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

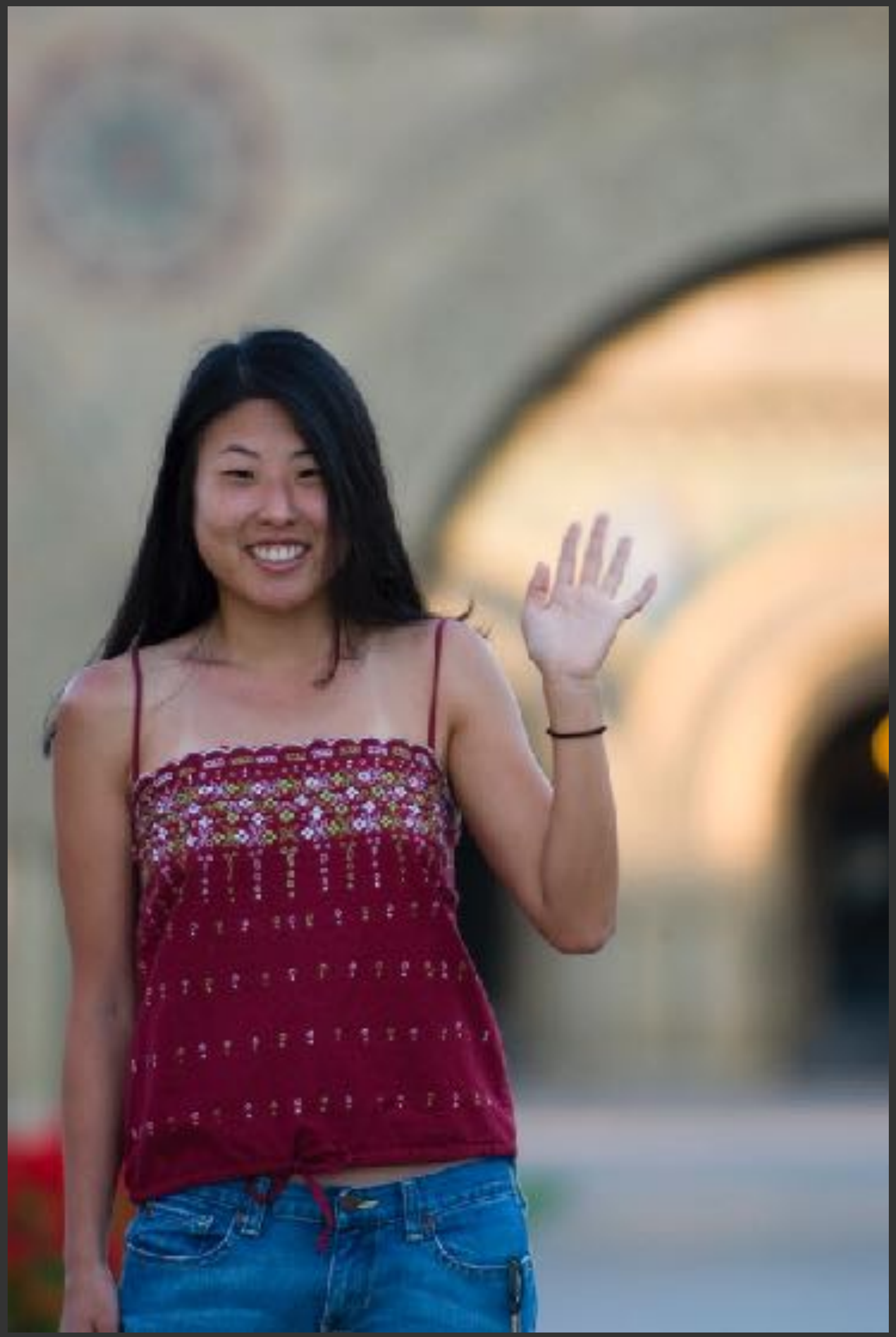
Three Focus-Related Problems in 2D Photography

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



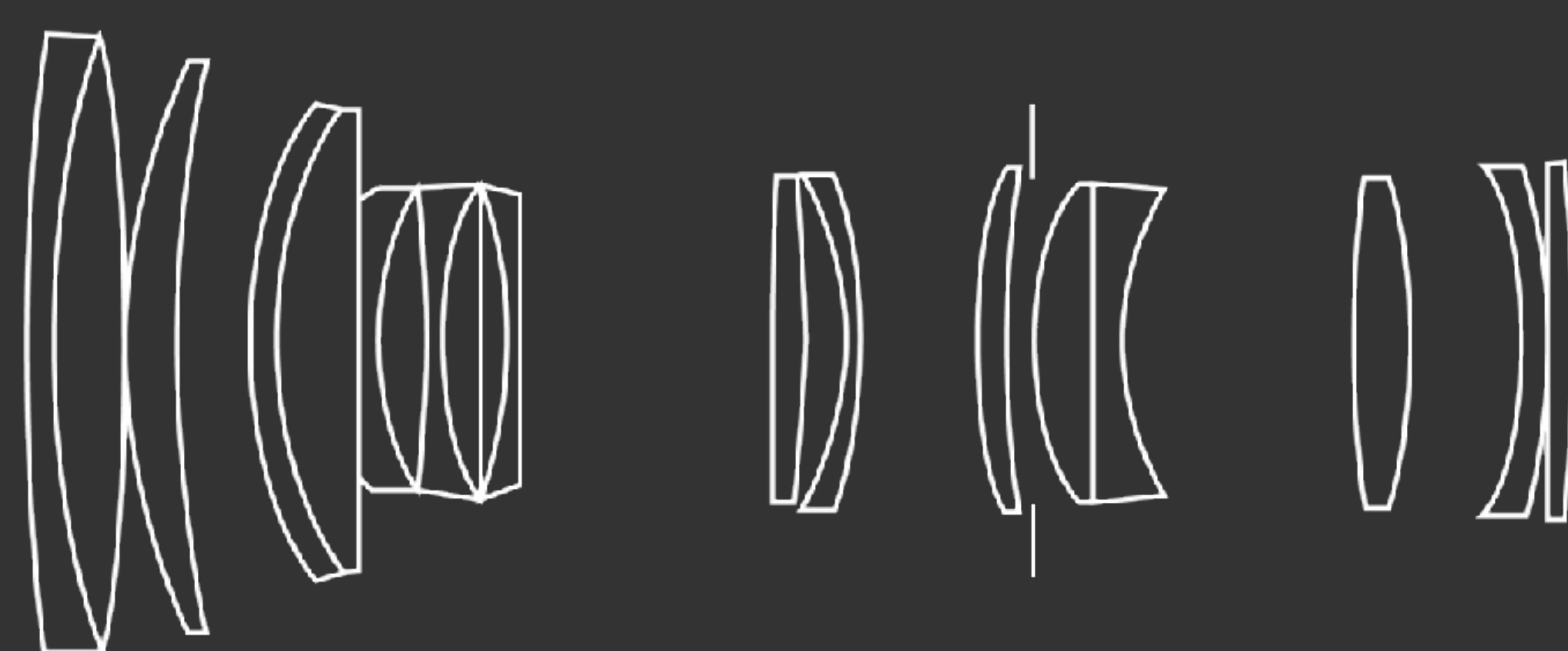
f / 4
0.01 sec

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

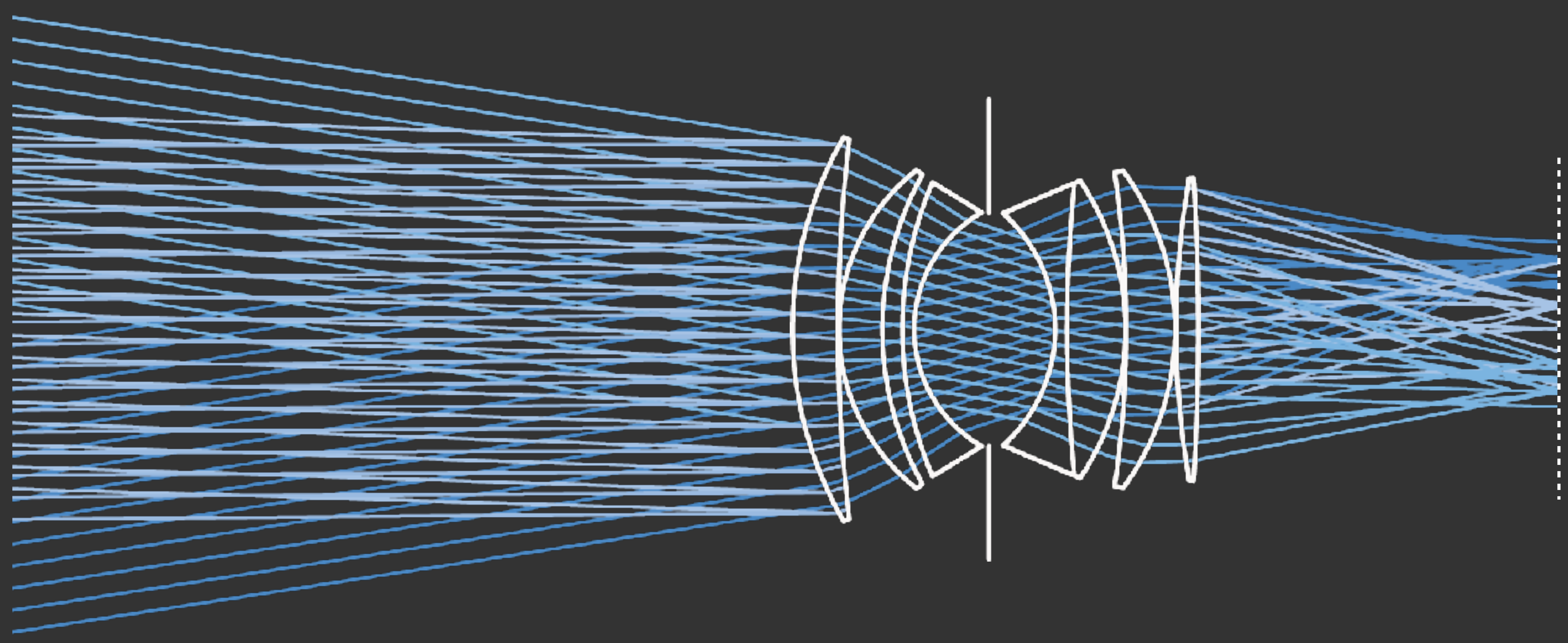
Light Field Photographs

Lens Designed For Light Field Computation

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

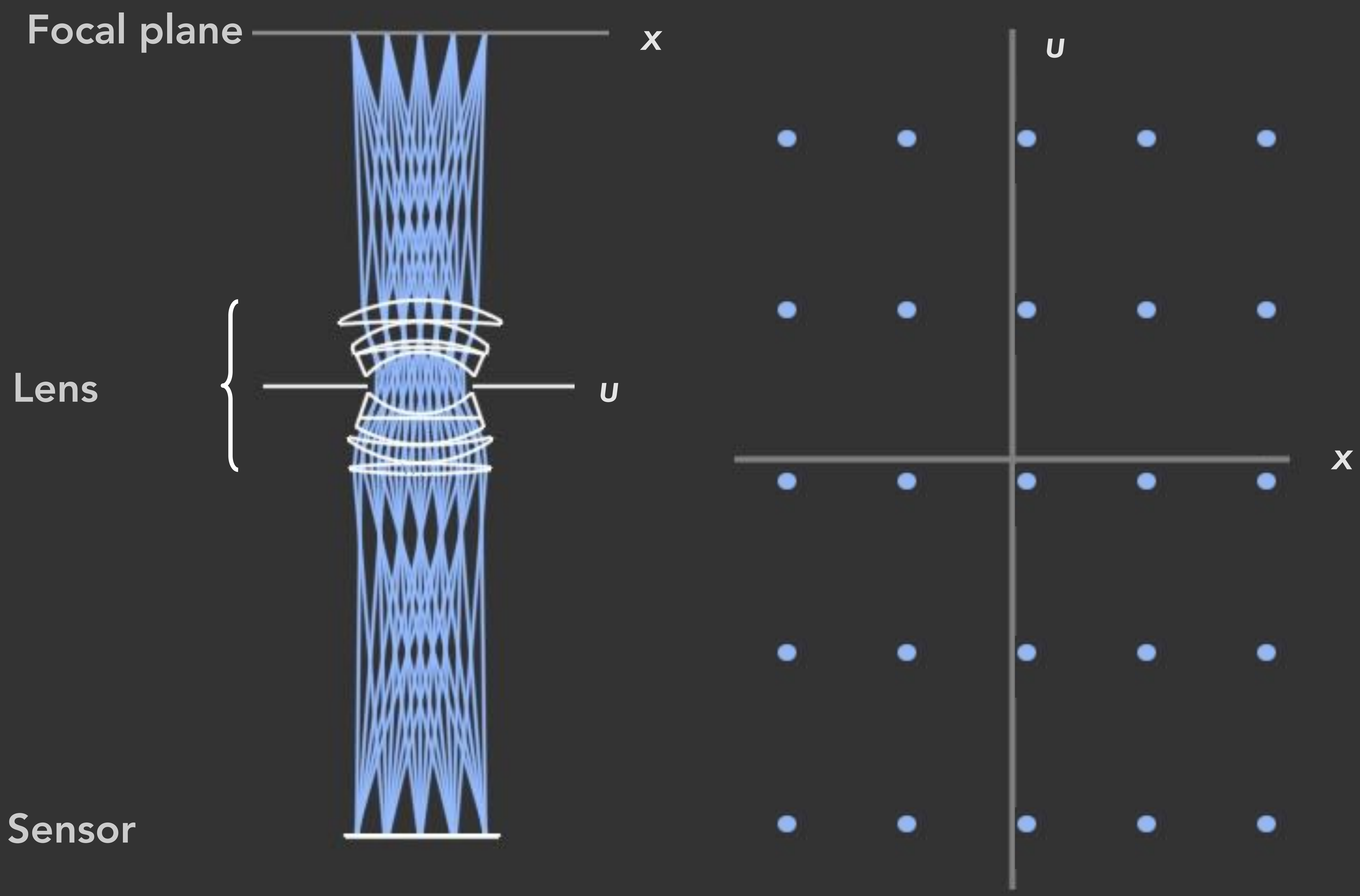
2D Photographs vs
4D Light Fields

2D Photographs vs 4D Light Fields

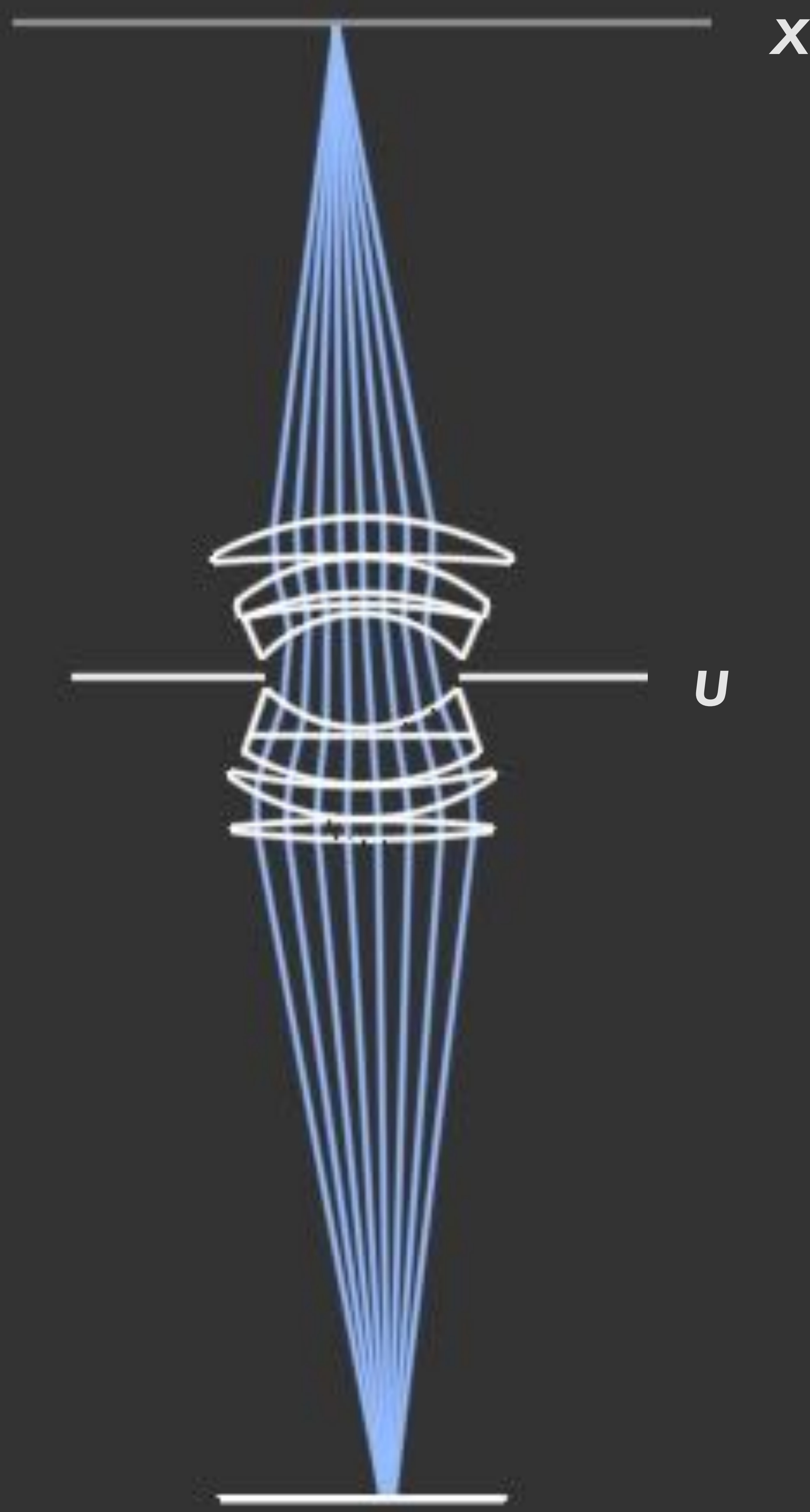


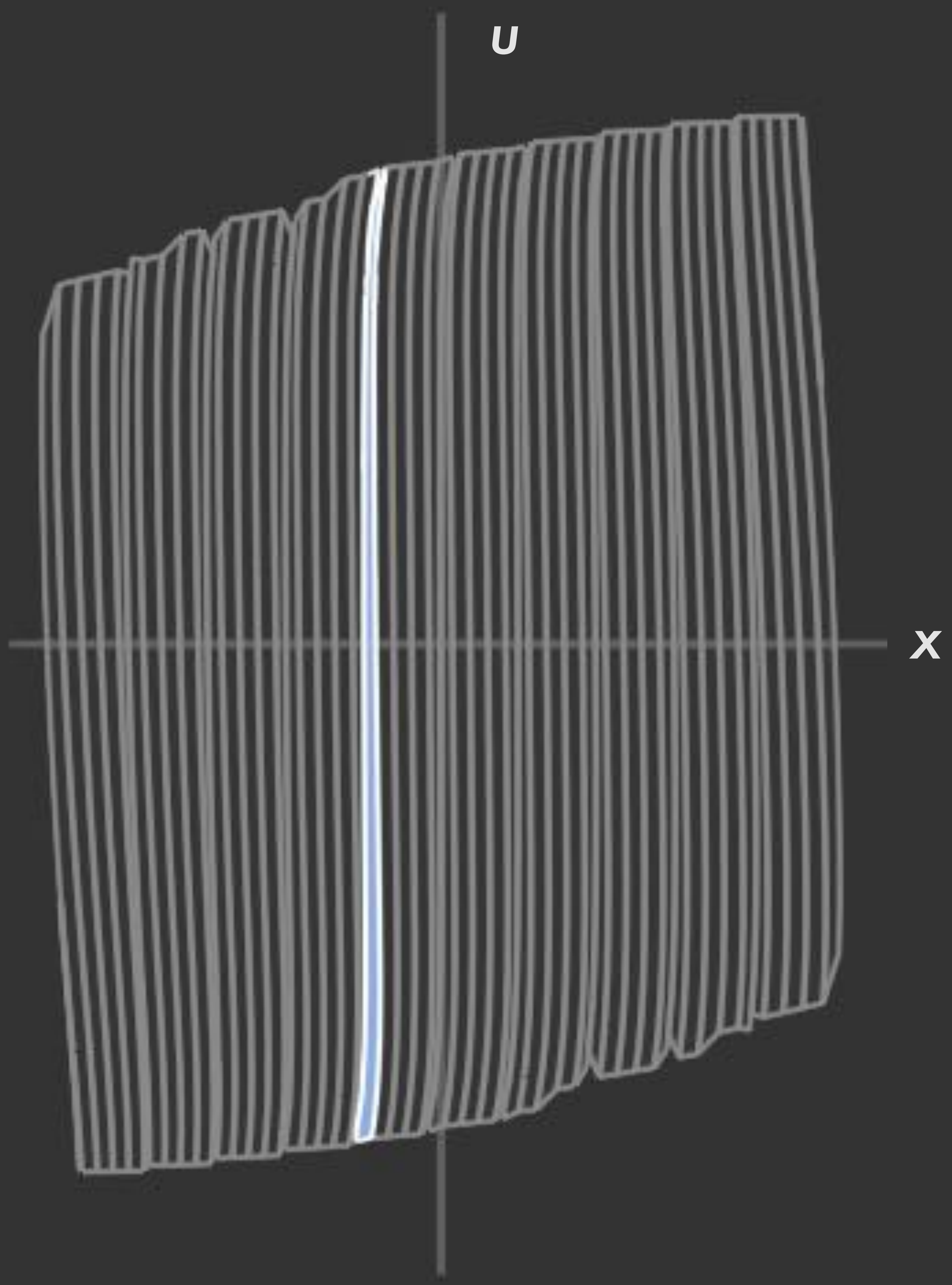
Photograph = irradiance at every pixel on plane (2D)
Light field = radiance flowing along every ray (4D)

The 4D Light Field Flowing Into A Camera

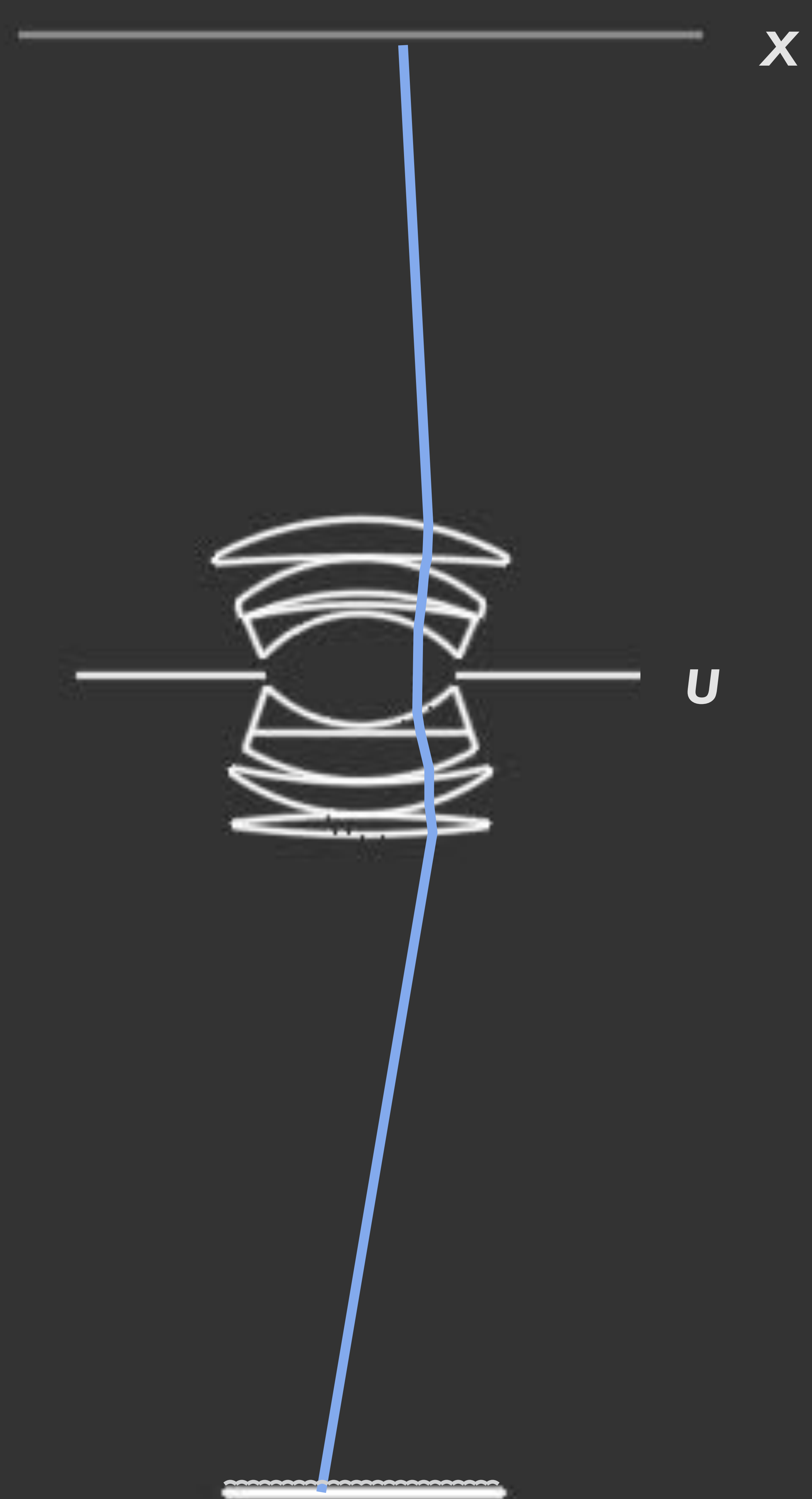


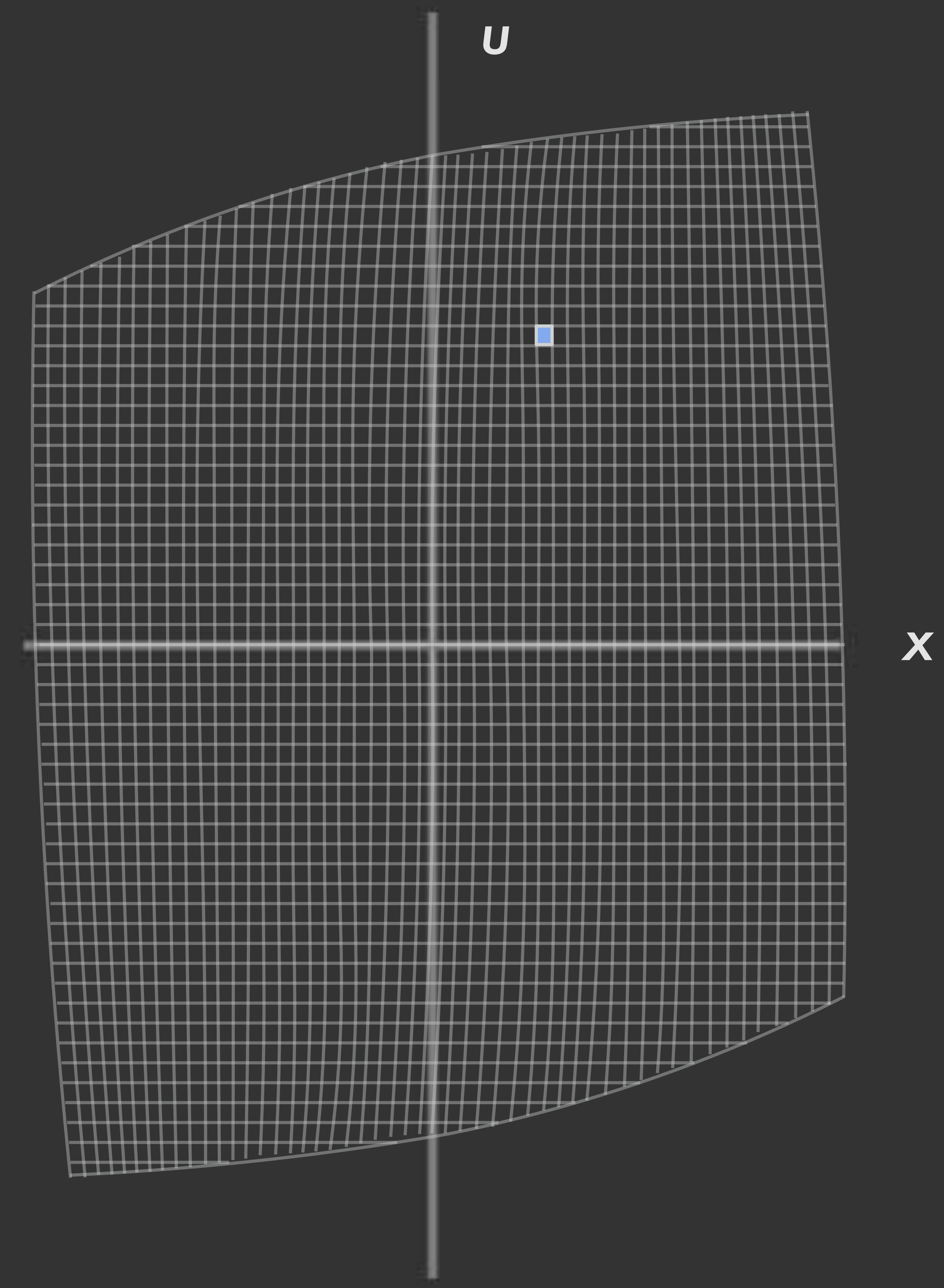
What Does a 2D Photograph Record?





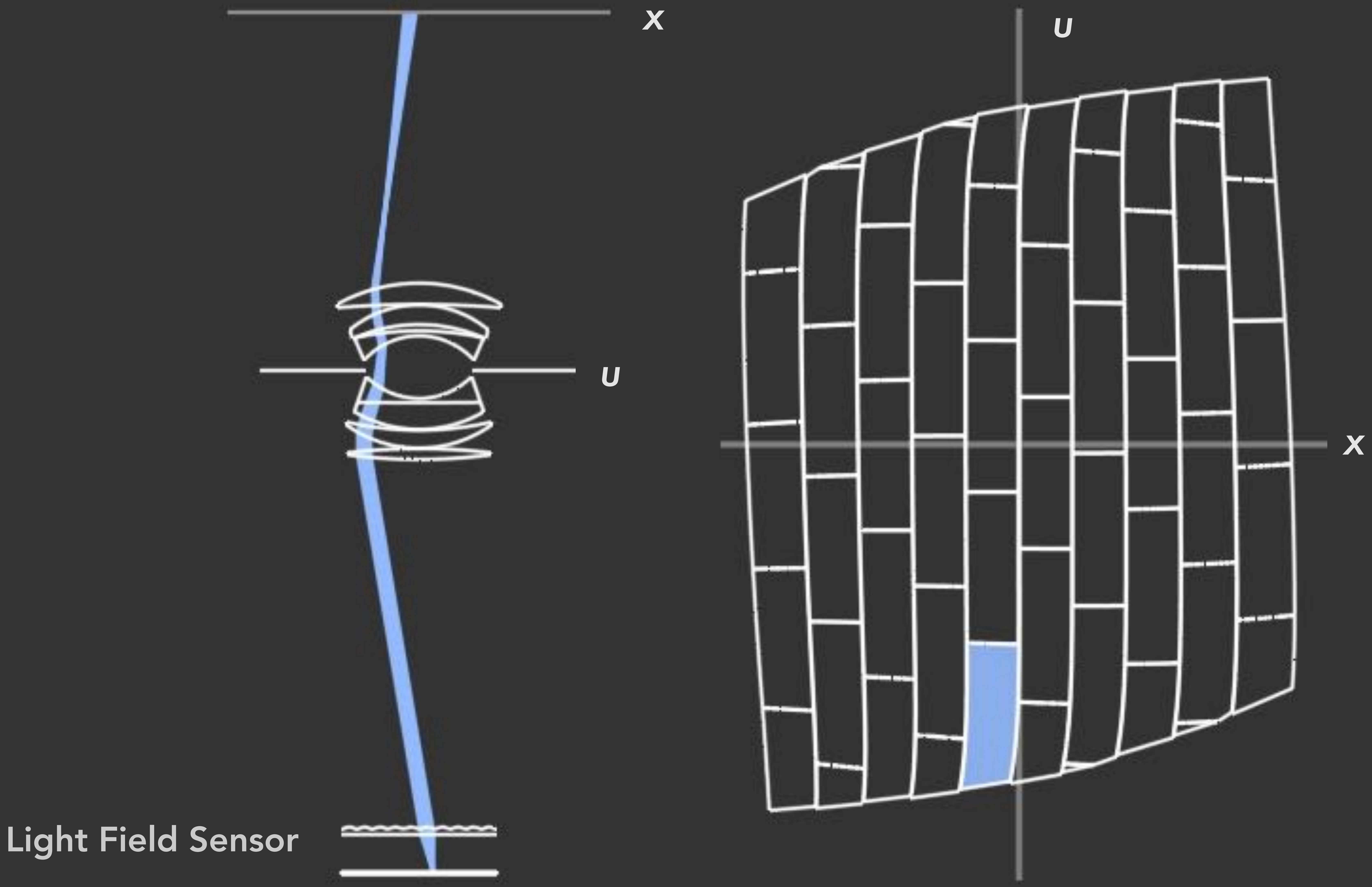
Imagine Recording the Entire 4D Light Field



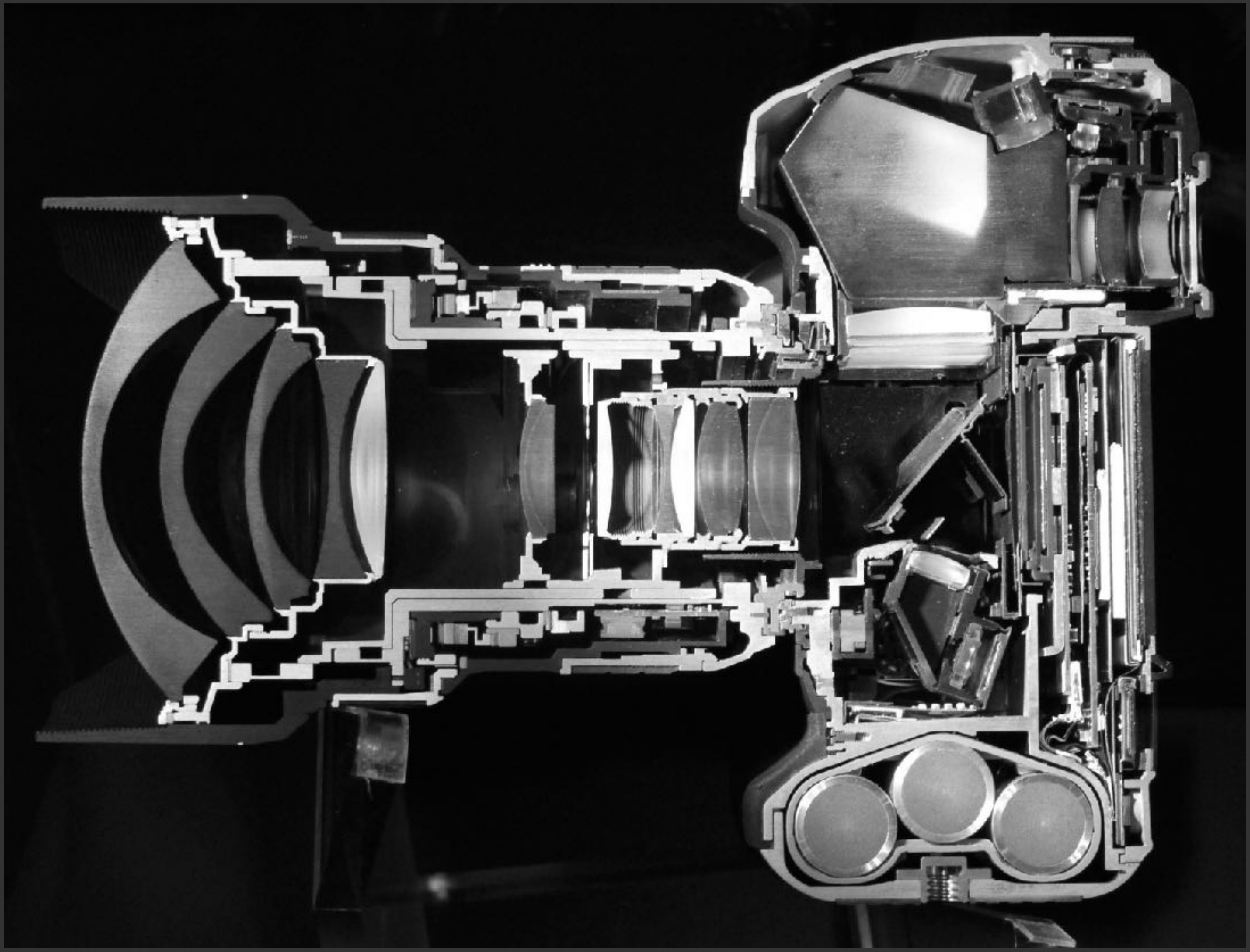


Capturing Light Fields

A Plenoptic Camera Samples The Light Field

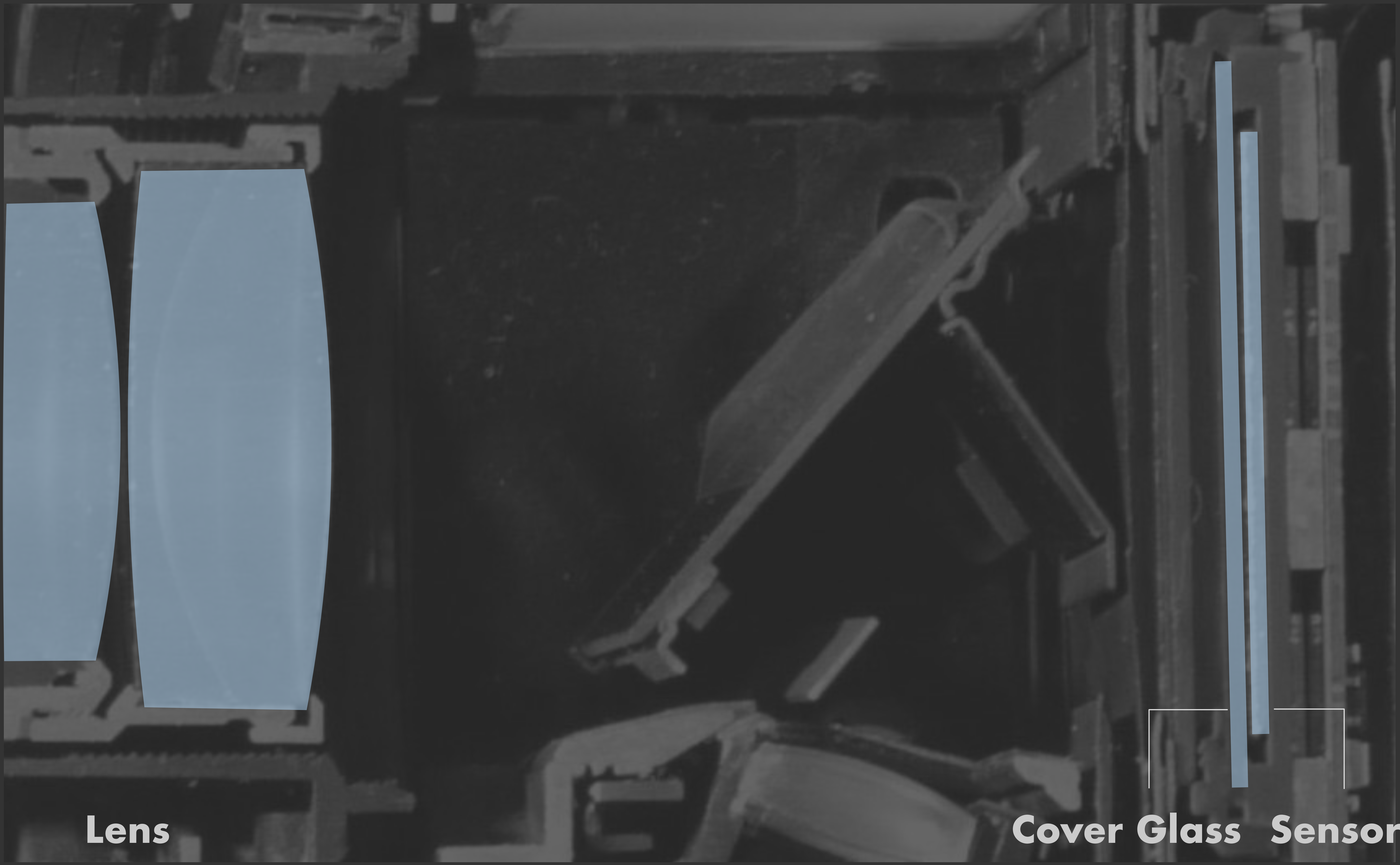


Where Microlenses Go Inside Camera

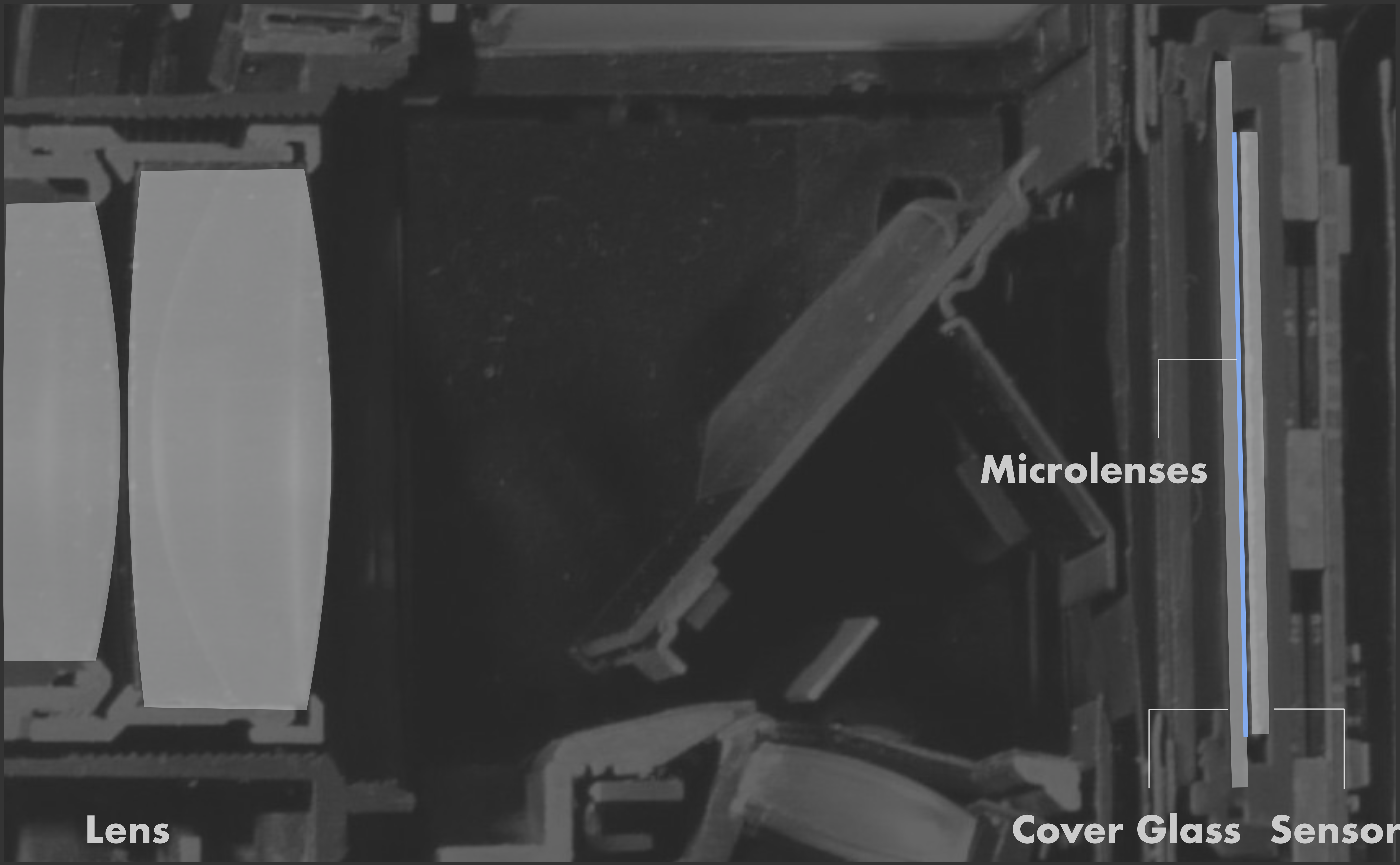


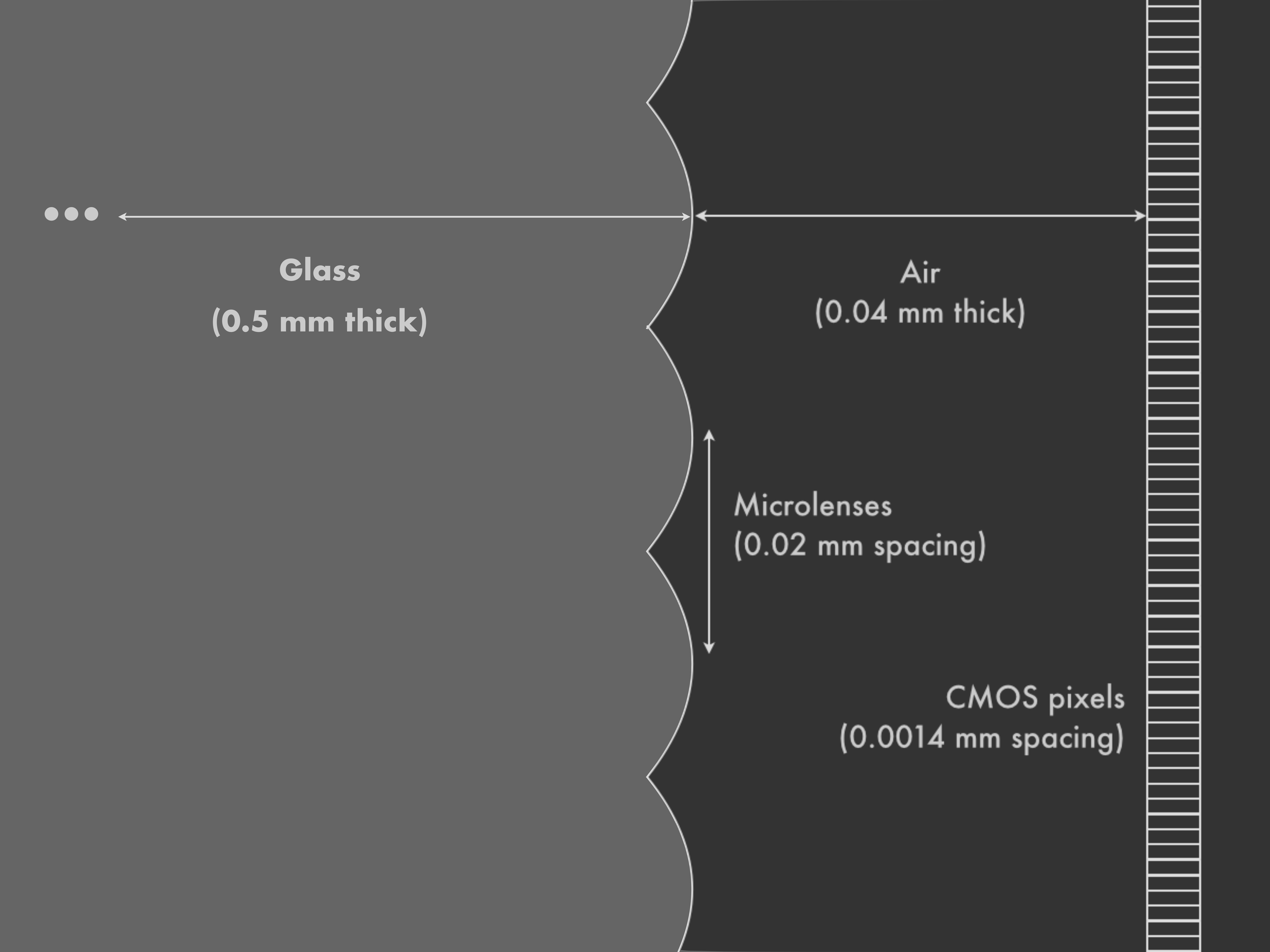
Cross-section of Nikon D3, 14-24mm F/2.8 lens

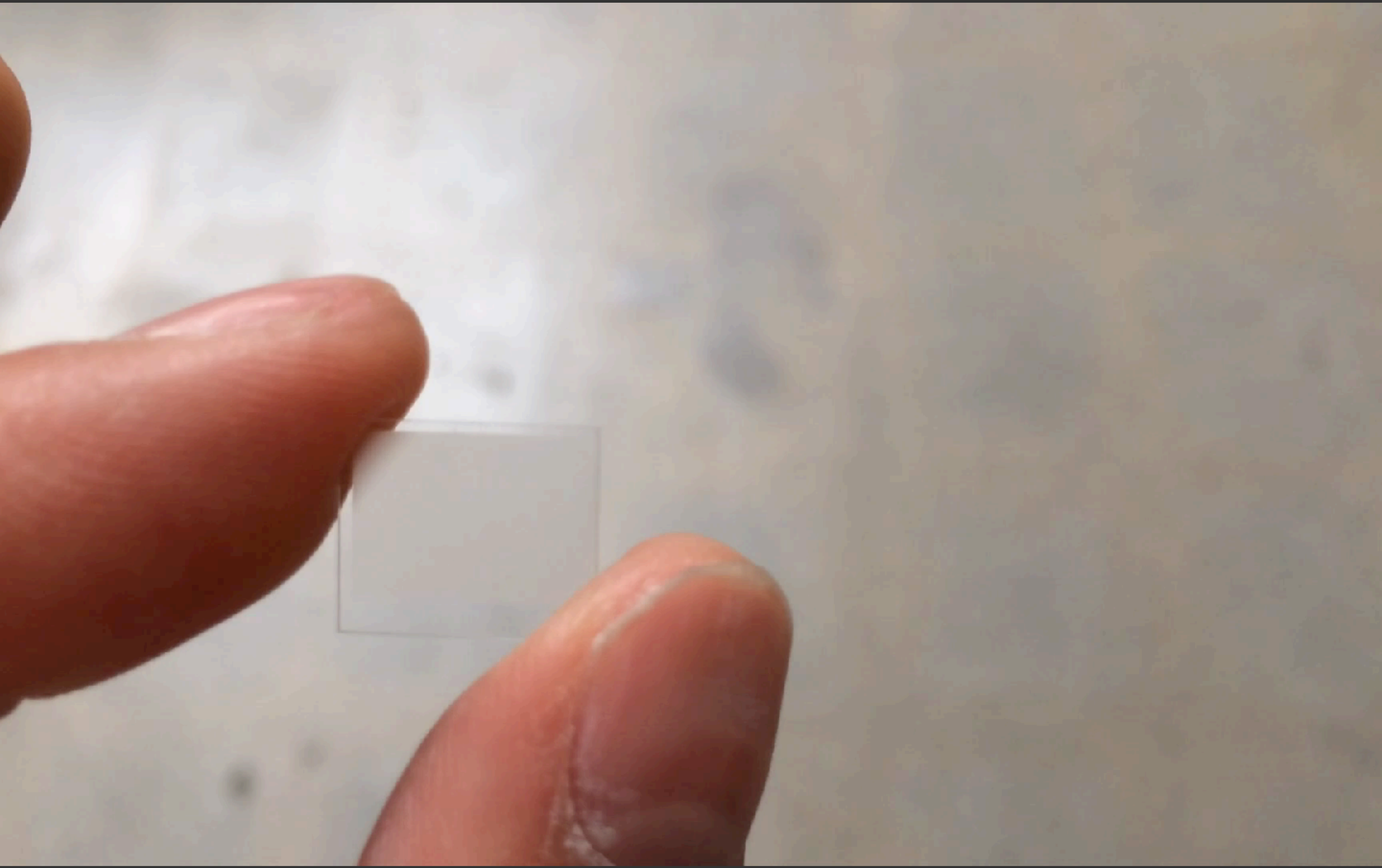
Where Microlenses Go Inside Camera

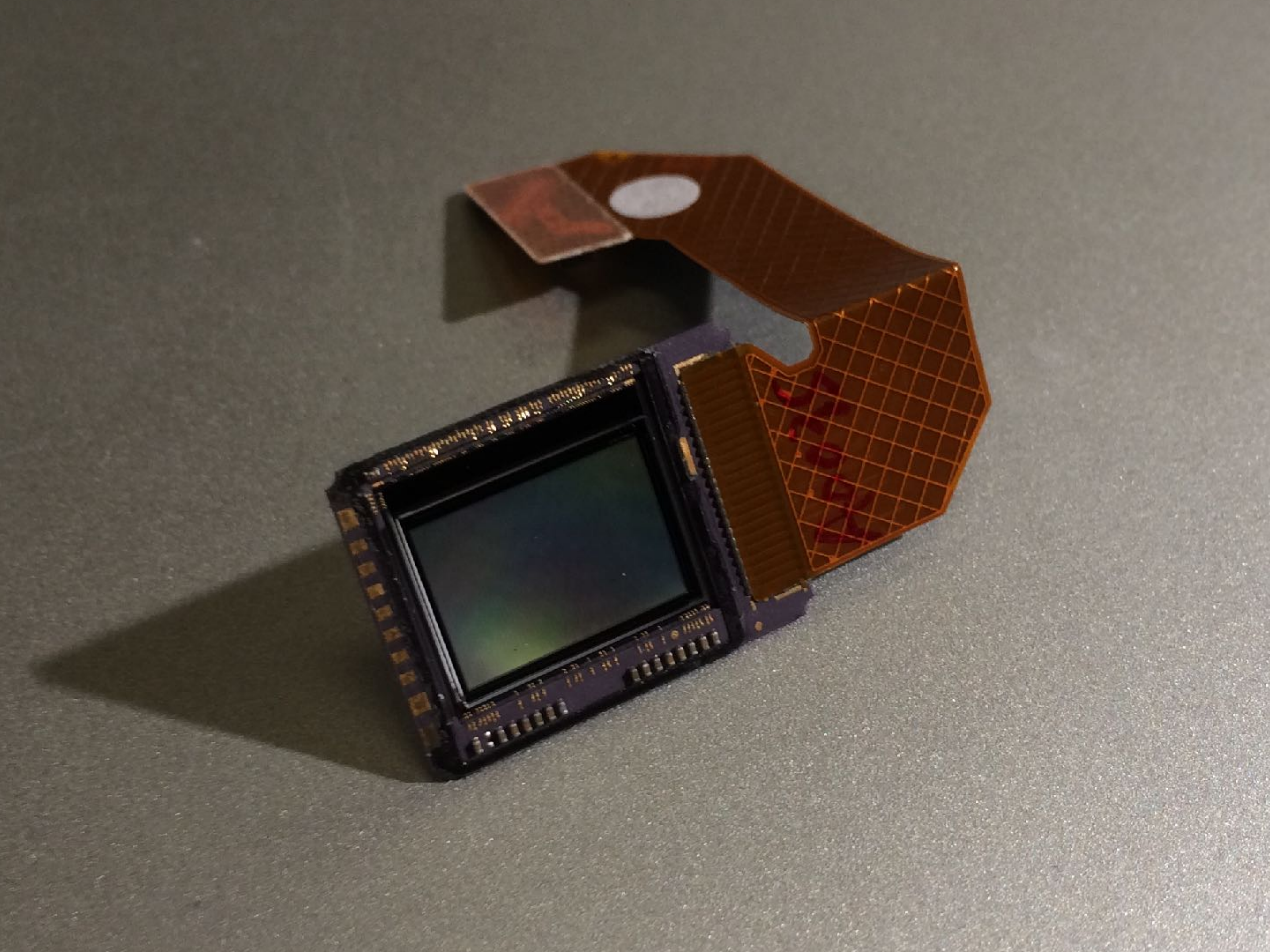


Where Microlenses Go Inside Camera




Glass
(0.5 mm thick)
Air
(0.04 mm thick)
Microlenses
(0.02 mm spacing)
CMOS pixels
(0.0014 mm spacing)





Raw Data From Light Field Sensor

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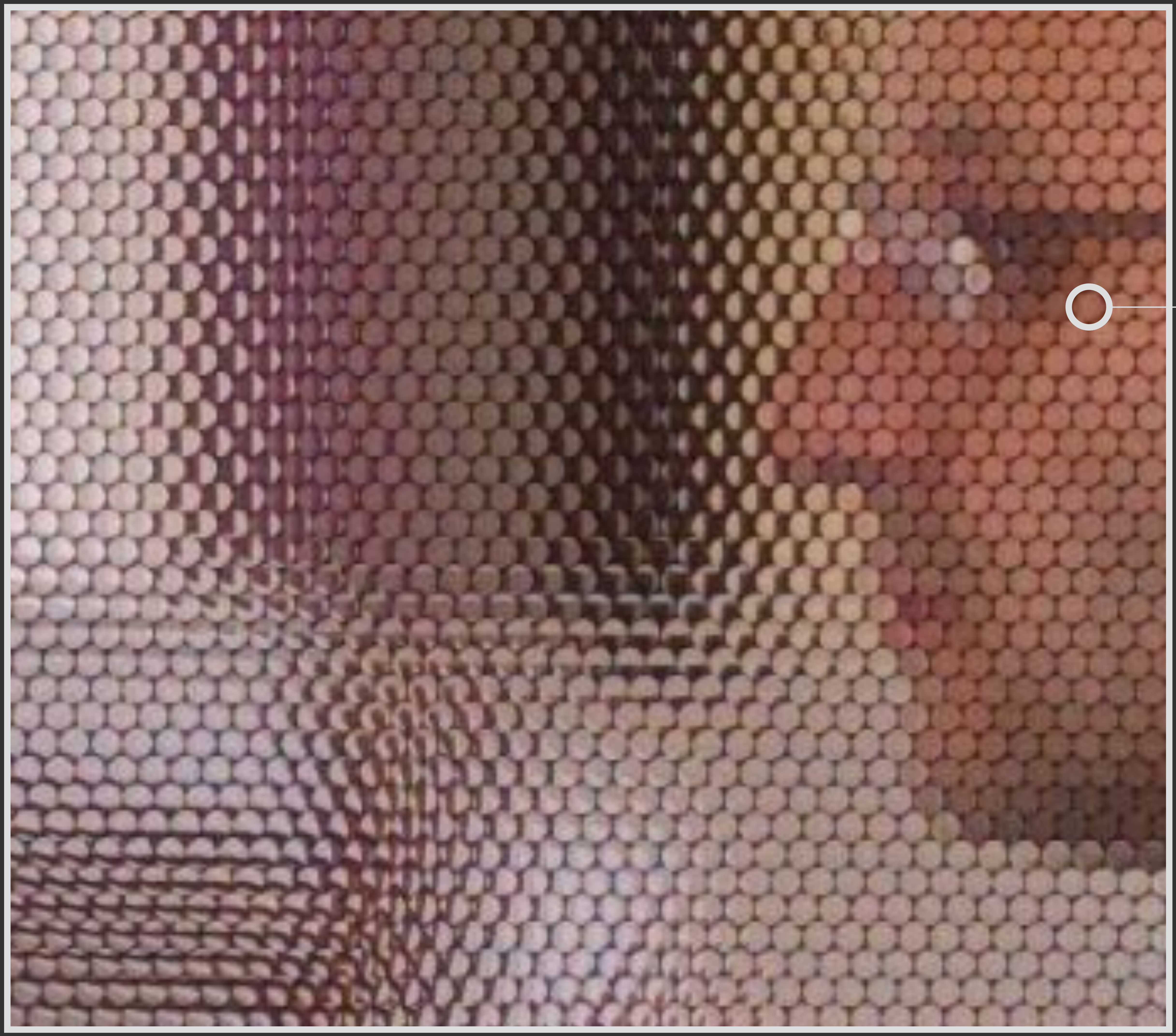
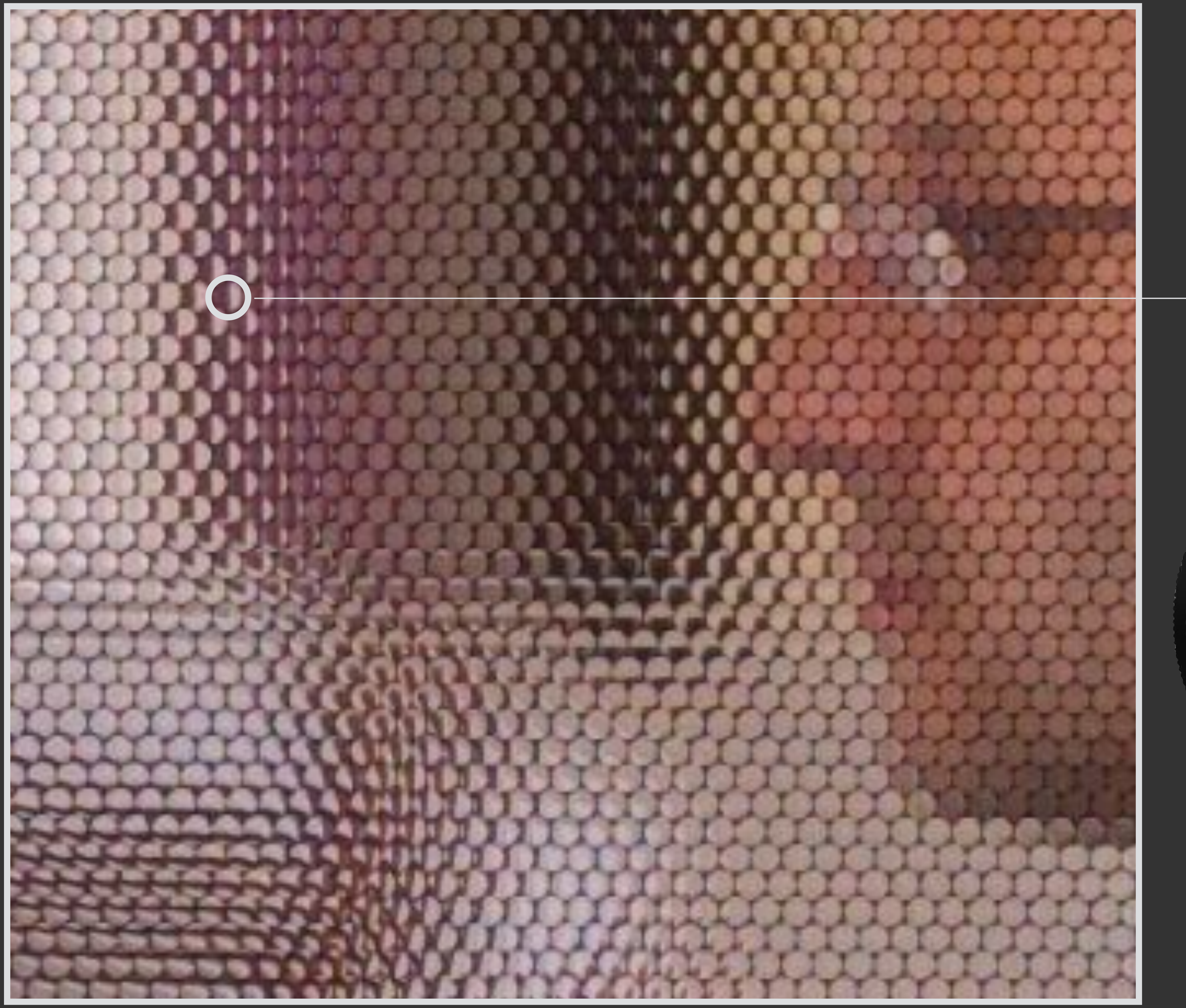
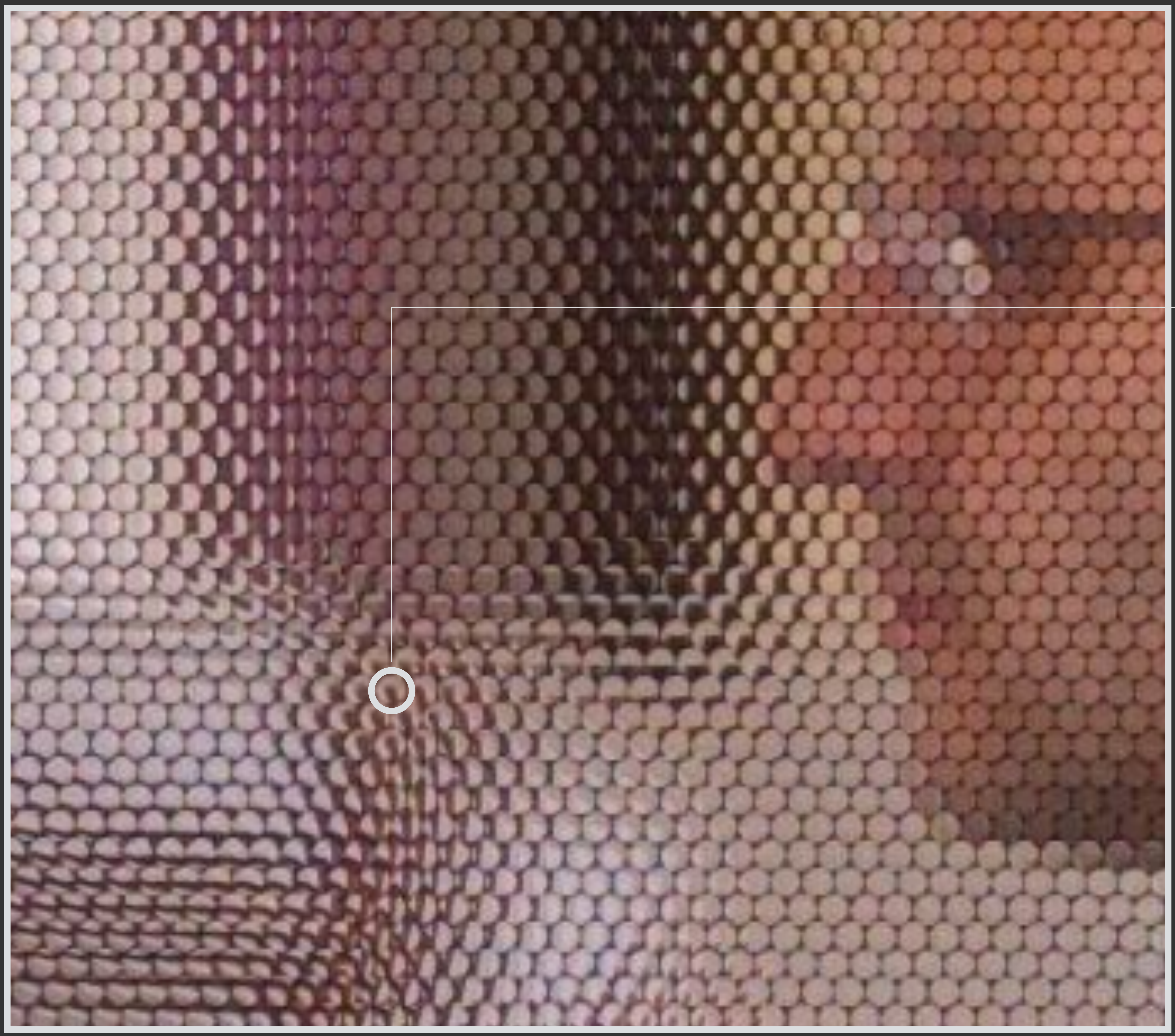


Raw Data From Light Field Sensor



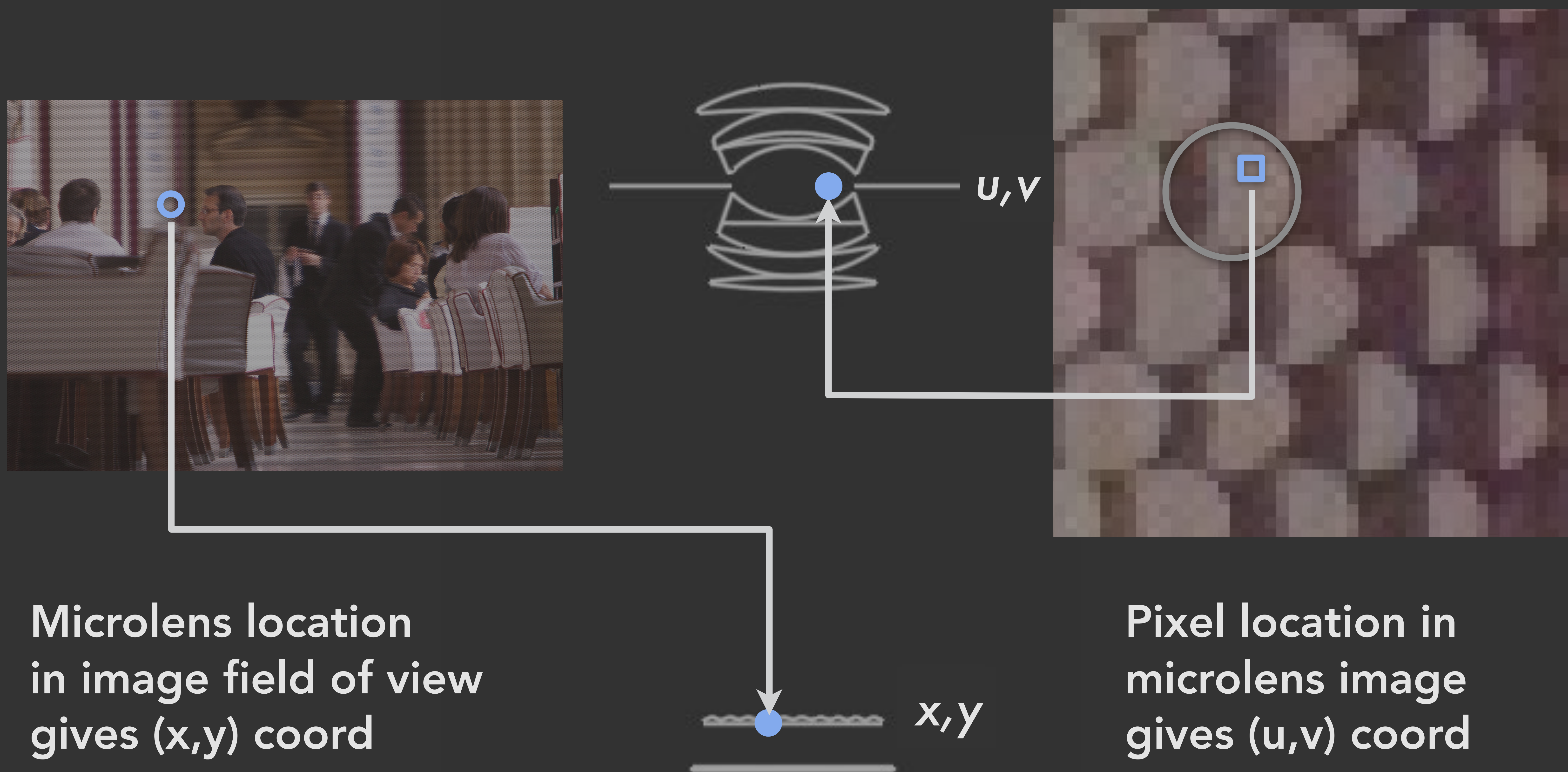
Raw Data From Light Field Sensor



One disk image

Raw Data From Light Field Sensor

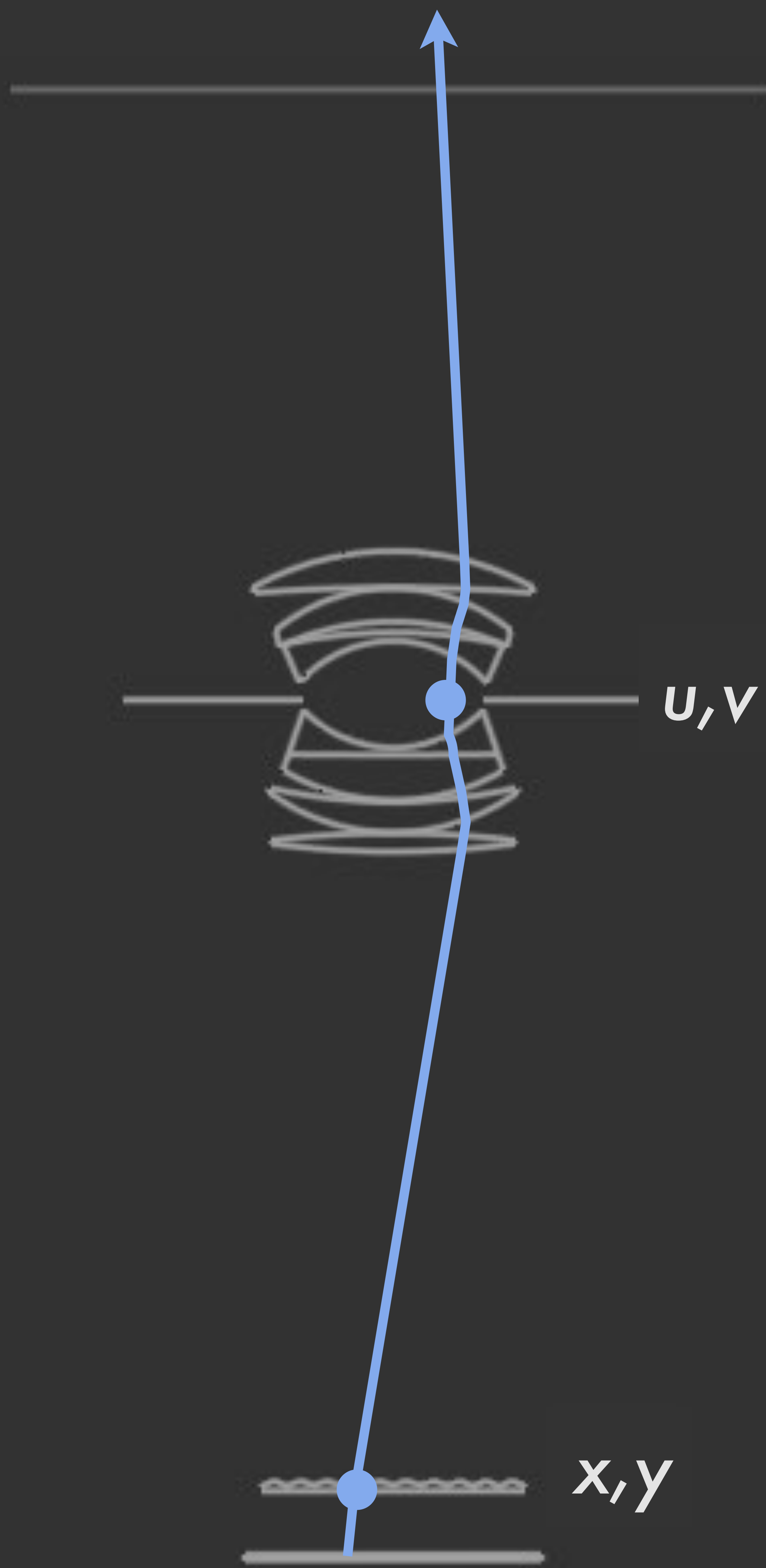
Mapping Sensor Pixels to (x,y,u,v) Rays

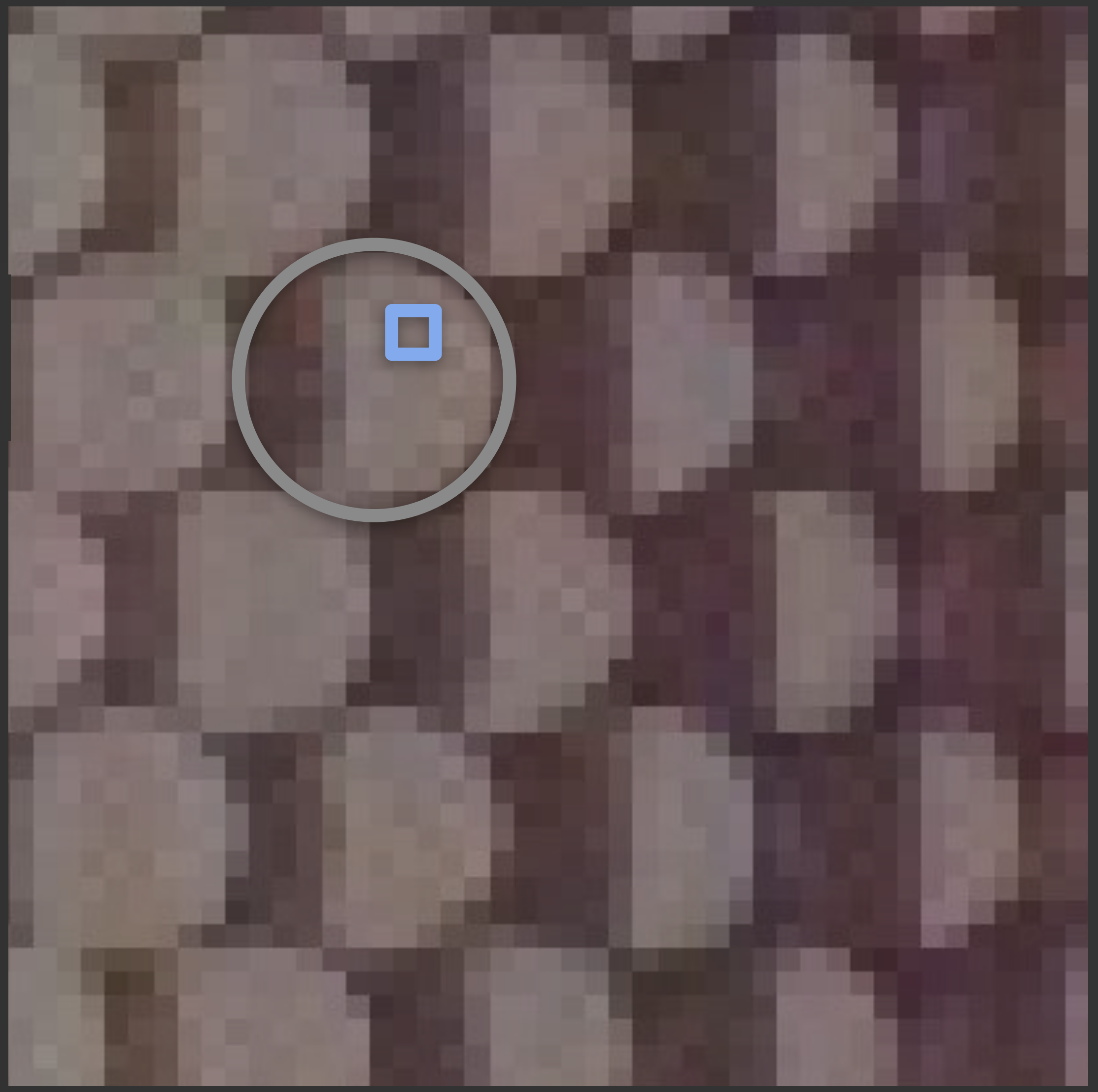


Microlens location in image field of view gives (x,y) coord

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

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



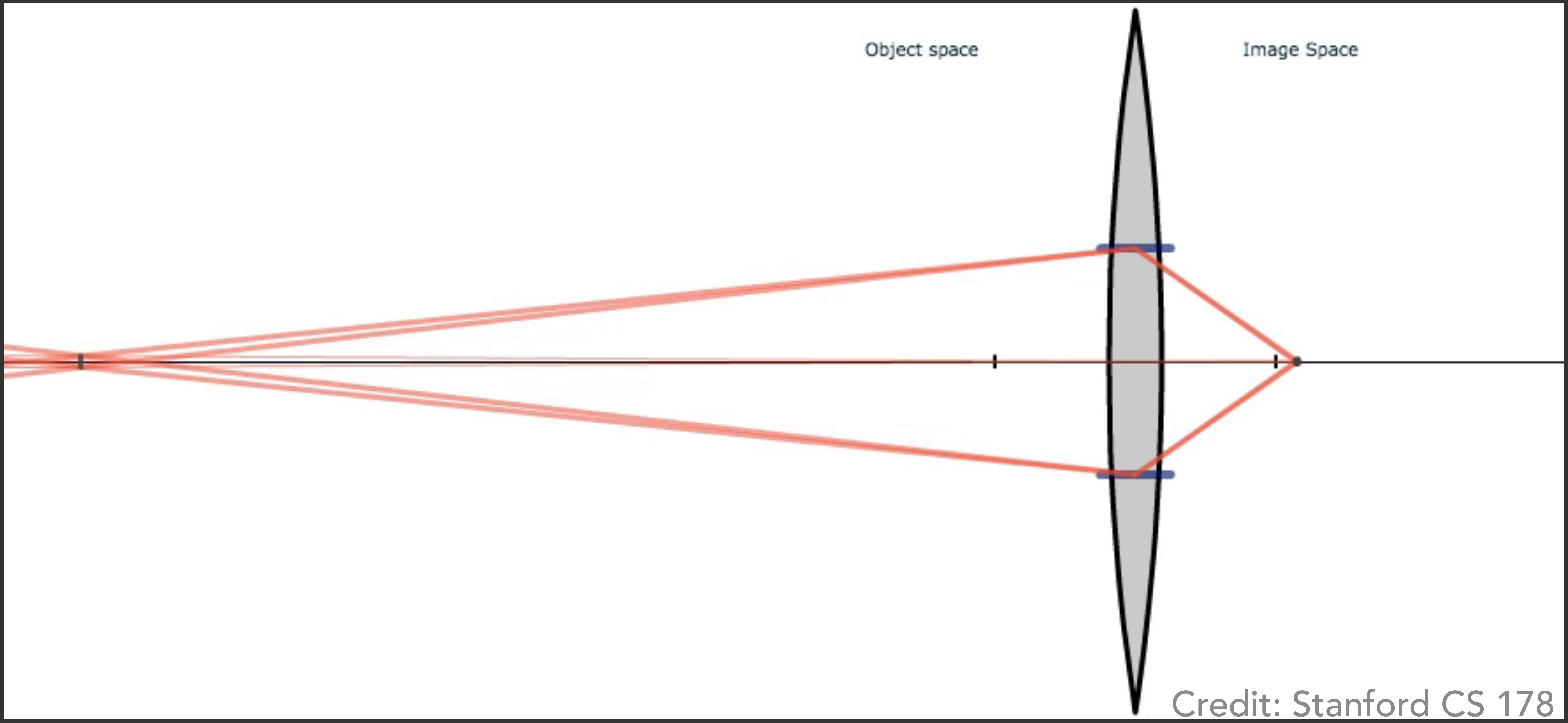


Microlens location in image field of view gives (x,y) coord

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

How Does Computational Refocusing Work?

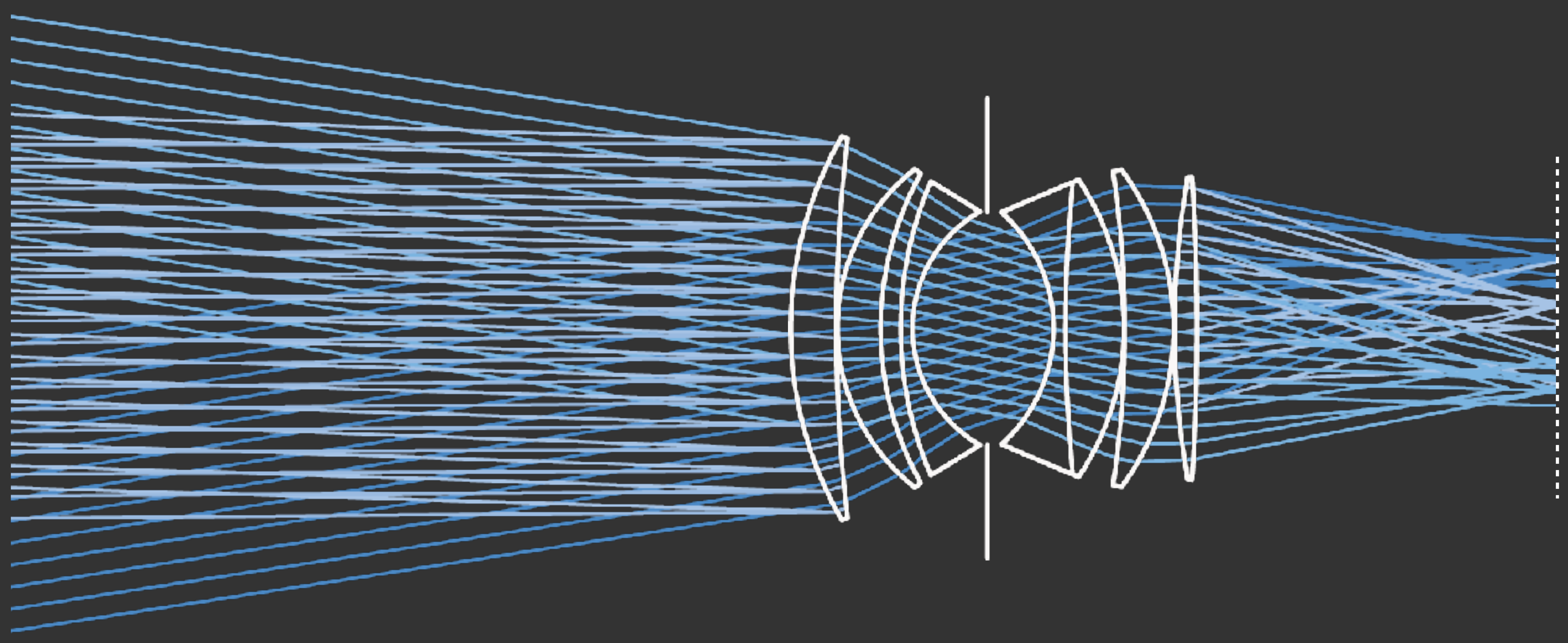
Recall: How Physical Focusing Works



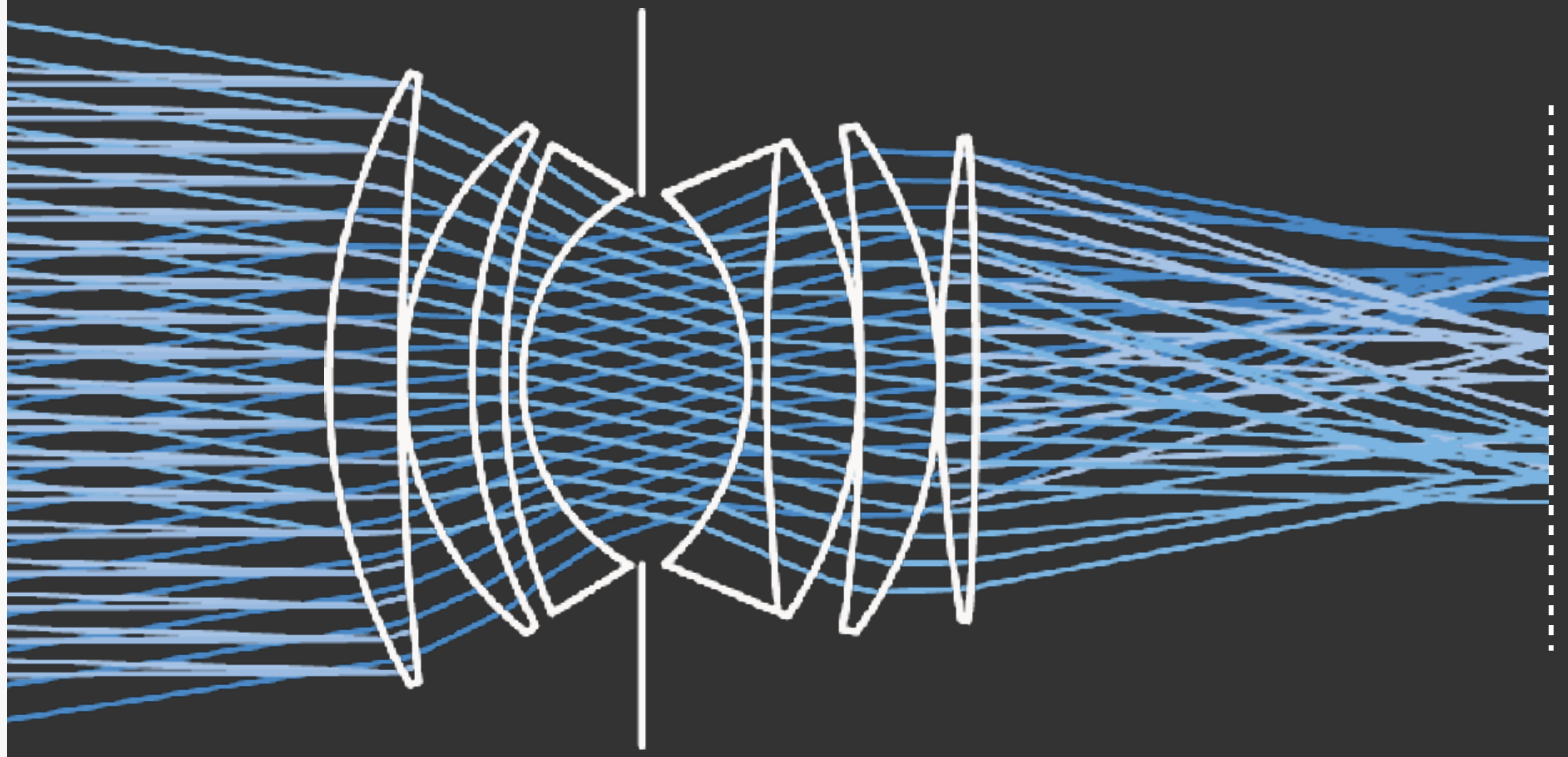
Sensor / lens gap determines plane of physical focus.

Computational Refocusing

Computational Refocusing

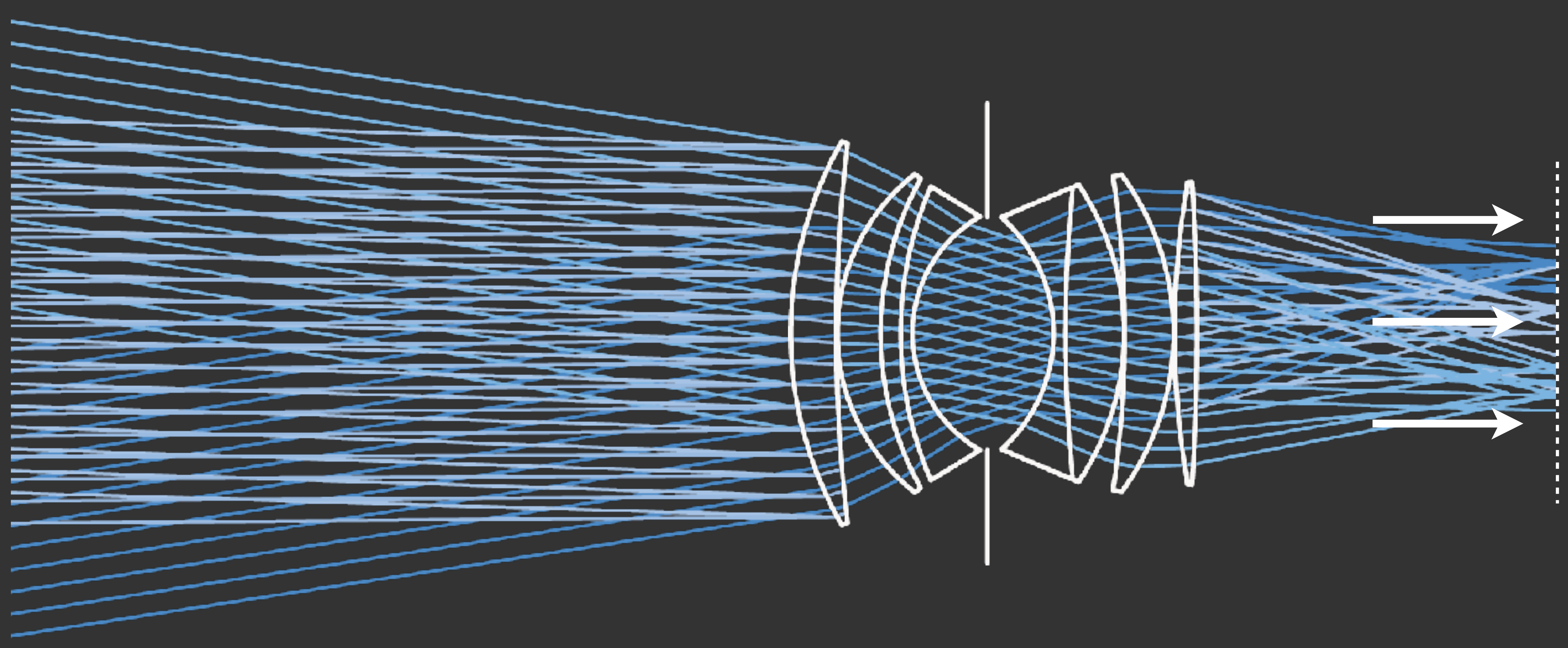


Computational Refocusing

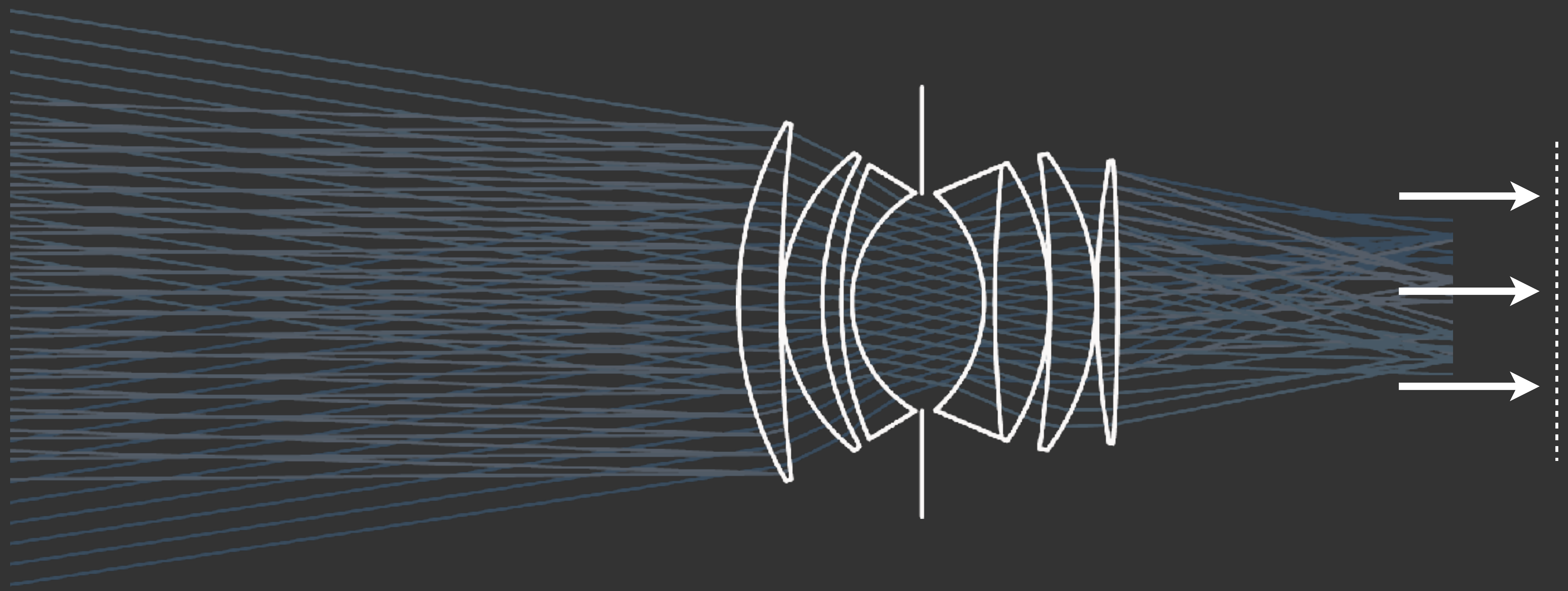


← focus far

Computational Refocusing

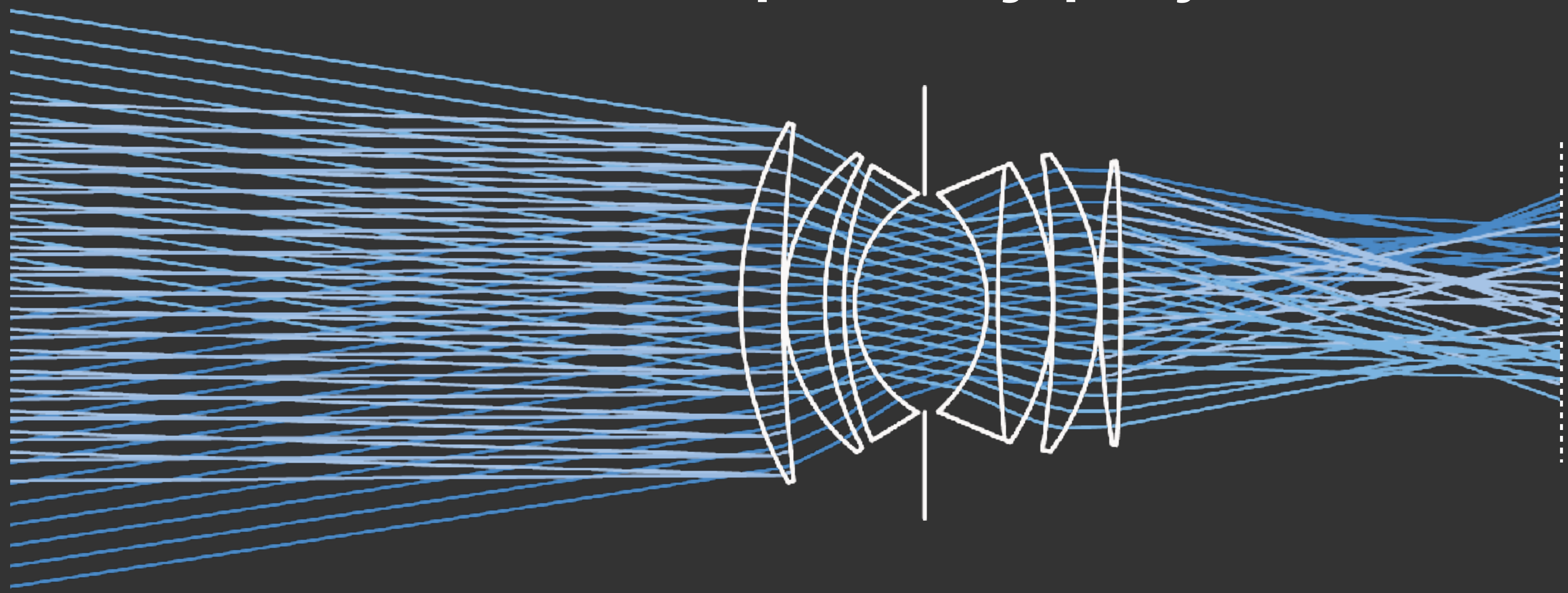


Computational Refocusing

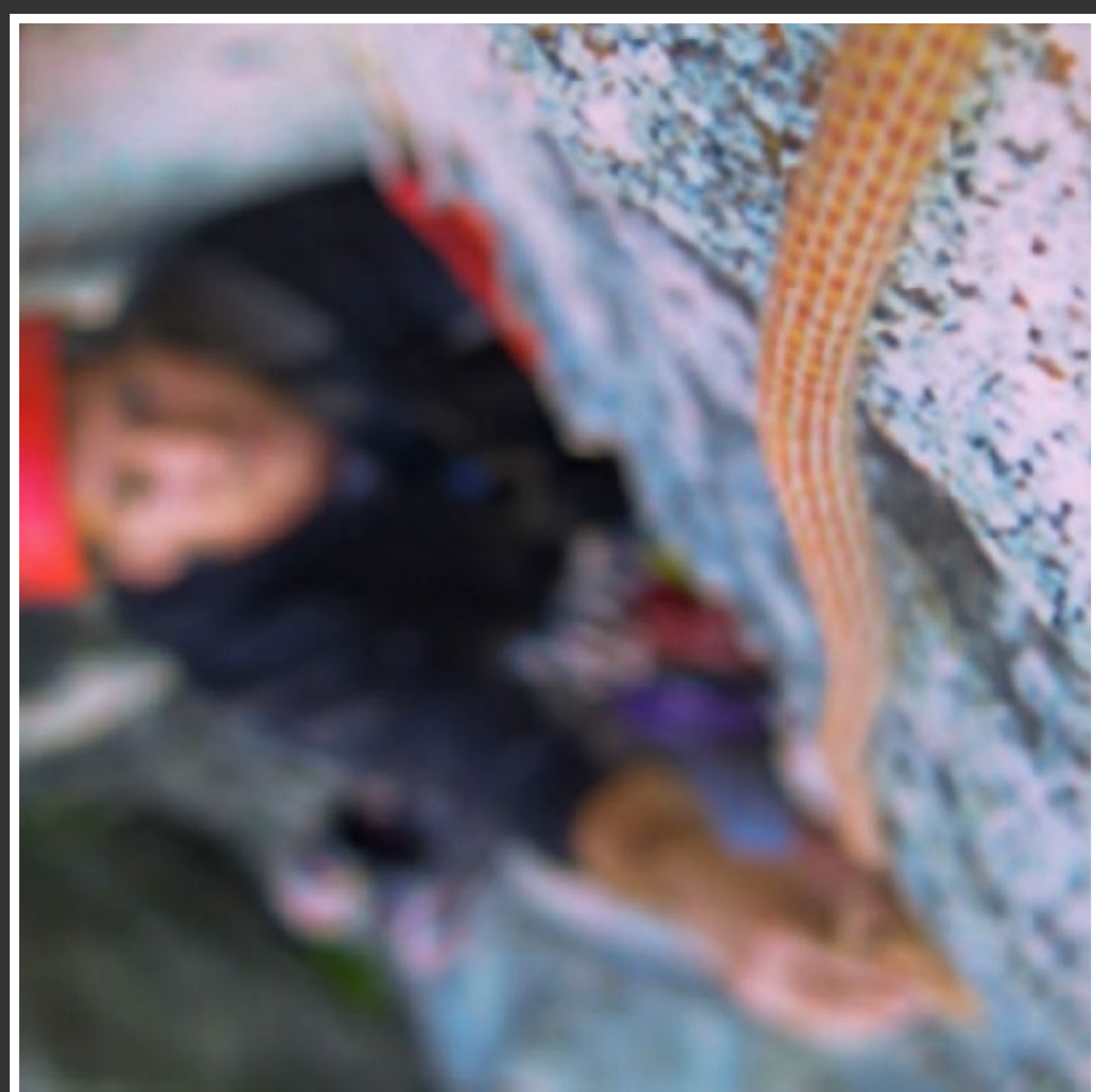


Computational Refocusing

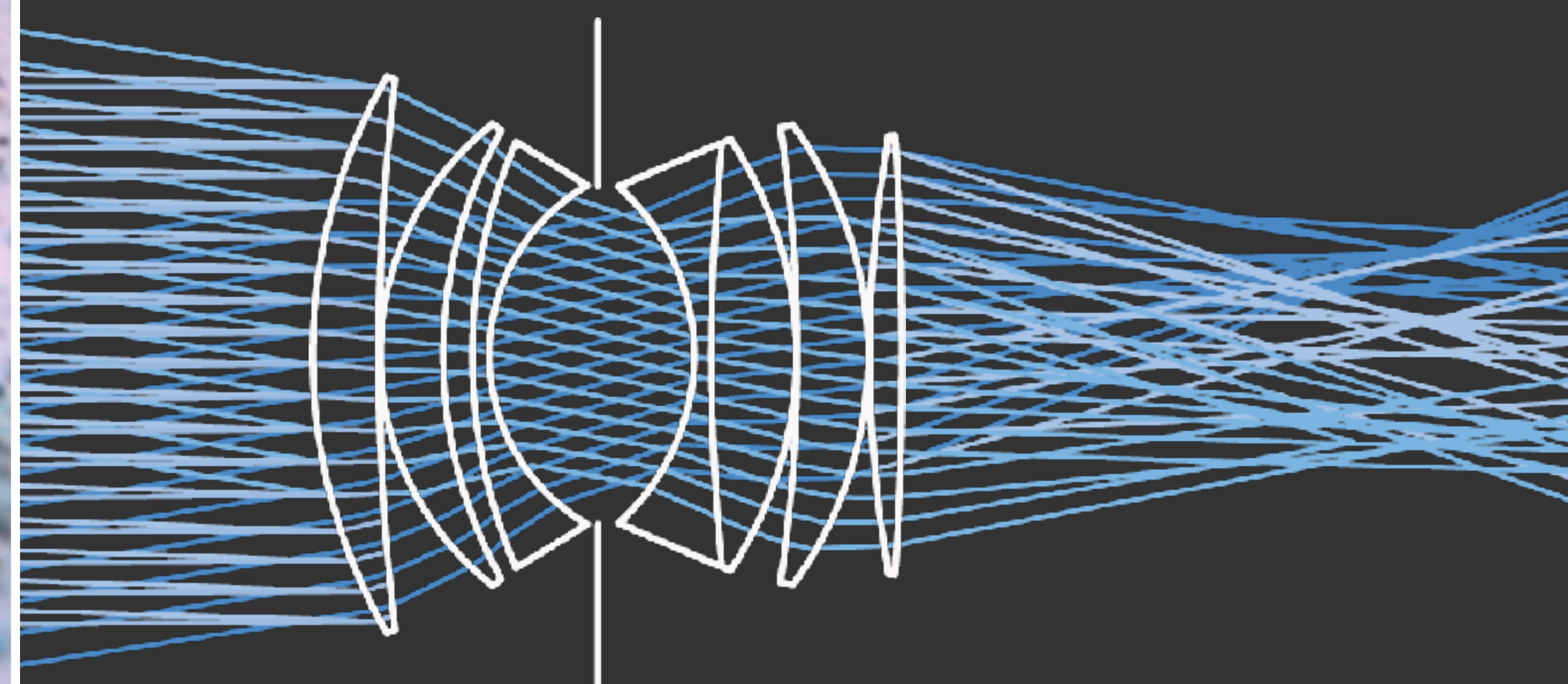
compute ray projection



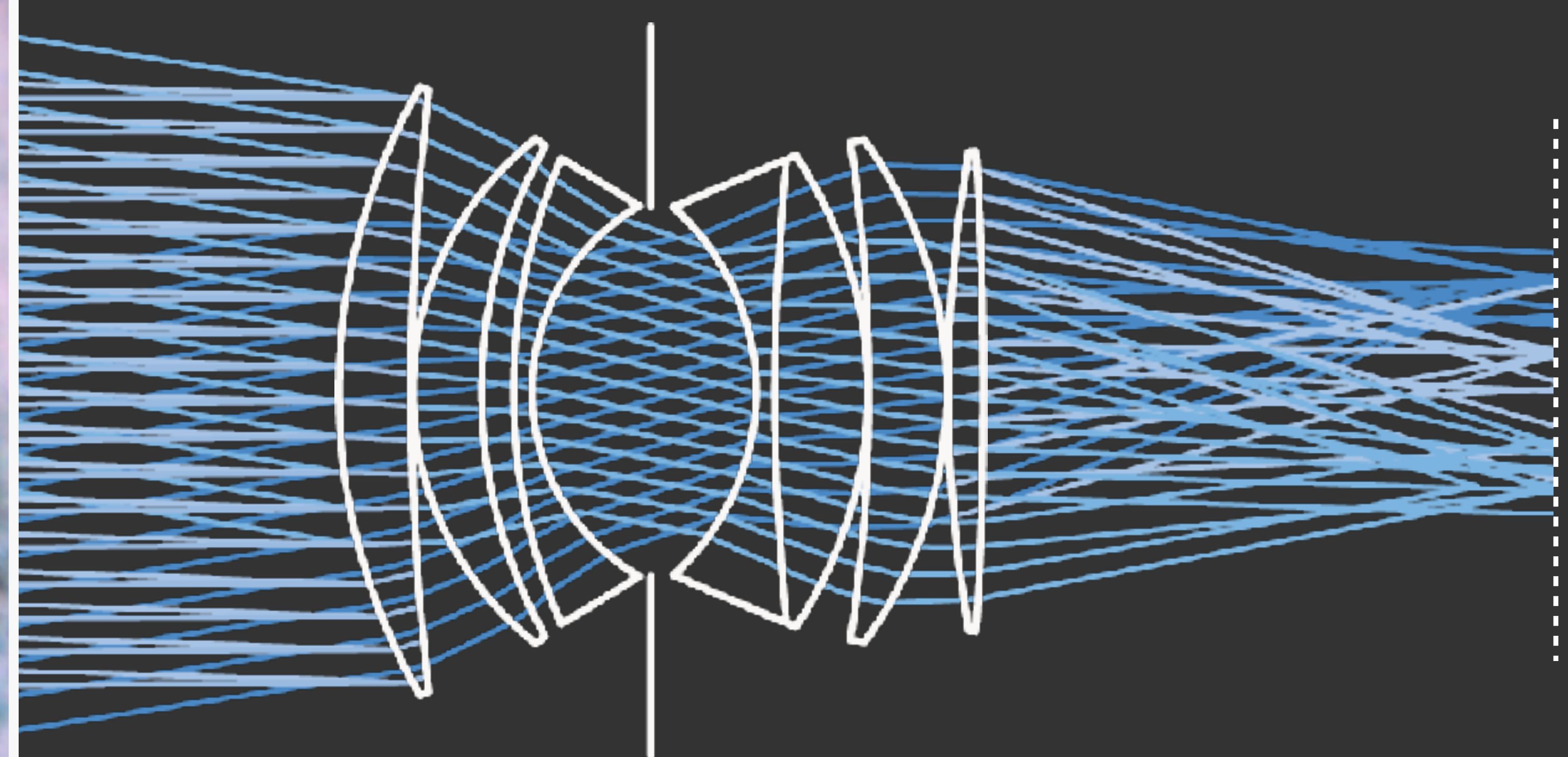
Computational Refocusing



← focus close

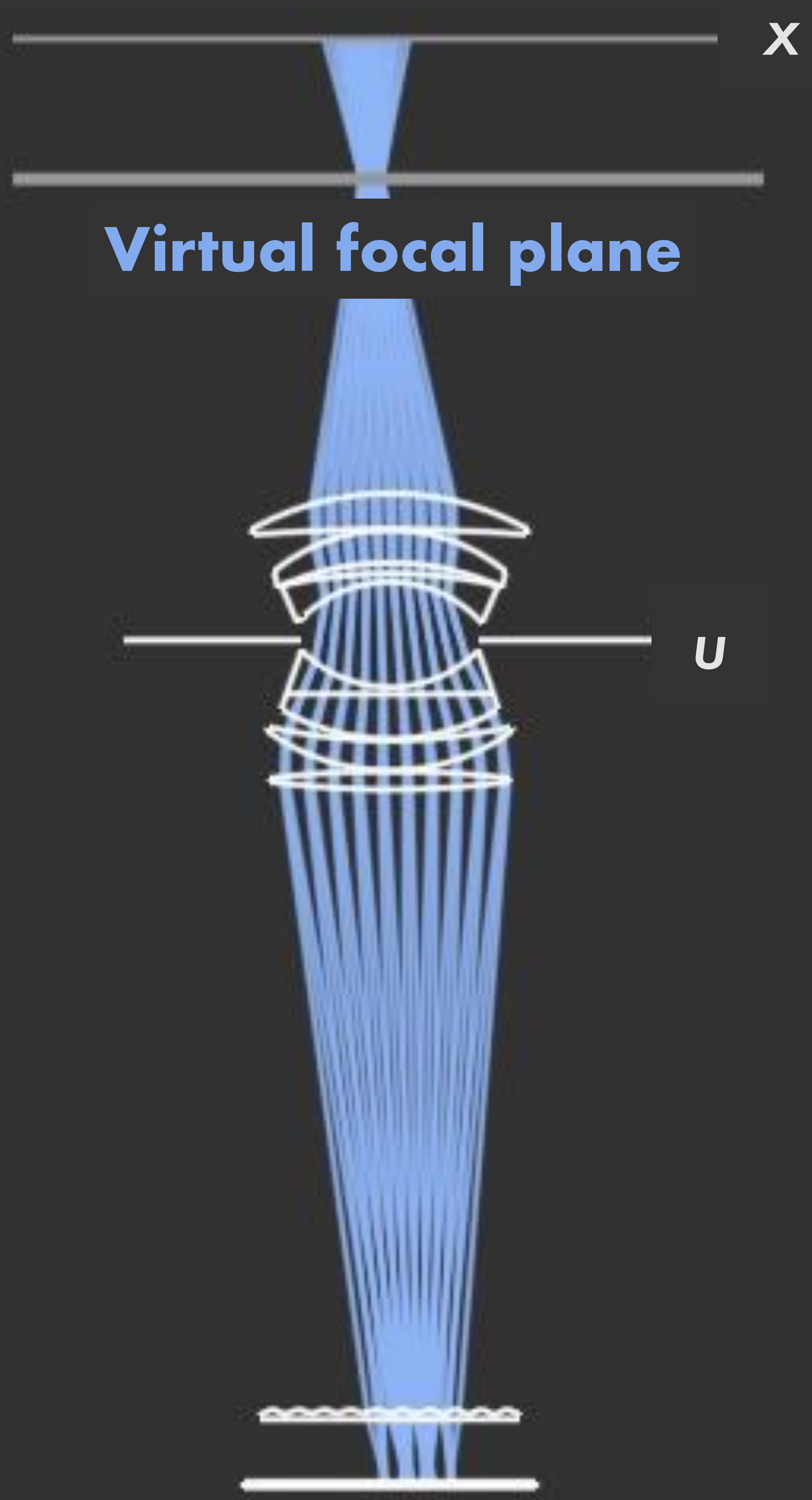


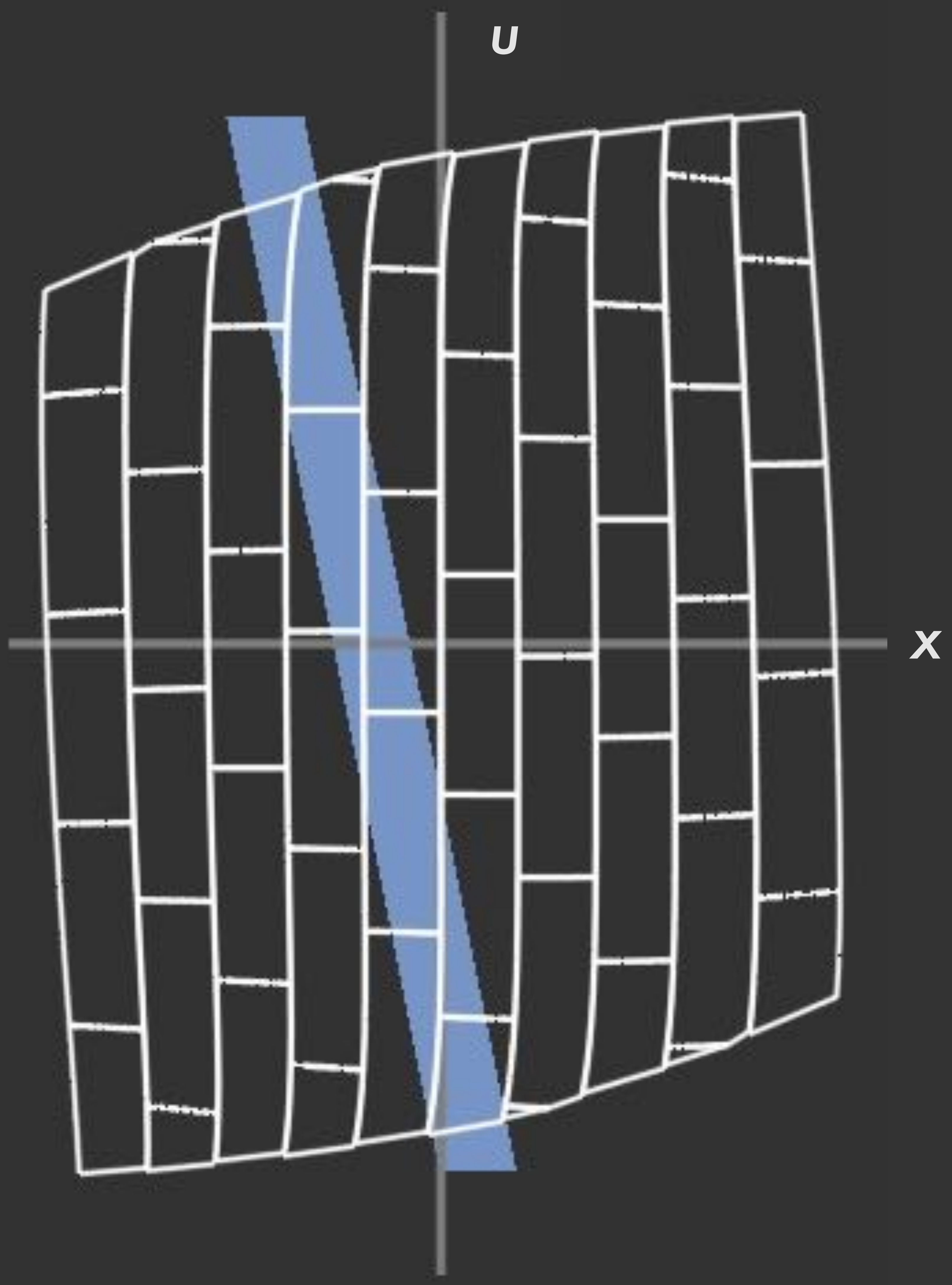
Computational Refocusing



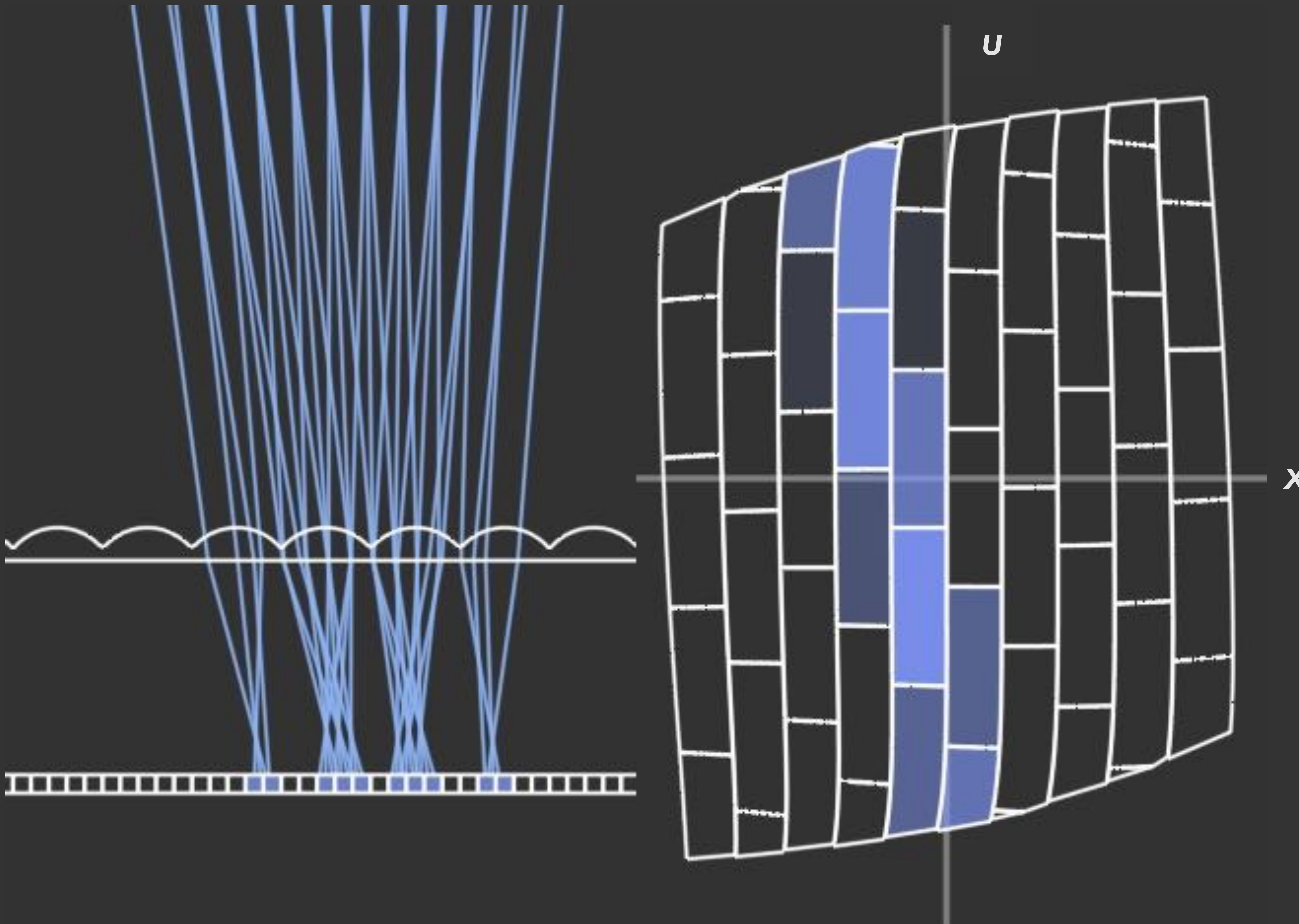
← focus far

Output Image Pixel is Sum of Many Sensor Pixels



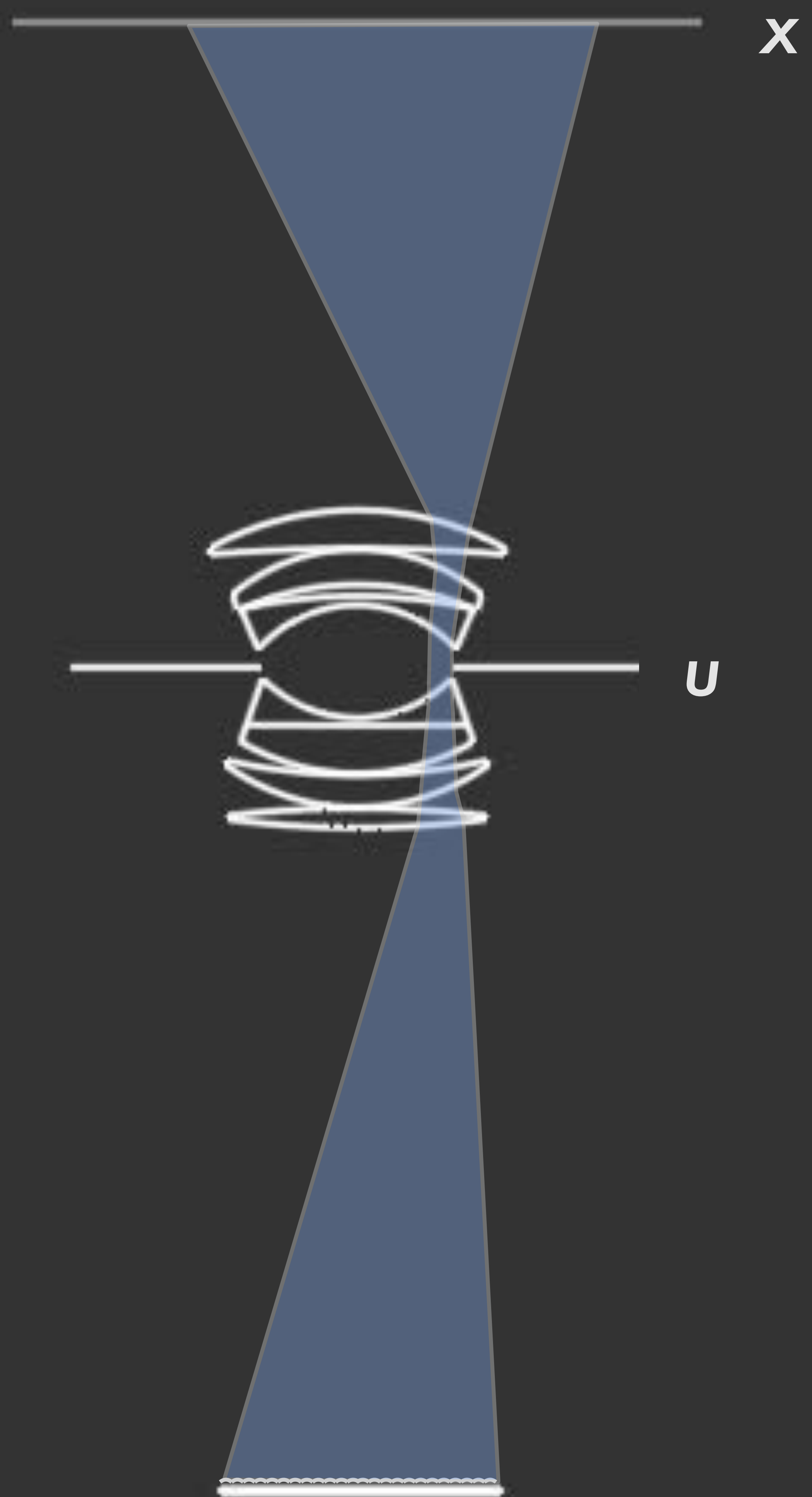


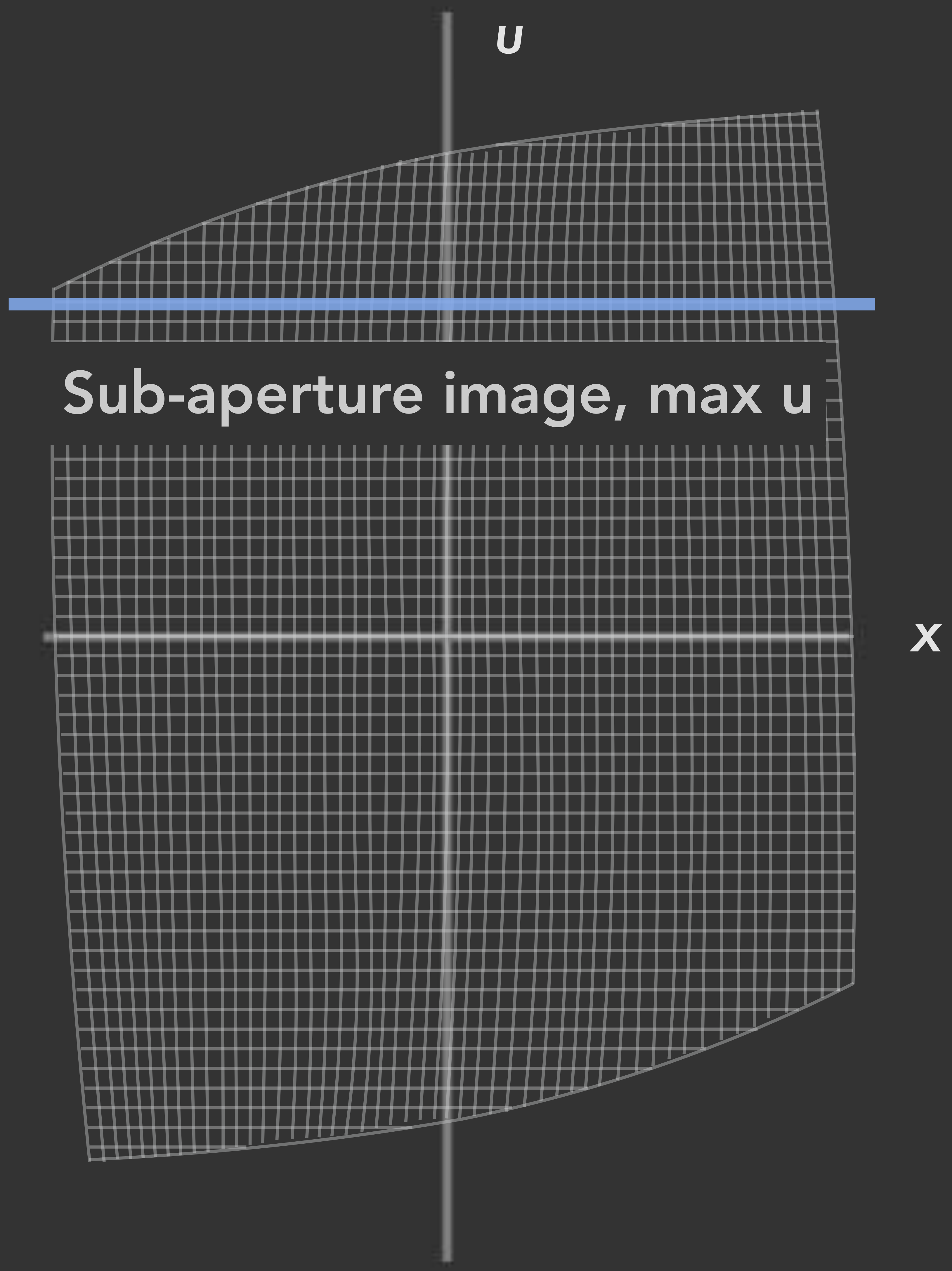
Output Image Pixel is Sum of Many Sensor Pixels



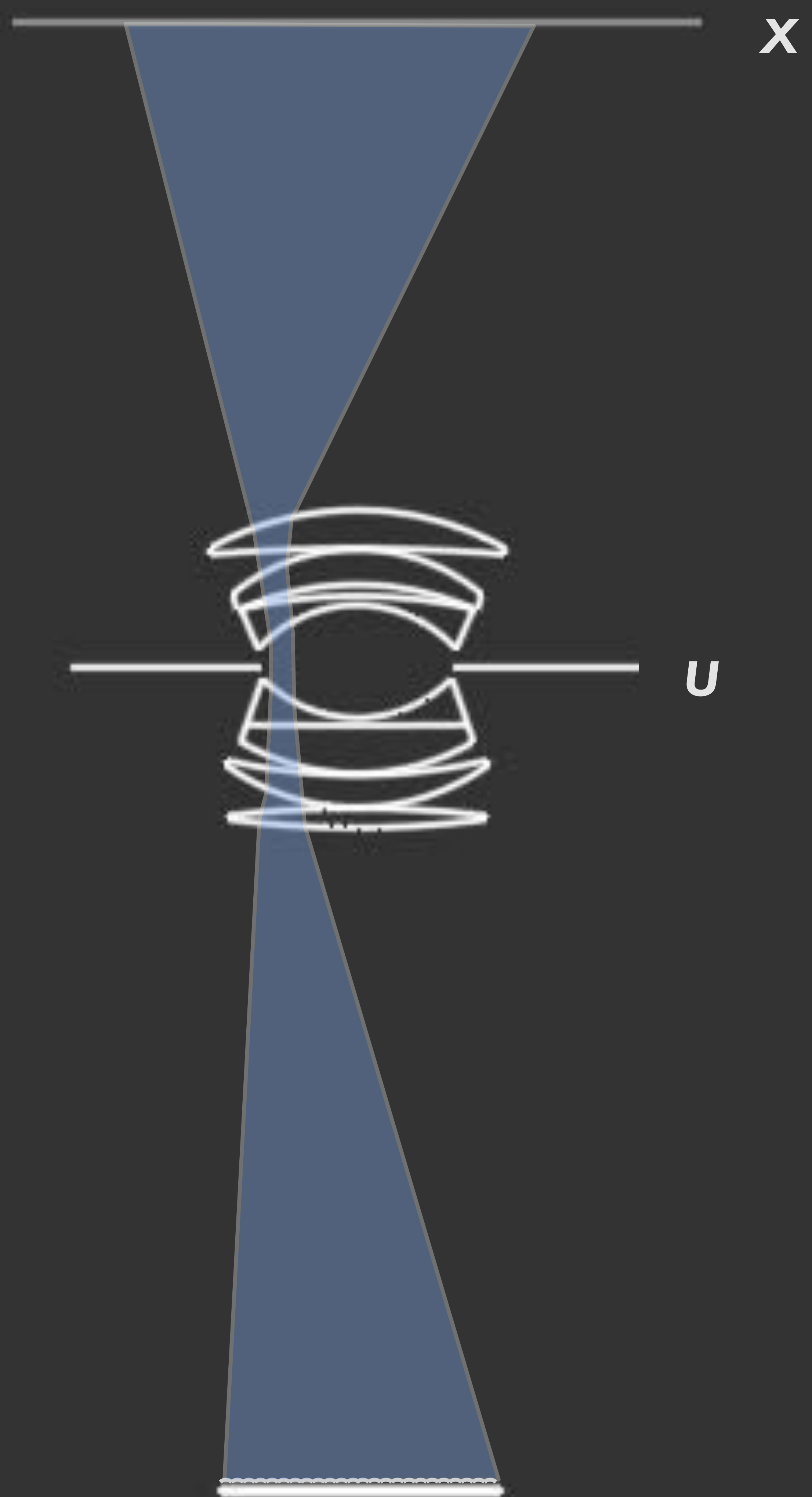
Light Field Camera = Multi-Camera Array

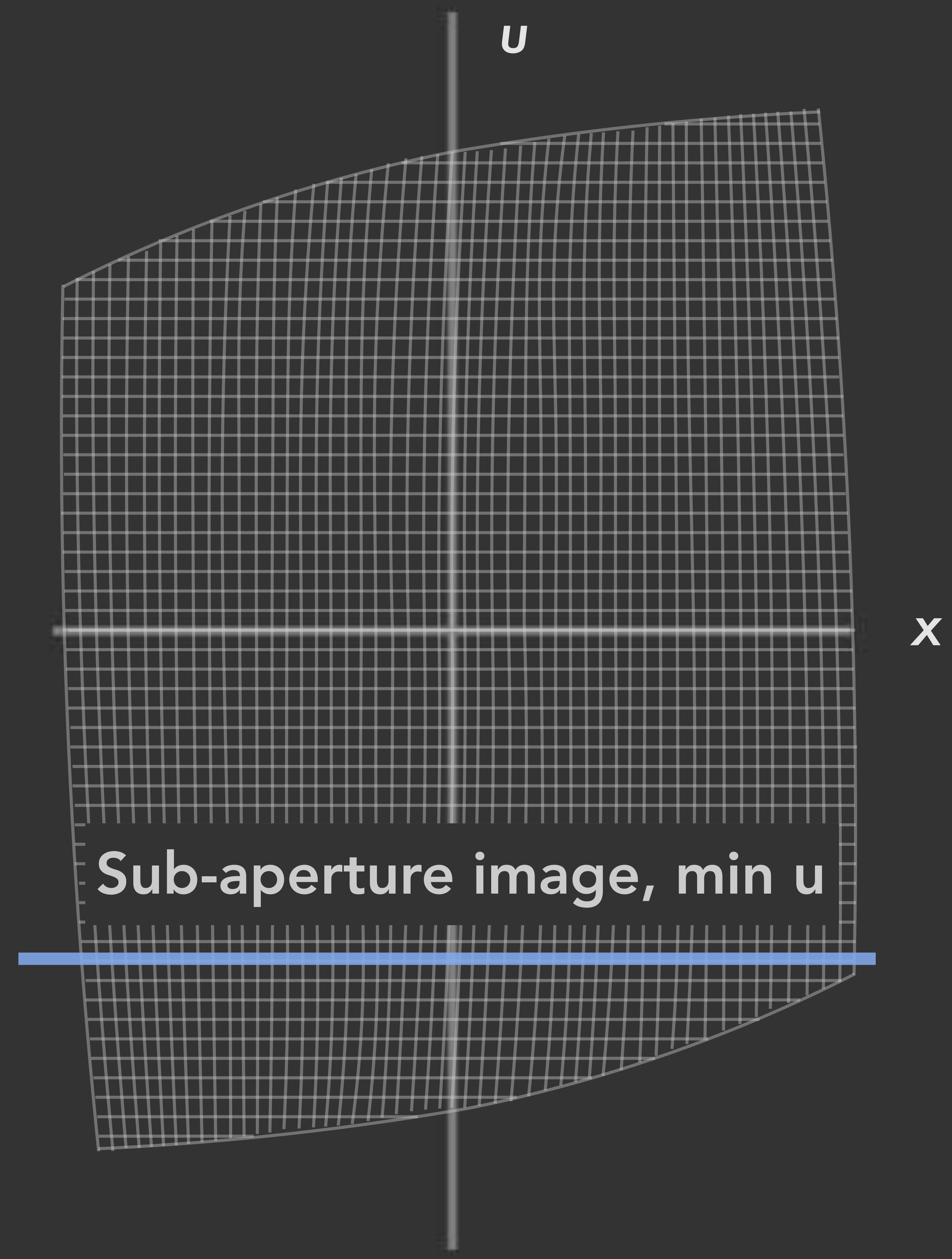
Sub-Aperture Images





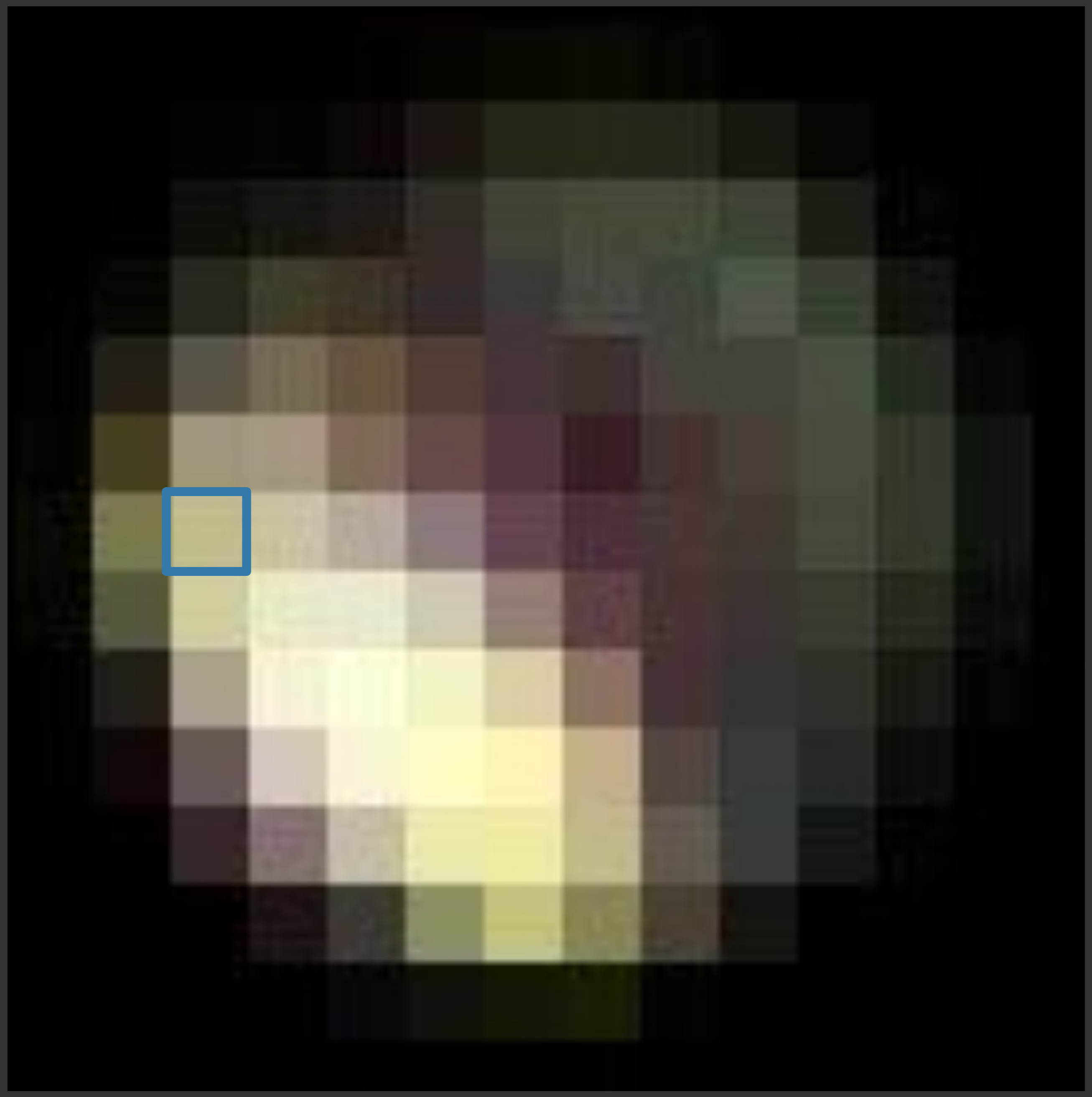
Sub-Aperture Images





Sub-Aperture Images

Image from selecting same pixel under every microlens



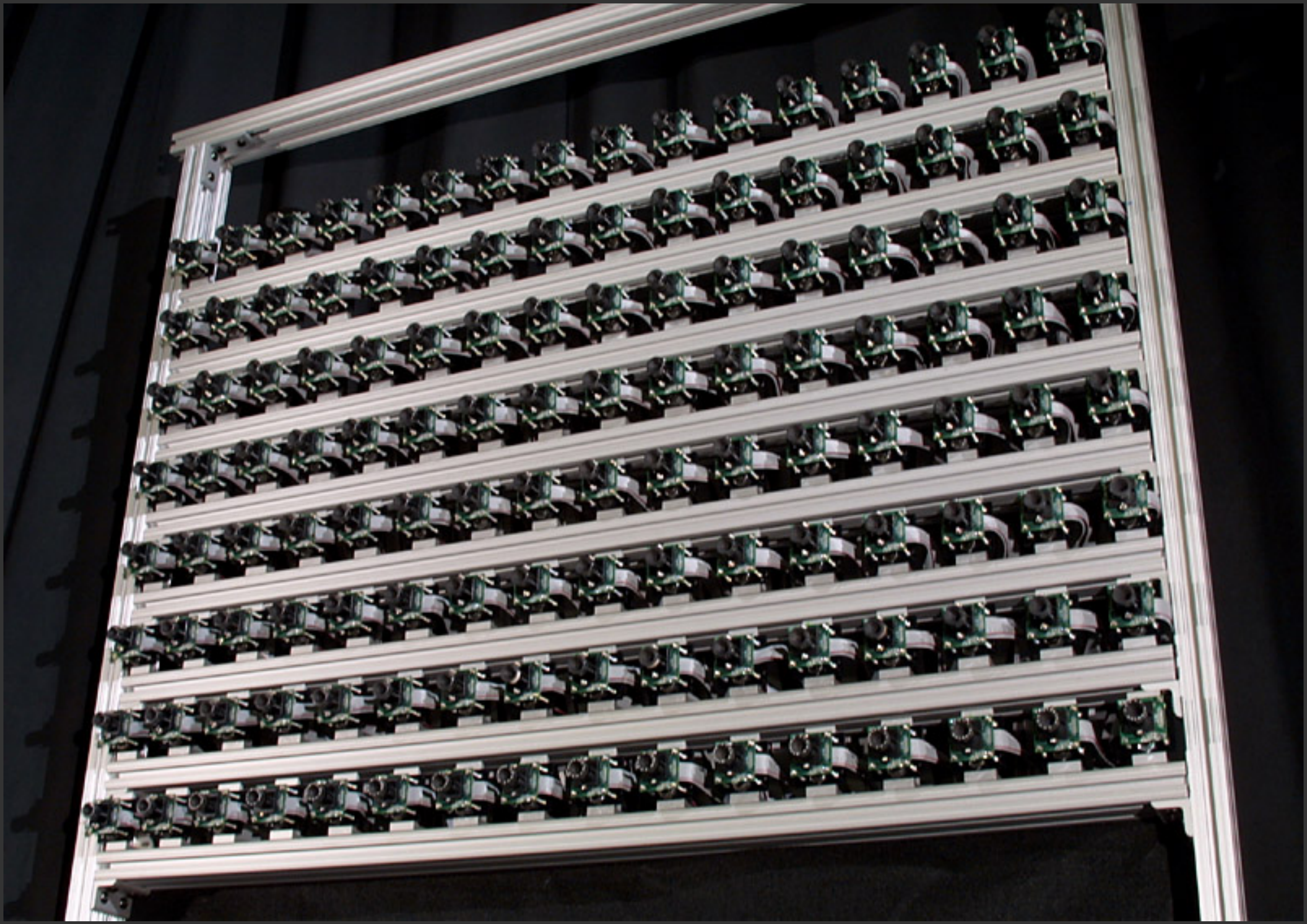
Sub-aperture image, min u

Sub-Aperture Images

Image from selecting same pixel under every microlens

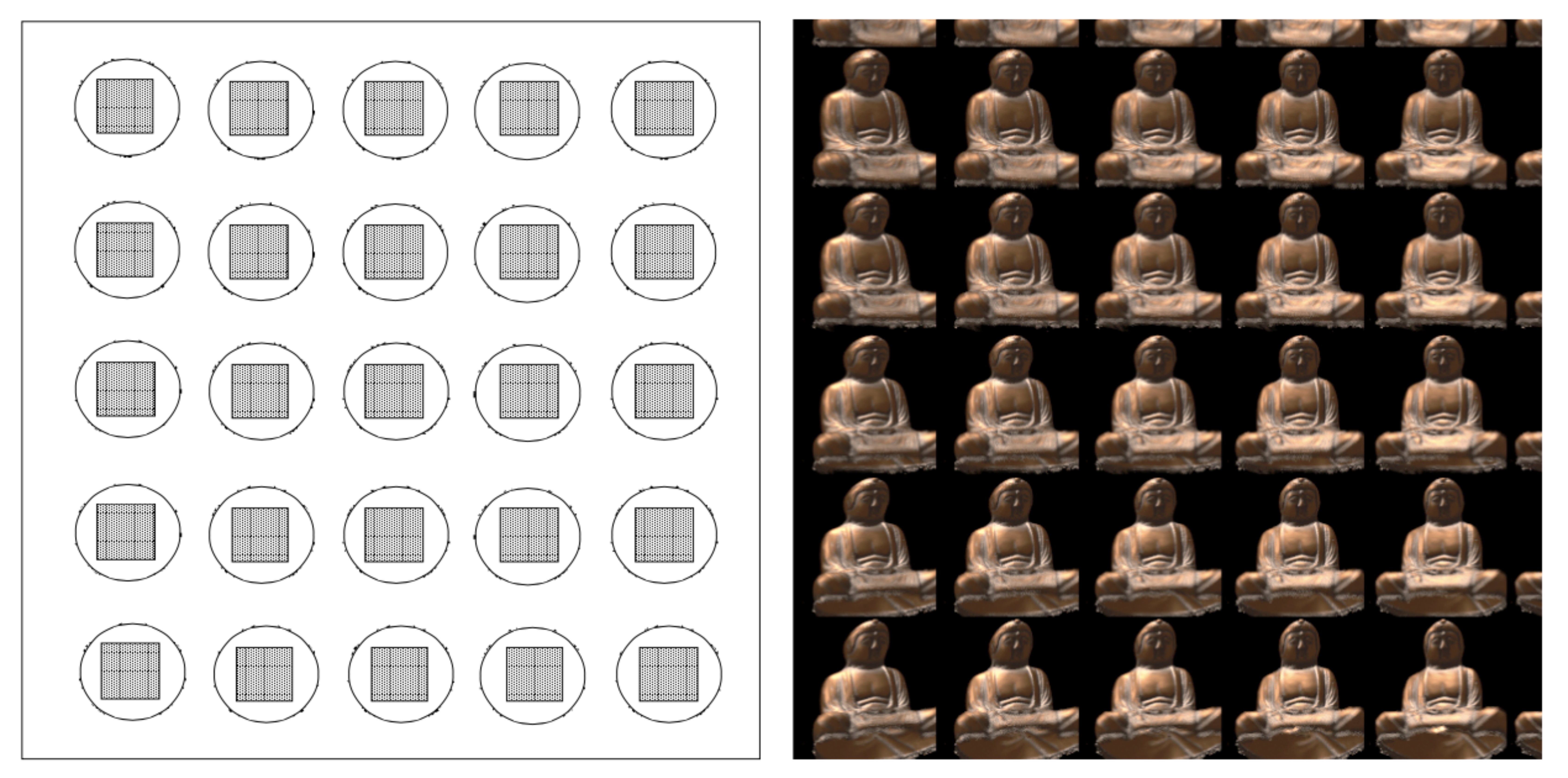
Sub-aperture image, max u

Multi-Camera Array = Light Field Camera



[Wilburn et al 2005]

Multi-Camera Array = Light Field Camera



2D Array of Cameras

2D Array of Images

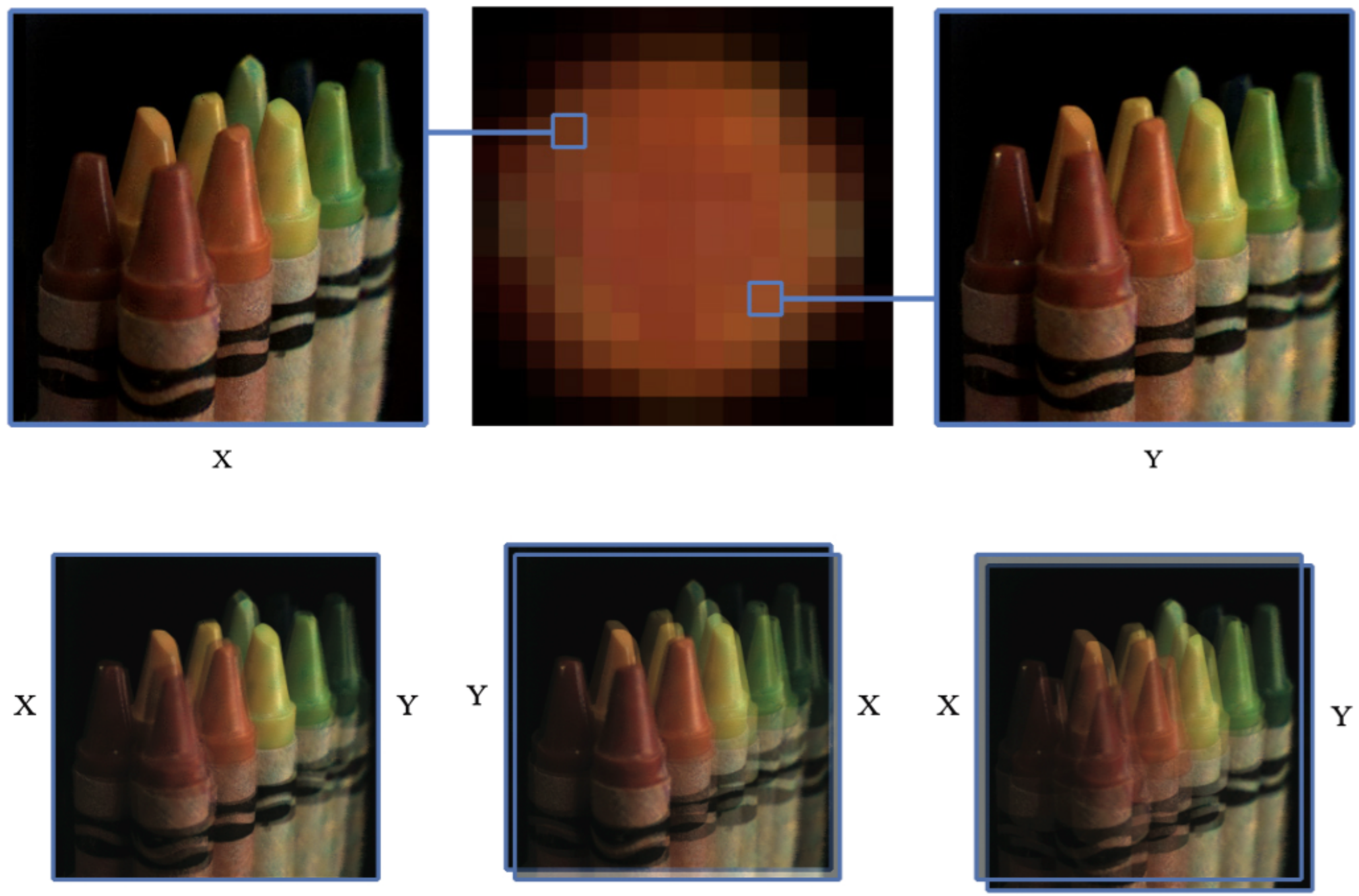
Slide credit: Pat Hanrahan

Multi-Camera Array = Light Field Camera

Very large “virtual aperture.” Very flexible imaging

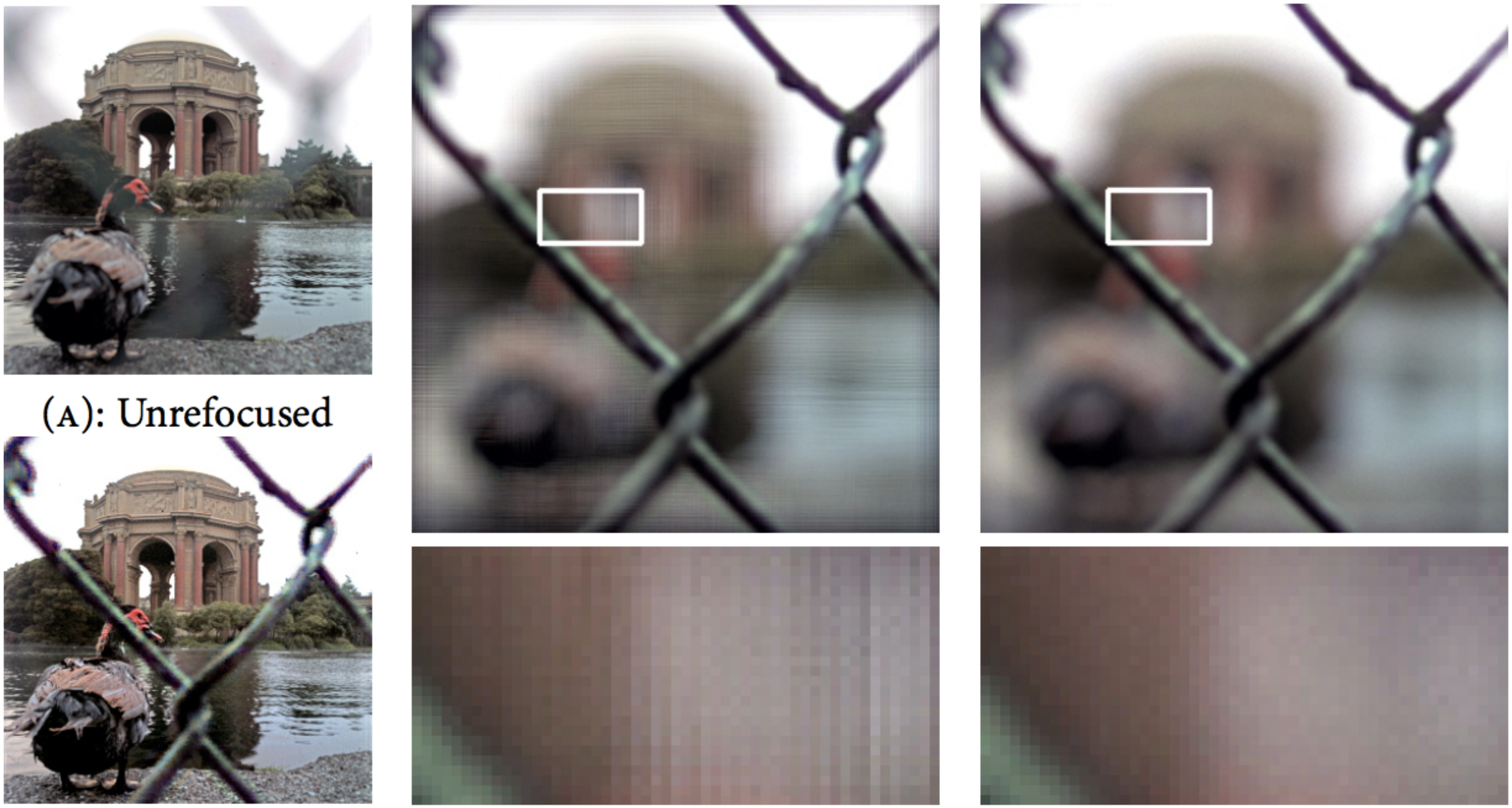
[Wilburn et al 2005] [Yang et al. 2002]

Shift-And-Add Algorithm



(A): No refocus (B): Refocus closer (C): Refocus further

Sampling & Aliasing in Shift-And-Add Algorithm



(A): Unrefocused

(B): Sub-aperture

(C1): Undersampled, aliased

(C2): Adequately sampled

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]

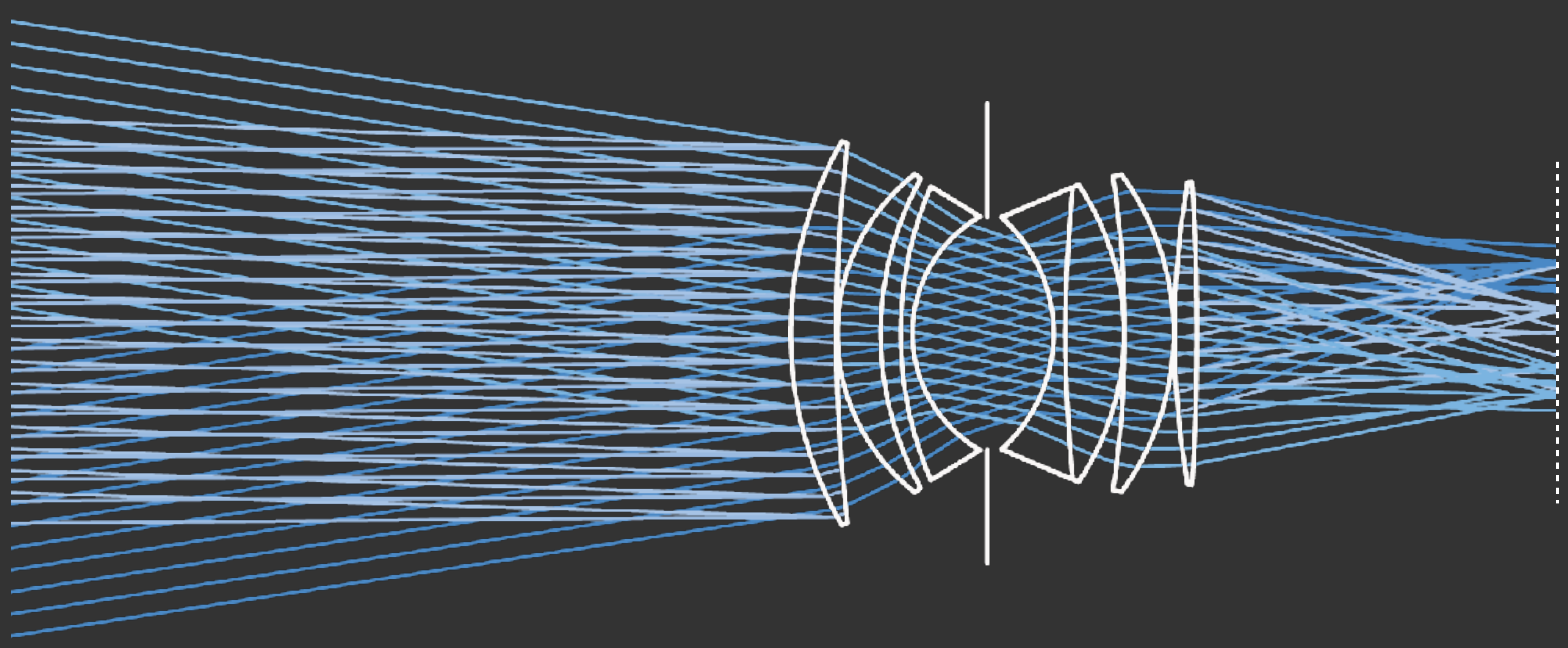
Partially Extended Depth of Field

Original
DOF

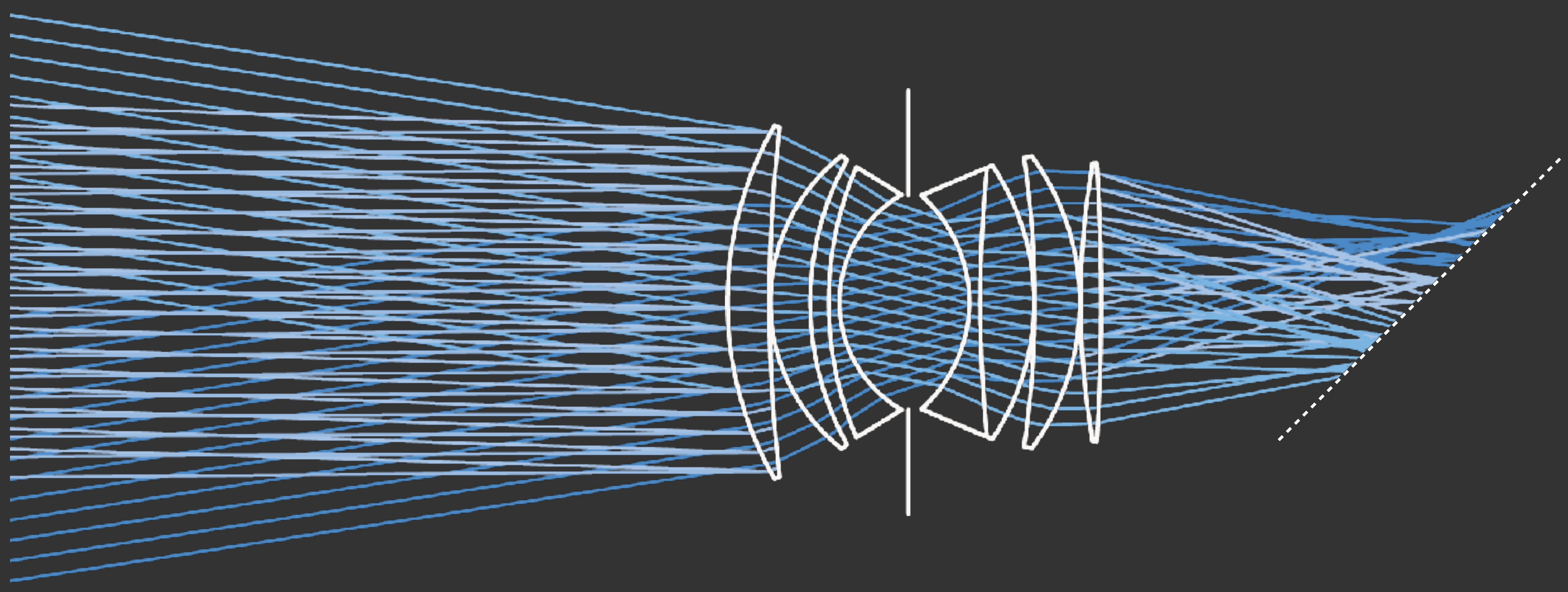
Extended
DOF

Partially Extended
DOF

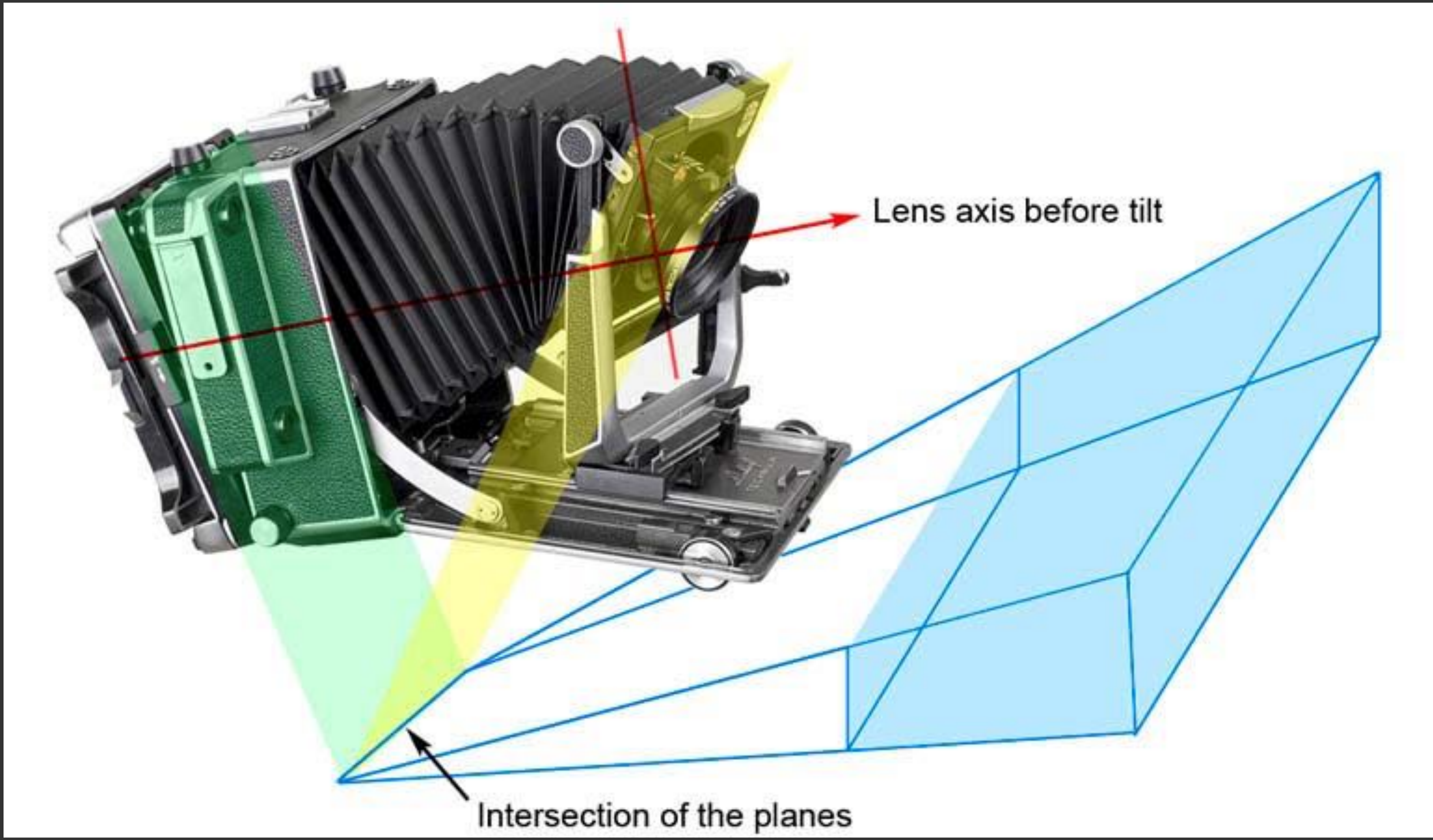
Tilted Focal Plane



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

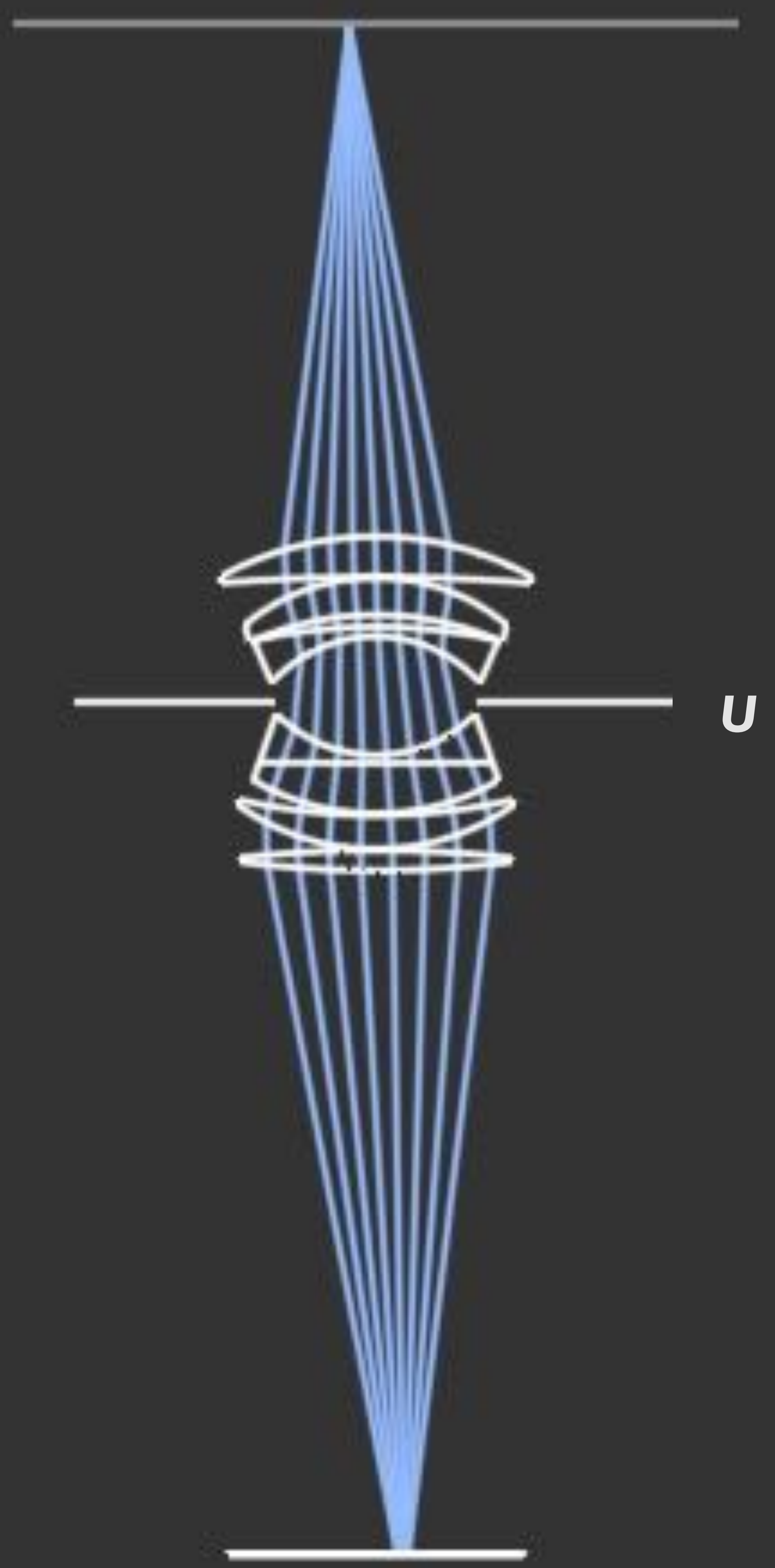
Forward movement
(wide angle effect)

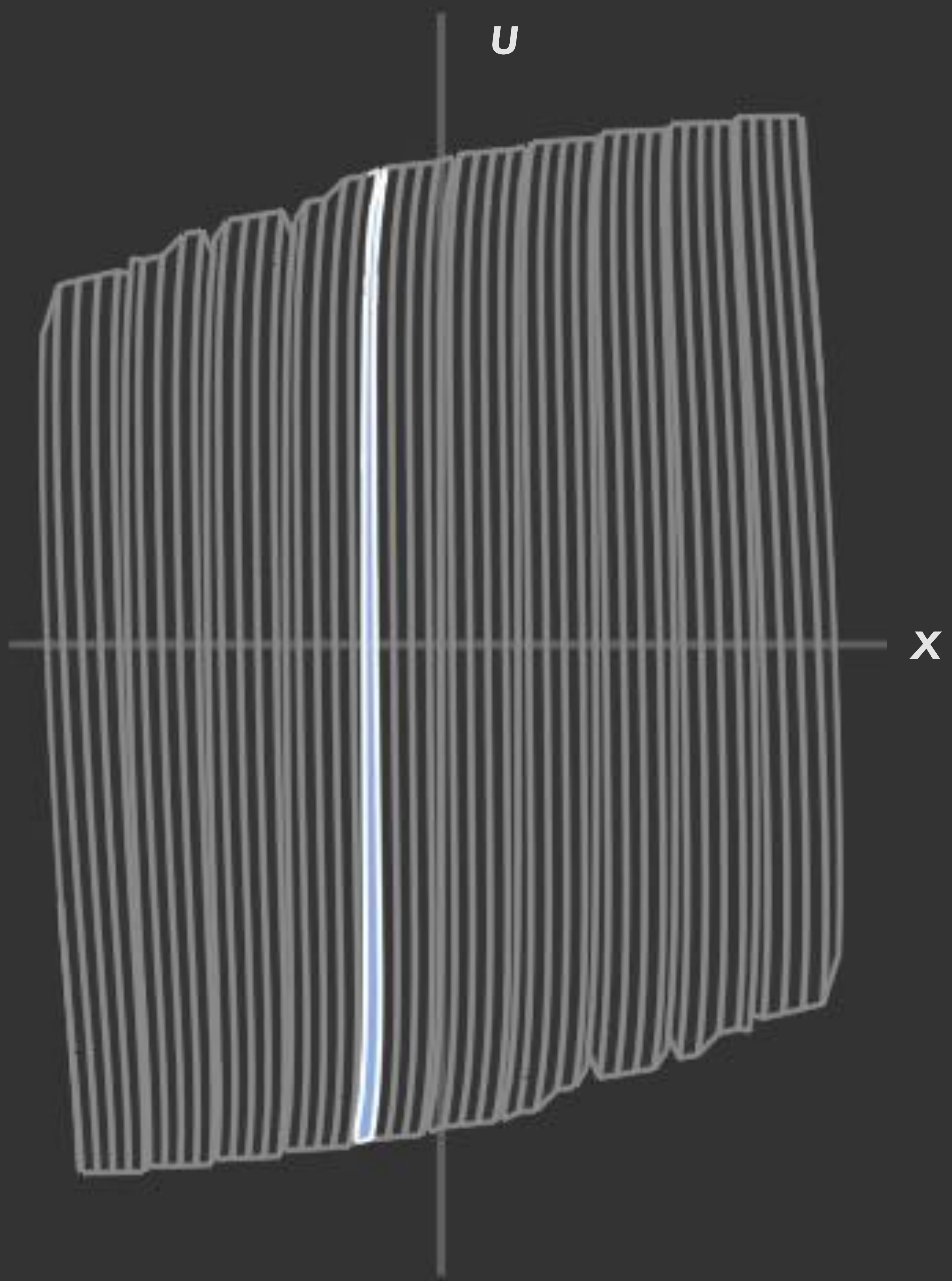
Computational Change of Viewpoint

Backward movement
(orthographic effect)

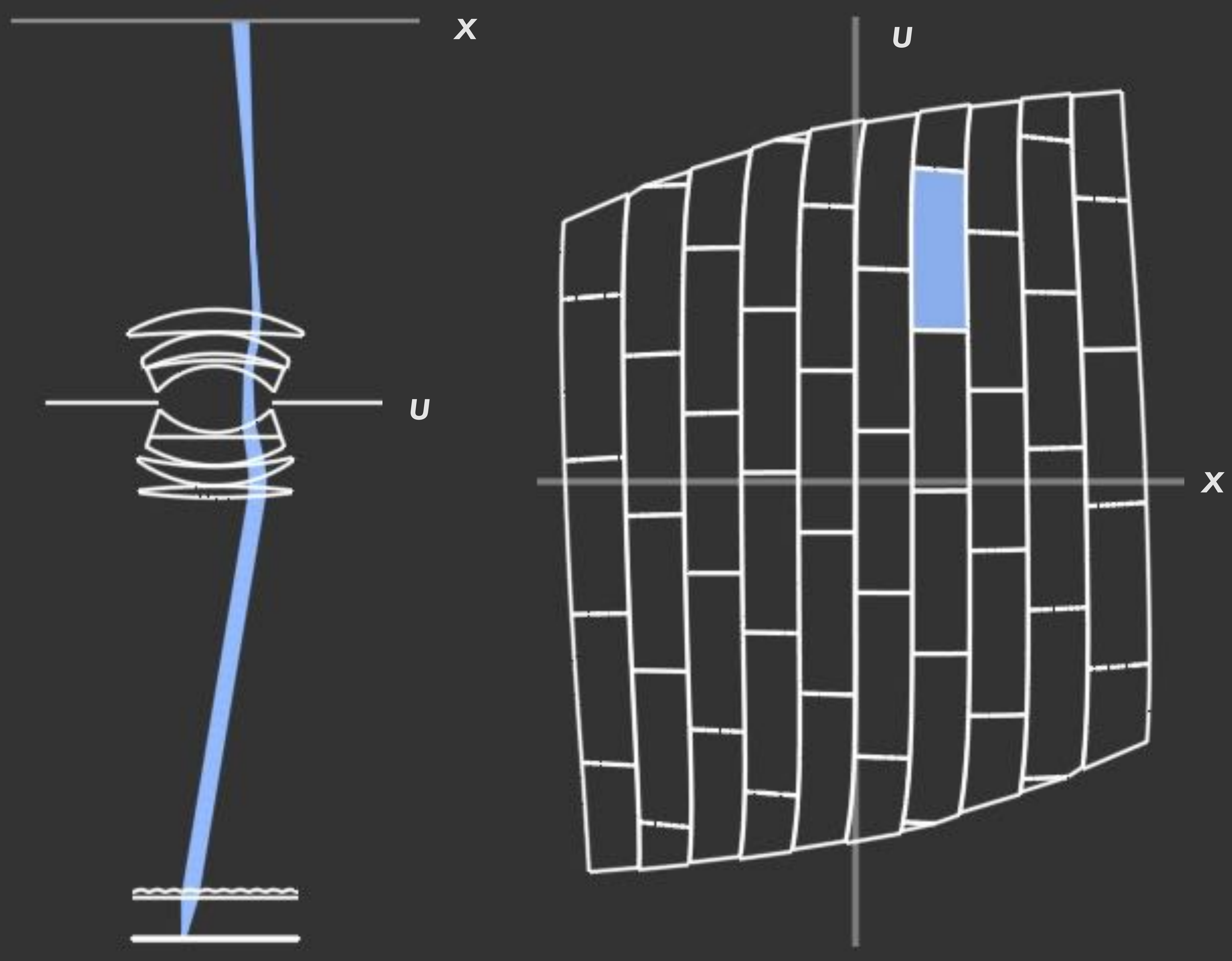
Light Field Sensor Resolution

2D vs 4D Resolution With Same CMOS Sensor

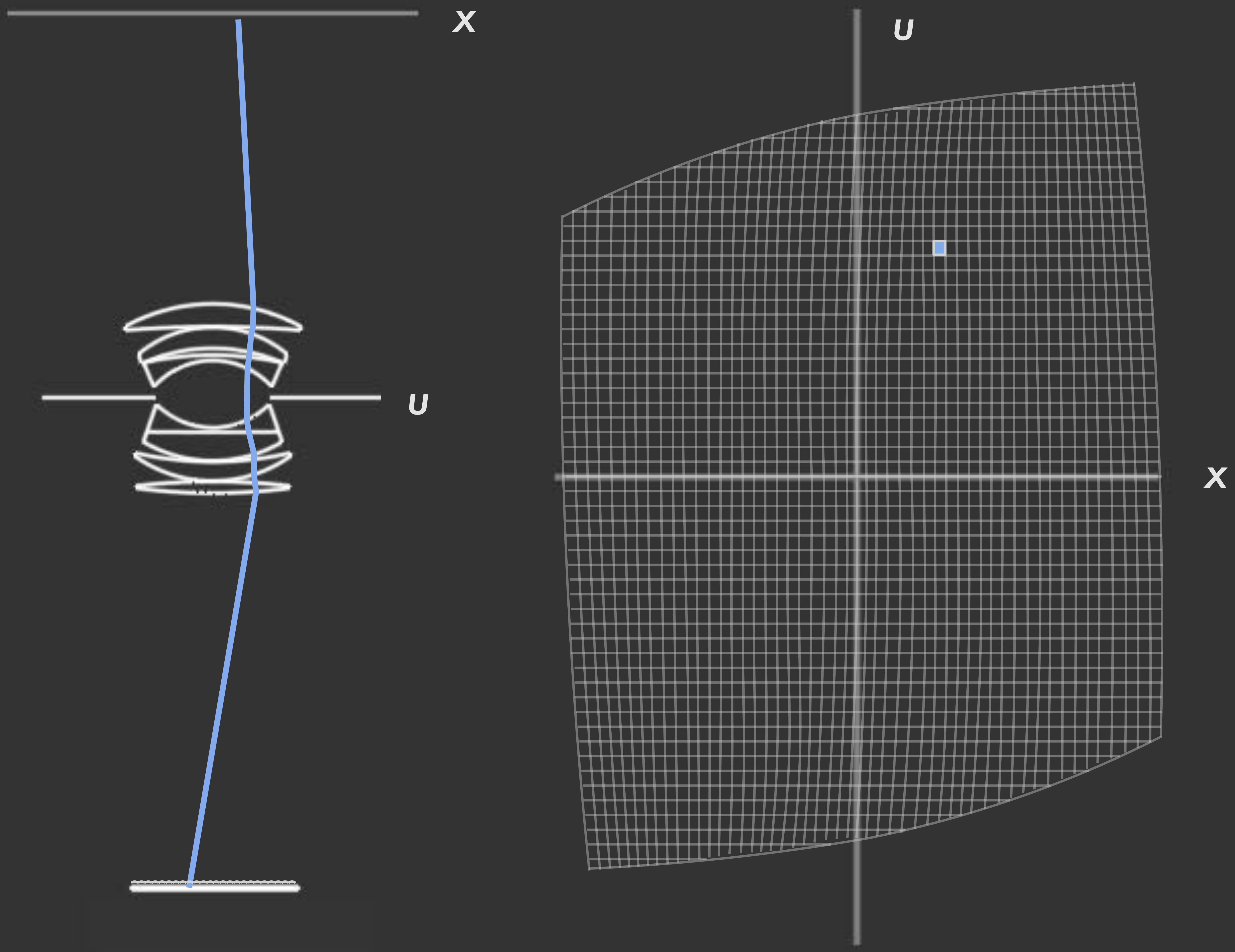




2D vs 4D Resolution With Same CMOS Sensor

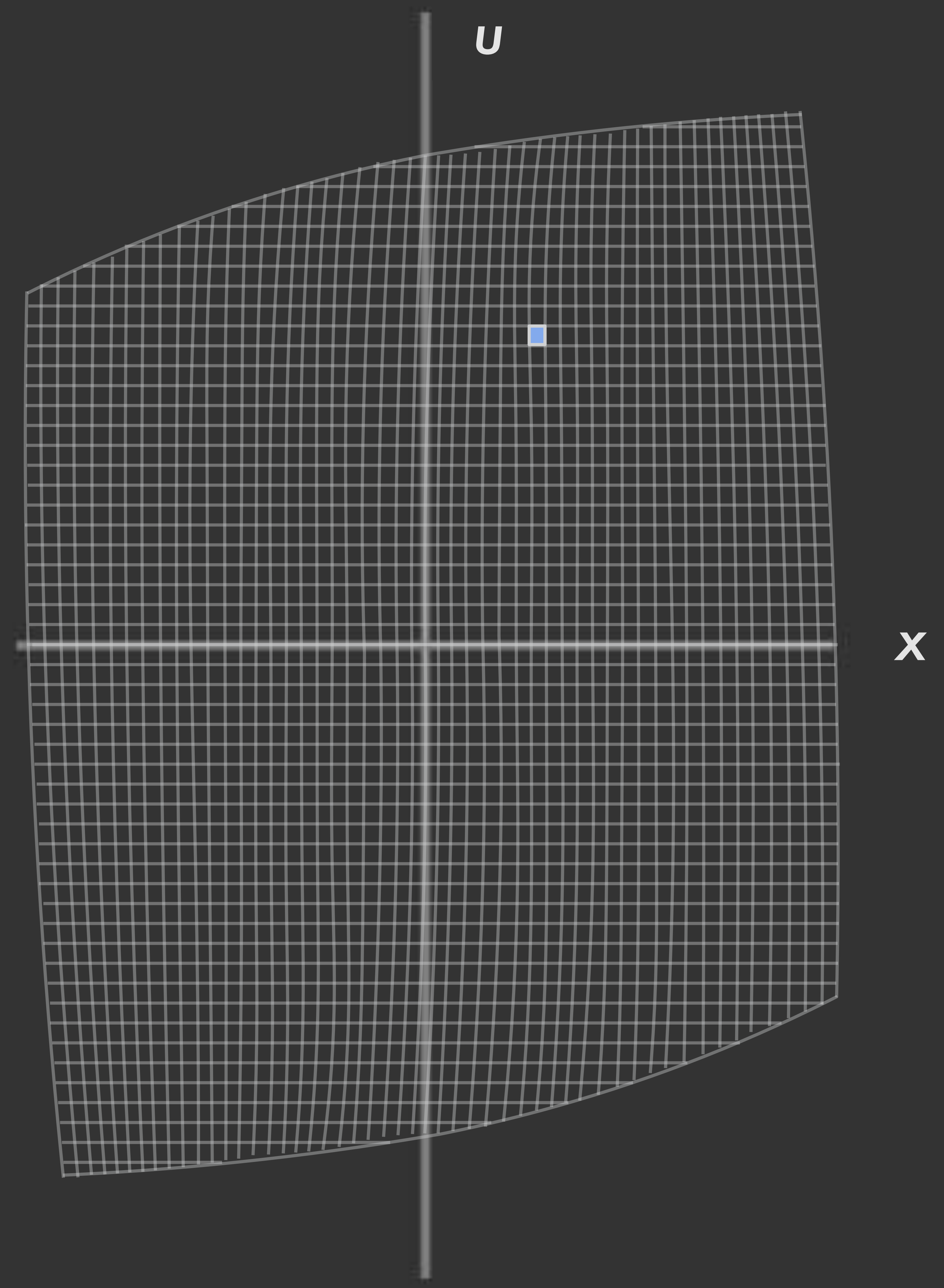


Light Fields Motivate Higher Sensor Resolution



4D Resolution Scaling

- More microlenses provide more vertical lines
- More pixels per microlens provide more horizontal lines

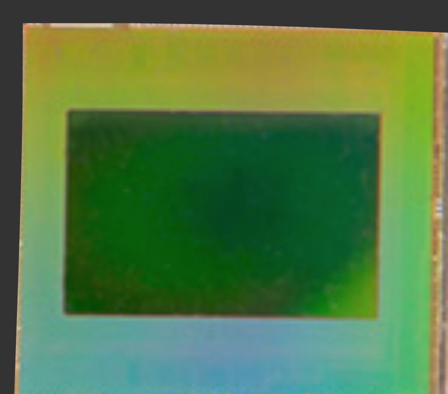


Consumer Light Field Resolutions Today

Lytro (2012)
10 MegaRay
~10 pixels / microlens

Lytro ILLUM (2014)
40 MegaRay
~14 pixels / microlens

Lytro Image Sensors



10 MP
2012

40 MP
2014

164 MP
2016

And Much Higher Resolution Sensors Are Possible

Mobile phone camera
16 MP
1.12 micron pixel

And Much Higher Resolution Sensors Are Possible

Credit: cameraegg.org

Full-frame sensor

50 MP

4.2 micron pixel

Pixel Readout Bandwidth is Growing Fast Too

CMOSIS CMV12000
12MP @ 300 fps
3.6 Gigapixel / sec

Forza
133 MP @ 60 fps
8.0 Gigapixel / sec

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

Extras

Many Ways to Capture Light Fields

Multi-Camera Array ⇒ 4D Light Field

Slide credit: Pat Hanrahan

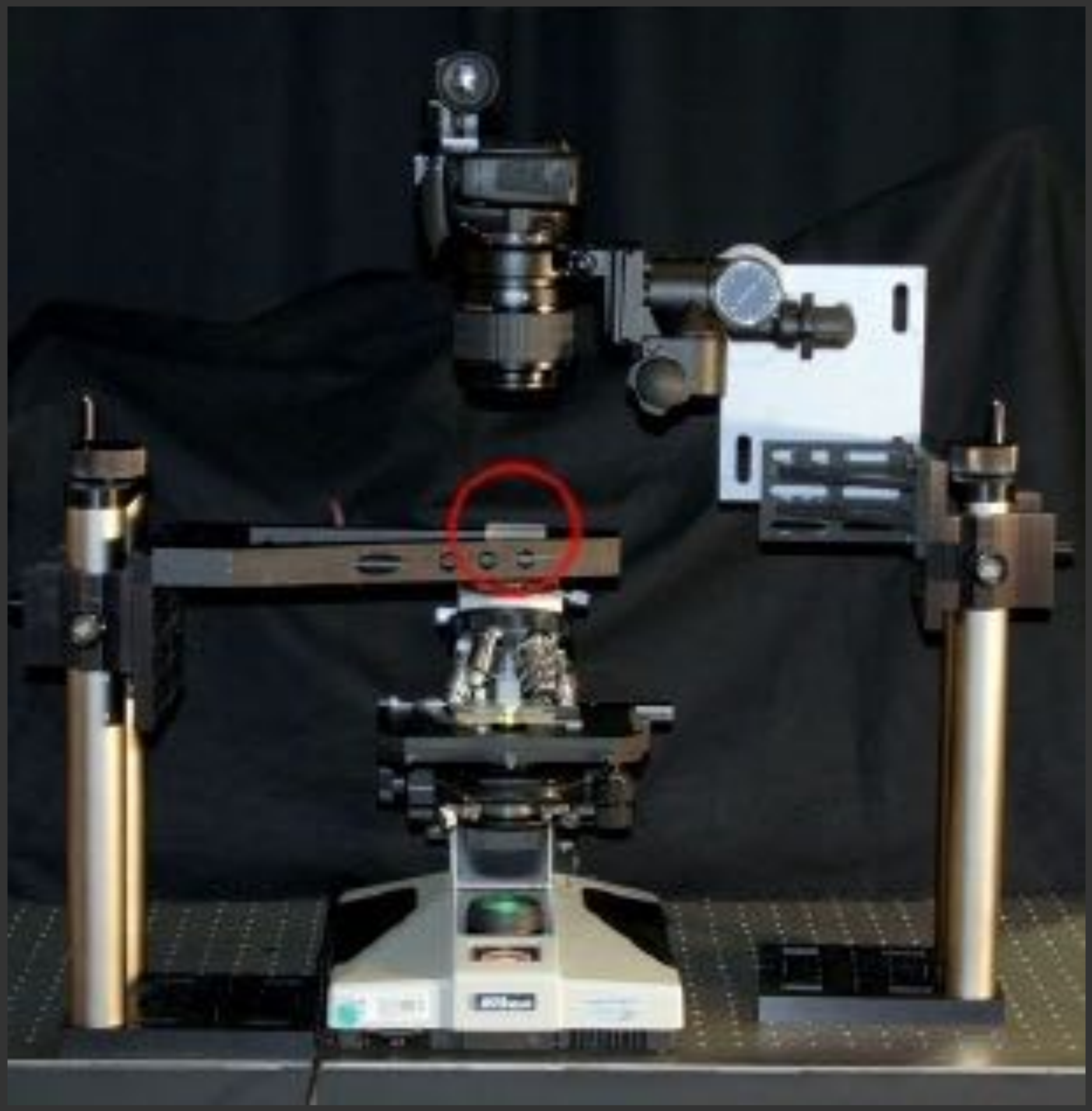
Programmable Aperture (LCD)

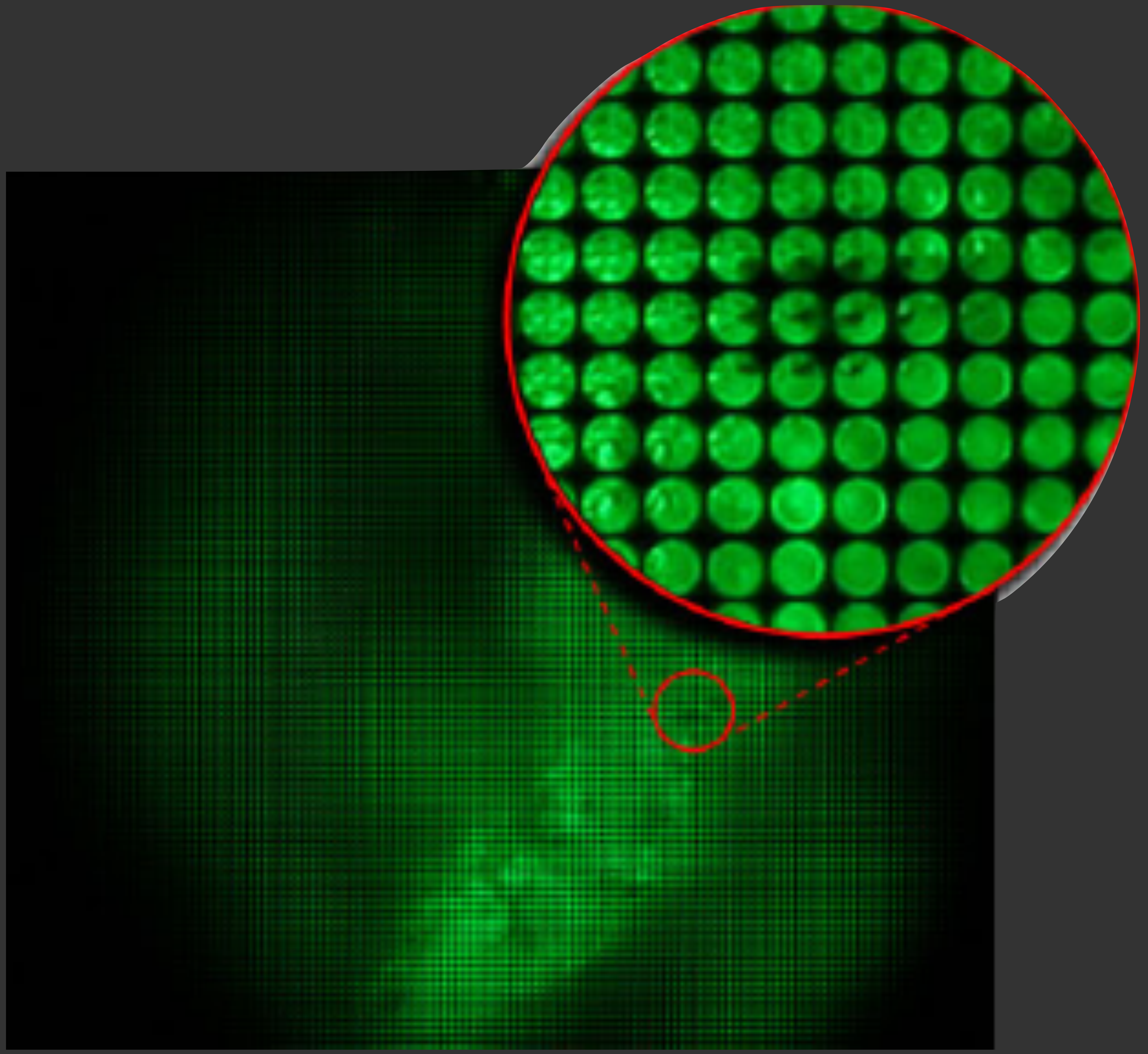
Scan out light field one sub-aperture image at a time

High res light fields, but requires lengthy scanning

[Liang et al 2008]

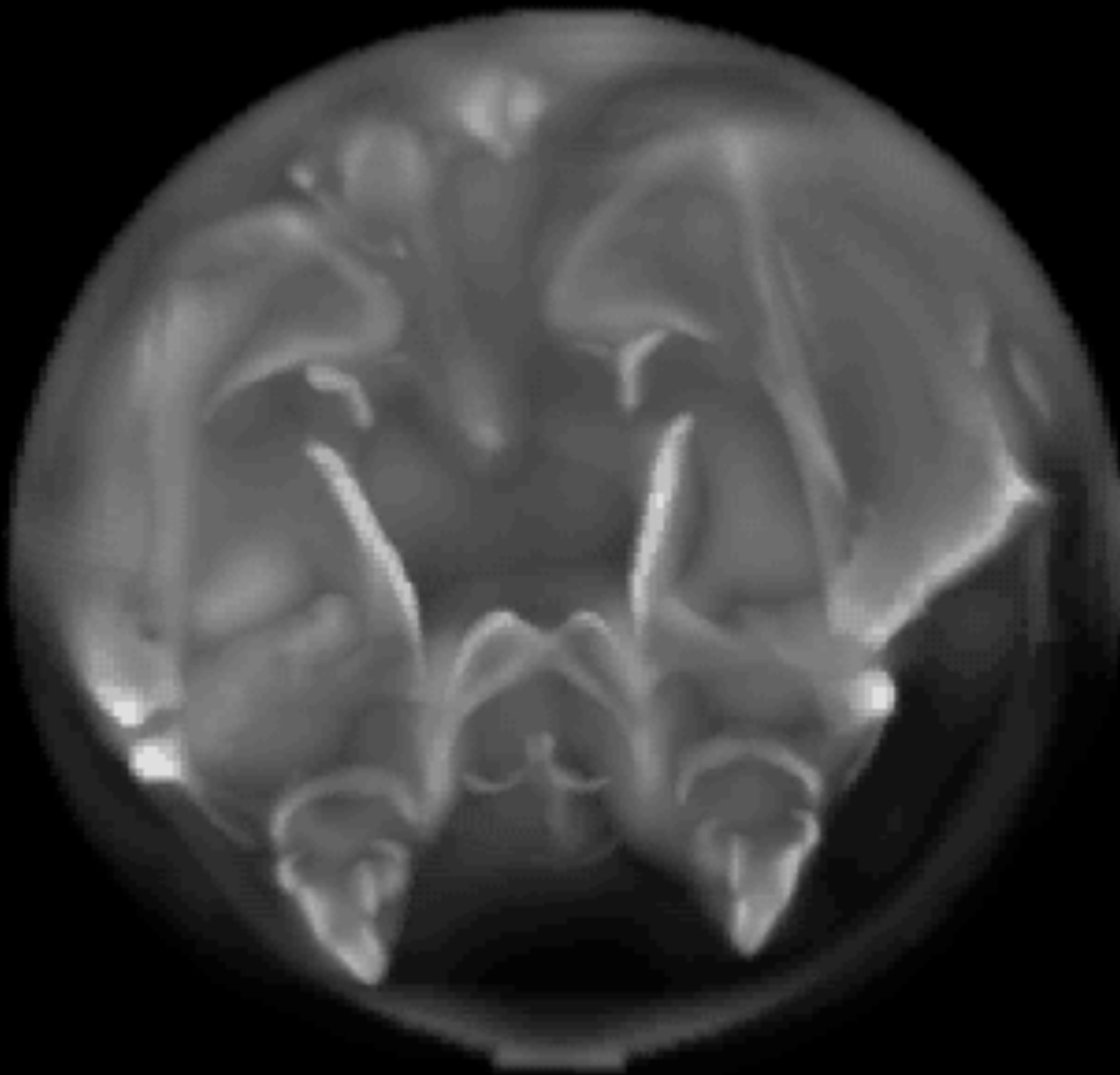
Light Field Microscope





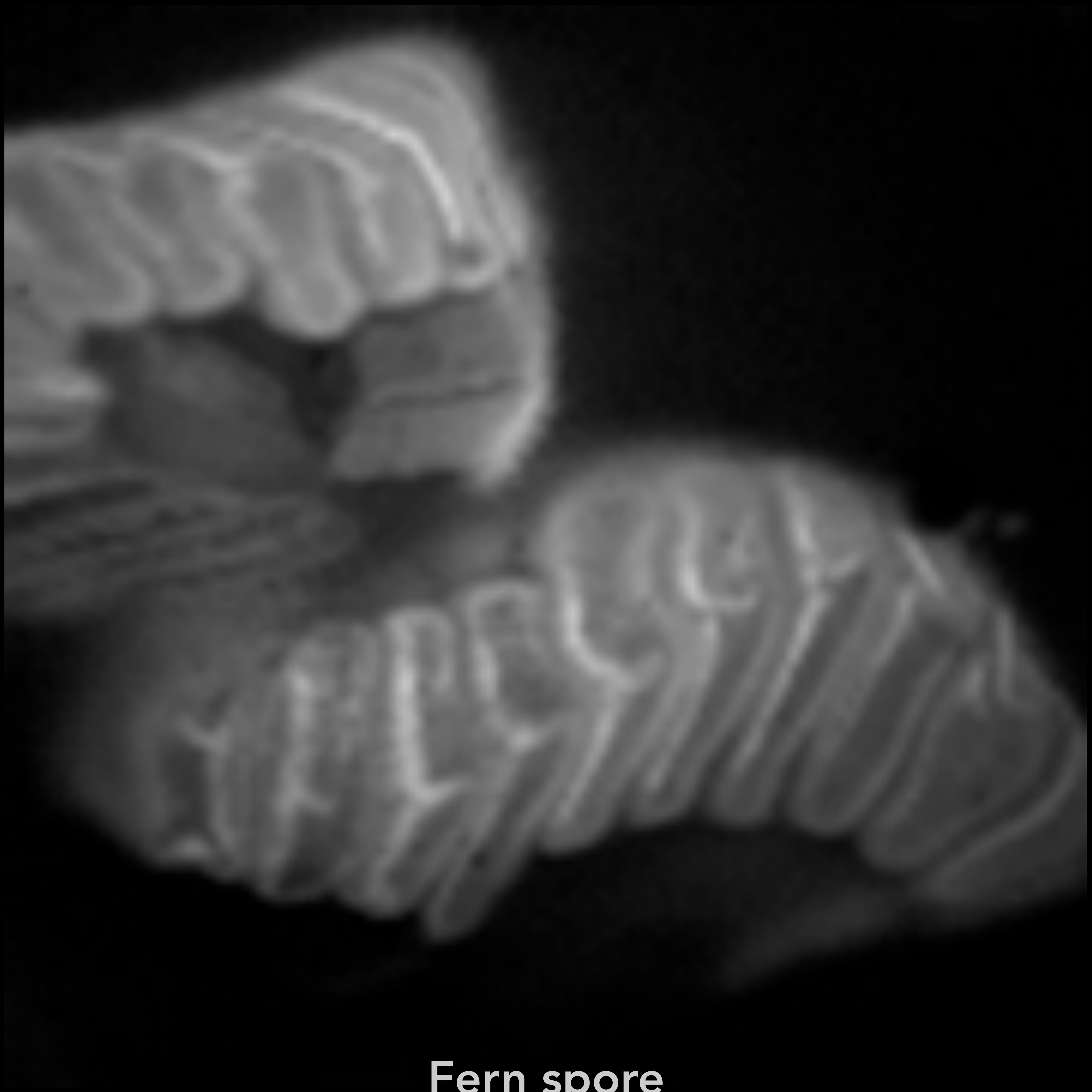
Use microlens in microscope imaging path

[Levoy et al 2006]



Mandibles of a silk worm

[Levoy et al 2006]



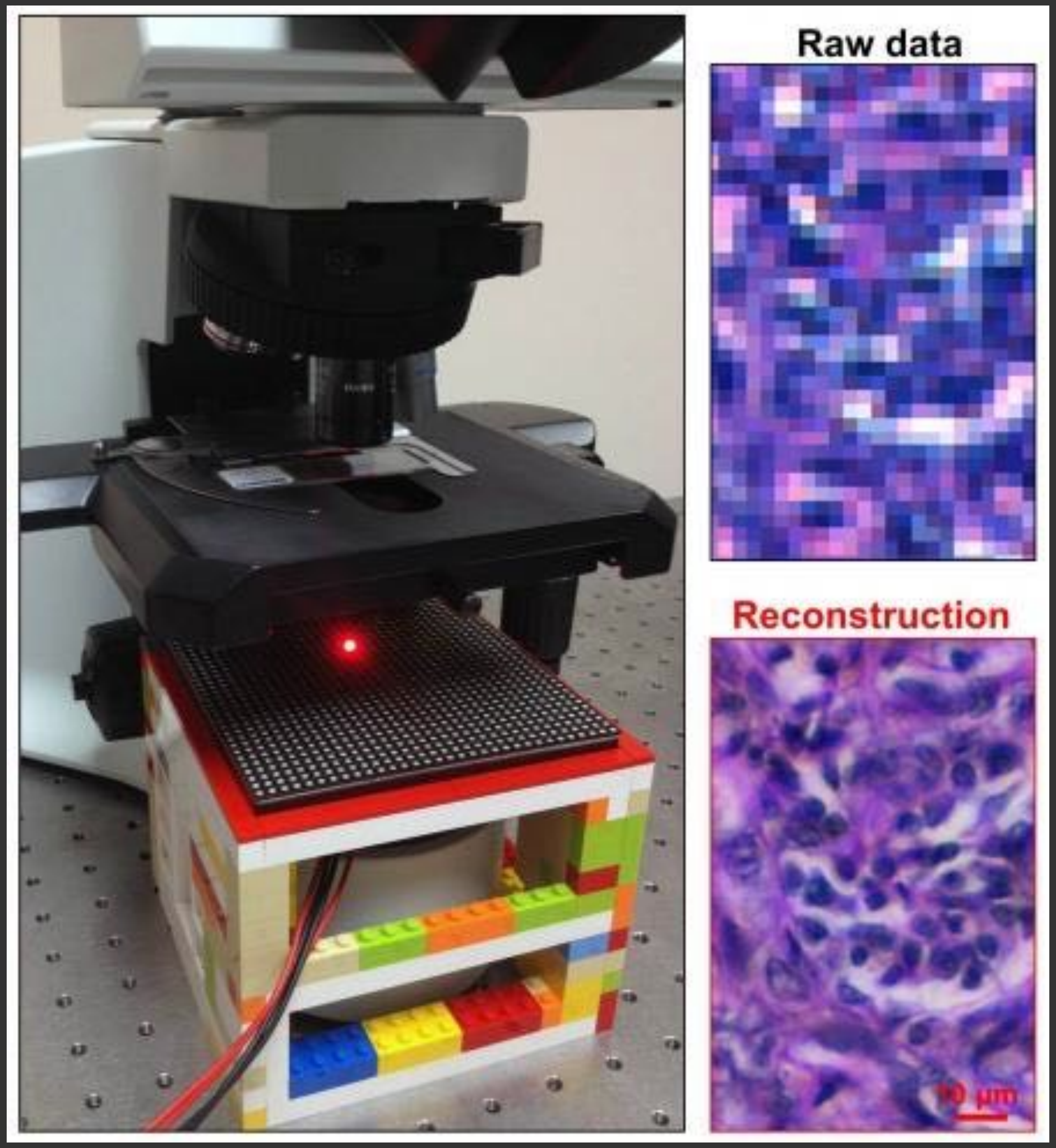
Fern spore

[Levoy et al, 2006]

LED Array Microscope

Scan light field by sequentially illuminating specimen with LEDs positioned at different angles

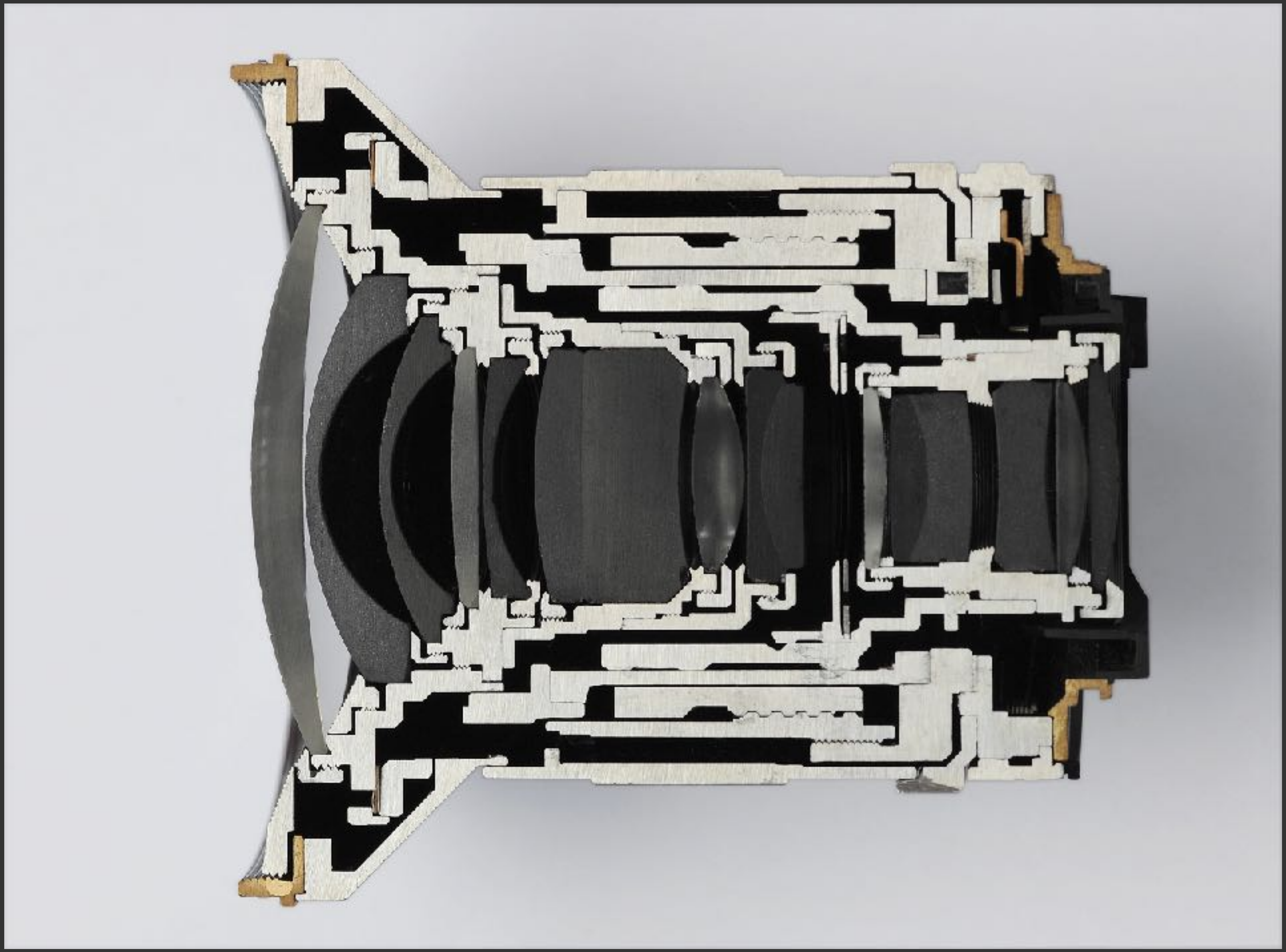
[Zheng et al 2013][Tian et al 2014]



[Zheng et al]

Light Field Imaging Lenses - Optics and Computation

Modern Lens Designs Are Highly Complex



Photographic lens cross section

Modern Lens Designs Are Highly Complex

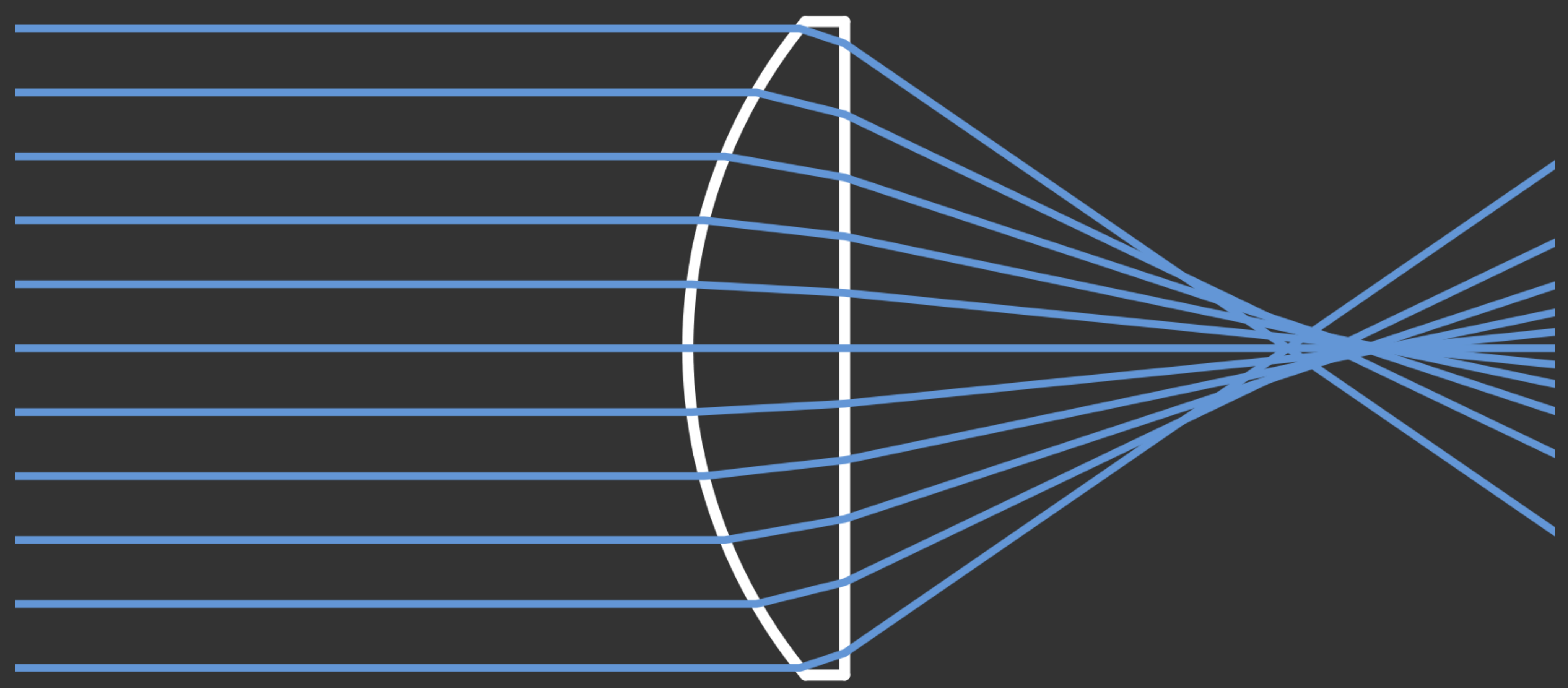
[Apple]

Modern Lens Designs Are Highly Complex

Zeiss flickr.com account

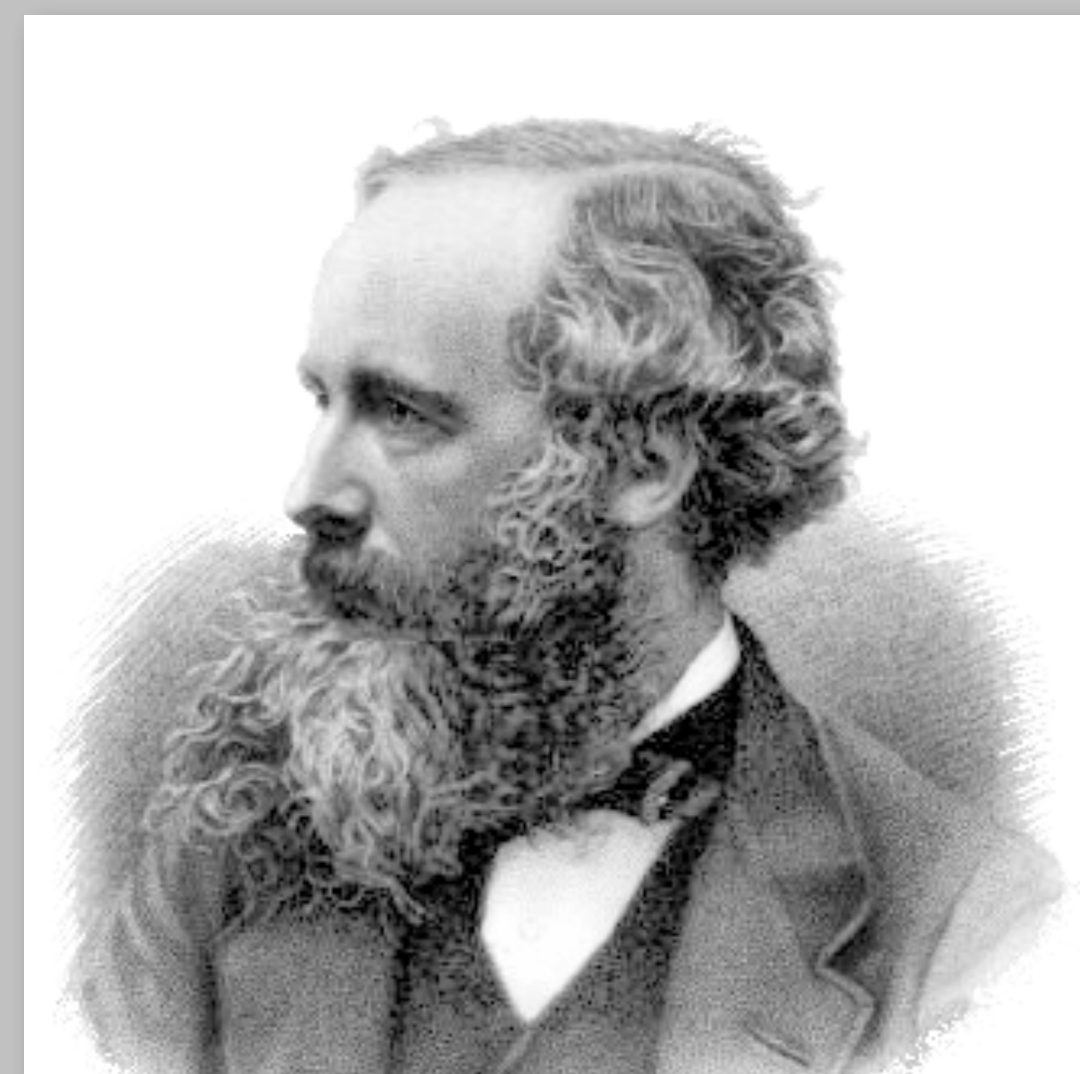
Microscope objective

Lens Aberration Example



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

Aberrations Are Fundamental & Unavoidable



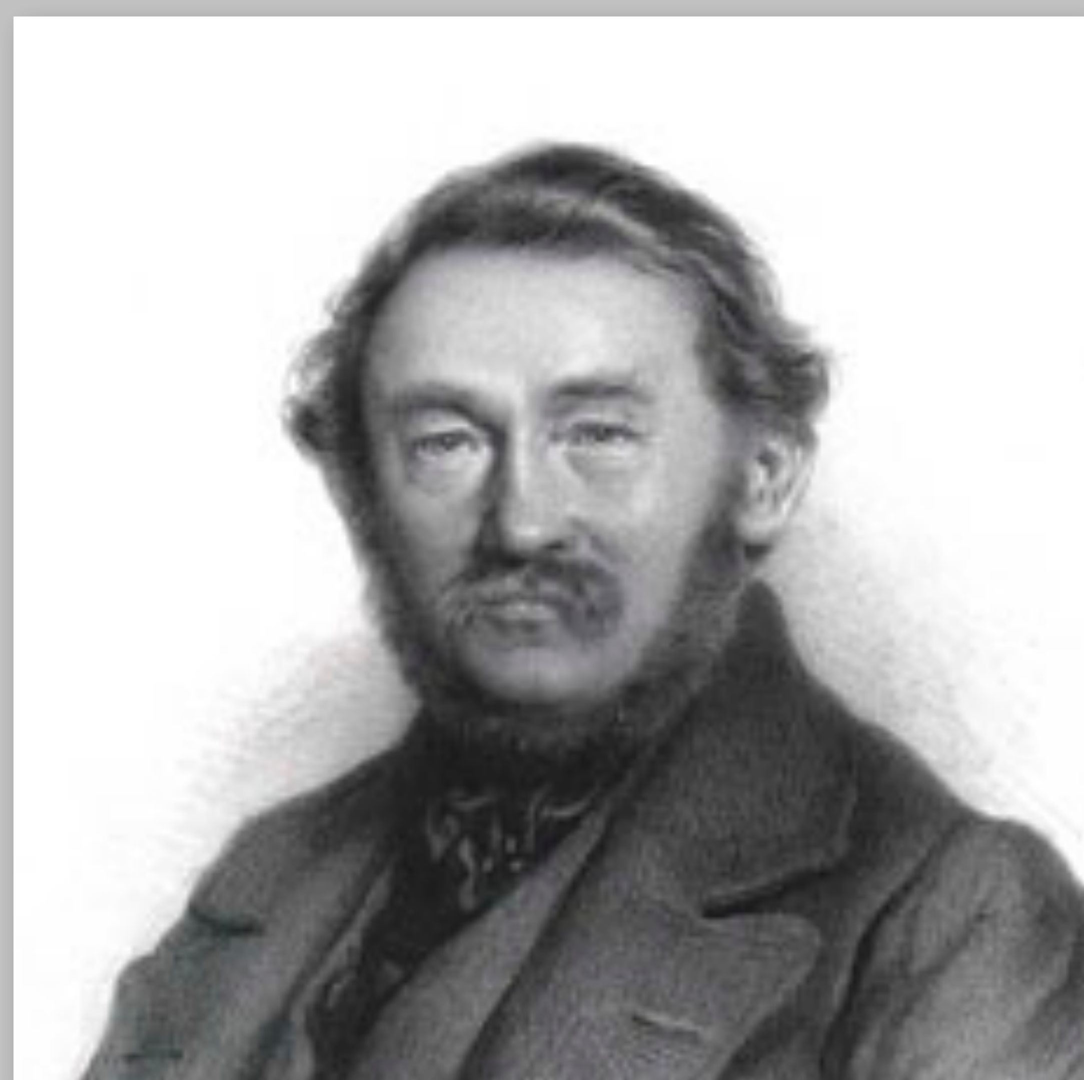
J. C. Maxwell, 1858. "On the general laws of optical instruments," The Quarterly Journal of Pure and Applied Mathematics 2, pp. 233–246, 1858.

Lens Design in 1839

Louis Daguerre

Chevalier Lens (f/16)

Lens Design in 1839

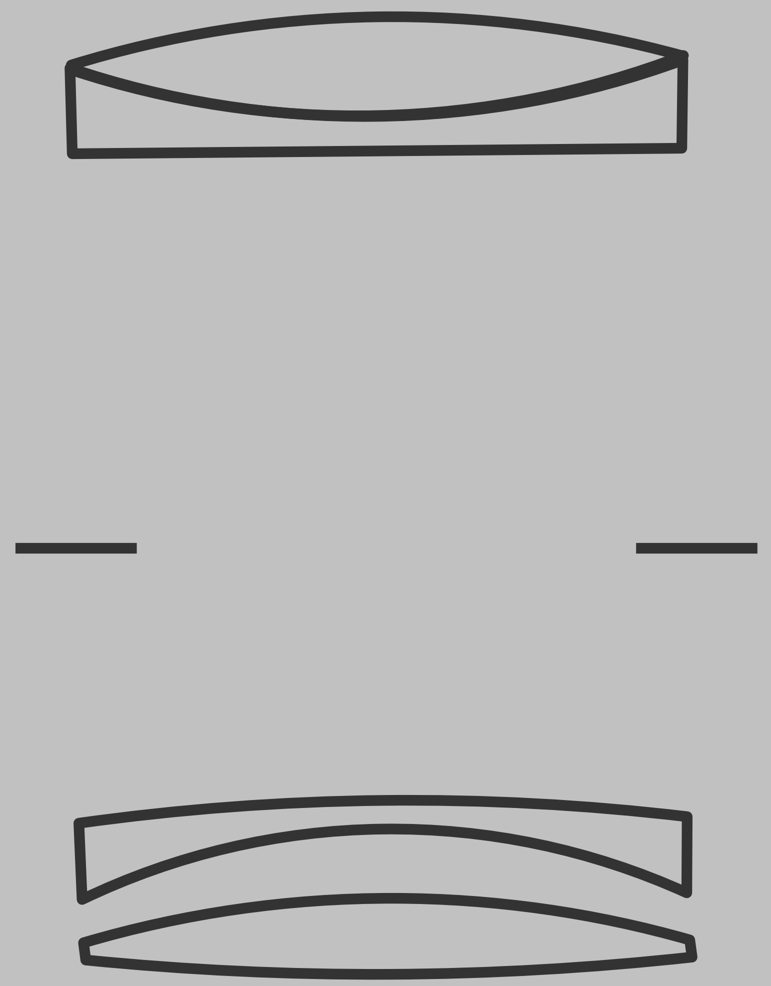


Joseph Petzval

Petzval Portrait Lens (f/3.6)

Lens Design in 1839

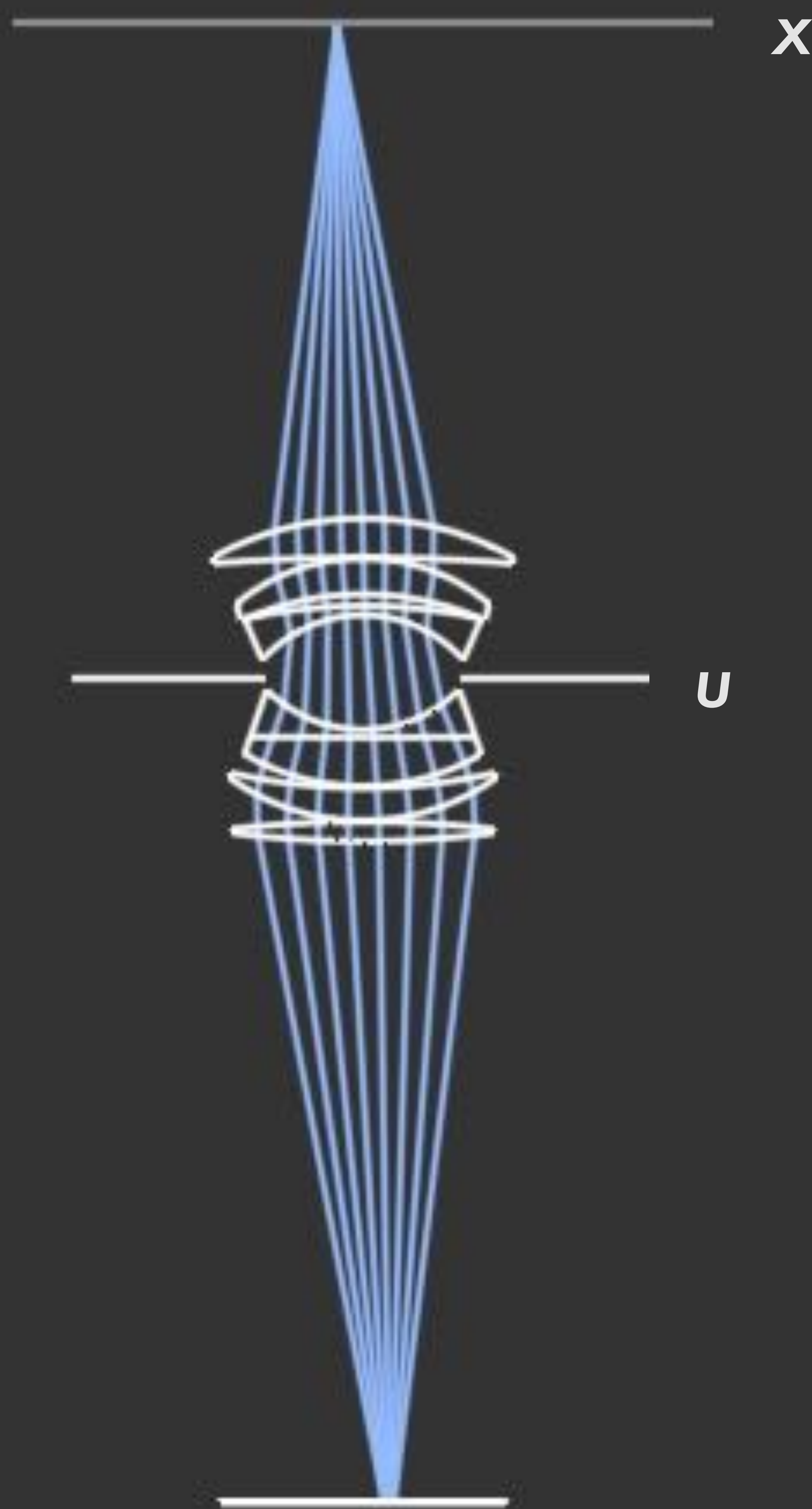
Joseph Petzval

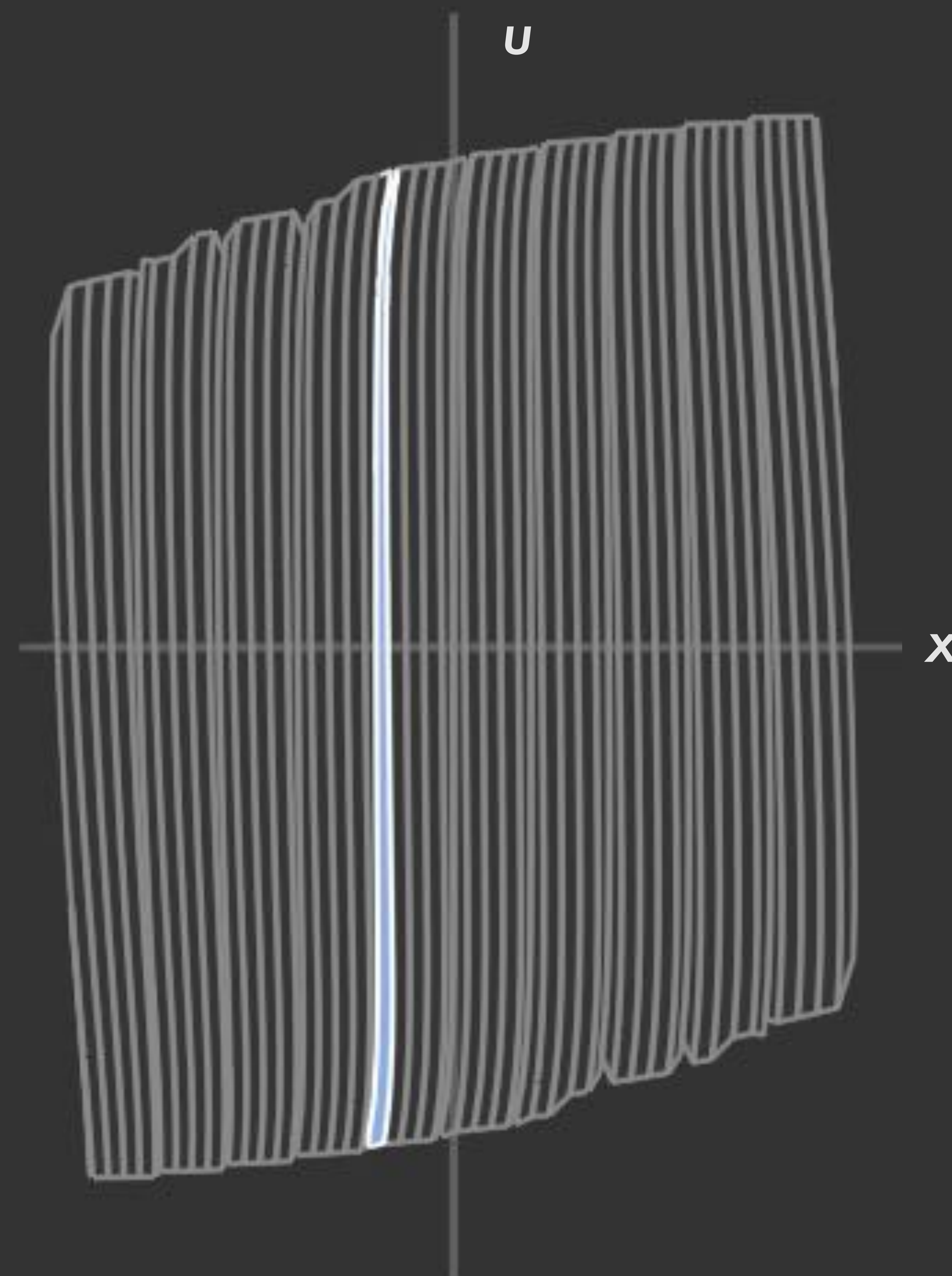


Petzval Portrait Lens (f/3.6)

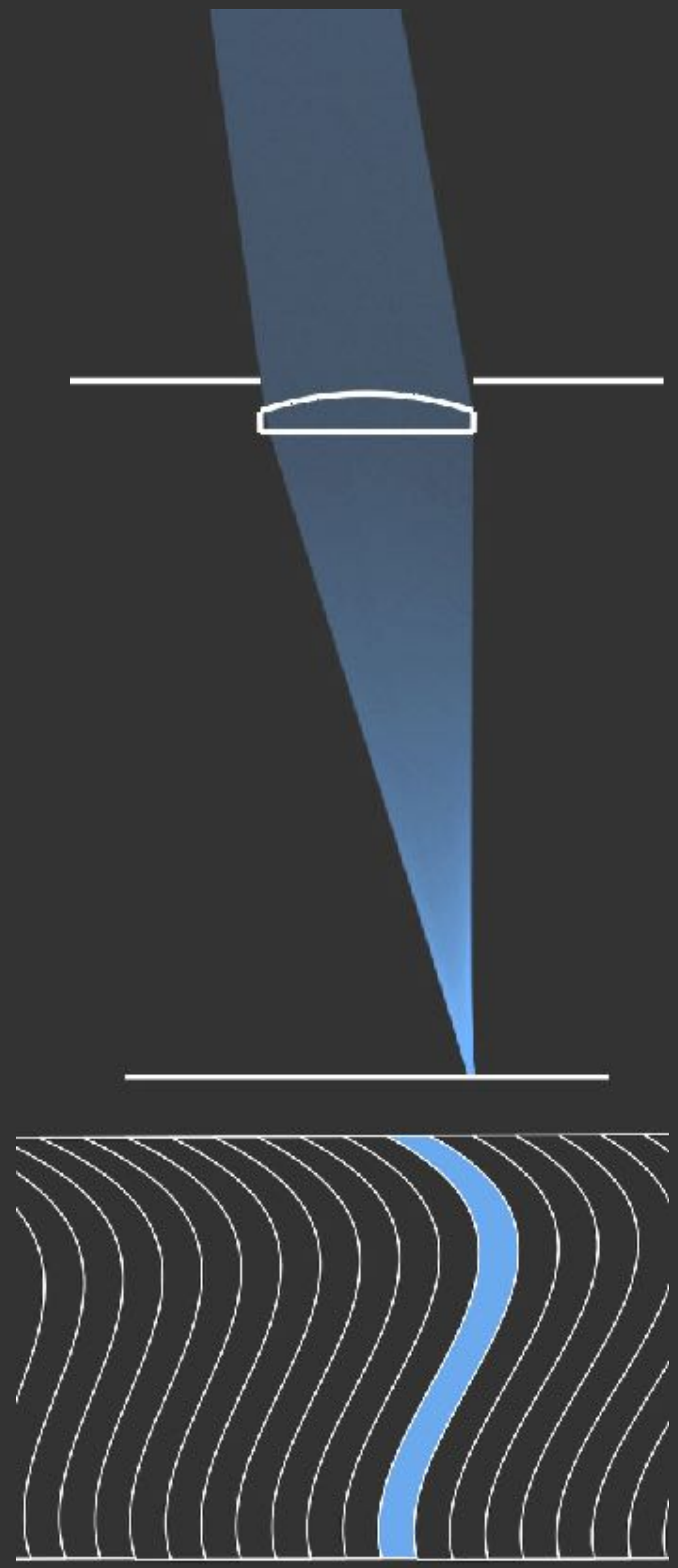
Petzval Portrait Lens

Recall: What Does a 2D Photograph Record?

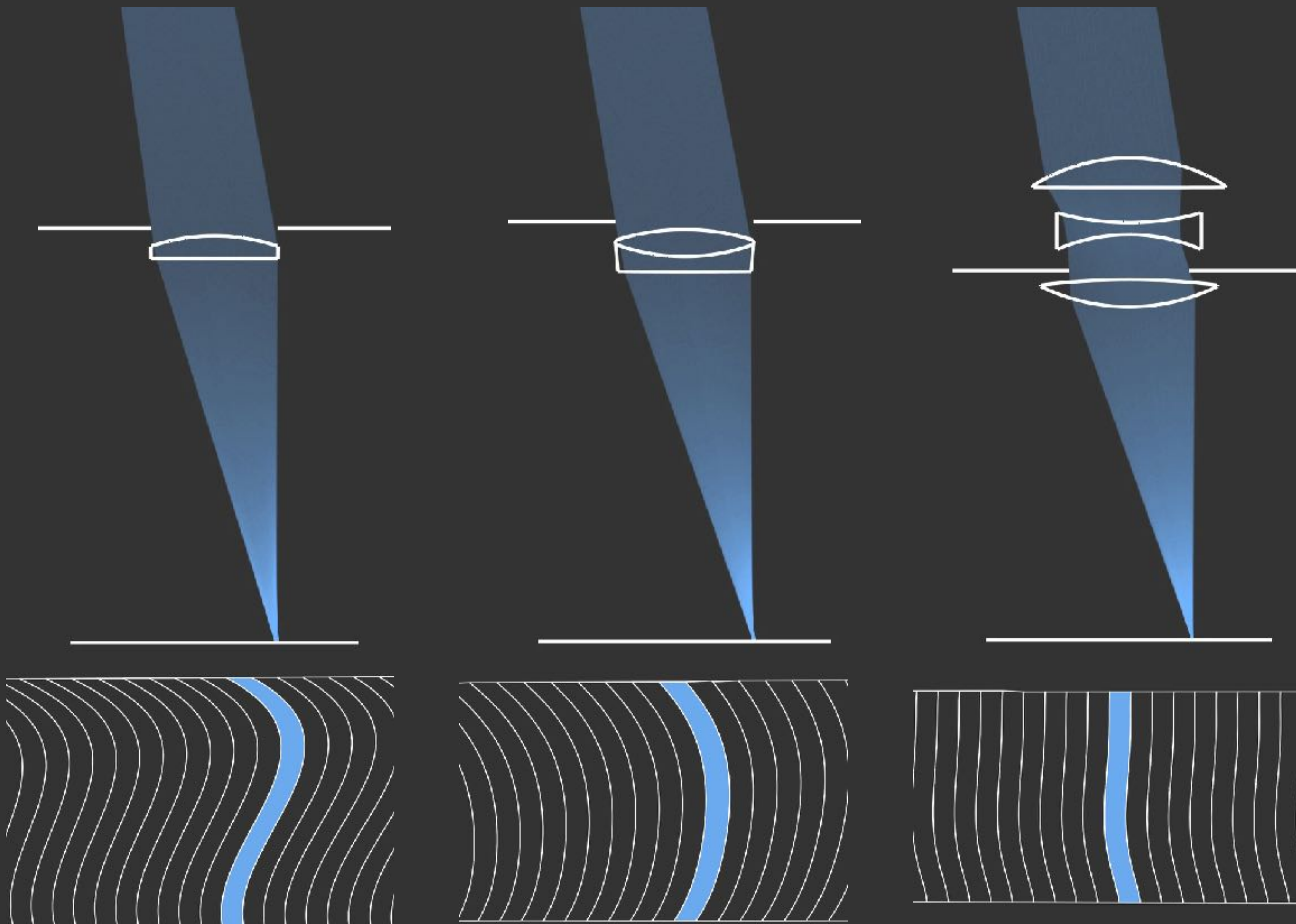




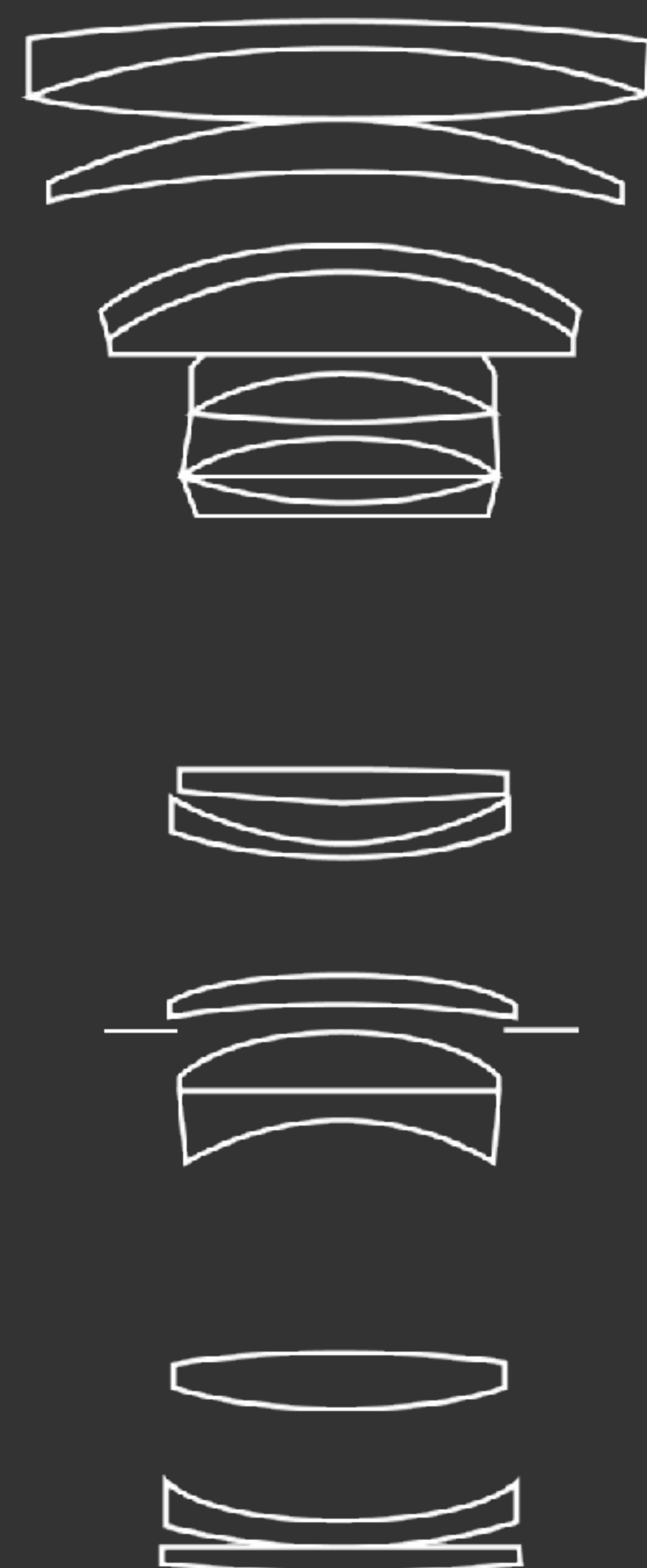
Aberrations Are Curvature in the Ray-Space



Aberration Correction by Adding Elements



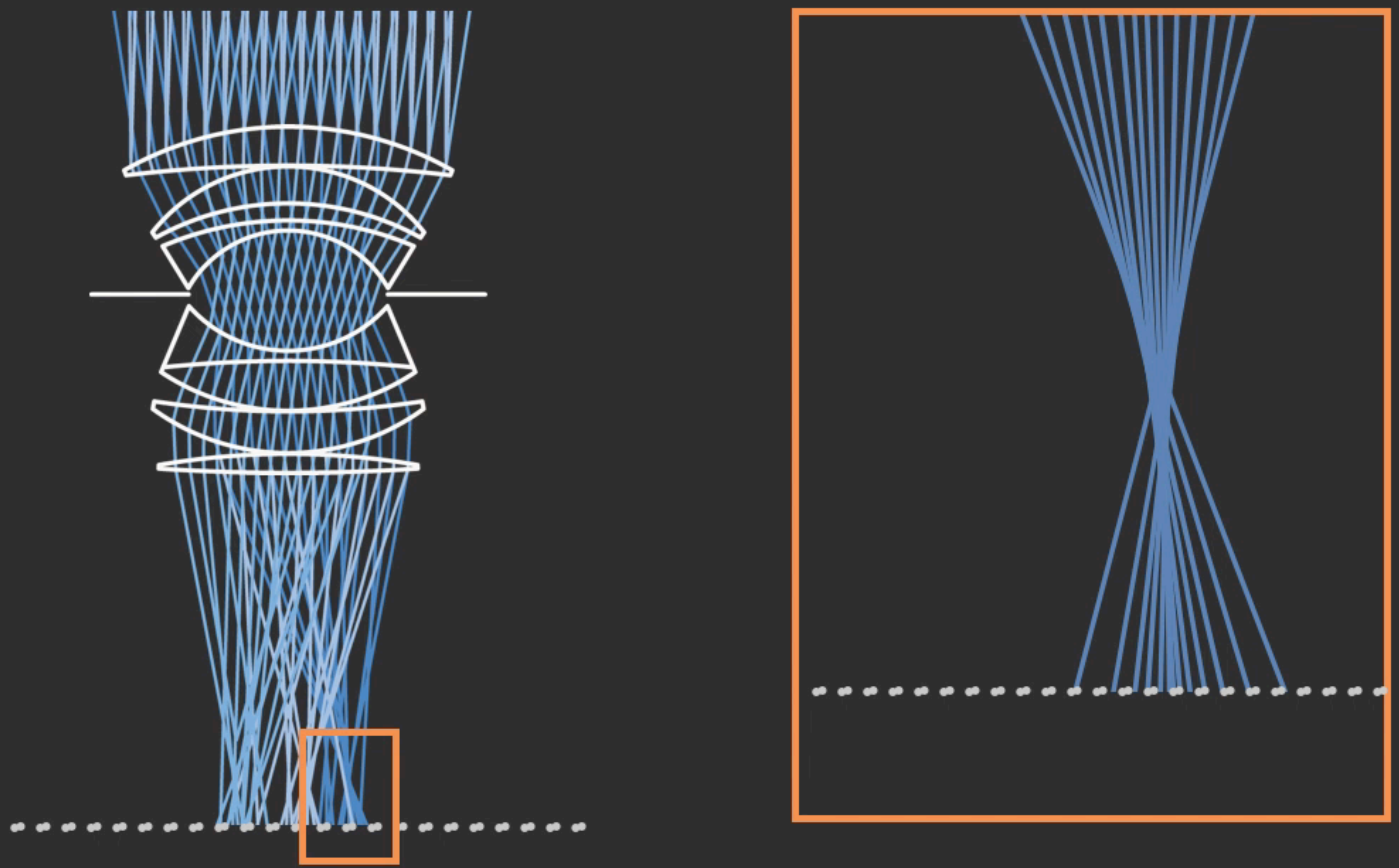
Aberration Correction by Adding Elements



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

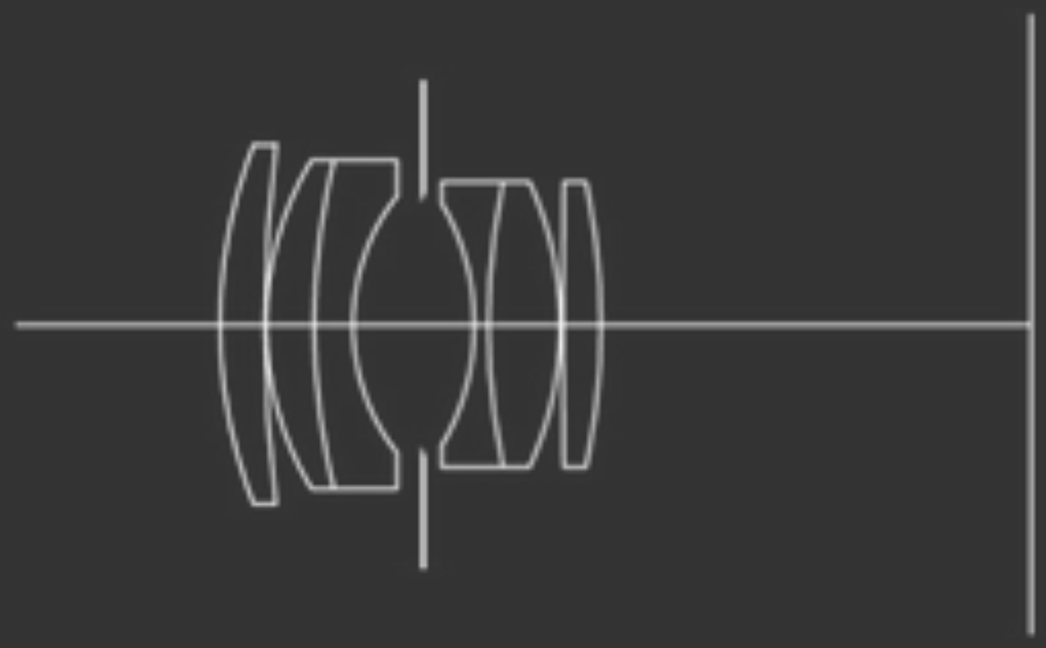
- Real: Geometrical optics (ray-tracing, aberrations)
- Ideal: Paraxial optics (matrix methods, aberration-free)

- 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

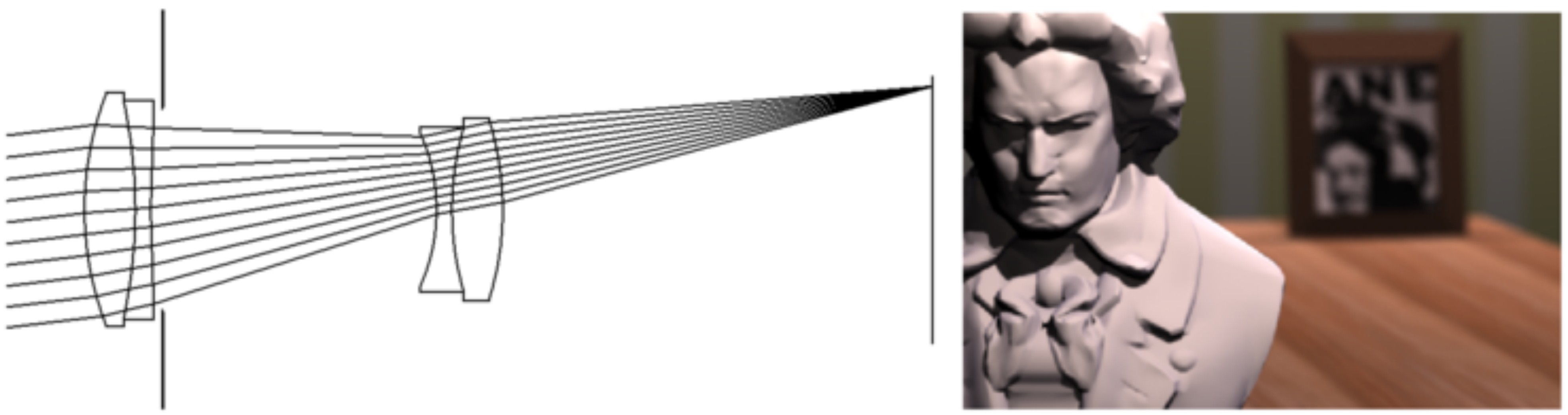
Double Gauss Lens

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

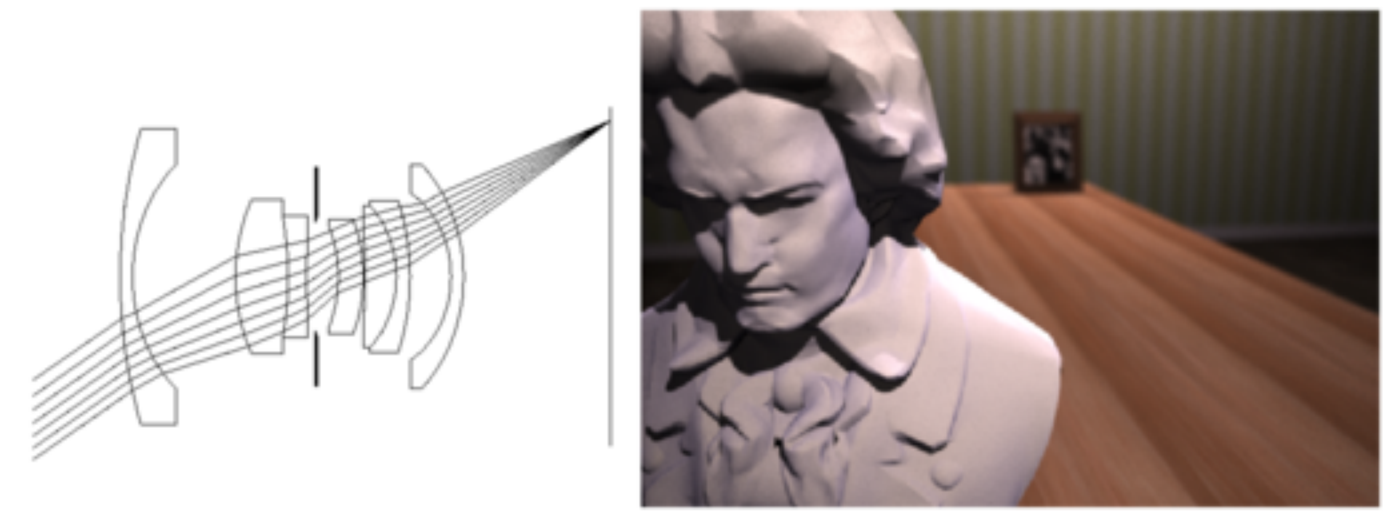


From W. Smith, Modern Lens Design, p. 312

Ray Tracing Through Real Lens Designs



200 mm telephoto



35 mm wide-angle

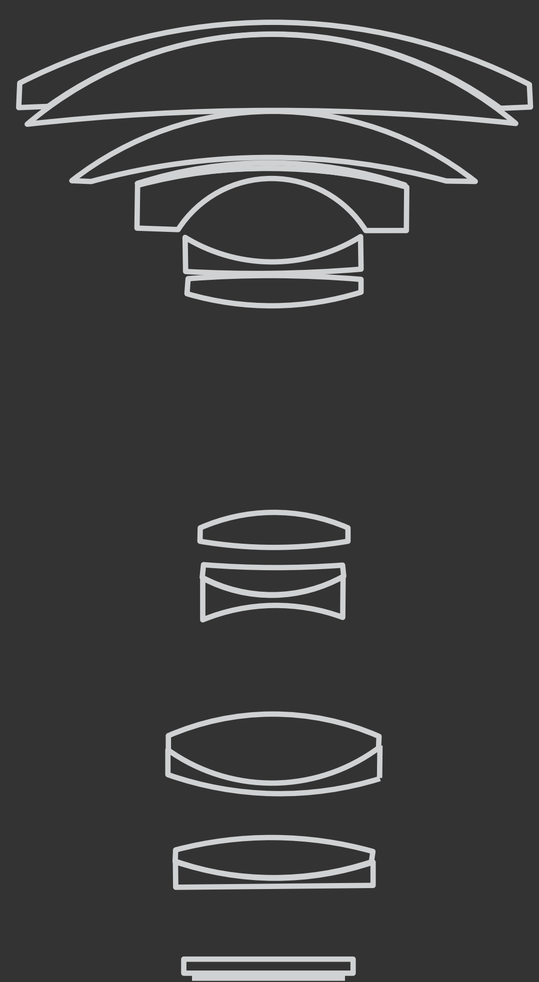
50 mm double-gauss

16 mm fisheye

From Kolb, Mitchell and Hanrahan (1995)

Design Better Lenses Assuming Light Field Imaging

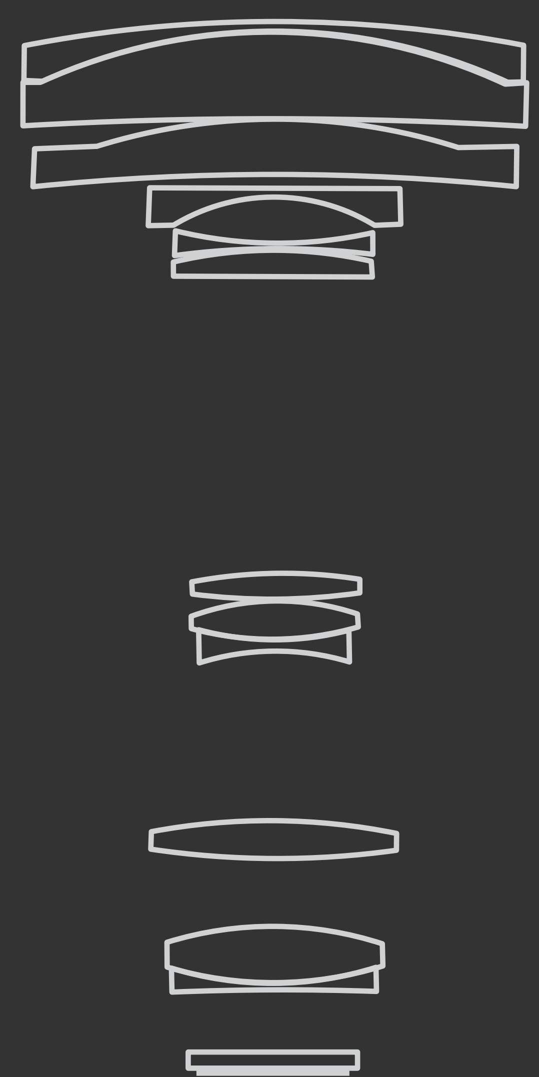
Without Light Field Correction



- F2 aperture
- >3x zoom not achievable

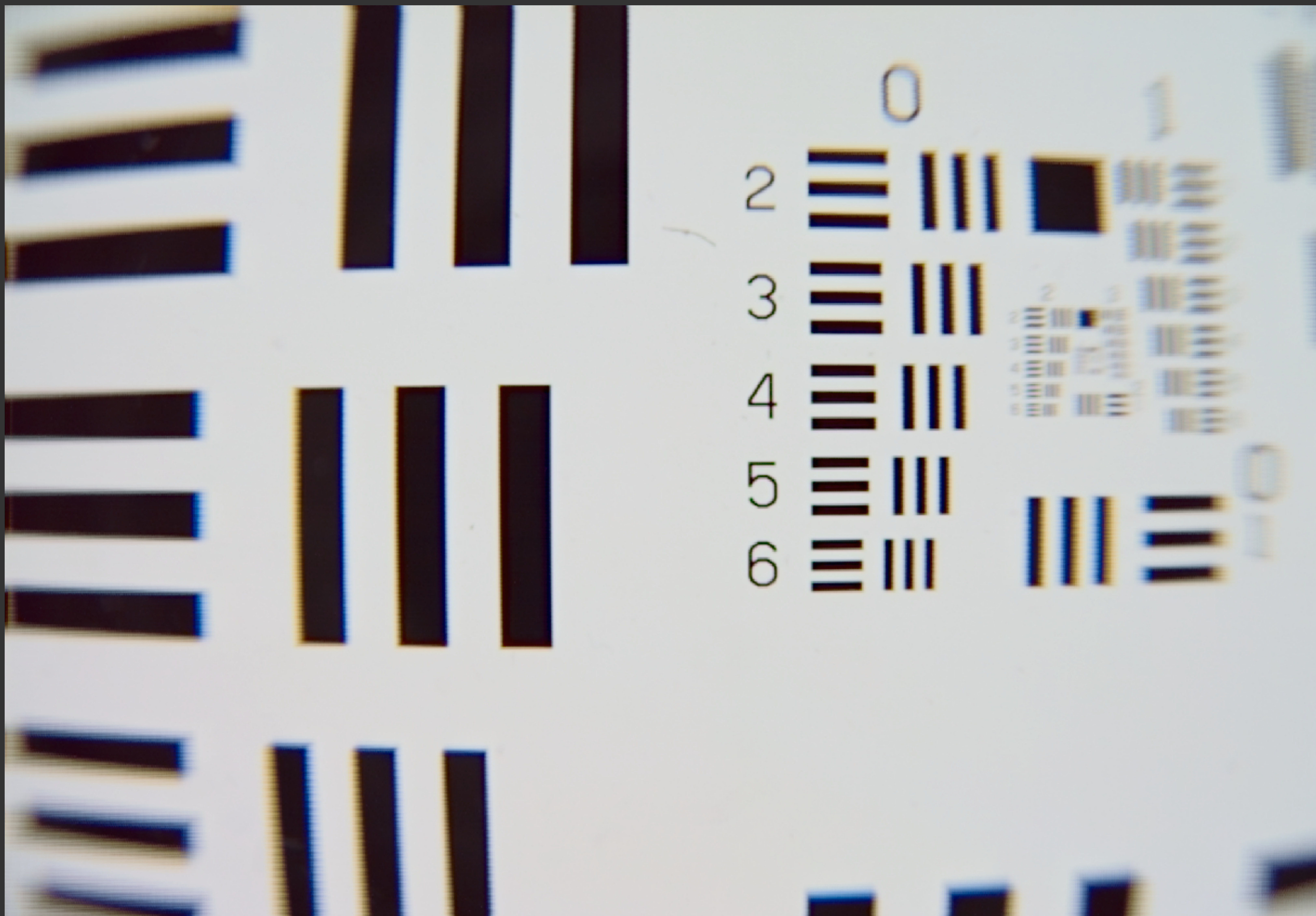
- 16 elements total
- 3 aspheric elements

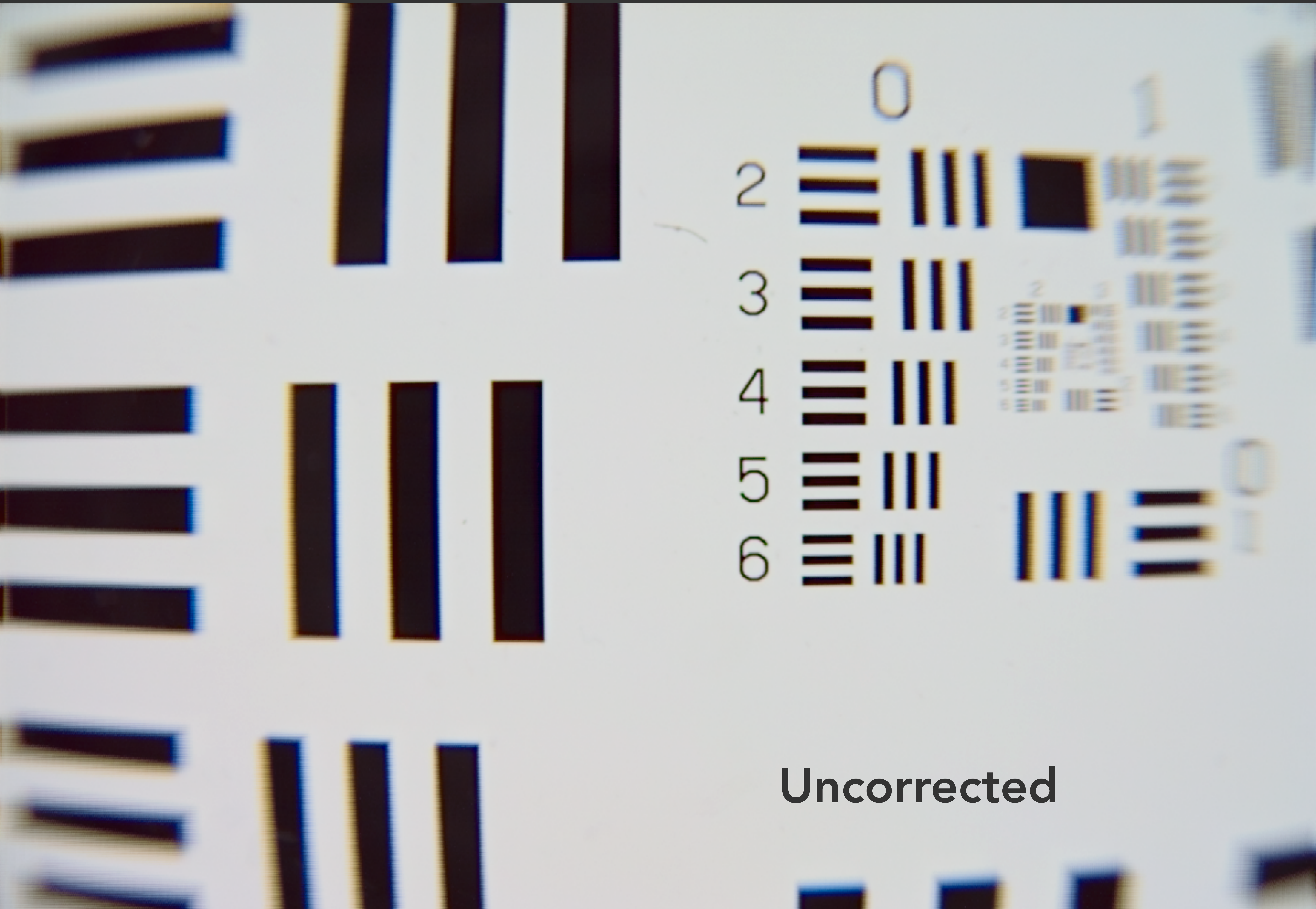
With Light Field Correction



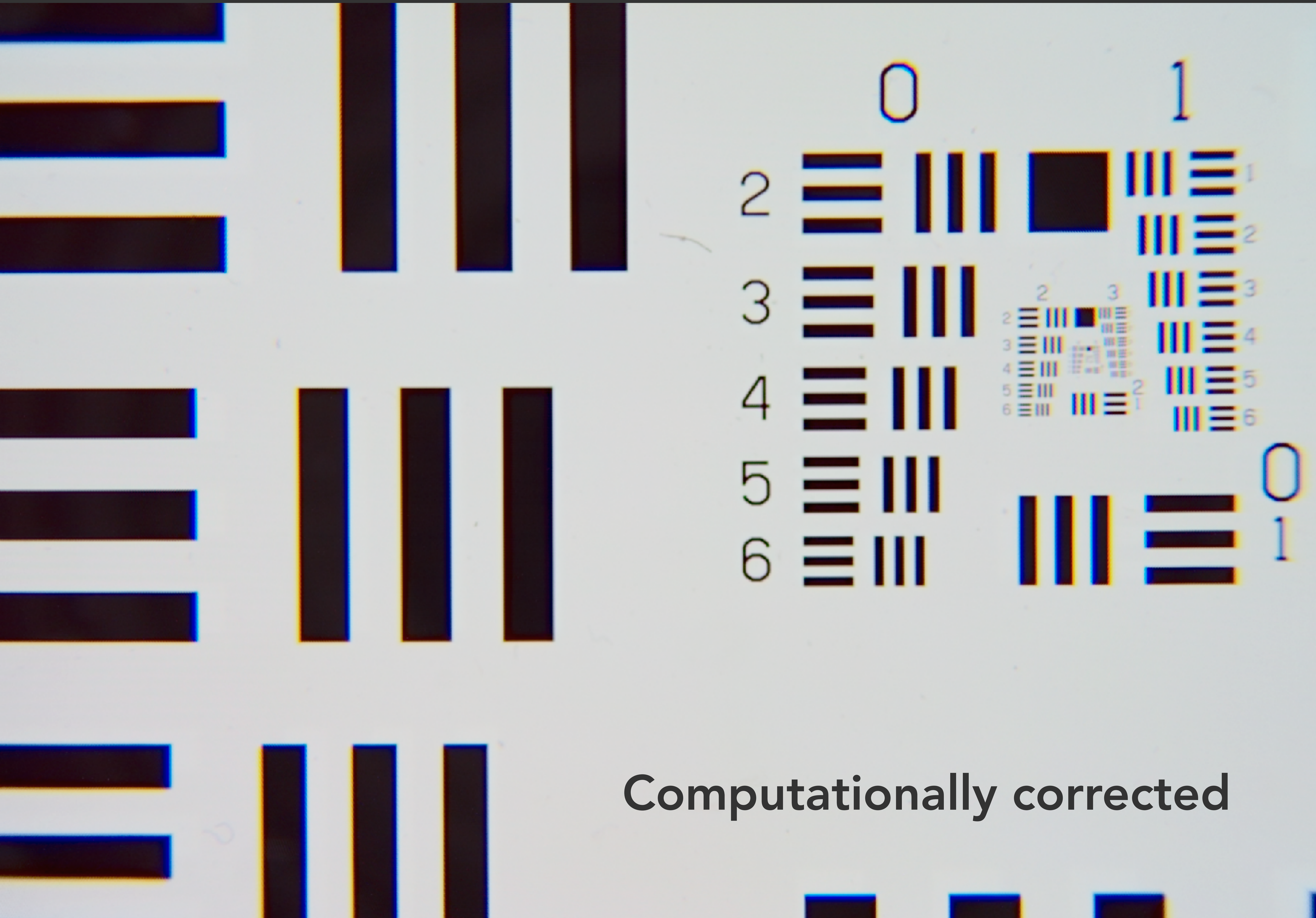
- F2 aperture
- 8x zoom
  2.83x larger max focal length
  20% longer lens
- 13 elements total
- 0 aspheric elements

Lens Needs Computation For Good Performance





Uncorrected



Computationally corrected


Uncorrected


Computationally corrected