Non-line-of-sight imaging

15-463, 15-663, 15-862
Computational Photography
Fall 2017, Lecture 25

http://graphics.cs.cmu.edu/courses/15-463

Course announcements

- Homework 6 will be posted tonight.
  - Will be due Sunday 10th.
  - Almost no coding, only data capture and using existing code.
  - You will need high-sensitivity cameras, so use the DSLRs you have picked up.

- Final project report deadline moved to December 15th.
  - Originally was December 11th.

Overview of today’s lecture

- The non-line-of-sight (NLOS) imaging problem.
- Active NLOS imaging using time-of-flight imaging.
- Active NLOS imaging using WiFi.
- Passive NLOS imaging using accidental pinholes.
- Passive NLOS imaging using accidental reflectors.
- Passive NLOS imaging using corners.

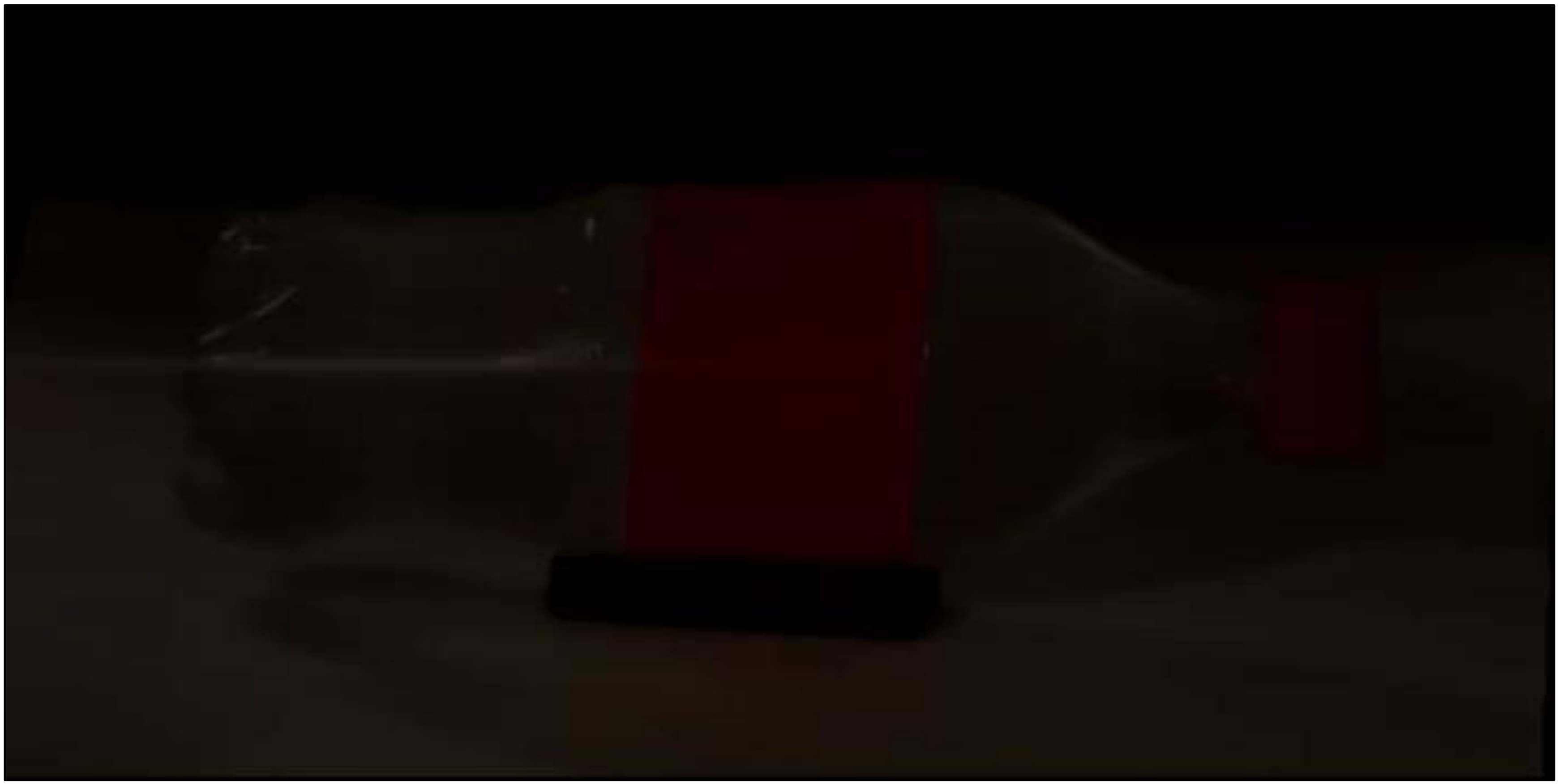
Slide credits

Many of these slides were directly adapted from:

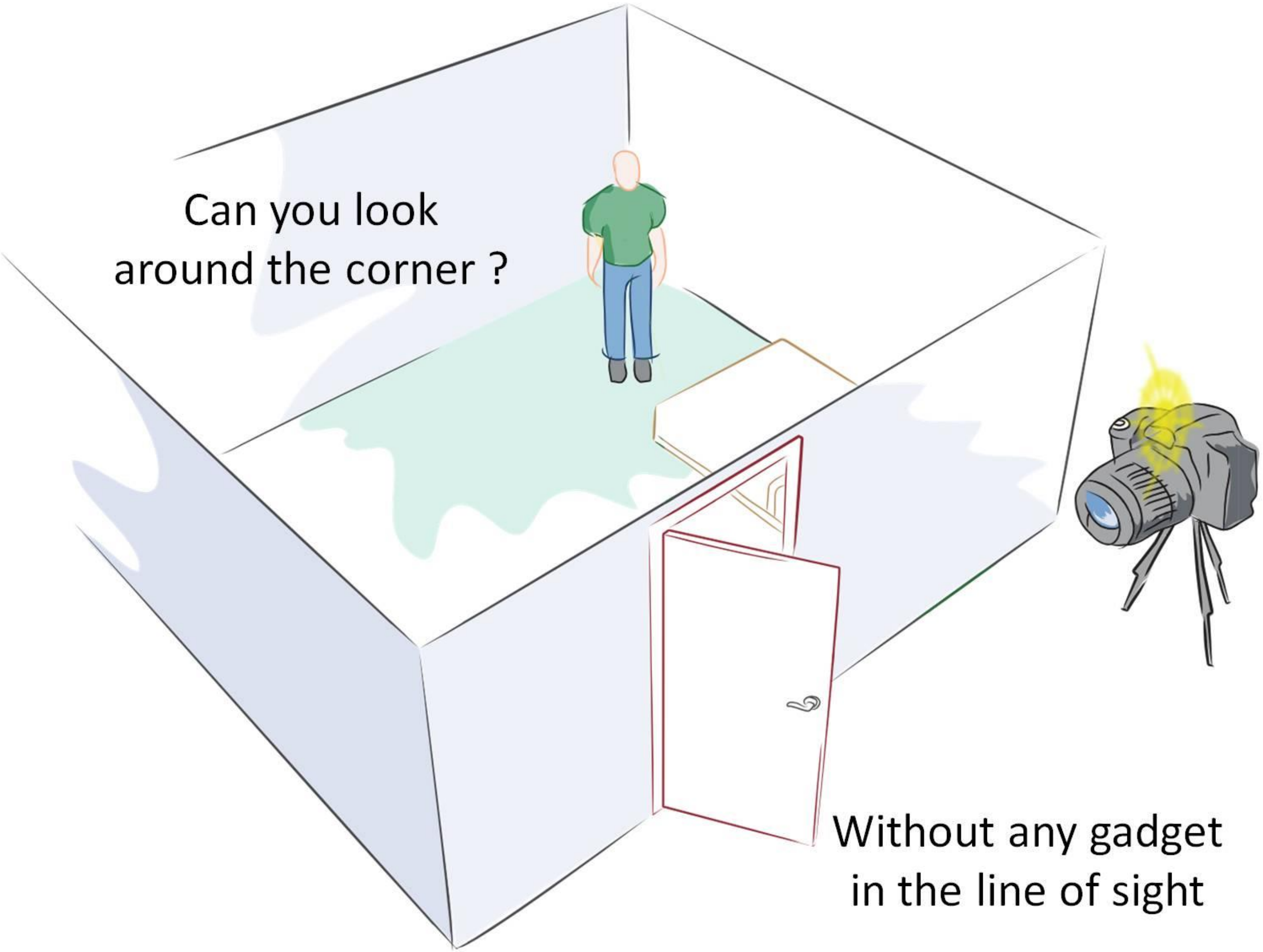
- Shree Nayar (Columbia).
- Fadel Adib (MIT).
- Katie Bouman (MIT).

The non-line-of-sight (NLOS) imaging problem

Time-of-flight (ToF) imaging



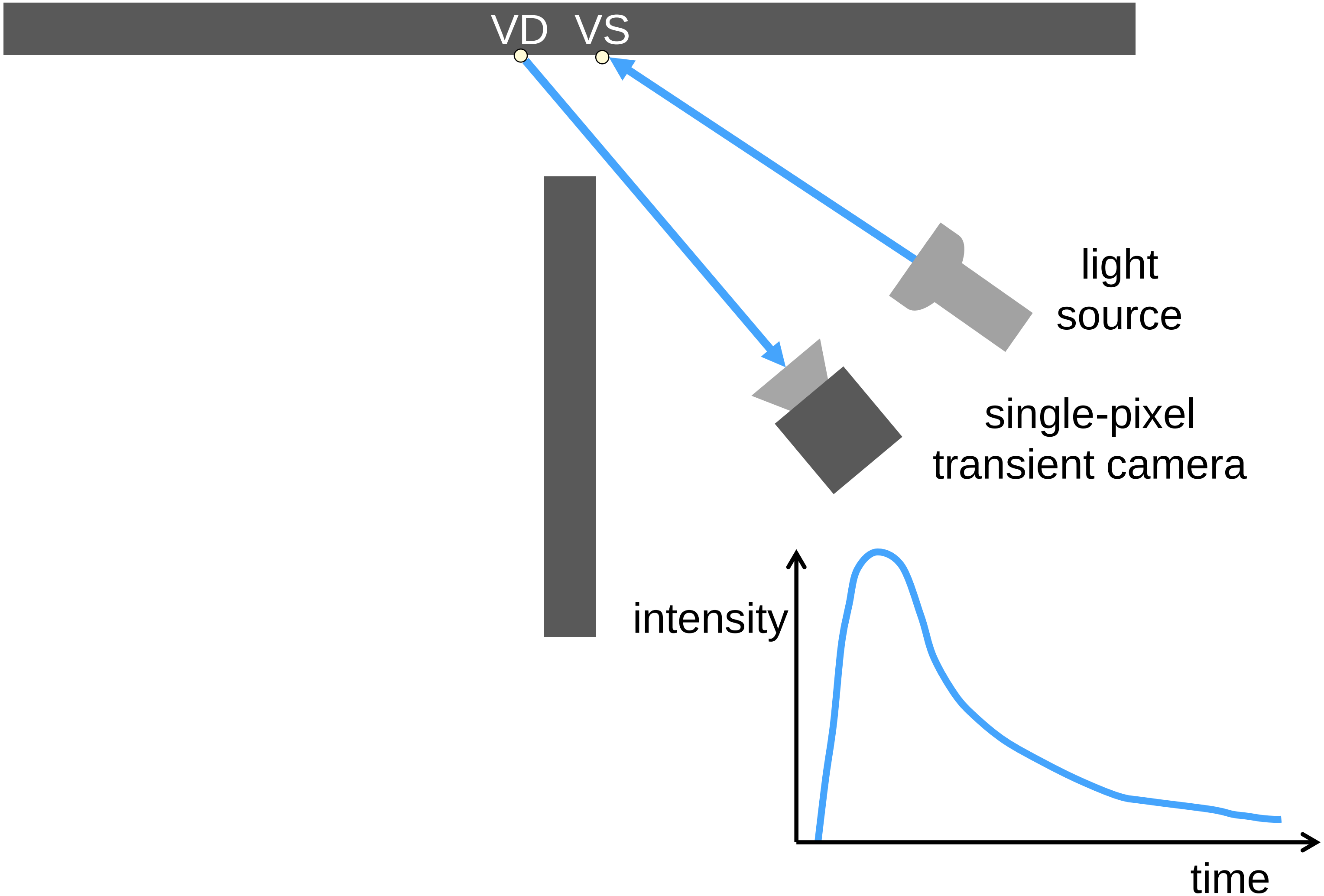
Looking around the corner



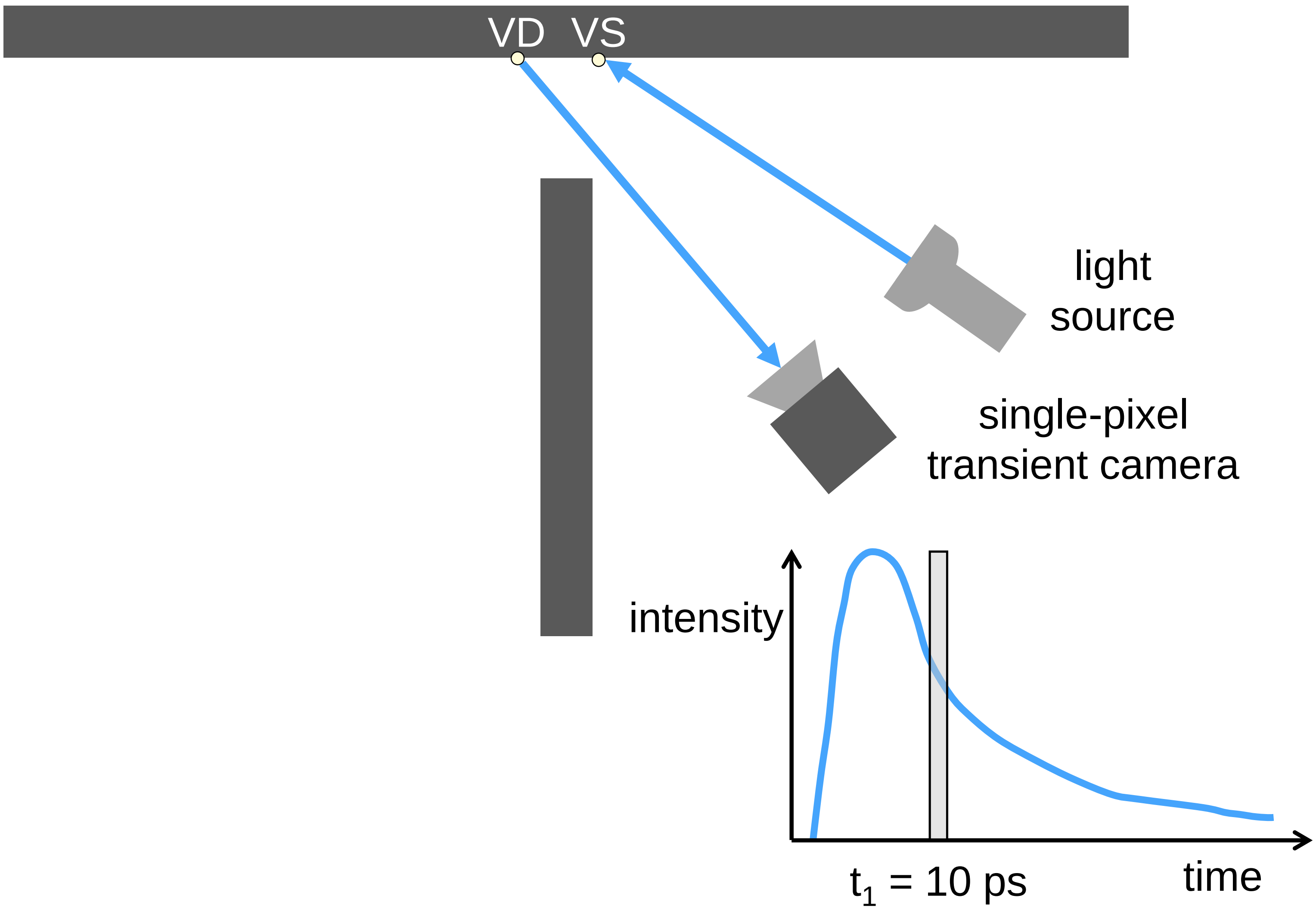
Looking around the corner

Active NLOS imaging using time-of-flight imaging

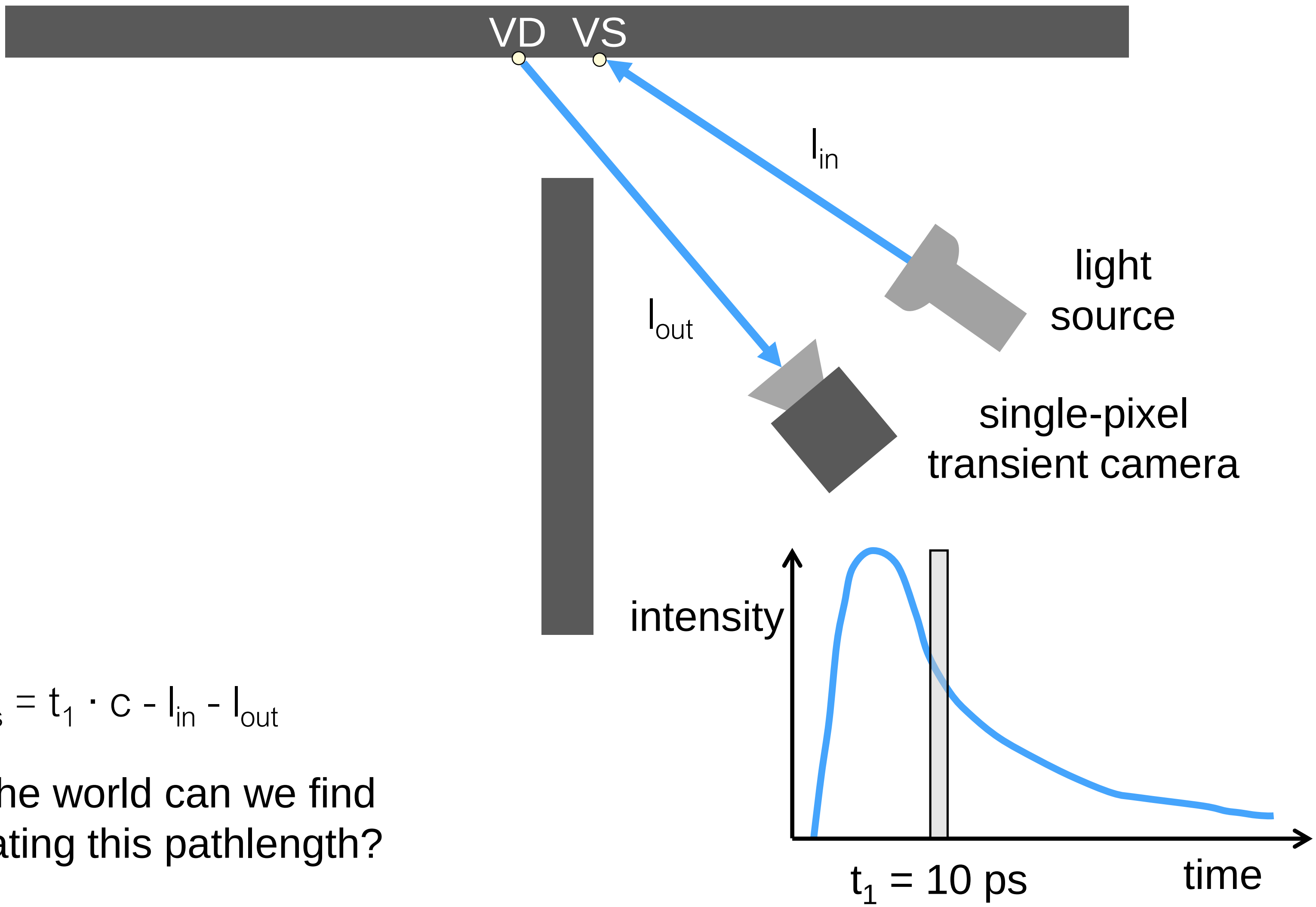
Processing a single-pixel transient



Processing a single-pixel transient



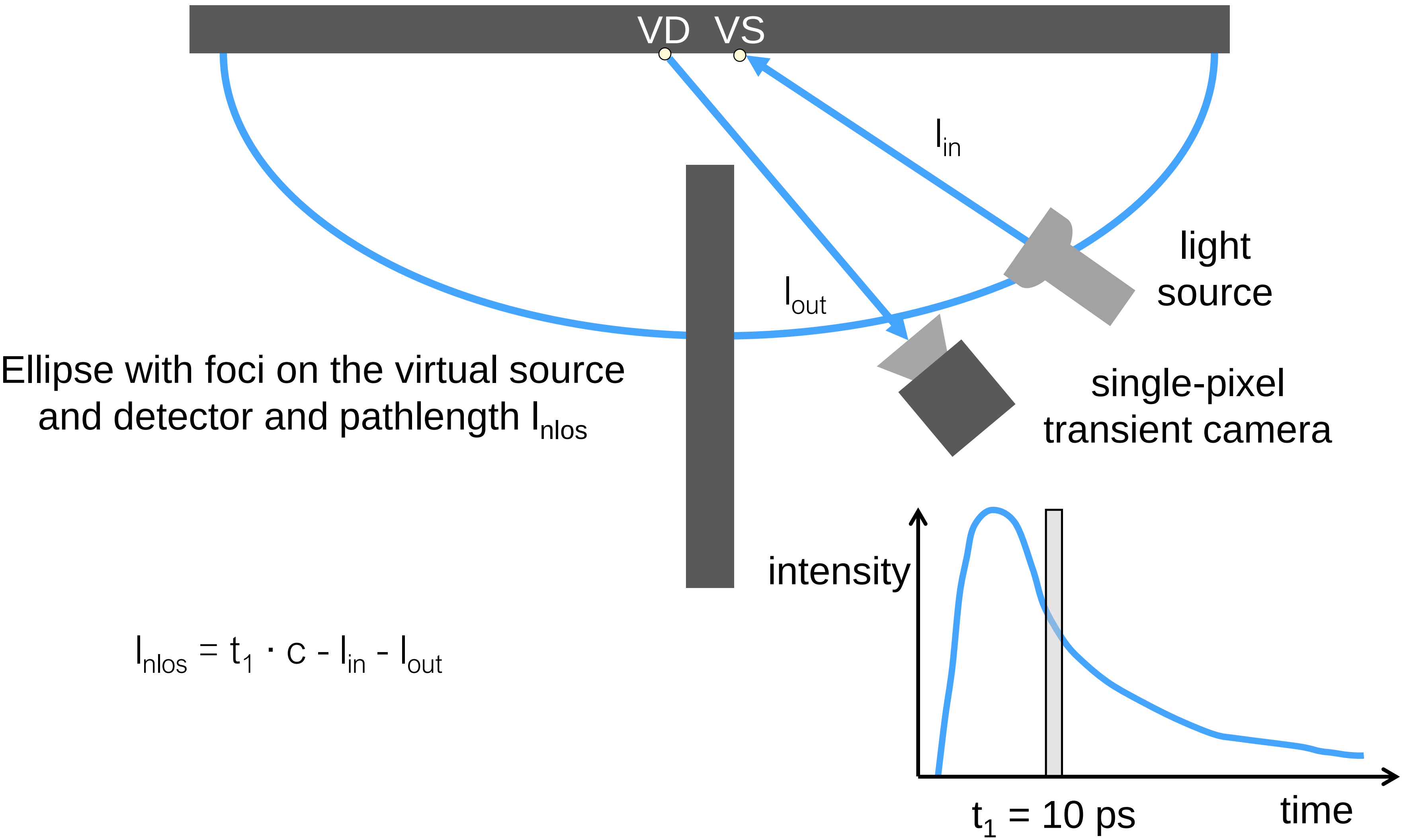
Processing a single-pixel transient



$l_{nlos} = t_1 \cdot c - l_{in} - l_{out}$

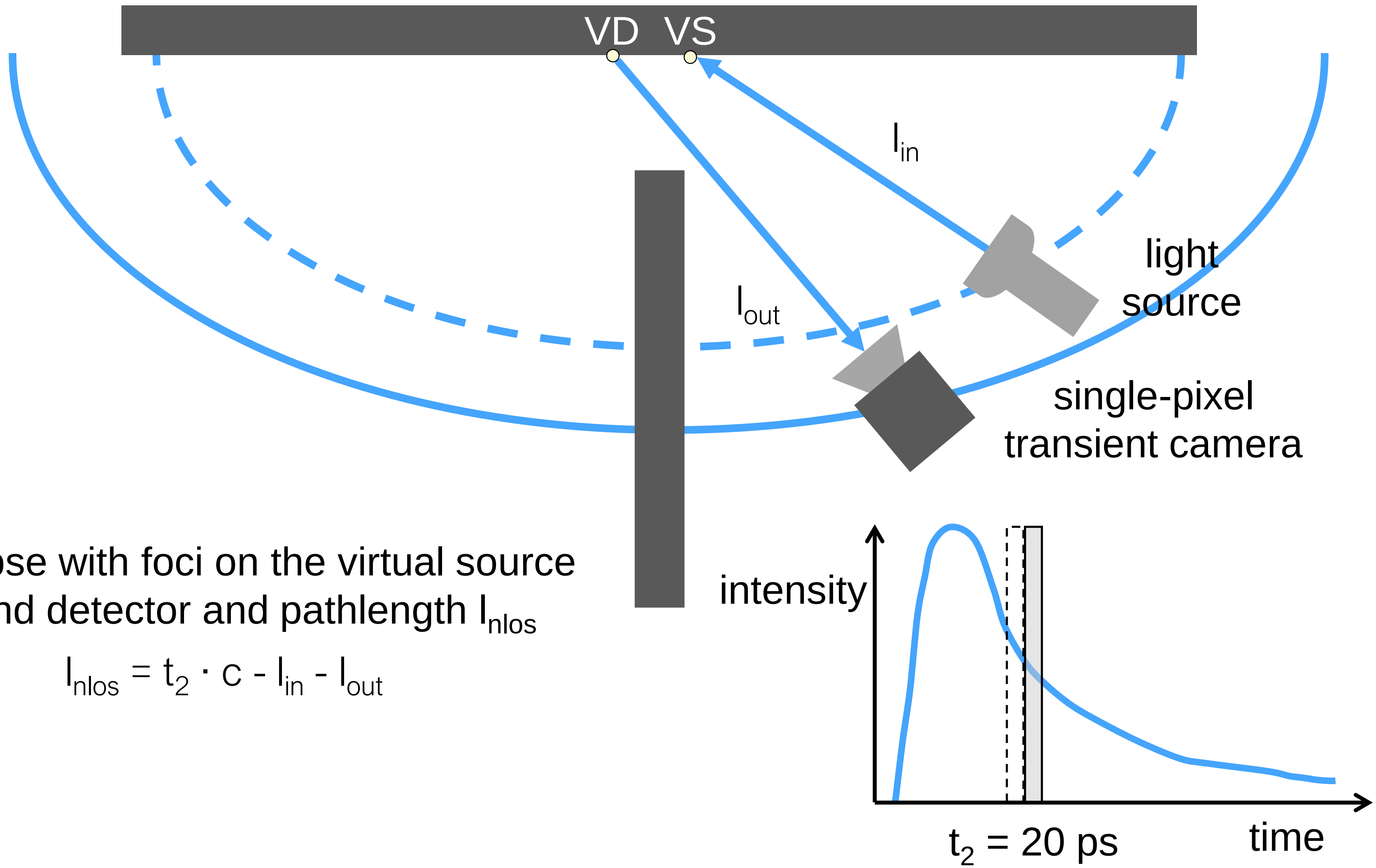
Where in the world can we find points creating this pathlength?

Processing a single-pixel transient



$$l_{nlos} = t_1 \cdot c - l_{in} - l_{out}$$

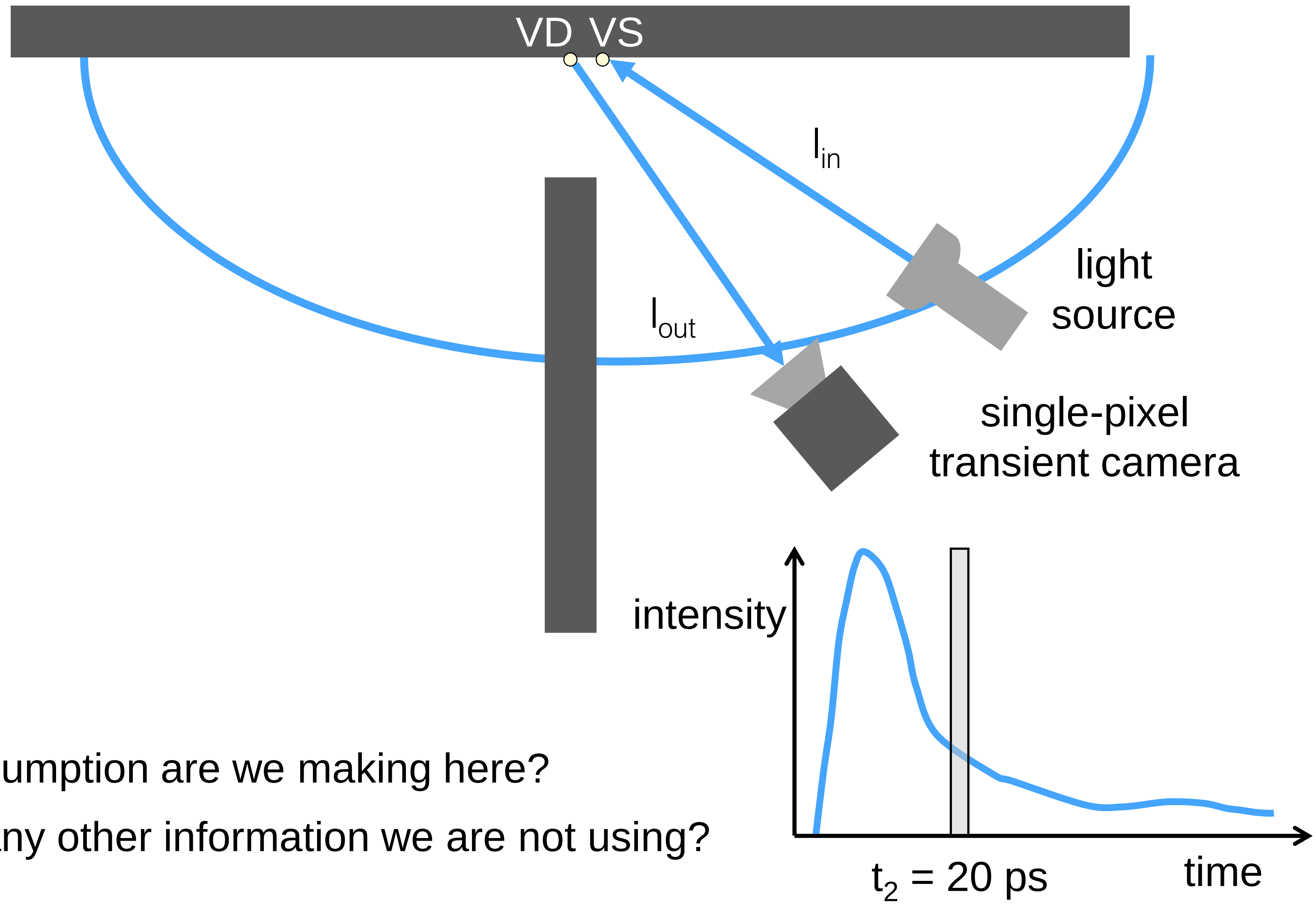
Processing a single-pixel transient



Ellipse with foci on the virtual source and detector and pathlength l_{nlos}

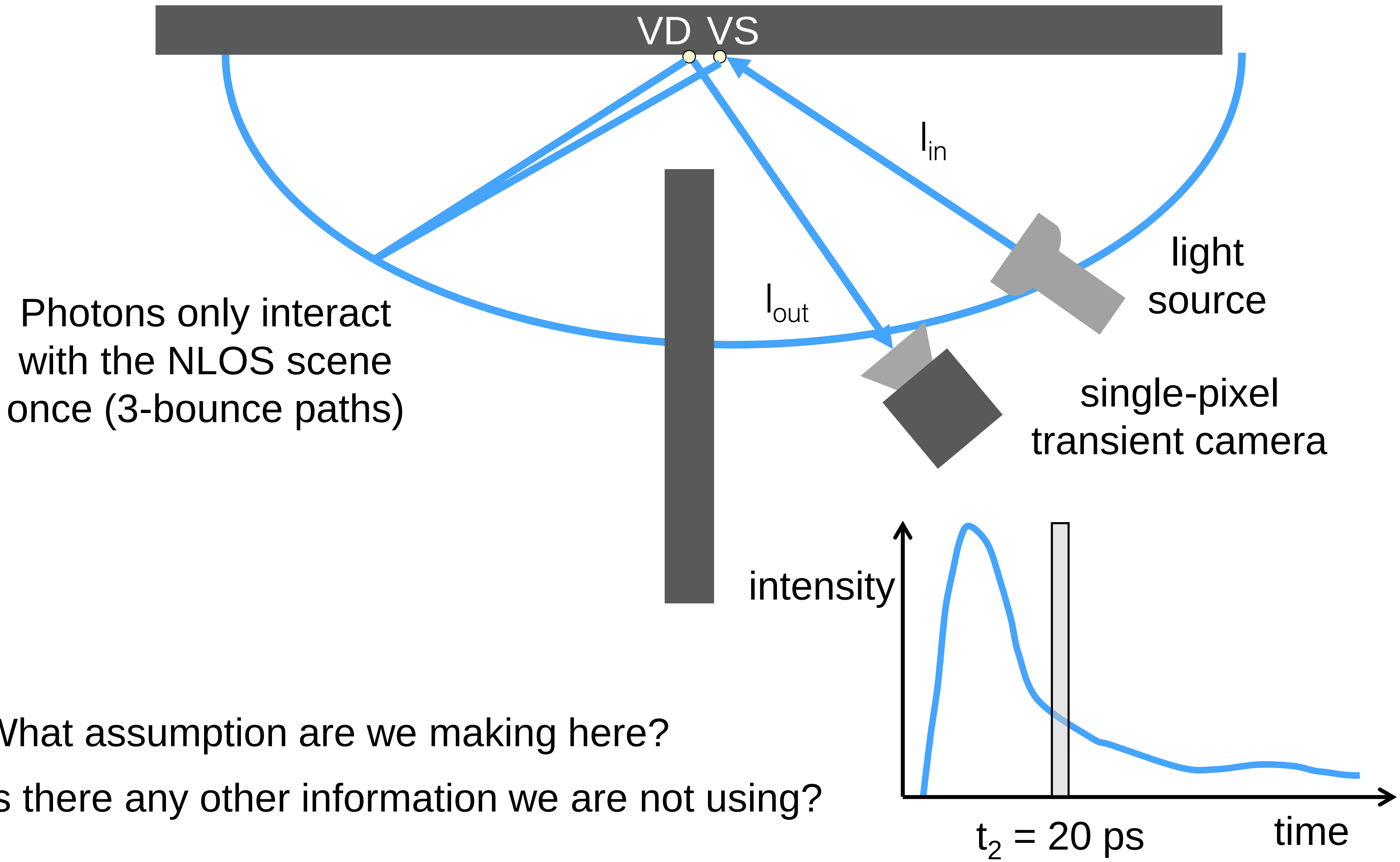
$$l_{nlos} = t_2 \cdot c - l_{in} - l_{out}$$

Processing another single-pixel transient



- What assumption are we making here?
- Is there any other information we are not using?

Processing another single-pixel transient



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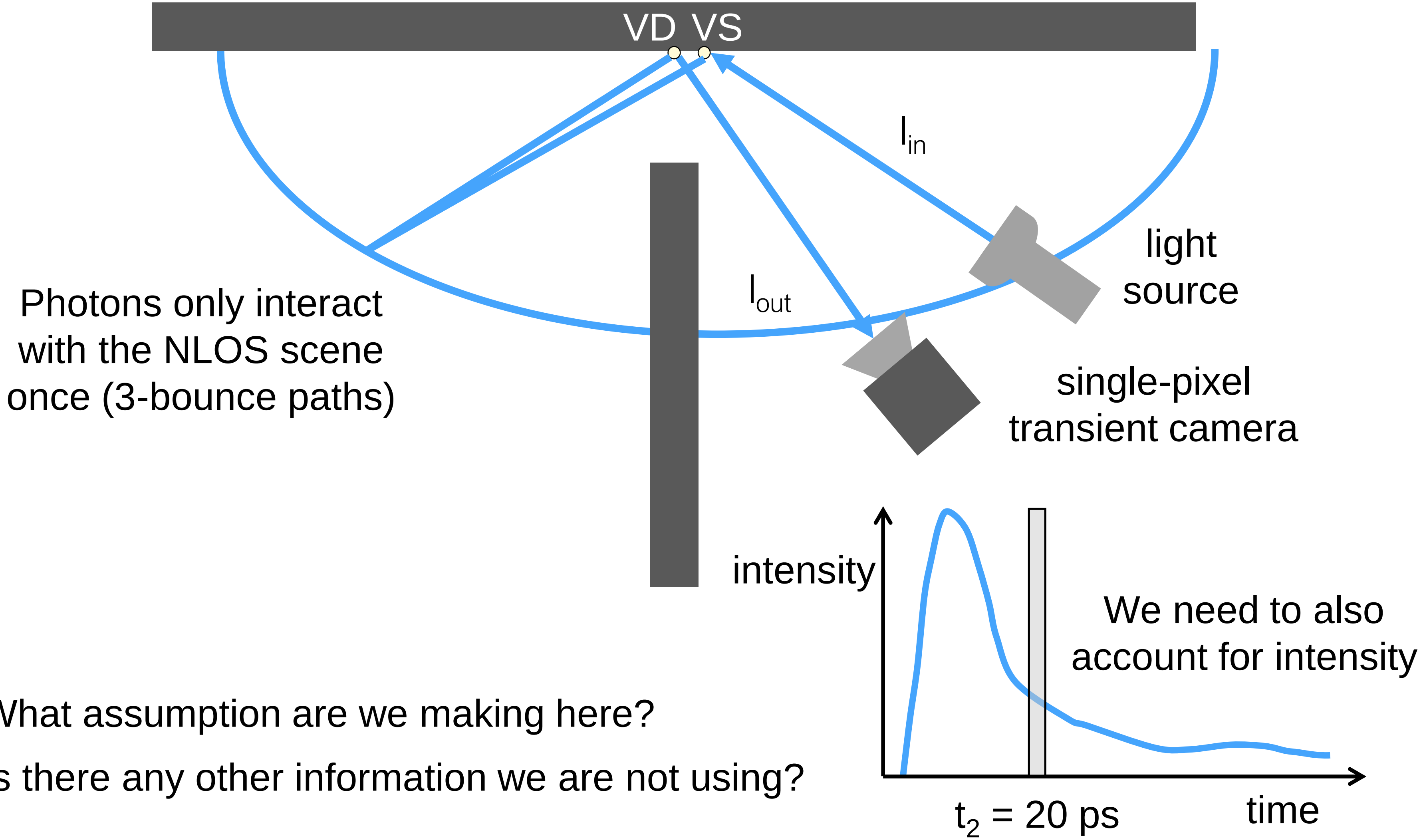
Processing another single-pixel transient



- What assumption are we making here?
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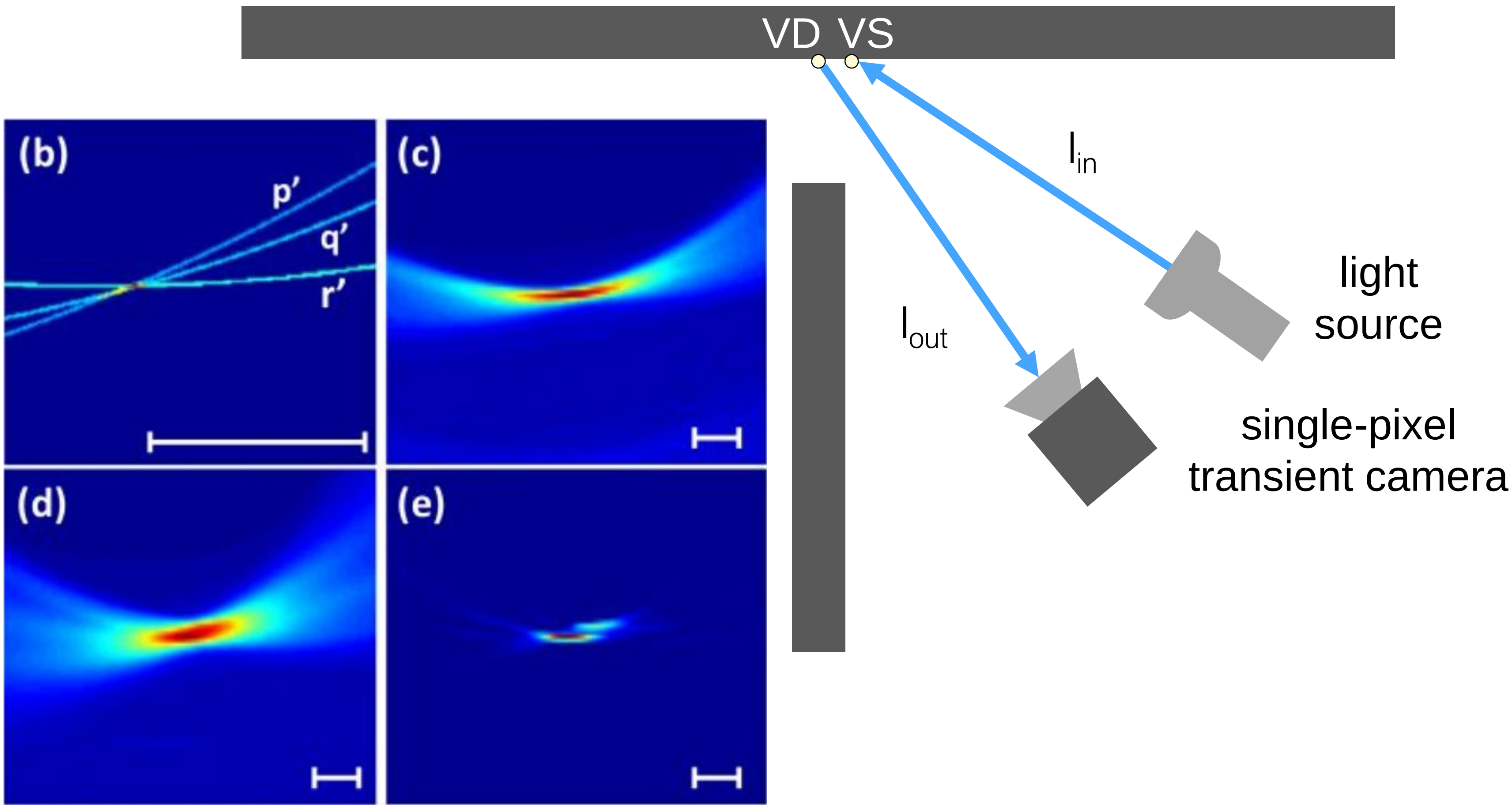
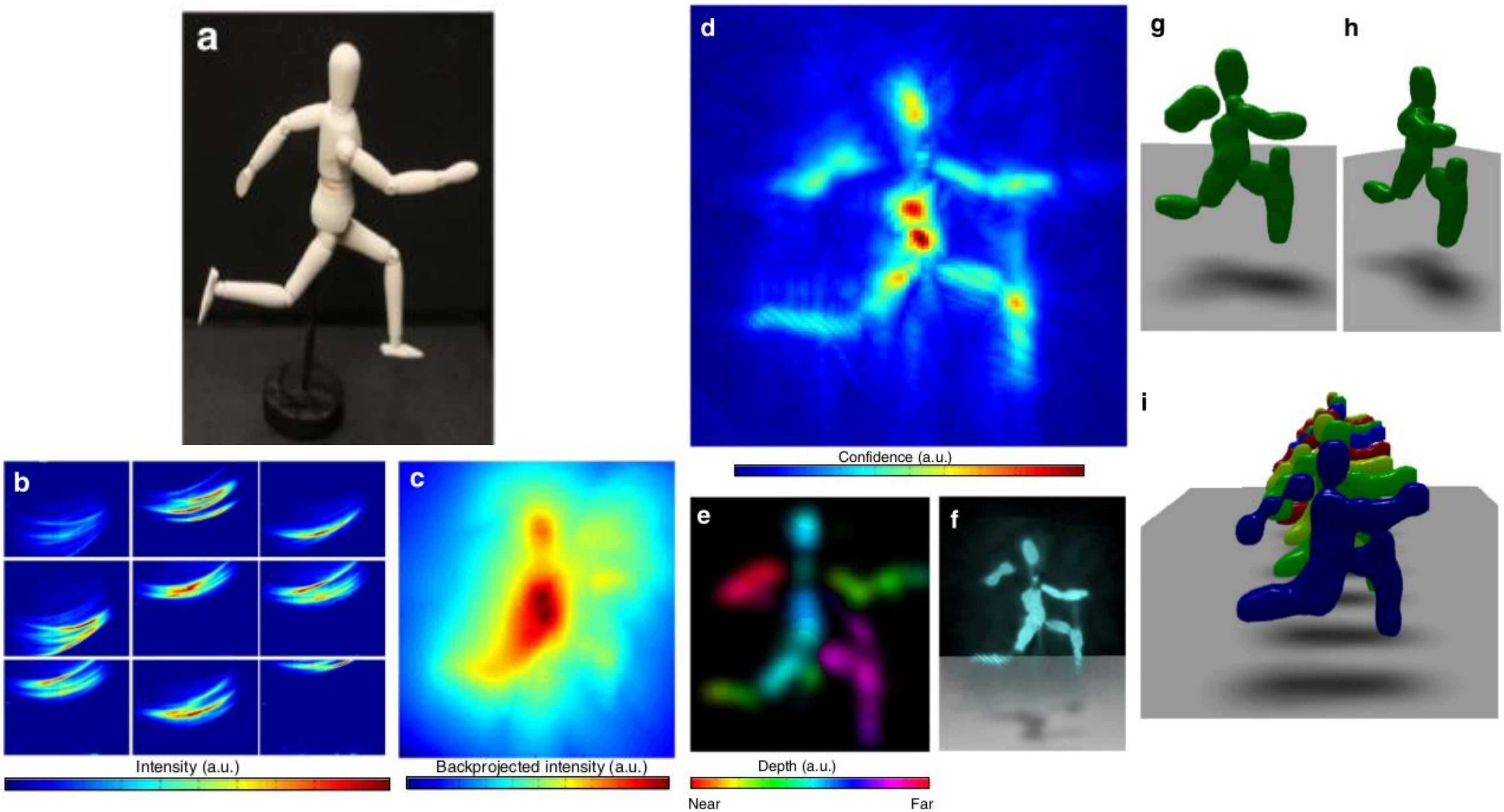
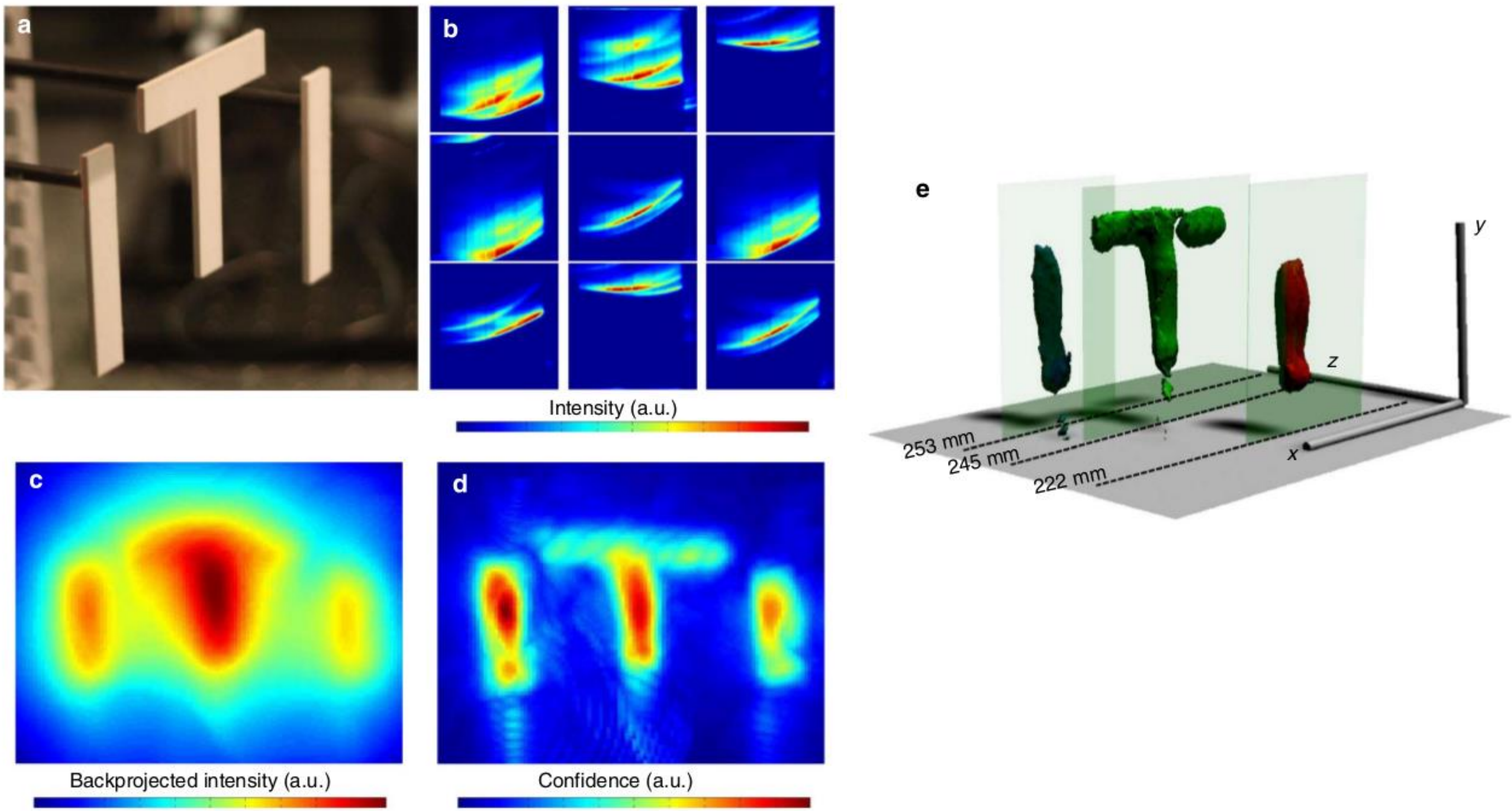
Elliptic backprojection



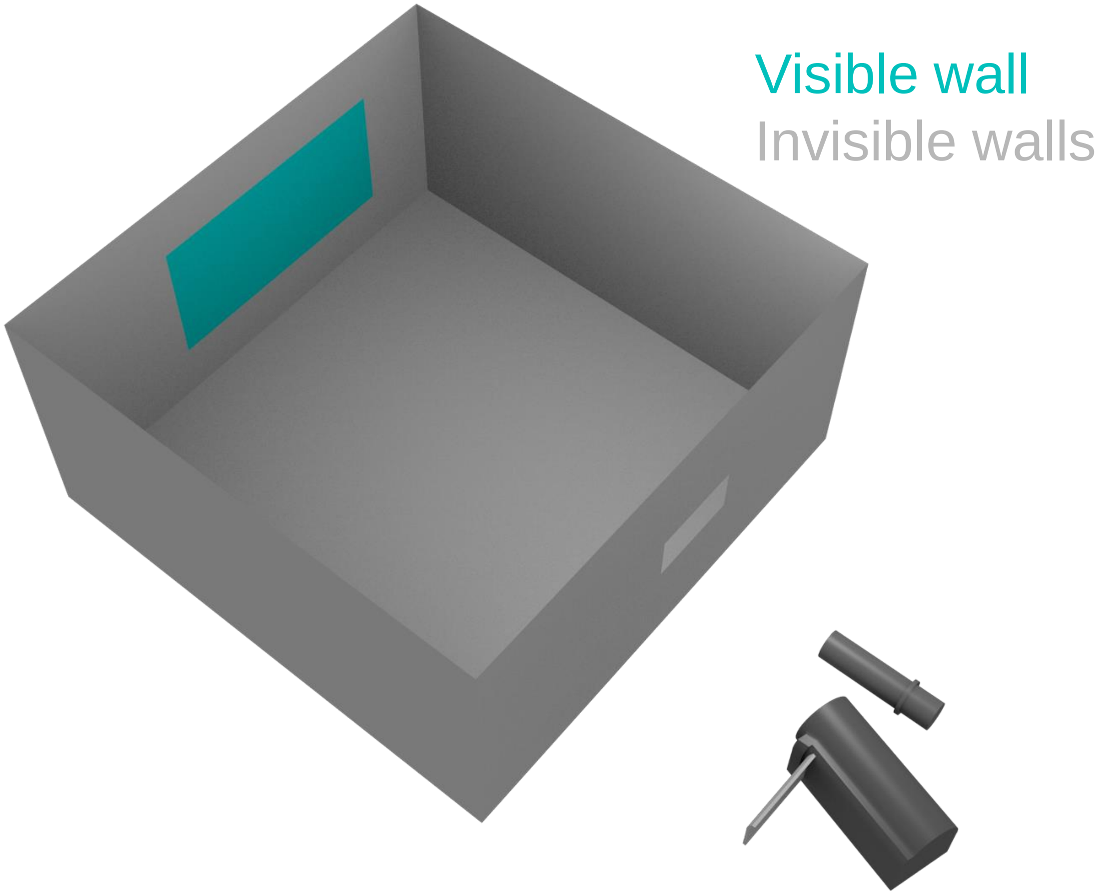
Elliptic backprojection



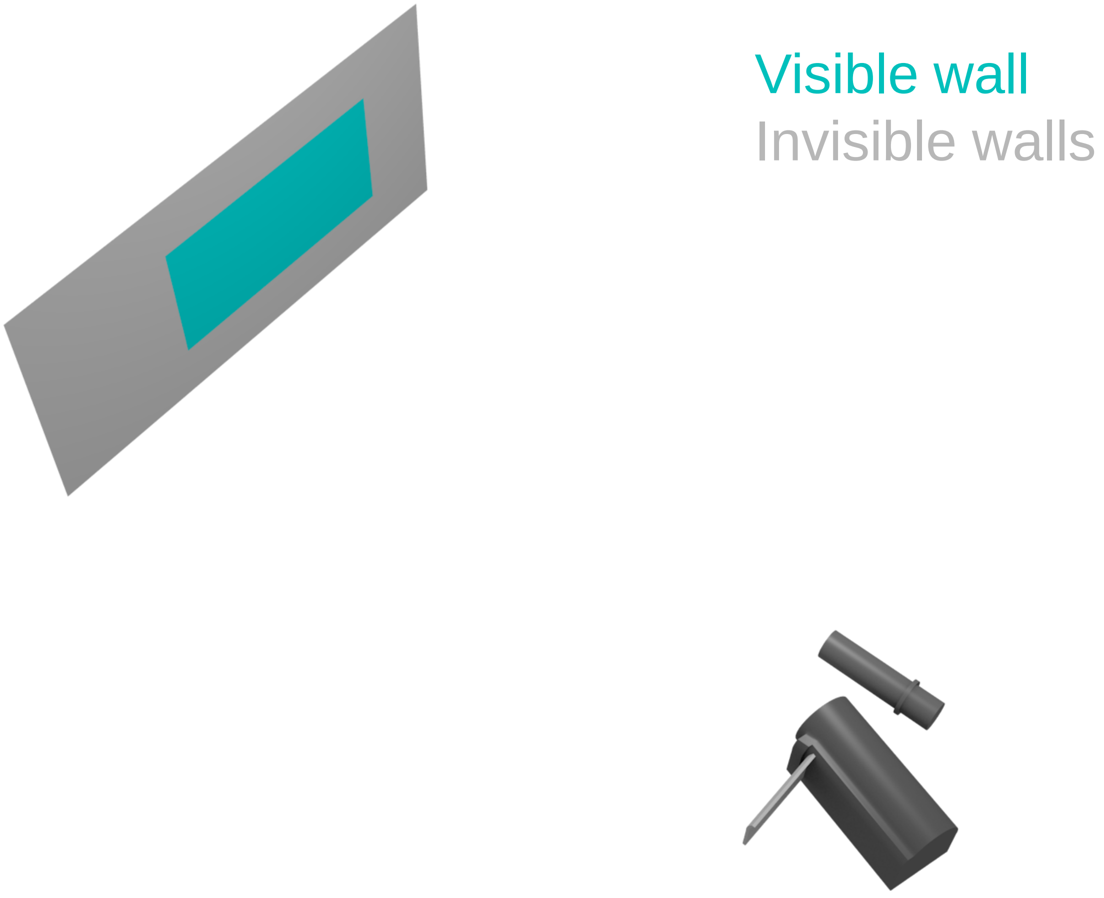
Elliptic backprojection



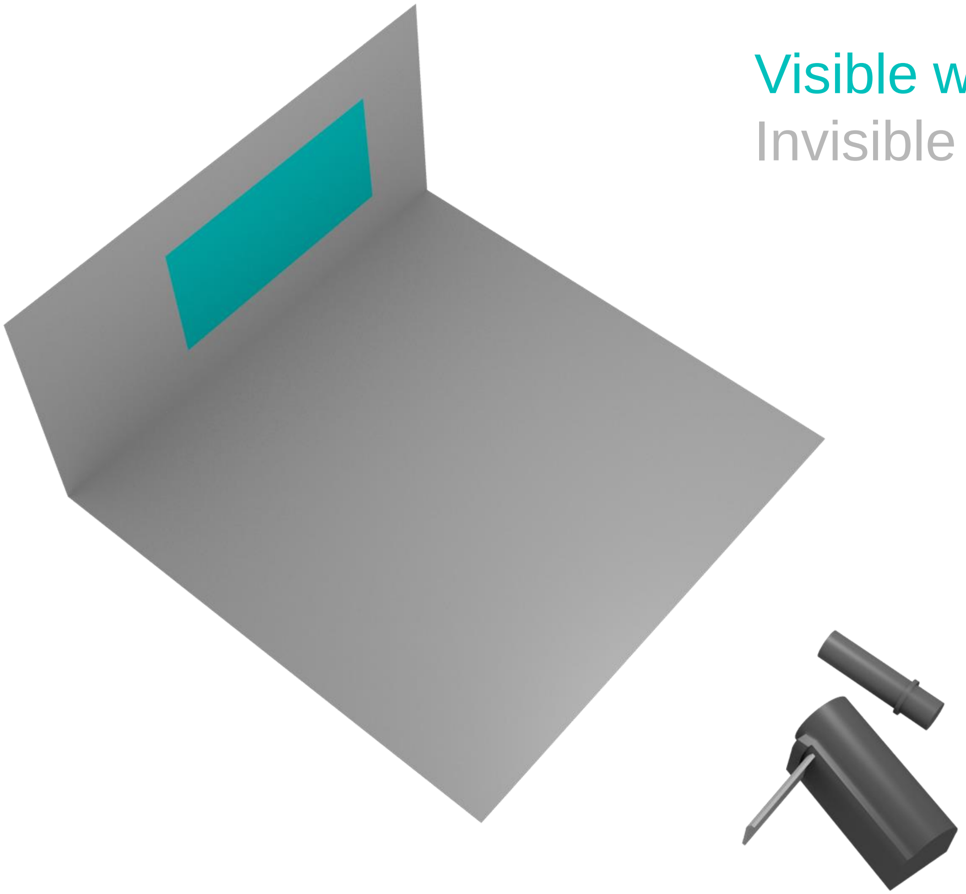
Reconstructing Hidden Rooms



Reconstructing Hidden Rooms: One plane at a time

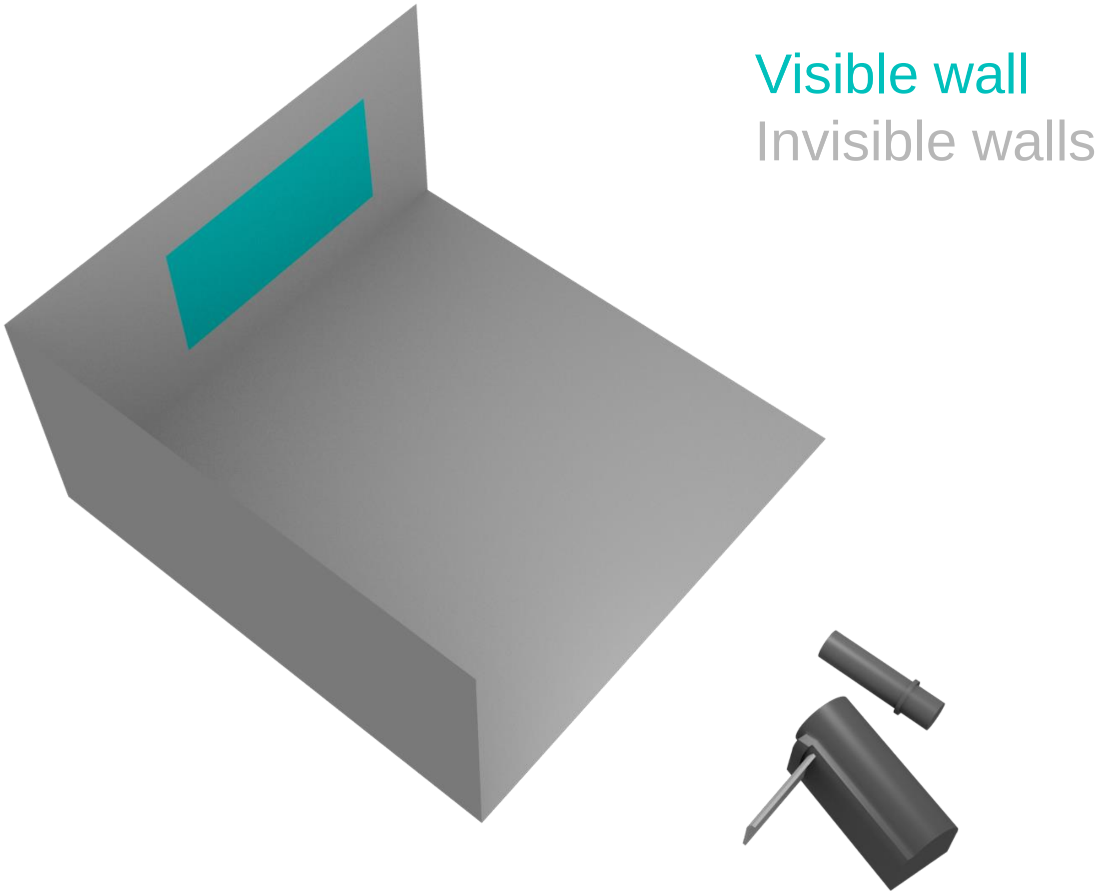


Reconstructing Hidden Rooms: One plane at a time

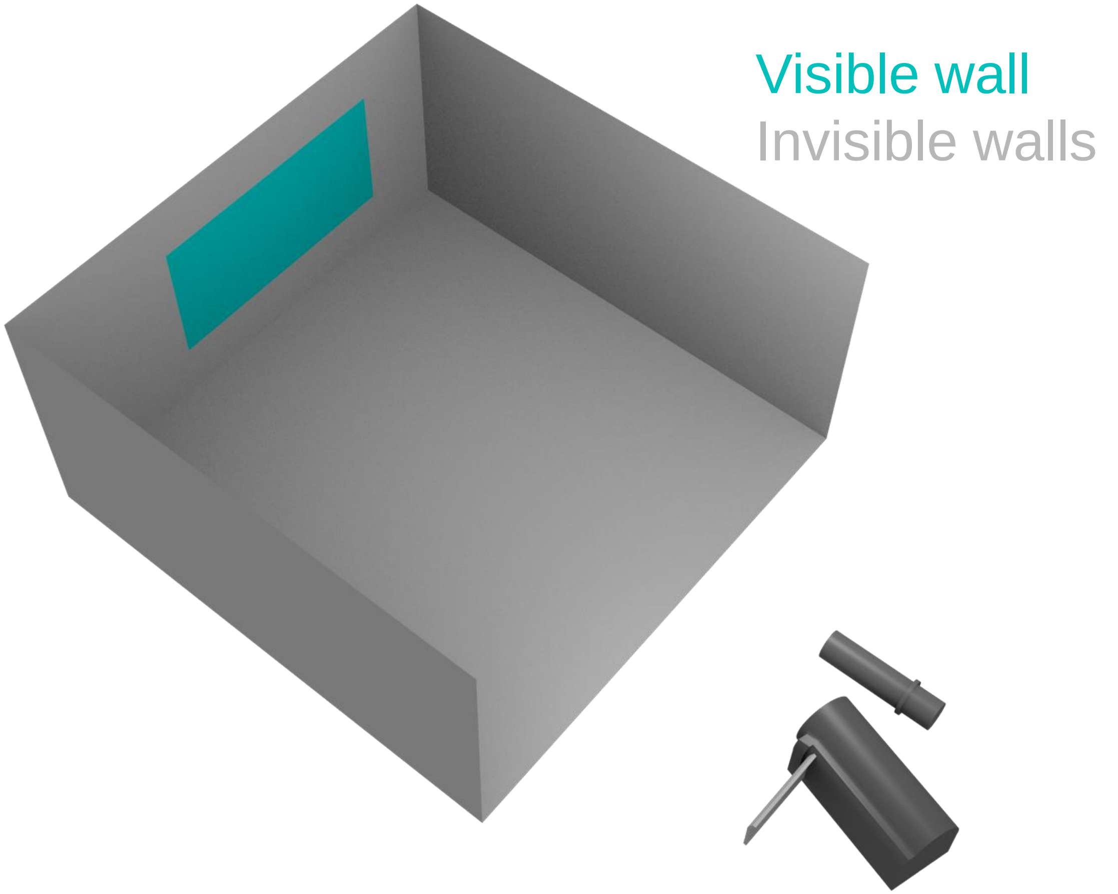


Visible wall
Invisible walls

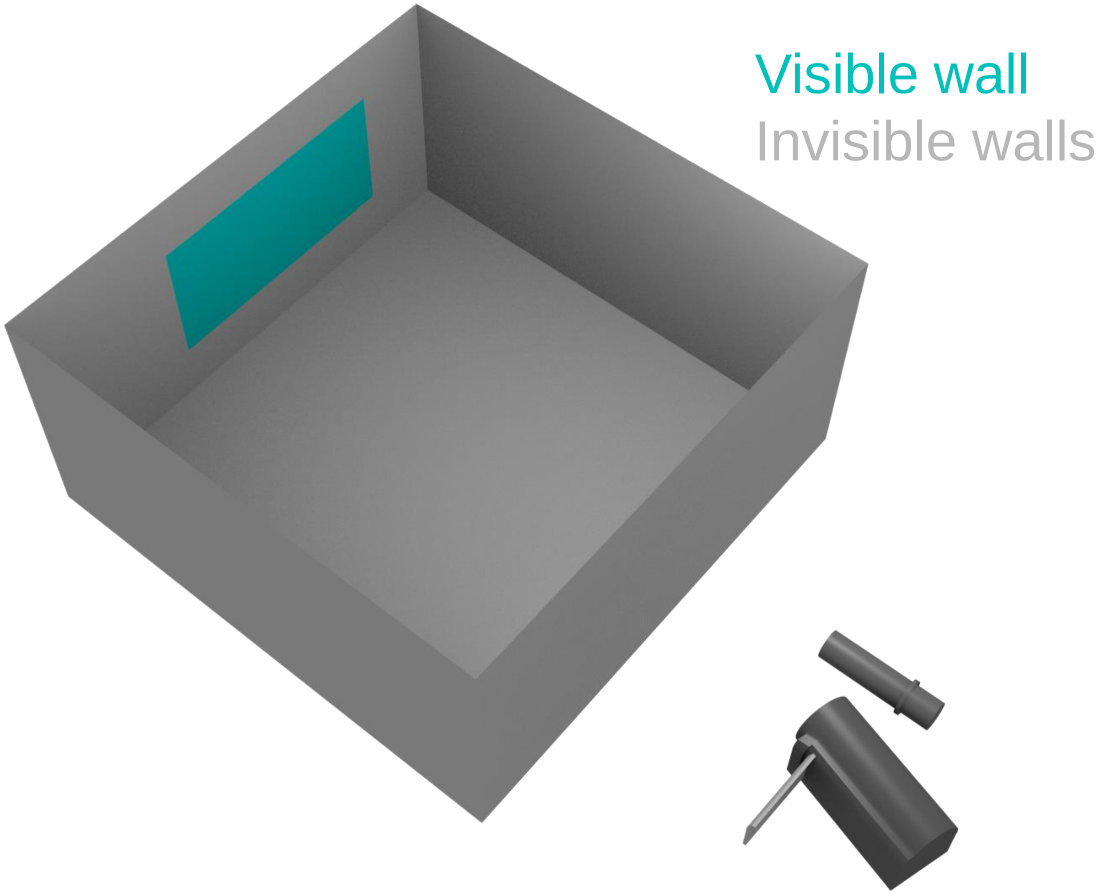
Reconstructing Hidden Rooms: One plane at a time



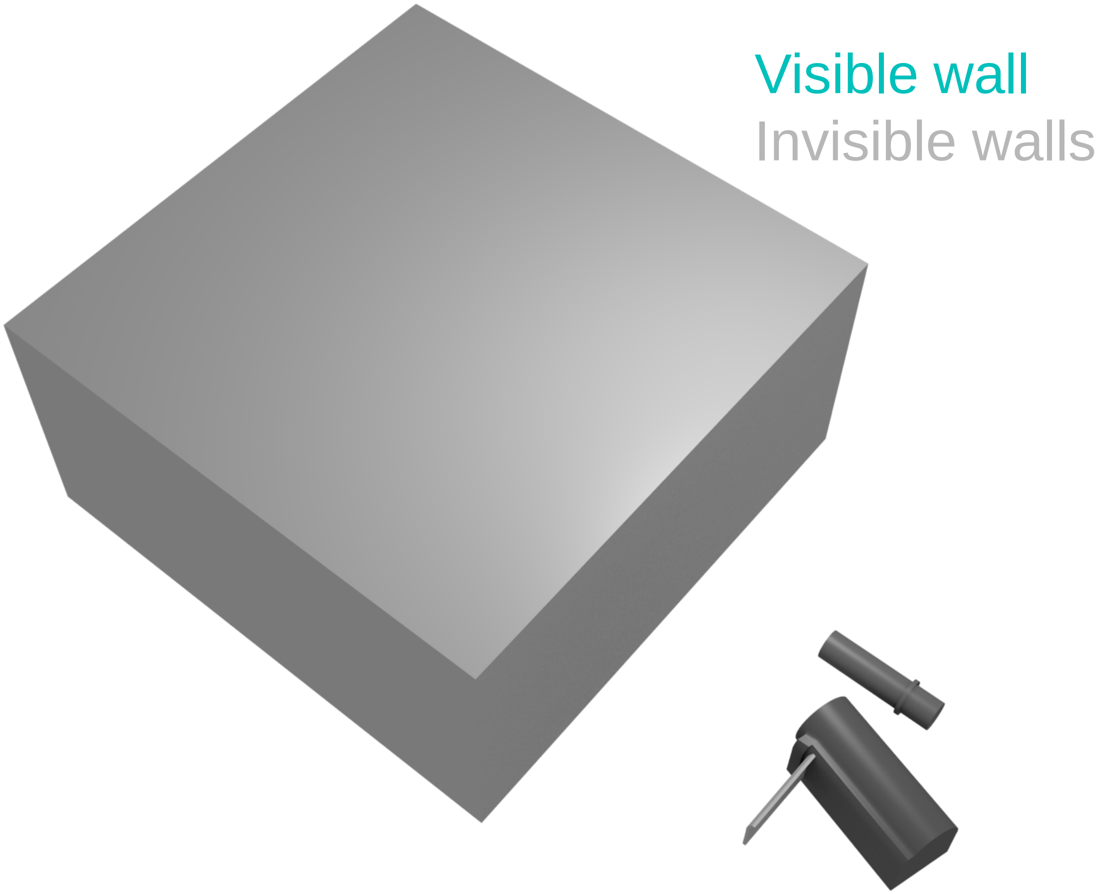
Reconstructing Hidden Rooms: One plane at a time



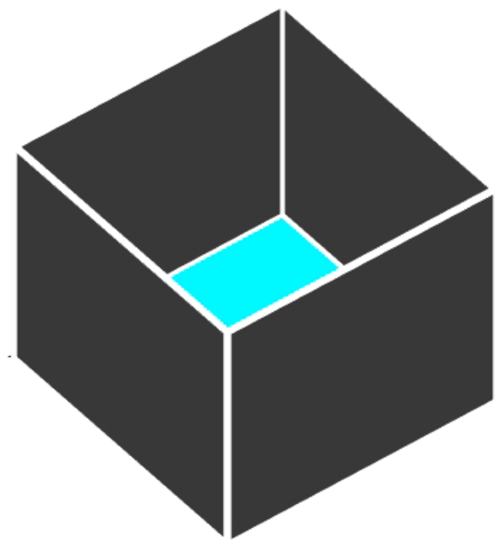
Reconstructing Hidden Rooms: One plane at a time



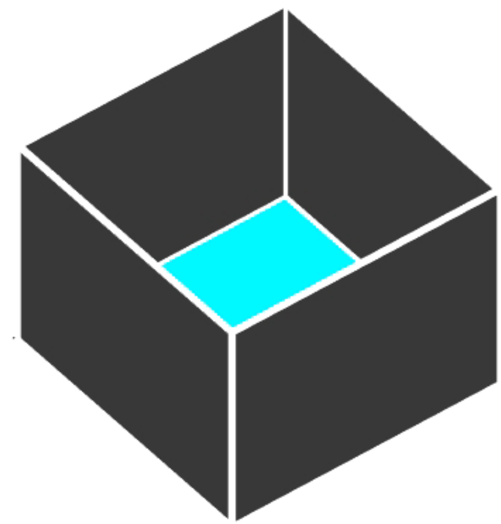
Reconstructing Hidden Rooms: One plane at a time



Reconstructing Rectangular Rooms



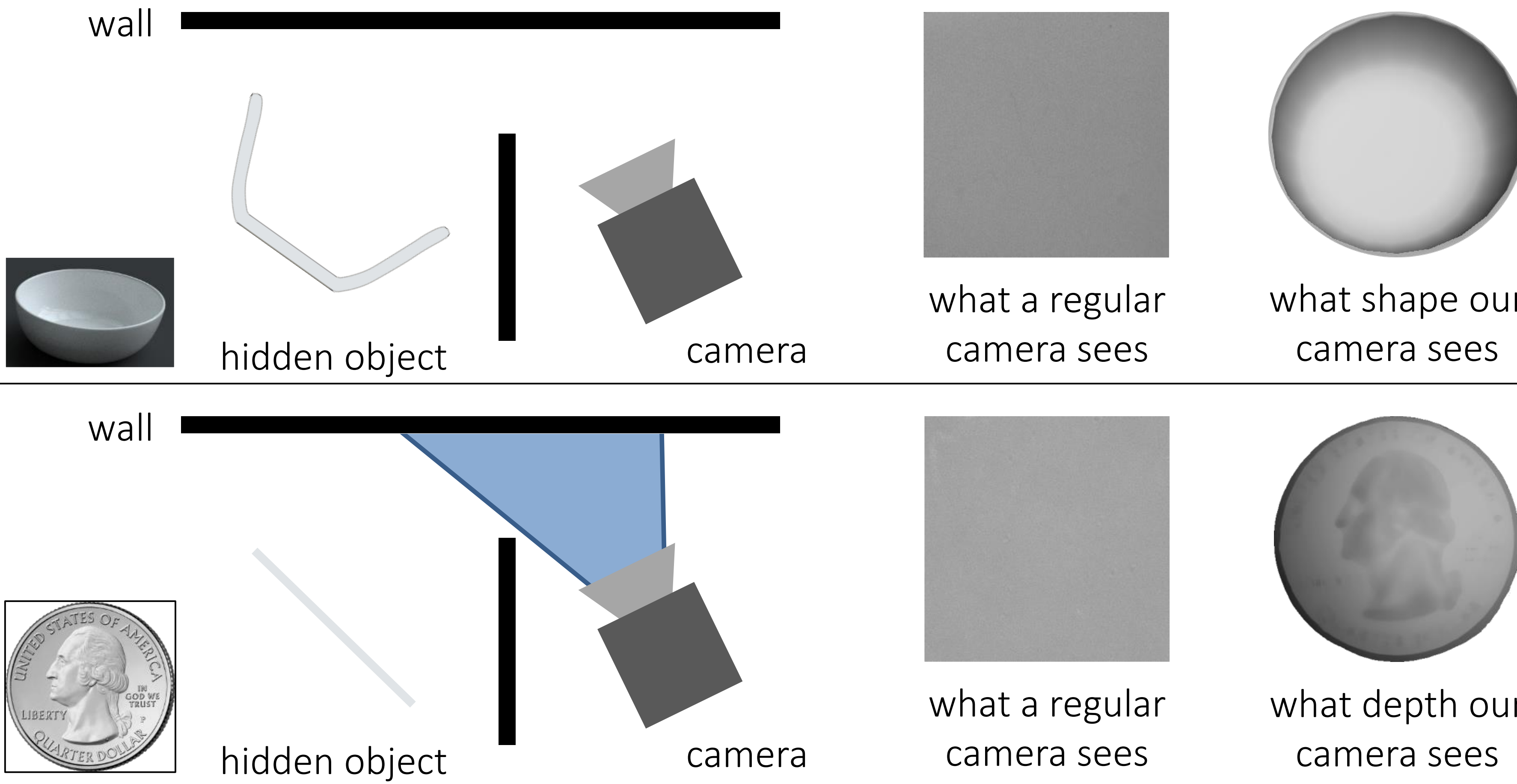
Original room



Reconstructed room

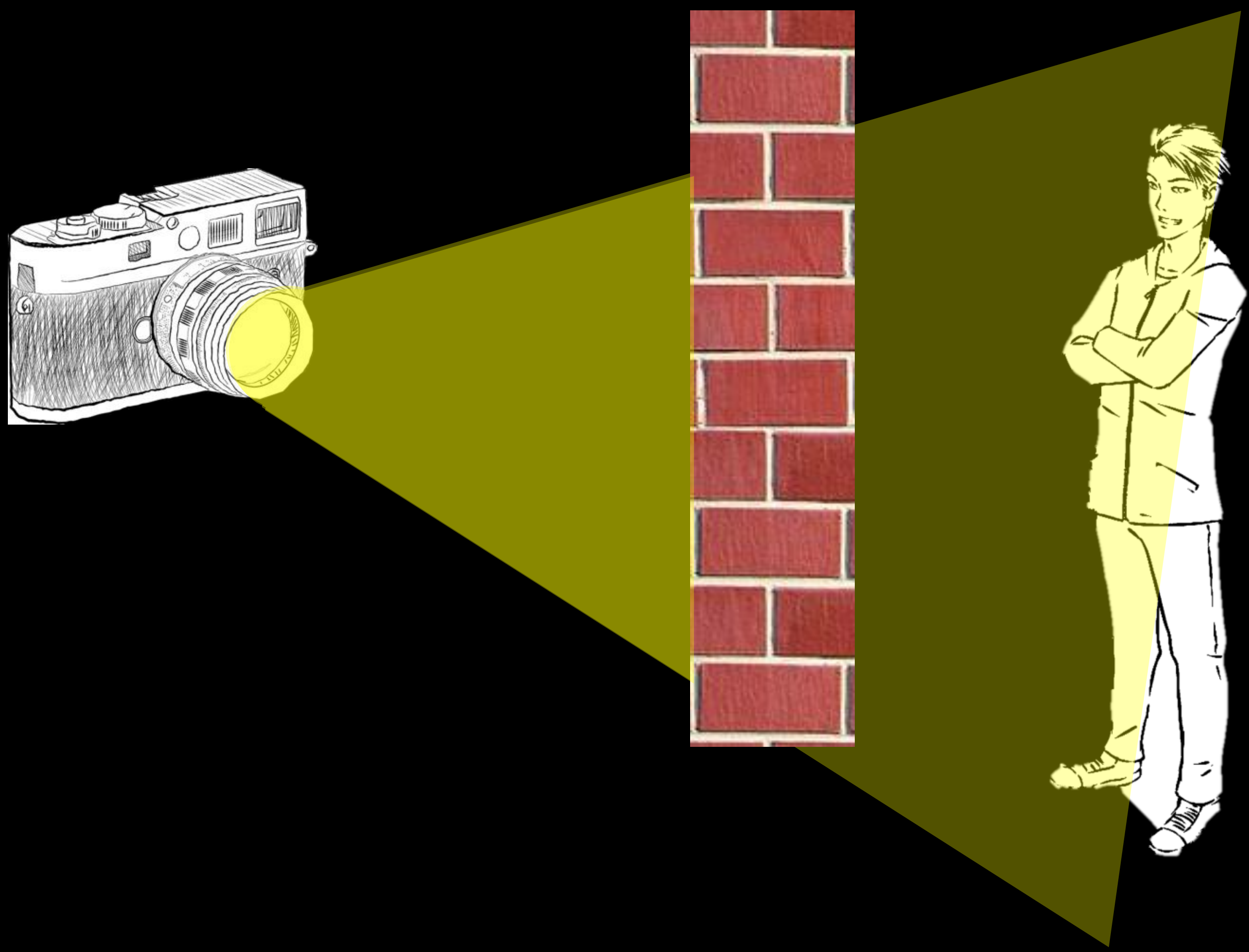
- Average AICP error for all the walls is TBD mm (TBD %). – Normalized with average room length of 1.1m

Reconstructing Complex Shape and Reflectance

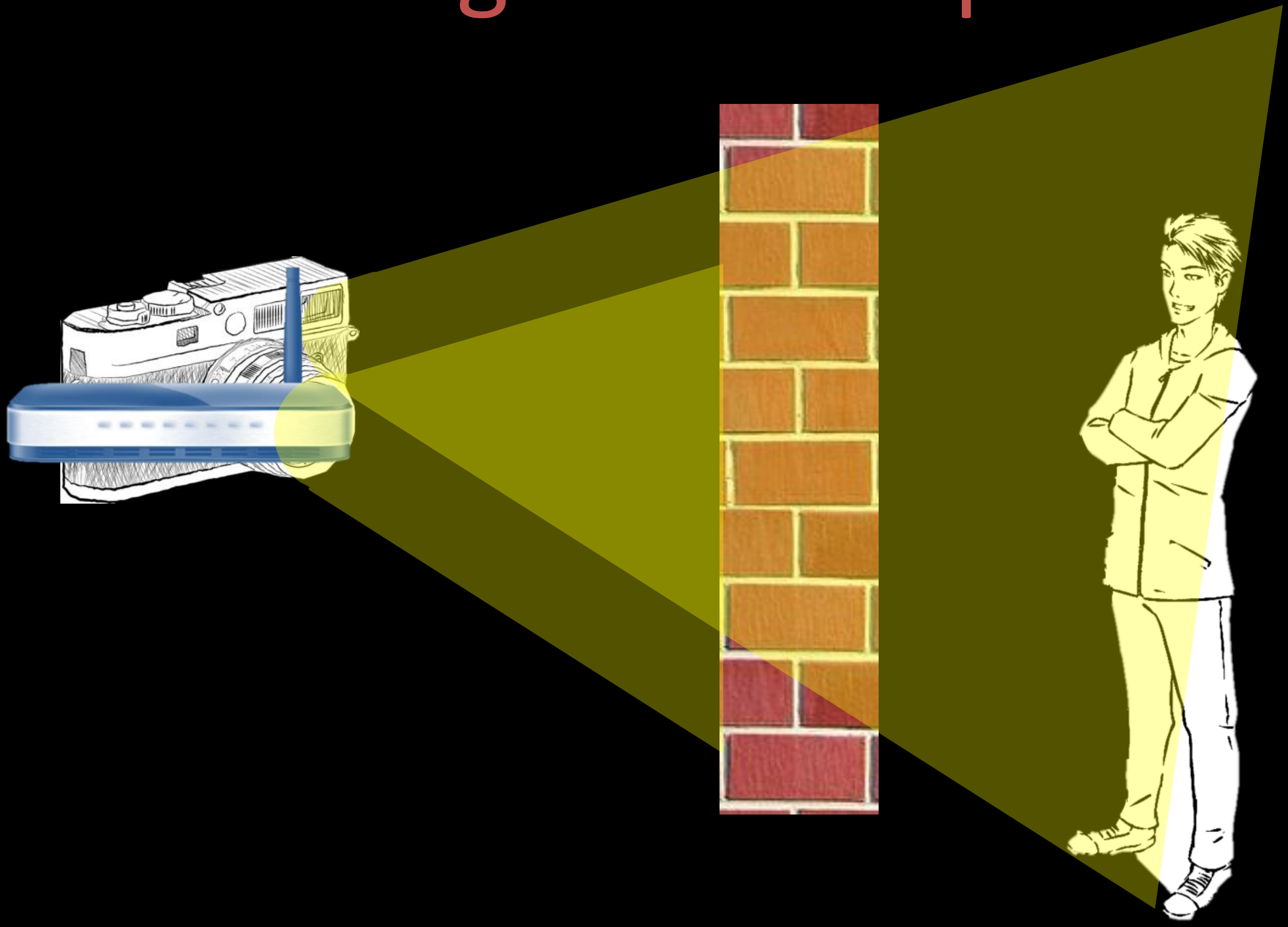


Active NLOS imaging using WiFi

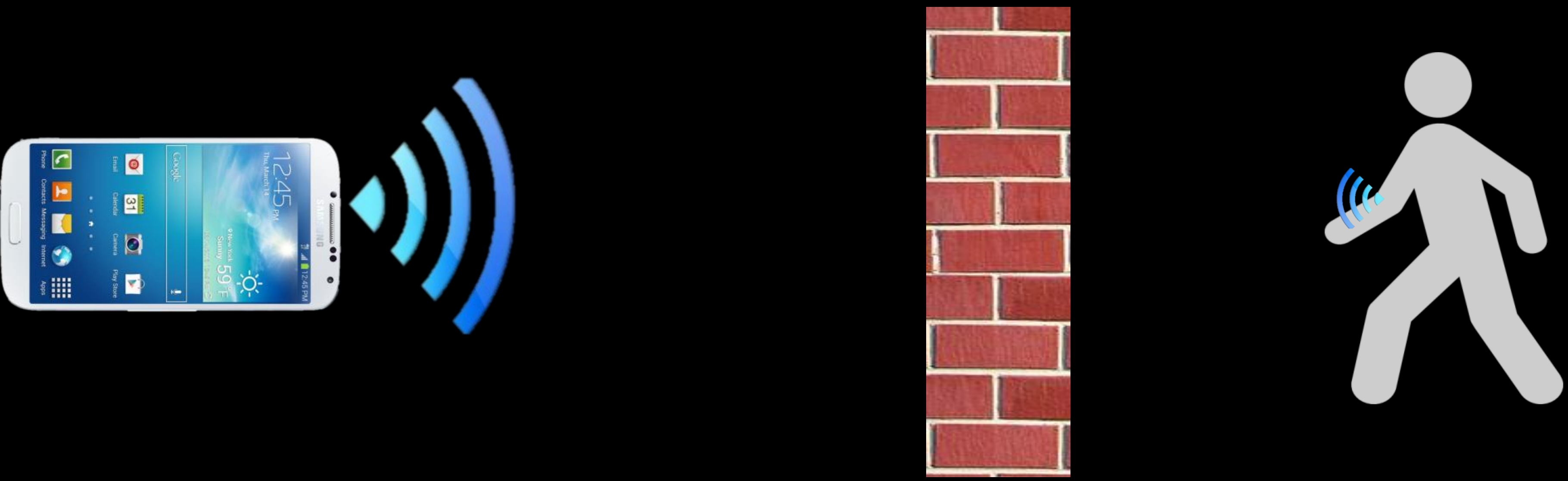
Imaging through occlusions



Imaging through occlusions
using radio frequencies



Key Idea



Challenges

Wall refection is 10,000x stronger than reflections coming from behind the wall

Tracking people from their reflections

Wi-Vi: Small, Low-Power, Wi-Fi

- Eliminate the wall’s reflection
- Track people from reflections
- Gesture-based interface
- Implemented on software radios

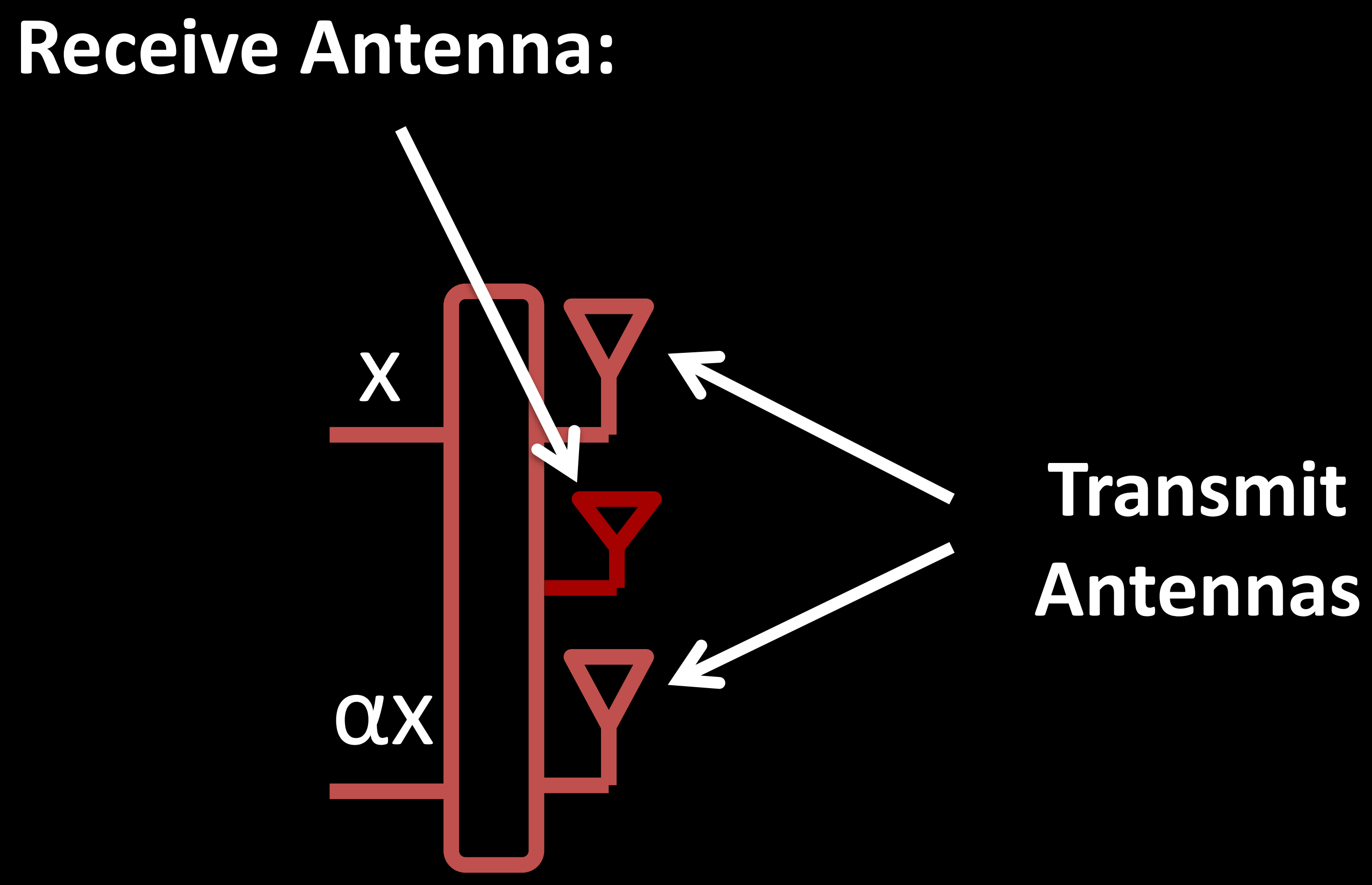
How Can We Eliminate the Wall's Reflection?

Idea: transmit two waves that cancel each other when they reflect off static objects but not moving objects

Wall is static → disappears

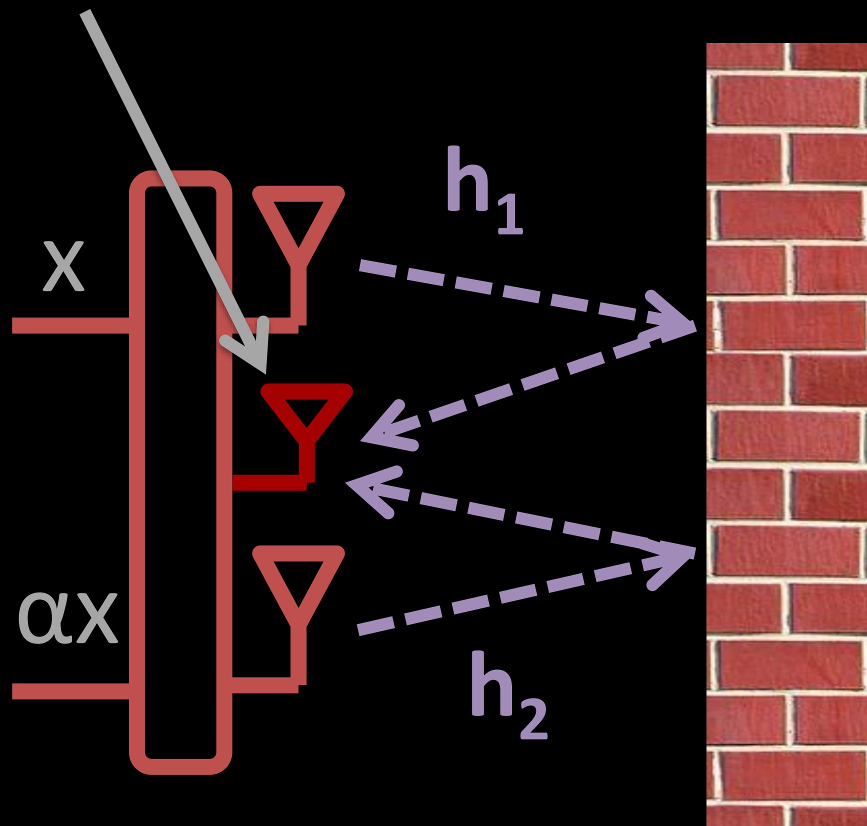
People tend to move → detectable

Eliminating the Wall's Reflection



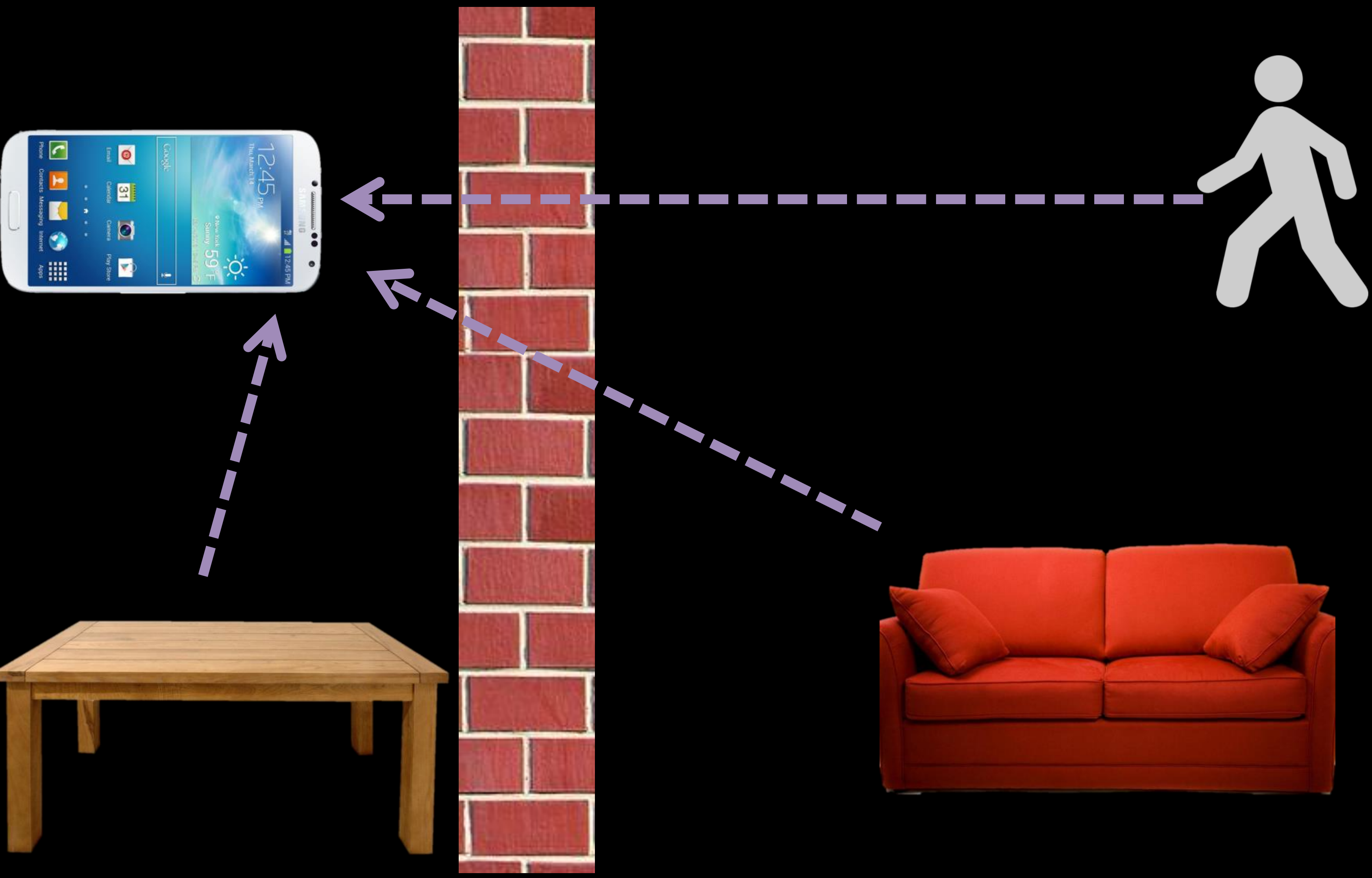
Eliminating the Wall's Reflection

Receive Antenna: $y = h_1 x + h_2 \alpha x$ → 0

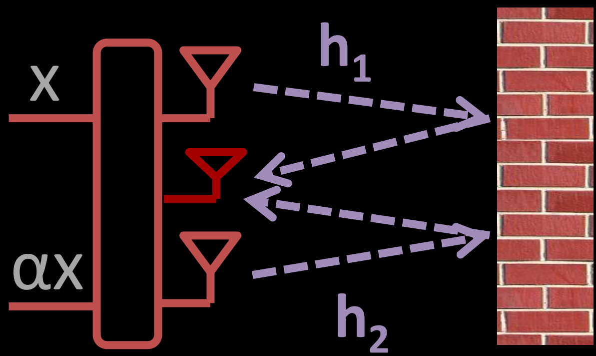


$\alpha = -h_1 / h_2$

Eliminating All Static Reflections



Eliminating All Static Reflections



$$y = h_1 x + h_2 \alpha x$$

Static objects (wall, furniture, etc.) have constant channels

$$y = h_1 x + h_2(- h_1 / h_2)x \rightarrow 0$$

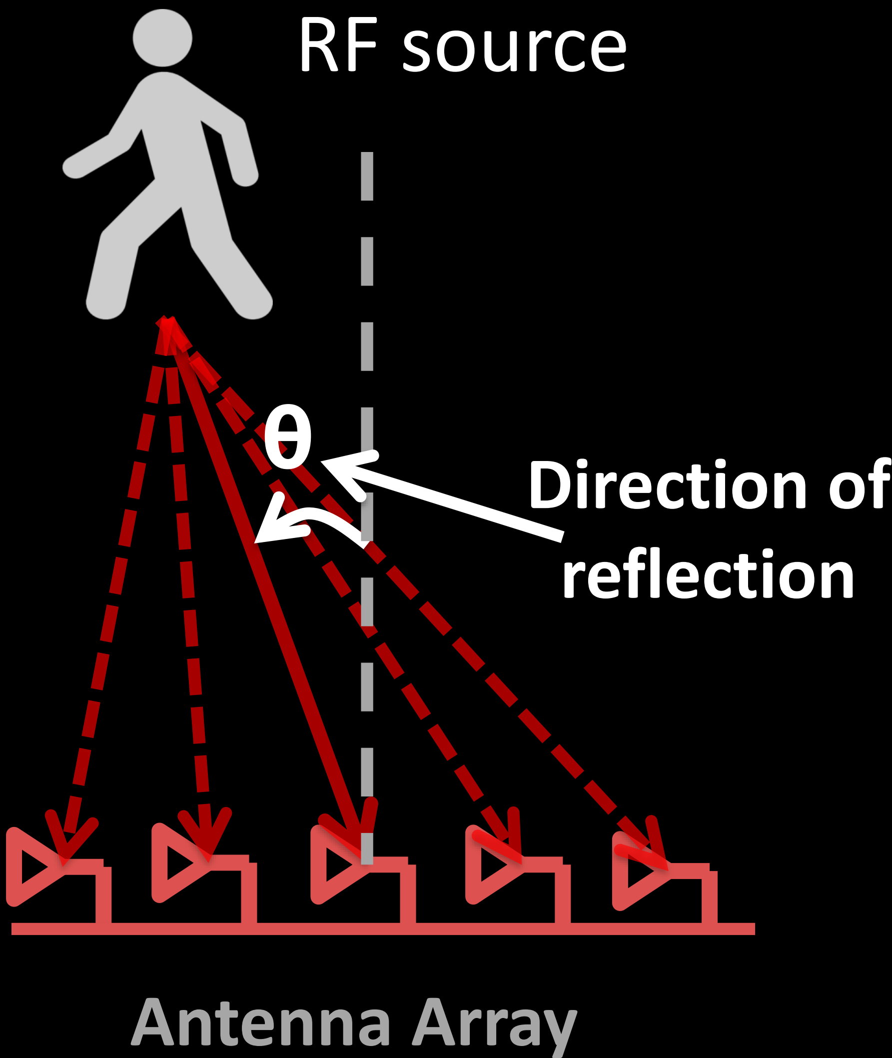
People move, therefore their channels change

$$y = h_1' x + h_2'(- h_1 / h_2)x$$

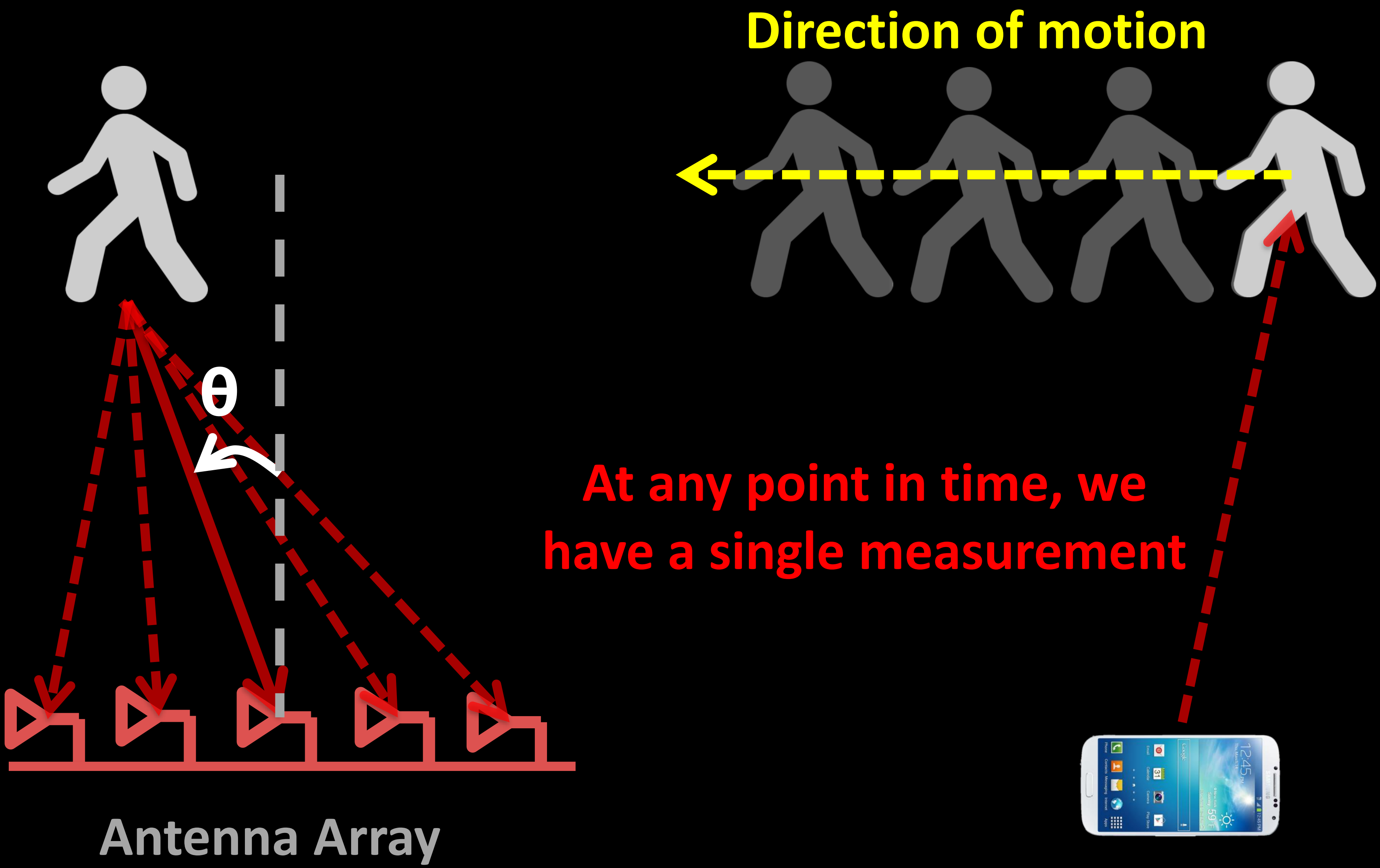
Not Zero

How Can We Track Using Reflections?

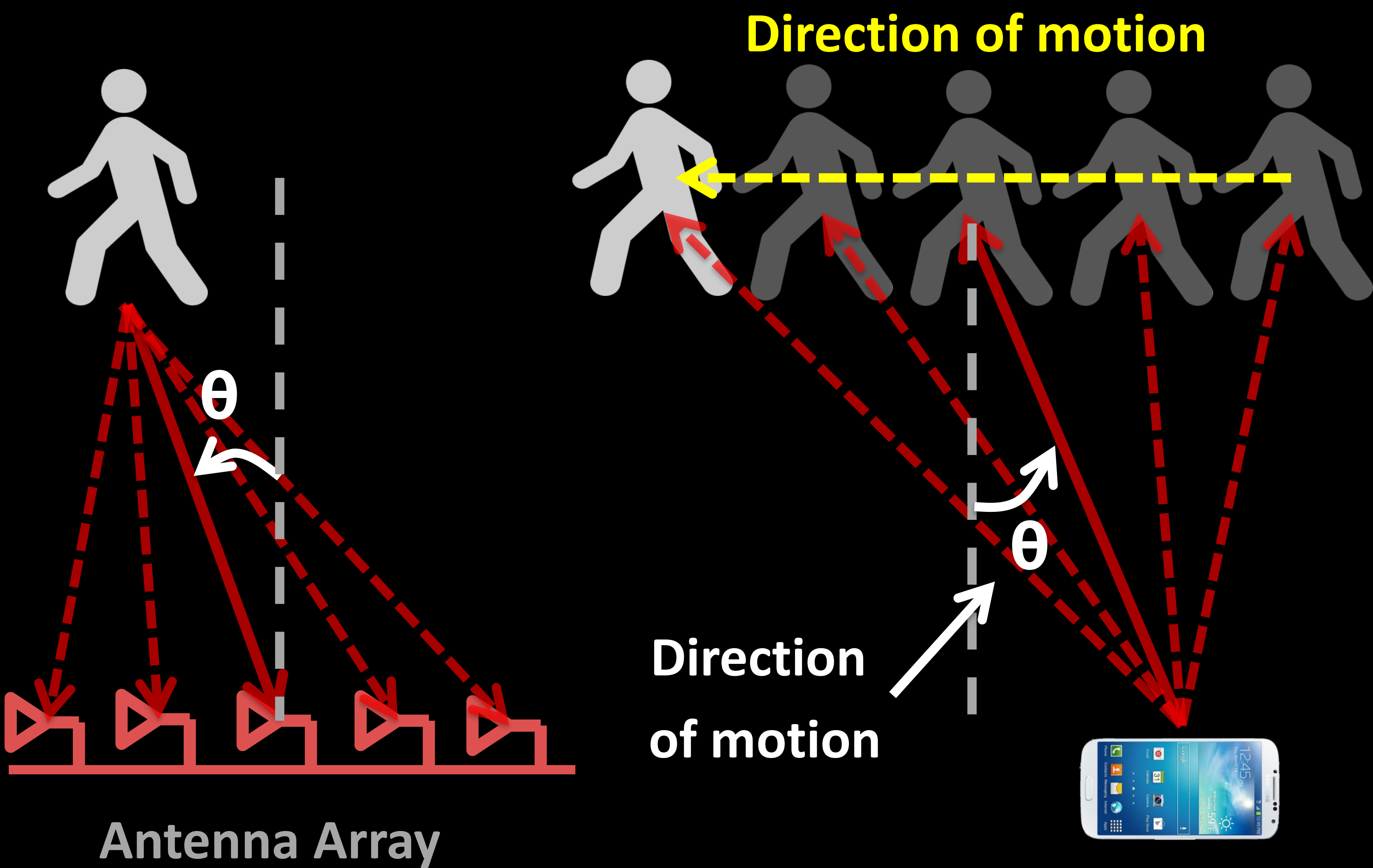
Tracking Motion



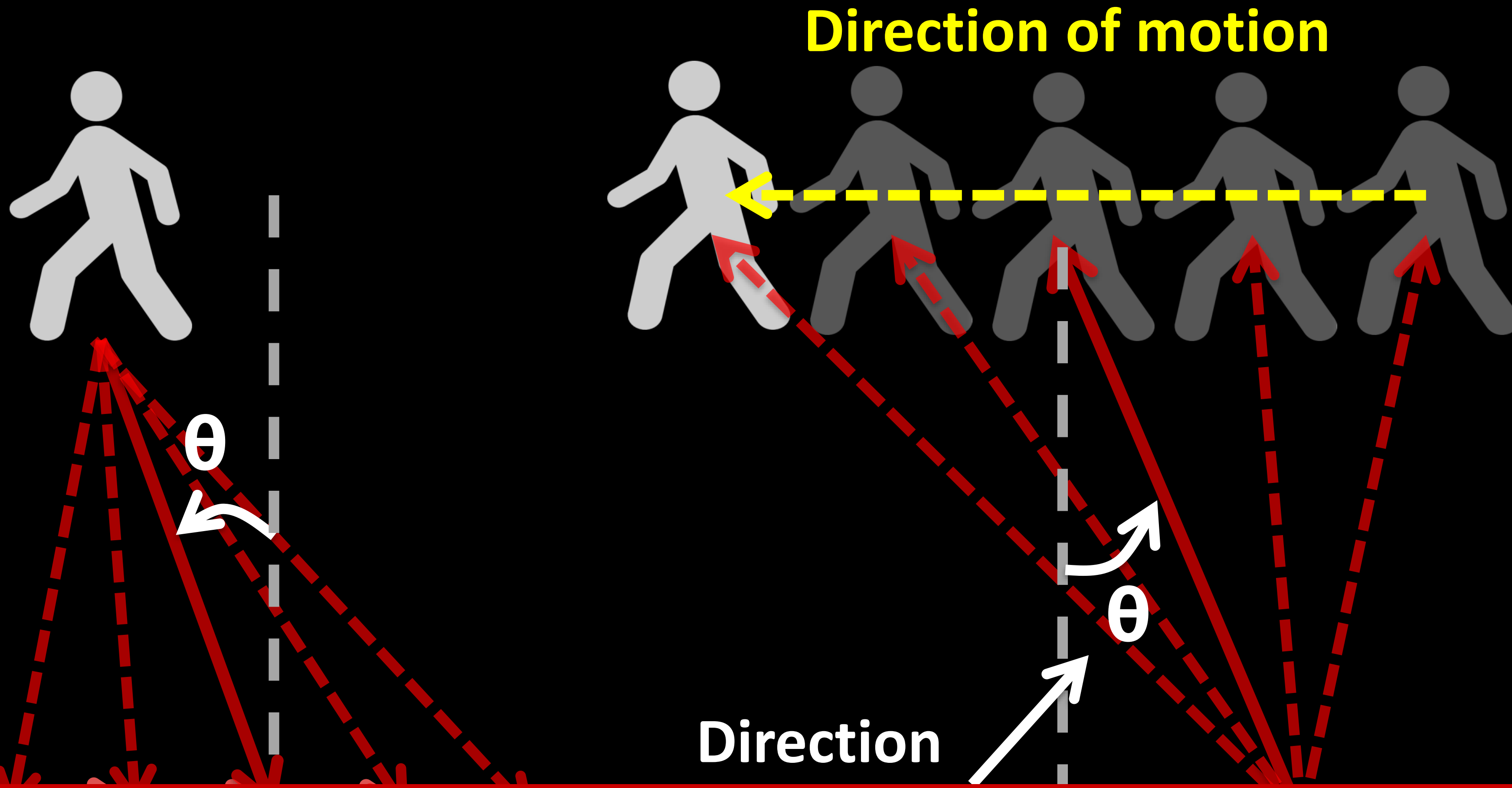
Tracking Motion



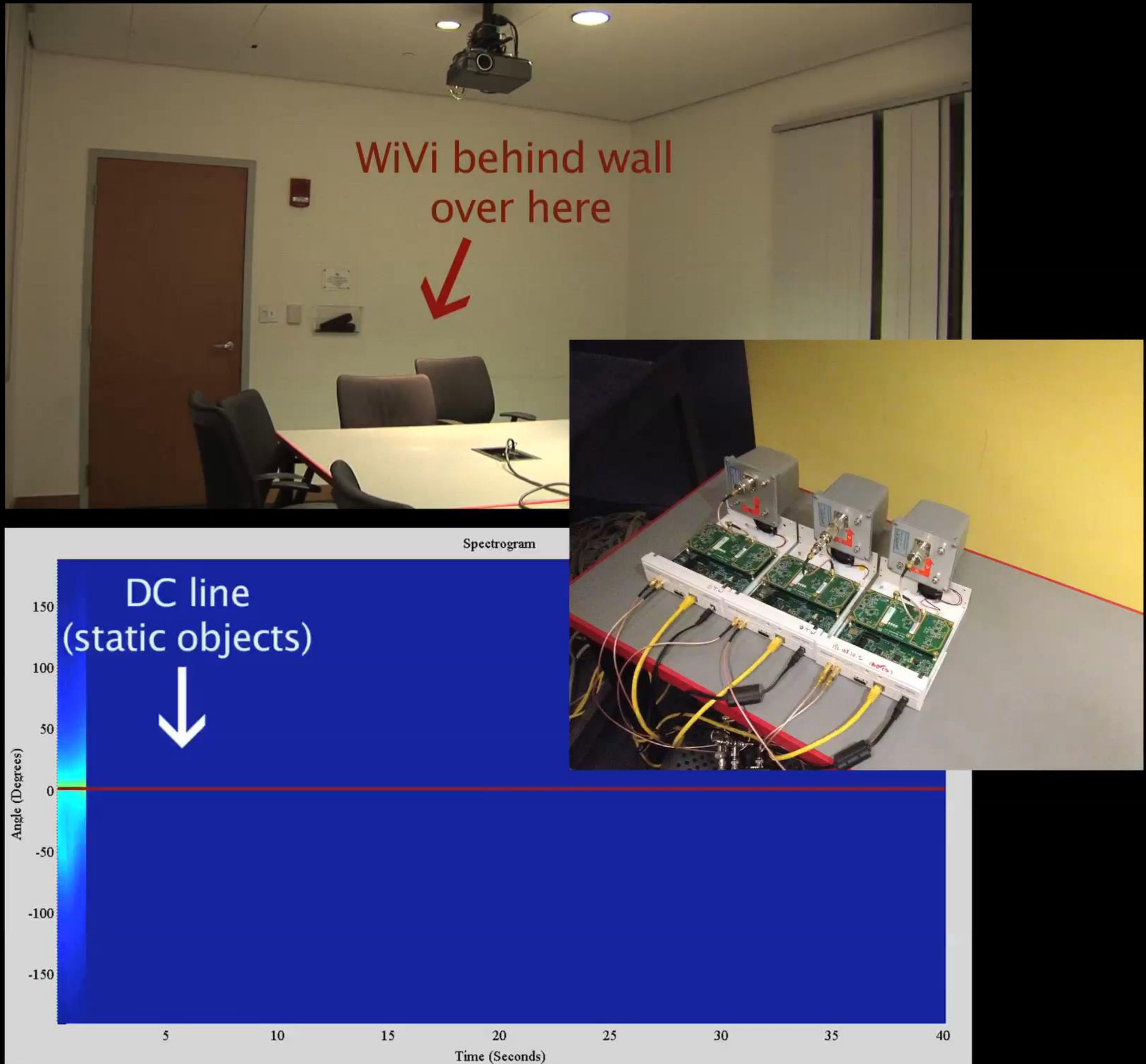
Tracking Motion



Tracking Motion



Human motion emulates antenna array


WiVi behind wall
over here
Spectrogram
DC line
(static objects)
Angle (Degrees)
150
100
50
0
-50
-100
-150
5
10
15
20
25
30
35
40
Time (Seconds)

A Through-Wall Gesture Interface

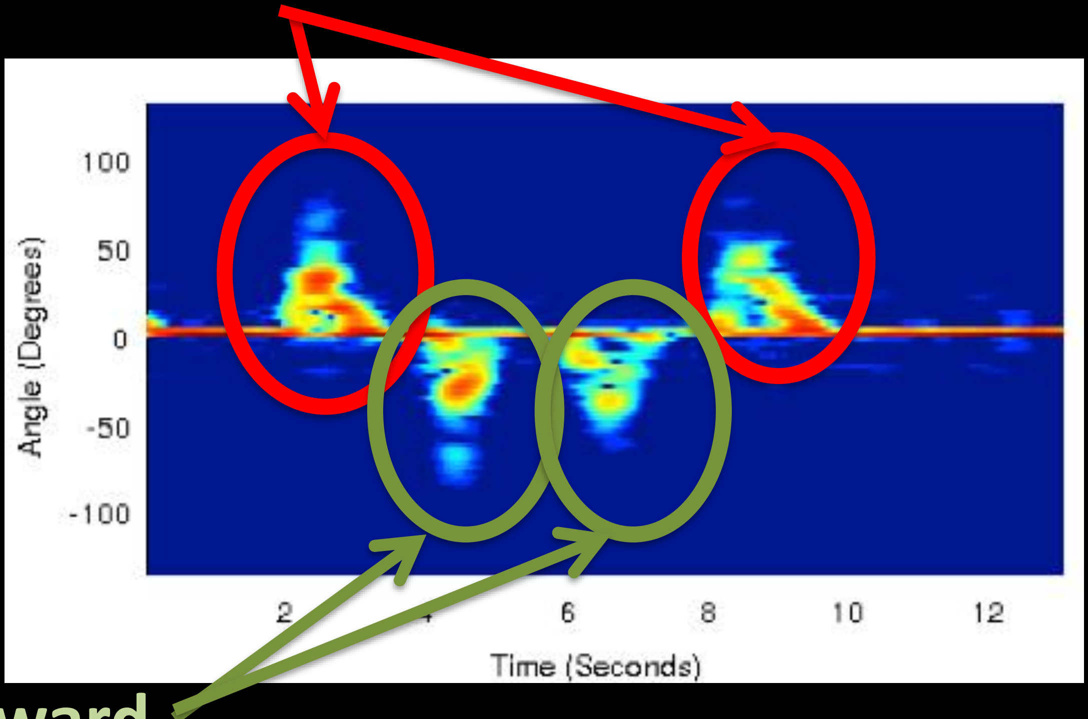
- Sending Commands with Gestures
- Two simple gestures to represent bit ‘0’ and bit ‘1’
- Can combine sequence of gestures to convey longer message

Gesture Encoding

Bit ‘0’: step forward followed by step backward

Bit ‘1’: step backward followed by step forward

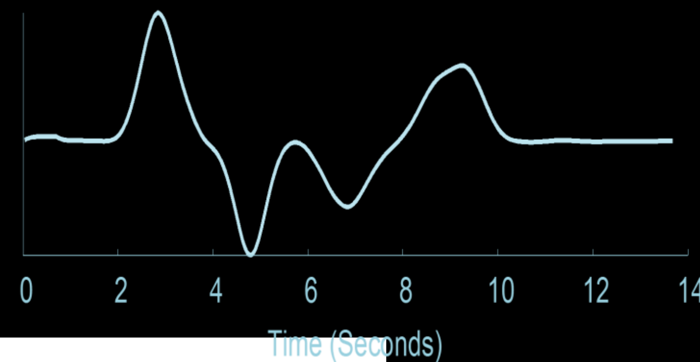
Step Forward



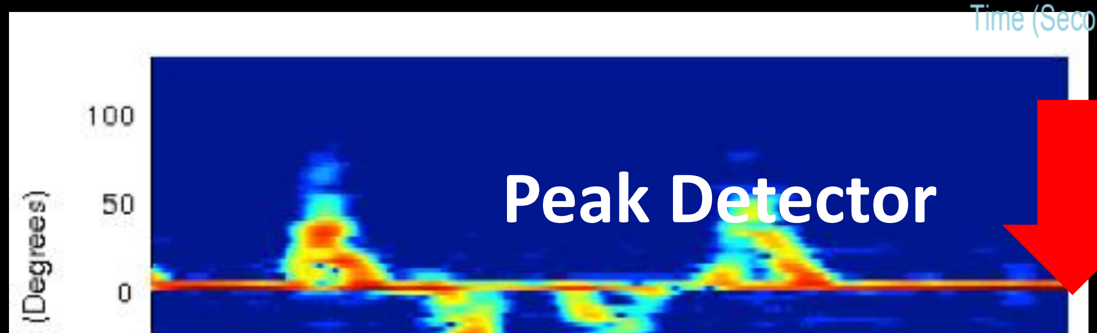
Step Backward

Gesture Decoding

Matched Filter

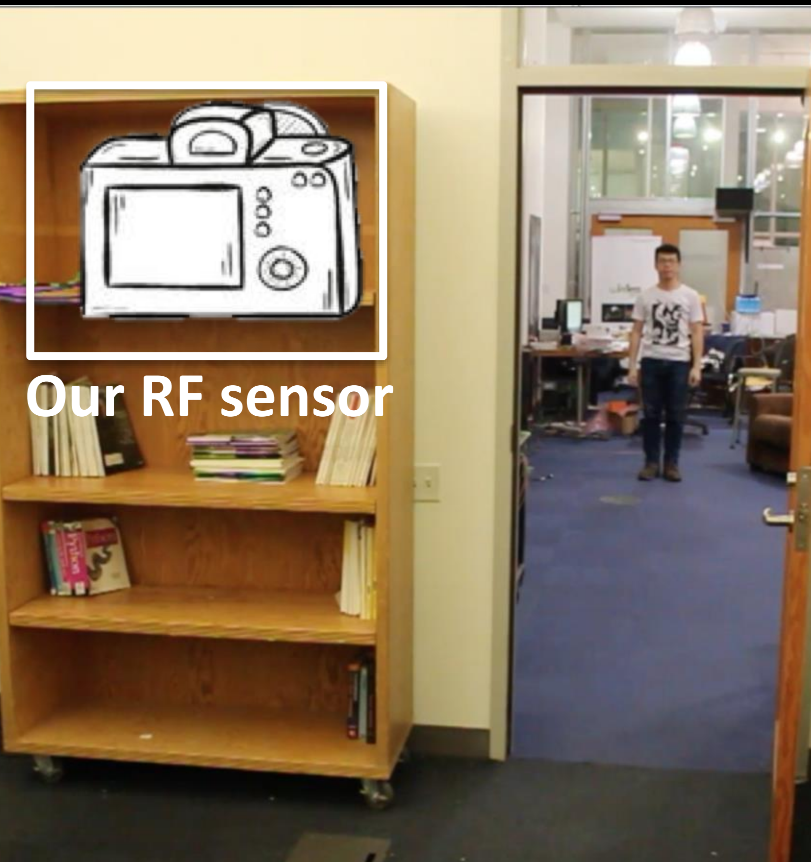


Peak Detector



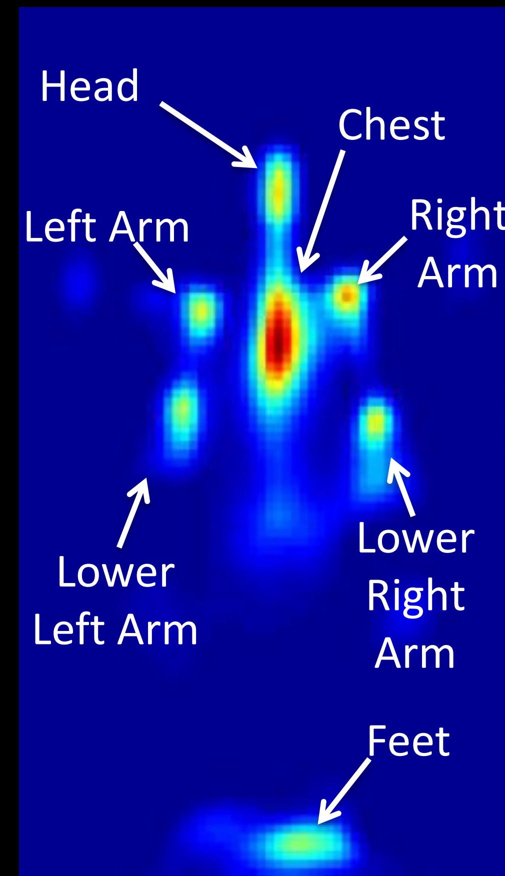
Gesture interface that works through walls and none-line-of-sight

Imaging through occlusions
using radio frequencies



Camera image

Our output

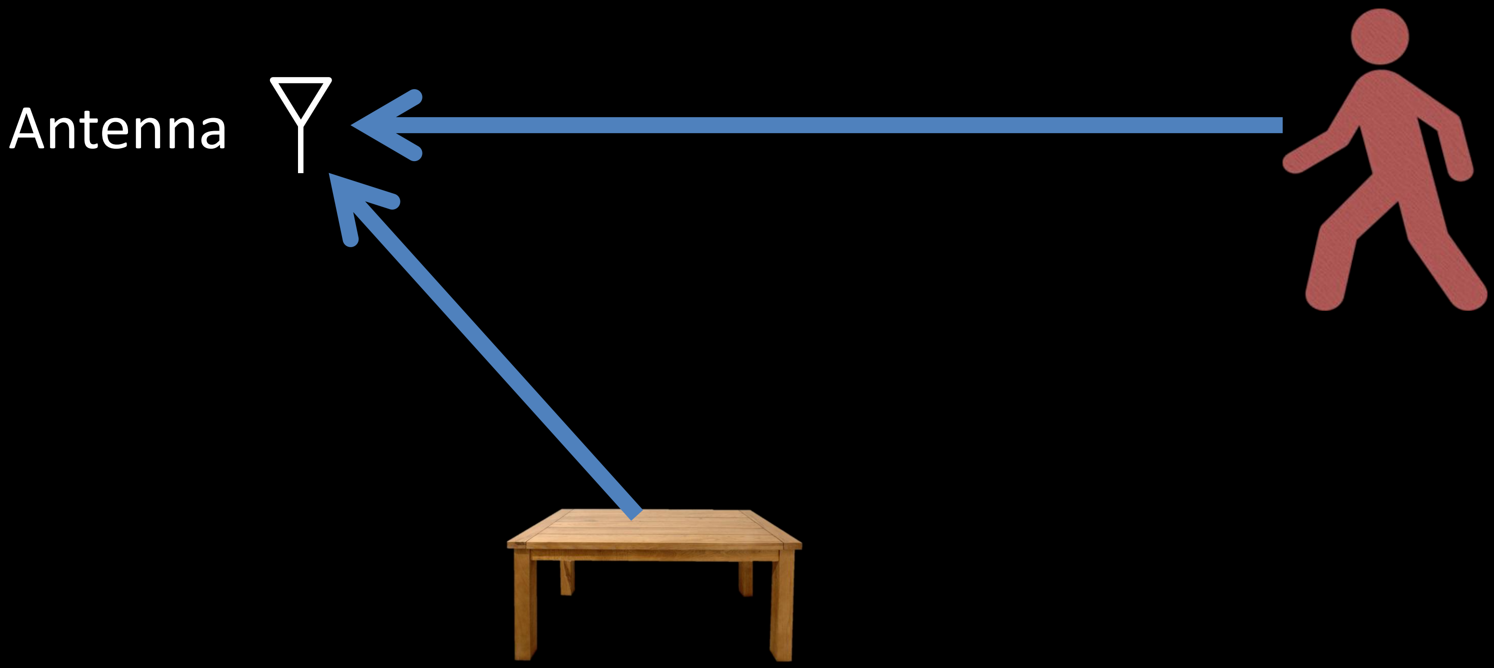


Traditional Imaging	RF Imaging
• Cannot image through occlusions like walls	+ Walls are transparent and can image through them
• Form 2D images using lenses	− No lenses at these frequencies

Imaging with RF

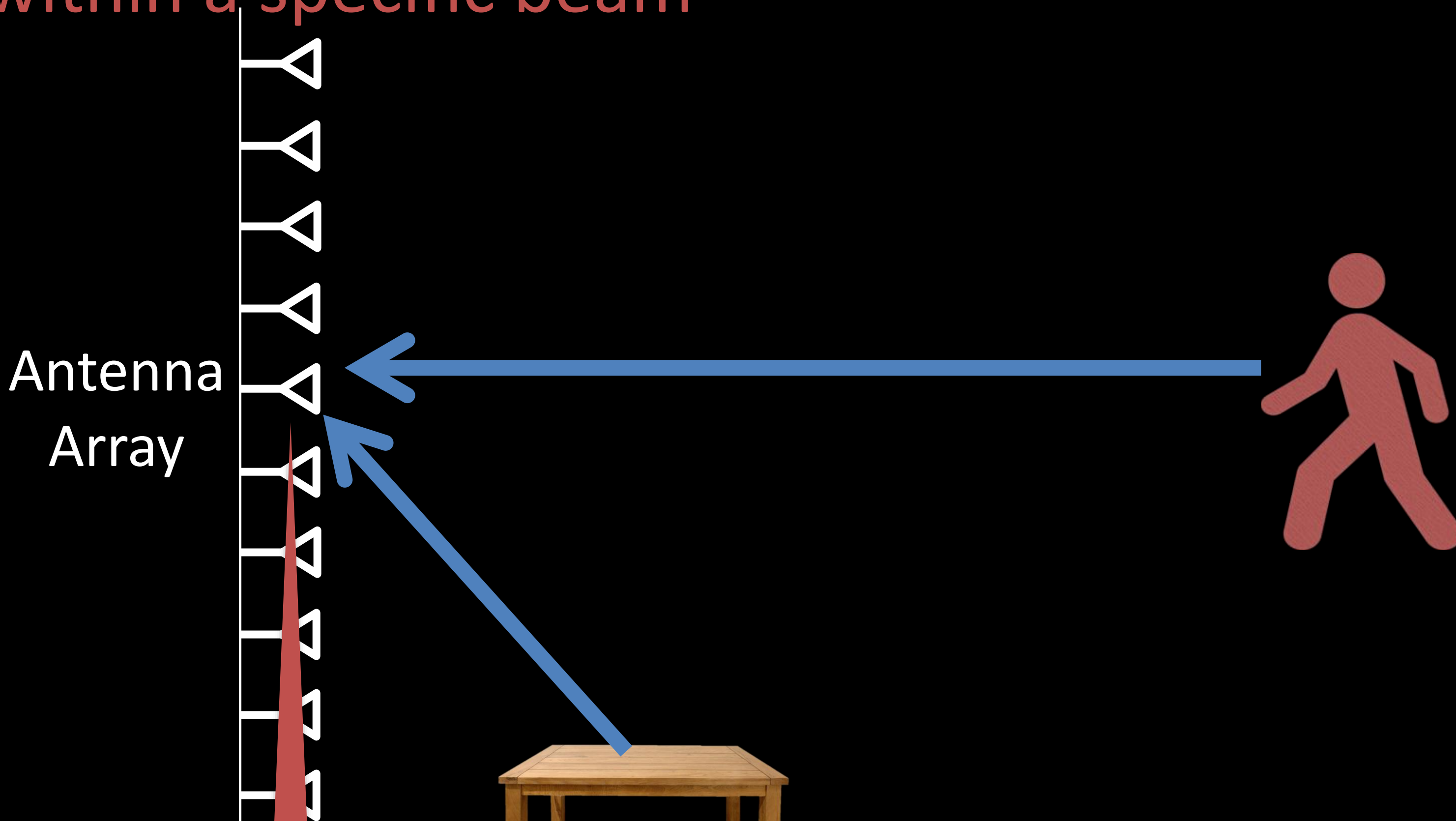
No lens at these frequencies

Antenna cannot distinguish bounces from different directions



Imaging with RF

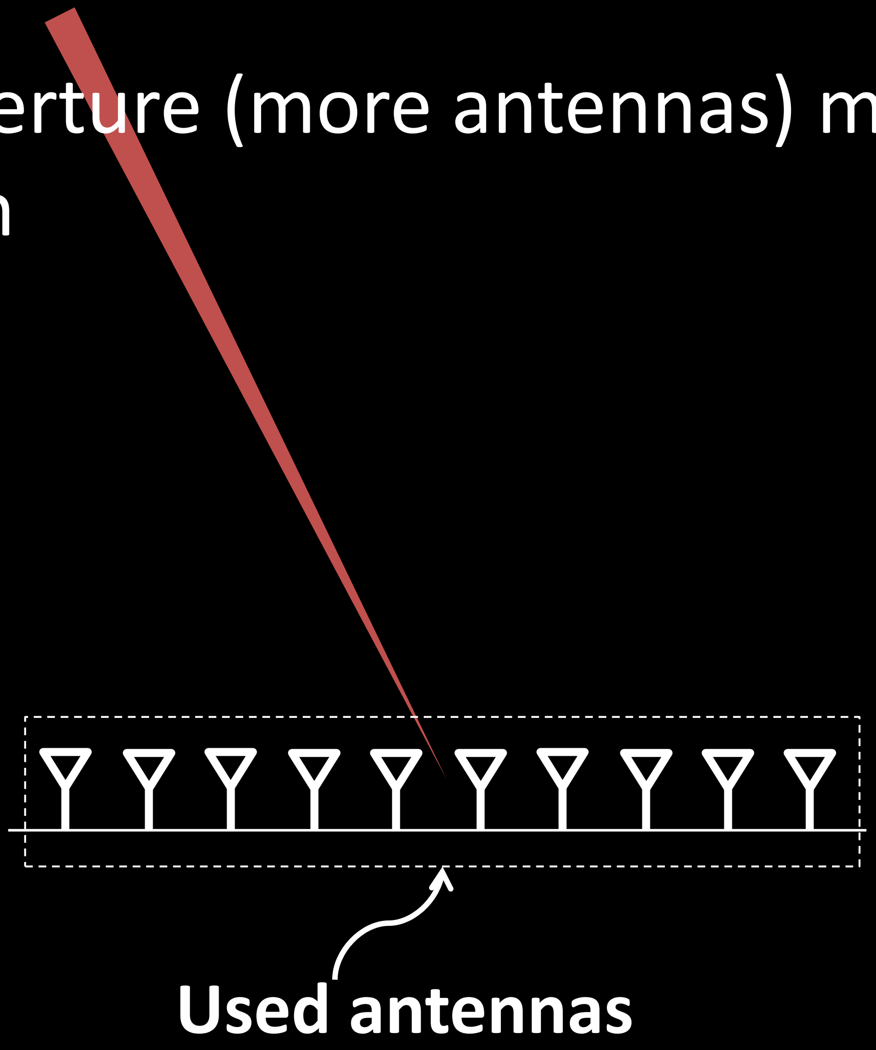
Beamforming: Use multiple antennas to scan reflections within a specific beam



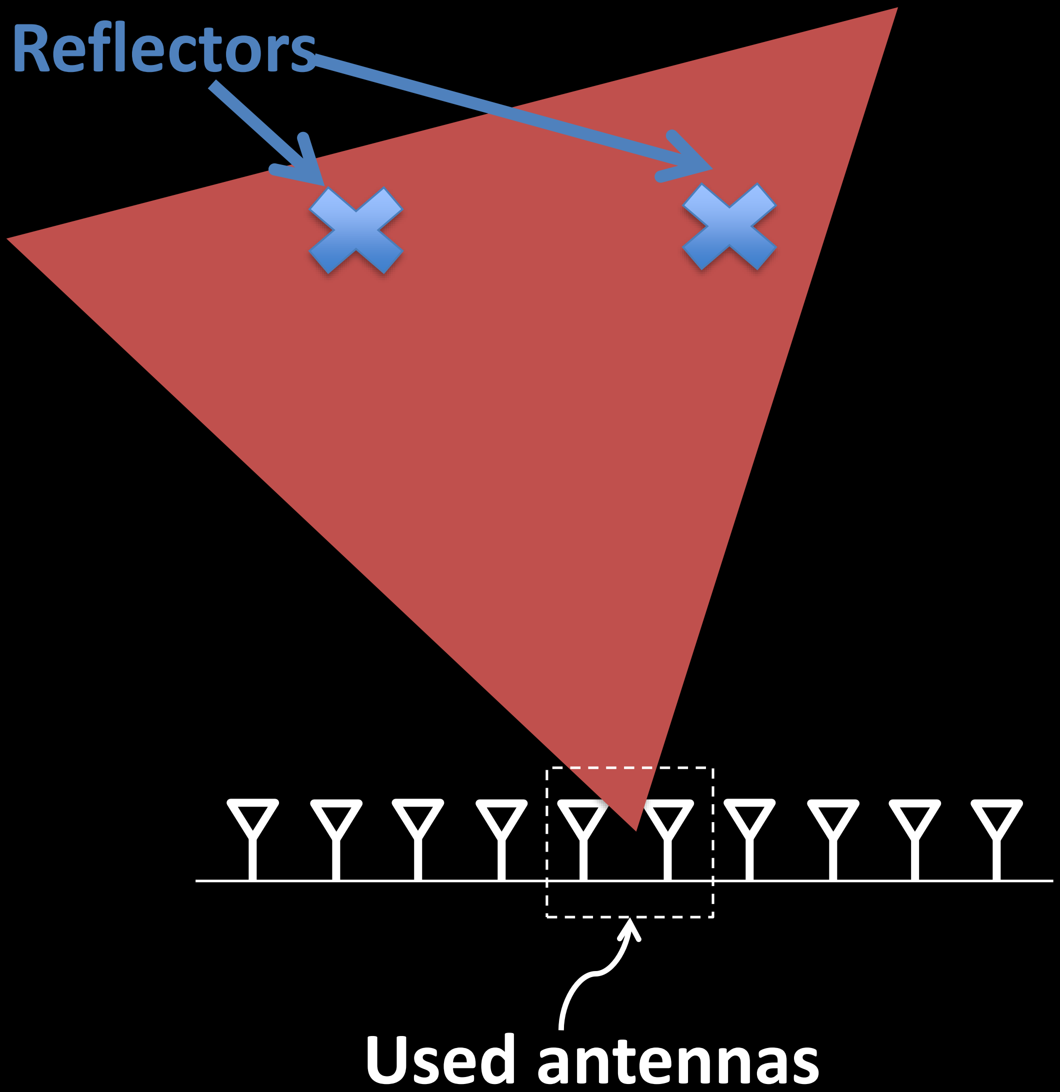
Extend to 3D with time-of-flight measurements by repeating this at every depth

Coarse-to-fine Scan

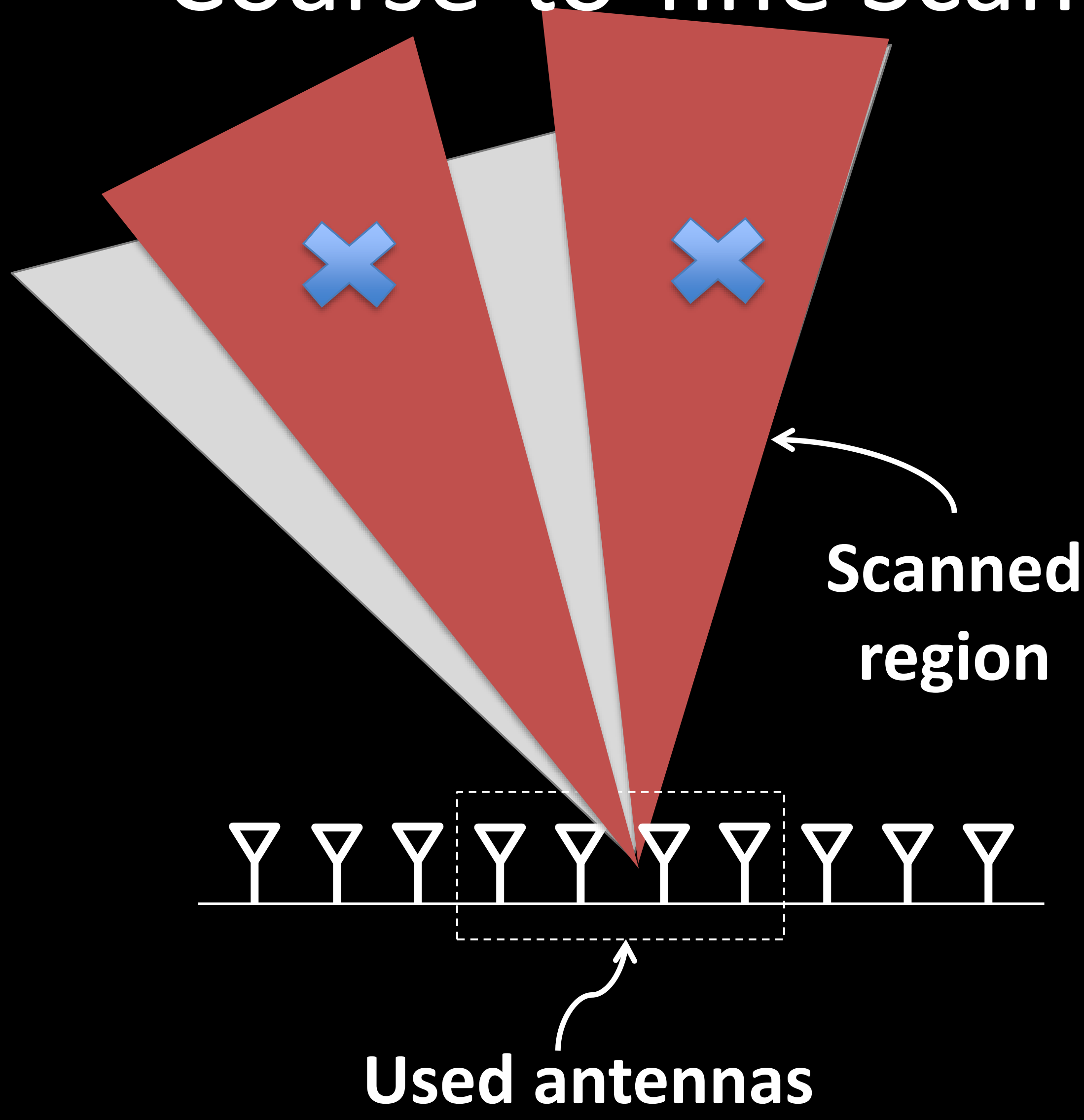
- Larger aperture (more antennas) means finer resolution



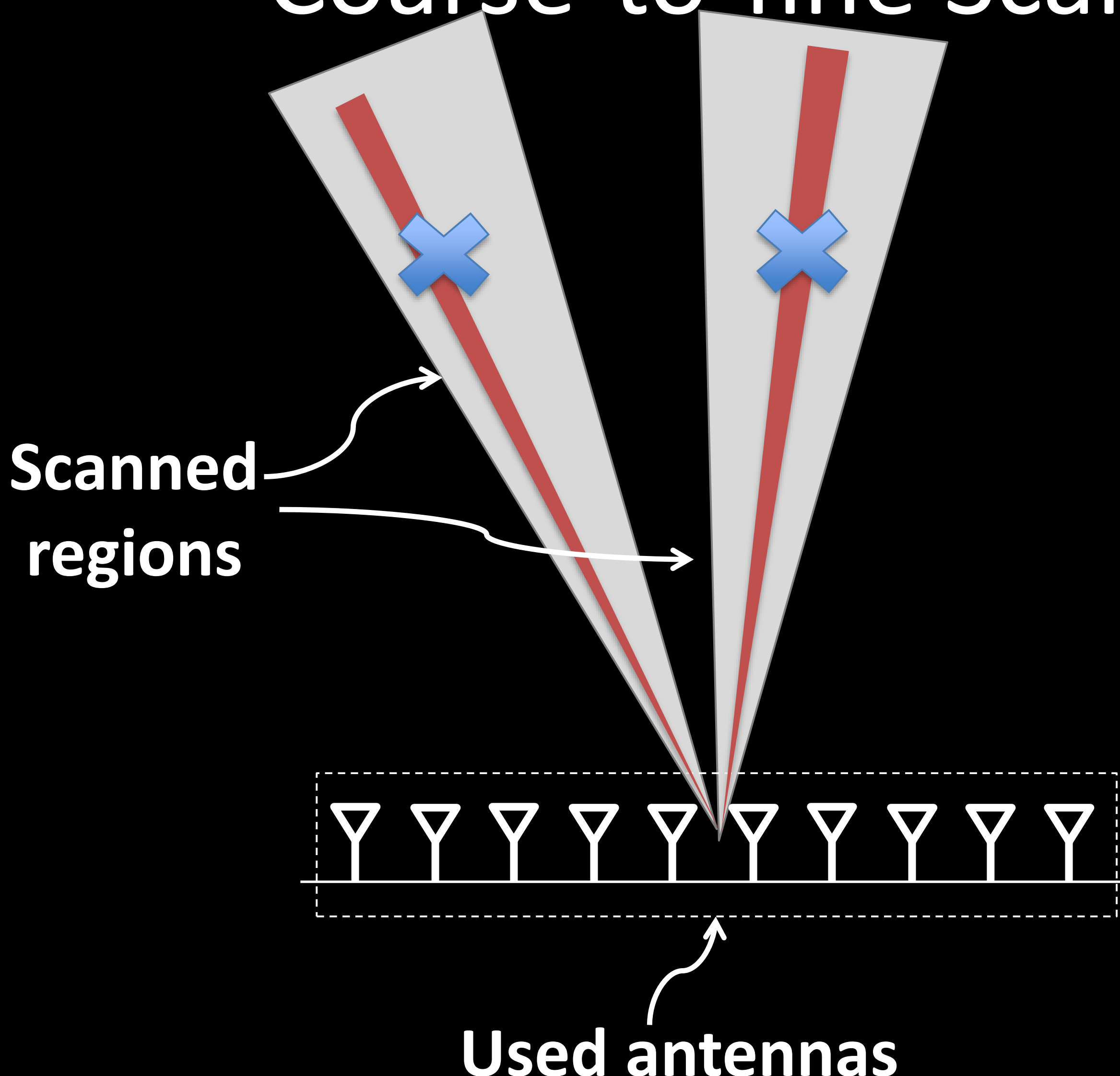
Coarse-to-fine Scan



Coarse-to-fine Scan



Coarse-to-fine Scan



Traditional Imaging

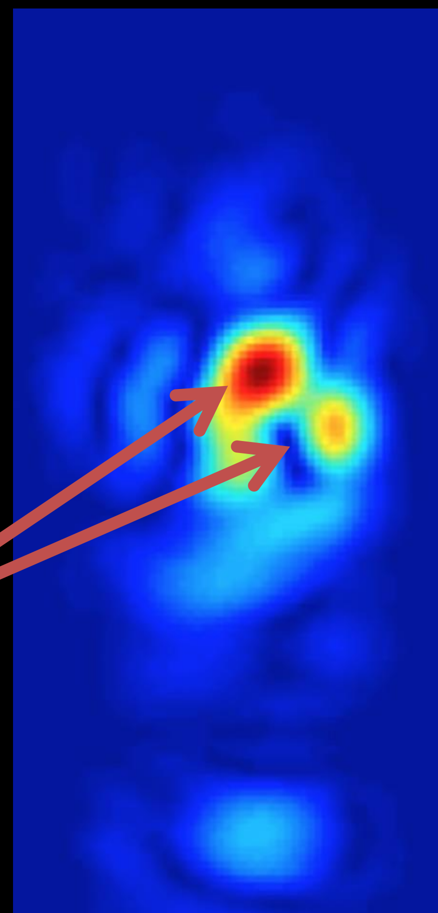
- Cannot image through occlusions like walls
- Form 2D images using lenses
- Get a reflection from all points: can image all the body

RF Imaging

+ Walls are transparent and can image through them
− No lenses at these frequencies
− No reflections from most points: all reflections are specular

Challenge: Don’t get reflections from most points in RF

Output of 3D RF Scan



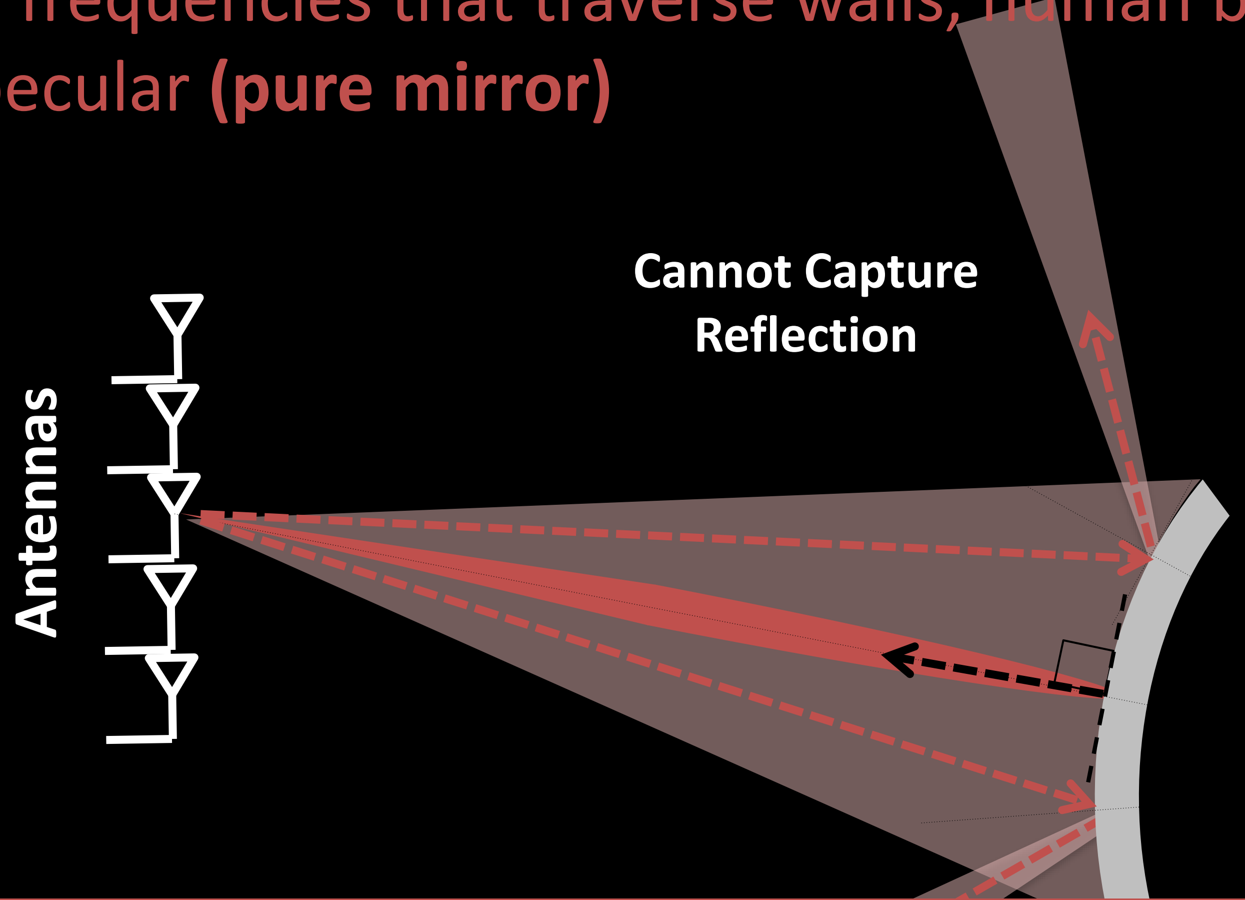
Blobs of reflection power

Challenge: Don't get reflections from most points in RF

At frequencies that traverse walls, human body parts are specular **(pure mirror)**

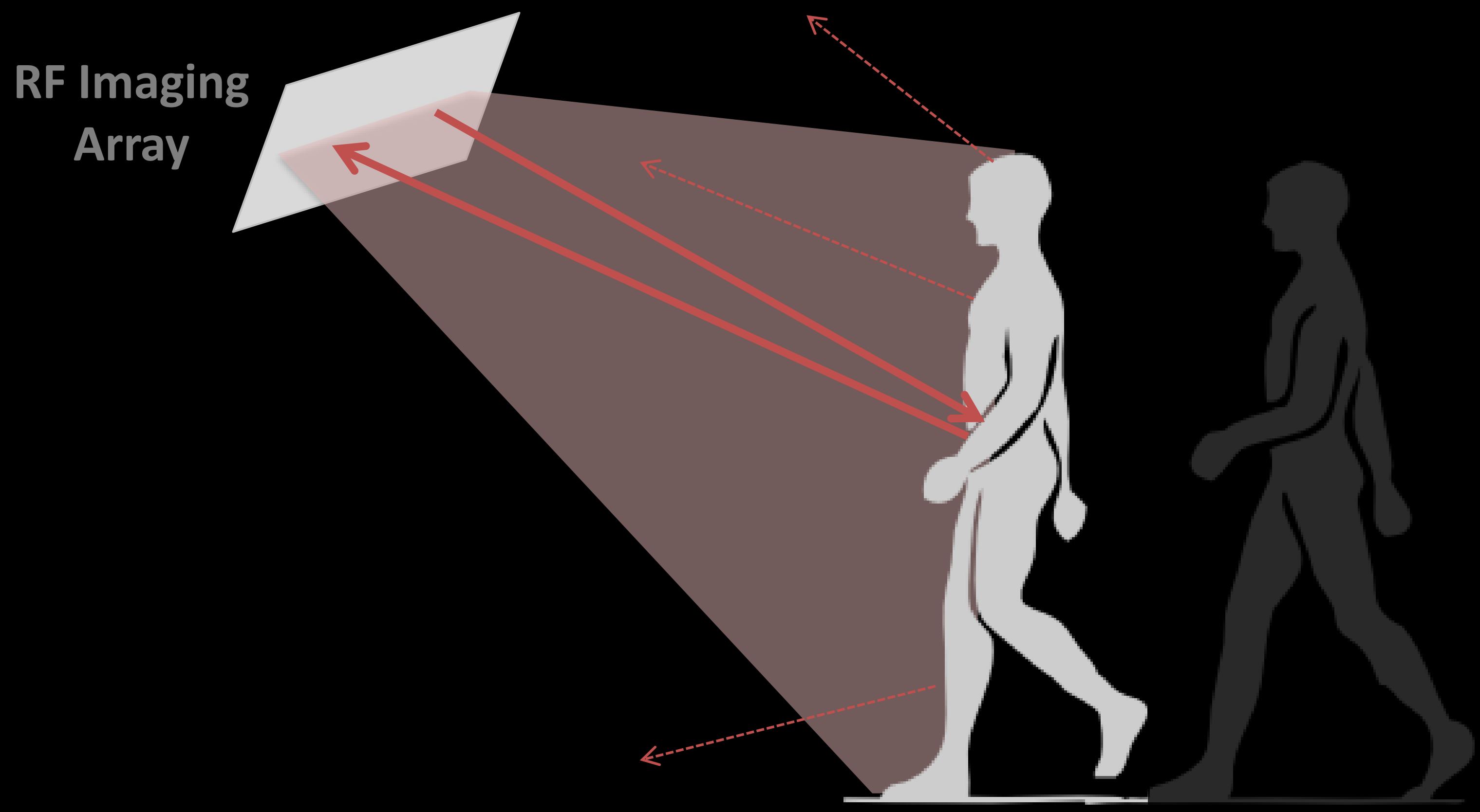
Challenge: Don't get reflections from most points in RF

At frequencies that traverse walls, human body parts are specular **(pure mirror)**



At every point in time, get reflections from only a subset of body parts

Solution Idea: Exploit Human Motion and Aggregate over Time



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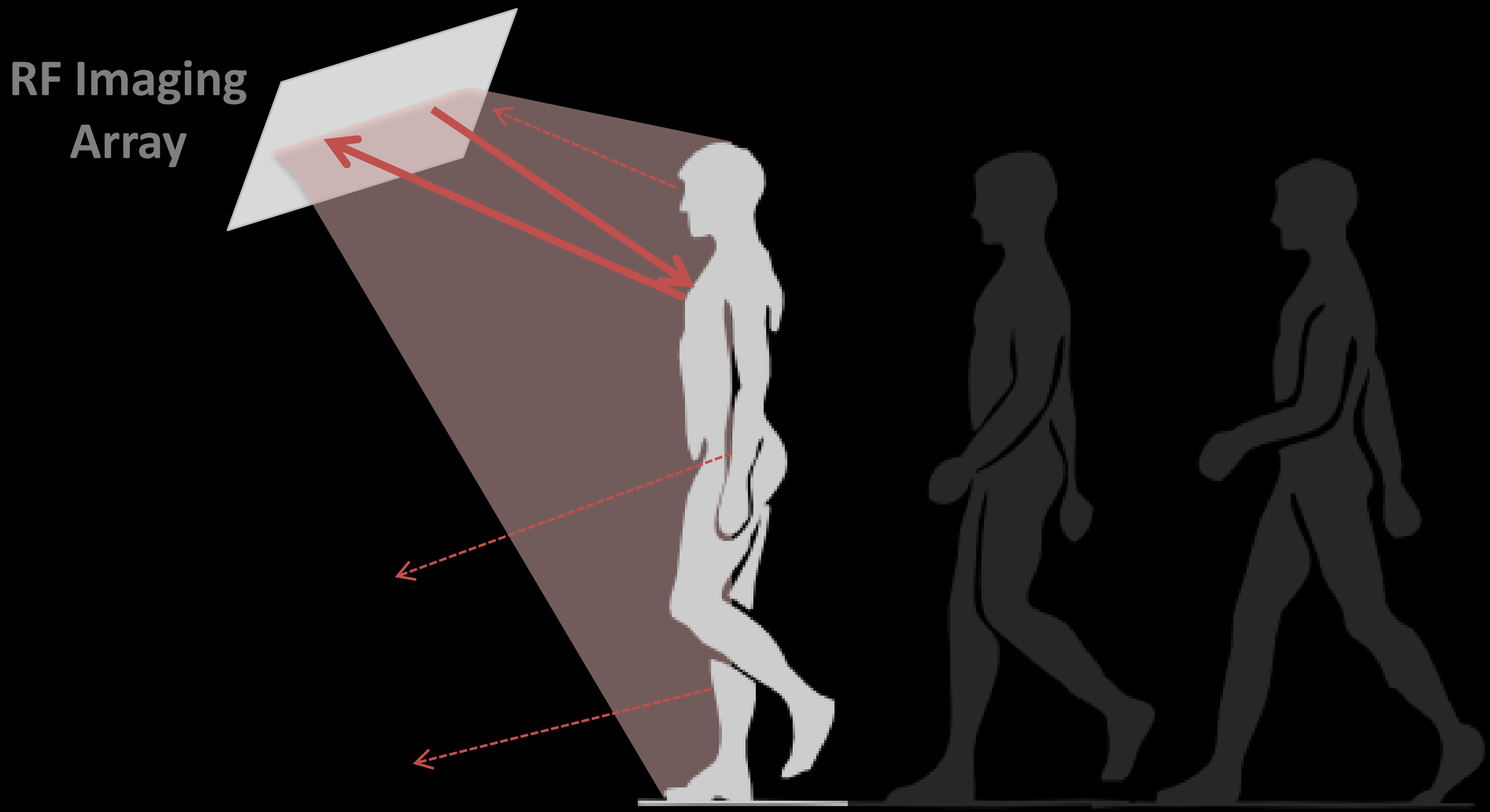
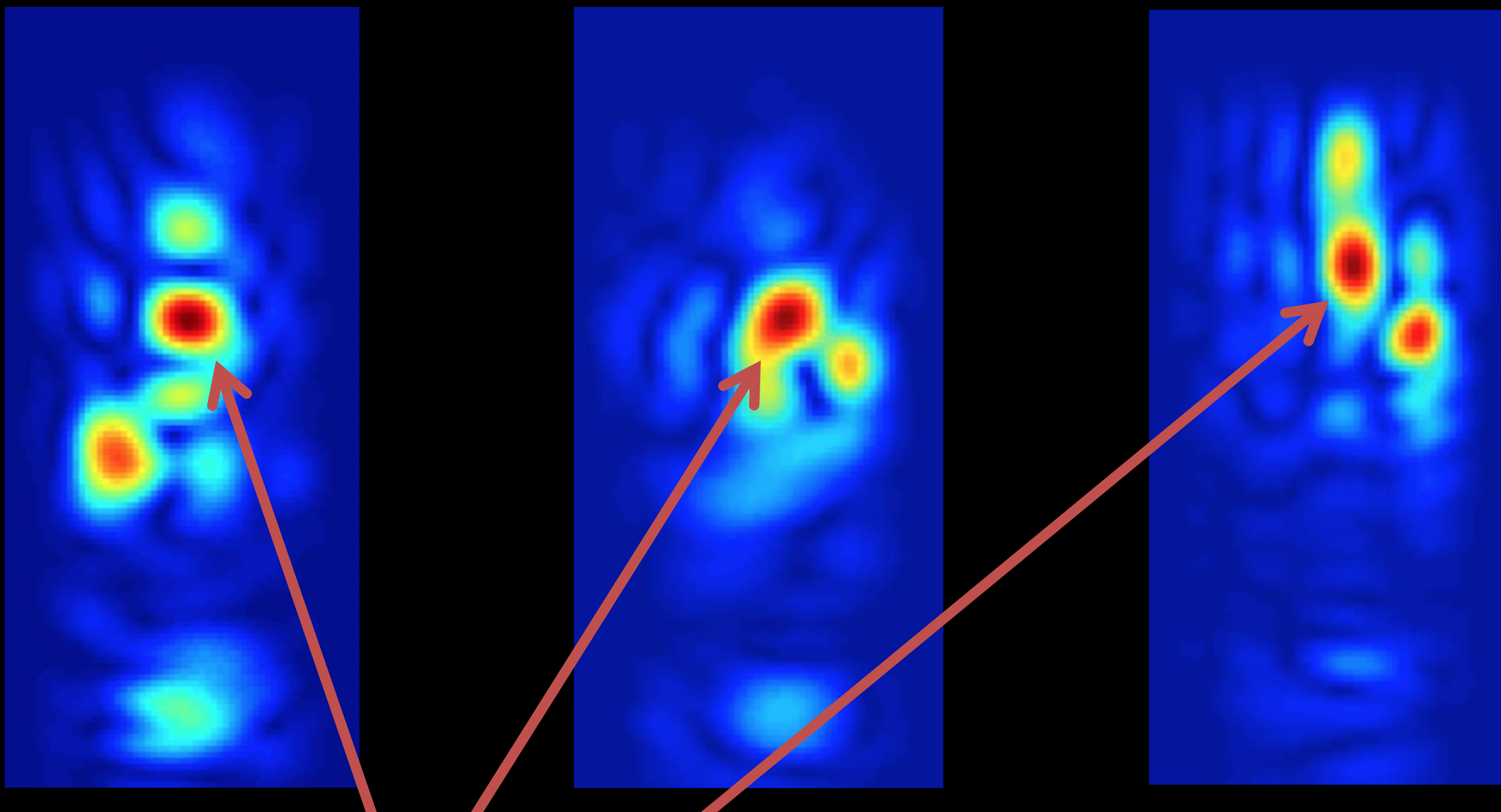
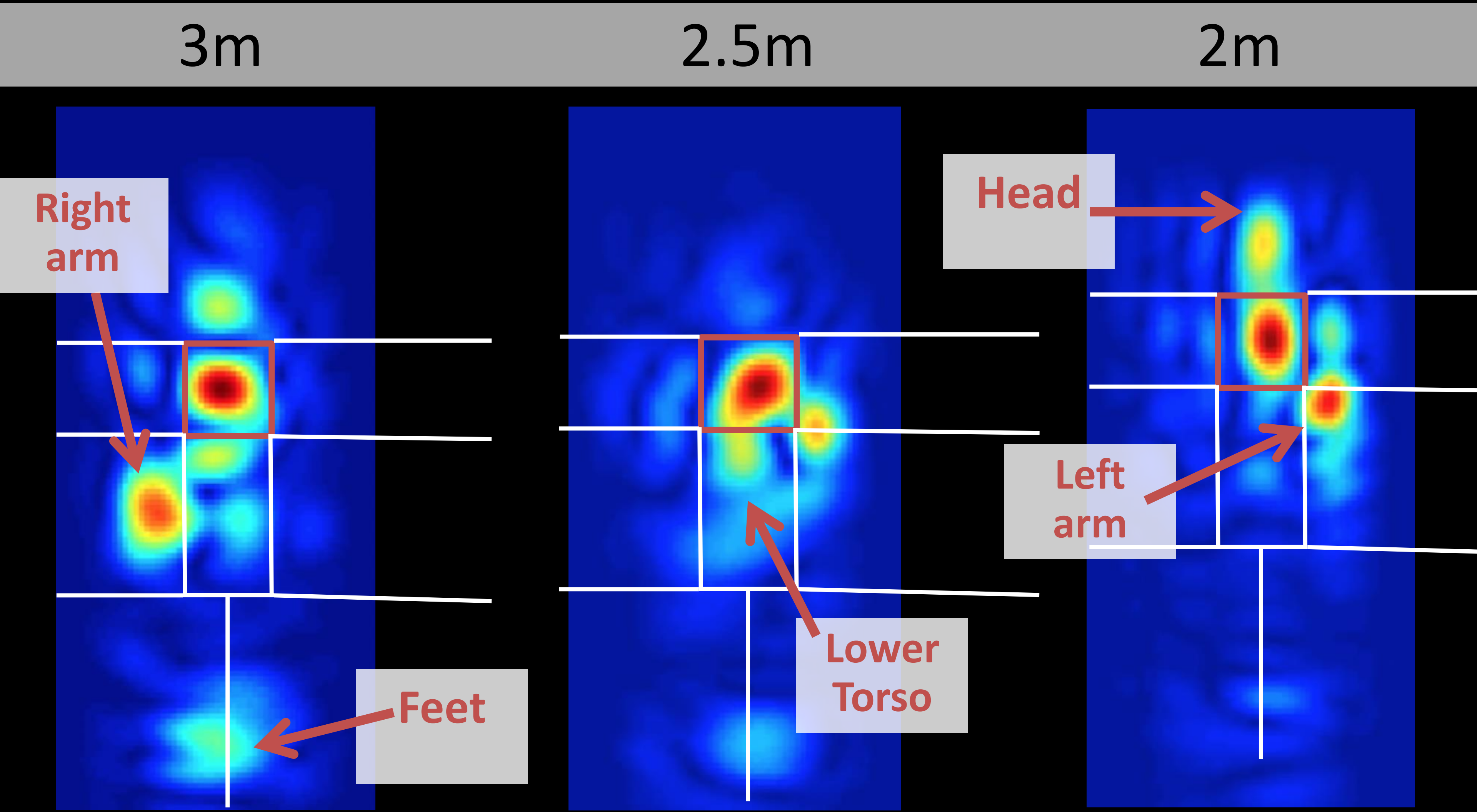


Human Walks toward Sensor



Human Walks toward Sensor

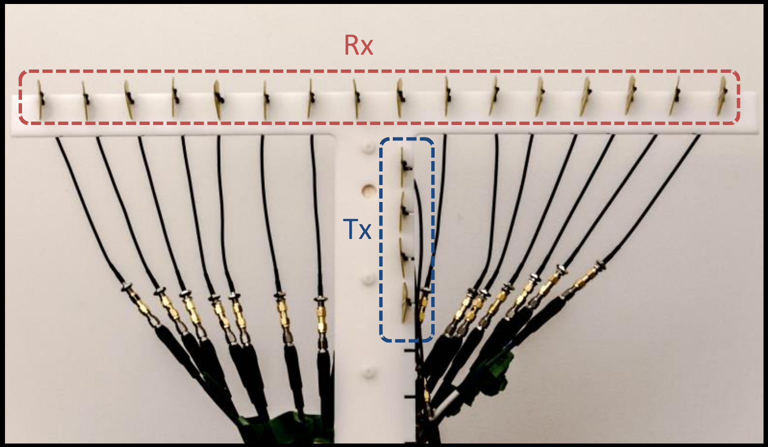


Combine the various snapshots

Human Walks toward Sensor

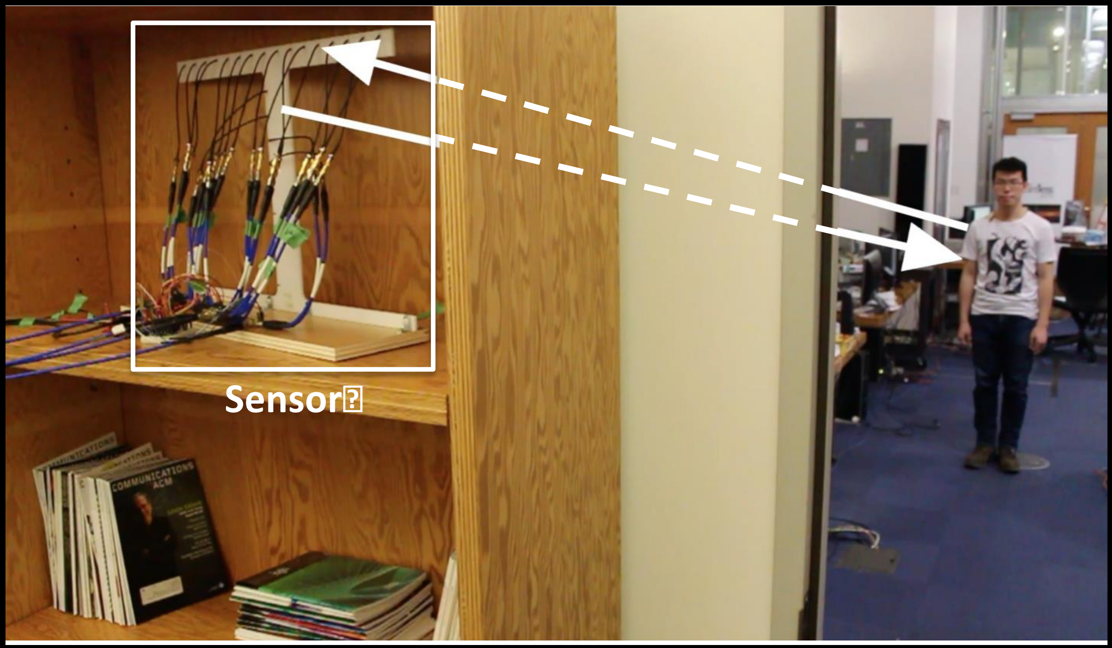
Implementation

- Hardware
  - 2D Antenna Array
  - Built RF circuit
    - 1/1,000 power of WiFi
    - USB connection to PC



- Software
  - Coarse-to-fine algorithm implemented in GPU to generate reflection snapshots in real-time

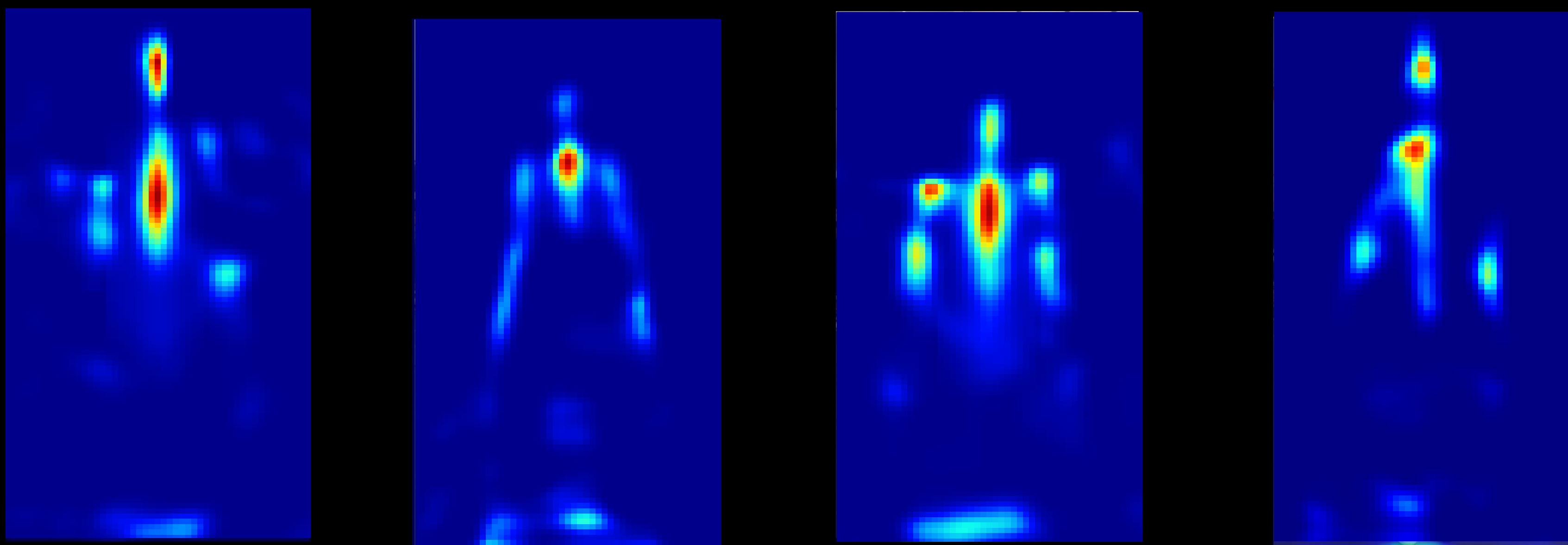
Evaluation



- RF-Capture sensor placed behind the wall
- 15 participants
- Use Kinect as baseline when needed

Sample Captured Figures through Walls

Sample Captured Figures through Walls

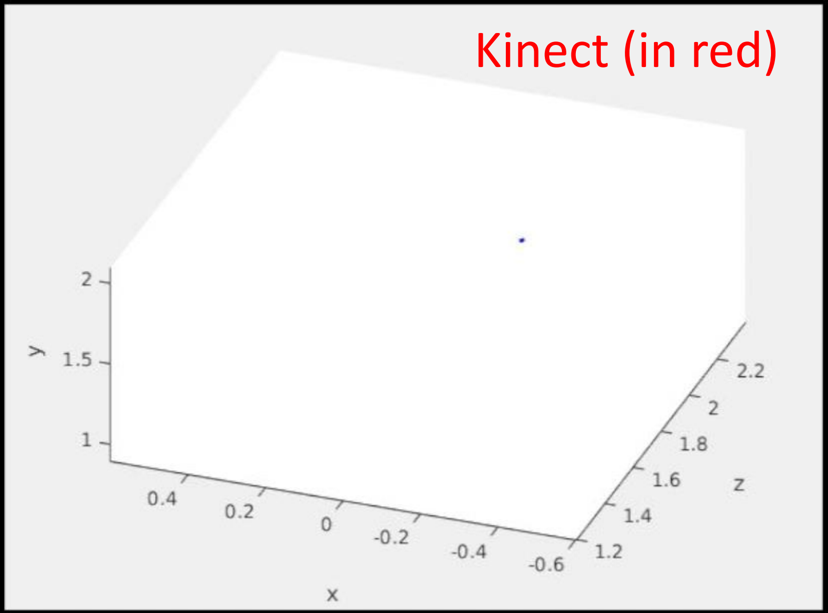


Tracking result

Writing in the air

Device

Our Tracking Result



Median Accuracy is 2cm

Passive NLOS imaging using accidental pinholes

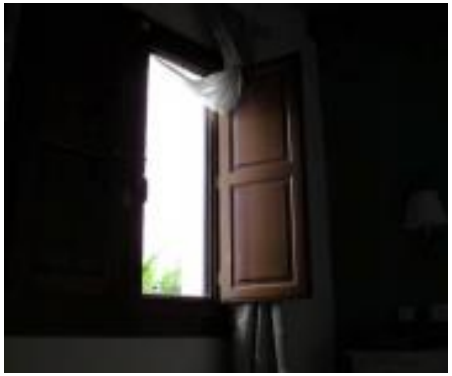
What does this image say about the world outside?

Accidental pinhole camera

Accidental pinhole camera

projected pattern on the wall

window with smaller gap

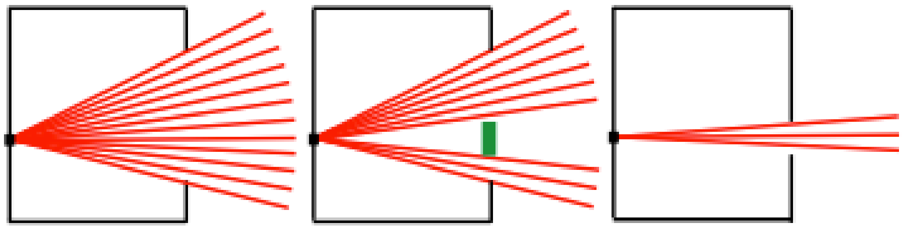


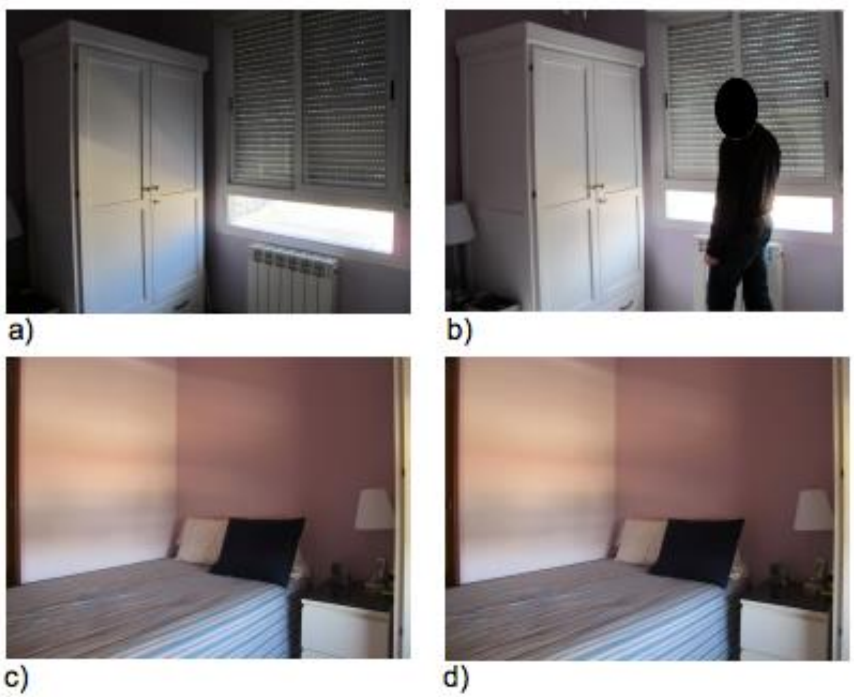
window is an aperture

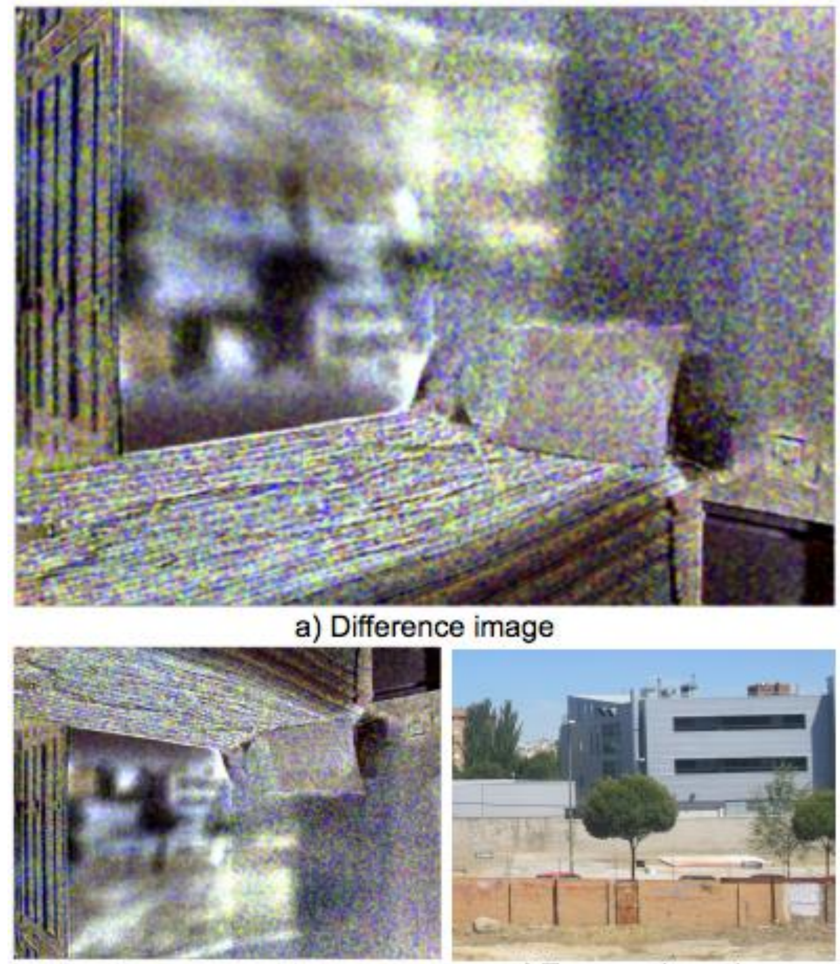
upside down

view outside window

Accidental pinspeck camera







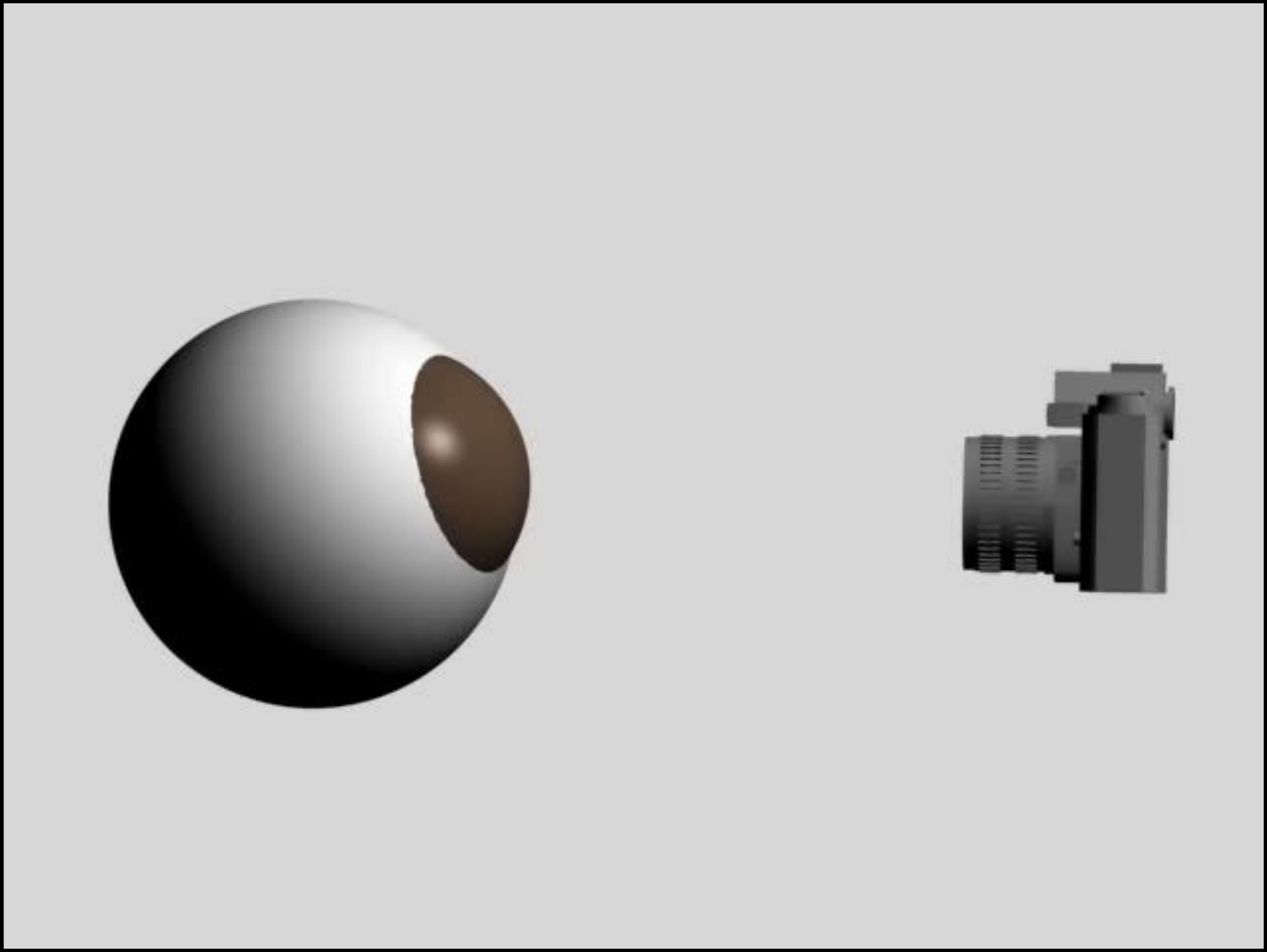
a) Difference image

b) Difference upside down

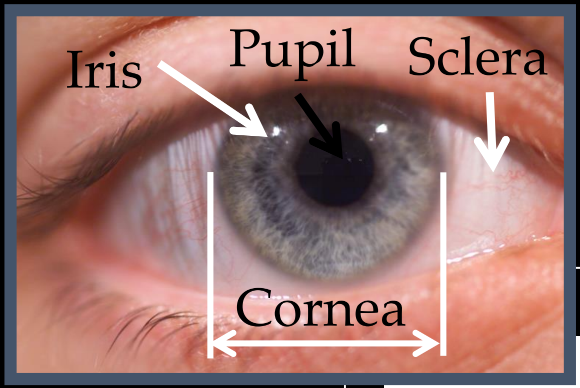
c) True outdoor view

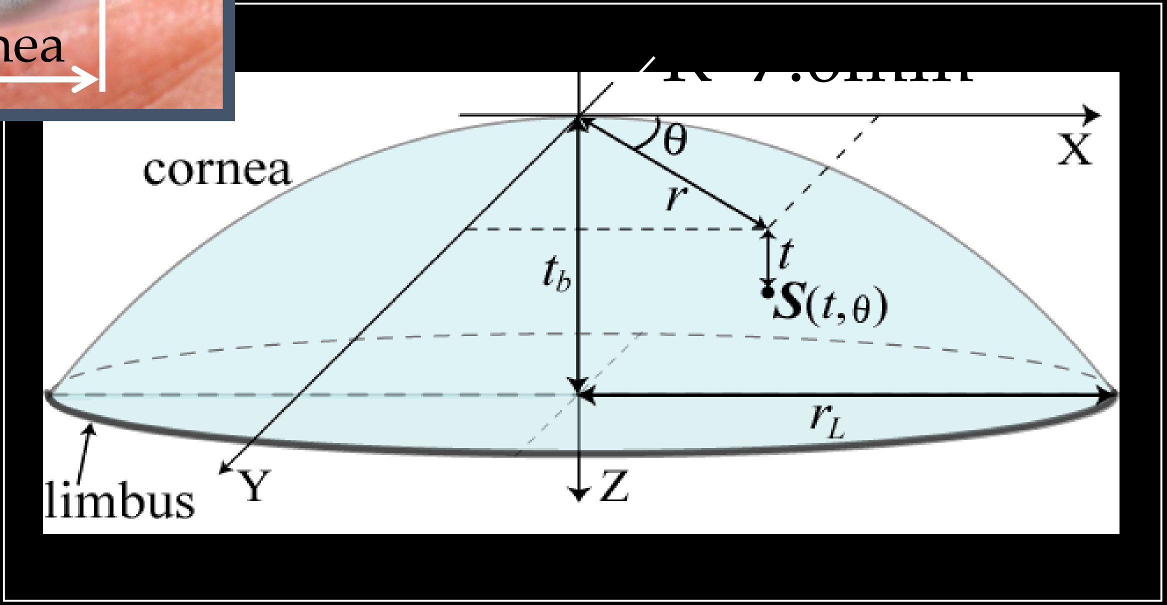
Passive NLOS imaging using accidental reflectors

Corneal Imaging System



Geometric Model of the Cornea





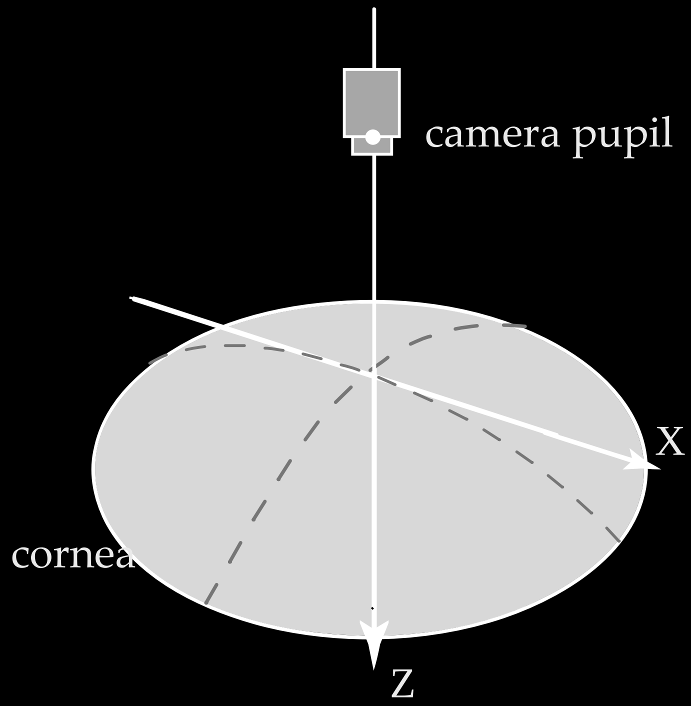
$$t_b = 2.18\text{mm} \qquad r_L = 5.5\text{mm}$$

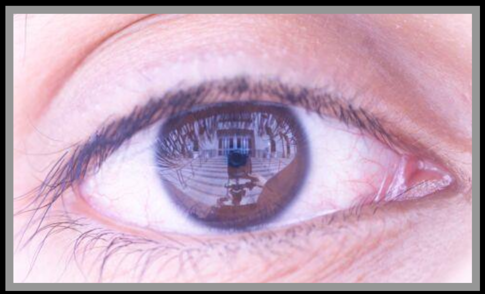
eccentricity = 0.5

Self-calibration:

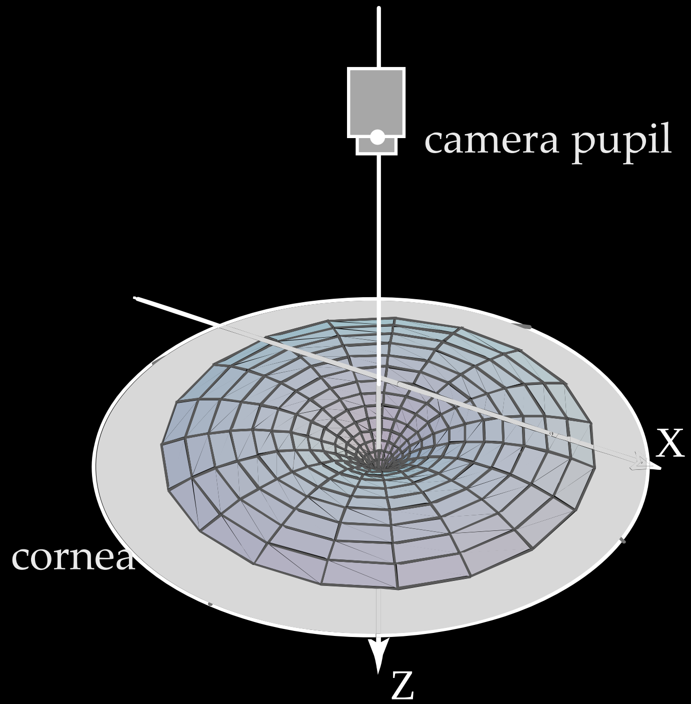
3D Coordinates, 3D Orientation

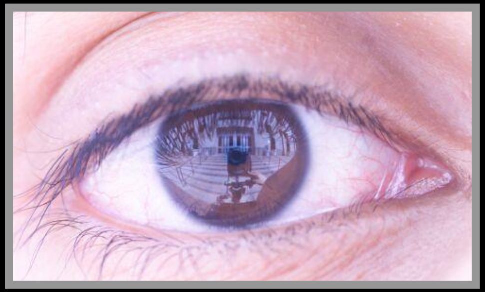
Viewpoint Loci



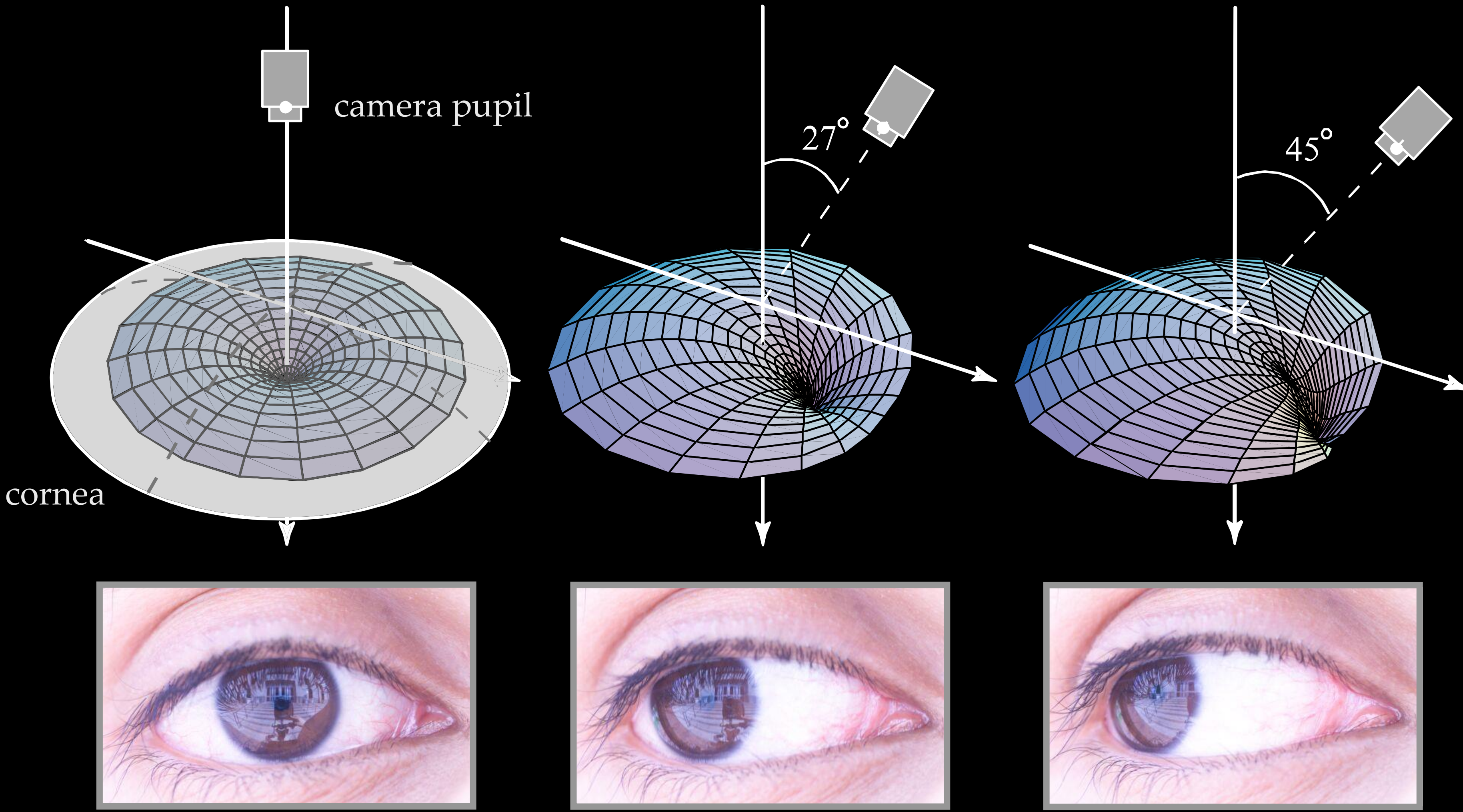


Viewpoint Loci

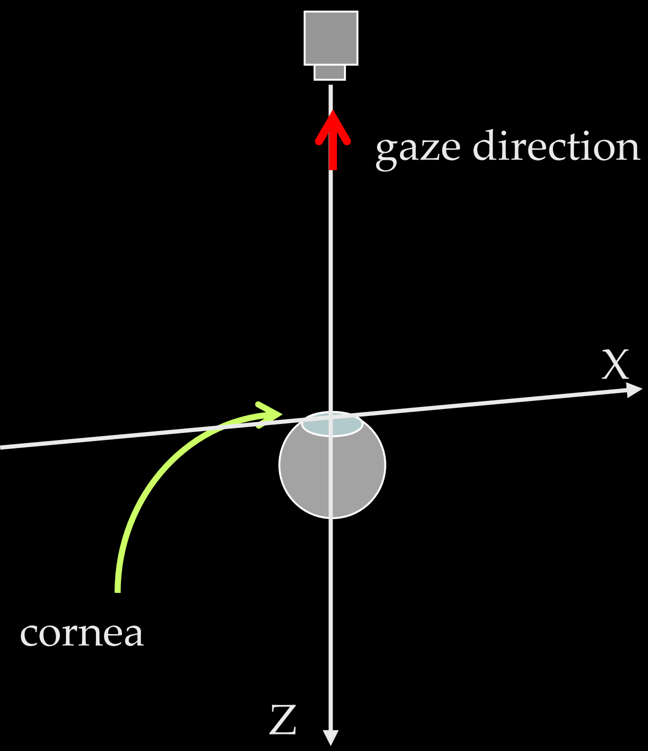




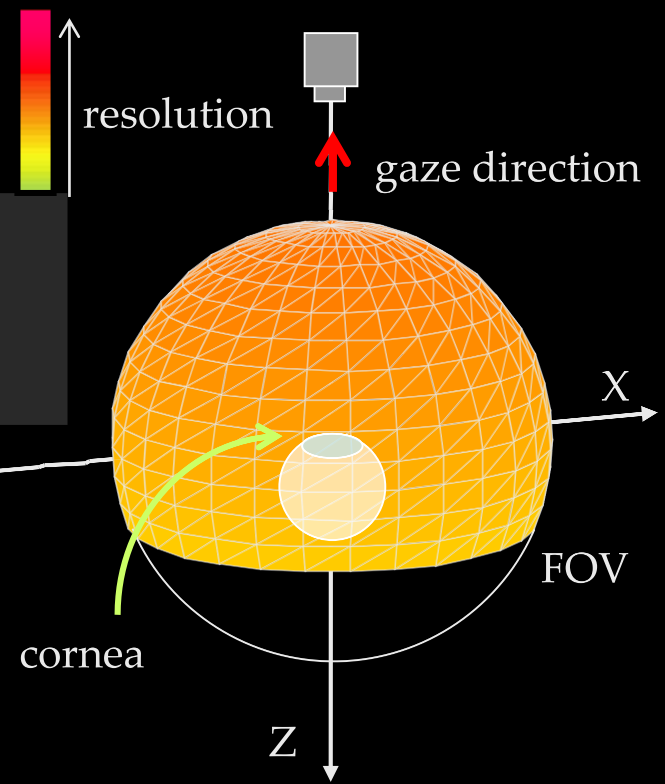
Viewpoint Loci

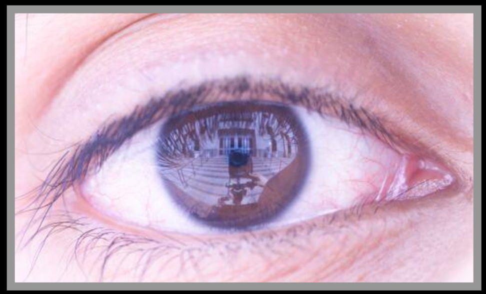


Resolution and Field of View

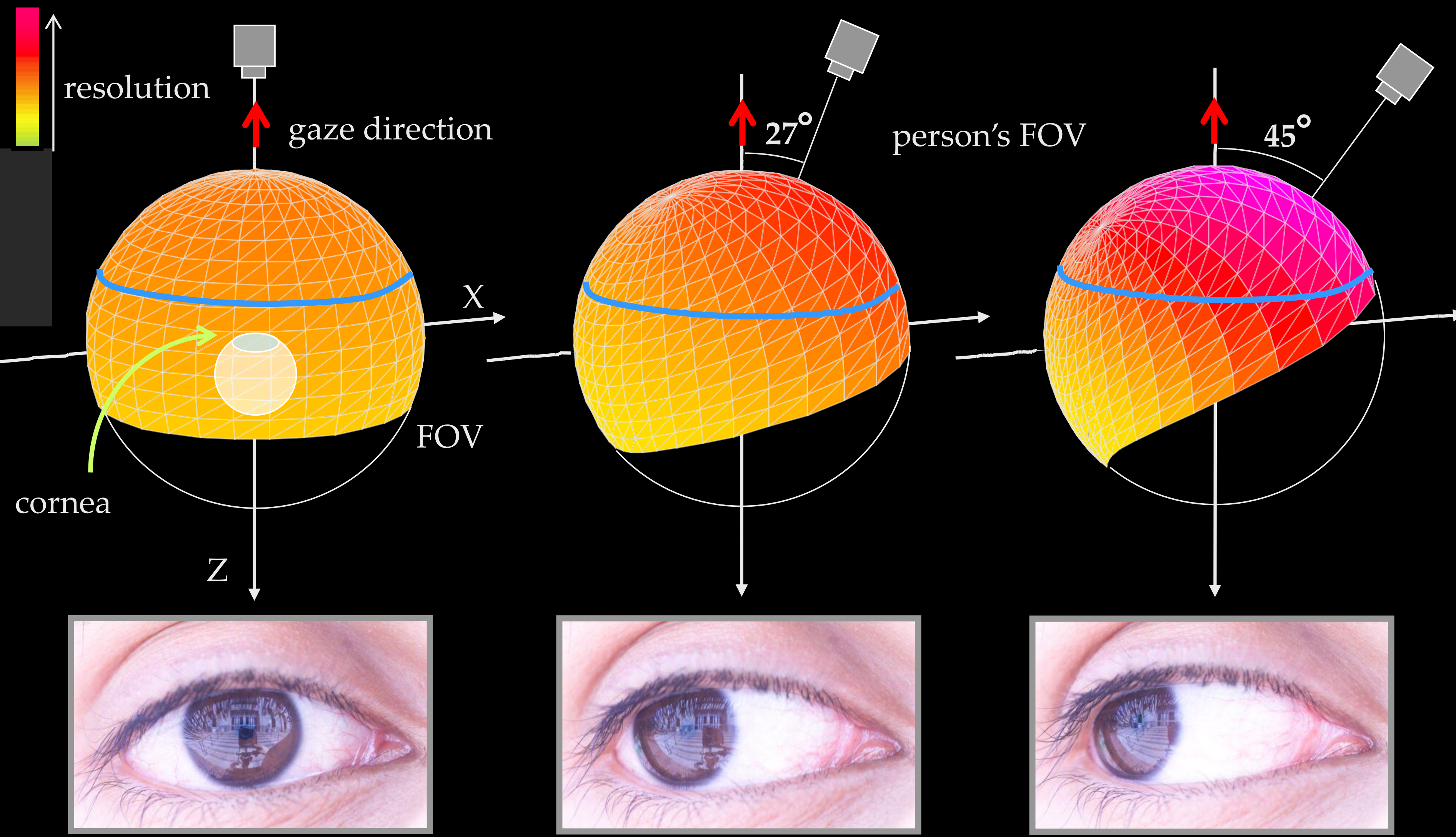


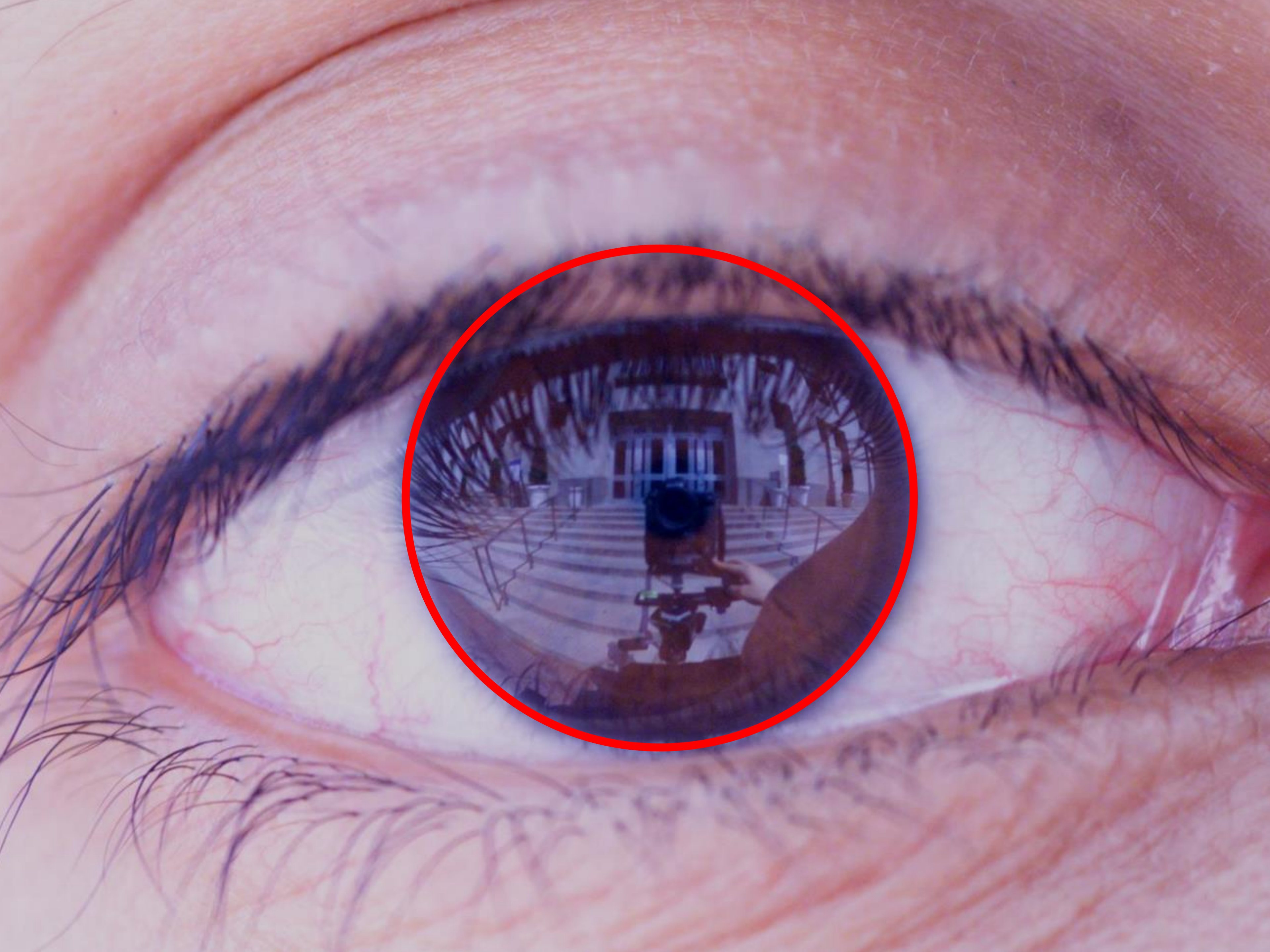
Resolution and Field of View





Resolution and Field of View

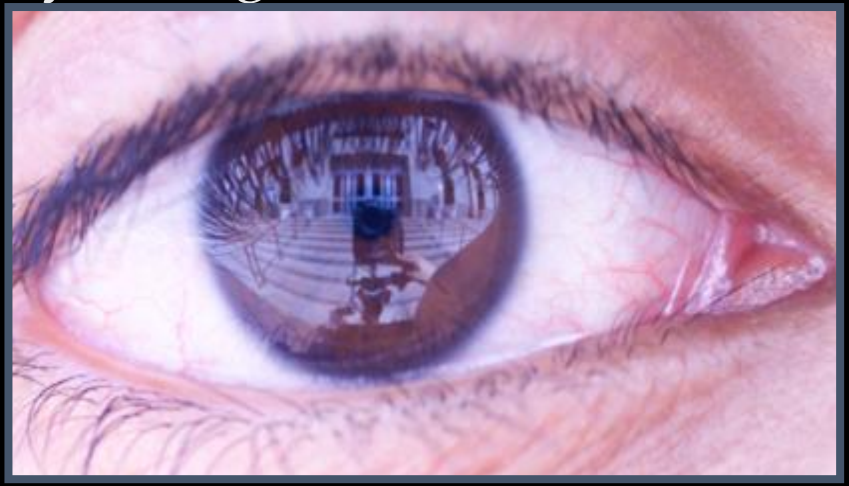




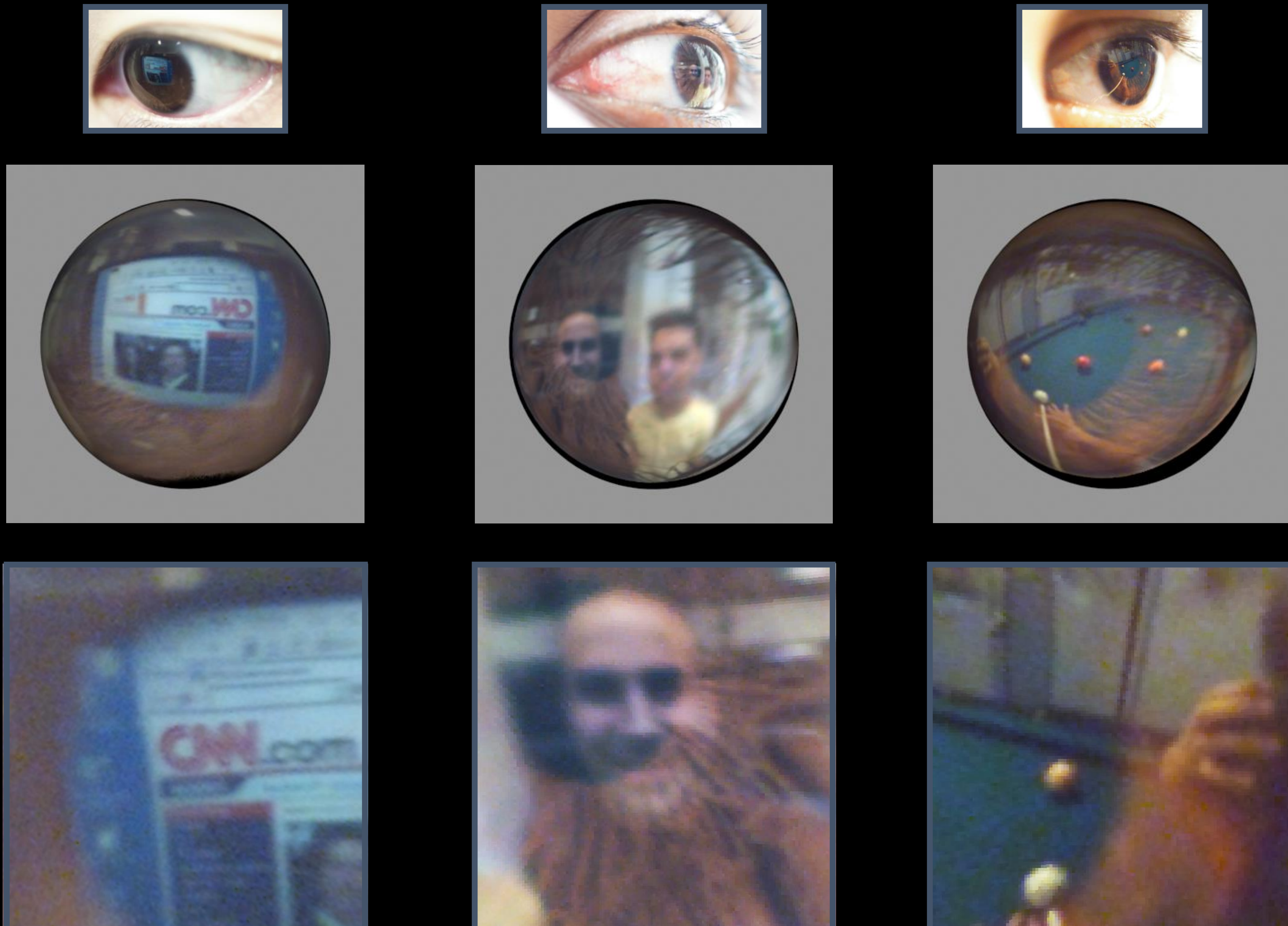
Environment Map from an Eye

What Exactly You are Looking At

Eye Image:

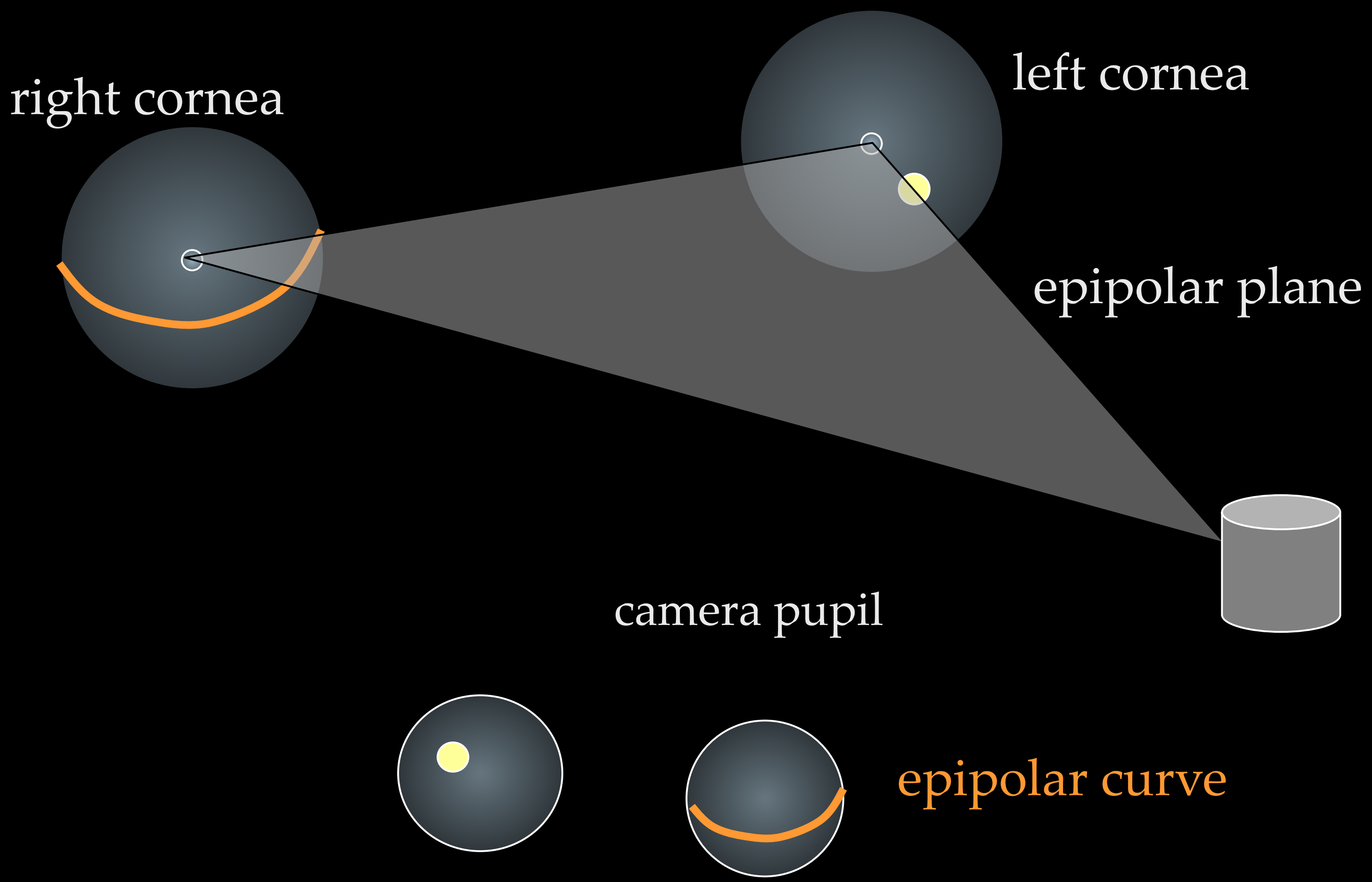


Computed Retinal Image:

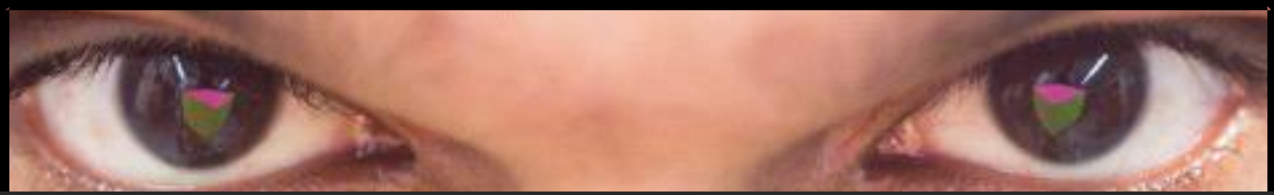

CNN.com

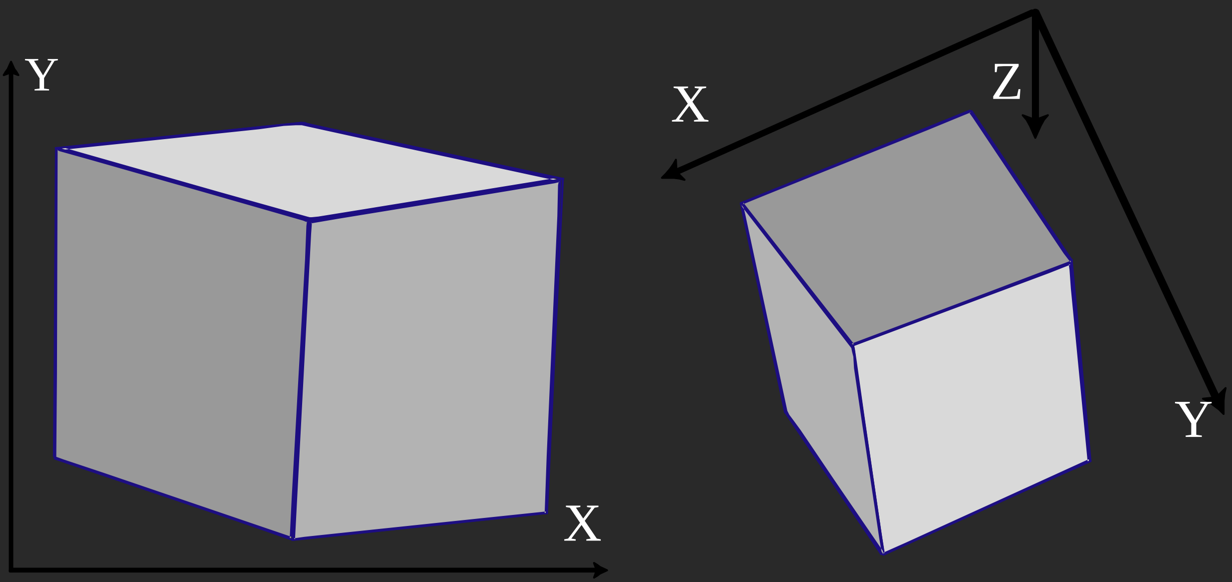
Watching a Bus

Corneal Stereo System



From Two Eyes in an Image …





Reconstructed Structure (frontal and side view)

Eyes Reveal …

- Where the person is
- What the person is looking at
- The structure of objects

Implications

Human Affect Studies: Social Networks

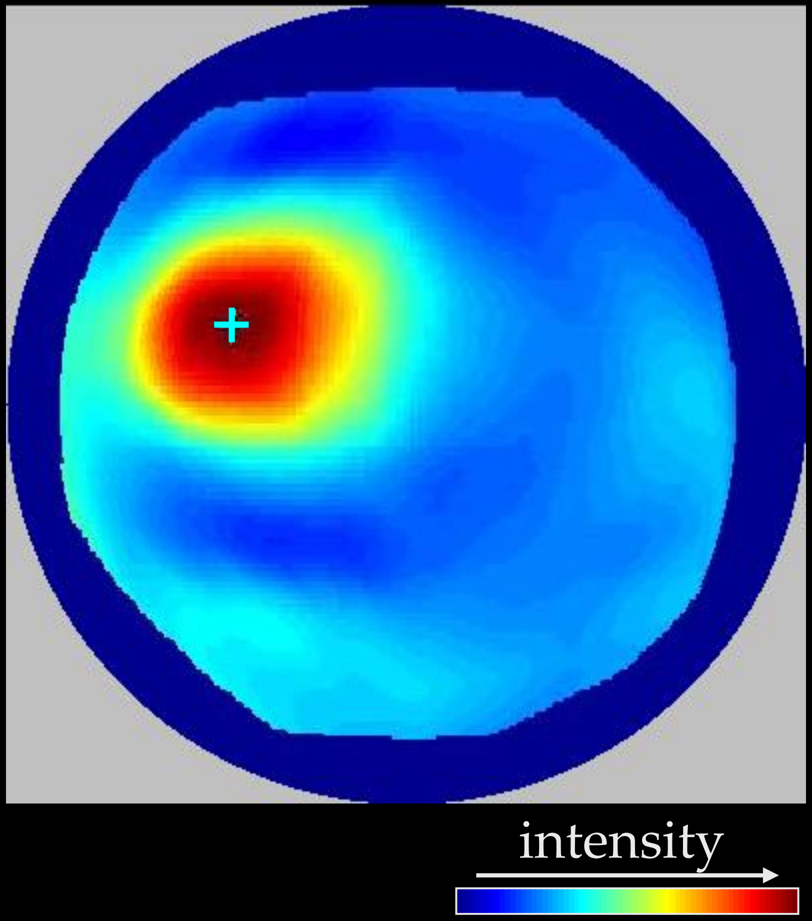
Security: Human Localization

Advanced Interfaces: Robots, Computers

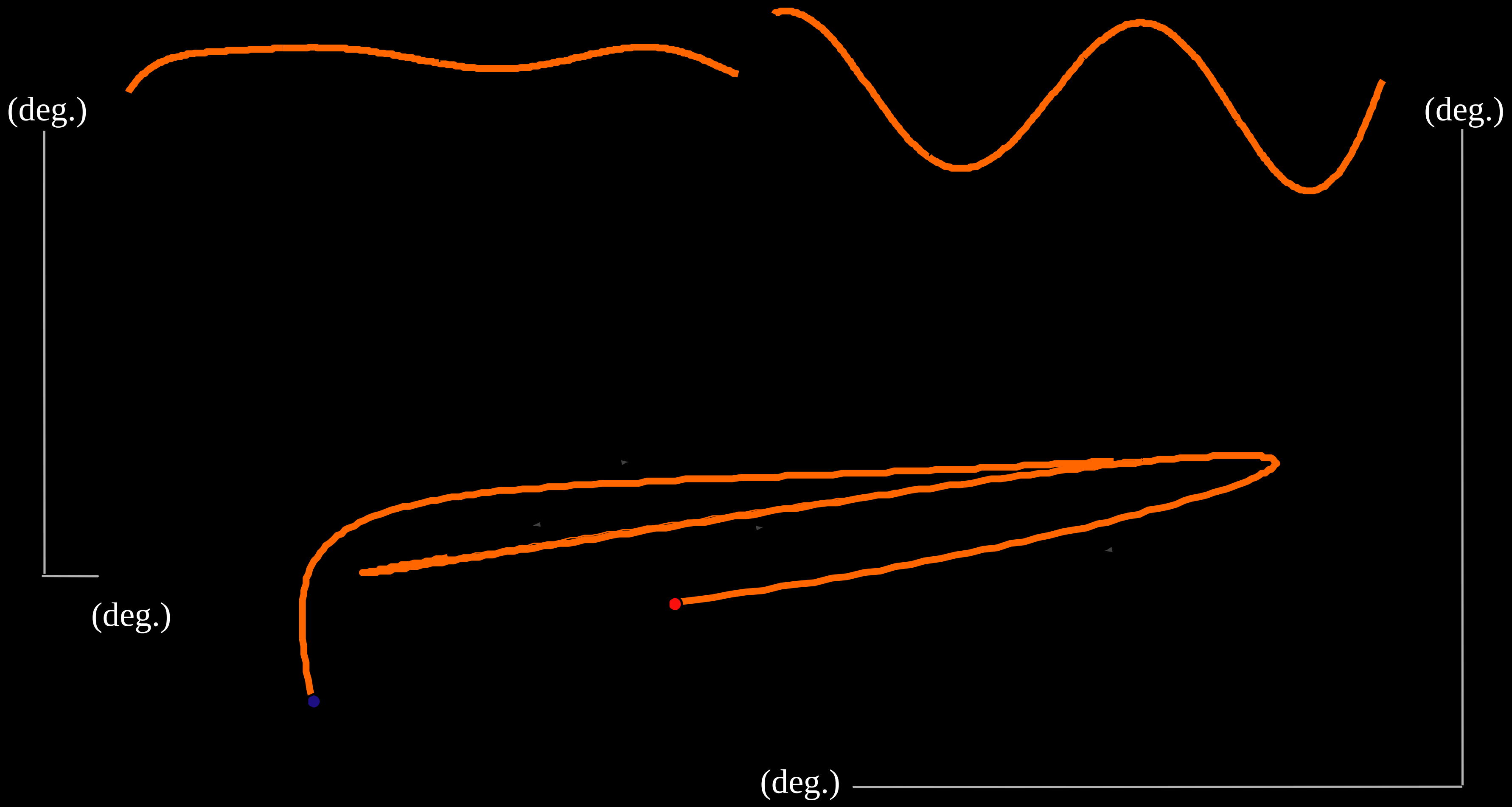
Computer Graphics: Relighting [SIGGRAPH 04]

Dynamic Illumination in a Video

Point Source Direction from the Eye



Point Source Trajectory from the Eye

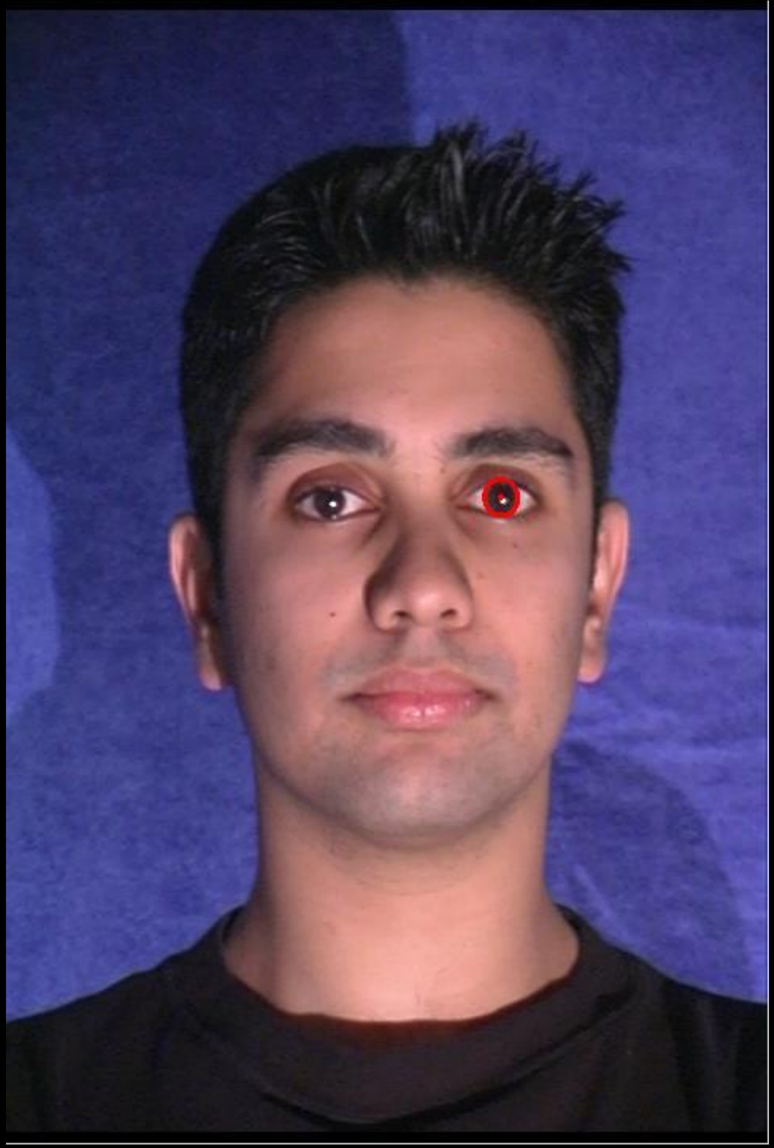


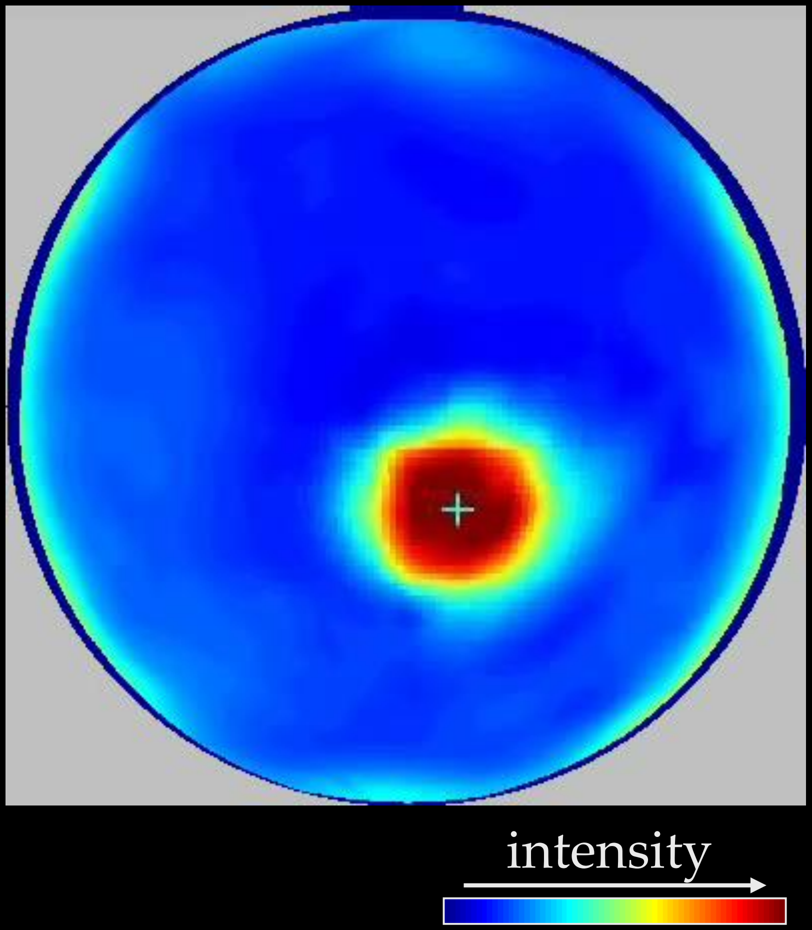
Inserting a Virtual Object

Sampling Appearance using Eyes

Sampling Appearance using Eyes

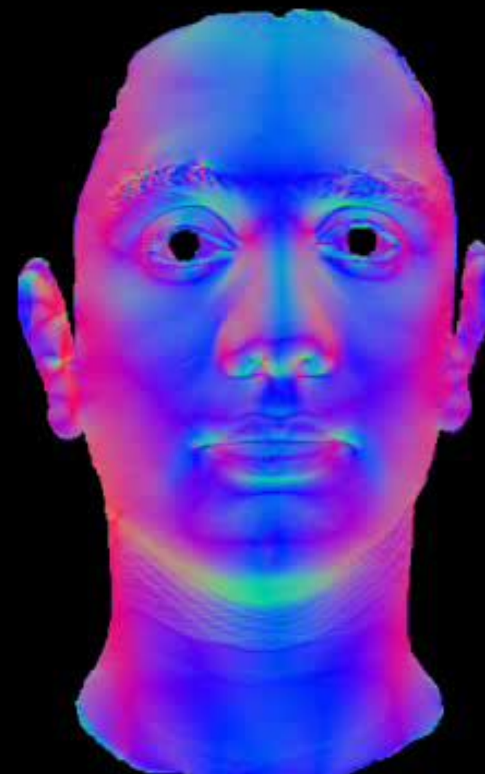
Computed Point Source Trajectory





Fitting a Reflectance Model

albedo map



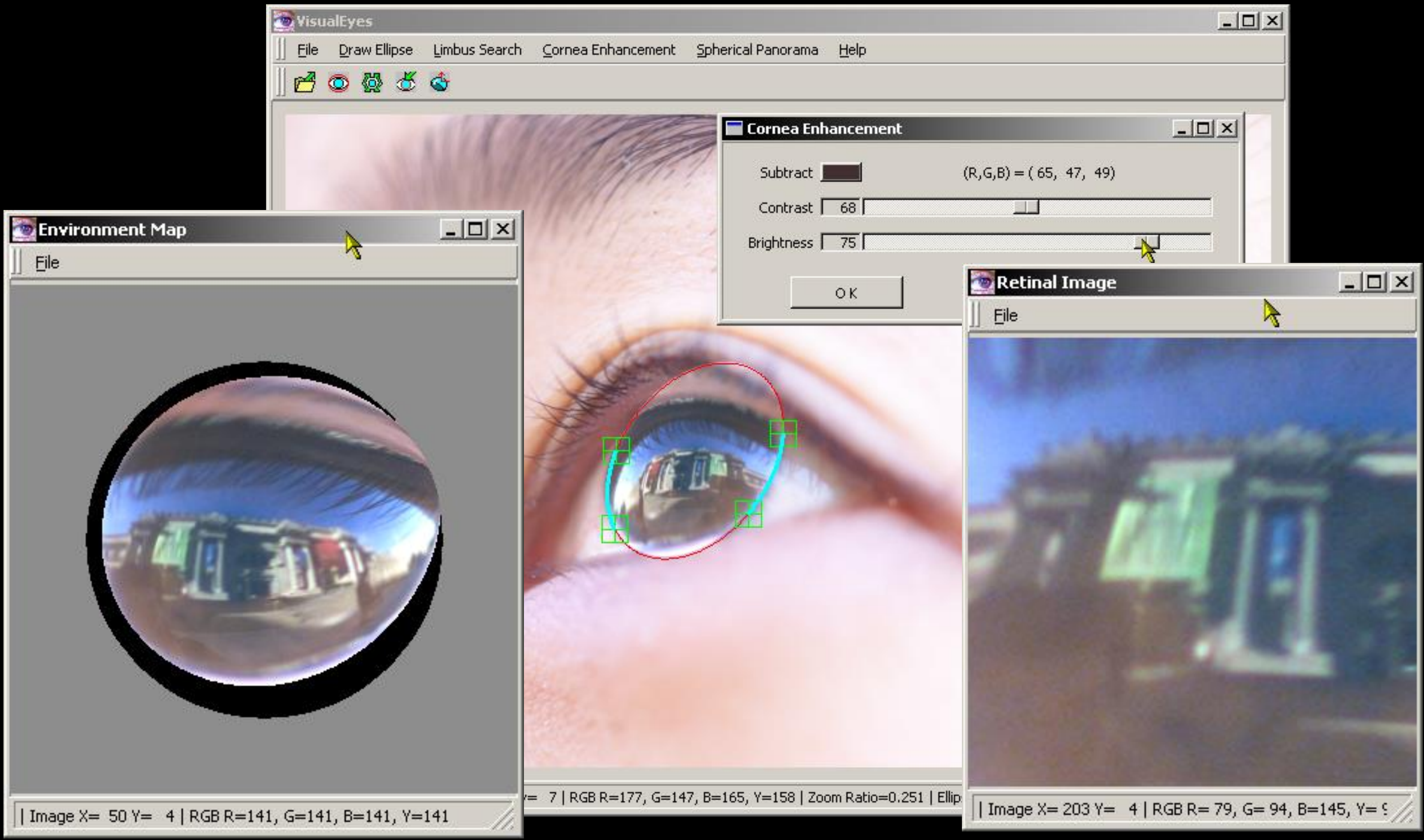
normal map

3D Model Reconstruction

albedo map　　　3D model

Relighting under Novel Illumination

VisualEyes™
http://www.cs.columbia.edu/CAVE/

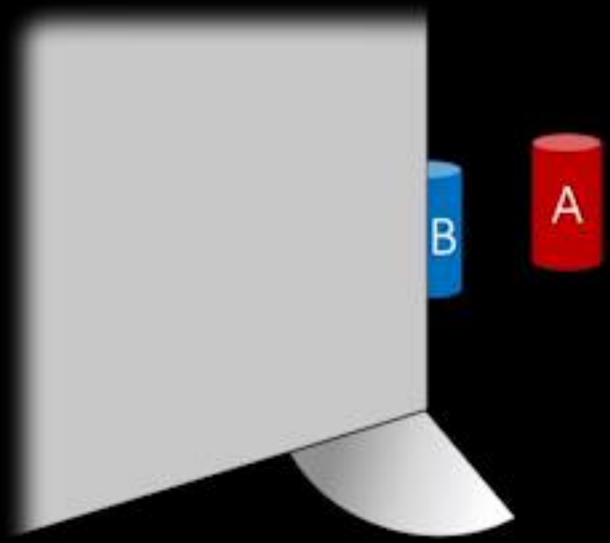


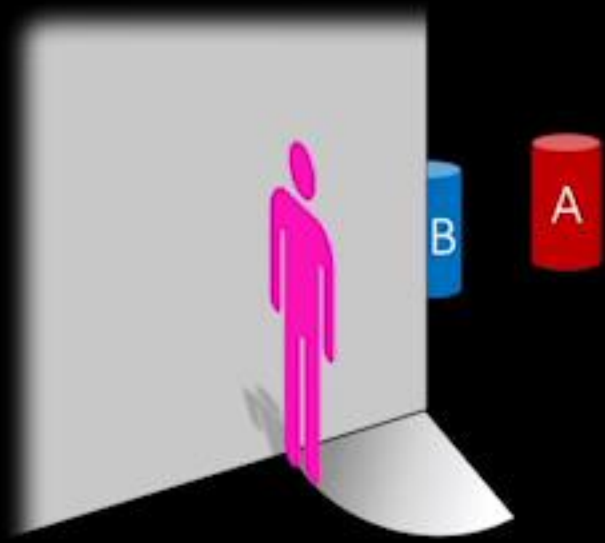
with Akira Yanagawa

Passive NLOS imaging using corners

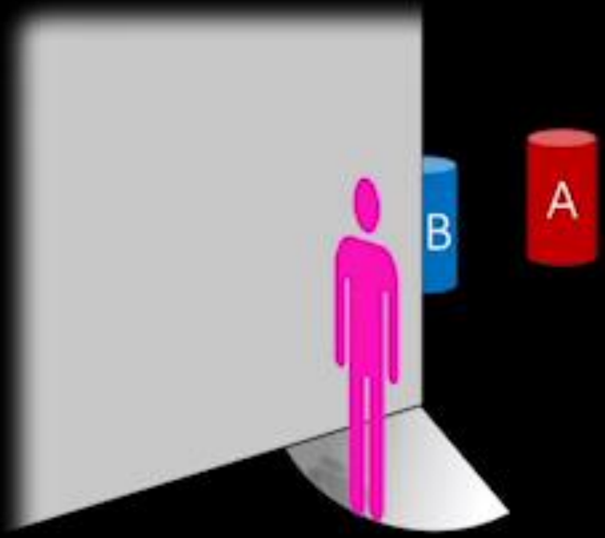
Hidden Scene

Video of the Corner

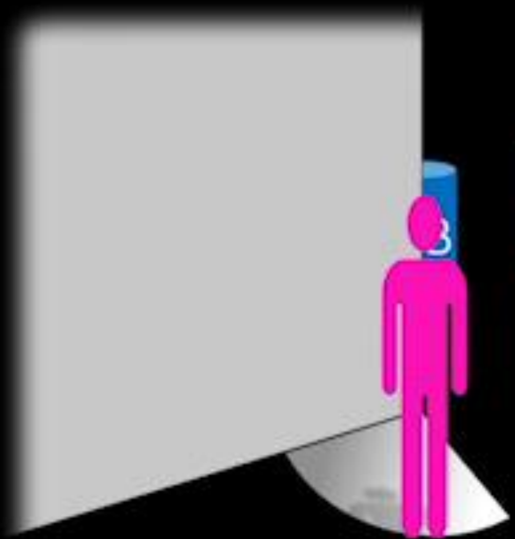

B
A



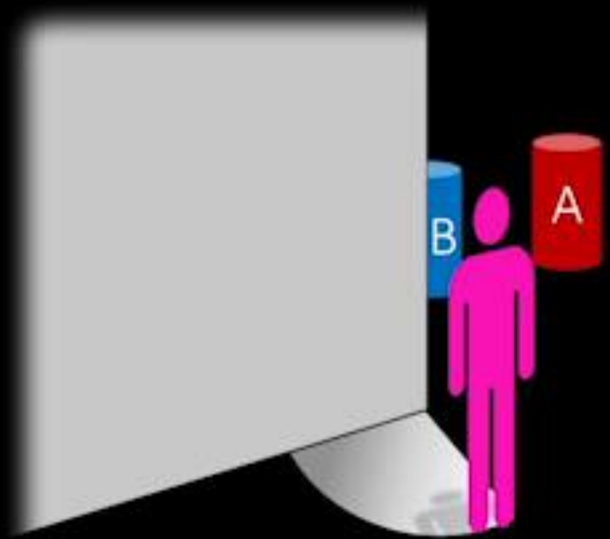
What You Would See



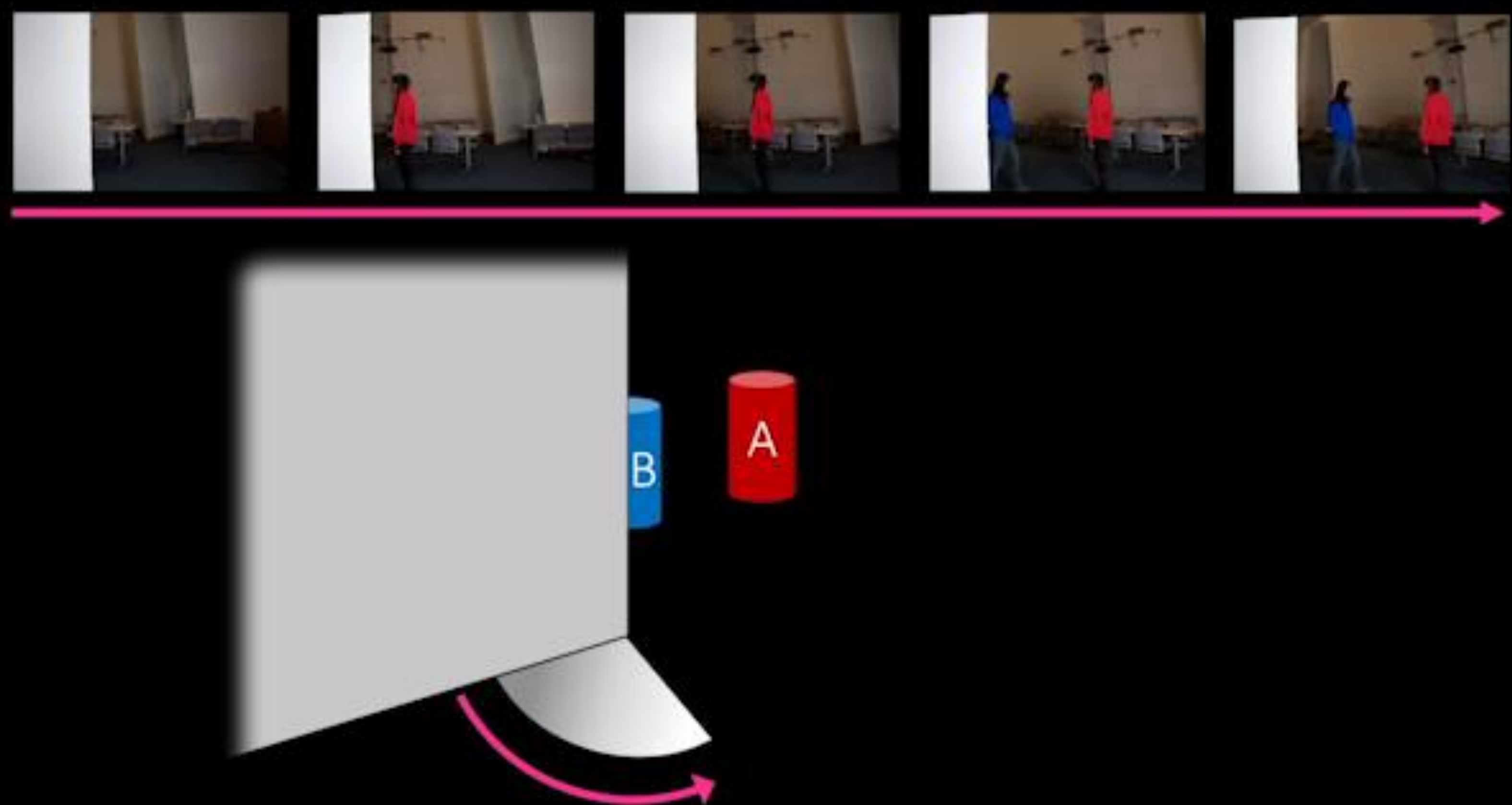
What You Would See

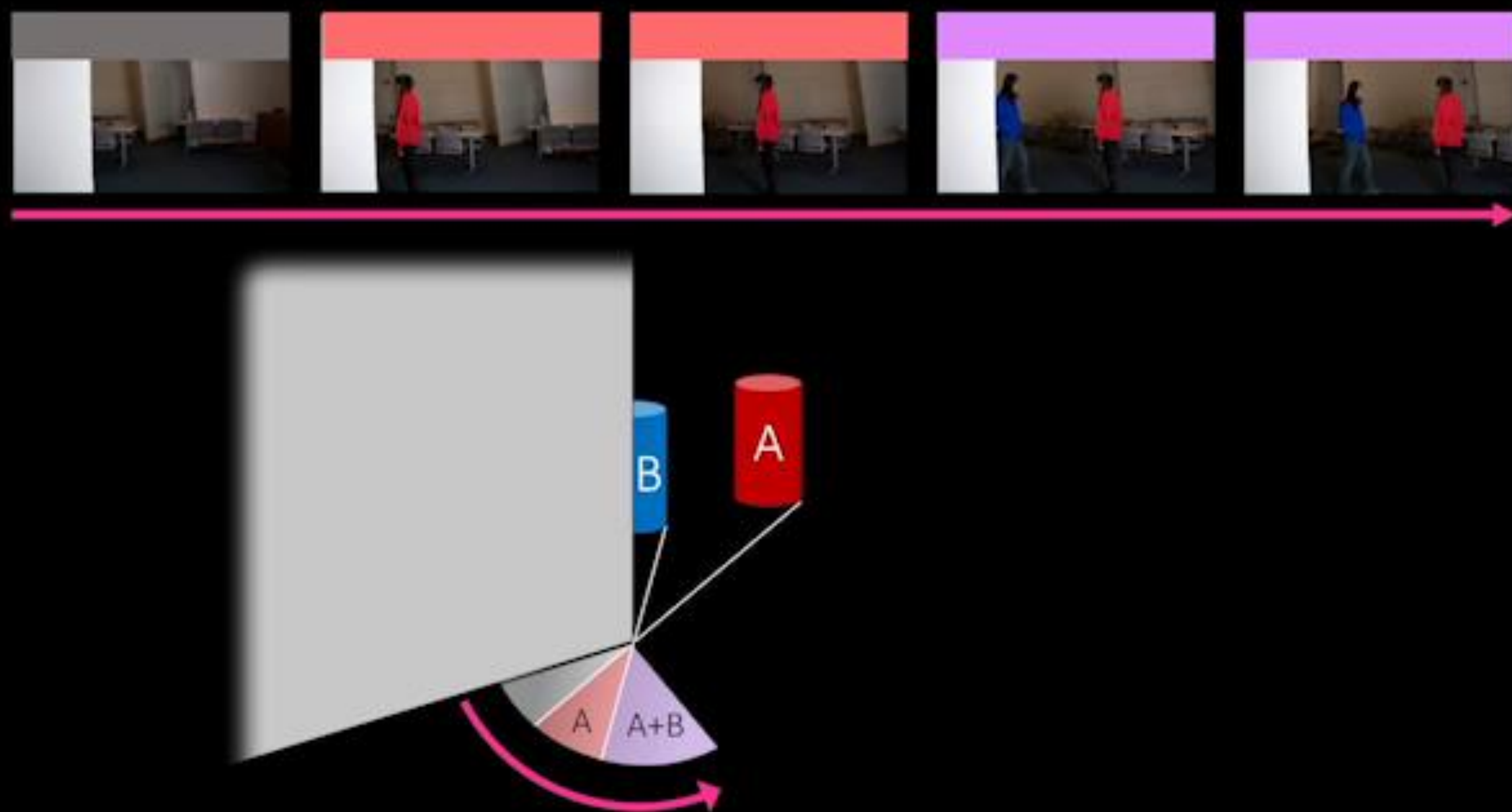


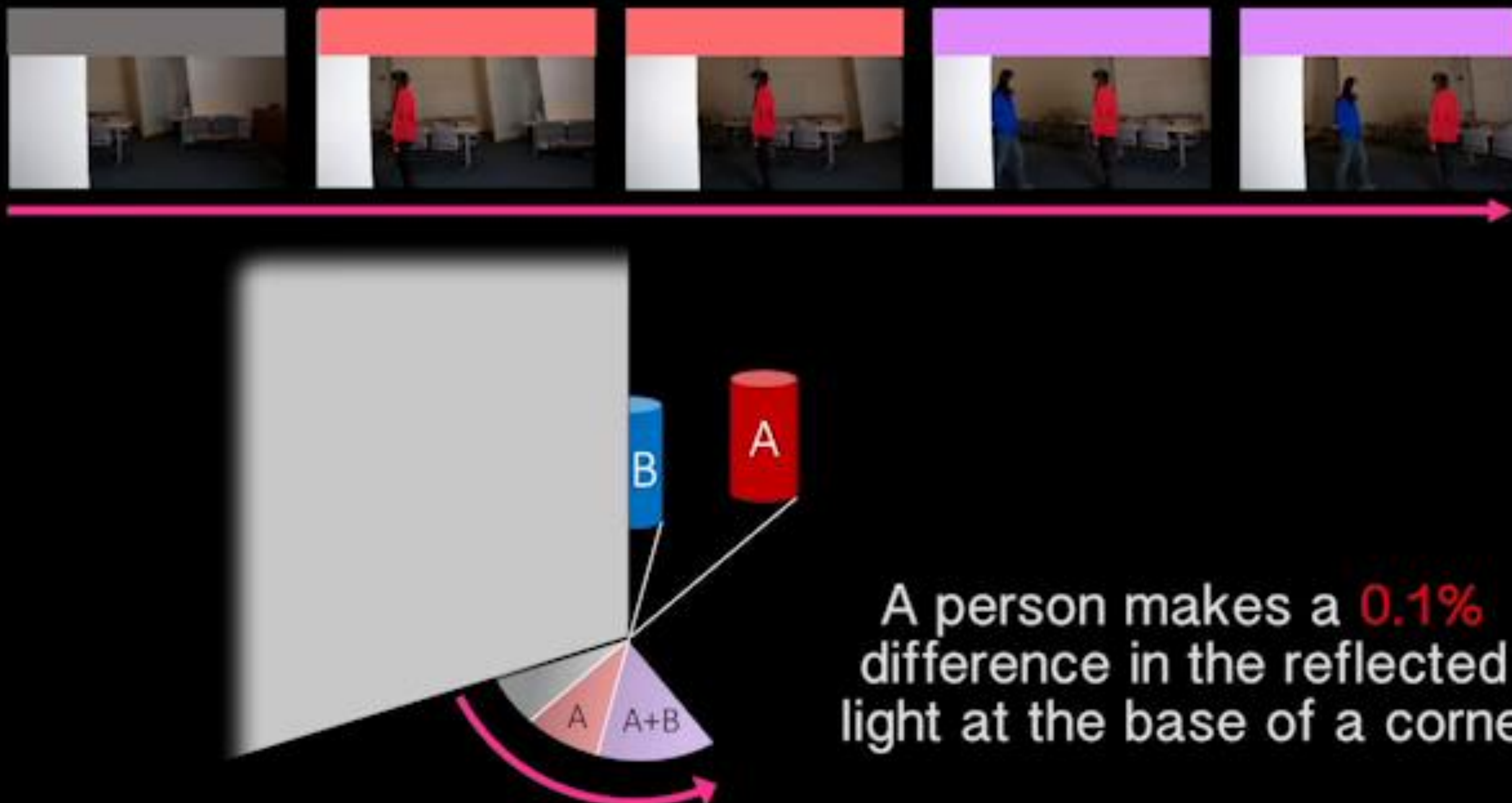
What You Would See



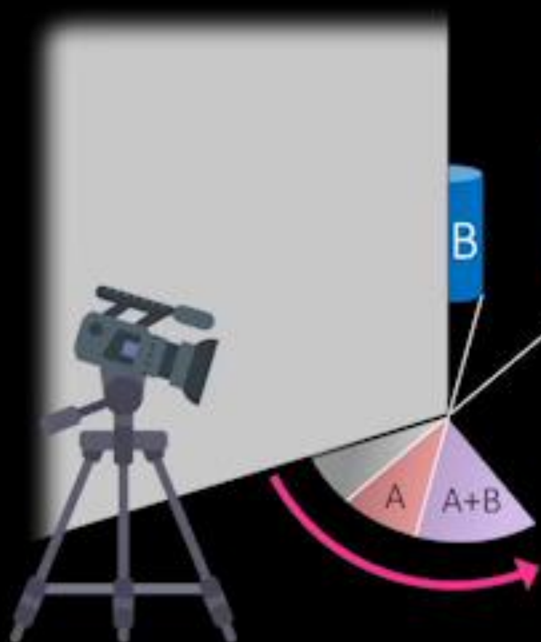
What You Would See


B
A

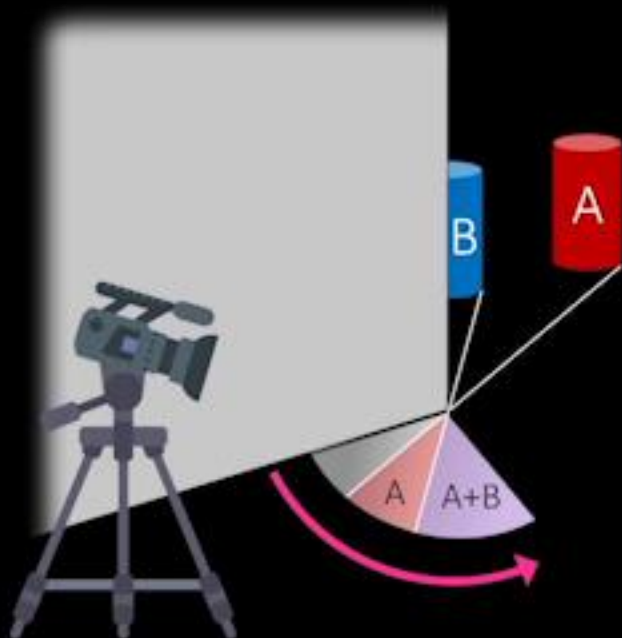

B
A
A
A+B



A person makes a 0.1% difference in the reflected light at the base of a corner



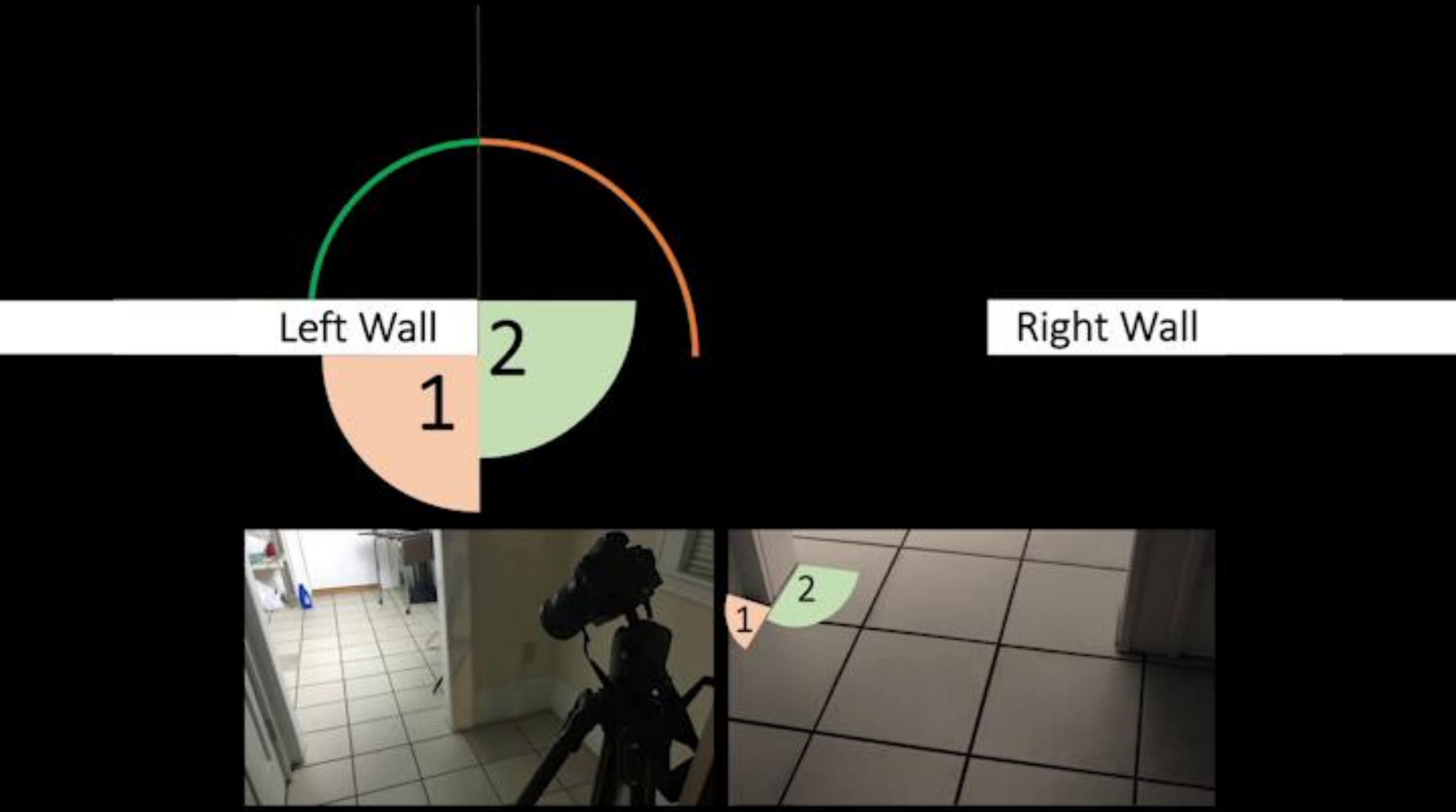
Original Frame

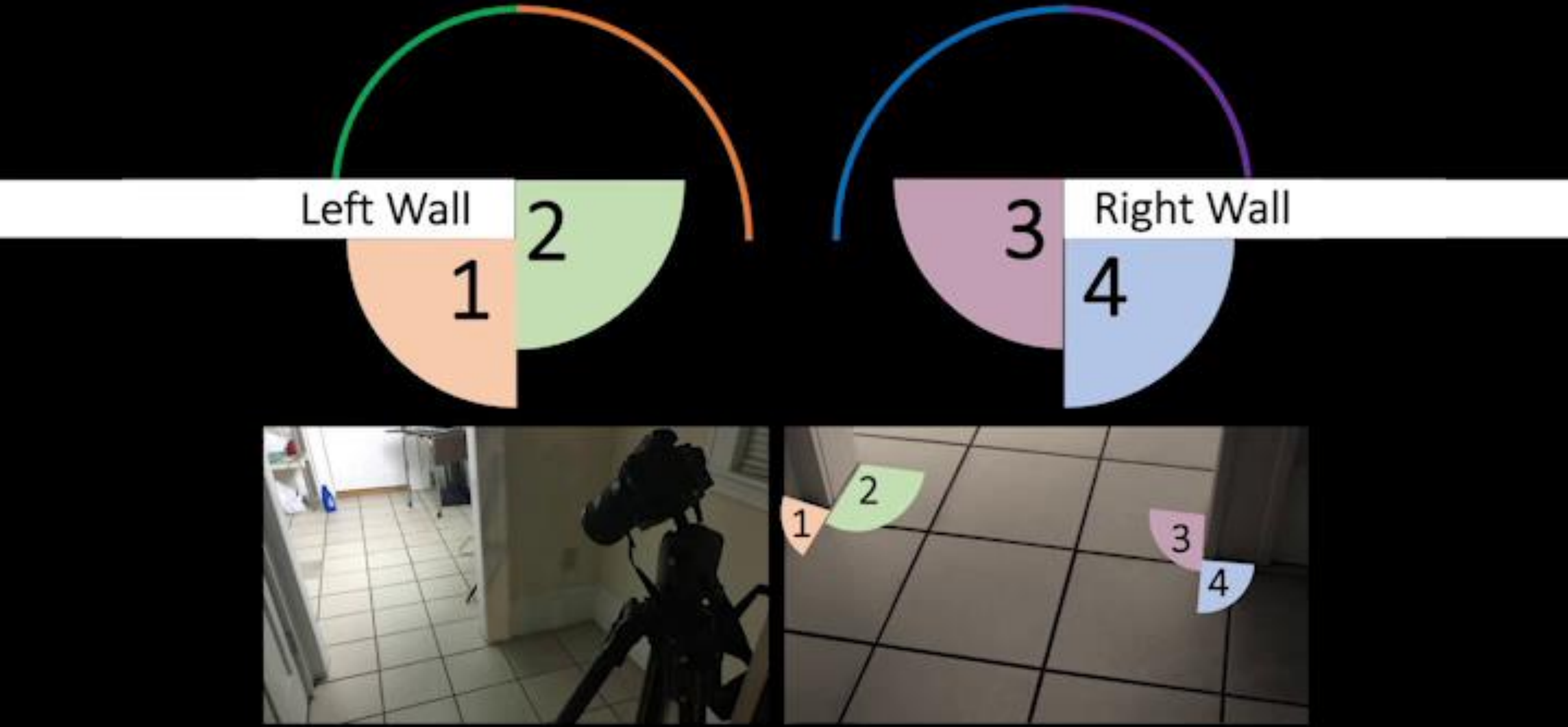


Color Magnified

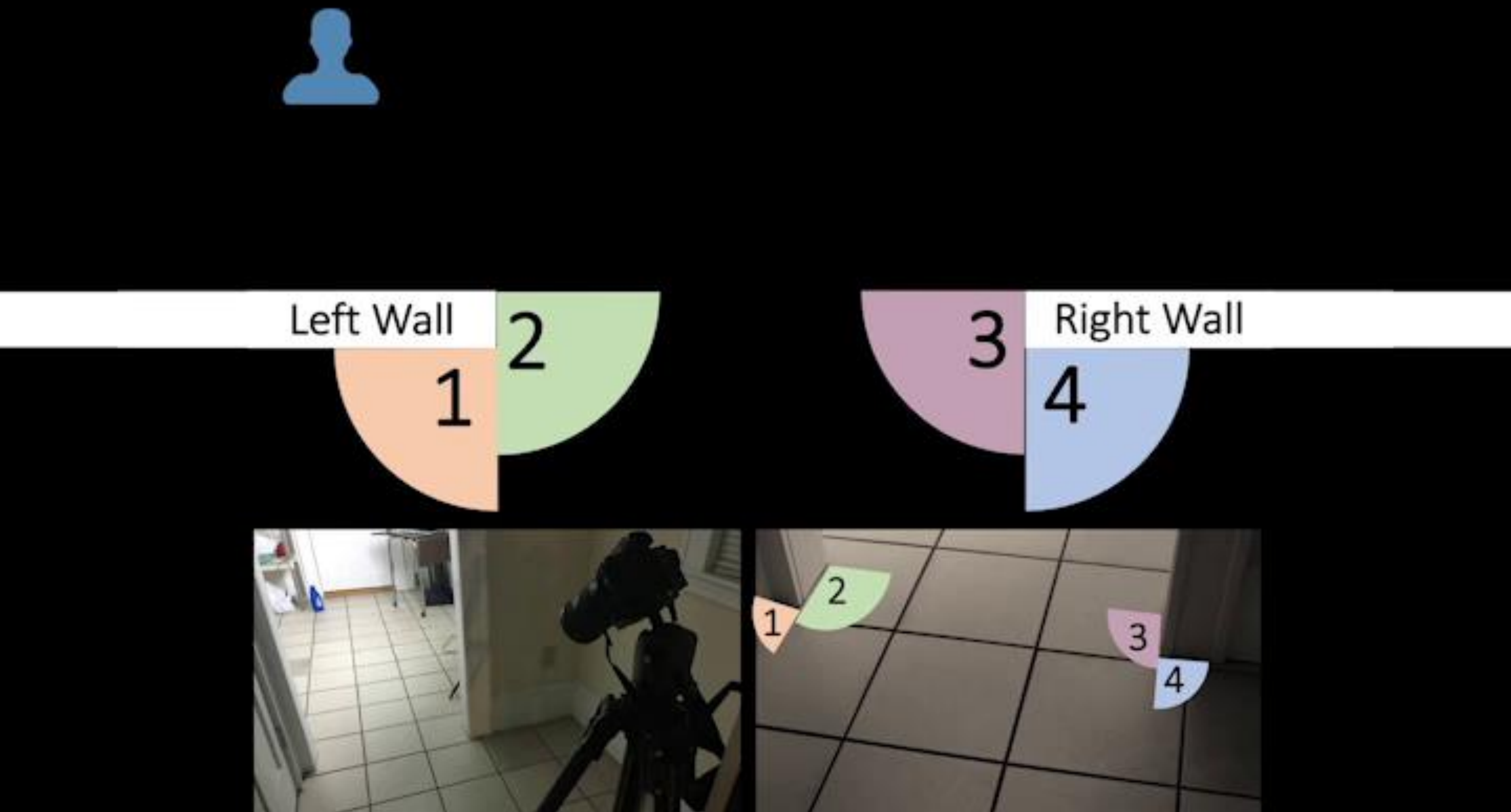
Left Wall

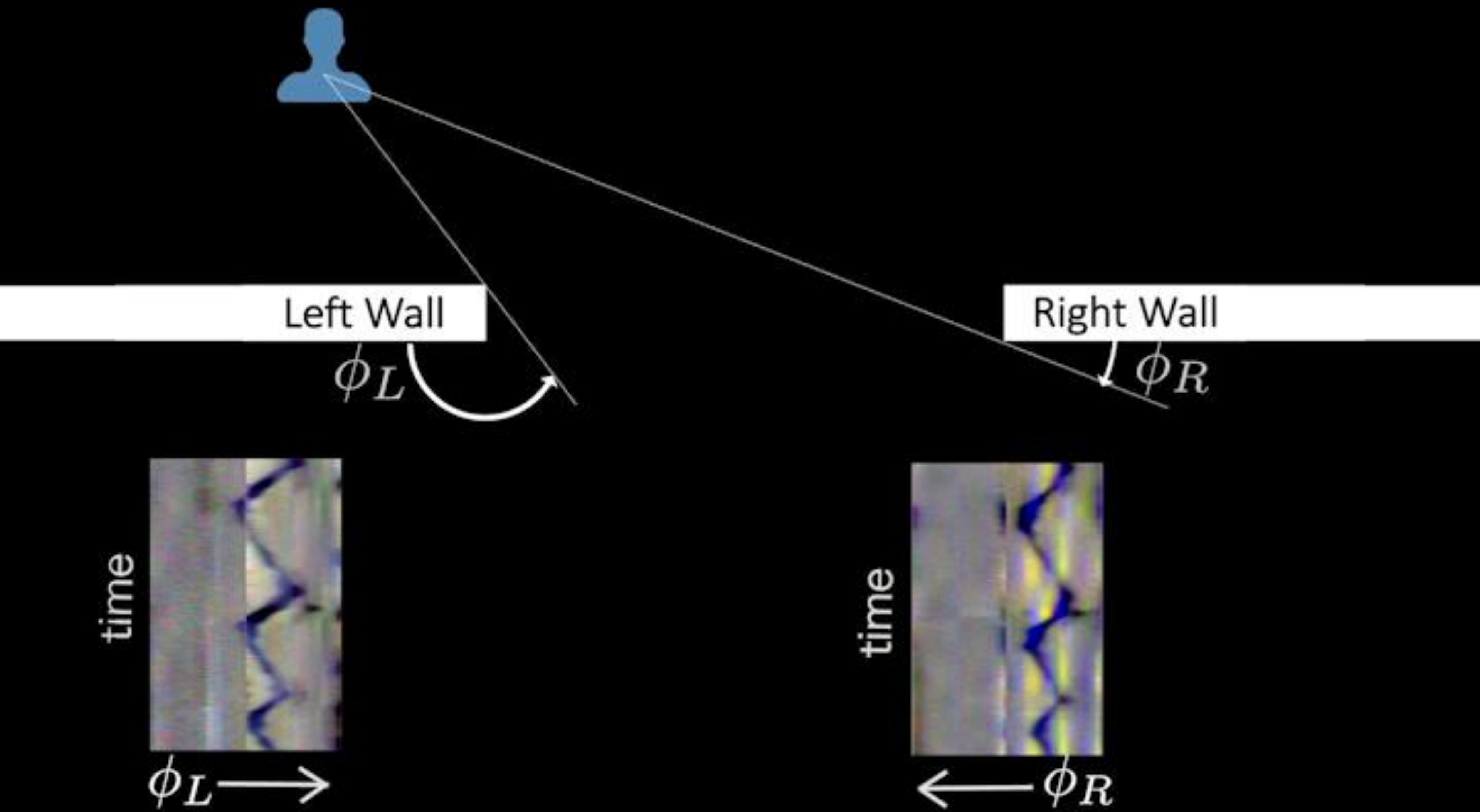
Right Wall


Left Wall
2
1
Right Wall
2
1

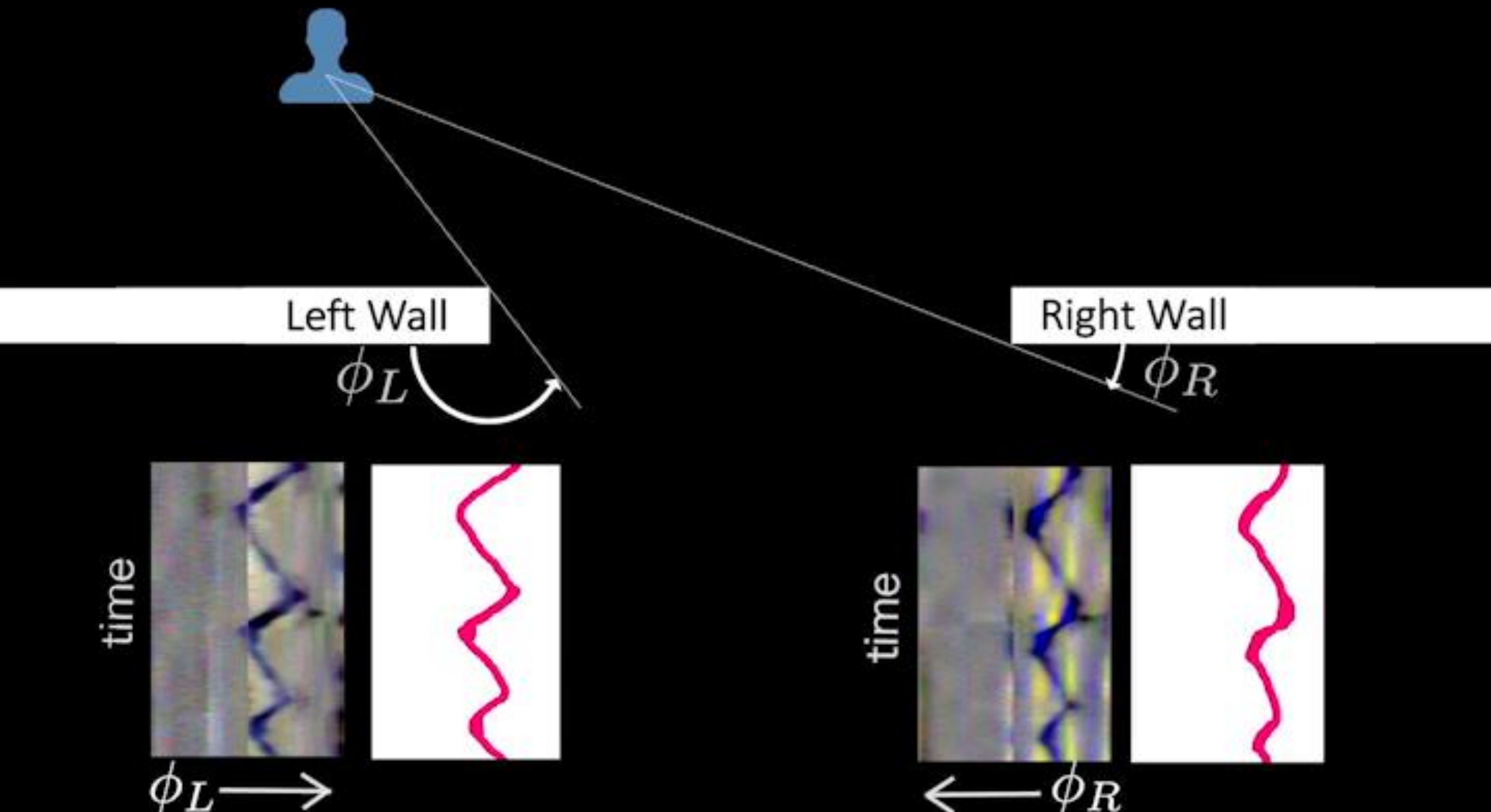


Left Wall
Right Wall
1
2
3
4

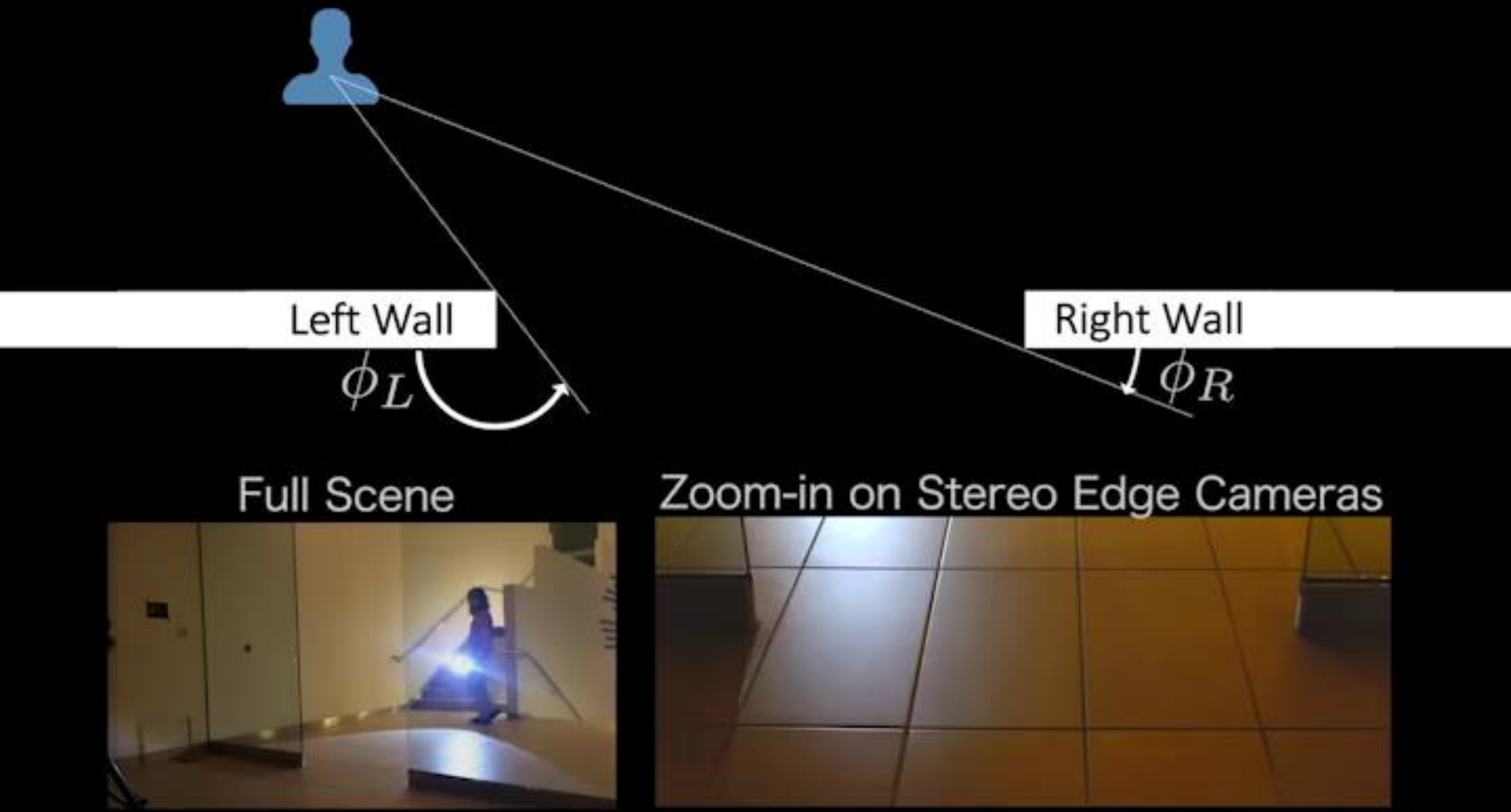

Left Wall
2
1
3
Right Wall
4
2
1
3
4



Left Wall
Right Wall
ϕ_L
ϕ_R
time
time
ϕ_L
ϕ_R



Left Wall
Right Wall
ϕ_L
ϕ_R
time
ϕ_L
time
ϕ_R


Left Wall
Right Wall
ϕ_L
ϕ_R
Full Scene
Zoom-in on Stereo Edge Cameras

References

Basic reading:

- Kirmani et al., “Looking around the corner using ultrafast transient imaging,” ICCV 2009 and IJCV 2011.
- Velten et al., “Recovering three-dimensional shape around a corner using ultrafast time-of-flight imaging,” Nature Communications 2012.

  the two papers showing how ToF imaging can be used for looking around the corner.
- Abib and Katabi, “See Through Walls with Wi-Fi!,” SIGCOMM 2013.
- Abib et al., “Capturing the Human Figure Through a Wall,” SIGGRAPH Asia 2015.

  the two papers showing that WiFi can be used to see through walls.
- Torralba and Freeman, “Accidental Pinhole and Pinspeck Cameras,” CVPR 2012.

  the paper discussing passive NLOS imaging using accidental pinholes.
- Nishimo and Nayar, “Corneal Imaging System: Environment from Eyes,” IJCV 2006.

  the paper discussing passive NLOS imaging using accidental reflectors.
- Bouman et al., “Turning corners into cameras: Principles and Methods,” ICCV 2017.

  the paper discussing passive NLOS imaging using corners.

Additional reading:

- Pediredla et al., “Reconstructing rooms using photon echoes: A plane based model and reconstruction algorithm for looking around the corner,” ICCP 2017.

  the paper on NLOS room reconstruction using ToF imaging.
- Nishimo and Nayar, “Eyes for relighting,” SIGGRAPH 2004.

  a follow-up paper to the paper on corneal imaging, show how similar ideas can be used for relighting and other image-based rendering tasks.