

# ATTENUATION-BASED LIGHT FIELD DISPLAYS

Bachelor Thesis

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Institut für Informatik und angewandte Mathematik

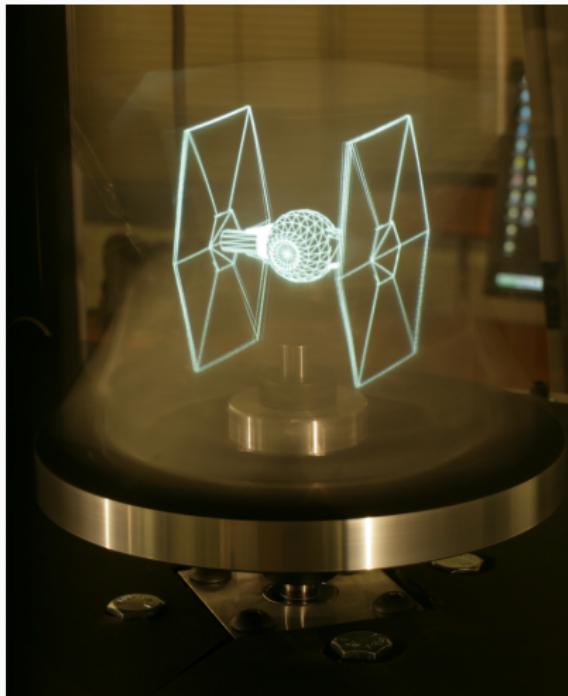
# OUTLINE

1. Introduction
2. Light Fields
3. Attenuation Display
4. Spectral Analysis
5. Conclusion

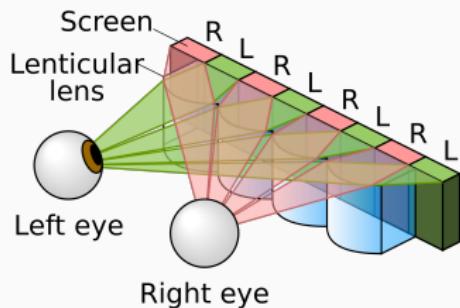
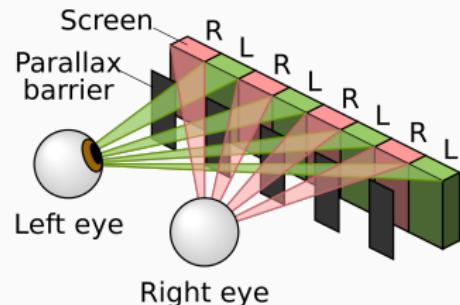
# INTRODUCTION

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# EXISTING 3D DISPLAYS



Jones et al. [2007]



[en.wikipedia.org/wiki/Autostereoscopy](http://en.wikipedia.org/wiki/Autostereoscopy)

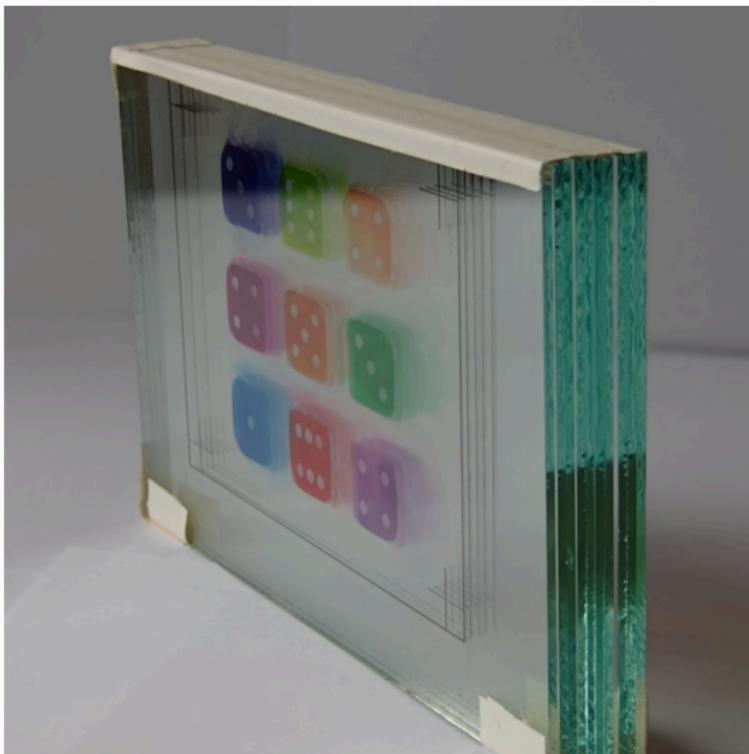
# EXISTING 3D DISPLAYS



# EXISTING 3D DISPLAYS



TODAY



# Layered 3D: Tomographic Image Synthesis for Attenuation-based Light Field and High Dynamic Range Displays

Wetzstein et al. [2011]

## Layered 3D: Tomographic Image Synthesis for Attenuation-based Light Field and High Dynamic Range Displays

Gordon Wetzstein<sup>1</sup> Douglas Lanman<sup>2</sup> Wolfgang Heidrich<sup>2</sup> Ramesh Raskar<sup>2</sup>  
<sup>1</sup>University of British Columbia <sup>2</sup>MIT Media Lab



**Figure 1:** Reconstructing a glass-free light field display using volumetric attenuation. (Left) A stack of optical light modulators (e.g., printed masks) reconstructs a target light field (here for a car) when illuminated by a lightfield. (Right) The target light field is shown in the upper left, together with the optimal five-layer decomposition, obtained with iterative tomographic reconstruction. (Middle) Optique projections for a viewer standing to the top left (magenta) and bottom right (cyan). Corresponding views of the target light field and five-layer prestige are shown on the left and right, respectively. Each attenuation-based 3D display allows accurate depth-resolution depiction of vector particles, occlusion, transmittance, and specularity, being exhibited in the front, the window, and the end of the road, respectively.

### 1 Introduction

We develop tomographic techniques for image synthesis on displays composed of compact volumes of light-attenuating material. Such attenuated attenuators reconstruct a 3D light field, according to the way it would have been observed by a lightfield. Since arbitrary oblique views may be incoherent with any single attenuator, iterative tomographic reconstruction minimizes the difference between the observed light field and the reconstructed light field, starting on attenuation. As multi-layer generalizations of conventional parallel barriers, such displays are shown, both by theory and experiment, to support depth, transmittance, and specularity architectures. For 3D display, spatial resolution, depth of field, and brightness are increased compared to parallel barriers. For a plane at 3 m, our displays have a resolution of 1000 × 1000 pixels, and a depth of high dynamic range displays, continuing existing barriers and providing the first extension to multiple, distinct layers. We consider two types of displays: volumetric displays using liquid crystal-based light field displays using an inexpensive fabrication method; separating multiple printed incompatibles with acrylic sheets.

**Keywords:** computational displays, light fields, autostereoscopic 3D displays, high dynamic range displays, tomography

**Links:** [DOI](#) [PDF](#) [WWW](#) [Video](#)

3D displays are designed to replicate as many perceptual depth cues as possible. As surveyed by Lipton [1982], these cues can be classified into three main categories: binocular disparity, motion parallax, and motion blur. Researchers have explored numerous cues, including perspective, shading, and occlusion, to obtain the illusion of depth with 2D images. Including motion parallax and accommodation, existing 2D displays are limited in their ability to create depth. As a result, 3D displays are designed to provide the lacking binocular cues of disparity and convergence, along with these missing monocular cues. Current 3D displays preserve disparity, but require special eyewear to view them. In contrast, we propose a new class of displays that monocularly displays disparity and motion parallax without encumbering the viewer. As categorized by Frahera [2005], we fall into the category of “light-field” displays, which include light-field cameras [Koenderink 1984] and integral imaging [Lippmann 1908], volumetric displays [Bhandal and Schatzke 1996], and holograms [Slinger et al. 1998]. Light-field displays are also called “3D displays” and primarily restricted to static scenes viewed under controlled illumination [Klag et al. 2001]. Research is addressing these issues [Kang et al. 2009; Koenig et al. 2010; Koenig et al. 2011]. Our displays remain practical alternatives utilizing well-established, low-cost fabrication. Furthermore, volumetric displays can replicate similar depth cues with faster free refresh rates [Frahera 2005].

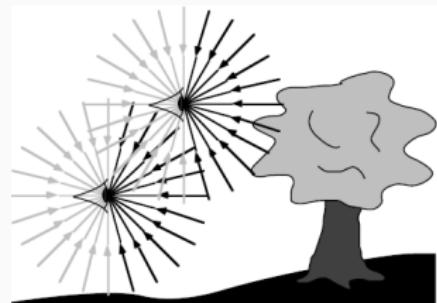
This paper continues our work on light-field computation, particularly the use of light-attenuating materials, which we dub “Layered 3D” displays. Differing from volumetric displays with light-emitting layers, overlaid attenuation patterns allow objects to appear in front of or behind other objects, supporting depth, transmittance, parallel, occlusion, and specularity. While our theoretical contributions apply equally well to dynamic displays, such as stacks of liquid crystal panels, we focus on static displays. This paper is organized to demonstrate the principles of tomographic image synthesis. Specifically, we produce multi-layer attenuators using 2D printed transparencies, separated by acrylic sheets (see Figures 1 and 2).

# LIGHT FIELDS

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# THE PLENOPTIC FUNCTION

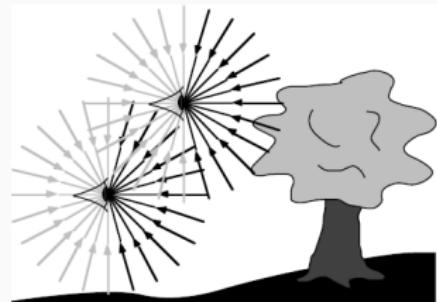
- Measures light in the world
- Position, viewing direction
- Time, Wavelength
- $P(x, y, z, \theta, \phi, t, \lambda)$
- 7D



Adelson and Bergen [1991]

# THE PLENOPTIC FUNCTION

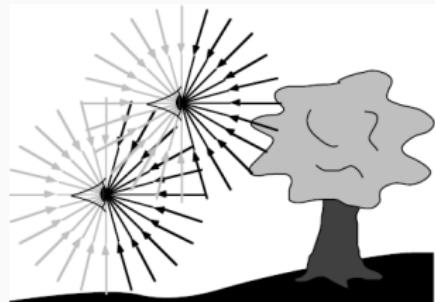
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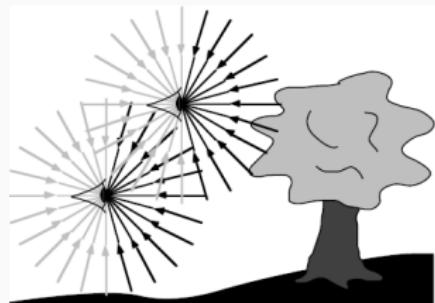
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Adelson and Bergen [1991]

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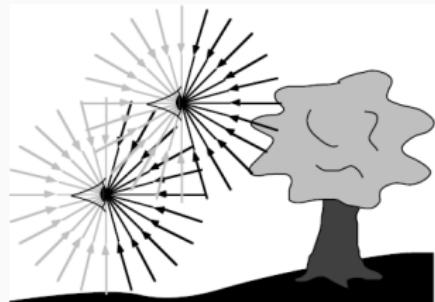
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Adelson and Bergen [1991]

# THE PLENOPTIC FUNCTION

- Measures light in the world
- Position, viewing direction
- Time, Wavelength
- $P(x, y, z, \theta, \phi, t, \lambda)$
- 7D



Adelson and Bergen [1991]

# THE 4D LIGHT FIELD

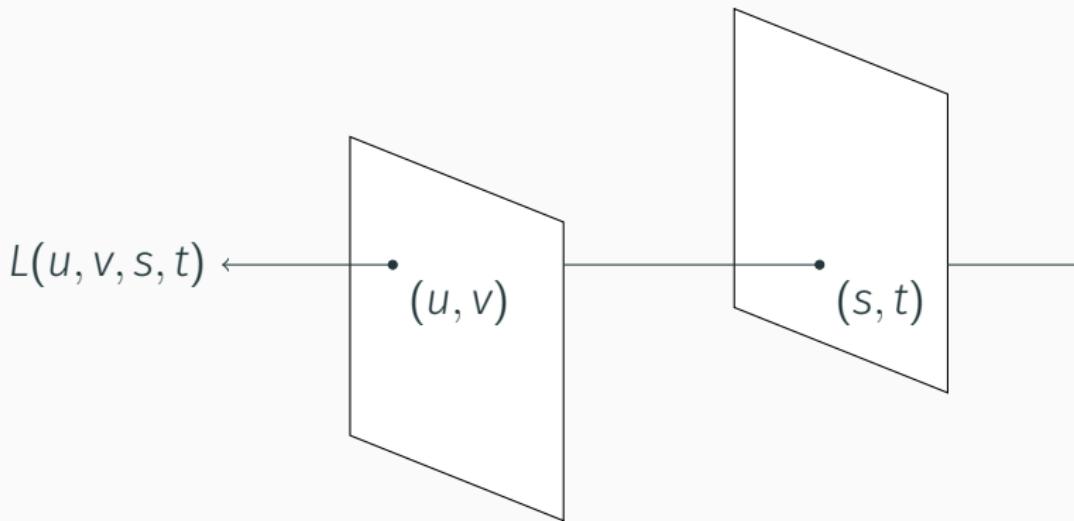
- Reduce dimensions of  $P$
- $L(u, v, s, t)$
- Defined by two planes

## THE 4D LIGHT FIELD

- Reduce dimensions of  $P$
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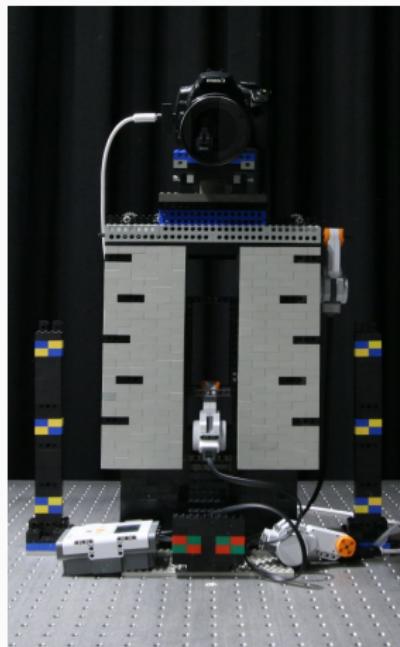


# LIGHT FIELD ACQUISITION



Stanford camera array. Source: [lightfield.stanford.edu](http://lightfield.stanford.edu)

# LIGHT FIELD ACQUISITION



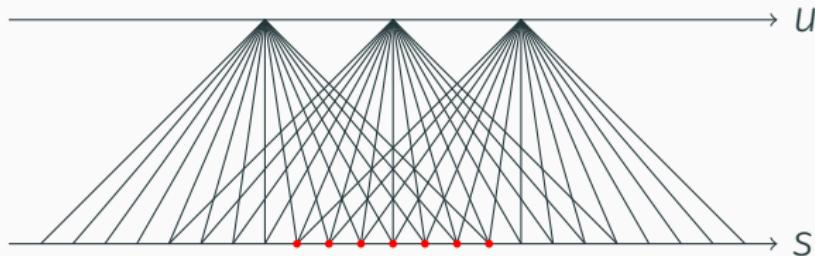
Lego gantry. Source: [lightfield.stanford.edu](http://lightfield.stanford.edu)

# LIGHT FIELD ACQUISITION

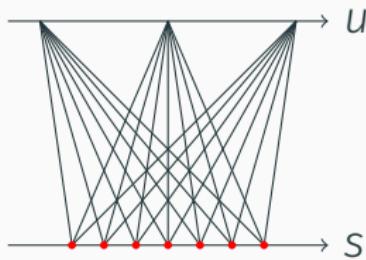
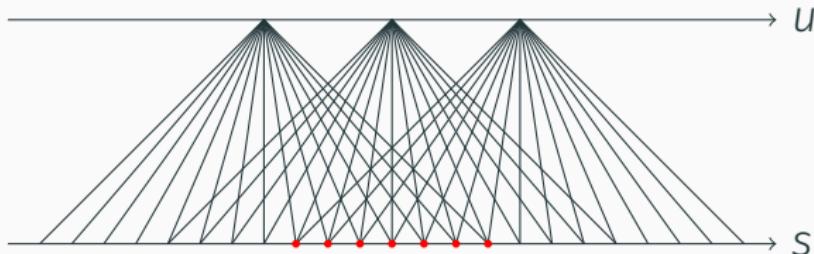


Lytro plenoptic camera. Source: [de.wikipedia.org/wiki/Lytro](https://de.wikipedia.org/wiki/Lytro)

# RE-PARAMETERIZATION TO GLOBAL COORDINATES



# RE-PARAMETERIZATION TO GLOBAL COORDINATES



# RE-PARAMETERIZATION TO GLOBAL COORDINATES

Raw



Rectified



# RE-PARAMETERIZATION TO GLOBAL COORDINATES

Raw



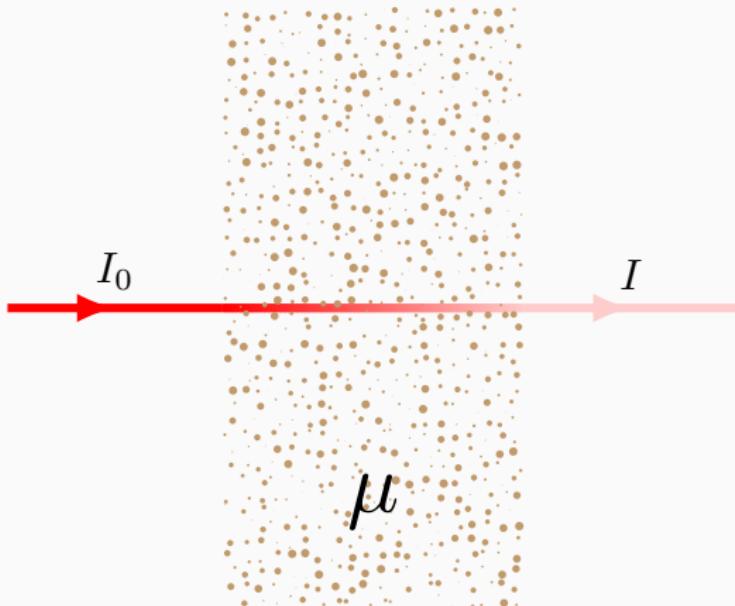
Rectified



# ATTENUATION DISPLAY

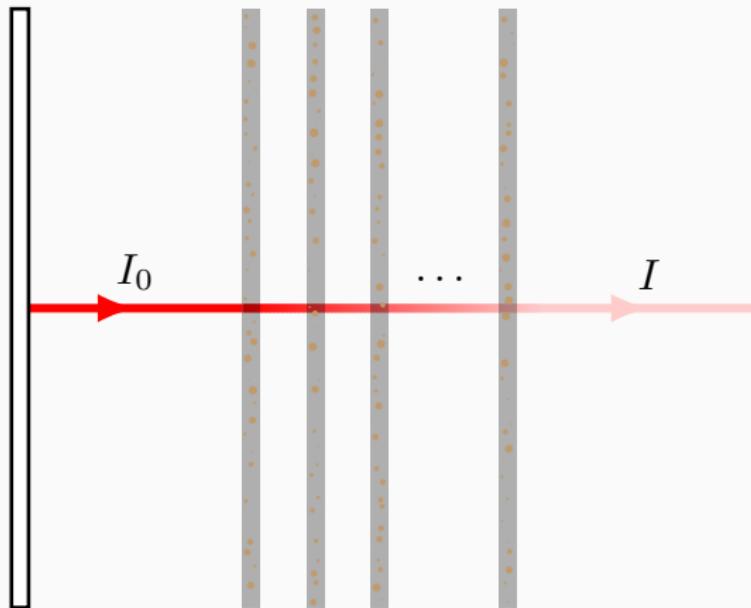
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# THE BEER-LAMBERT LAW



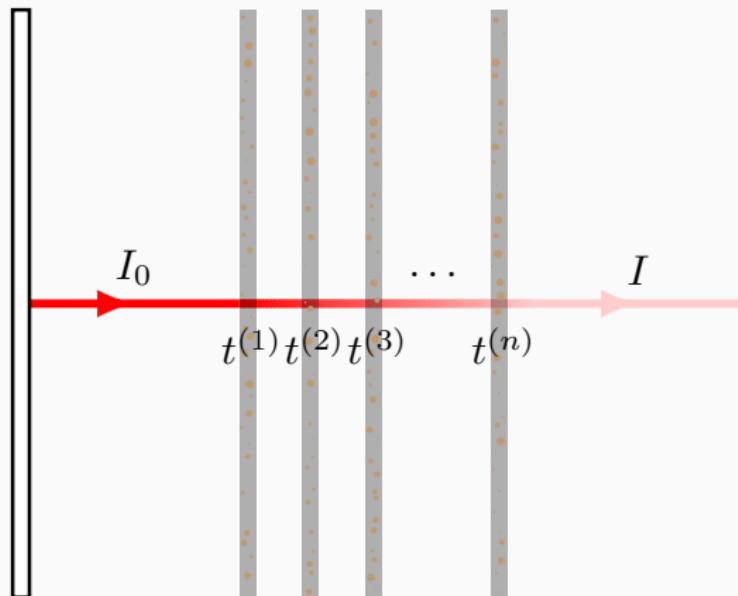
$$\frac{I}{I_0} = \exp \left( - \int_{\mathcal{R}} \mu(r) dr \right)$$

# THE BEER-LAMBERT LAW



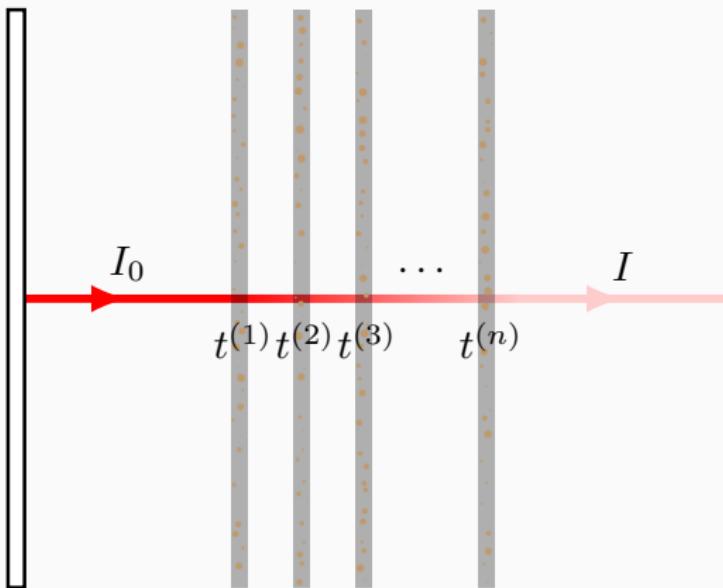
$$\frac{I}{I_0} = \exp \left( - \int_{\mathcal{R}} \mu(r) dr \right)$$

# THE BEER-LAMBERT LAW



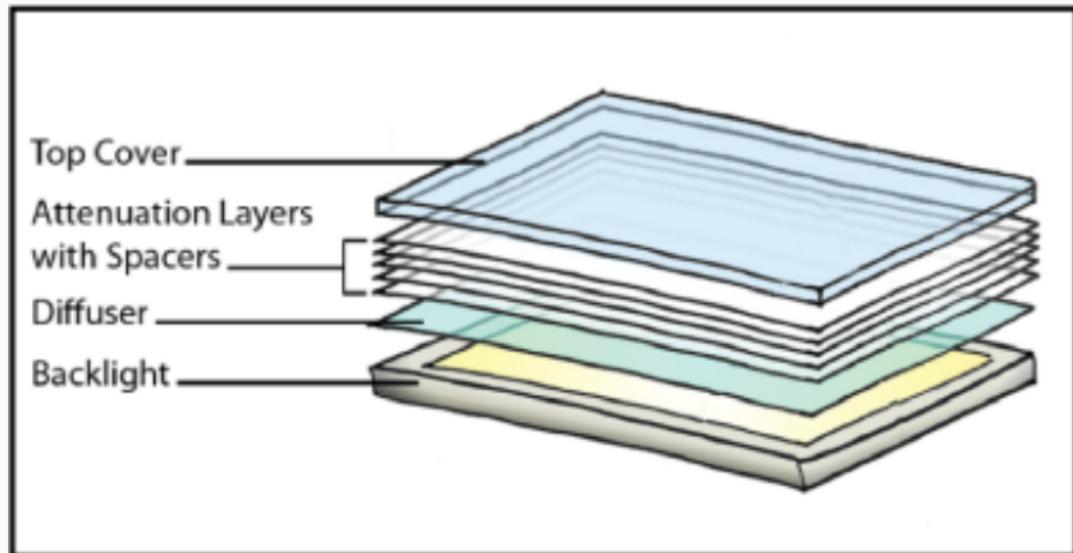
$$\frac{I}{I_0} = \exp \left( - \int_{\mathcal{R}} \mu(r) dr \right) = \prod_i t^{(i)}$$

# THE BEER-LAMBERT LAW



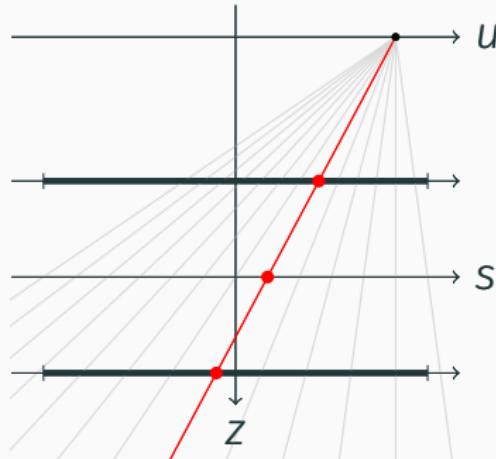
$$\frac{I}{I_0} = \exp \left( - \int_{\mathcal{R}} \mu(r) dr \right) = \prod_i t^{(i)} = \exp \left( - \sum_i a^{(i)} \right)$$

# DISPLAY ARCHITECTURE



Wetzstein et al. [2011]

# LIGHT TRANSMISSION



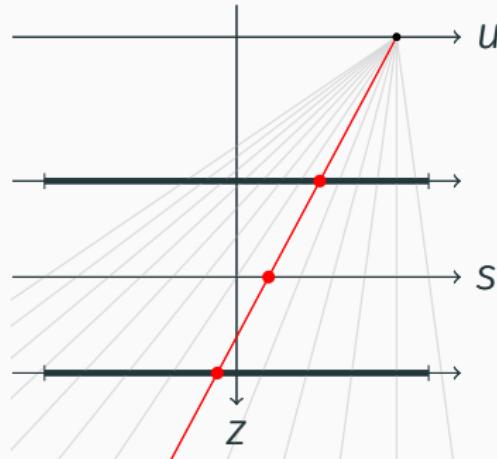
$$L_m = L_0 \prod_{n=1}^N t^{(n)}(h(m, n))$$

$L_m$  Color of ray  $m$

$t$  Transmission

$h$  Intersection

# LIGHT TRANSMISSION



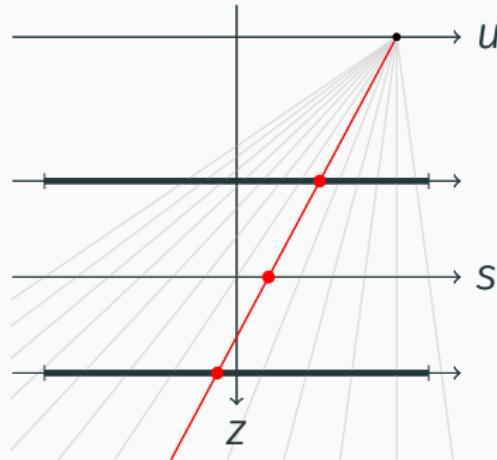
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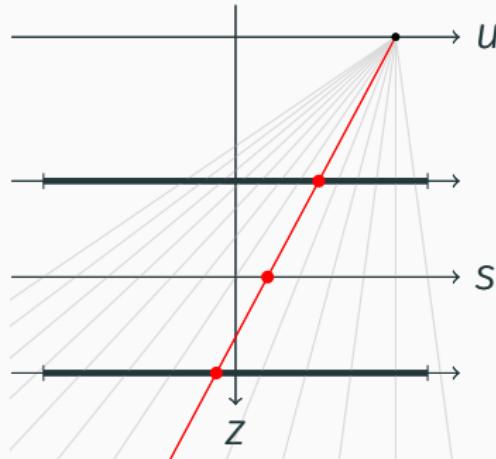
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# LIGHT TRANSMISSION



$$L_m = L_0 \prod_{n=1}^N t^{(n)}(h(m, n))$$

$L_m$  Color of ray  $m$

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$h$  Intersection

From now on:  $L_0 = 1$

# FROM TRANSMISSION TO ABSORBANCE

- Transmission values unknown

$$L_m = \prod_{n=1}^N t^{(n)}(h(m, n))$$

## FROM TRANSMISSION TO ABSORBANCE

- Transmission values unknown
- Solve equations simultaneously for all rays

$$L_m = \prod_{n=1}^N t^{(n)}(h(m, n))$$

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- Solve equations simultaneously for all rays
- This is hard

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## FROM TRANSMISSION TO ABSORBANCE

- Transmission values unknown
- Solve equations simultaneously for all rays
- This is hard
- Transform to log-domain

$$L_m = \prod_{n=1}^N t^{(n)}(h(m, n))$$

  $t = e^{-a}$

$$\log(L_m) = - \sum_{n=1}^N a^{(n)}(h(m, n))$$

## FROM TRANSMISSION TO ABSORBANCE

- Transmission values unknown
- Solve equations simultaneously for all rays
- This is hard
- Transform to log-domain
- **Solve for absorbance**

$$L_m = \prod_{n=1}^N t^{(n)}(h(m, n))$$

  $t = e^{-a}$

$$\log(L_m) = - \sum_{n=1}^N a^{(n)}(h(m, n))$$

# RAY CASTING

- One linear constraint per ray
- Create a big matrix  $P$
- Matrix encodes intersections

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# RAY CASTING

$$P = \begin{pmatrix} & \alpha_1 & \alpha_2 & \alpha_3 & \alpha_4 & \alpha_5 & \alpha_6 & \alpha_7 & \alpha_8 & \alpha_9 & \alpha_{10} \\ \bar{L}_1 & & & 1 & & & 1 & & & & \\ \bar{L}_2 & & & & 1 & & 1 & & & & \\ \bar{L}_3 & 1 & & & & & & 1 & & & \\ \bar{L}_4 & & 1 & & & & & & & 1 & \\ \hline \bar{L}_5 & & & & 1 & & & & 1 & & \\ \bar{L}_6 & & & 1 & & & 1 & & & & \\ \bar{L}_7 & 1 & & & & & & & & 1 & \\ \hline \bar{L}_8 & & & & 1 & & & 1 & & & \\ \hline \bar{L}_9 & & 1 & & & & & 1 & & & \\ \bar{L}_{10} & & & 1 & & & & & 1 & & \\ \bar{L}_{11} & & & 1 & & & & & & 1 & \\ \bar{L}_{12} & & 1 & & & & & & & & 1 \end{pmatrix}$$

# THE EQUATION

$$\log(L) = -P\alpha$$

- $\log(L)$  Vectorized log light field
- $\alpha$  Vector holding unkowns

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$$\log(L) = -P\alpha$$

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## OPTIMIZATION PROBLEM

$$\operatorname{argmin}_{\alpha} \|P\alpha + \log(L)\|^2$$

subject to  $\alpha \geq 0.$

- Proposed by Wetzstein et al. [2011]
- System is overdetermined
- Need iterative solver

## THE CONSTRAINT $\alpha \geq 0$

- Negative absorption ( $\alpha < 0$ ) is physically not possible
- The theoretical model supports negative absorption
- Constraint reduces the space of possible solutions

## EXAMPLE: LEGO TRUCK



$6 \times 6 \times 480 \times 640$   
 $\sim 2$  minutes

## EXAMPLE: LEGO TRUCK

Goal: Simulate viewing experience before assembly

$$I = e^{-P\alpha}$$

Original

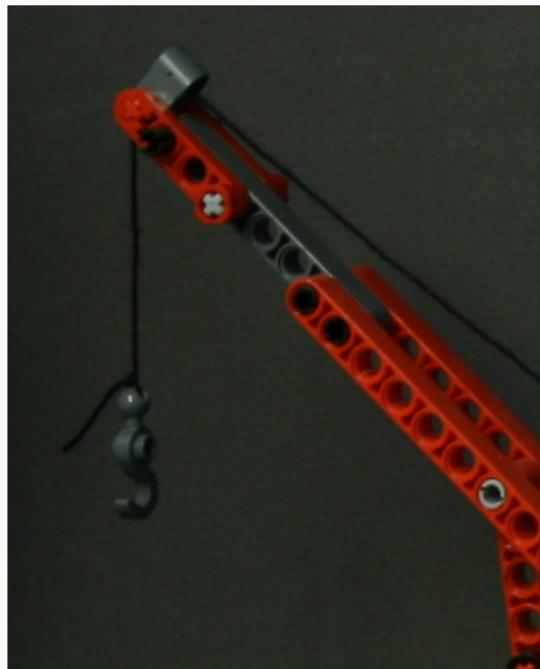


Simulation

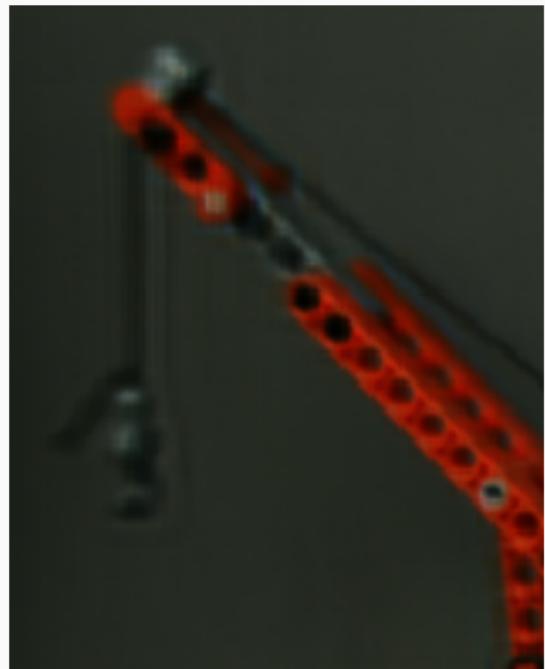


# 3 LAYERS

Original

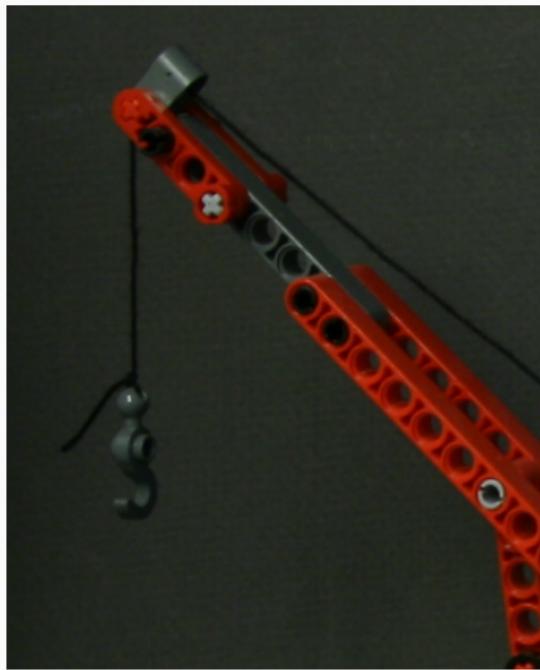


Simulation

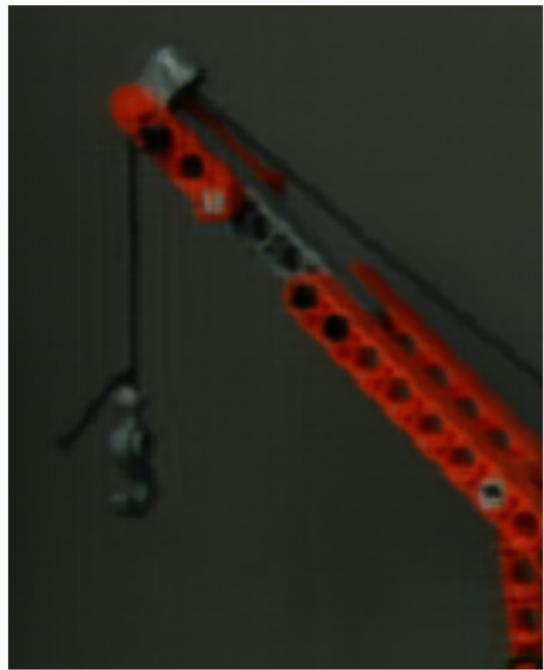


# 5 LAYERS

Original

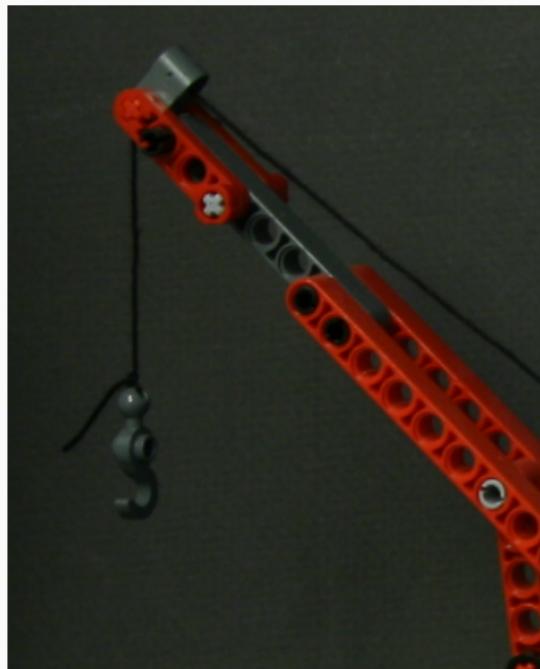


Simulation

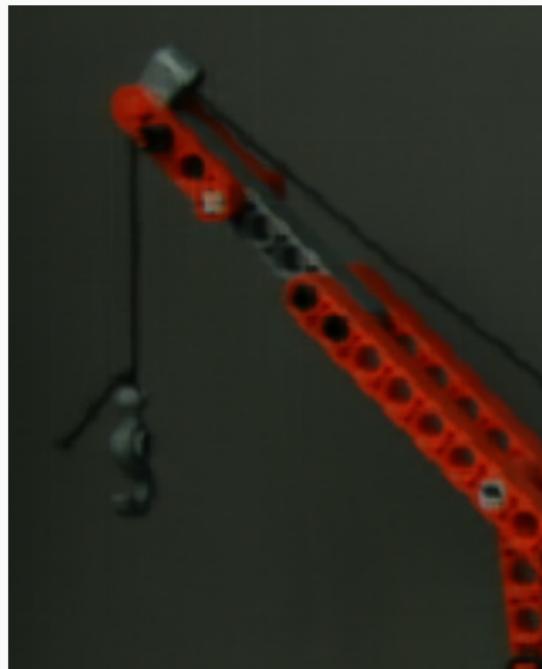


# 10 LAYERS

Original

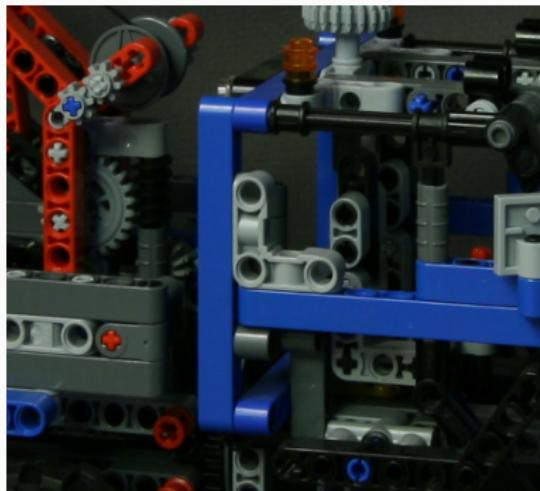


Simulation

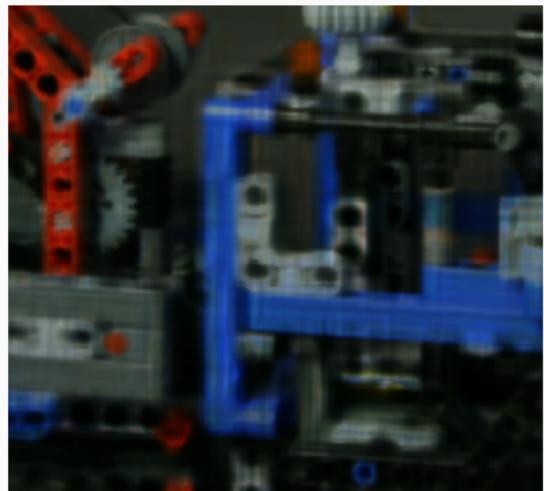


# 3 LAYERS

Original

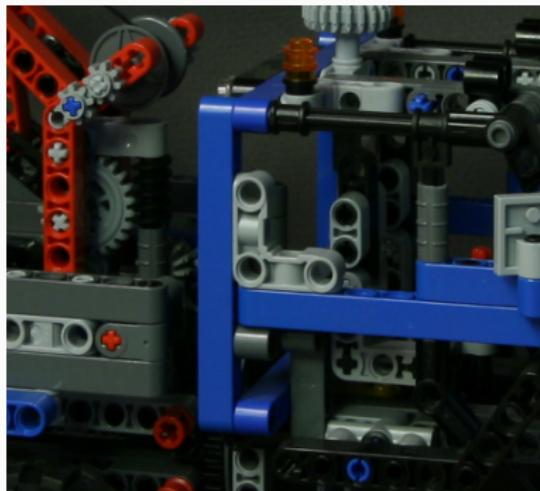


Simulation

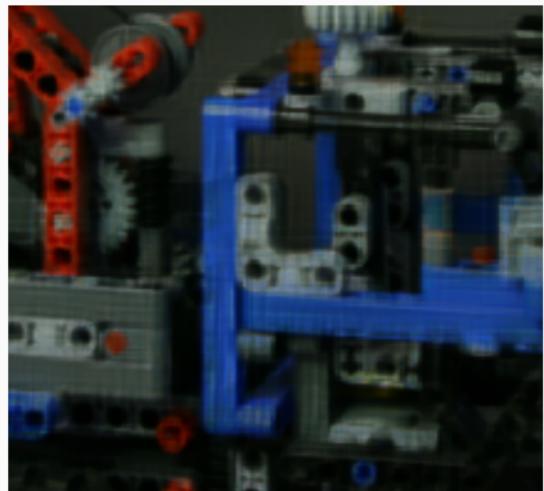


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Original

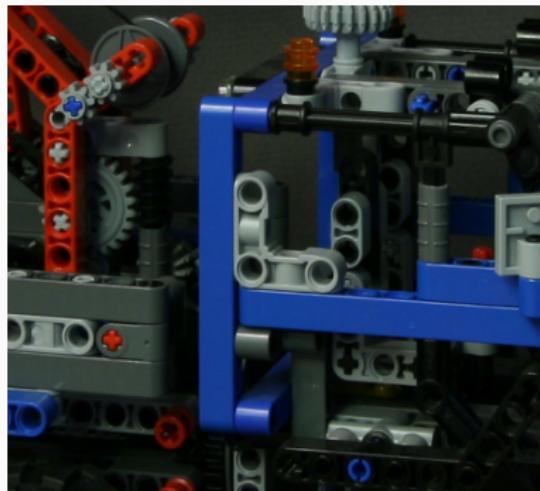


Simulation

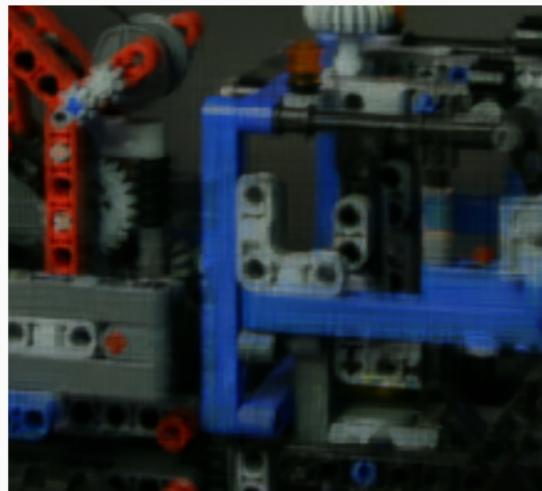


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Original

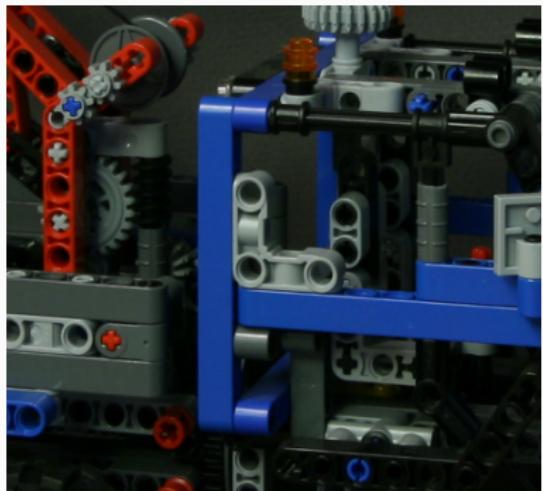


Simulation

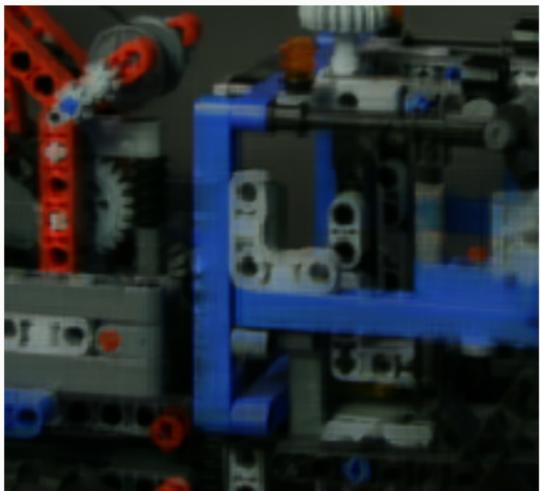


# 10 LAYERS, HIGHER ANGULAR RESOLUTION

Original



Simulation



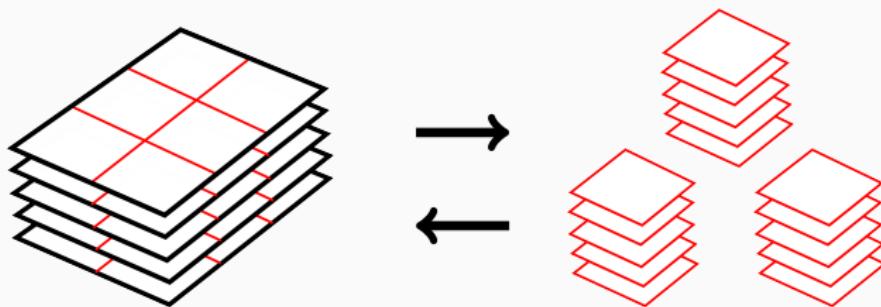
## EXAMPLE: LEGO TRUCK



- A lot of memory is needed:
  - Light field (uncompressed)
  - Propagation matrix (? nnz entries)
  - Additional matrices for solver
- Memory usage grows with resolution
- Solution: Slice the attenuator

# ATTENUATOR TILING

1. Slice attenuator into smaller pieces
2. Solve optimization problem for every slice
3. Reconnect the slices



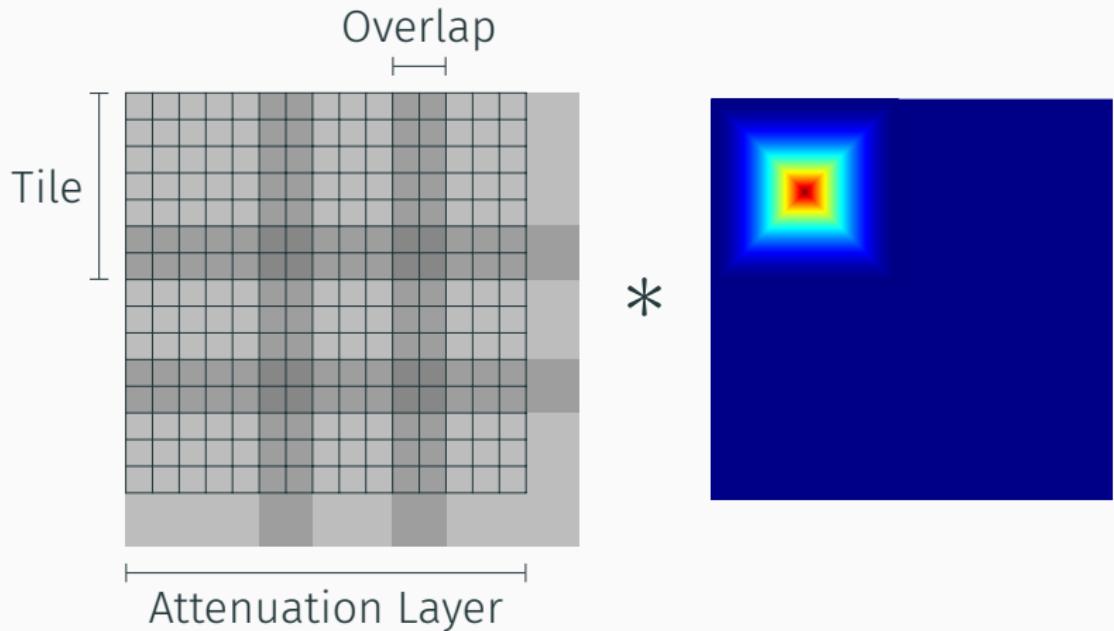
# ATTENUATOR TILING

- Problem: Rays can overlap with multiple slices at borders
- Slices need to overlap too
- Blend slices with mask

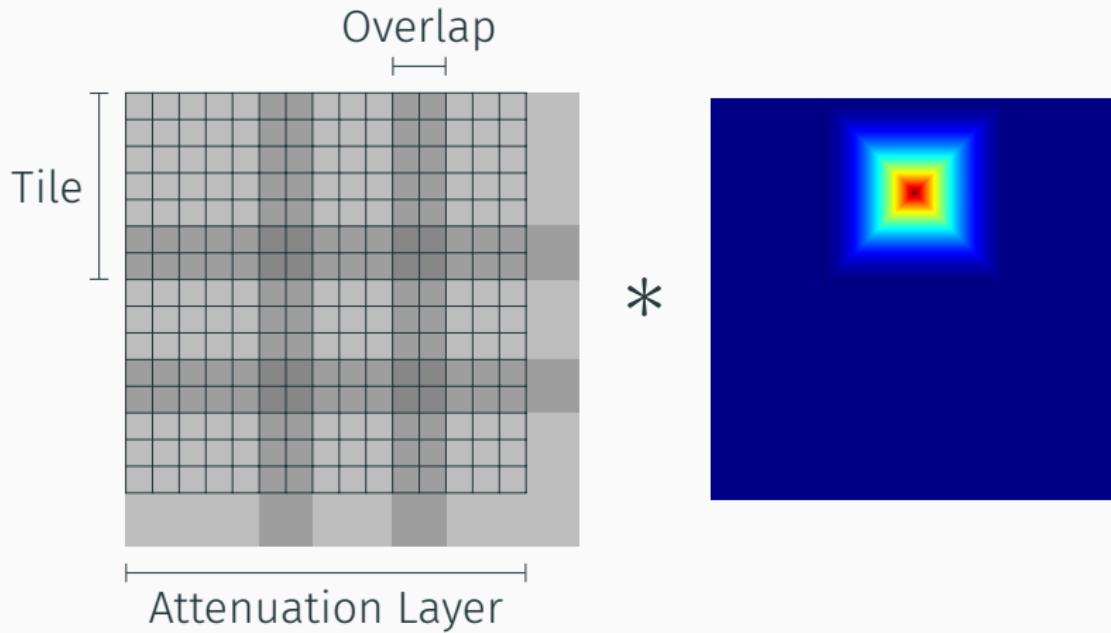


Simulation

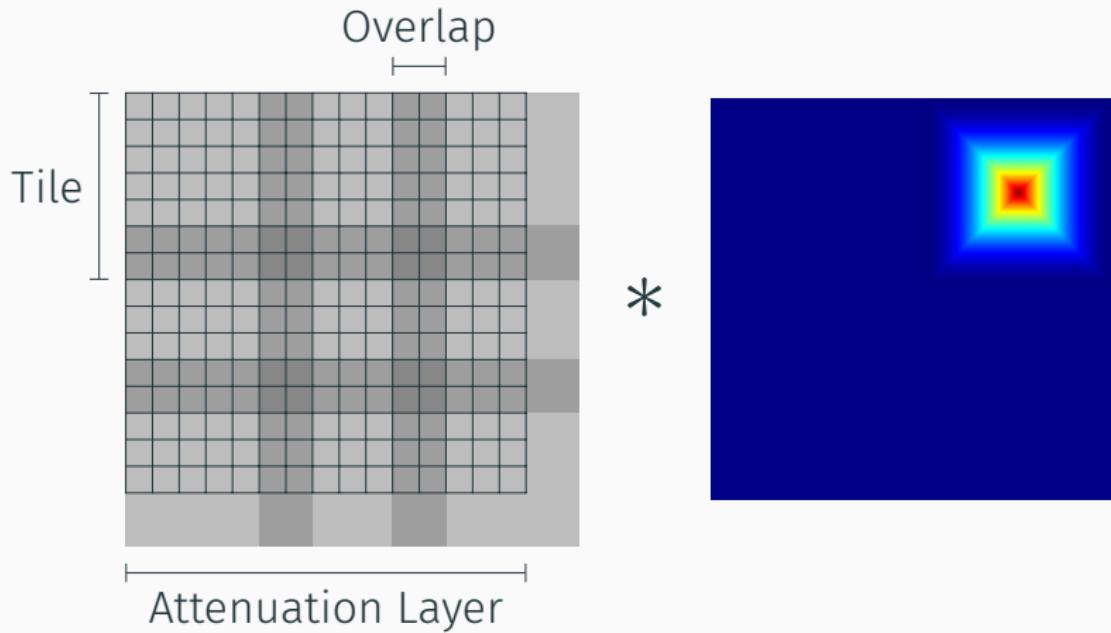
# TILE BLENDING



# TILE BLENDING



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# TILE BLENDING



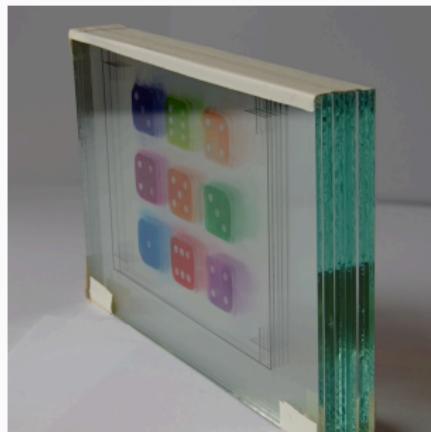
No overlap



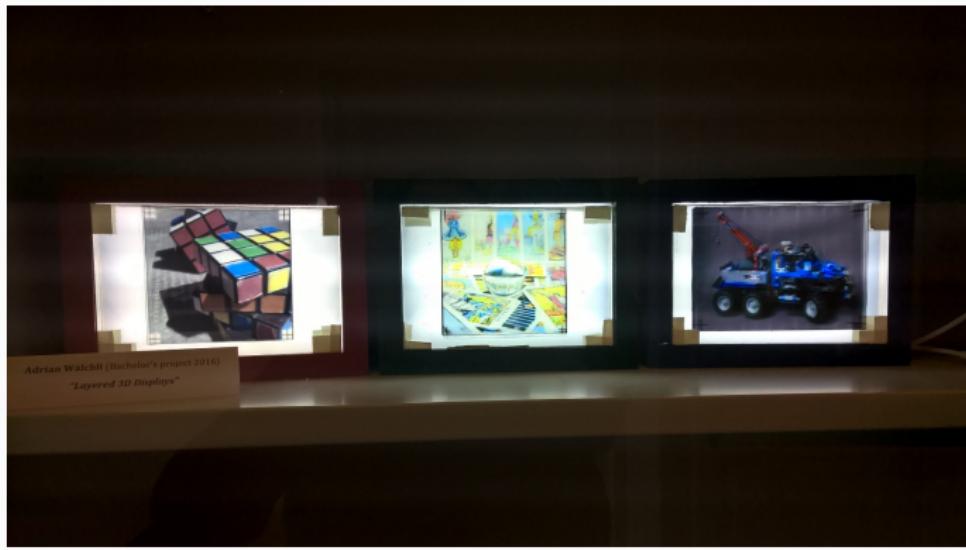
30% overlap

# THE FINISHED PRODUCT

- Finally, print images on transparent sheets
- Glass plates hold sheets in place
- Combine with backlight



# THE FINISHED PRODUCT



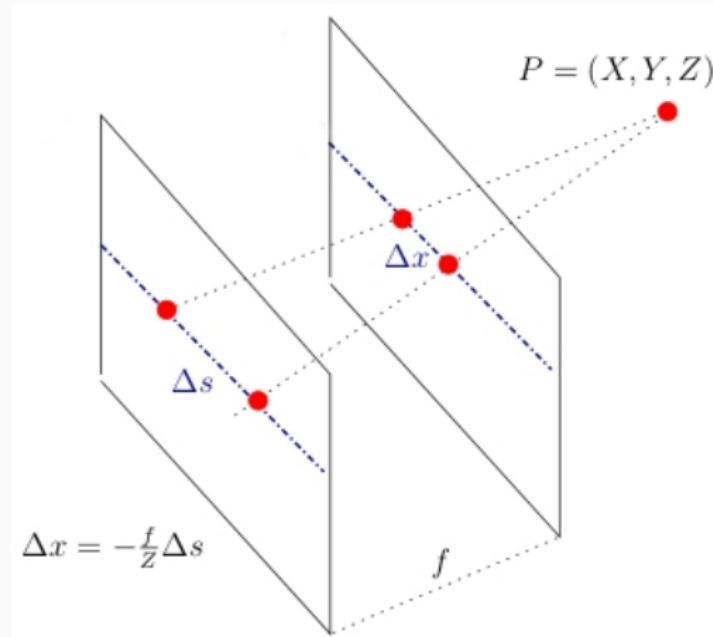
# QUESTIONS

- Impact of more layers?
- Does thickness of display matter?
- Is it possible to show objects outside the display?
- What are the limitations?

# SPECTRAL ANALYSIS

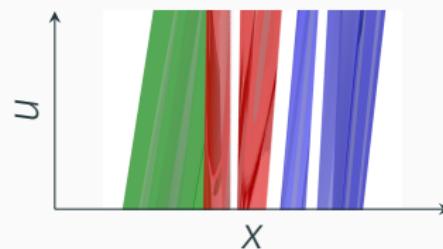
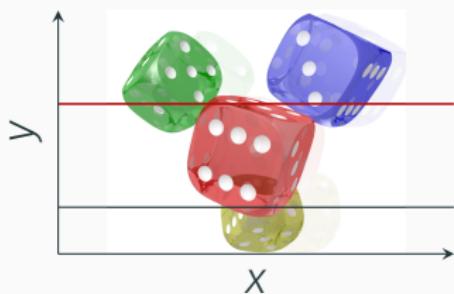
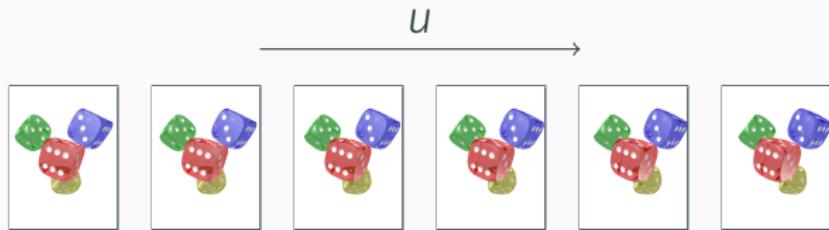
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# EPIPOLAR PLANE GEOMETRY

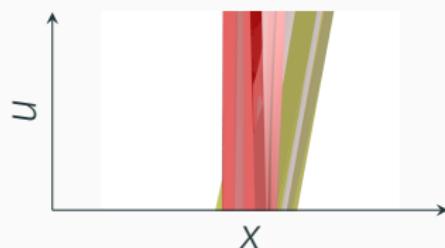
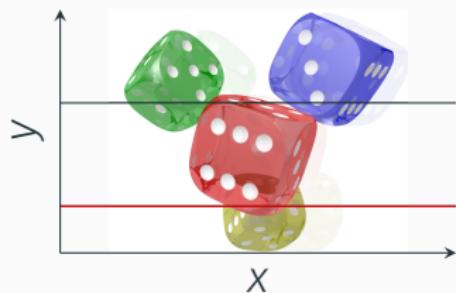
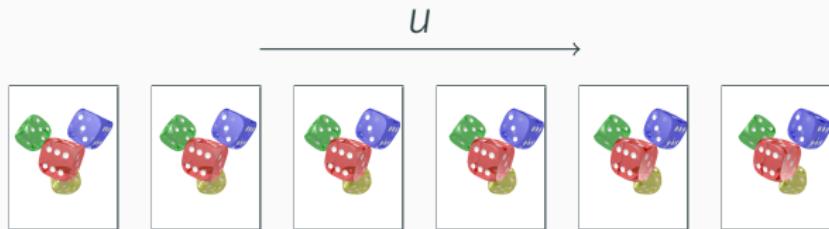


Source: klimt.iwr.uni-heidelberg.de

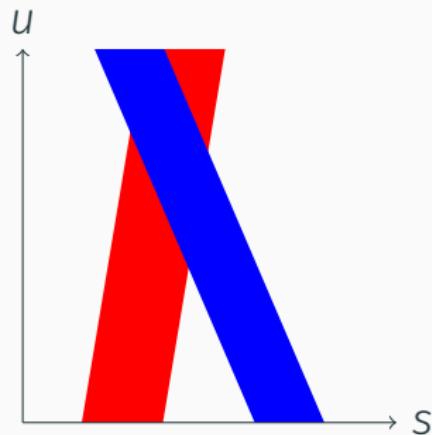
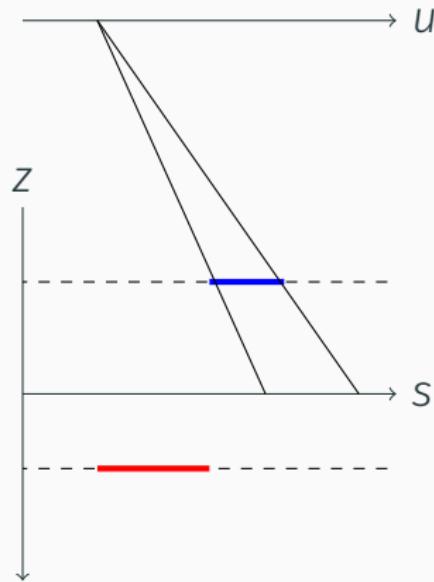
# EPIPOLAR PLANE IMAGE



# EPIPOLAR PLANE IMAGE

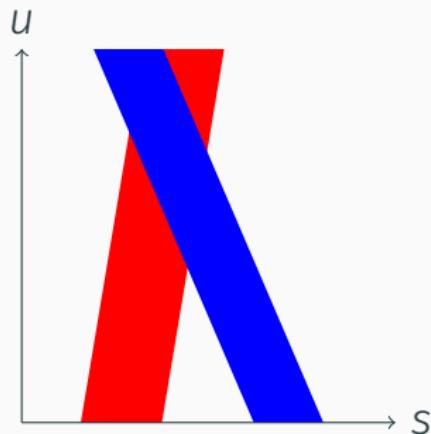
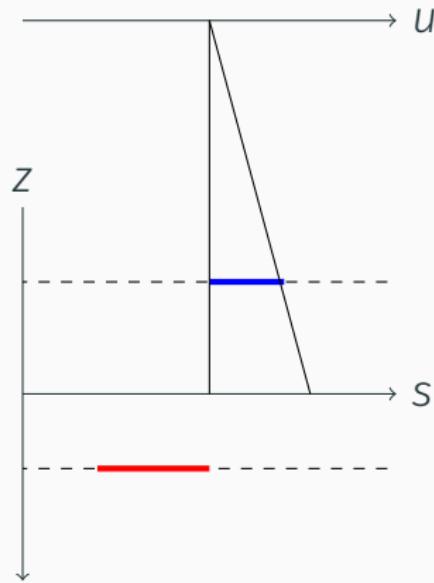


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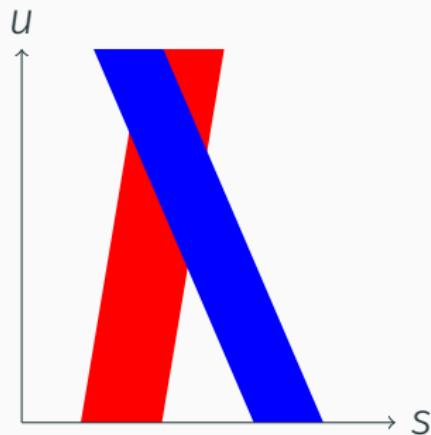
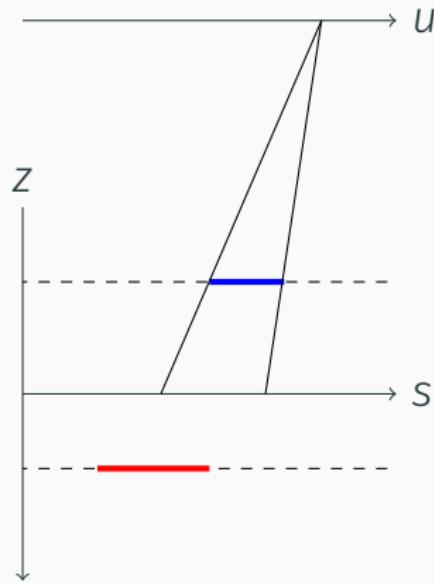
$$\frac{du}{ds} = \frac{z - Z_u}{z - Z_s}$$

# EPIPOLAR PLANE IMAGE



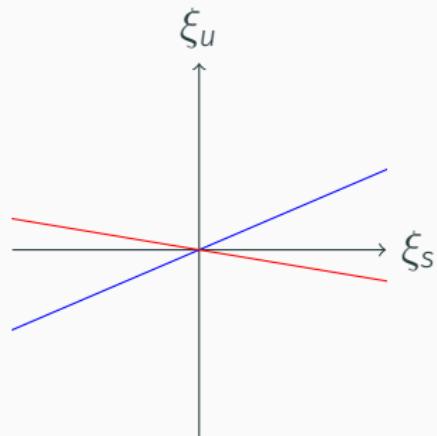
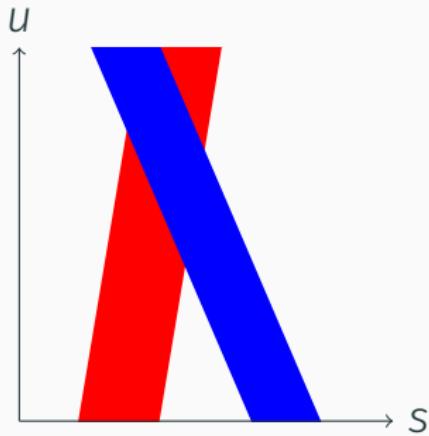
$$\frac{du}{ds} = \frac{z - Z_u}{z - Z_s}$$

# EPIPOLAR PLANE IMAGE



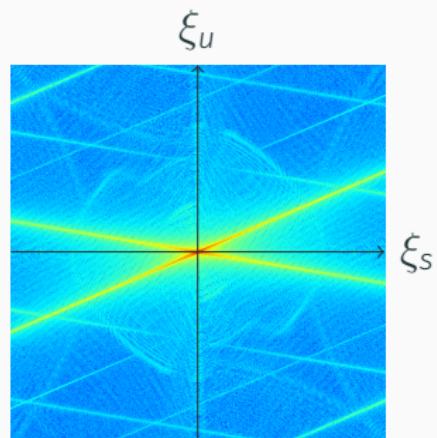
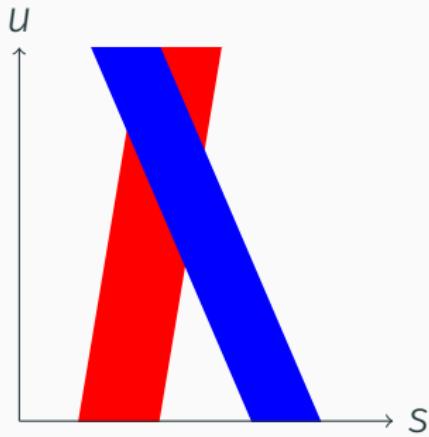
$$\frac{du}{ds} = \frac{z - Z_u}{z - Z_s}$$

# SPECTRAL PROPERTIES OF LIGHT FIELDS



Frequency Response  
(Amplitude)

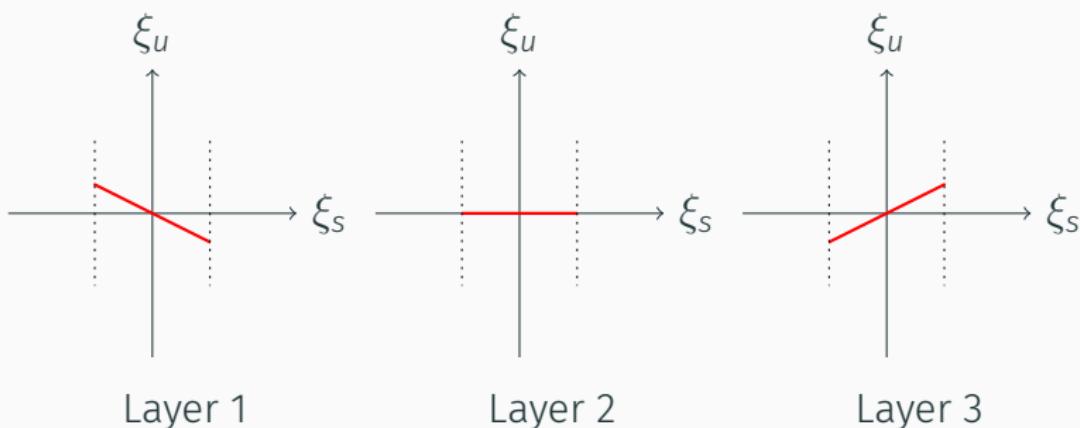
# SPECTRAL PROPERTIES OF LIGHT FIELDS



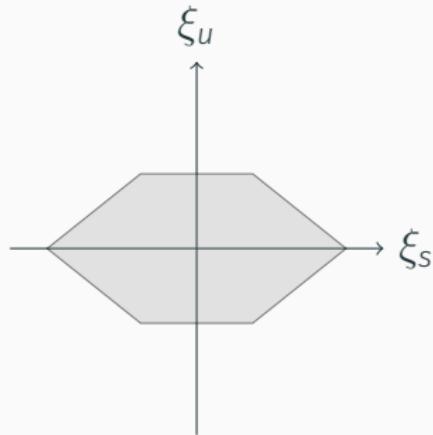
Frequency Response  
(Amplitude)

# SPECTRAL PROPERTIES OF DISPLAY

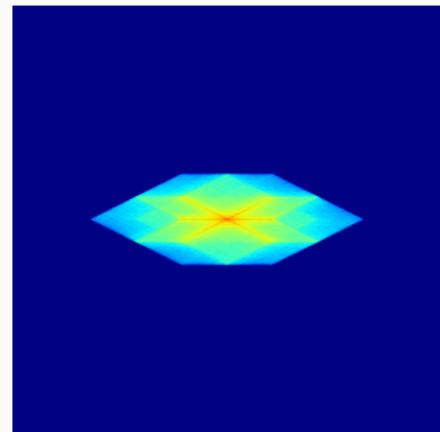
- Every layer creates a light field  $L_n$
- Stack of layers creates  $L' = L_0 \cdot L_1 \cdots L_N$
- What does  $L'$  look like in frequency domain?



# SPECTRAL PROPERTIES OF DISPLAY

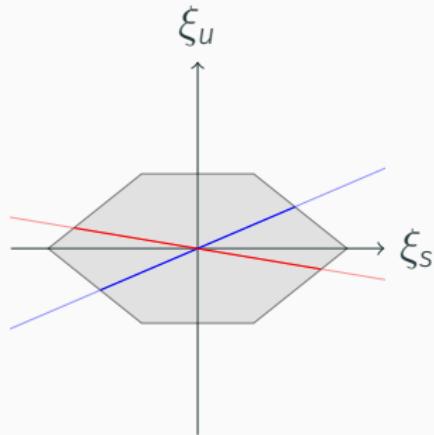


Spectral Support

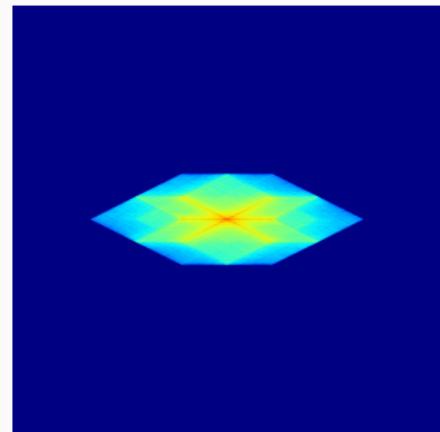


Frequency Response  
(Amplitude)

# SPECTRAL PROPERTIES OF DISPLAY



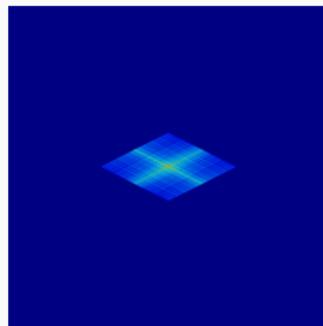
Spectral Support



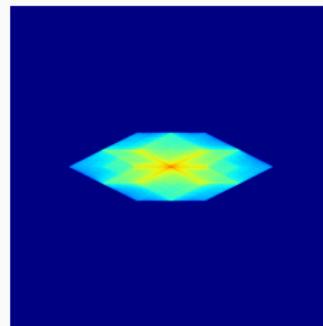
Frequency Response  
(Amplitude)

# SPECTRAL PROPERTIES OF DISPLAY

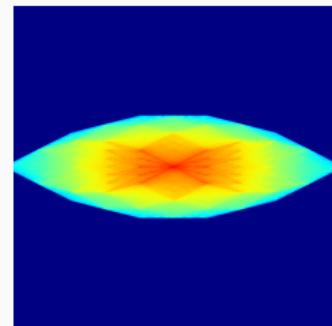
- Spectral support increases with more layers
- Highest response in center



2 Layers

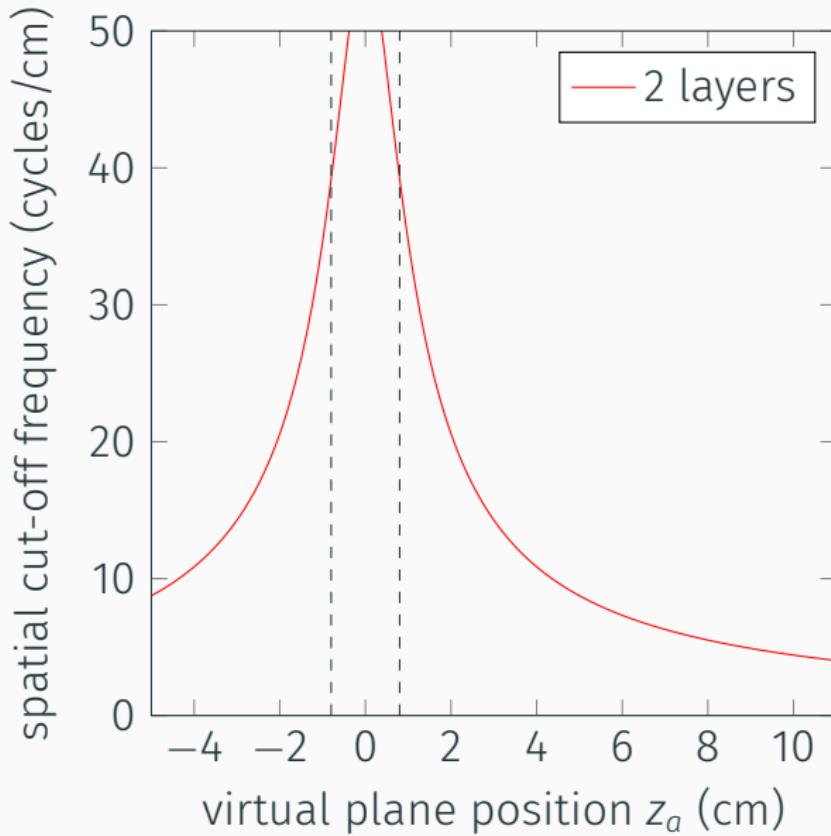


3 Layers

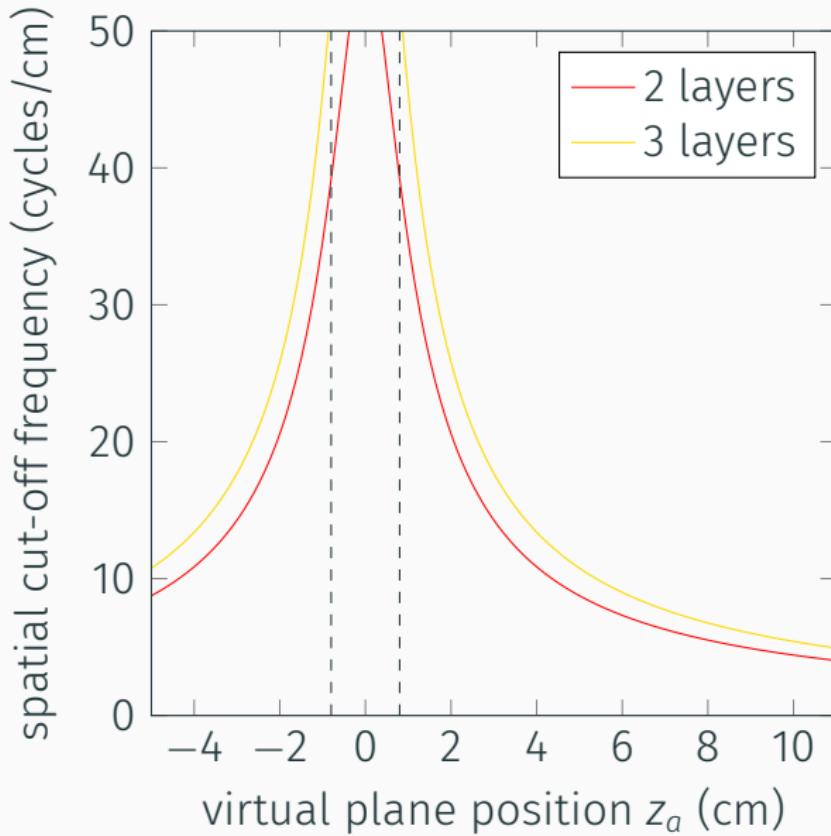


5 Layers

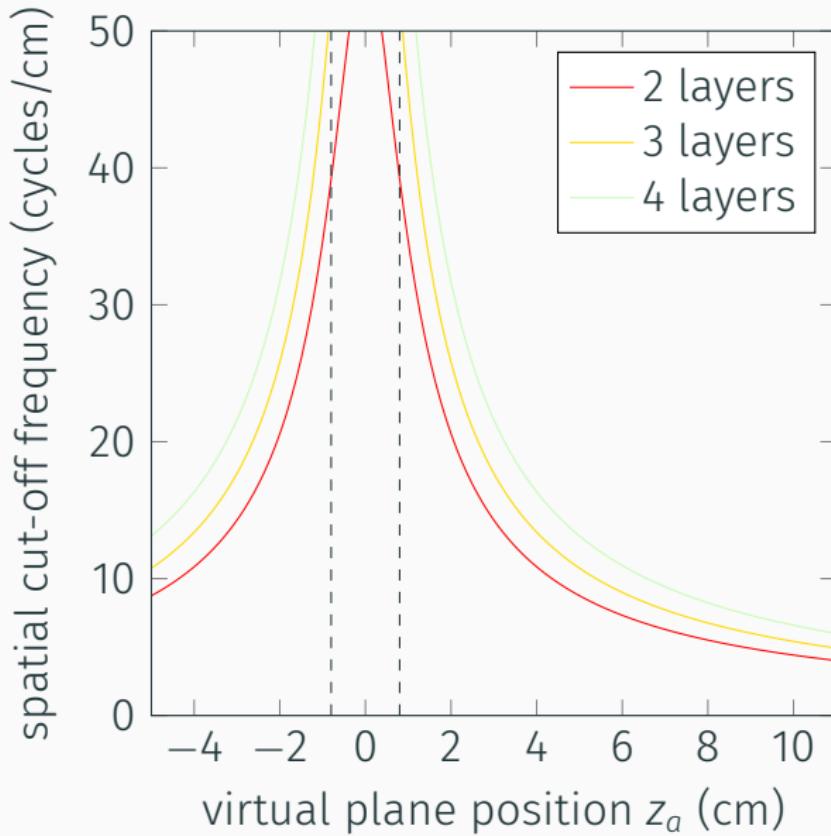
## DEPTH OF FIELD



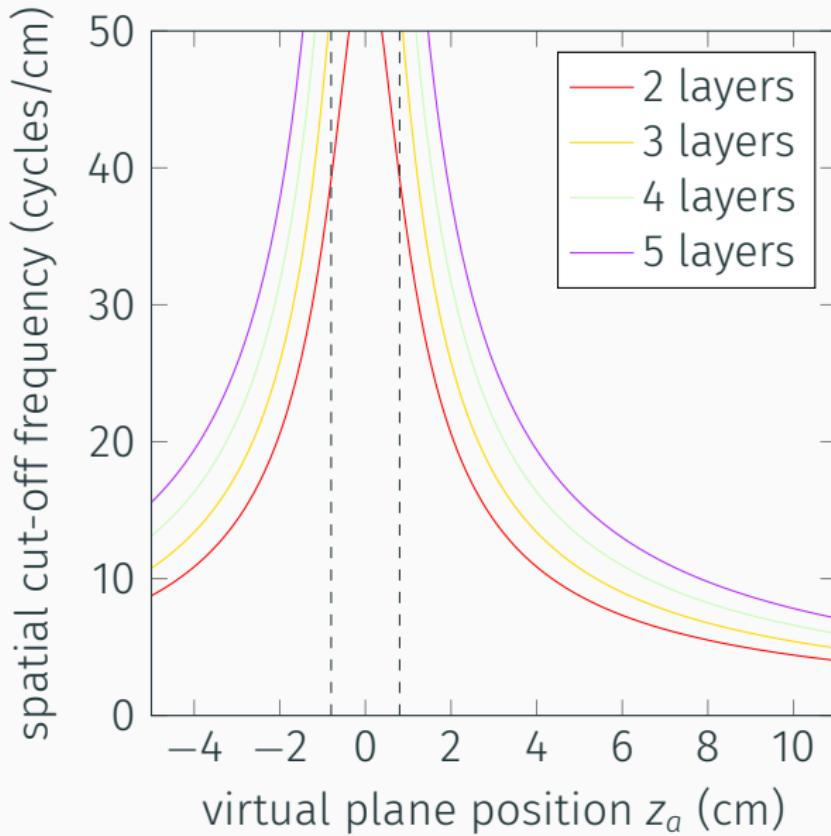
# DEPTH OF FIELD



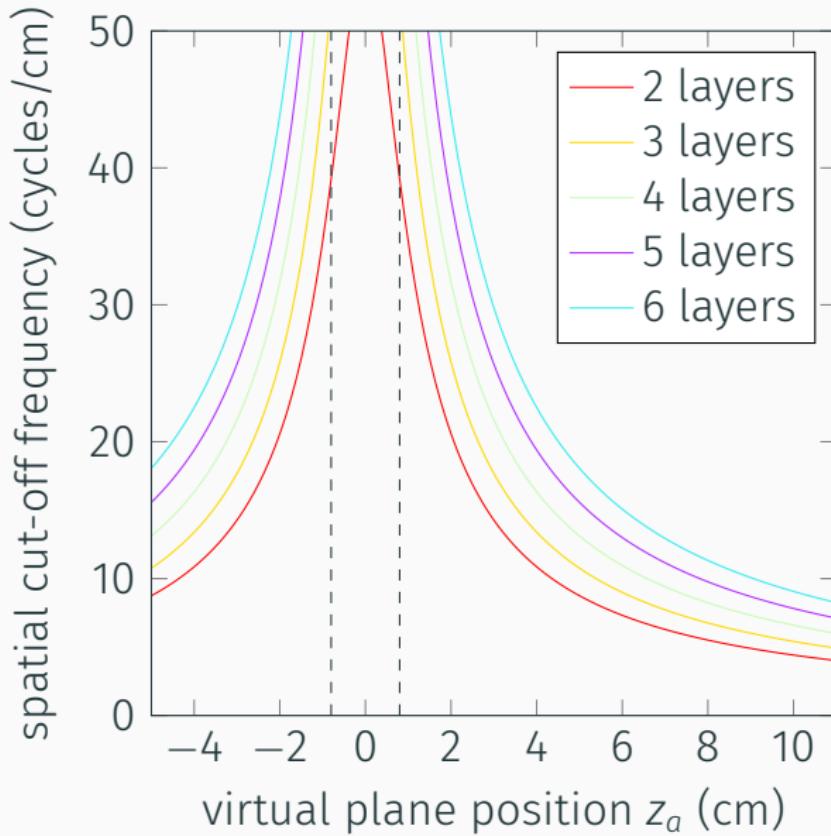
# DEPTH OF FIELD



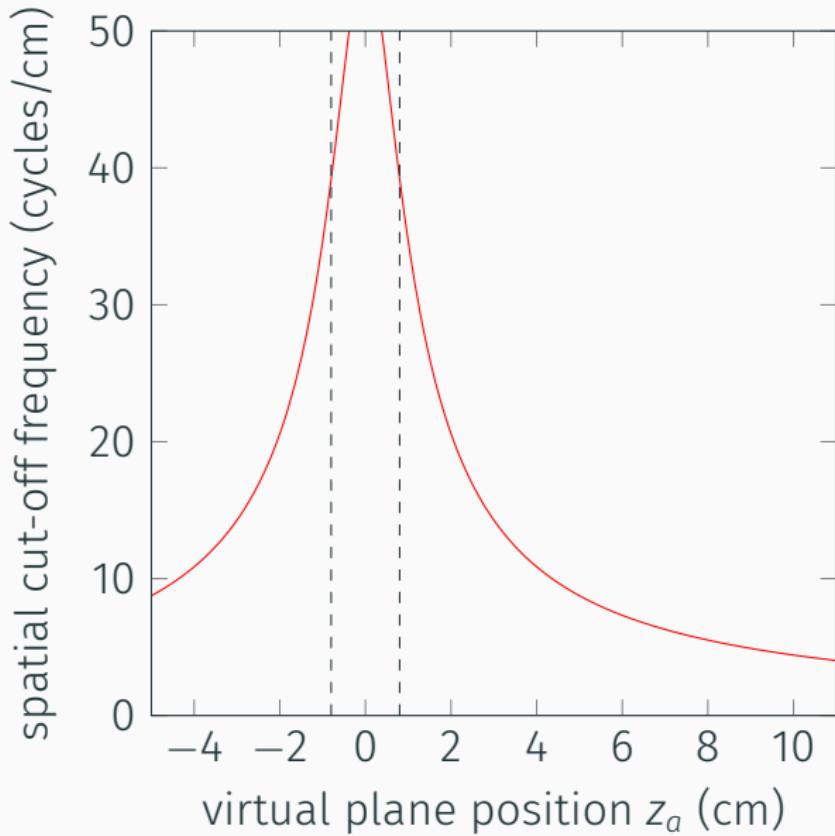
# DEPTH OF FIELD



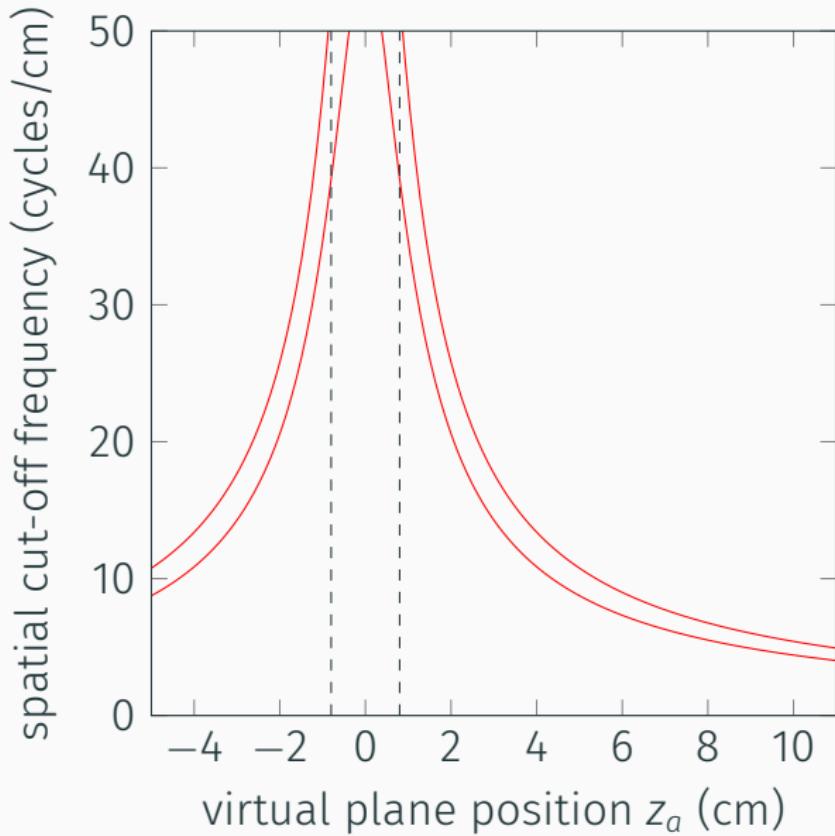
# DEPTH OF FIELD



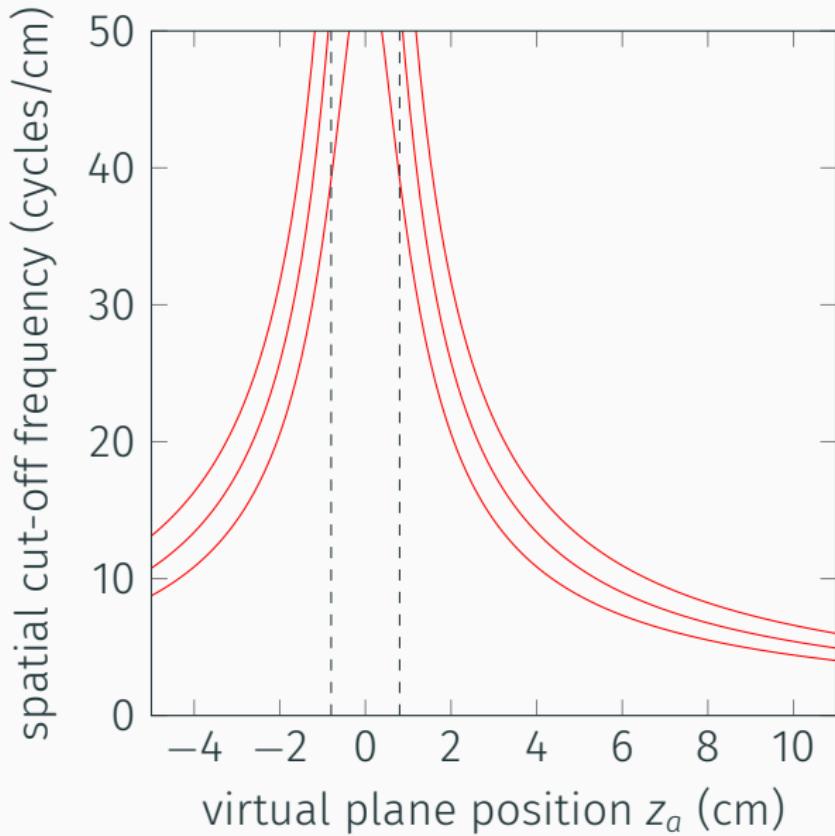
# DEPTH OF FIELD



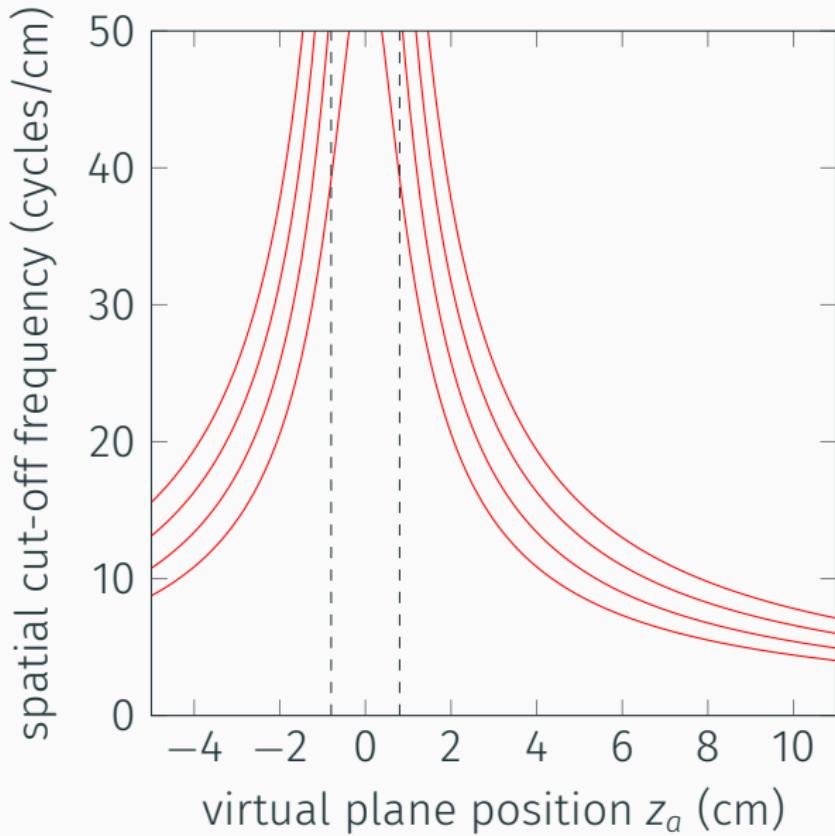
# DEPTH OF FIELD



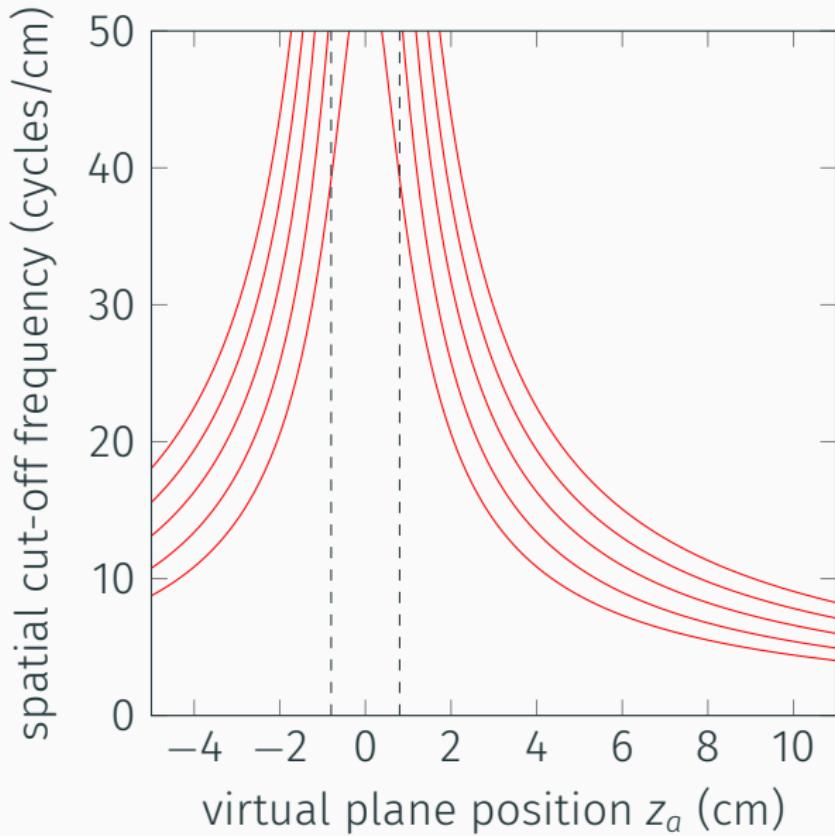
# DEPTH OF FIELD



# DEPTH OF FIELD



# DEPTH OF FIELD



# CONCLUSION

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## THE GOOD

- No trade-off between angular- and spatial resolution
- Extended spectral support
- Works with different types of light fields
  - Oblique Projections (synthetic scenes)
  - Perspective Projections (cameras)
  - Lytro

## THE BAD

- Very small viewing angles
- Depth of field highly dependent on thickness
  - Light field's depth of field needs to match
  - For fixed thickness, need to squeeze baseline
- Need many layers to eliminate halo artefacts
- Manual layer alignment is hard

# Your Questions

# ACKNOWLEDGEMENTS

Supervision by

Prof. Dr. Matthias Zwicker  
Siavash Bigdeli

## MORE INFORMATION

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### Thesis and Resources

[github.com/awaelchli/bachelor\\_thesis](https://github.com/awaelchli/bachelor_thesis)

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- A. Jones, I. McDowall, H. Yamada, M. Bolas, and P. Debevec. Rendering for an interactive 360° light field display. In *ACM SIGGRAPH 2007 Papers*, SIGGRAPH '07, New York, NY, USA, 2007. ACM.
- G. Wetzstein, D. Lanman, W. Heidrich, and R. Raskar. Layered 3D: Tomographic image synthesis for attenuation-based light field and high dynamic range displays. *ACM Trans. Graph.*, 30(4):95:1–95:12, 2011.