

Lecture 16:

Light Field Cameras

Computer Graphics and Imaging
UC Berkeley CS184/284A

Topics

2D Photographs vs 4D Light Fields

Capturing Light Fields With Plenoptic Cameras

Computational Refocusing

Computational Correction of Lens Aberrations

Other Light Field Capture Systems

Three Focus-Related Problems in 2D Photography

1. Need to focus before taking the shot



Simon Bruty, Sports Illustrated

Three Focus-Related Problems in 2D Photography

2. Trade-off between depth of field and motion blur



$f / 4$
0.01 sec



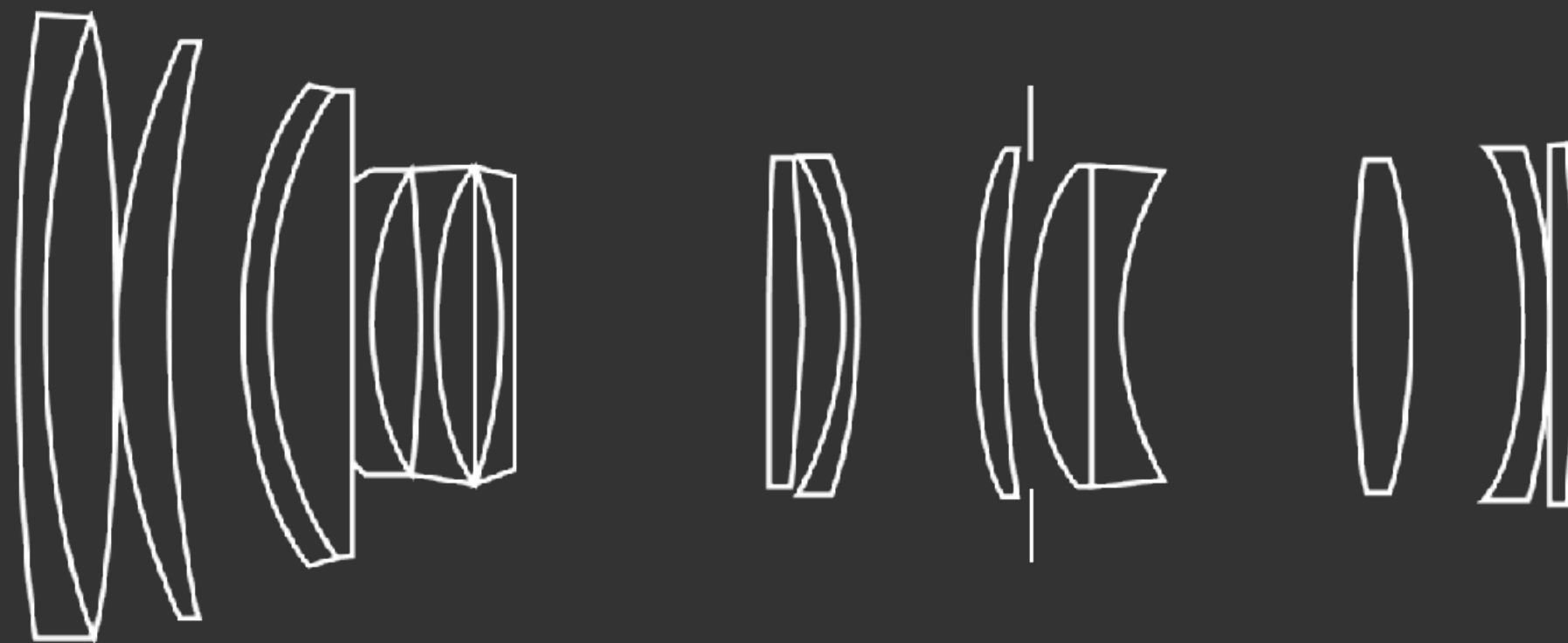
$f / 11$
0.1 sec



$f / 32$
0.8 sec

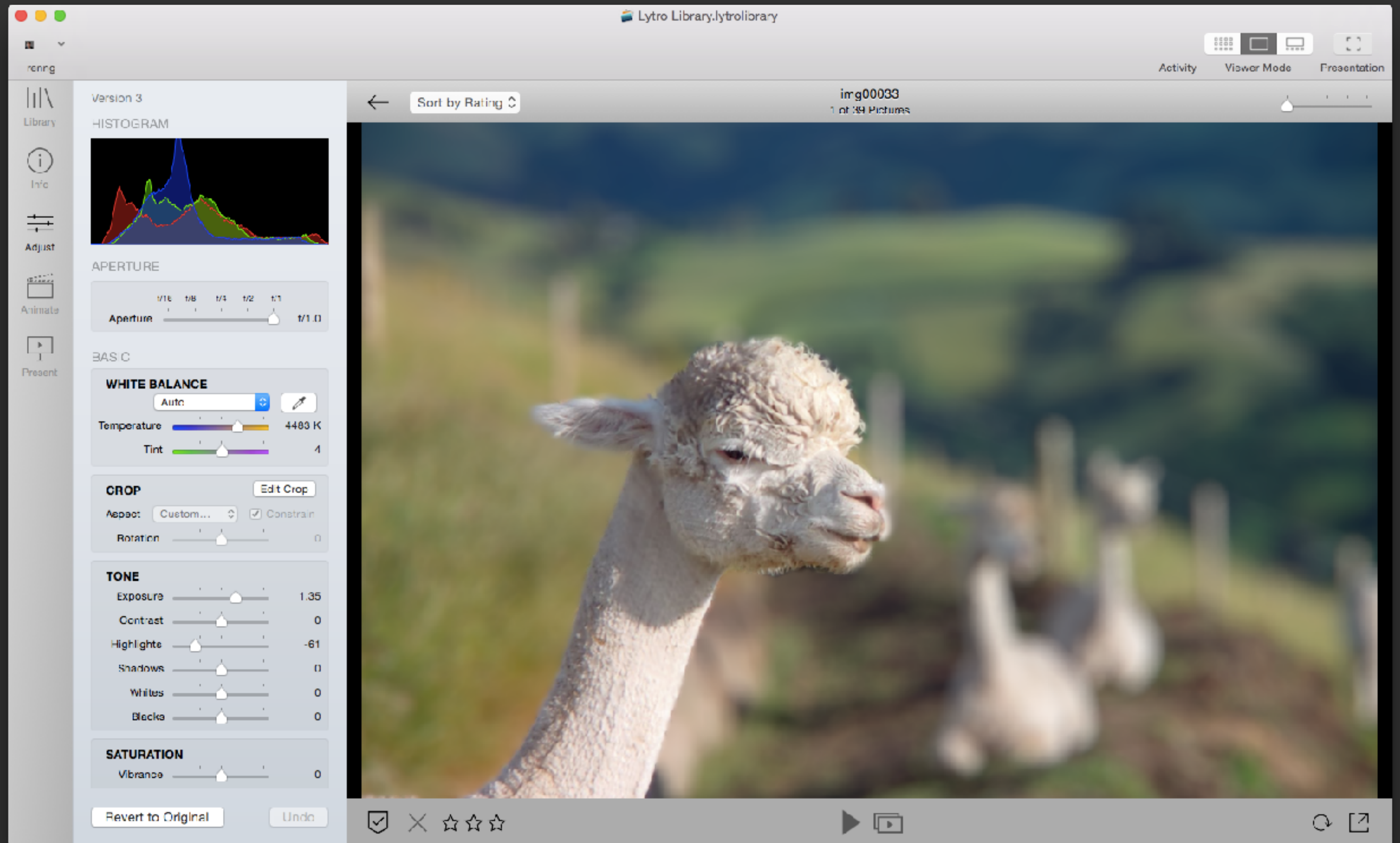
Three Focus-Related Problems in 2D Photography

3. Lens designs are complex due to optical aberrations



Light Field Photography Demo

Light Field Photographs



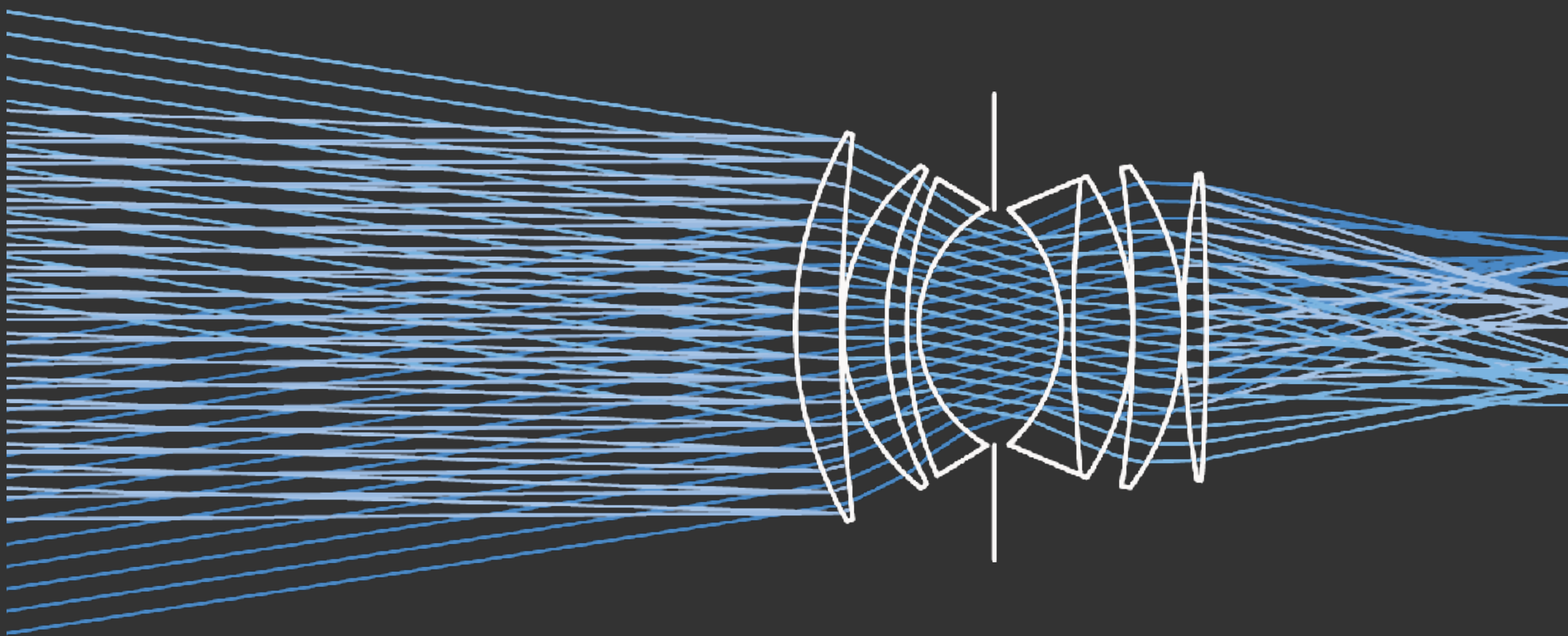
Lens Designed For Light Field Computation



Lytro ILLUM with 30-250mm (equiv) lens F/2

2D Photographs vs 4D Light Fields

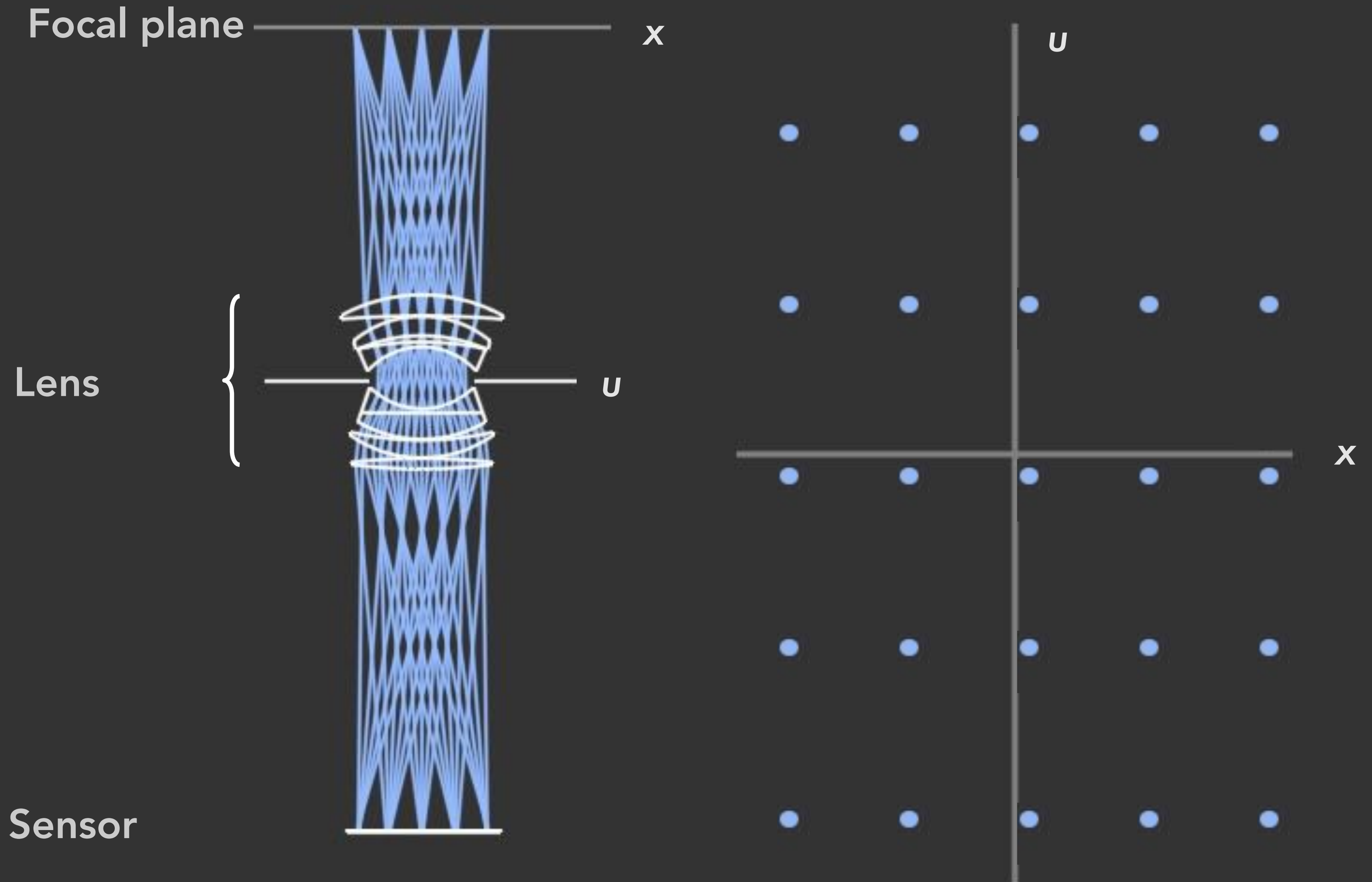
2D Photographs vs 4D Light Fields



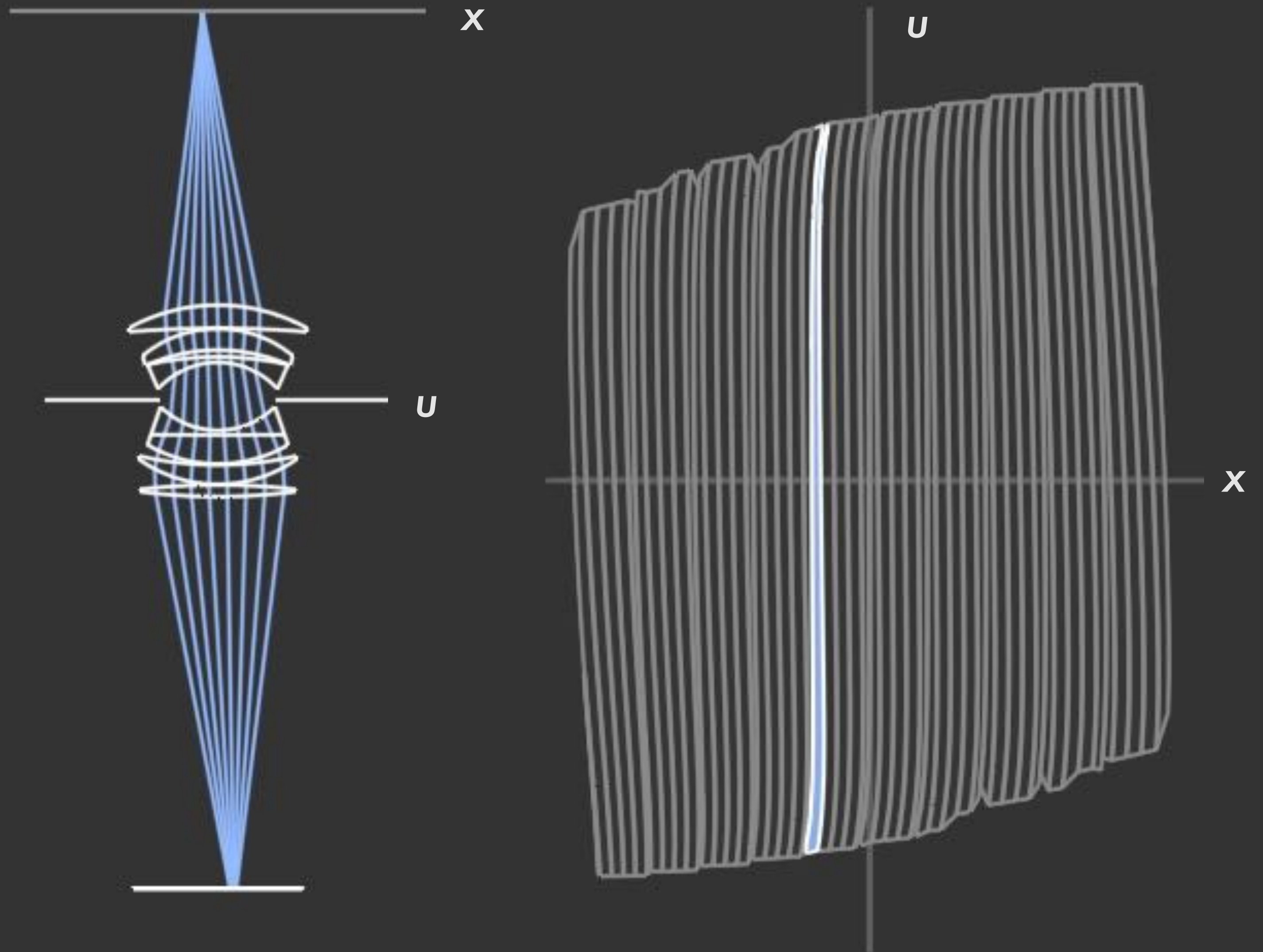
Photograph = irradiance at every pixel on plane (2D)

Light field = radiance flowing along every ray (4D)

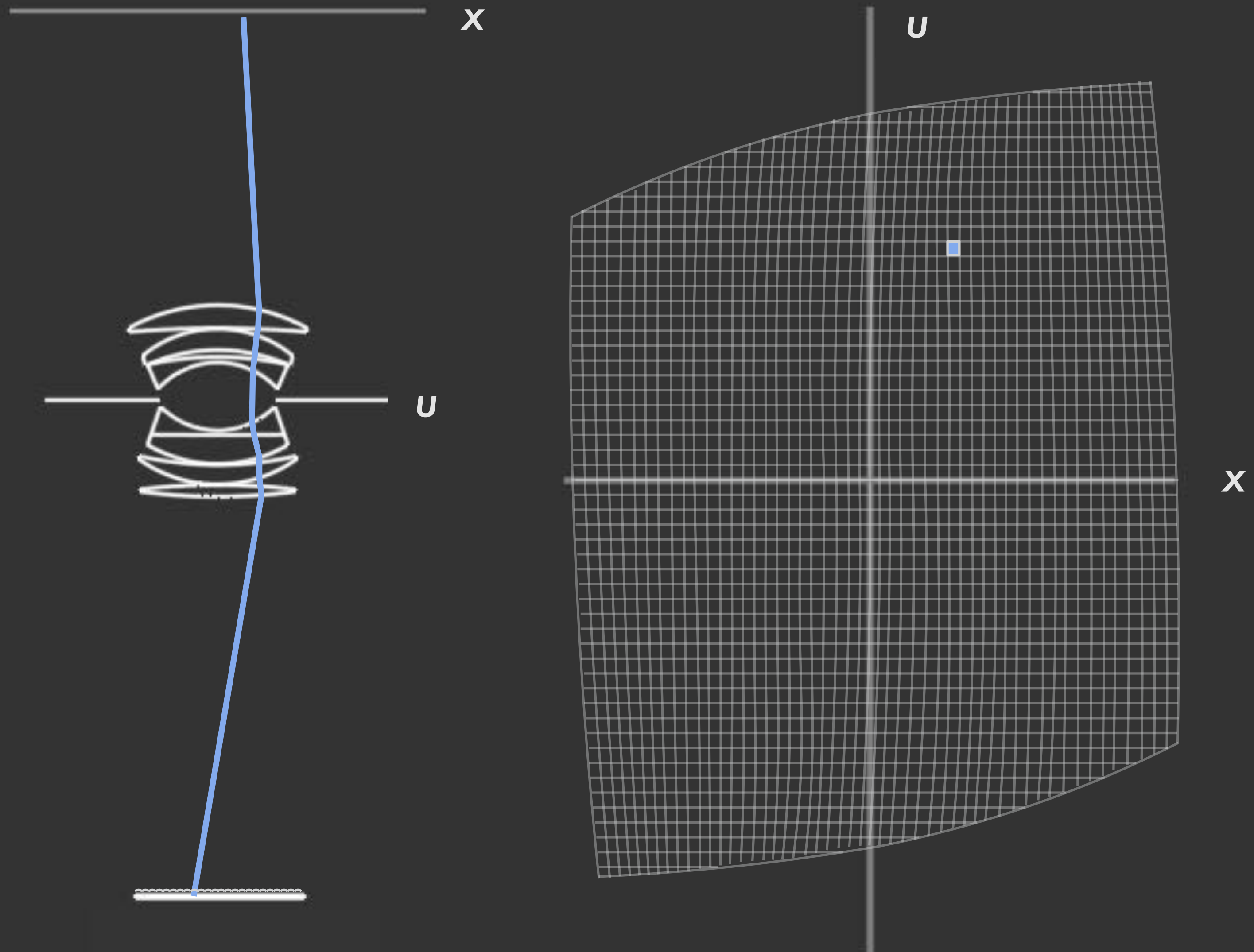
The 4D Light Field Flowing Into A Camera



What Does a 2D Photograph Record?

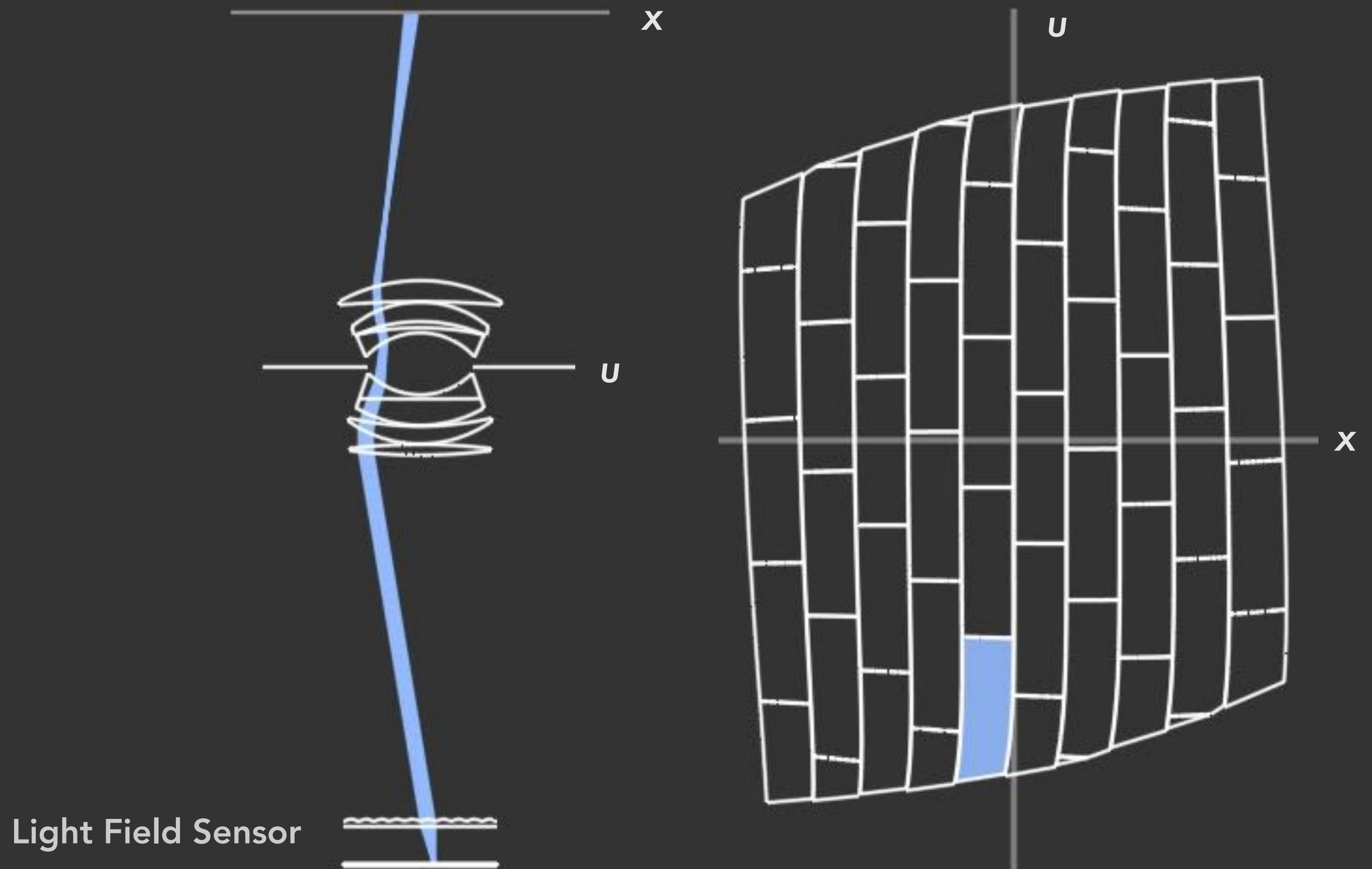


Imagine Recording the Entire 4D Light Field

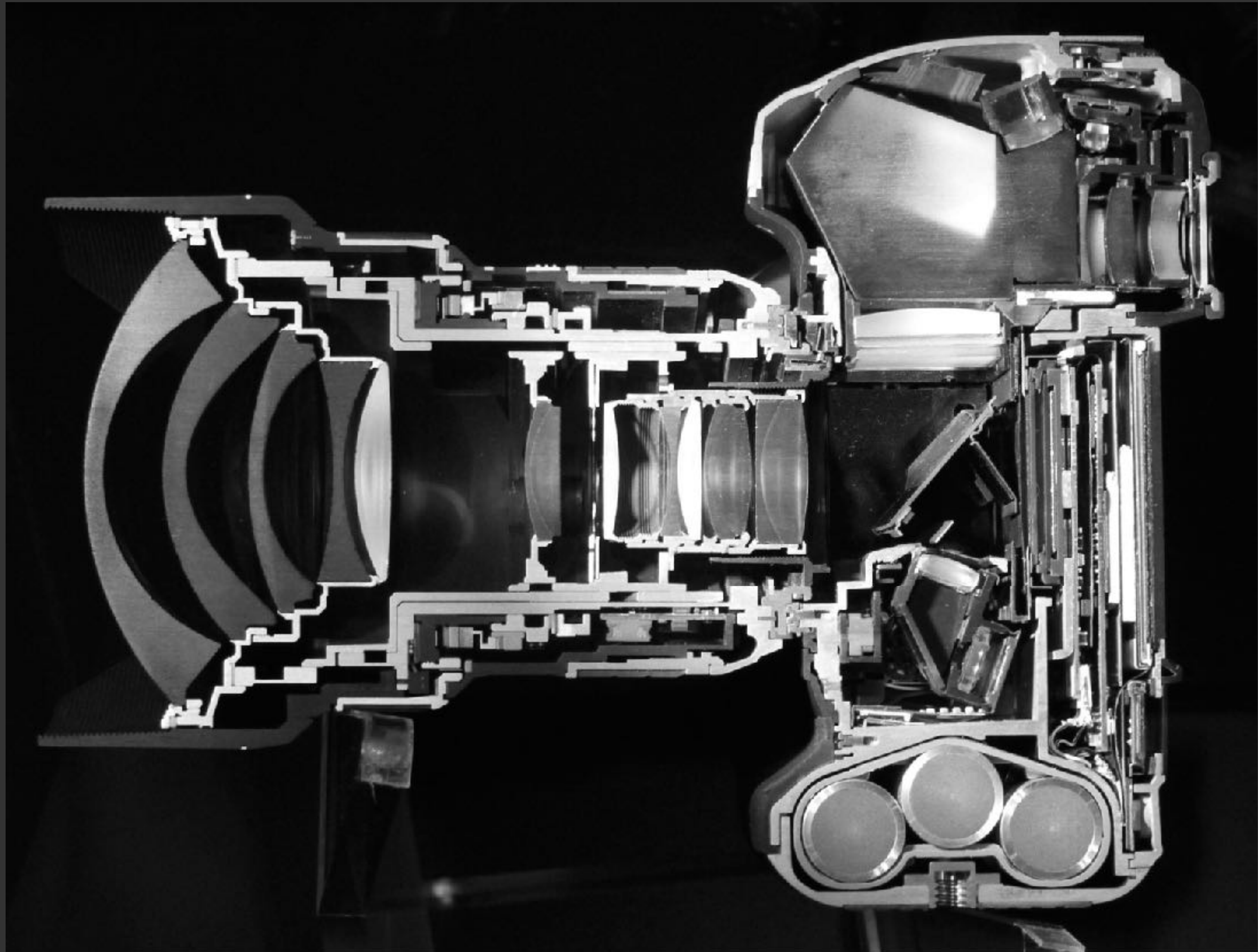


Capturing Light Fields

A Plenoptic Camera Samples The Light Field

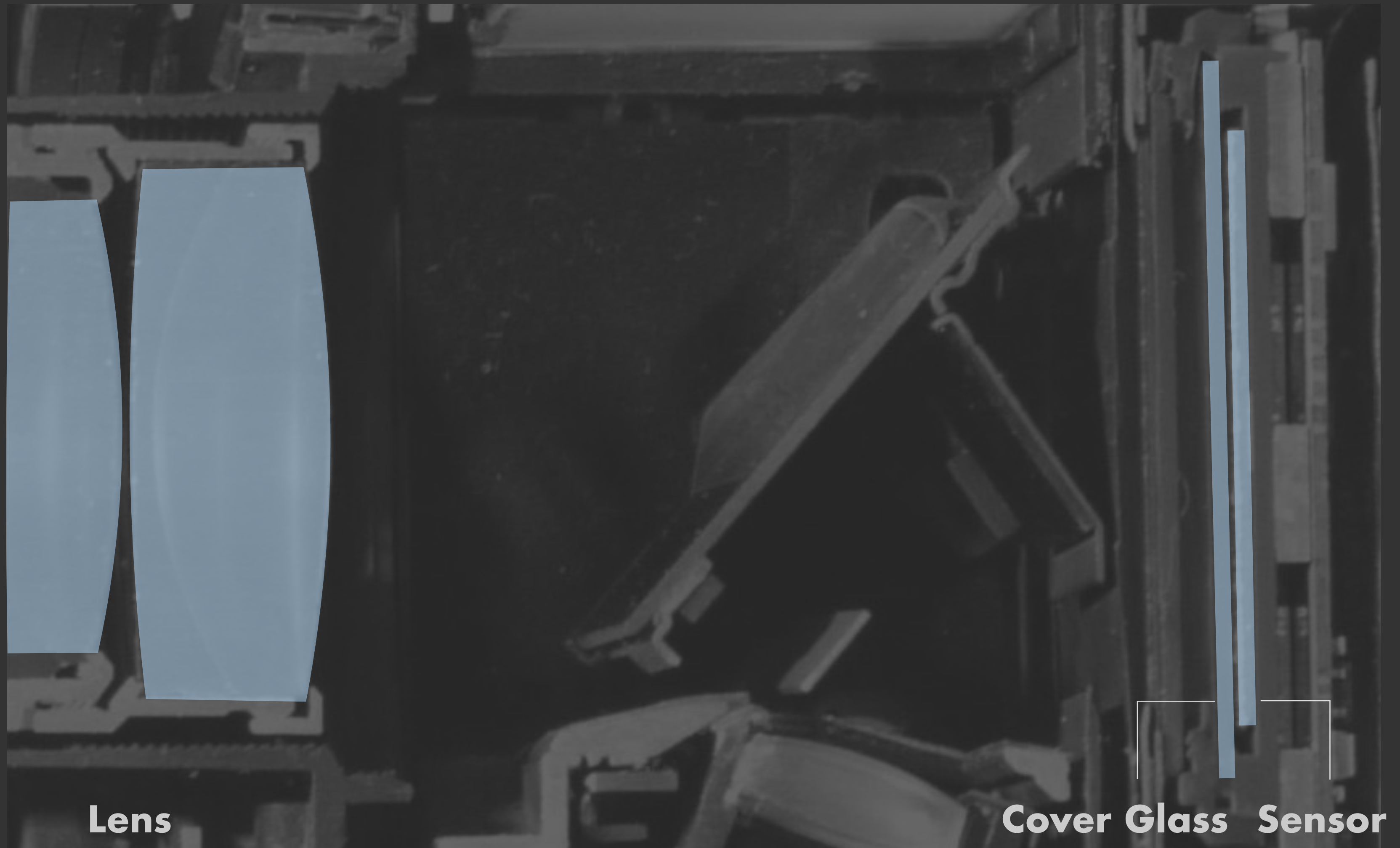


Where Microlenses Go Inside Camera

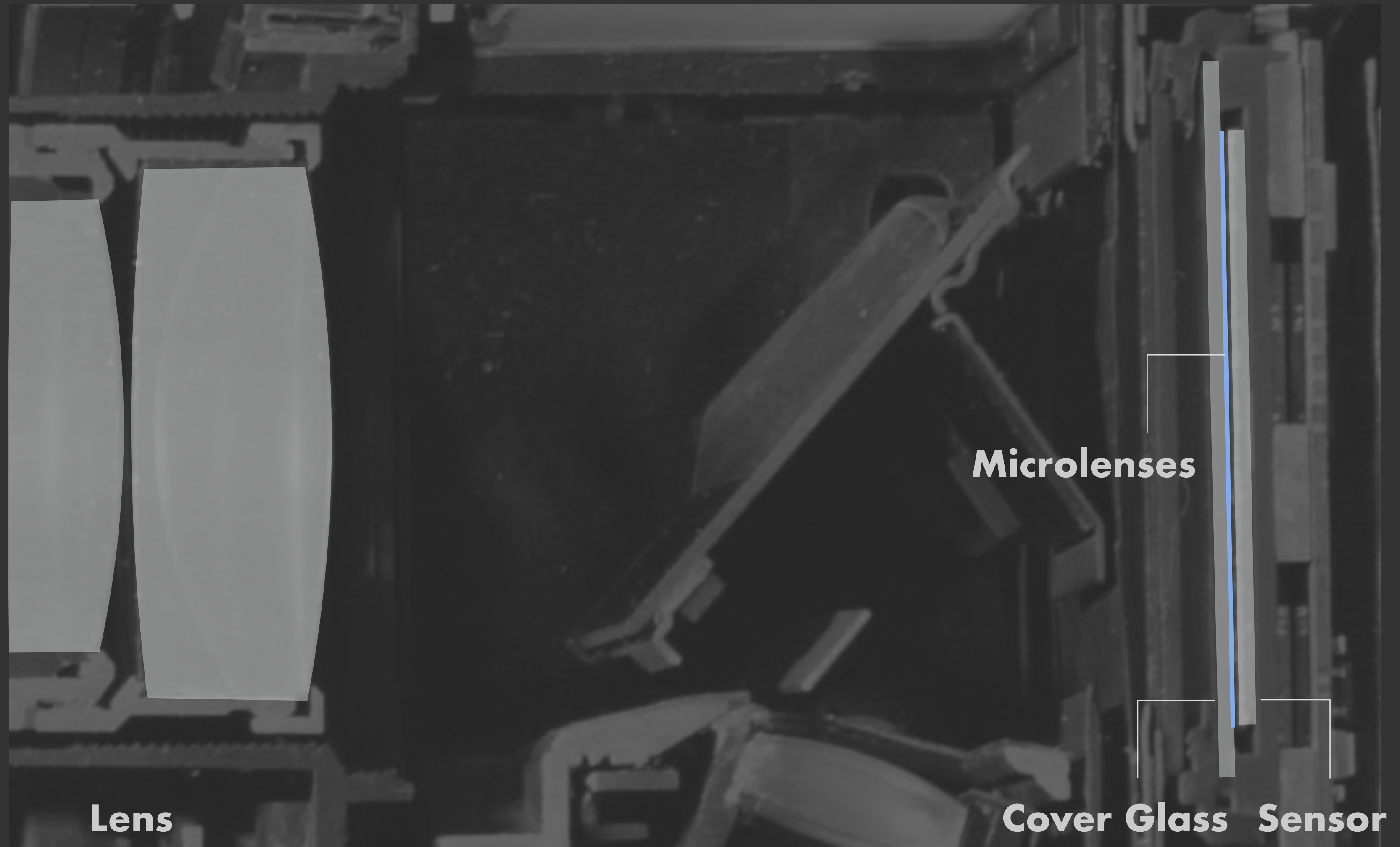


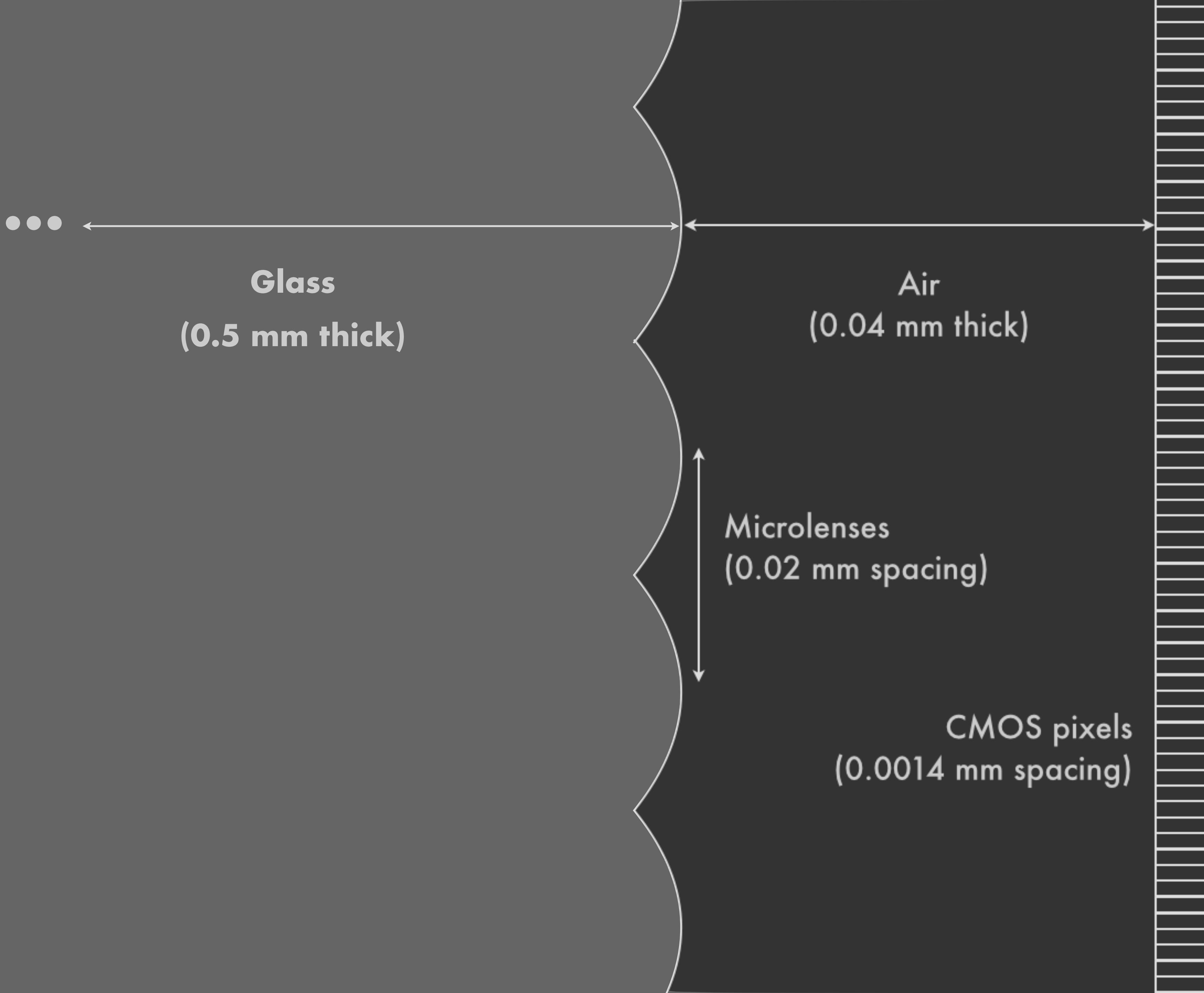
Cross-section of Nikon D3, 14-24mm F/2.8 lens

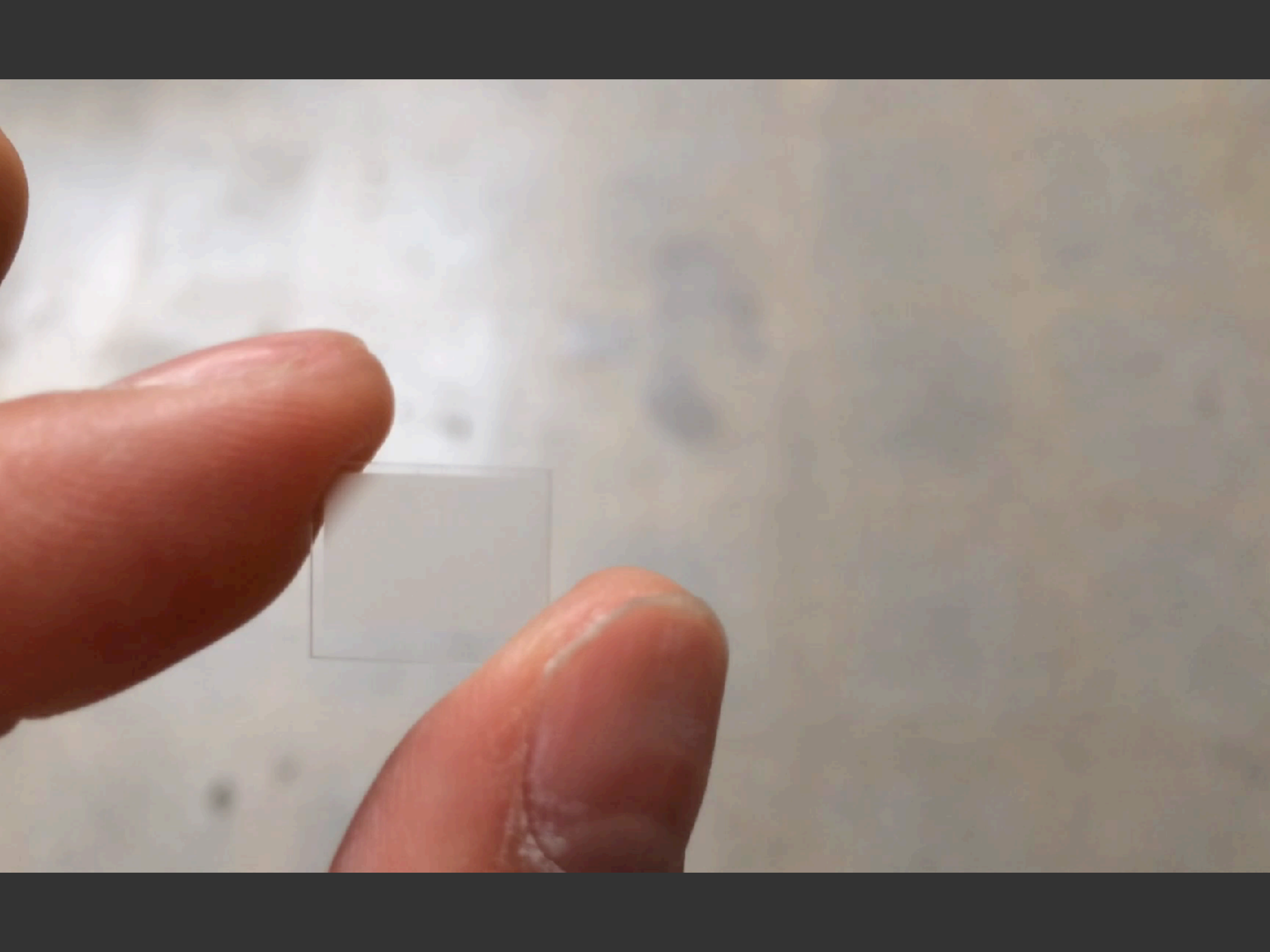
Where Microlenses Go Inside Camera

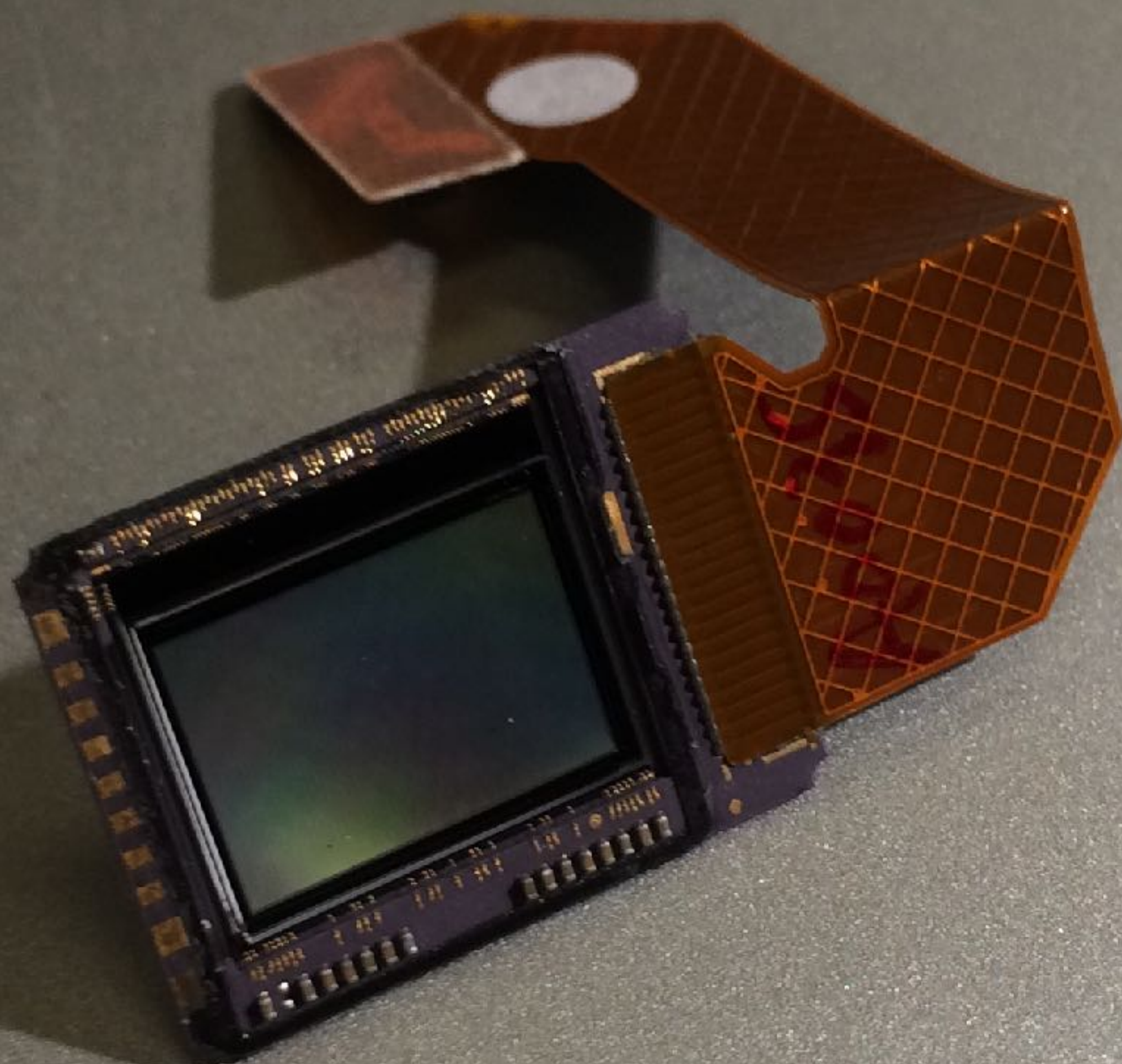


Where Microlenses Go Inside Camera









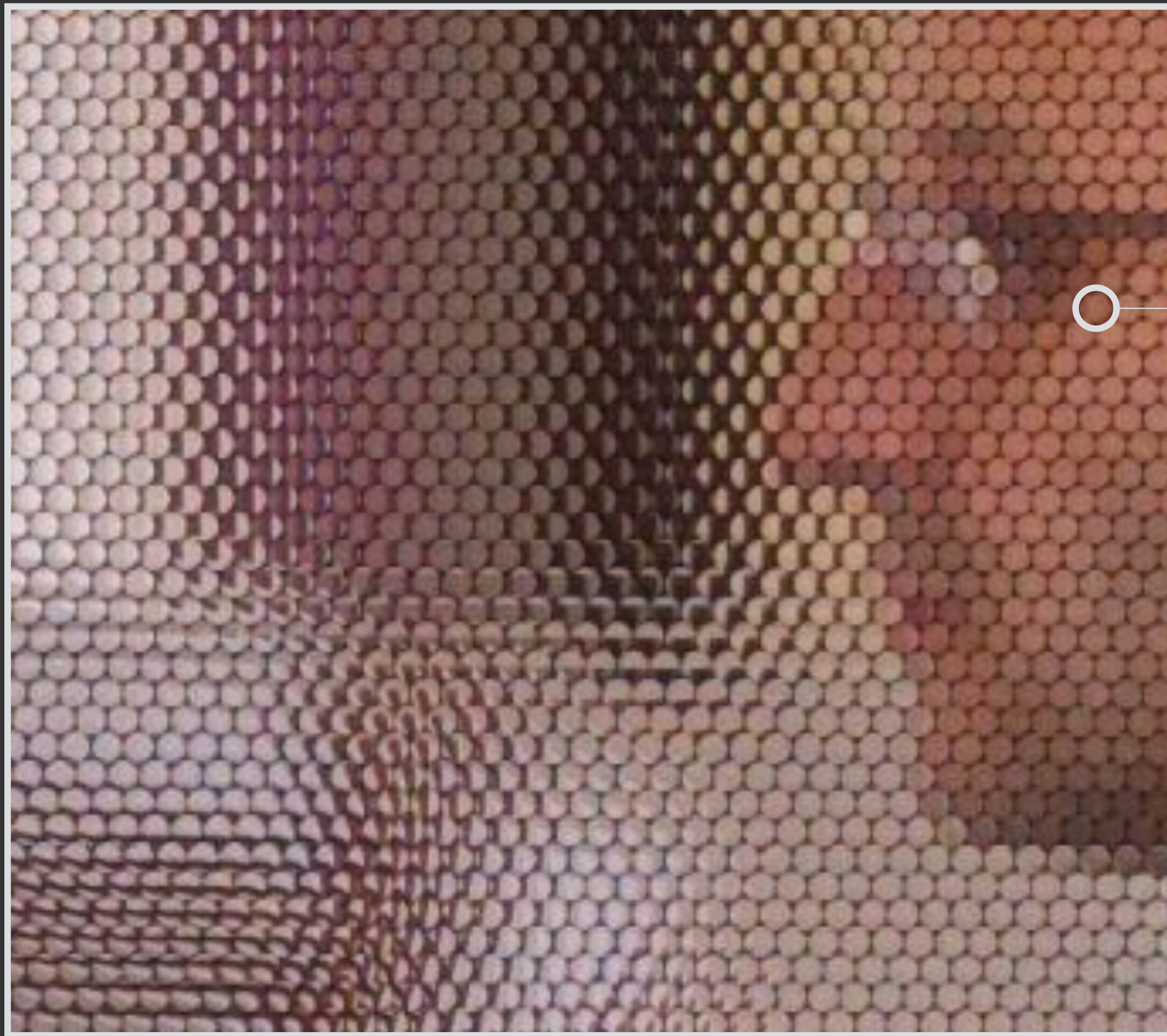
Raw Data From Light Field Sensor



Raw Data From Light Field Sensor



Raw Data From Light Field Sensor



○ — One disk image



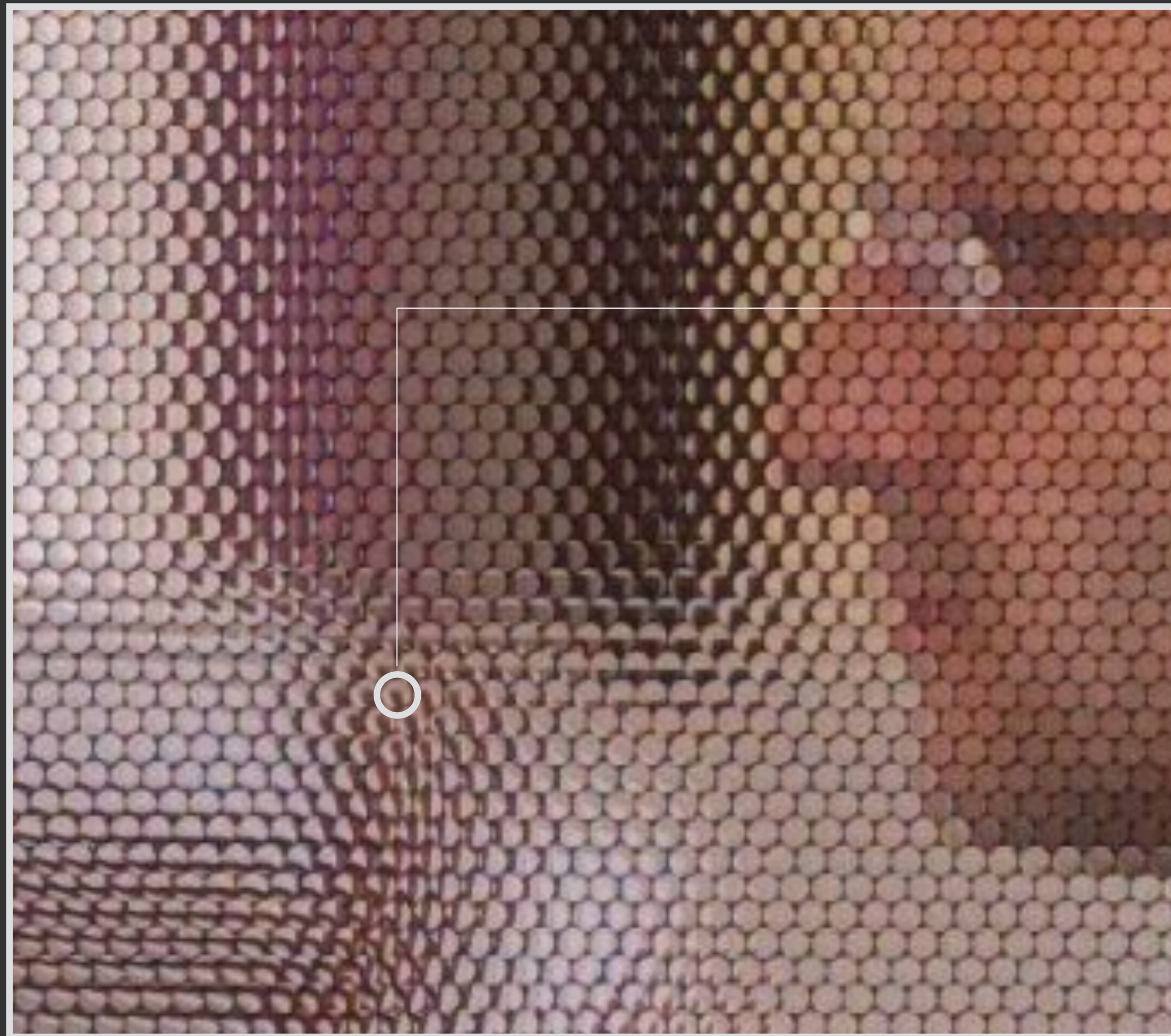
Raw Data From Light Field Sensor



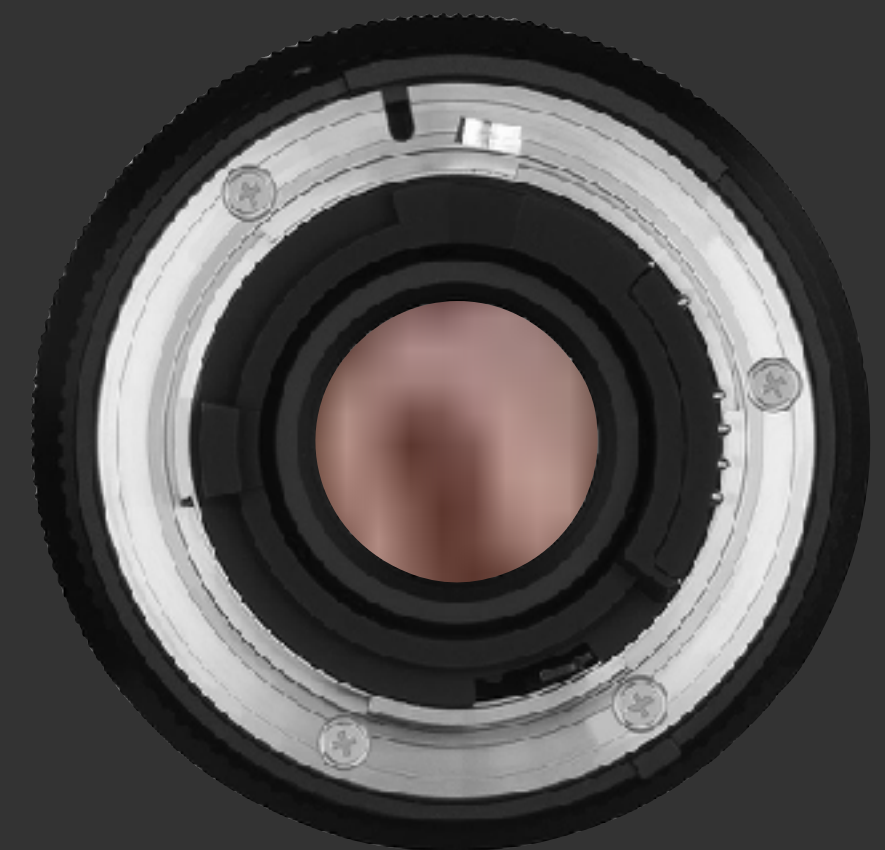
One disk image



Raw Data From Light Field Sensor



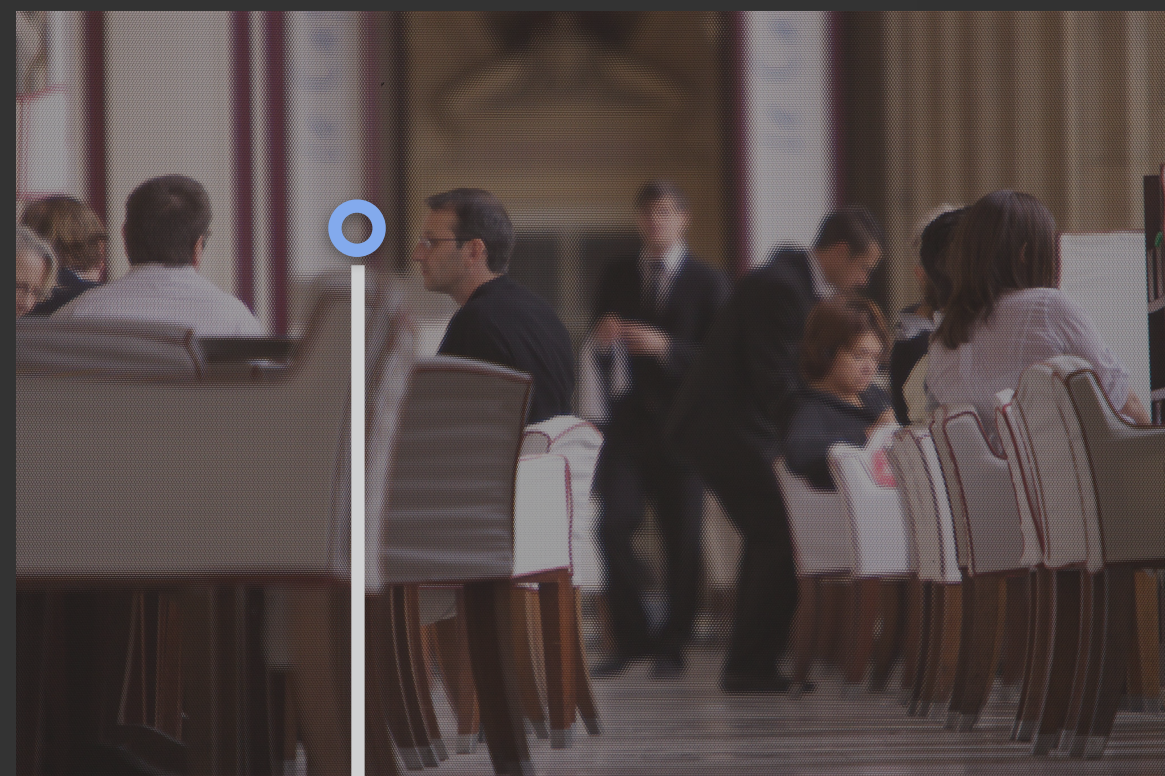
One disk image



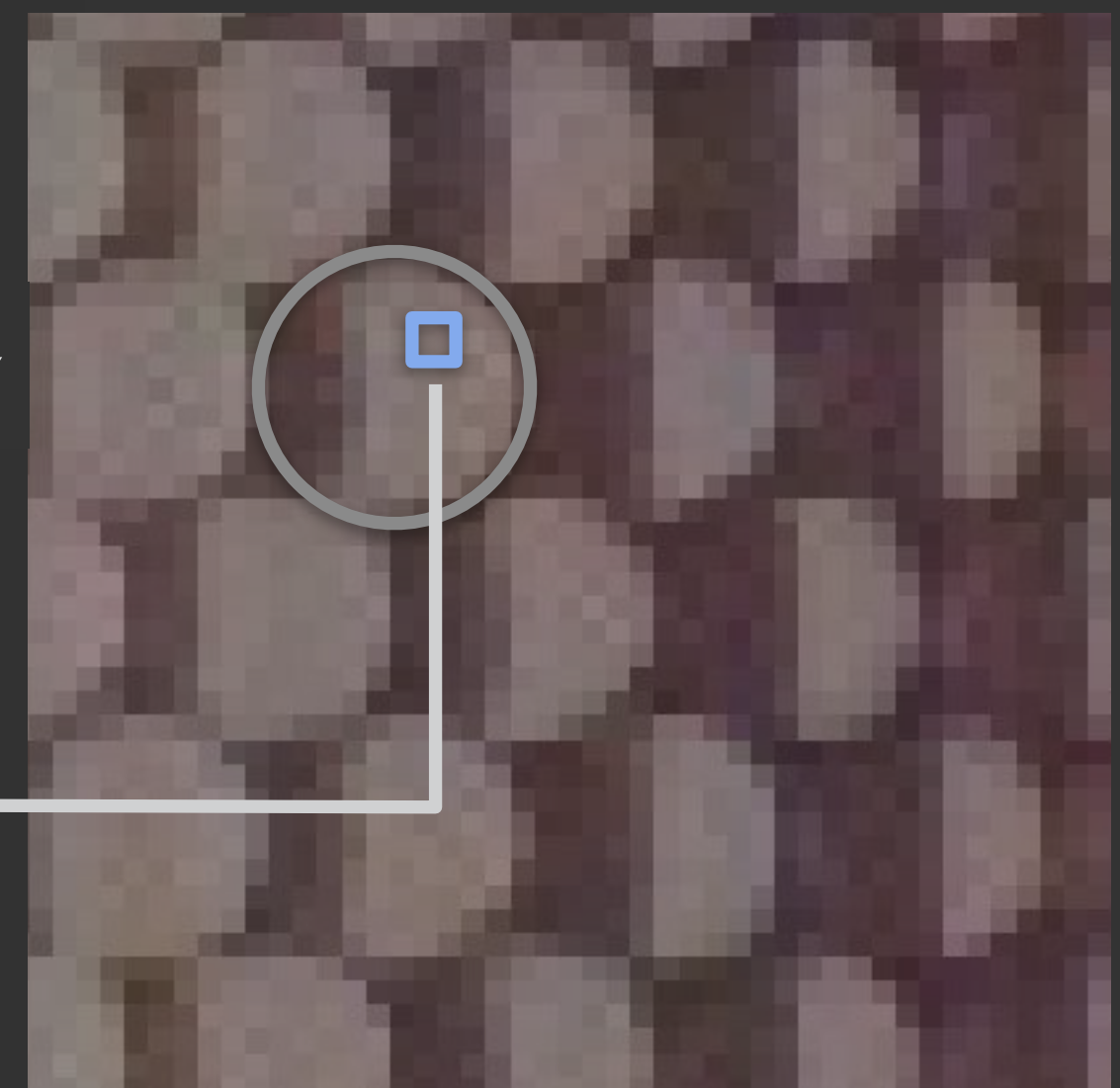
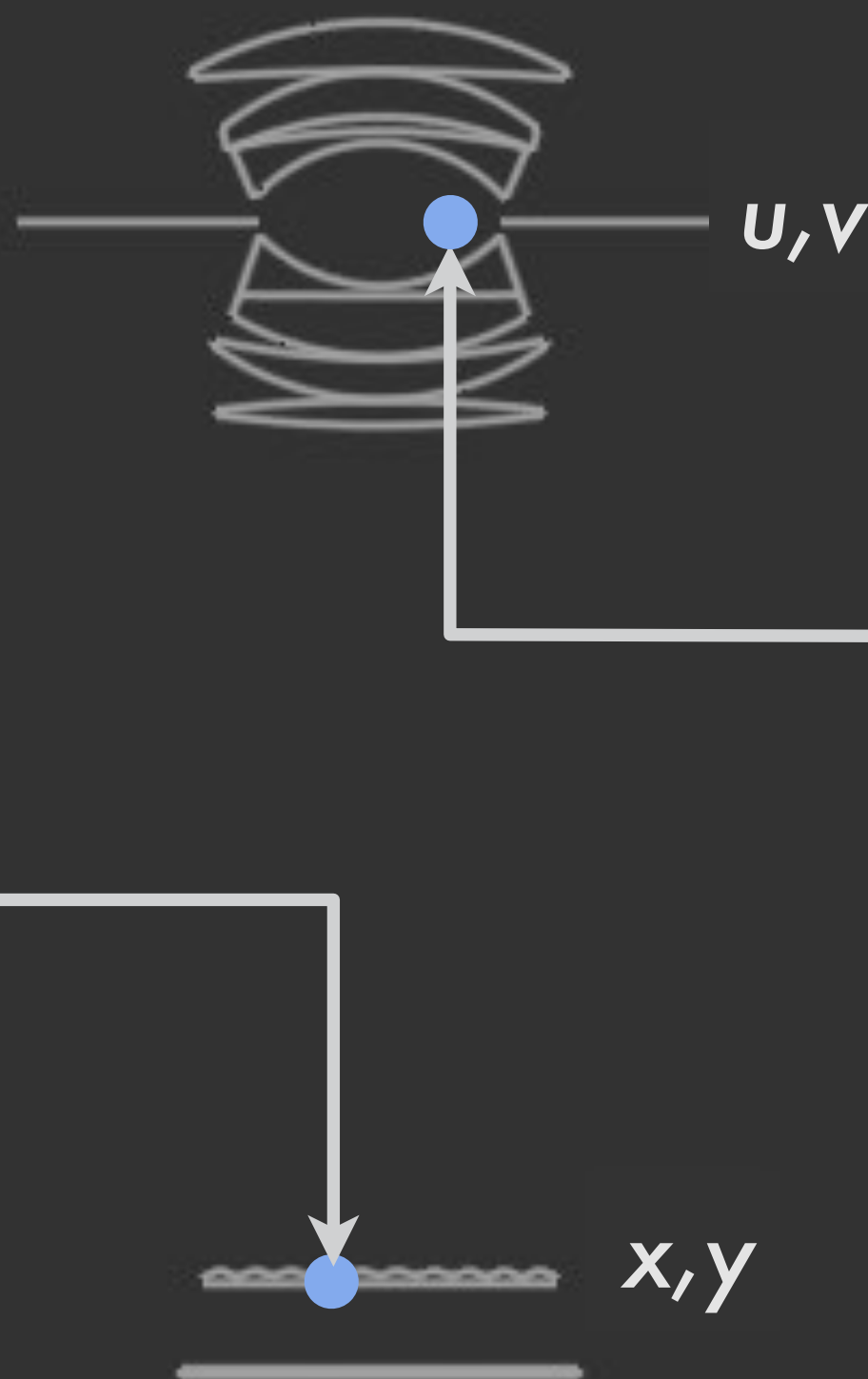
Raw Data From Light Field Sensor



Mapping Sensor Pixels to (x,y,u,v) Rays



Microlens location
in image field of view
gives (x,y) coord

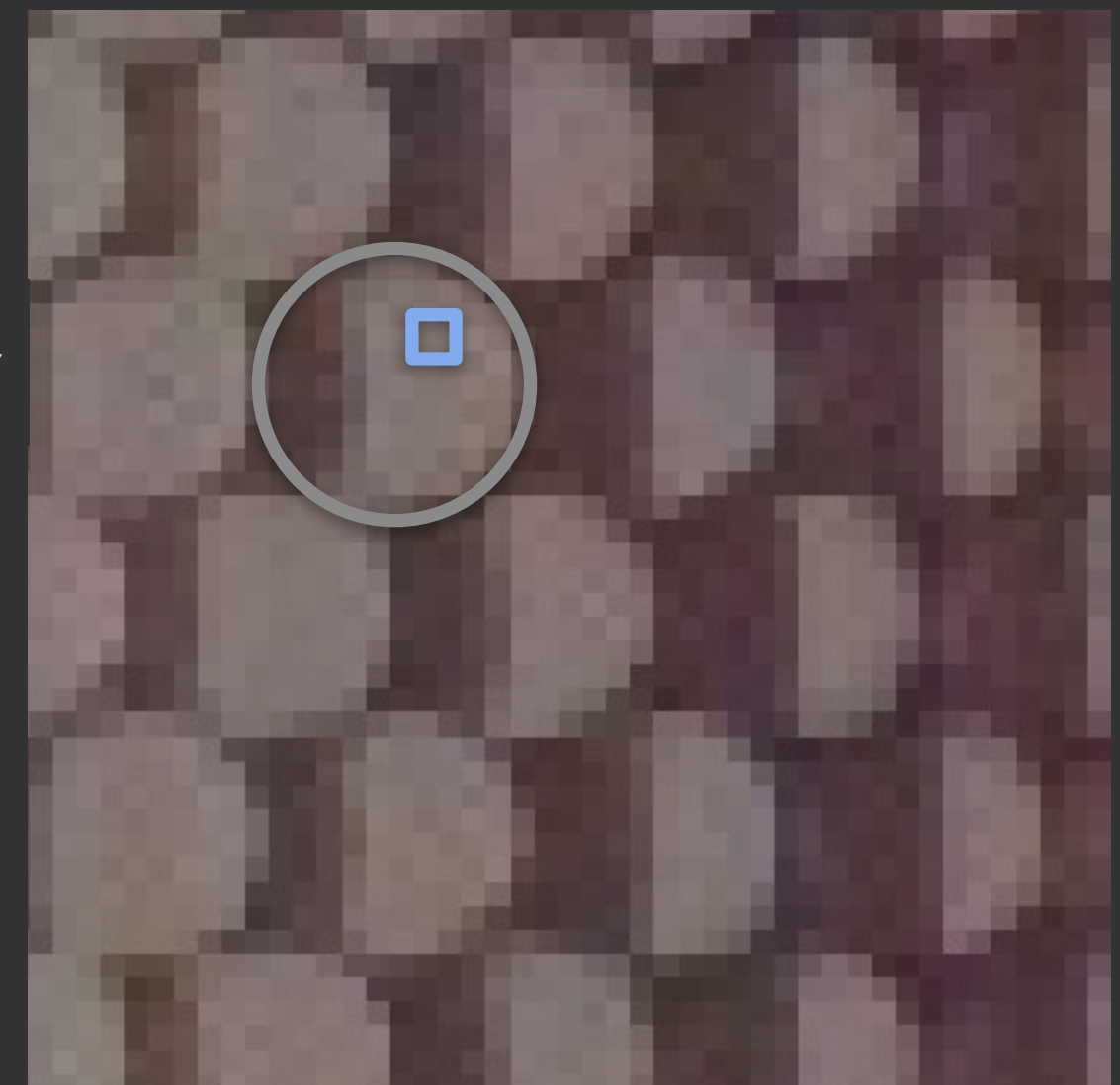
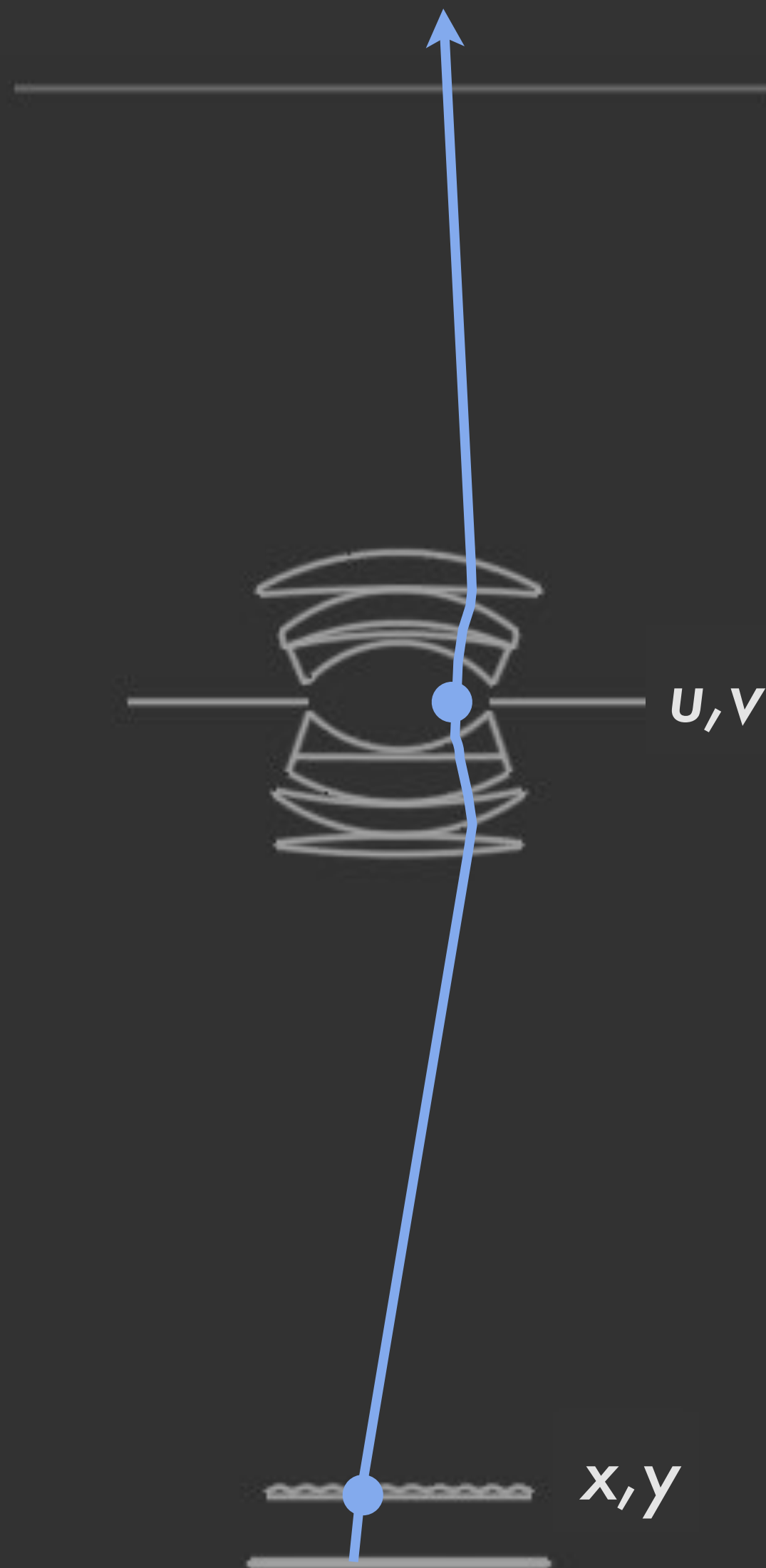


Pixel location in
microlens image
gives (u,v) coord

Mapping Sensor Pixels to (x,y,u,v) Rays



Microlens location
in image field of view
gives (x,y) coord



Pixel location in
microlens image
gives (u,v) coord







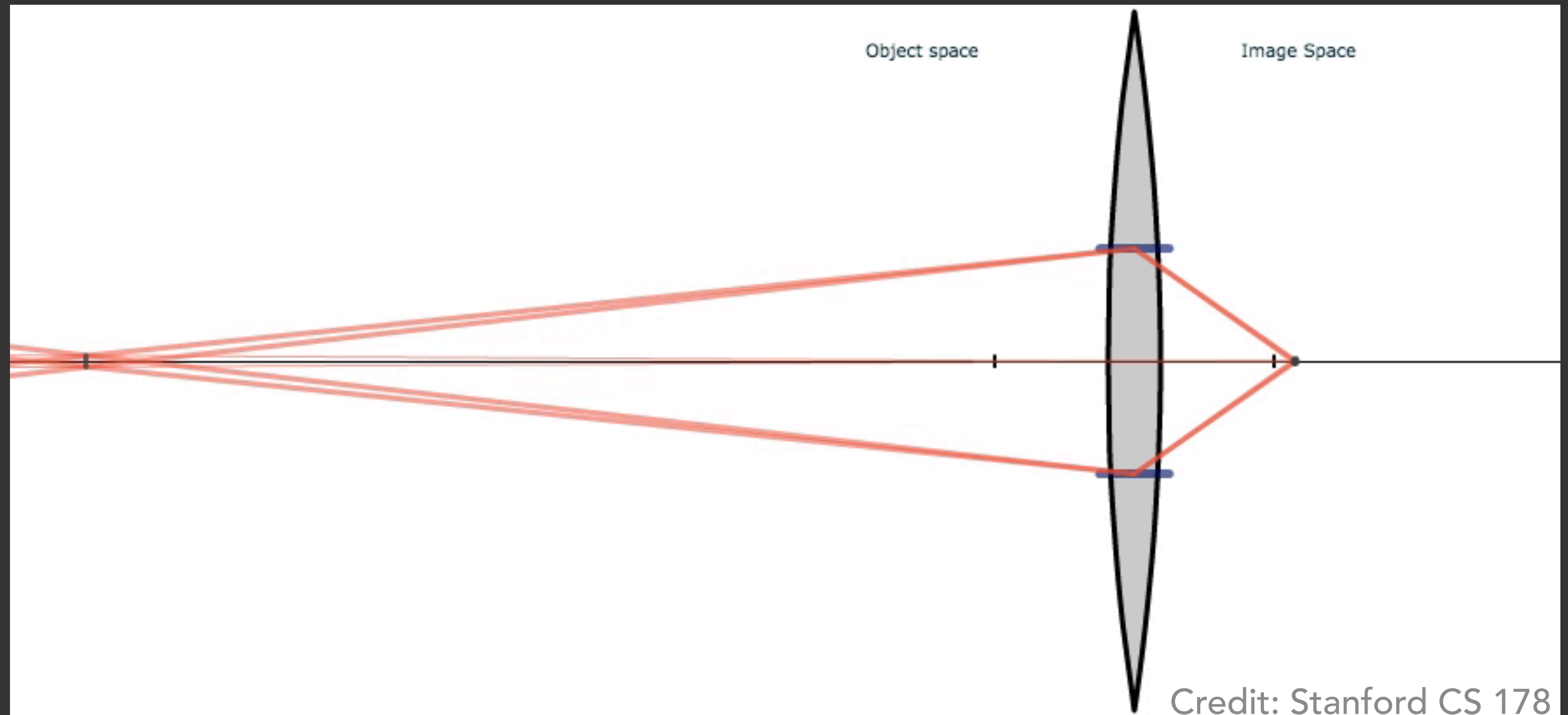






How Does Computational Refocusing Work?

Recall: How Physical Focusing Works

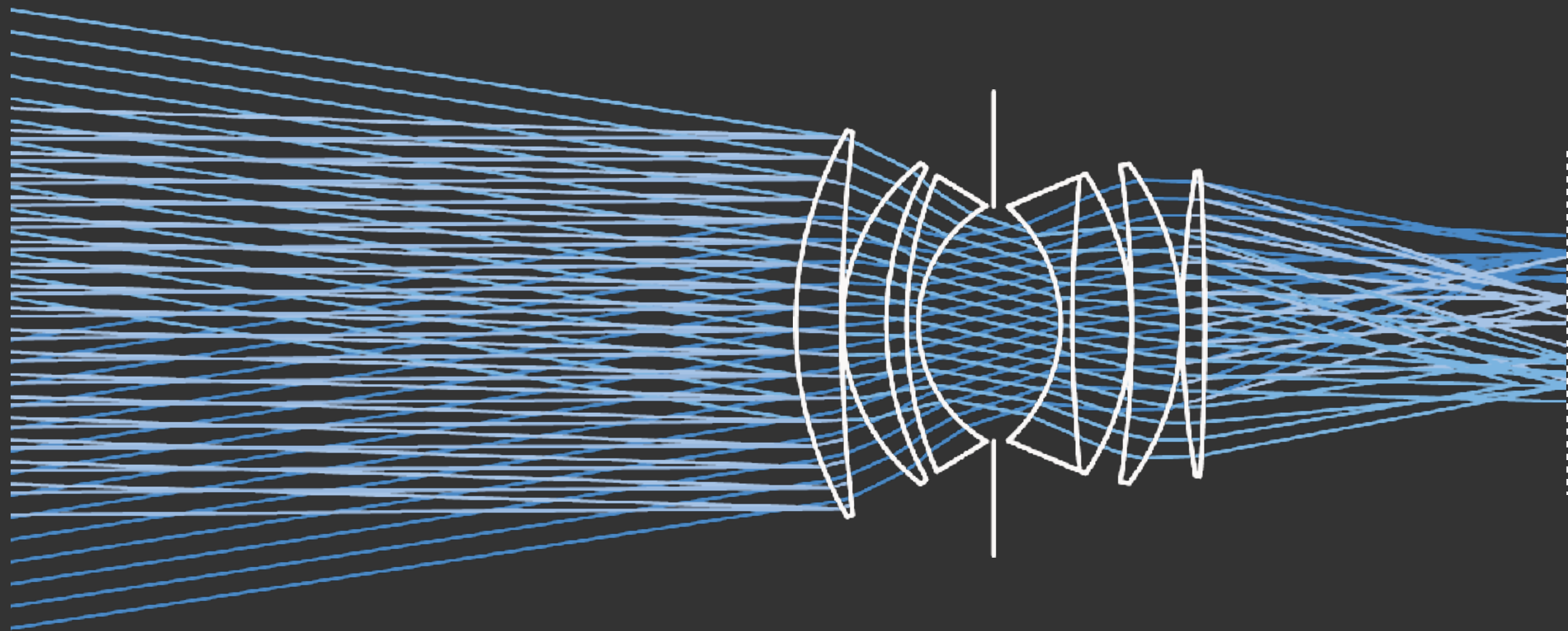


Sensor / lens gap determines plane of physical focus.

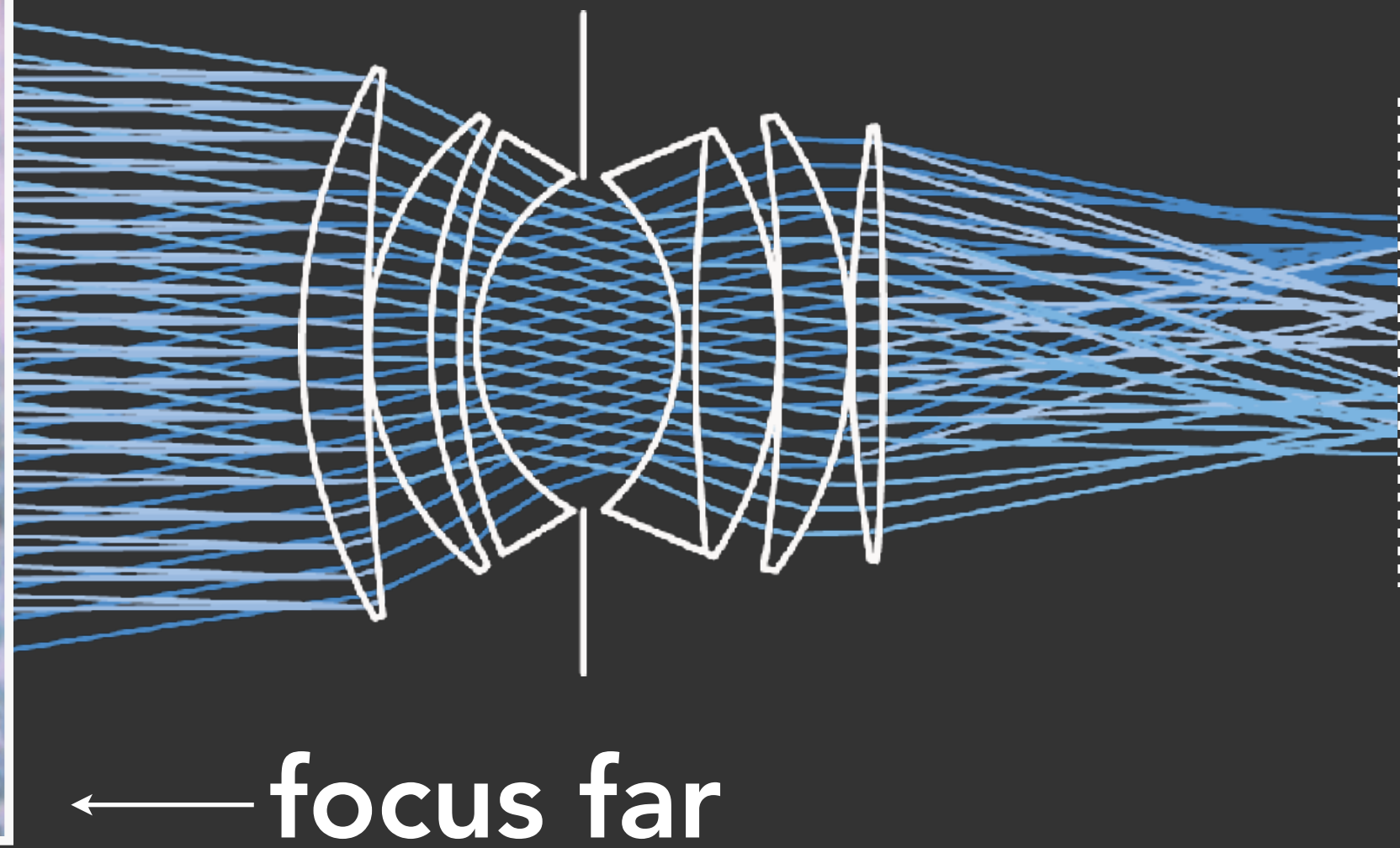
Computational Refocusing



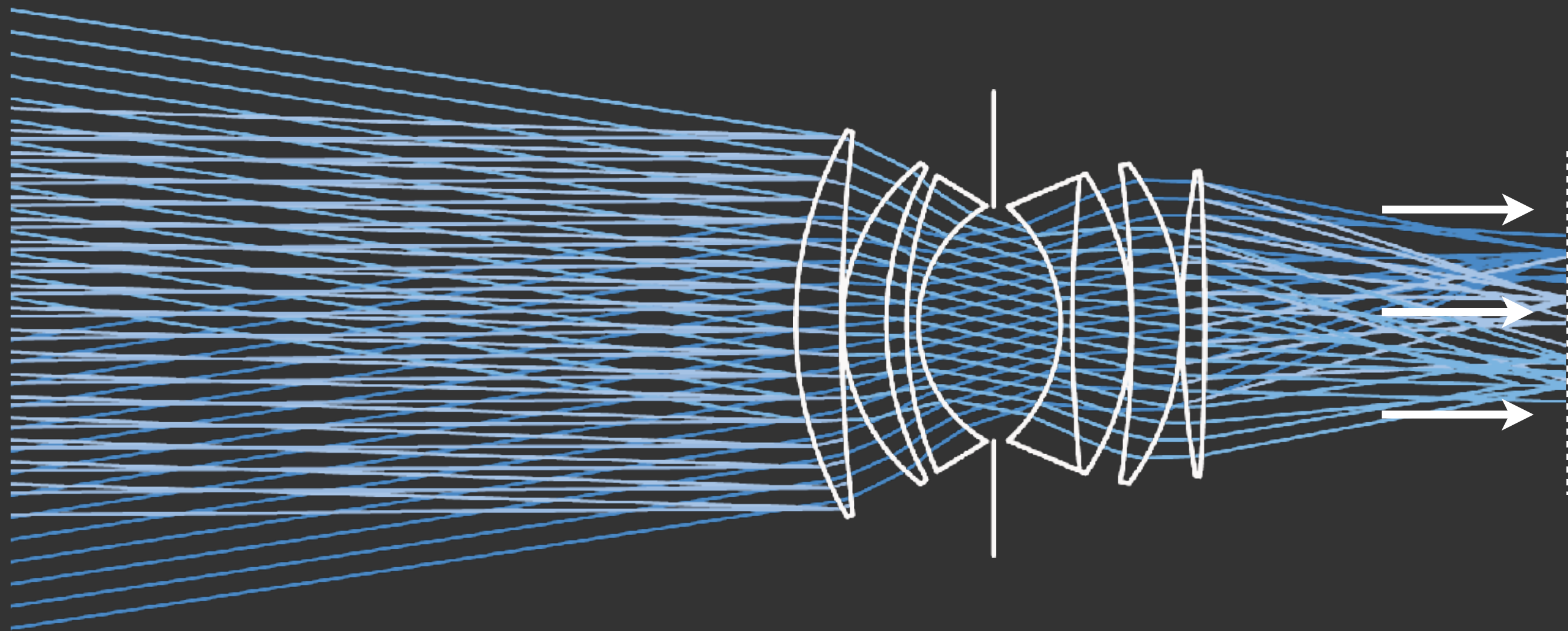
Computational Refocusing



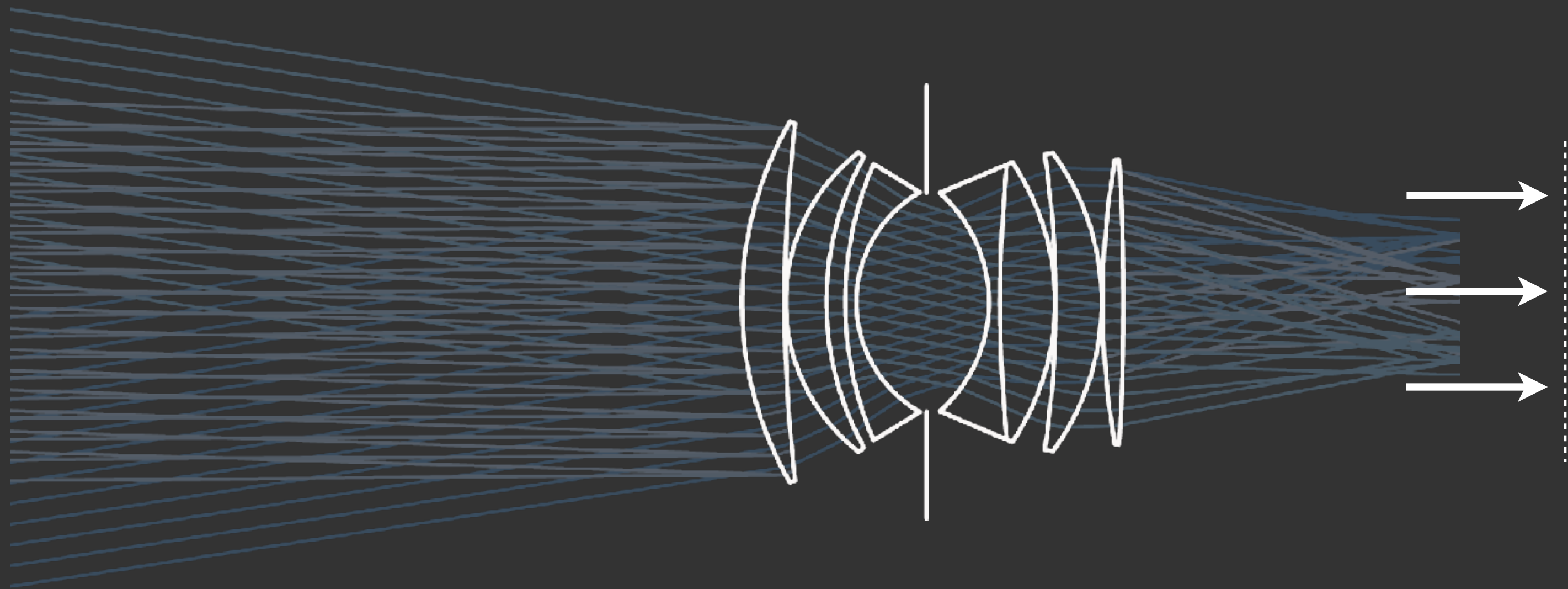
Computational Refocusing



Computational Refocusing

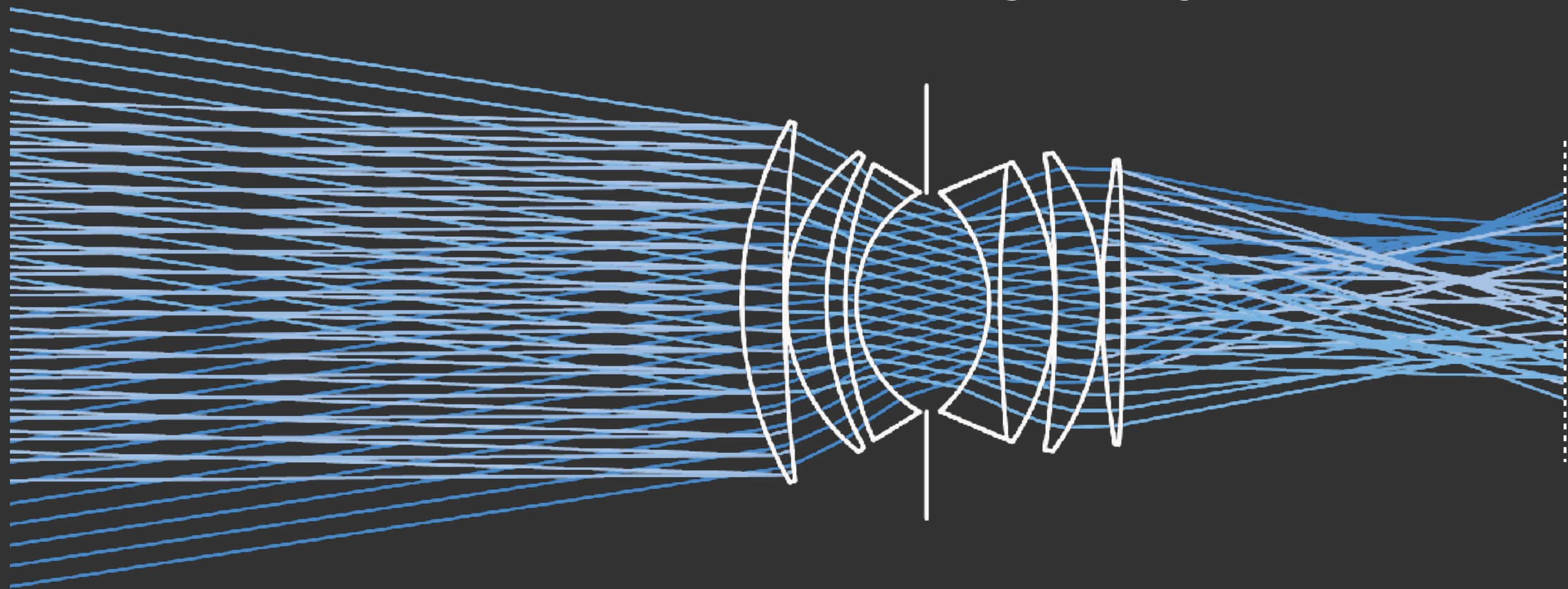


Computational Refocusing

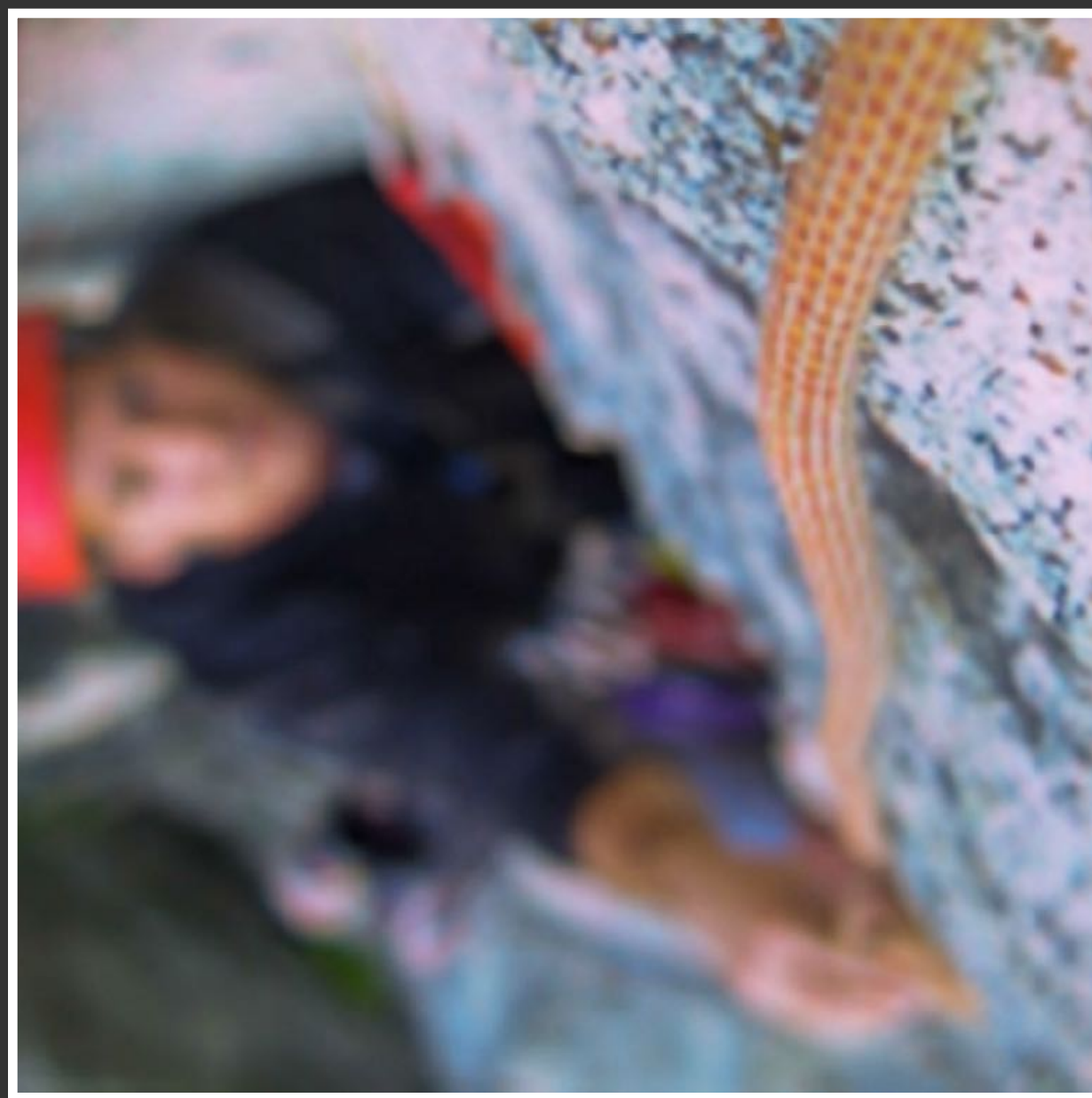


Computational Refocusing

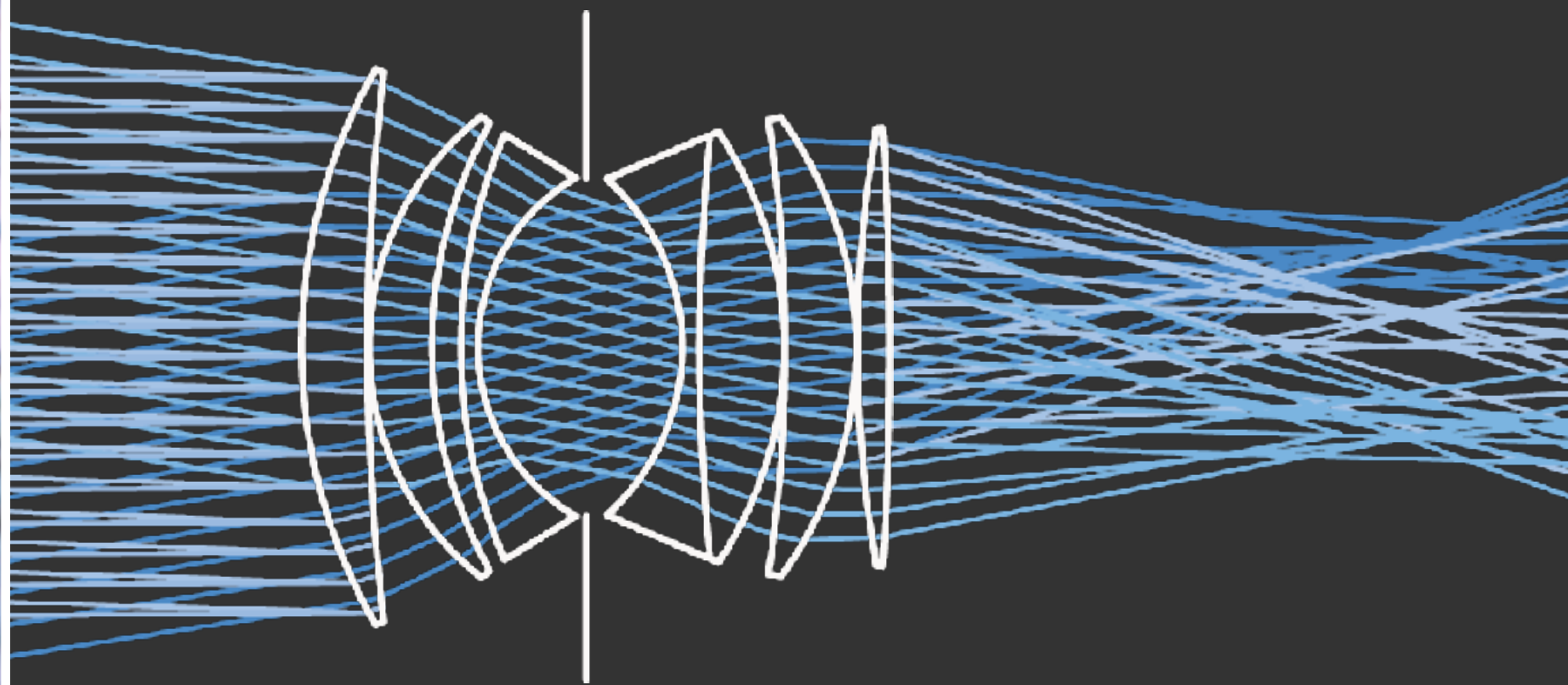
compute ray projection →



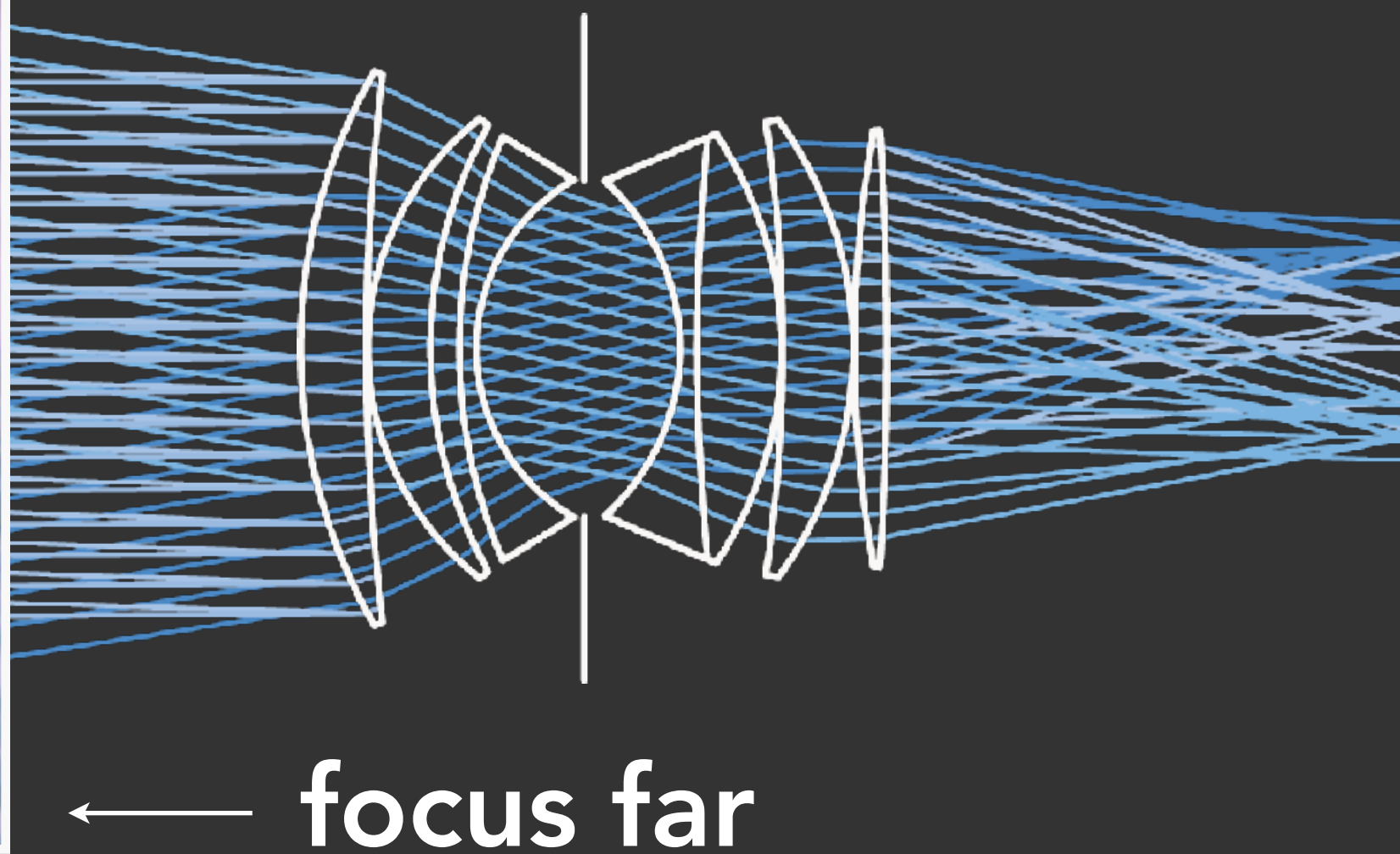
Computational Refocusing



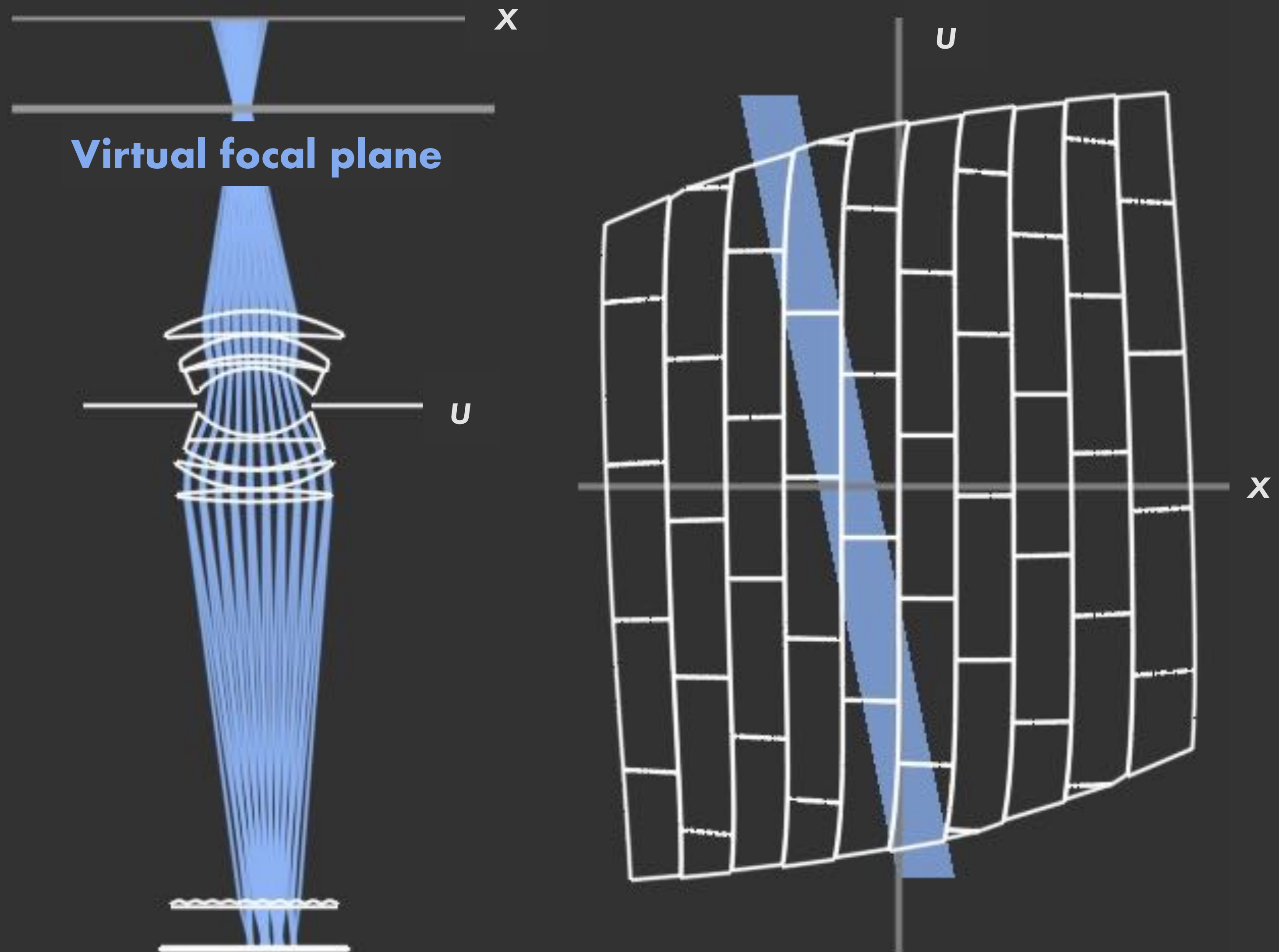
← focus close



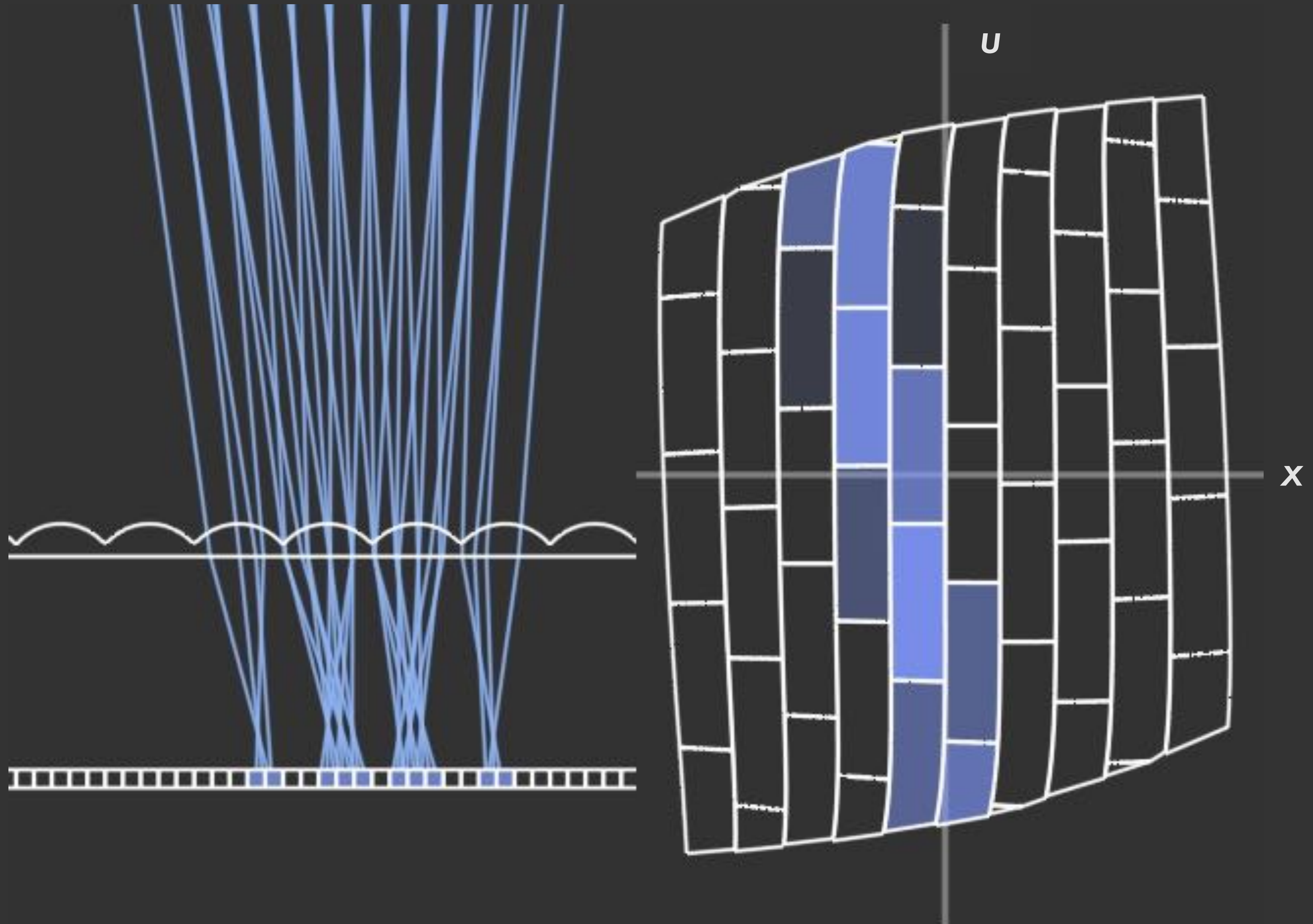
Computational Refocusing



Output Image Pixel is Sum of Many Sensor Pixels



Output Image Pixel is Sum of Many Sensor Pixels



Computationally Changing Depth of Field and Viewpoint

Computationally Extended Depth of Field



Conventional

Lens at f/4

Conventional

Lens at f/22

Light Field

Lens at f/4, all-focus algorithm
[Agarwala 2004]

Partially Extended Depth of Field



Original
DOF

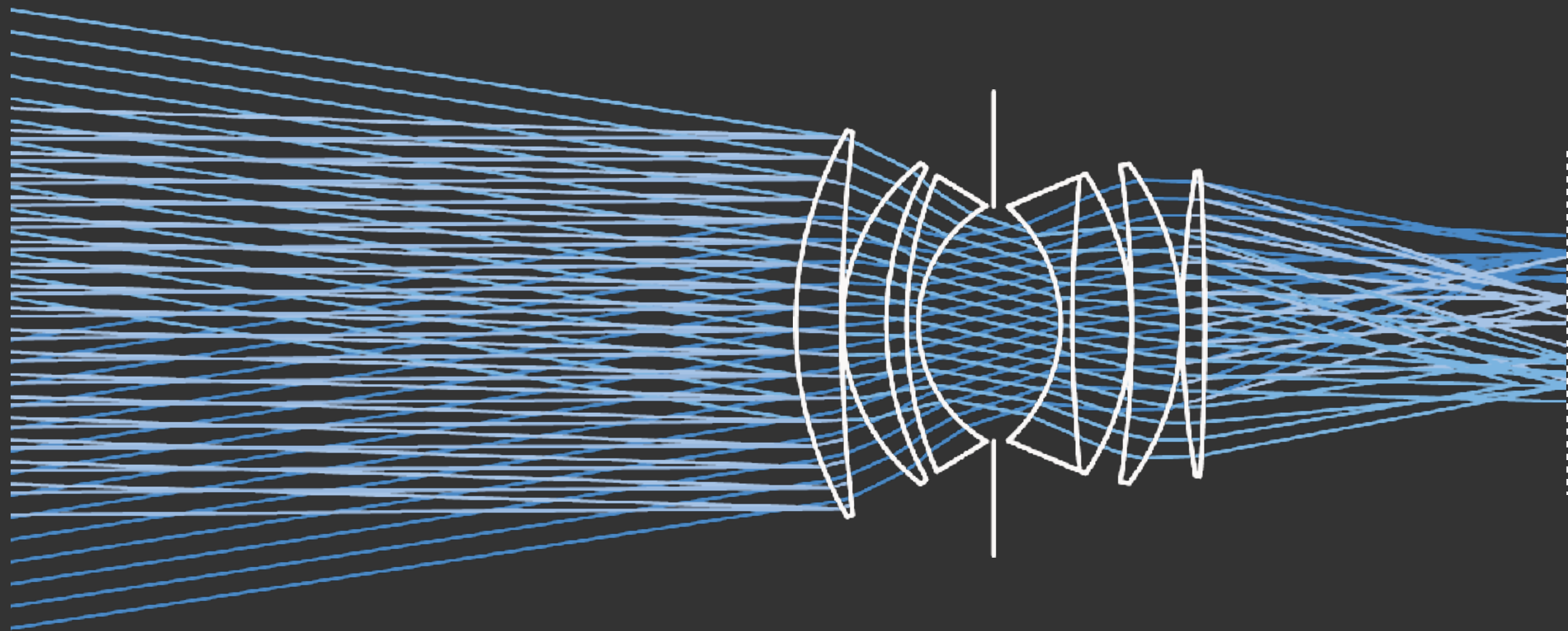


Extended
DOF

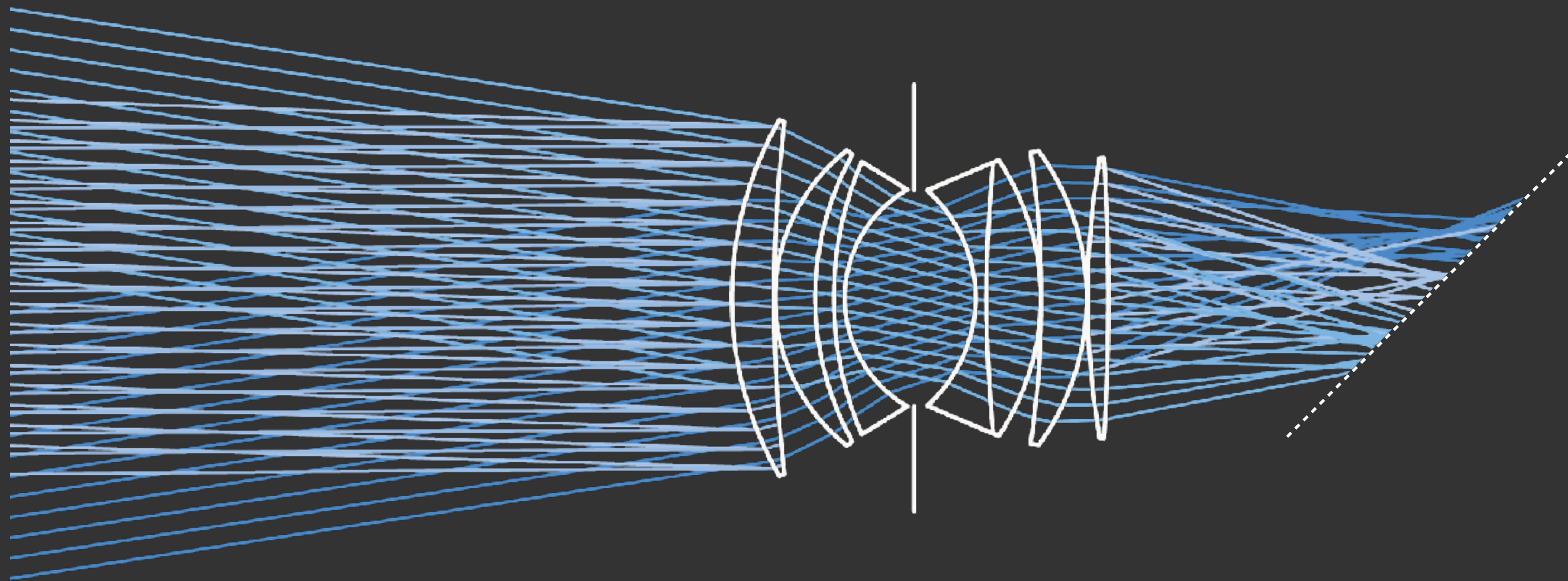


Partially Extended
DOF

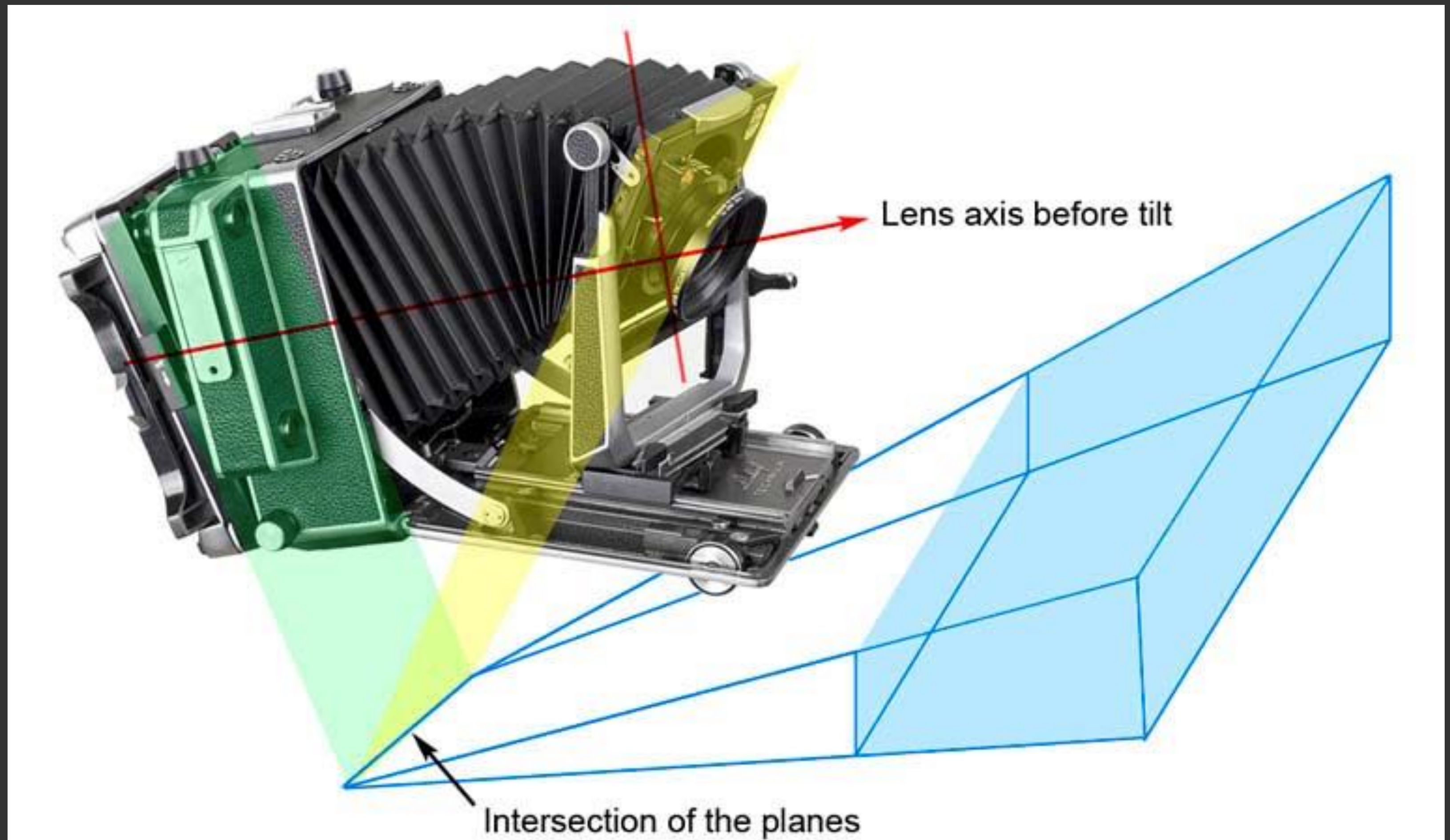
Tilted Focal Plane



Tilted Focal Plane



View Camera, Scheimpflug Rule



Source: David Summerhayes, <http://www.luminous-landscape.com/tutorials/focusing-ts.shtml>

Computational Change of Viewpoint



Lateral movement (left)

Computational Change of Viewpoint



Lateral movement (right)

Computational Change of Viewpoint



Forward movement
(wide angle effect)

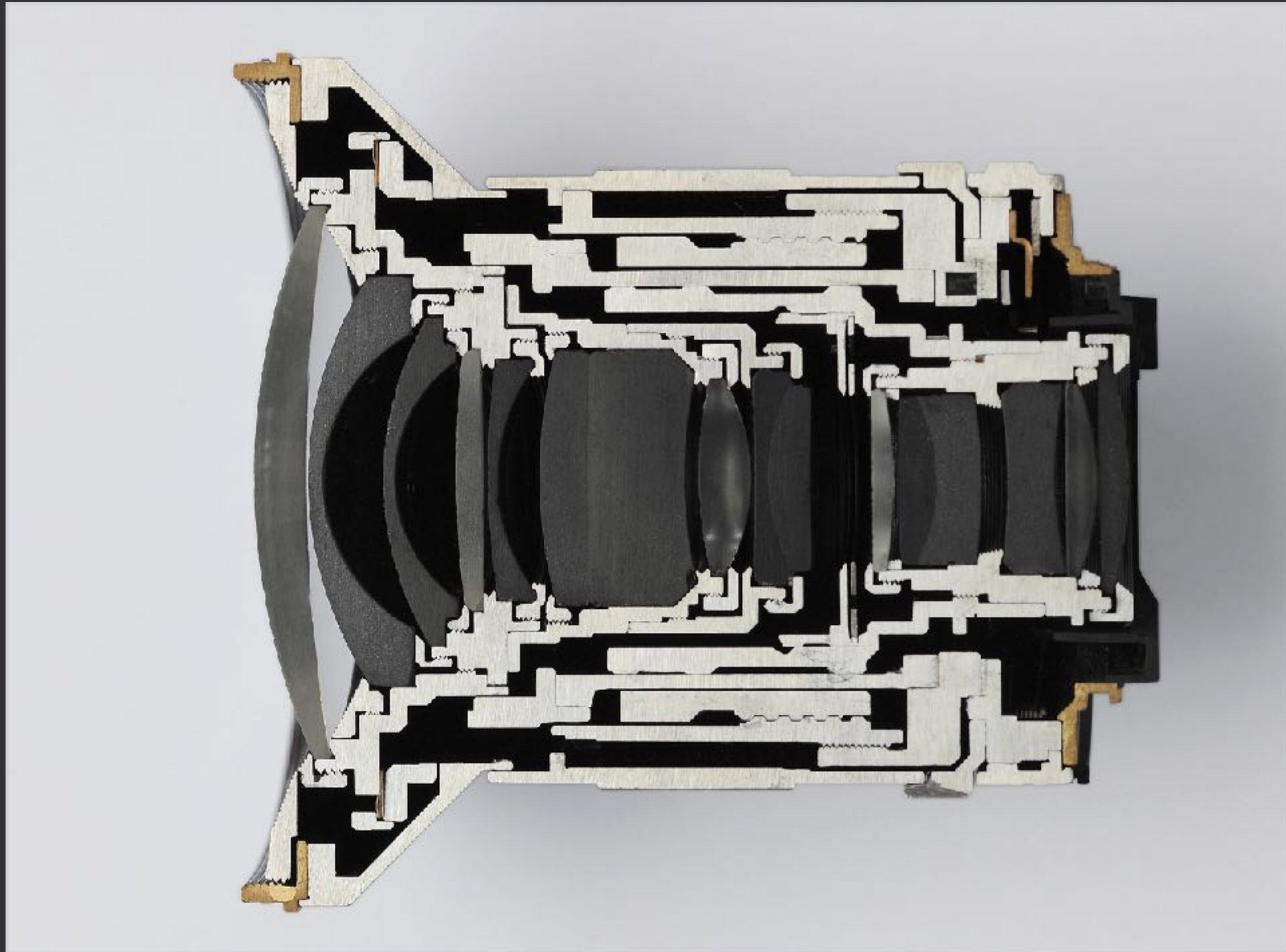
Computational Change of Viewpoint



Backward movement
(orthographic effect)

Light Field Imaging Lenses - Optics and Computation

Modern Lens Designs Are Highly Complex



ilovephotography.com

Photographic lens cross section

Modern Lens Designs Are Highly Complex



[Apple]

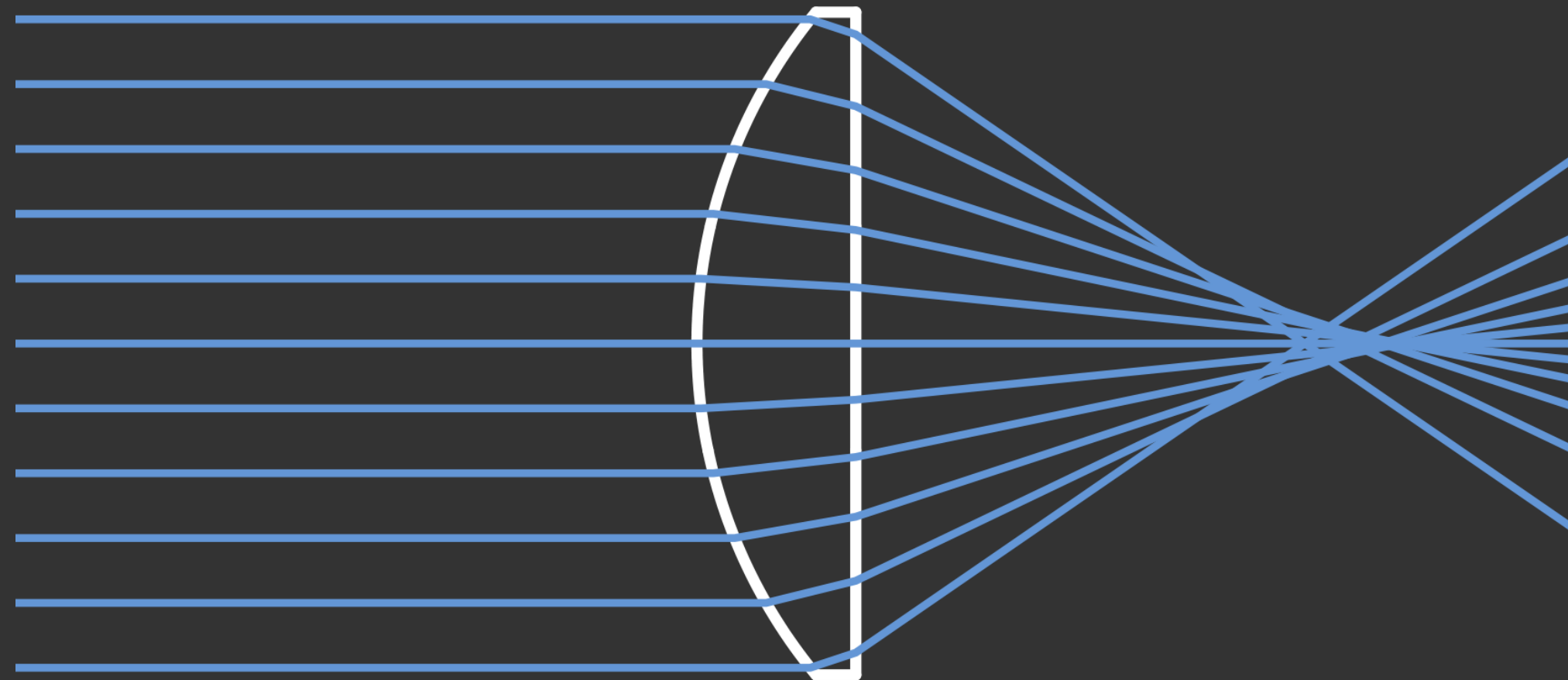
Modern Lens Designs Are Highly Complex



Zeiss flickr.com account

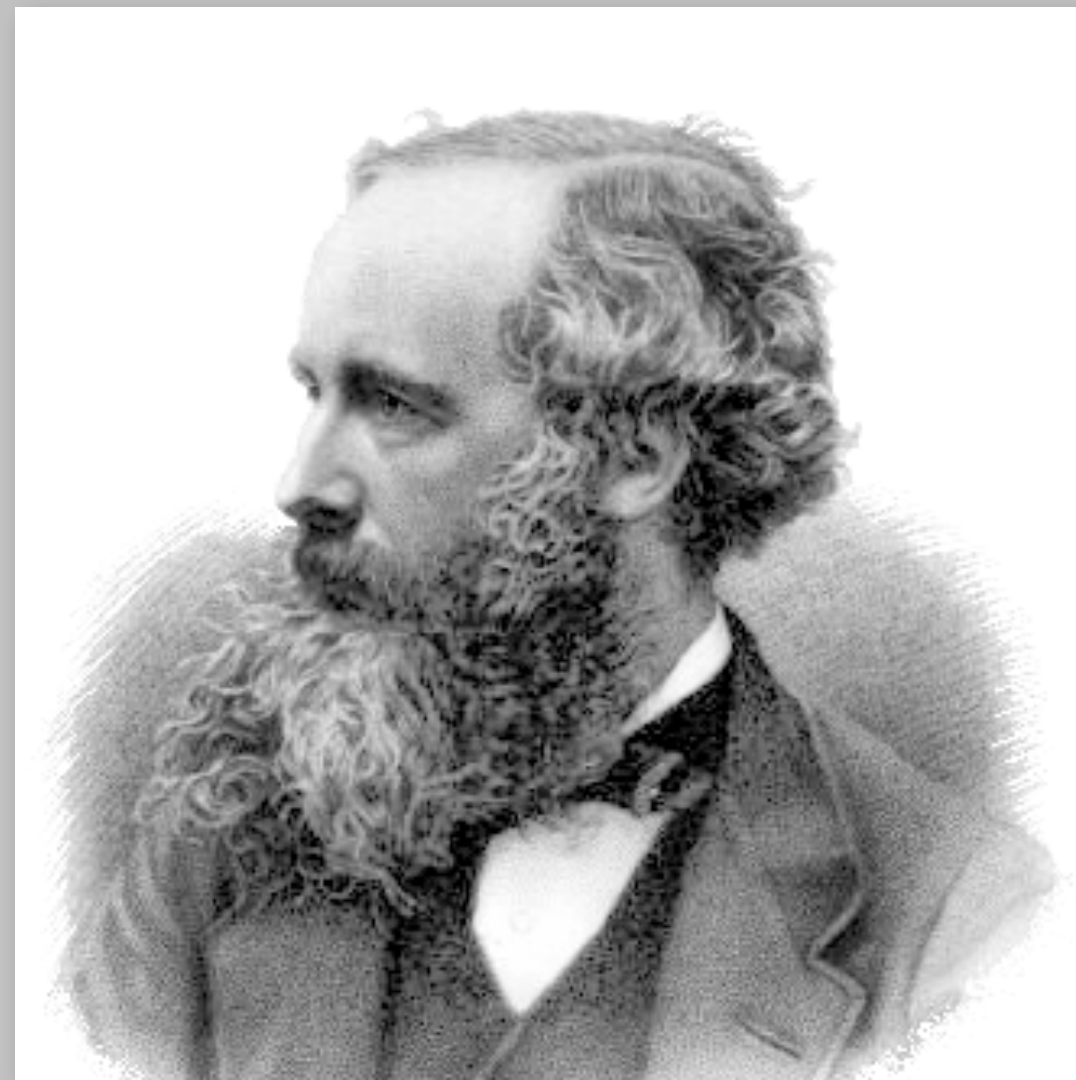
Microscope objective

Lens Aberration Example



Real spherical lens does not converge
rays to a single point.

Aberrations Are Fundamental & Unavoidable



J. C. Maxwell, 1858. "On the general laws of optical instruments," *The Quarterly Journal of Pure and Applied Mathematics* 2, pp. 233–246, 1858.

Lens Design in 1839



Louis Daguerre



Chevalier Lens (f/16)

Lens Design in 1839



Joseph Petzval

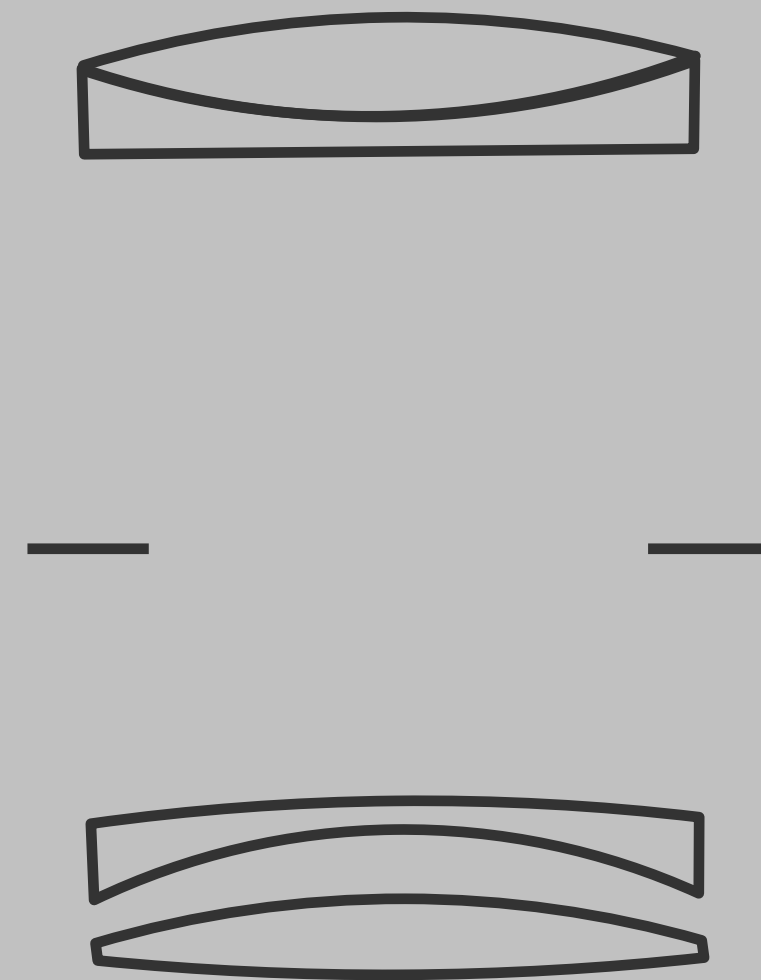


Petzval Portrait Lens (f/3.6)

Lens Design in 1839



Joseph Petzval



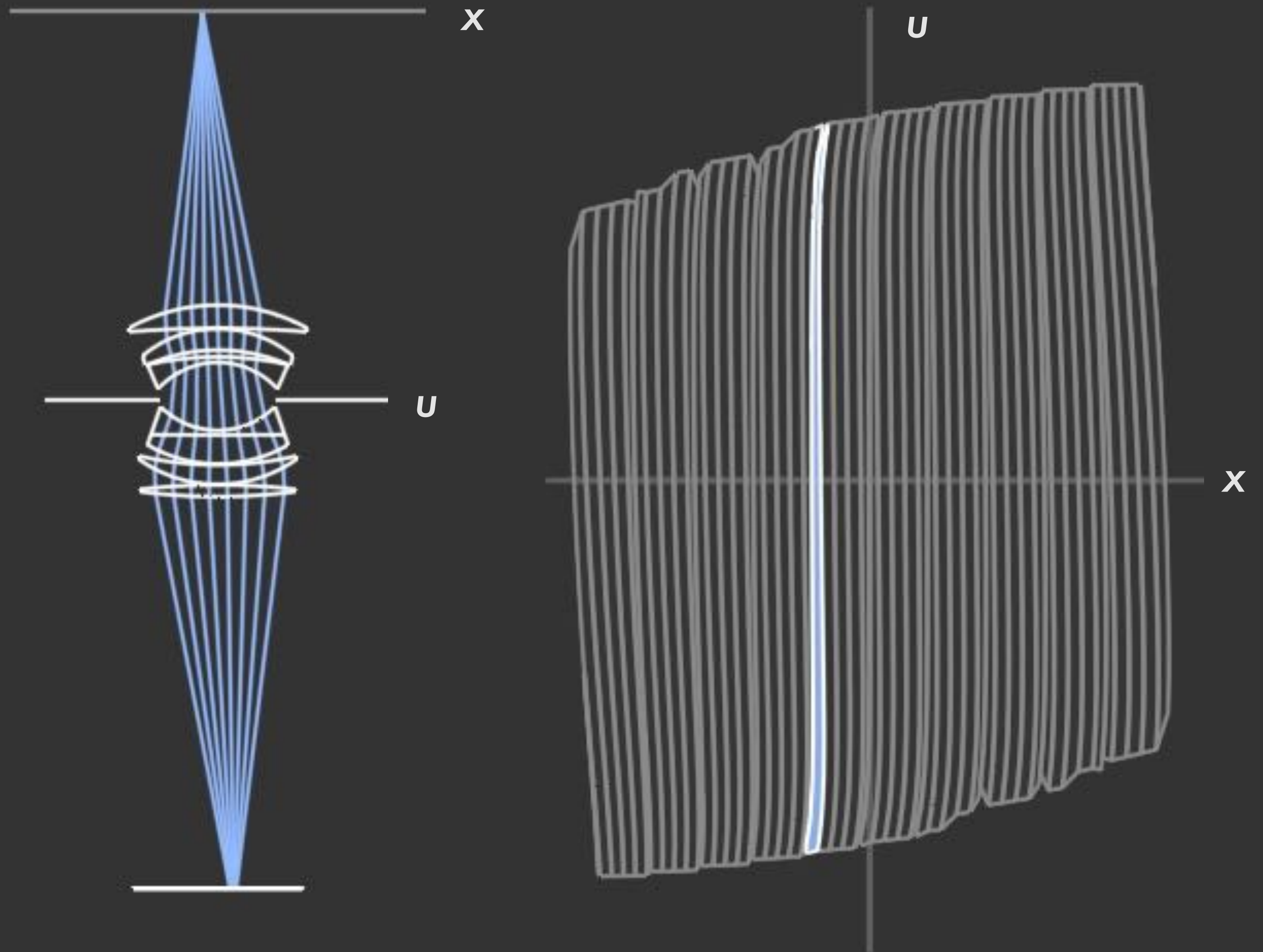
Petzval Portrait Lens (f/3.6)

Petzval Portrait Lens

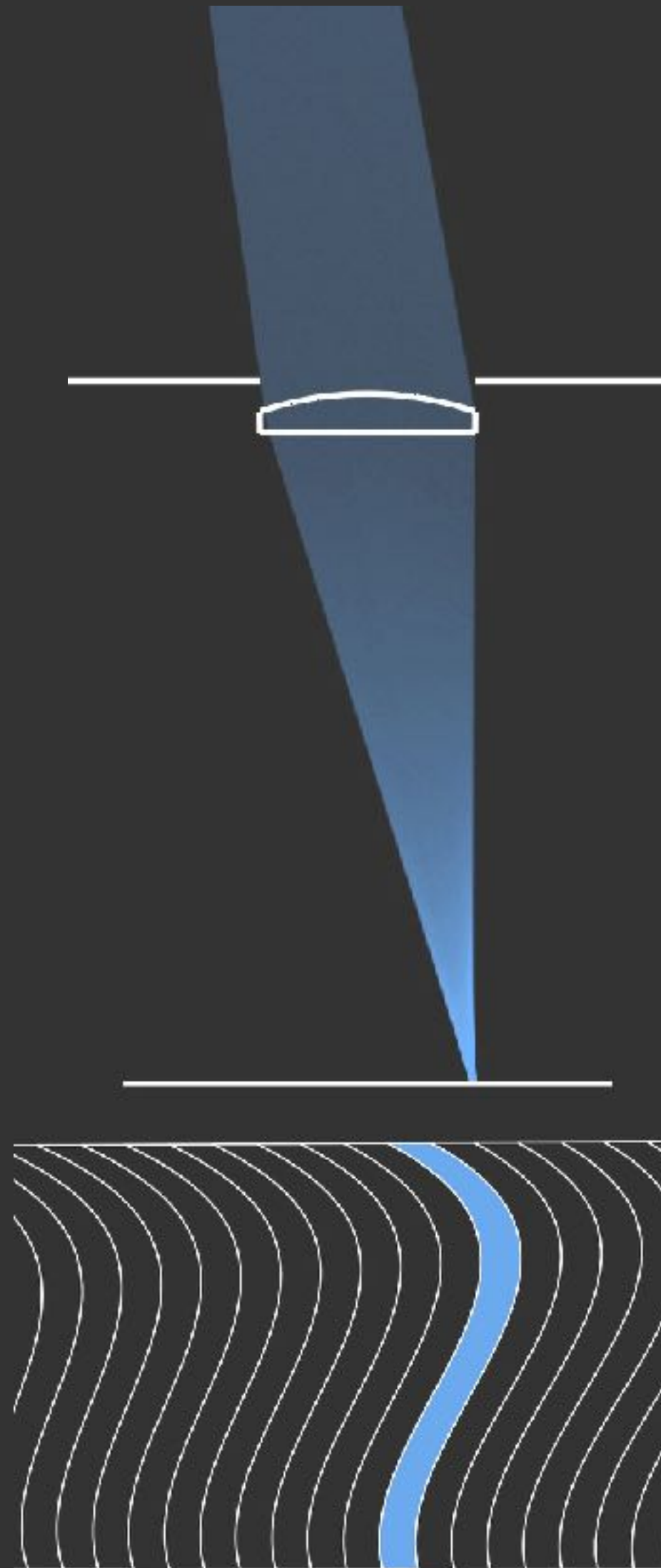


David Kashevaroff

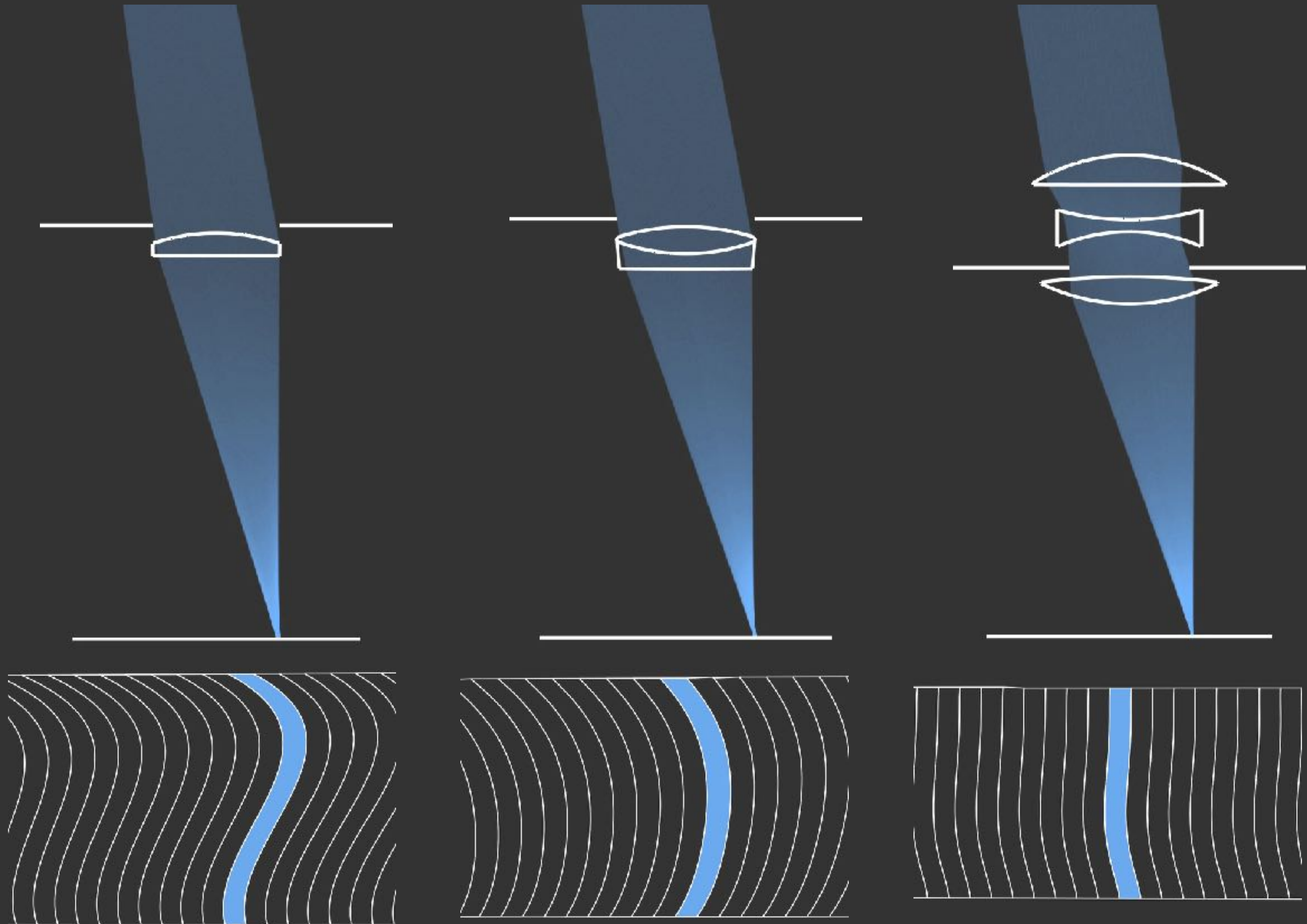
Recall: What Does a 2D Photograph Record?



Aberrations Are Curvature in the Ray-Space



Aberration Correction by Adding Elements



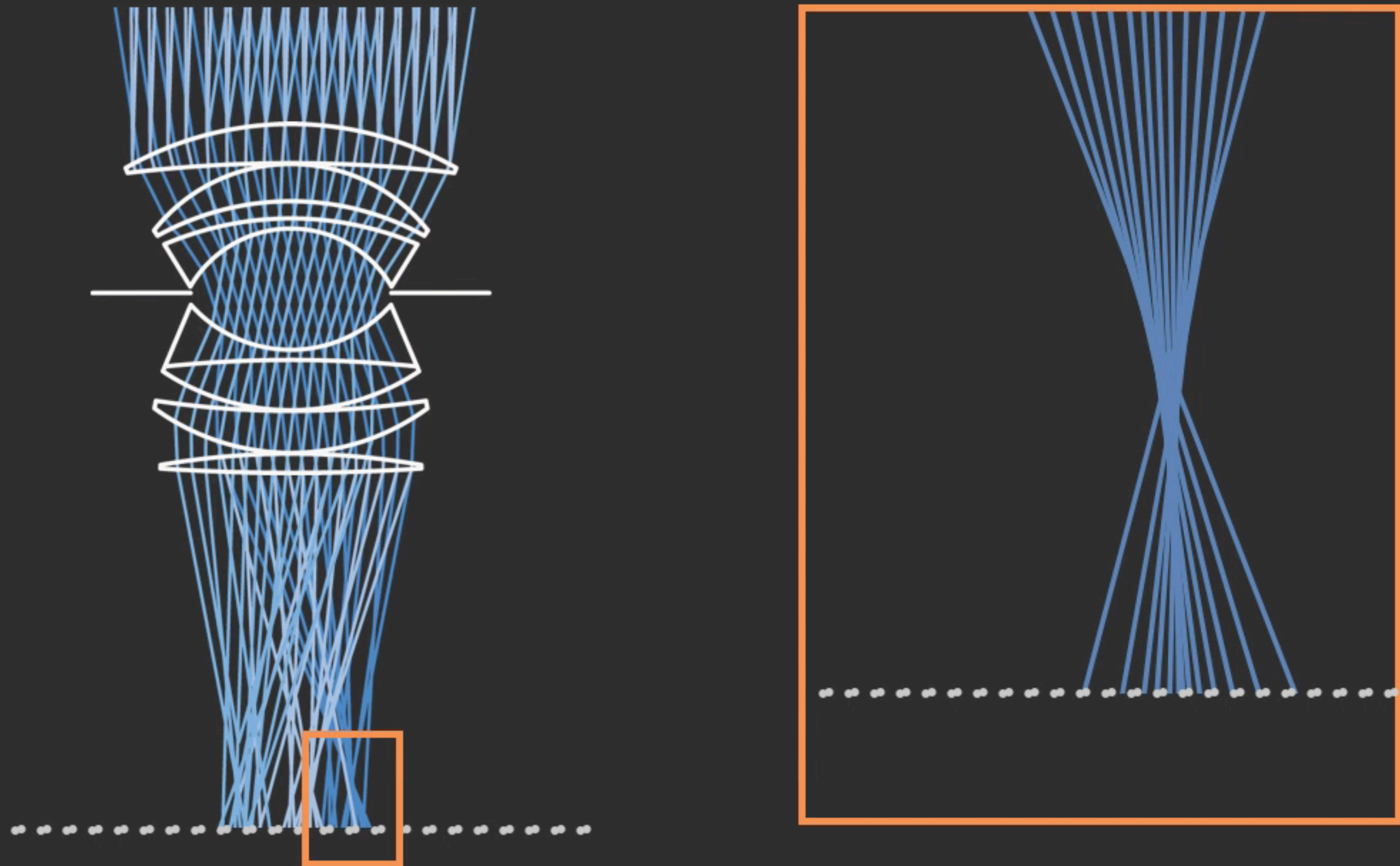
Aberration Correction by Adding Elements



Canon 70-200mm F2.8. 23 glass elements, 3.28 lbs.

Computational Aberration Correction

Light Field Correction of Aberrations



Computationally redirect rays from physical trajectory to ideal location

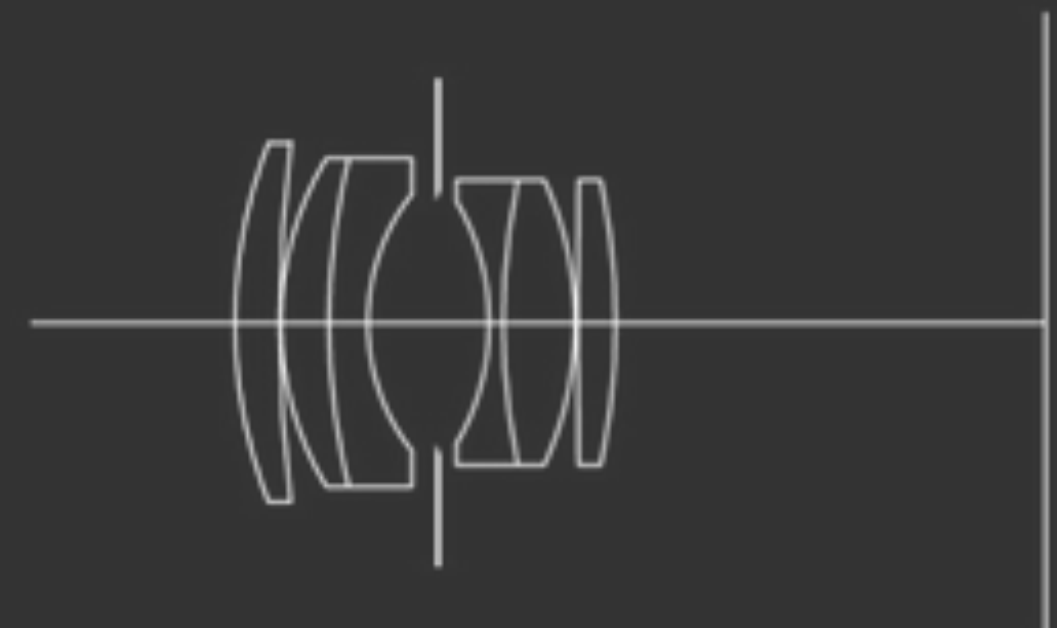
Compute Difference Between Real and “Ideal” Imaging

- Real: Geometrical optics (ray-tracing, aberrations)
- Ideal: Paraxial optics (matrix methods, aberration-free)
- Sketch of Algorithm
- For each light field ray with radiance L
 - Compute the (x, y, u, v) “real” ray inside camera
 - From real camera ray, compute corresponding “real” world ray (x_w, y_w, u_w, v_w) using geometrical optics (ray-trace out through real lens system)
 - From real world ray, compute “idealized” ray inside camera from by using paraxial optics (matrix method)
 - Use “idealized” ray for image synthesis

Use Detailed Lens Formula For Ray-Tracing

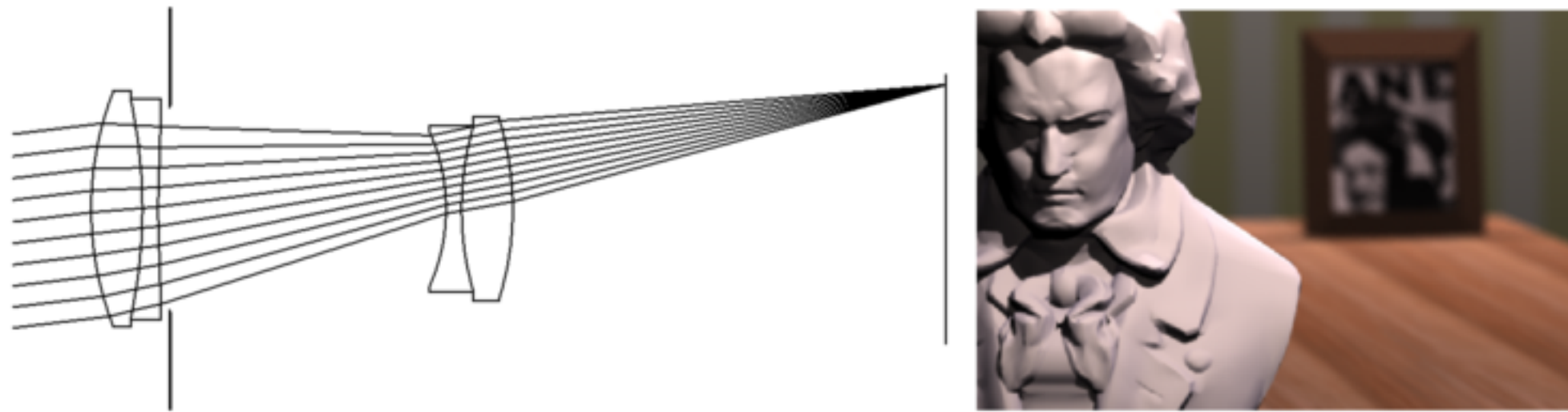
Double Gauss Lens

Radius (mm)	Thick (mm)	n	V-no	aperture
58.950	7.520	1.670	47.1	50.4
169.660	0.240			50.4
38.550	8.050	1.670	47.1	46.0
81.540	6.550	1.699	30.1	46.0
25.500	11.410			36.0
	9.000			34.2
-28.990	2.360	1.603	38.0	34.0
81.540	12.130	1.658	57.3	40.0
-40.770	0.380			40.0
874.130	6.440	1.717	48.0	40.0
-79.460	72.228			40.0



From W. Smith, Modern Lens Design, p. 312

Ray Tracing Through Real Lens Designs



200 mm telephoto



35 mm wide-angle



50 mm double-gauss

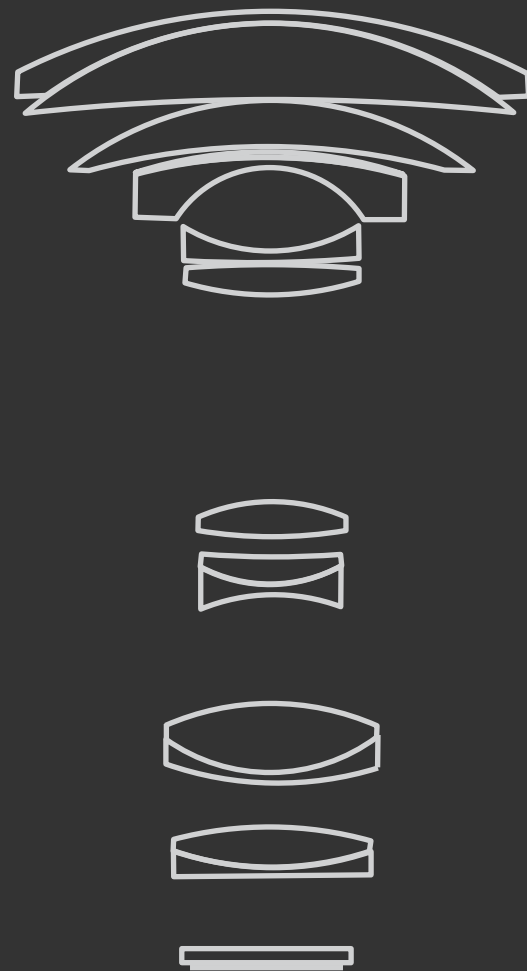


16 mm fisheye

From Kolb, Mitchell and Hanrahan (1995)

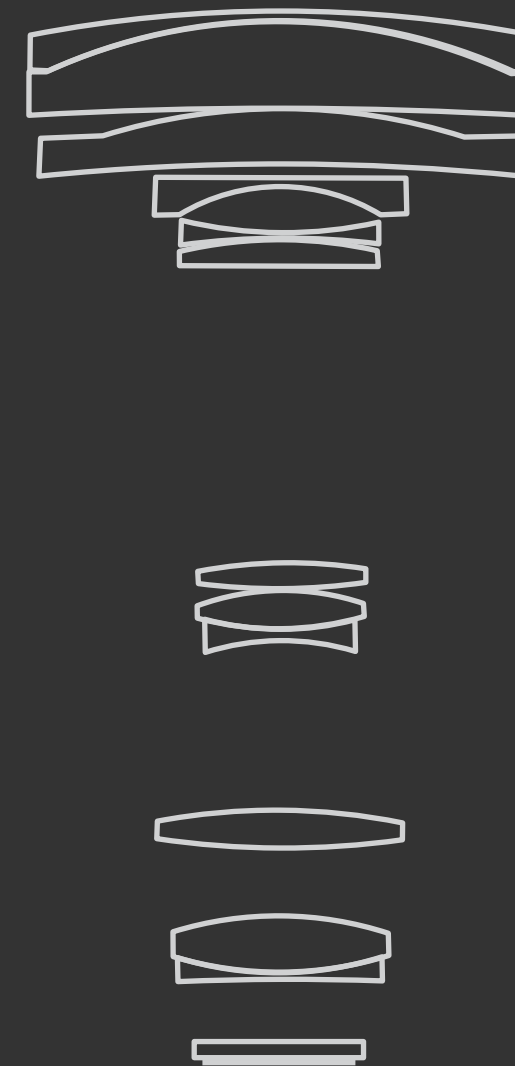
Design Better Lenses Assuming Light Field Imaging

Without Light Field Correction



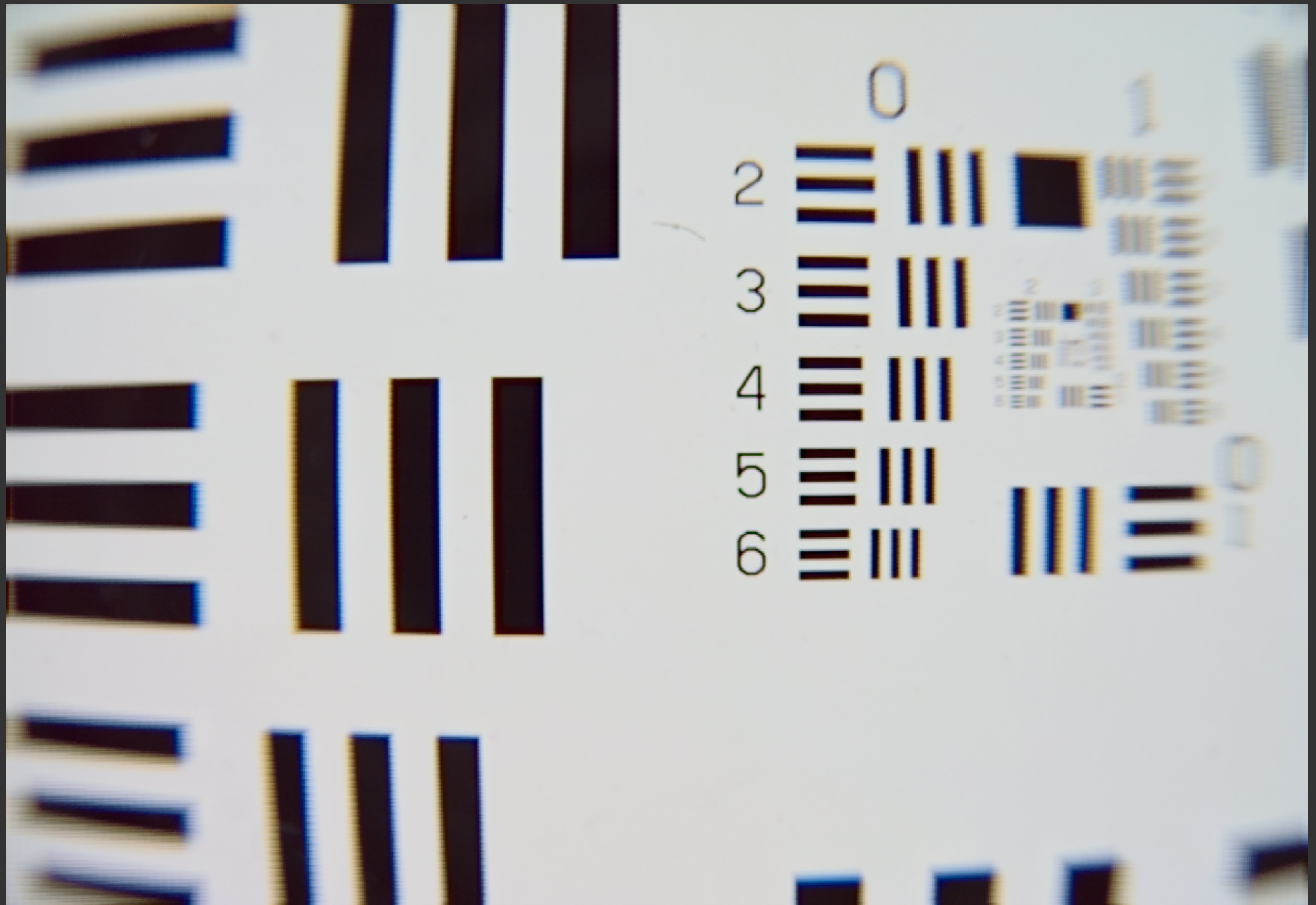
- F2 aperture
- >3x zoom not achievable
- 16 elements total
- 3 aspheric elements

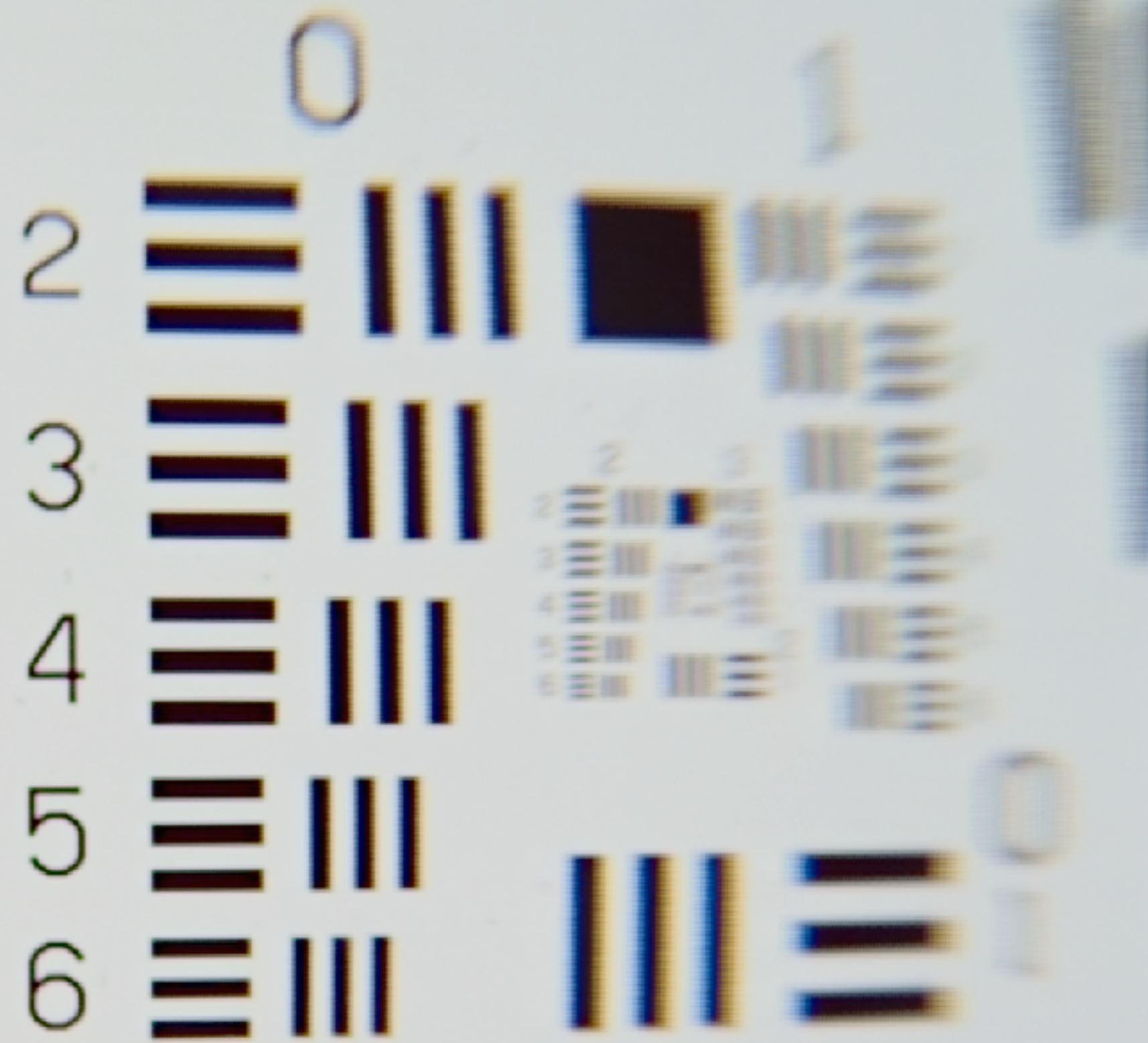
With Light Field Correction



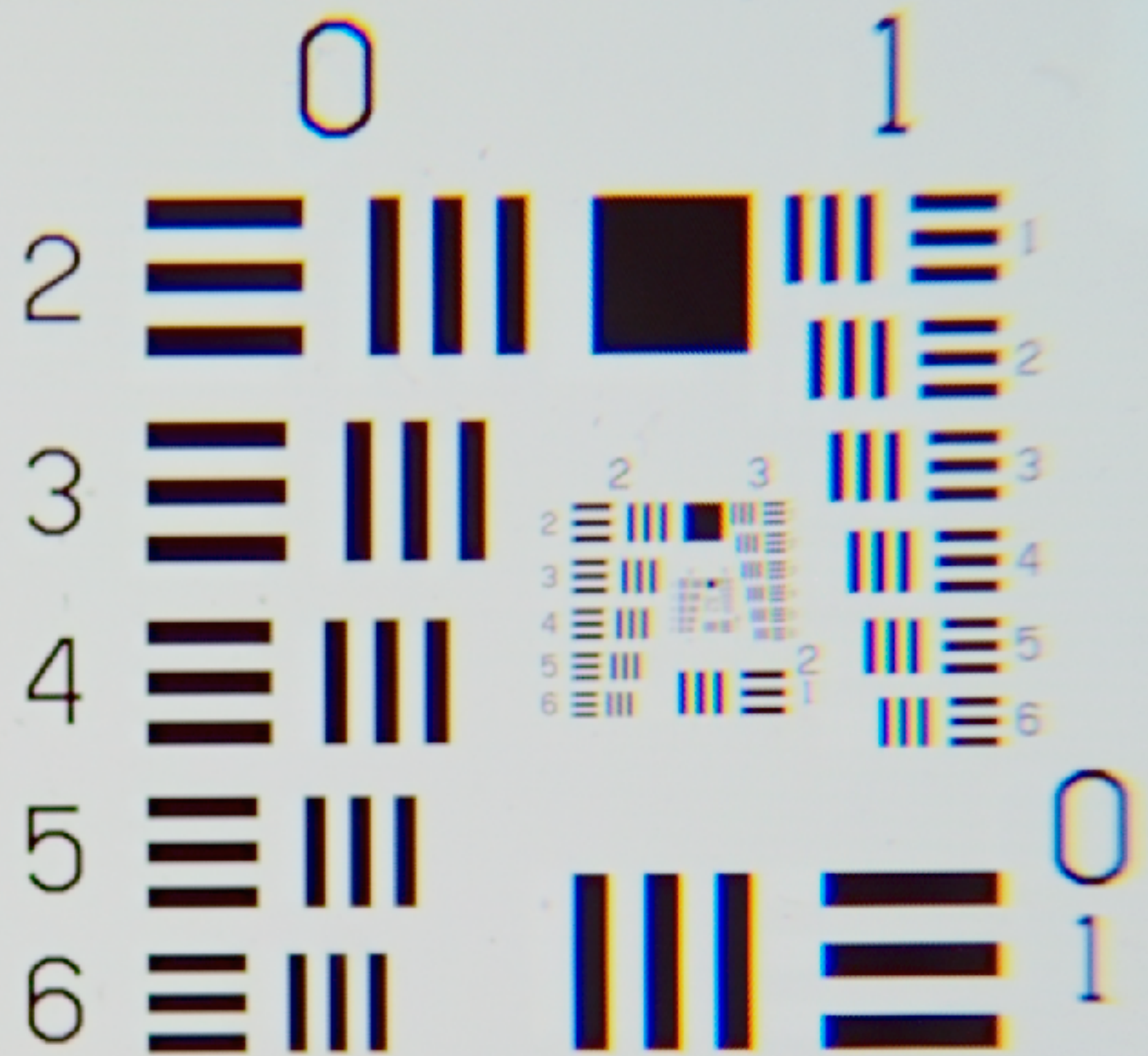
- F2 aperture
- 8x zoom
2.83x larger max focal length
20% longer lens
- 13 elements total
- 0 aspheric elements

Lens Needs Computation For Good Performance

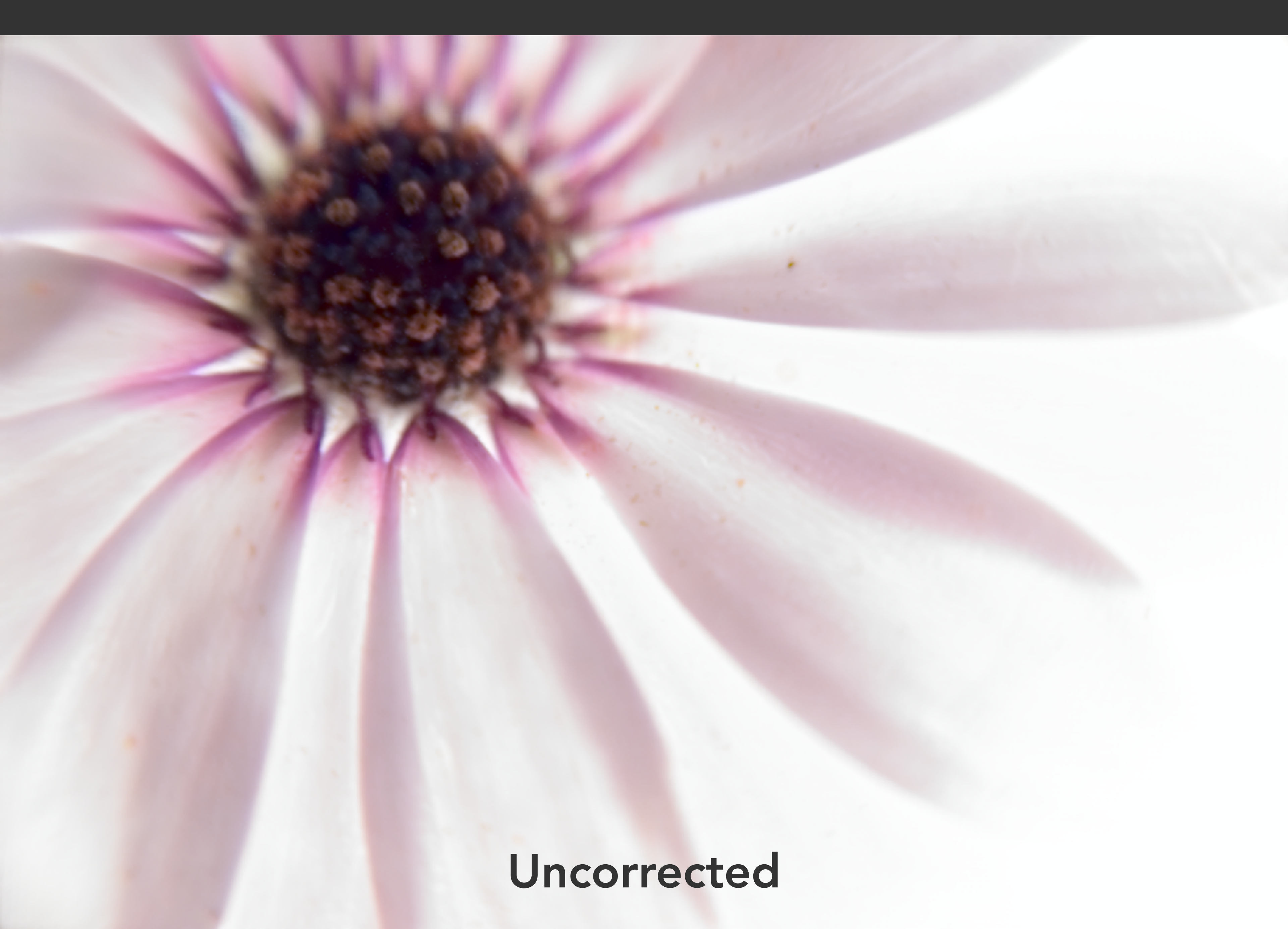




Uncorrected



Computationally corrected



Uncorrected



Computationally corrected

Things to Remember

4D light field: radiance along every ray

Light field camera

- Capture light field flowing into lens in every shot
- Light field sensor = microlens array in front of sensor

Computational refocusing

- Refocusing = reproject rays assuming new sensor depth
- Can think of this as shift-and-add of sub-aperture images

Computational lens aberration correction with light fields

- Correction = reproject rays assuming no aberrations

Art Competition #1 Results

Art Competition #1 – 3rd Place Winner



Ashley Zhang

Caption: Crescendo of hues / Scarlet flames dance and rejoice / No magenta here!

Approach (short version):

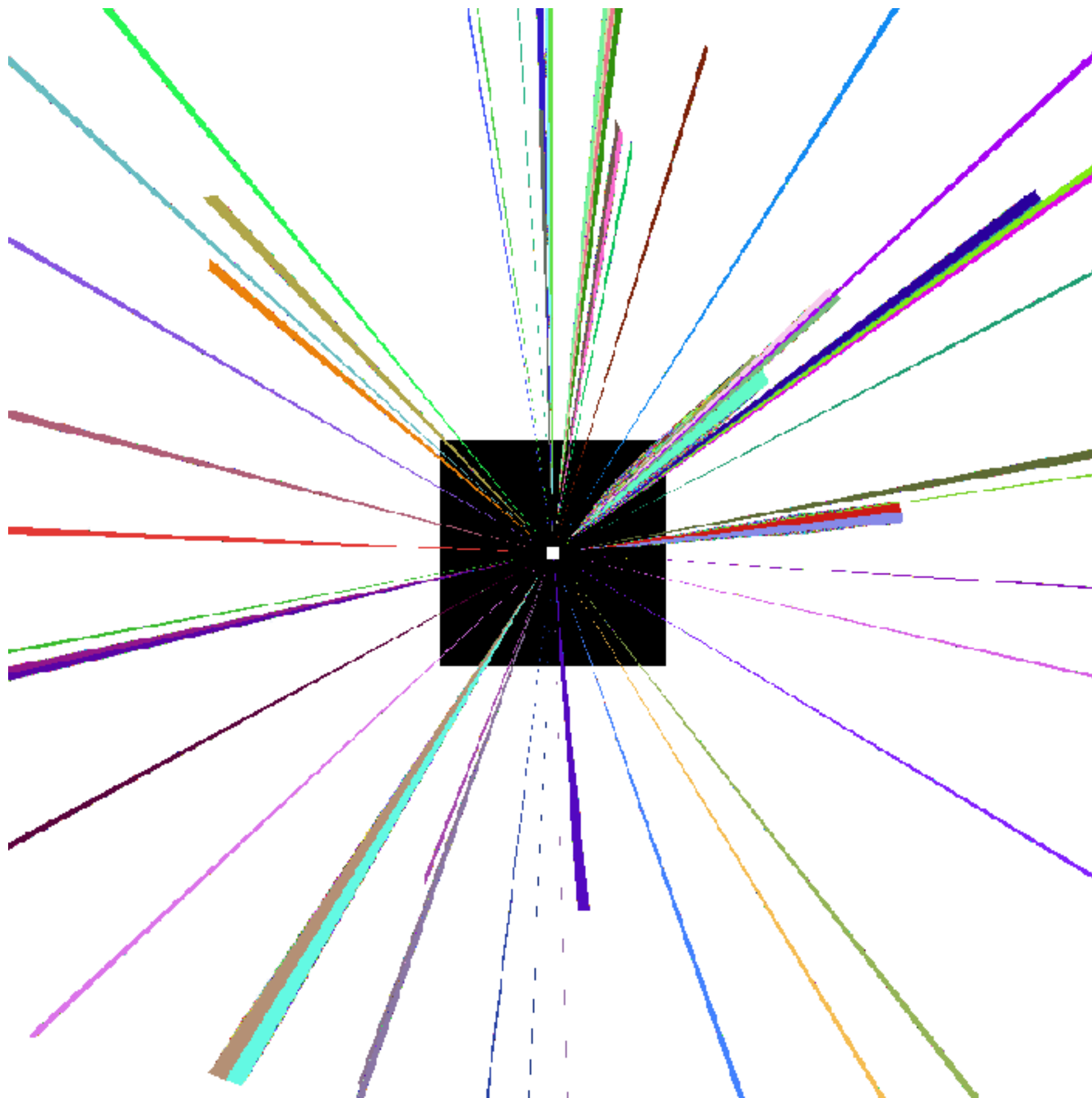
1. Create the SVG in Adobe Illustrator
2. Once the SVG has been exported from Illustrator, further processing is necessary in a text editor.
3. Save. The SVG is now ready to be displayed by the rasterizer!

Art Competition #1 – 2nd Place Winner

Tianqi Yang

Caption: It is the best of light. It is the worst of light. --Space light

Approach: I write a python to generate the code. It generates numbers of "lights" and rotates and scales them randomly. I repeatedly generate it from a small number of lights to large and put all screenshots as a GIF by an online animated GIF Maker.



Art Competition #1 – 1st Place Winner

Jamie Ip

Caption: .∴*∴. ☆. ∴*∴. °. ∴ °. ∴°?

Approach: I created this GIF by downloading a picture of Oski and Nyancat, then drawing and coloring triangles over them with Adobe Illustrator. I repeated this 6 times to create 6 different frames. I exported each frame as an svg and used RegEx to transform them into a readable format for the project. I then rendered each frame at a resolution of 800x800 with a sample rate of 16 and stitched them together.

