



# Contactless Material Identification with Millimeter Wave Vibrometry

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\* indicates equal contribution.



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# Material sensing opens up many applications!

Robotic Grasping



Quality Control



Waste Sorting



Liquid & Food Control



# Material sensing opens up many applications!

Robotic Grasping



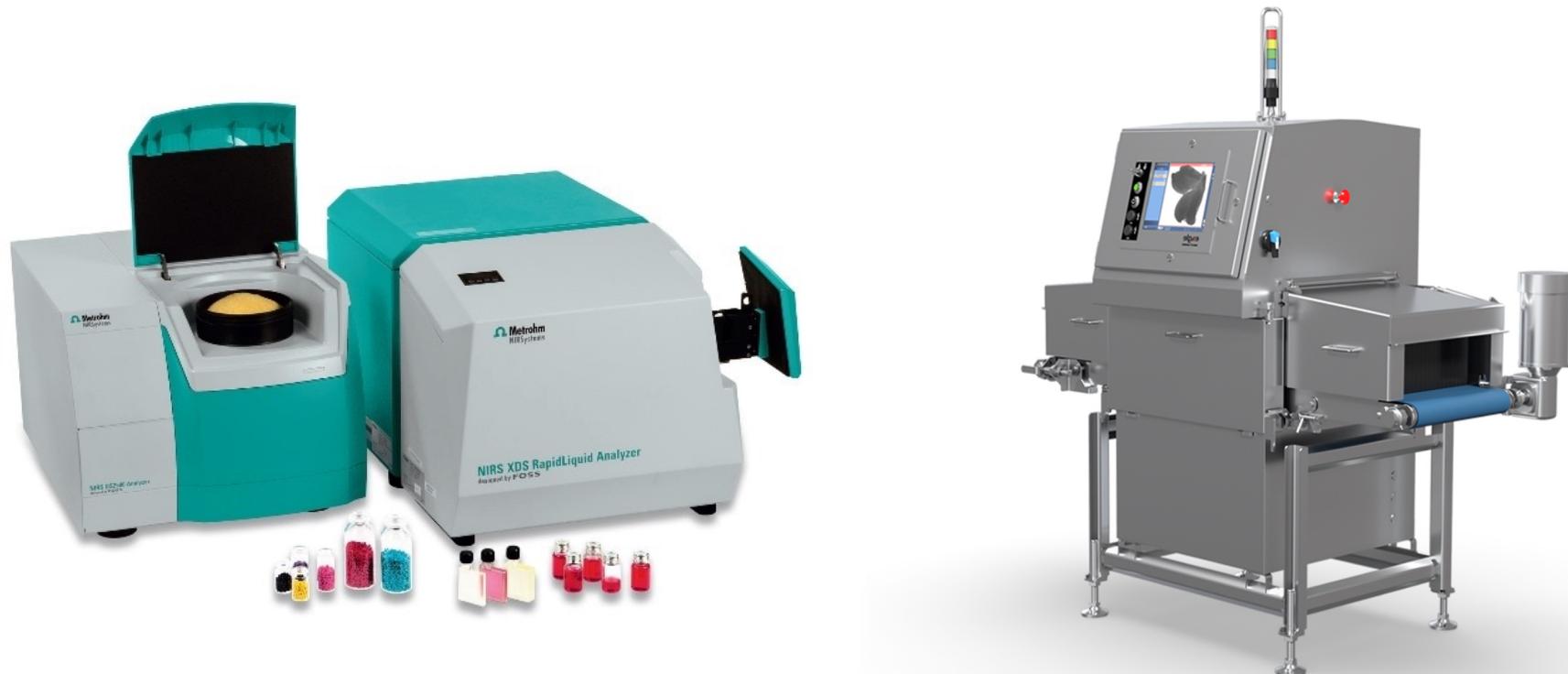
Quality Control



Practical & Scalable → Non-Invasive & Inexpensive!



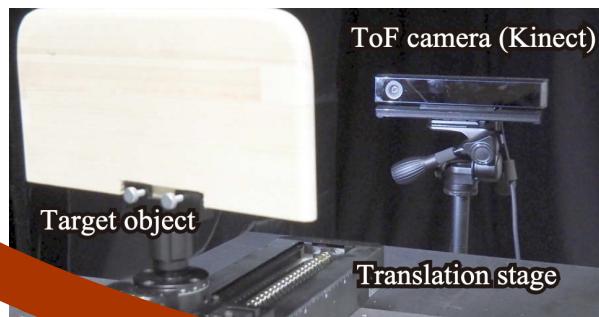
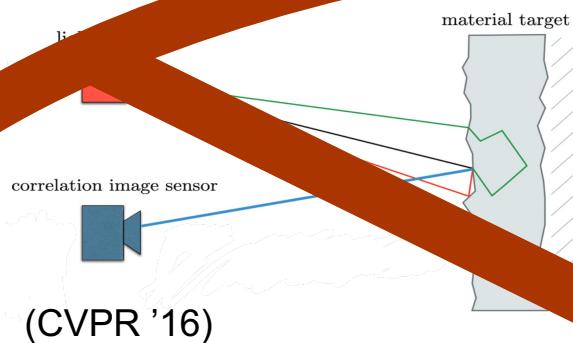
# Systems used today



Bulky and expensive!

# Material sensing solutions...

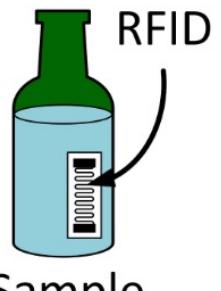
VISION SOLUTIONS



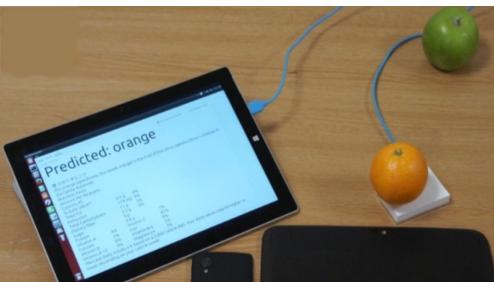
# Material sensing solutions...

## Wireless Solutions

RFID & Touch



Sample  
(NSDI '20)

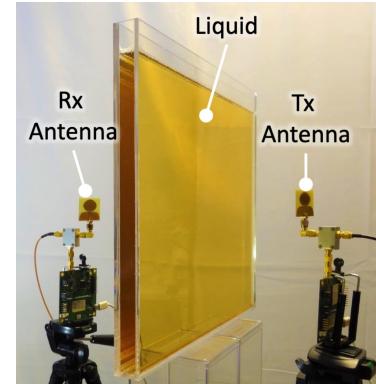


(UIST '16)

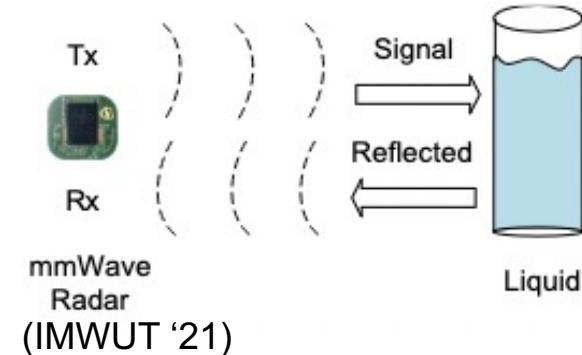


(MobiCom '17)

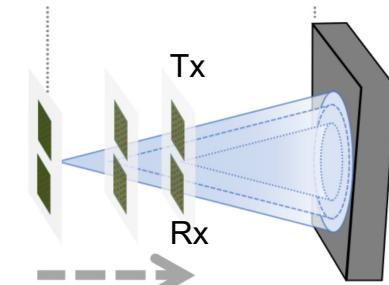
Liquids



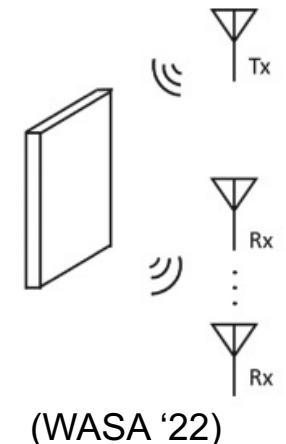
(MobiSys '16)



Reflection Based



(IMWUT '20)



(WASA '22)

# Material sensing solutions...

## Wireless Solutions

RFID & Touch

Liquids

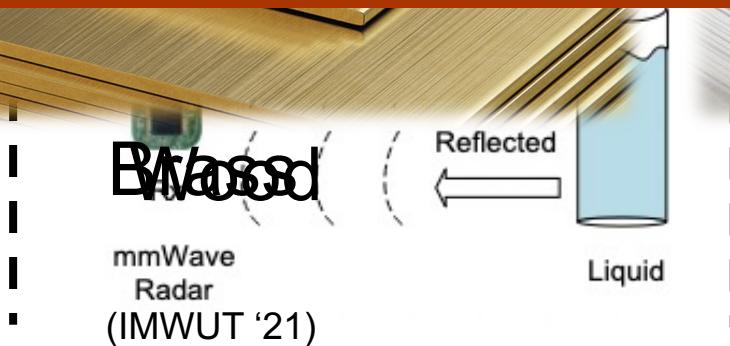
Reflection Based



Reflected power is not enough!



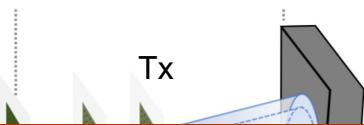
(MobiCom '17)



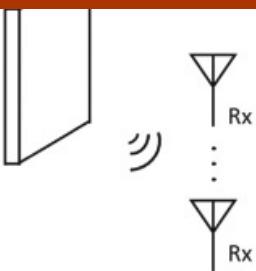
# Material sensing solutions...

Wireless Solutions

Reflection Based



Reflected power is not enough!

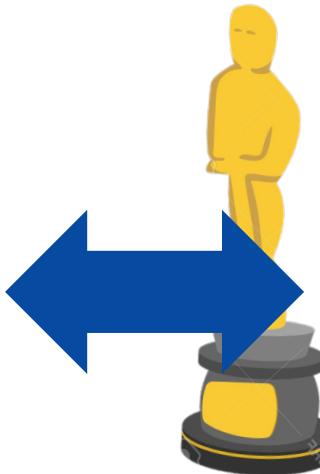
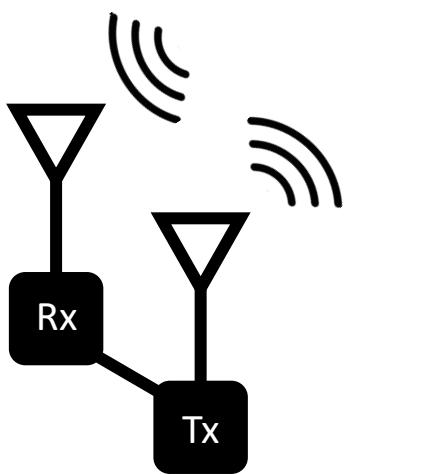


Brass

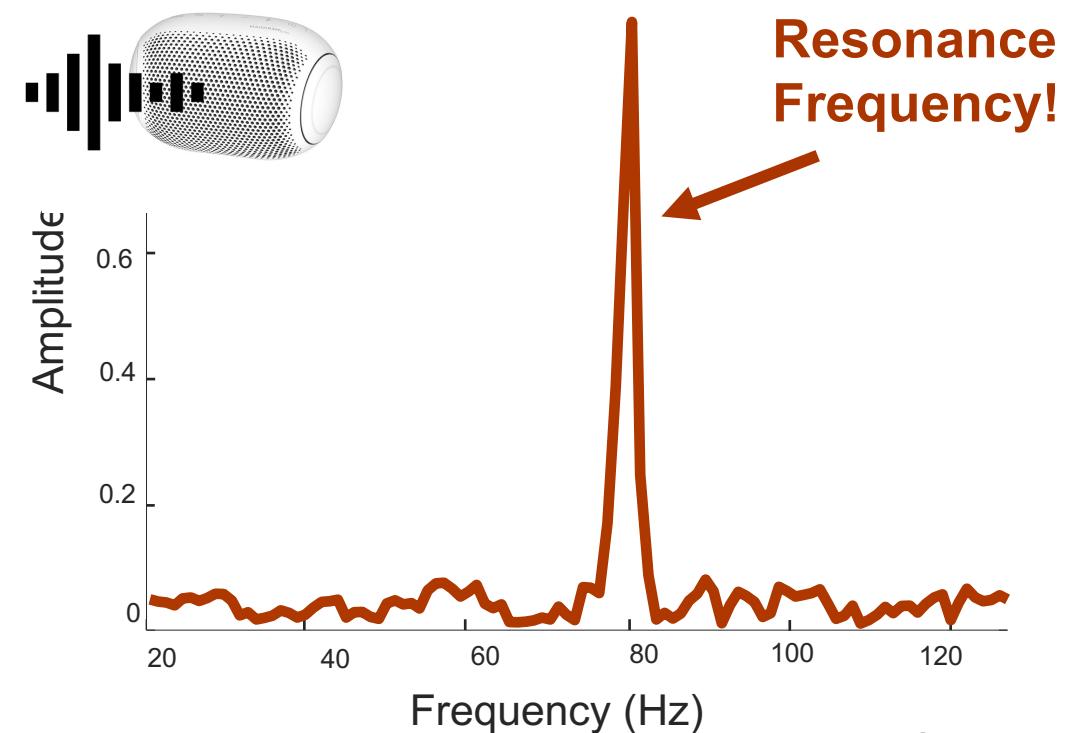


Aluminum

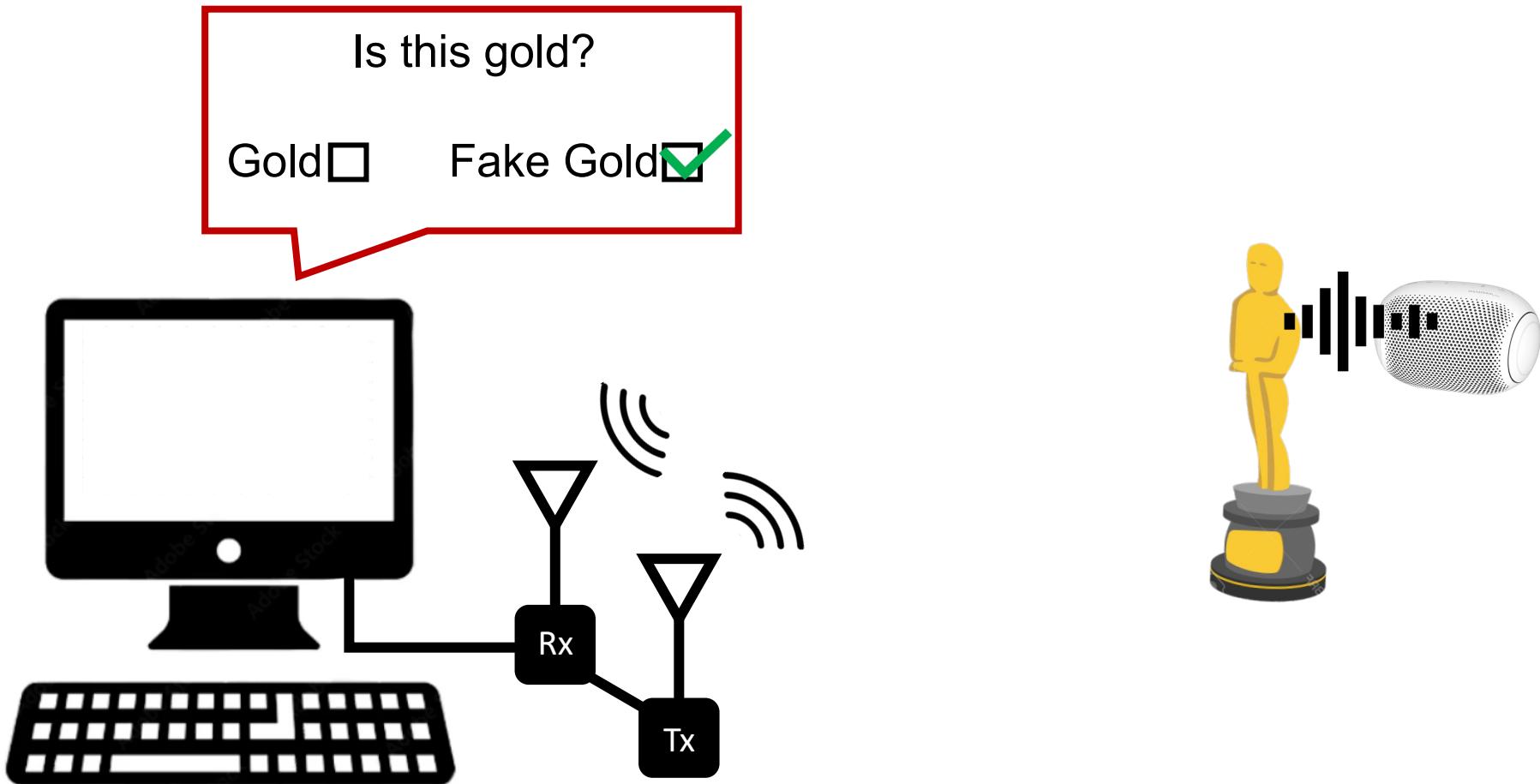
# Combine acoustics and RF!



Visible Vibration Frequencies

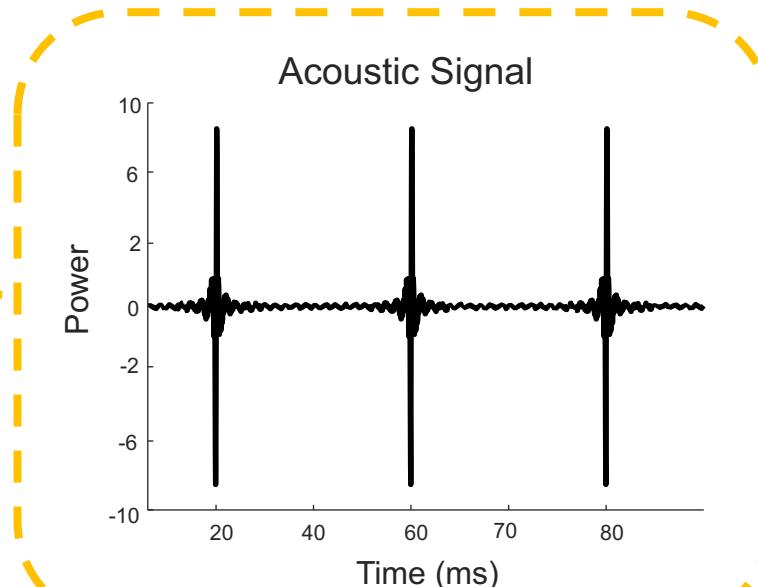
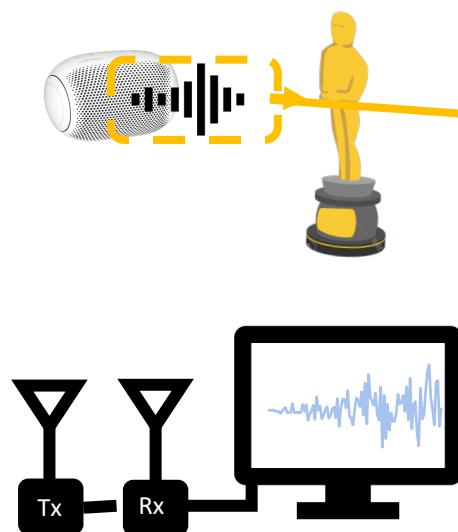


# We present RFVibe...



# Challenges

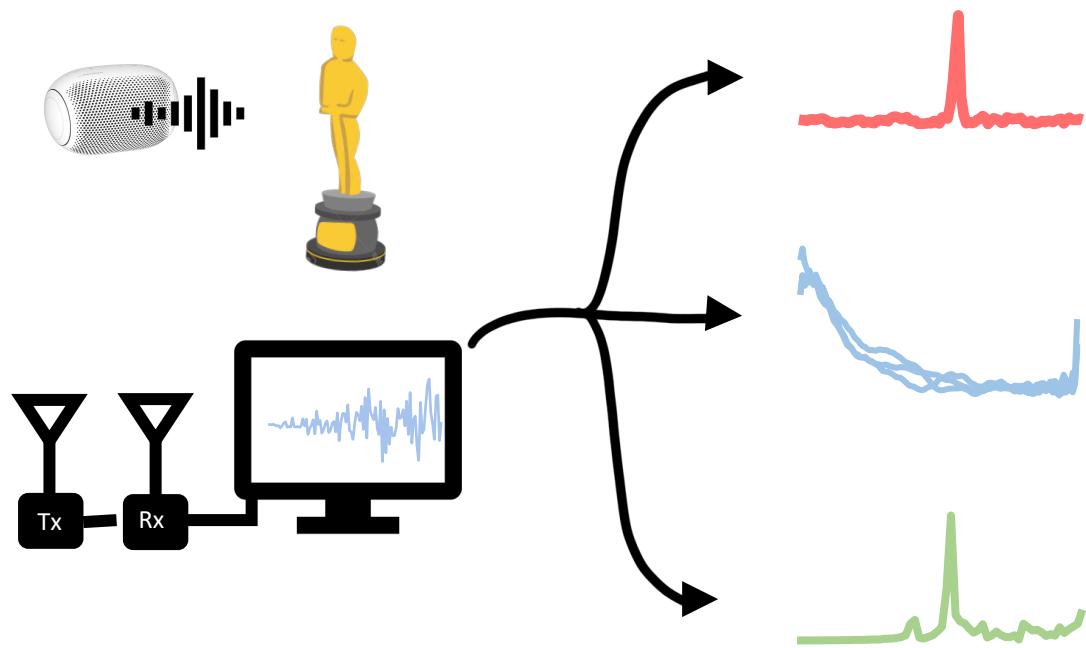
## 1. What acoustic source to extract vibrations?



# Challenges

1. What acoustic source to extract vibrations?

2. How to process the raw data to get useful information?

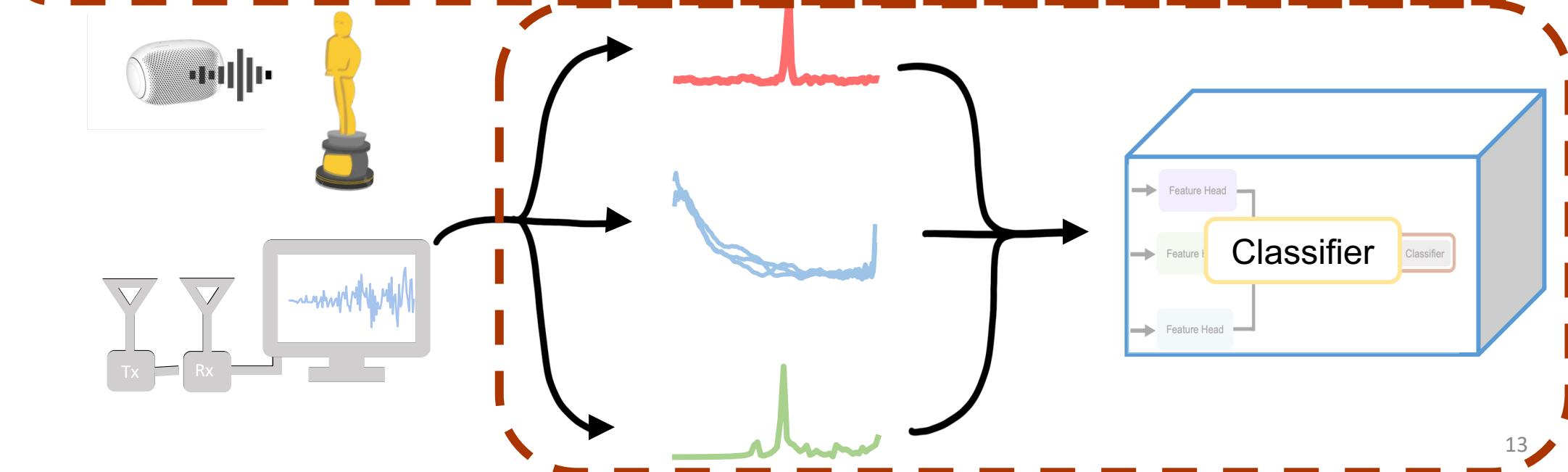


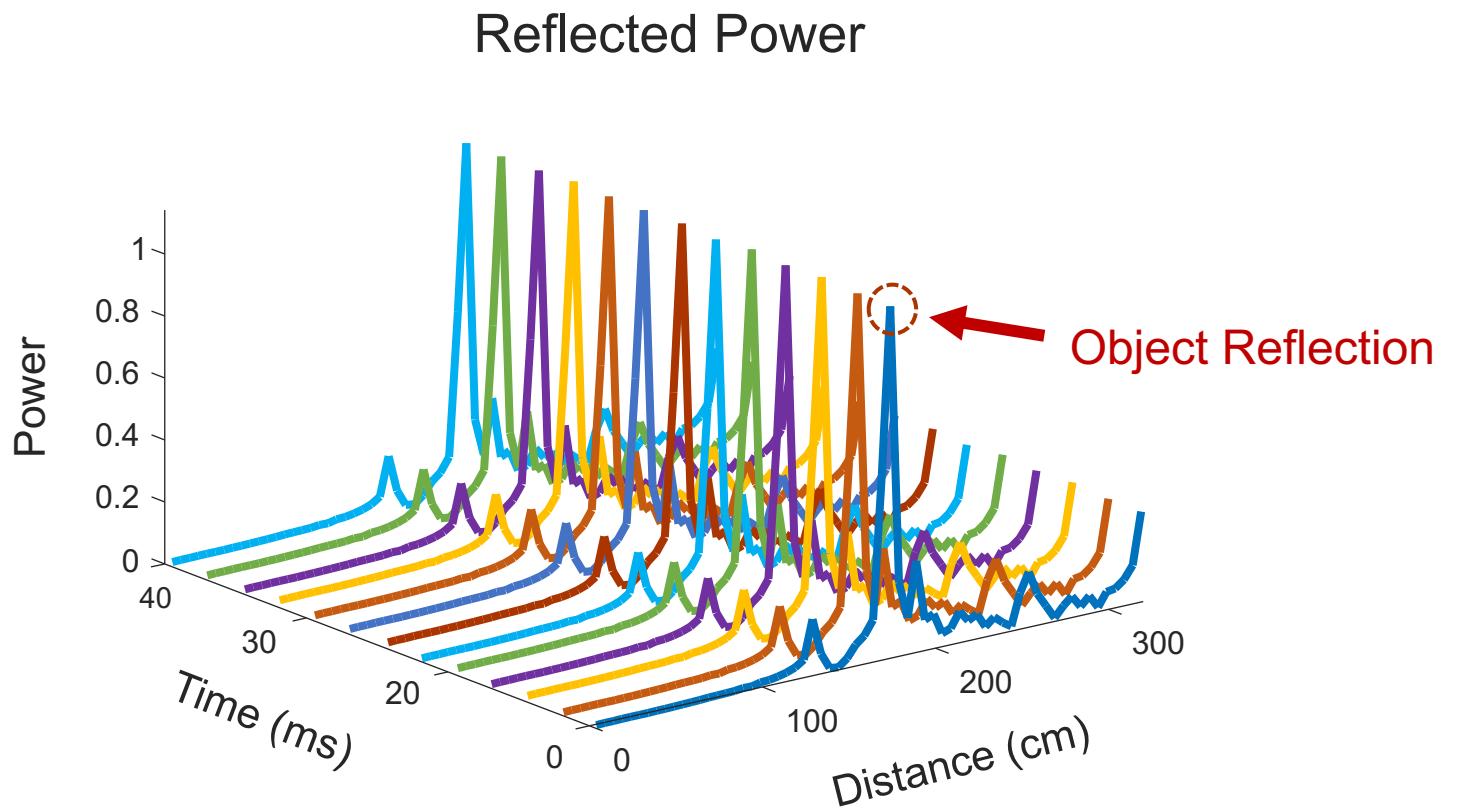
# Challenges

1. What acoustic source to extract vibrations?

2. How to process the raw data to get useful information?

3. How to combine the extracted information for material classification?





coarse-grained      fine-grained

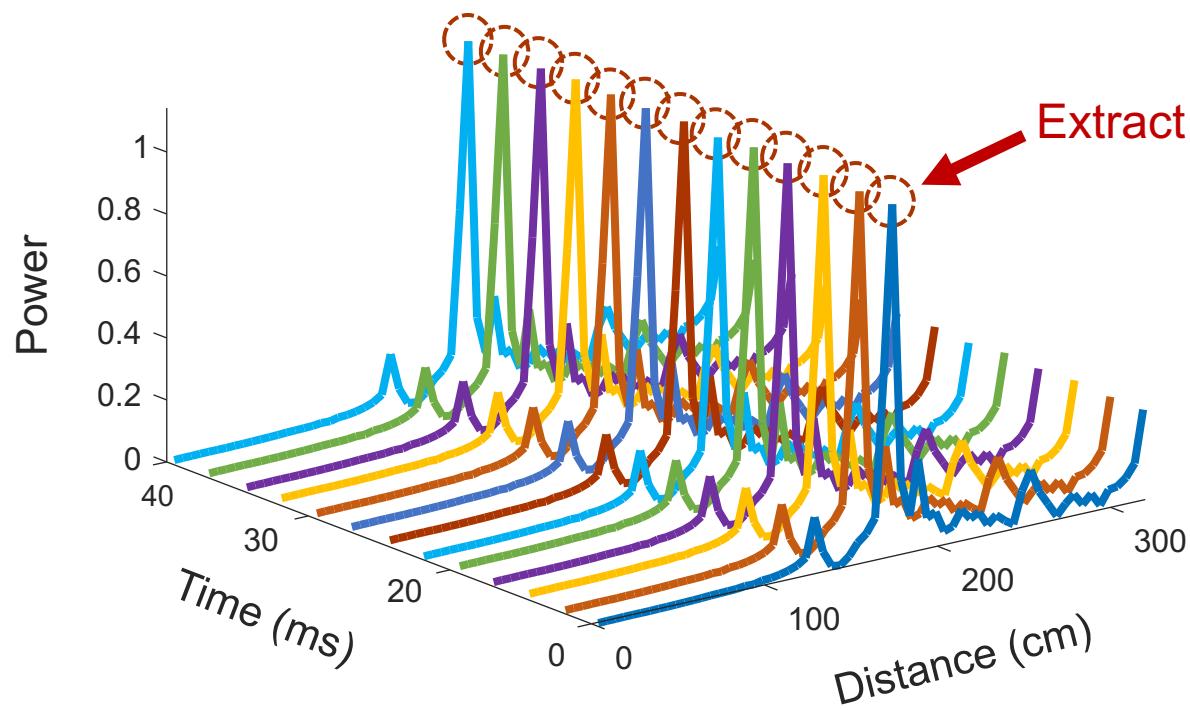
Object reflects  $\rightarrow Ae^\phi$

$$\phi = \frac{2\pi d}{\lambda} \propto d = \text{distance of object}$$

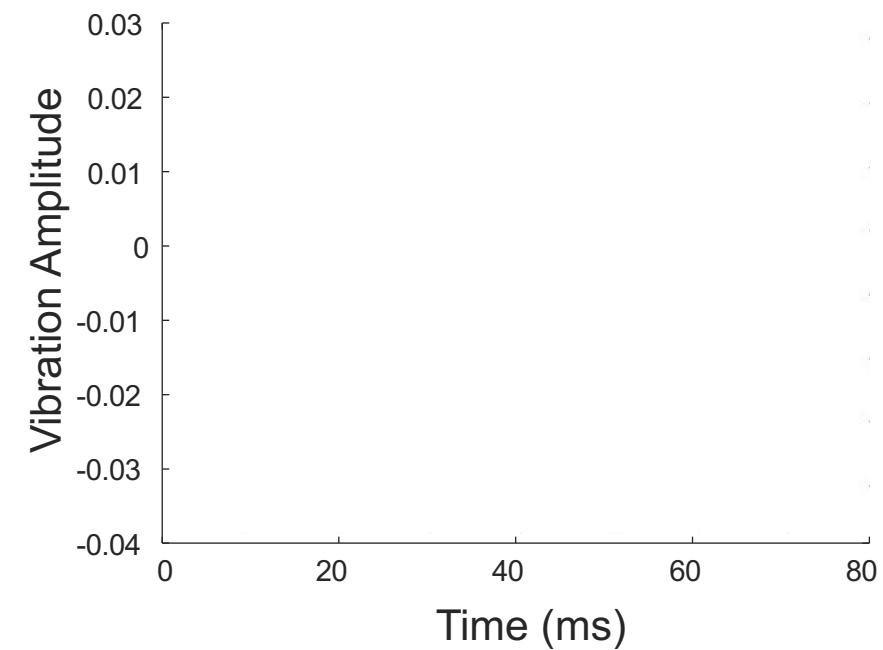
# Vibrations are reflected in the phase!

Object reflects  $\rightarrow Ae^\phi$

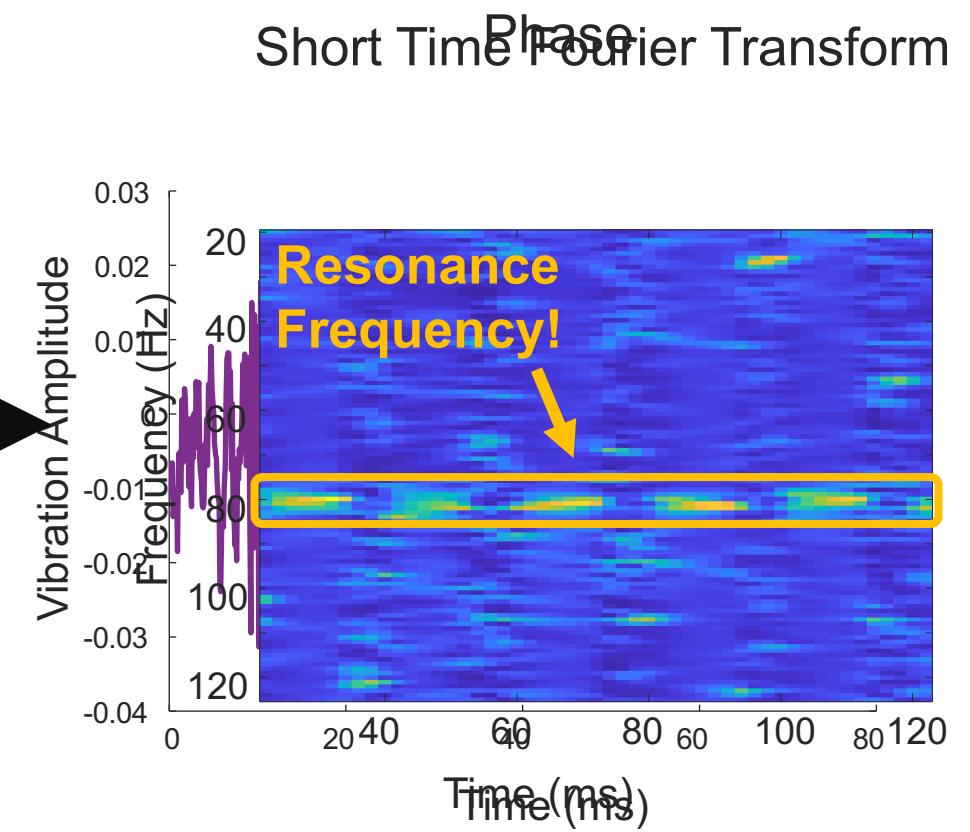
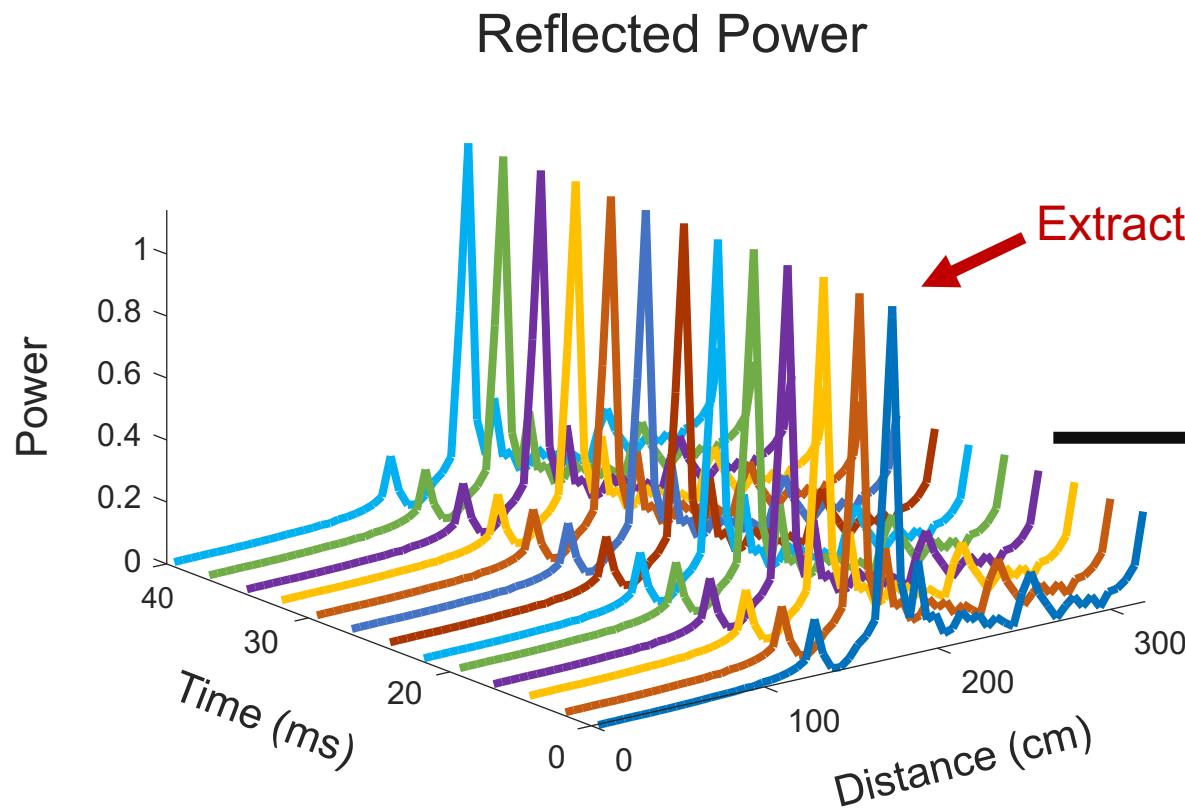
Reflected Power



Phase

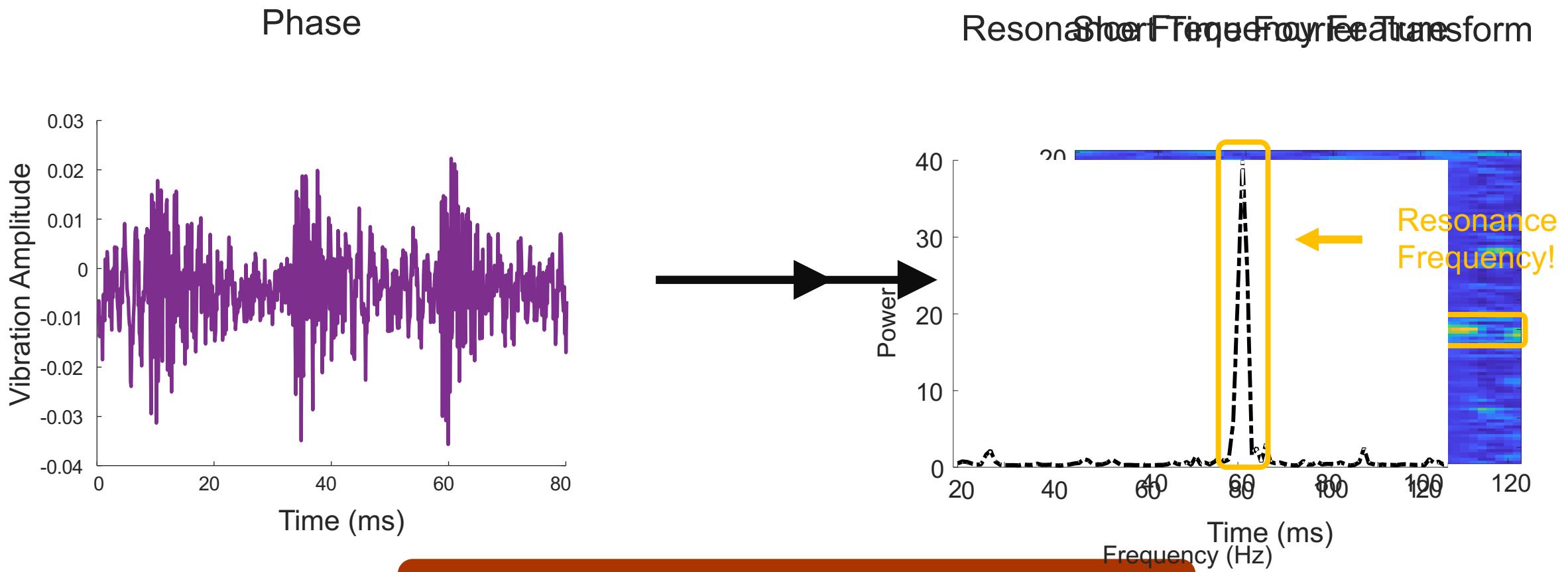


# Feature 1: Resonance Frequency



Visible frequencies are noisy!

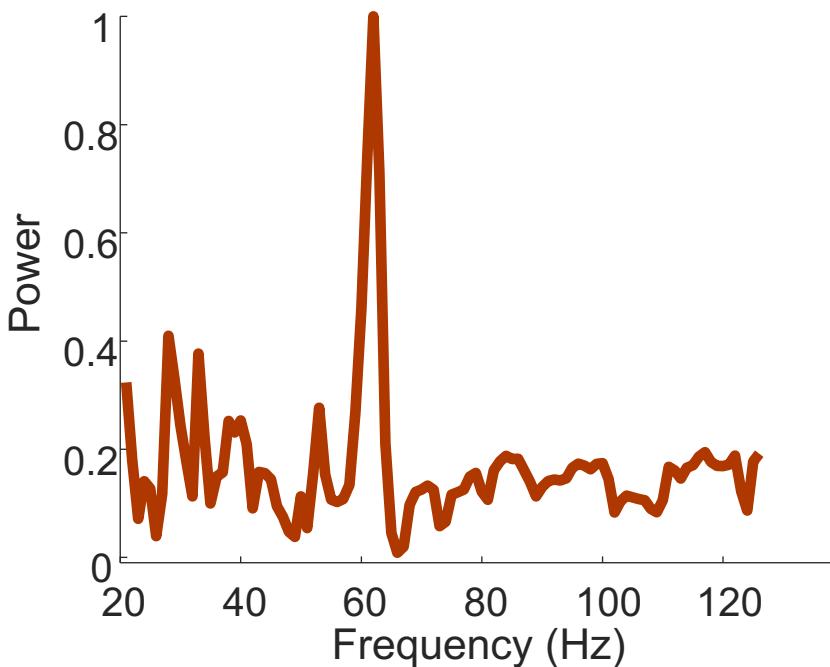
# Feature 1: Resonance Frequency



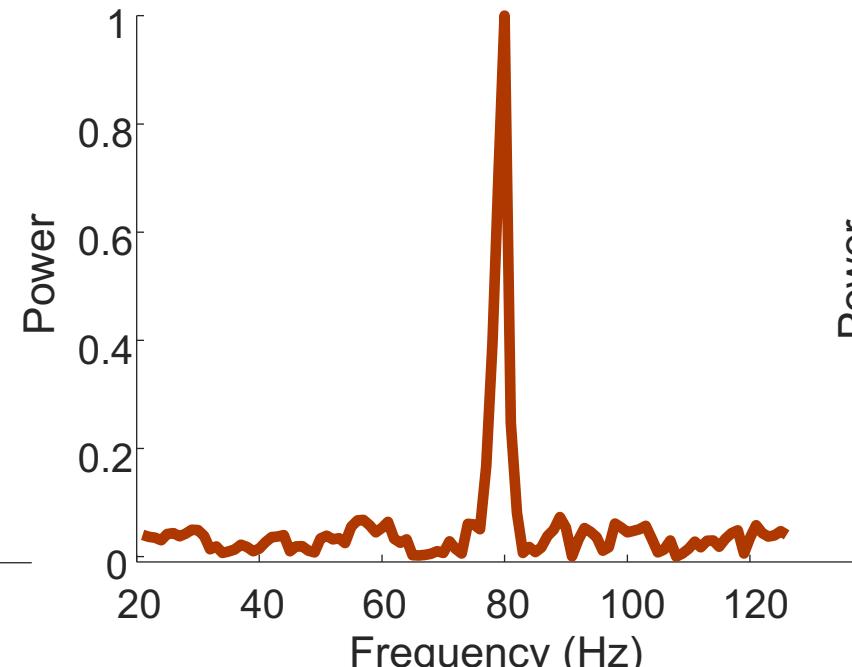
Visible frequencies are noisy!

# Resonance frequency shows up differently in different materials!

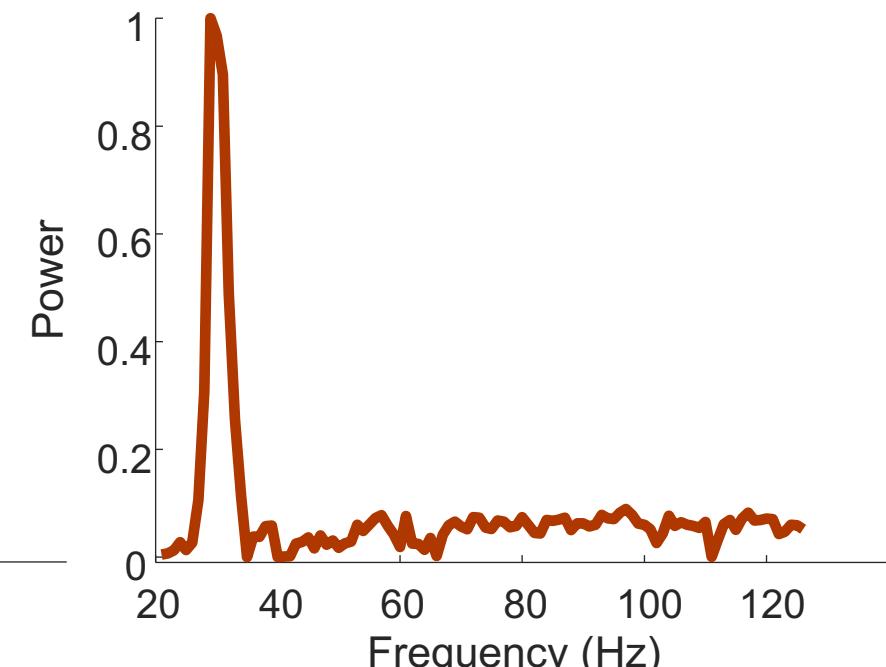
Plastic



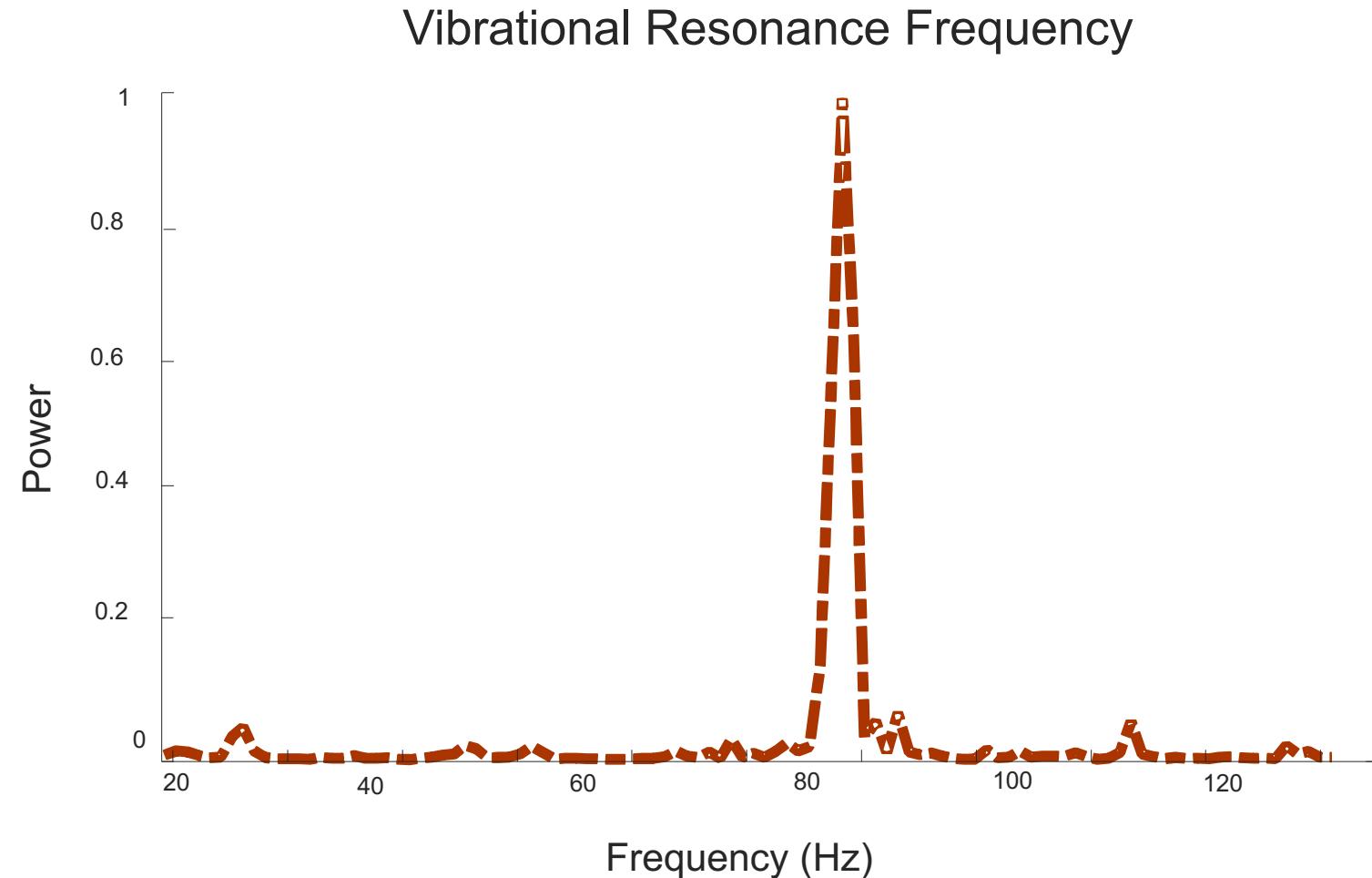
Aluminum



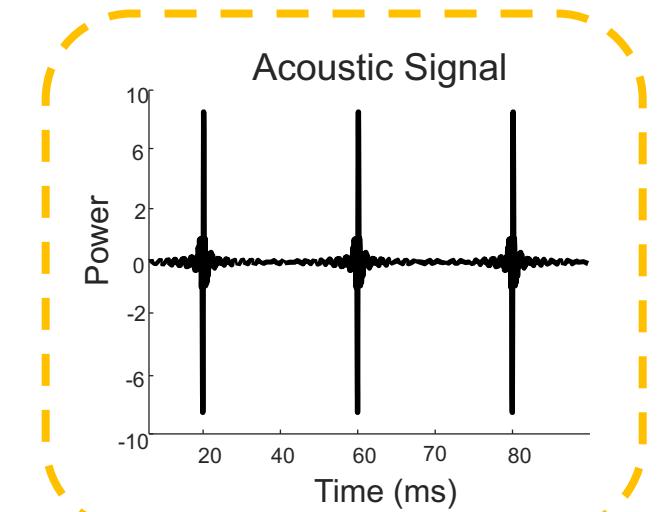
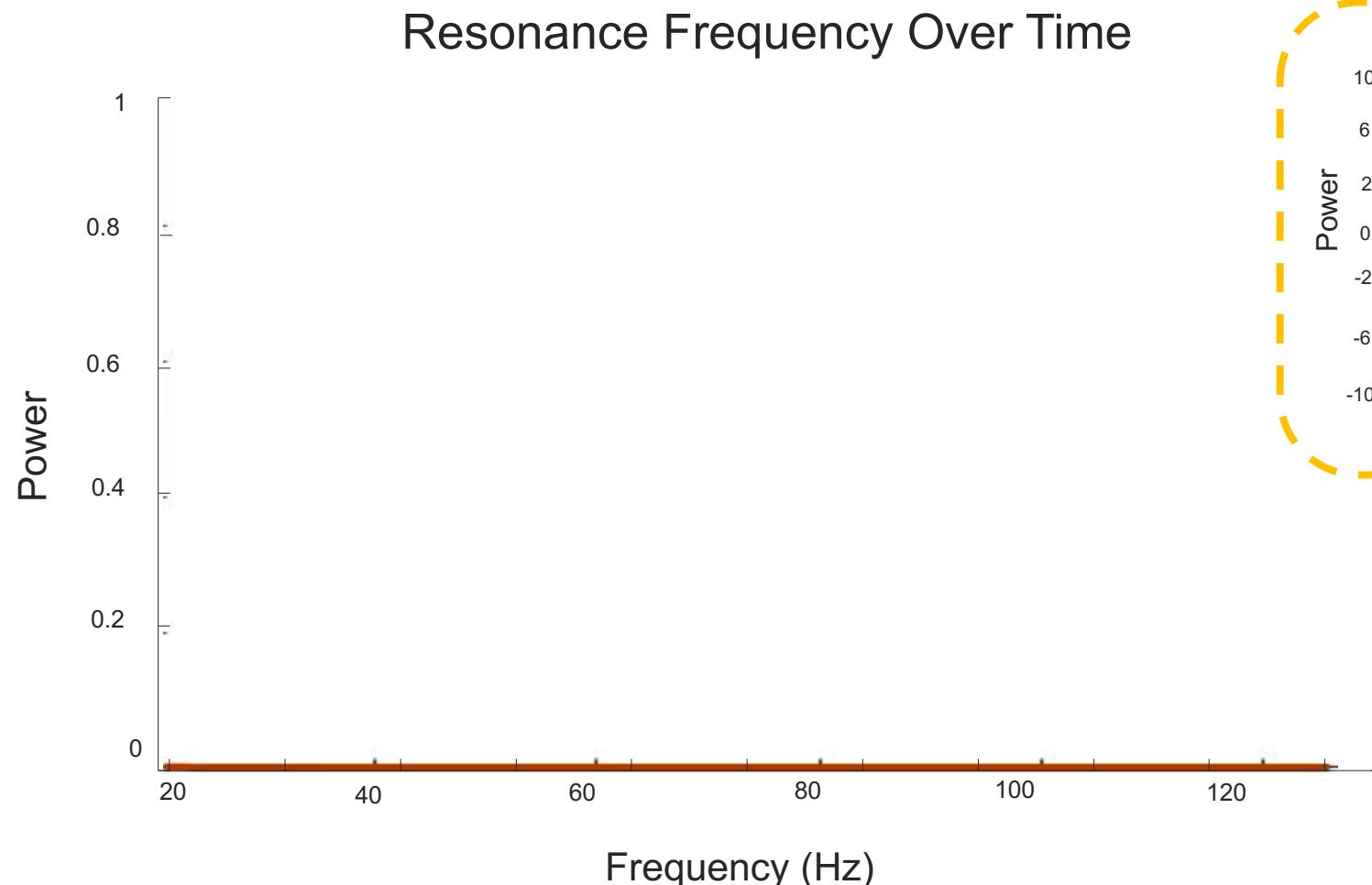
Wood



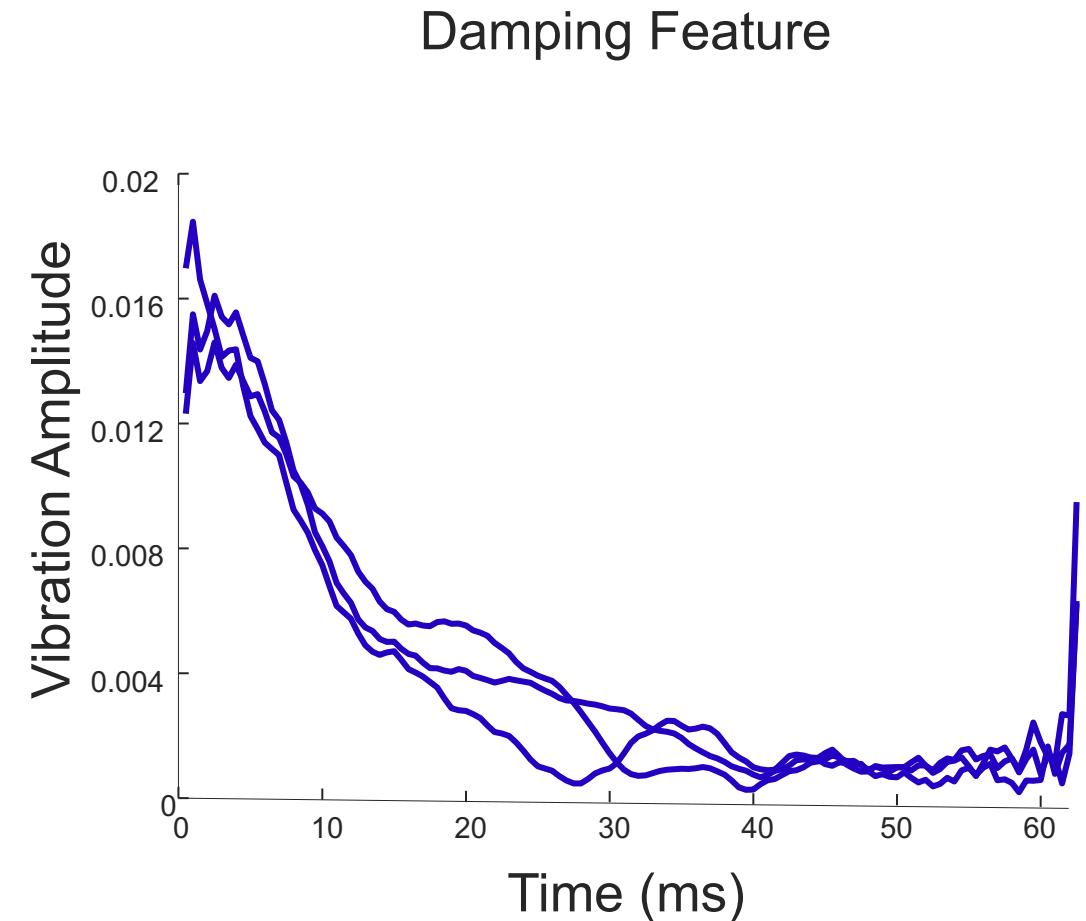
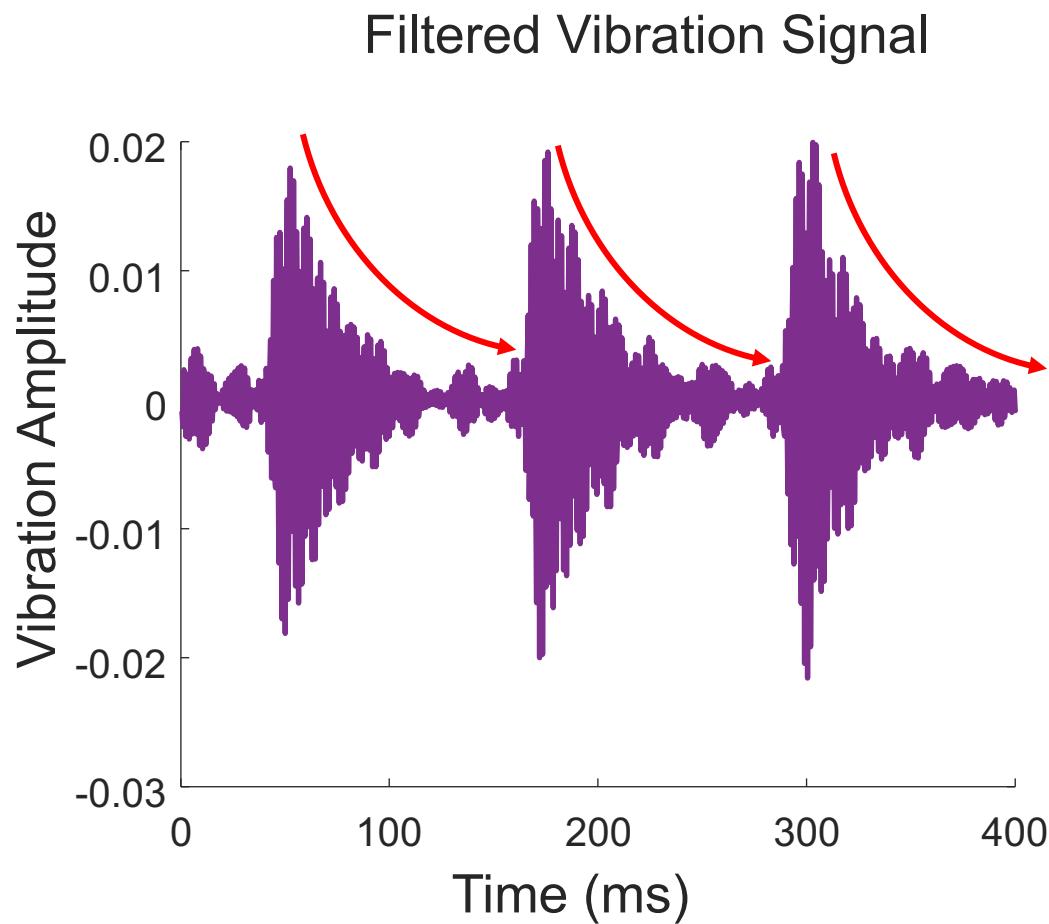
# Resonance frequency shows up differently in different materials!



# Speed of damping can help characterize materials!

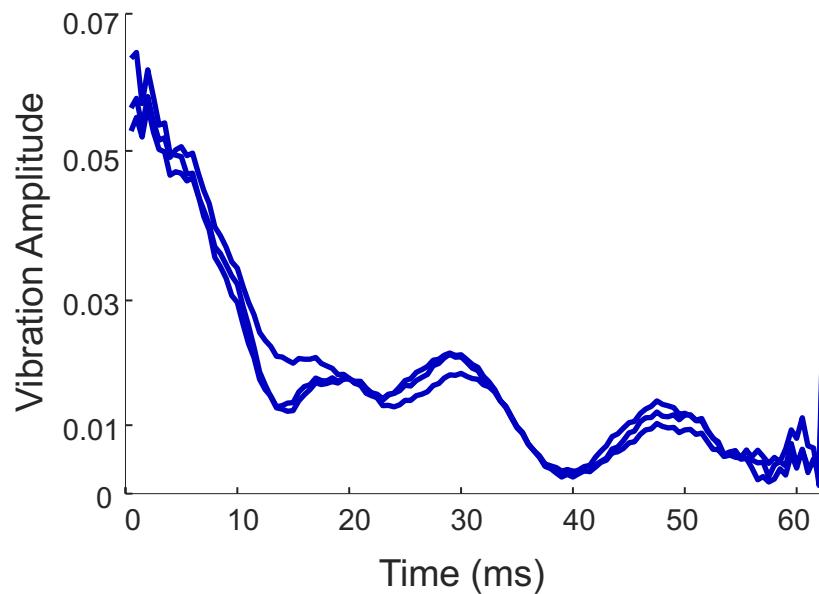


# Feature 2: Damping

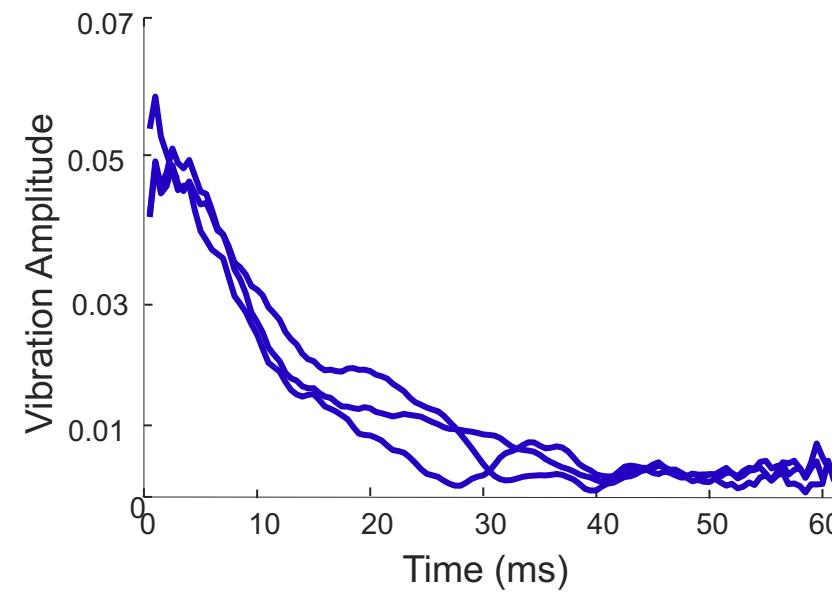


# Damping speeds vary based on material!

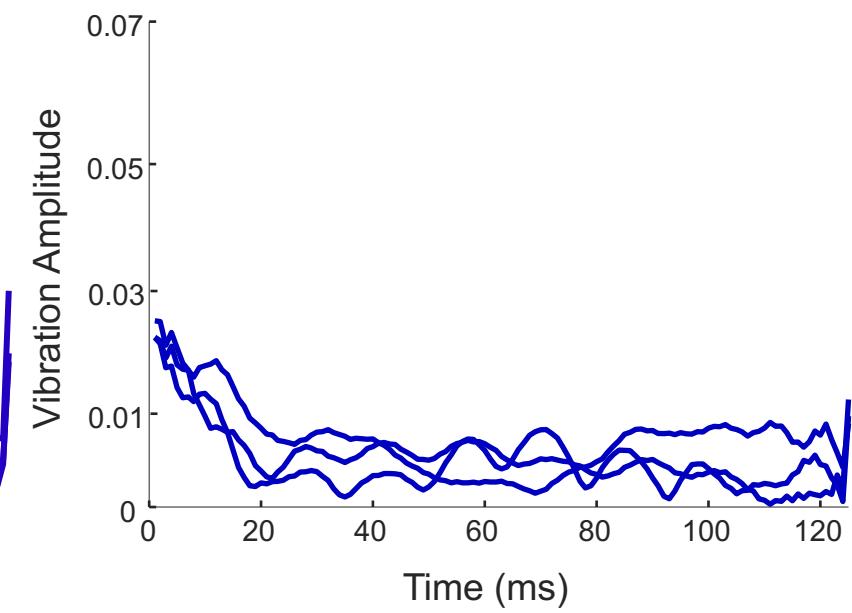
Plastic



Aluminum

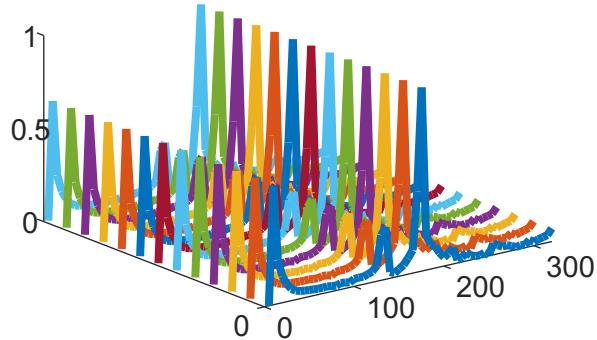


Wood

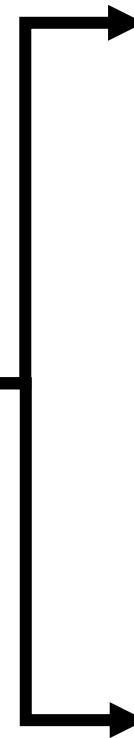


Resonance Frequency

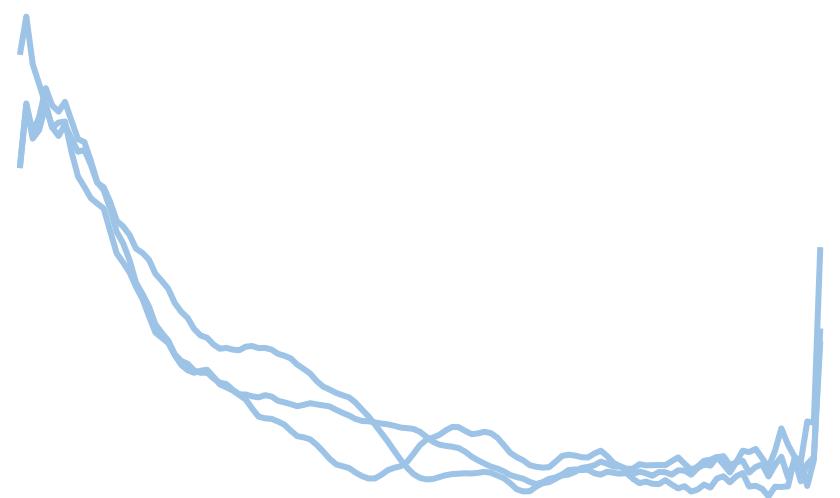
Raw Signal



Extract phase:  $\phi$

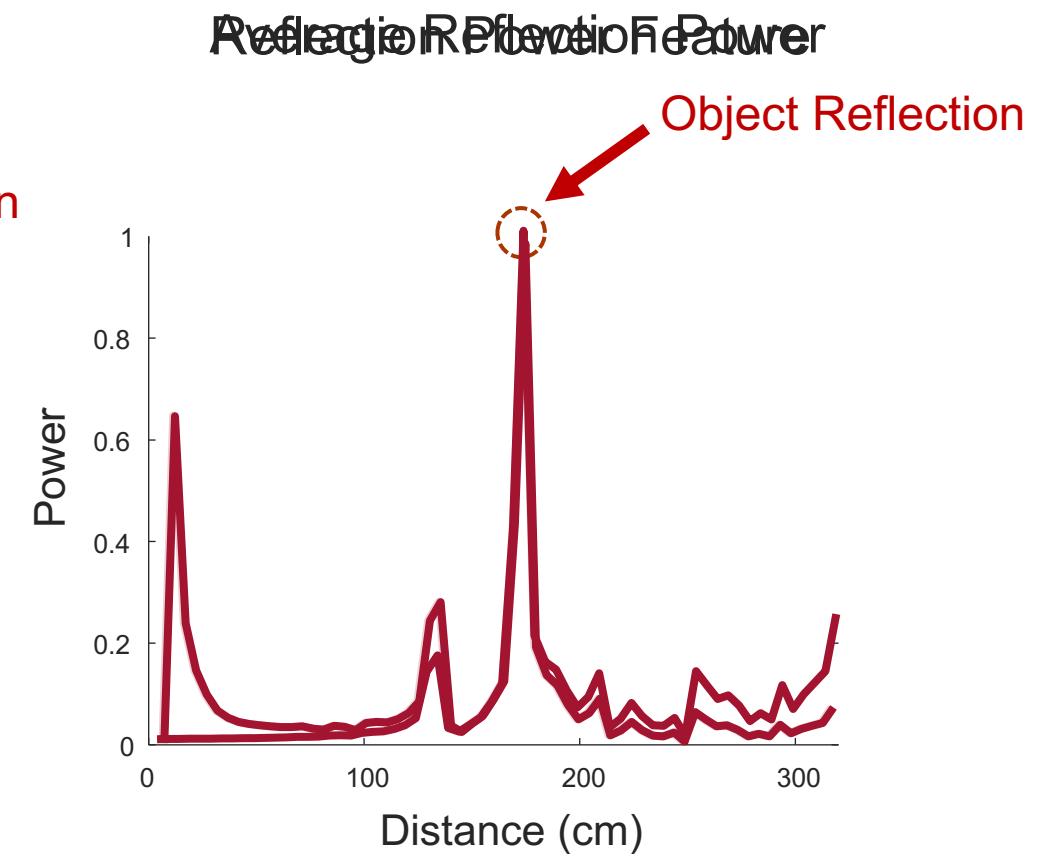
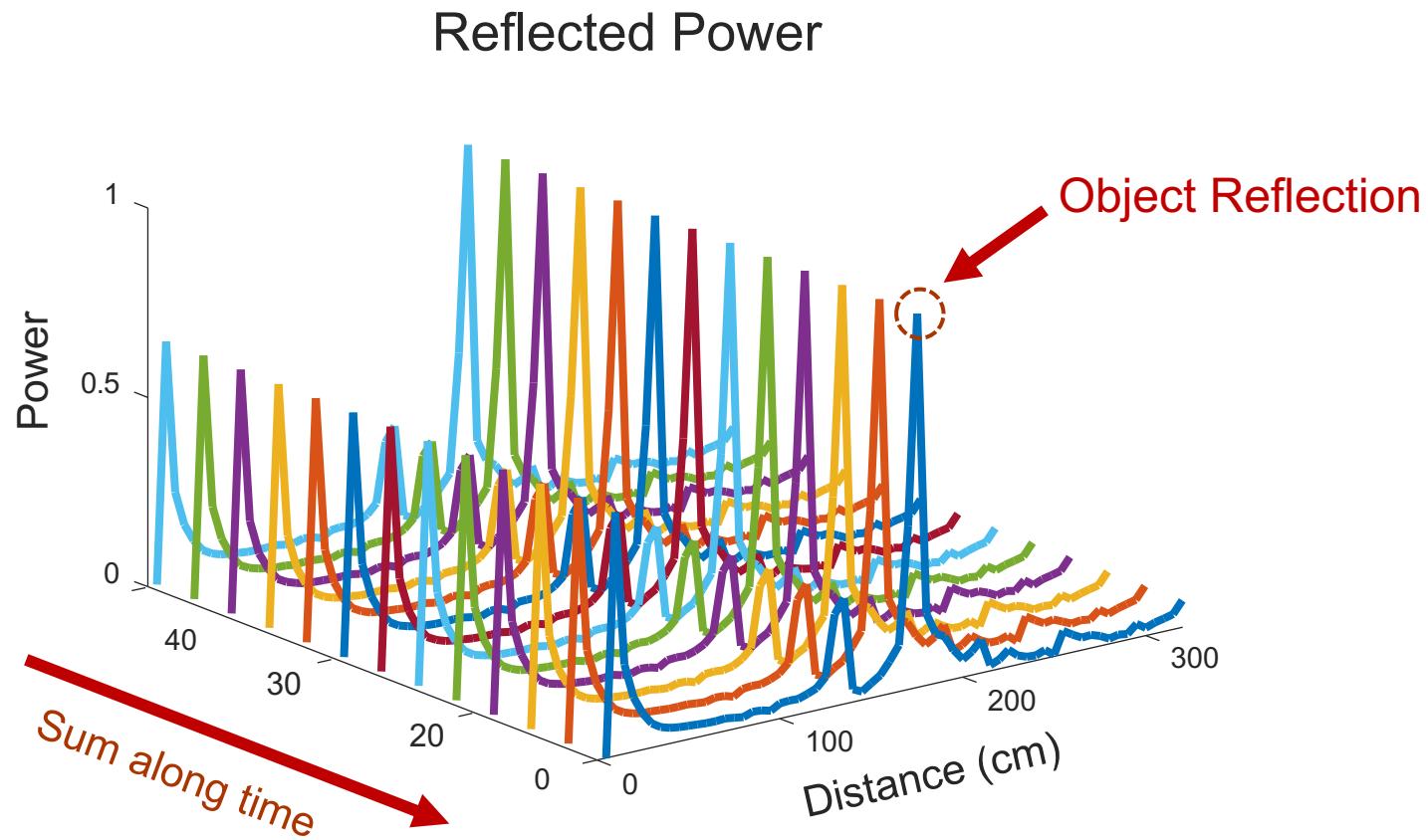


Damping Speed

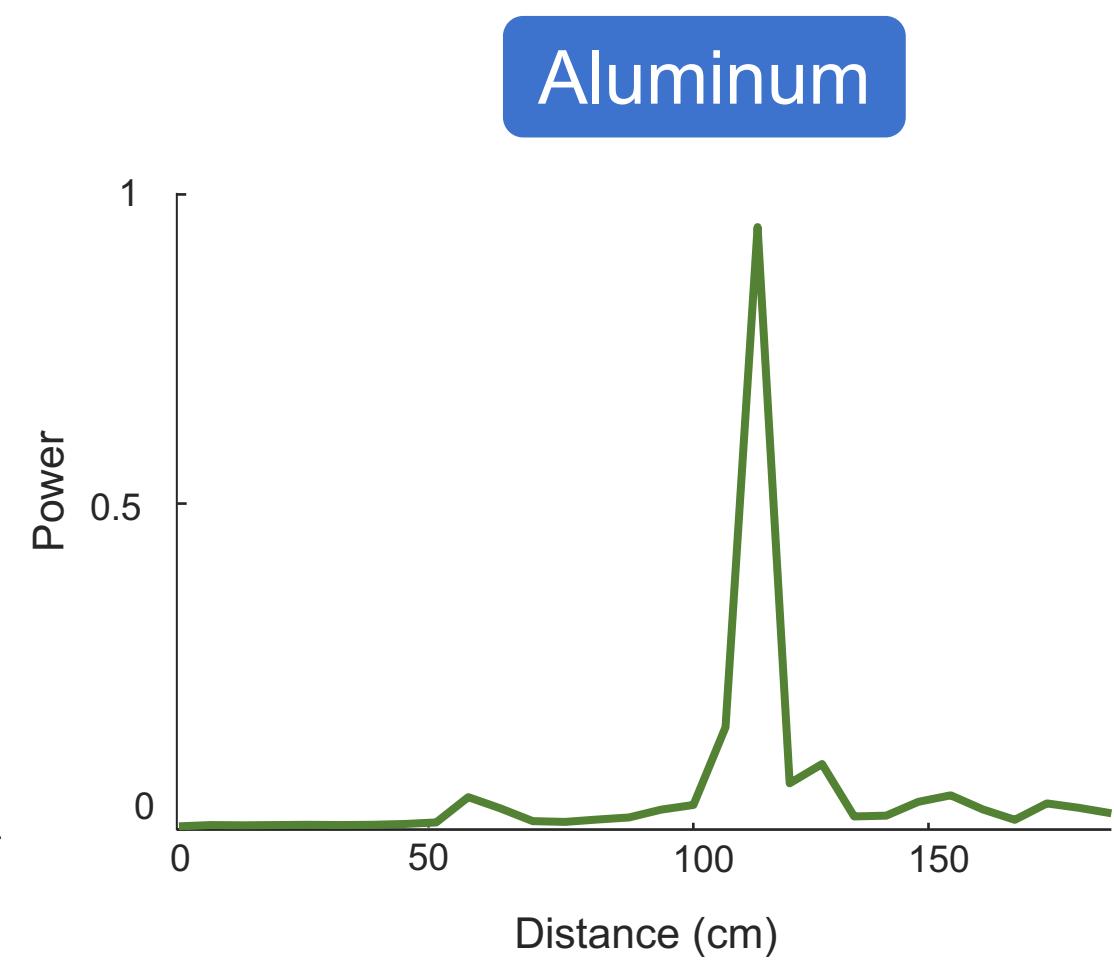
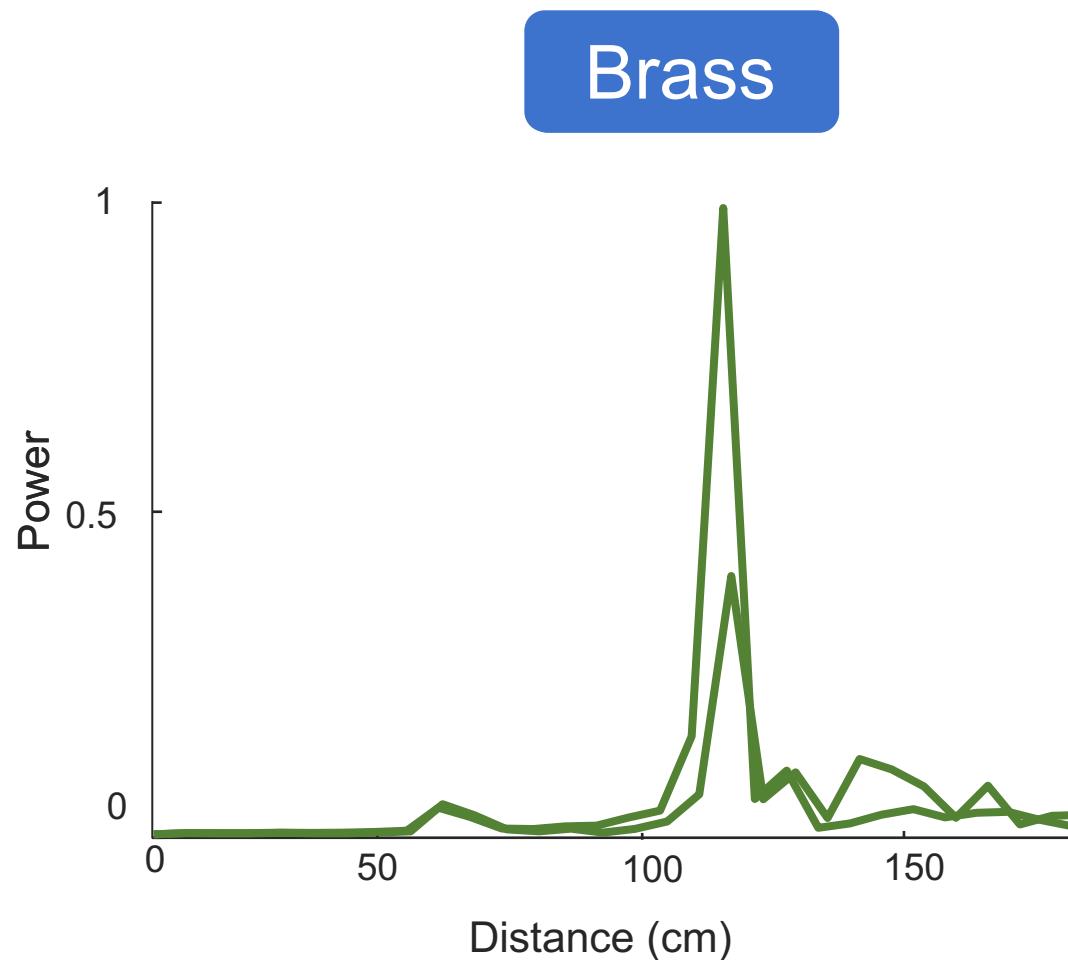


# Feature 3: Reflection Power

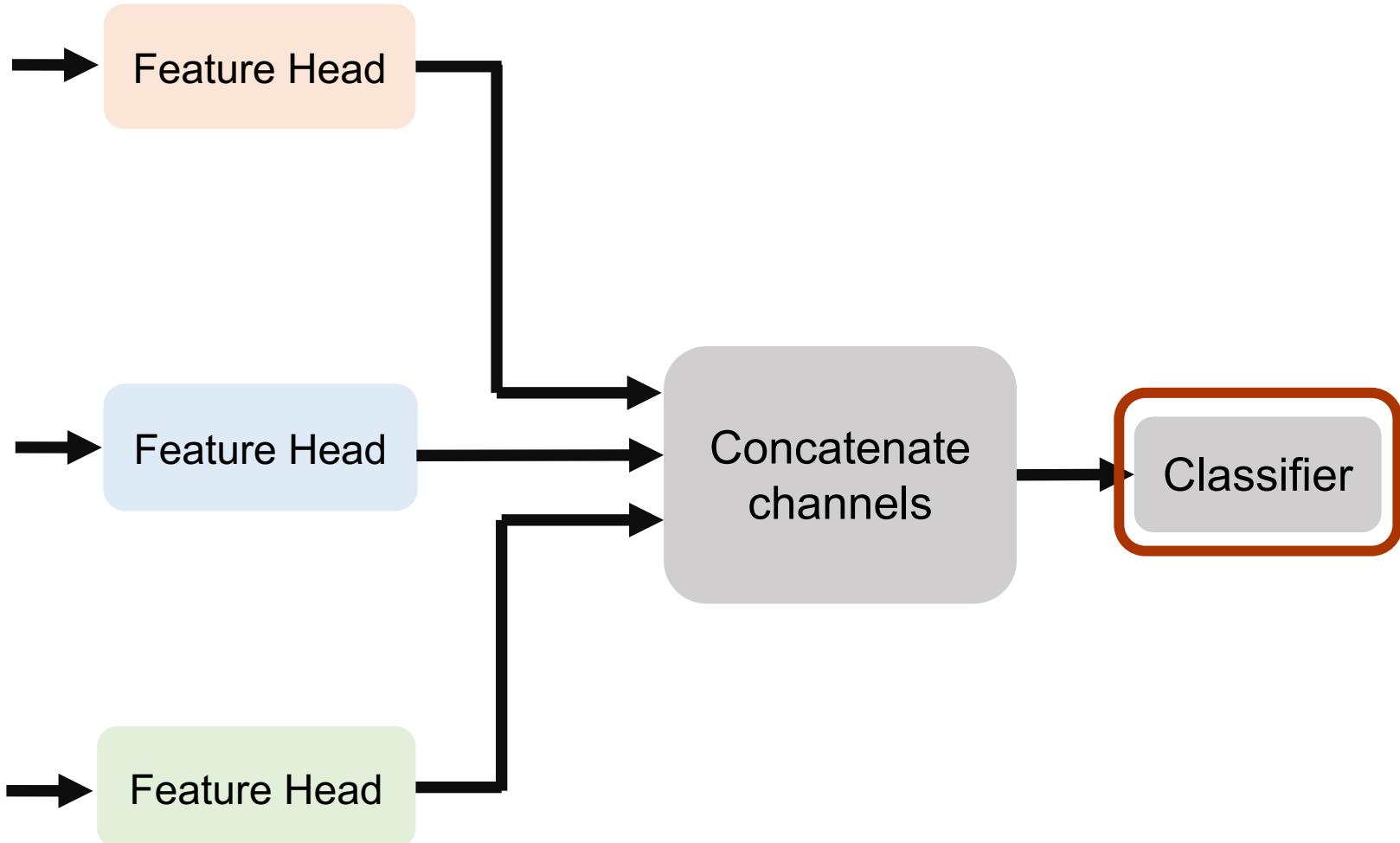
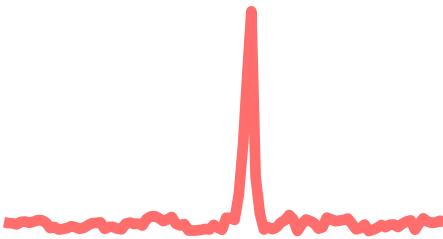
$$\text{Object reflects} \rightarrow Ae^\phi$$

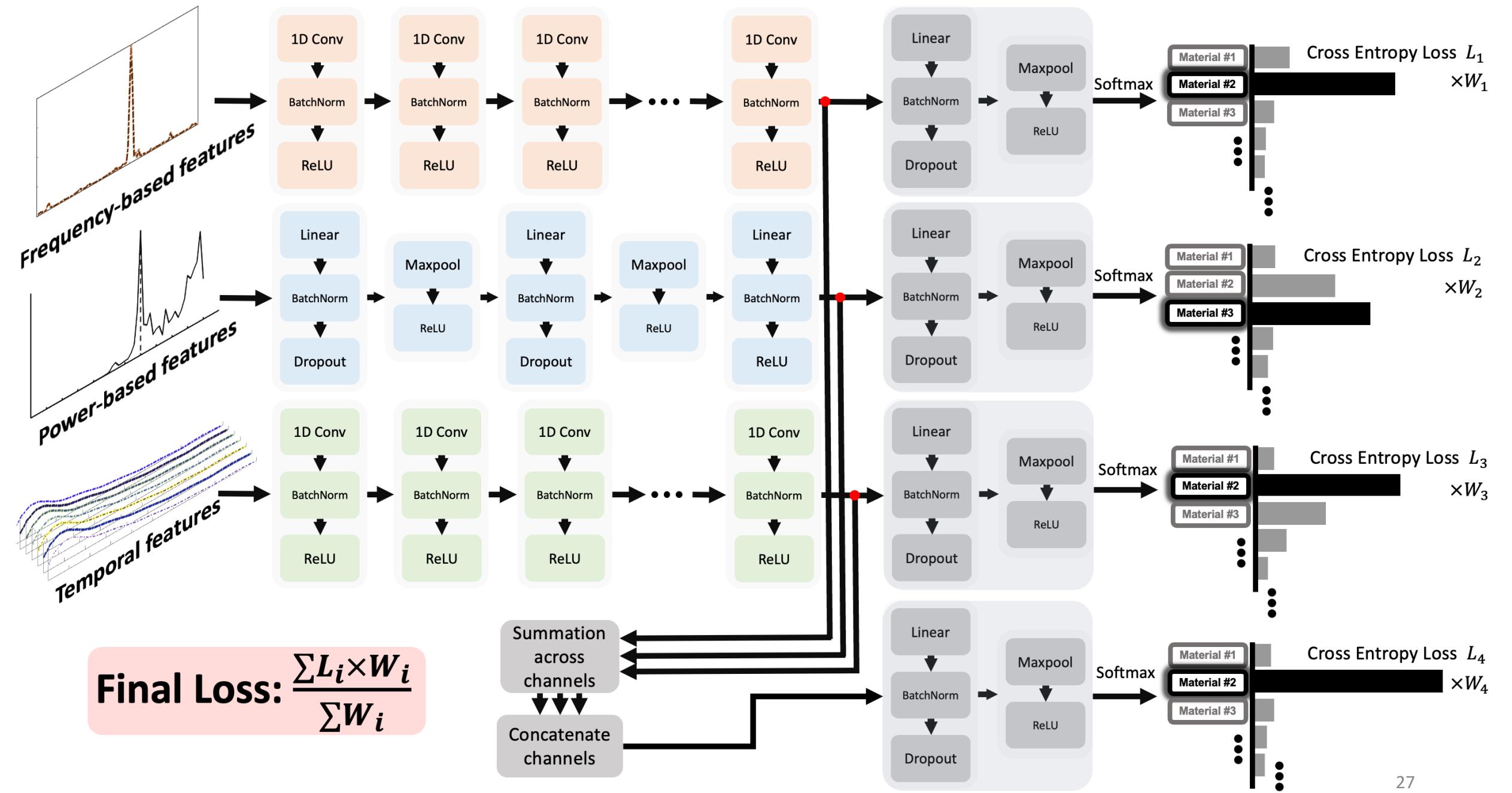


# Reflection powers vary based on material, but is not enough!

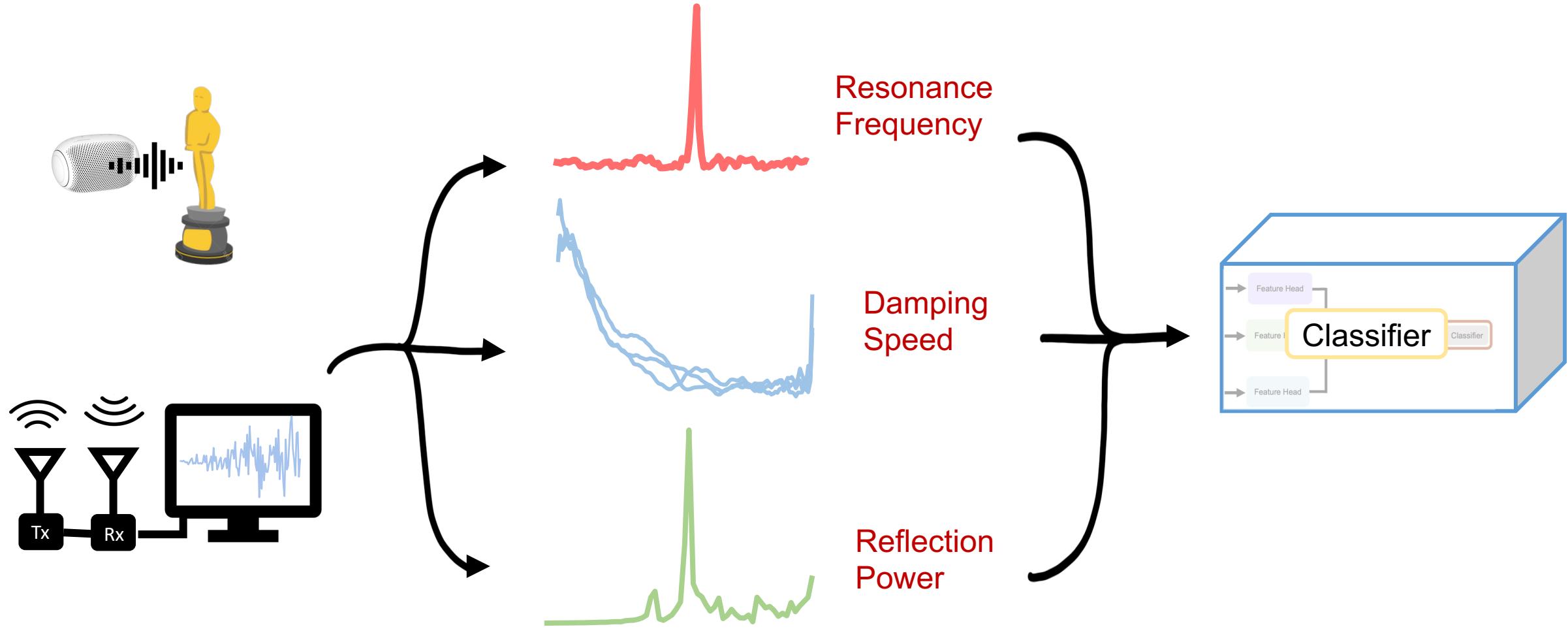


Resonance Frequency



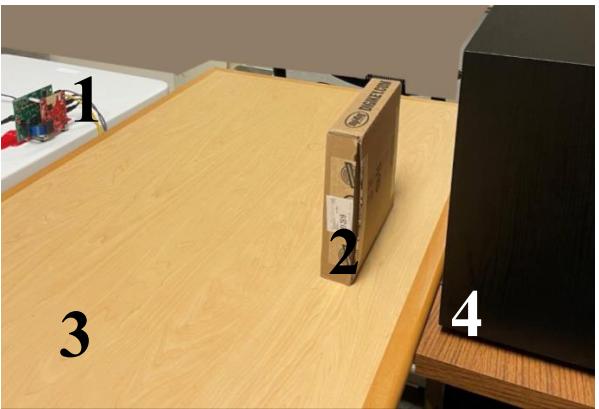


# Putting it all together...

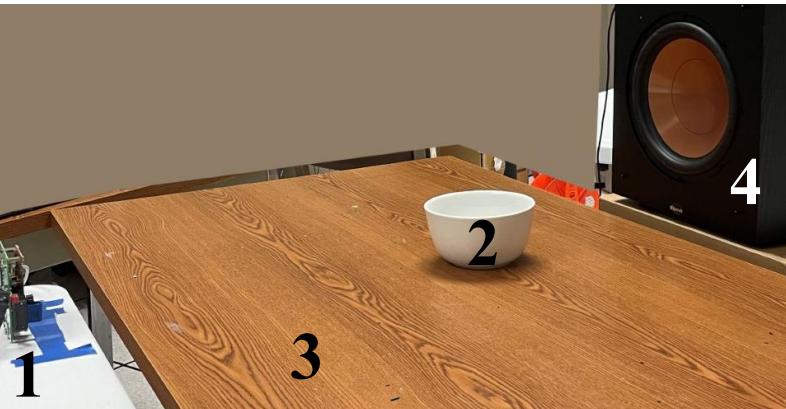


# Experimental Setup

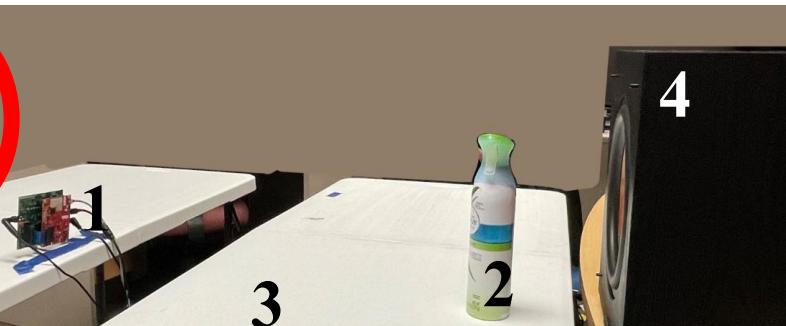
1: Radar



2: Object of Interest

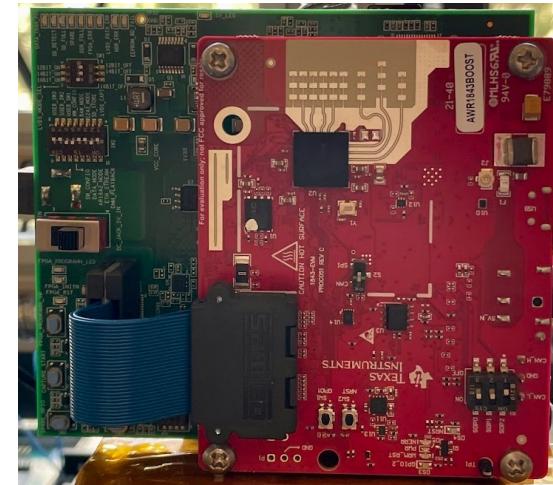


3: Base Table



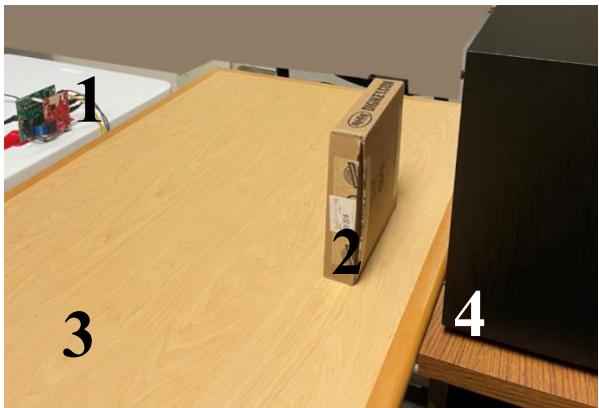
4: Speaker

TI's AWR1843 Radar

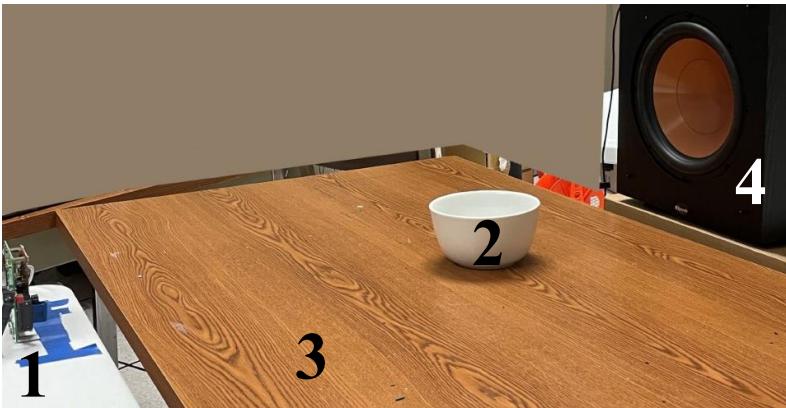


# Experimental Setup

1: Radar



2: Object of Interest



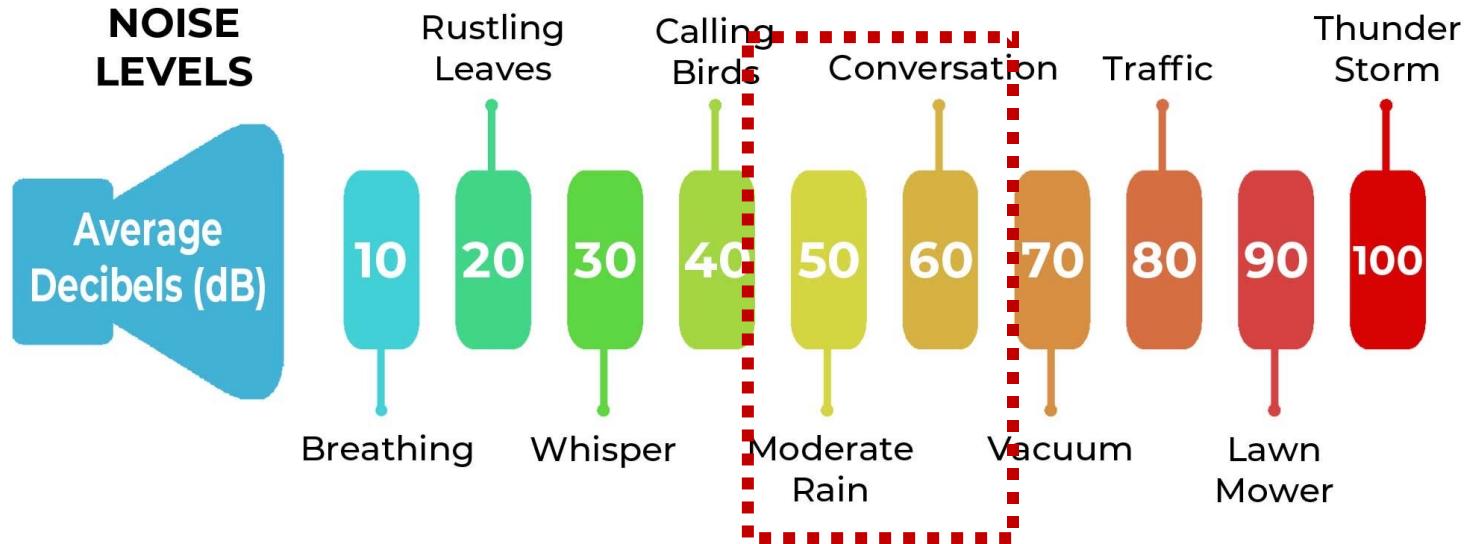
3: Base Table



4: Speaker

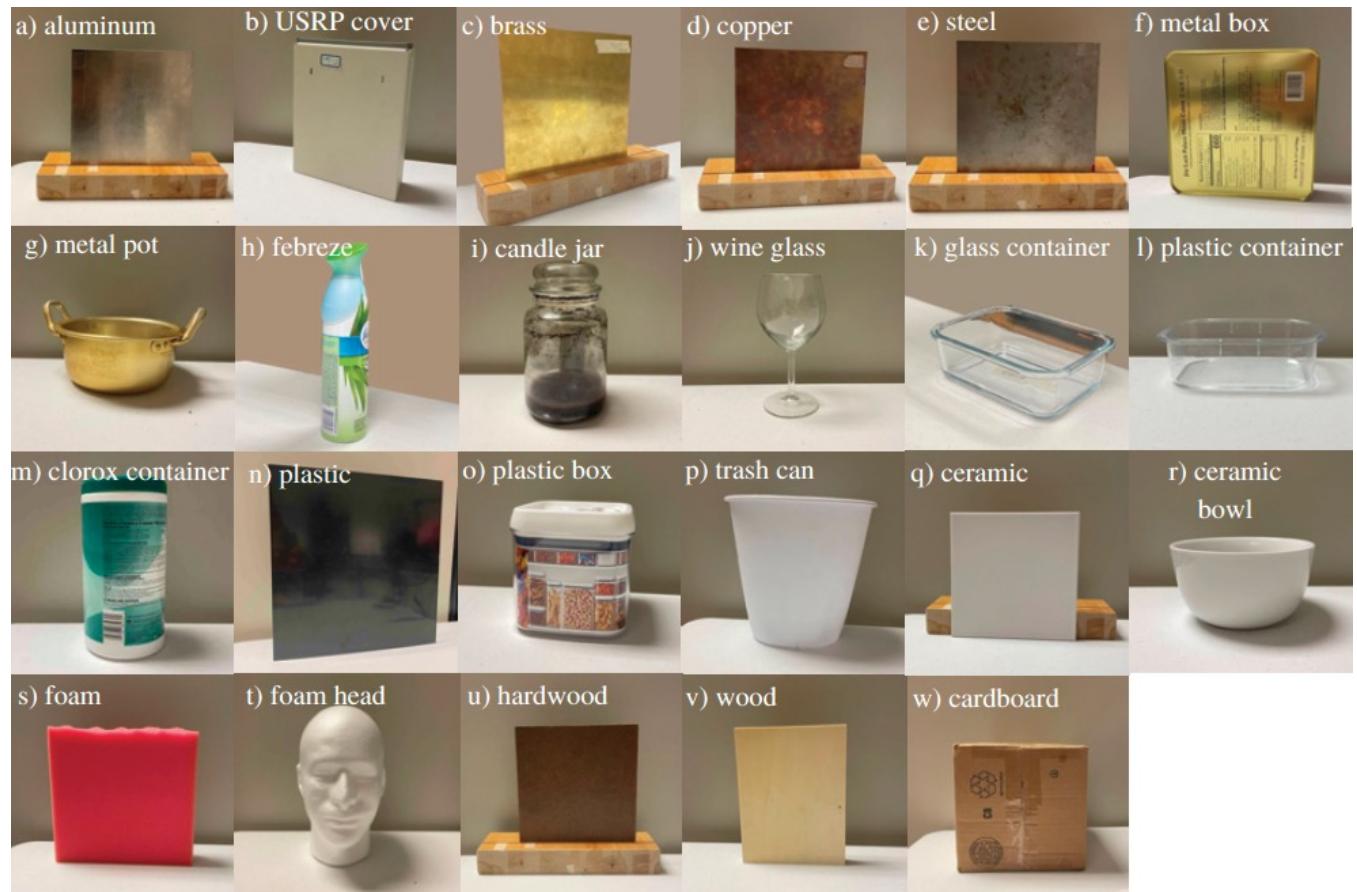


**Power: 58 dB**

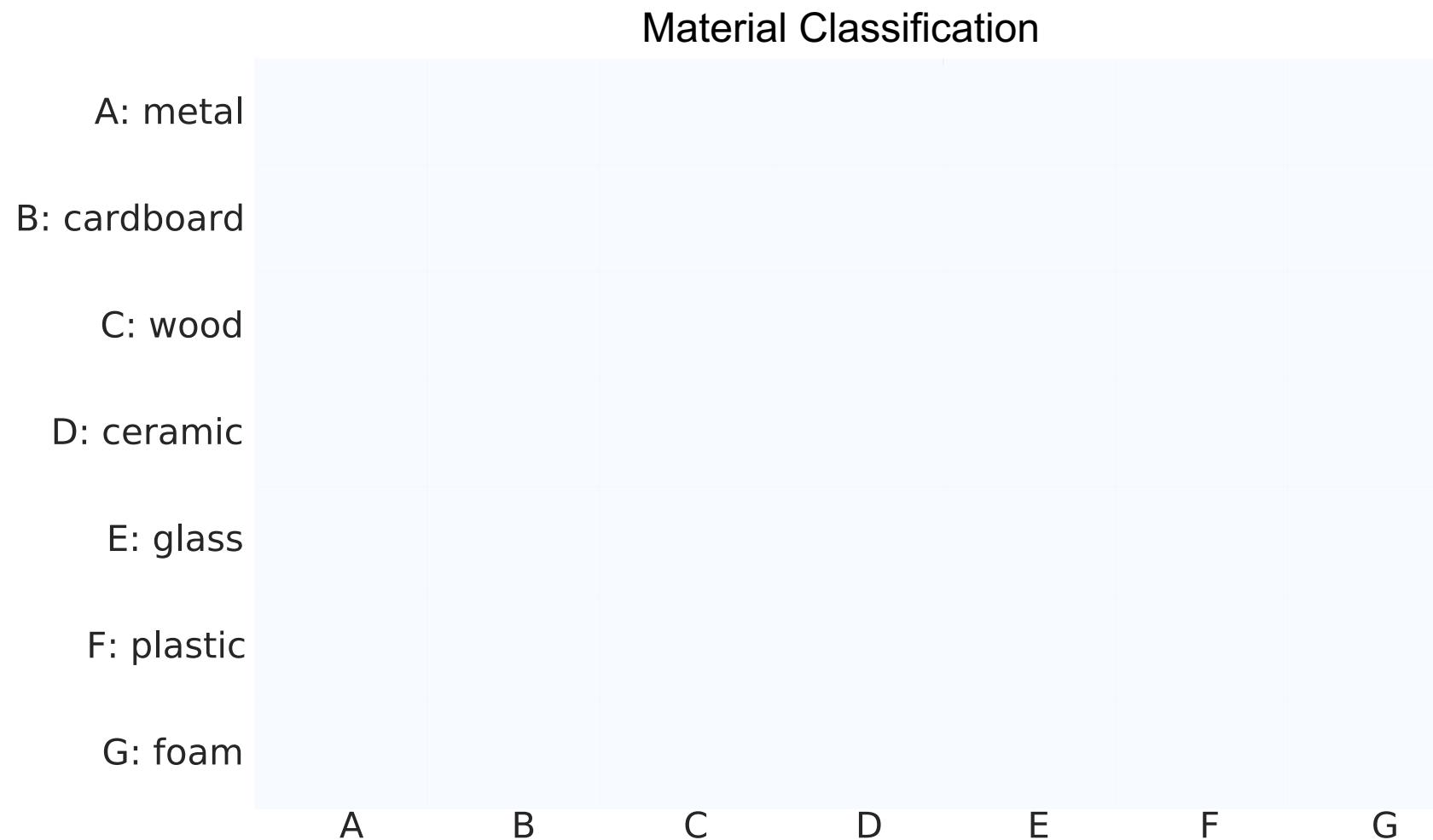


# Evaluation Details

- Experiment Objects:
  - 23 everyday objects, including curved and small objects
  - 7 different materials
- Environment
  - 3 different room: 2 office spaces, 1 lab space

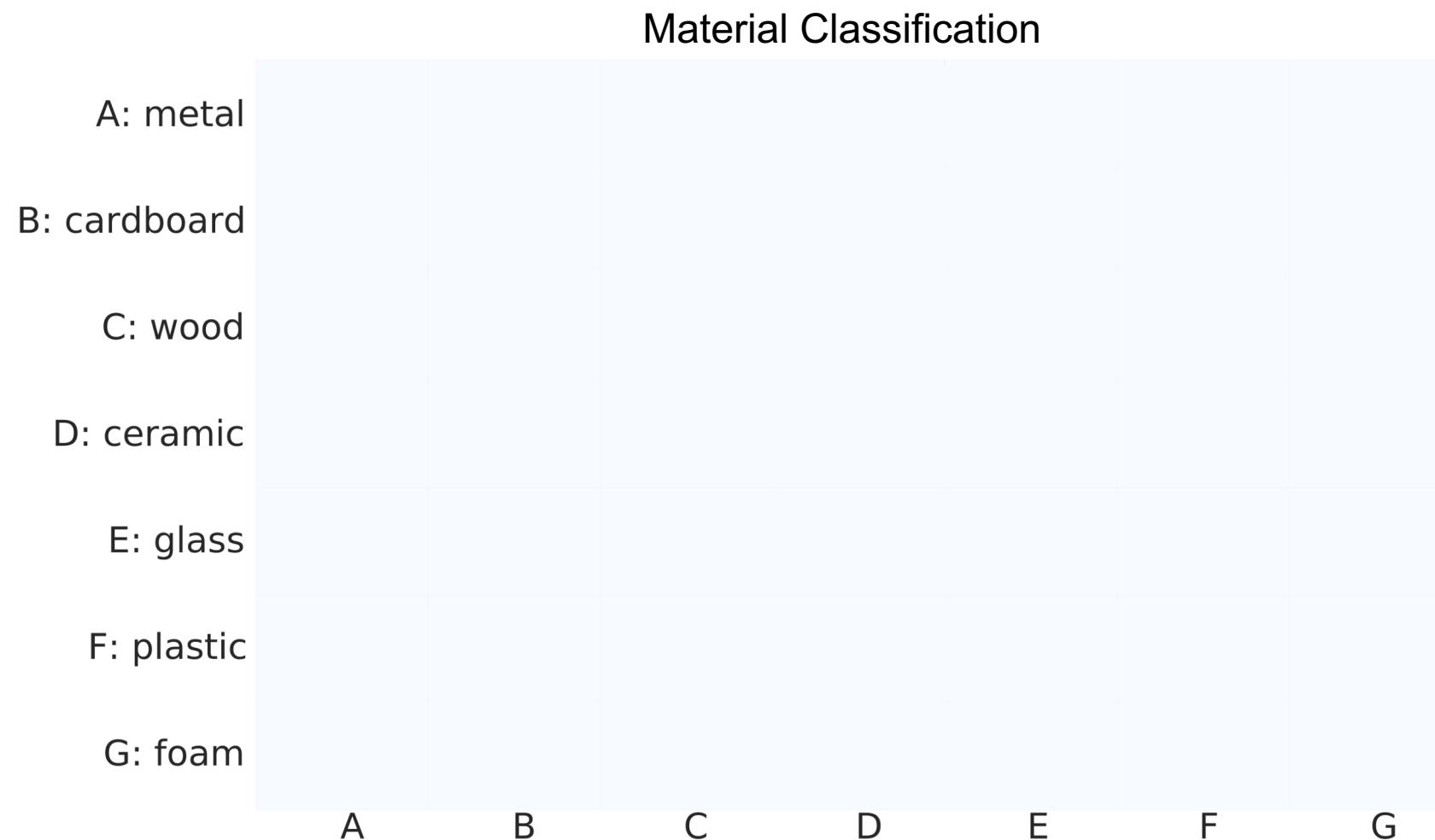


# Main Results



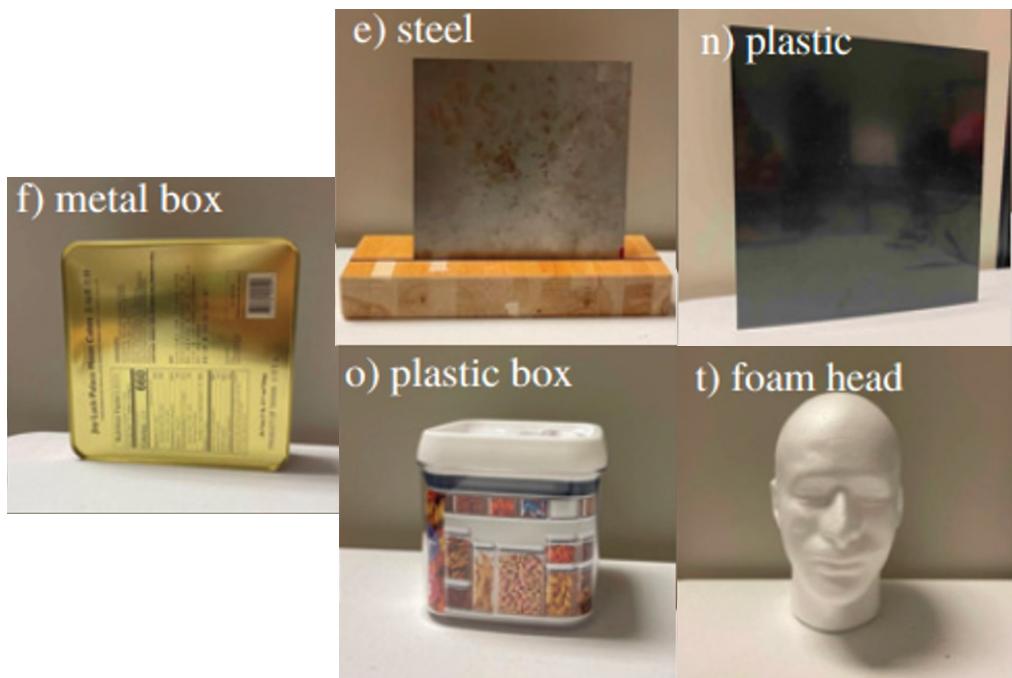
**Accuracy: 81%, 4 materials have over 90%**

# Main Results – Different Train/Test Environments



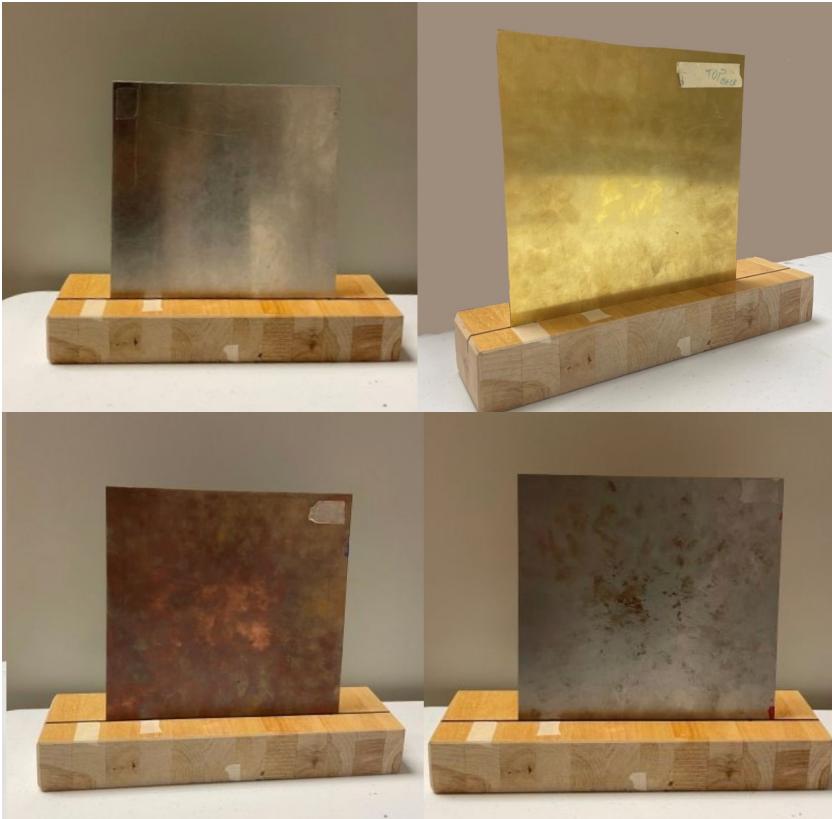
**Accuracy: 73%, 3 materials have over 80%**

# Objects not seen by the network



Unseen Object	Acc (%)	STD
Steel	99.9	0.01
Plastic Sheet	90.5	13.3
Metal Box	80.7	10.3
Plastic Box	53.5	6.0
Foam Head	47.0	9.5

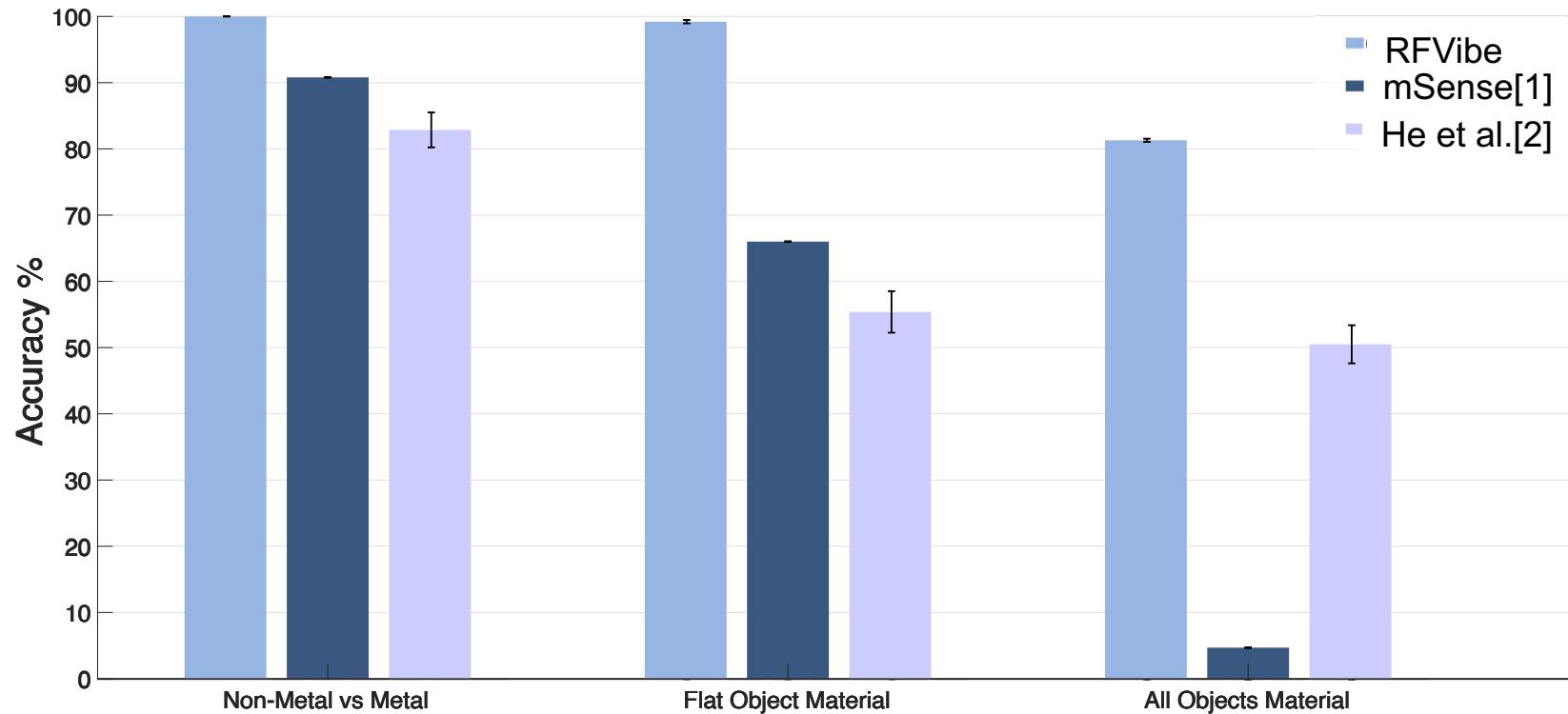
# Metal Classification



Metal Name	Acc (%)	STD
Aluminum	98.7	5.6
Brass	68.4	7.1
Copper	58.6	10.1
Steel	98.0	0.8

**Accuracy: 83%**

# Comparison with Baselines



[1] C. Wu, F. Zhang, B. Wang, and K. R. Liu. msense: Towards mobile material sensing with a single millimeter-wave radio. *IMWUT '20*

[2] S. He, Y. Qian, H. Zhang, G. Zhang, M. Xu, L. Fu, X. Cheng, H. Wang, and P. Hu. Accurate contact-free material recognition with millimeter wave and machine learning. *WASA '2022*

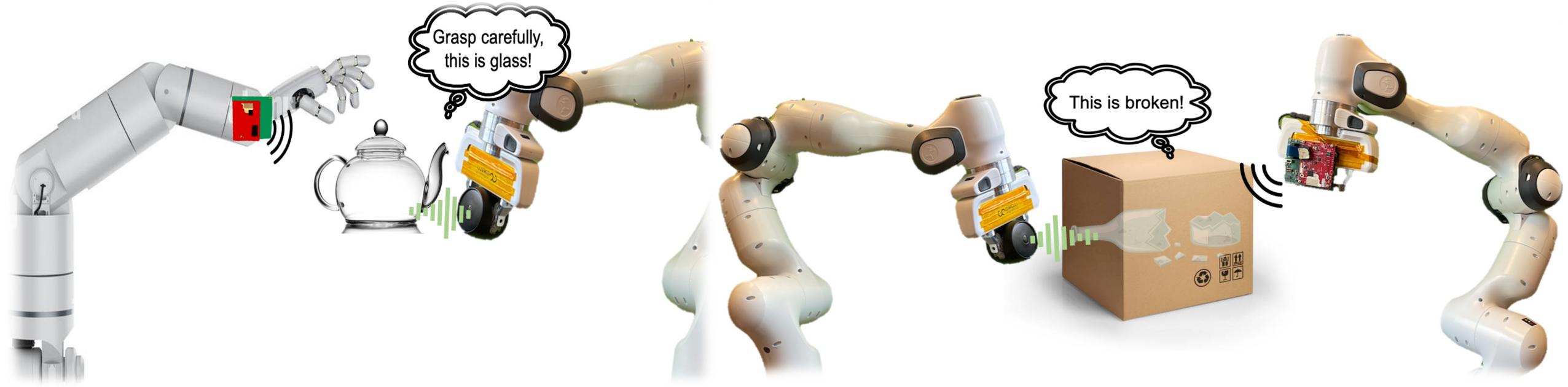
# Hidden Objects



Hidden Method	Acc (%)	STD
Uncovered	83.2	3.3
Paper Cover	70.0	4.4
In Bag	73.0	4.8
Painted	69.8	3.6

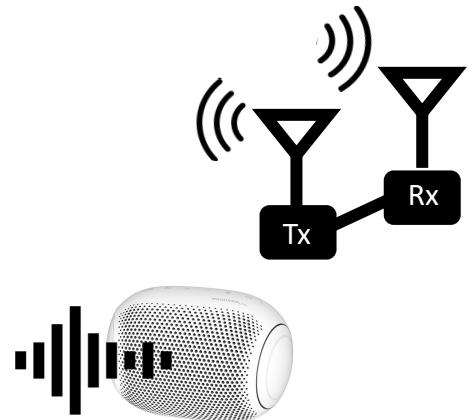
# More microphonebenchmarks in the paper!

- *Unseen Boundary Conditions*
- *Unseen Rotation*
- *Unseen Distance of Object to Speaker*
- *Object Classification*
- *Different Speakers*
- *Impact of Individual Features*
- *Length of Vibration Time Used*
- *Comparison with Basic Classifiers*
- *Effect of Weight*
- *Background Noise*



# Limitations

## Speaker Location



## Multiple Objects



## More Data



# RFVibe



- Material sensing system combining RF and acoustics to achieve high accuracy
- Resonance frequency, damping speeds and reflection power contain unique information about material properties
- Opens up the door for many applications in wireless material sensing

**Please see our code & dataset at:  
[https://github.com/hailanzs/contactless-mat-id.](https://github.com/hailanzs/contactless-mat-id)**