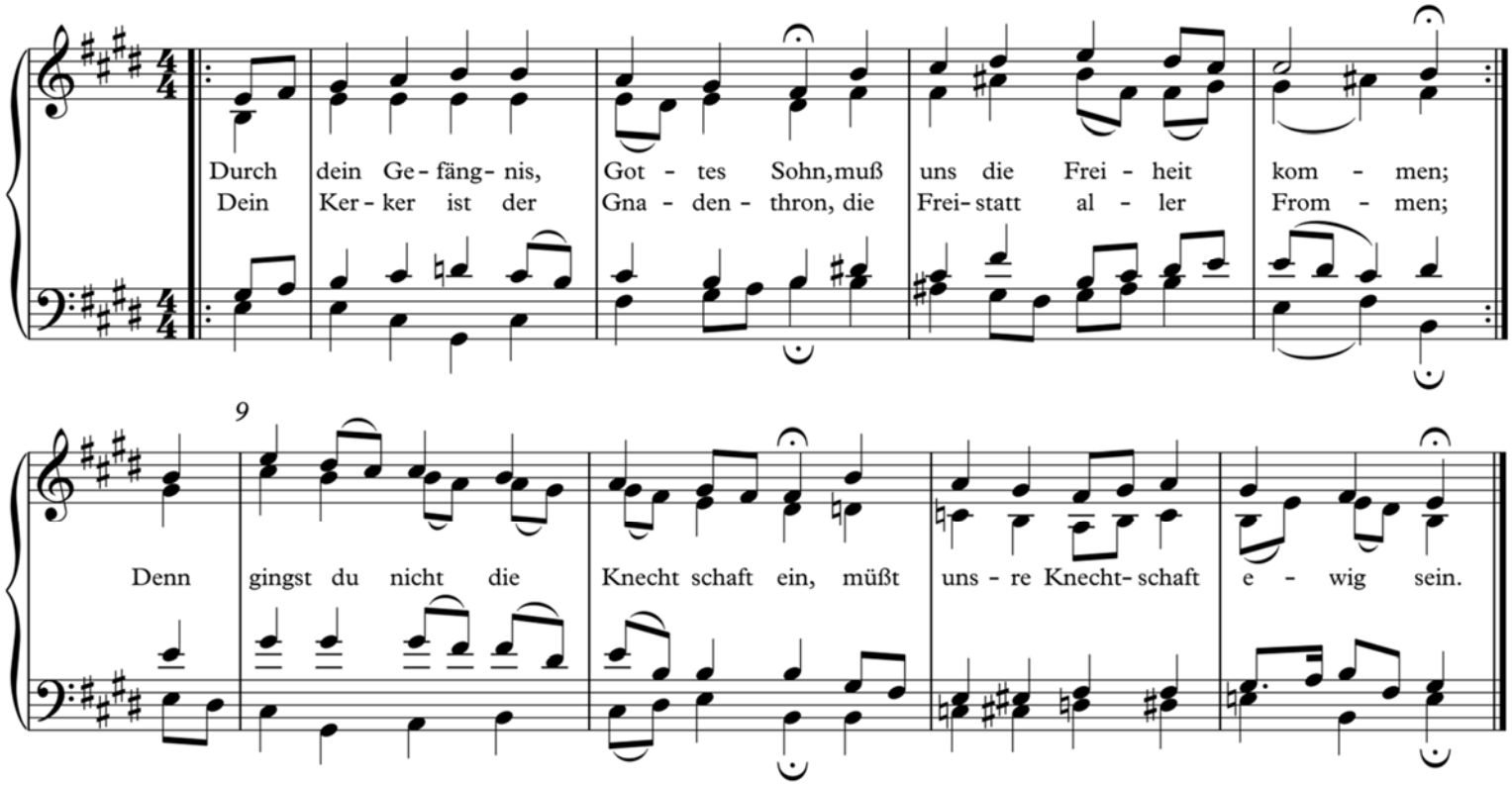
# Local Key Detection

- Key as an important musical concept (*"Symphony in C major"*)
- Modulations → Local approach
- Diatonic Scales
  - Simplification of keys
  - Perfect-fifth relation



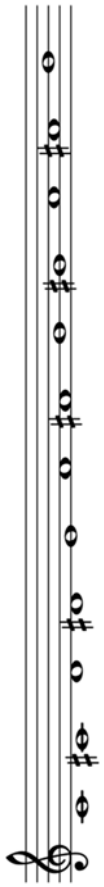
# Local Key Detection

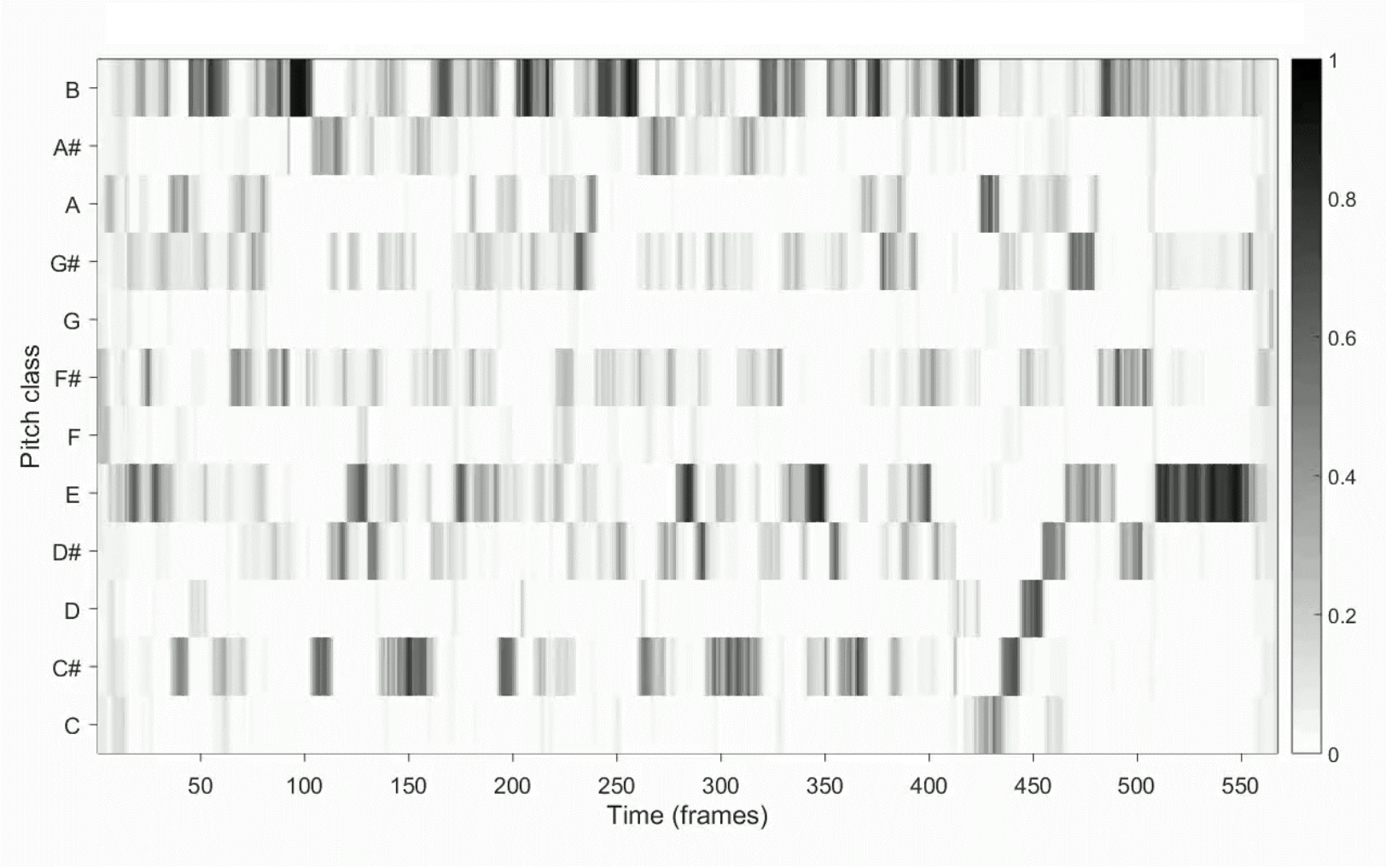
- Example: J.S. Bach, Choral "Durch Dein Gefängnis" (*Johannespassion*)
- **Score** – Piano reduction



# Local Key Detection: Chroma Features

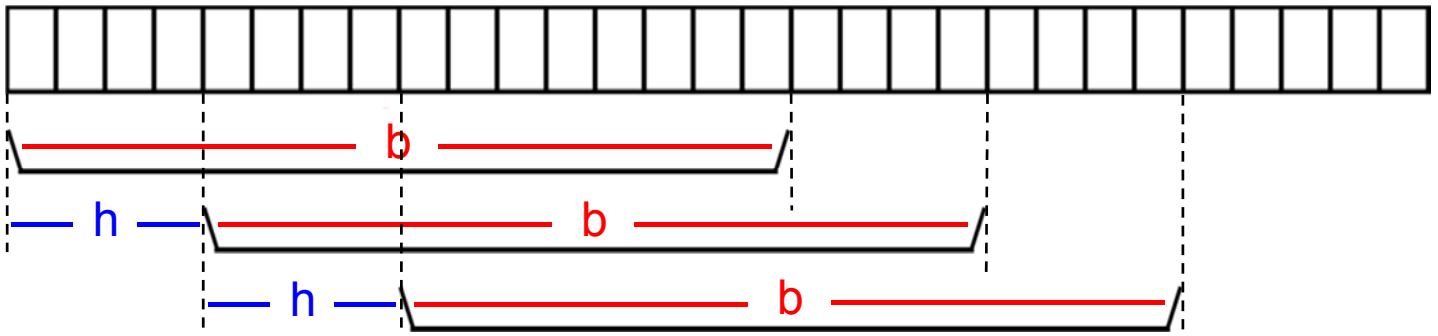
- Example: J.S. Bach, Choral "Durch Dein Gefängnis" (*Johannespassion*)
- **Audio** – Chroma features (Scholars Baroque Ensemble, Naxos 1994)





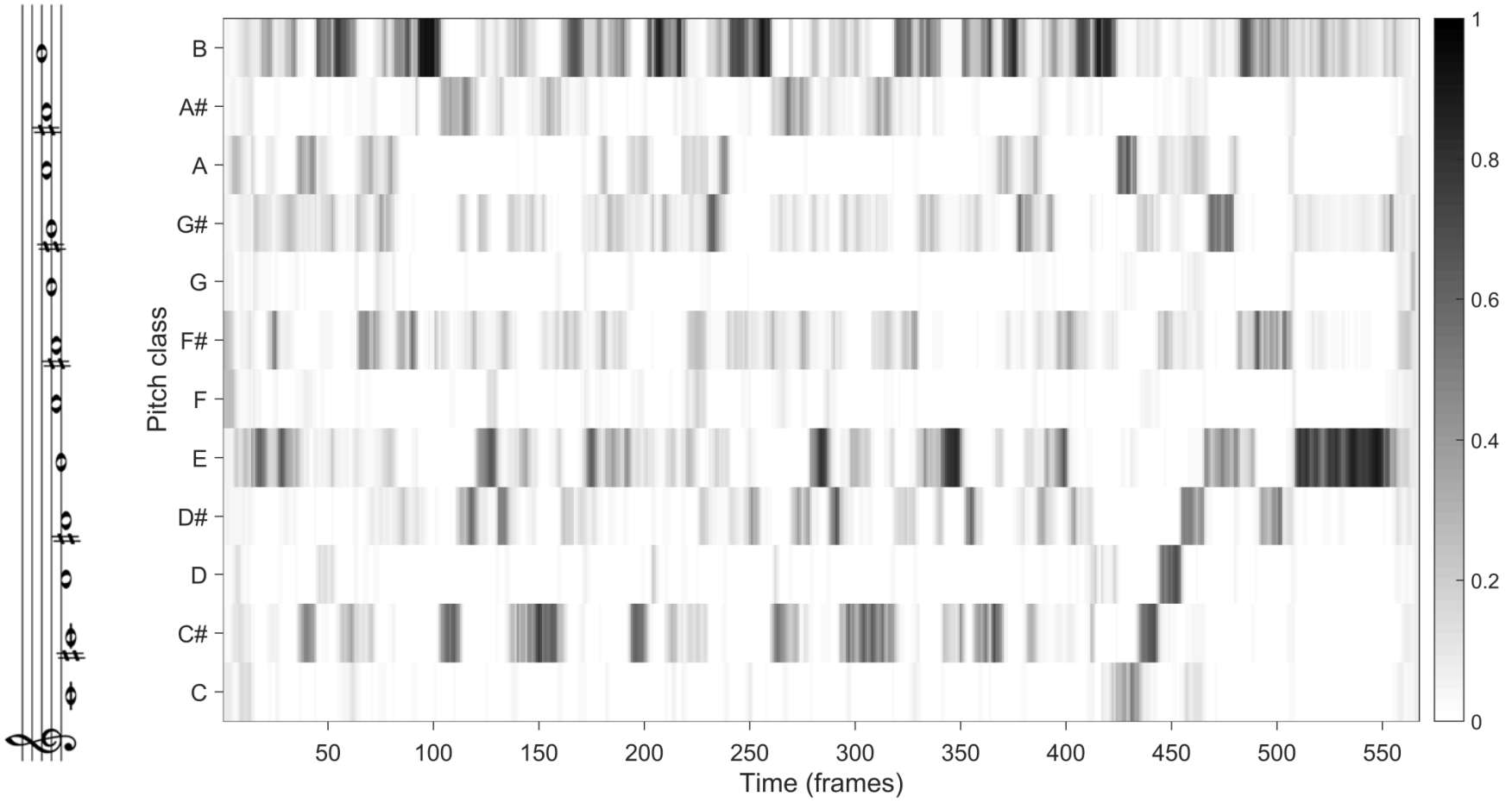
# Local Key Detection: Chroma Smoothing

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



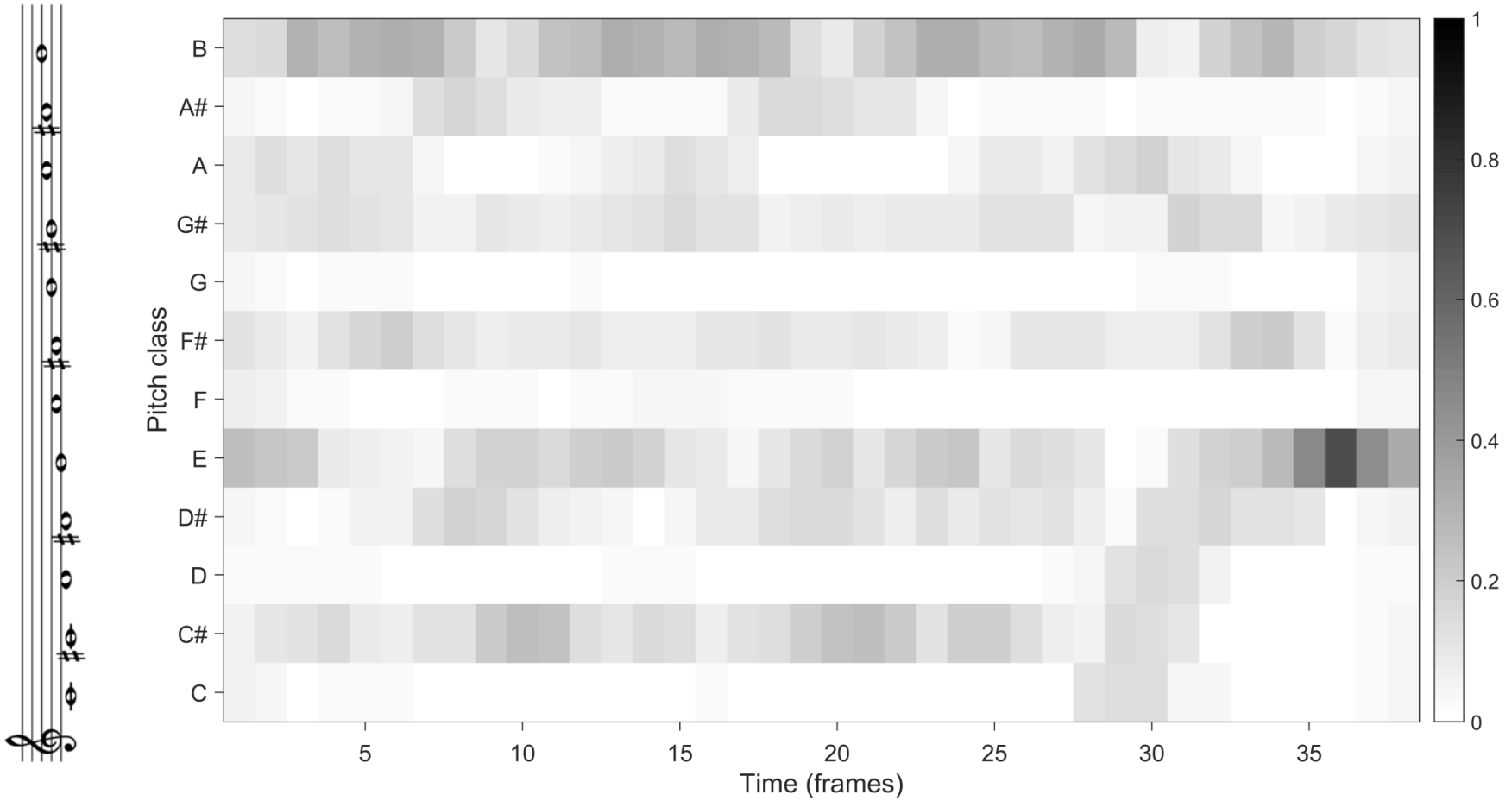
# Local Key Detection: Chroma Smoothing

- Choral (Bach)



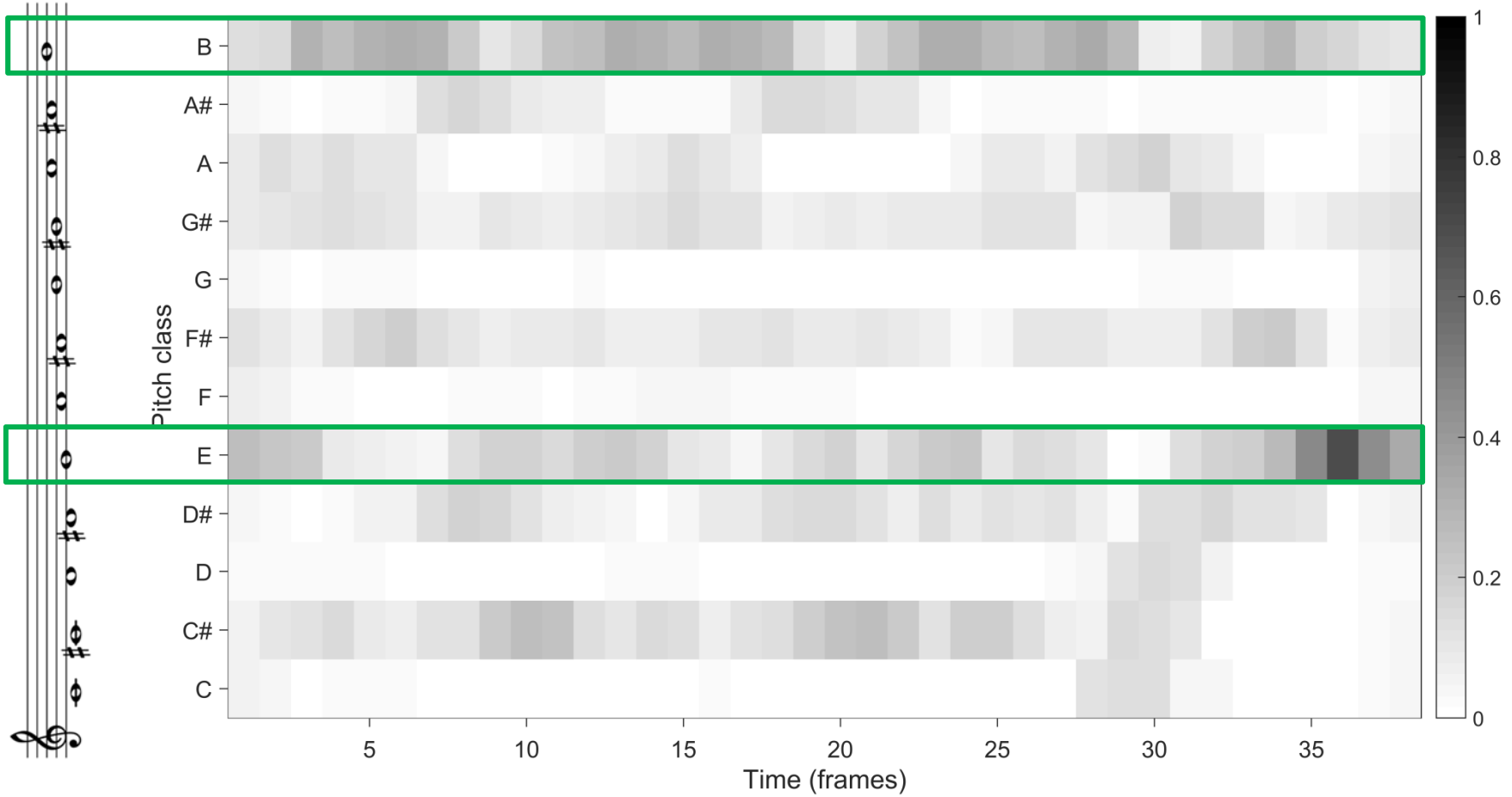
# Local Key Detection: Chroma Smoothing

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



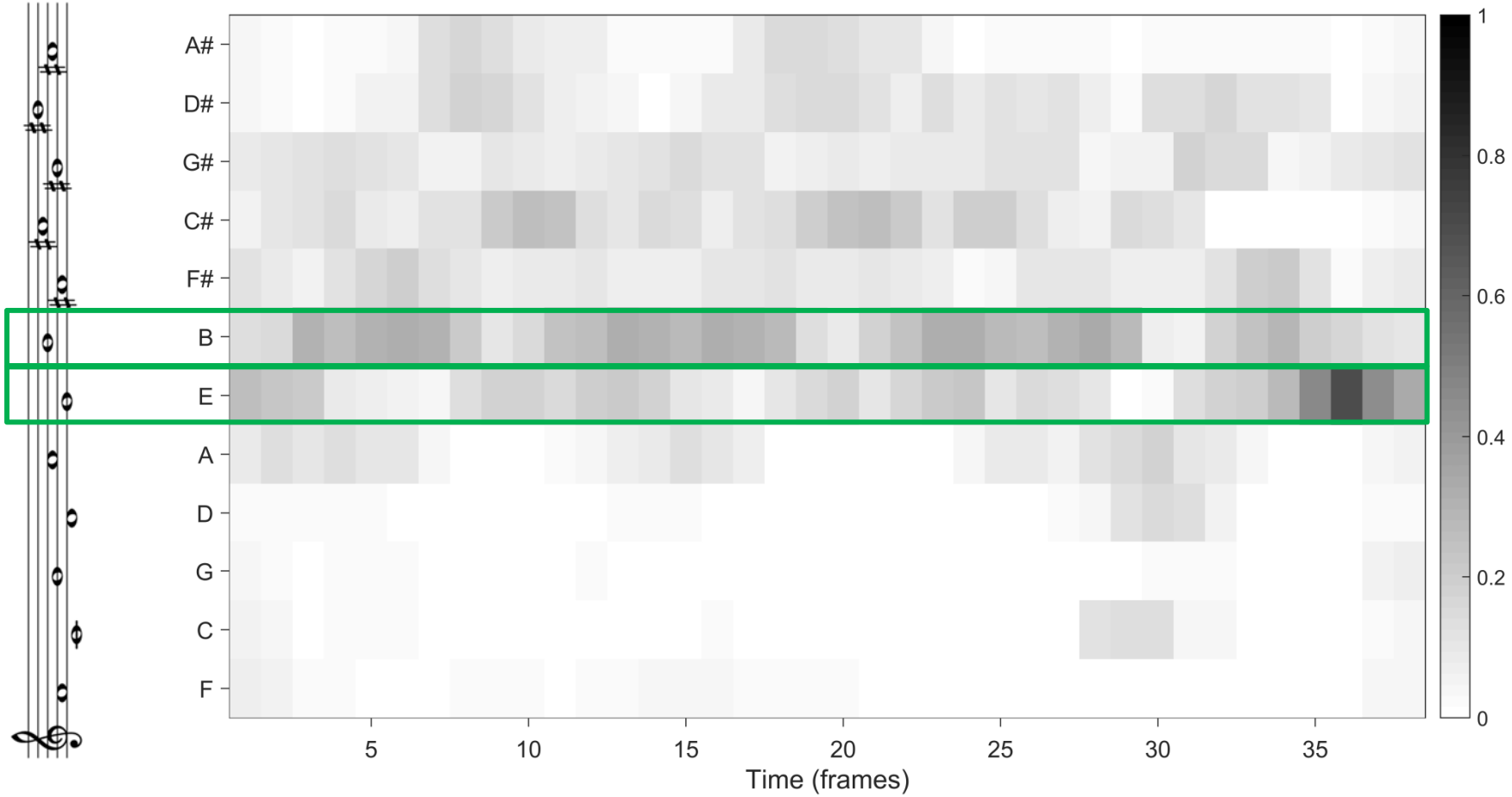
# Local Key Detection: Diatonic Scales

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



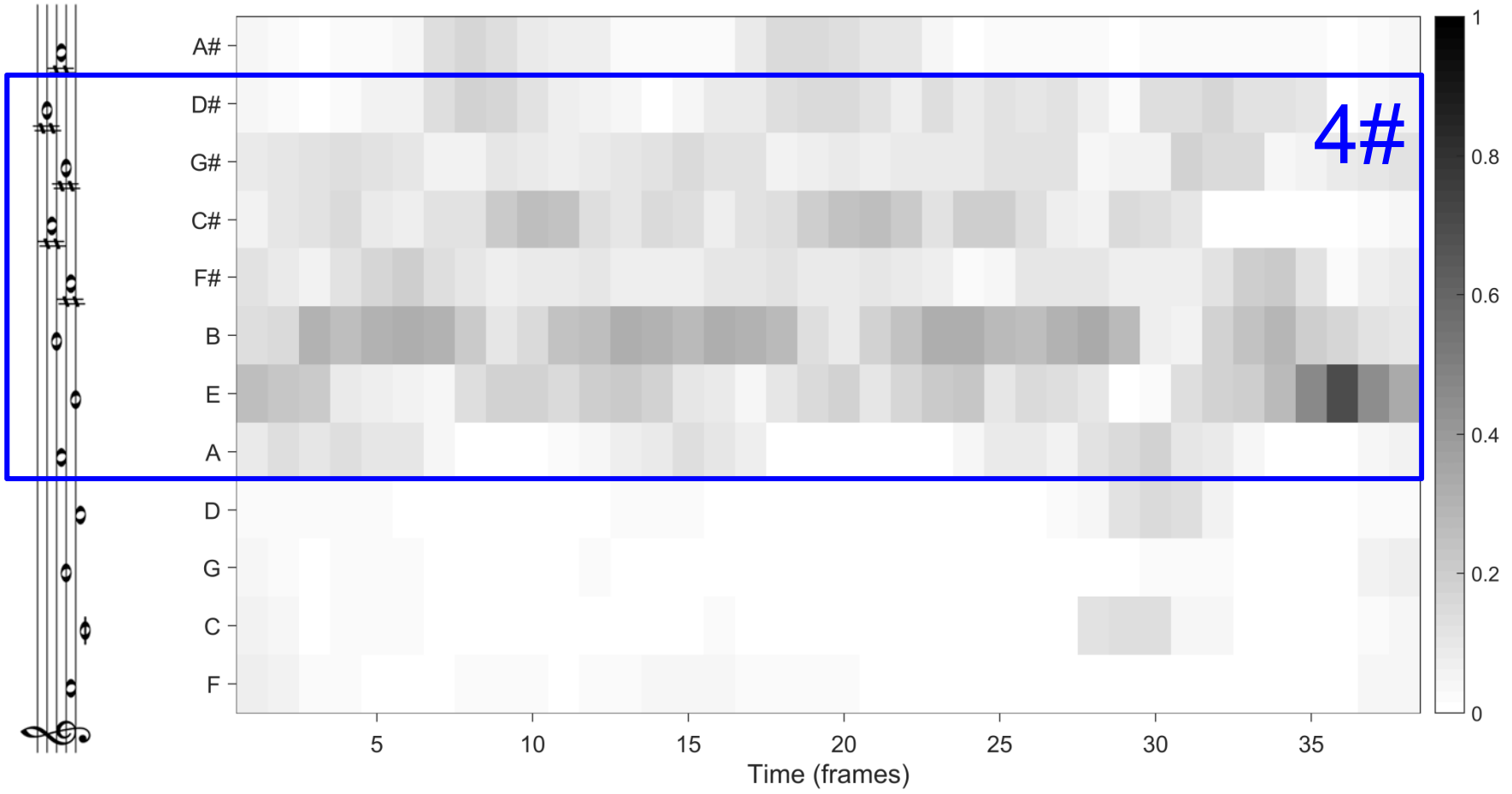
# Local Key Detection: Diatonic Scales

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



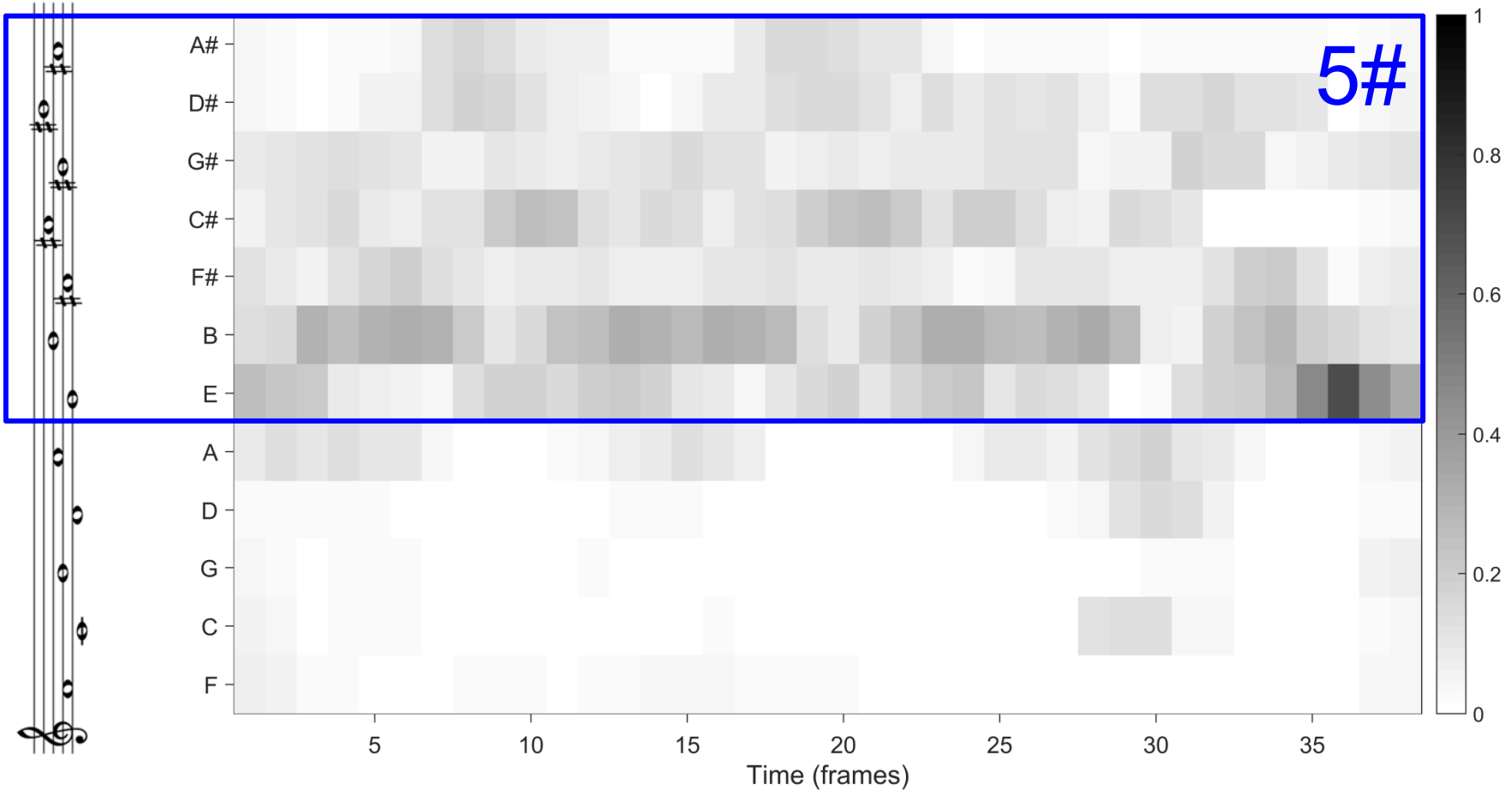
# Local Key Detection: Diatonic Scales

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



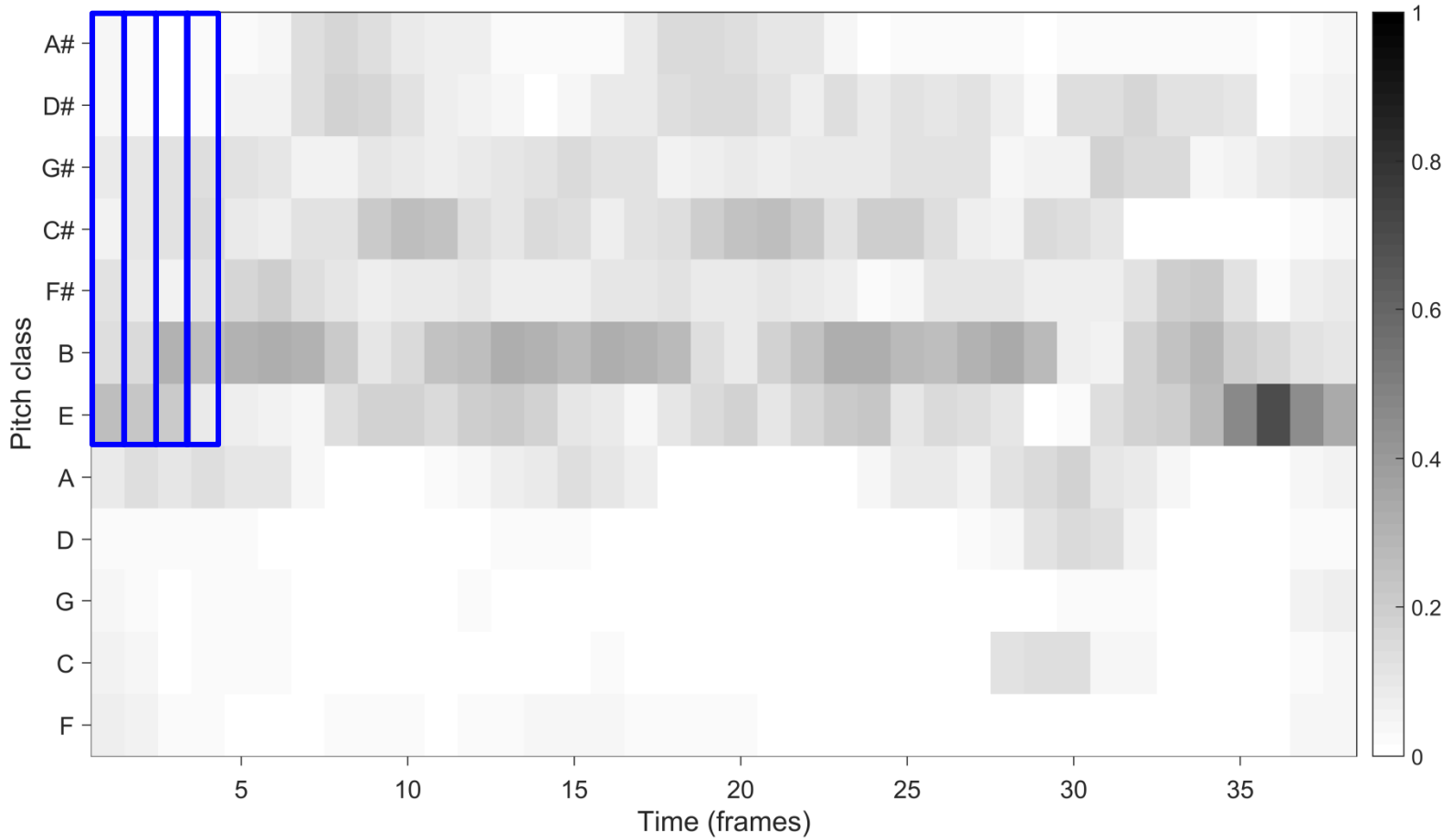
# Local Key Detection: Diatonic Scales

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



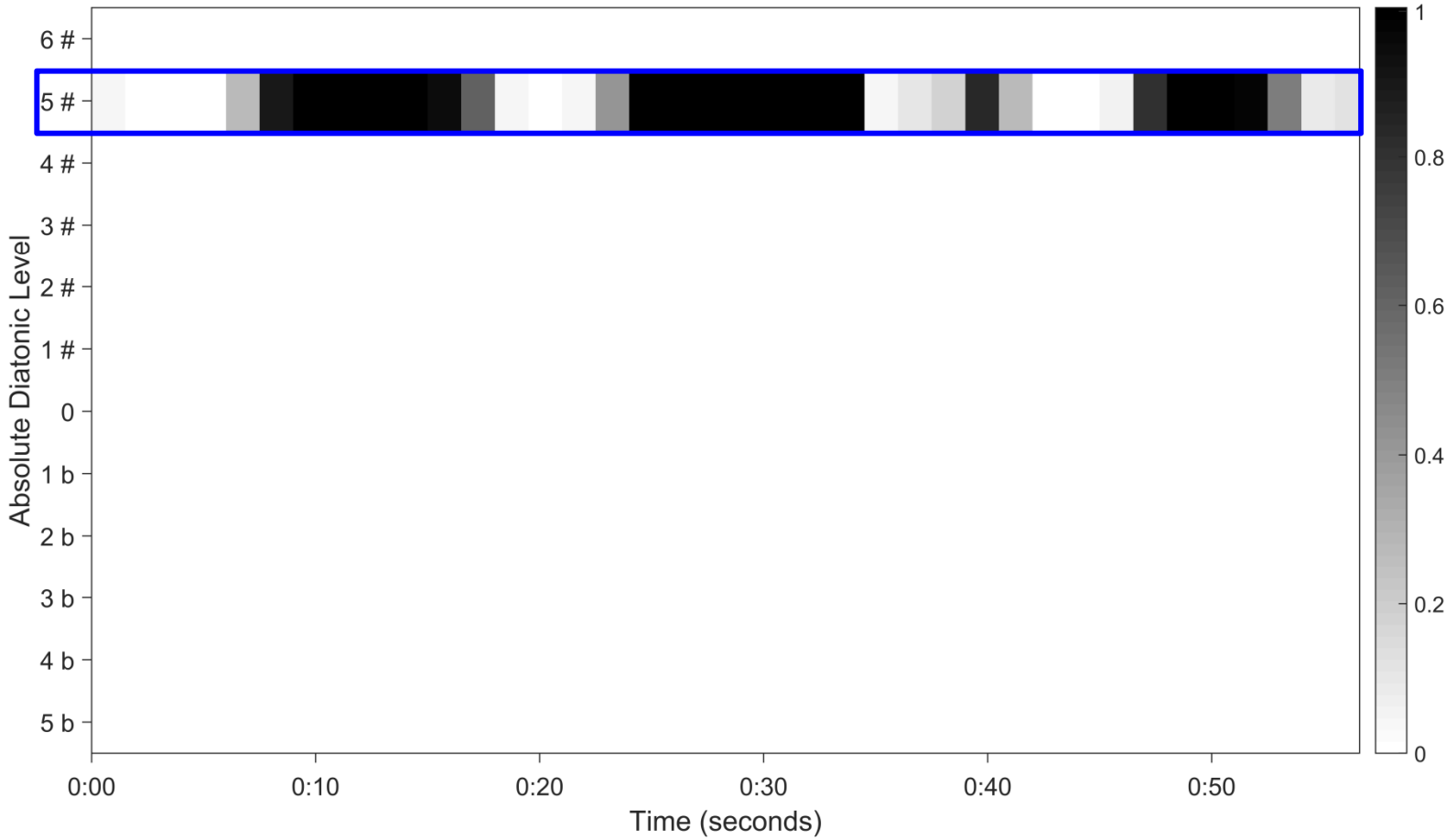
# Local Key Detection: Diatonic Scales

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



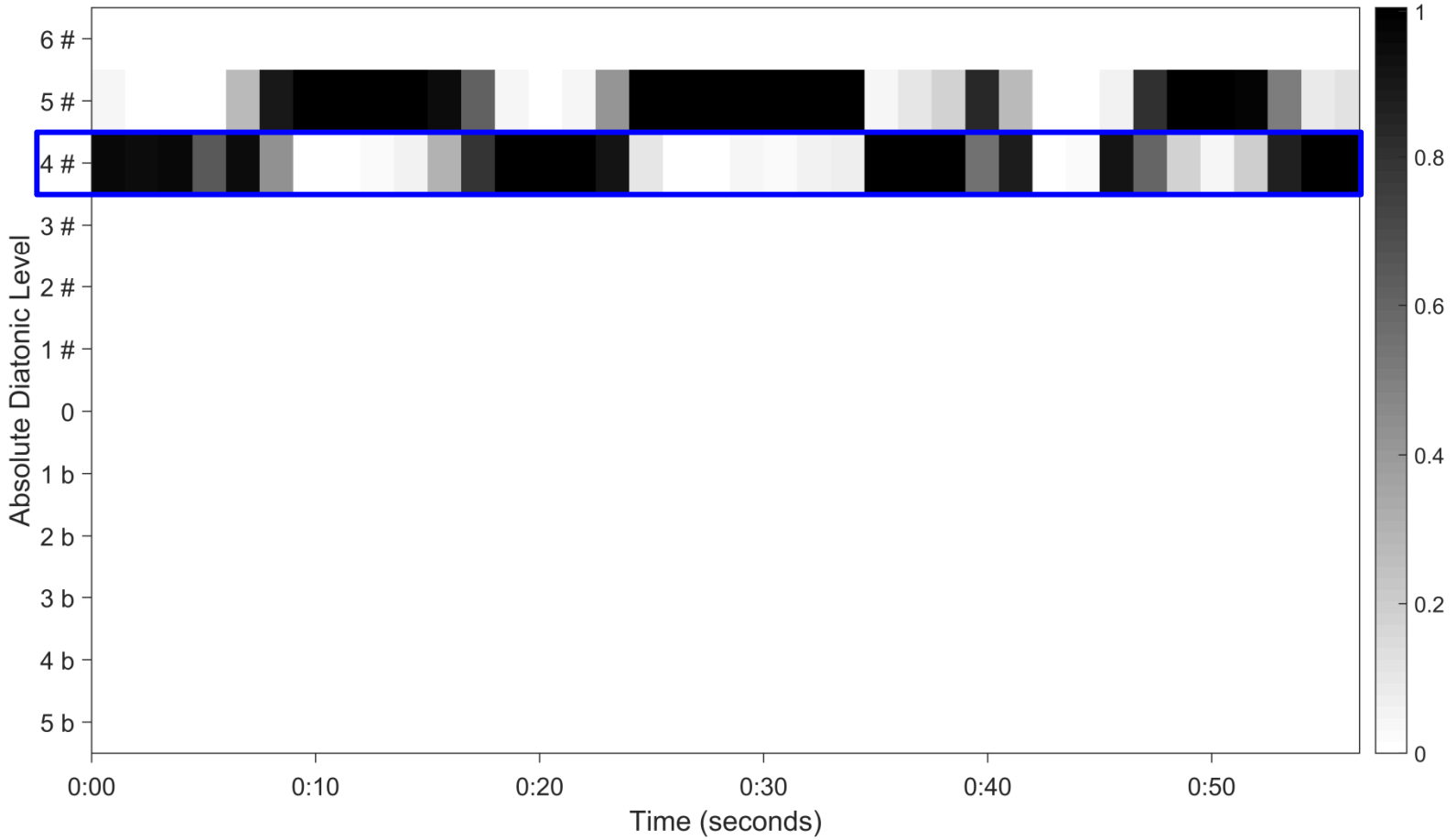
# Local Key Detection: Diatonic Scales

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



# Local Key Detection: Diatonic Scales

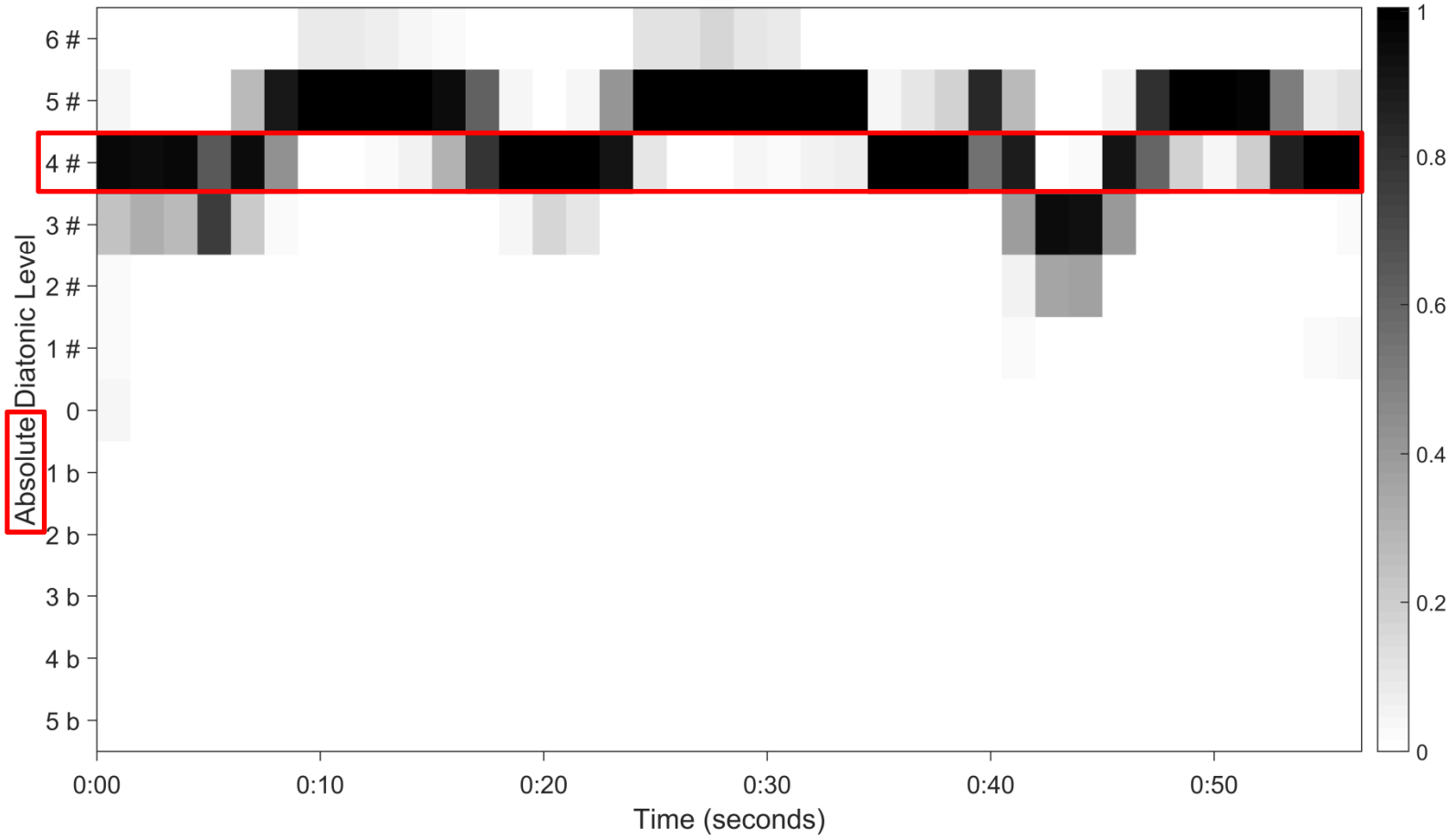
- Choral (Bach) — Diatonic Scale Estimation



# Local Key Detection: Diatonic Scales

- Choral (Bach) — Diatonic Scale Estimation

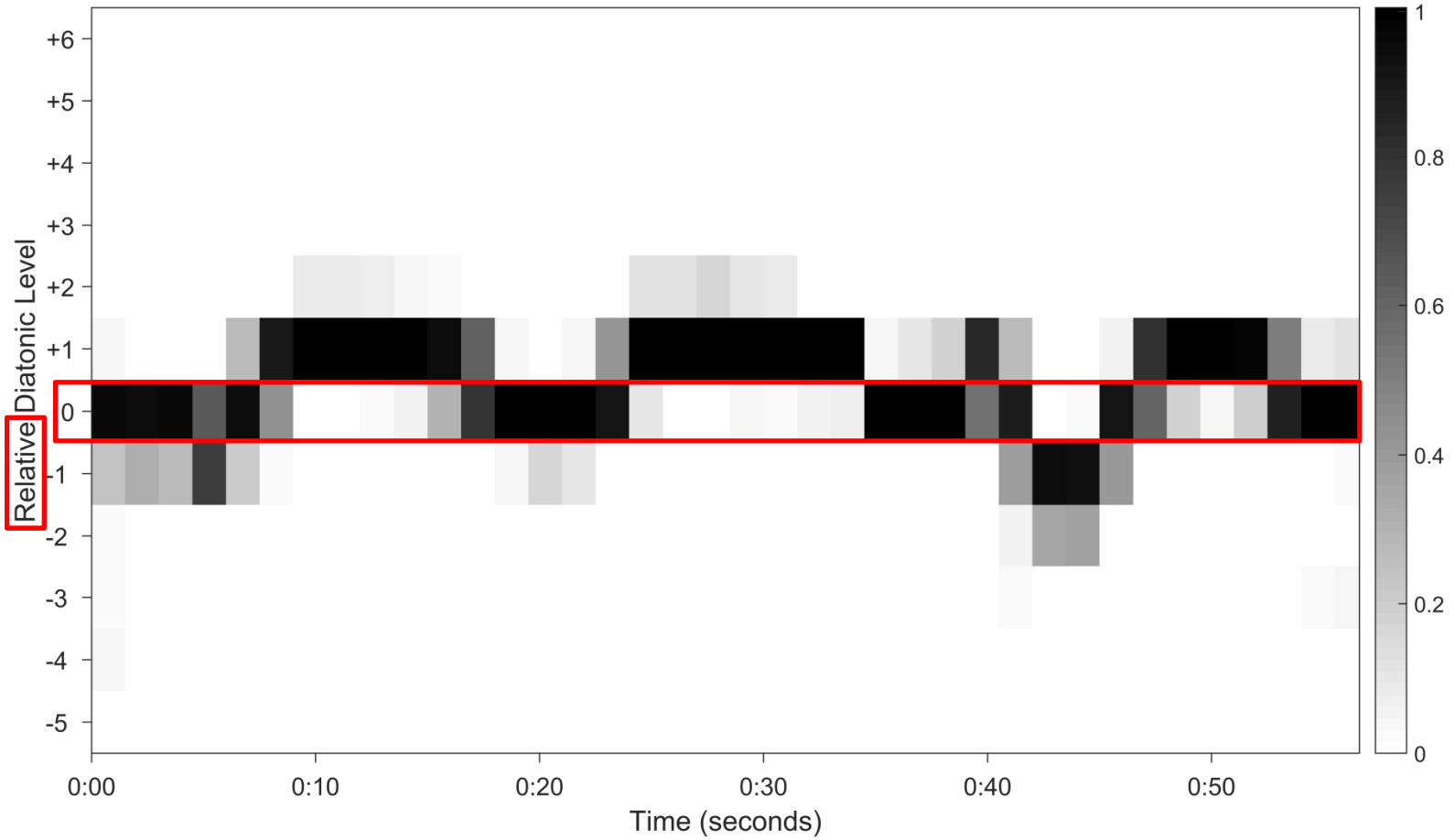
4 #
(E major)



# Local Key Detection: Diatonic Scales

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

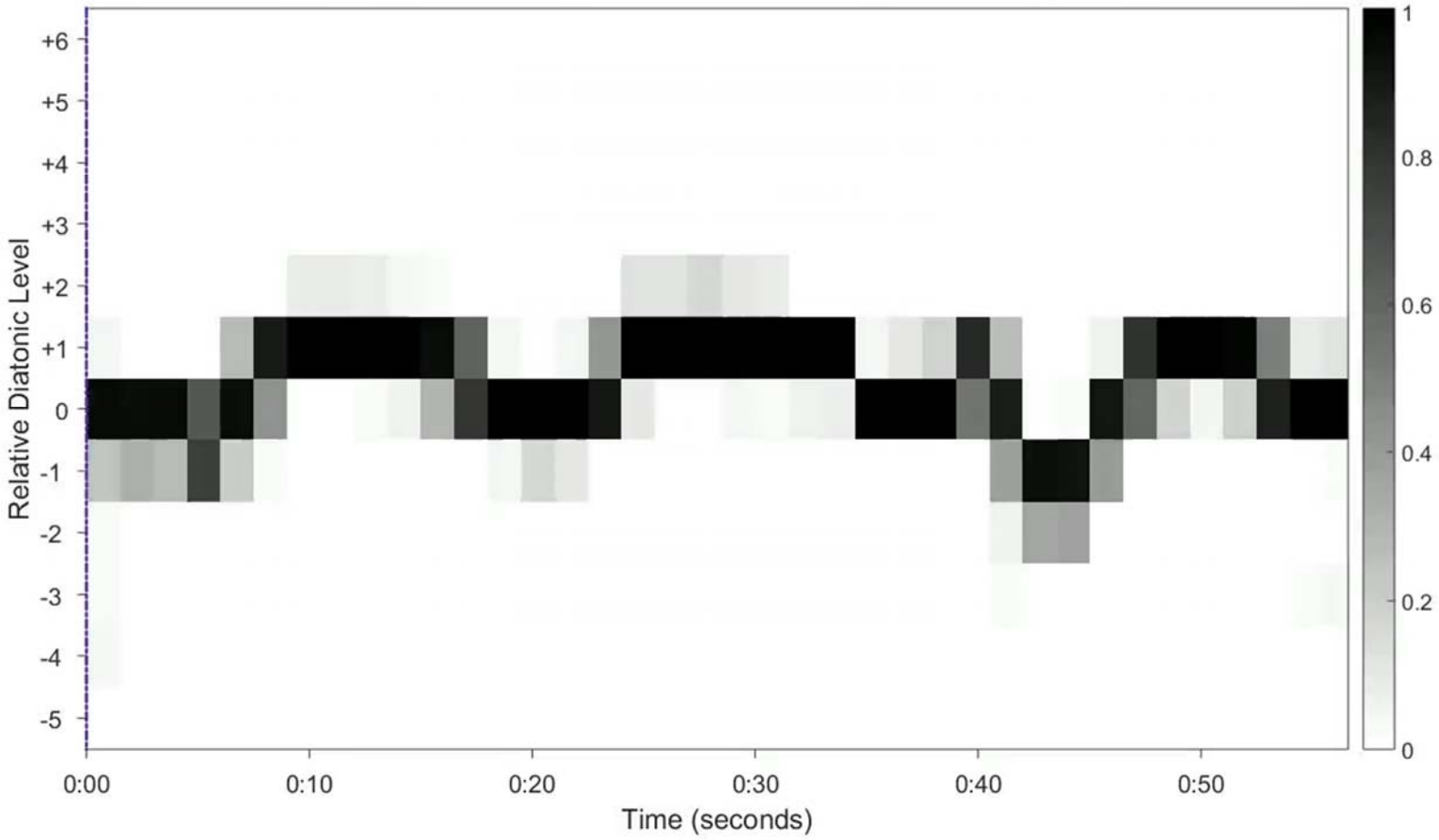
4 #
(E major)



# Local Key Detection: Diatonic Scales

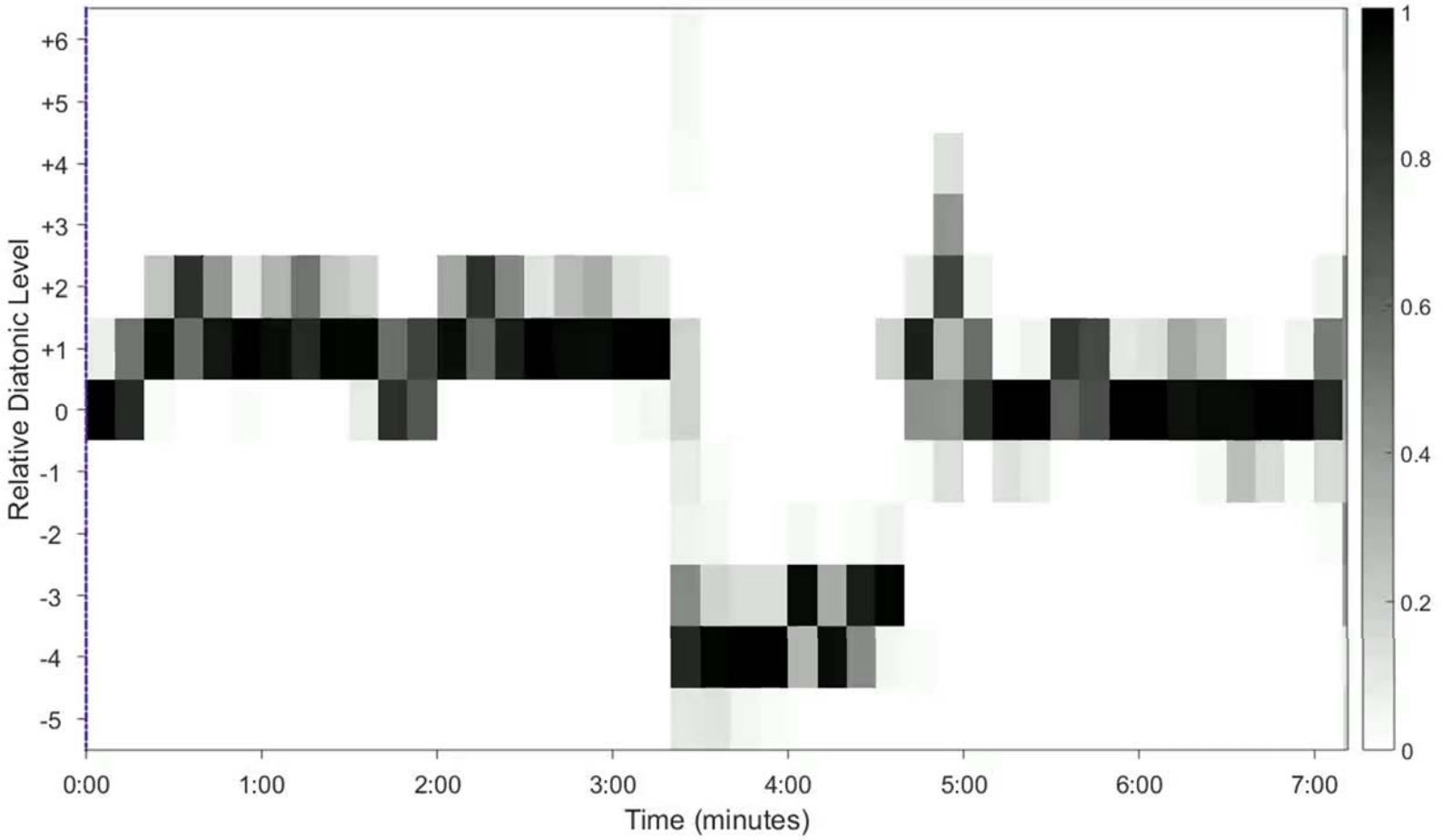
- Choral (Bach) — 0 ≙ 4#

Weiss / Habryka, *Chroma-Based Scale Matching for Audio Tonality Analysis*, CIM 2014



# Local Key Detection: Examples

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



# Local Key Detection: Examples

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