Slides: https://tvanwate.github.io/iwaenc2022.pdf

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Spatial acquisition, digital archiving, and interactive auralization of church acoustics

IWAENC 2022, Bamberg, Germany, Sept. 2022

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Context & Motivation

Ghent Altarpiece (J. & H. van Eyck, 1432)

Flemish primitives

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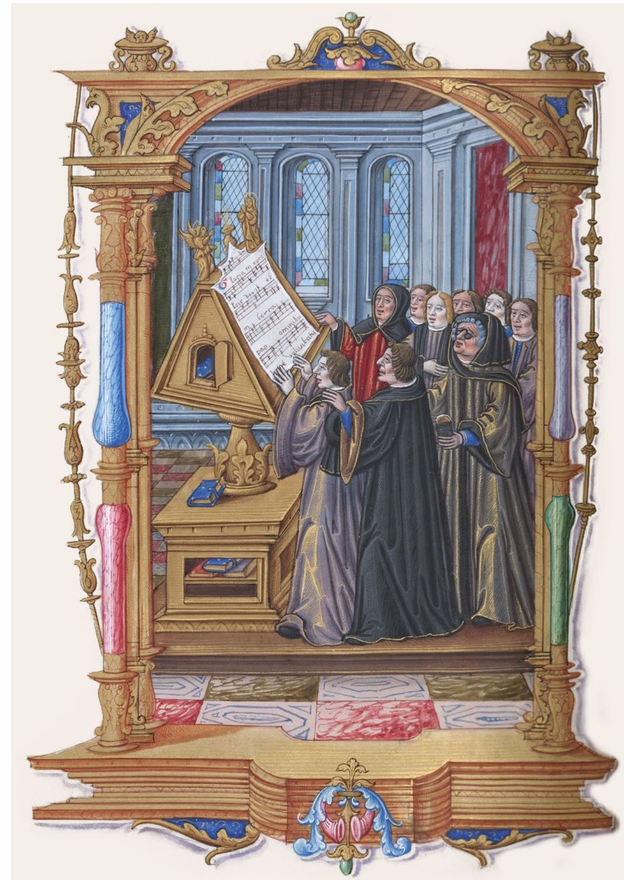
Context & Motivation

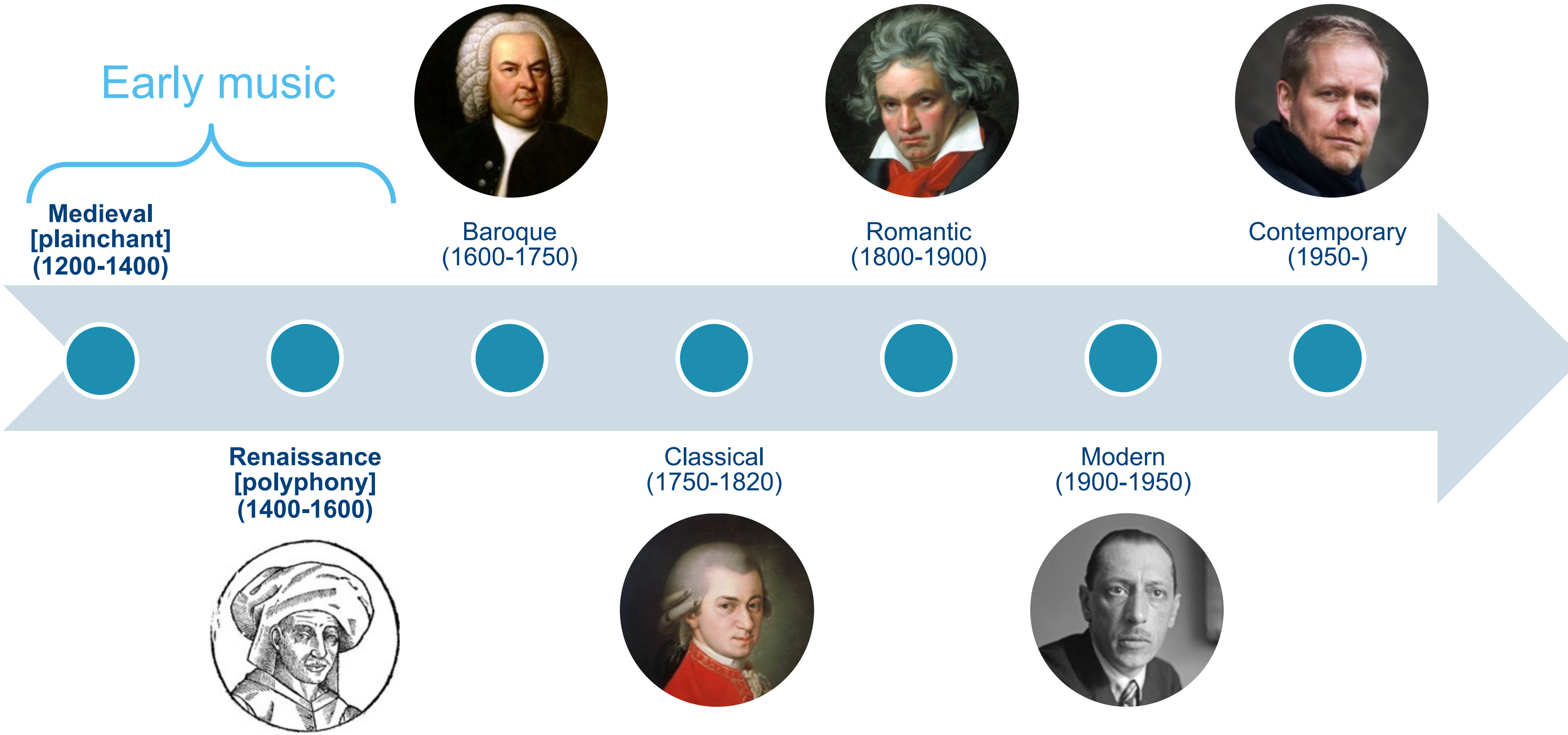


Nymphes des bois (J. des Prez, 1497, performed by Capella Pratensis)

Franco-Flemish polyphony

Image credits: Biblioteca Medicea Laurenziana, Bibliothèque nationale de France – *Audio credit:* Capella Pratensis

Context & Motivation



A concise timeline of Western music

Image credits: Wikimedia Commons, US Library of Congress, Mike Terry

Context & Motivation

Early Music Research

Source

Performer

Environment

Image credits: Alamire Foundation, Cappella Pratensis, TvW

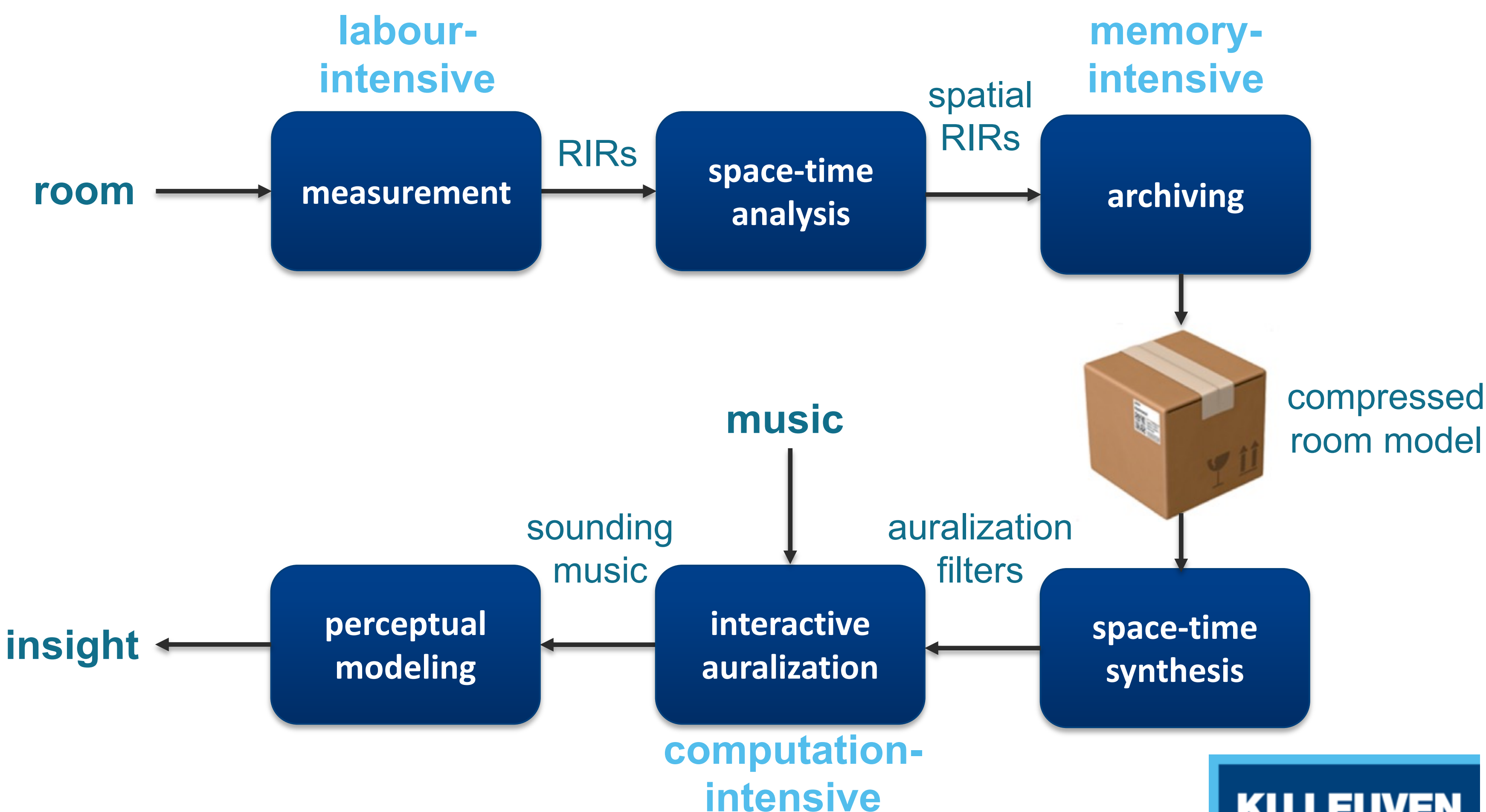
Context & Motivation

- **Research questions**
  - How to **capture** the acoustics of a space to auralize/reproduce it at a different time and place?
  - How to **archive** the acoustics of a historically valuable space for later reuse?
  - How to achieve **interactive auralization** in a flexible and ecological manner?
  - How to increase **understanding** of the relevance and quality of the acoustic characteristics of a space for musical performance?

Image credits: Alamire Foundation, Cappella Pratensis, TvW

Outline

- **System overview & challenges**



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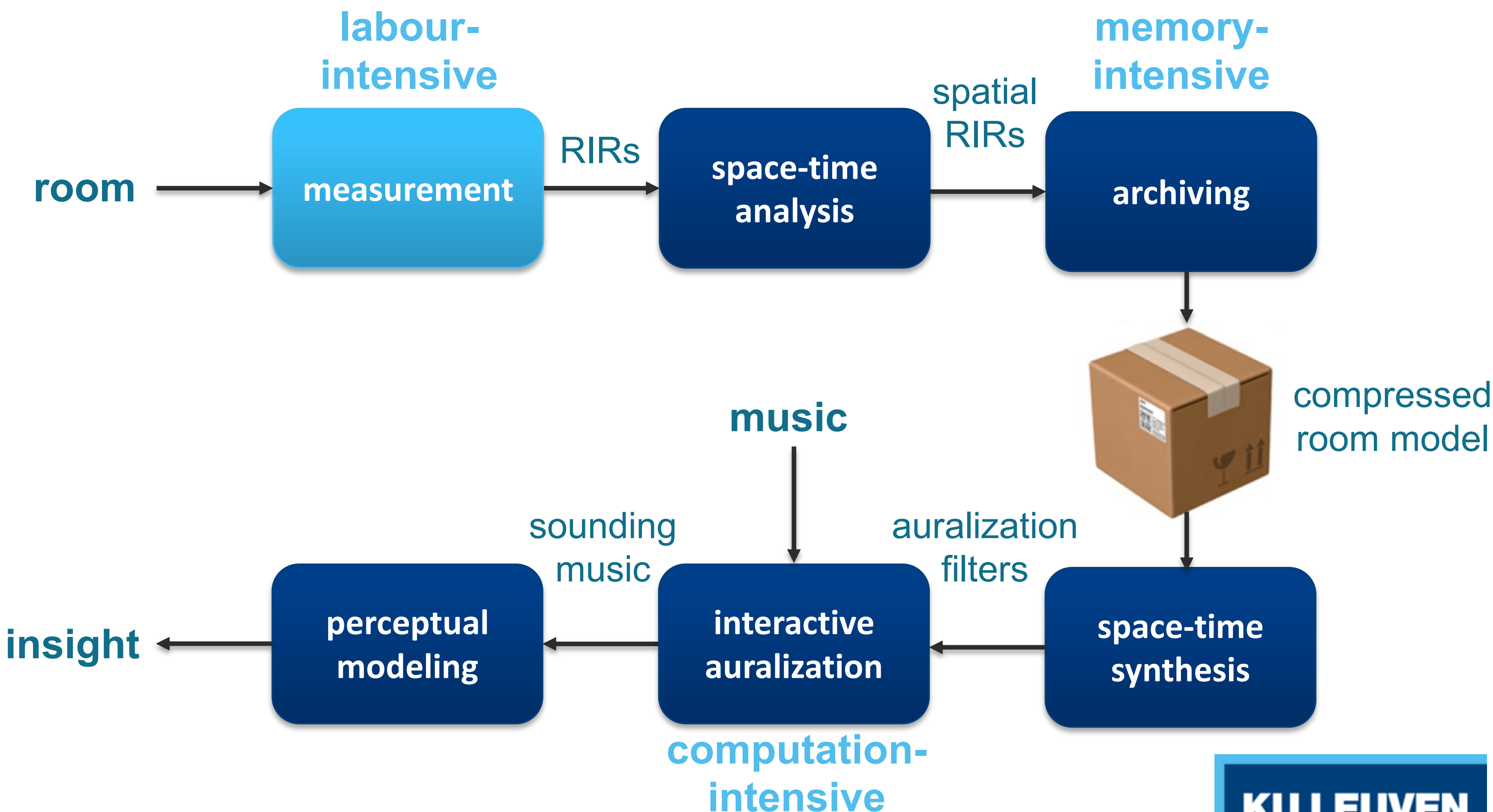

Measurement

- **RIR measurement**
  = well-established procedure
- **Challenges:**
  – (Nightly) access to venue
  – Ownership of measurements
  – Labour-intensive
  – RIR = point-to-point model

⇢ *how to choose source/mic positions?*

Case study: Nassau Chapel, Royal Library Brussels

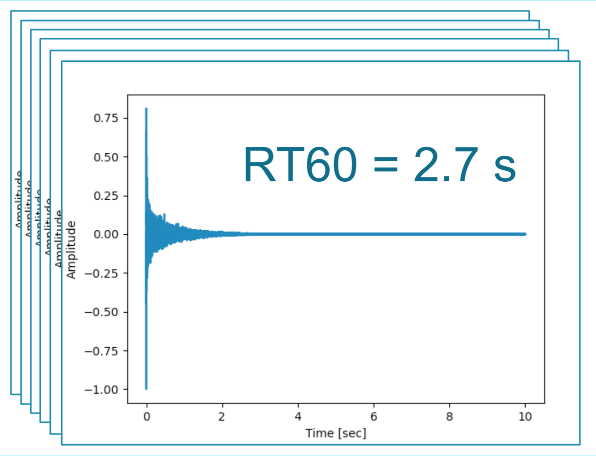

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Image credits: Hannes Rosseel, TvW – *Reference:* A. Novak, P. Lotton, and L. Simon, “Synchronized Swept-Sine: Theory, Application, and Implementation,” *J. Audio Eng. Soc.*, vol. 63, no. 10, pp. 786–798, Nov. 2015.

Measurement

- **Key idea: RIR measurement at "few" positions + RIR interpolation**
  - Reduce labor-intensity
  - Expand potential use to other positions than those measured
  - Reduce memory required for archiving
  - Allow for auralization with moving sources/listeners
- **RIR interpolation problem:**

given RIR measurements

$$\tilde{\mathbf{P}} = [\tilde{\mathbf{p}}_0 \ldots \tilde{\mathbf{p}}_{N_m - 1}]$$

find RIR for same source at any mic position **r** in Ω

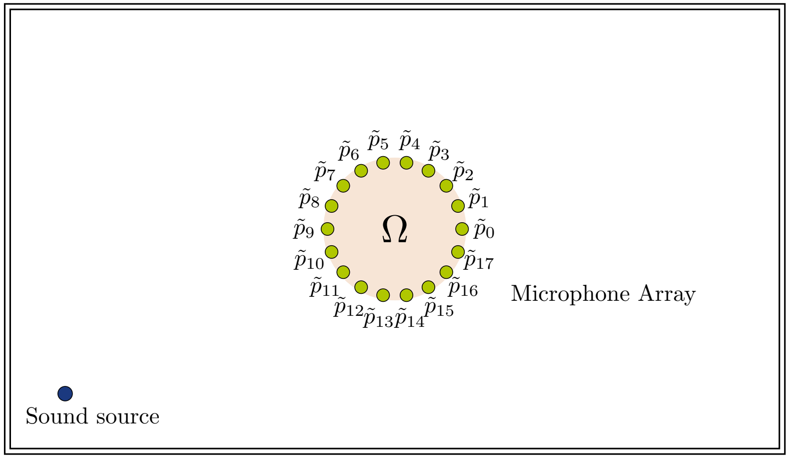

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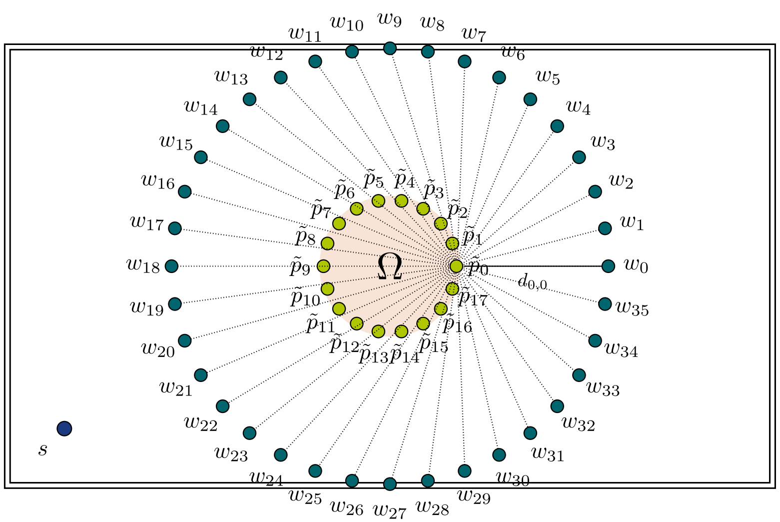
Image credit: Niccolò Antonello – *Reference:* N. Antonello, E. De Sena, M. Moonen, P. A. Naylor, and T. van Waterschoot, "Room impulse response interpolation using a sparse spatio-temporal representation of the sound field," *IEEE/ACM TASLP*, 25(10): 1929-1941, 2017.

Measurement

- **Time-domain equivalent source method (TESM)**
  - Model RIR $h(t,\mathbf{r})$ for mic position $\mathbf{r}$ in Ω as sum of propagating equivalent source signals $w_l(t) \neq \delta(t)$

$$h(t,\mathbf{r}) = \sum_{l=0}^{N_w-1} \frac{1}{4\pi d_l(\mathbf{r})} \delta\big(t - d_l(\mathbf{r})/c\big) * w_l(t) = \mathcal{D}(\mathbf{r})[\mathbf{W}]$$



independent of **r** !

$$\mathbf{W} = \left[\mathbf{w}_0 \ldots \mathbf{w}_{N_w-1}\right]$$

$$\mathcal{D}(\mathbf{r})[\cdot] = \text{linear operator}$$

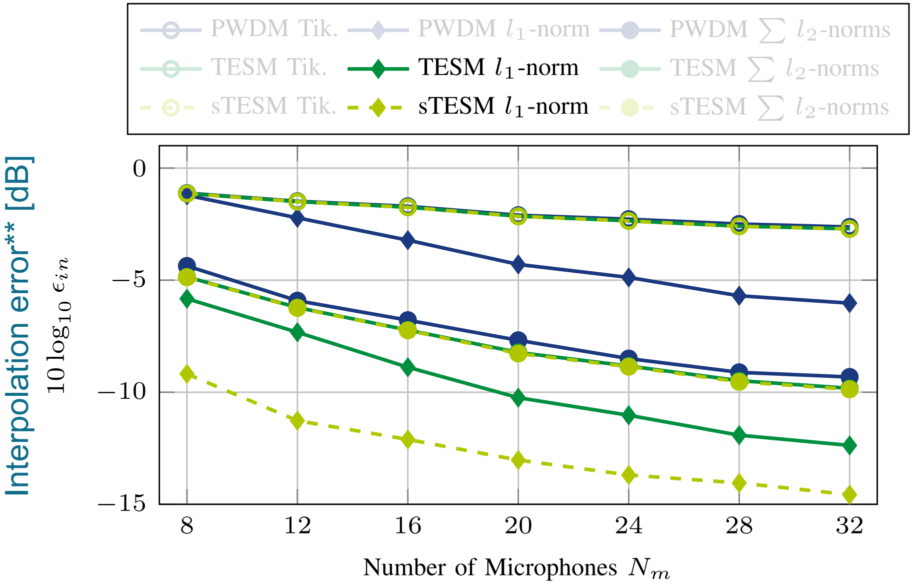
$$(\text{delays} + \text{attenuations})$$

Image credit: Niccolò Antonello – *Reference:* N. Antonello, E. De Sena, M. Moonen, P. A. Naylor, and T. van Waterschoot, "Room impulse response interpolation using a sparse spatio-temporal representation of the sound field," *IEEE/ACM TASLP*, 25(10): 1929-1941, 2017.

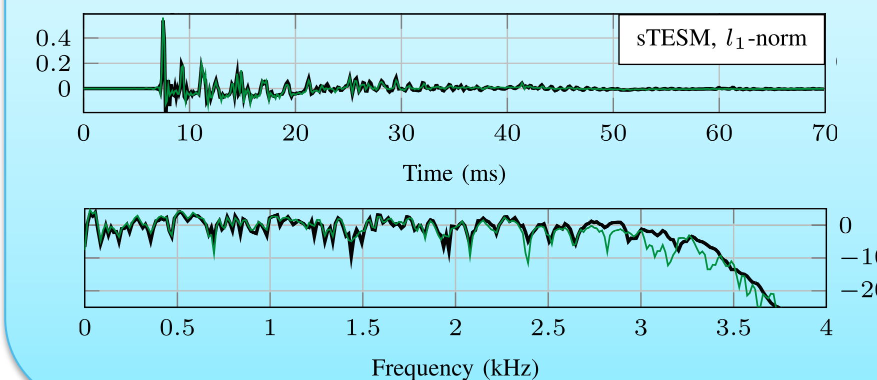
Measurement

- **Time-domain equivalent source method (TESM)**
  - Finding TESM signals $w_l(t)$ by matching pressure signals $\tilde{p}_m(t)$ (= measured RIR) at microphones = **underdetermined** problem
  - Regularization by imposing spatio-temporal **sparsity**

$$\min_{\mathbf{W}} \|D(\mathbf{W}) - \tilde{\mathbf{P}}\|_F^2 + \lambda \|\mathrm{vec}(\mathbf{W})\|_1$$



Interpolated RIR + magnitude response*



*worst case result
**average result

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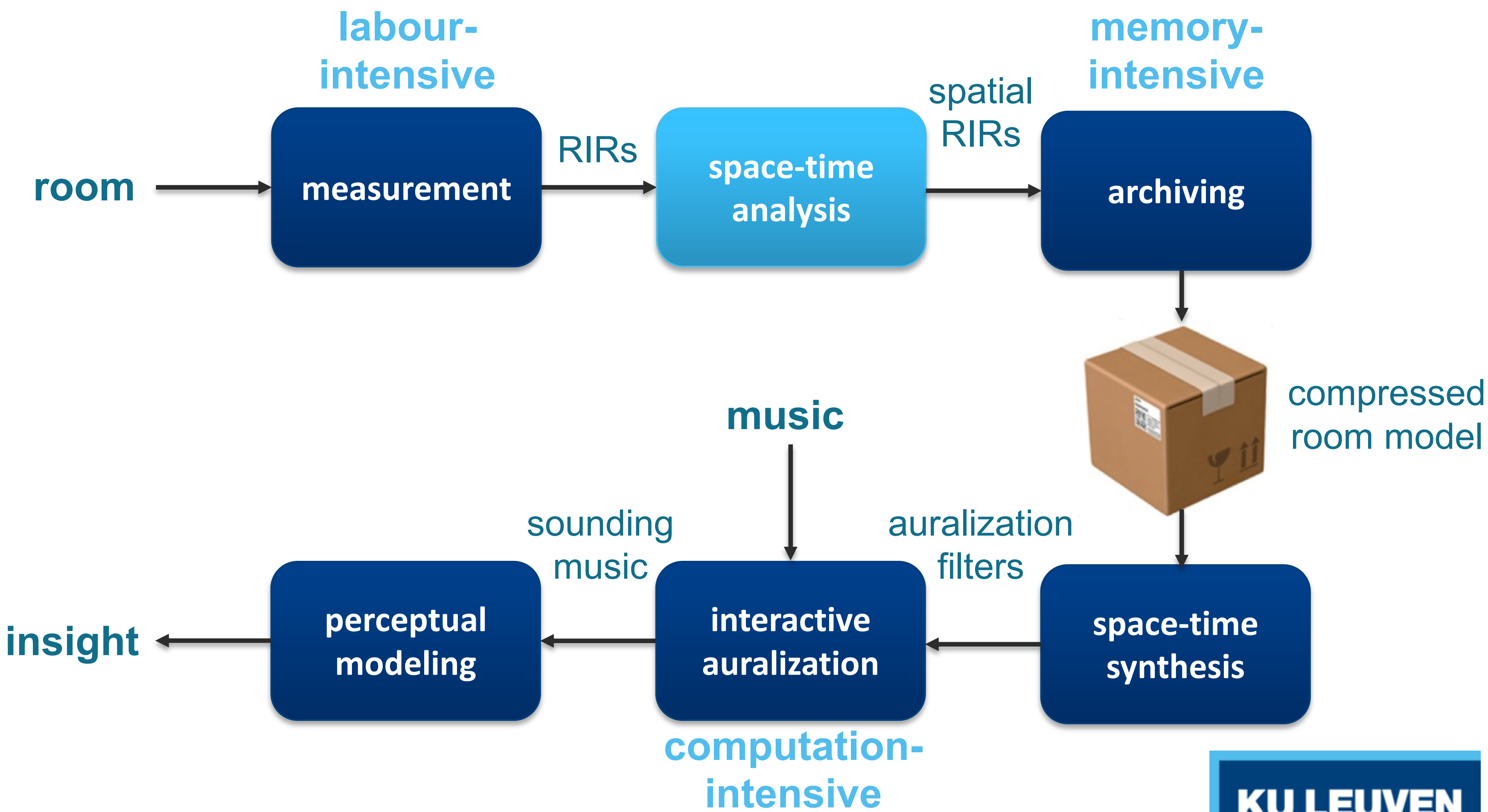
Image credit: Niccolò Antonello – *Reference:* N. Antonello, E. De Sena, M. Moonen, P. A. Naylor, and T. van Waterschoot, "Room impulse response interpolation using a sparse spatio-temporal representation of the sound field," *IEEE/ACM TASLP*, 25(10): 1929-1941, 2017.

Outline

- **System overview & challenges**



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Space-time analysis

- **Key model: Spatial room impulse response (SRIR)**
  - Include **direction of arrival information** (azimuth and elevation angles θ,ϕ) to each RIR “peak” representing room reflection
- **Key method: Spatial decomposition method (SDM)**
  - TDOA estimation of corresponding RIR “peaks” in each mic pair
  - Least-squares DOA estimation from TDOAs of all mic pairs in array

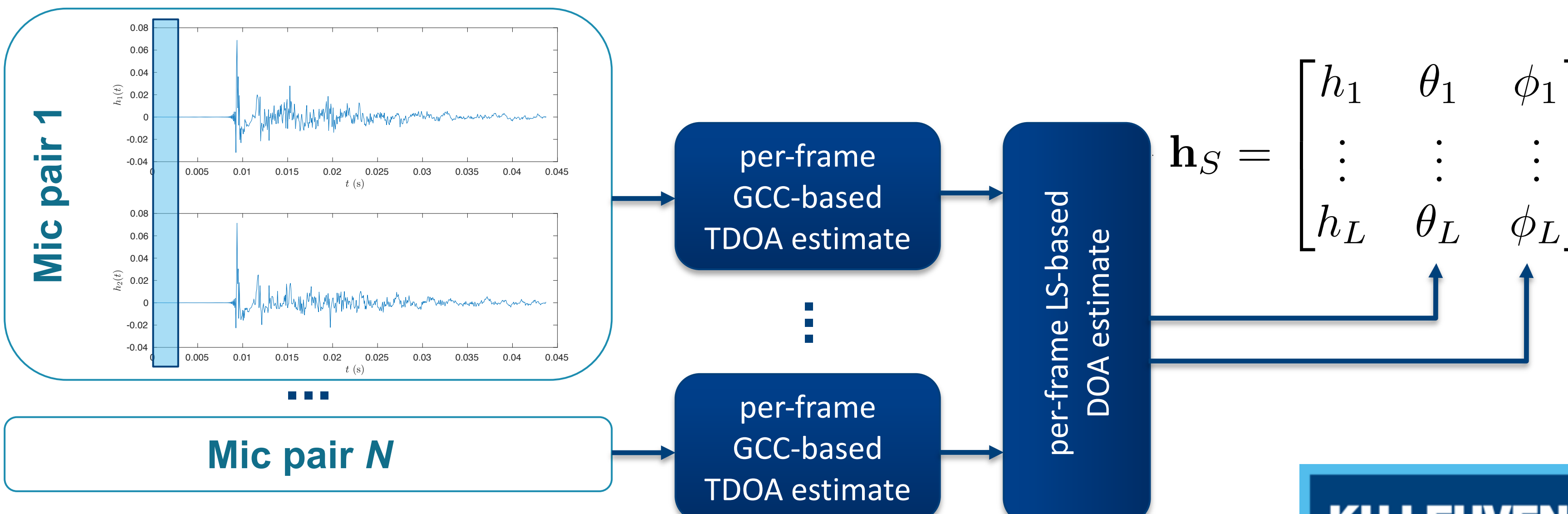

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Image credit: TvW – *References:* J. Merimaa and V. Pulkki, “Spatial impulse response rendering I: Analysis and synthesis,” *JAES*, 53(12): 1115-1127, 2005. – S. Tervo, J. Pätynen, A. Kuusinen, and T. Lokki, “Spatial decomposition method for room impulse responses,” *JAES*, 61(1/2): 17–28, 2013.

Space-time analysis

- **SDM challenges**
  - Find phase-matched microphones 💸💸💸
  - Find RIR "peaks"
  - Match "peaks" in different RIRs ⇢ *generalized cross-correlation (GCC)*
  - Estimate TDOAs with subsample accuracy ⇢ *TDOA interpolation*
- **Subsample TDOA estimation**
  - Due to bandlimited nature of measurement system, RIR "peaks" are sinc functions rather than impulse functions
  - GCC $R_{m,n}(t)$ of two time-shifted sinc functions = sinc function
  - Optimal subsample TDOA estimation method is hence based on sinc interpolation rather than parabolic/Gaussian interpolation

$$\tau_{\text{sinc}} = \arg\min_{\tau} \int_{-\infty}^{\infty} \left| \text{sinc}(\pi f_s (t-\tau)) - \frac{R_{m,n}(t)}{\max(R_{m,n}(t))} \right|^2 dt$$

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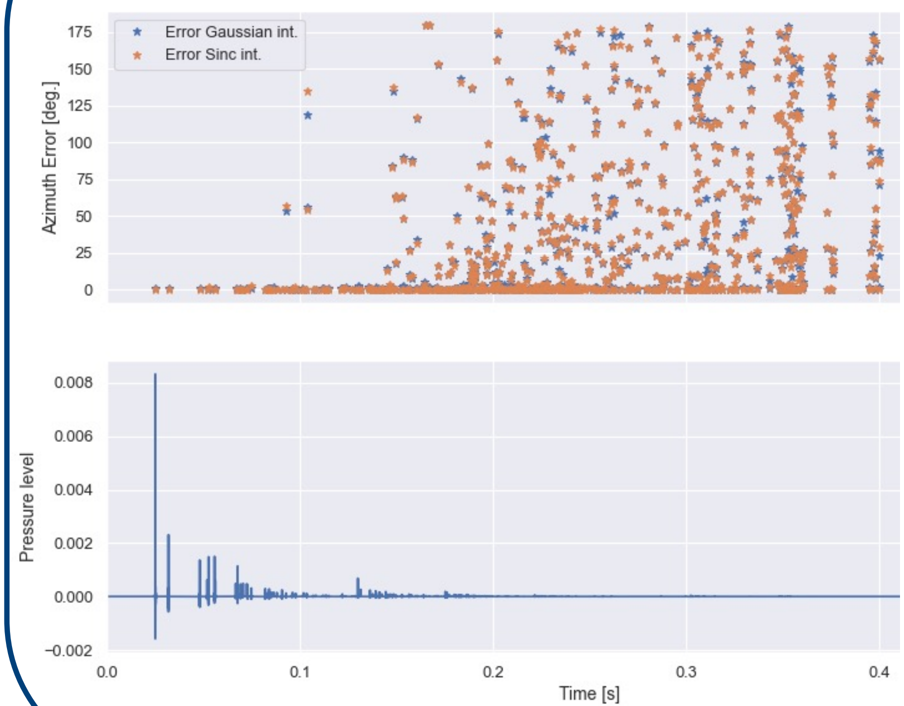
Image credit: G.R.A.S. – *Reference:* H. Rosseel and T. van Waterschoot, "Improved acoustic source localization by time delay estimation with subsample accuracy," in *Proc. Int. Conf. Immersive & 3D Audio (I3DA '21)*, Bologna, Sep. 2021.

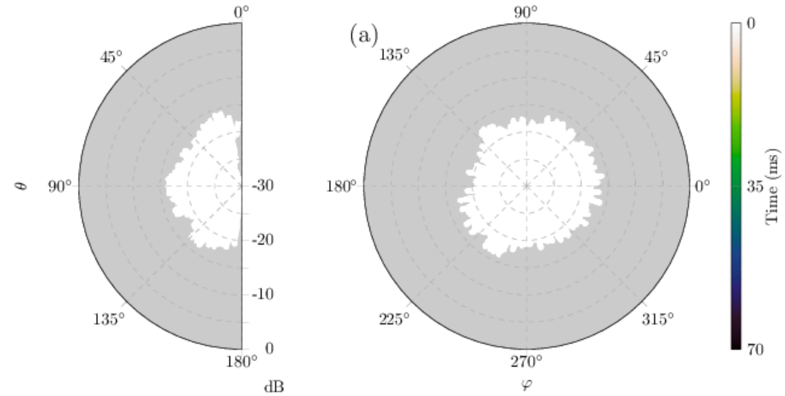
Space-time analysis

- **Resulting space-time model**

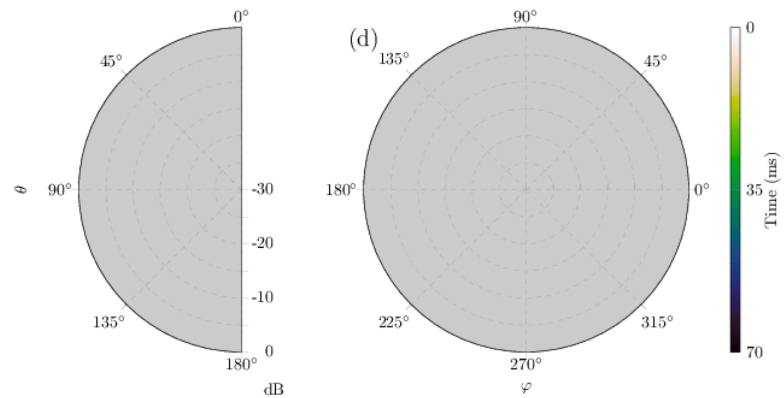
TDOA estimation errors



SRIR visualization of **interpolated** RIRs



without sparse regularization



with sparse regularization

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Image credits: H. Rosseel, N. Antonello – *Reference:* N. Antonello, E. De Sena, M. Moonen, P. A. Naylor, and T. van Waterschoot, ”Room impulse response interpolation using a sparse spatio-temporal representation of the sound field,” *IEEE/ACM TASLP*, 25(10): 1929-1941, 2017.

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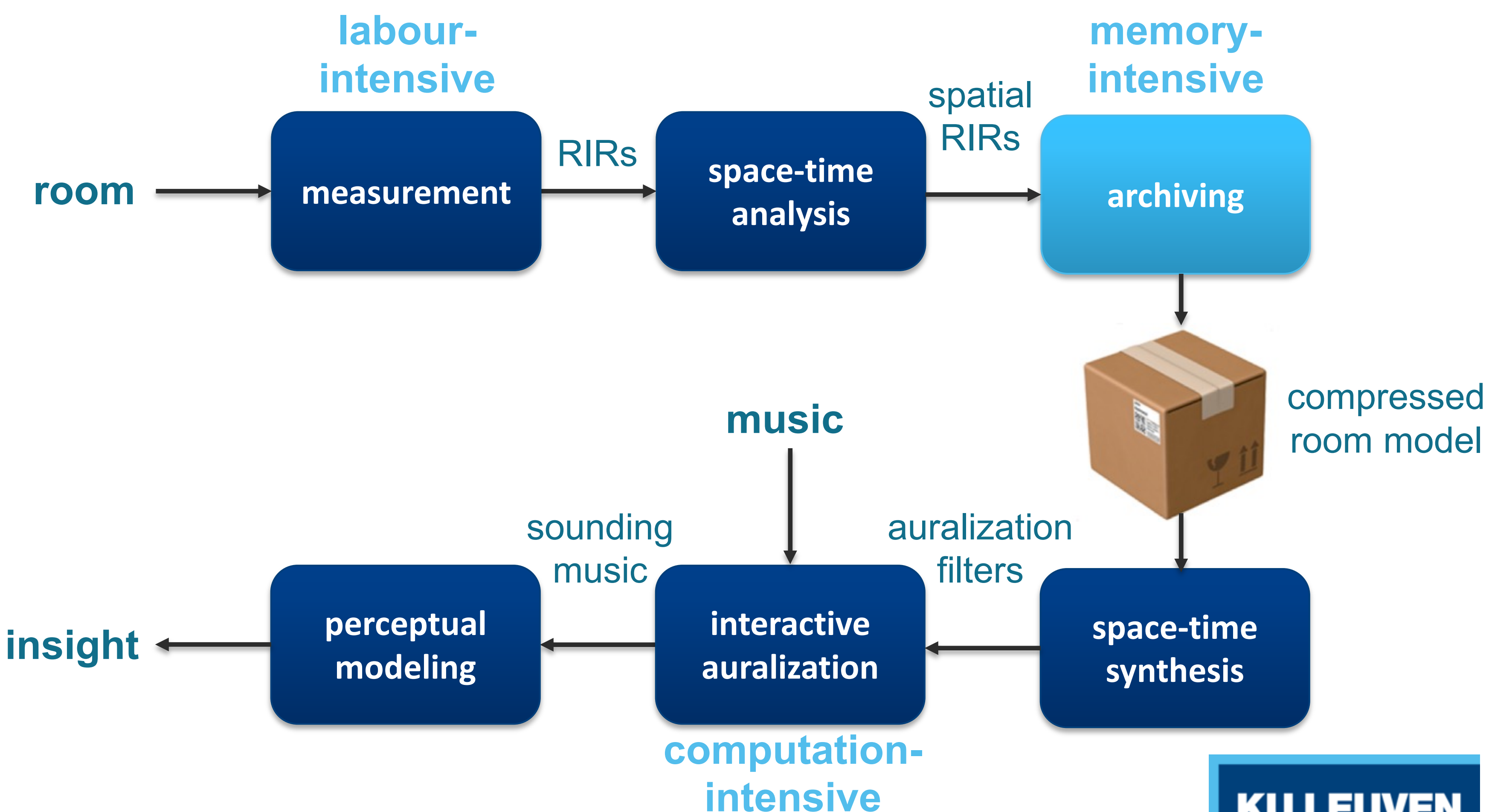

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Archiving

- **Why is archiving of church acoustics a challenge?**
  - Impulse response contains $L \sim 10^4$ samples $\sim 10^5$ bits
  - 1 spatial impulse response = 6 impulse responses $\sim 10^6$ bits
  - Plenacoustic sampling theory: accurate sound field reconstruction requires spatial resolution of ~ 10 cm

    ~ $(100)^3$ source positions x $(100)^3$ observer positions

    ~ 10^{12} spatial impulse responses ~ 10^{18} bits ~ **100 petabyte**

Image credit: Elbowroom – *Reference:* T. Ajdler, L. Sbaiz, and M. Vetterli, "The plenacoustic function and its sampling," *IEEE Trans. Signal Process.*, vol. 54, no. 10, pp. 3790 –3804, Oct. 2006.

Archiving

- **How to "compress" a room impulse response?**
  - Truncation
  - Hard thresholding
  - Sparse approximation
  - Low-rank approximation

Physical justification

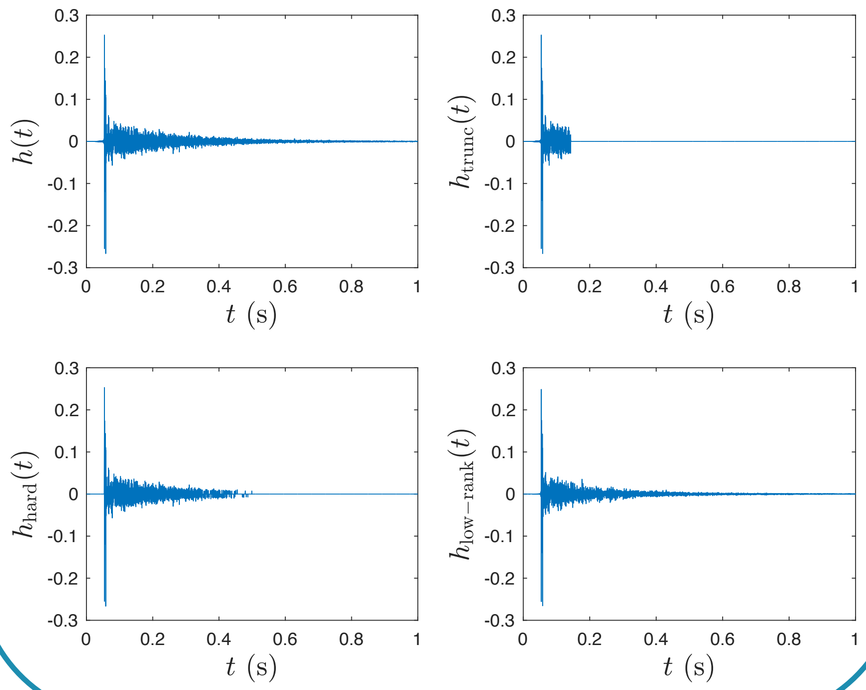
non-homogenous Helmholtz equation

$$(\nabla^2 + k^2)H(\mathbf{r}, \mathbf{r}_s, \omega) = -j\omega\rho_0 Q\,\delta(\mathbf{r} - \mathbf{r}_s)$$

RIR ≈ sum of damped sinusoids

$$h(t) \approx \sum_{m=1}^{M} \mu_m e^{-\beta_m t} \cos(\omega_m t + \phi_m),\ t \geq 0$$

RIR with three compression methods
(compression rate = 85 %)

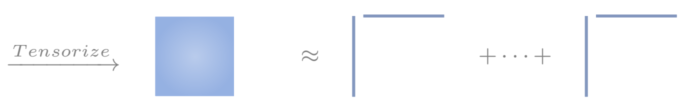


Archiving

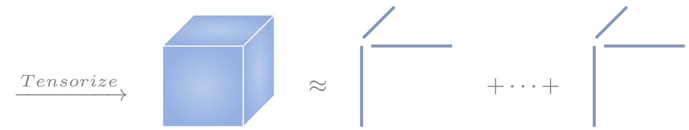
- **Key idea:** **Sum of *M* (damped) sinusoids admits matricization/tensorization of rank 2*M***
  - Impulse response vector **h** (= 1-D array) of length *L* can be **reshaped** into *N*-D array of dimensions $\sqrt[N]{L} \times \sqrt[N]{L} \times \ldots \times \sqrt[N]{L}$
  - *N*-D array can be **approximated** as sum of *2M* rank-1 terms (SVD or canonical polyadic decomposition)

$$\mathbf{h} = \begin{bmatrix} h_1 \\ h_2 \\ h_3 \\ \vdots \\ h_L \end{bmatrix}$$

example: 2-D tensorization



3-D tensorization

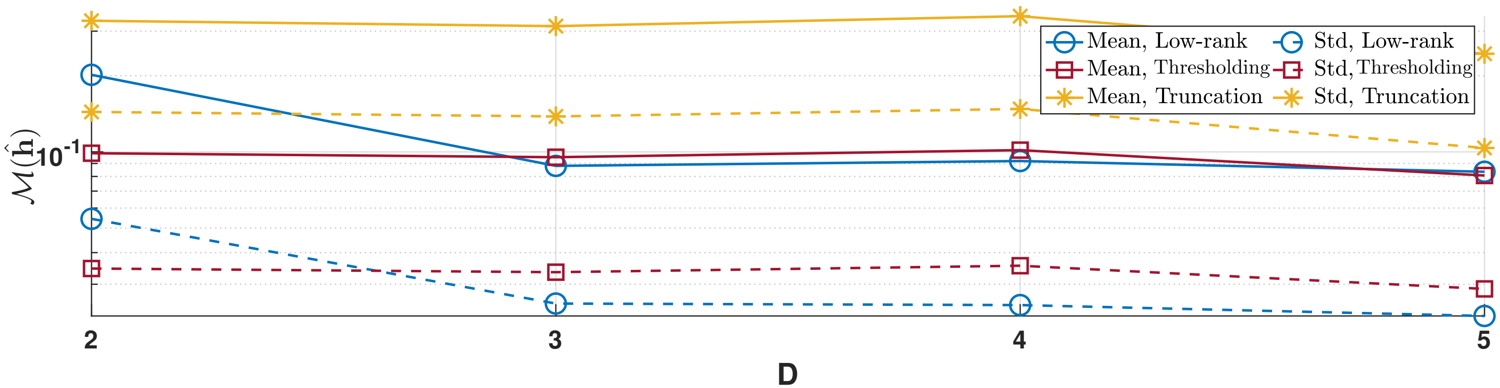


$$\mathbf{h} = \mathrm{vec}\left(\sum_{m=1}^{2M} \mathbf{u}_m^{(1)} \circ \mathbf{u}_m^{(2)} \circ \ldots \circ \mathbf{u}_m^{(N)} \right)$$

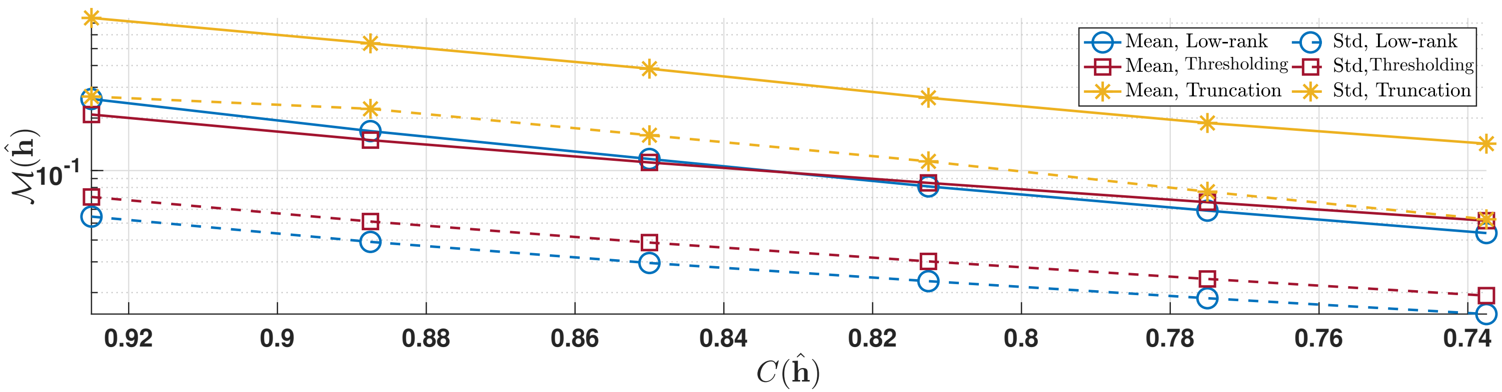
Image credit: Martijn Boussé – *Reference:* M. Jälmby, F. Elvander, and T. van Waterschoot, “Low-rank tensor modeling of room impulse responses,” in *Proc. EUSIPCO 2021*, pp. 111–115, 2021.

Archiving

- **Misadjustment results after RIR compression**
  - Methods: truncation, hard thresholding, low-rank approximation
  - Misadjustment vs. tensorization dimension *D* & compression rate *C*



C = 80 %



D = 3

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Image credit: Martin Jälmby – *Reference:* M. Jälmby, F. Elvander, and T. van Waterschoot, “Low-rank tensor modeling of room impulse responses,” in *Proc. EUSIPCO 2021*, pp. 111–115, 2021.

Outline

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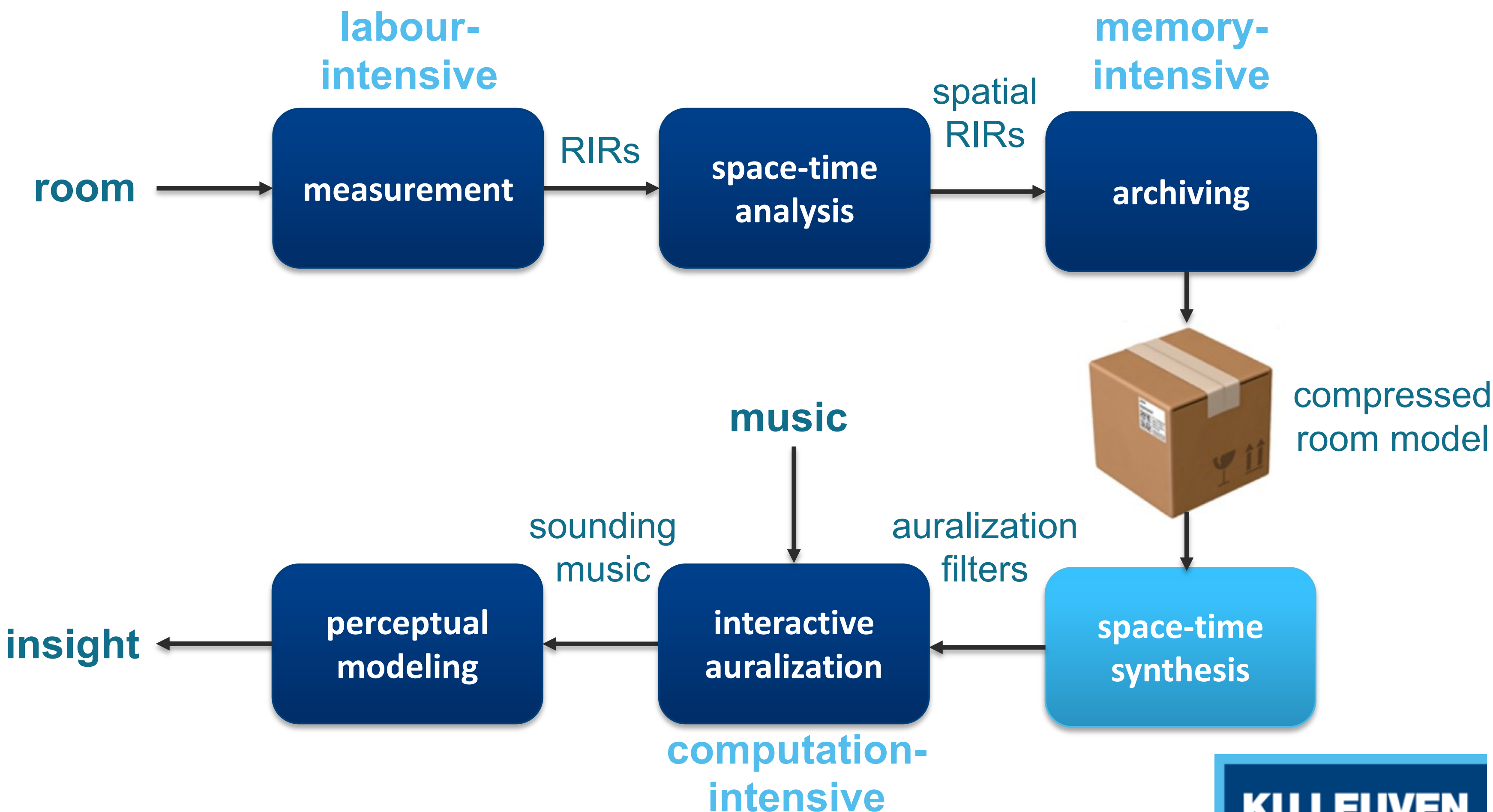
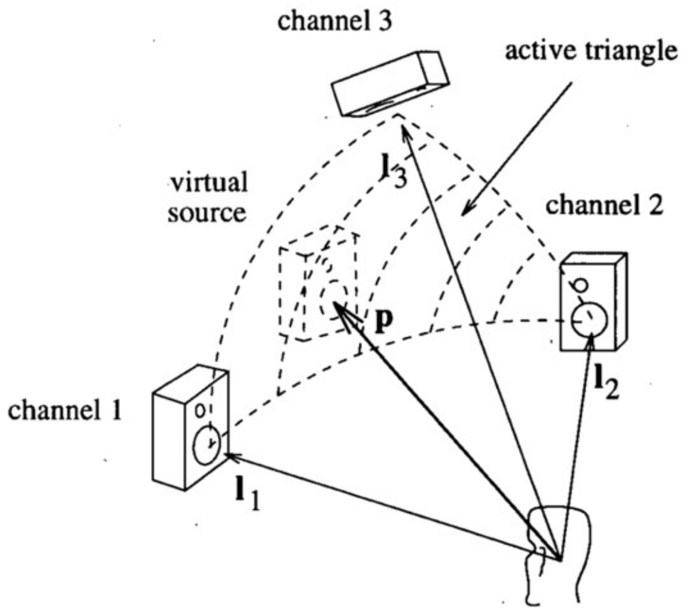


Space-time synthesis

- **Key idea: Mapping of room reflections to loudspeakers**
  - Conversion of SRIR to set of per-loudspeaker impulse responses
    - Vector base amplitude panning (VBAP)
    - Nearest-loudspeaker mapping



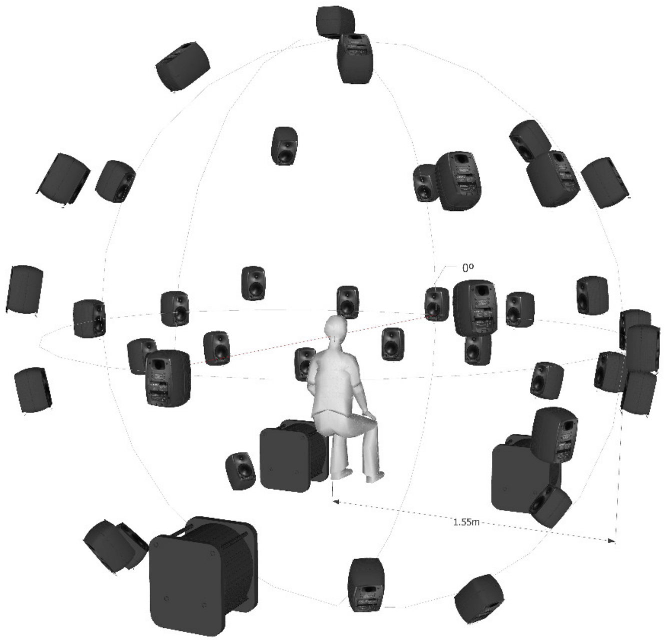


Image credits: Ville Pulkki, Neo Kaplanis – *Reference:* V. Pulkki, "Virtual sound source positioning using vector base amplitude panning," *J. Audio Eng. Soc.*, vol. 45, no. 6, pp. 456–466, 1997.

Space-time synthesis

- **Loudspeaker set-up: Library of Voices (Leuven)**
  - 3-D array of 20–24 Martin Audio 6,5” CDD loudspeakers
  - Reproduction room: RT60 = 0.5 s (with curtains closed)

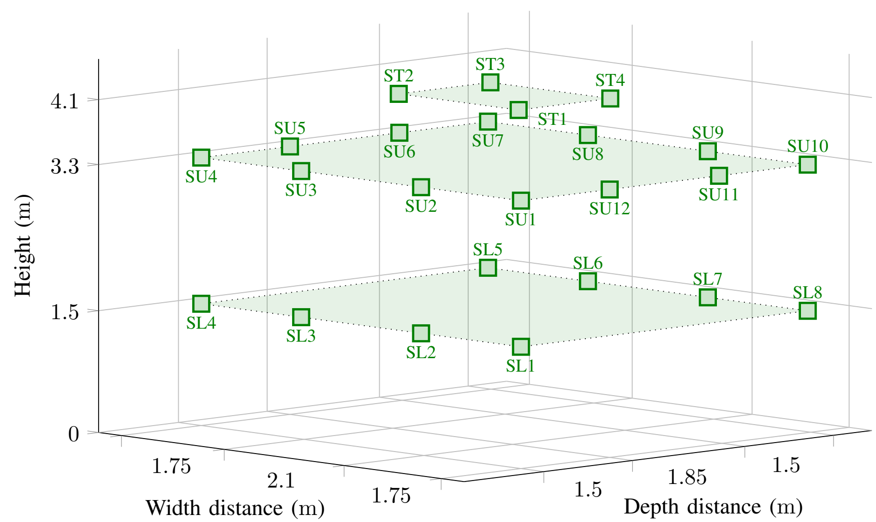


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Image credits: FACE, Thomas Dietzen – *Acknowledgement:* FWO Large-scale research infrastructure "The Library of Voices - Unlocking the Alamire Foundation’s Music Heritage Resources Collection through Visual and Sound Technology" (I013218N)

Outline

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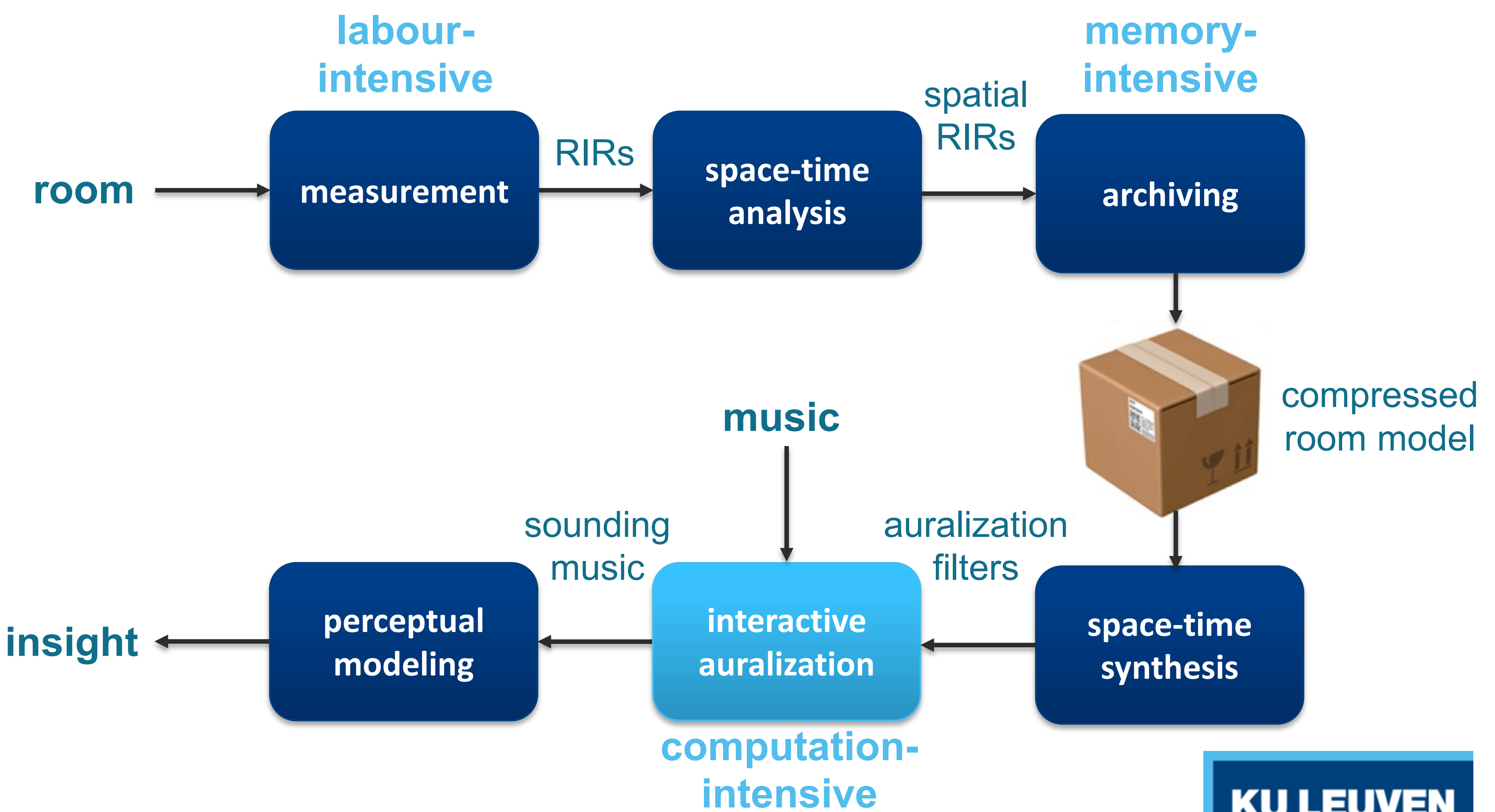


Interactive auralization

- **Challenges:**
  - Multi-channel acoustic feedback control
  - Low-latency real-time multi-channel convolution

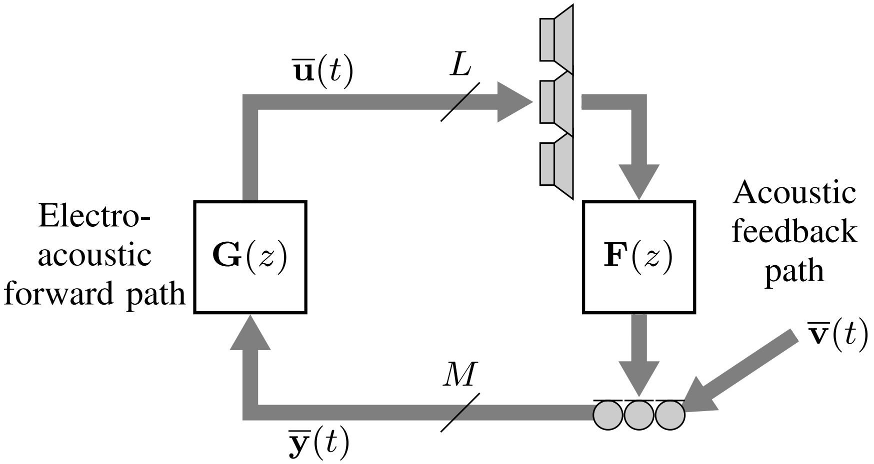
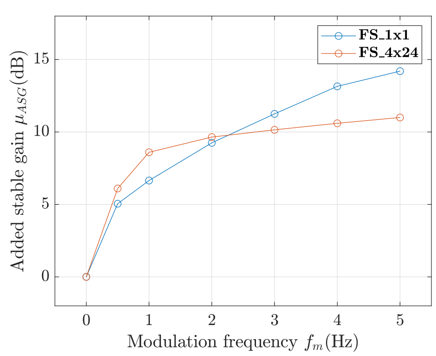
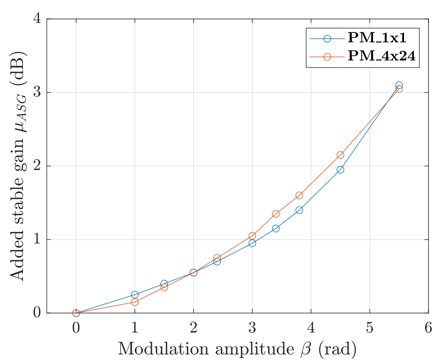


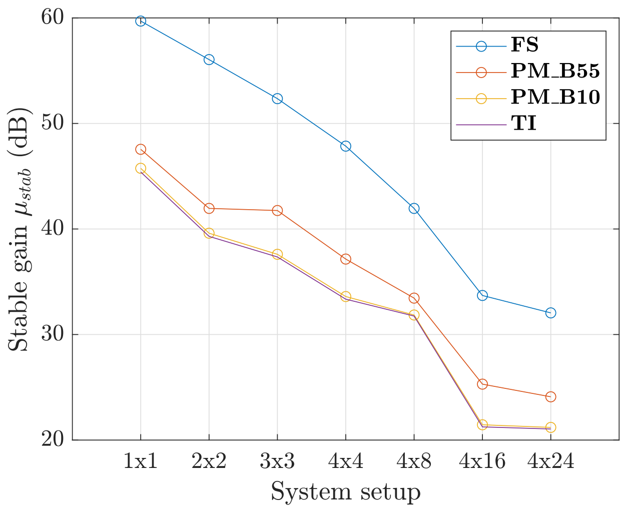
Image credits: TvW, David Pelegrin Garcia – *Audio credit:* TvW, Capella Pratensis

Interactive auralization

- **Multi-channel acoustic feedback control**
  - Gain before instability decreases with increasing # channels
  - Feedback-related artefacts: howling, ringing, coloration
- **Acoustic feedback control methods:**
  - Phase modulation methods ⇢ *Reverberation enhancement systems*
  - Gain reduction methods
  - Spatial filtering methods
  - Room modeling methods







FS = frequency shifting (5 Hz)
PM = phase modulation with modulation index β=1.0 or 5.5

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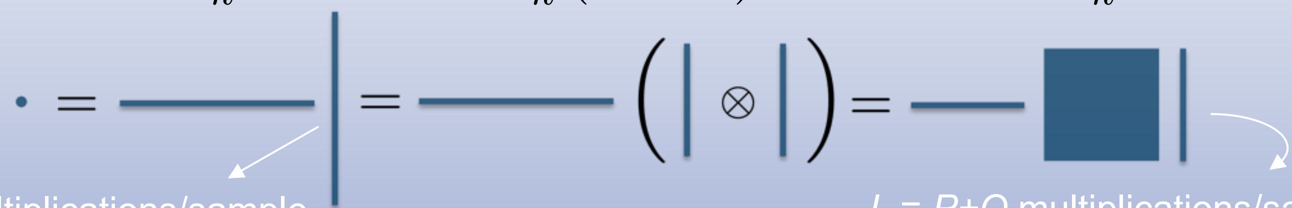
Image credit: Wannes Van Ransbeeck – *References:* M. A. Poletti, "The stability of multichannel sound systems with frequency shifting," *JASA*, 116(2): 853–871, Aug. 2004. – P. Svensson, "On reverberation enhancement in auditoria," Ph.D. dissertation, *Chalmers Univ. Technol.*, 1994. – T. van Waterschoot and M. Moonen, Fifty years of acoustic feedback control: state of the art and future challenges, *PIEEE*, 99(2): 288-327, 2011.

Interactive auralization

- **Low-latency real-time multi-channel convolution**
  - Key idea: Rewrite convolution operation using compressed RIR
    - **Low latency:** no buffering required by staying in time domain
    - **Real-time:** reduced # input buffer reads and # FLOPS
      - Truncation ⇢ shorter FIR filter
      - Hard thresholding ⇢ FIR filter with fewer non-zero coefficients
      - Sparse approximation ⇢ short "warped" FIR filter (mixed-Kautz model)
      - Low-rank approximation ⇢ "low-rank convolution"

Low-rank convolution: illustration for rank-1 model $\mathbf{h}_{L\times 1} = \mathbf{u}_{P\times 1} \otimes \mathbf{v}_{Q\times 1}$

$$y_k = \mathbf{x}_k^T \mathbf{h} = \mathbf{x}_k^T (\mathbf{u} \otimes \mathbf{v}) = \mathbf{v}^T \mathbf{X}_k^T \mathbf{u}$$



L = *PQ* multiplications/sample

L = *P*+*Q* multiplications/sample

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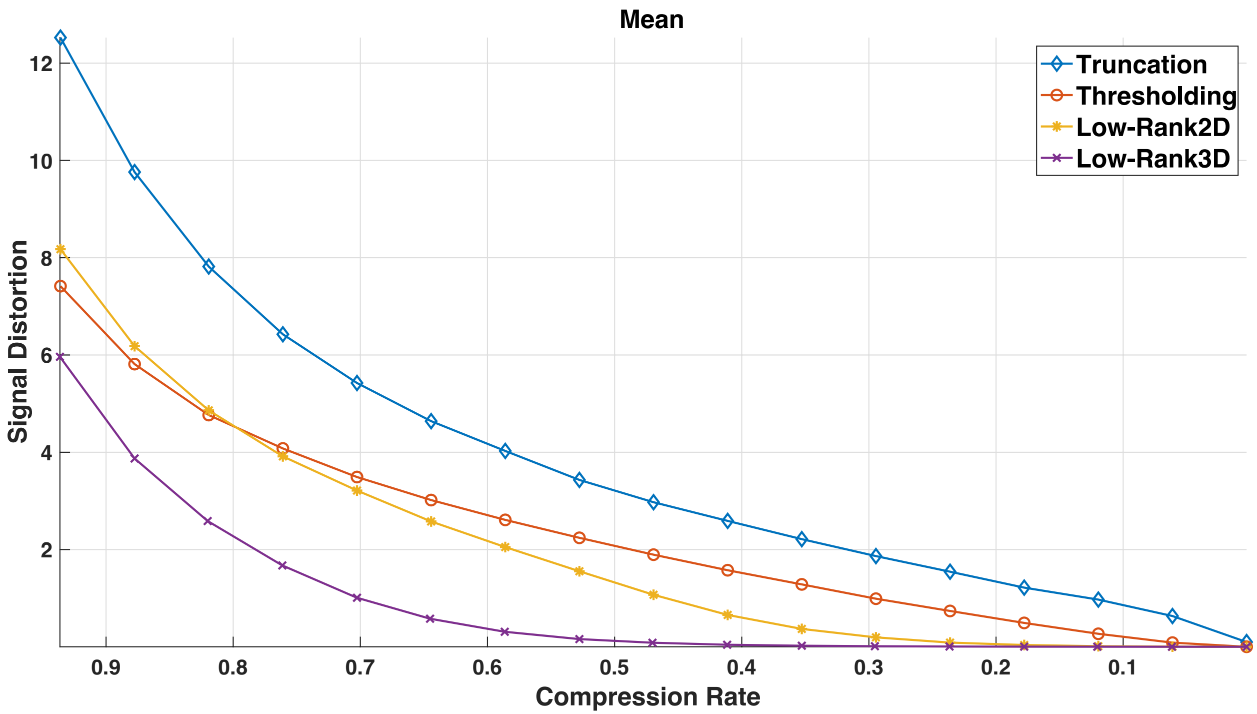
Image credit: TvW – *References:* G. Vairetti, E. De Sena, M. Catrysse, S. H. Jensen, M. Moonen, and T. van Waterschoot, "A scalable algorithm for physically motivated and sparse approximation of room impulse responses with orthonormal basis functions," *IEEE TASLP*, 25(7): 1547-1561, 2017. – M. Jälmby and T. van Waterschoot, "Low-rank convolution," *Tech. Rep.*, KU Leuven, 2022.

Interactive auralization

- **Signal distortion after compressed RIR convolution**
  - Methods: truncation, hard thresholding, low-rank approximation
  - Mean ERB-weighted signal distortion vs. RIR compression rate *C*

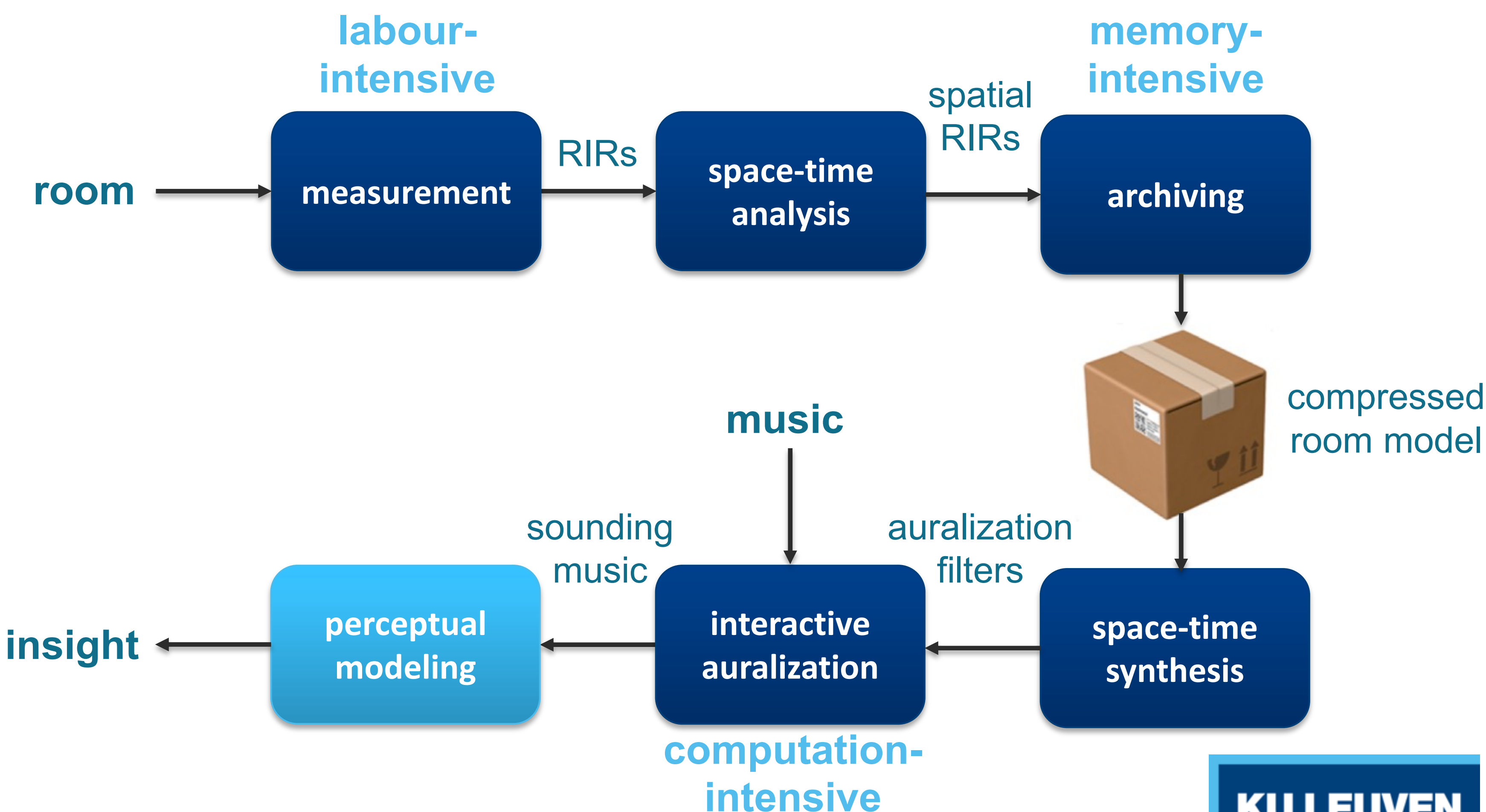


input = dry vocal music
RIR = Nassau Chapel RIR,
RT60 = 2.7 s, L = 117649

Image credit: Martin Jälmby – *Reference:* M. Jälmby and T. van Waterschoot, “Low-rank convolution,” *Tech. Rep.*, KU Leuven, 2022.

Outline

- **System overview & challenges**



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Perceptual modeling

- **Aim:** understand relation between acoustic characteristics of church and their perceived quality (broadly defined)
- **Key methodology: Flash Profile rapid sensory analysis**
  - Originally developed in frame of **food tasting** experiments
  - Validated for perceptual modeling of virtual acoustics **by listening** (e.g. auralization of concert halls, car cabins, domestic rooms)
  - Evaluated in preliminary experiments for perceptual modeling of virtual church acoustics **by listening while singing**

Materials

- 6 virtual acoustic spaces
- 4 expert listeners: male singers from Cappella Pratensis
- 2 pieces: plainchant + polyphonic

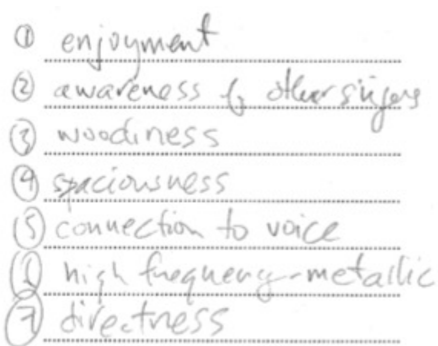
Image credit: TvW – *References:* V. Dairou and J. M. Sieffermann, “A comparison of 14 jams characterized by conventional profile and a quick original method, the flash profile”, *J. Food Sci*. 67, 2002. – N. Kaplanis, S. Bech, T. Lokki, T. van Waterschoot, and S. H. Jensen, Perception and preference of reverberation in small listening rooms for multi-loudspeaker reproduction, *JASA*, 146(5): 3562-3576, 2019.

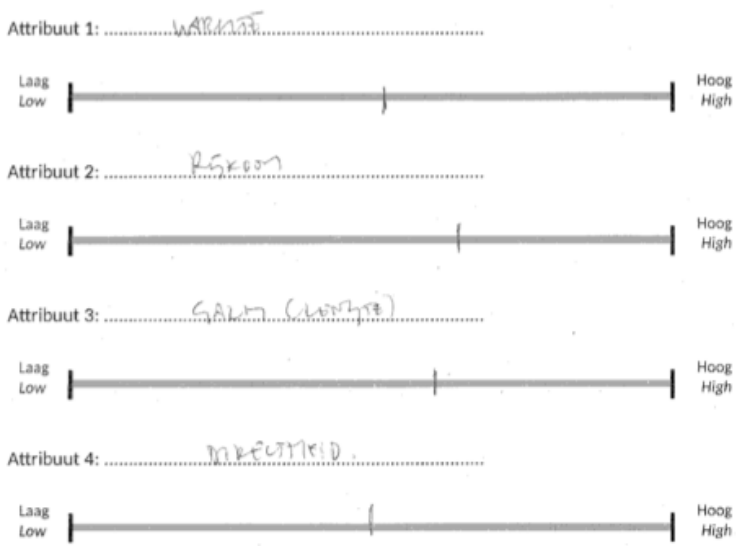
Perceptual modeling

- **Flash Profile Methodology:** experiment design
  - **1) Elicitation phase:** individual semantic definition of perceptual attributes to characterize differences between virtual spaces
  - **2) Ranking phase:** continuous-scale (low-high) quantification of each perceptual attribute for each virtual space

Expert 1

Expert 2





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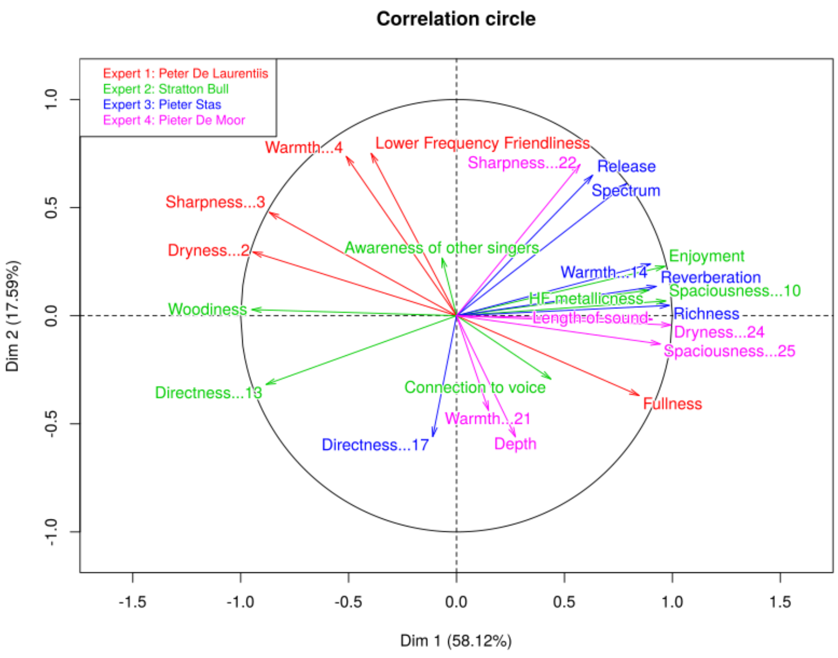
Perceptual modeling

- **Flash Profile Methodology:** statistical data analysis
  - Multi-factor principal component analysis + clustering



- 75% of perceived variance among spaces is modeled by two largest principal components
- two largest prinicipal components correlate to perceptual attributes of **spaciousness/reverberance** (Dim 1) and **spectral content** (Dim 2)
- six virtual spaces can then be mapped into this 2-D principal component subspace

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Conclusion

- **Some take-home messages...**
  - **Acoustic signal processing in digital humanities:** case studies in humanities/musicology/cultural heritage/... may carry remarkably many research challenges relevant to our community
  - **Fundamental signal processing research** (sampling & interpolation, sparse & low-rank modeling, ...) can be highly relevant to address application-specific bottlenecks relating to labour, memory, and computational resources
  - **Interdisciplinary research** is much more than putting together diverse team – it requires to learn common language and mutual scientific understanding, attract funding, develop proper research methodology, ... which is not easy but very enriching
  - Looking for challenging research topic in acoustic signal enhancement? Consider **multi-channel acoustic feedback control**

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Slides: https://tvanwate.github.io/iwaenc2022.pdf

Thank you...

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