Lecture 15 / 16:

Cameras & Lenses

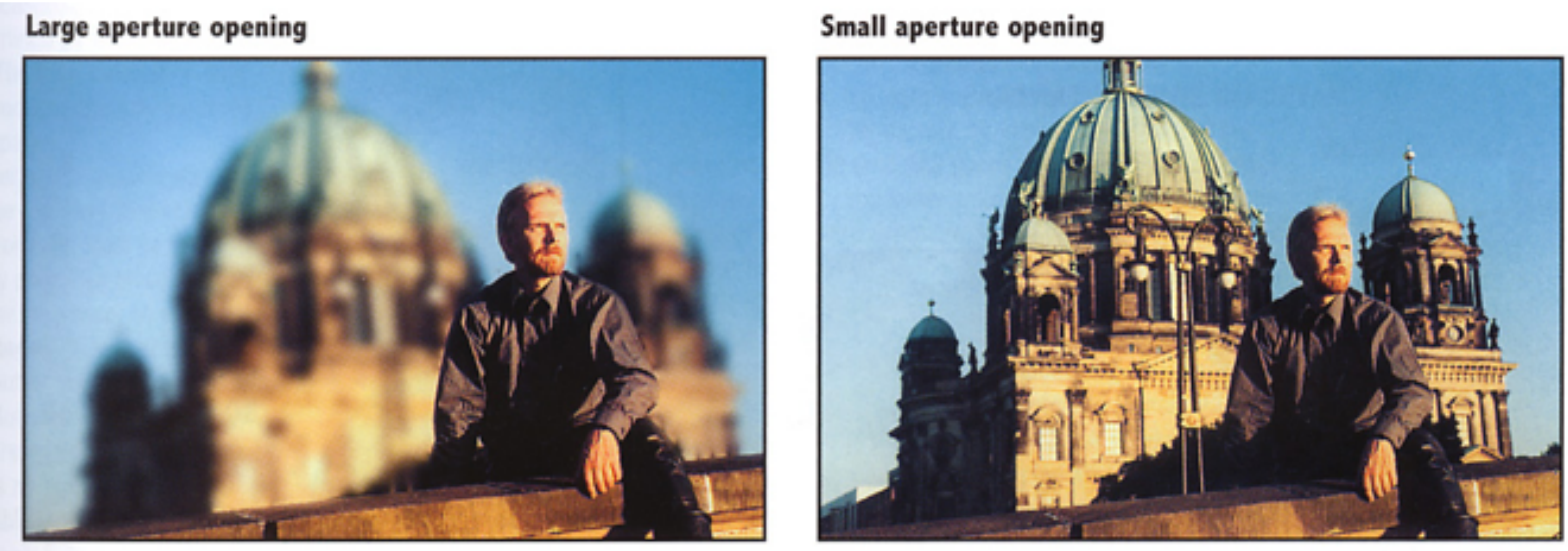
Computer Graphics and Imaging

UC Berkeley CS184/284A

Continued…

Depth of Field

Depth of Field (DOF)



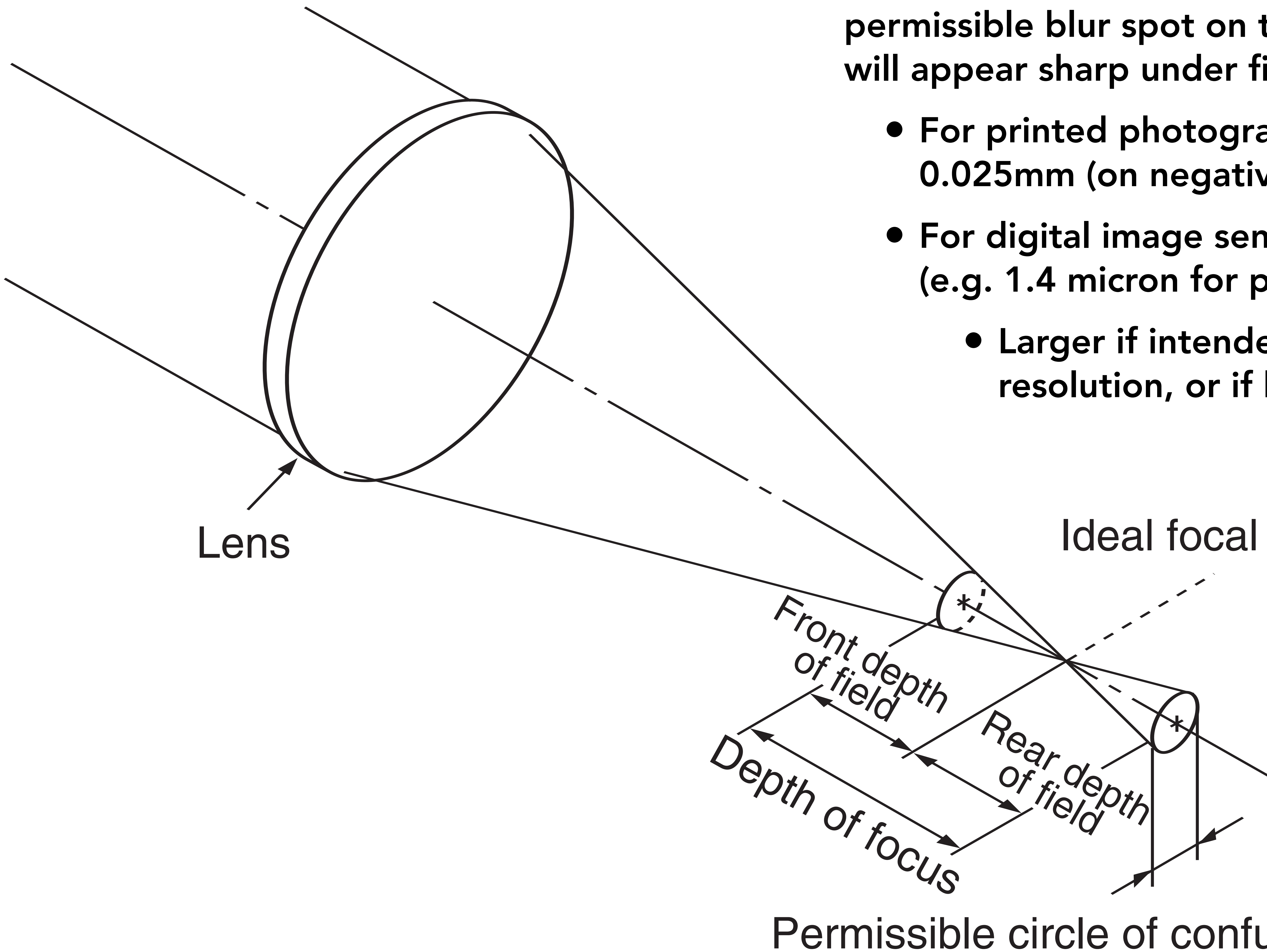
From London and Upton

- Depth of field is the range of object depths that are rendered with acceptable sharpness in an image

Circle of Confusion for Depth of Field

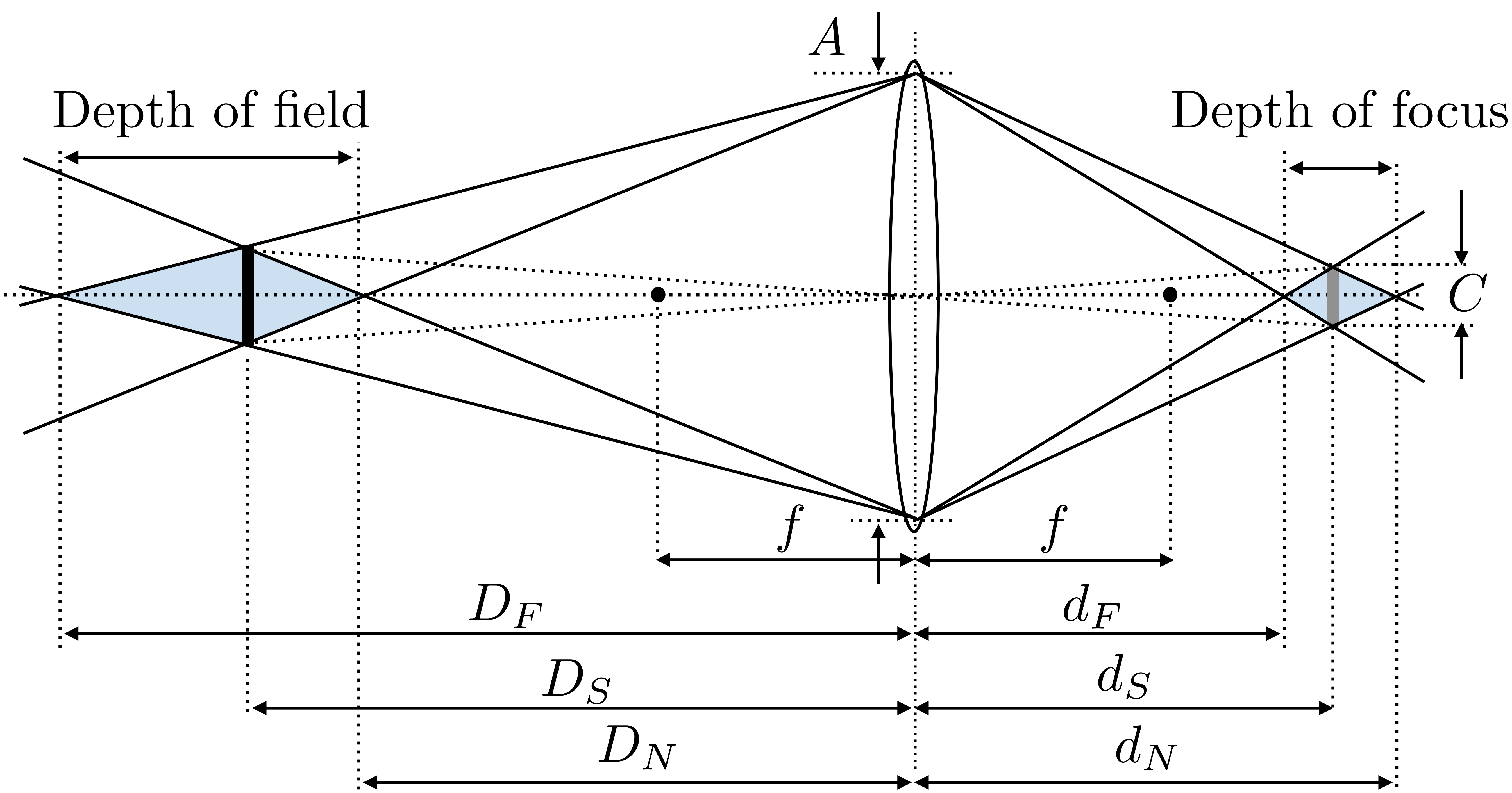
Set circle of confusion as the maximum permissible blur spot on the image plane that will appear sharp under final viewing conditions

- For printed photographs from 35mm film, 0.025mm (on negative) is typical
- For digital image sensors, 1 pixel is typical (e.g. 1.4 micron for phones)
  - Larger if intended for viewing at web resolution, or if lens is poor



[Canon, EF Lens Work III]

Depth of Field



$$\frac{d_N - d_S}{d_N} = \frac{C}{A}$$

$$\frac{d_S - d_F}{d_F} = \frac{C}{A}$$

$$N = \frac{f}{A}$$

$$\frac{1}{D_F} + \frac{1}{d_F} = \frac{1}{f}$$

$$\frac{1}{D_S} + \frac{1}{d_S} = \frac{1}{f}$$

$$\frac{1}{D_N} + \frac{1}{d_N} = \frac{1}{f}$$

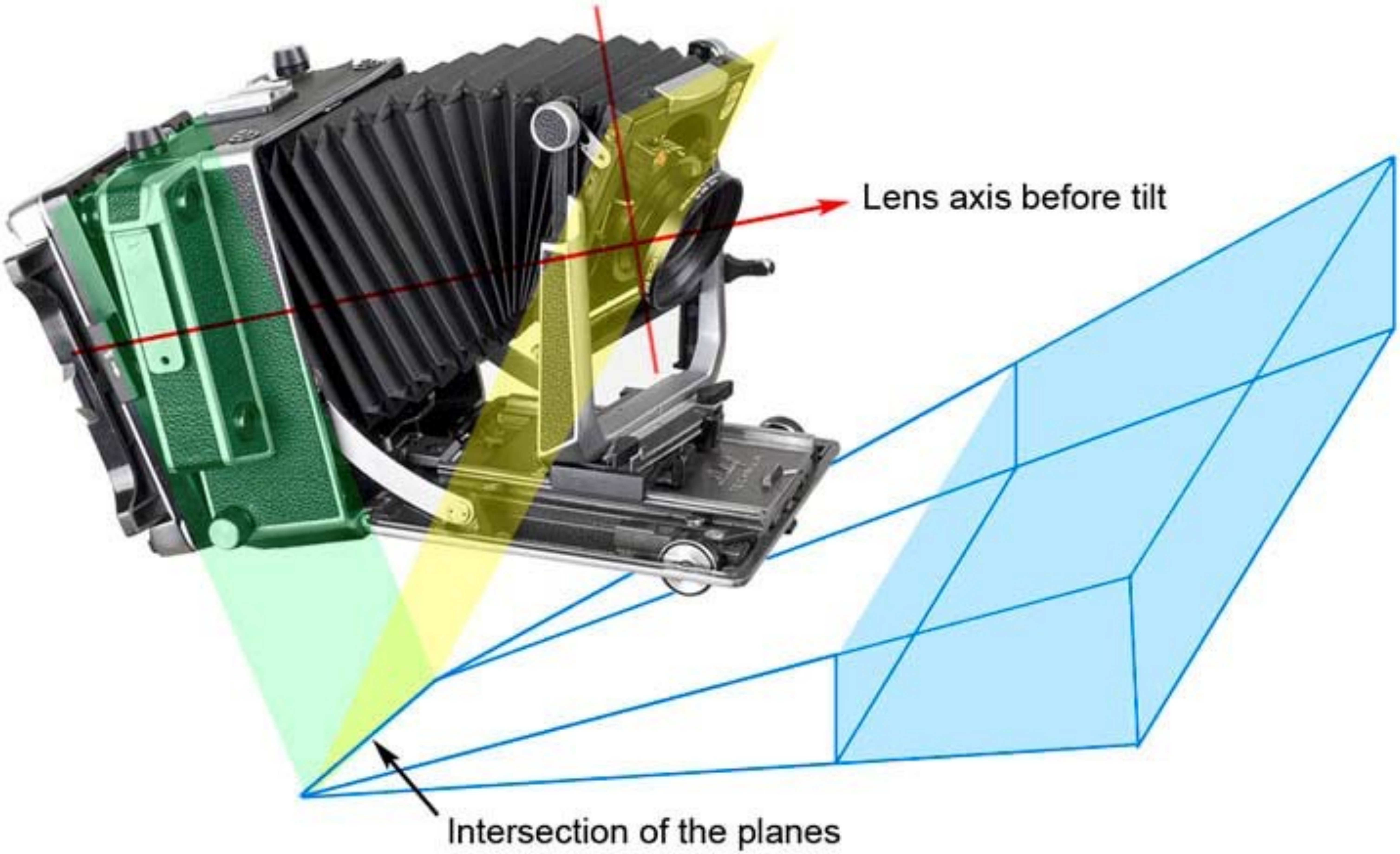
$$\mathrm{DOF} = D_F - D_N$$

$$D_F = \frac{D_S f^2}{f^2 - NC(D_S - f)} \qquad D_N = \frac{D_S f^2}{f^2 + NC(D_S - f)}$$

Other Focus / DOF Situations to Consider

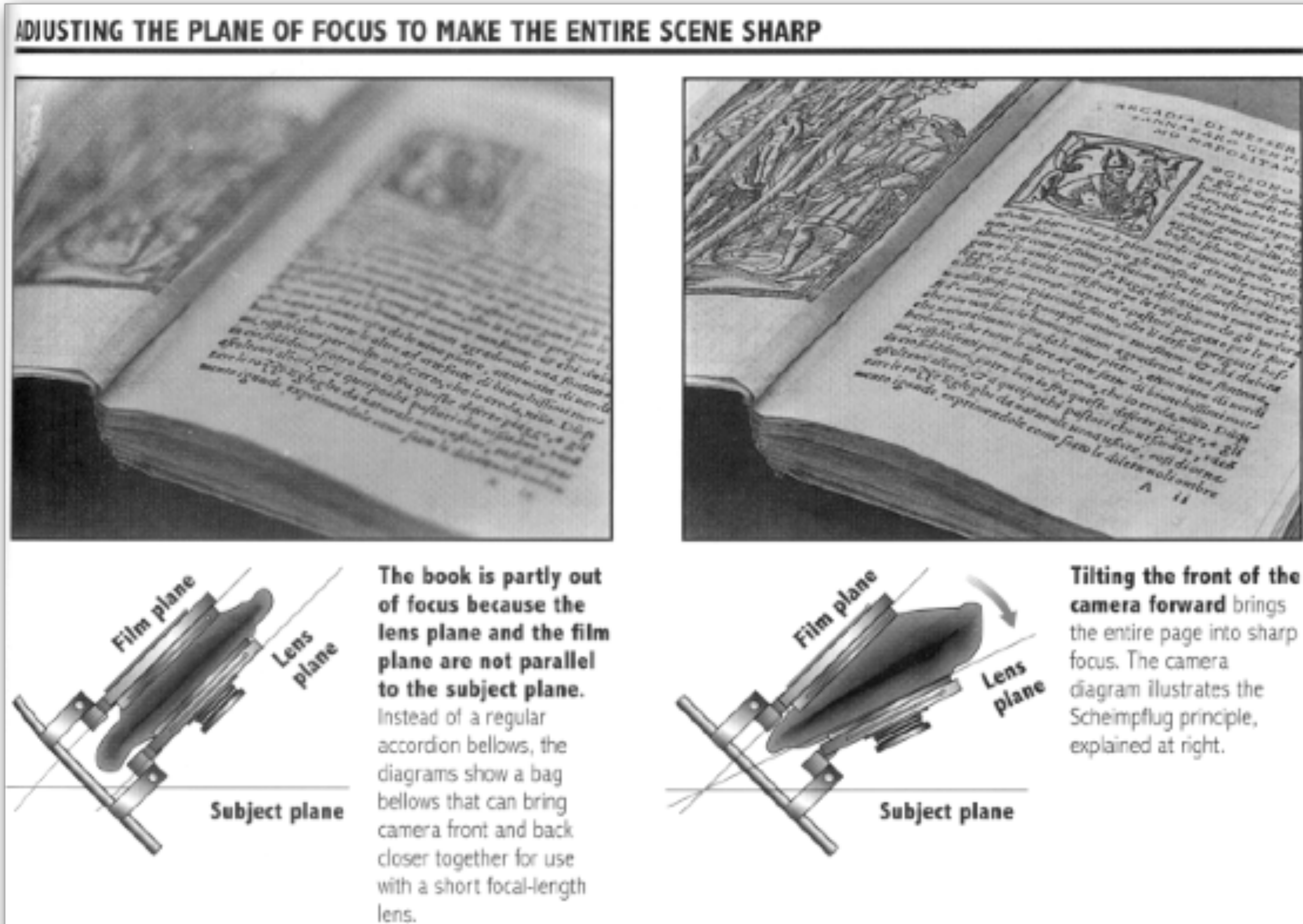
- How does sensor size affect defocus blur and DOF?
  - E.g. consider cell phone vs 35mm format sensors
- For a given lens & f-stop, how does moving closer/further from the subject (and adjusting focus onto subject) affect defocus / DOF of other objects?
- In 1:1 macro, does focal length affect DOF?
- What is the lens-sensor separation for hyperfocal condition (largest DOF possible), for full-resolution viewing vs web-resolution viewing?

View Camera, Scheimpflug Rule



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

View Camera, Scheimpflug Rule



[London]

Ray Tracing Ideal Thin Lenses

Example of Rendering with Lens Focus

Credit: Bertrand Benoit. “Sweet Feast,” 2009. [Blender /VRay]

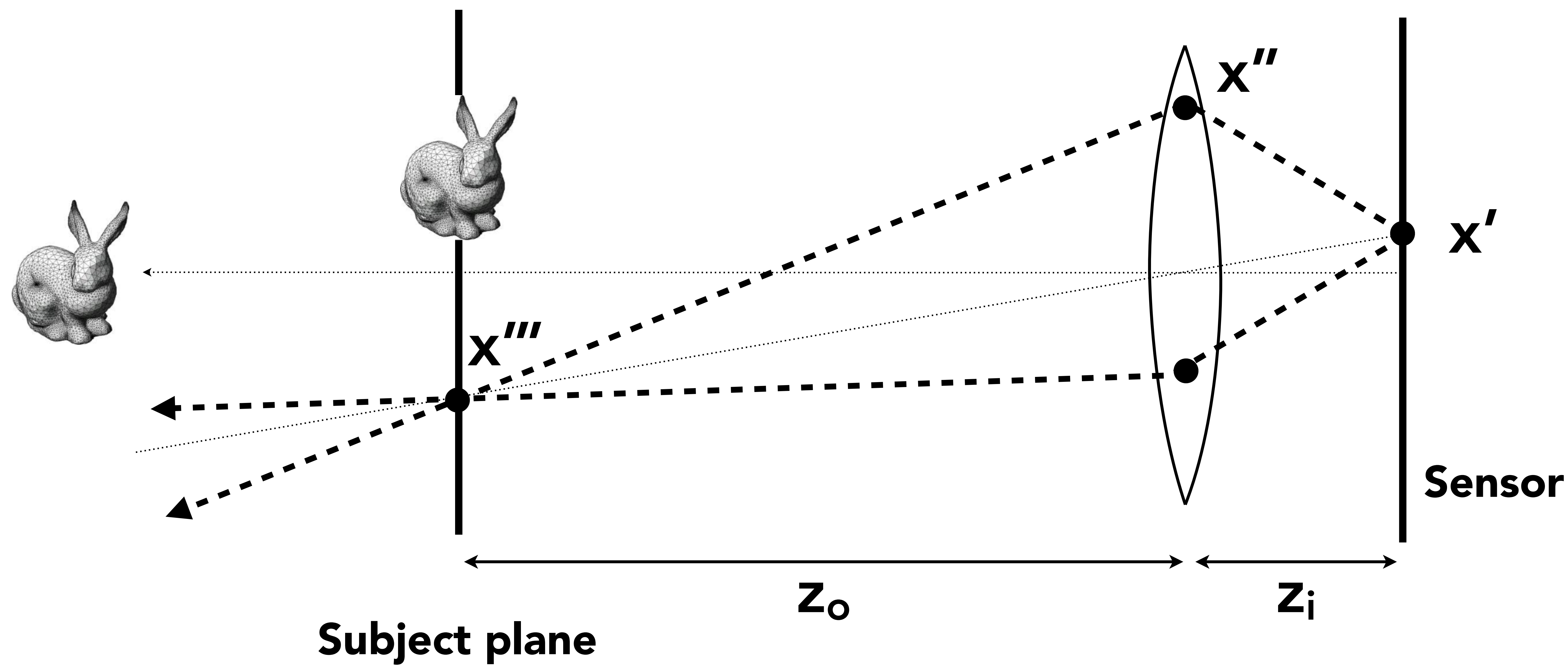
Example of Rendering with Lens Focus

Credit: Giuseppe Albergo. “Colibri” [Blender]

Example of Rendering with Lens Focus

Pharr and Humphreys

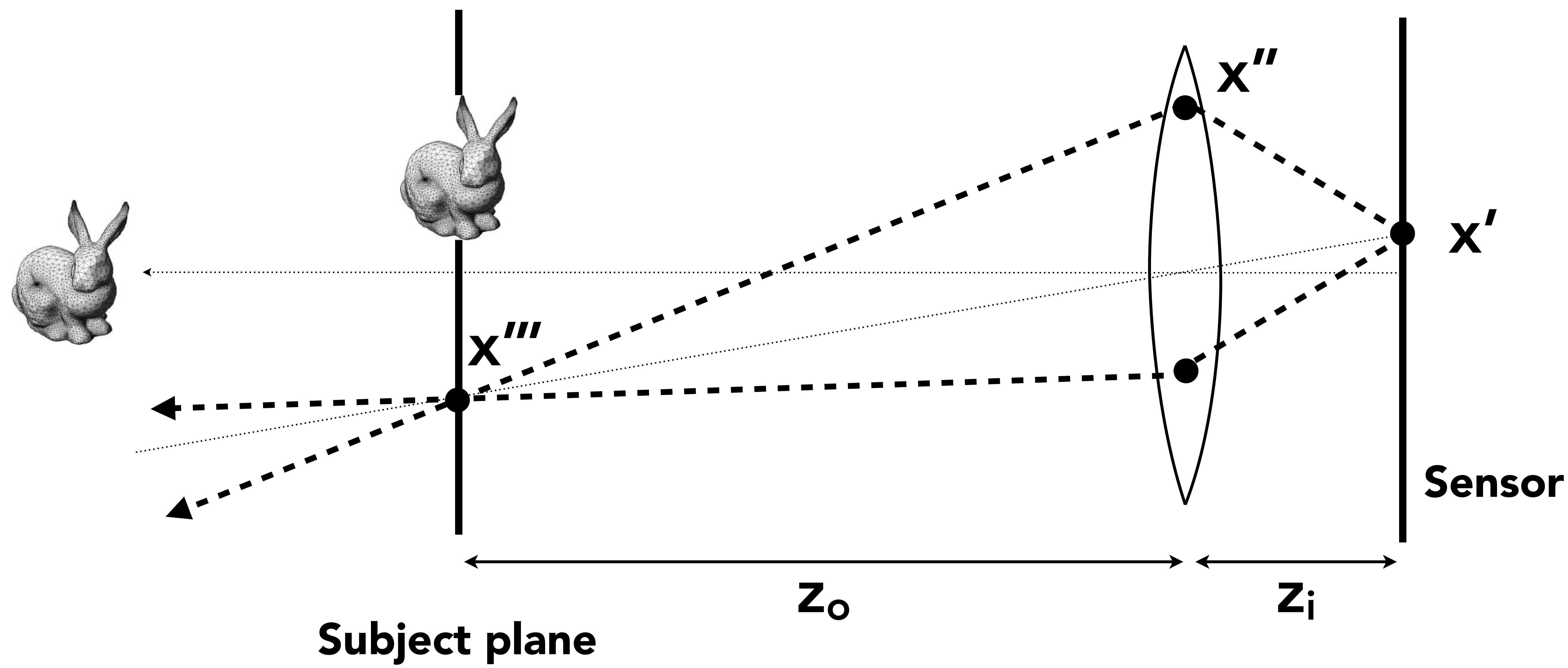
Ray Tracing for Defocus Blur (Thin Lens)



Setup (photography composition principles)

- Choose sensor size, lens focal length and aperture size
- Choose depth of subject of interest z_o
  - Calculate corresponding depth of sensor z_i from thin lens equation (focusing)

Ray Tracing for Defocus Blur (Thin Lens)



To compute value of pixel at position x′ by Monte Carlo integration:

- Select random points x″ on lens plane
- Rays pass from point x′ on image plane z_i through points x″ on lens
- Each ray passes through conjugate point x‴ on the plane of focus z_o
  - Can determine x‴ from Gauss′ ray diagram
  - So just trace ray from x″ to x‴
- Estimate radiance on rays using path-tracing, and sum over all points x″

Example of Rendering with Lens Focus

Pharr and Humphreys

Bokeh

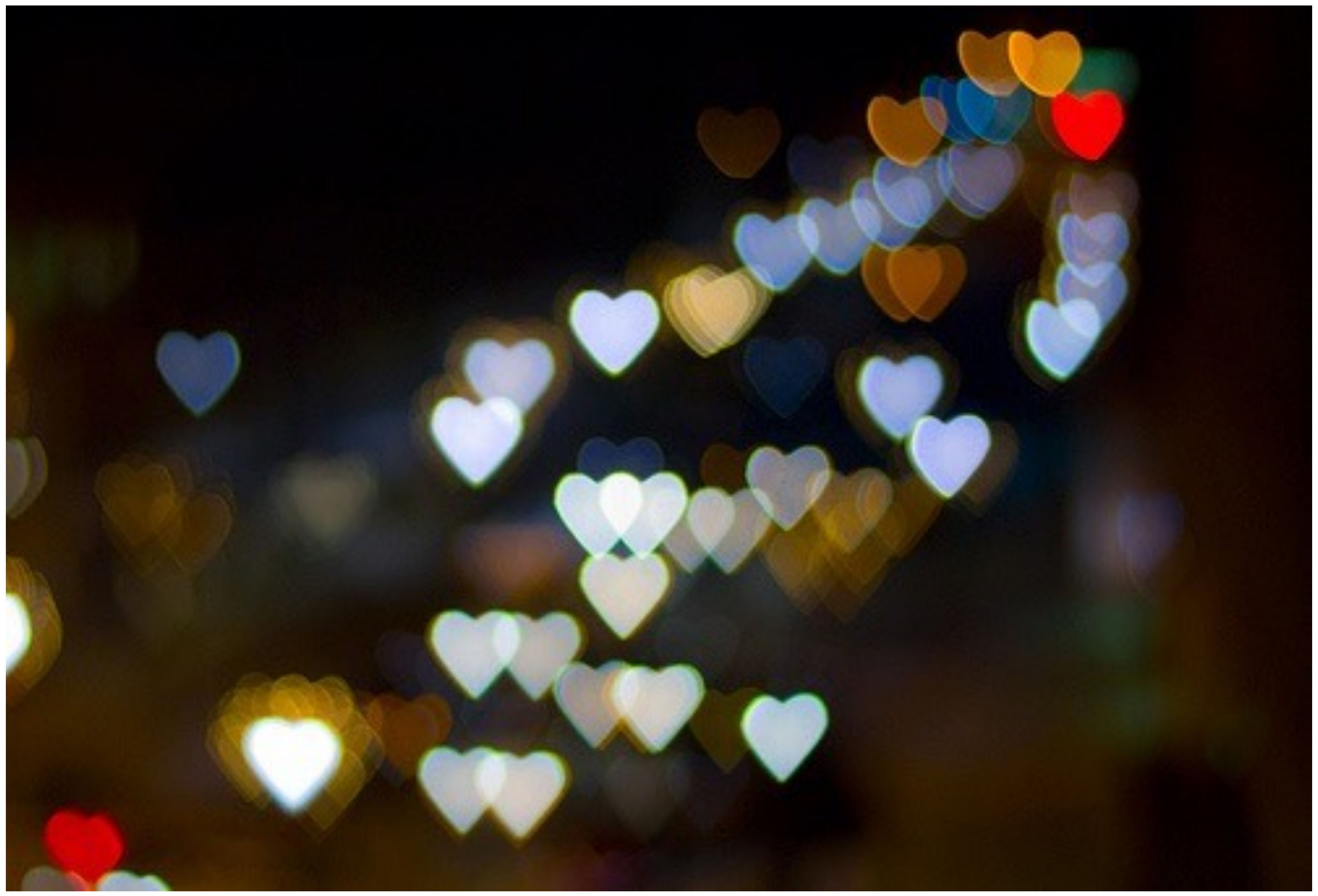
Bokeh

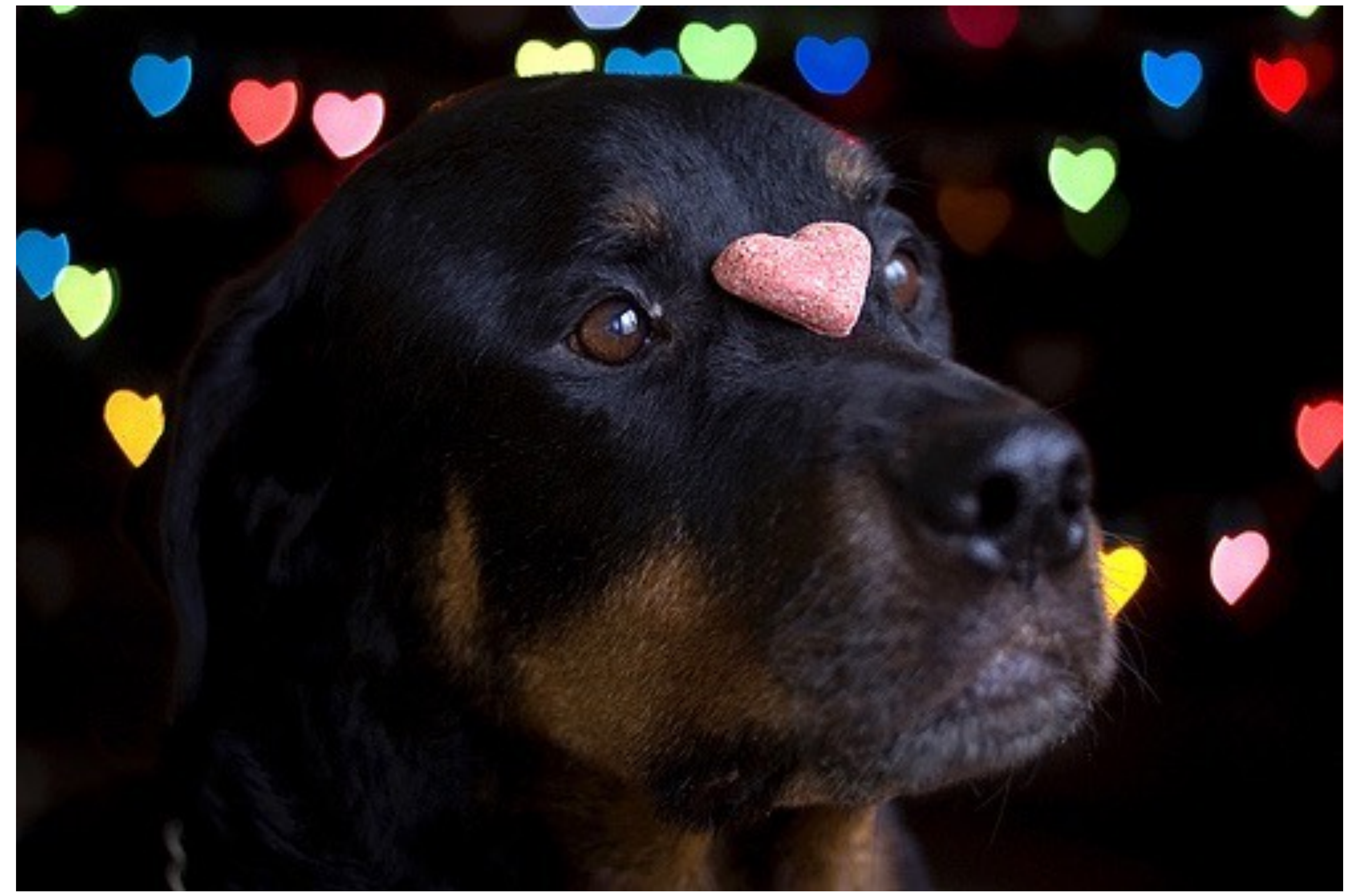
Bokeh is the shape and quality of out-of-focus blur

- For small, out-of-focus lights, bokeh takes on the shape of the lens aperture

M Yashna, flickr, 40mm f/3.0

Bokeh





diyphotography.net

Heart-shaped bokeh?

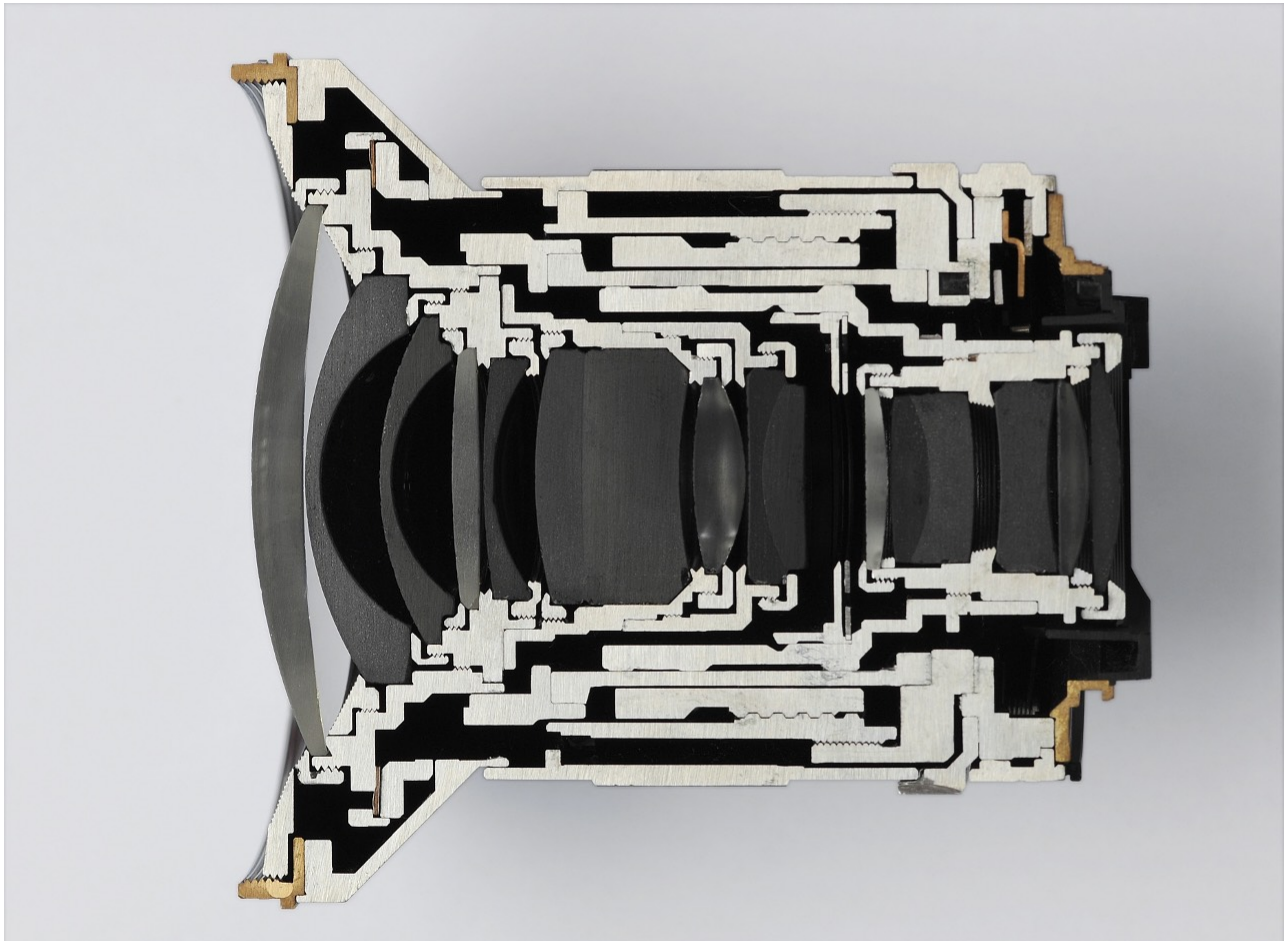
Bokeh

Dino Quinzani, Leica Noctilux 50mm, f/0.95

Why does the bokeh vary across the image?

Real Compound Lenses

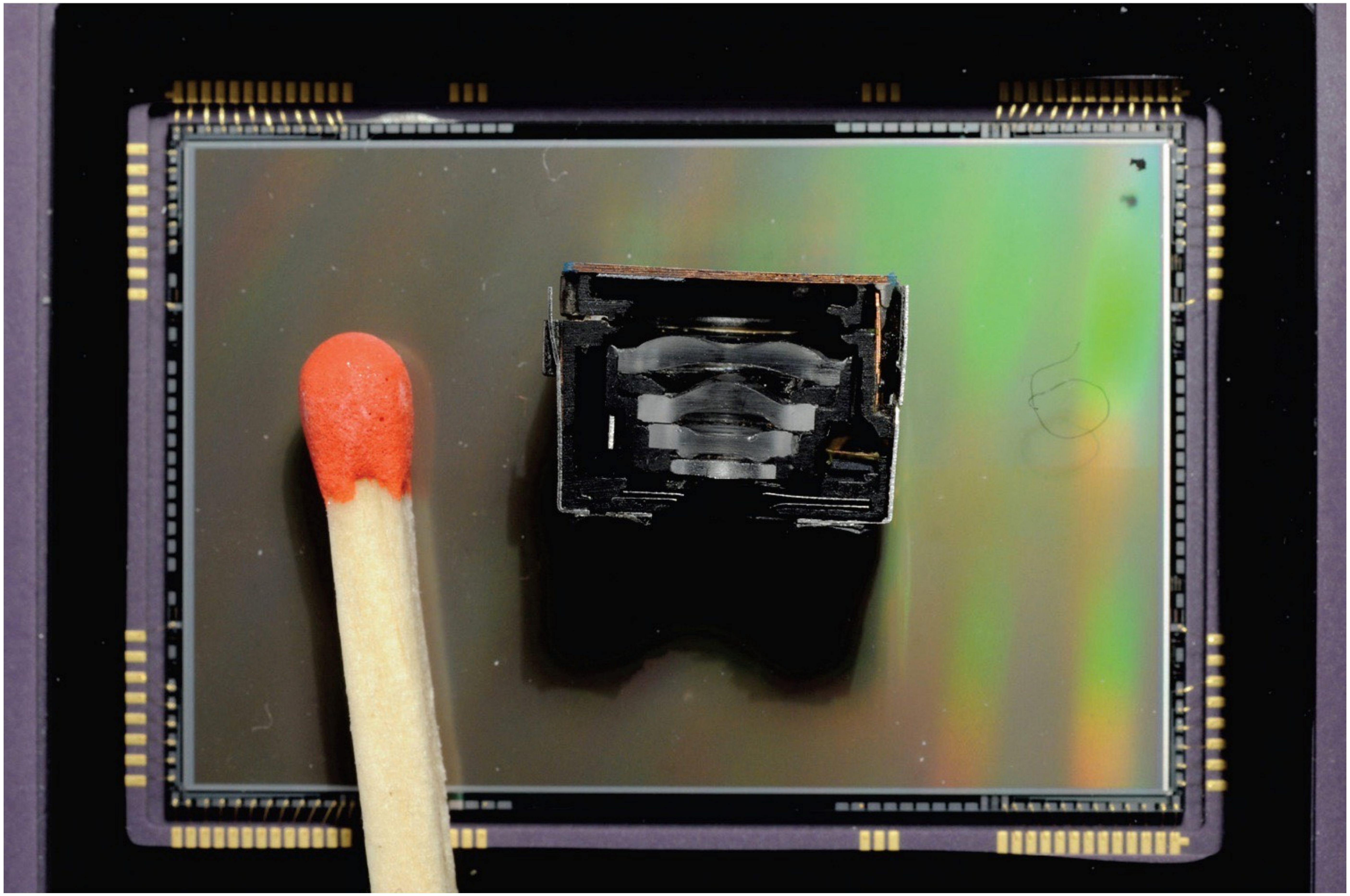
Modern Lens Designs Are Highly Complex



ilovephotography.com

Photographic lens cross section

Modern Lens Designs Are Highly Complex



ilovehatephoto.com

4 element mobile phone lens (on 24x36mm sensor)

Modern Lens Designs Are Highly Complex

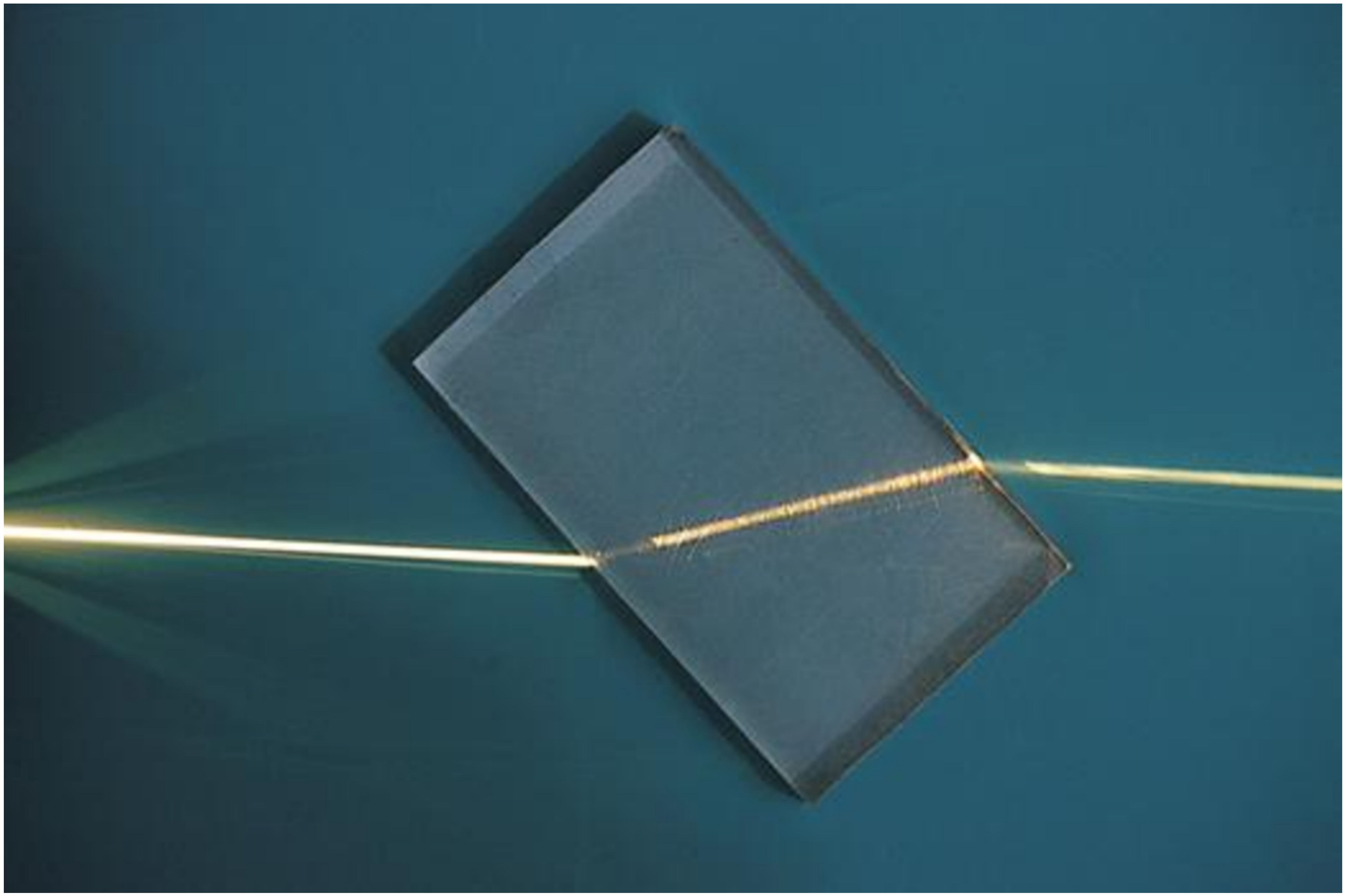
[Apple]

Modern Lens Designs Are Highly Complex

Zeiss flickr.com account

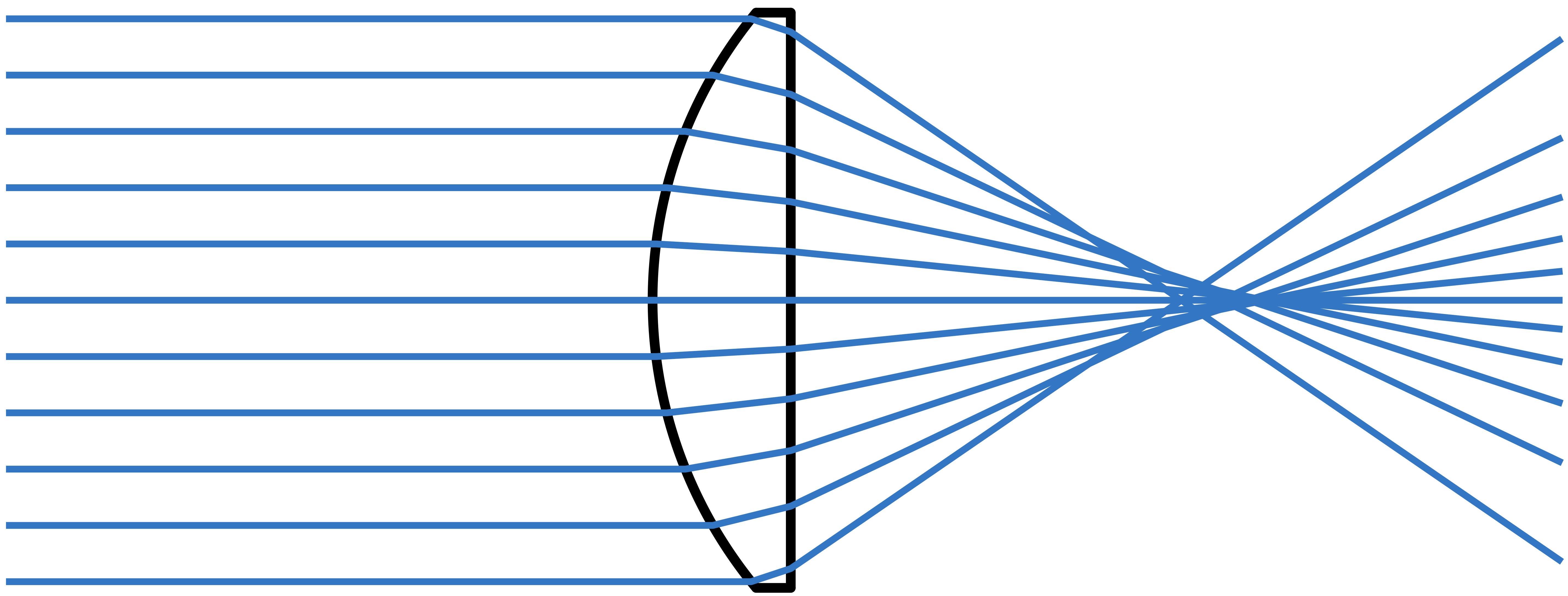
Microscope objective

Recall: Snell's Law of Refraction



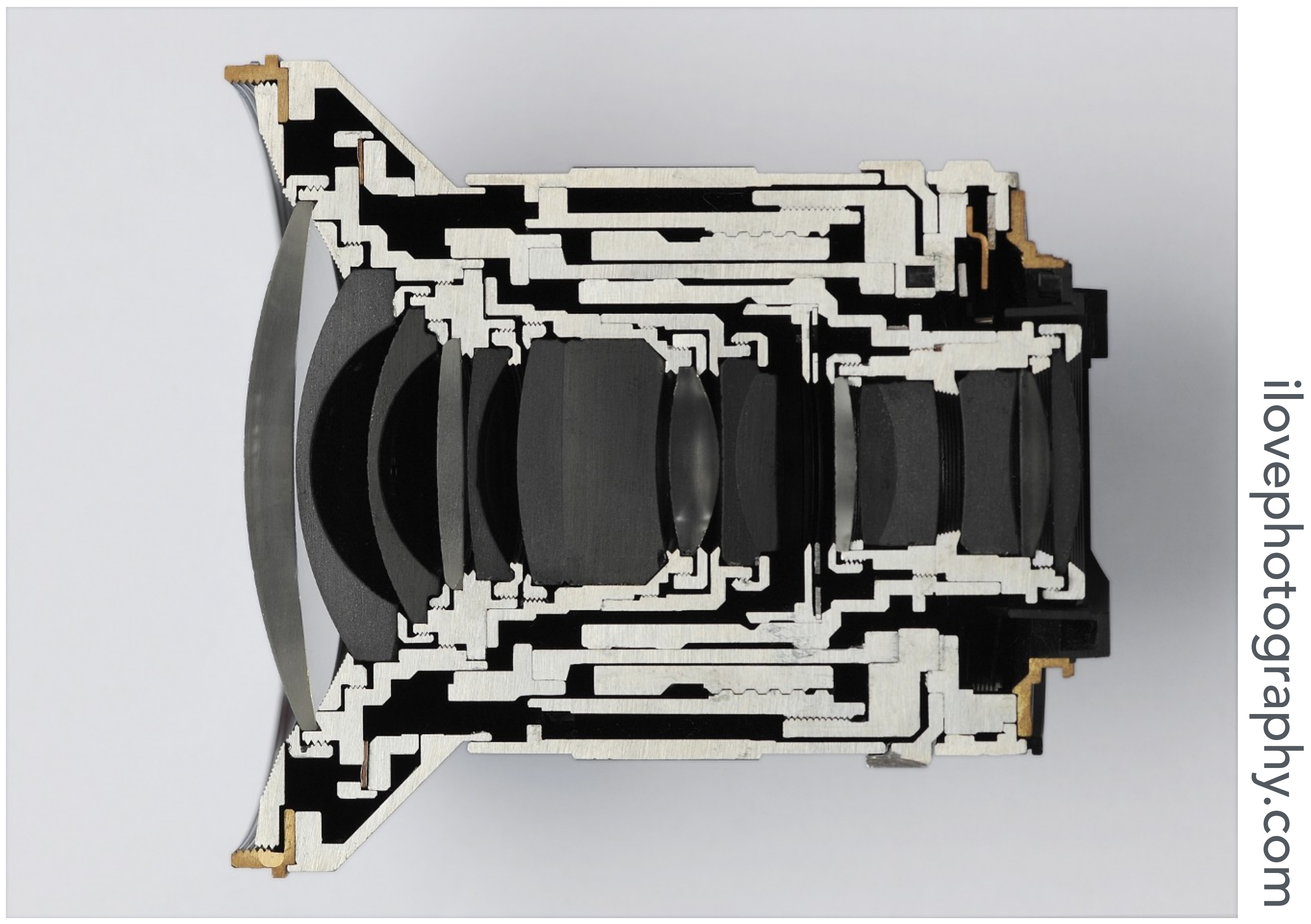
$$\eta_i \sin \theta_i = \eta_t \sin \theta_t$$

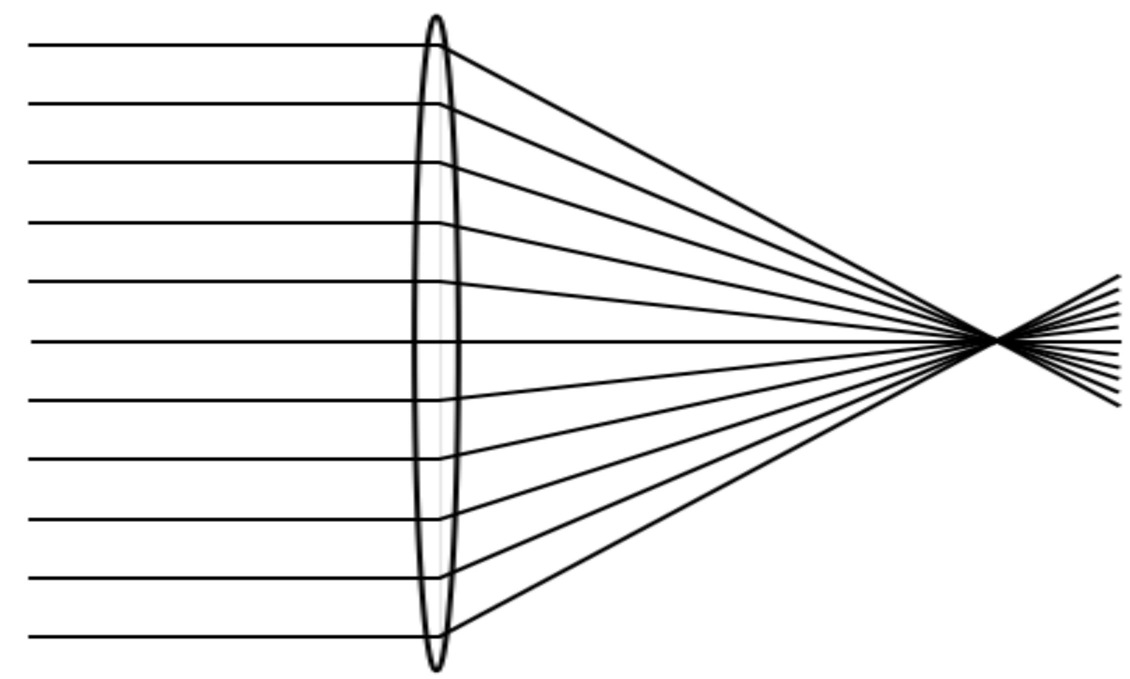
Real Refraction Through A Lens Is Not Ideal – Aberrations



Real plano-convex lens (spherical surface shape).
Lens does not converge rays to a point anywhere.

Real Lenses vs Ideal Thin Lenses





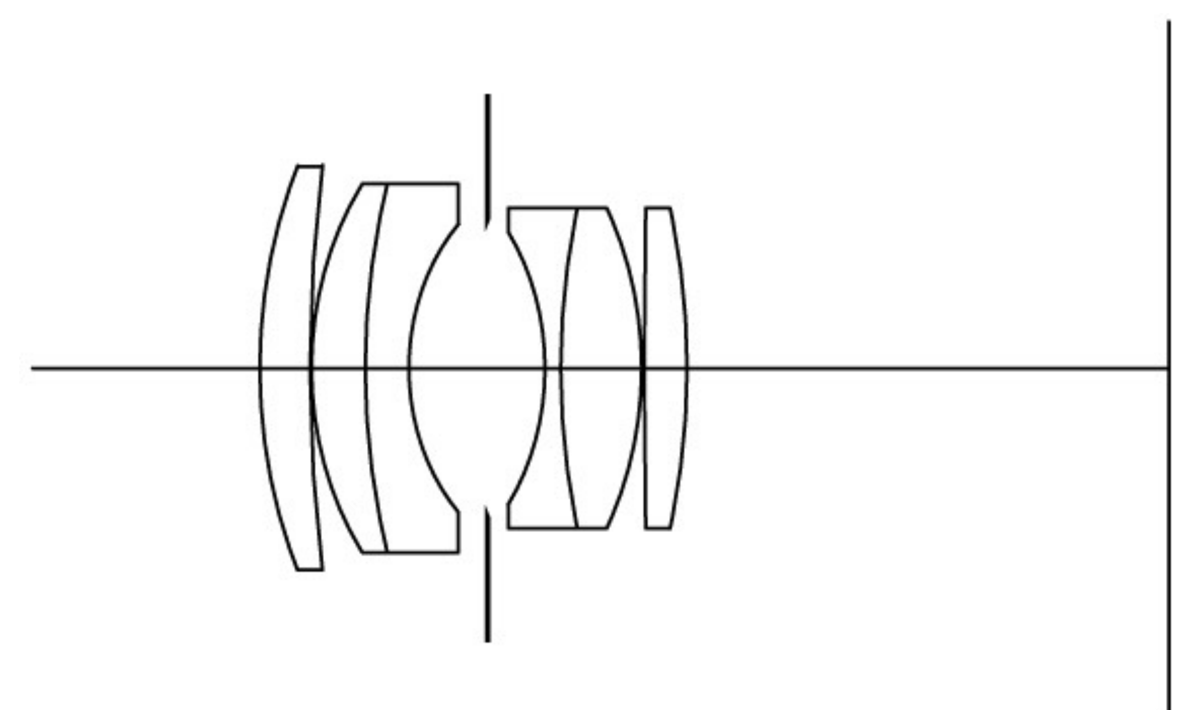
- Real optical system
- Multiple physical elements in compound design
- Optical aberrations prevent rays from converging perfectly

- Theoretical abstraction
- Assume all rays refract at a plane & converge to a point
- Quick and intuitive calculation of main imaging effects

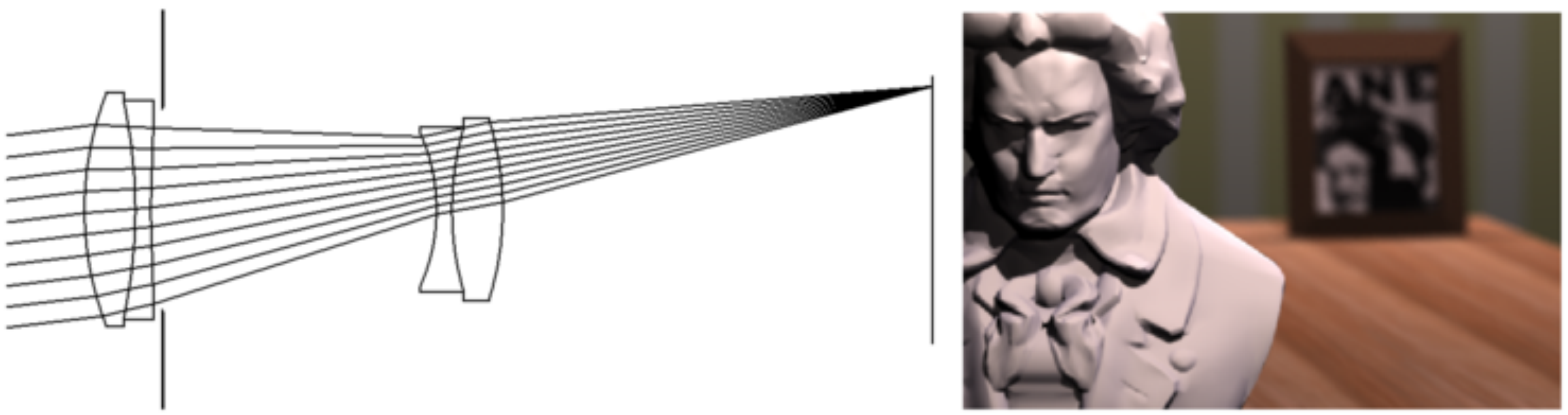
Example Lens Formula: Double Gauss

Data from W. Smith, Modern Lens Design, p 312

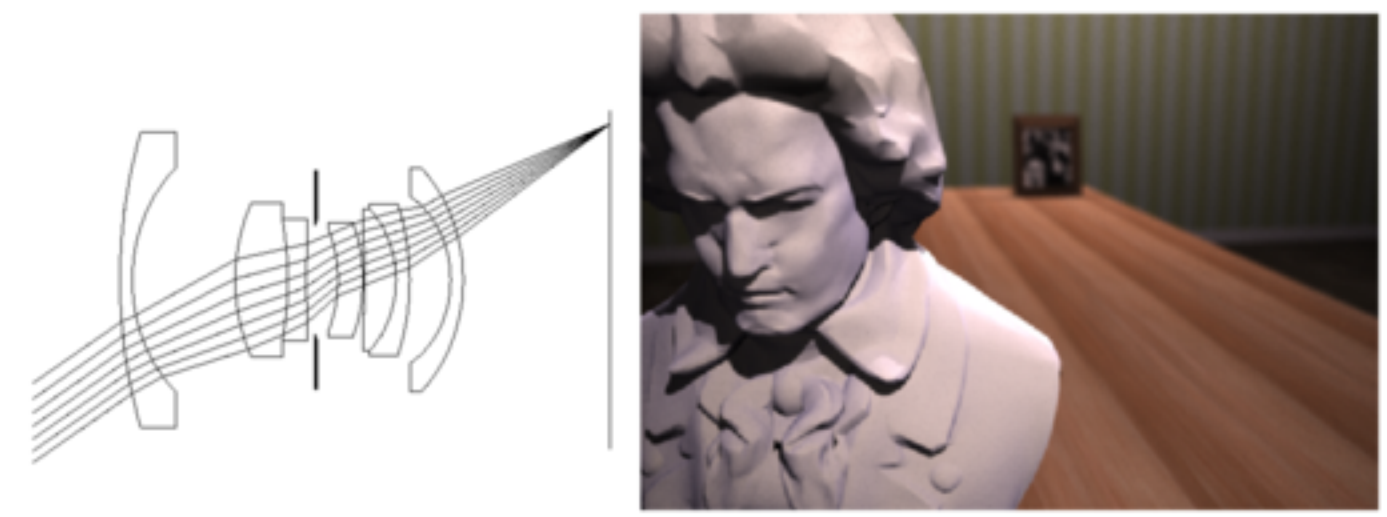
Radius (mm)	Thick (mm)	n_d	V-no	Aperture (mm)
58.950	7.520	1.670	47.1	50.4
169.660	0.240			50.4
38.550	8.050	1.670	47.1	46.0
81.540	6.550	1.699	30.1	46.0
25.500	11.410			36.0
	9.000			34.2
–28.990	2.360	1.603	38.0	34.0
81.540	12.130	1.658	57.3	40.0
–40.770	0.380			40.0
874.130	6.440	1.717	48.0	40.0
–79.460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



Ray Tracing Through Real Lens Designs



200 mm telephoto



35 mm wide-angle

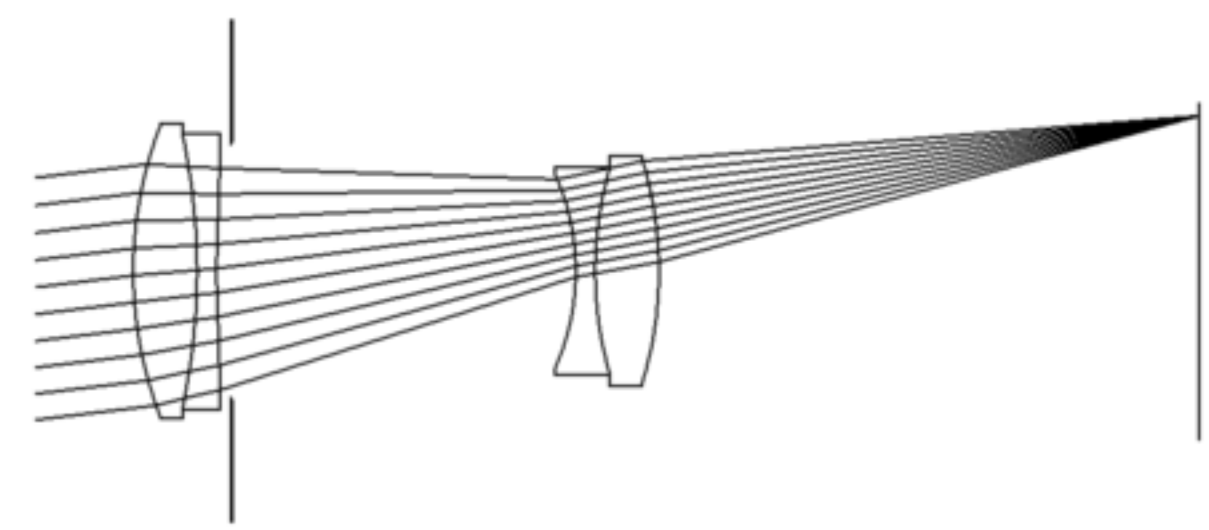
50 mm double-gauss

16 mm fisheye

From Kolb, Mitchell and Hanrahan (1995)

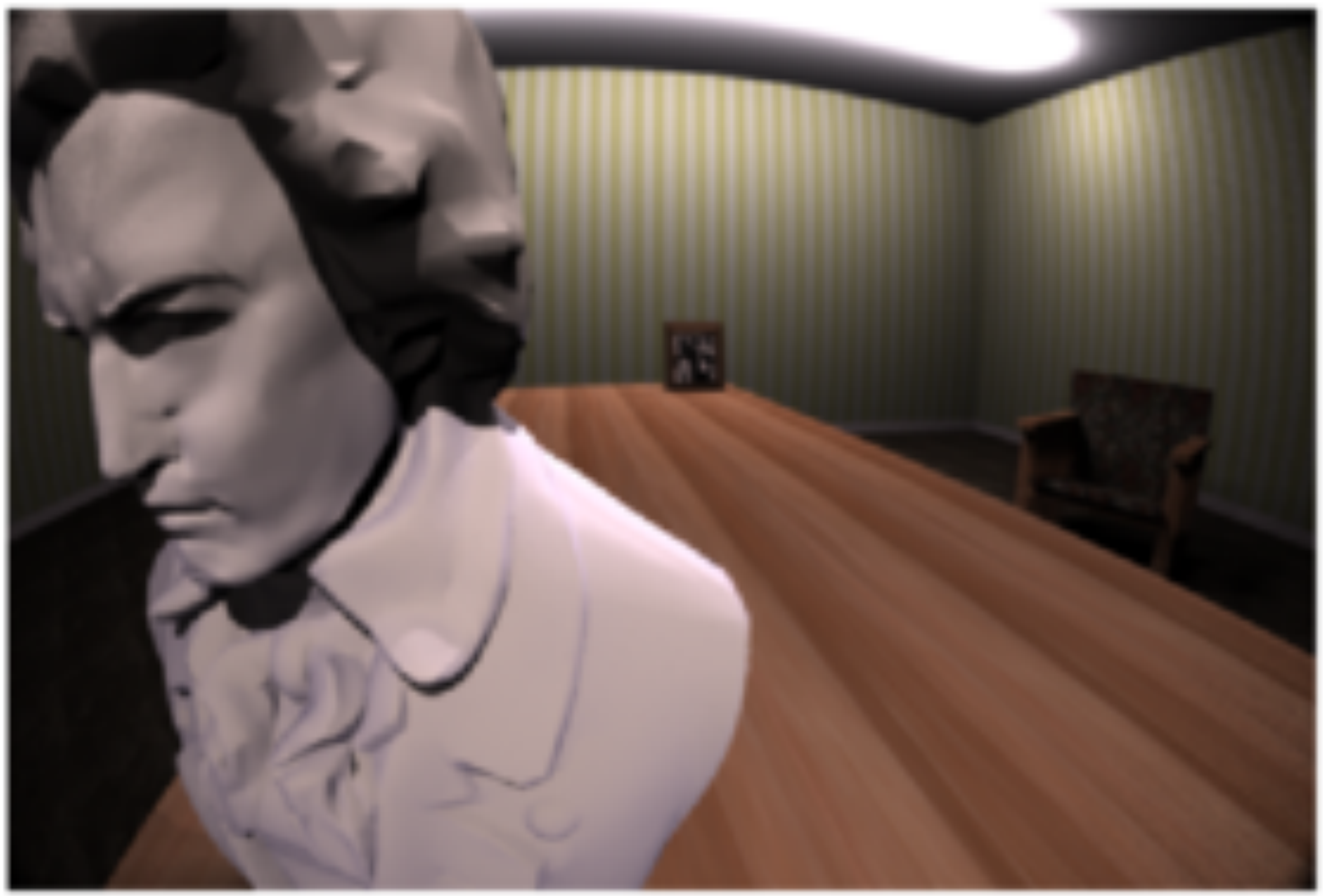
Ray Tracing Through Real Lens Designs

200 mm telephoto

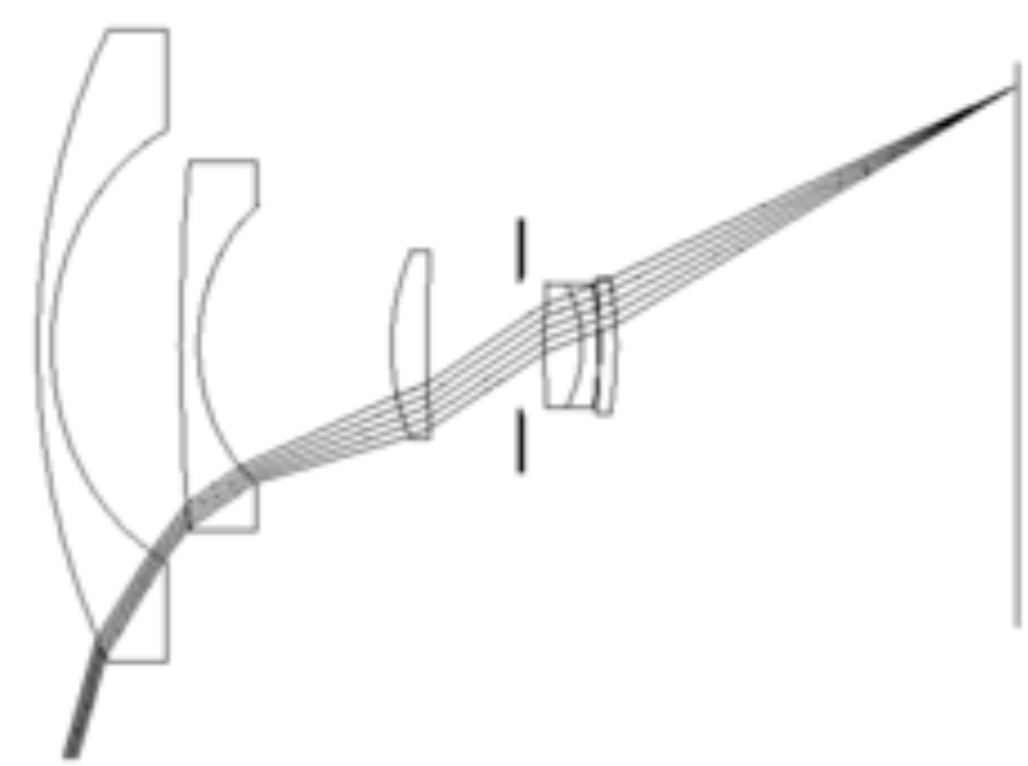


Notice shallow depth of field (out of focus background)

Ray Tracing Through Real Lens Designs



16 mm fisheye



Notice distortion in the corners (straight lines become curved)

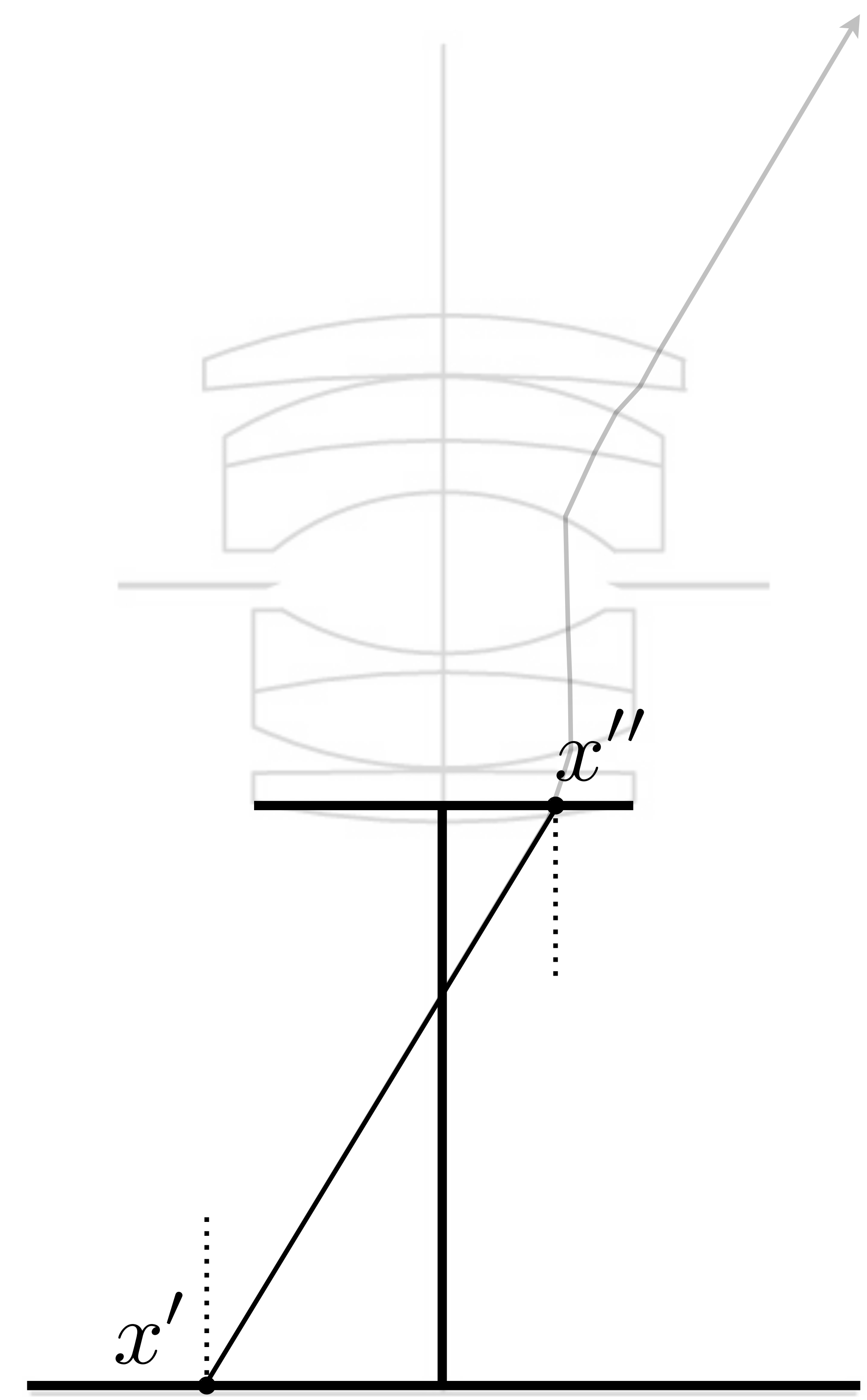
Ray Tracing Real Lens Designs

Monte Carlo approach

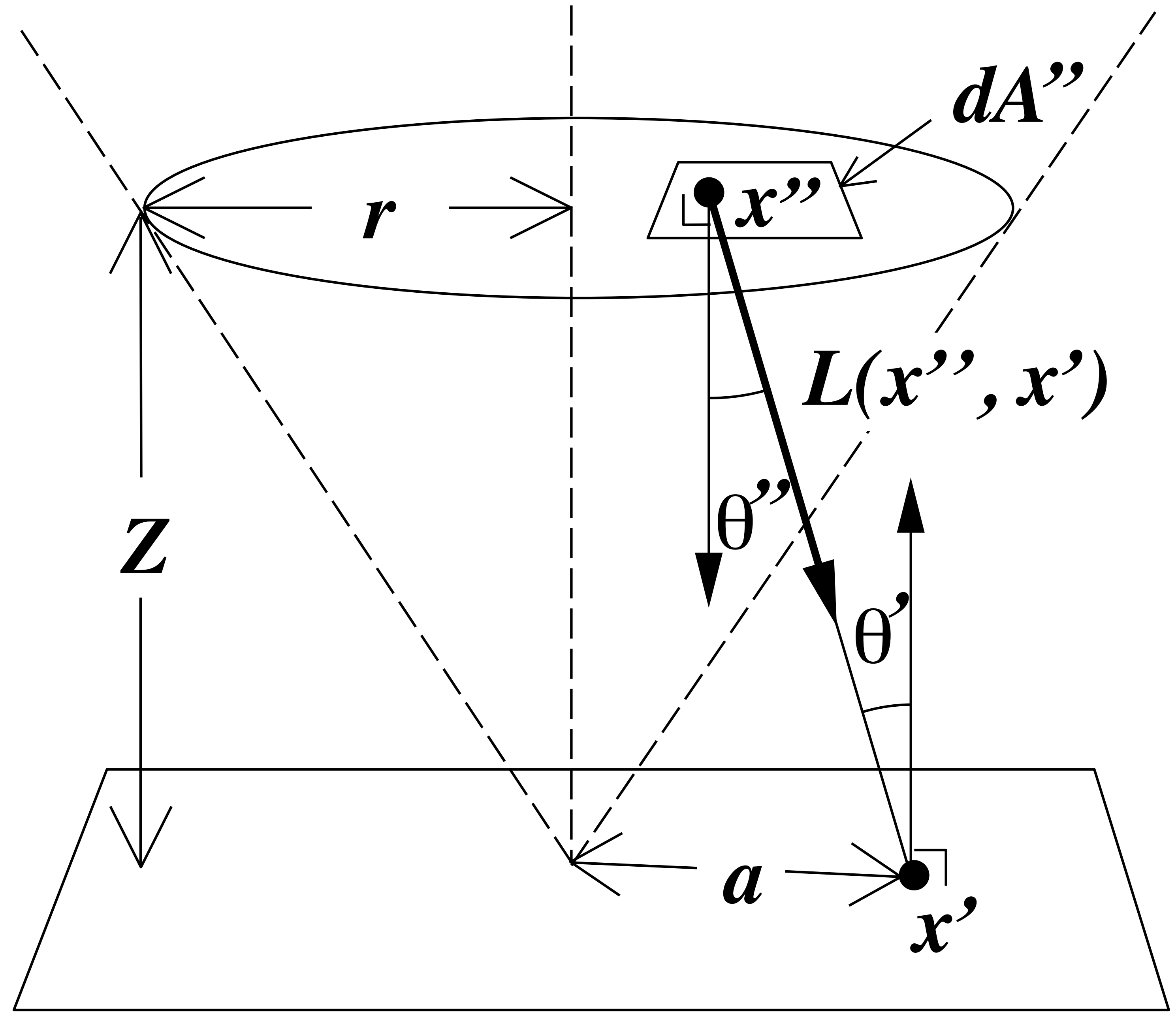
- At every sensor pixel, compute integral of rays incident on pixel area arriving from all paths through the lens

Algorithm (for a pixel)

- Choose N random positions in pixel
- For each position x', choose a random position on the back element of the lens x"
- Trace a ray from x' to x", trace refractions through lens elements until it either misses the next element (terminate ray) or exits the lens (path trace through the scene)
- Weight each ray according to radiometric calculation on next slide to estimate power falling on the pixel



Radiometry for Tracing Lens Designs



$$E(x') = \int_{x'' \in D} L(x'' \to x') \frac{\cos\theta' \cos\theta''}{||x'' - x'||^2} dA''$$

$$= \frac{1}{Z^2} \int_{x'' \in D} L(x'' \to x') \cos^4 \theta dA''$$

Light Field Photography

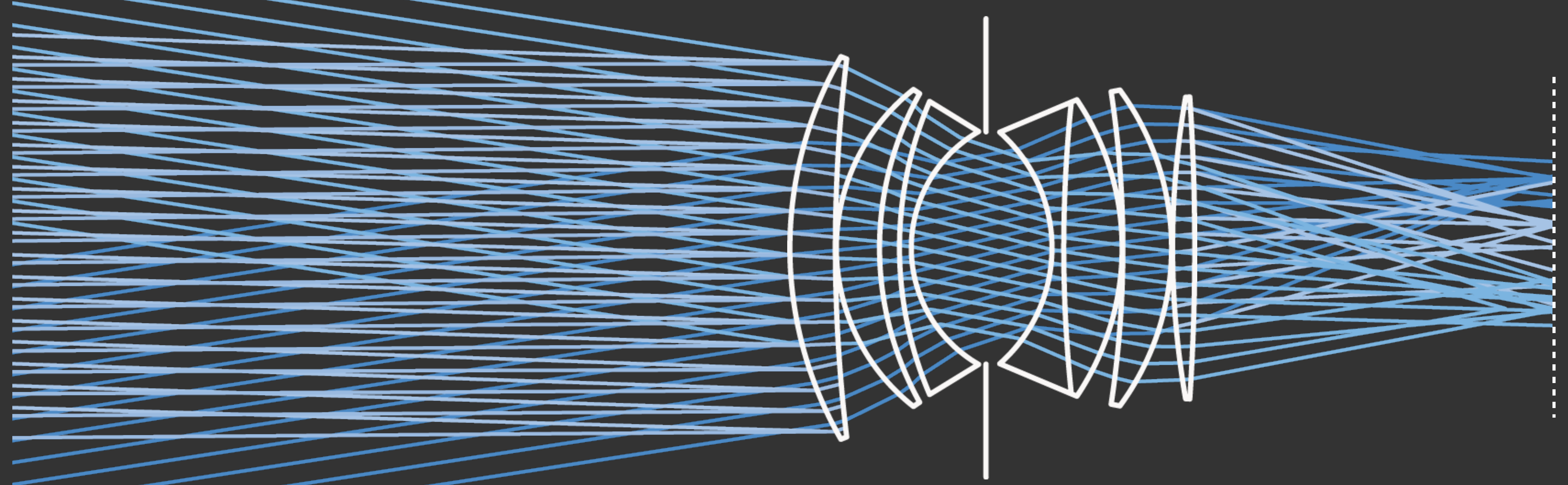
Light Field Camera

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

Light Field Photography Demo

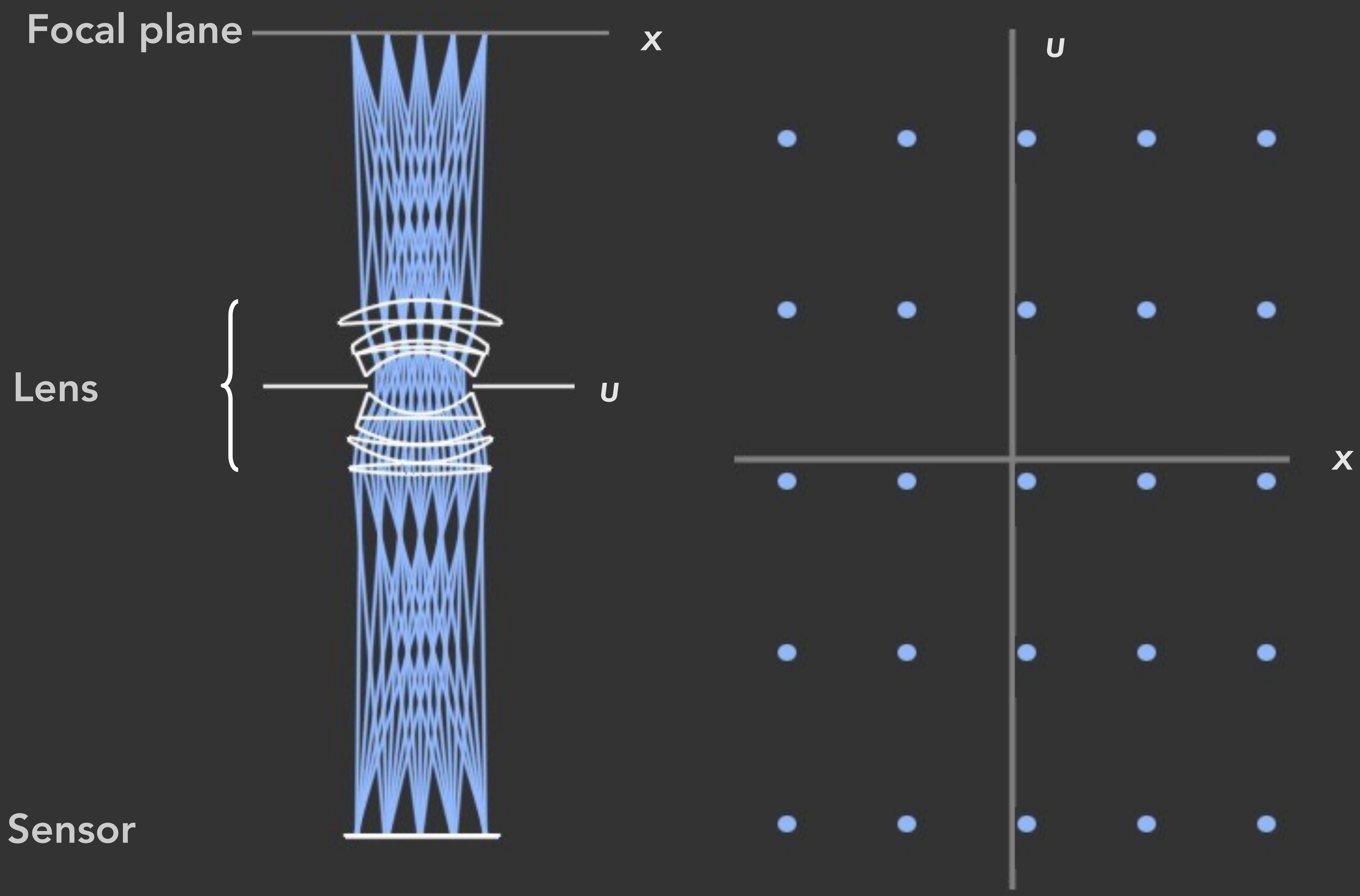
2D Photographs vs
4D Light Fields

2D Photographs vs 4D Light Fields

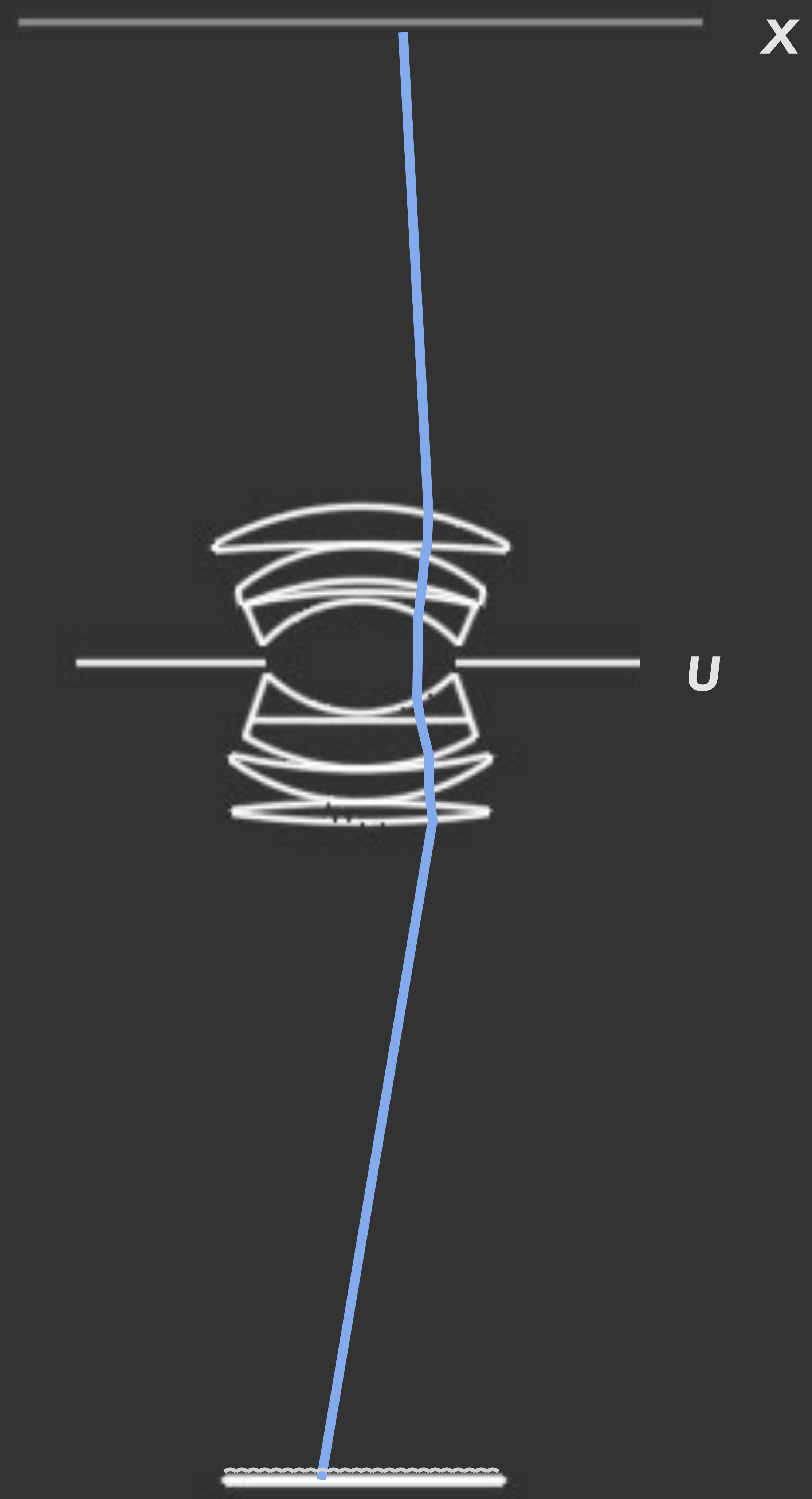


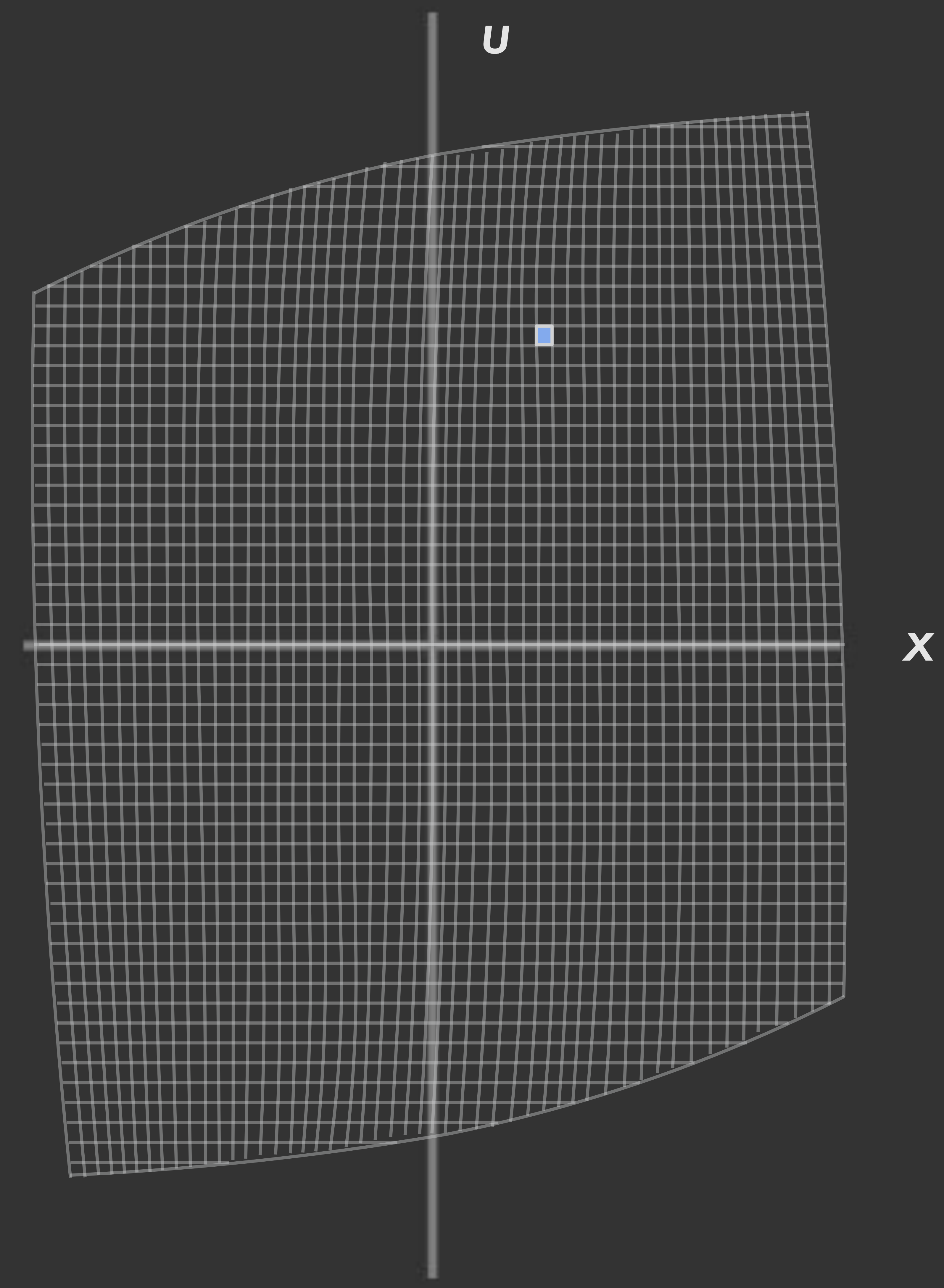
Photograph = irradiance at every pixel on plane (2D)
Light field = radiance flowing along every ray (4D)

The 4D Light Field Flowing Into A Camera

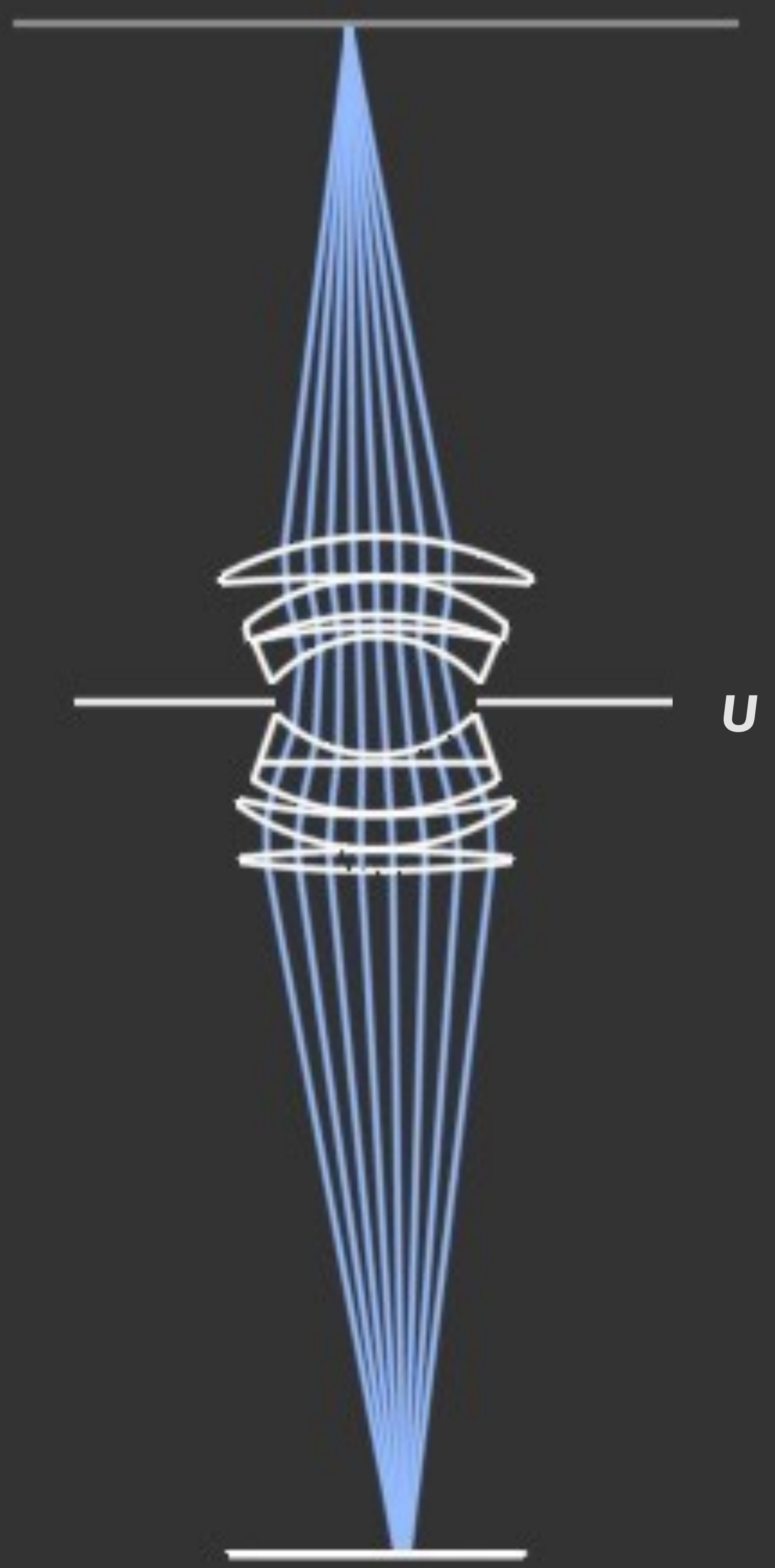


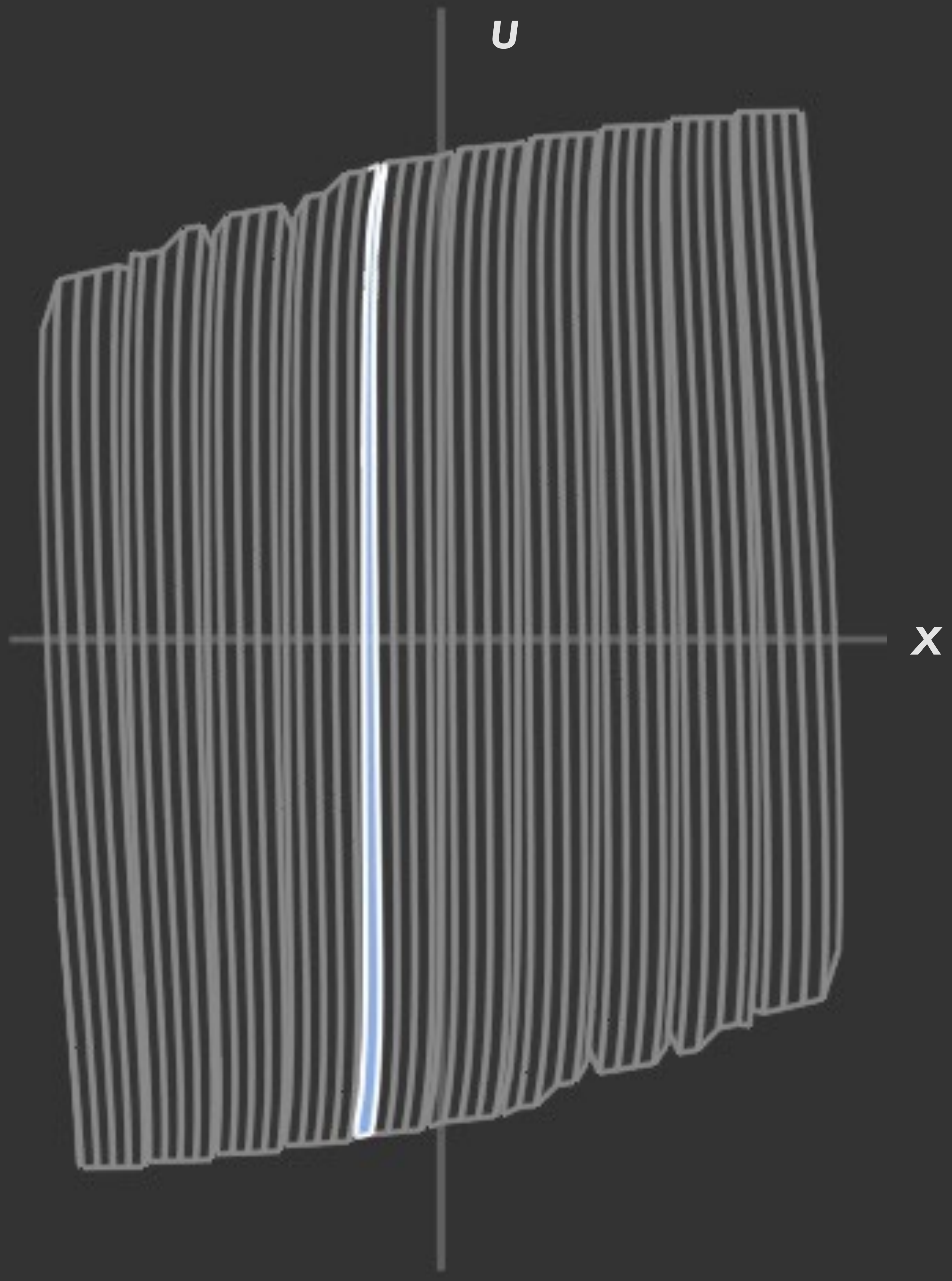
Light Field Cameras Aim to Sample the Light Field



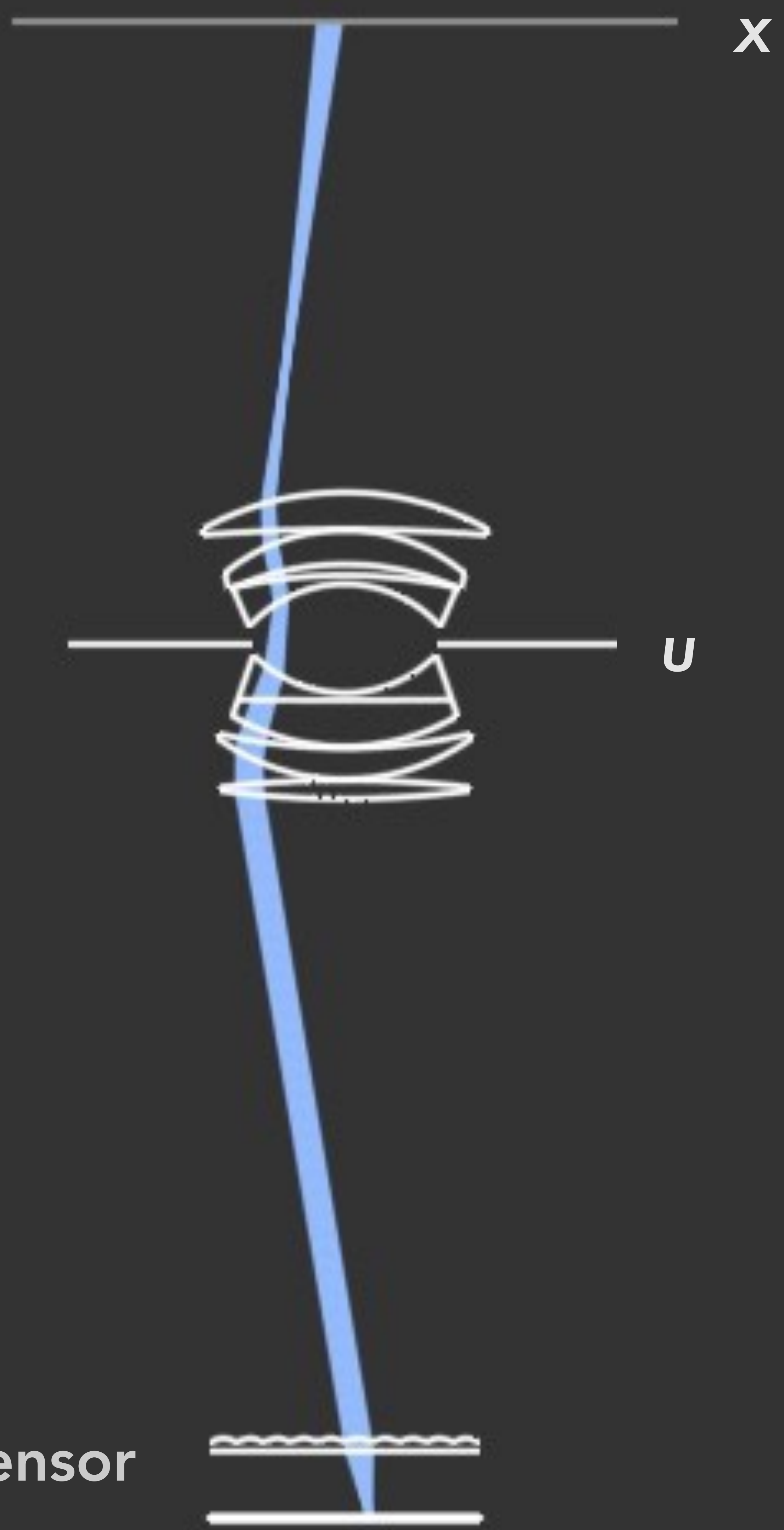


What Does a 2D Photograph Record?

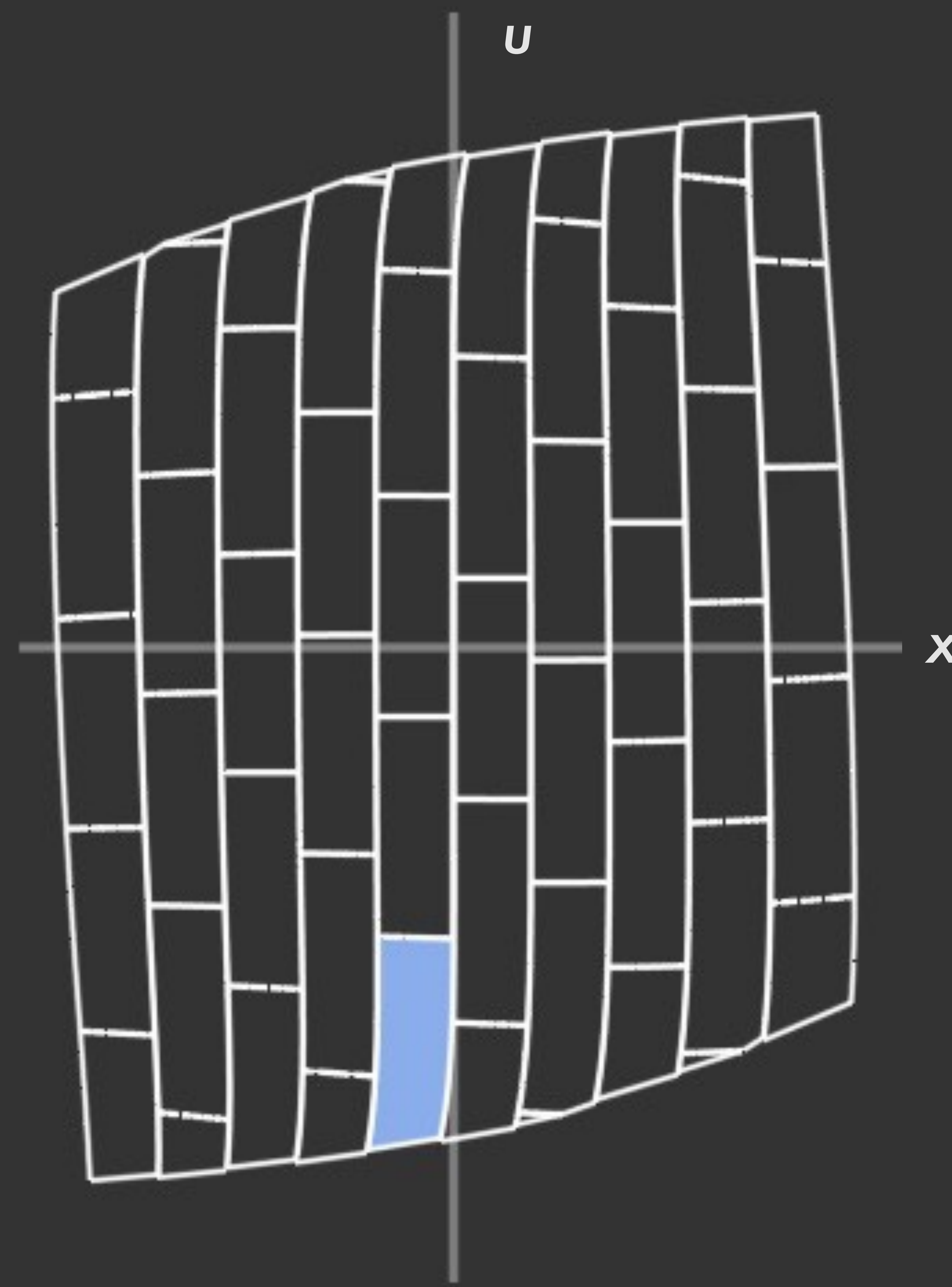




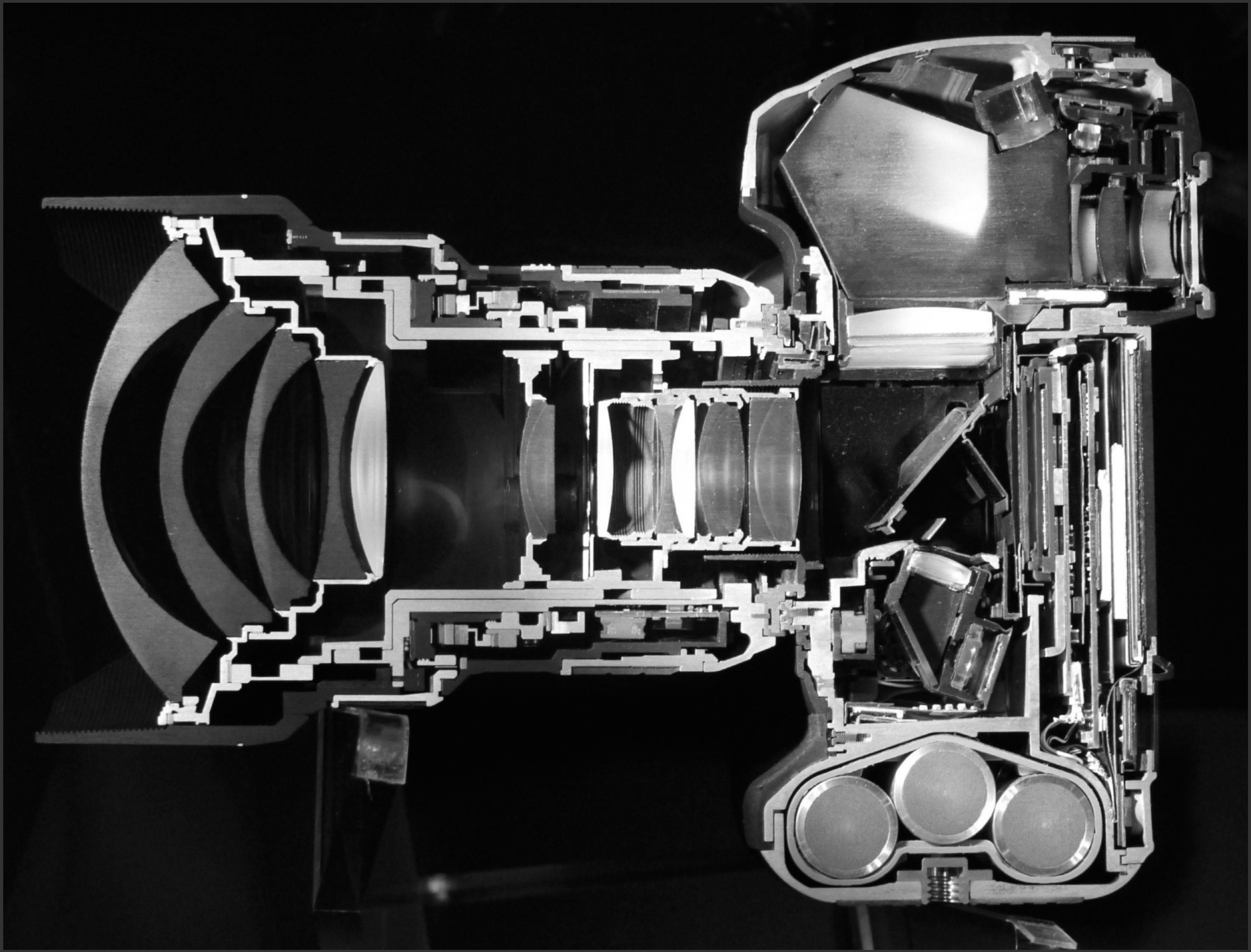
A Plenoptic Camera Samples The Light Field



Light Field Sensor

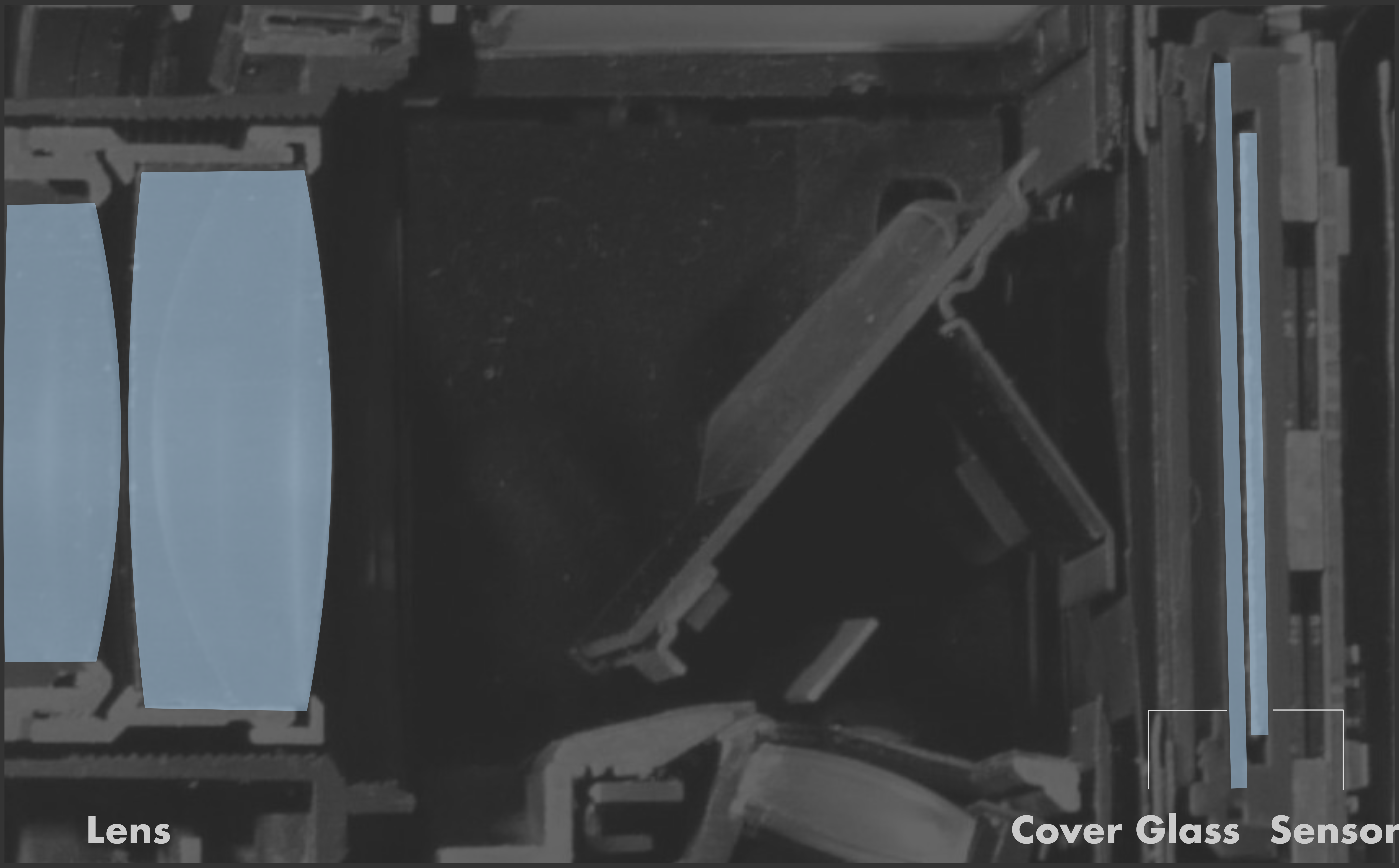


Where Microlenses Go Inside Camera

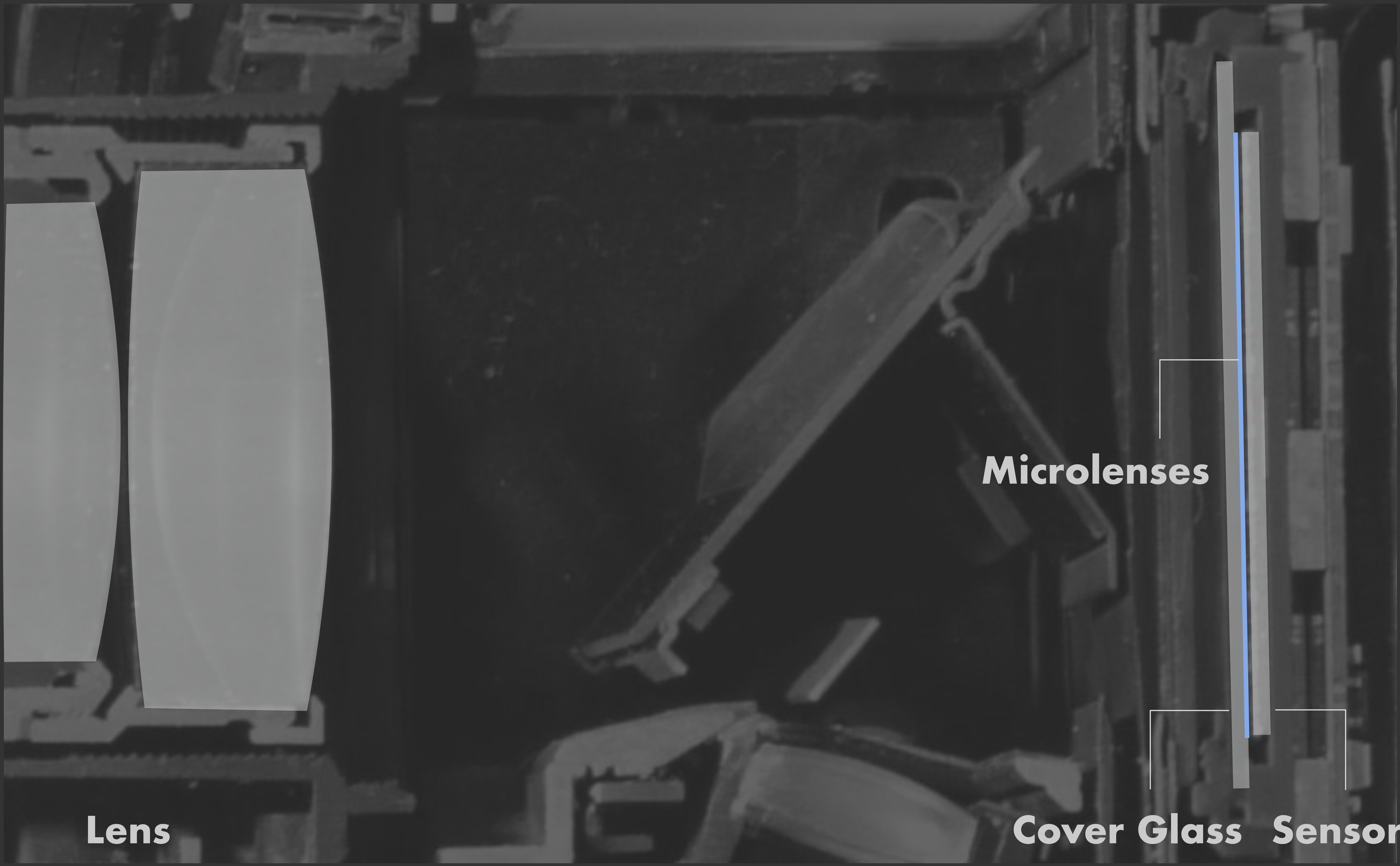


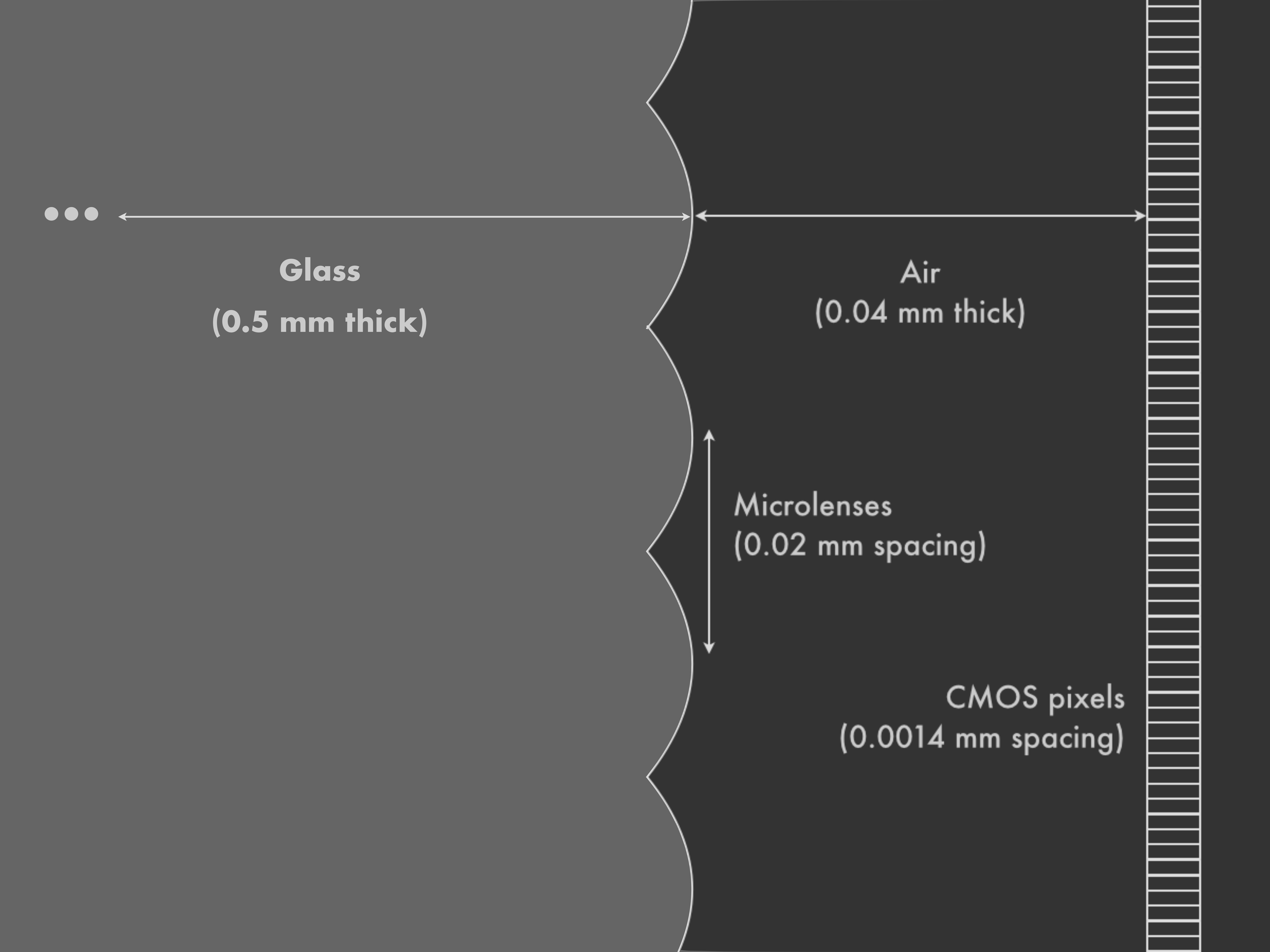
Cross-section of Nikon D3, 14-24mm F/2.8 lens

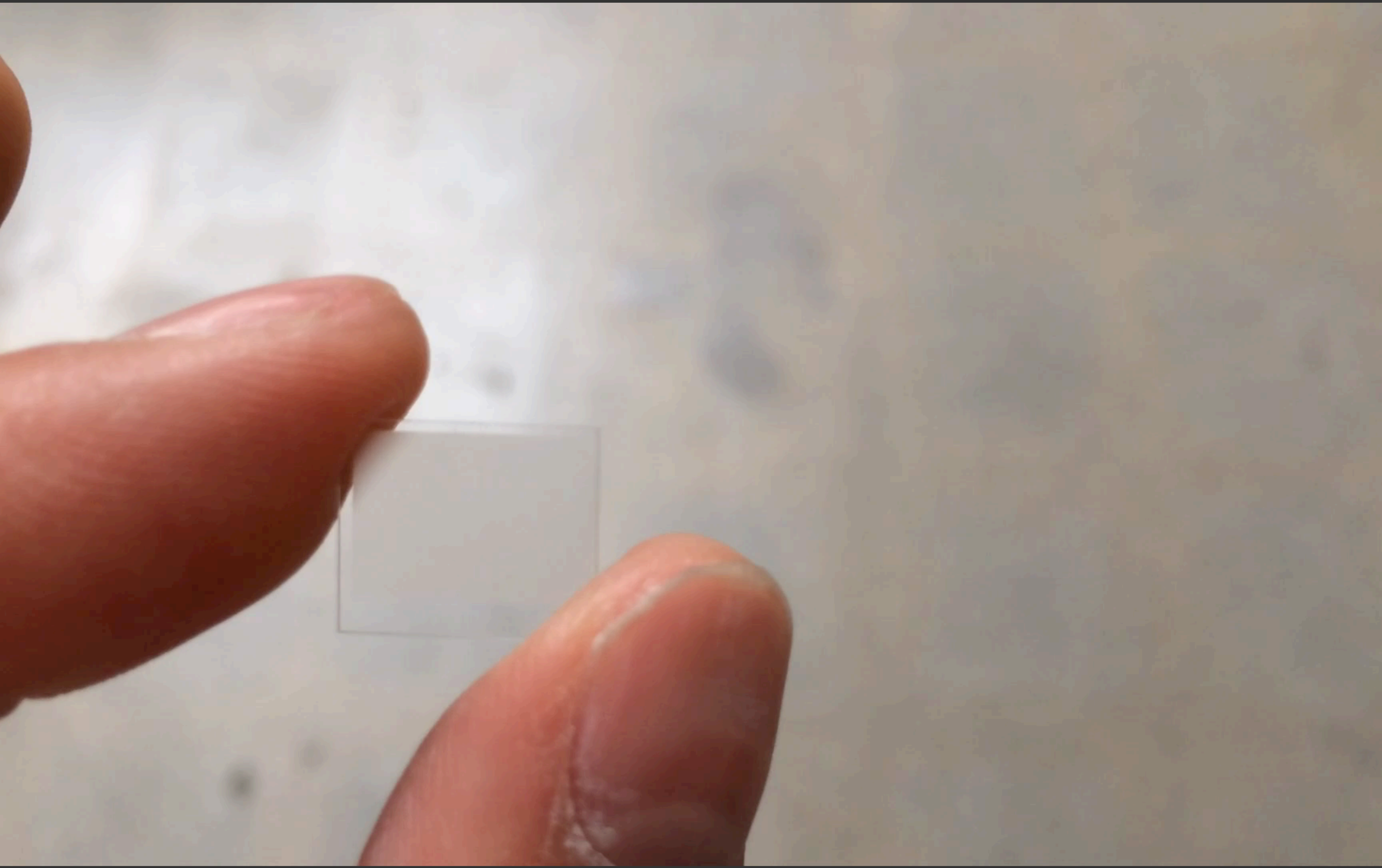
Where Microlenses Go Inside Camera

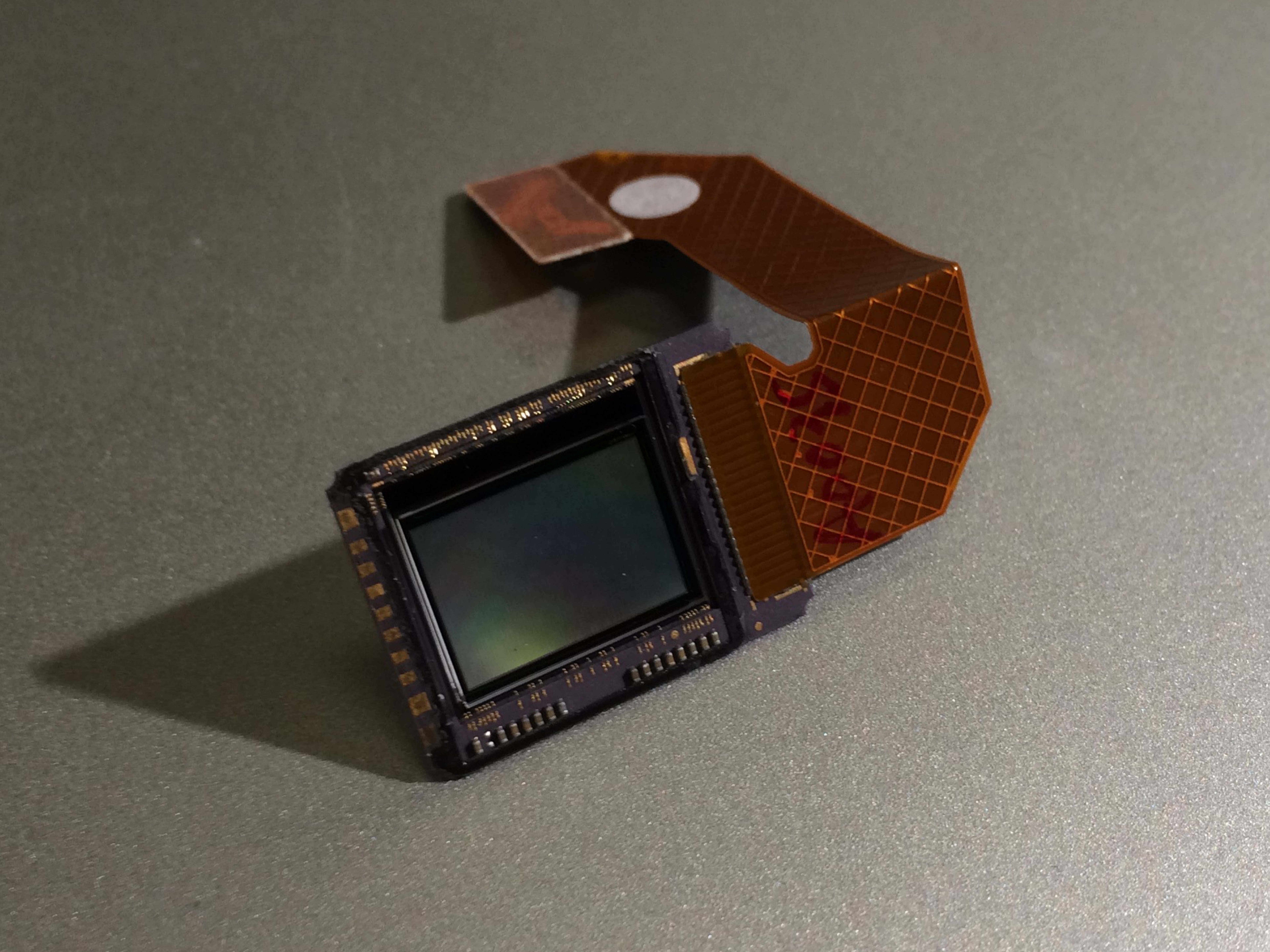


Where Microlenses Go Inside Camera




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

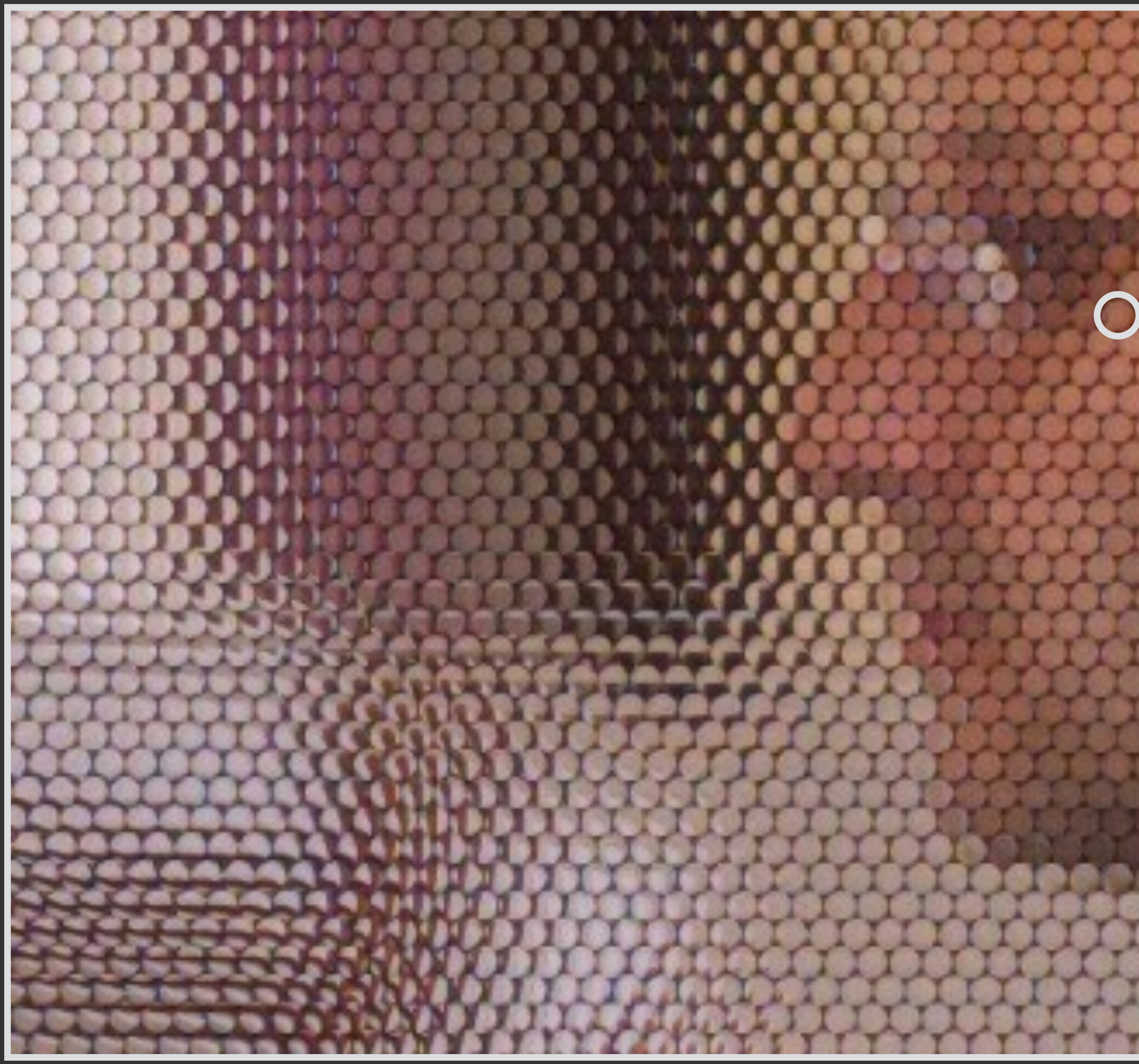




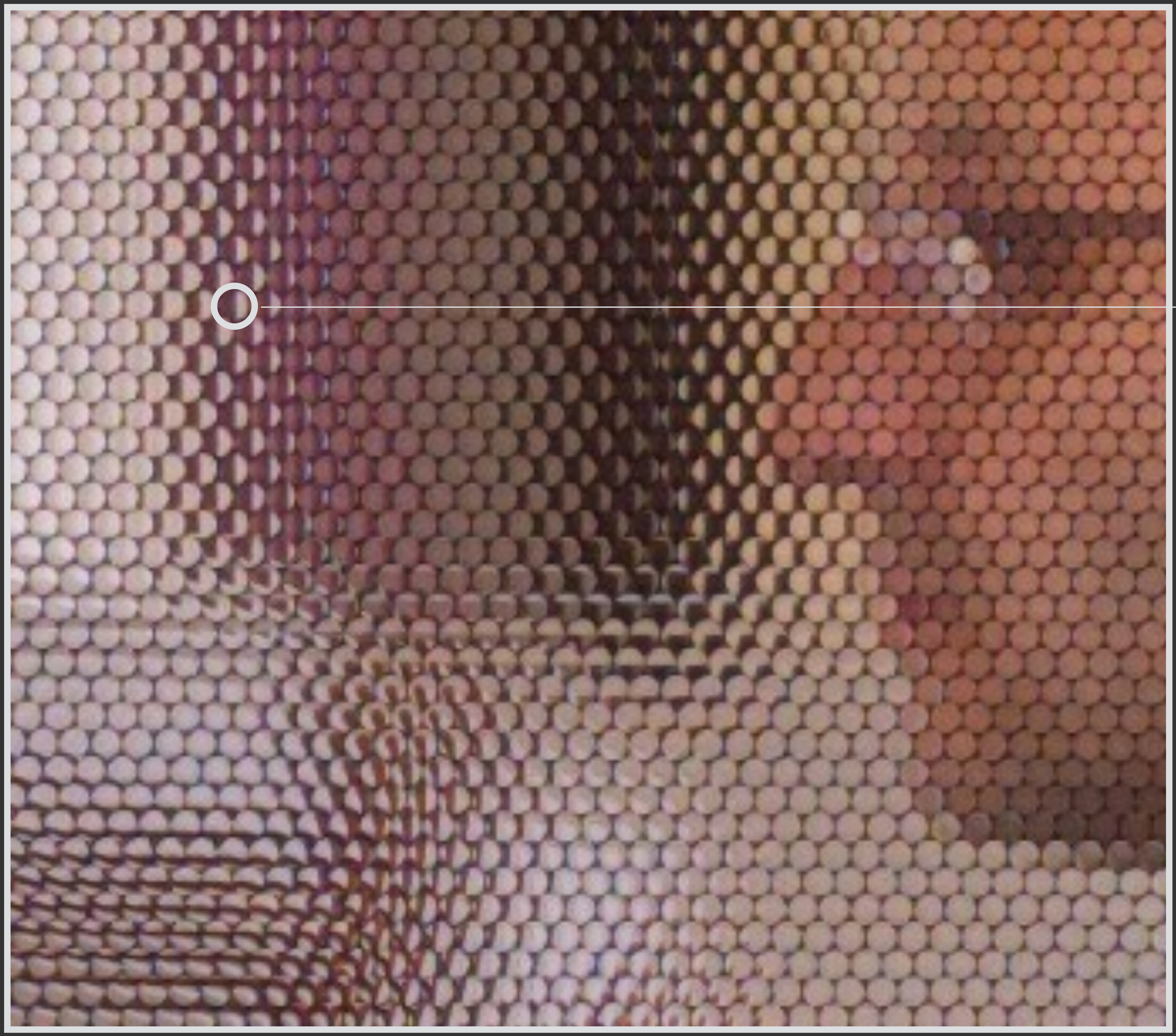
Raw Data From Light Field Sensor

Raw Data From Light Field Sensor

Raw Data From Light Field Sensor



Raw Data From Light Field Sensor



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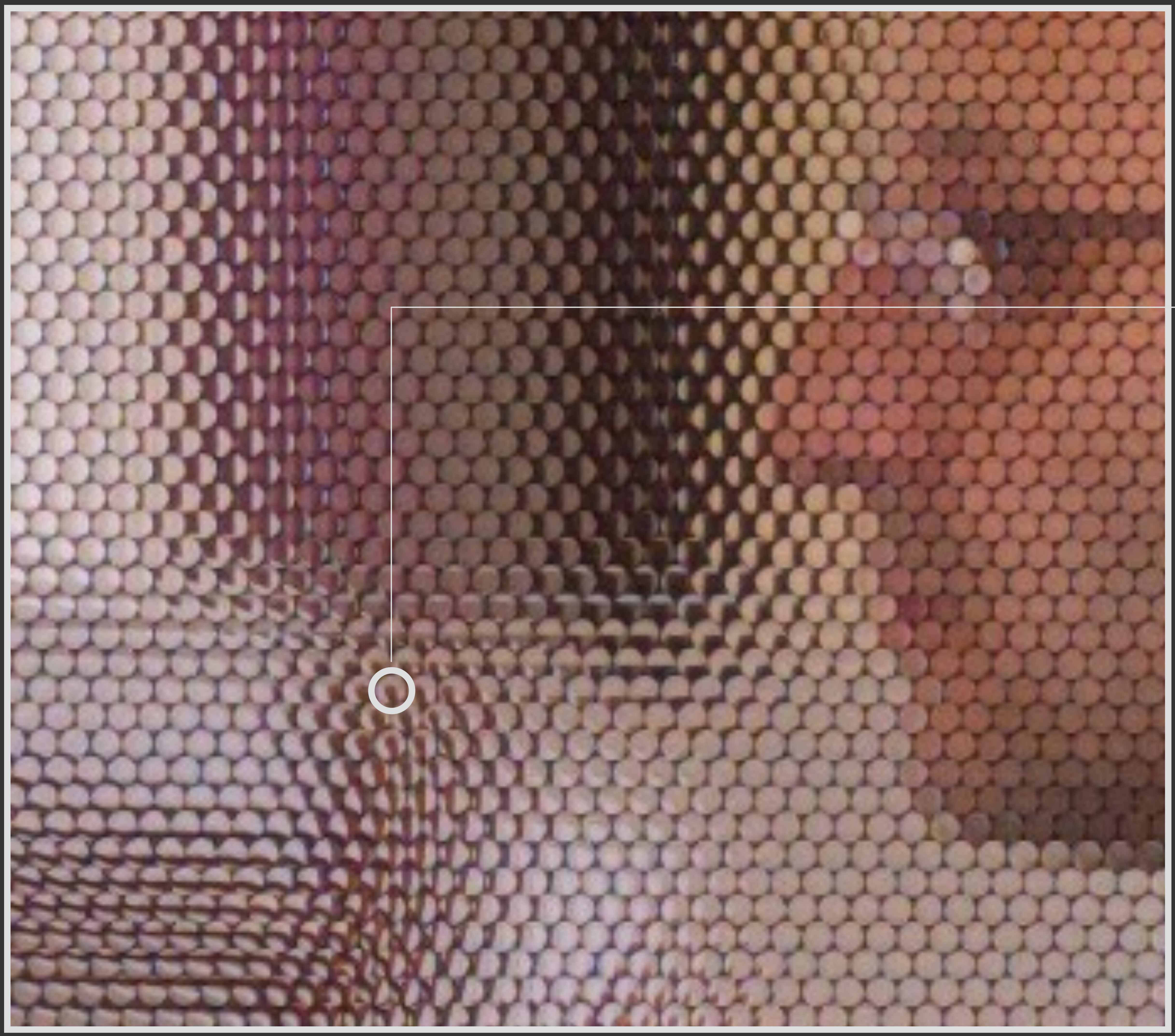
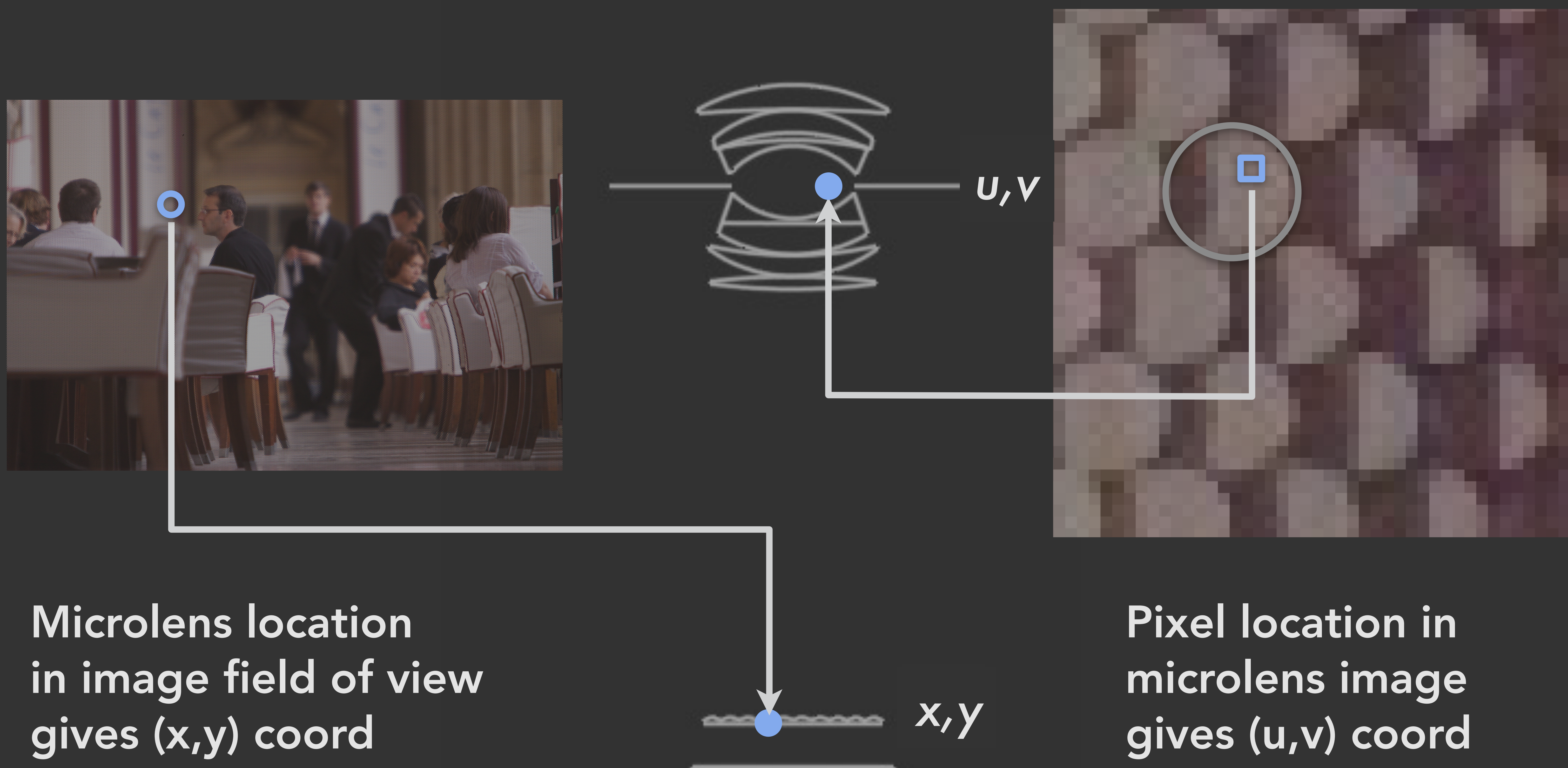
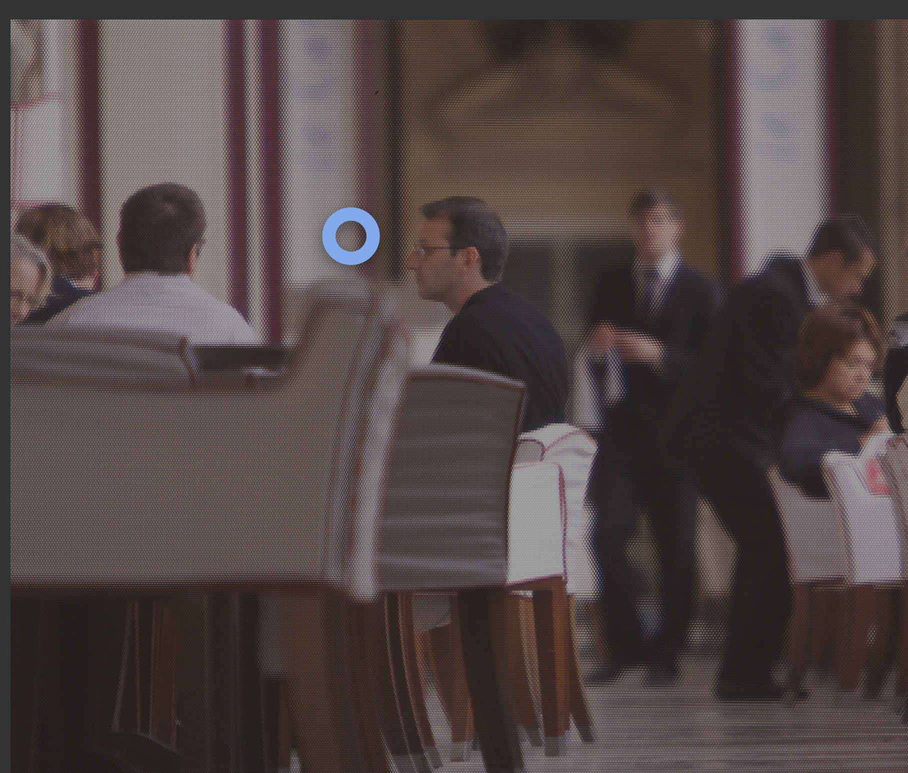


Raw Data From Light Field Sensor

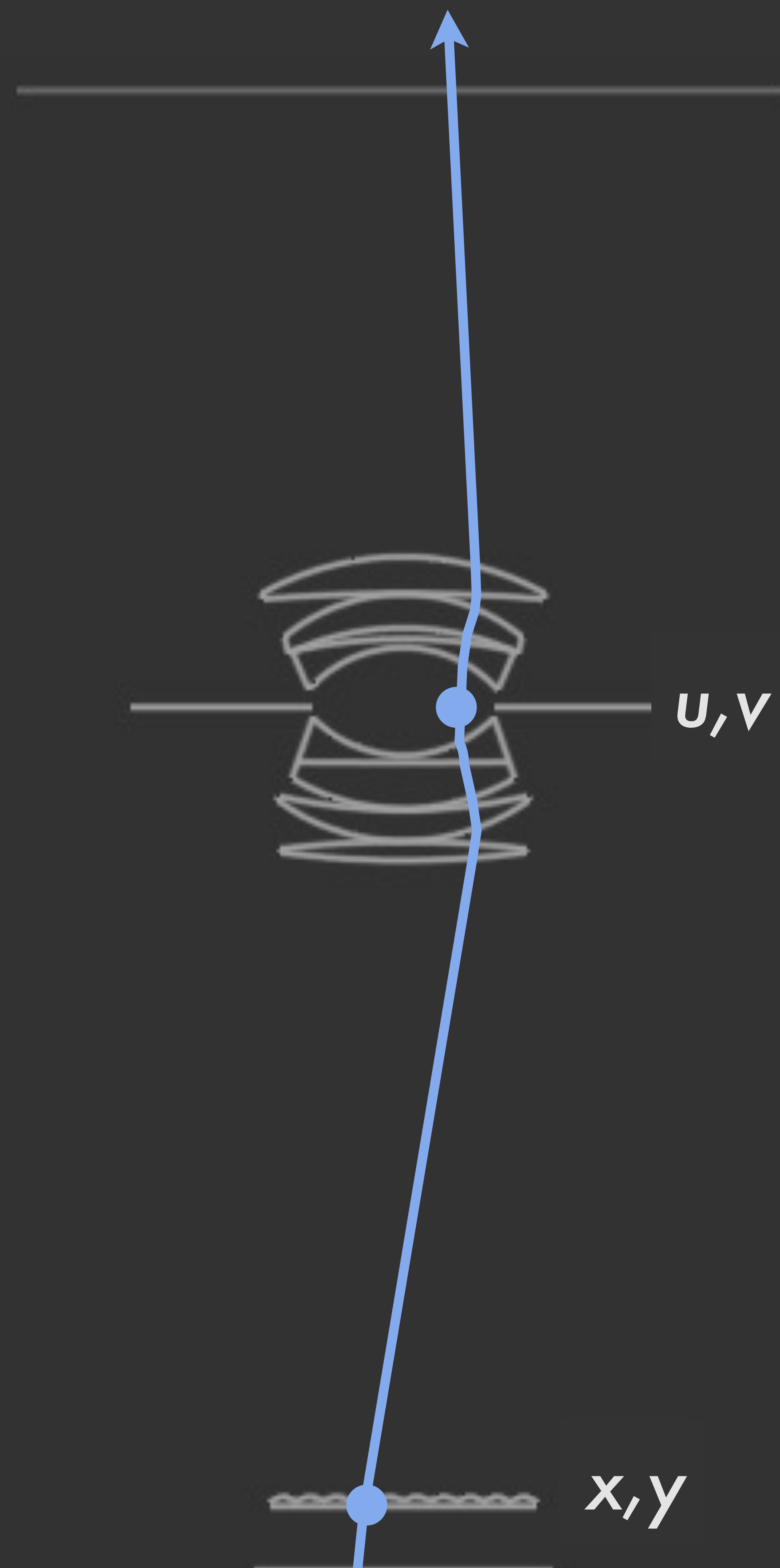
Mapping Sensor Pixels to (x,y,u,v) Rays

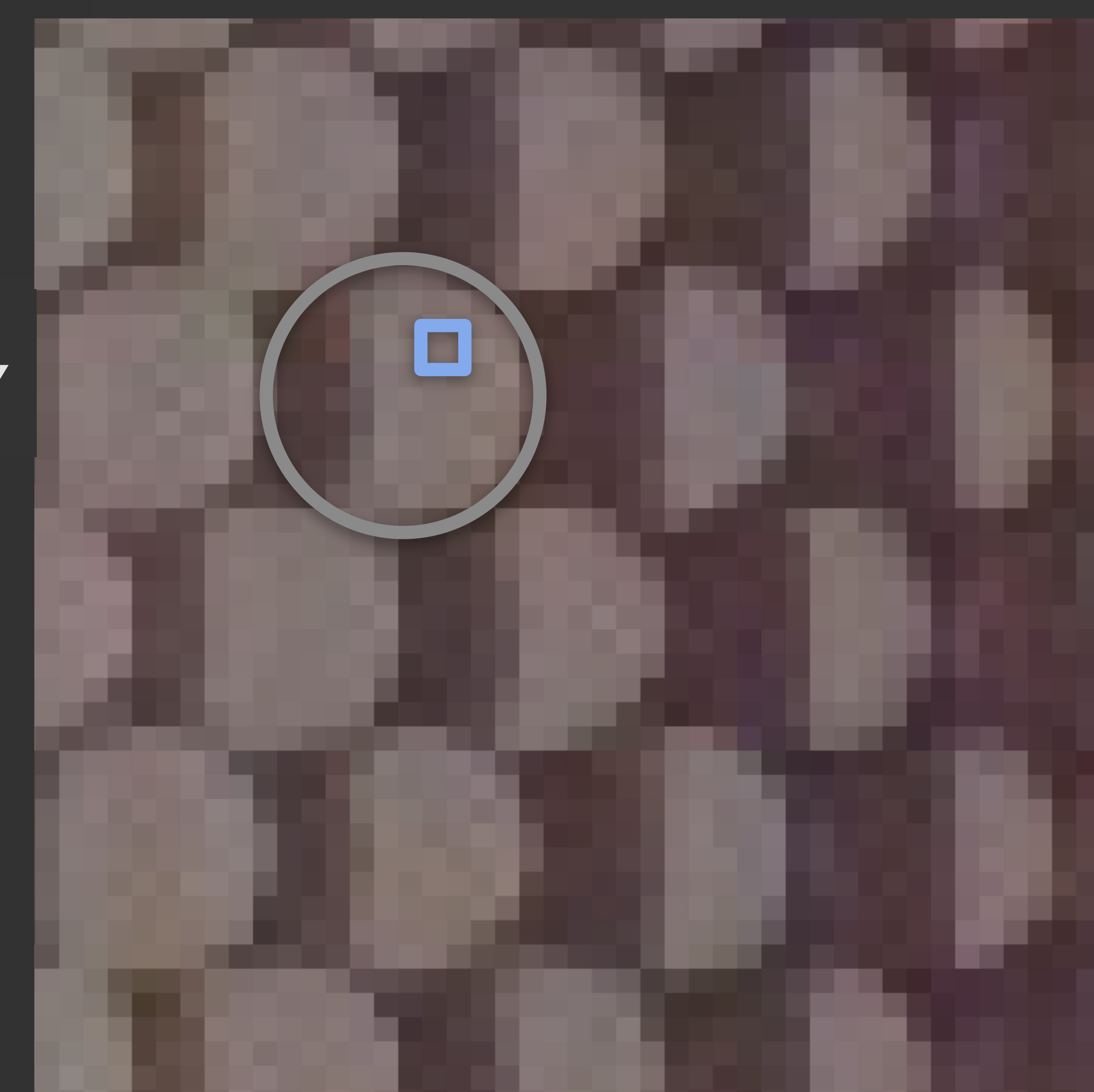


Mapping Sensor Pixels to (x,y,u,v) Rays



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

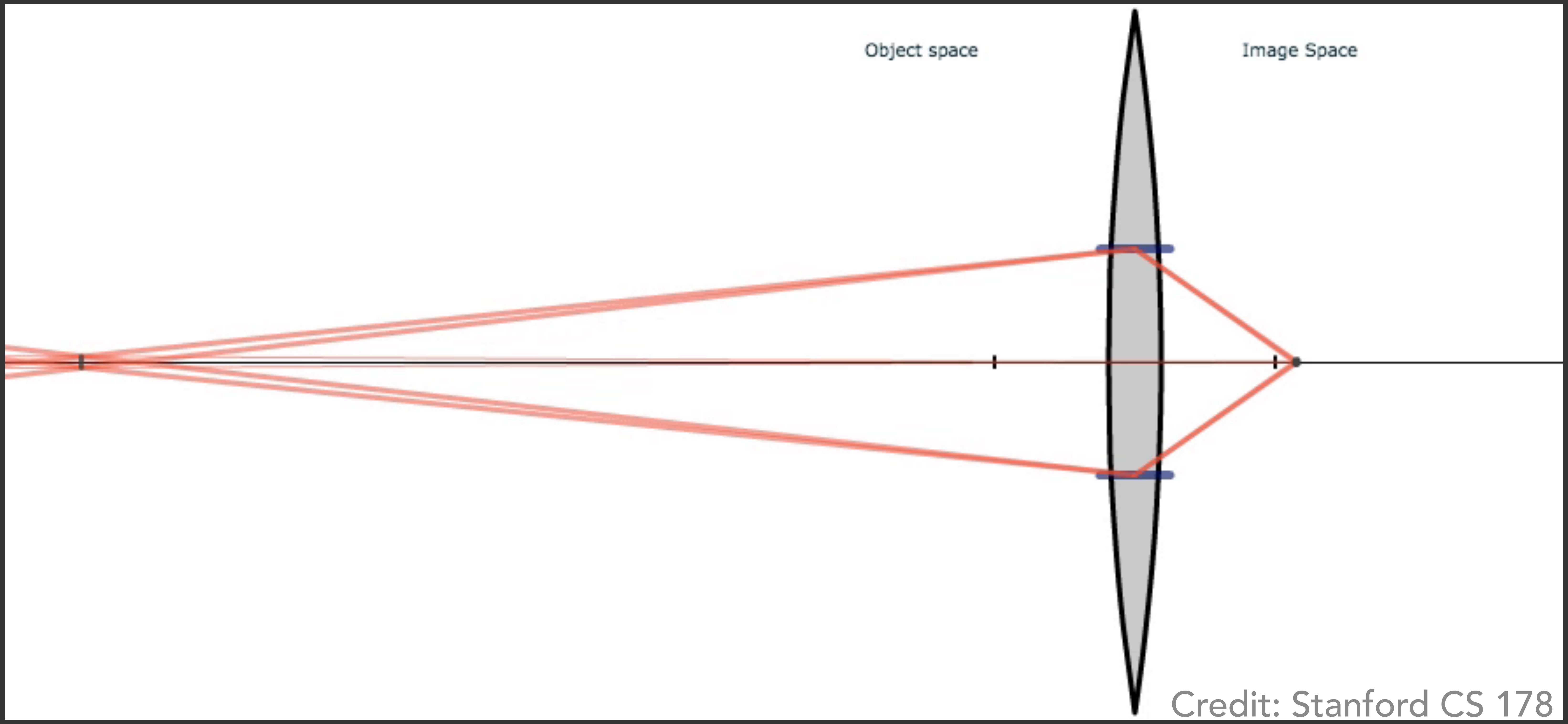




Pixel location in
microlens image
gives (u,v) coord

How Does Computational Refocusing Work?

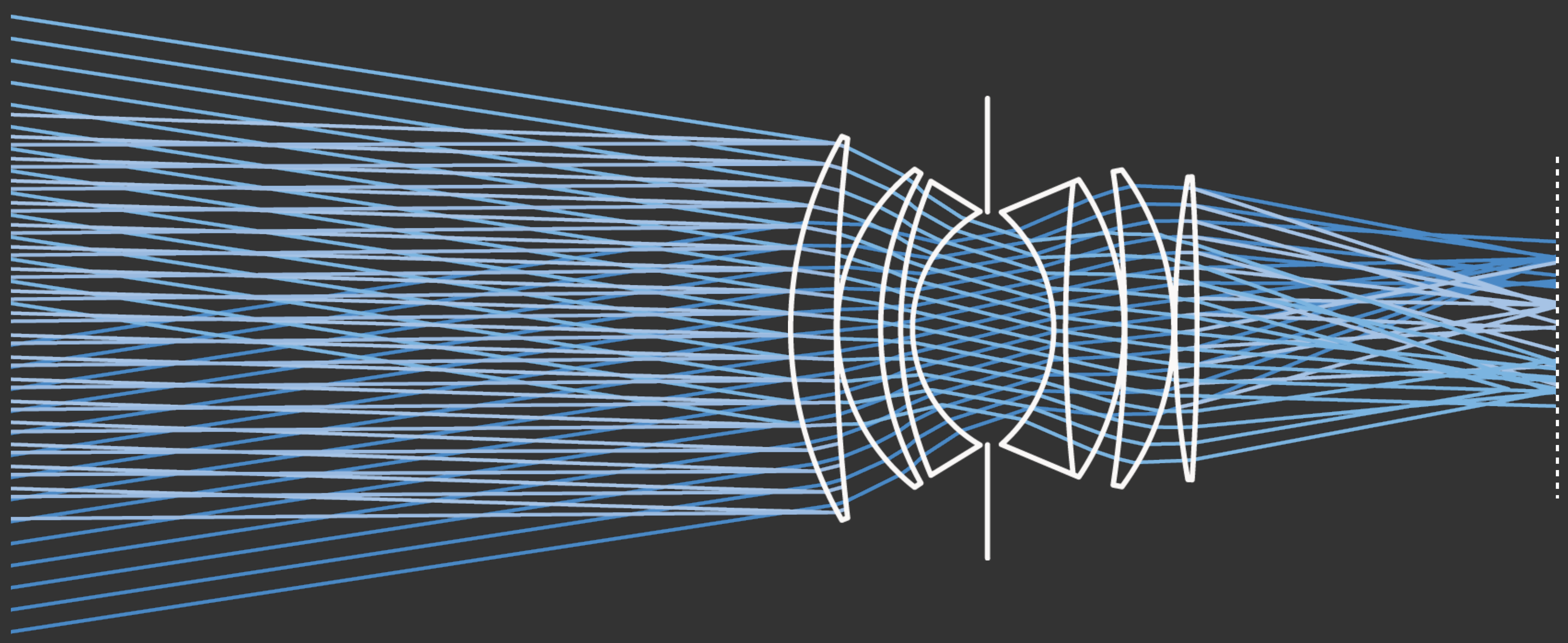
Recall: How Physical Focusing Works



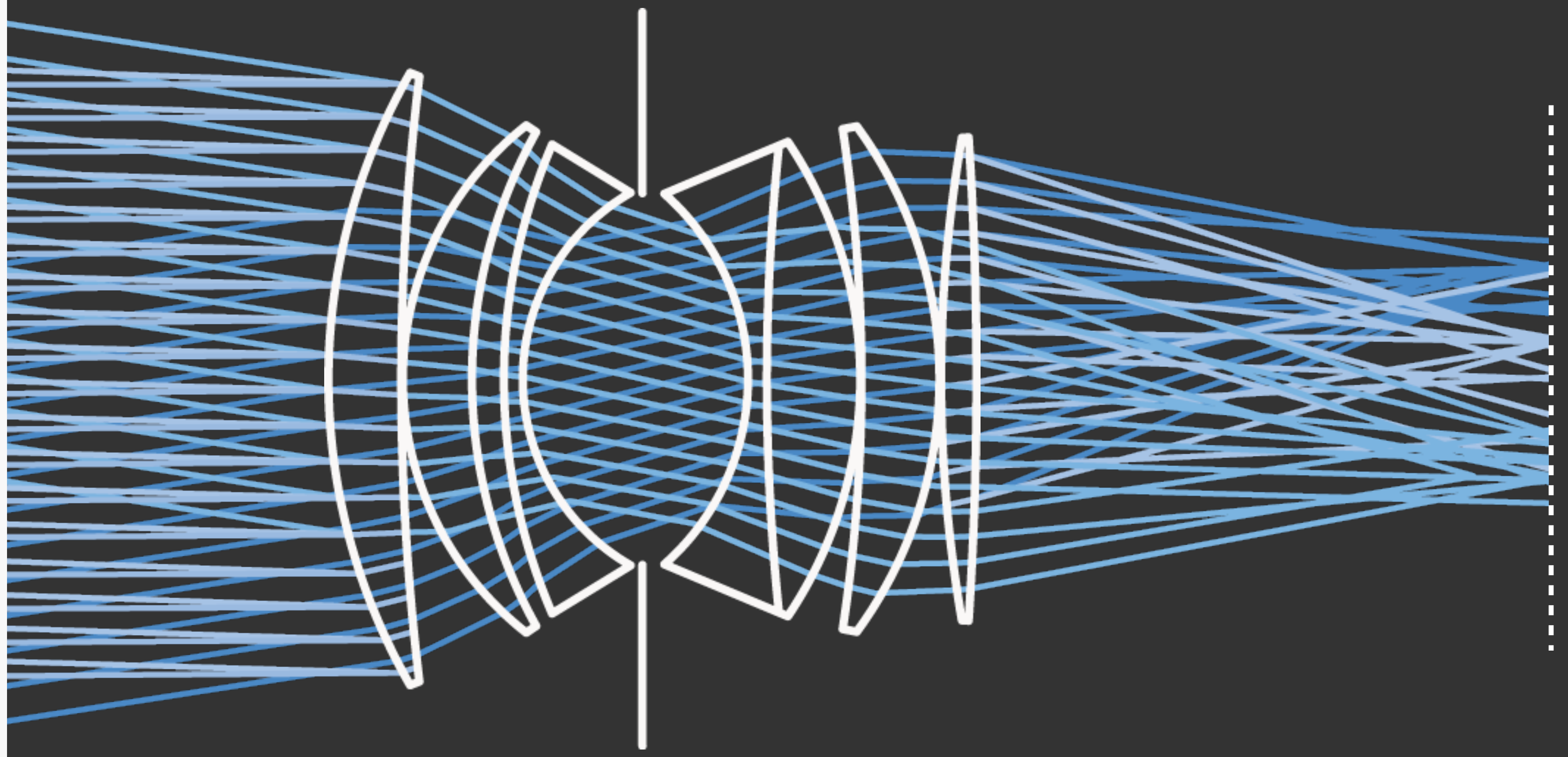
Sensor / lens gap determines plane of physical focus.

Computational Refocusing

Computational Refocusing

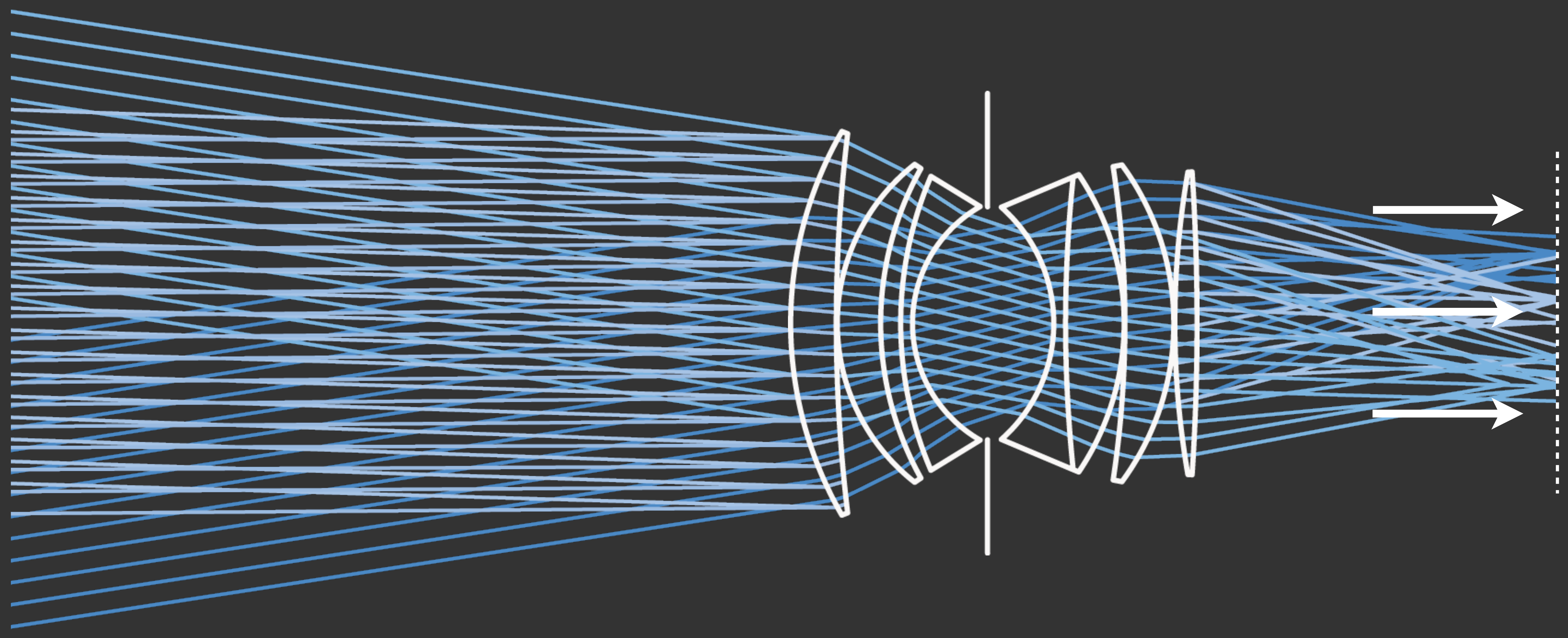


Computational Refocusing

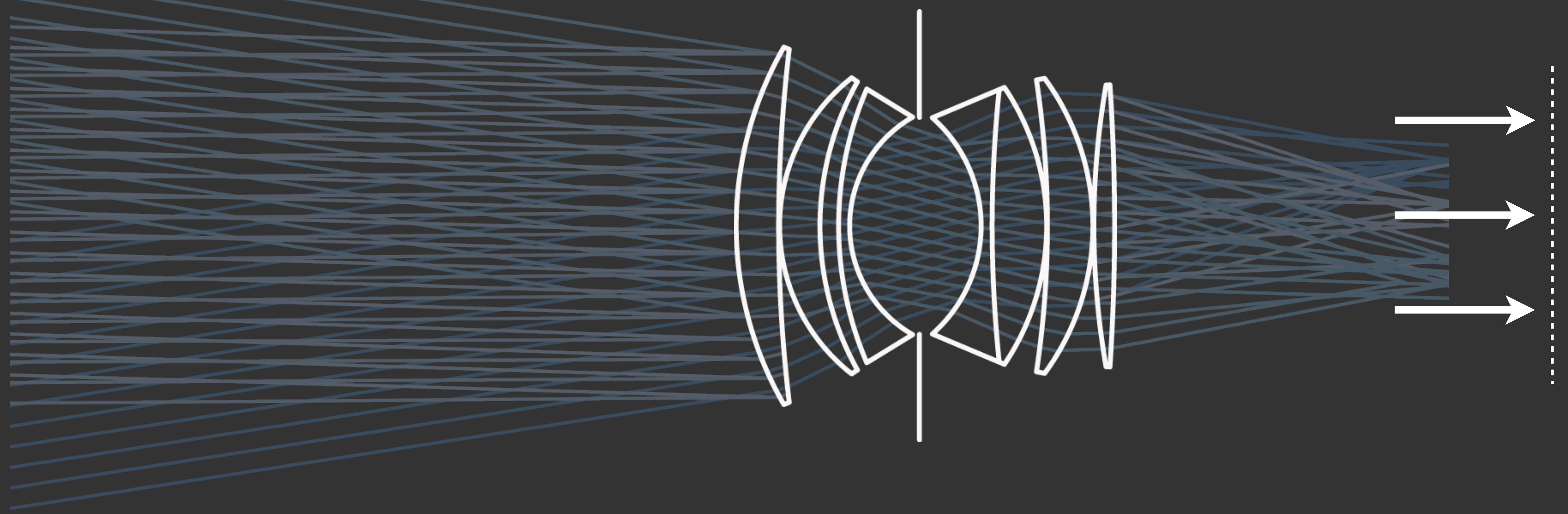


← focus far

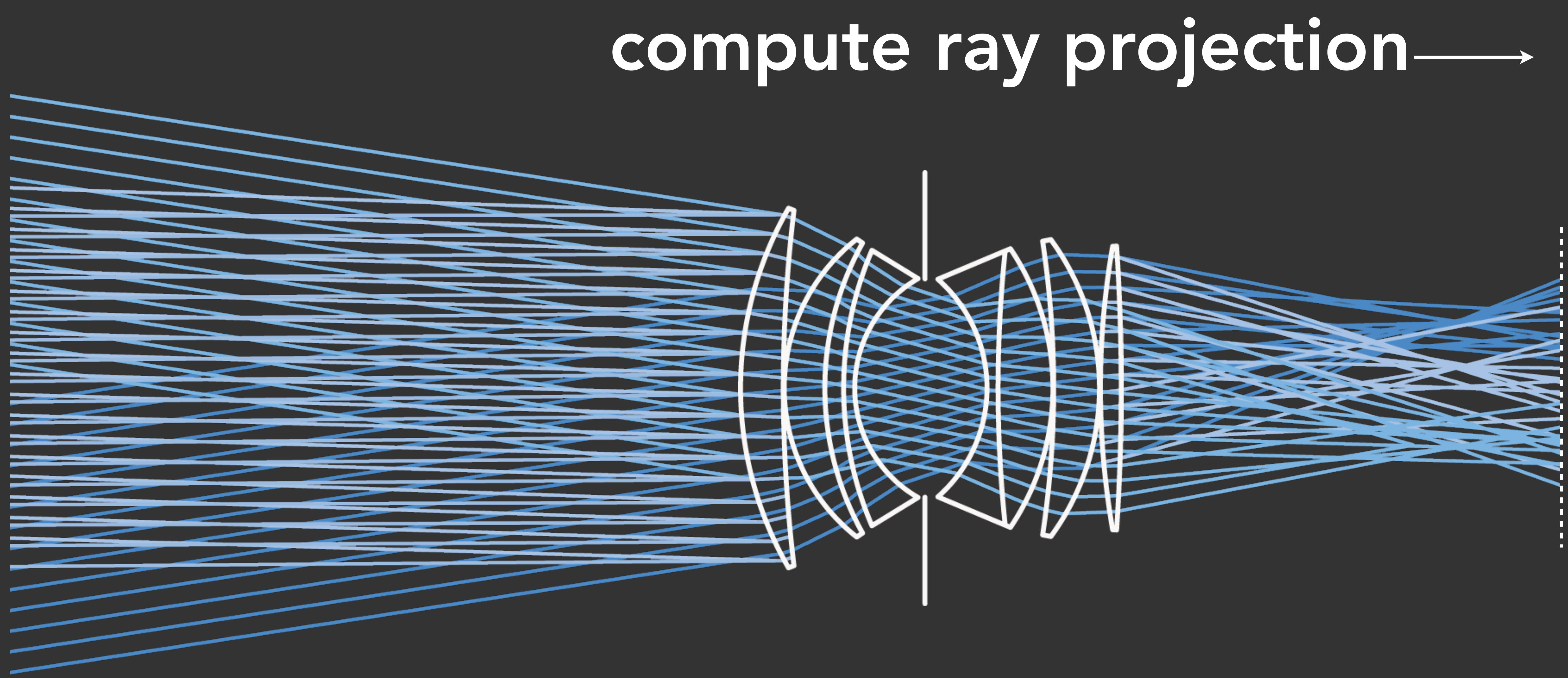
Computational Refocusing



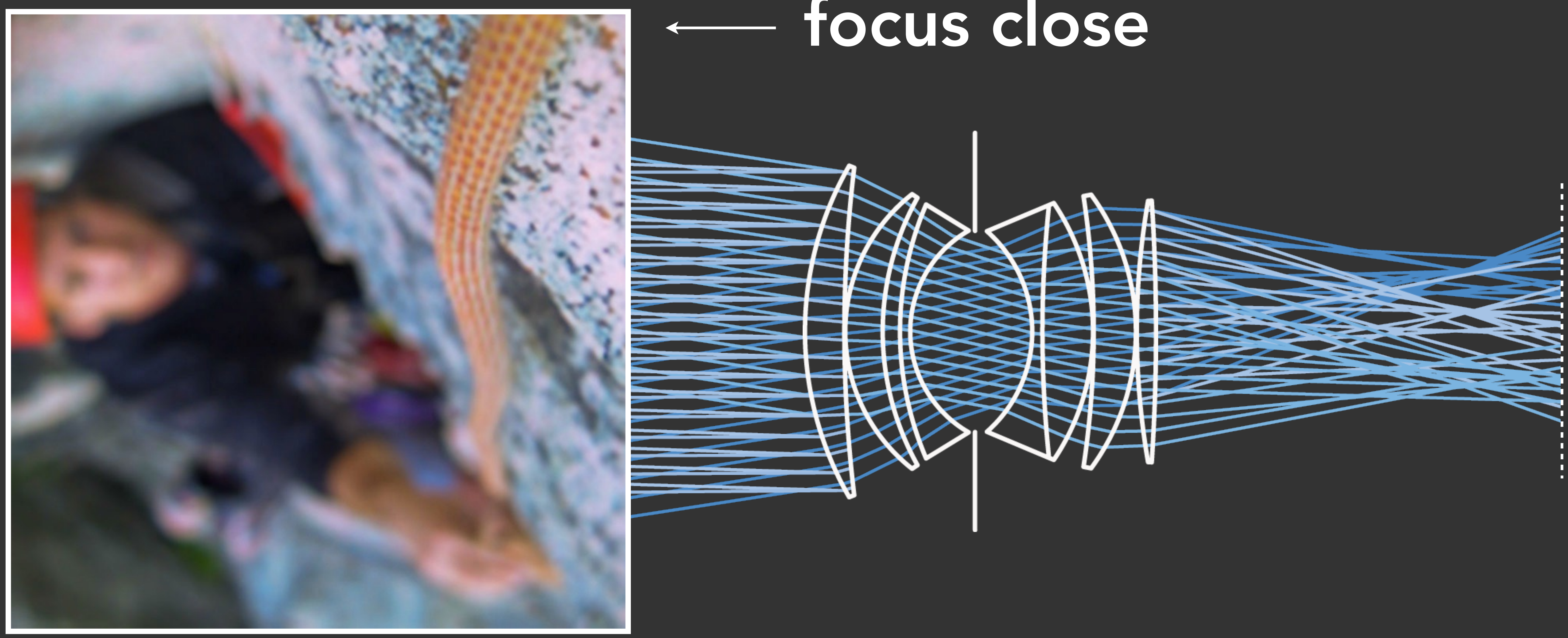
Computational Refocusing



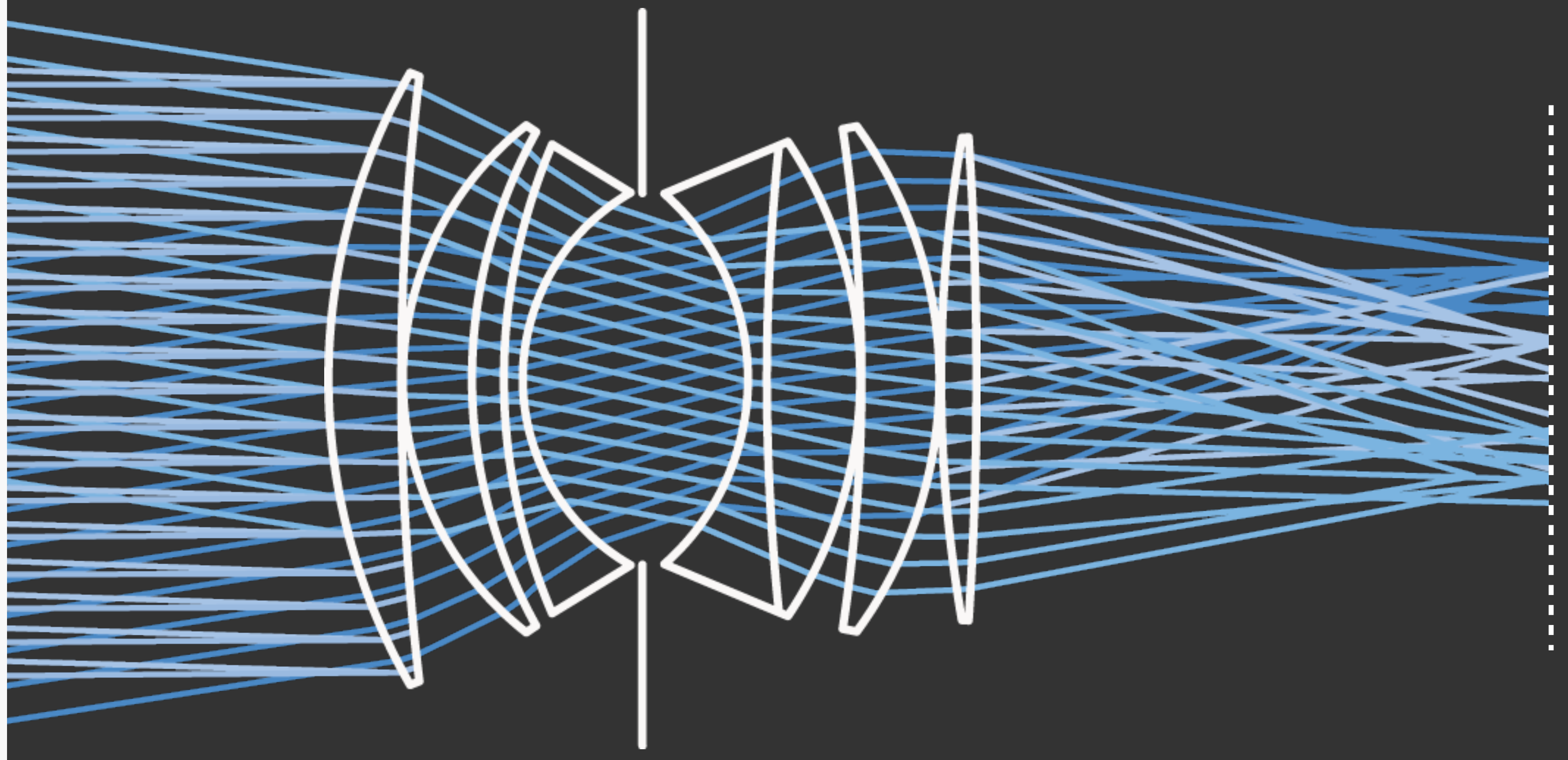
Computational Refocusing



Computational Refocusing



Computational Refocusing



← focus far

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]

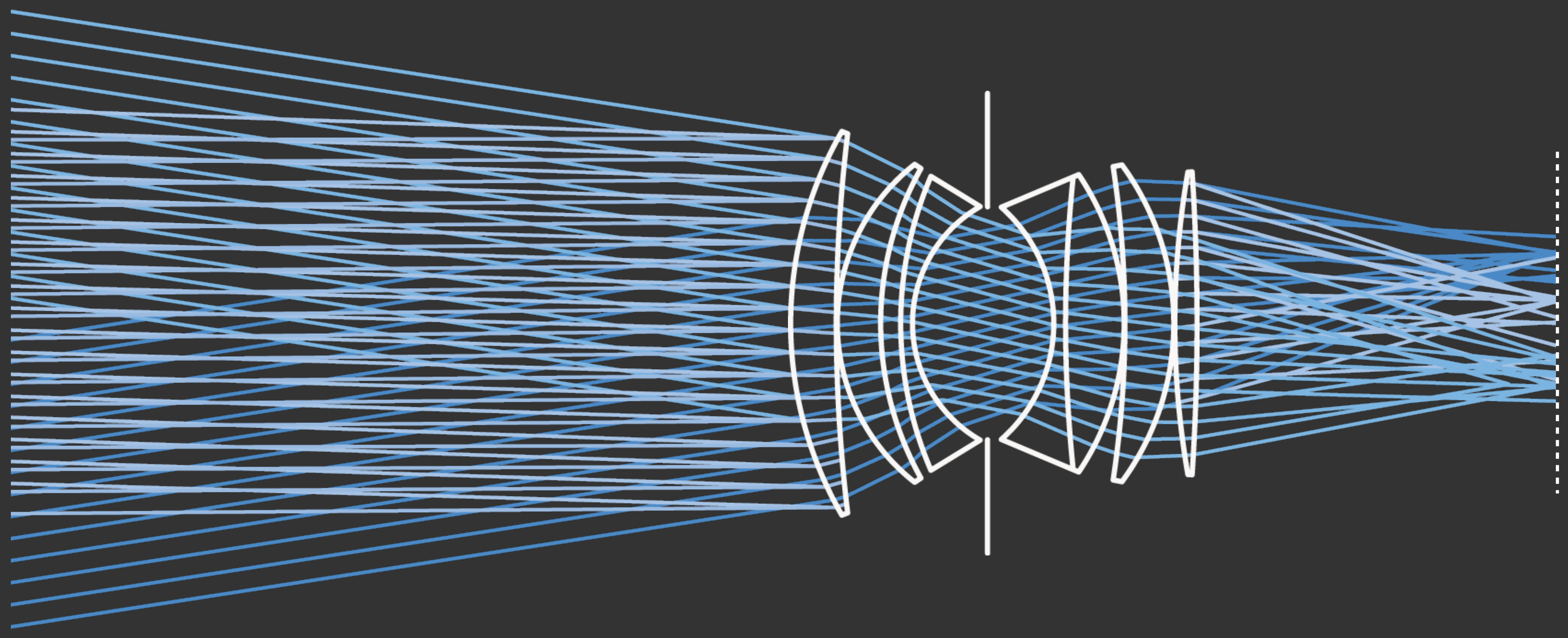
Partially Extended Depth of Field

Original
DOF

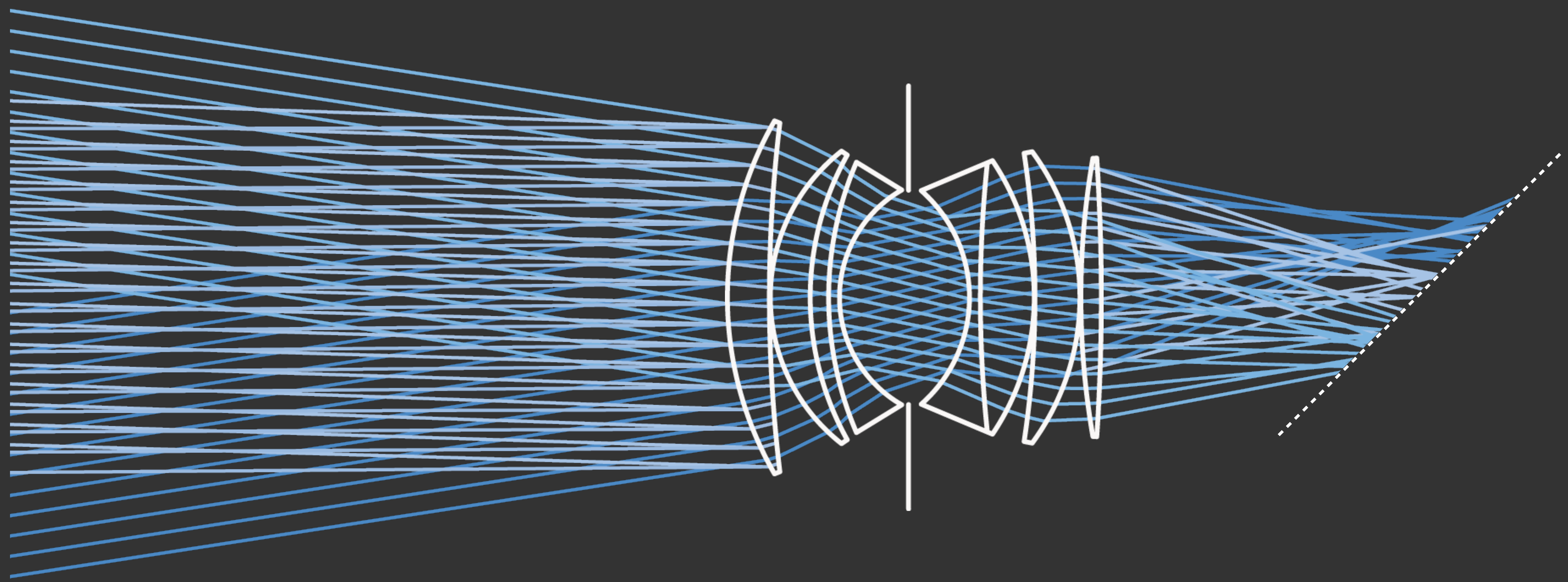
Extended
DOF

Partially Extended
DOF

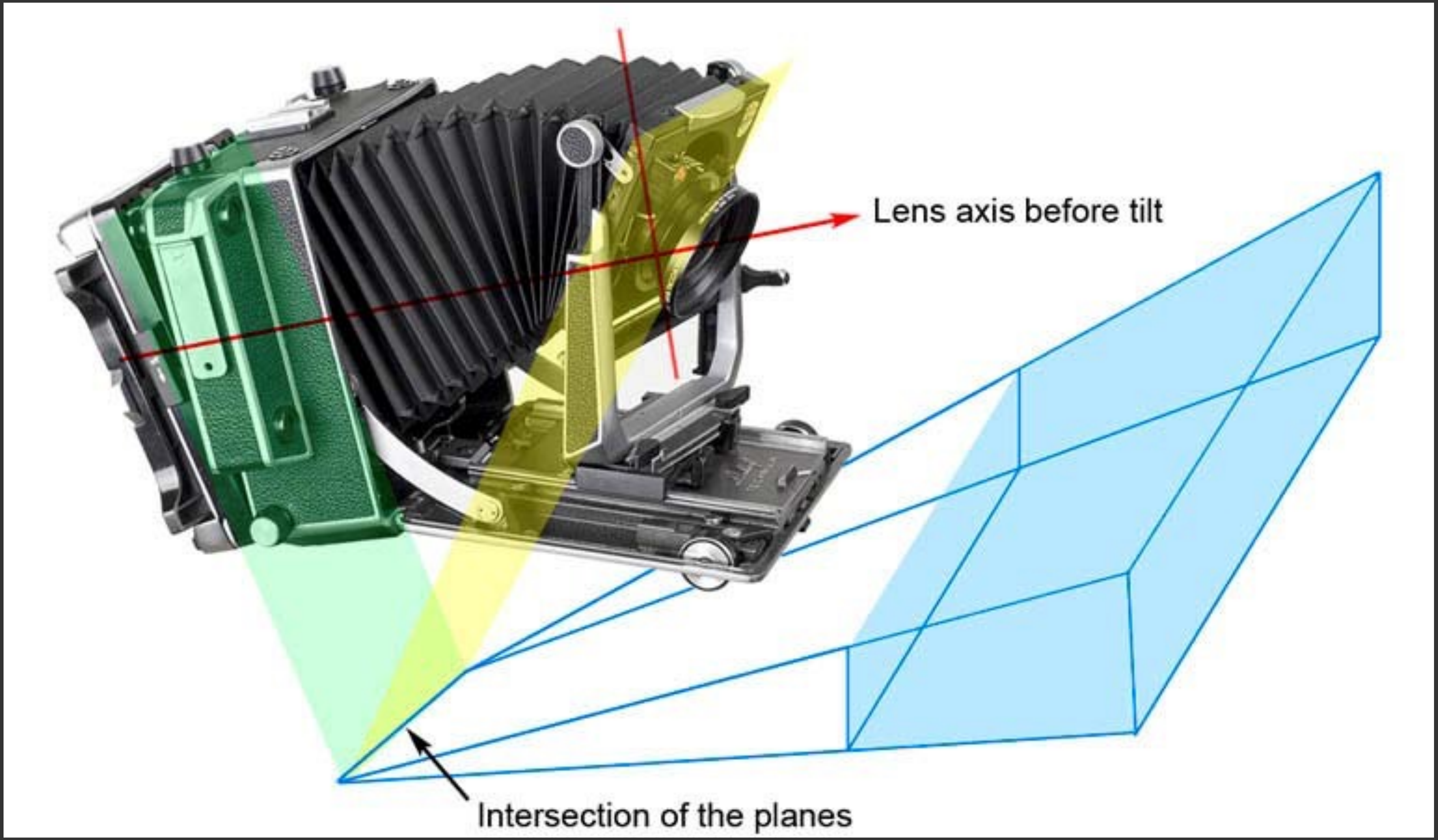
Tilted Focal Plane



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)

Things to Remember

- Field of view depends on focal length and sensor size
- Perspective composition - focal length and camera position
- Exposure — aperture, shutter, gain (ISO)
- Deriving the thin lens equation from Gauss' ray diagram
- Defocus blur, circle of confusion, depth of field
- Using ideal thin lenses, or real compound lens optical designs, in ray tracing
- 4D light field cameras, plenoptic sensors (microlens arrays) and refocusing by ray-tracing

Acknowledgments

Many thanks to Marc Levoy, who created many of these slides, and Pat Hanrahan.

- London, Stone, and Upton, Photography (9th ed.), Prentice Hall, 2008.
- Peterson, Understanding Exposure, AMPHOTO 1990.
- The Slow Mo Guys
- bobatkins.com
- Hari Subramanyan
- Canon EF Lens Work III

Extra

Auto Focus

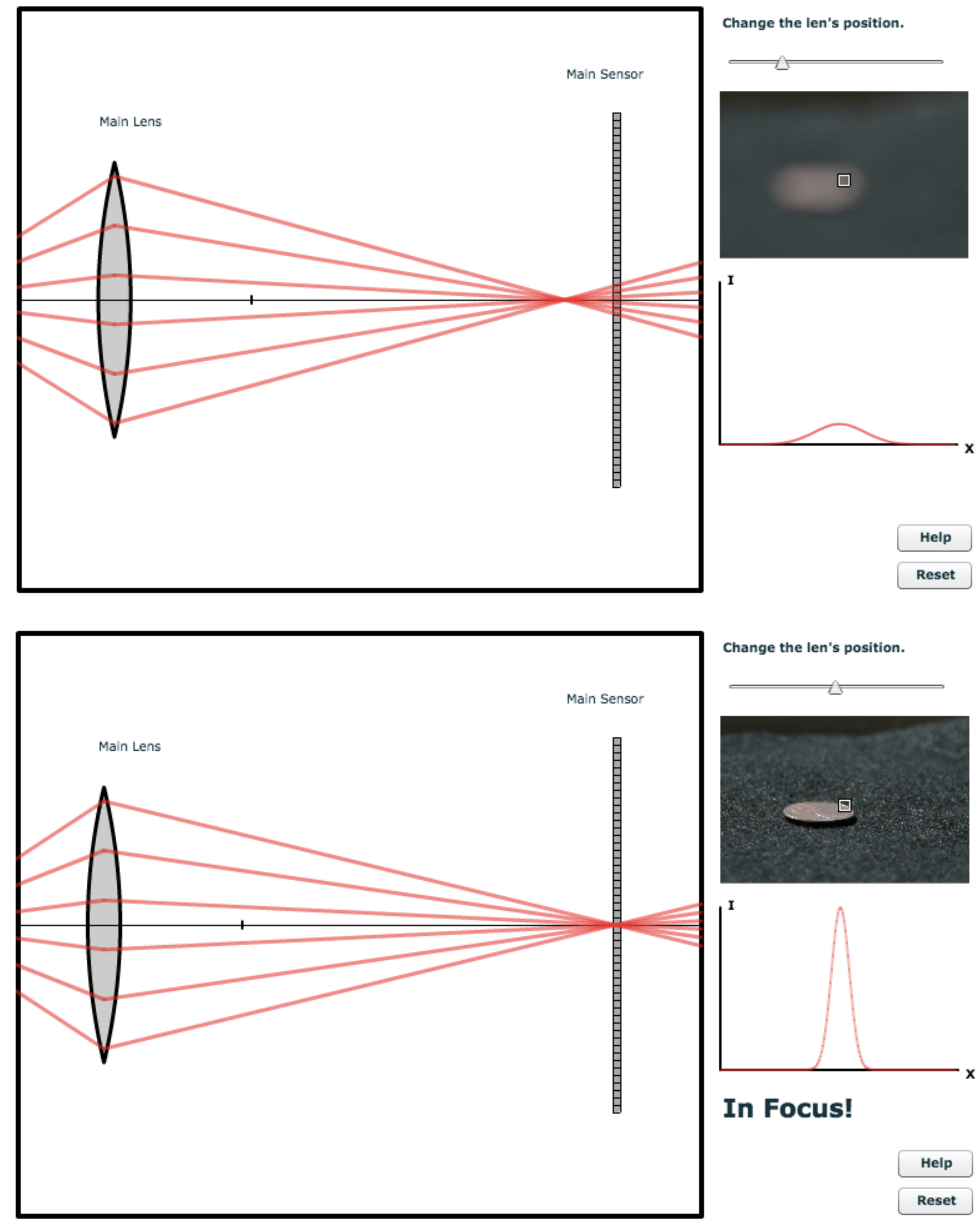
Contrast Detection Autofocus

A target object is imaged through the lens to an image patch on the sensor.

The contrast of this image patch is high if the object is in focus, low otherwise.

The physical focus of the lens is adjusted until the contrast of this image patch is maximized.

Many ways to estimate how in-focus the image patch is: gradient, Sum Modified Laplacian (Nayar), variance…



Demo (Levoy, Willet, Adams)

https://graphics.stanford.edu/courses/cs178-10/applets/autofocusCD.html

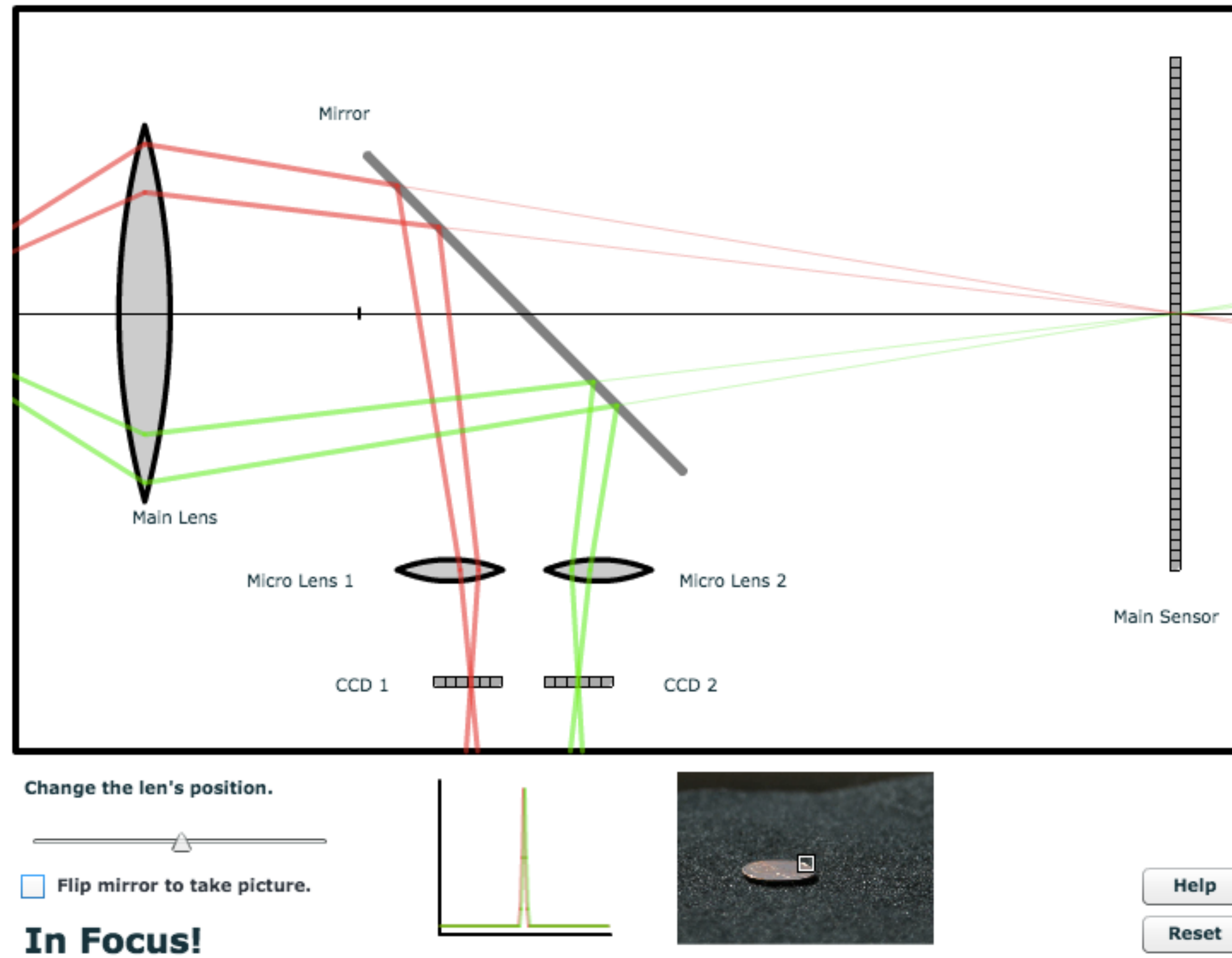
Phase Detection Autofocus

Ray bundles from a target object converge to points at different depths in the camera depending on the lens focus.

In a phase detection AF system ray bundles passing through different portions of the lens (red and green shown) are brought to focus on separate lenslets with separate AF sensors.

Depending on depth of focus point, the ray bundles converge to different positions on their respective AF sensors (see interactive demo).

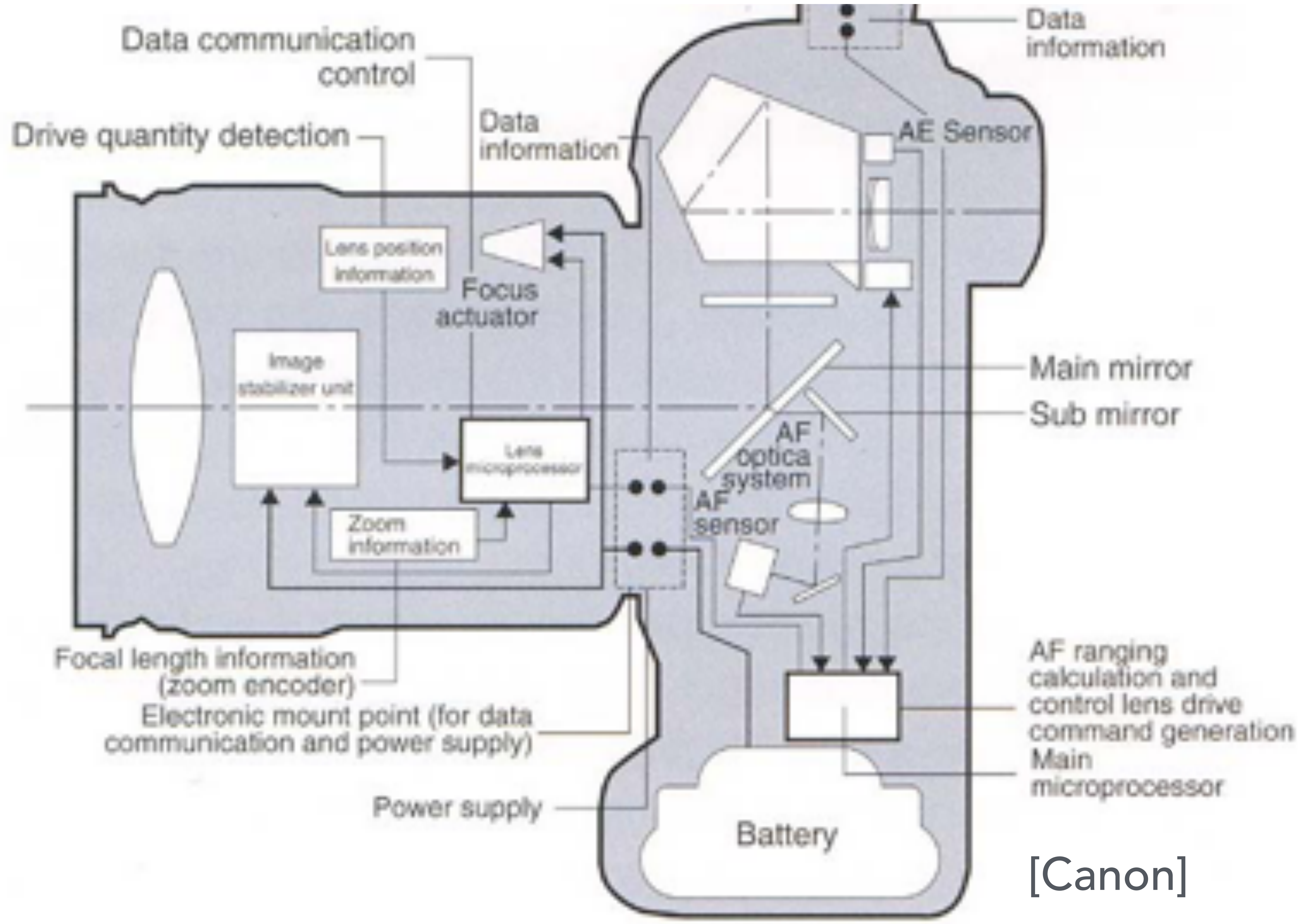
A certain spacing (disparity) between these images is "in focus"



Demo (Levoy, Willet, Adams)

https://graphics.stanford.edu/courses/cs178-10/applets/autofocusPD.html

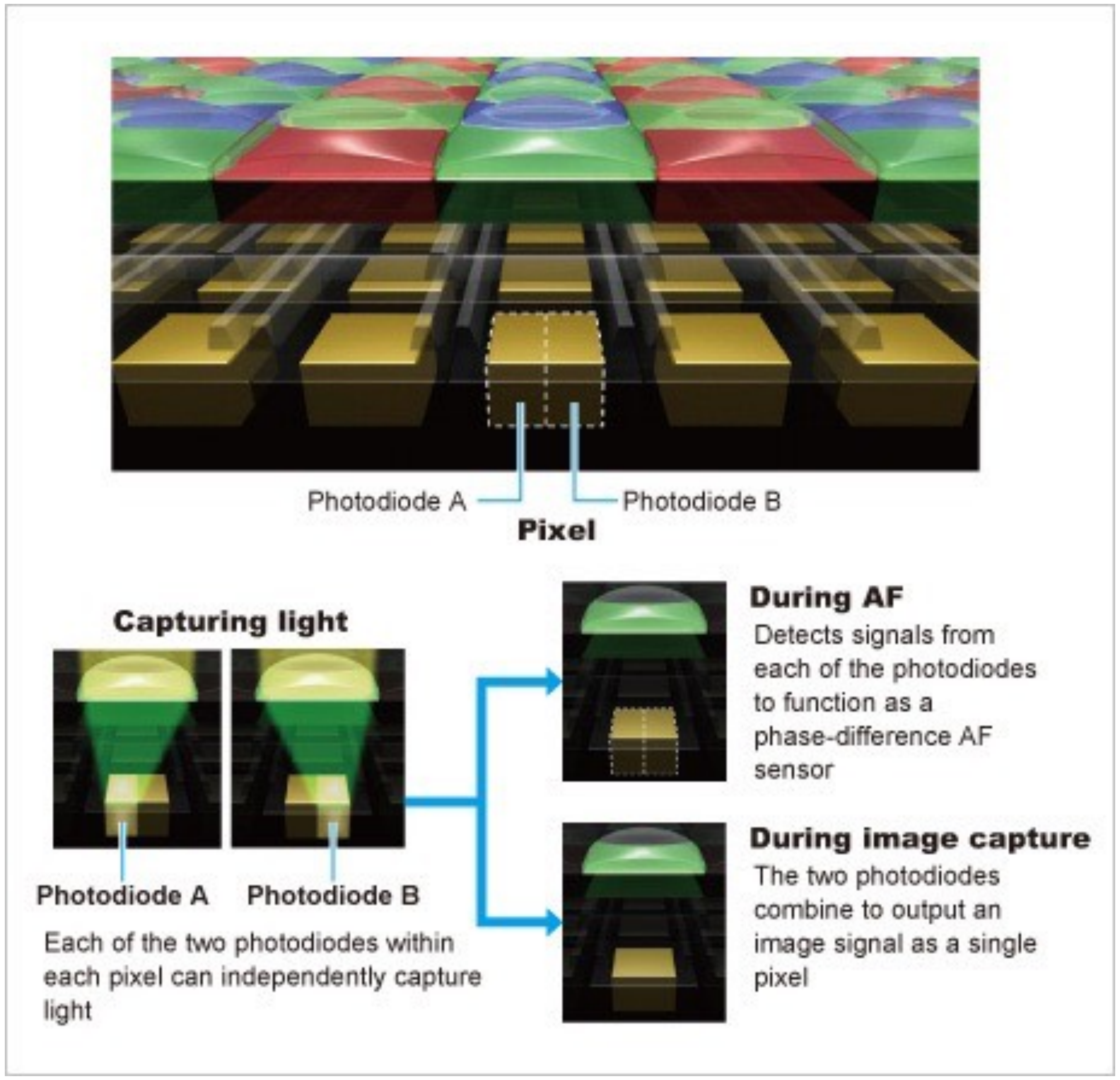
Phase Detection AF Used in DSLRs

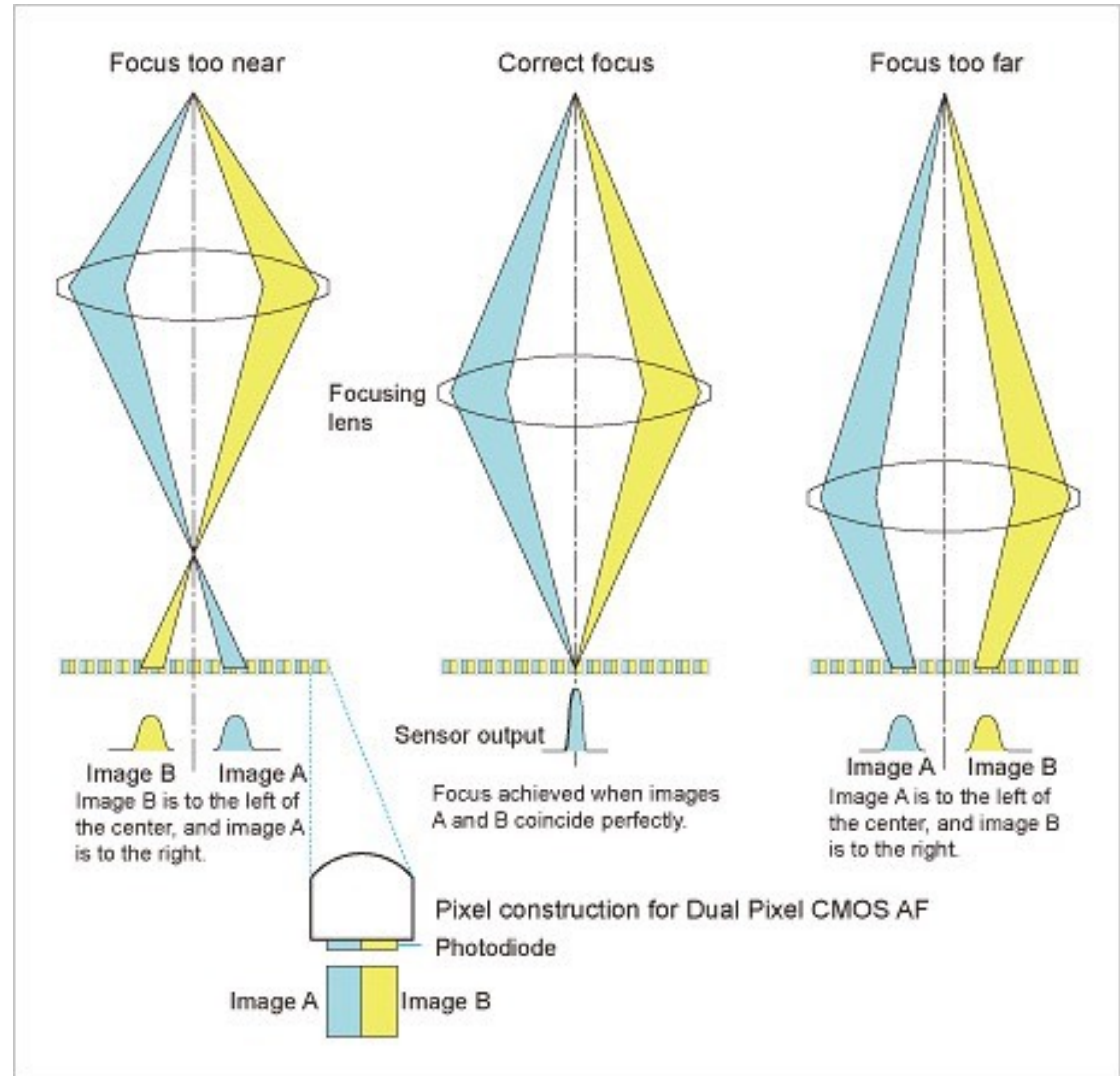


[Canon]

- Distance between phase-detect images correlates to distance in focus to target object (allows "jumping" to the right focus)
- Separate AF units cannot be used with "live view" or video recording

Phase Detection Pixels Embedded in Sensor





Canon

- Modern image sensors have small pixels, and may embed phase detection pixels directly into sensor image arrays