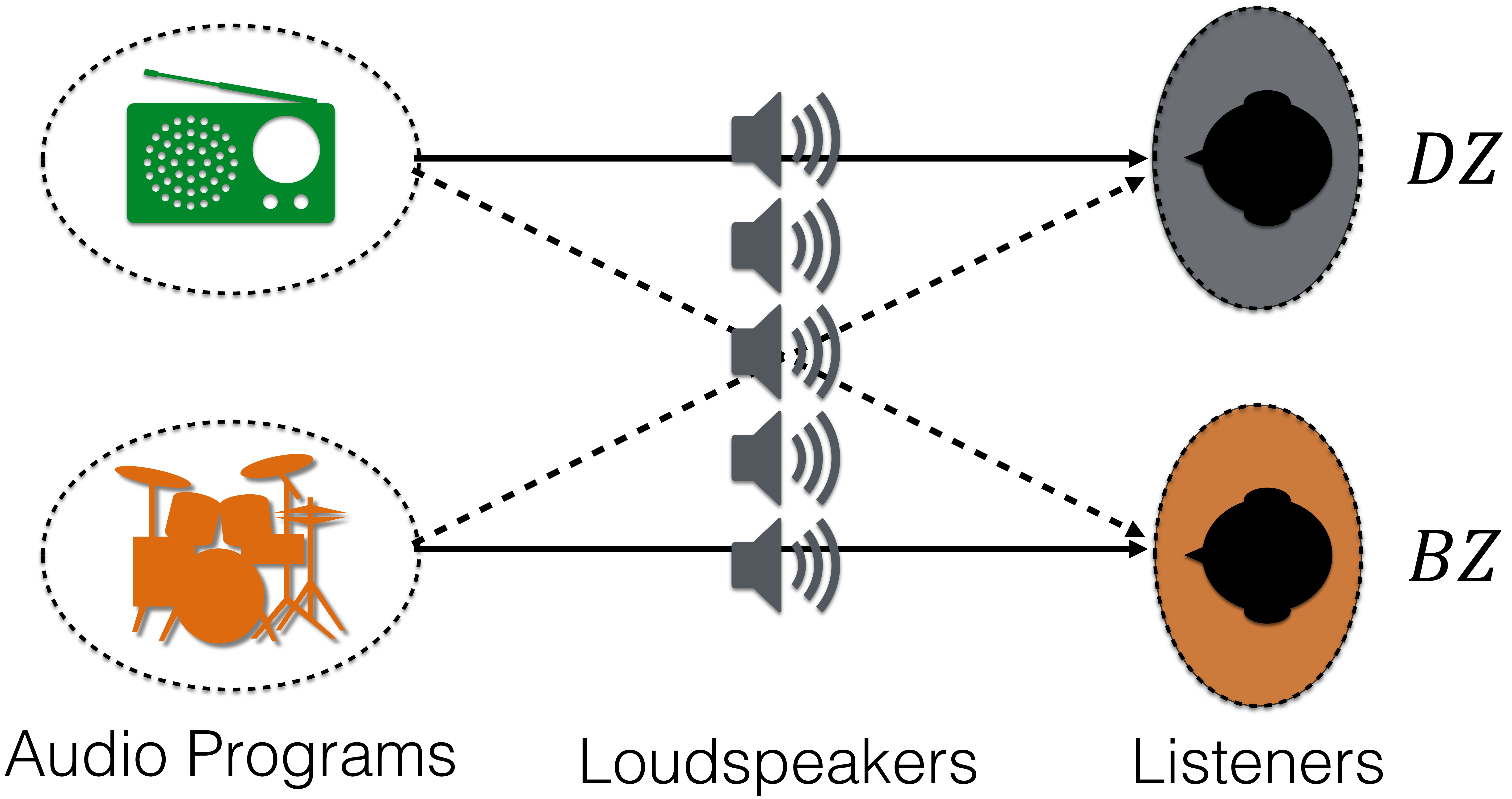
Experimental evaluation of bilateral Ambisonics-based binaural room transfer function synthesis with application to personal sound zones

Yue Qiao* (presenter) & Edgar Choueiri
3D Audio and Applied Acoustics (3D3A) Lab
Princeton University

Presented at Acoustics 2023 Sydney
Dec 6, 2023

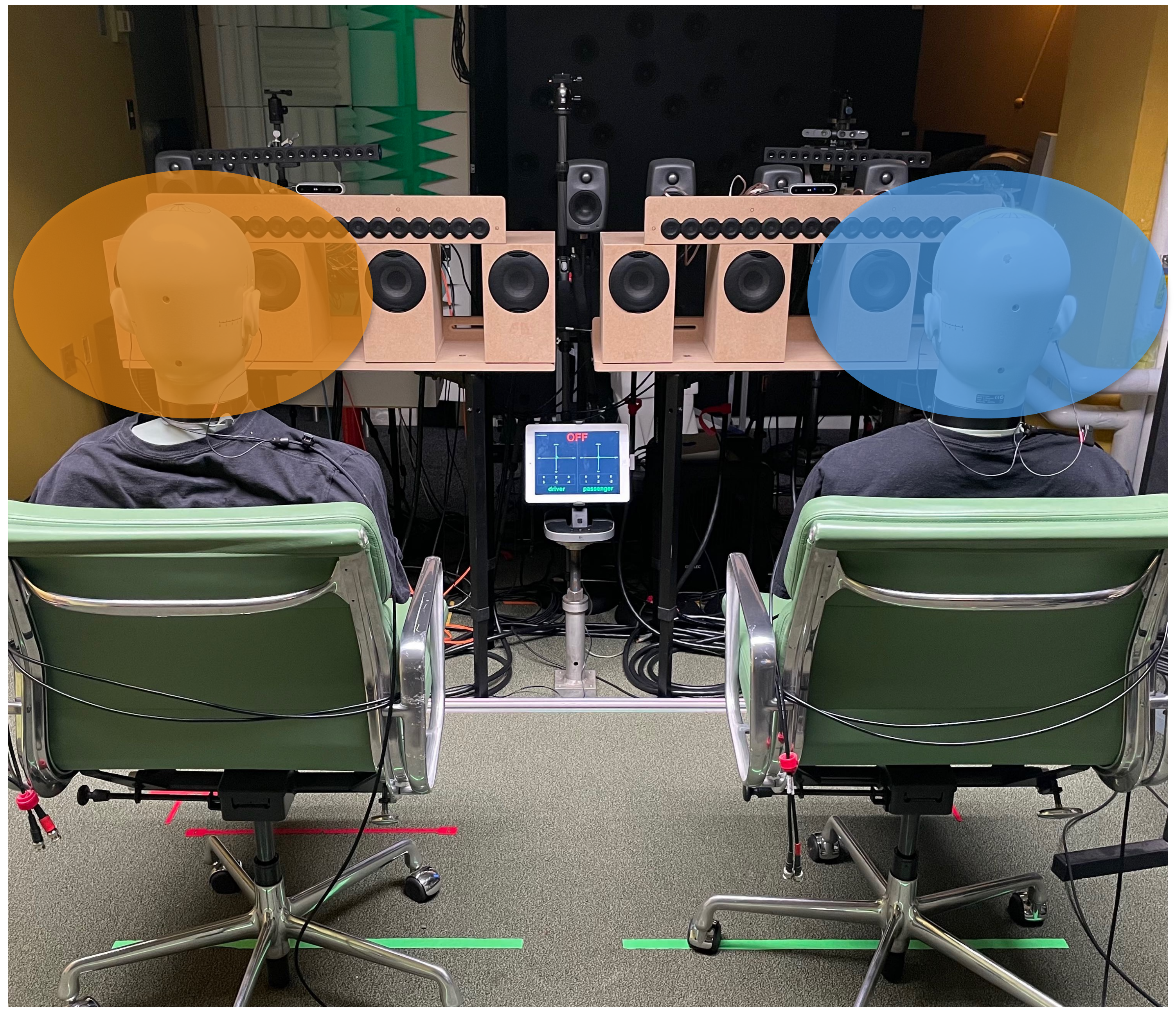
*E-mail: yqiao@princeton.edu

Personal Sound Zones[1]



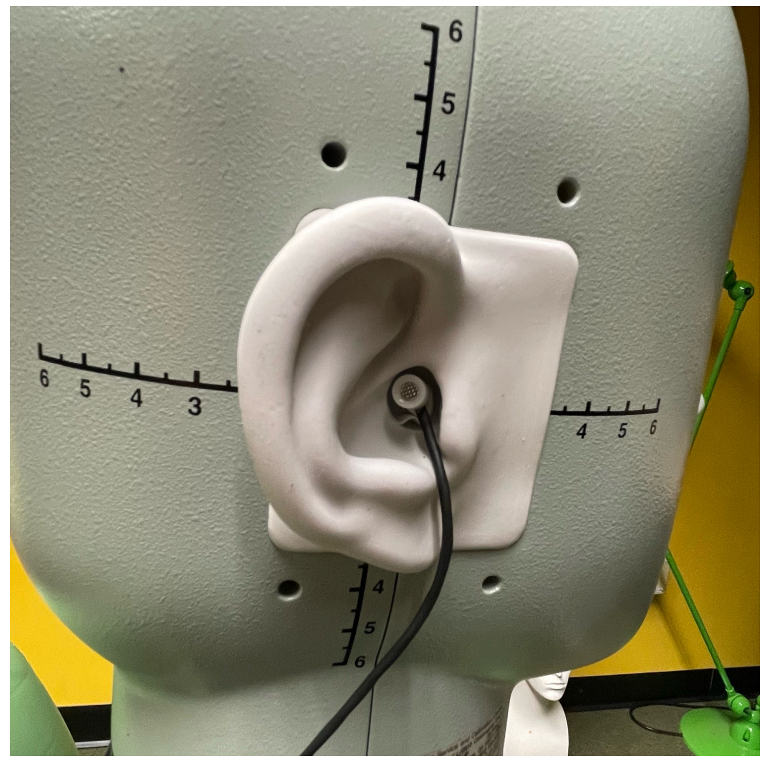
[1] Druyvesteyn and Garas, JAES, 1997

Generating high-isolation sound zones

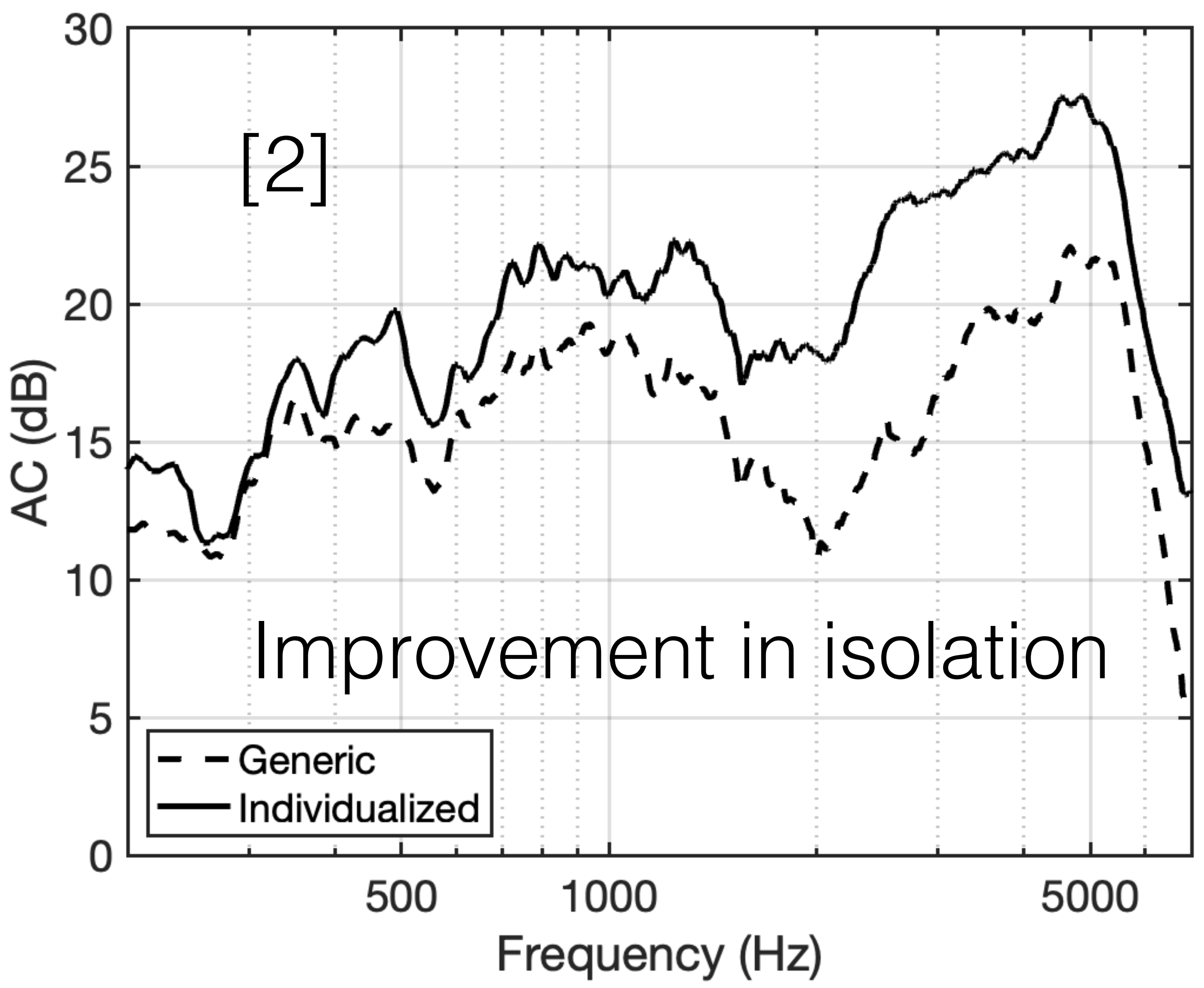


Practical PSZ system

With "in-situ", individualized measurements…



Binaural microphones

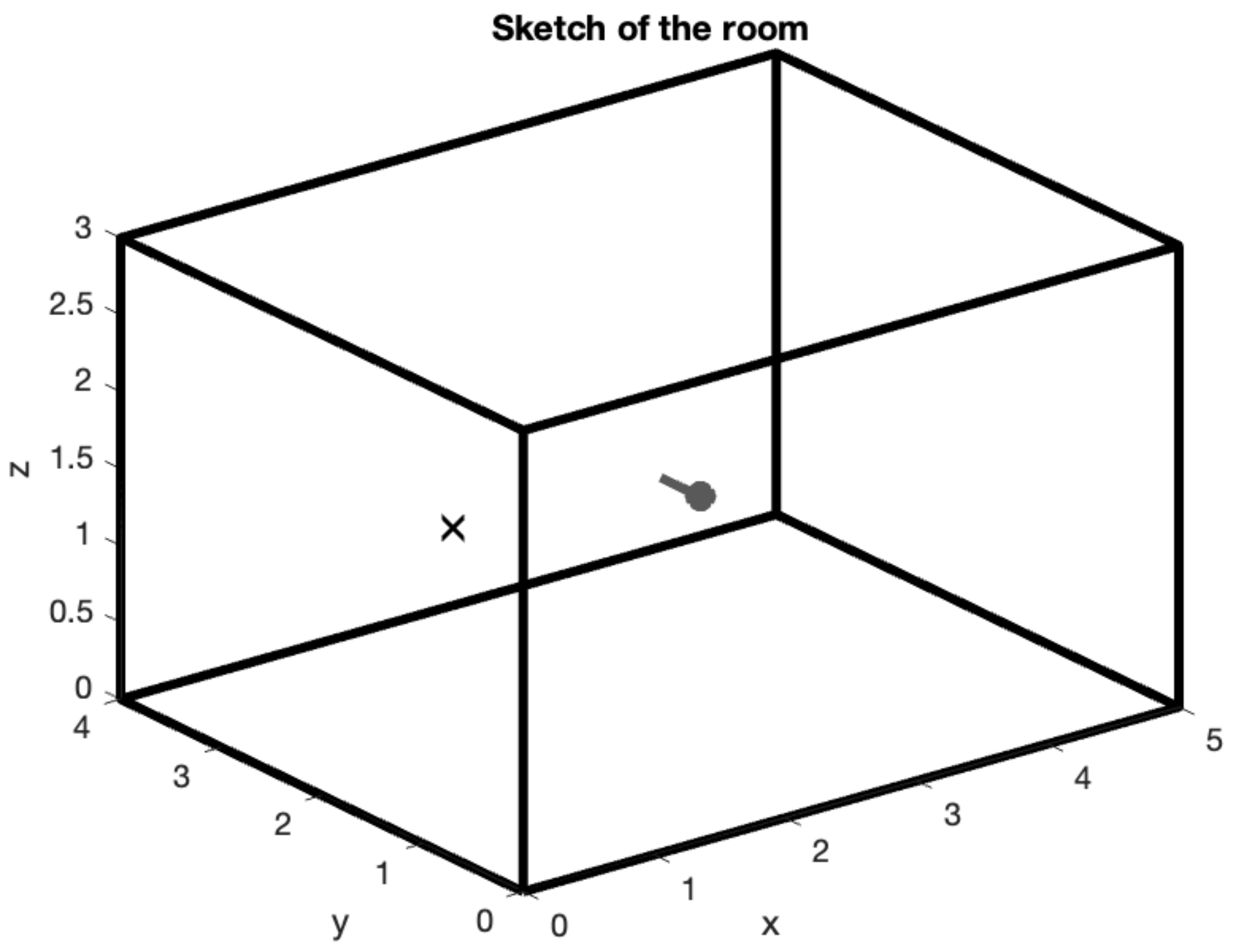


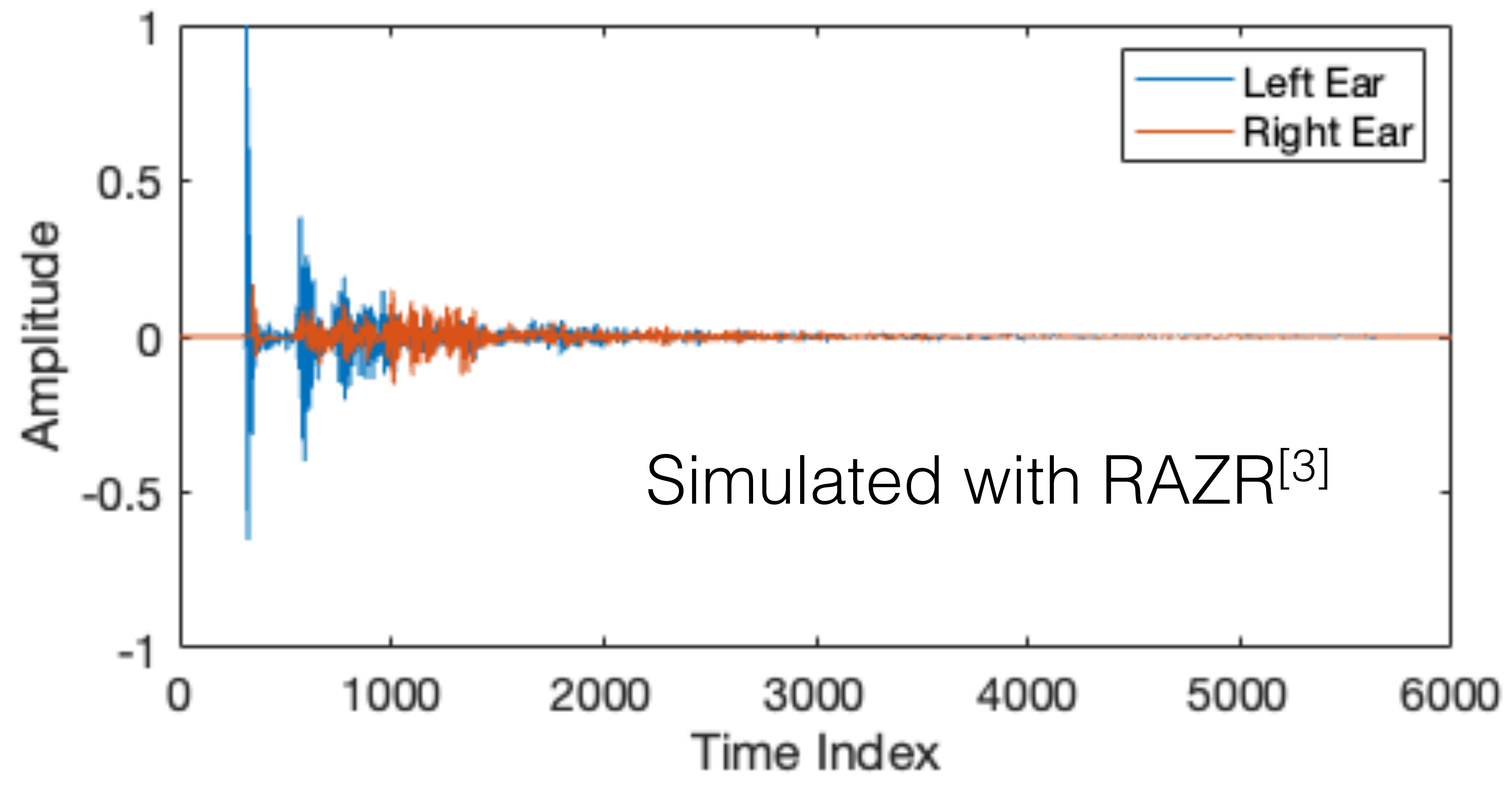
However, such measurements are practically infeasible…

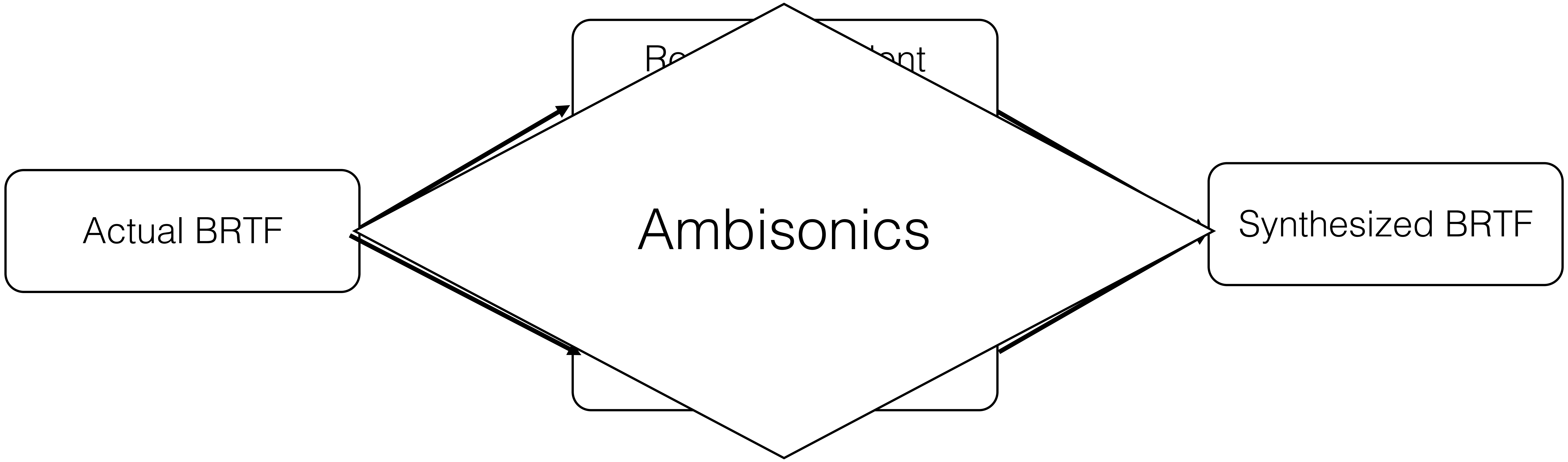
How to achieve high isolation in practical PSZ systems without in-situ measurements?

[2] Qiao and Choueiri, AES 152 Convention, 2022.

Proposed approach: Decoupling the binaural room transfer function (BRTF)

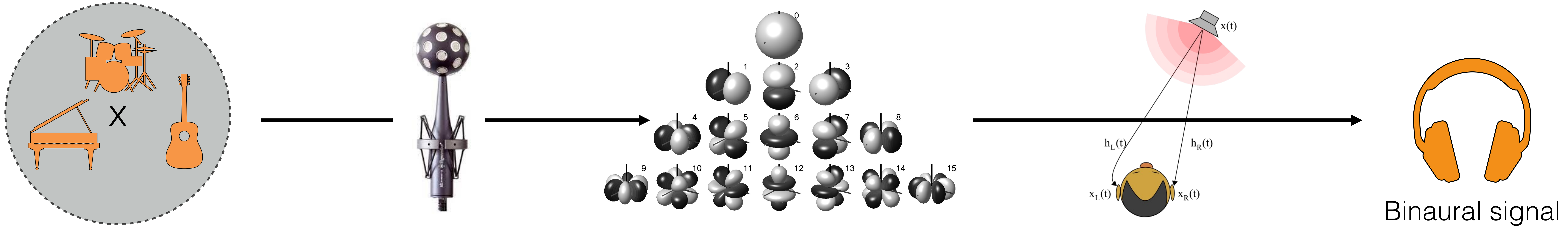






[3] Wendt et al., JAES, 2014.

Binaural reproduction with Ambisonics



Example: reproducing sound field at the left ear

$$p_L(k) = \int_\Omega a(k,\Omega) h^L(k,\Omega) d\Omega = \sum_{n,m} [\tilde{a}_{nm}(k)]^* h_{nm}(k)$$

Plane-wave density function at head center

HRTF for the left ear

SH-domain functions

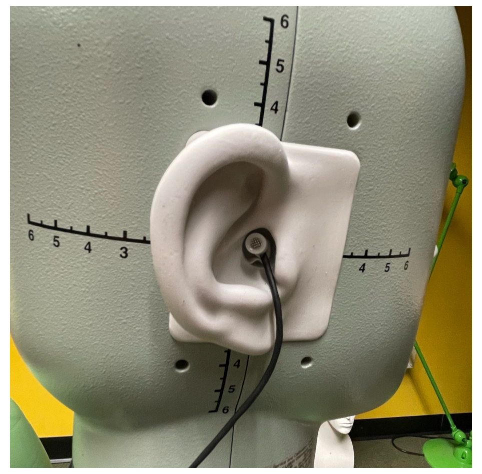
Proposed workflow for BRTF synthesis & PSZ generation

Individual loudspeakers

Capture at listening position

→ Spatial Room Transfer Function (SRTF)

Databases OR



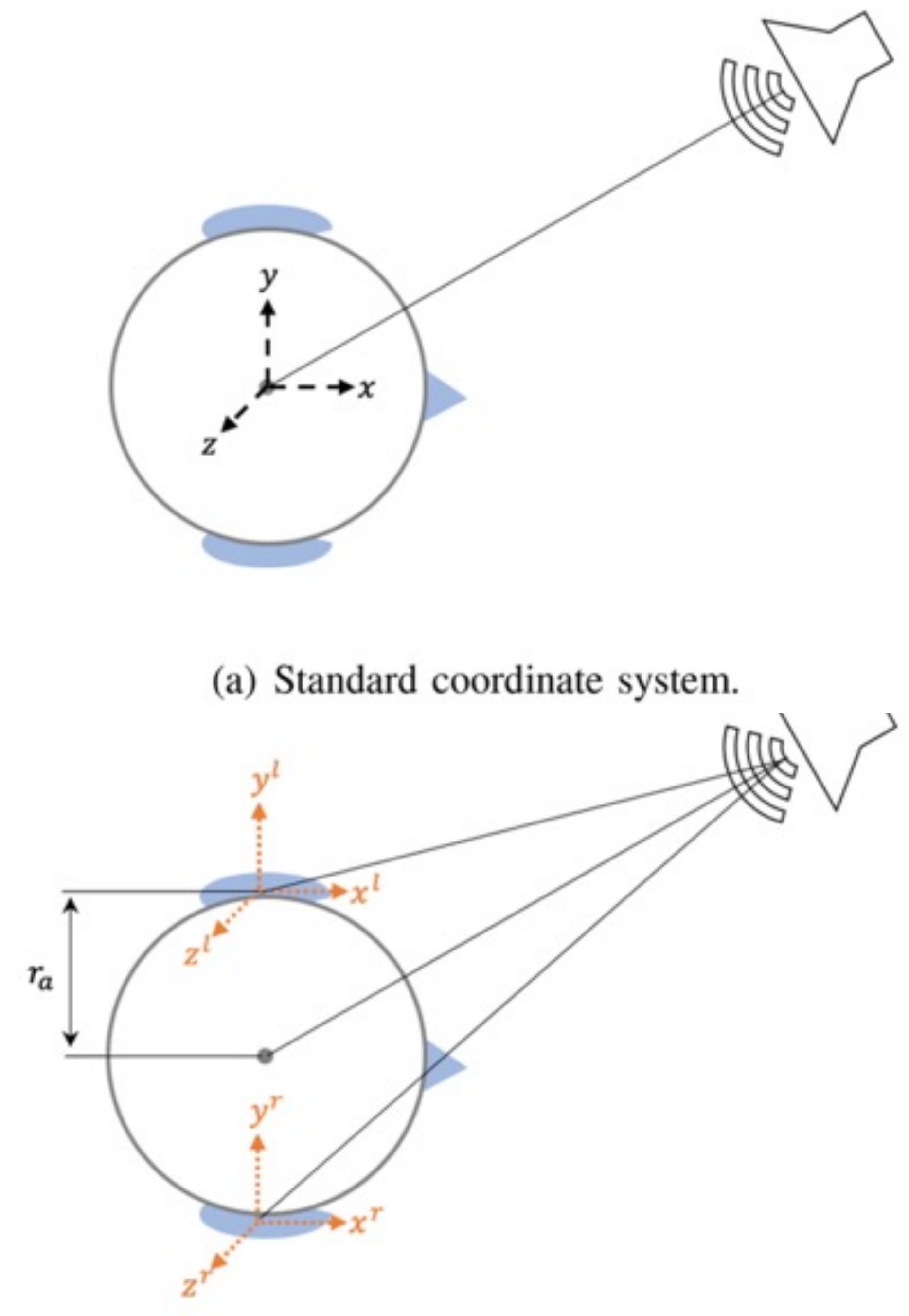
Individualized measurements

→ Head-Related Transfer Function (HRTF)

SRTF + HRTF → Ambisonics Processing → Binaural Room Transfer Function (BRTF) → Pressure Matching, Acoustic Contrast Control, … → PSZ Filters

Practical issue with (basic) Ambisonics

- For perfect reconstruction, $n = \infty$ is required in $\sum_n \sum_m [\tilde{a}_{nm}(k)]^* h_{nm}(k)$
- However, the order is limited by # of microphones, $N \leq (Q+1)^2$
- Finite order leads to errors in BRTF estimation, proportional to (kr)



(a) Standard coordinate system.

(b) Bilateral coordinate system.

Bilateral Ambisonics to the rescue!

- Firstly introduced as “binaural B-format”[4]
- Later generalized to arbitrary SH order[5]

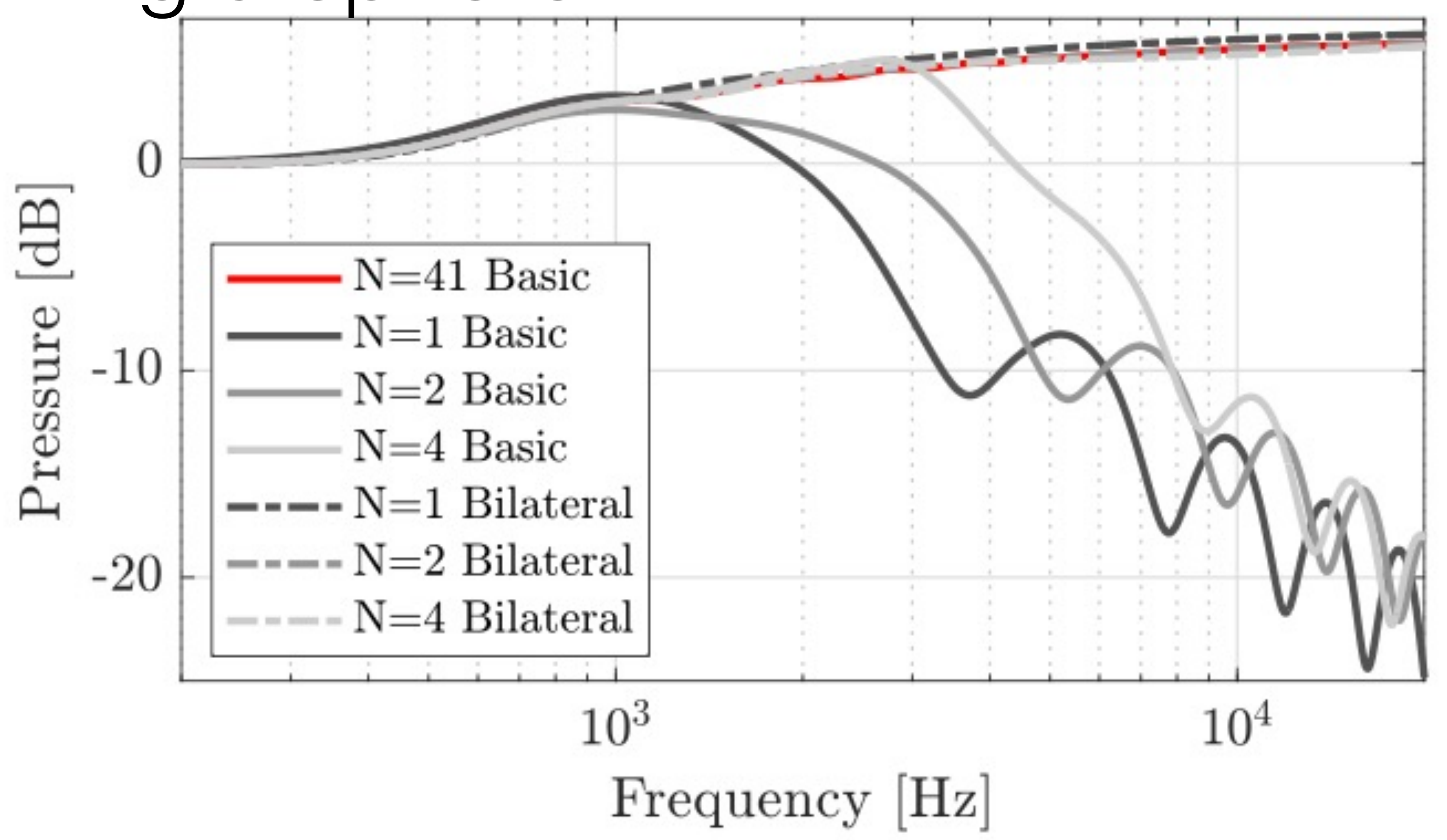
$$p_L(k) = \int_\Omega a^L(k,\Omega) h_a^L(k,\Omega) d\Omega = \sum_{n,m} [\tilde{a}_{nm}^L(k)]^* h_{a,nm}^L(k)$$

Plane-wave density function at the left ear — Ear-aligned HRTF — SH representation

$$h_a^L(k,\Omega) = h^L(k,\Omega) e^{-ikr_a \cos\Theta_L}$$

HRTF ear alignment

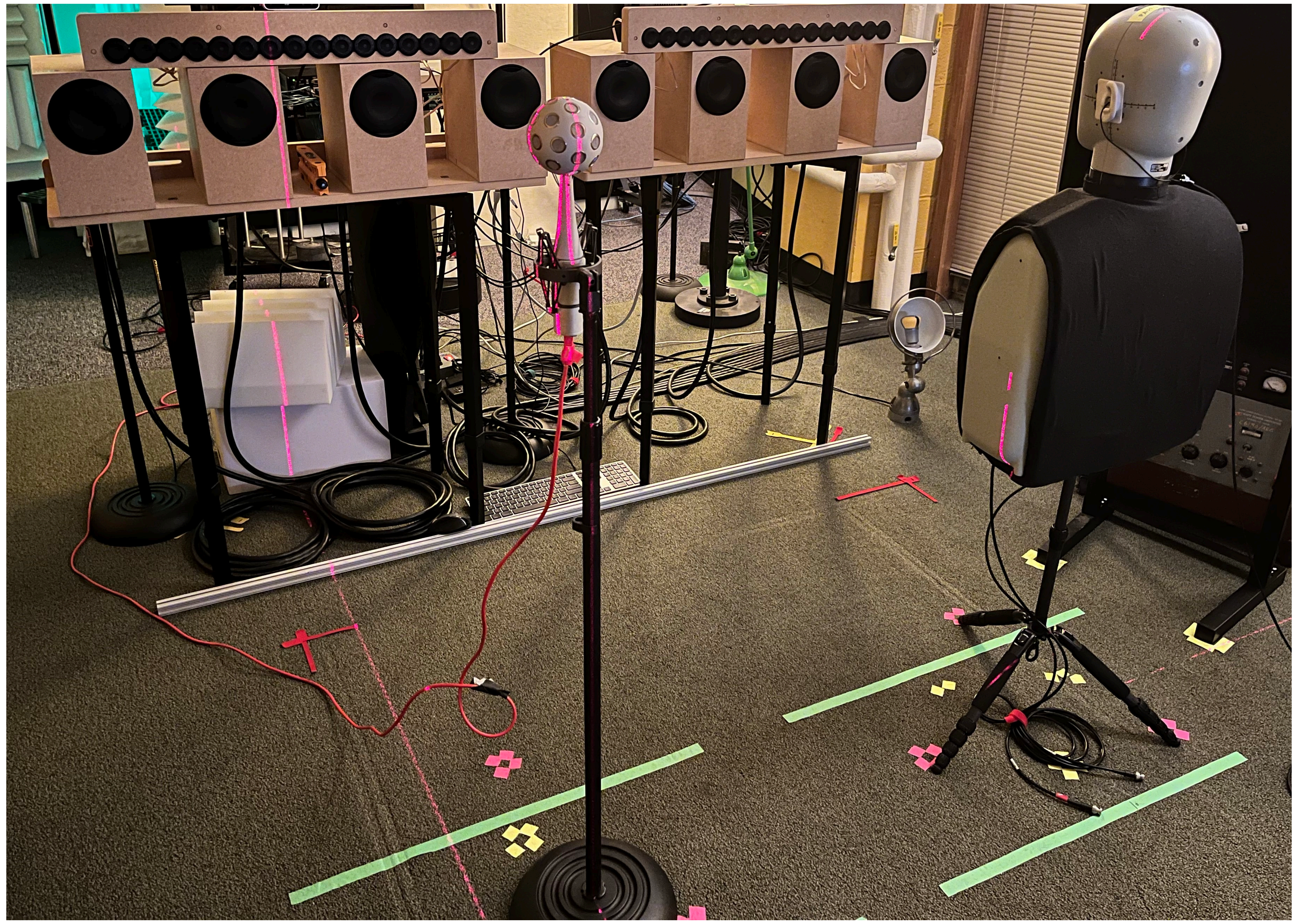
Rigid sphere HRTF



Experimental validation

- Compare synthesized BRTFs with in-situ measured BRTFs
- Evaluate the isolation performance with PSZ filters generated using different BRTFs

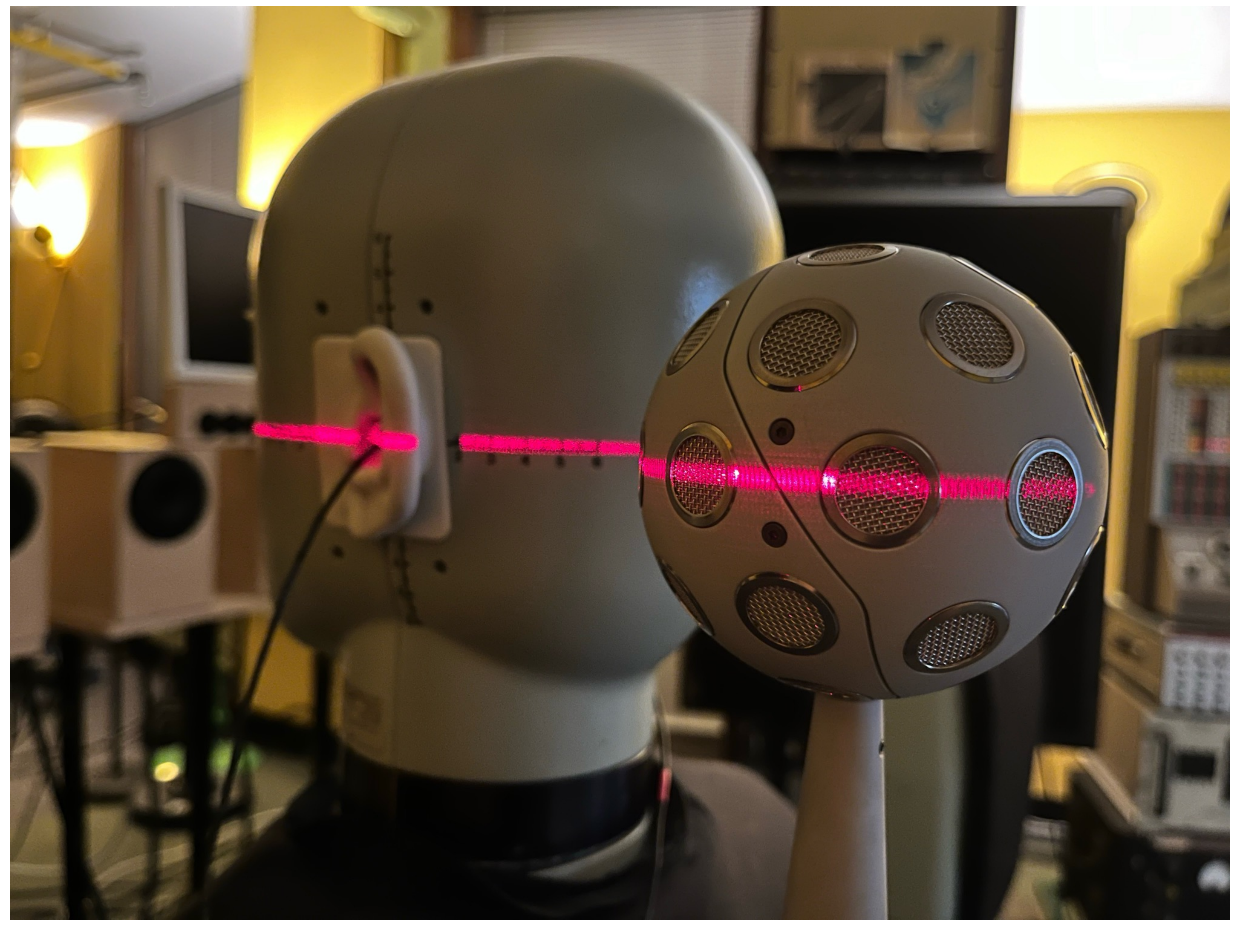
In-situ measurement



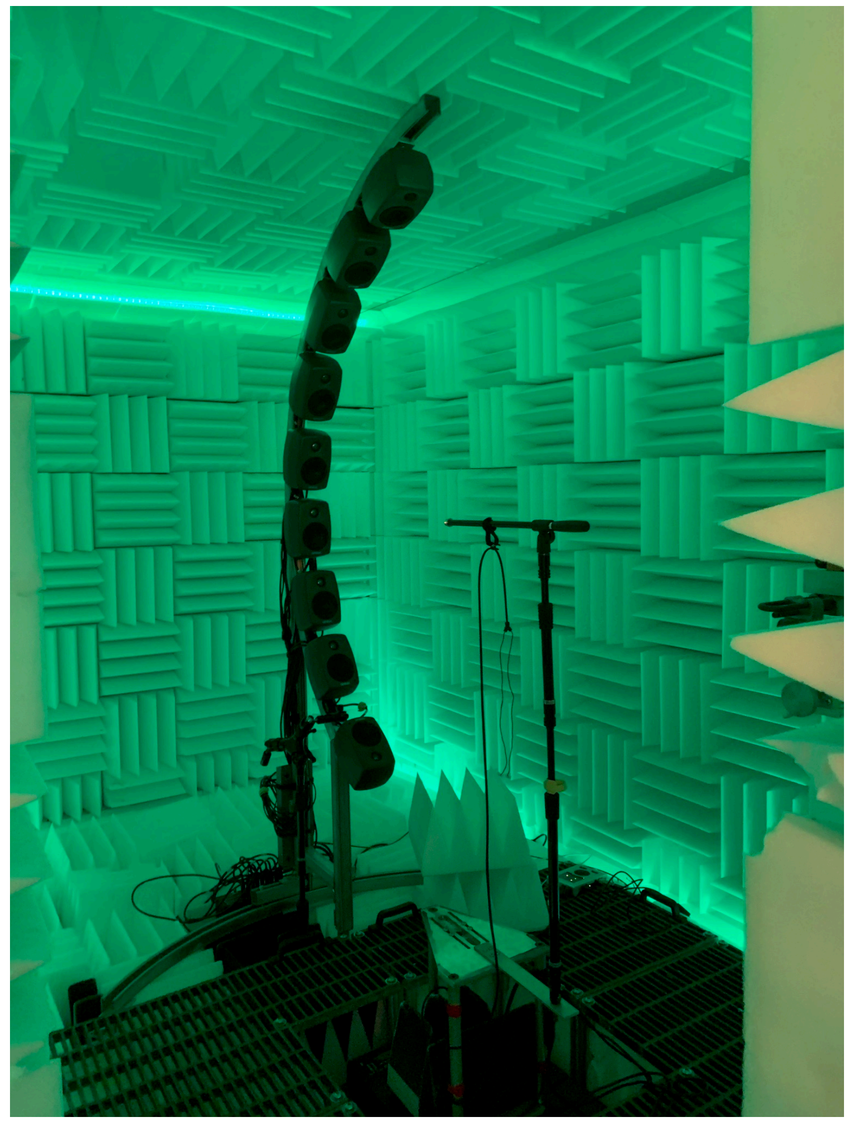
Microphone array measurement

BRTF synthesis with bilateral Ambisonics

- Microphone array (Eigenmike) measured at the two ears
- 4th-order SH representation
- In-house HRTFs measured for the listener (B&K HATS)[6]

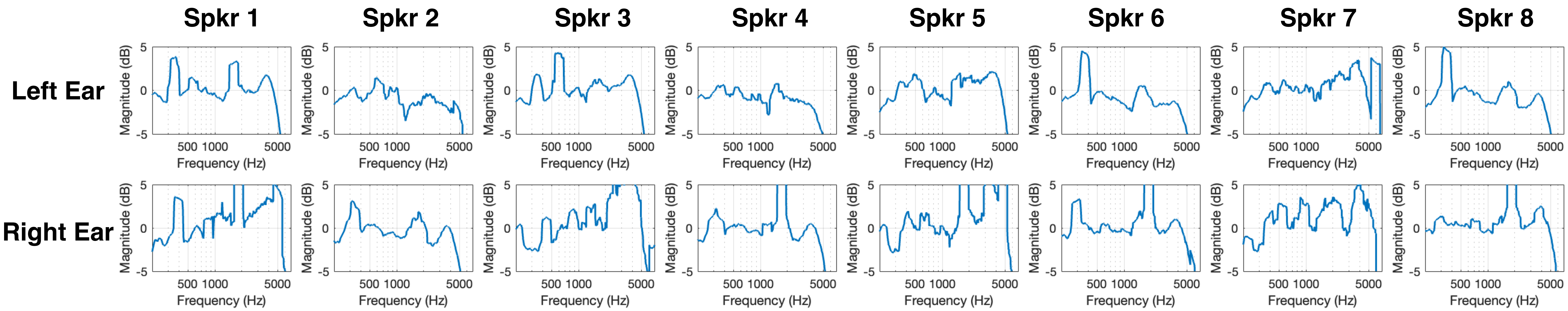


Laser alignment



HRTF measurement

Error analysis



[6] Sridhar et al., AES Conv., 2017.

PSZ Filter Generation

- Frequency-domain Pressure Matching[7] with constant regularization ($\beta = 10^{-3}$)
- Single-channel (mono) target program
- Time-domain truncation of BRTFs to increase filter robustness

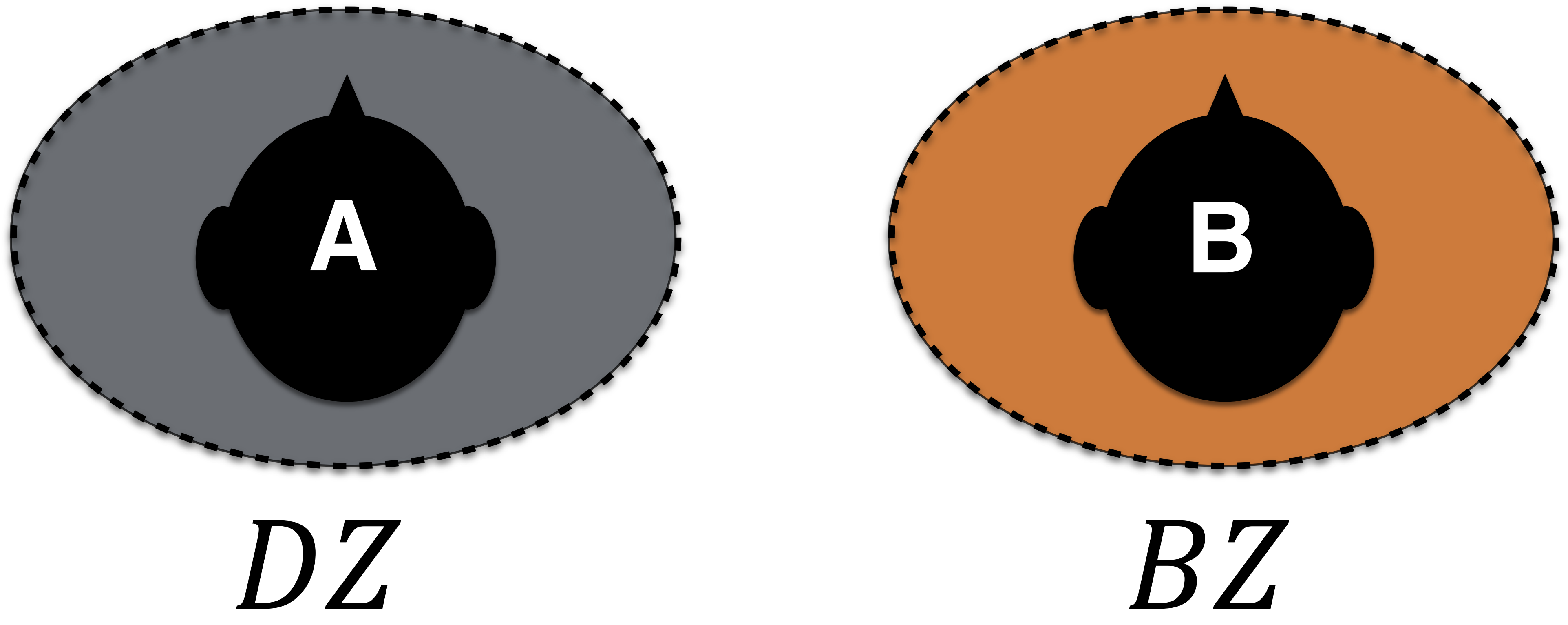
$$\mathbf{g}^* = \underset{\mathbf{g}}{\mathrm{arg}min} \parallel \mathbf{p}_T - \mathbf{H} \cdot \mathbf{g} \parallel^2 + \beta \parallel \mathbf{g} \parallel^2$$

- $\mathbf{g}^*$: PSZ Filters
- $\mathbf{p}_T$: Target Pressure
- $\mathbf{H}$: BRTF
- $\beta \parallel \mathbf{g} \parallel^2$: Regularization

Isolation Performance Evaluation

- Inter-Zone Isolation (IZI)[8]
- Equivalent to Acoustic Contrast in this case

$$IZI = \frac{\parallel \mathbf{H}_B \mathbf{g}^* \parallel^2}{\parallel \mathbf{H}_A \mathbf{g}^* \parallel^2}$$

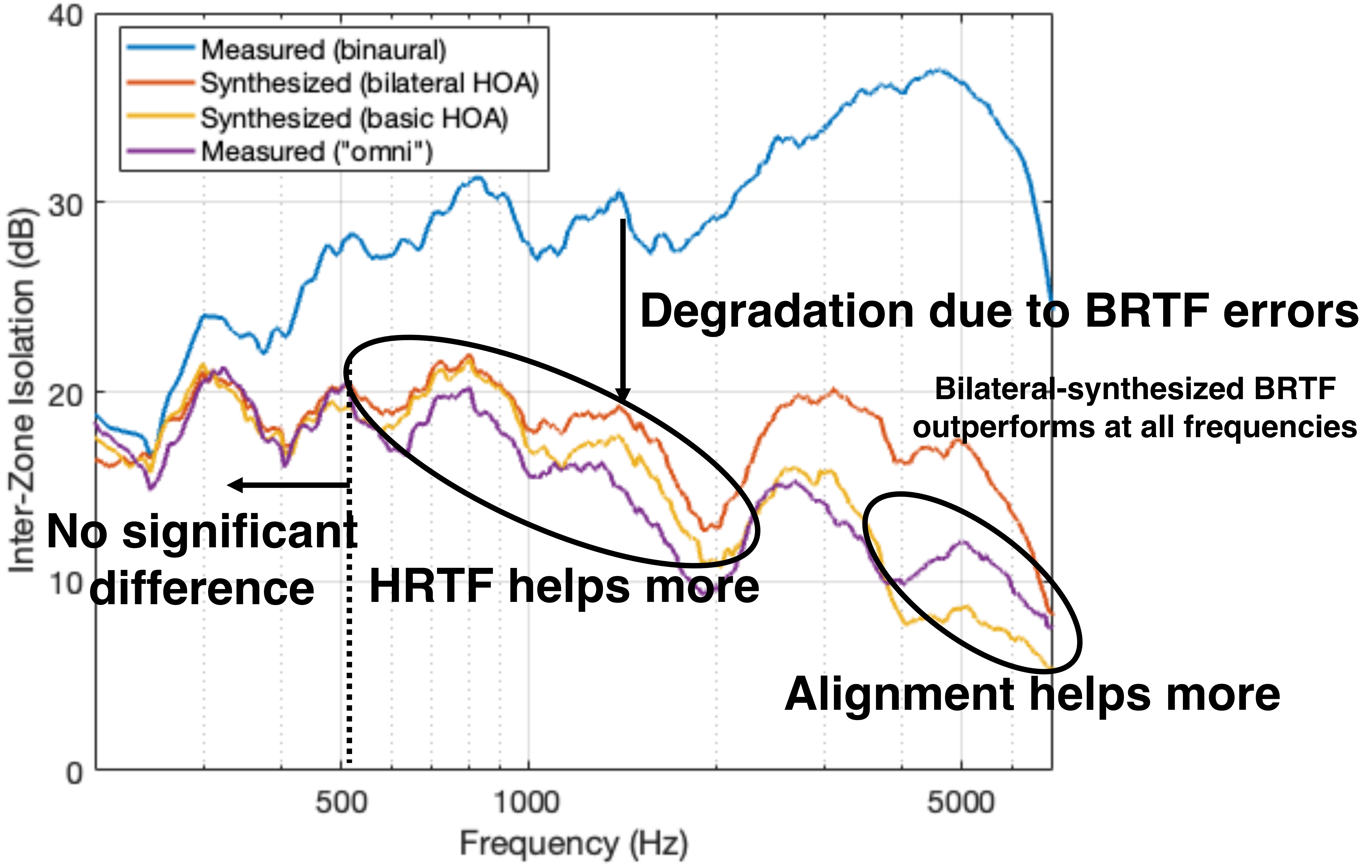


[7] Poletti, AES Conv. 125, 2008. [8] Qiao et al., JASA Express Lett., 2022.

Isolation performance comparison

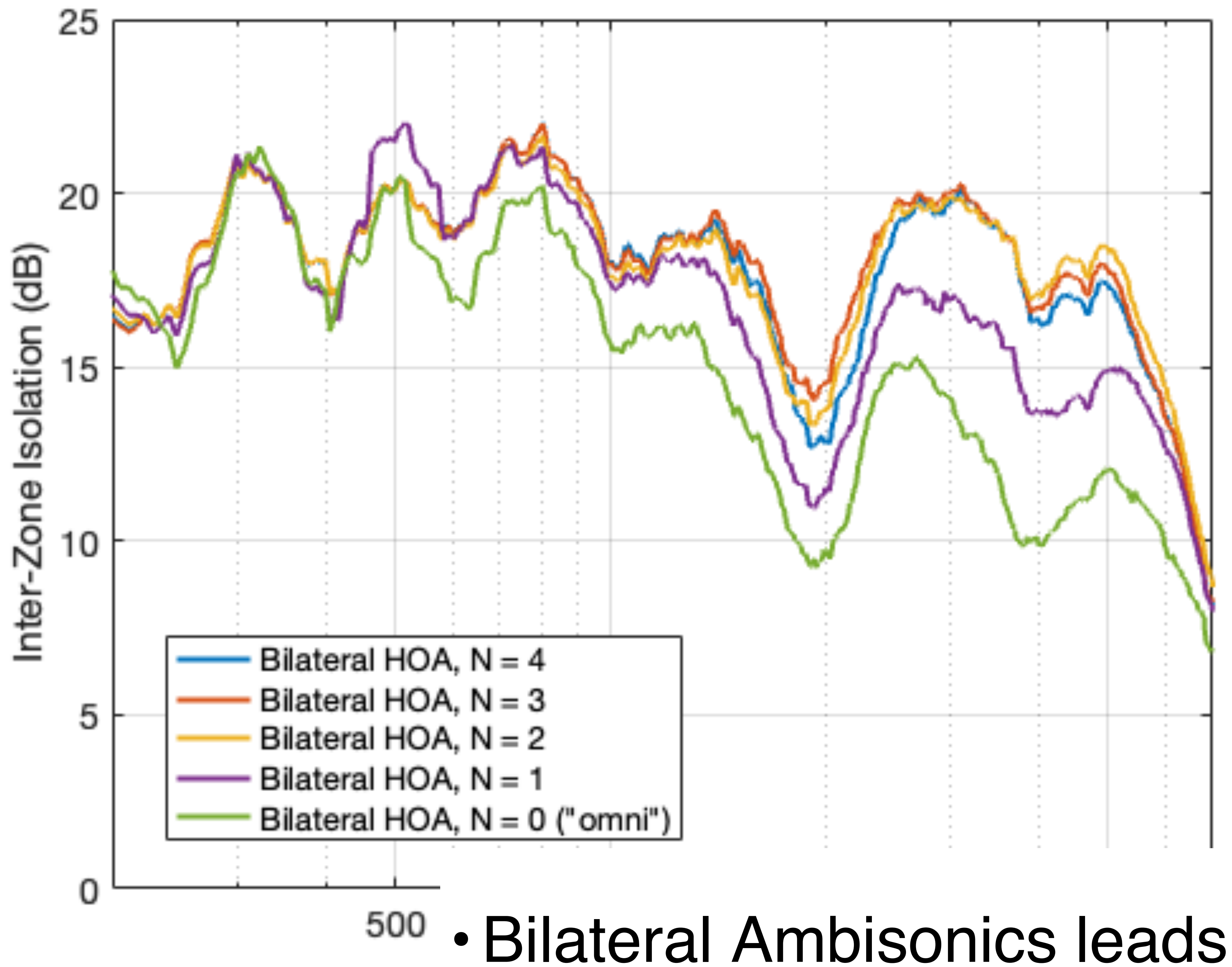
BRTF Candidates

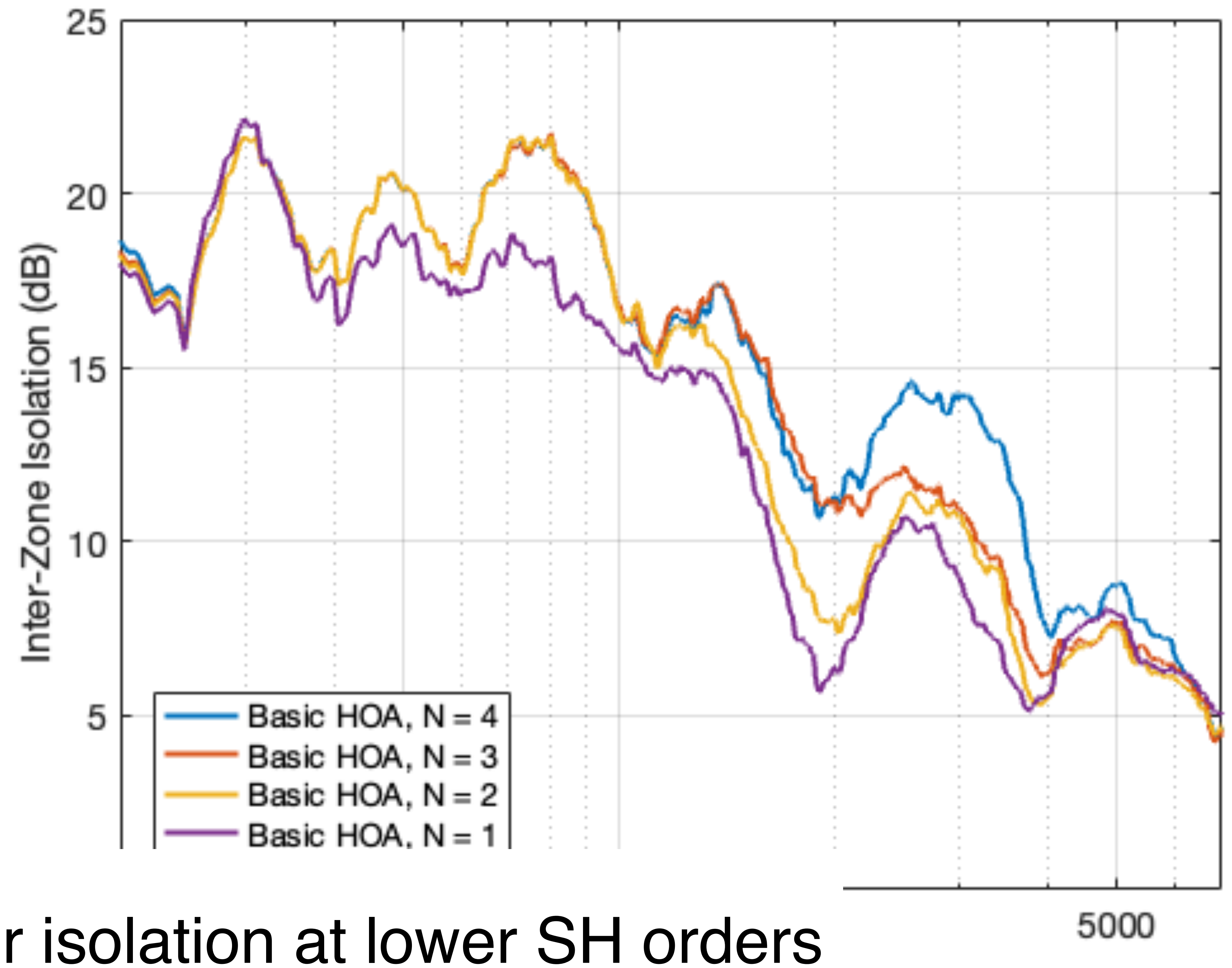
- Measured
  - with binaural microphones
  - with “omni channel” of the microphone array
- Synthesized
  - with bilateral Ambisonics (4th order)
  - with basic Ambisonics (4th order)



Effects of synthesis parameters

Effect of Ambisonics order





- Bilateral Ambisonics leads to higher isolation at lower SH orders
- Bilateral Ambisonics is more robust against order decrease

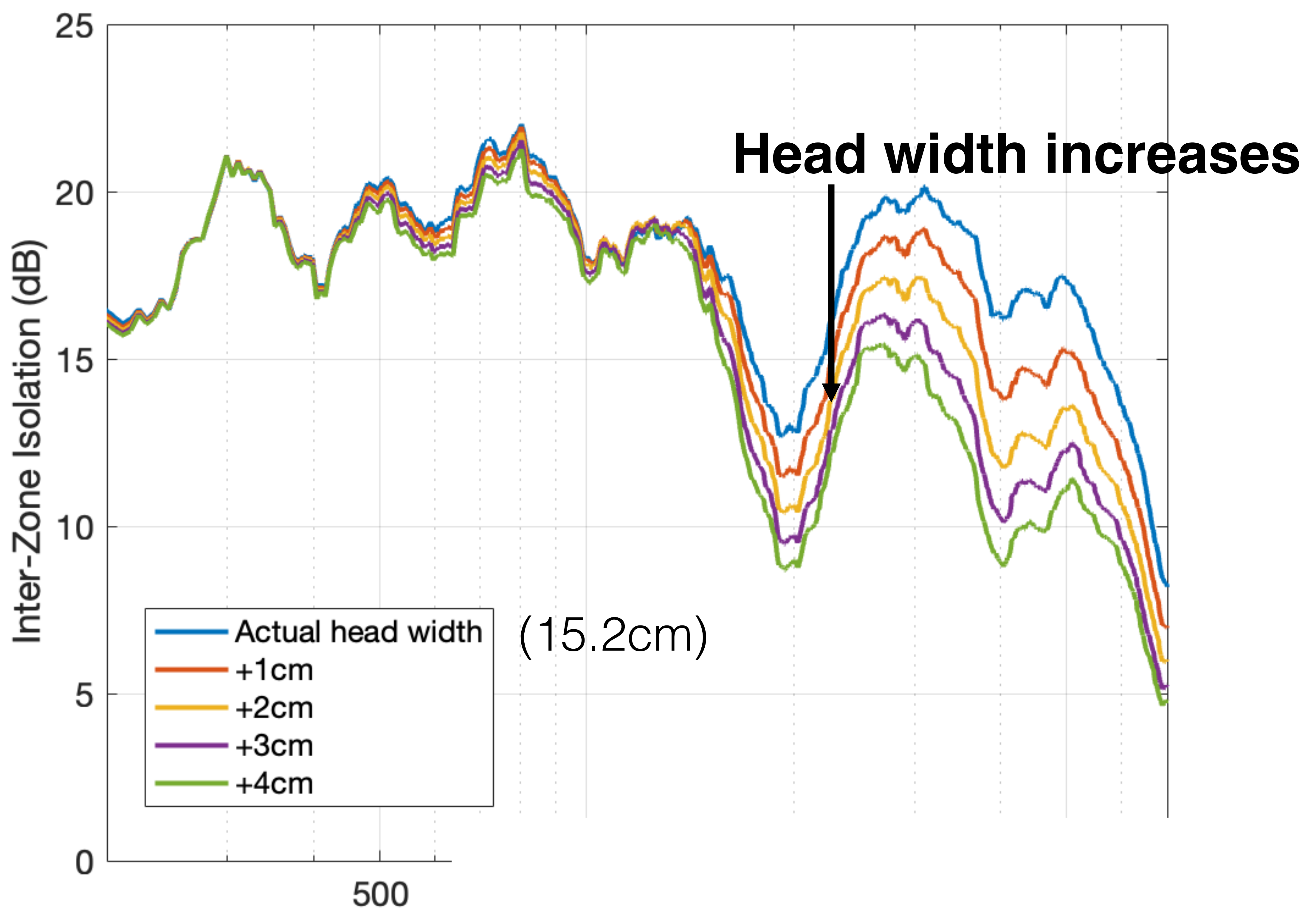
Bilateral Amb

ular HRTF

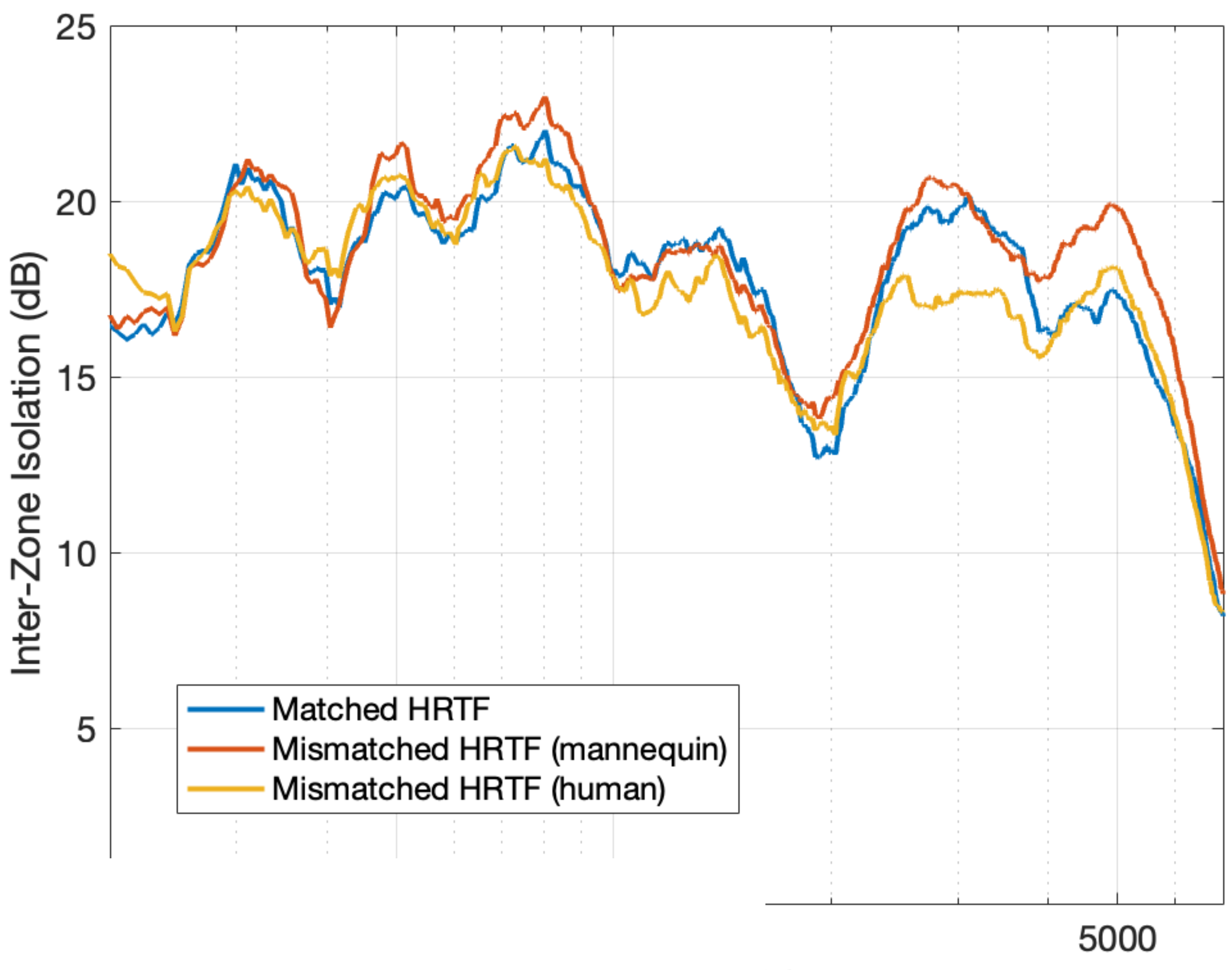
PRINCETON UNIVERSITY 3D3A

Effects of synthesis parameters

Effect of head width (for HRTF ear-alignment)



Effect of HRTF individualization



- Ear alignment is more important than HRTF individualization

Conclusion

- Bilateral Ambisonics offers an effective way to decouple the room and the listener, making high-isolation PSZ more practical to implement
- Such a decoupling also introduces a multitude of errors, which requires careful compensation

Experimental evaluation of bilateral Ambisonics-based binaural room transfer function synthesis with application to personal sound zones

Yue Qiao* (presenter) & Edgar Choueiri
3D Audio and Applied Acoustics (3D3A) Lab
Princeton University

Presented at Acoustics 2023 Sydney
Dec 6, 2023

*E-mail: yqiao@princeton.edu

Discussion

- Potential sources of errors
  - Ambisonics encoding errors from the microphone array, especially at high frequencies
  - HRTF distance mismatch (far-field assumption vs. near-field sources)
  - Position/orientation mismatch between the microphone array and the ears
- Pros and Cons of bilateral Ambisonics
  - Pros: higher accuracy with lower orders
  - Cons: 2x measurement required, difficult for head rotations