

# ATTENUATION-BASED LIGHT FIELD DISPLAYS

Bachelor Thesis

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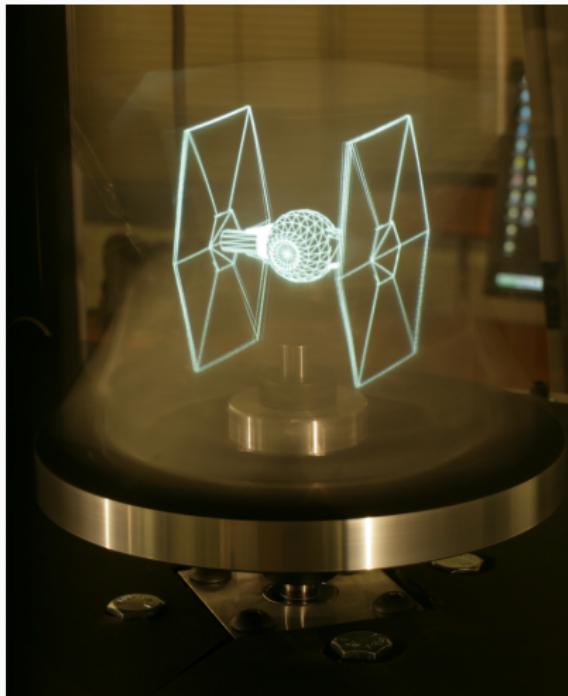
# OUTLINE

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

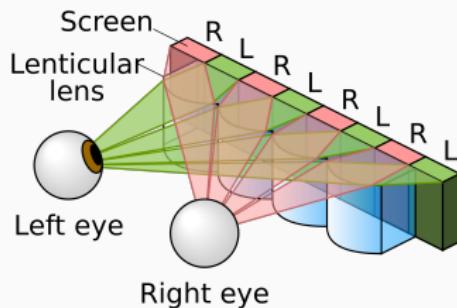
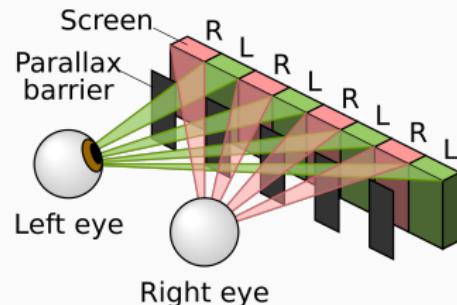
# INTRODUCTION

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# EXISTING 3D DISPLAYS



Jones et al. [2007]



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

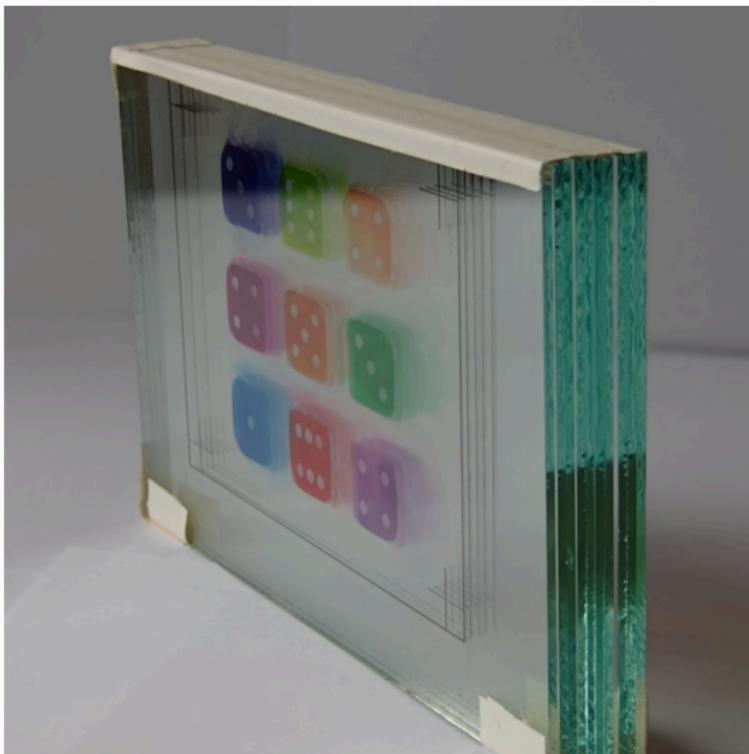
# EXISTING 3D DISPLAYS



# 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:** Inexpensive, glasses-free light field displays using volumetric attenuators. (Left) A stack of spaced light-field attenuators (e.g., press-molded translucent plastic light fields for a car) are stacked by a mold cavity. (Right) The target light field is shown in the upper left, together with the synthesized five-layer decomposition, obtained with iterative tomographic reconstruction. The bottom row shows a car for a viewer standing to the top left (magenta) and bottom right (cyan). Corresponding views of the target light field and five-layer prototype are shown on the left and right, respectively. Such attenuation-based 3D displays allow accurate, high-resolution depiction of motion parallax, occlusion, transparency, and specularity, being exhibited by the track, the window, and the roof of the car, respectively.

### Abstract

We develop tomographic techniques for image synthesis on displays composed of compact volumes of light-absorbing materials. Such volumetric attenuators require a 4D light field or light-volume representation, which means that arbitrary depth and arbitrary oblique slices may be inconsistent with any single attenuator. Iterative tomographic reconstruction minimizes the difference between the target light field and the volume, while it also physically constraints on attenuation. As multi-layer generalizations of common parallel barriers, such displays are shown, both by theory and experiments, to outperform the performance of existing light-field architectures. For 3D displays, our performance is higher, and brightness are increased, compared to parallel barriers. For a plane of a fixed depth, our optimization also allows optimal construction of high dynamic range displays, and provides a new way of providing the first extension to multiple, disjoint layers. We conclude by demonstrating the benefits and limitations of attenuation-based displays, and by showing how they can be used to separate multiple printed inks/paints with acrylic sheets.

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

[Links](#) [DL](#) [PDF](#) [Wiki](#) [Video](#)

### 1 Introduction

3D displays are designed to replicate as many perceptual depth cues as possible. As surveyed by Lipkin [1982], these cues can be classified by those that require one eye (monocular) or both eyes (binocular). These include motion parallax, motion blur, stereopsis, shading, and occlusion, to obtain the illusion of depth with 2D media. Including motion parallax and accommodation, existing 2D displays are not able to provide these cues. Glasses-free 3D displays are designed to provide the lacking binocular cues of disparity and convergence, along with three missing monocular cues.

Current 3D displays preserve disparity, but square spatial cuspacy (e.g., LCD shear, polarizers, or mirrors) is often used to convert 3D images to 2D images, and thereby reduce artifacts without encumbering the viewer. As categorized by Pandura (2008), such glasses-free displays include parallel barriers [Ives 1903; Kellomäki 1998], volume displays [Huang et al. 1999], light-field displays [Bhandarkar and Schwartz 1999], and holograms [Blinberg et al. 2005]. Holograms present all depth cues, but are expensive and difficult to produce. Light-field displays use a light-field illuminator [Majluf et al. 2001]. Research is addressing these issues [Blanche et al. 2010], yet parallel barriers and volumetric displays are the most promising technologies for low-cost, mass-market 3D displays. Furthermore, volumetric displays can replicate similar depth cues with flicker-free refresh rates [Froehlich 2005].

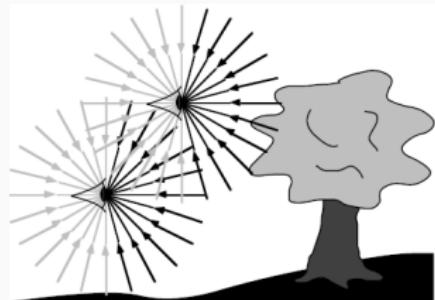
This paper concerns volumetric displays composed of compact volumes of light-absorbing materials, which we call “attenuated 3D” displays. Differing from volumetric displays with light-emitting layers, overlaid attenuating patterns allow objects to appear beyond the display enclosure, and the depiction of motion parallax, occlusion, and transparency. While parallel barriers and volumetric displays work well for static images, our prototype uses static prints of liquid-crystal display (LCD) panels, our prototype uses static prints to demonstrate the potential of this approach to 3D displays. 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

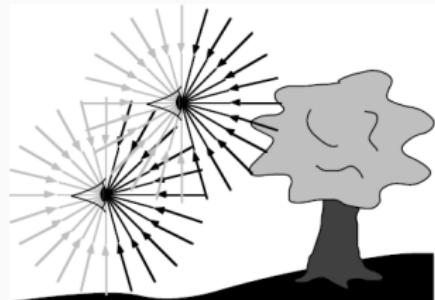
- Measures light in the world
- Position, viewing direction
- Time, Wavelength
- $P(x, y, z, \theta, \phi, t, \lambda)$
- 7D



Adelson and Bergen [1991]

# THE PLENOPTIC FUNCTION

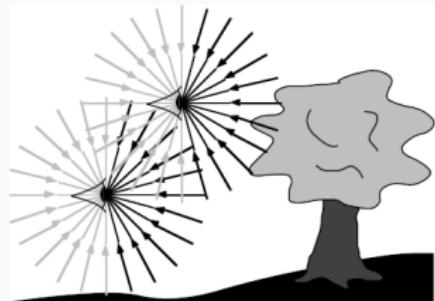
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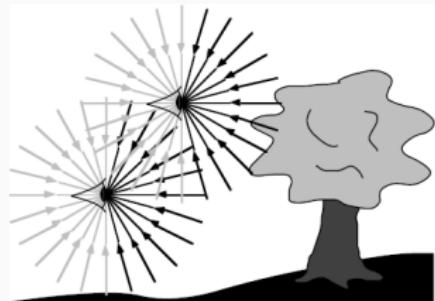
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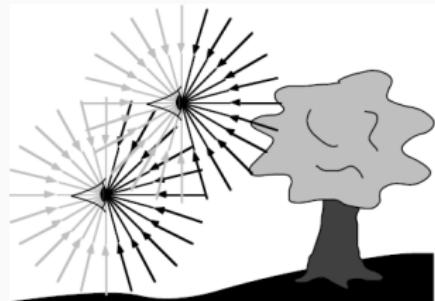
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Adelson and Bergen [1991]

# THE PLENOPTIC FUNCTION

- Measures light in the world
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- 7D



Adelson and Bergen [1991]

# THE 4D LIGHT FIELD

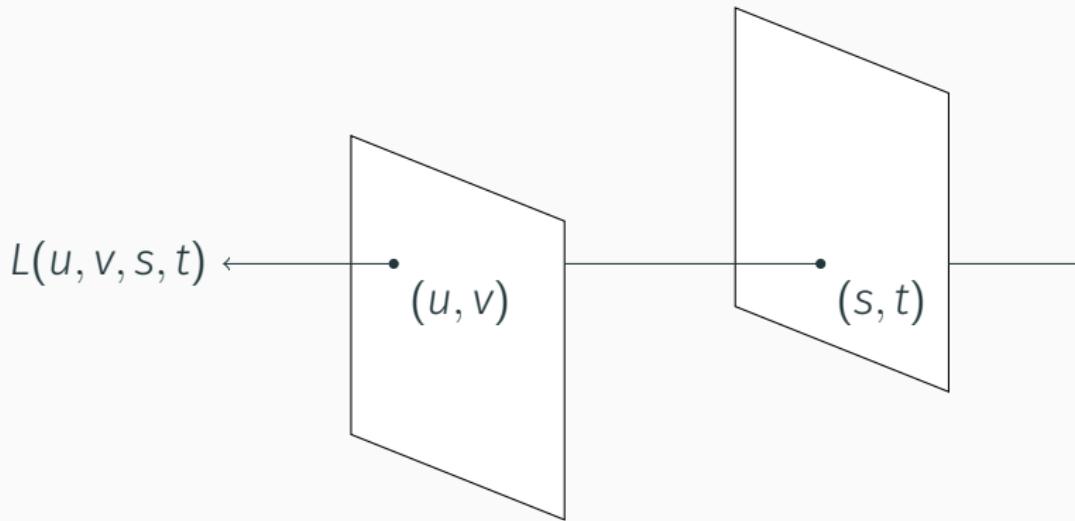
- Reduce dimensions of  $P$
- $L(u, v, s, t)$
- Defined by two planes

## THE 4D LIGHT FIELD

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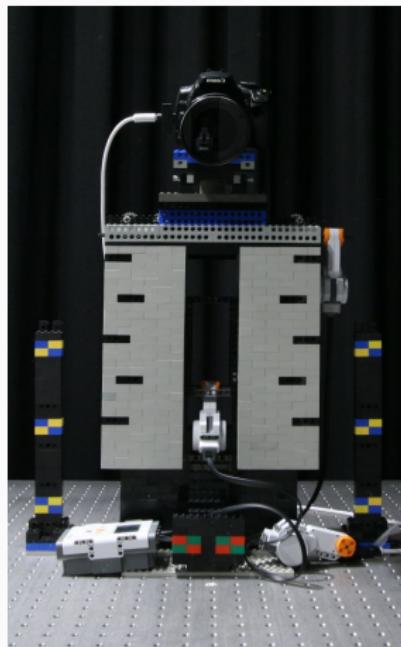


# LIGHT FIELD ACQUISITION



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

# LIGHT FIELD ACQUISITION



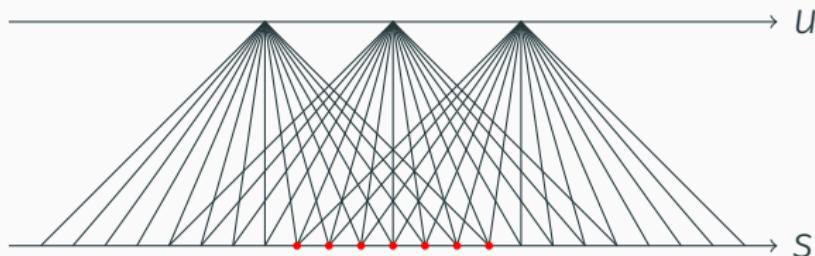
Lego gantry. Source: [lightfield.stanford.edu](http://lightfield.stanford.edu)

# LIGHT FIELD ACQUISITION

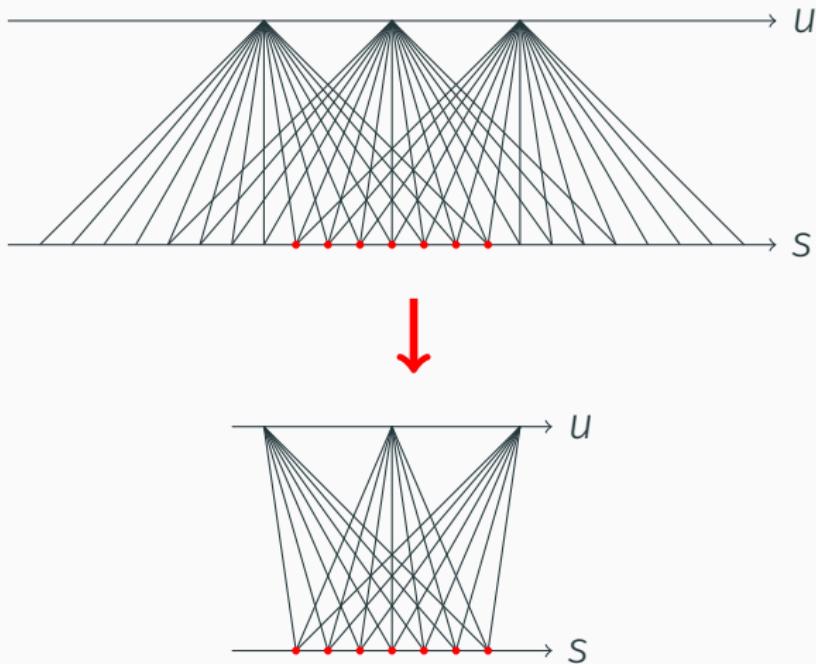


Lytro plenoptic camera. Source: [de.wikipedia.org/wiki/Lytro](https://de.wikipedia.org/wiki/Lytro)

# RE-PARAMETERIZATION TO GLOBAL COORDINATES



# RE-PARAMETERIZATION TO GLOBAL COORDINATES



# RE-PARAMETERIZATION TO GLOBAL COORDINATES

Raw



Rectified



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Raw



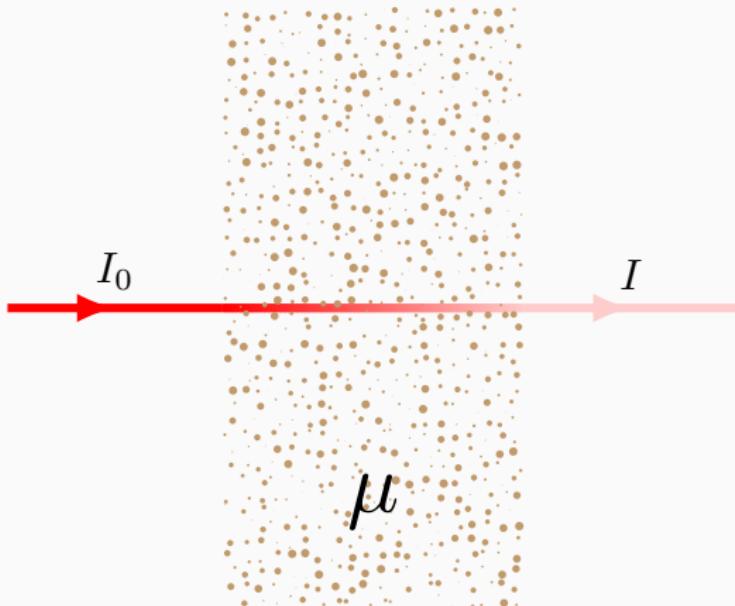
Rectified



# ATTENUATION DISPLAY

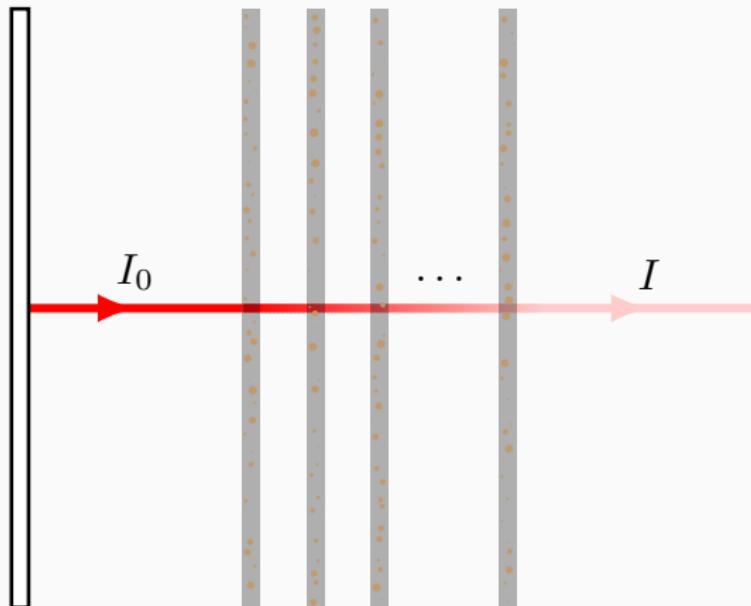
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# THE BEER-LAMBERT LAW



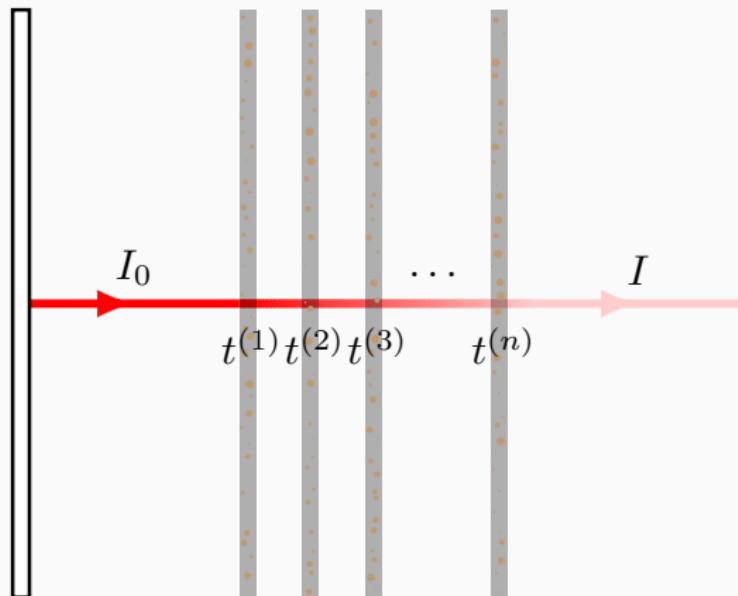
$$\frac{I}{I_0} = \exp \left( - \int_{\mathcal{R}} \mu(r) dr \right)$$

# THE BEER-LAMBERT LAW



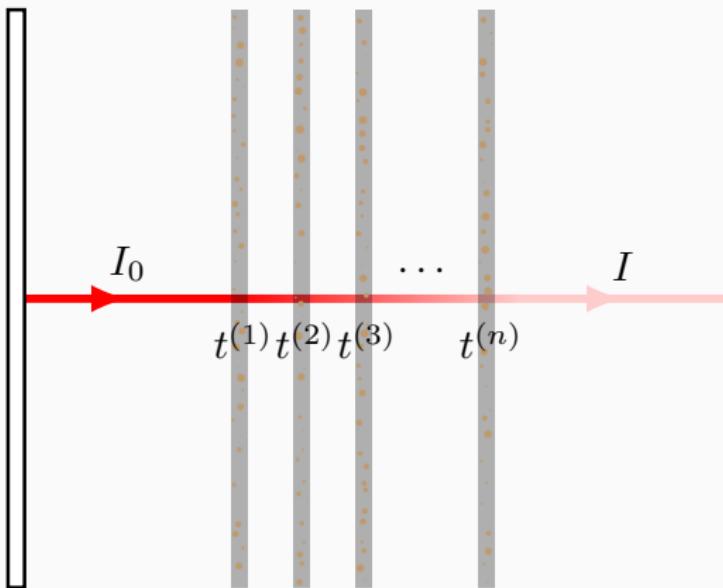
$$\frac{I}{I_0} = \exp \left( - \int_{\mathcal{R}} \mu(r) dr \right)$$

# THE BEER-LAMBERT LAW



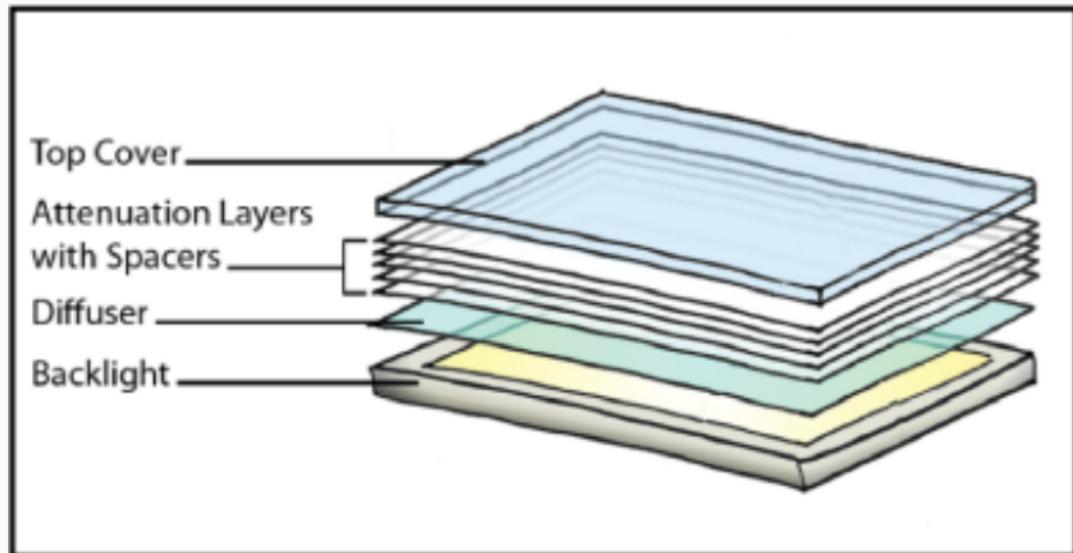
$$\frac{I}{I_0} = \exp \left( - \int_{\mathcal{R}} \mu(r) dr \right) = \prod_i t^{(i)}$$

# 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



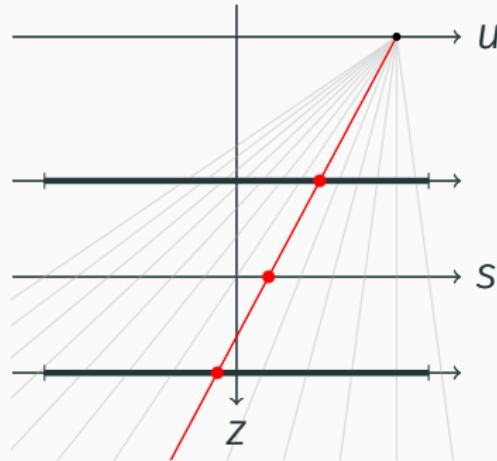
Wetzstein et al. [2011]

## PROBLEM STATEMENT

Given a light field

Produce layers that attenuate light from  
backlight such that display creates the given  
light field

# LIGHT TRANSMISSION



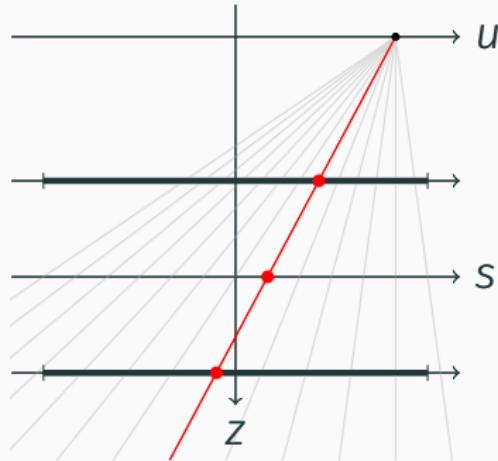
$$L_m = L_0 \prod_{n=1}^N t^{(n)}(h(m, n))$$

$L_m$  Color of ray  $m$

$t$  Transmission

$h$  Intersection

# LIGHT TRANSMISSION



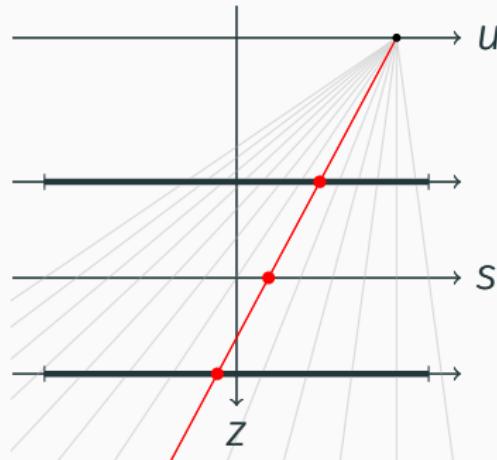
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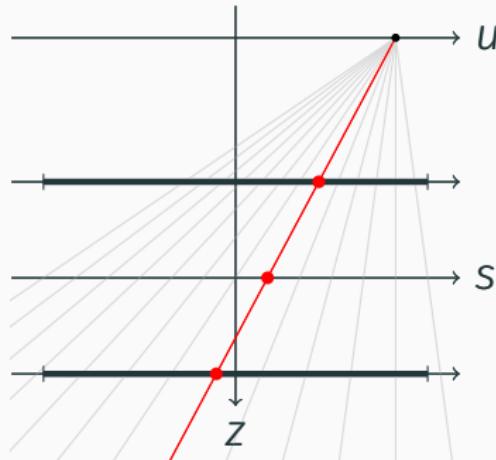
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$$L_m = L_0 \prod_{n=1}^N t^{(n)}(h(m, n))$$

$L_m$  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

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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

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

# THE EQUATION

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

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

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## 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



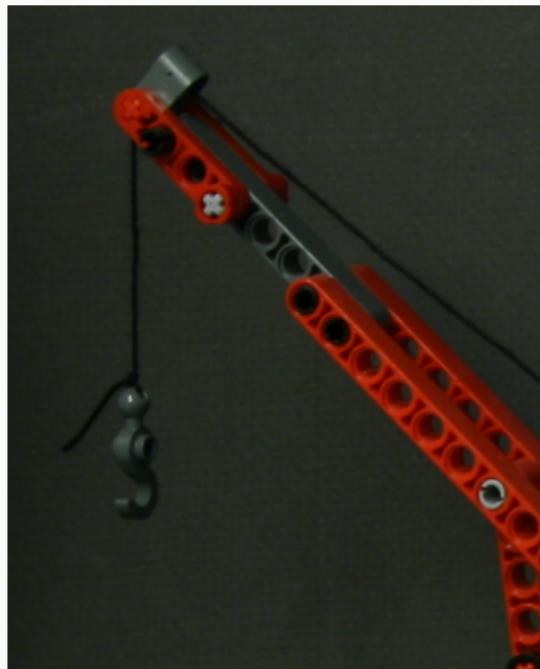
Simulation



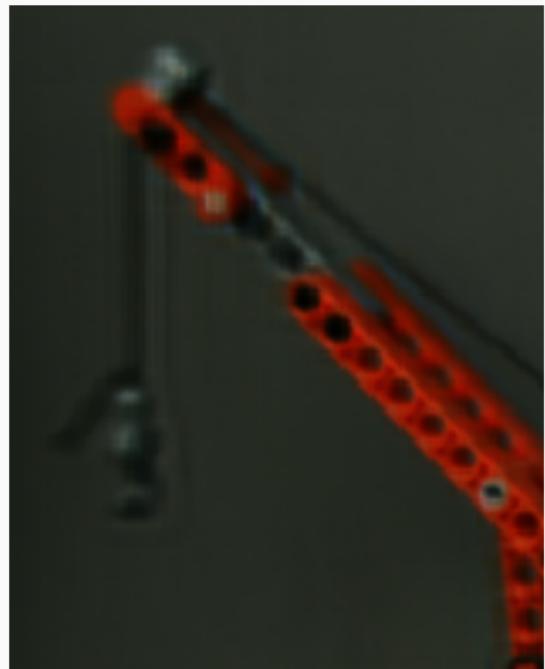
Light field courtesy: Stanford Light Field Archive

# 3 LAYERS

Original

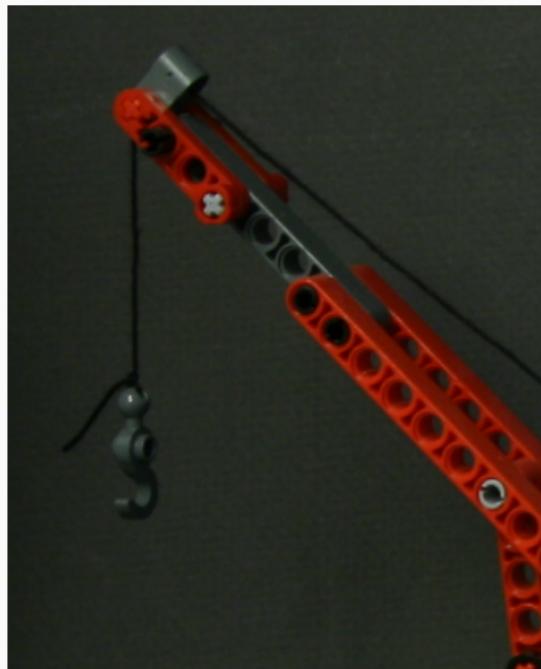


Simulation

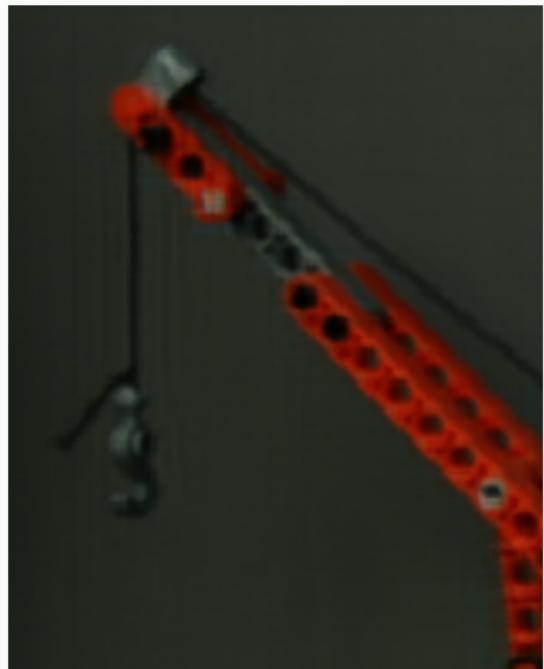


# 5 LAYERS

Original

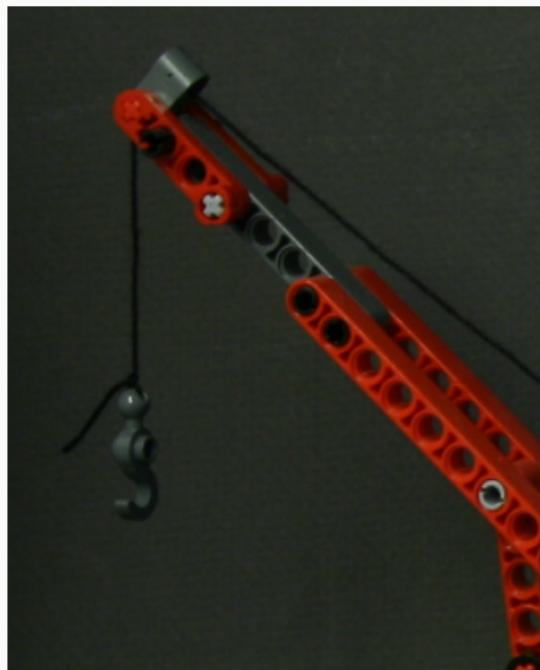


Simulation

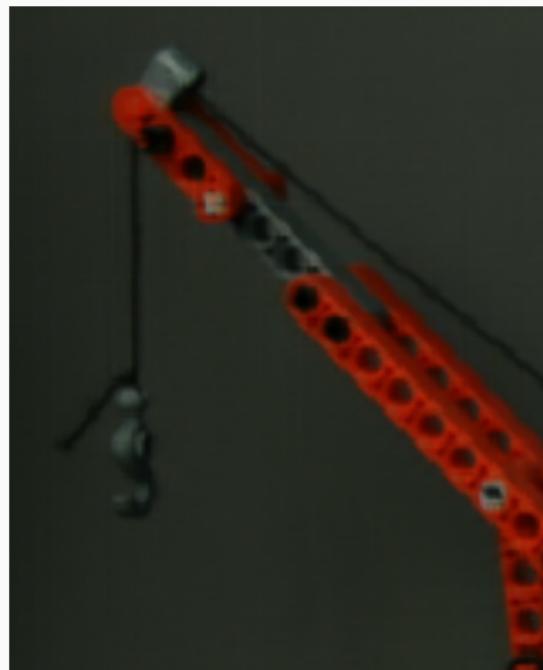


# 10 LAYERS

Original

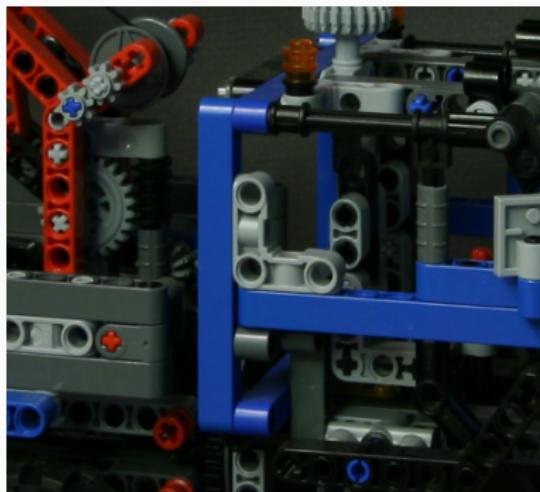


Simulation

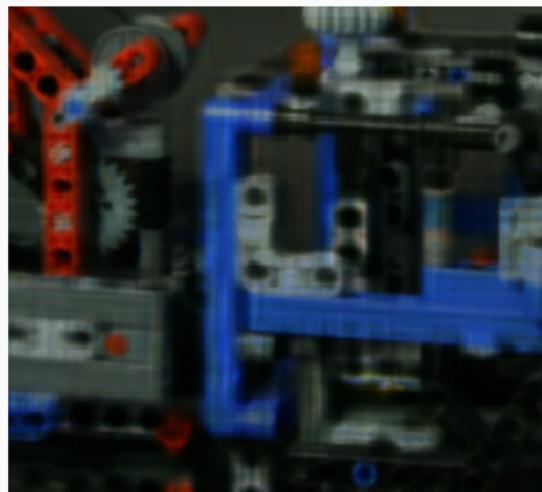


# 3 LAYERS

Original

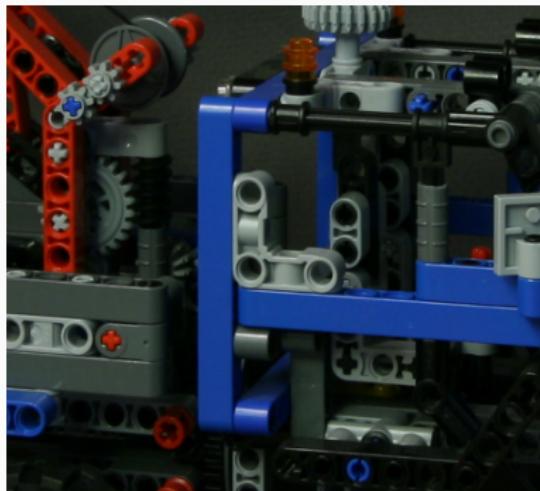


Simulation

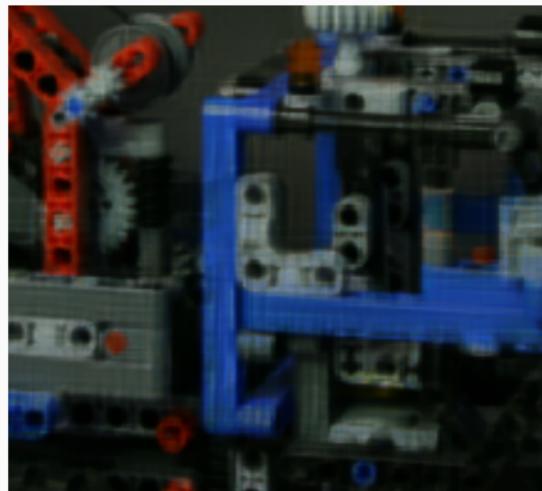


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Original

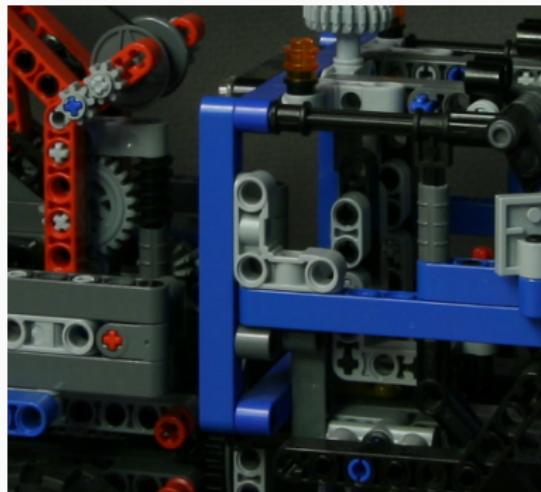


Simulation

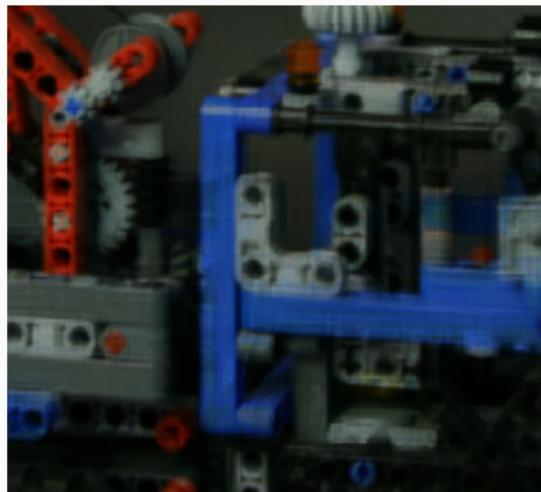


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Original

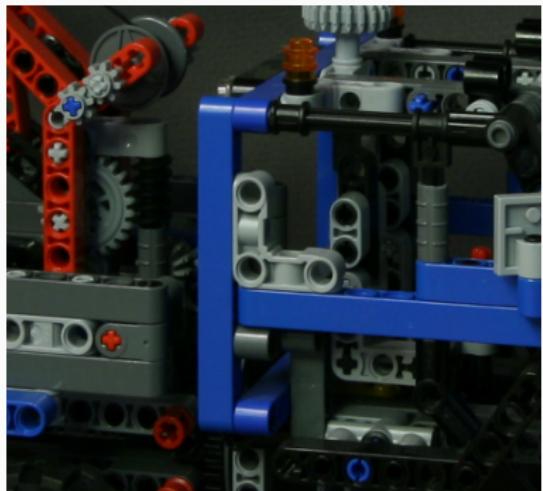


Simulation

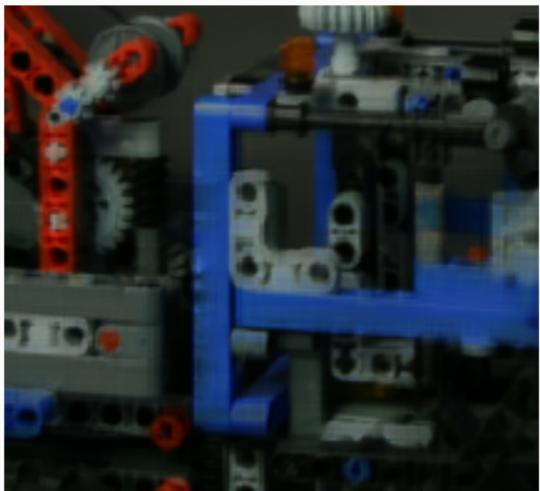


# 10 LAYERS, HIGHER ANGULAR RESOLUTION

Original



Simulation



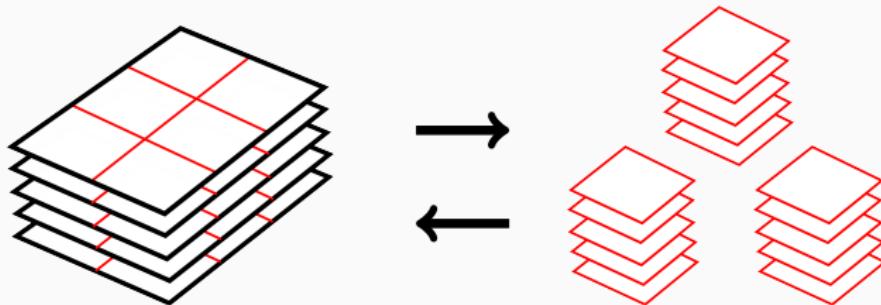
## EXAMPLE: LEGO TRUCK



- 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



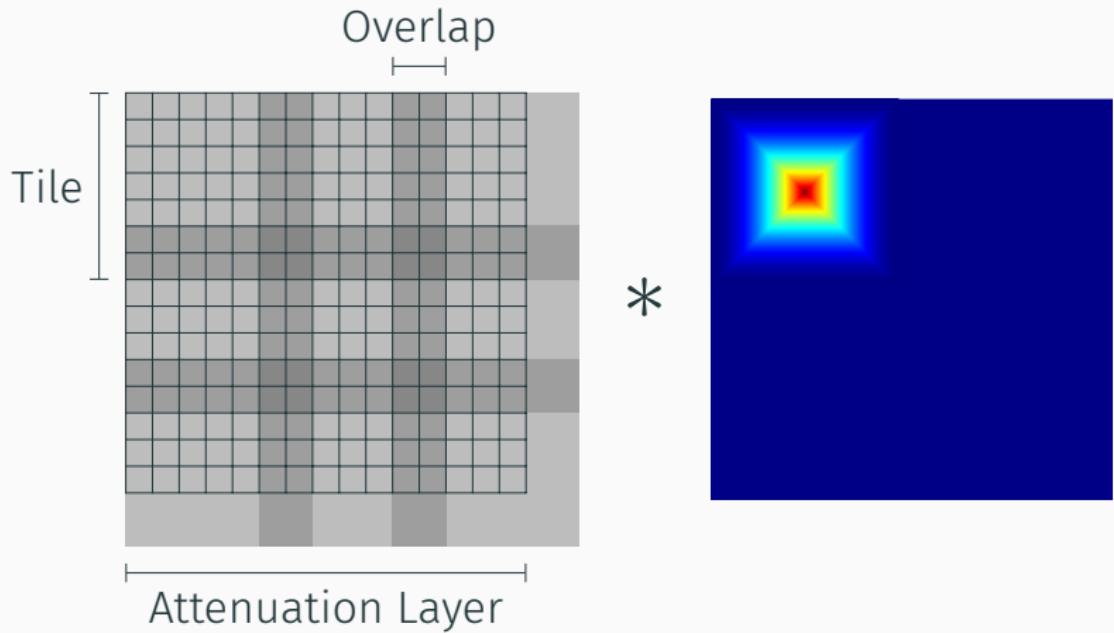
Original



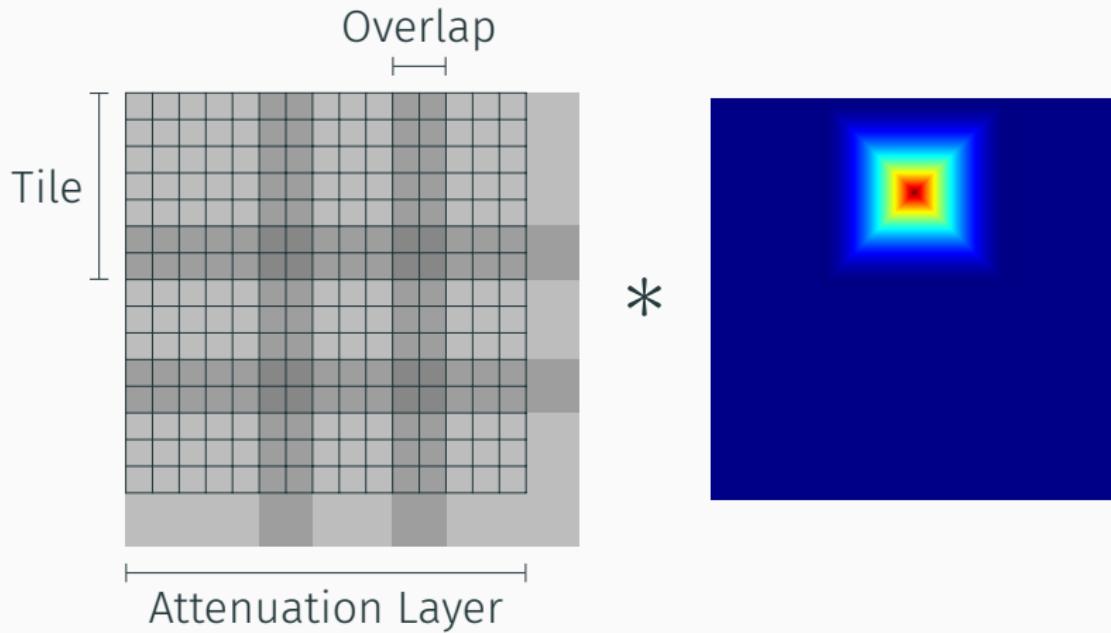
Simulation

Light field courtesy: Stanford Light Field Archive

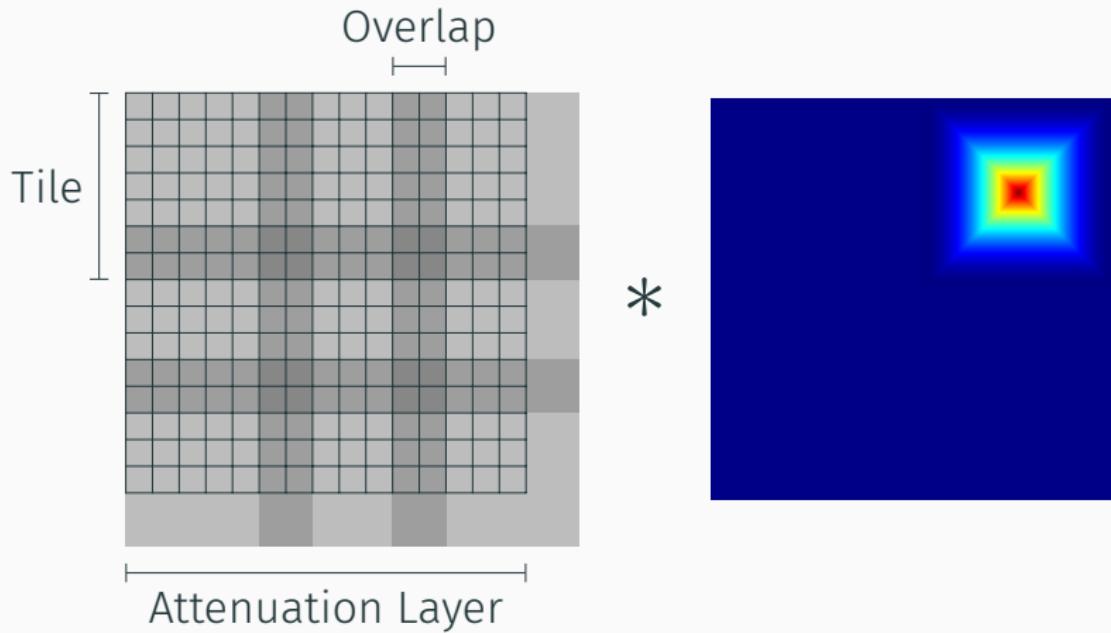
# TILE BLENDING



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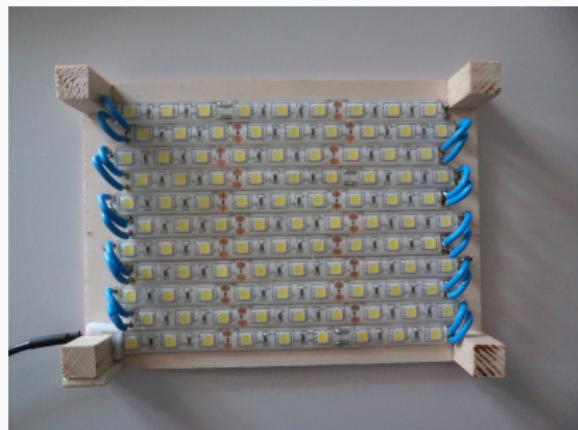
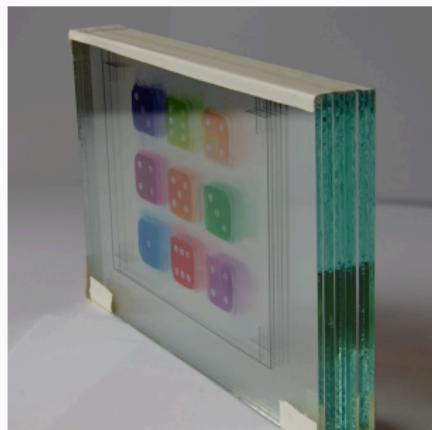
No overlap



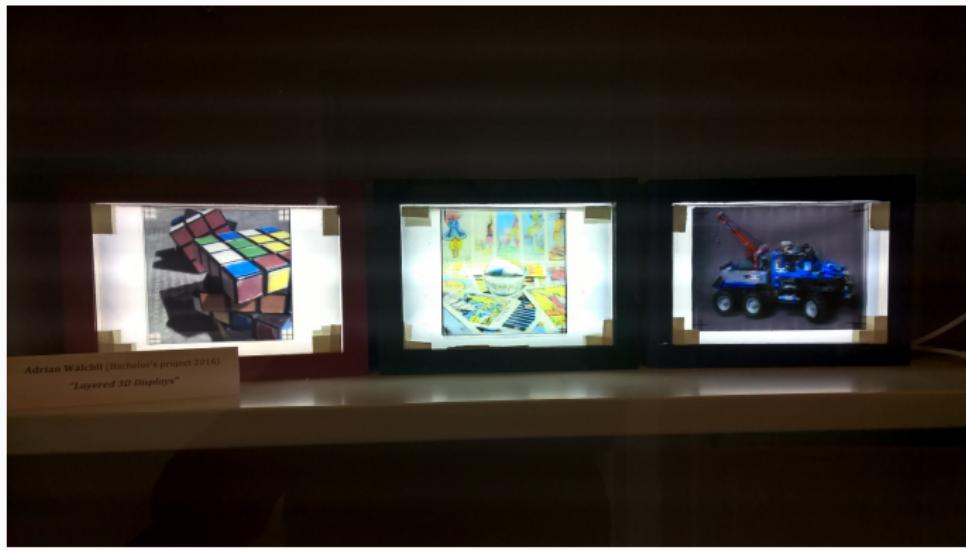
30% overlap

# THE FINISHED PRODUCT

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



# THE FINISHED PRODUCT



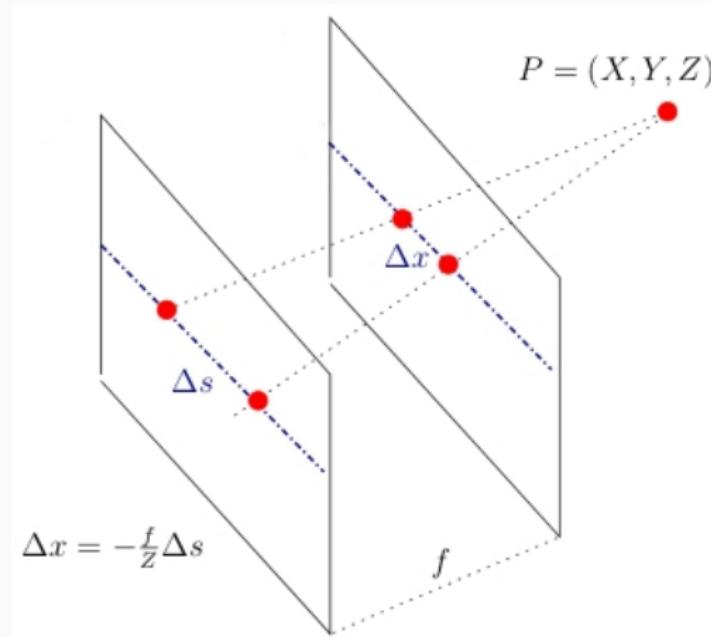
# QUESTIONS

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

# SPECTRAL ANALYSIS

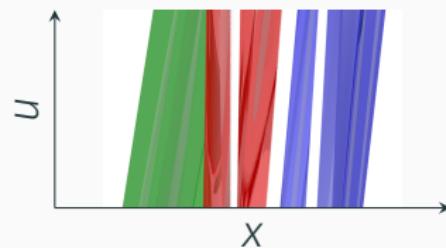
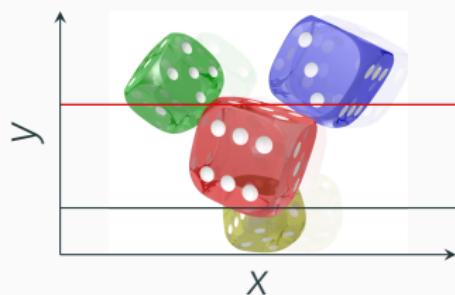
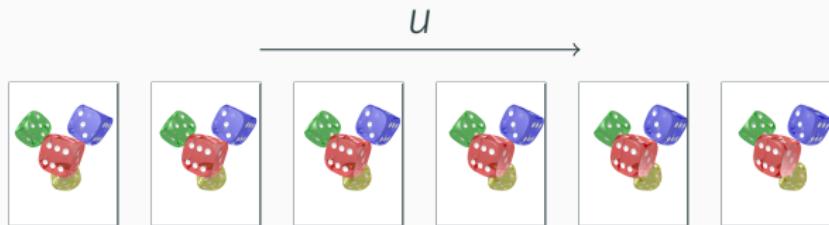
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# EPIPOLAR PLANE GEOMETRY

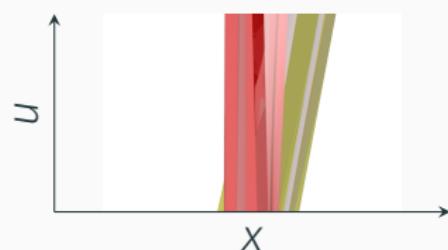
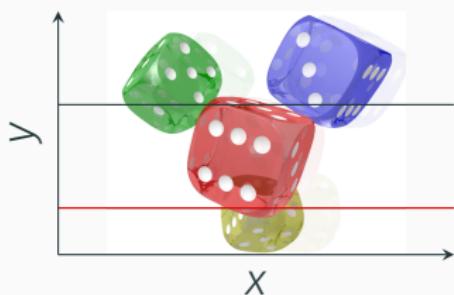
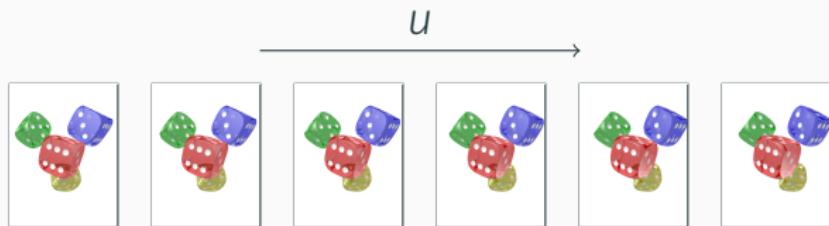


Source: klimt.iwr.uni-heidelberg.de

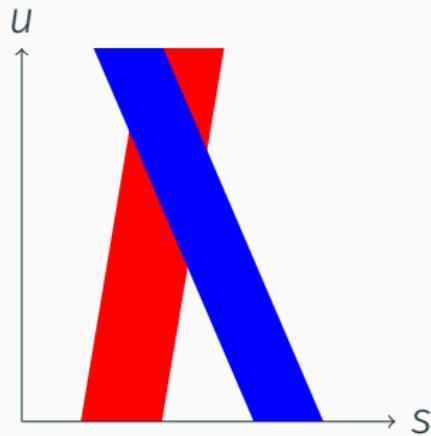
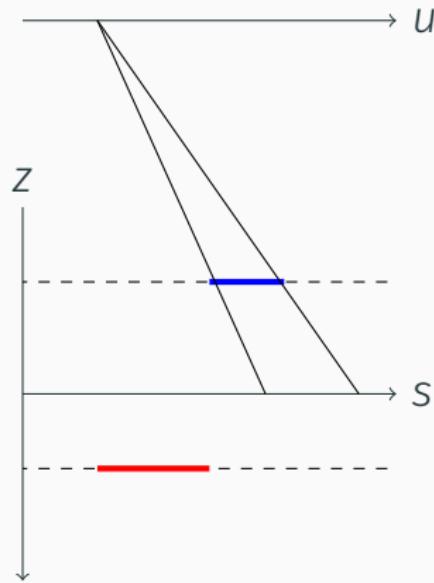
# EPIPOLAR PLANE IMAGE



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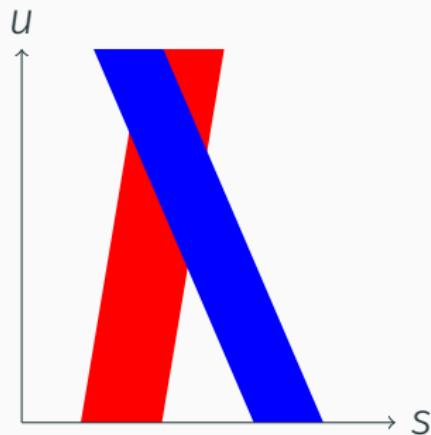
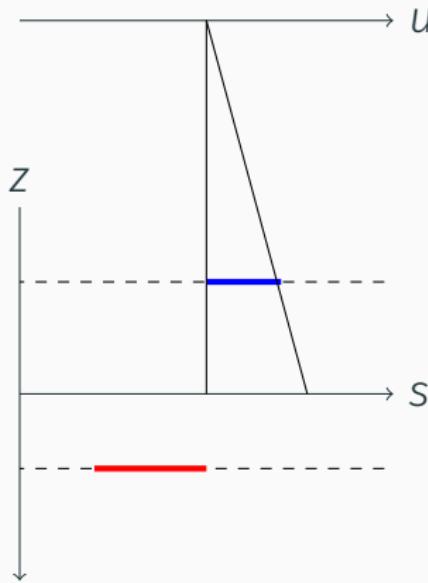


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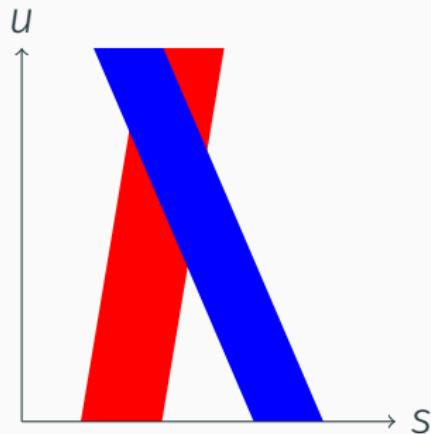
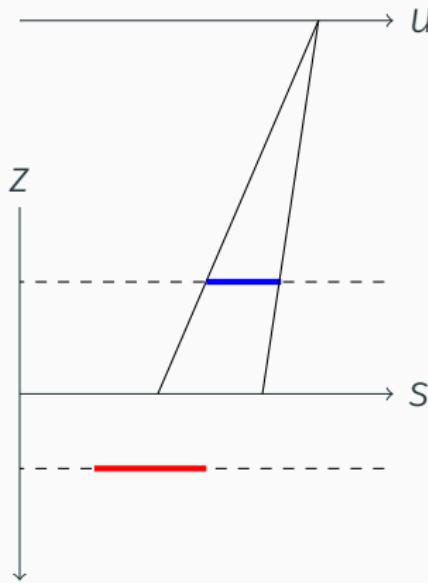
$$\frac{du}{ds} = \frac{z - Z_u}{z - Z_s}$$

# EPIPOLAR PLANE IMAGE



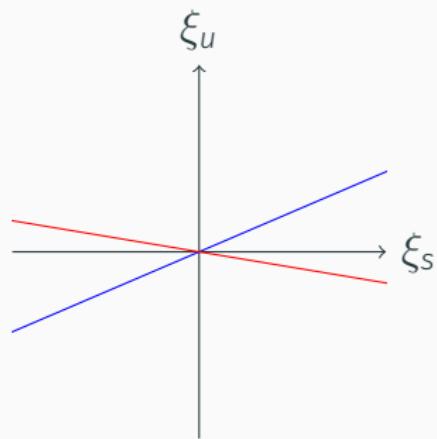
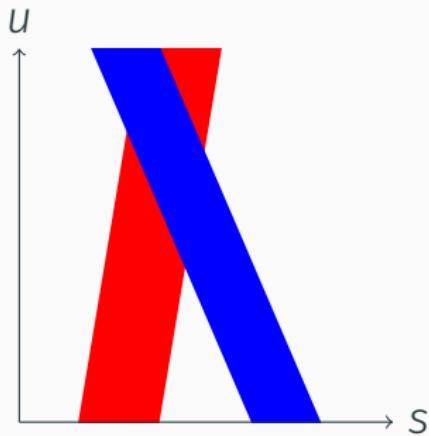
$$\frac{du}{ds} = \frac{z - Z_u}{z - Z_s}$$

# EPIPOLAR PLANE IMAGE



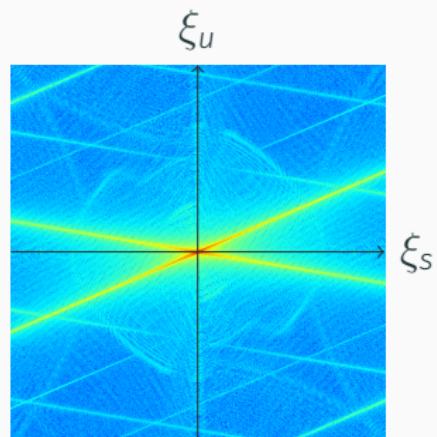
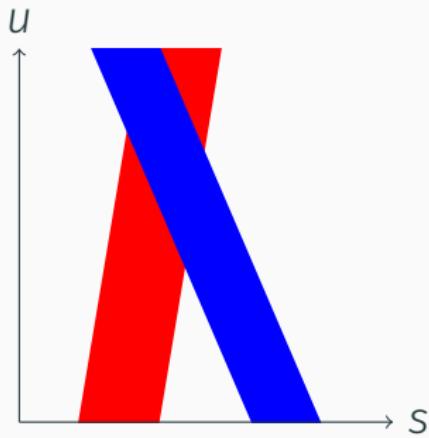
$$\frac{du}{ds} = \frac{z - Z_u}{z - Z_s}$$

# SPECTRAL PROPERTIES OF LIGHT FIELDS



Frequency Response  
(Amplitude)

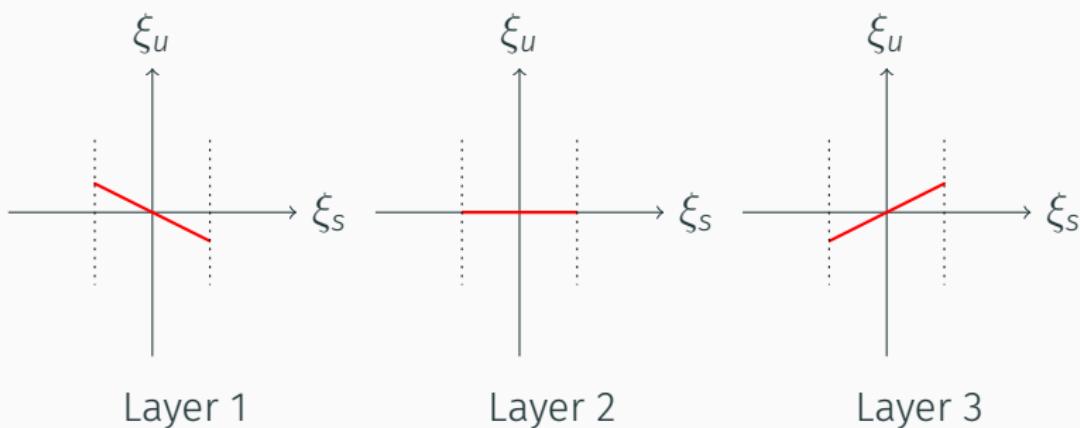
# SPECTRAL PROPERTIES OF LIGHT FIELDS



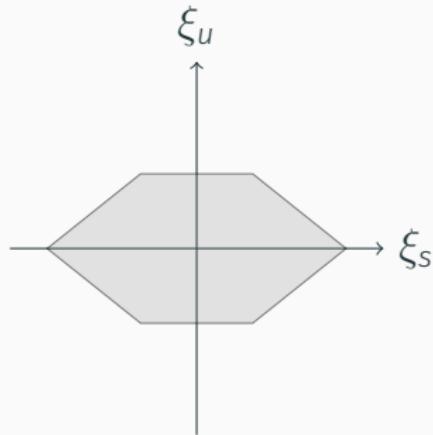
Frequency Response  
(Amplitude)

# SPECTRAL PROPERTIES OF DISPLAY

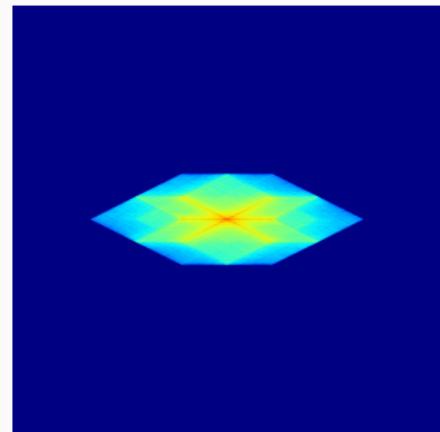
- Every layer creates a light field  $L_n$
- Stack of layers creates  $L' = L_0 \cdot L_1 \cdots L_N$
- What does  $L'$  look like in frequency domain?



# SPECTRAL PROPERTIES OF DISPLAY

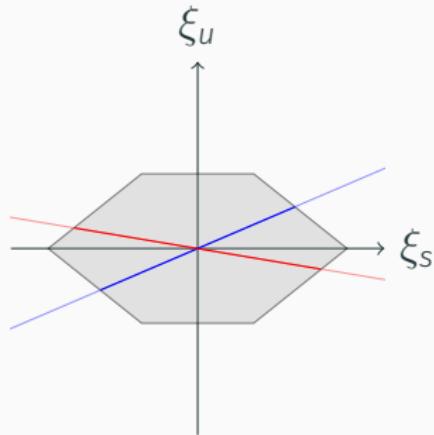


Spectral Support

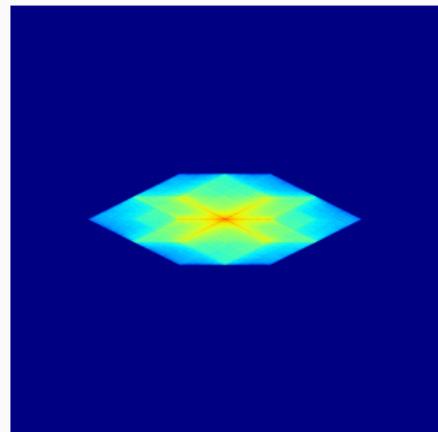


Frequency Response  
(Amplitude)

# SPECTRAL PROPERTIES OF DISPLAY



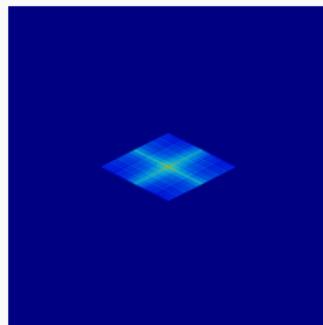
Spectral Support



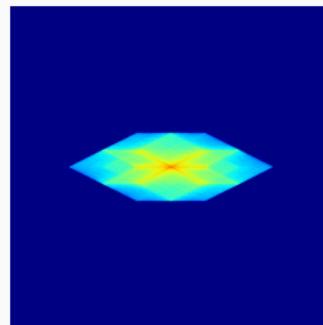
Frequency Response  
(Amplitude)

# SPECTRAL PROPERTIES OF DISPLAY

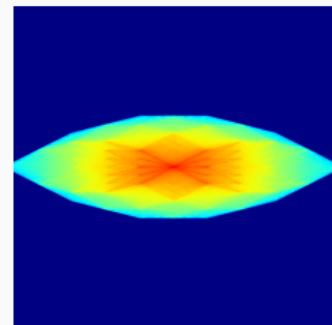
- Spectral support increases with more layers
- Highest response in center



2 Layers

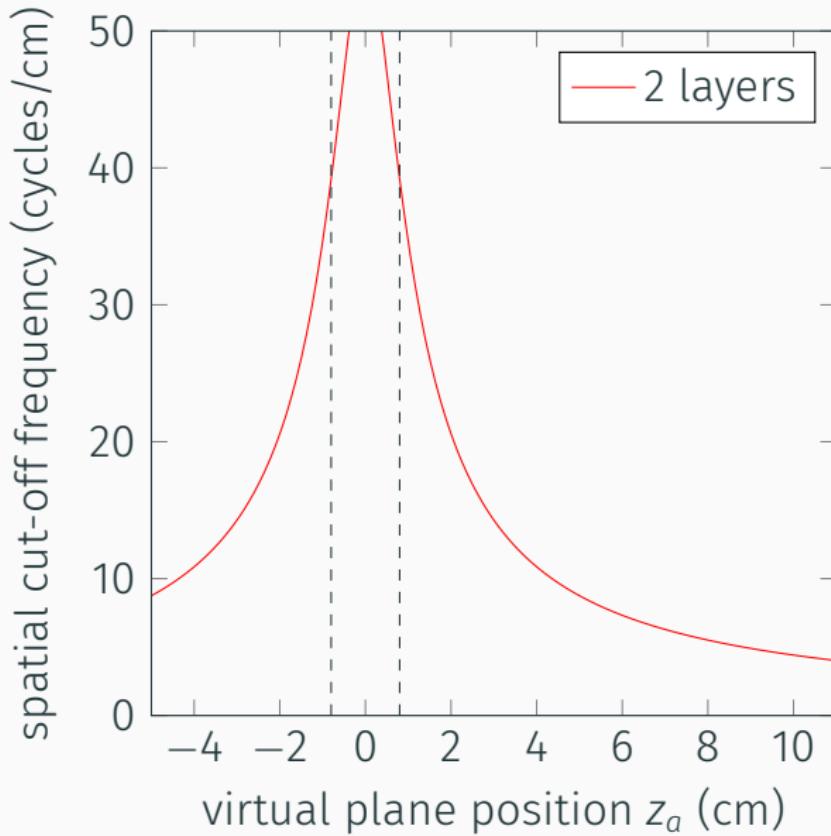


3 Layers

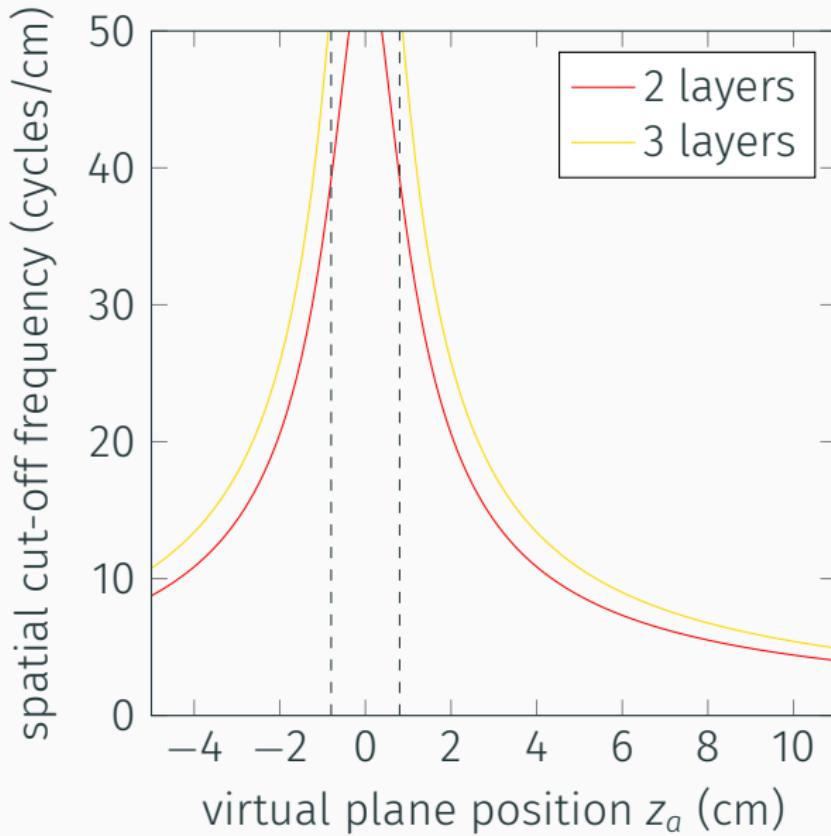


5 Layers

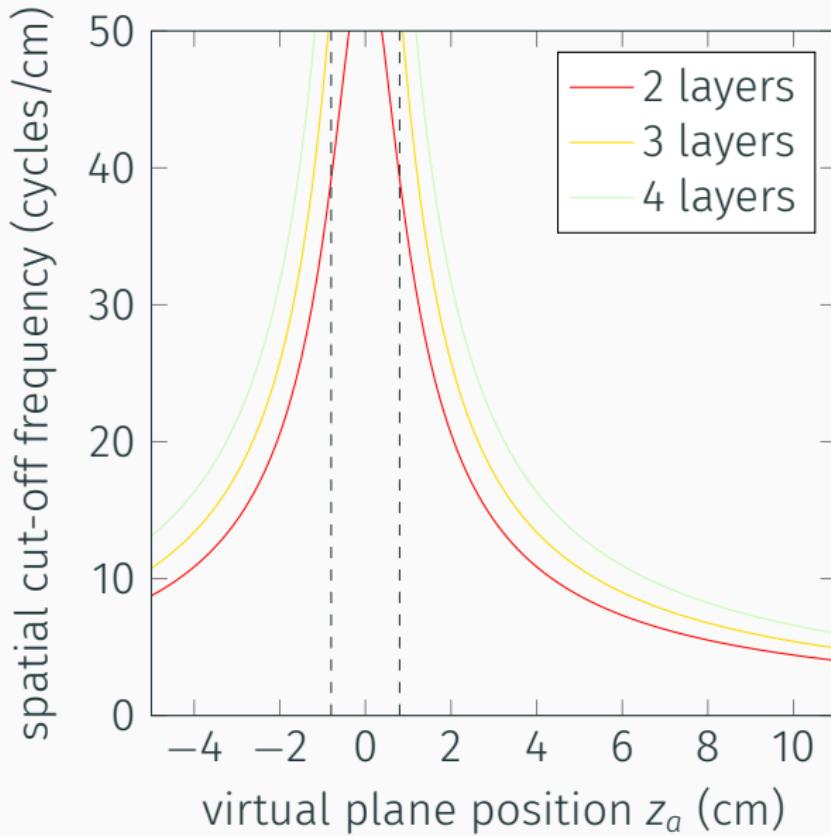
# DEPTH OF FIELD



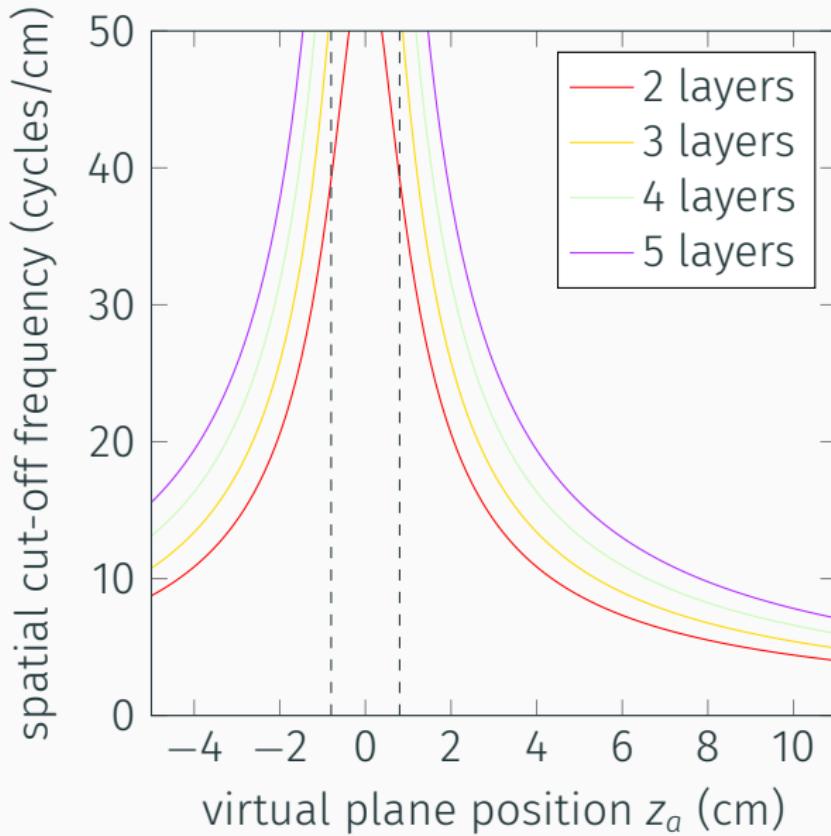
# DEPTH OF FIELD



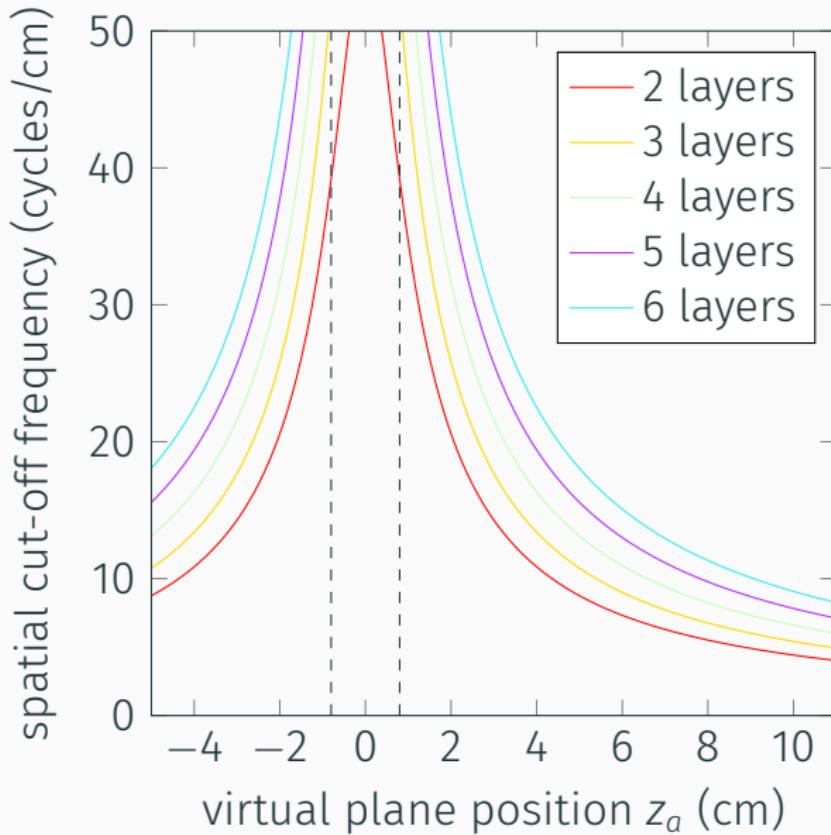
# DEPTH OF FIELD



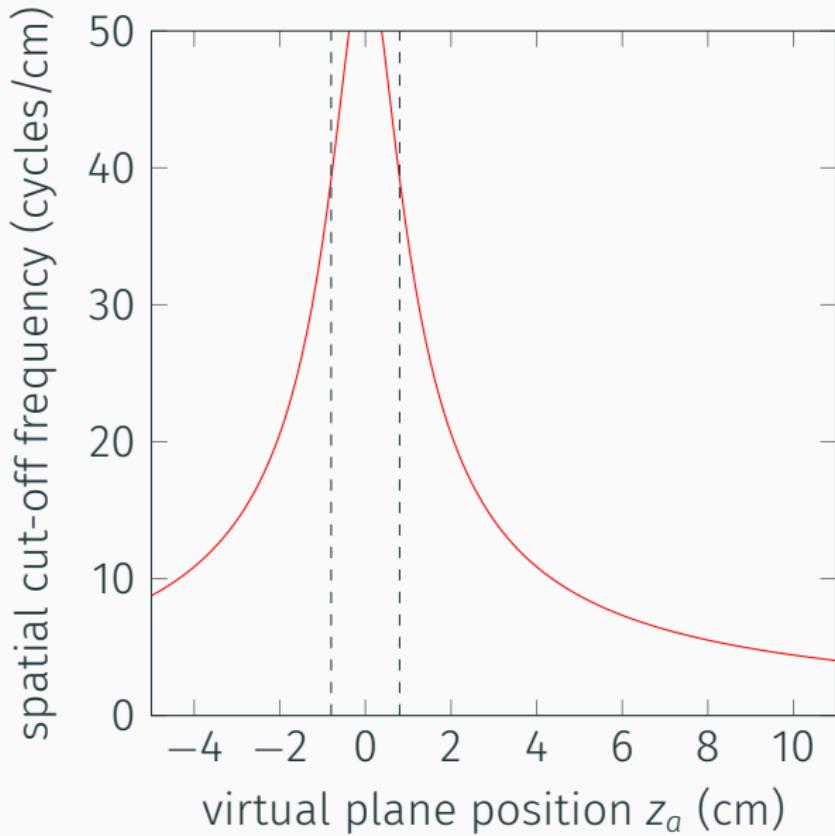
# DEPTH OF FIELD



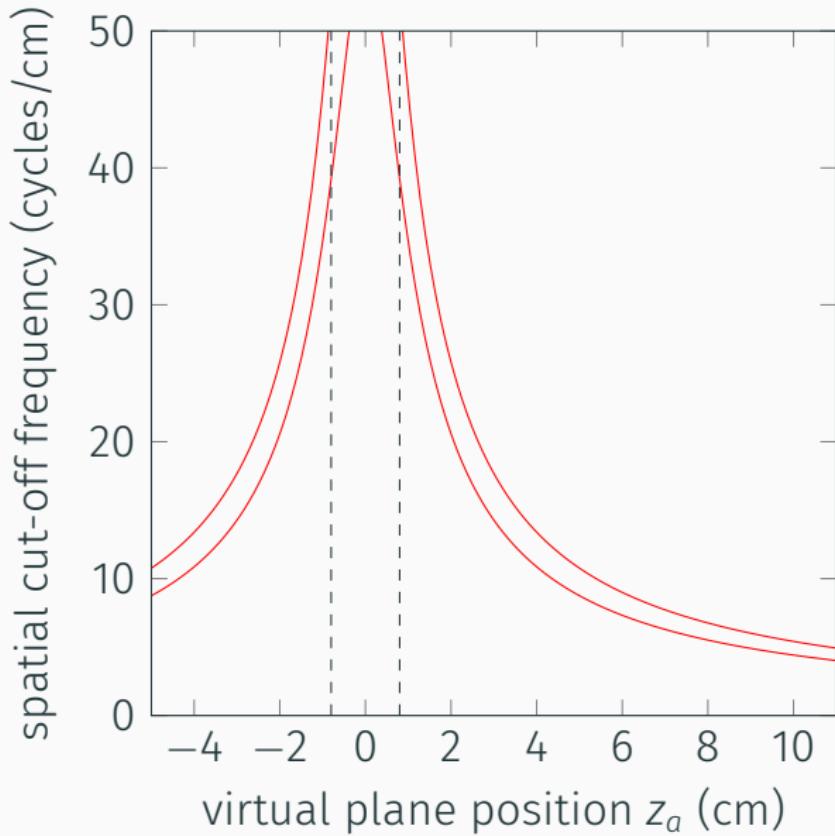
# DEPTH OF FIELD



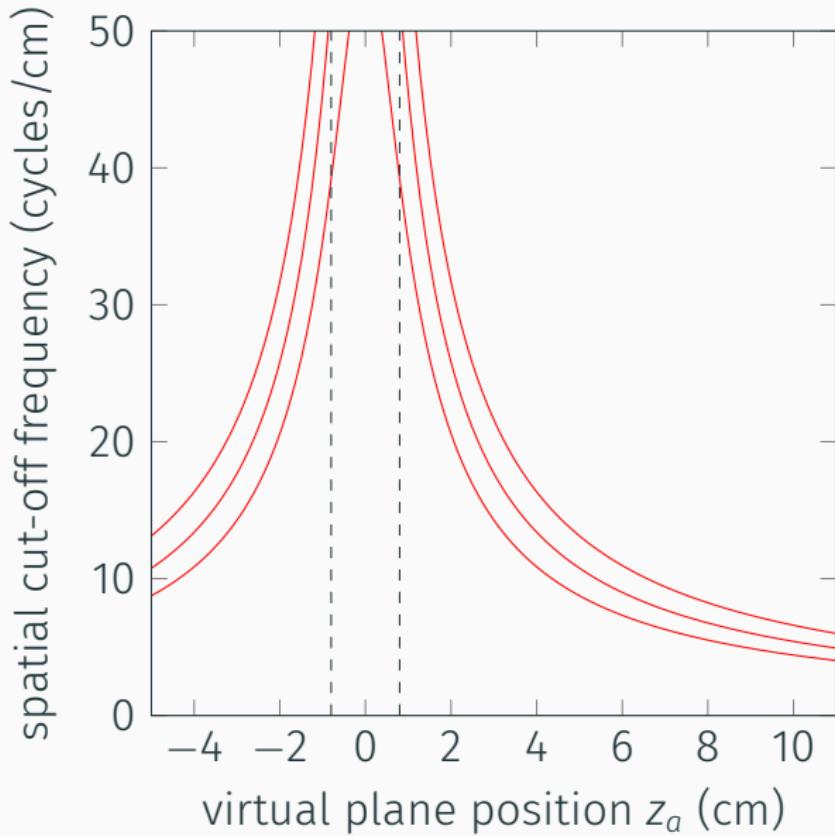
# DEPTH OF FIELD



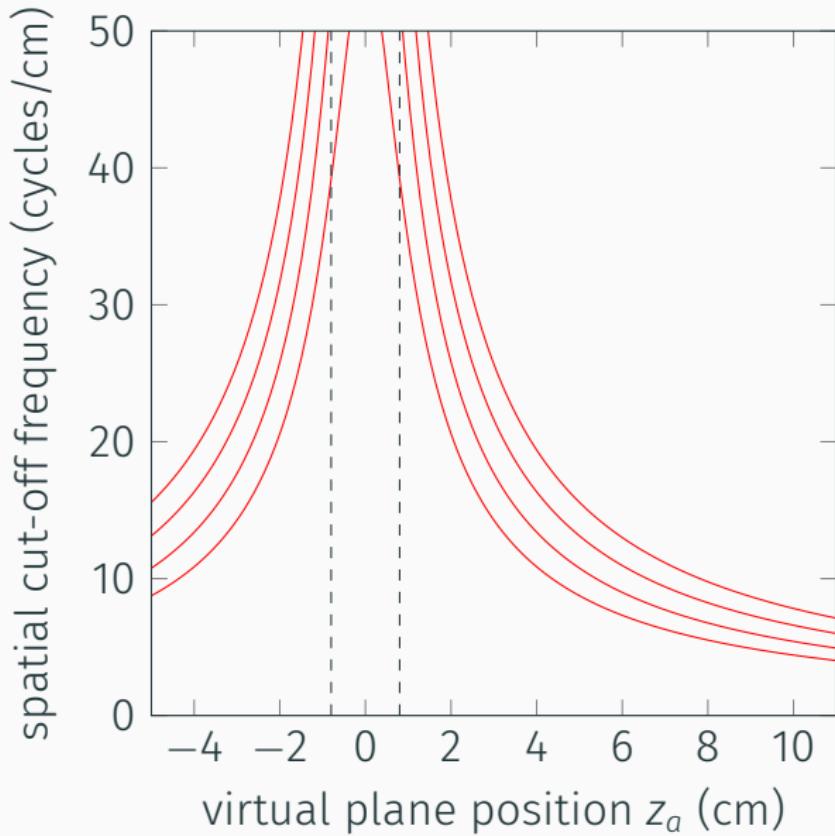
# DEPTH OF FIELD



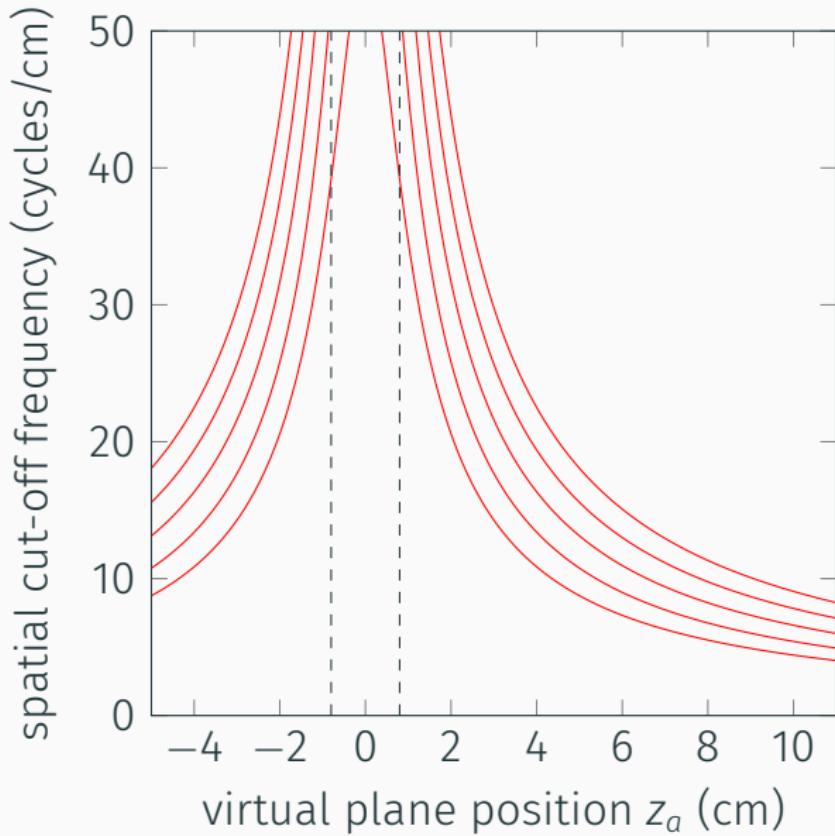
# DEPTH OF FIELD



# DEPTH OF FIELD



# DEPTH OF FIELD



# DISPLAY THICKNESS



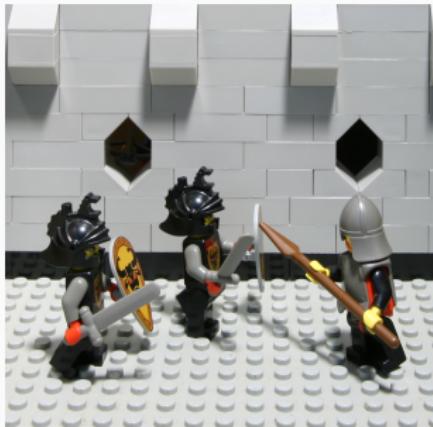
Original



16 mm thick

Light field courtesy: Stanford Light Field Archive

# DISPLAY THICKNESS



Original



30 mm thick

Light field courtesy: Stanford Light Field Archive

# 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 adjust baseline
- Need many layers to eliminate halo artifacts
- Manual layer alignment is hard

# Your Questions

# ACKNOWLEDGEMENTS

Supervision by

Prof. Dr. Matthias Zwicker  
Siavash Bigdeli

## MORE INFORMATION

### Contact

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### Thesis and Resources

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

## REFERENCES

- E. H. Adelson and J. Bergen. The plenoptic function and the elements of early vision. *Computational Models of Visual Processing*, pages 3–20, 1991.
- 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.