

Lecture 25:

The Light Field and Computational Cameras

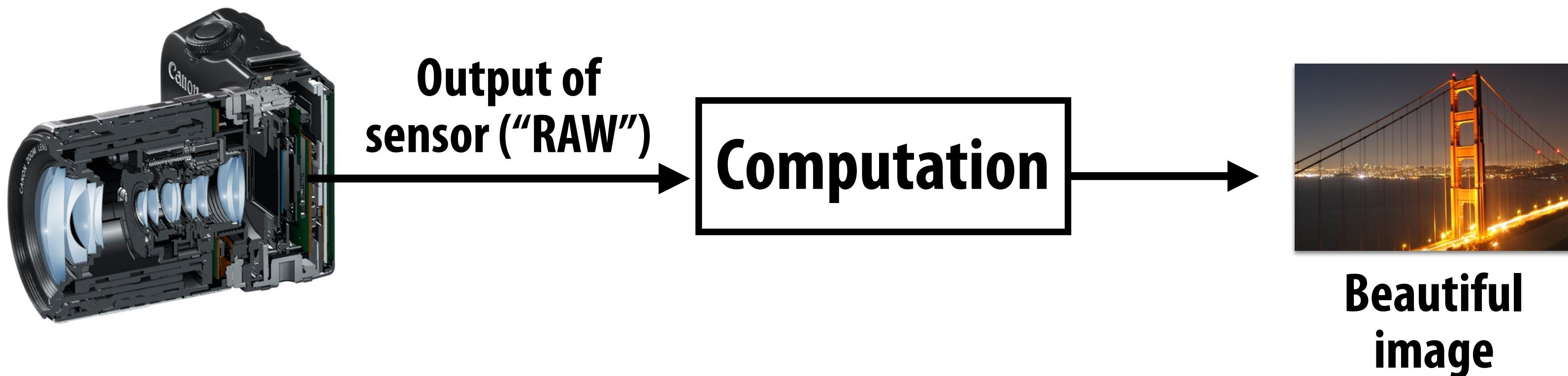
**Computer Graphics
CMU 15-462/15-662, Fall 2015**

Credit: light-field camera slides courtesy of Ren Ng

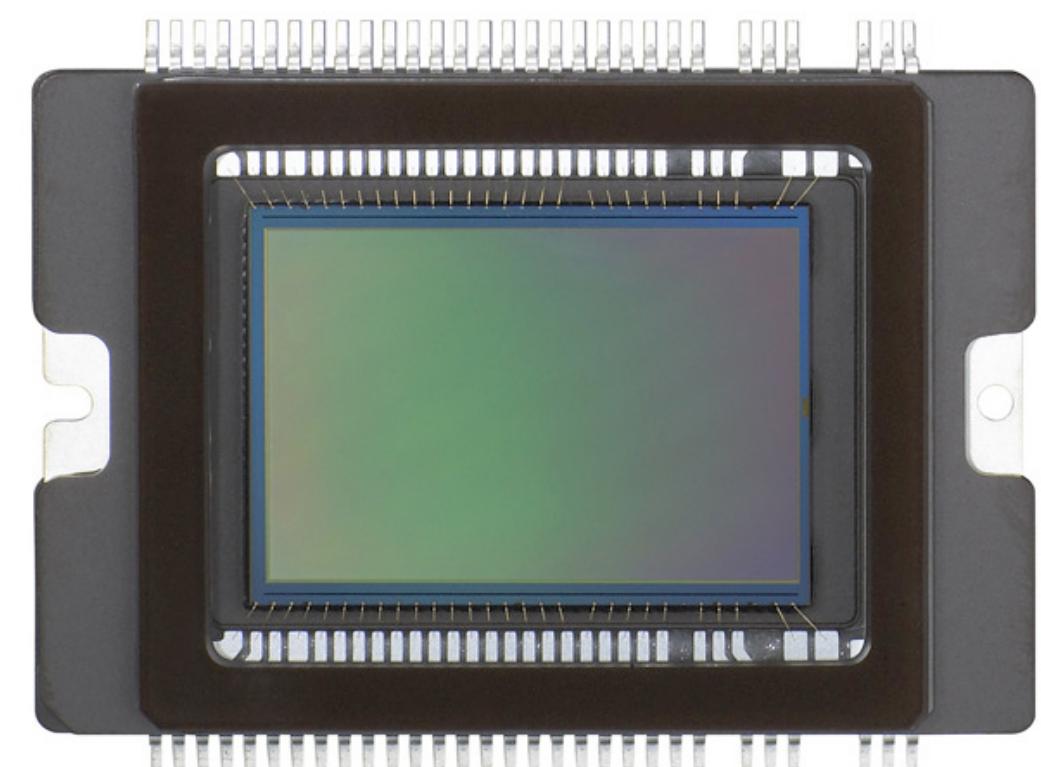
Takeaway from today's lecture

**The values of pixels in photograph you see on screen
are quite different than the values output by the
photosensor in a modern digital camera.**

**Computation is now a fundamental aspect of
producing high-quality good pictures.**



Camera's lens system focuses light on sensor



**Canon 14 MP CMOS Sensor
(14 bits per pixel)**

CMOS sensor pixel

Anatomy of the Active Pixel Sensor Photodiode

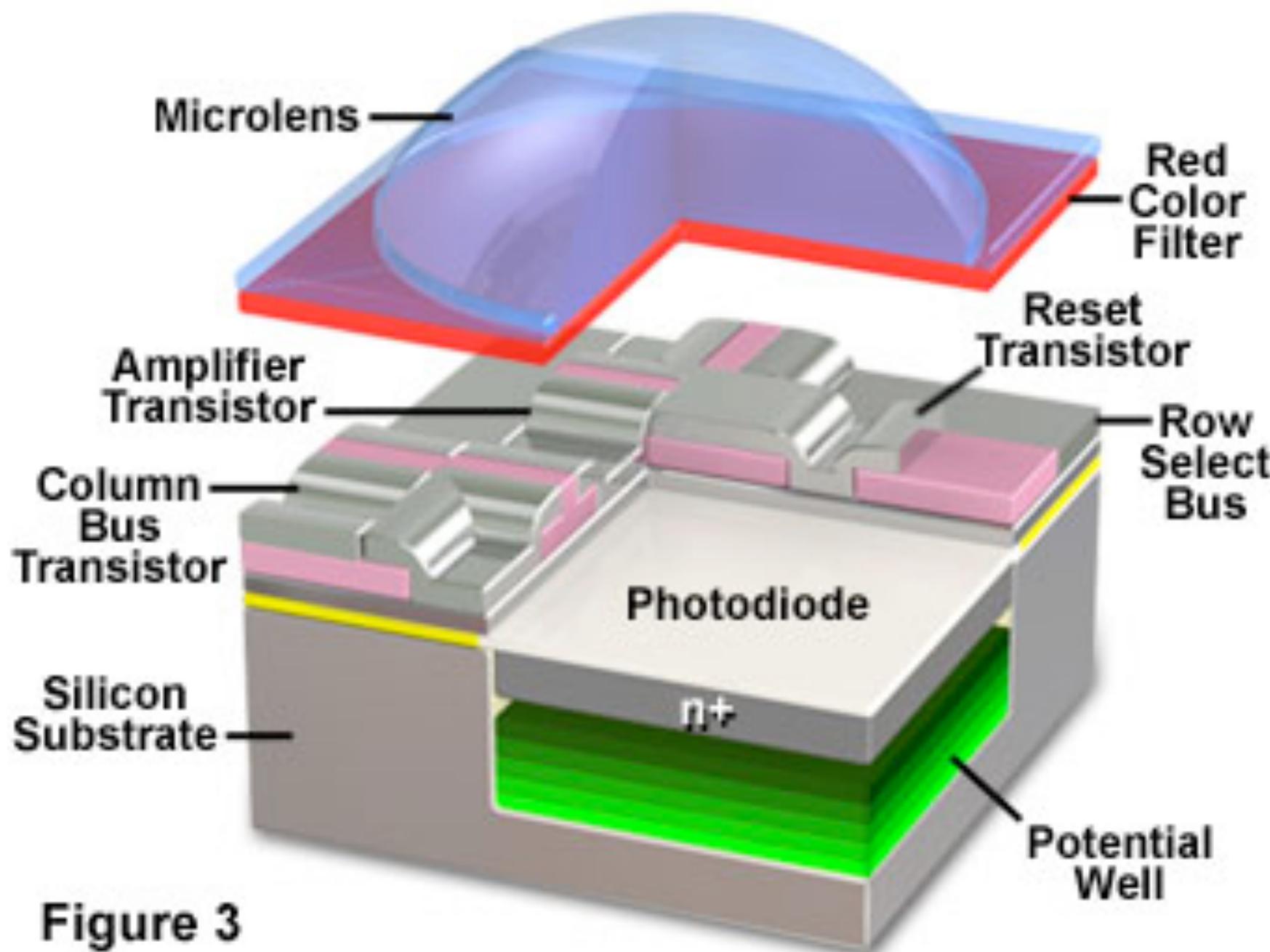


Figure 3

**Color filter attenuates light
(more on this soon)**

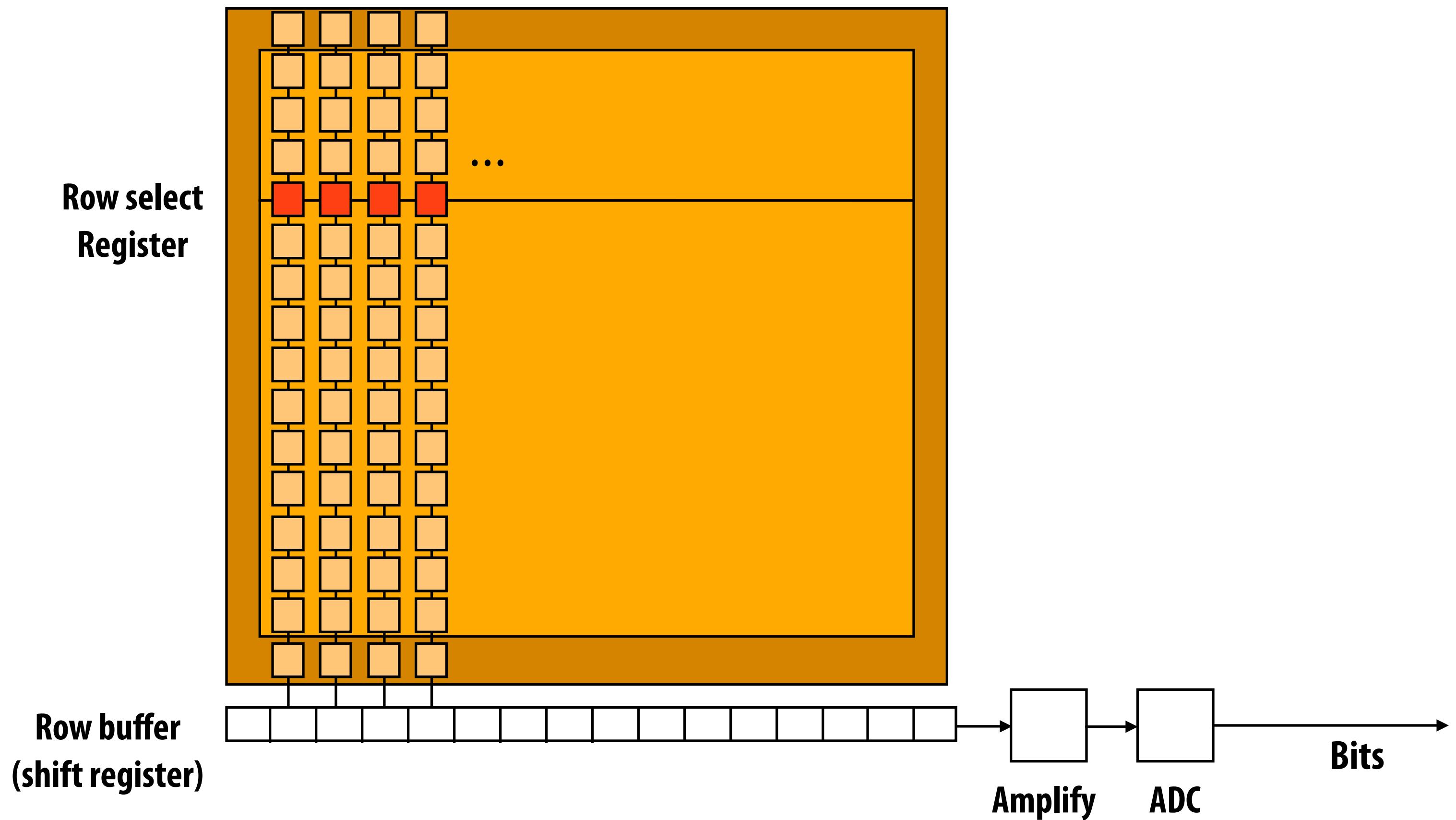
Fill factor: fraction of surface area used for light gathering

**Microlens (a.k.a. lenslet) steers light toward photo-sensitive region
(increases light-gathering capability)**

Microlens also serves to prefilter signal. Why?

Quantum efficiency of photodiode in typical digital camera ~ 50%

Reading sensed signal off sensor



Measurement noise

■ Photon shot noise:

- Photon arrival rates feature poisson distribution
- Standard deviation = \sqrt{N}
- Signal-to-noise ratio: N/\sqrt{N}

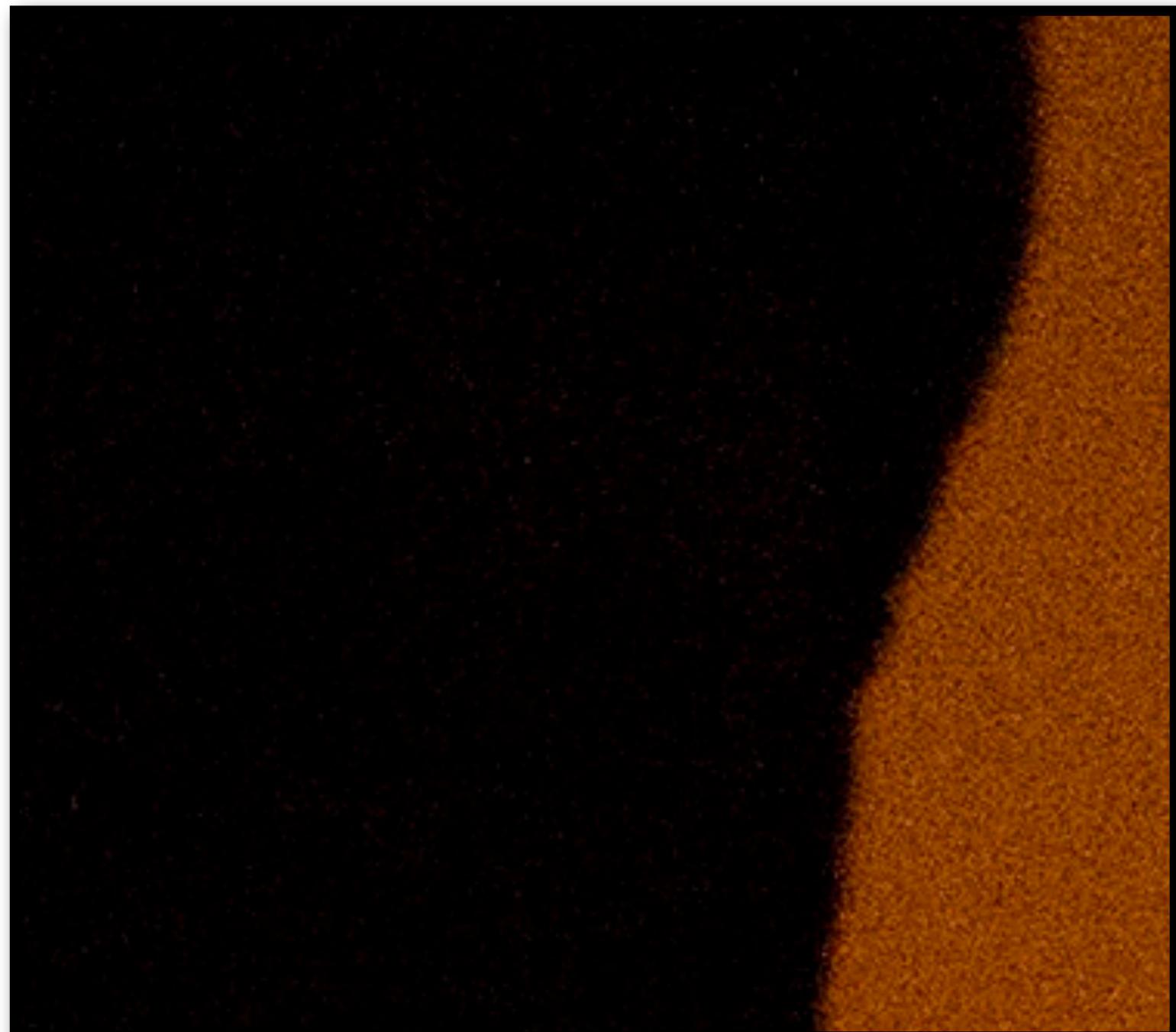
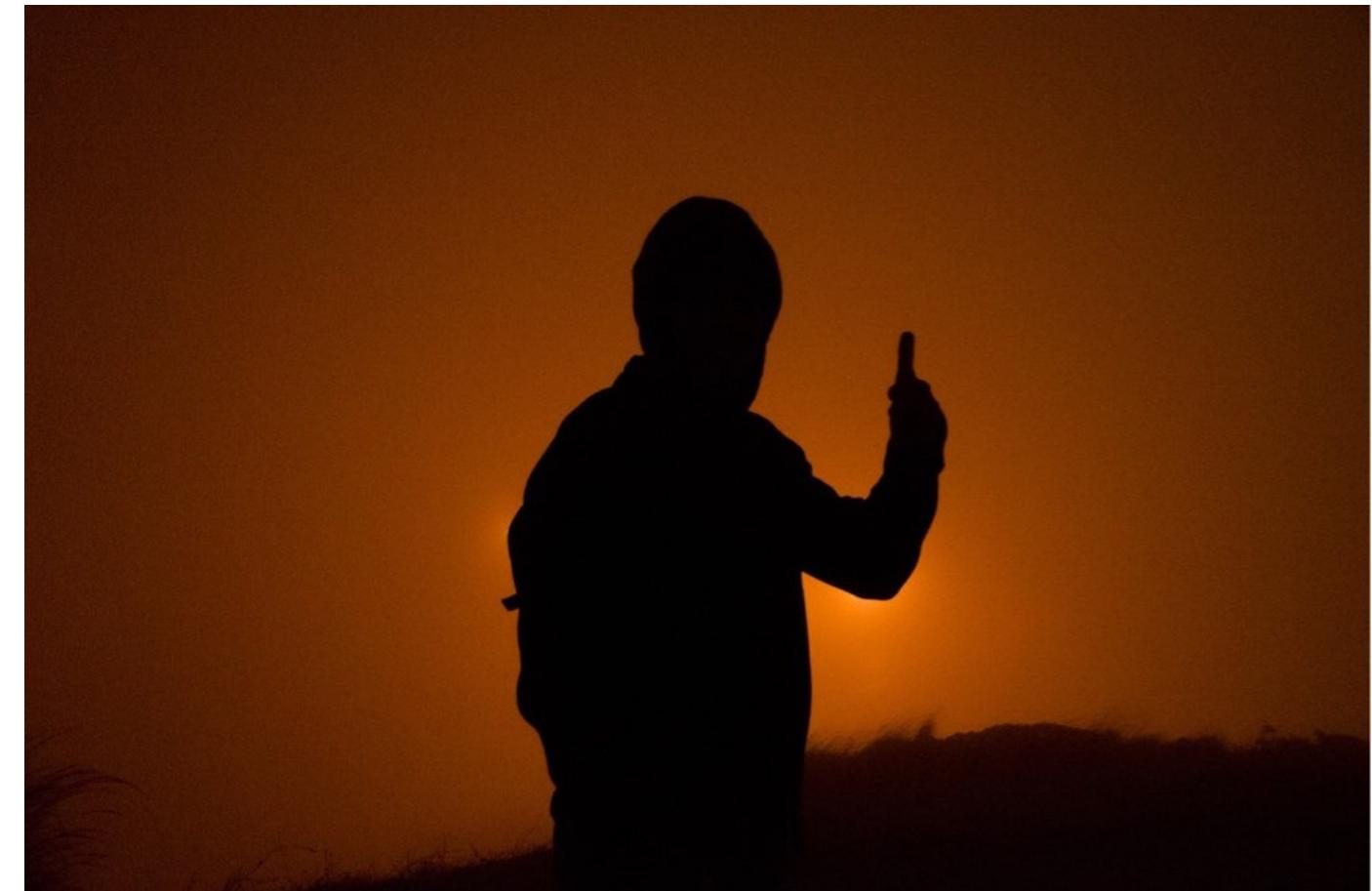
■ Dark-shot noise

- Due to leakage current

■ Non-uniformity of pixel sensitivity

■ Read noise

- e.g., due to amplification prior to ADC

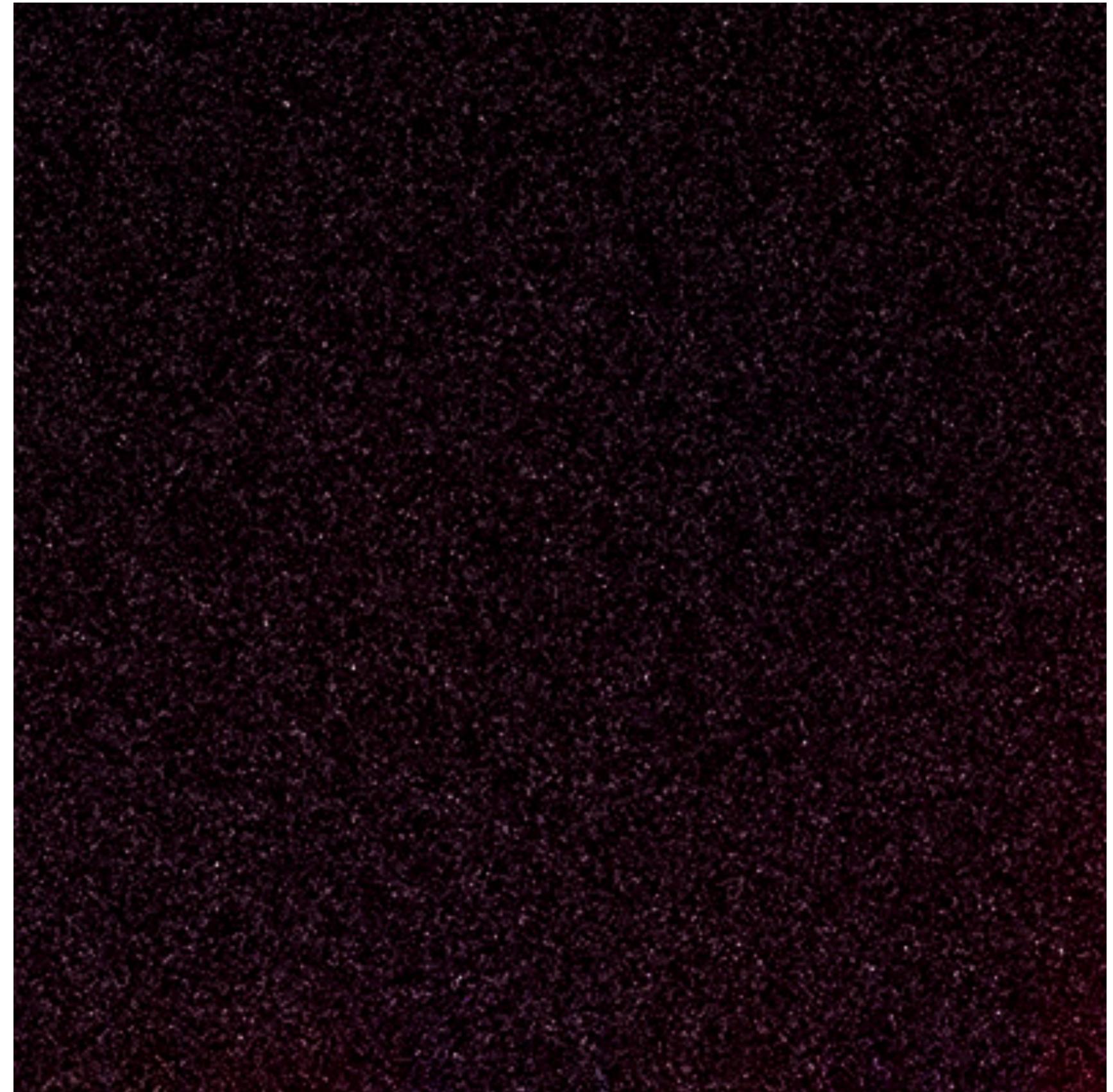


Noise

Black image examples: Nikon D7000, High ISO



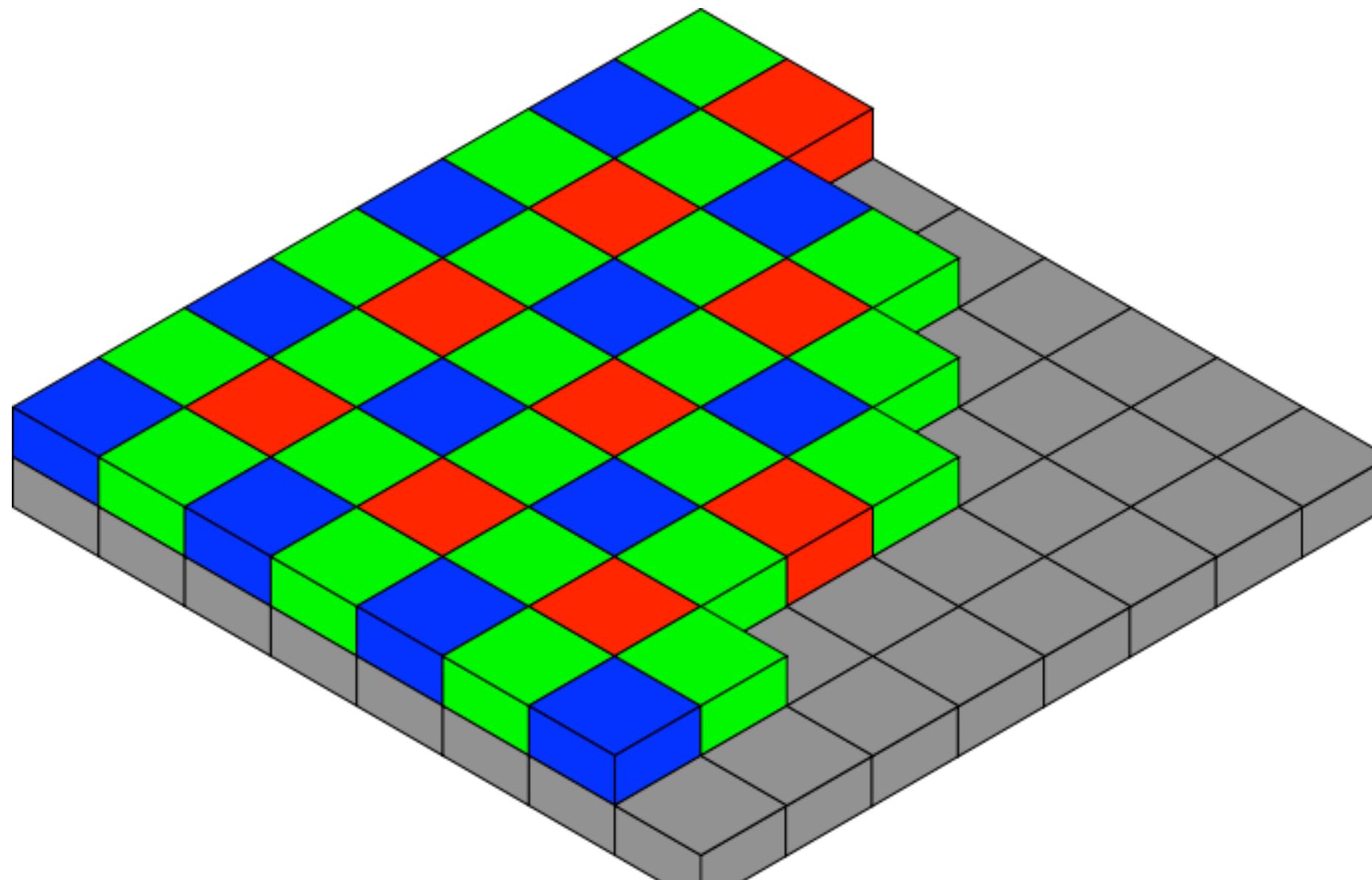
1/60 sec exposure



1 sec exposure

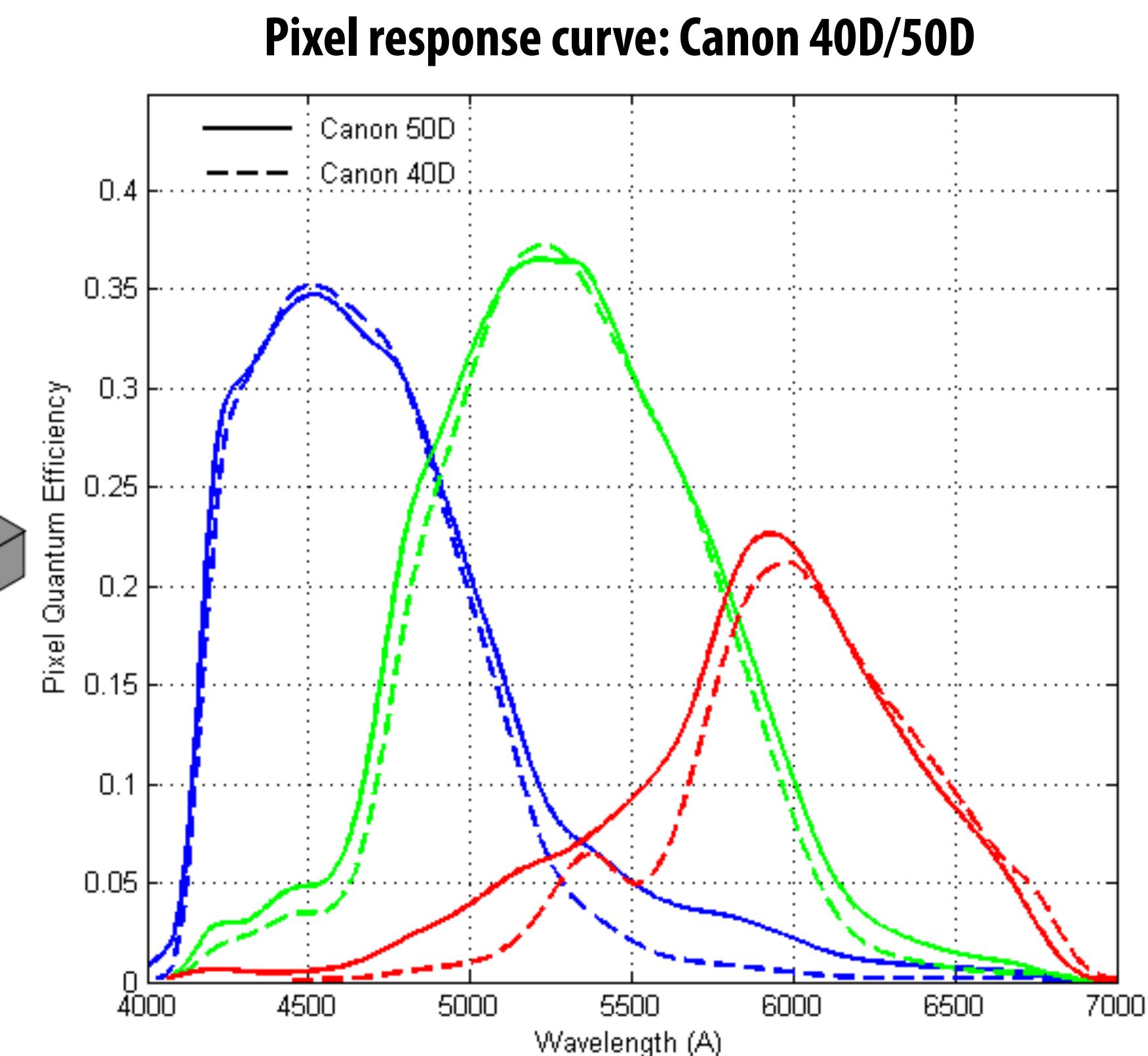
Color filter array (Bayer mosaic)

- Color filter array placed over sensor
- Result: each pixel measures red, green, or blue light
- 50% of pixels are green pixels



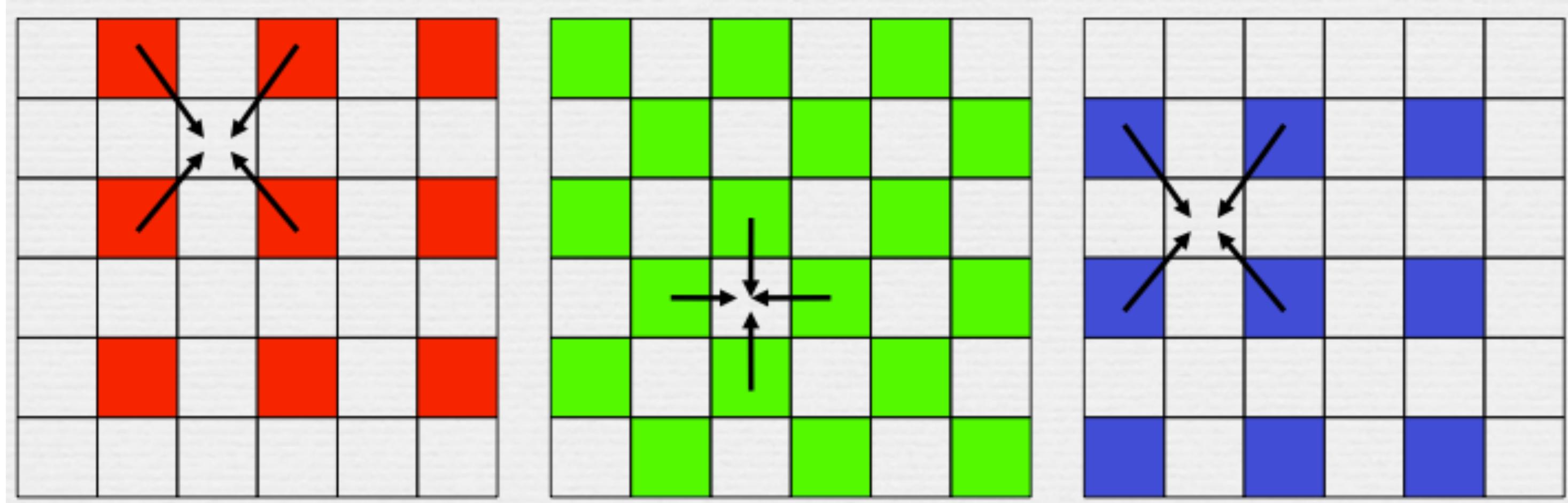
Traditional Bayer mosaic

(other filter patterns exist: e.g., Sony's RGBE)



Demosiac

- Produce RGB image from mosaiced input image
- Basic algorithm: bilinear interpolation of mosaiced values (need 4 neighbors)
- More advanced algorithms:
 - Bicubic interpolation (wider filter support region... may overblur)
 - Good implementations attempt to find and avoid interpolation across edges



RAW sensor output (simulated data)

Light Hitting Sensor

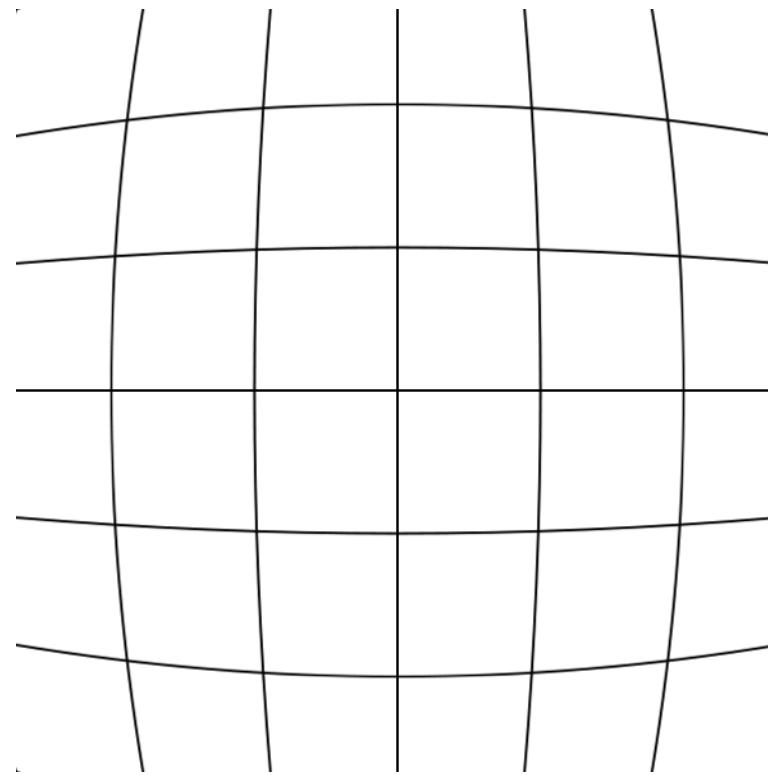


RAW output of sensor

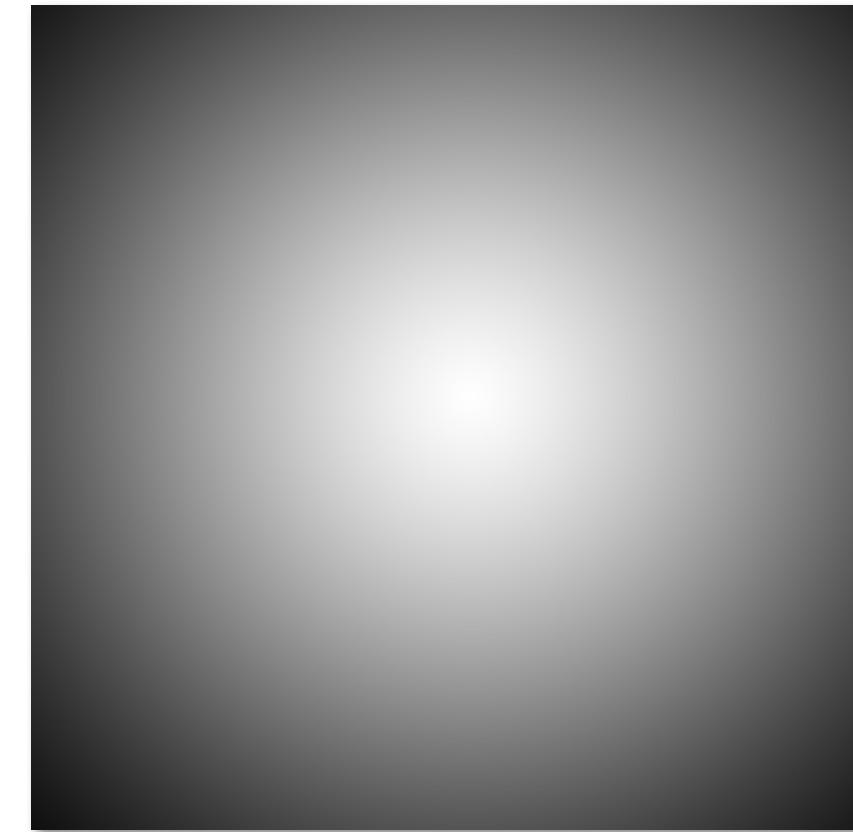


Other corrections

- Dead pixels
- Vignetting (optical and pixel)
- Lens distortion
- ...



Pincushion distortion



Vignetting
(less light at corner pixels)

Takeaway: a complex pipeline of image processing operations is required to convert the output of a sensor to an image that you'd actually want to see.

Light L16 camera



16 synchronized cameras: allows for varying exposure, zoom, focal depth, etc..

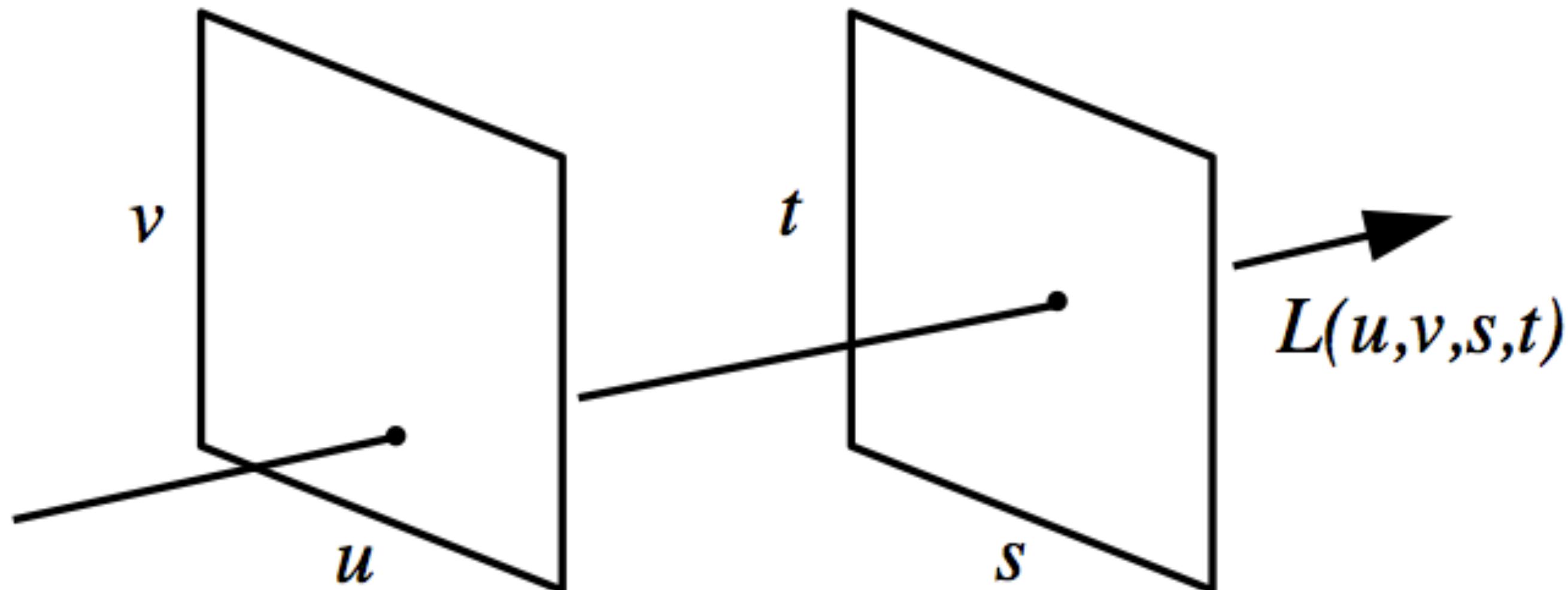
The light field

[Levoy and Hanrahan 96]

[Gortler et al., 96]

Light-field parameterization

Light field is a 4D function (represents light in free space: no occlusion)



[Image credit: Levoy and Hanrahan 96]

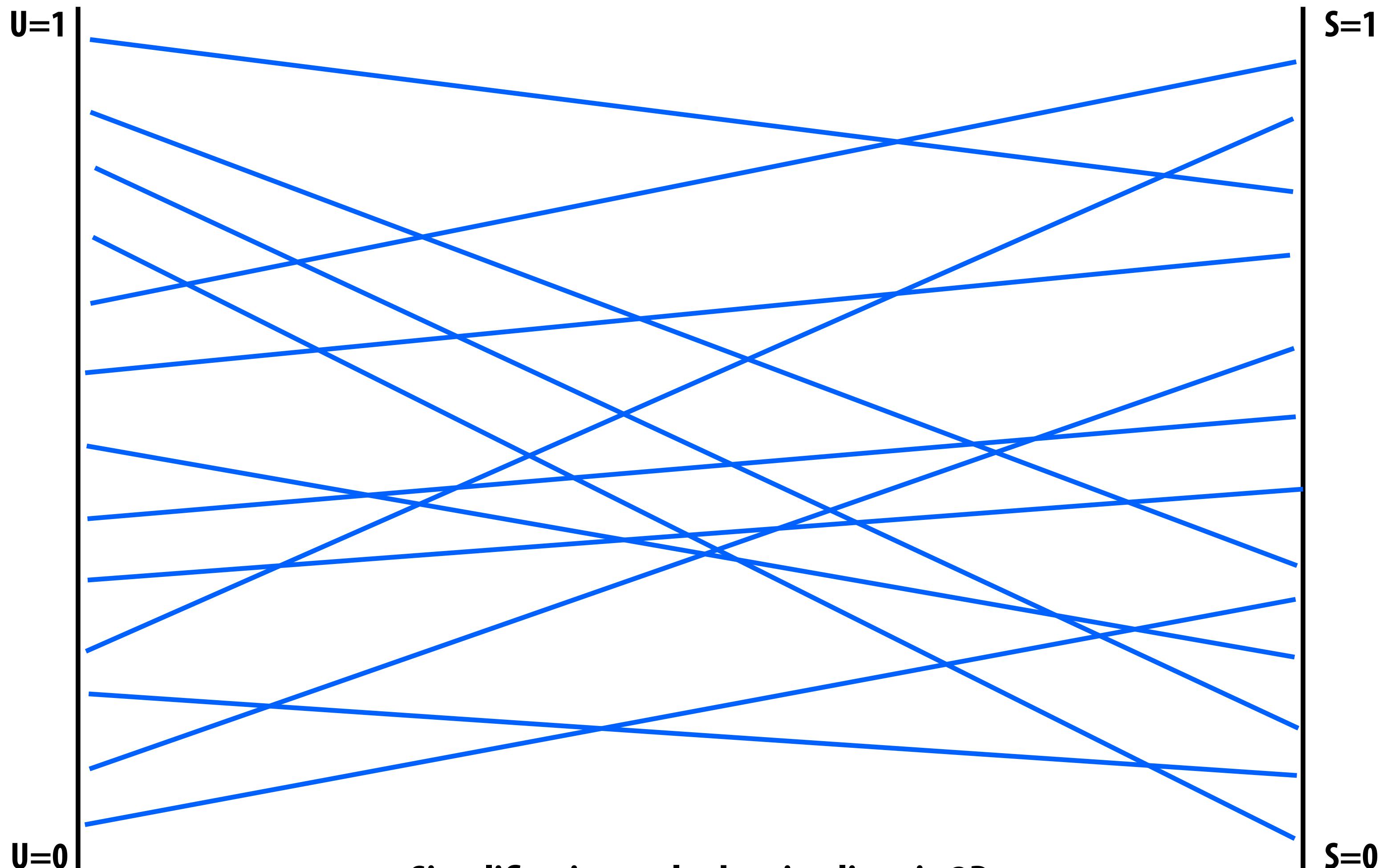
Efficient two-plane parameterization

Line described by connecting point on (u,v) plane with point on (s,t) plane

If one of the planes placed at infinity: point + direction representation

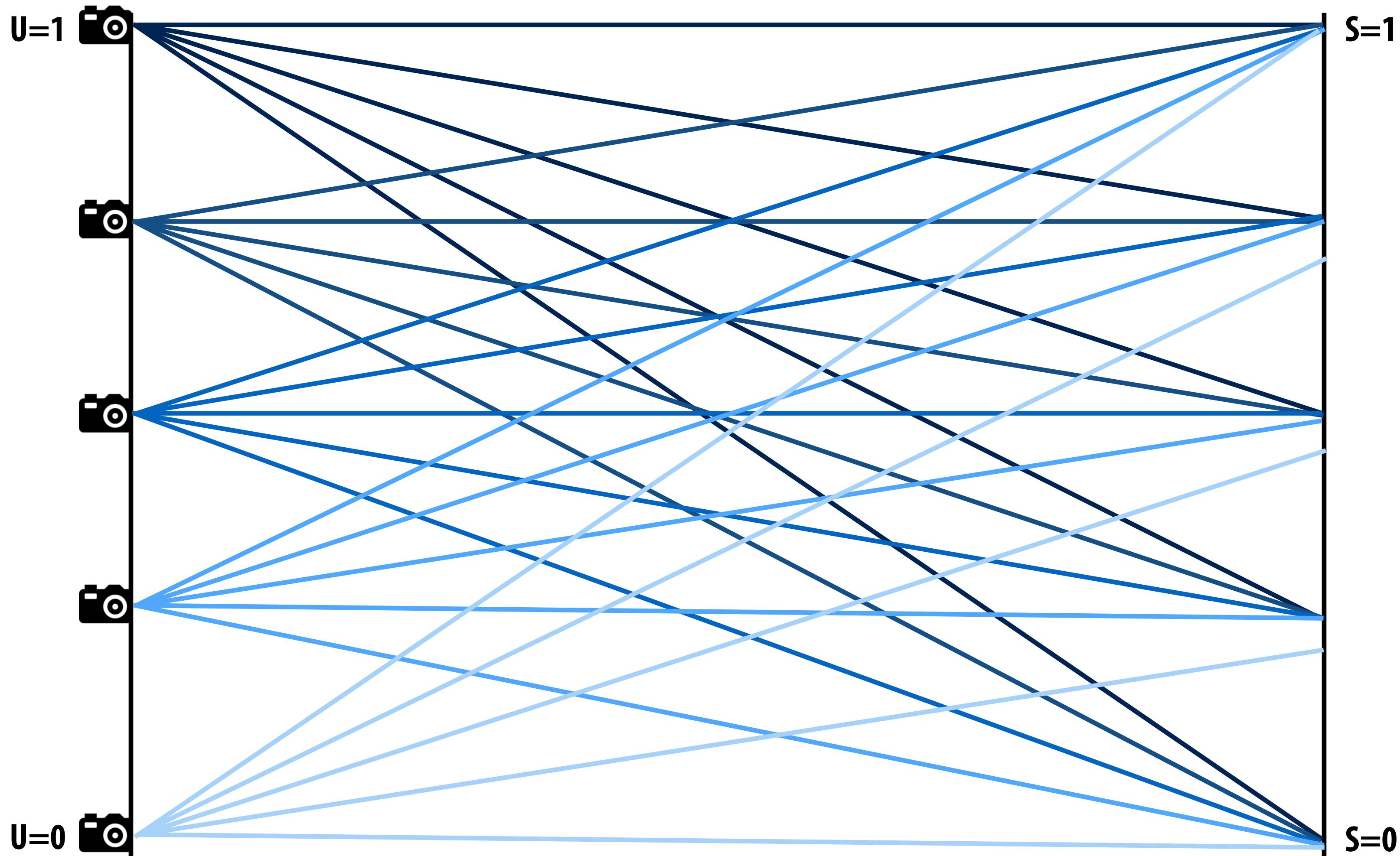
Levoy/Hanrahan refer to representation as a “light slab”: beam of light entering one quadrilateral and exiting another

Sampling the light field



**Simplification: only showing lines in 2D
(full light field is 4D function)**

Sampling the light field by taking pictures



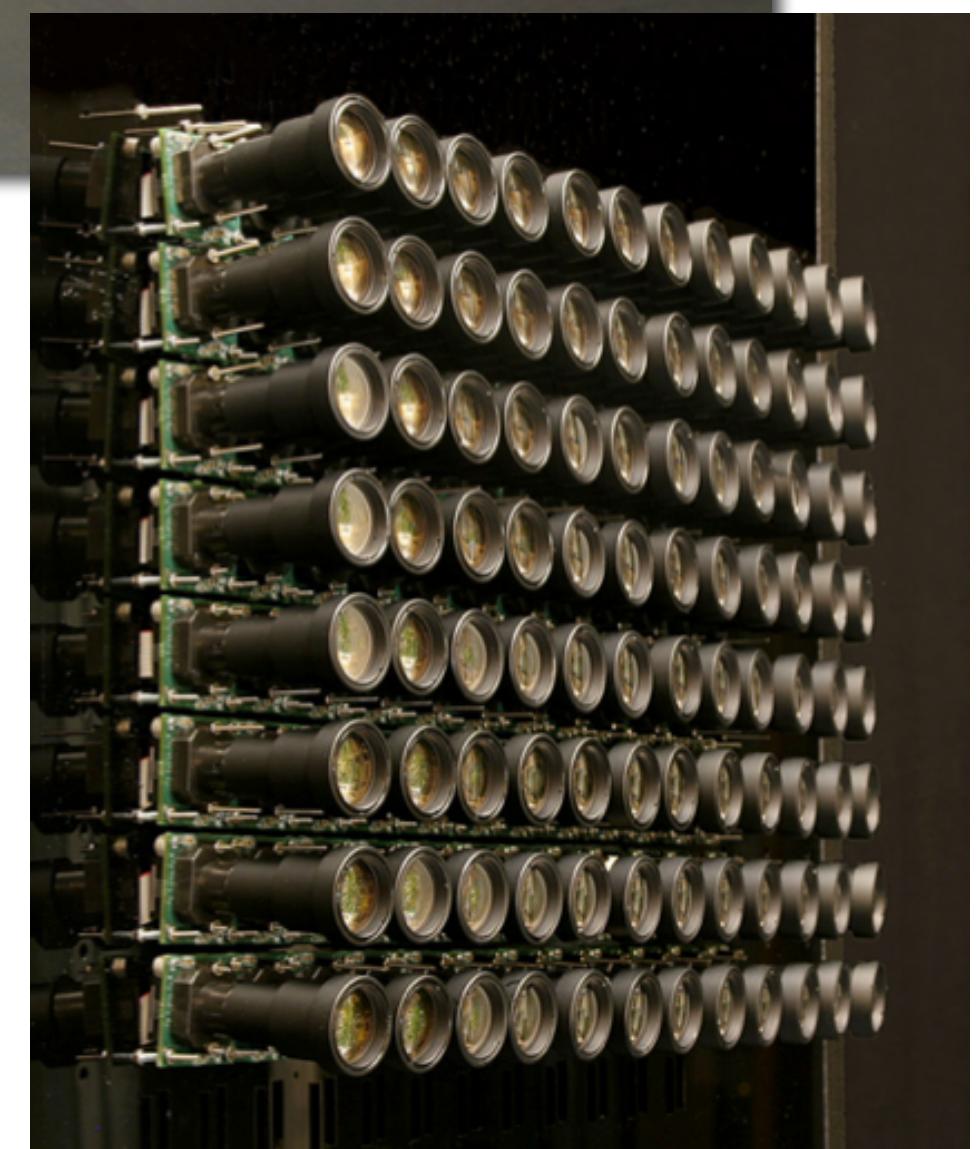
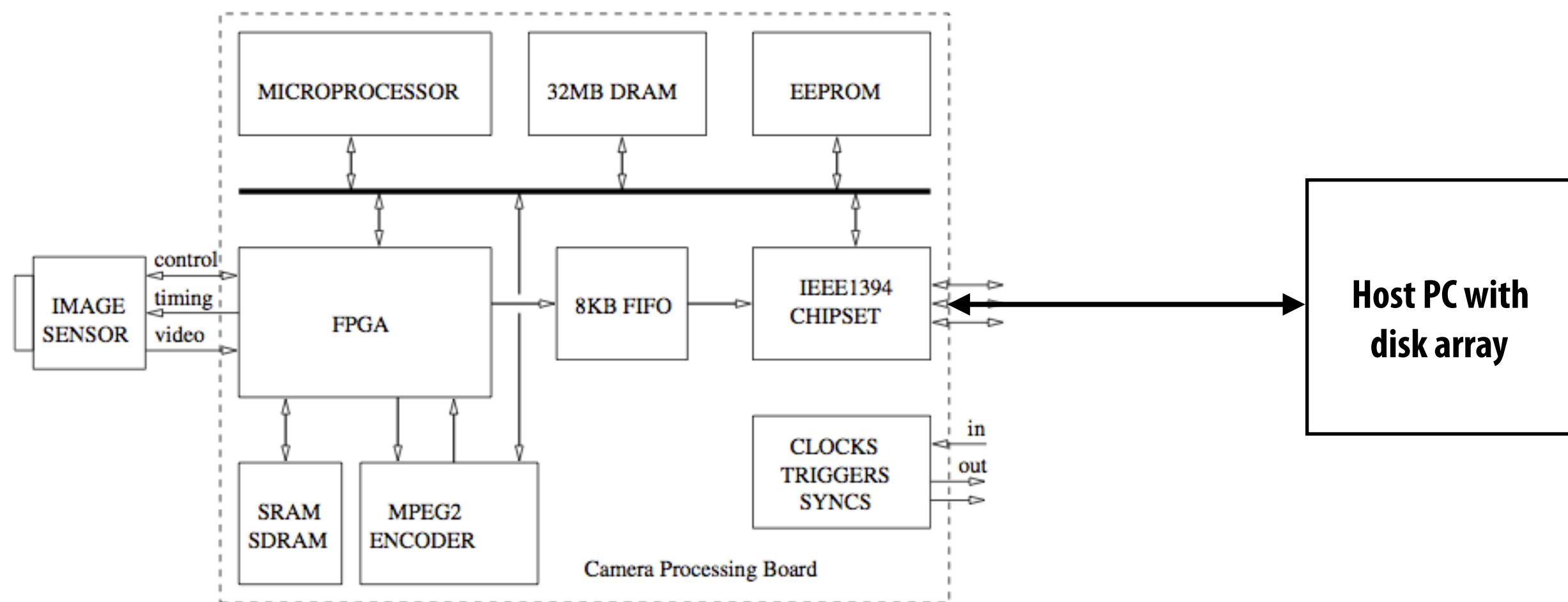
Stanford Camera Array

Wilburn et al. 2005

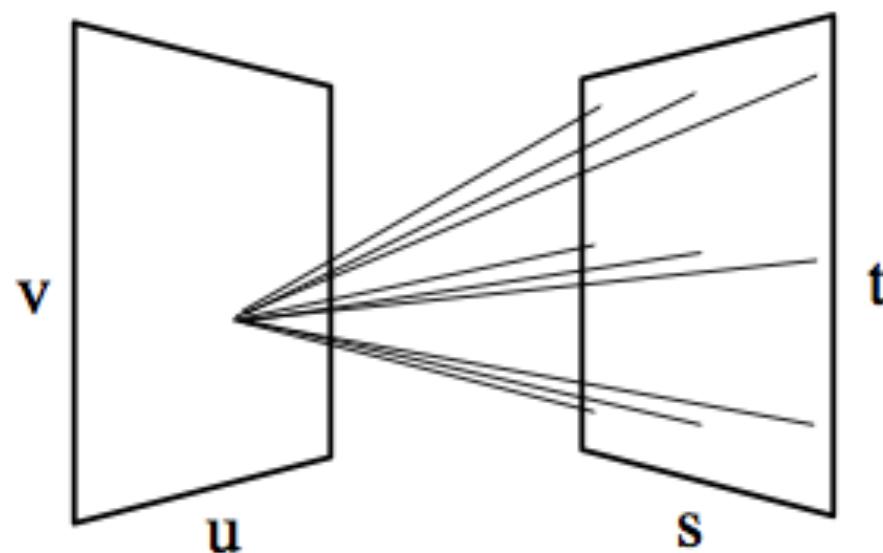
640 x 480 tightly synchronized,
repositionable cameras

Custom processing board per camera

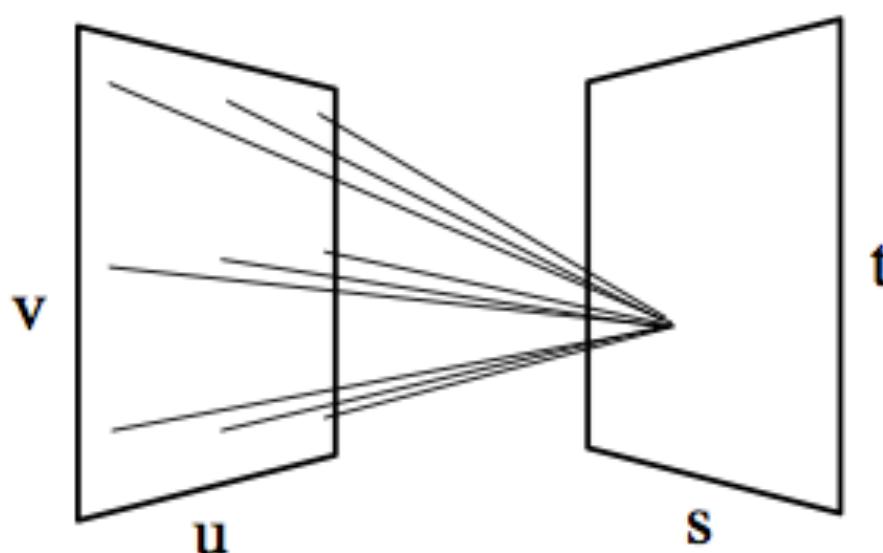
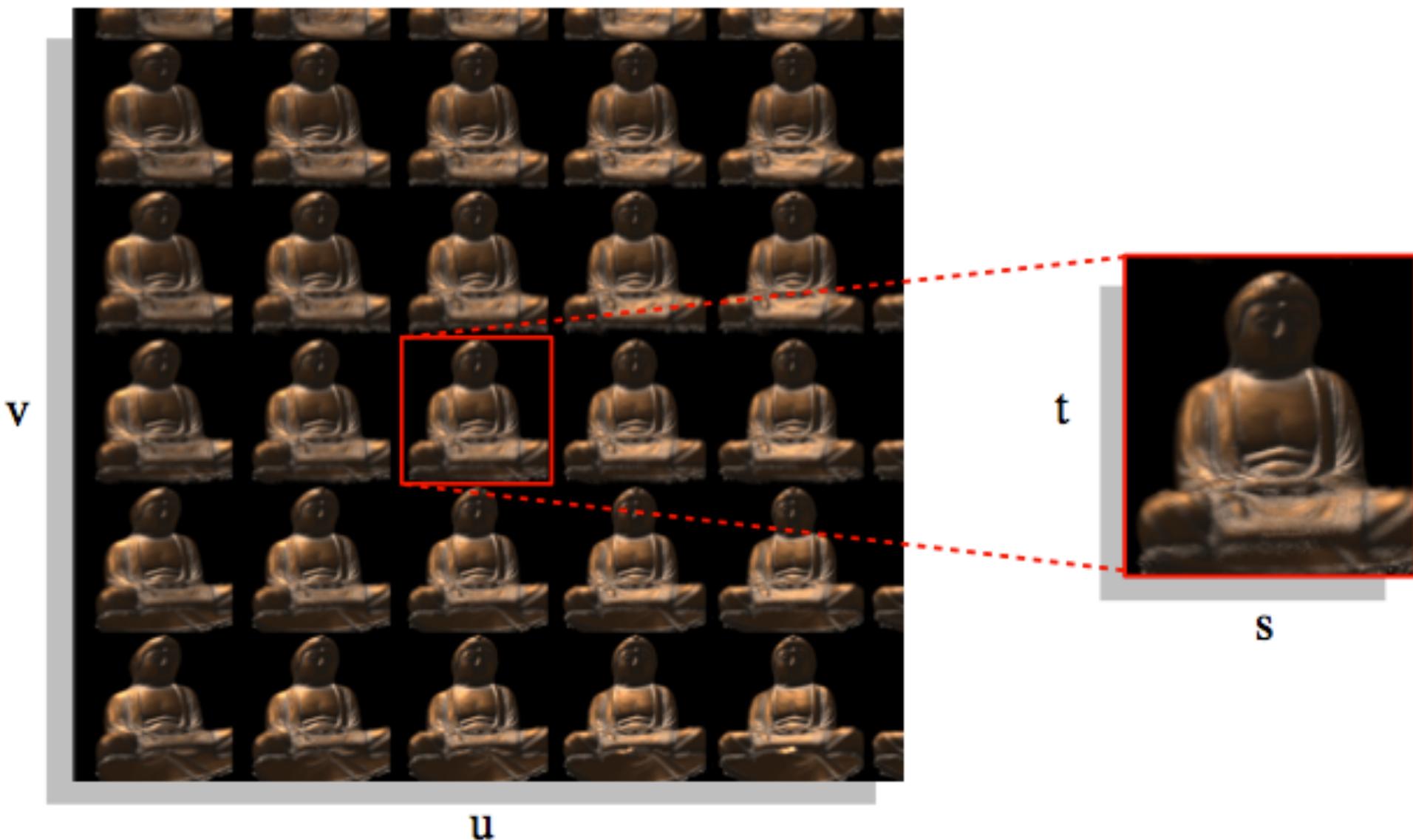
Tethered to PCs for additional
processing/storage



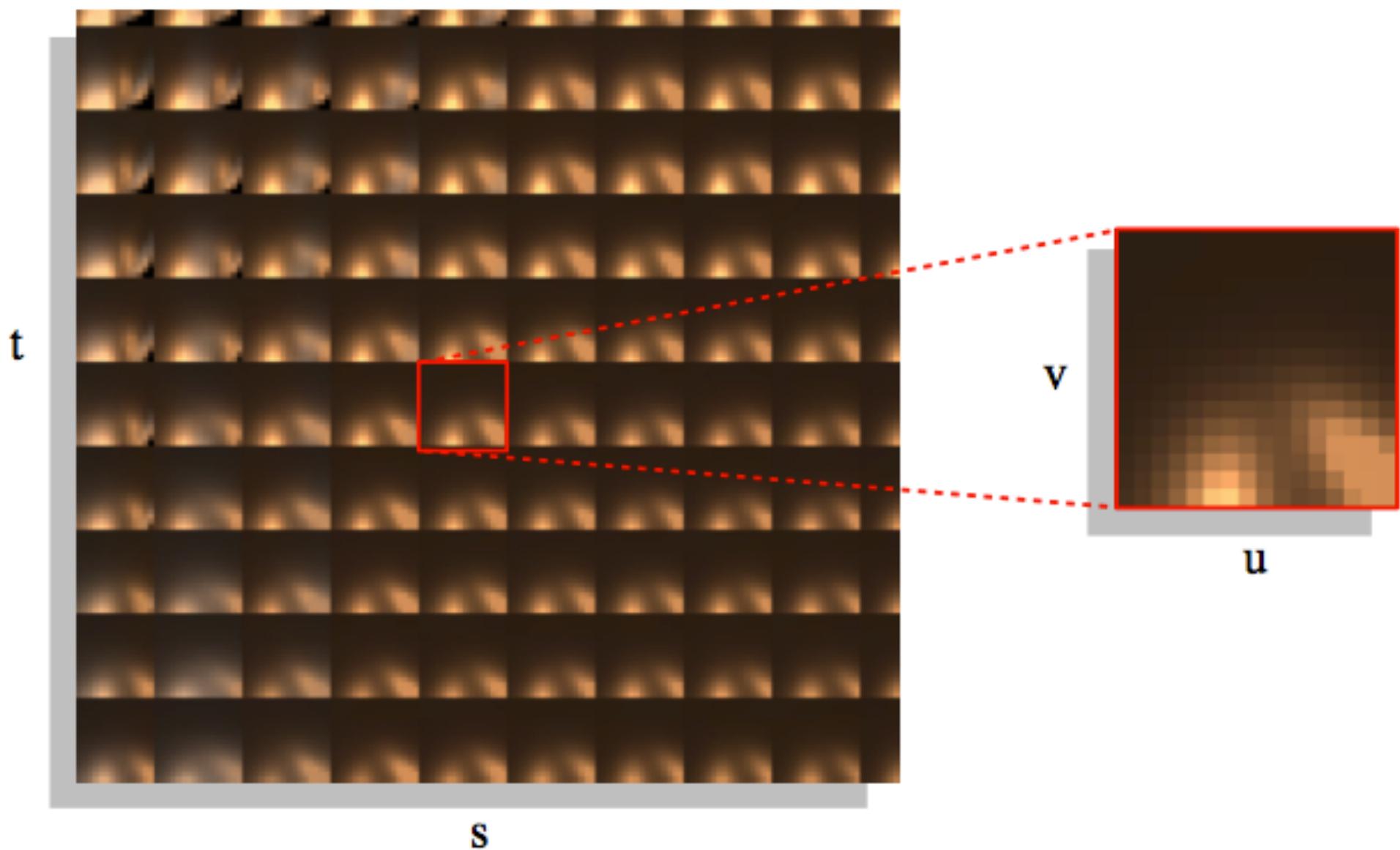
Light field storage layouts



(a)

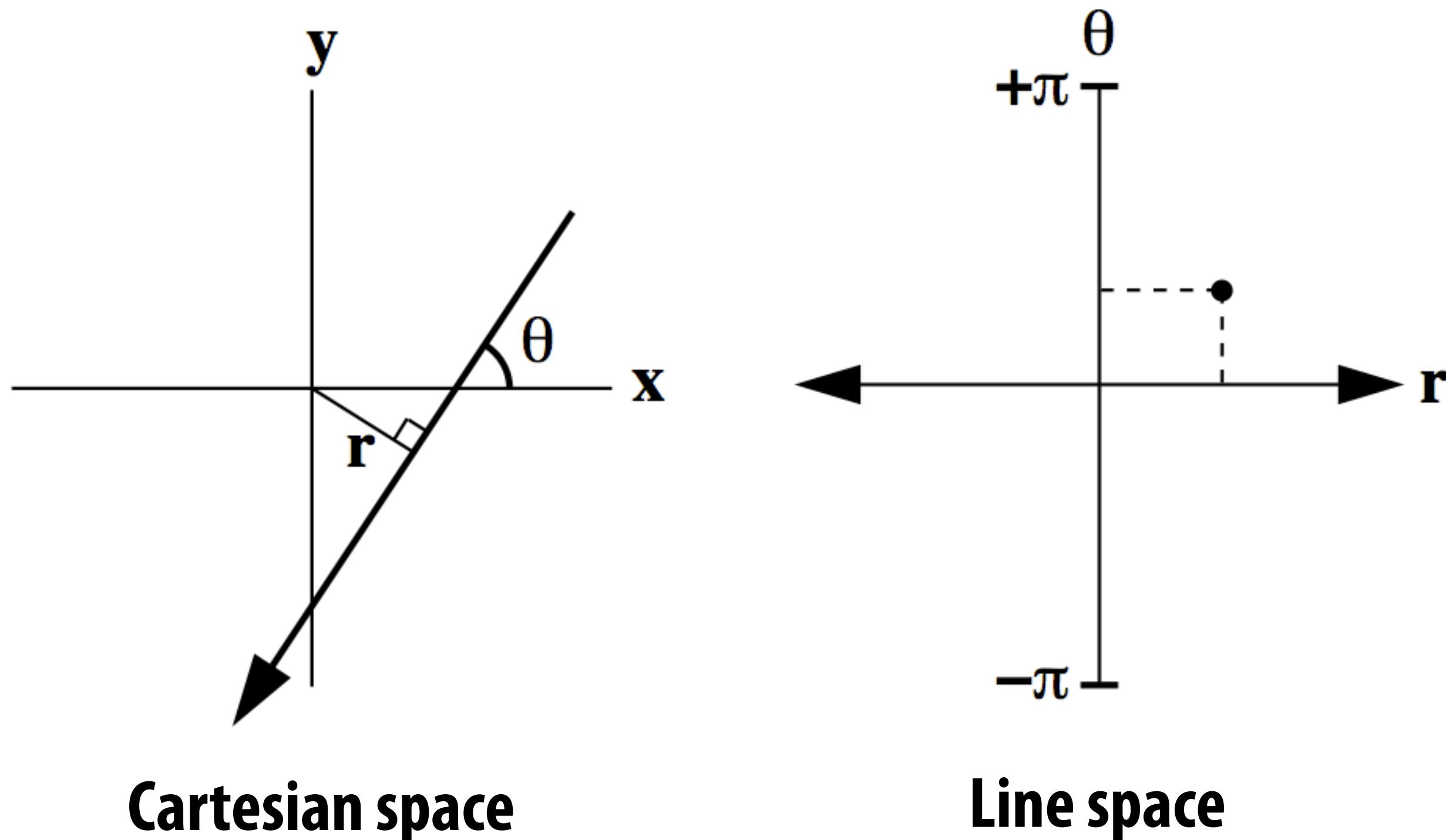


(b)



Line-space representation

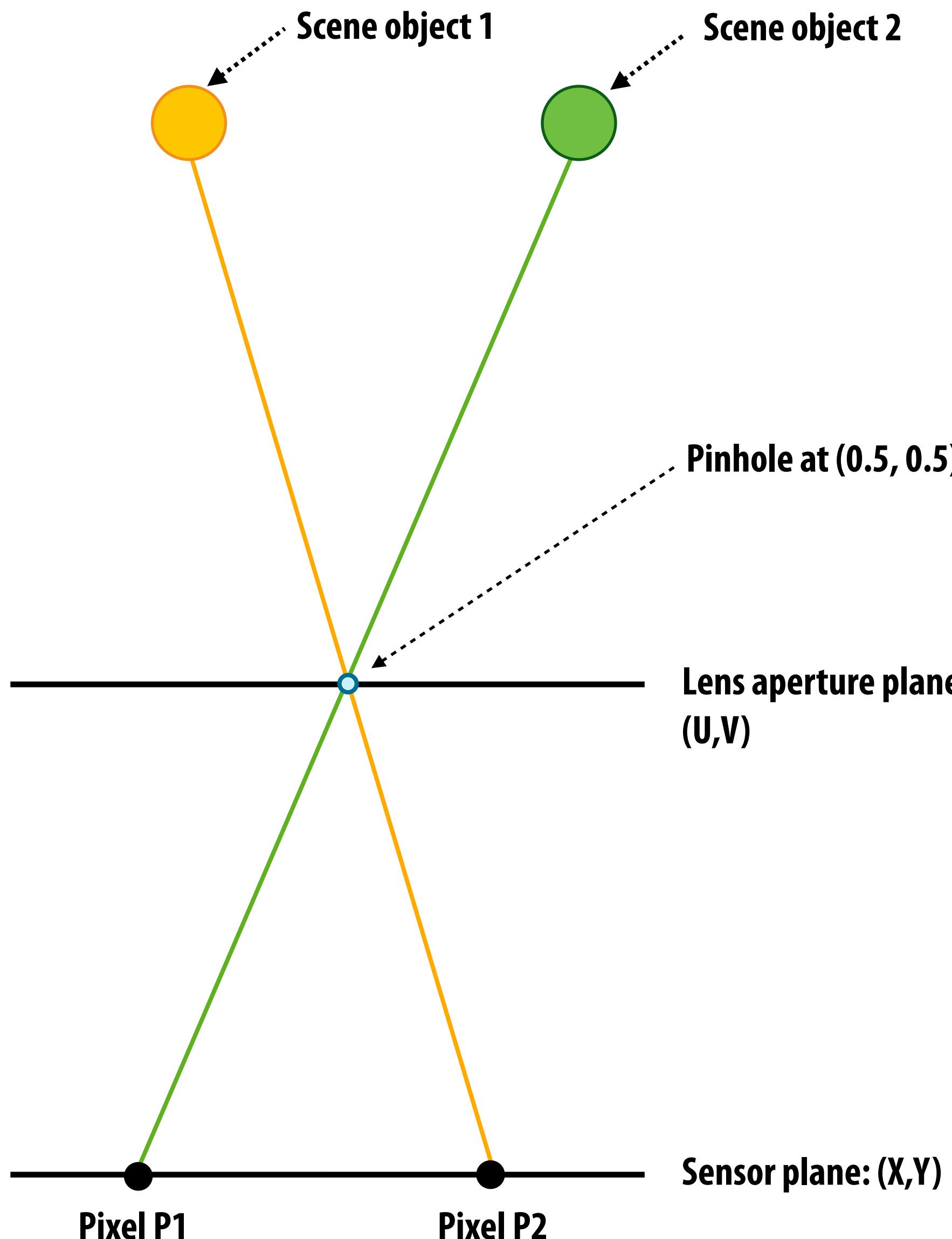
Each line in Cartesian space* is represented by a point in line space



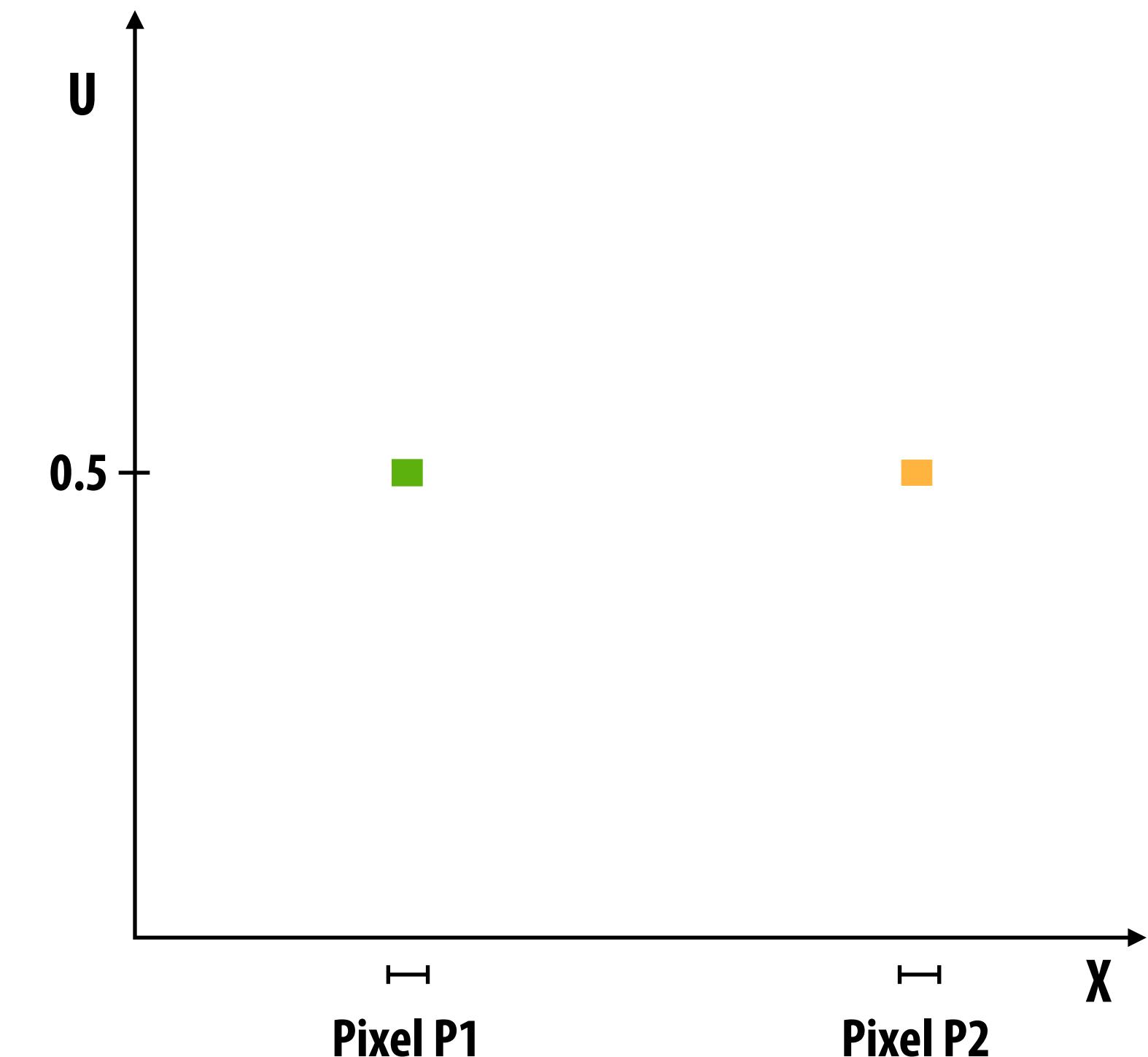
* Shown here in 2D, generalizes to 3D Cartesian lines

[Image credit: Levoy and Hanrahan 96]

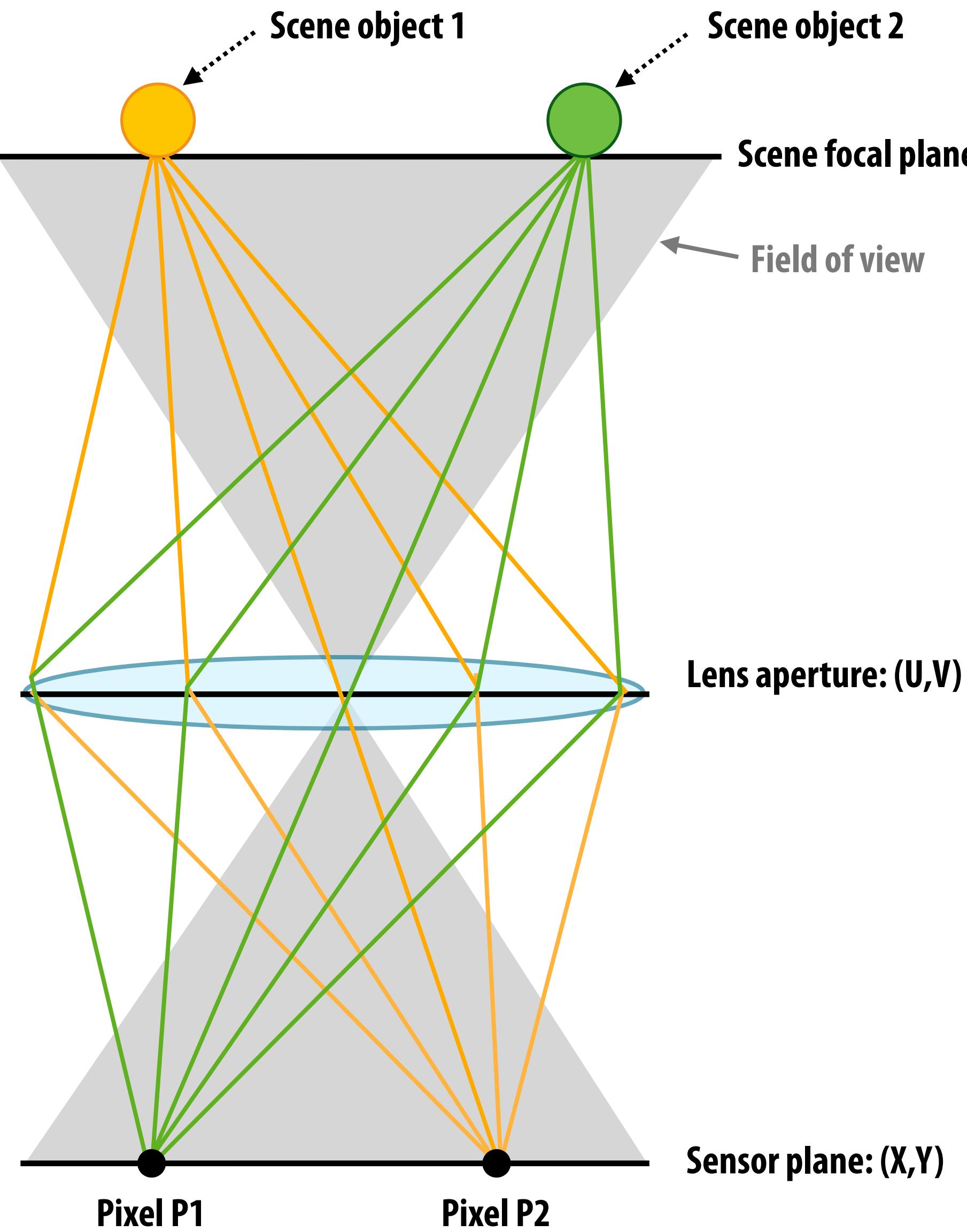
Light field inside a pinhole camera



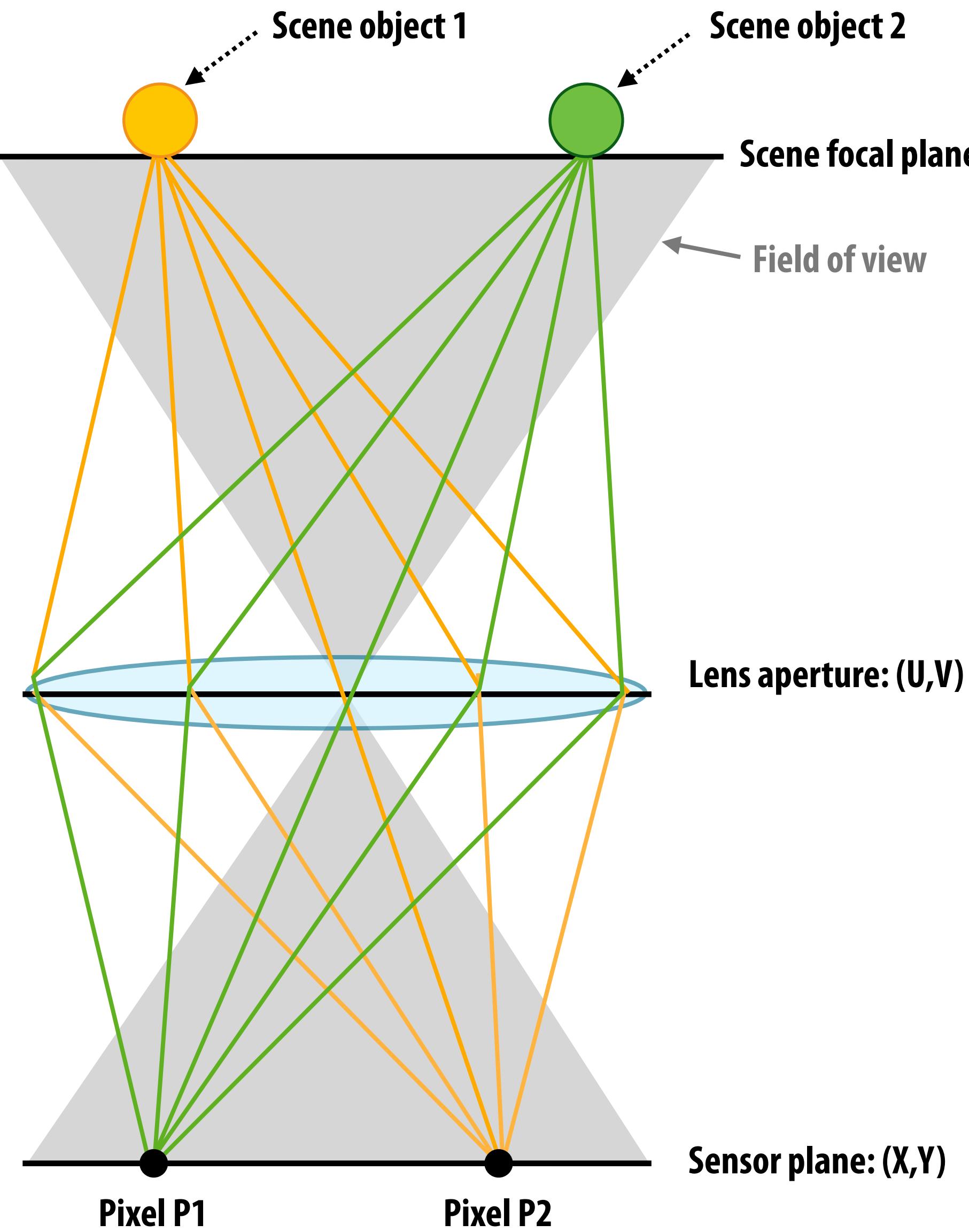
Ray space plot



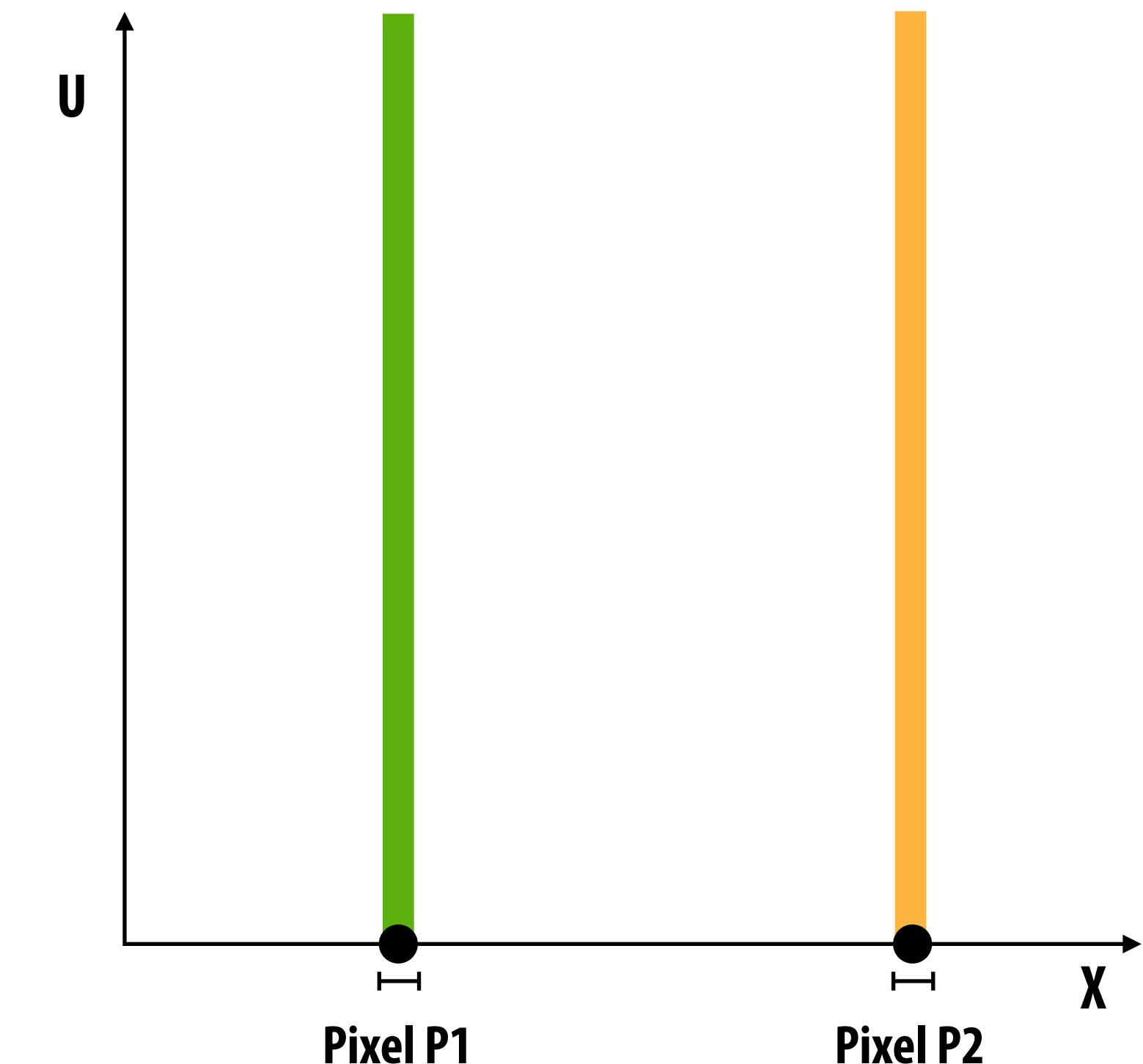
Review: camera with finite aperture



Light field inside a camera

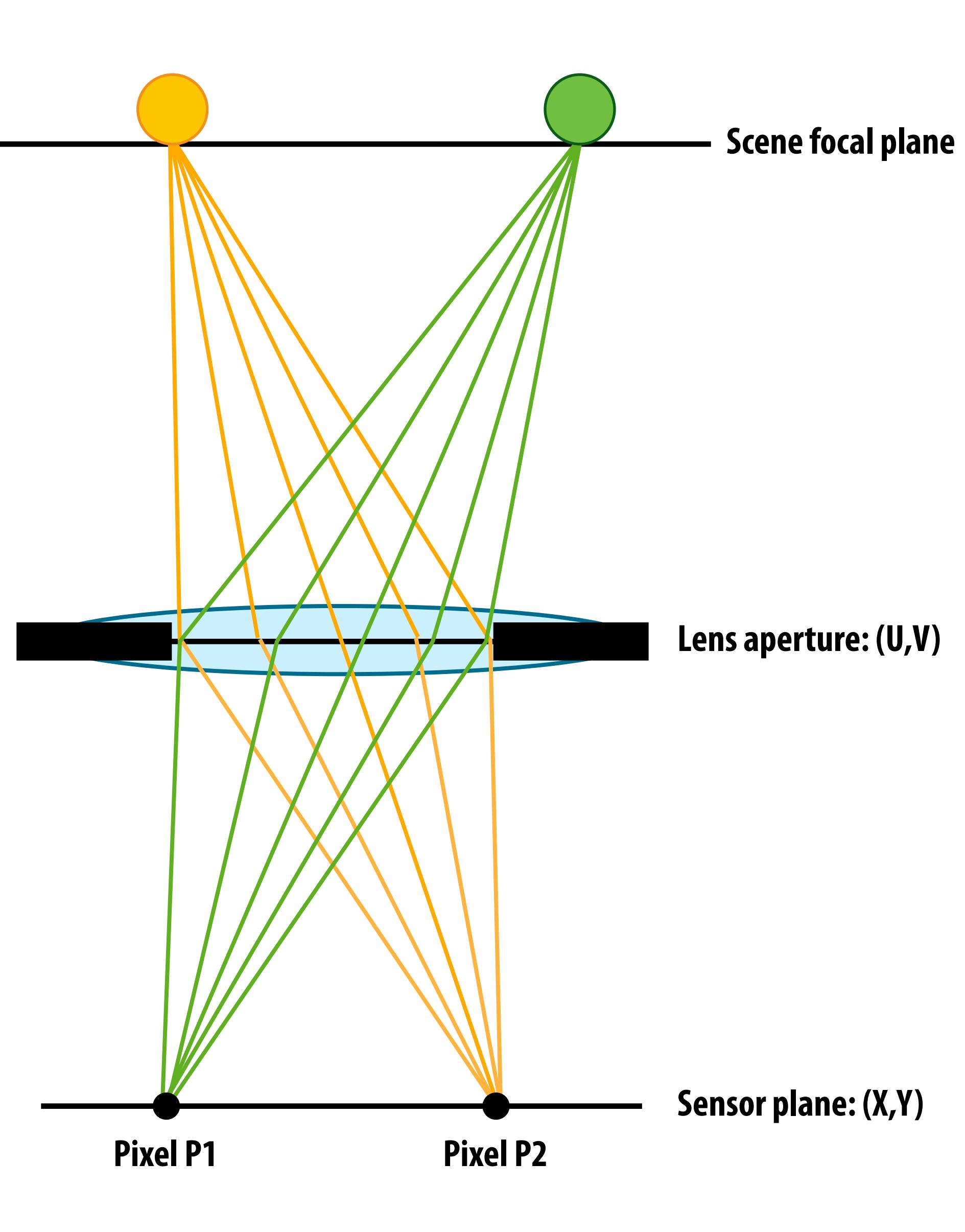


**Ray space plot
(only showing X-U 2D projection)**

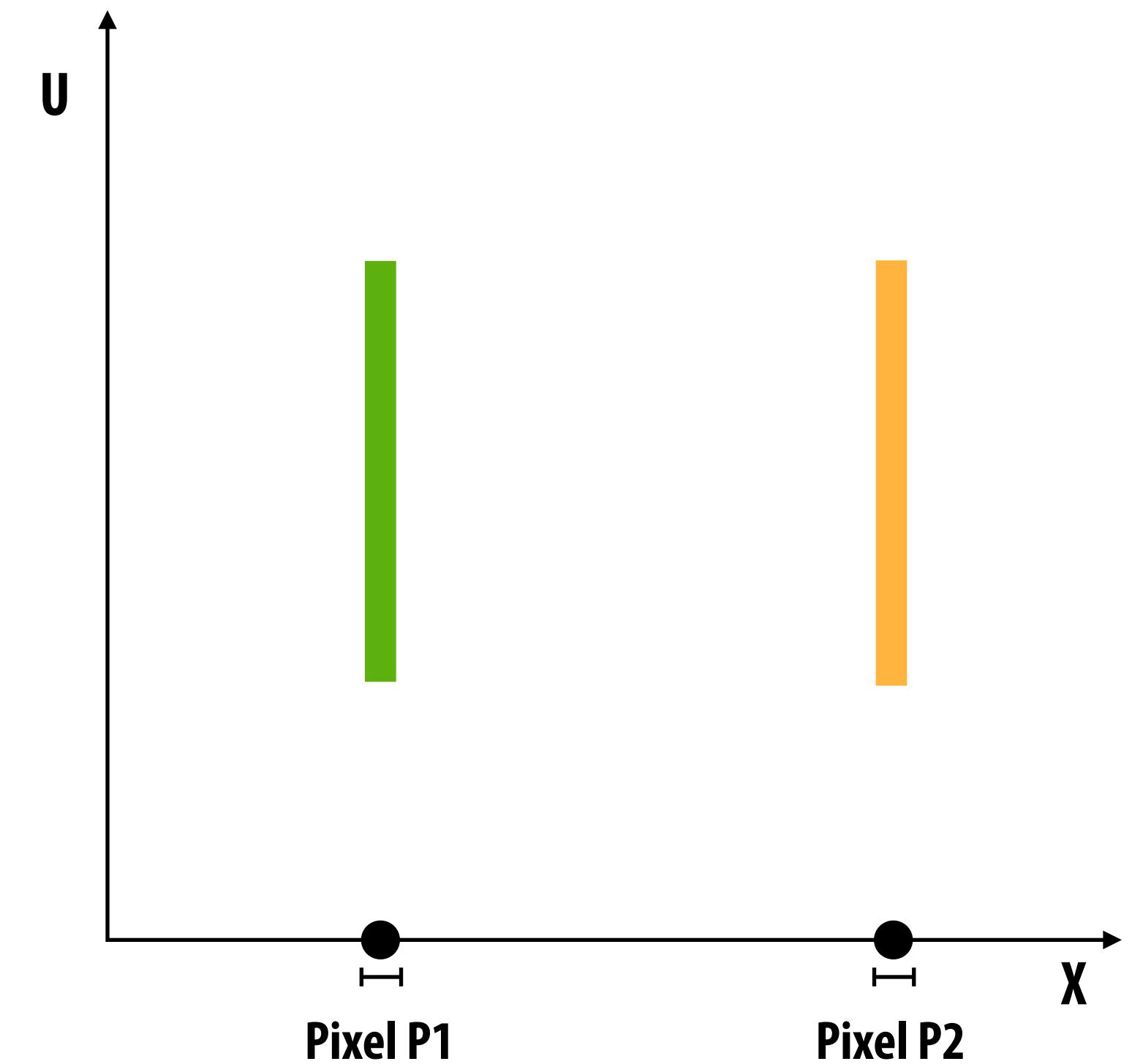


Sensor pixels measure integral of energy from all rays of light passing through points on the aperture and a pixel-sized area of the sensor.

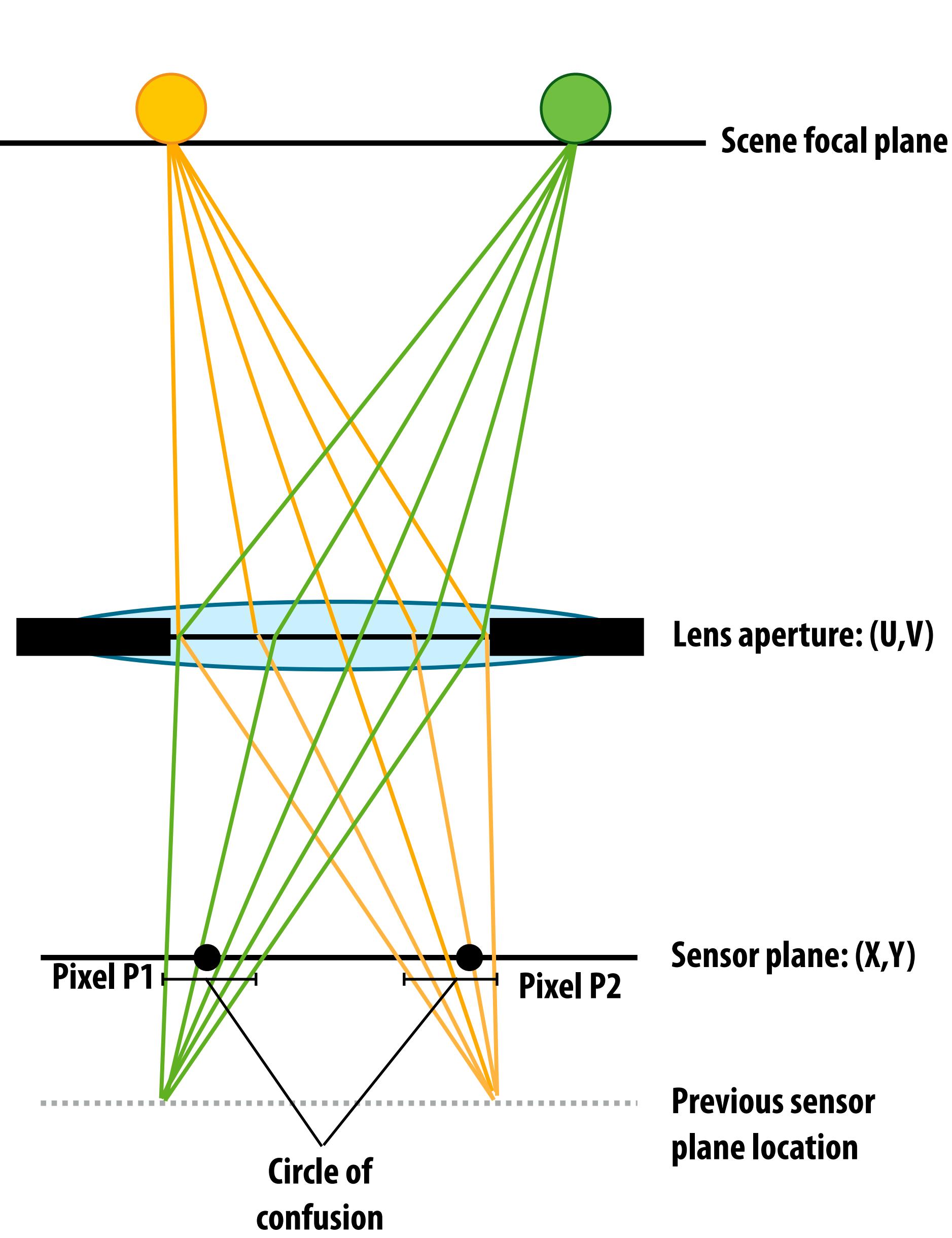
Decrease aperture size



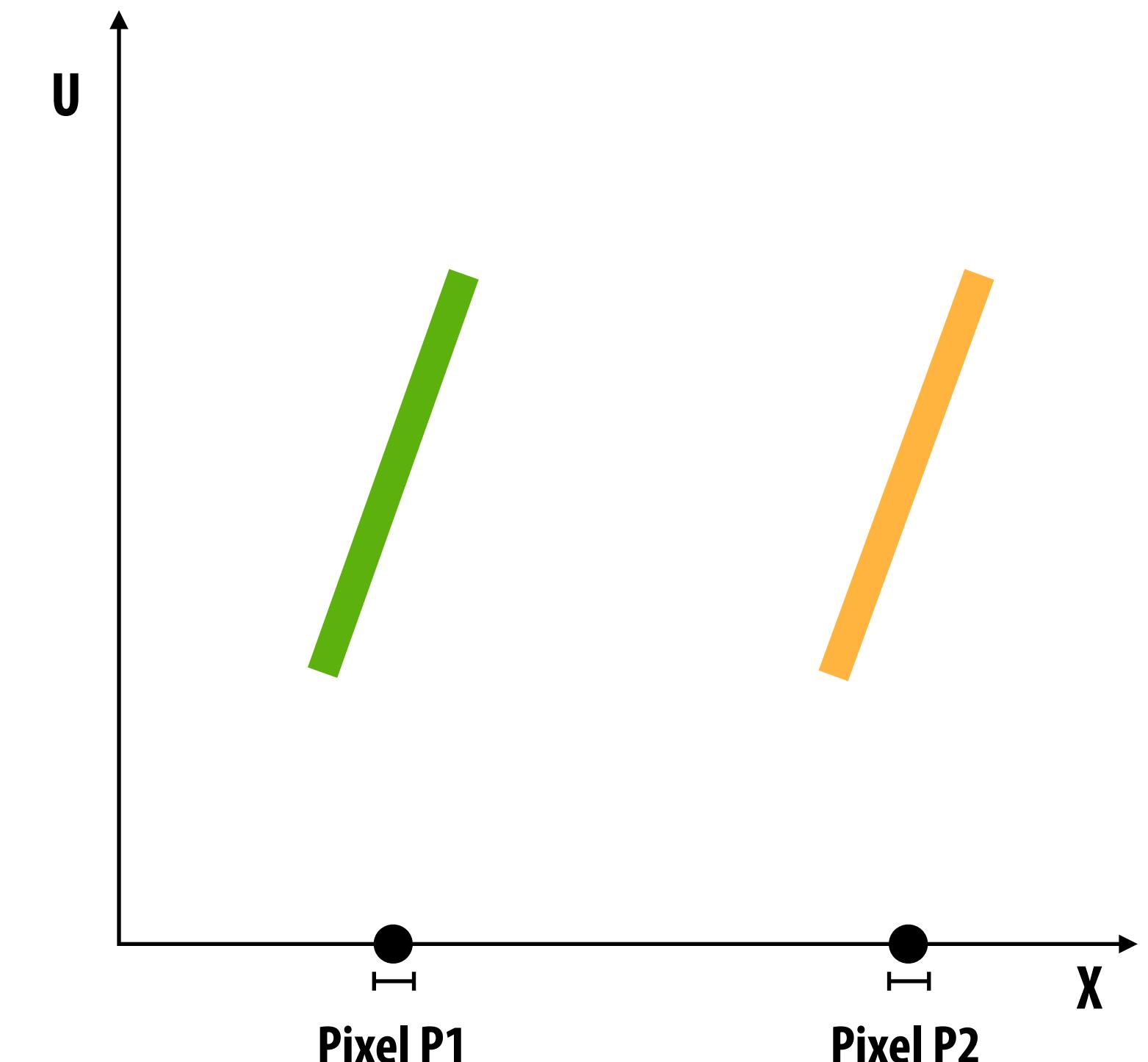
Ray space plot



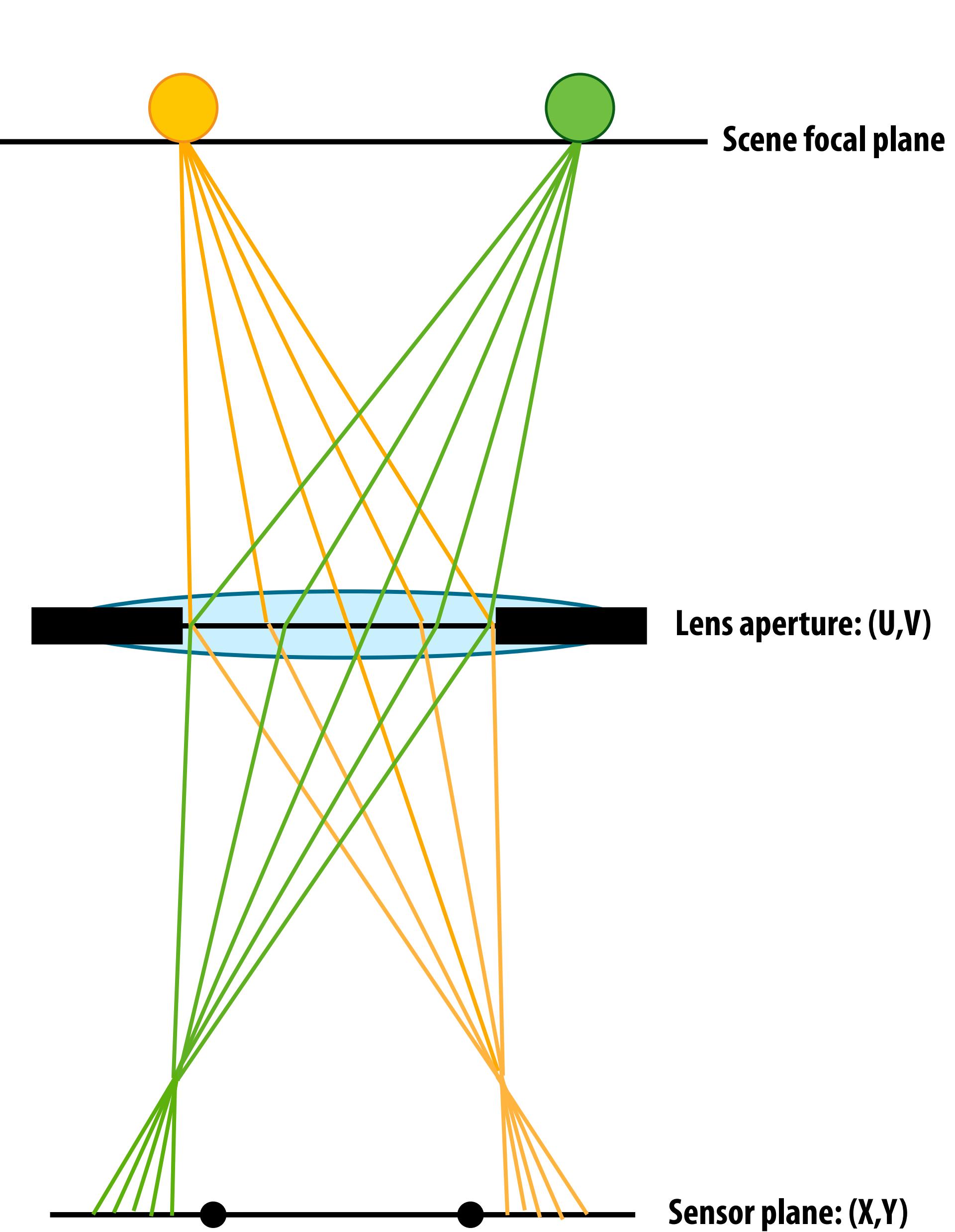
Defocus



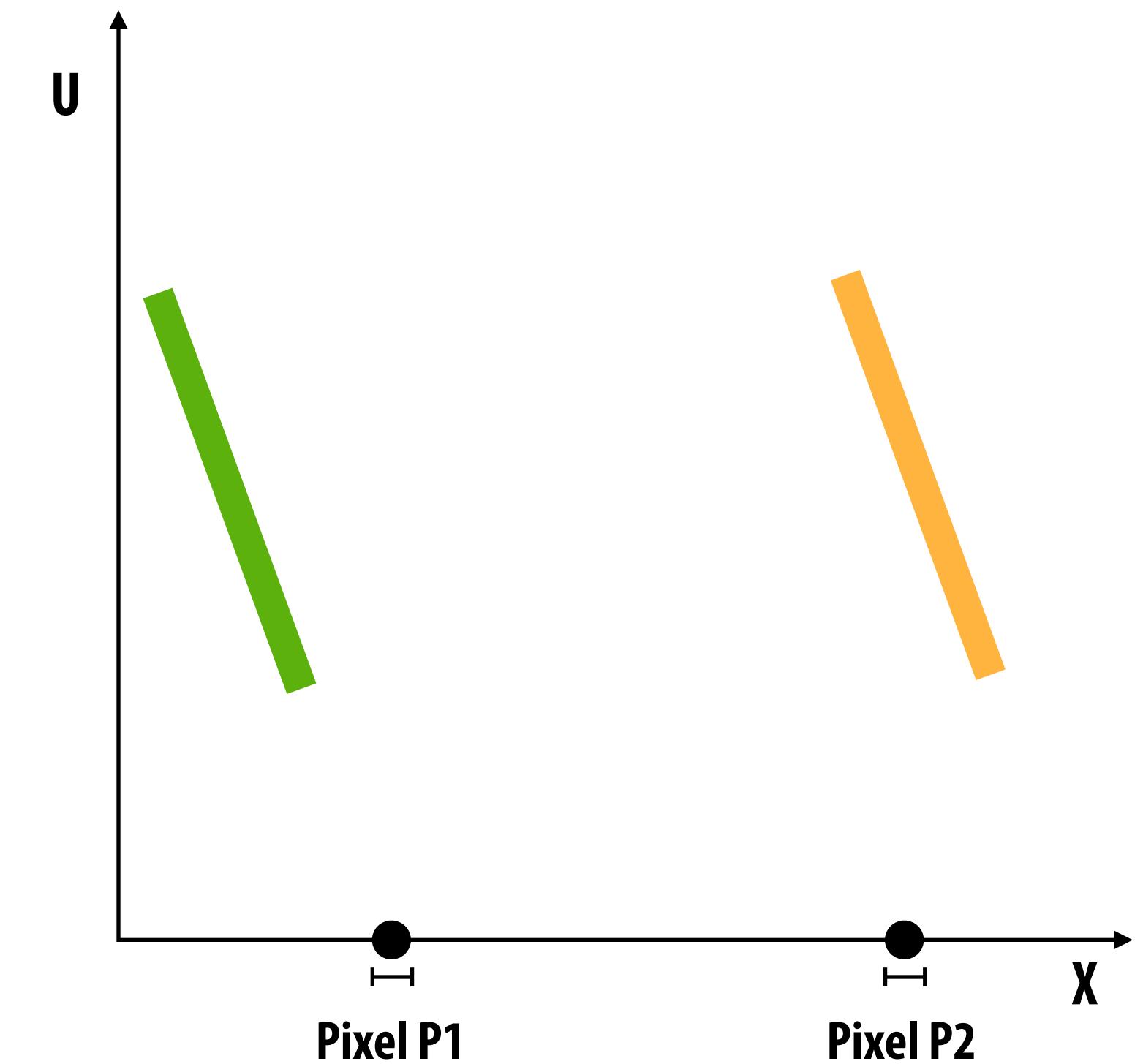
Ray space plot



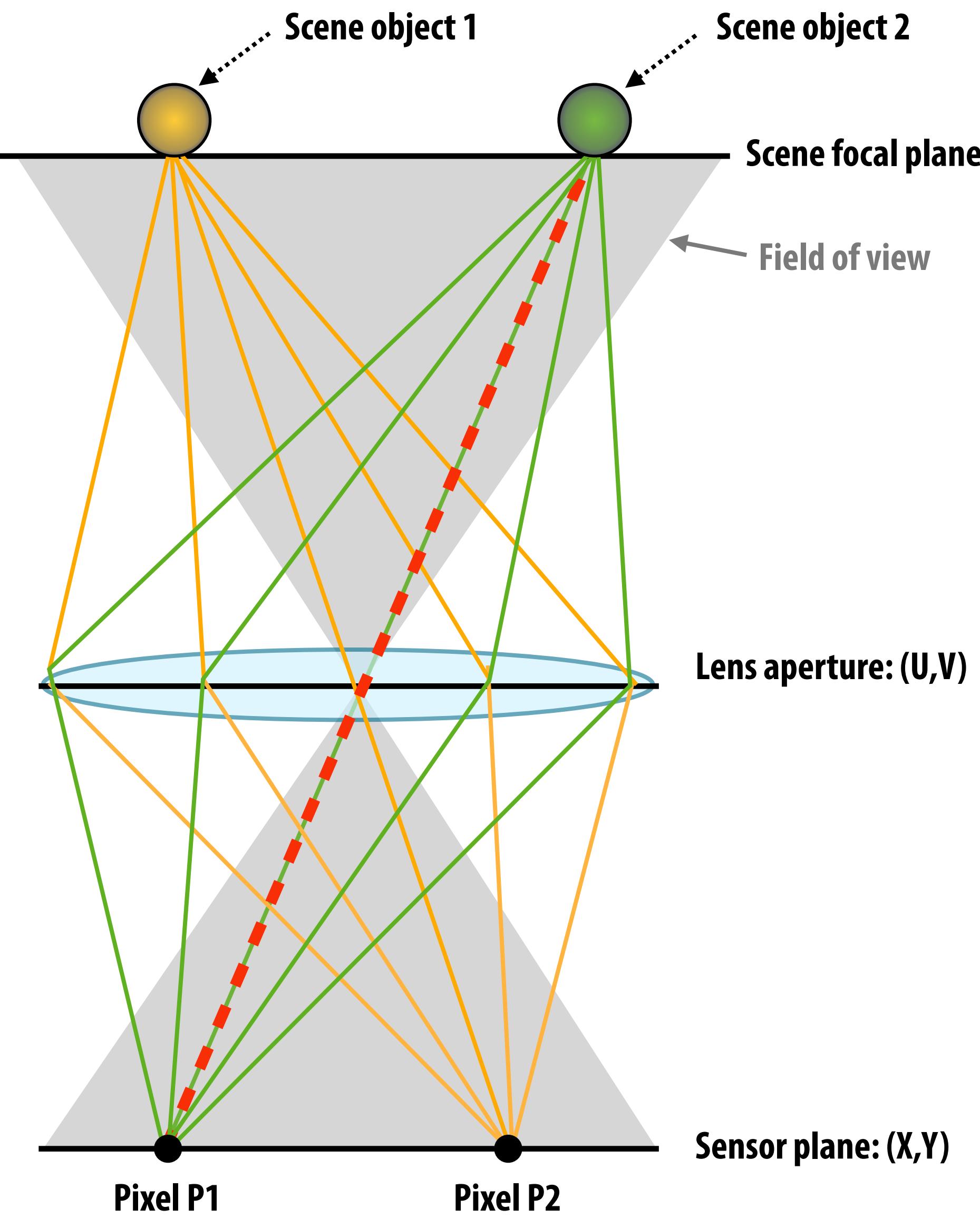
Defocus



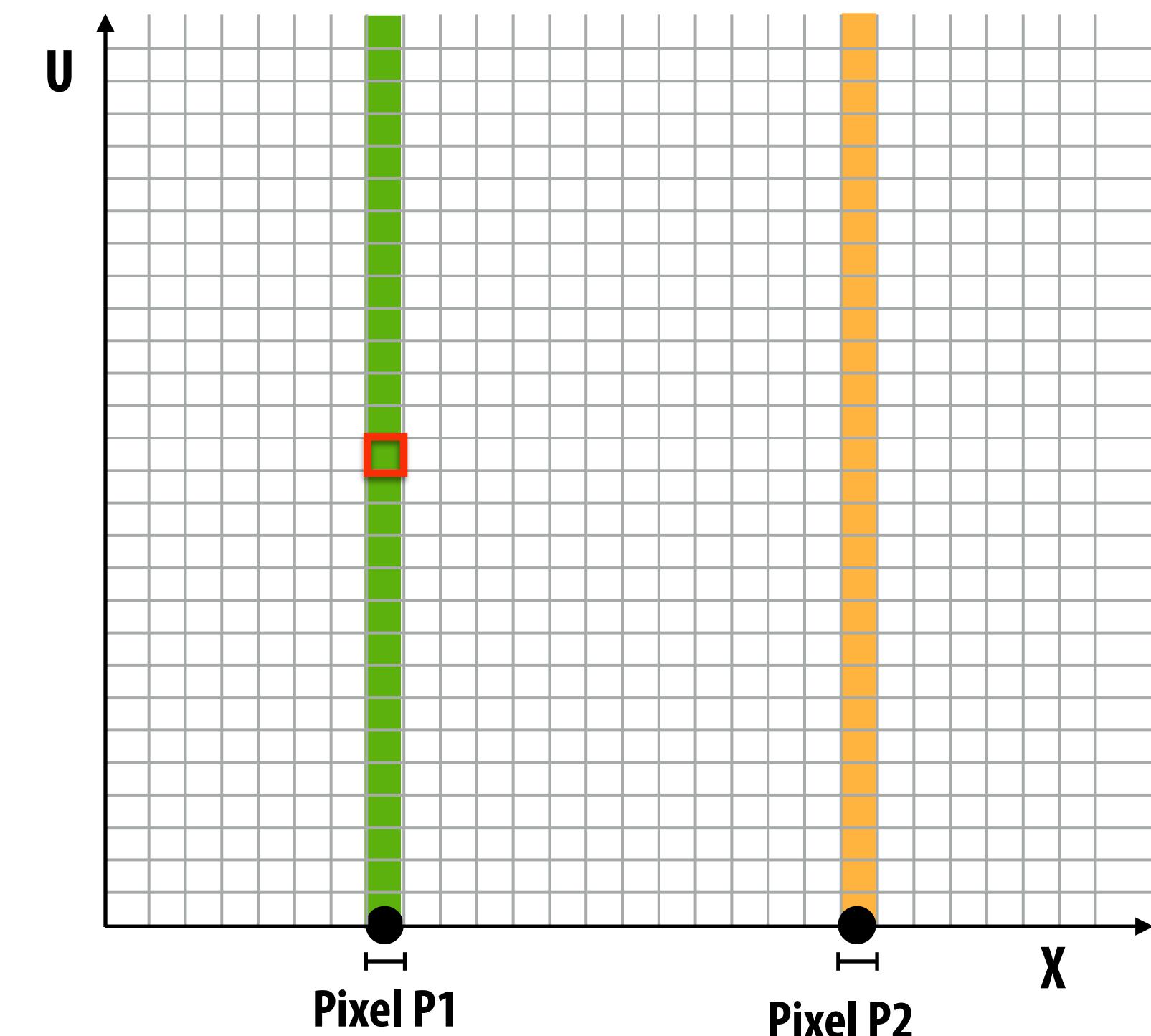
Ray space plot



How might we measure the light field inside a camera?

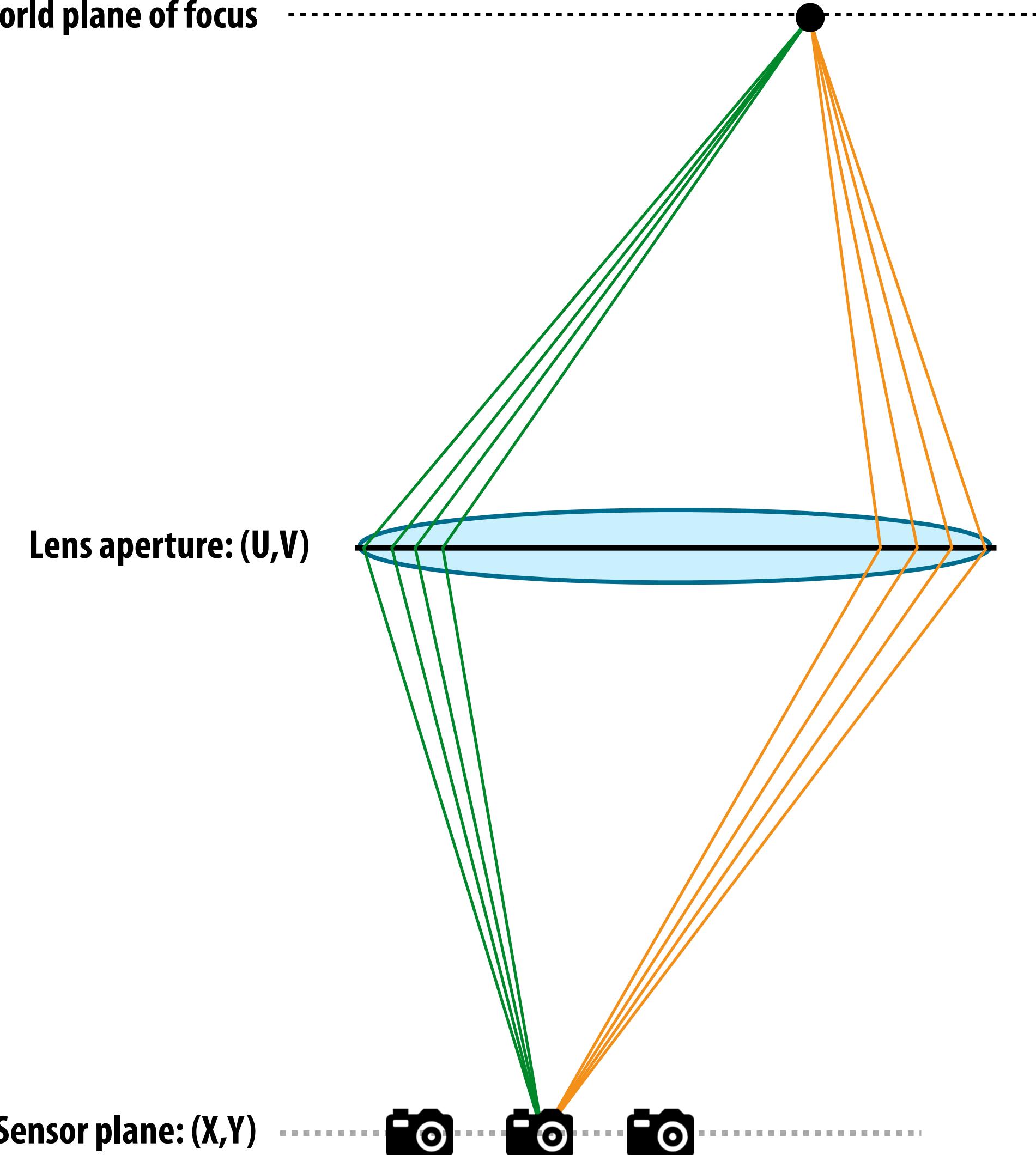


**Ray space plot
(only showing X-U 2D projection)**



Intuition: handheld light field camera

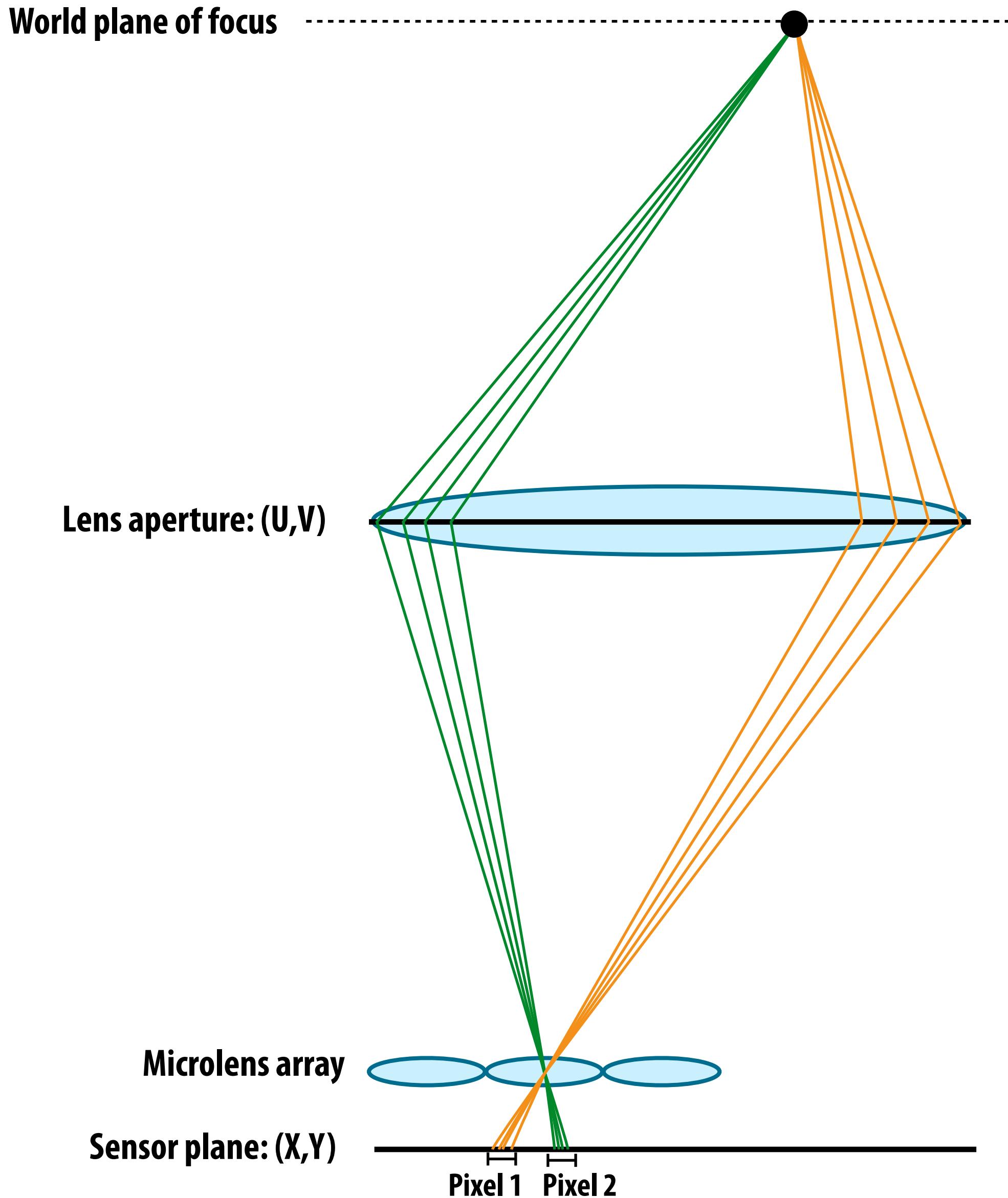
World plane of focus



Intuition: build an optical system where each region of the sensor “takes” a picture of the aperture of the main lens

Sensor plane: (X, Y)

Handheld light field camera

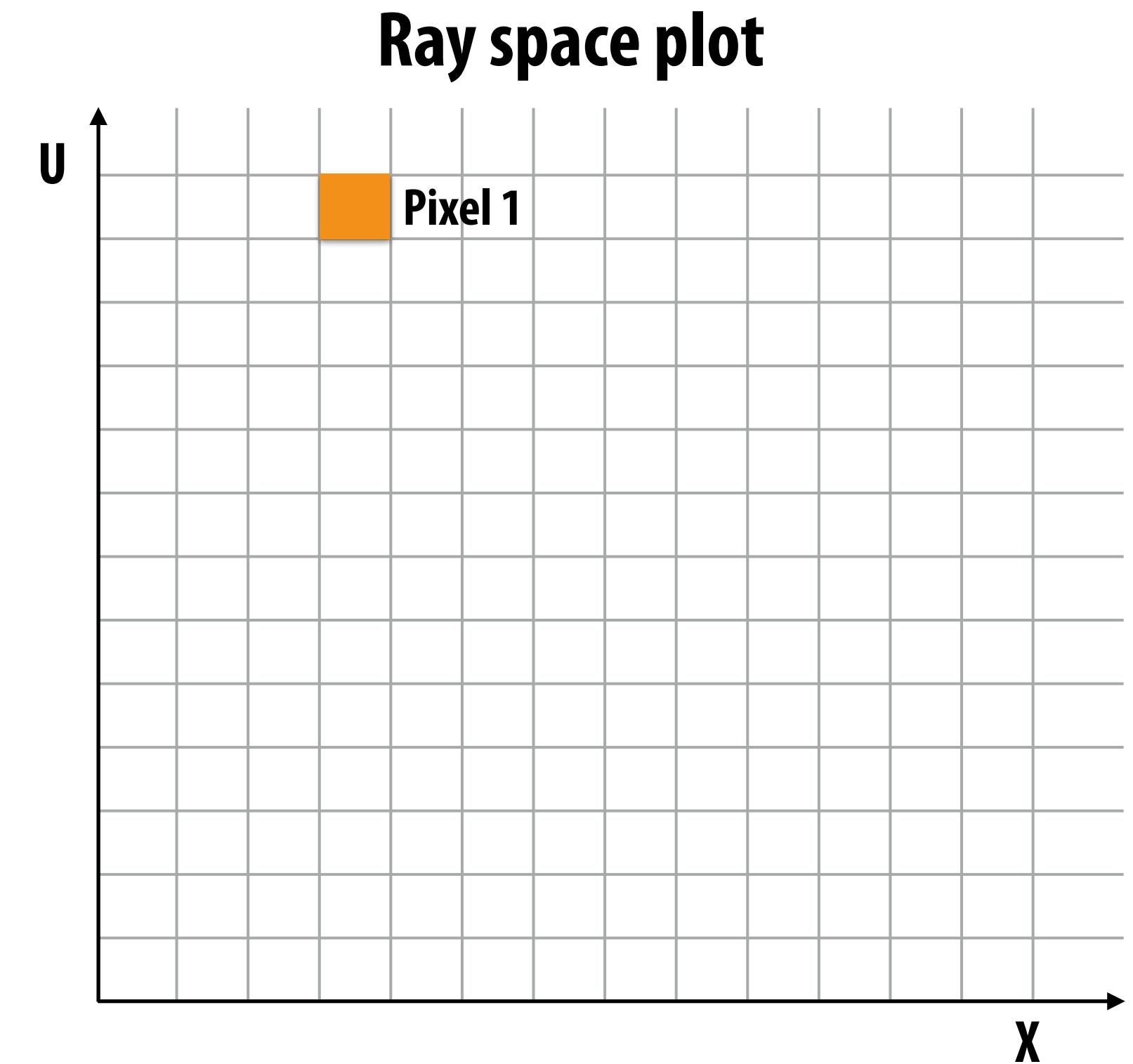
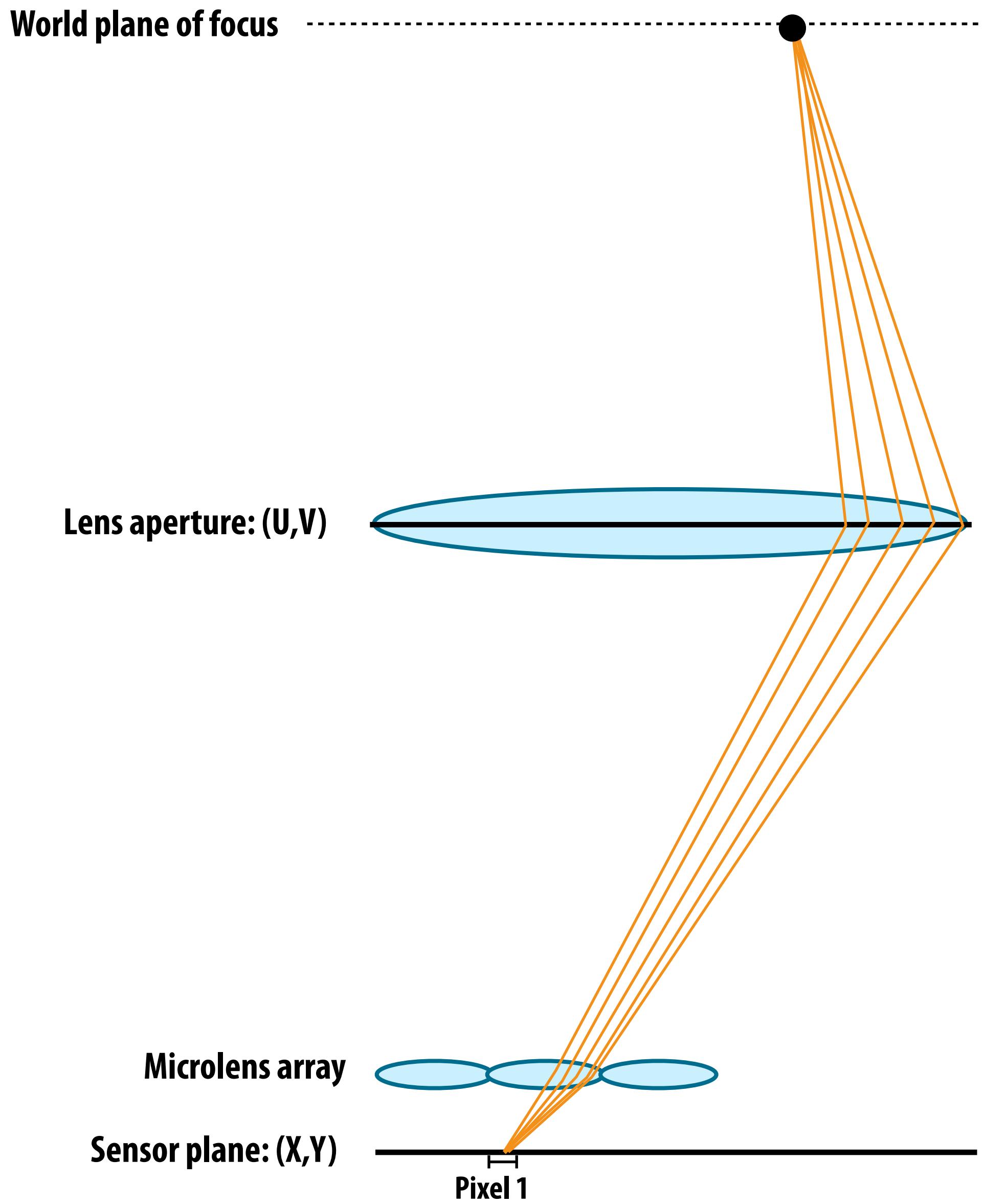


[Ng et al. 2005]

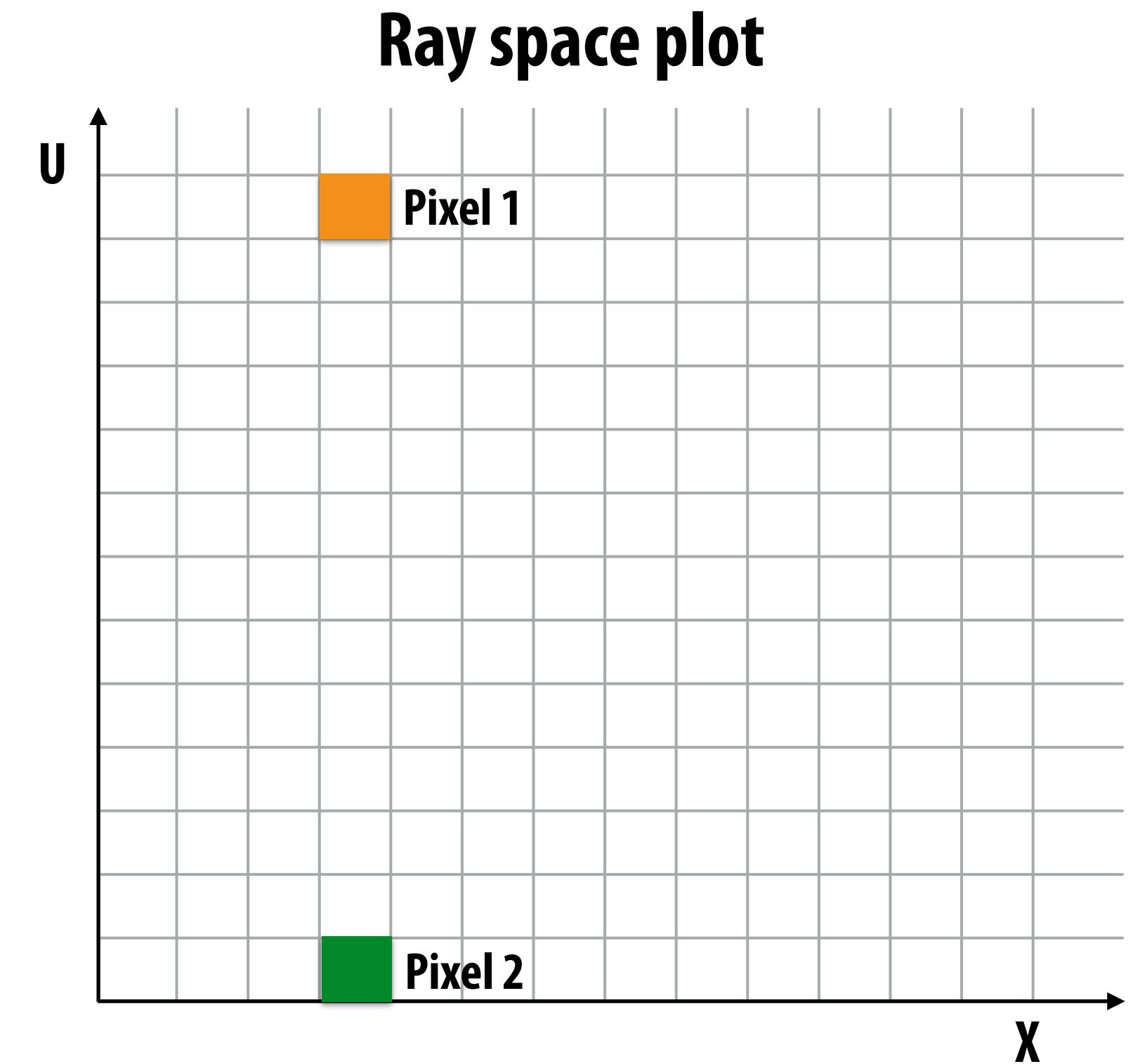
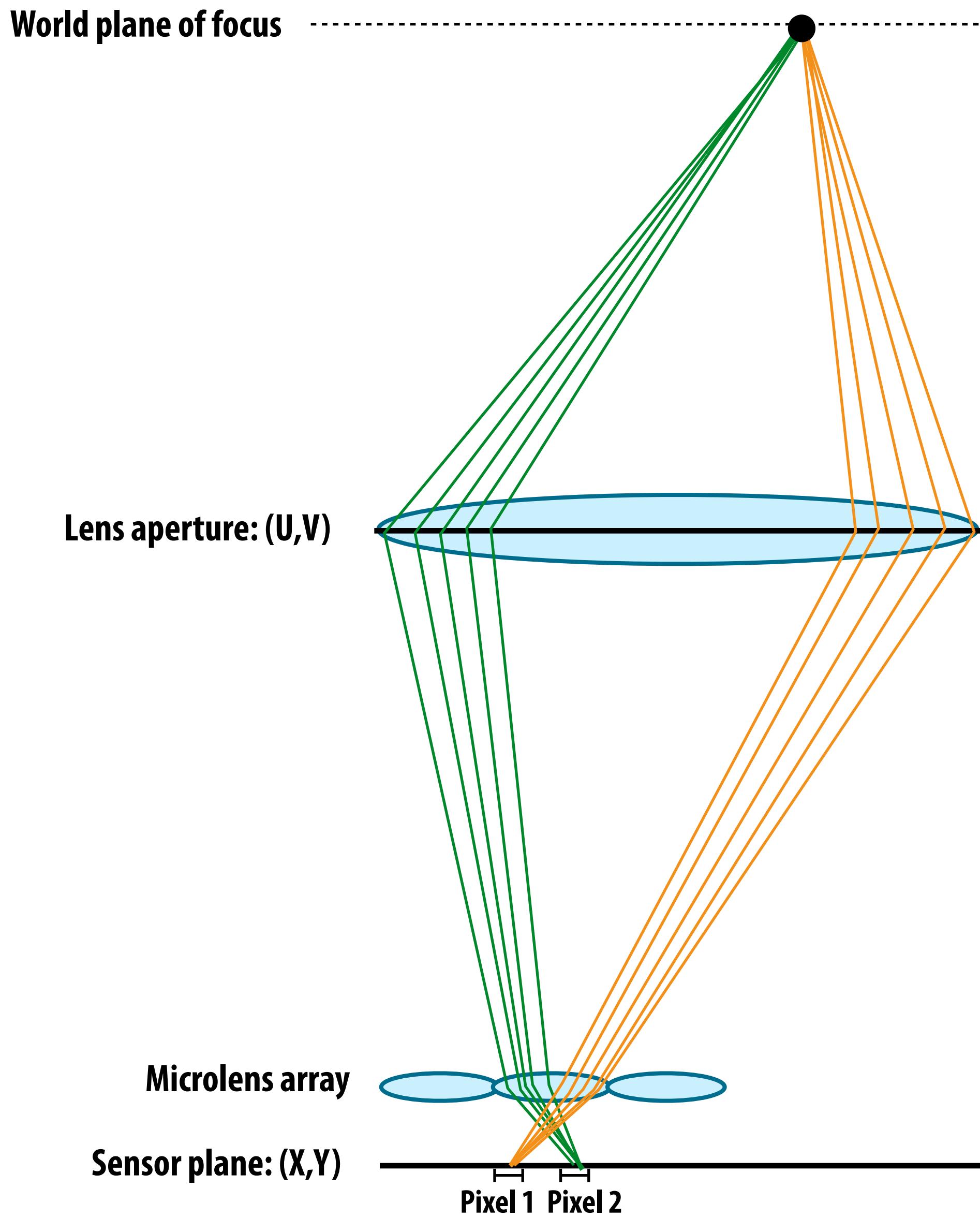
[Adelson and Wang, 1992]

Implementation: microlens array placed just on top of the sensor.

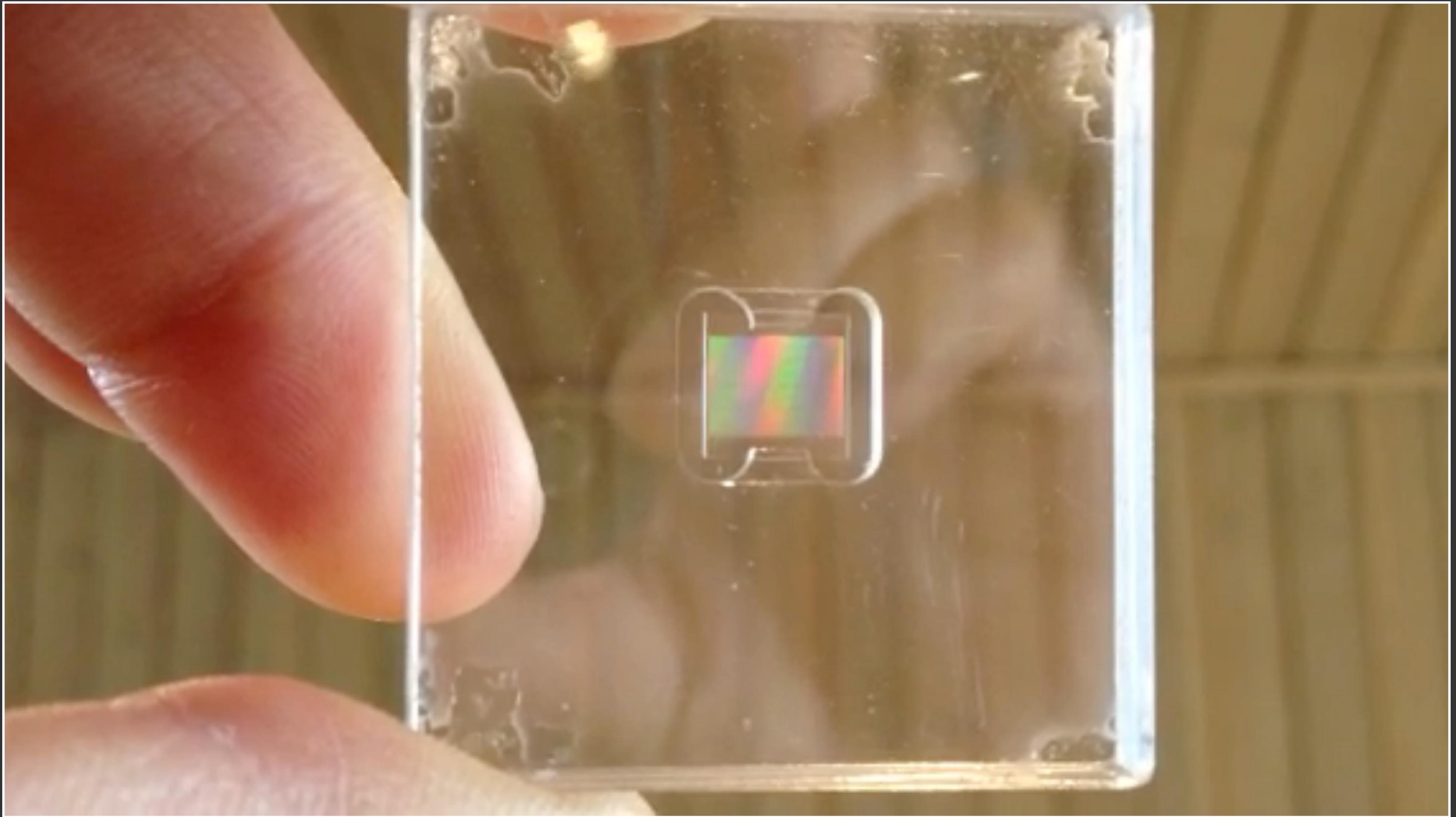
Each sensor pixel records a small beam of light inside the camera



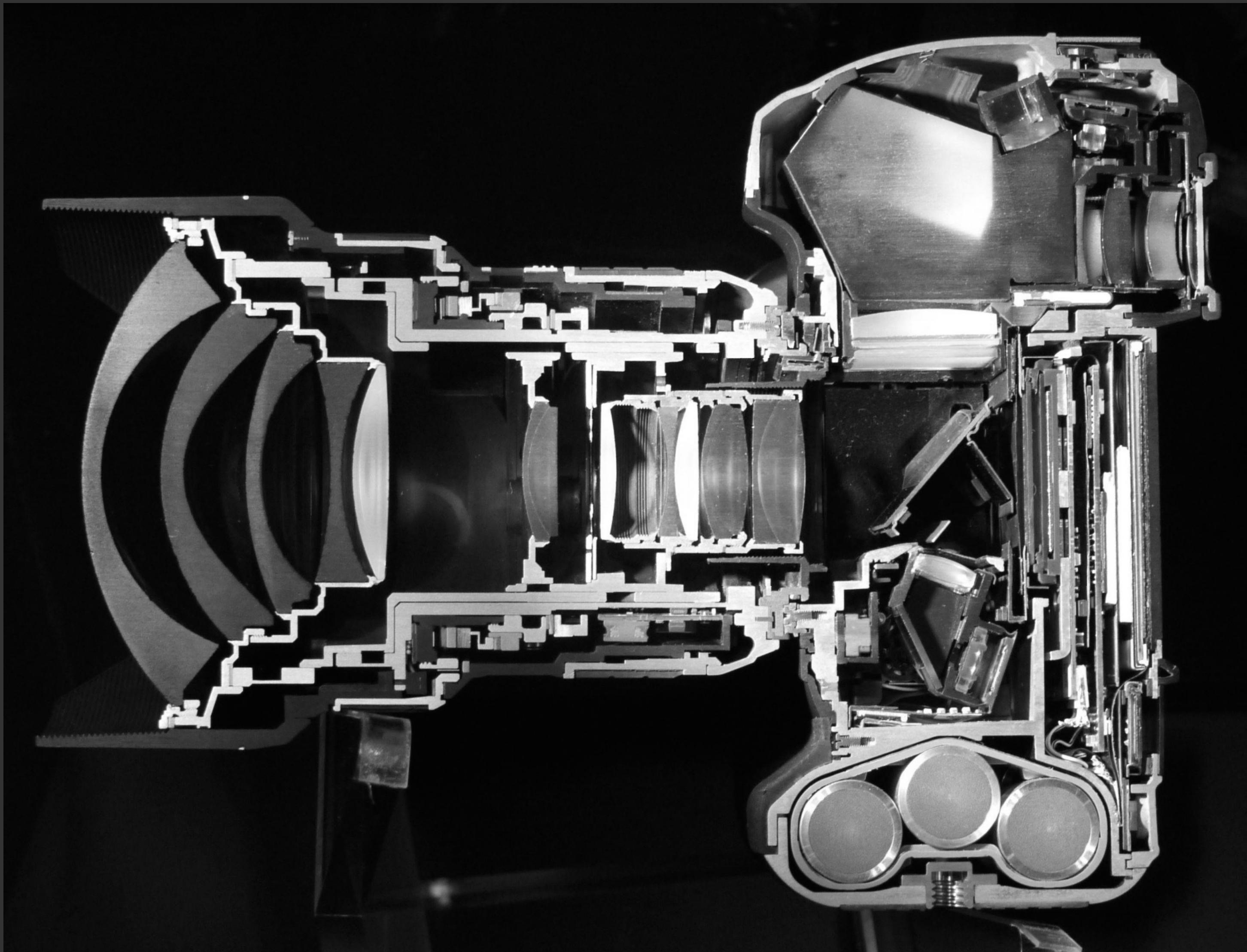
Each sensor pixel records a small beam of light inside the camera



Microlens Array

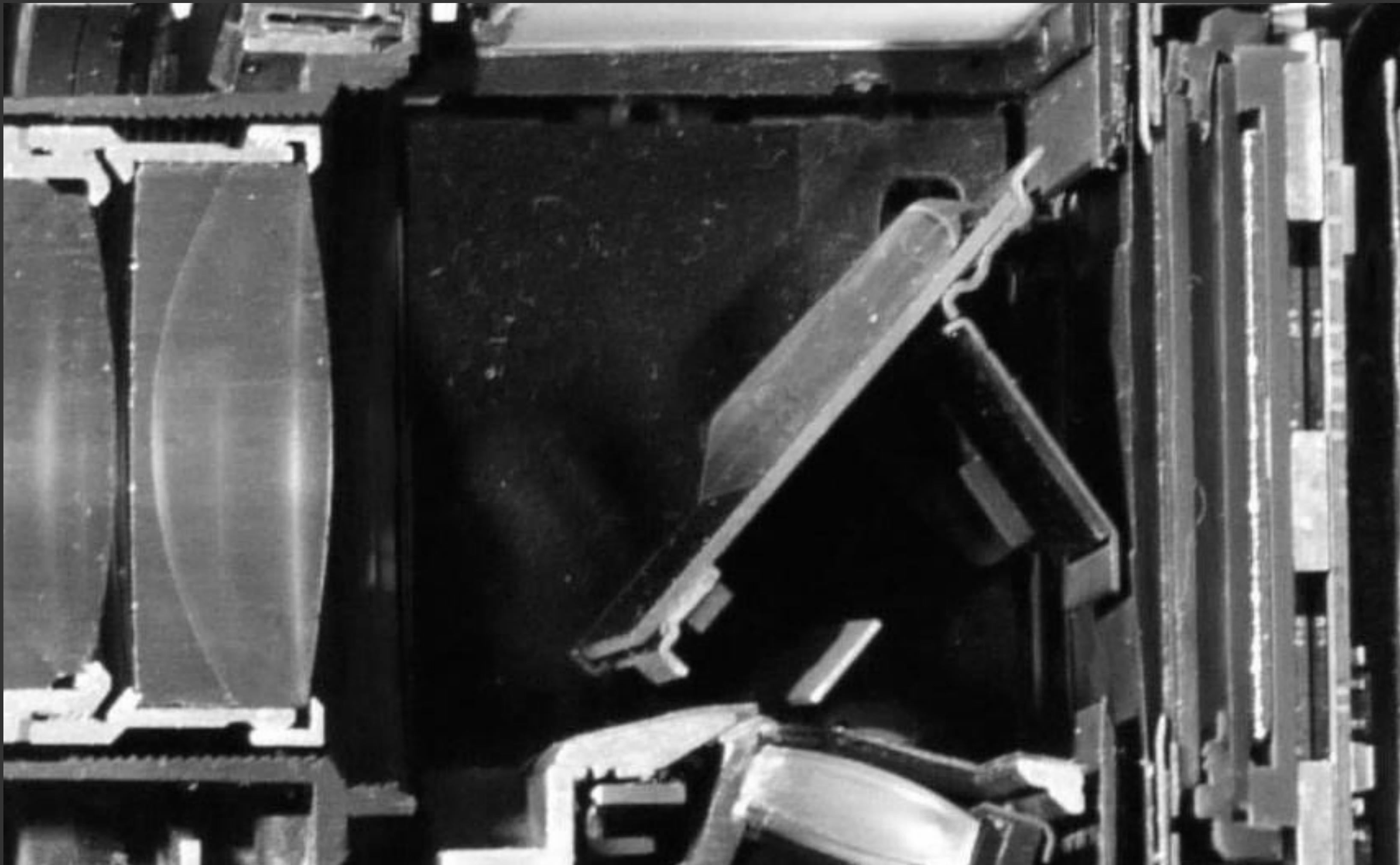


Where Microlenses Go Inside Camera

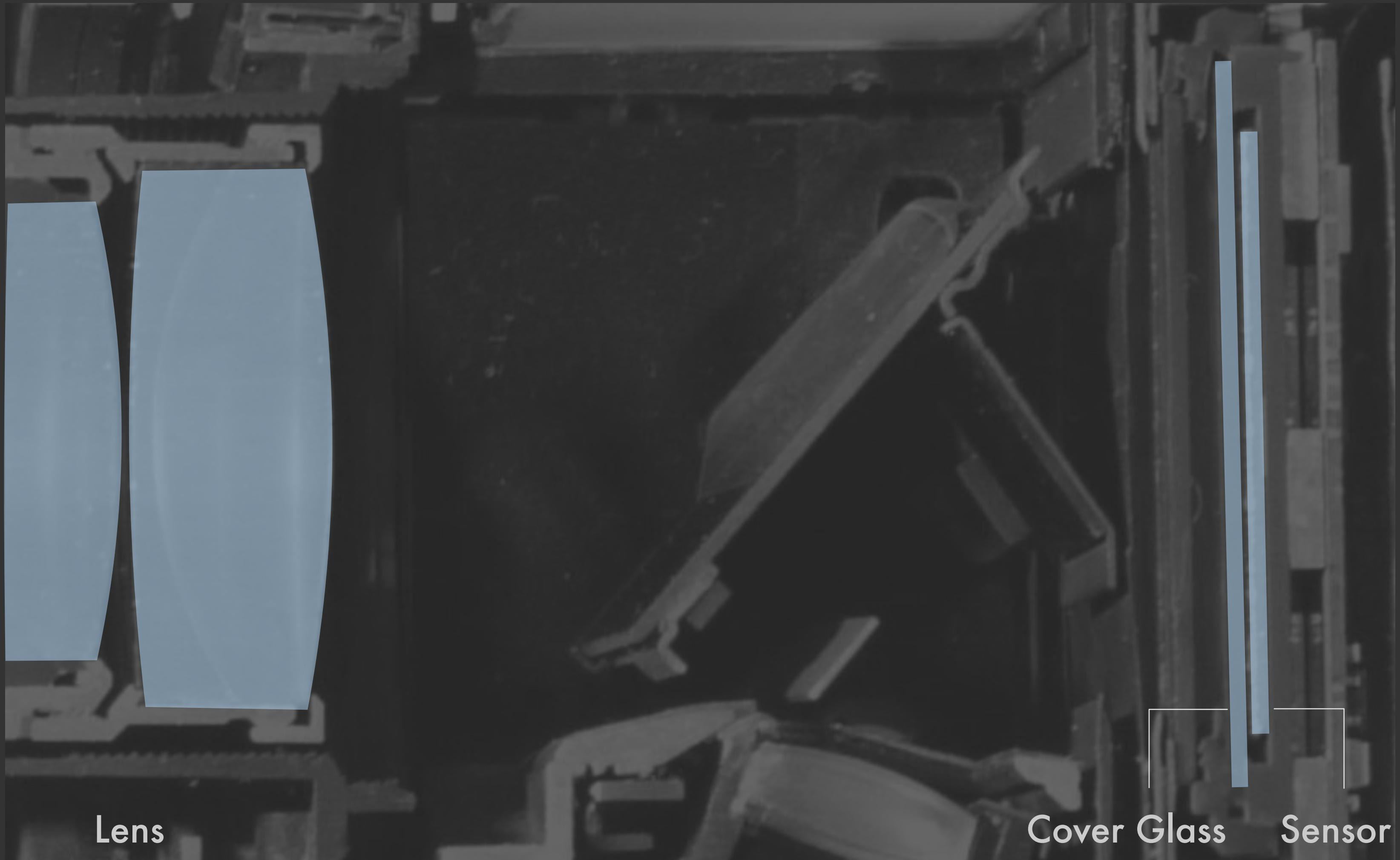


Cross-section of Nikon D3, 14-24mm F2.8 lens, Credit: ??

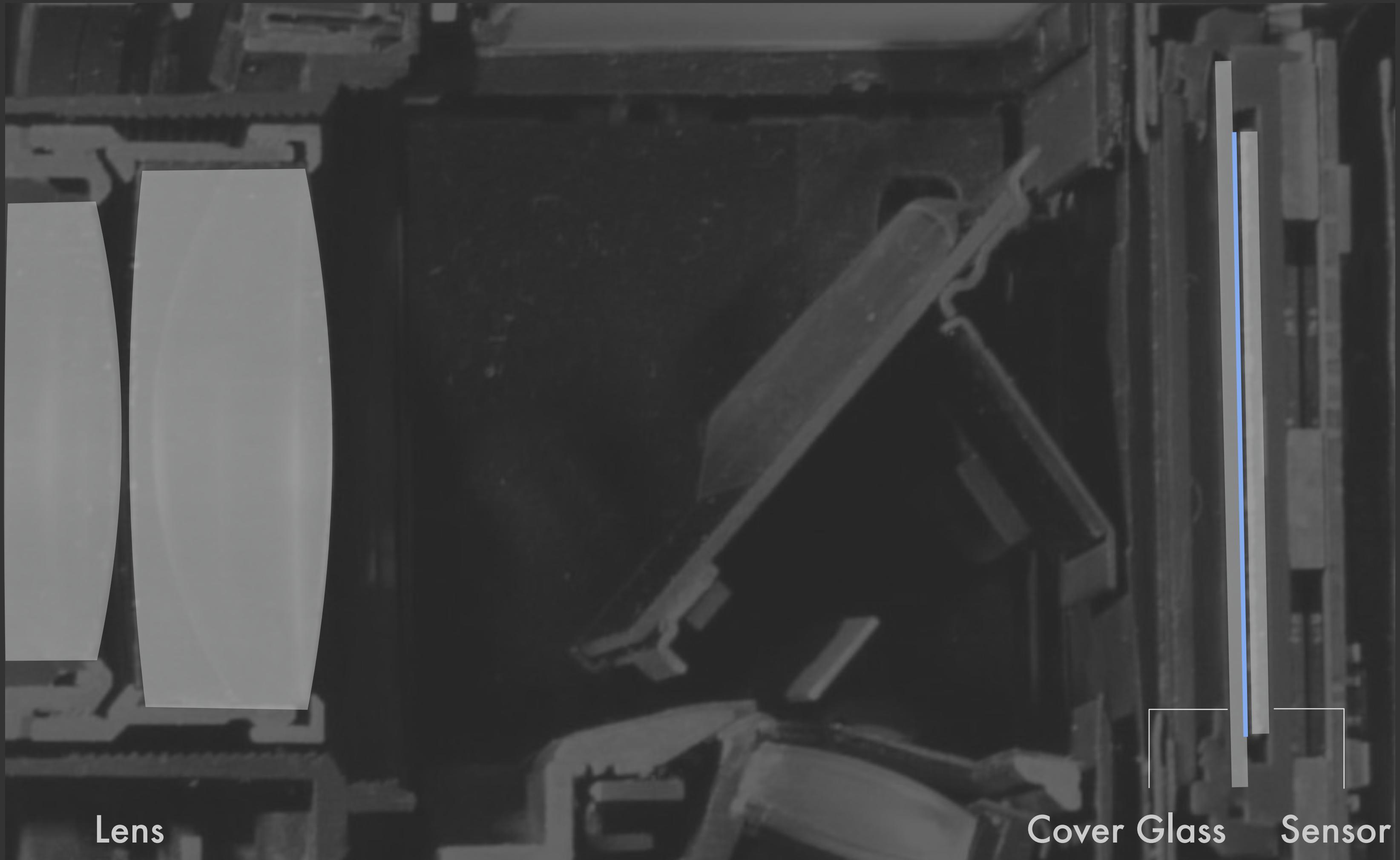
Where Microlenses Go Inside Camera



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

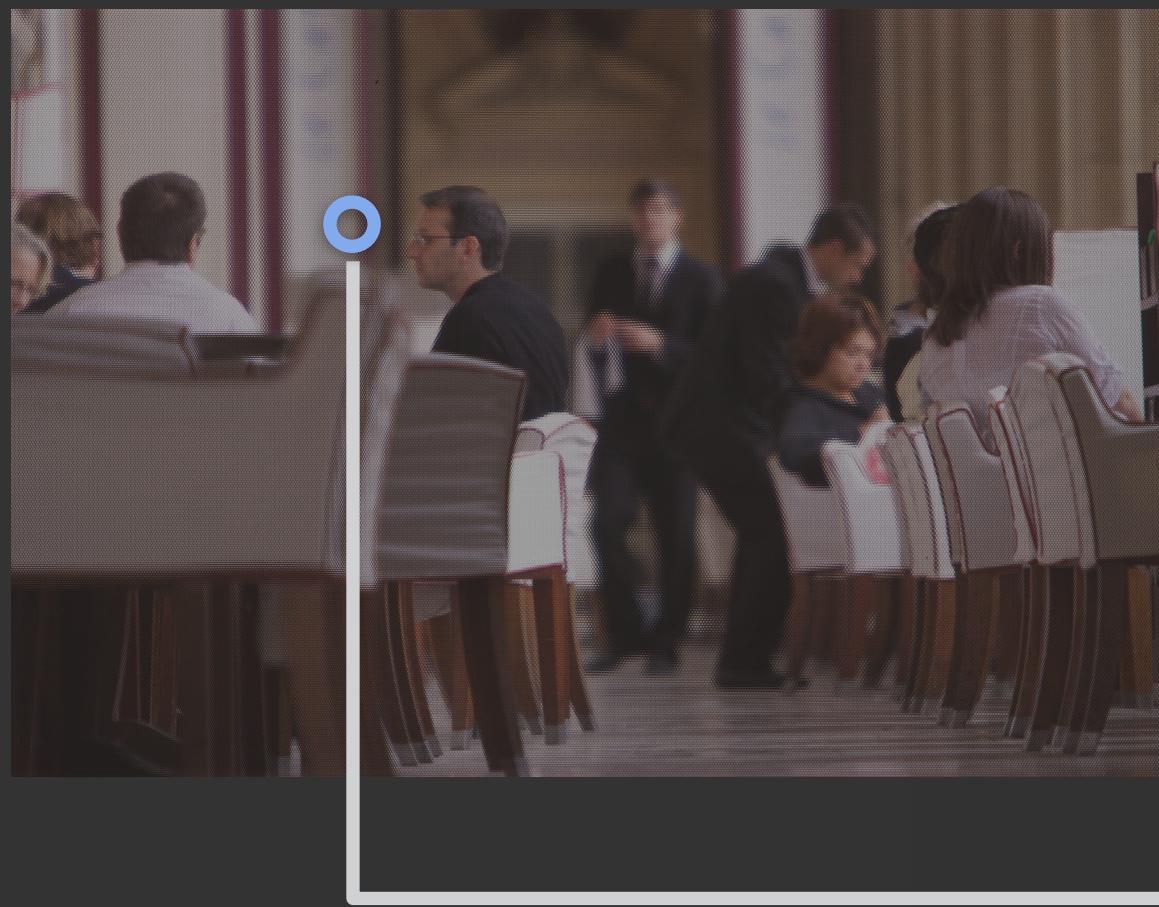


One disk image

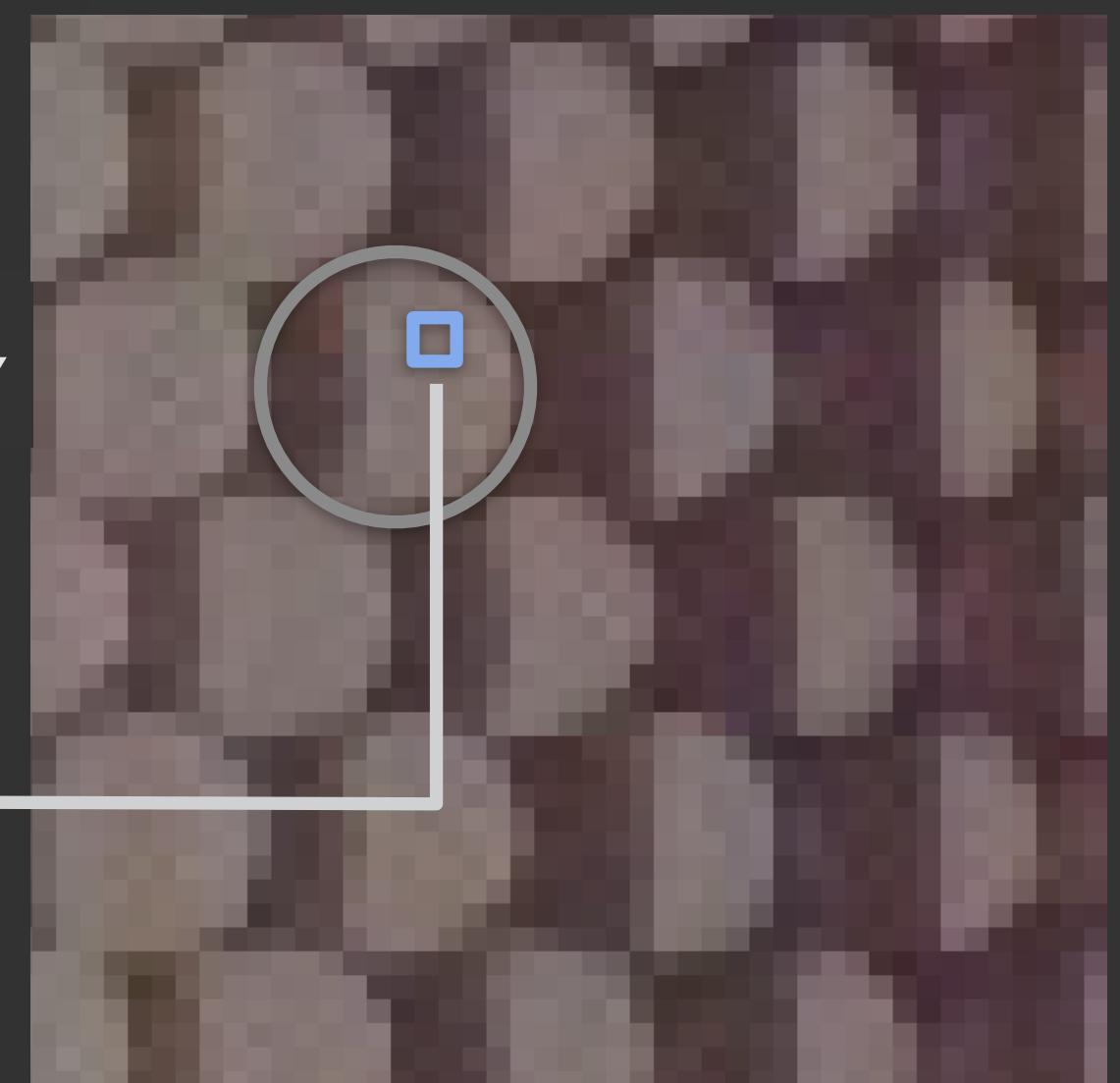
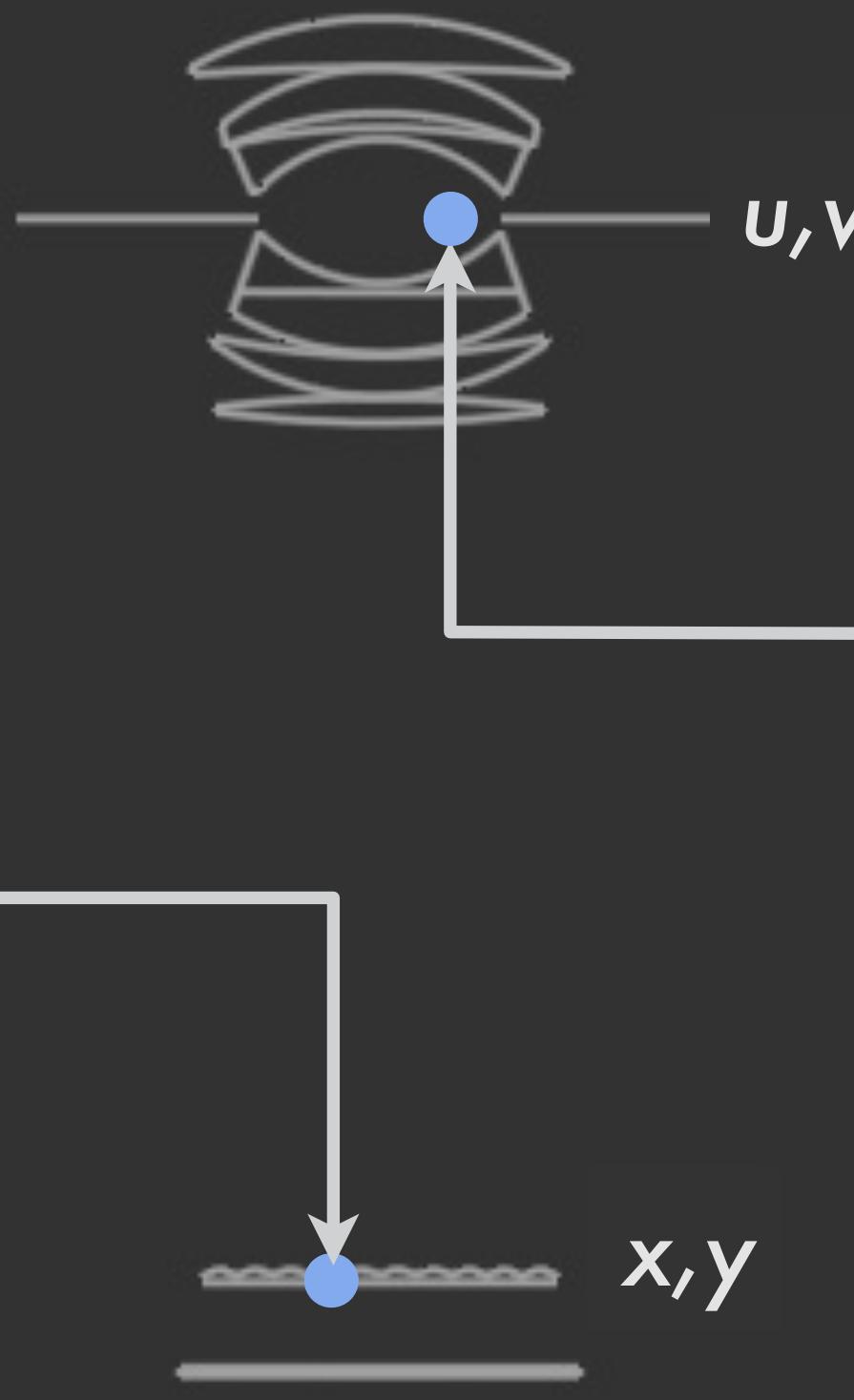
Raw Data From Light Field Sensor



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



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

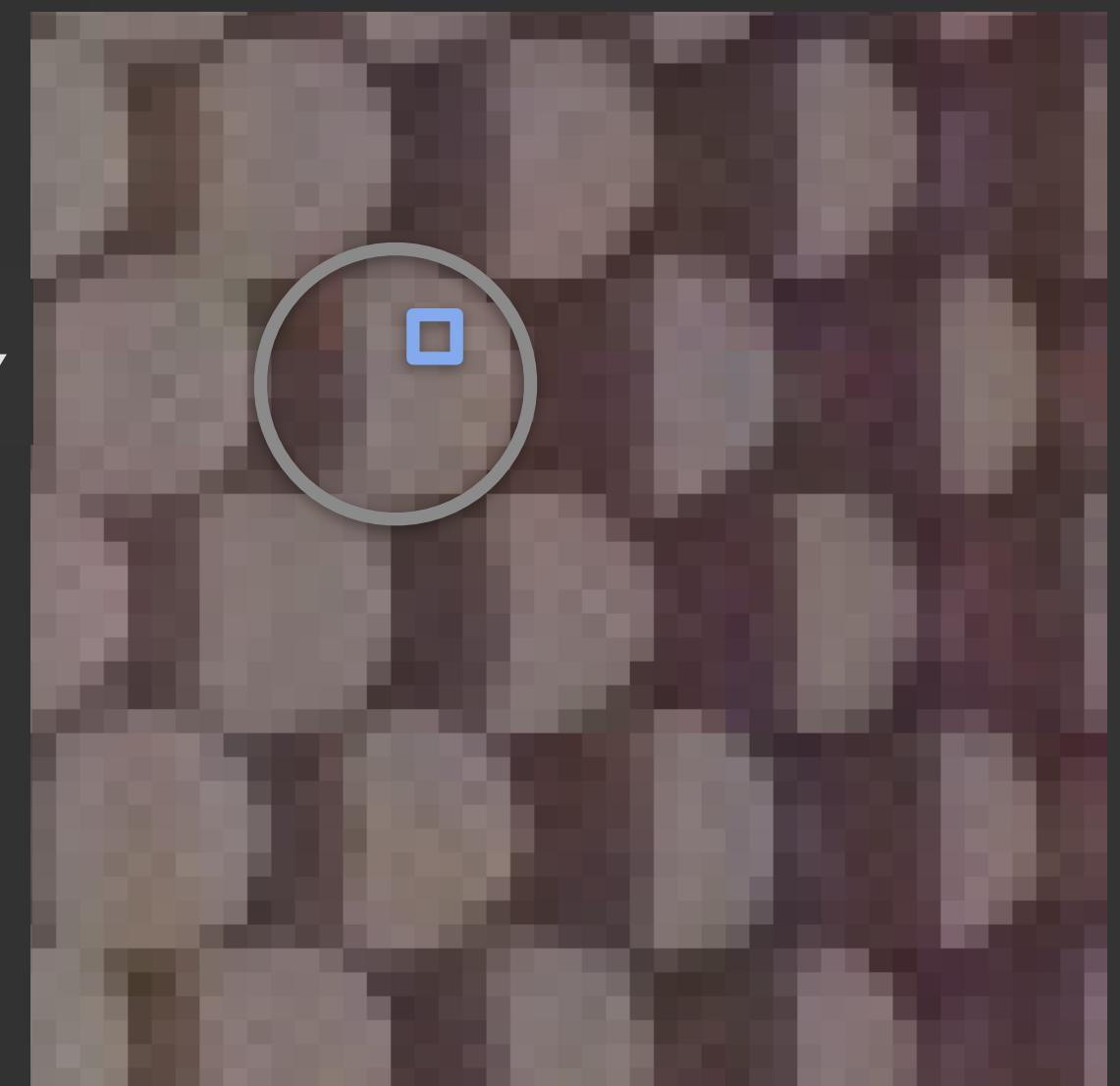
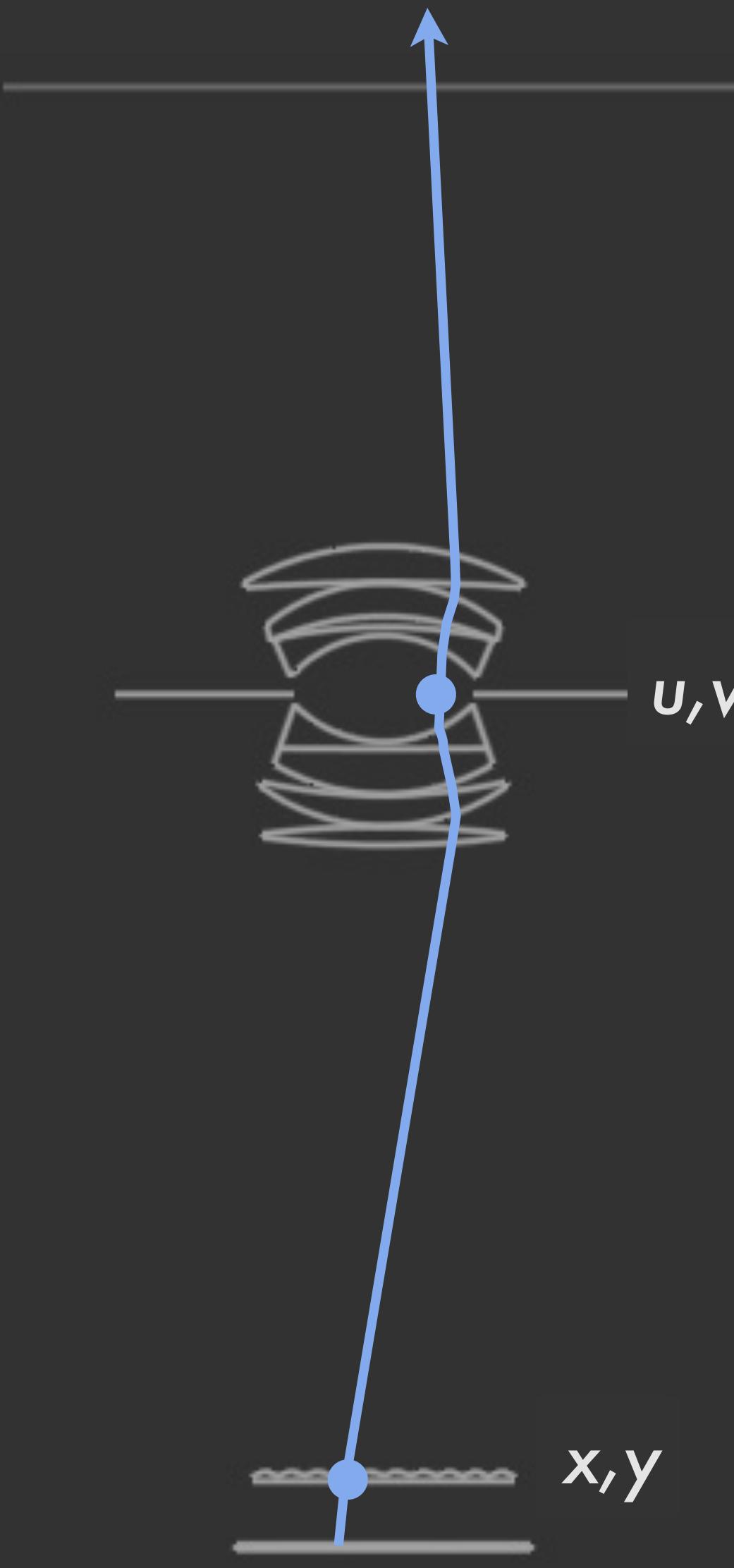


Pixel location in
microlens image
gives (u,v) coord

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

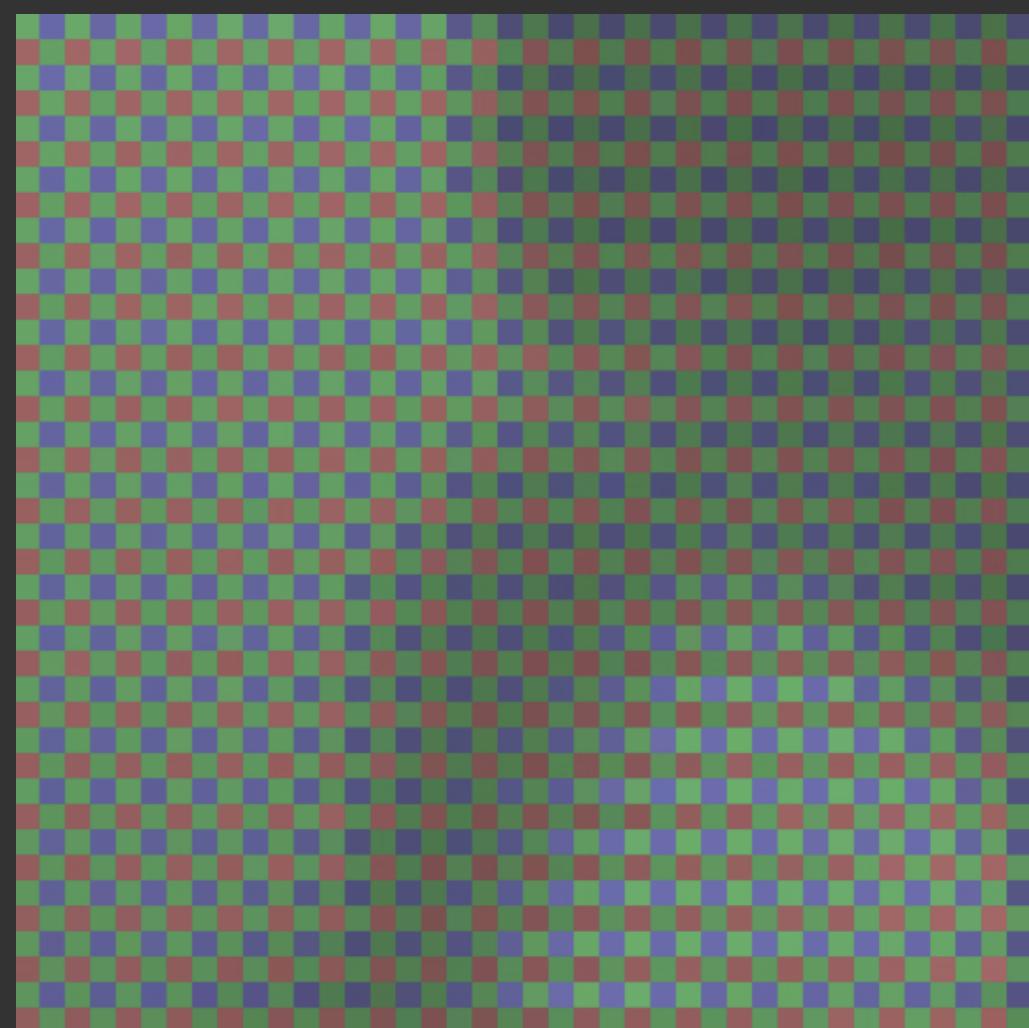


Microlens location
in image field of view
gives (x,y) coord



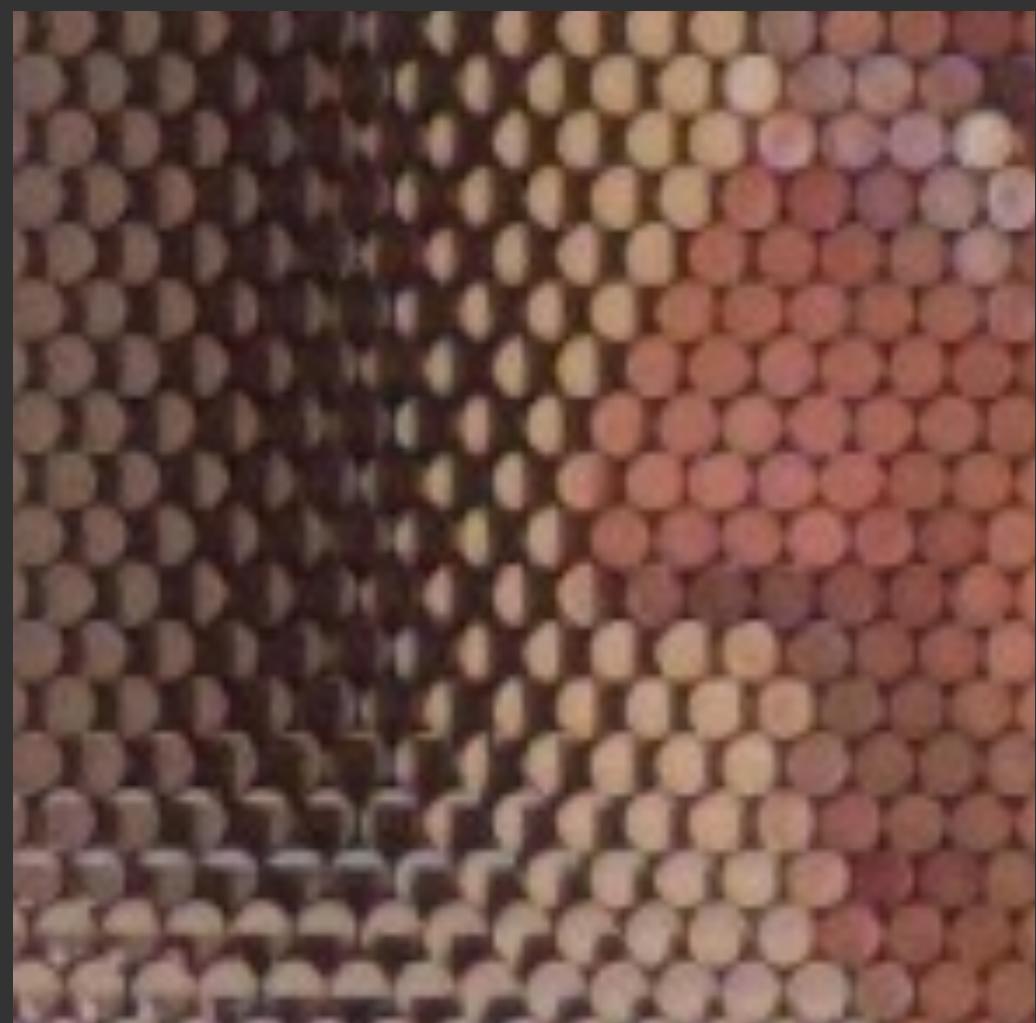
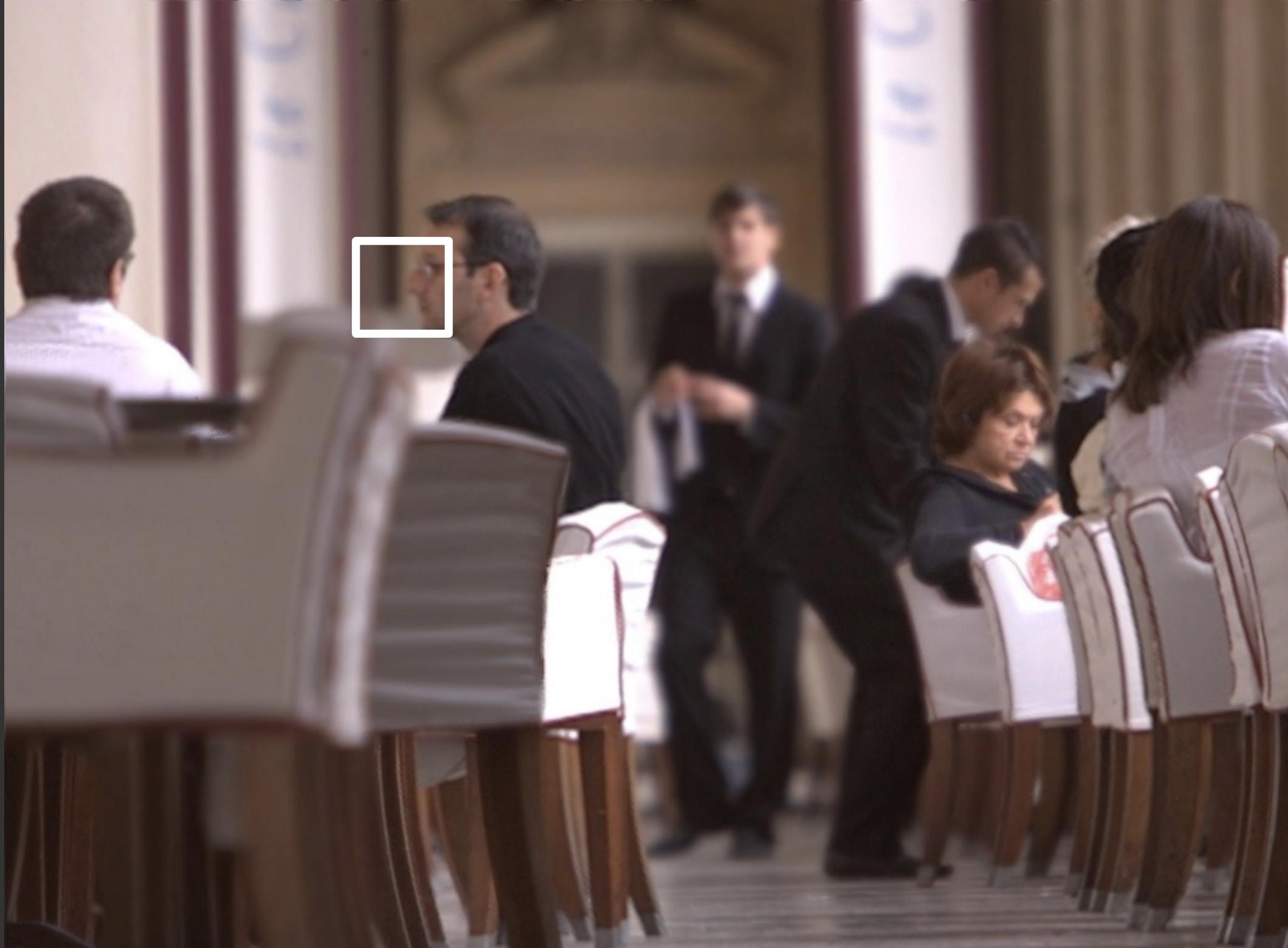
Pixel location in
microlens image
gives (u,v) coord

Analogy: Shooting RAW vs JPG (2D Photos)



RAW Bayer 14-bit data preserves intensity information, and provides flexibility over exposure and color.

Shooting 4D Light Field vs 2D Photographs



Light field data preserves directional intensity information, and provides flexibility over focus and aberrations.

Check your understanding

Sub-Aperture Images

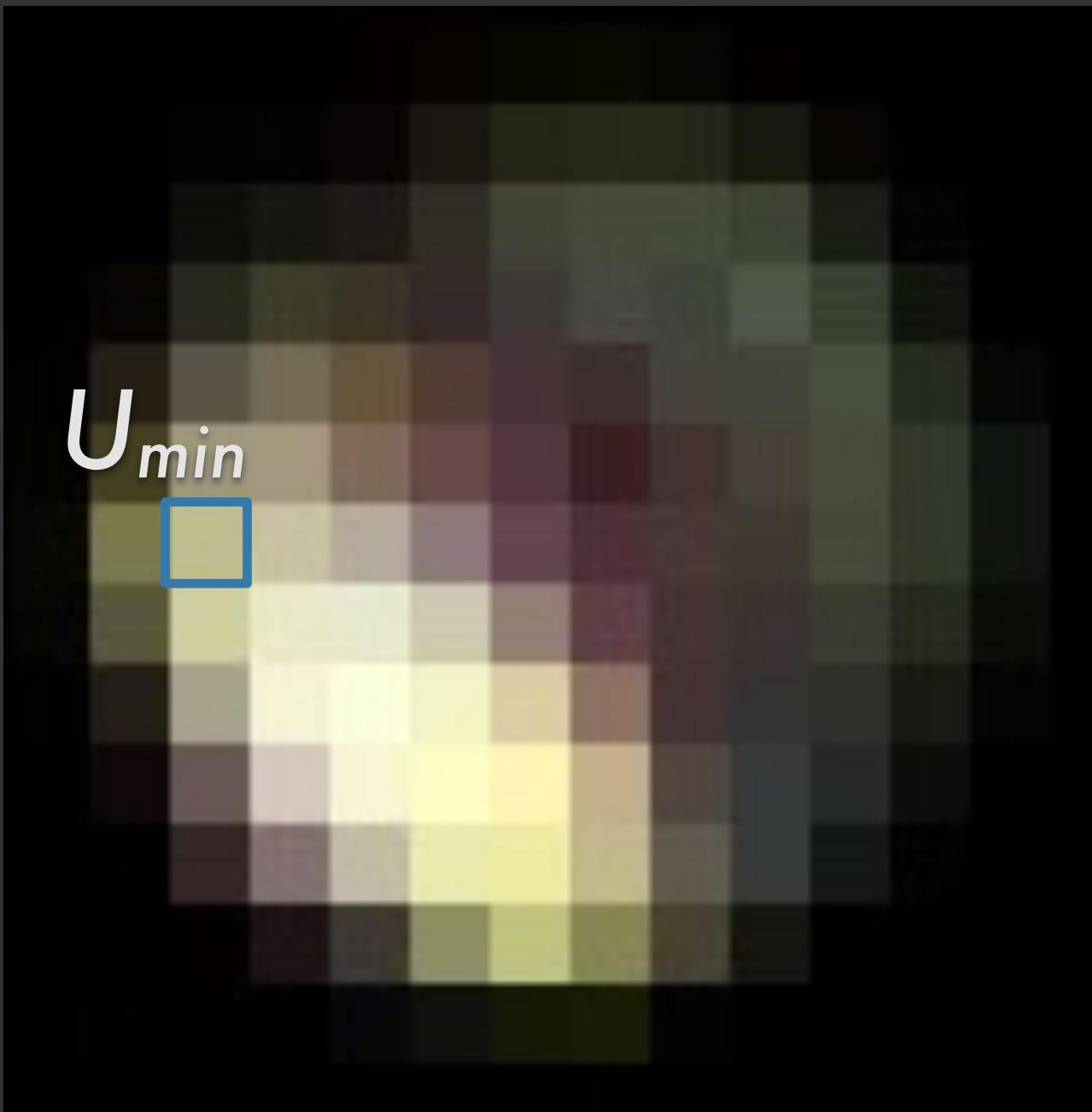


Image from selecting the same pixel under every microlens

Sub-Aperture Images

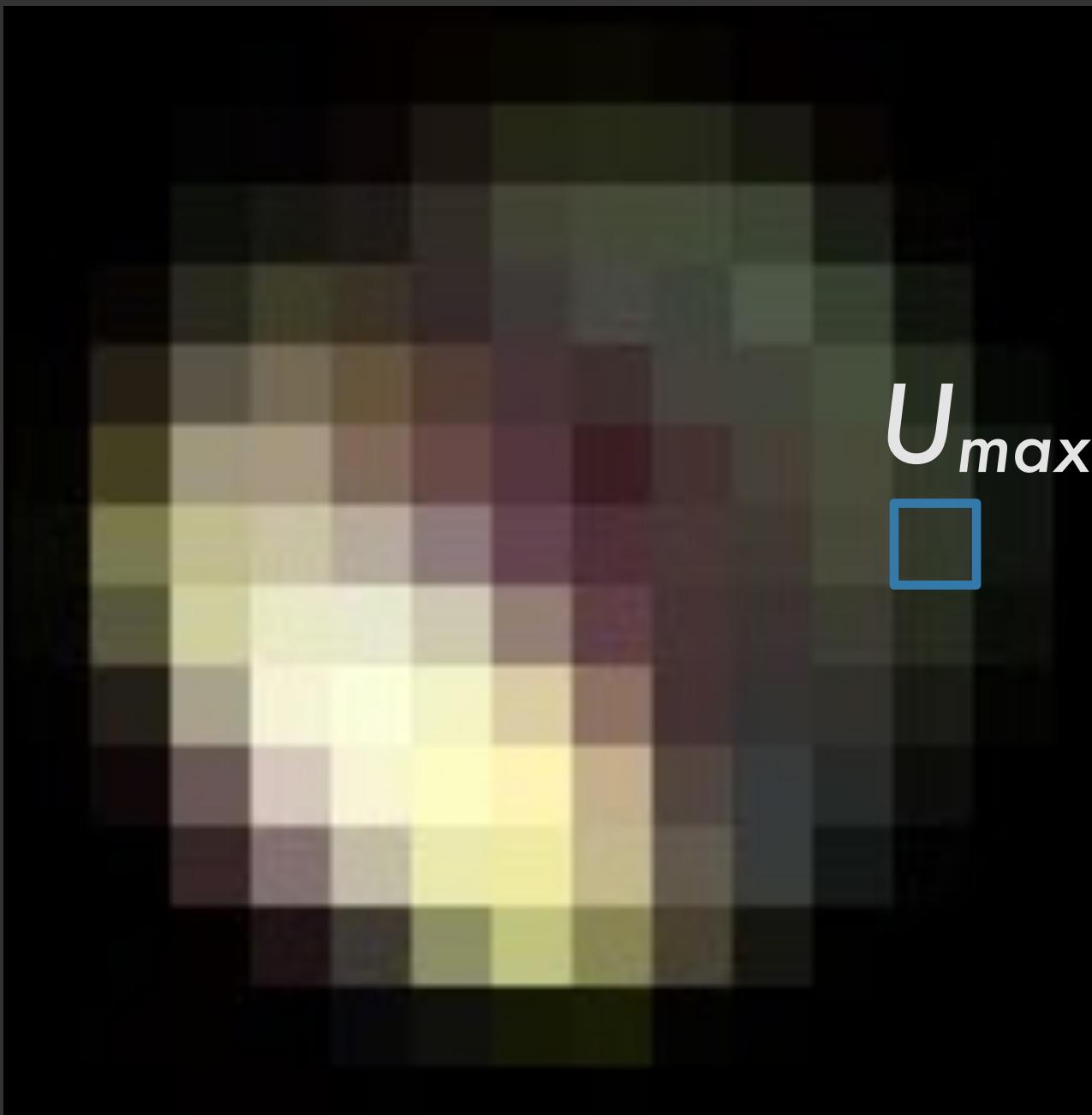
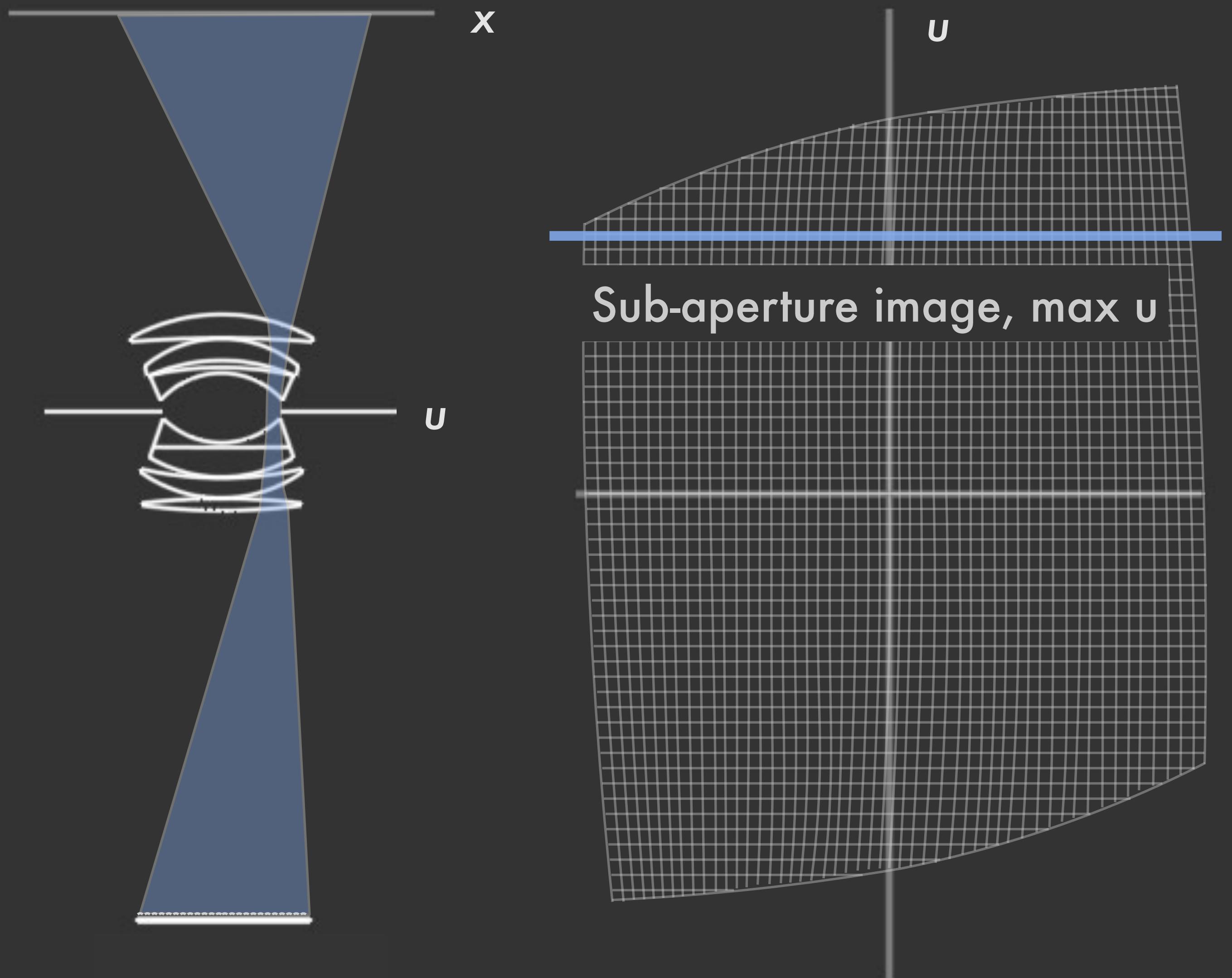
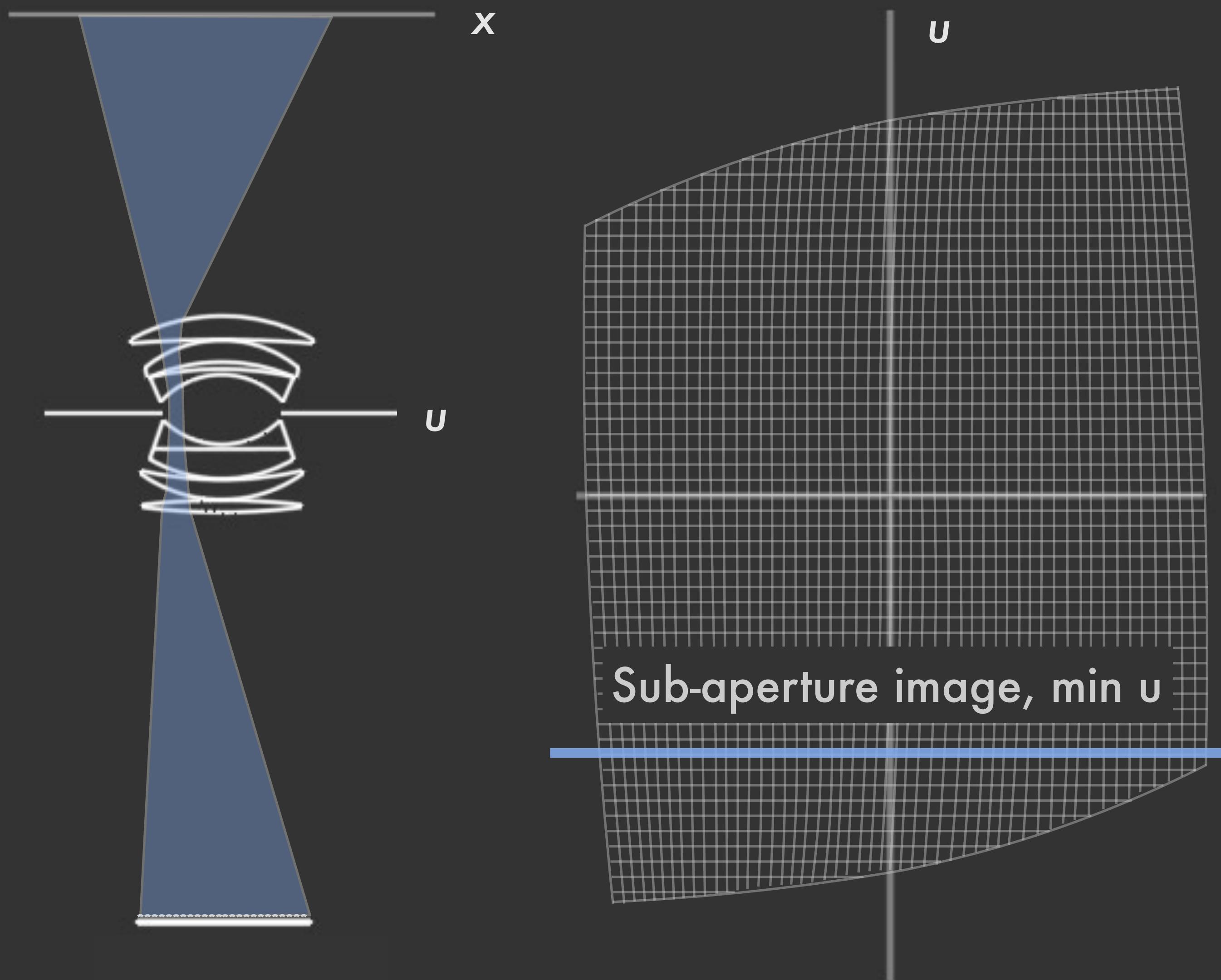


Image from selecting same pixel under every microlens

Sub-Aperture Images



Sub-Aperture Images



Application: computational Change of Viewpoint



Lateral movement (left)

Application: computational Change of Viewpoint



Lateral movement (right)

How do you compute a photograph from a light field?

Computing a photograph from a light field

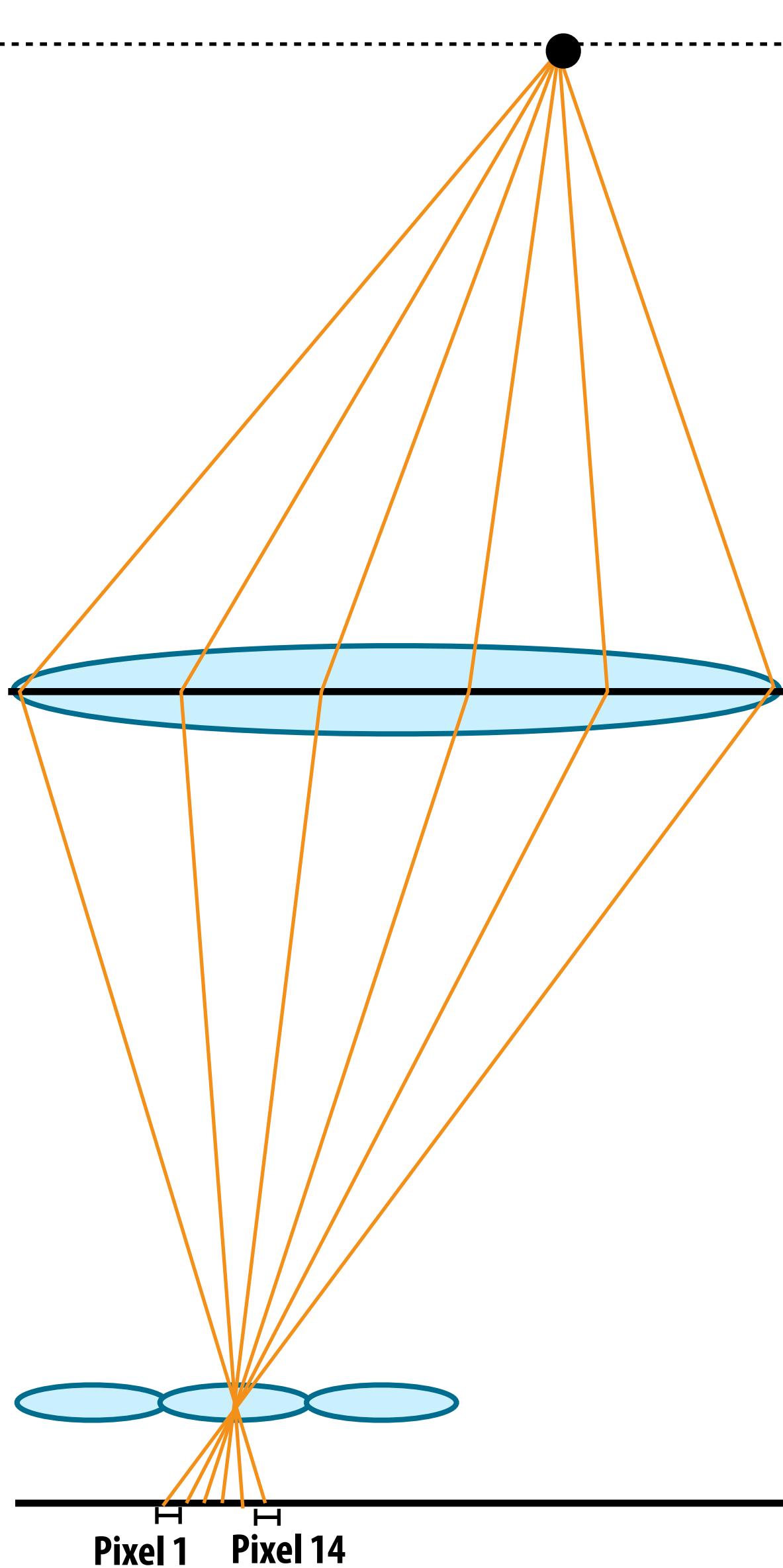
World plane of focus

Lens aperture: (U, V)

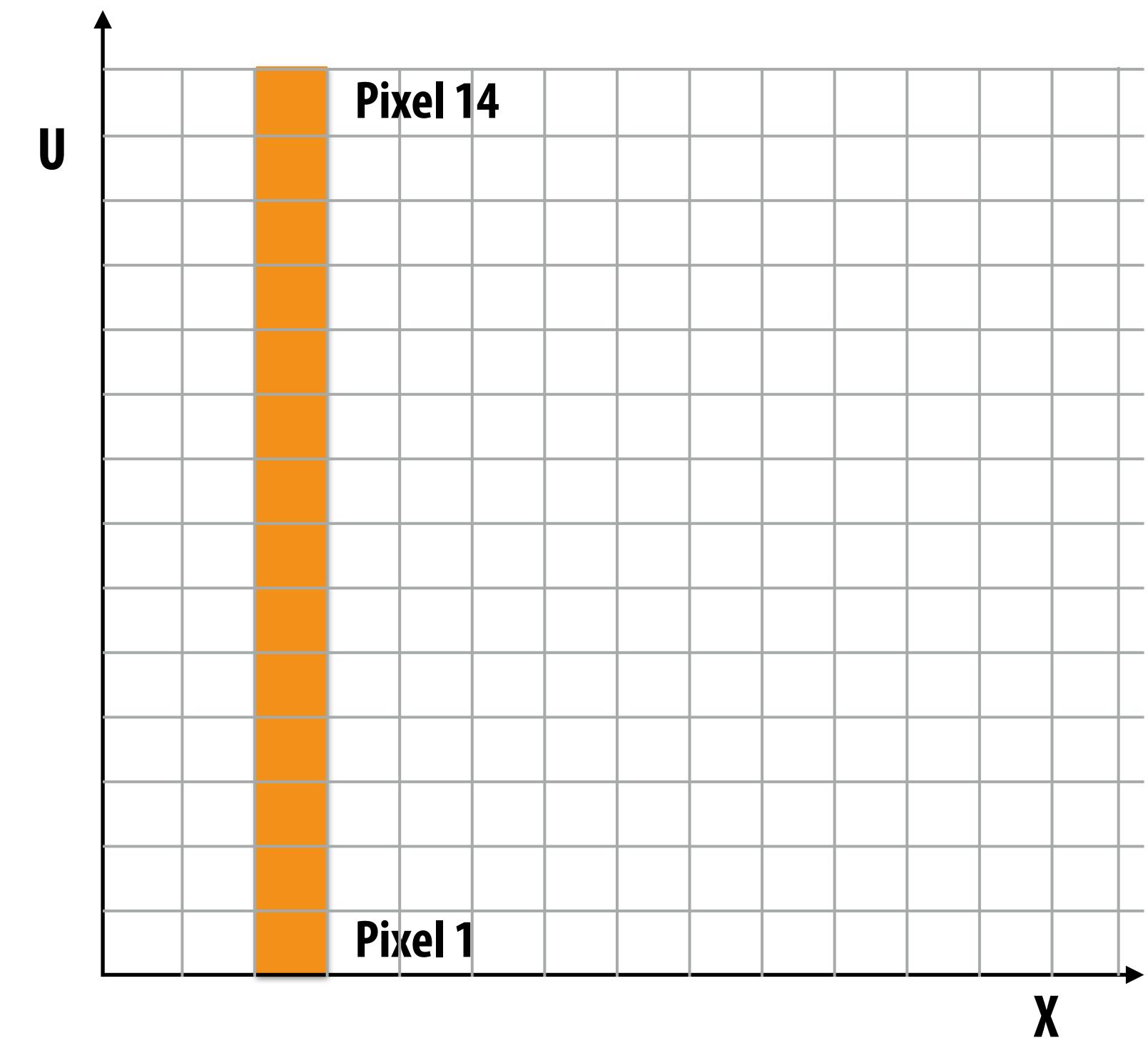
Microlens array

Sensor plane: (X, Y)

Pixel 1 Pixel 14

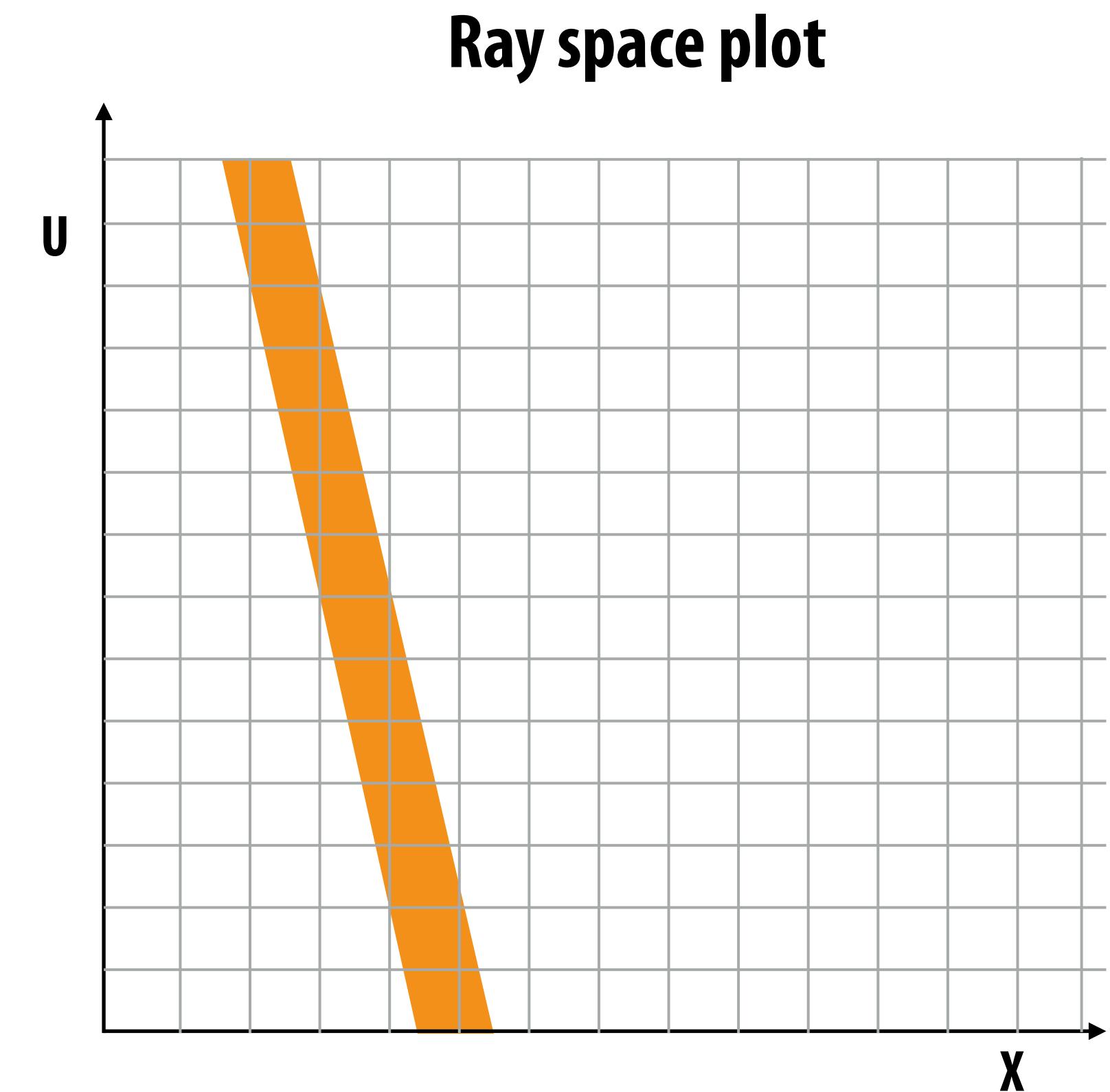
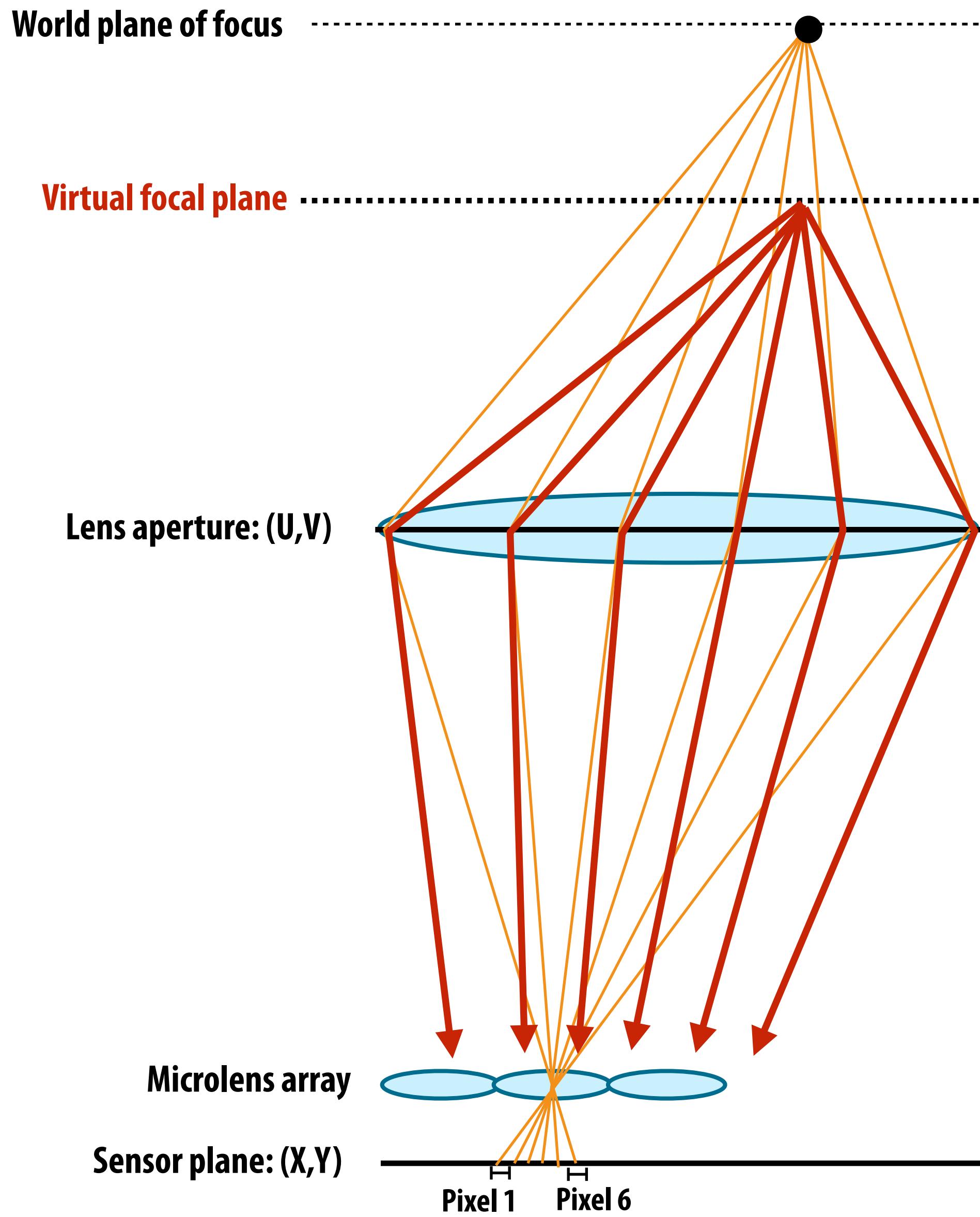


Ray space plot



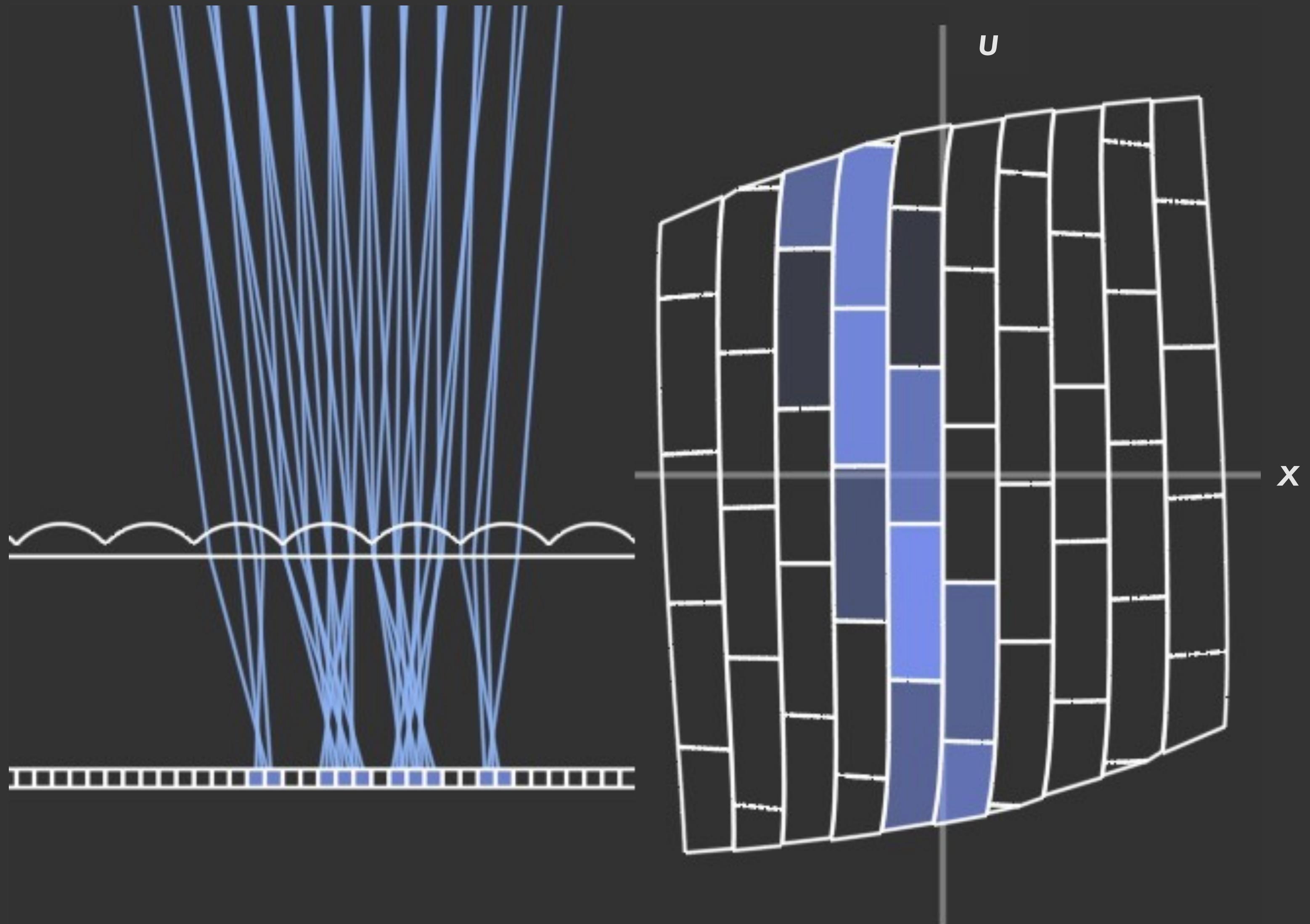
Computing photograph is integral projection
(Output image pixel is sum of highlighted light-field sensor pixels)

Computing a photograph at a new focal plane



Computing photograph is integral projection
(Output image pixel is integral over highlighted
region: resample)

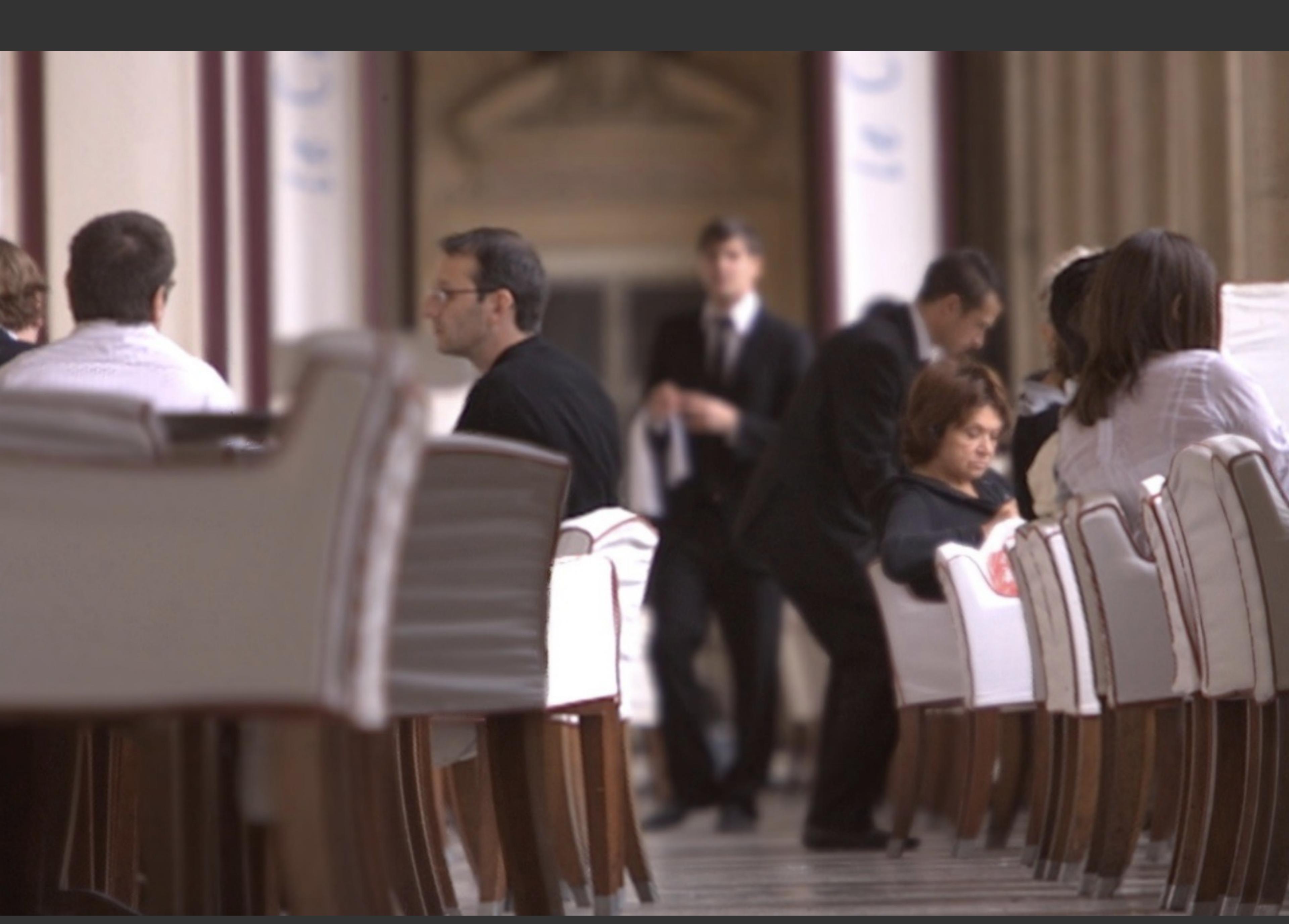
Output Image Pixel is Sum of Many Sensor Pixels

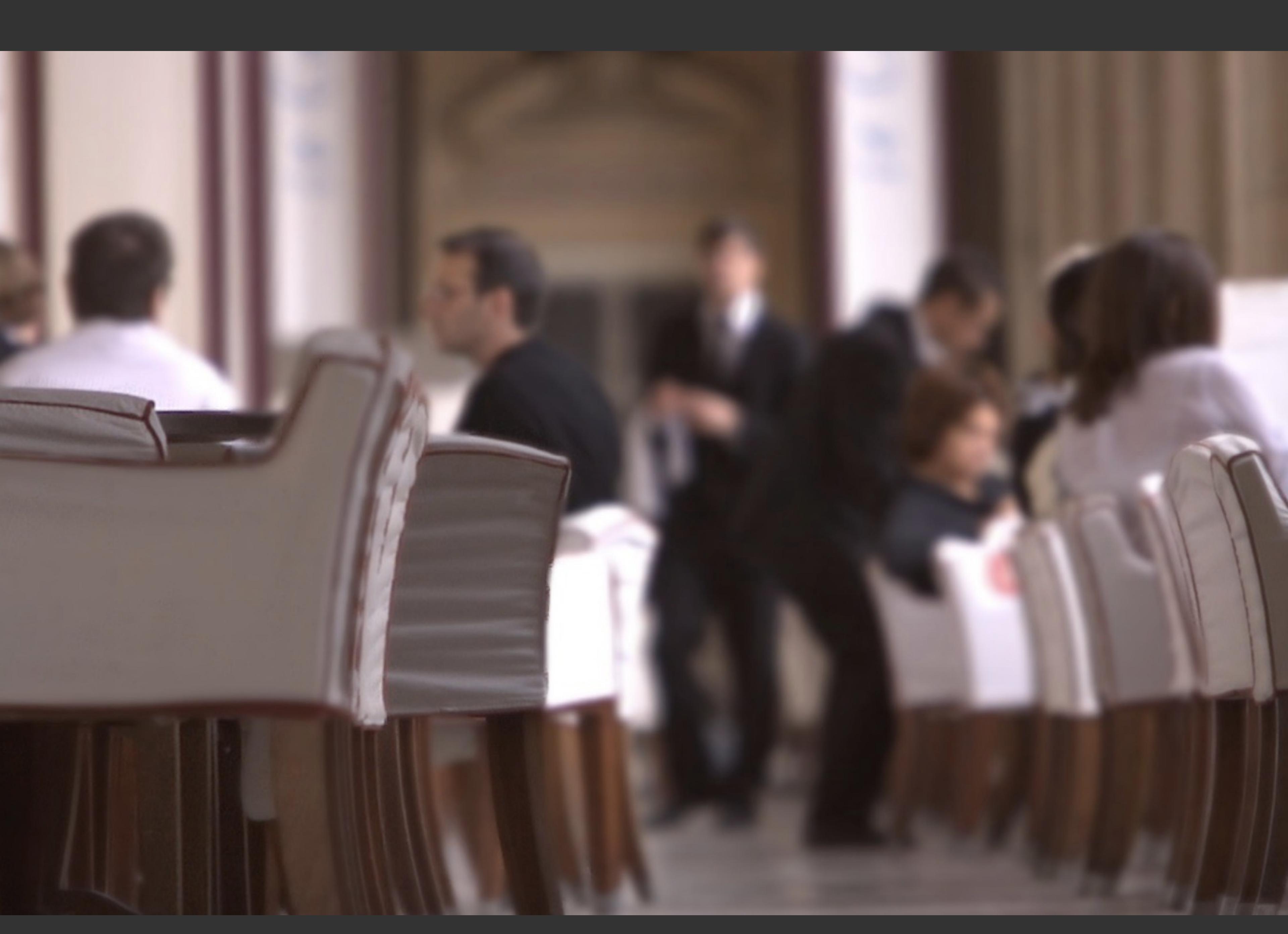


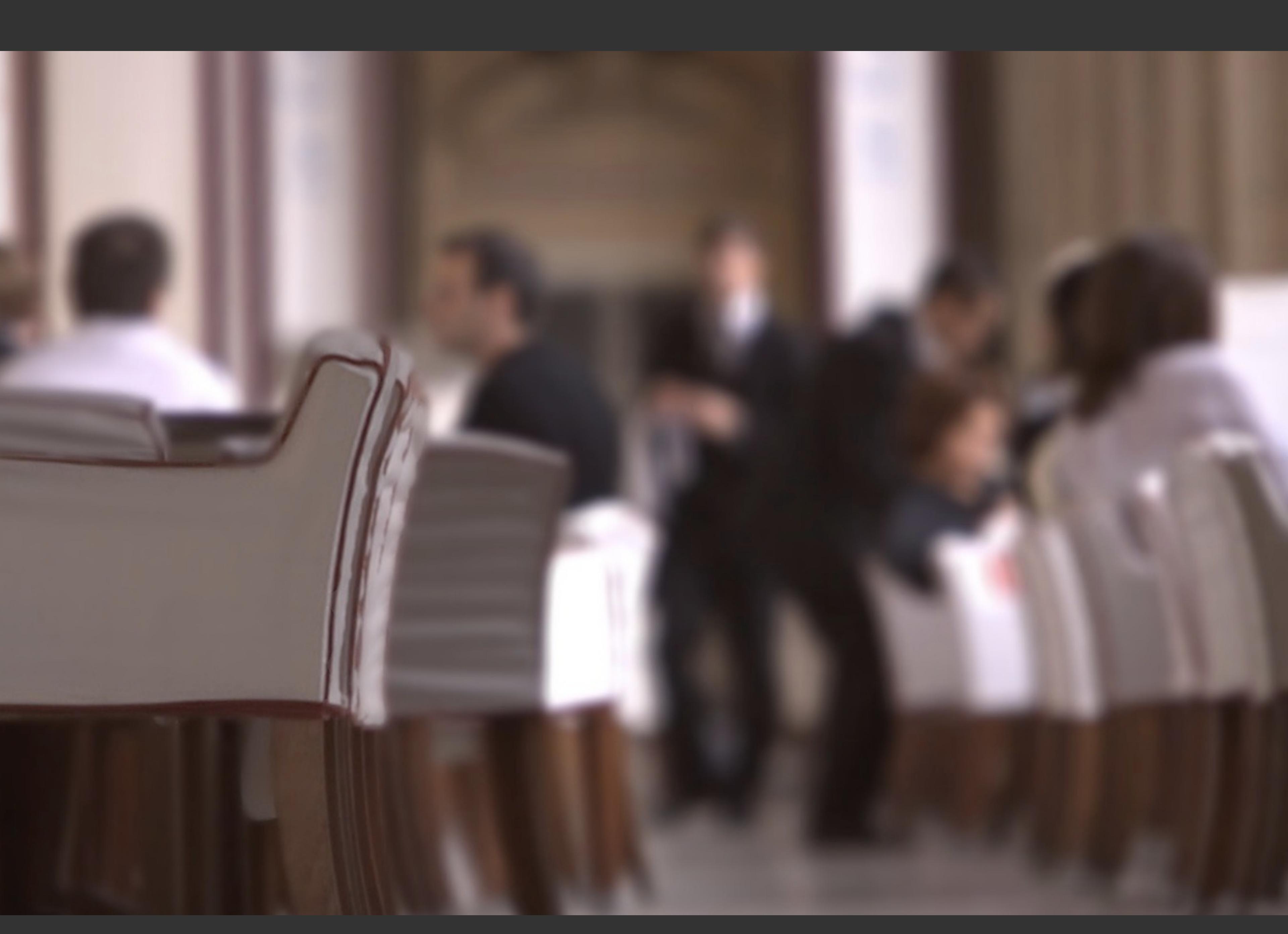












Consumer Light Field Resolutions Today

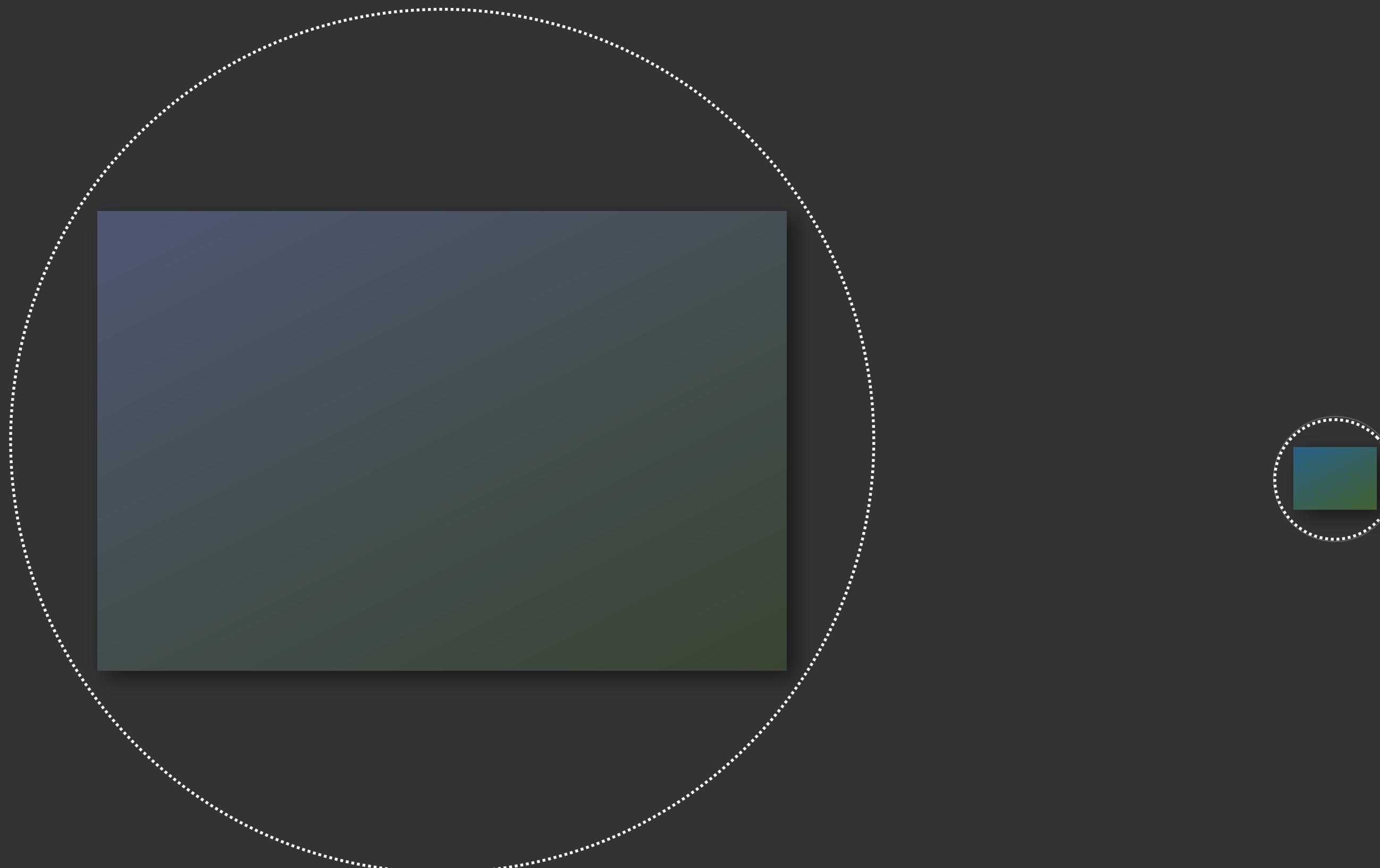


Lytro (2012)
10 MegaRay
~10 pixels / microlens



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

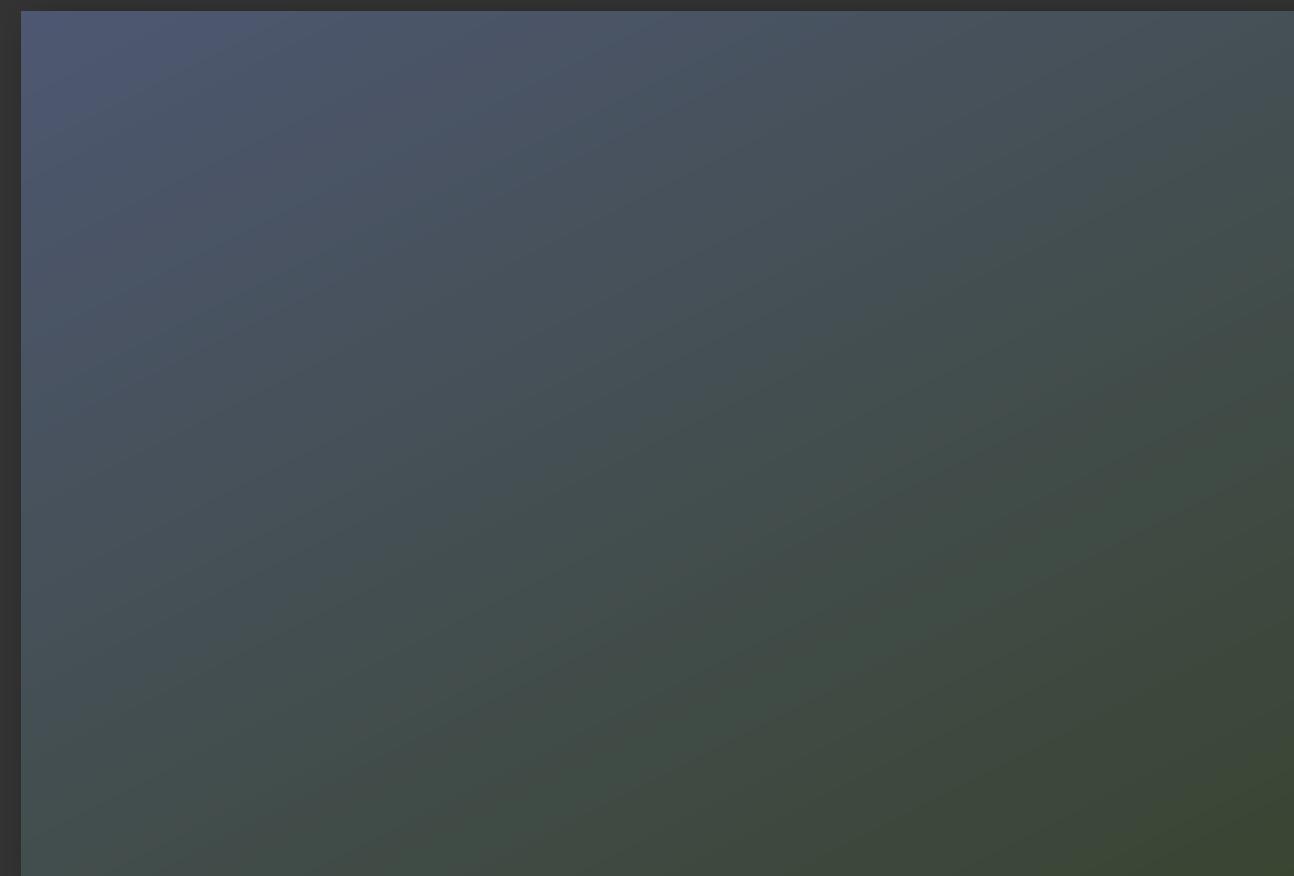
Sensor Industry Has Large Untapped Resolution



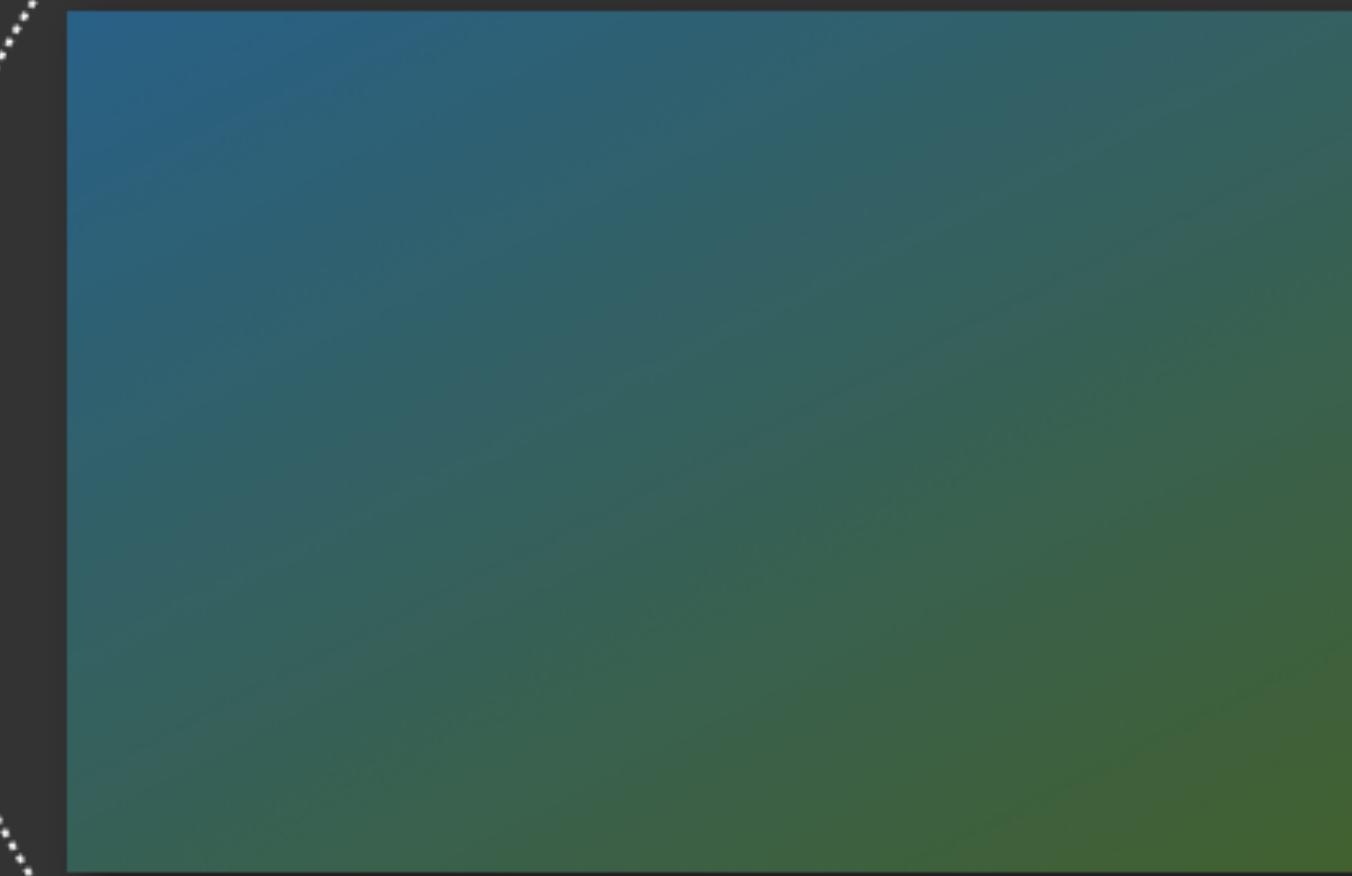
Full-Frame Sensor
 36×24 mm
Up to 36 MP
4.9 micron pixel

1/3" Sensor
 4.8×3.6 mm
Up to 13 MP
1.12 micron pixel

Sensor Industry Has Large Untapped Capability



Full-Frame Sensor
 $36 \times 24 \text{ mm}$
Up to 36 MP
4.9 micron pixel



Full-Frame Sensor
 $36 \times 24 \text{ mm}$
688 MP
1.12 micron pixel

New photography applications

- **Single shot capture of information that can be used to generate many different photographs**

- Digital (post shot) refocusing
- Parallax (computational change of viewpoint)
- Extended depth of field (put entire image in focus)
- Stereo images

- Better camera performance:

- Reduced shutter lag: in the limit, no need for autofocus
- Potential for better low-light performance (always shoot with wide aperture, since misfocus due to shallow depth-of-field can be corrected after the shot)
- Correction of lens aberrations

Trends

- **No free lunch: measure directional information at cost of spatial resolution**
 - Ng's original prototype: 16 MP sensor, but output was 300x300 images
 - Original Lytro camera: 11MP sensor, ~1MP output images
- **Light field cameras can make use of increasing sensor pixel densities**
 - More directional resolution = increased refocusing capability
 - More spatial resolution at fixed directional resolution
 - Few motivations high-pixel-count sensors for traditional cameras today
- **High-resolution cameras introduce computational challenges**
 - Processing challenges
 - Storage challenges
 - Data-transfer challenges