## Lecture 18:

# Light field cameras (plenoptic cameras)

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**Visual Computing Systems**
**CMU 15-869, Fall 2013**

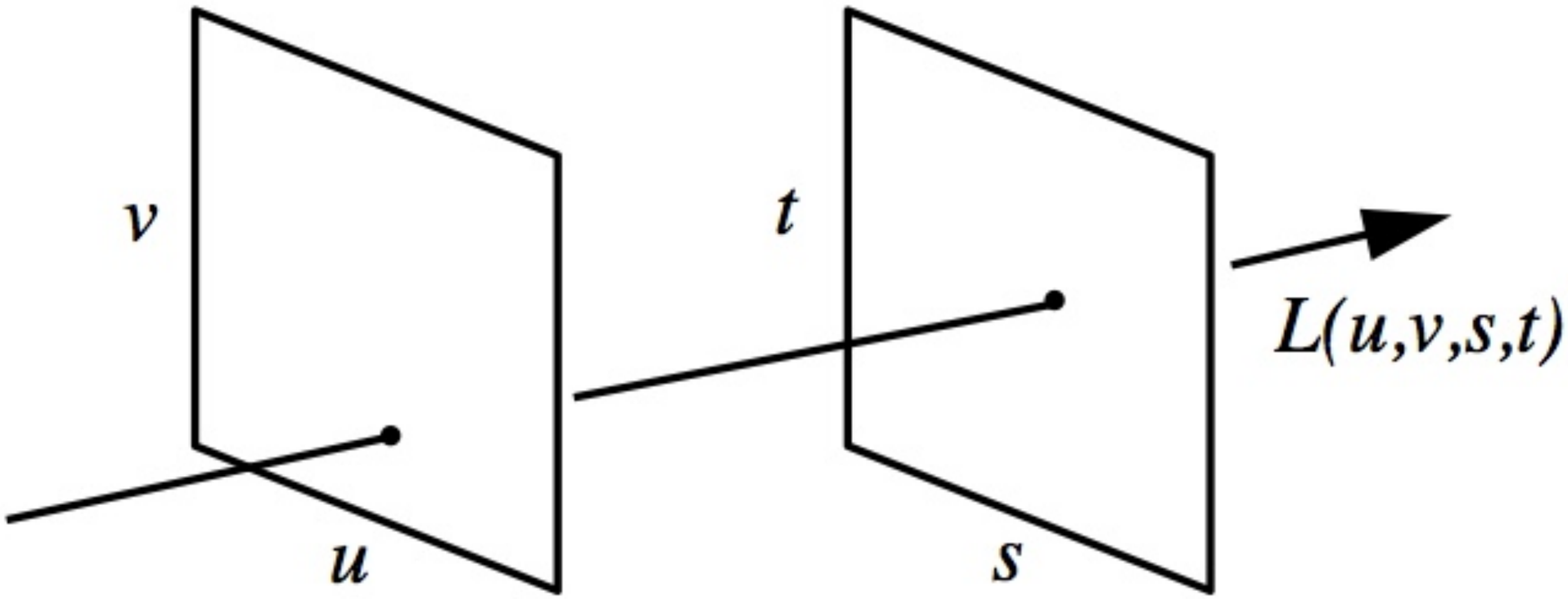
# Continuing theme: computational photography

- Cameras capture light, then extensive processing produces the desired image

- Today:
  - Capturing light fields (not just photographs) with a handheld camera
  - Implications for photography

# Recall: the light-field

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




[Image credit: Levoy and Hanrahan 96]

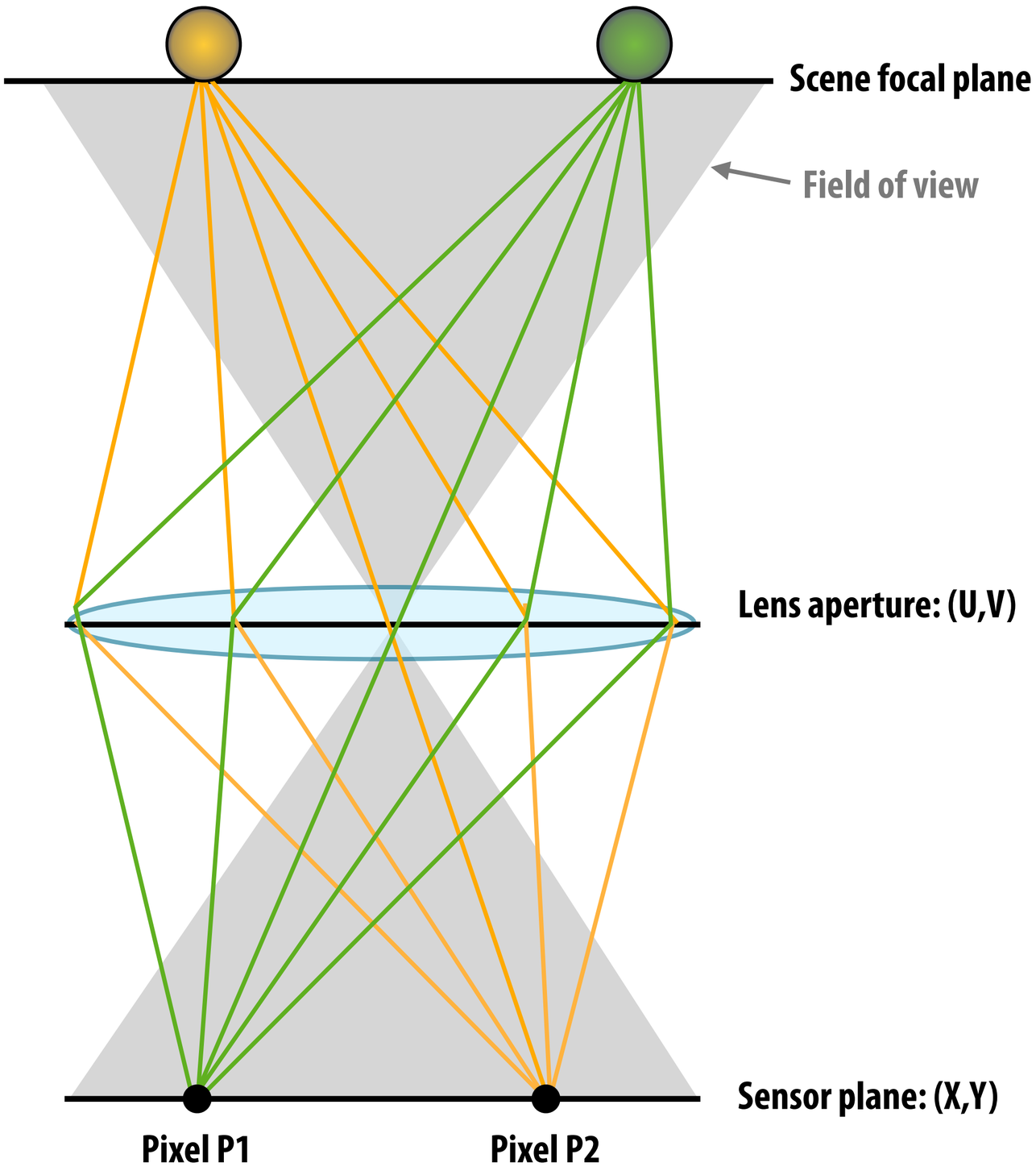
**Two-plane parameterization:**

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

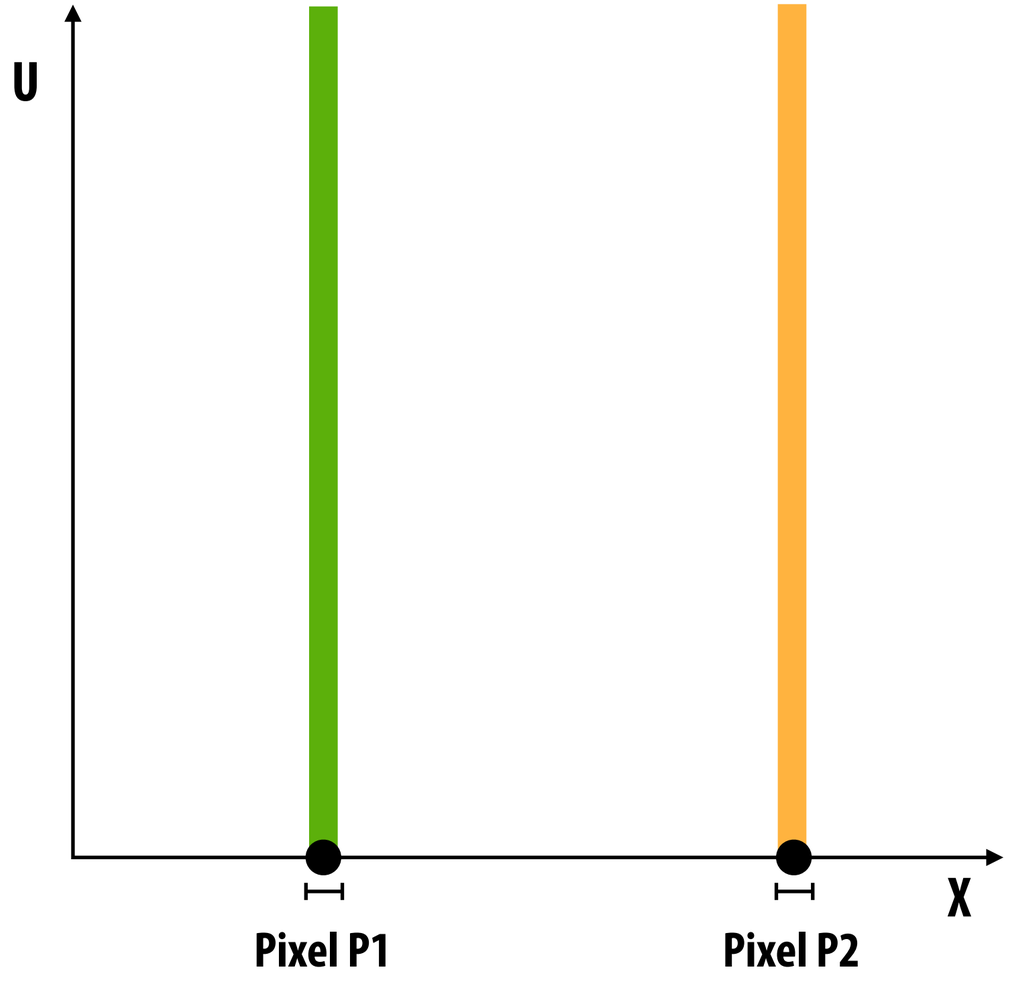
**More general: plenoptic function (Adelson and Bergen 1991)**

$$P = P(x, y, \lambda, t, V_x, V_y, V_z)$$

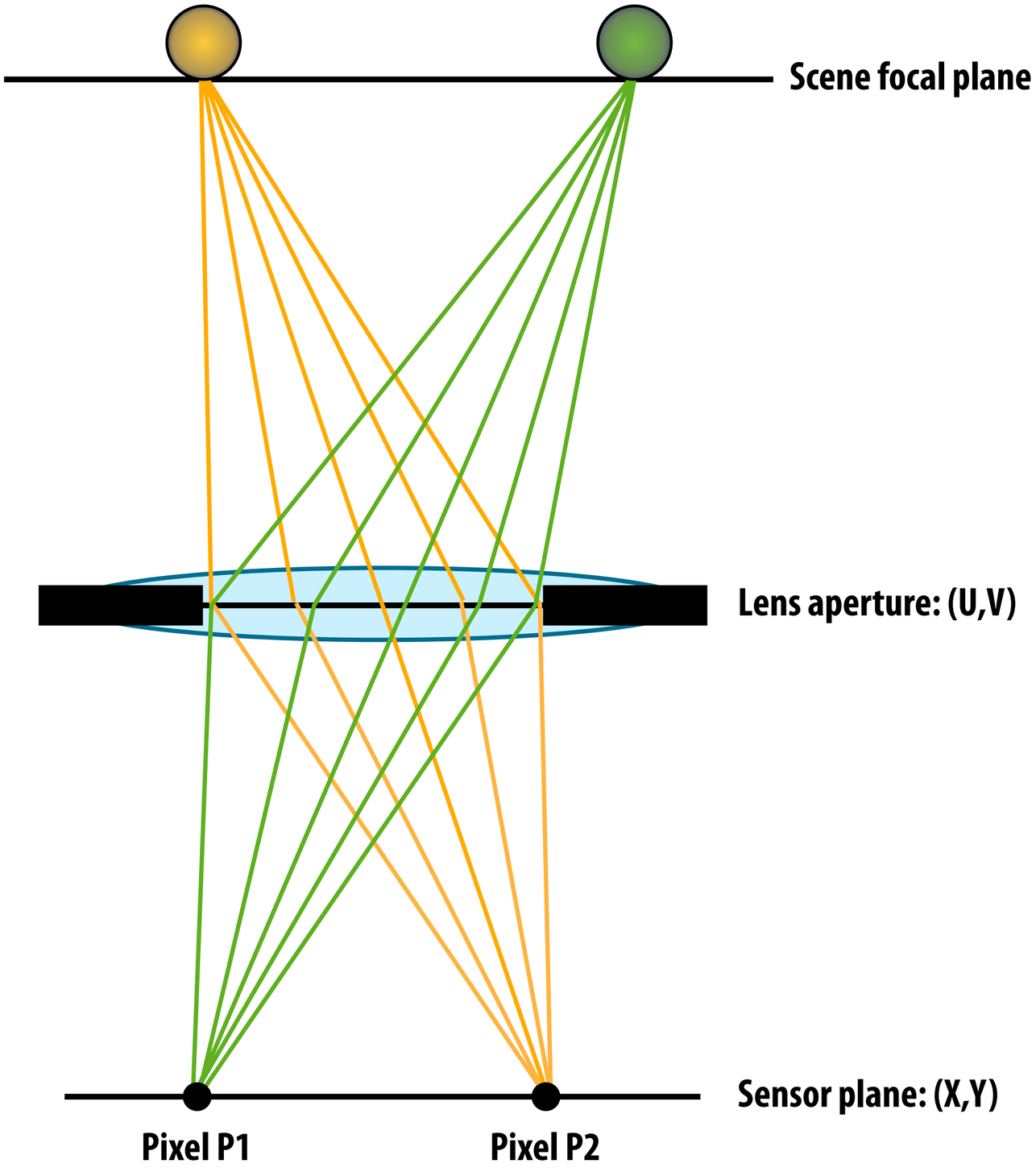
# Light field inside a camera



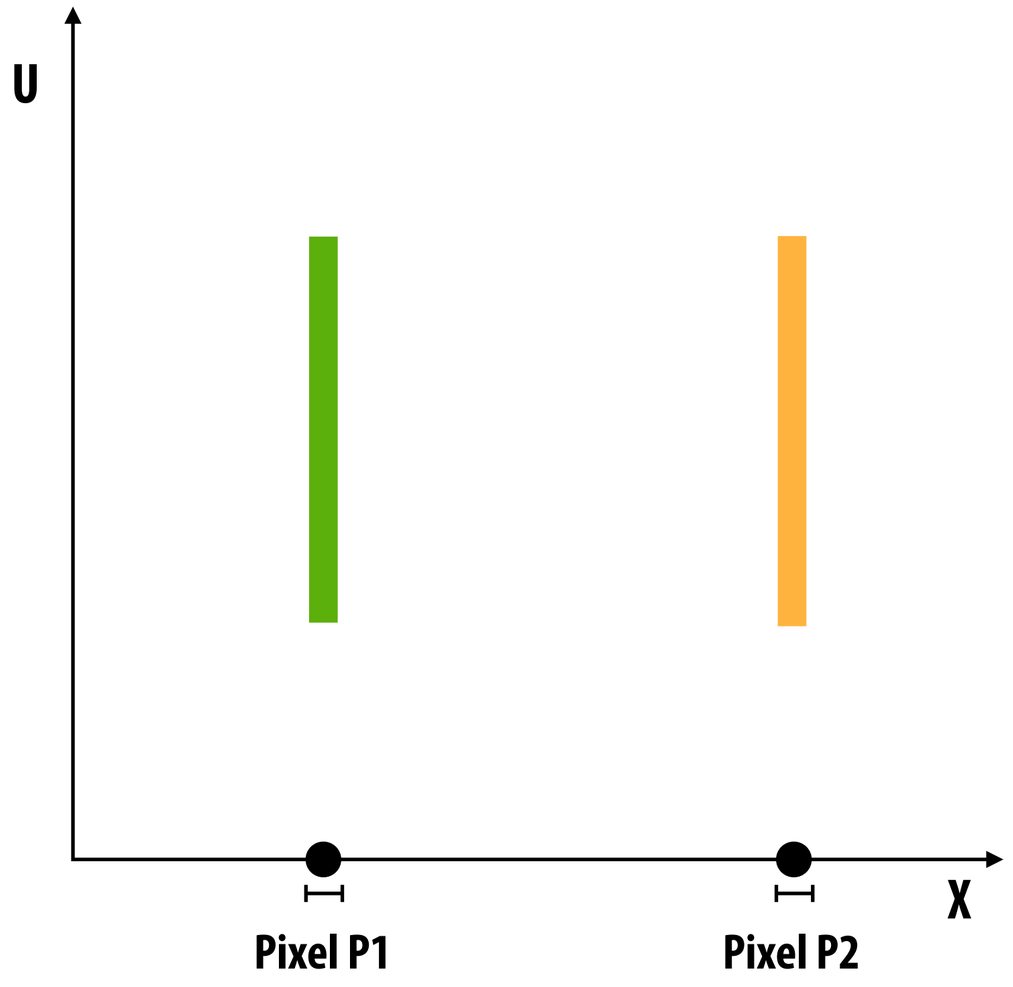

## Ray space plot
## (only showing X-U 2D projection)



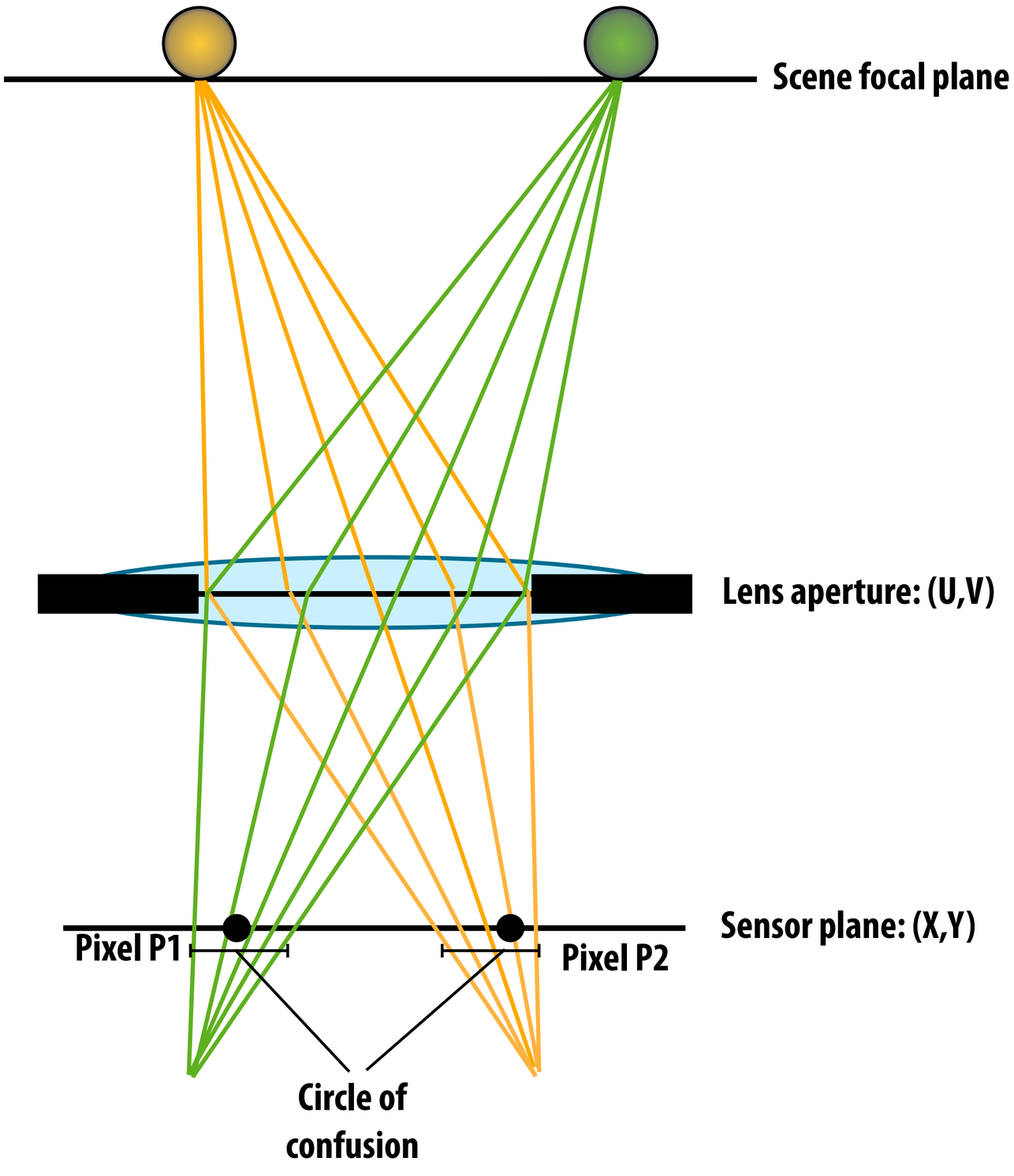
# Decrease aperture size



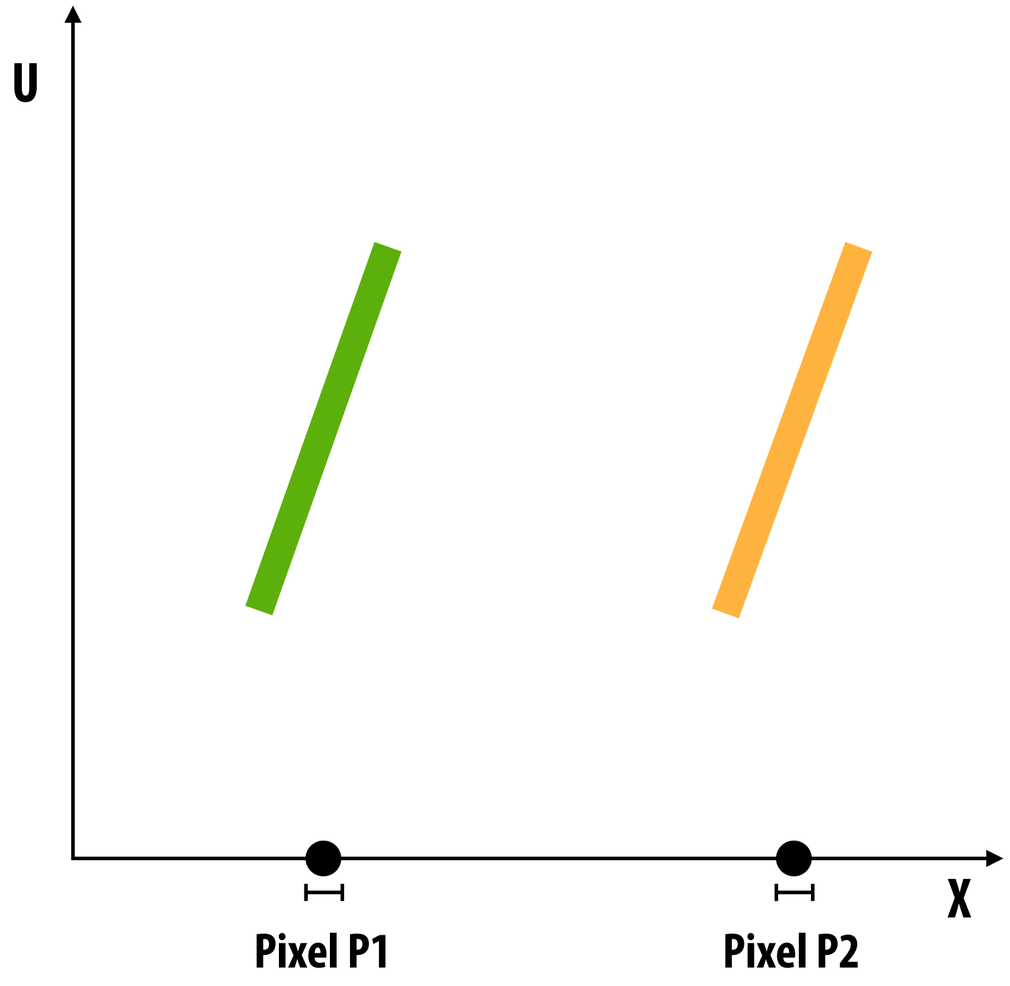

## Ray space plot



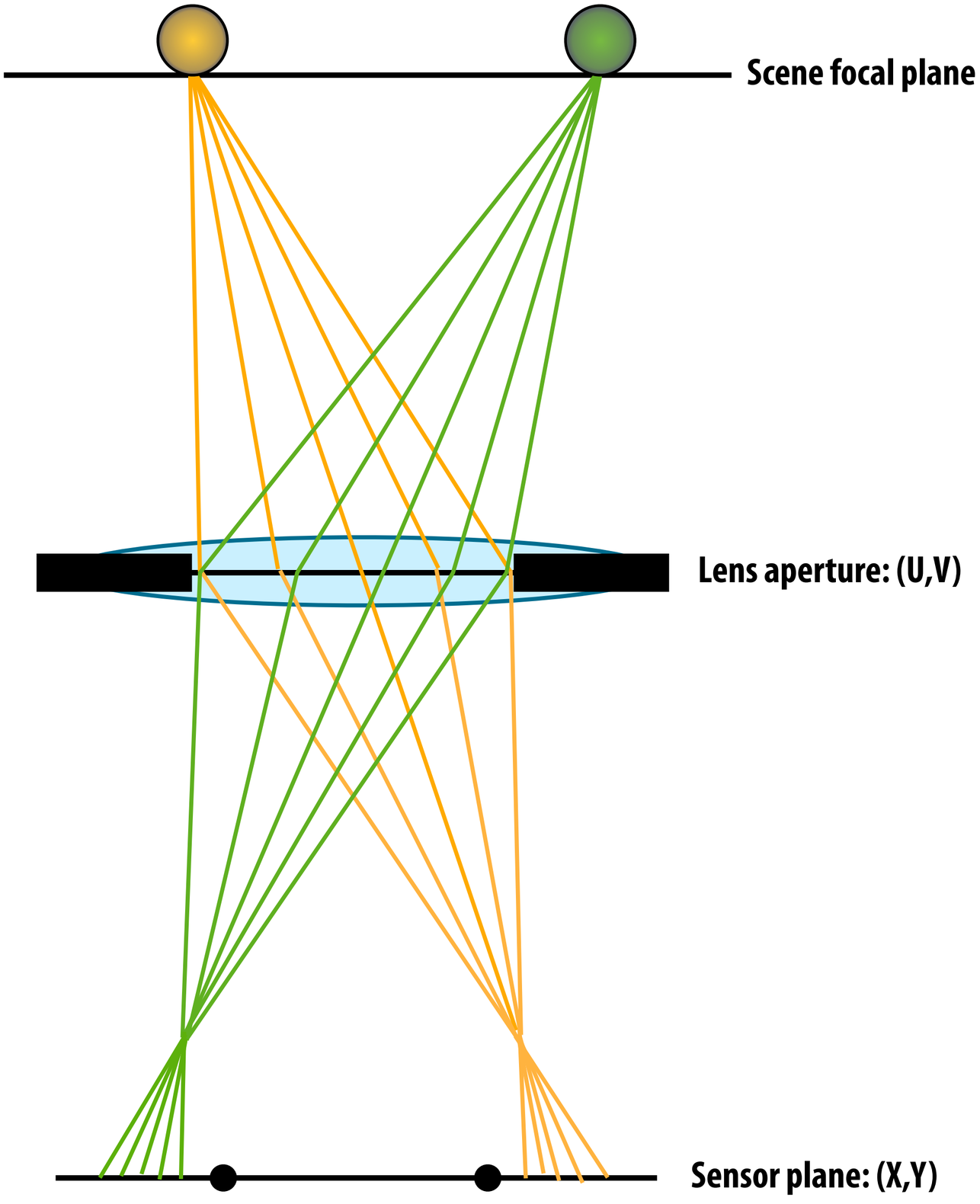
# Defocus



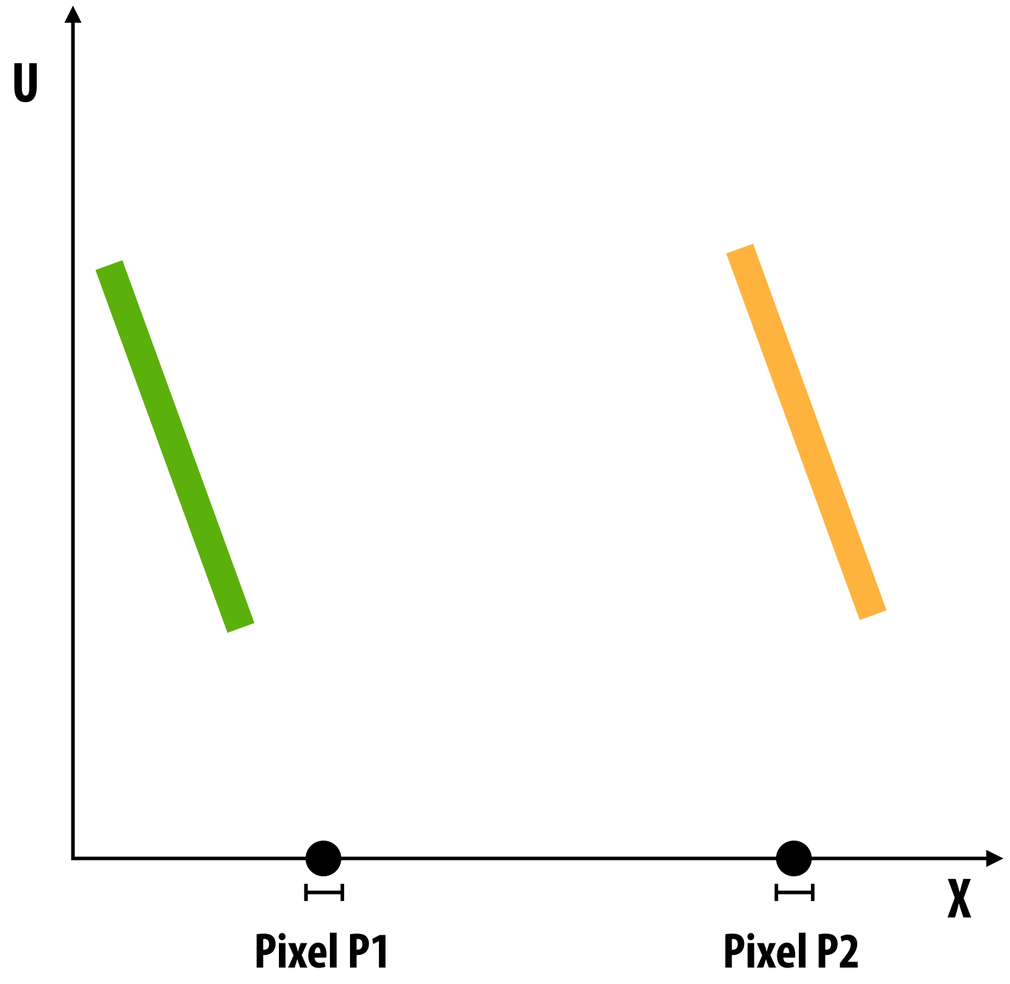

## Ray space plot



# Defocus




## Ray space plot



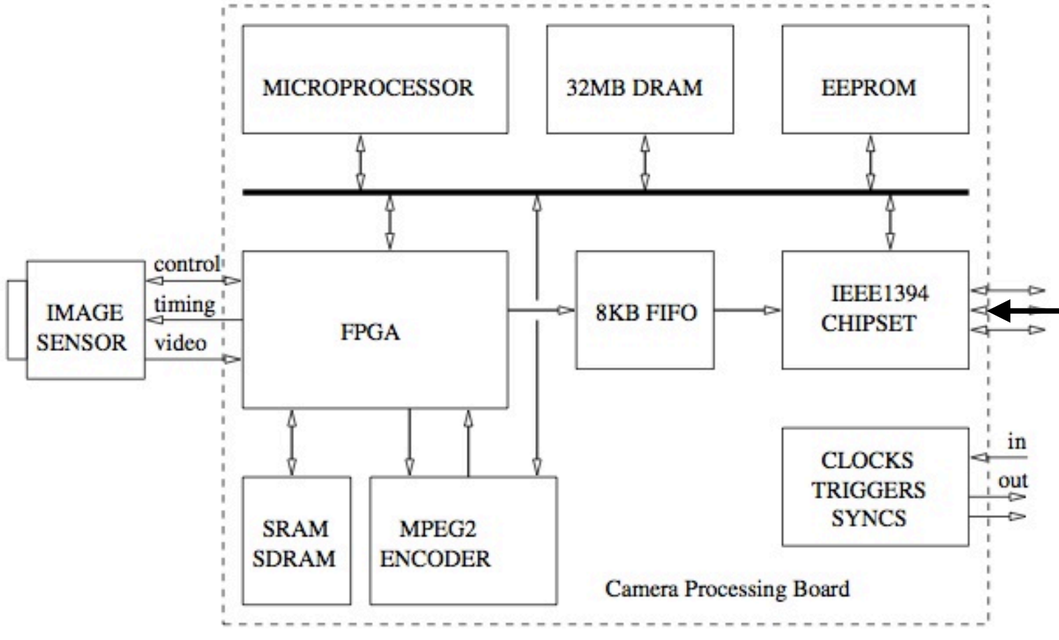
# Stanford Camera Array

Wilburn et al. 2005

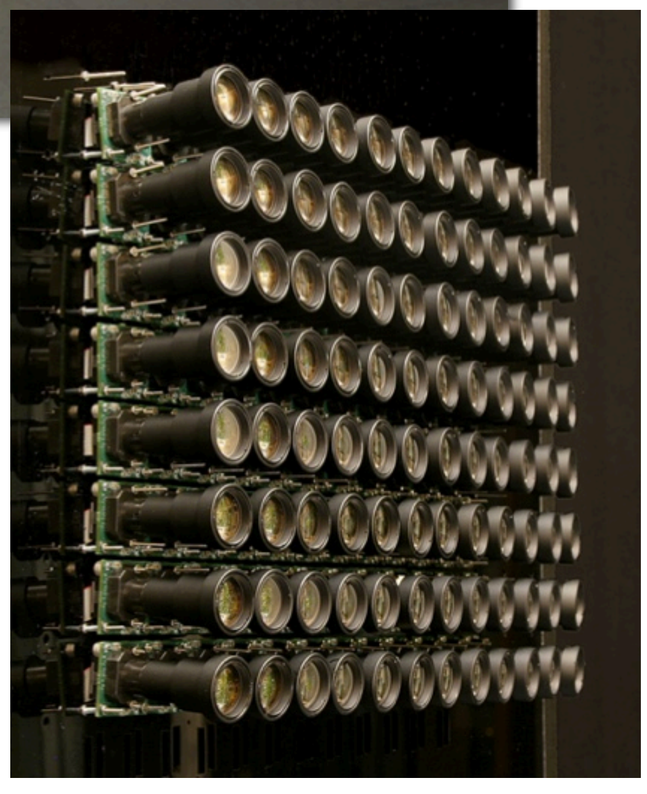
640 x 480 tightly synchronized, repositionable cameras

Custom processing board per camera

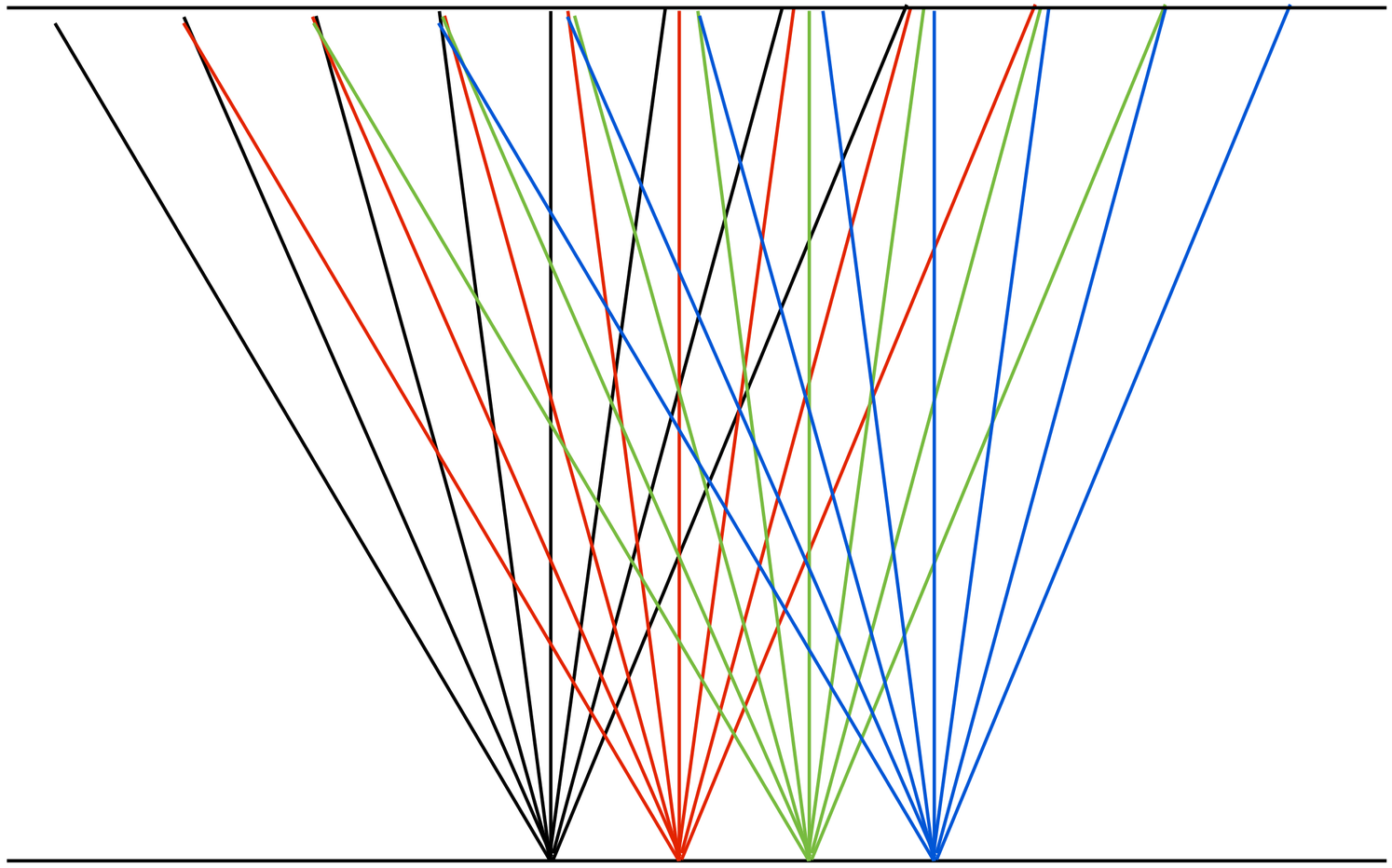
Tethered to PCs for additional processing/storage




Host PC with disk array



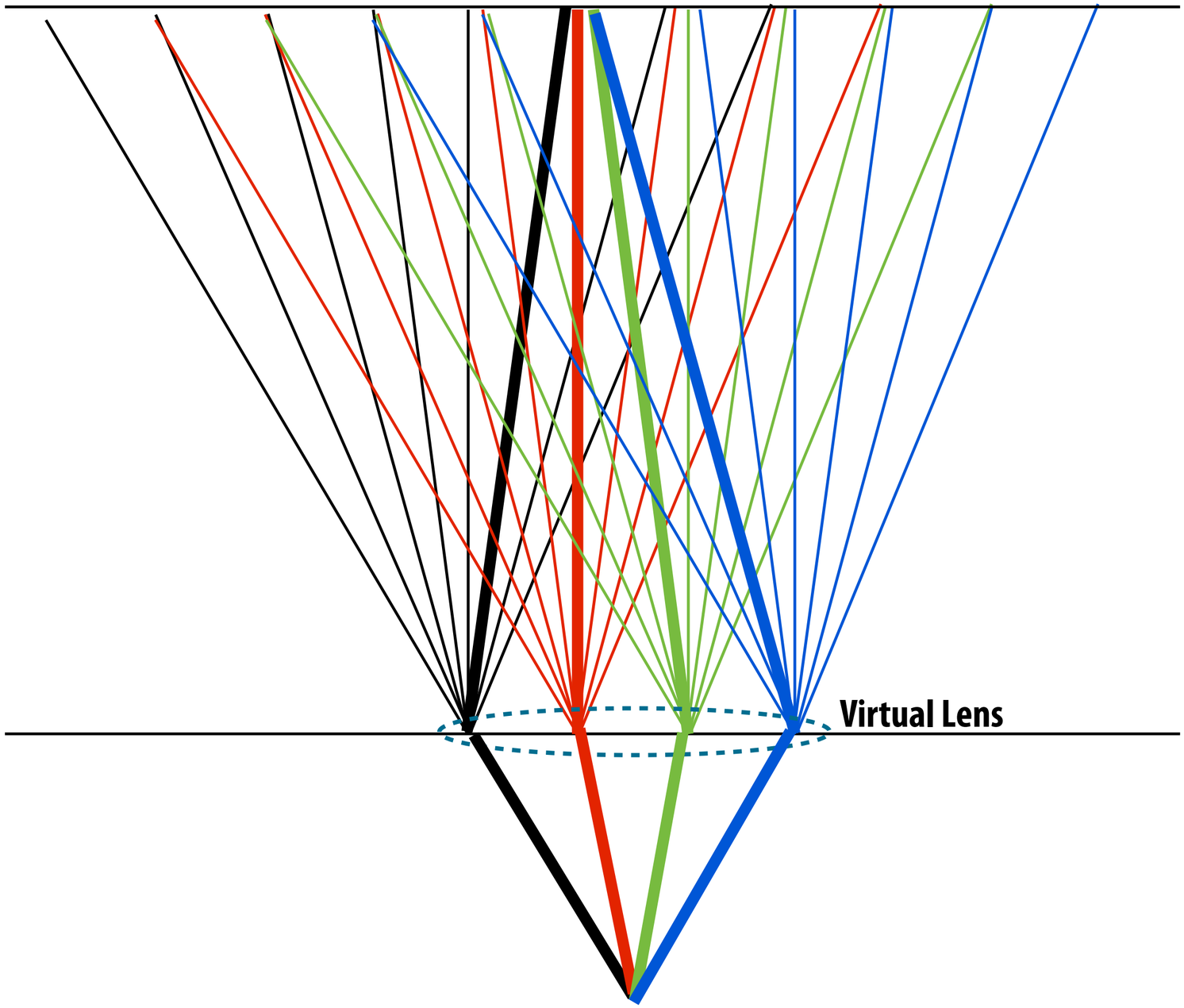
# Capturing a light field



# Synthetic aperture

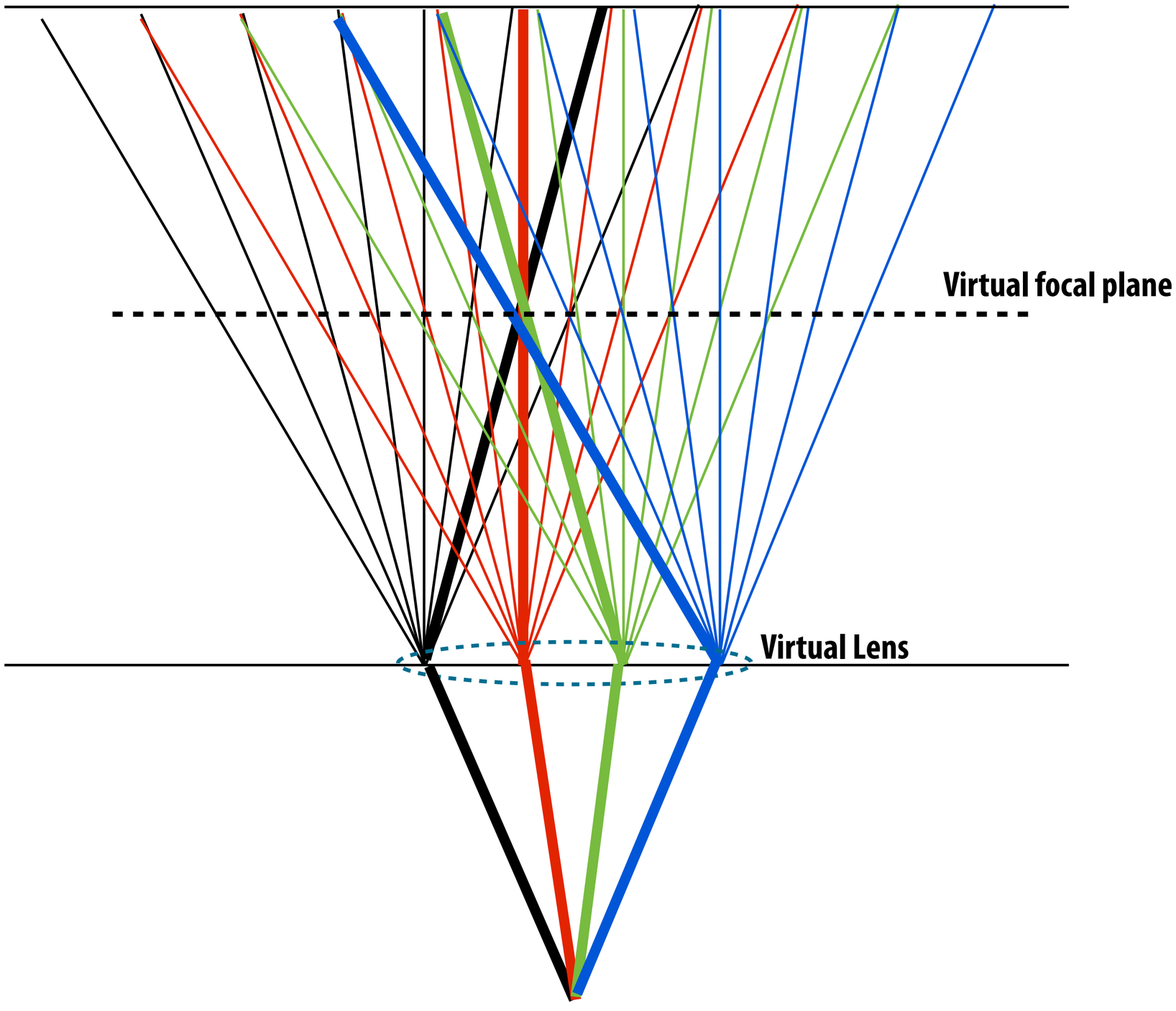
**Simulate image formation by virtual camera with large aperture**

**Shift and add images**



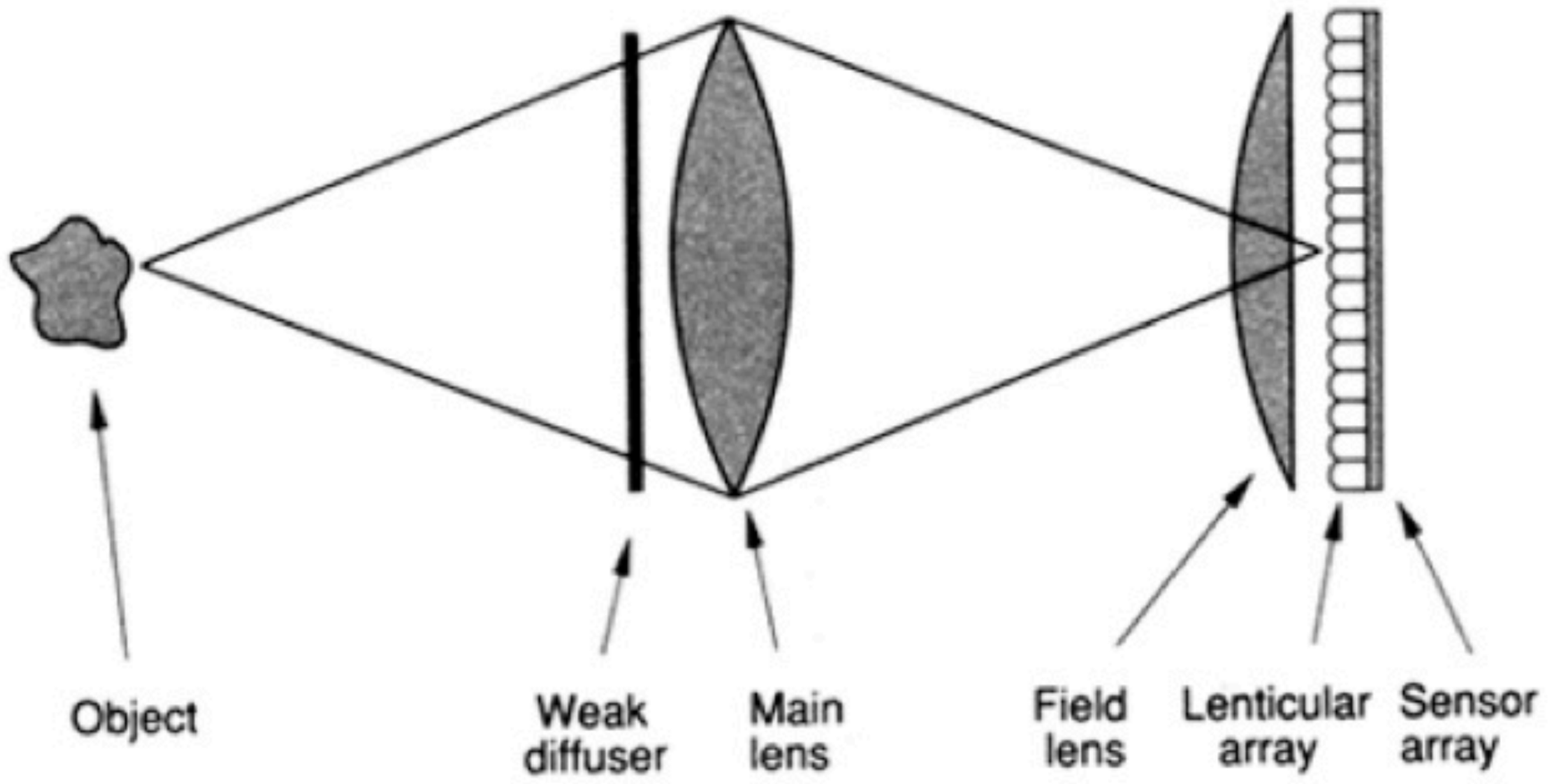
Wilburn et al. 2005

# Refocused synthetic aperture image

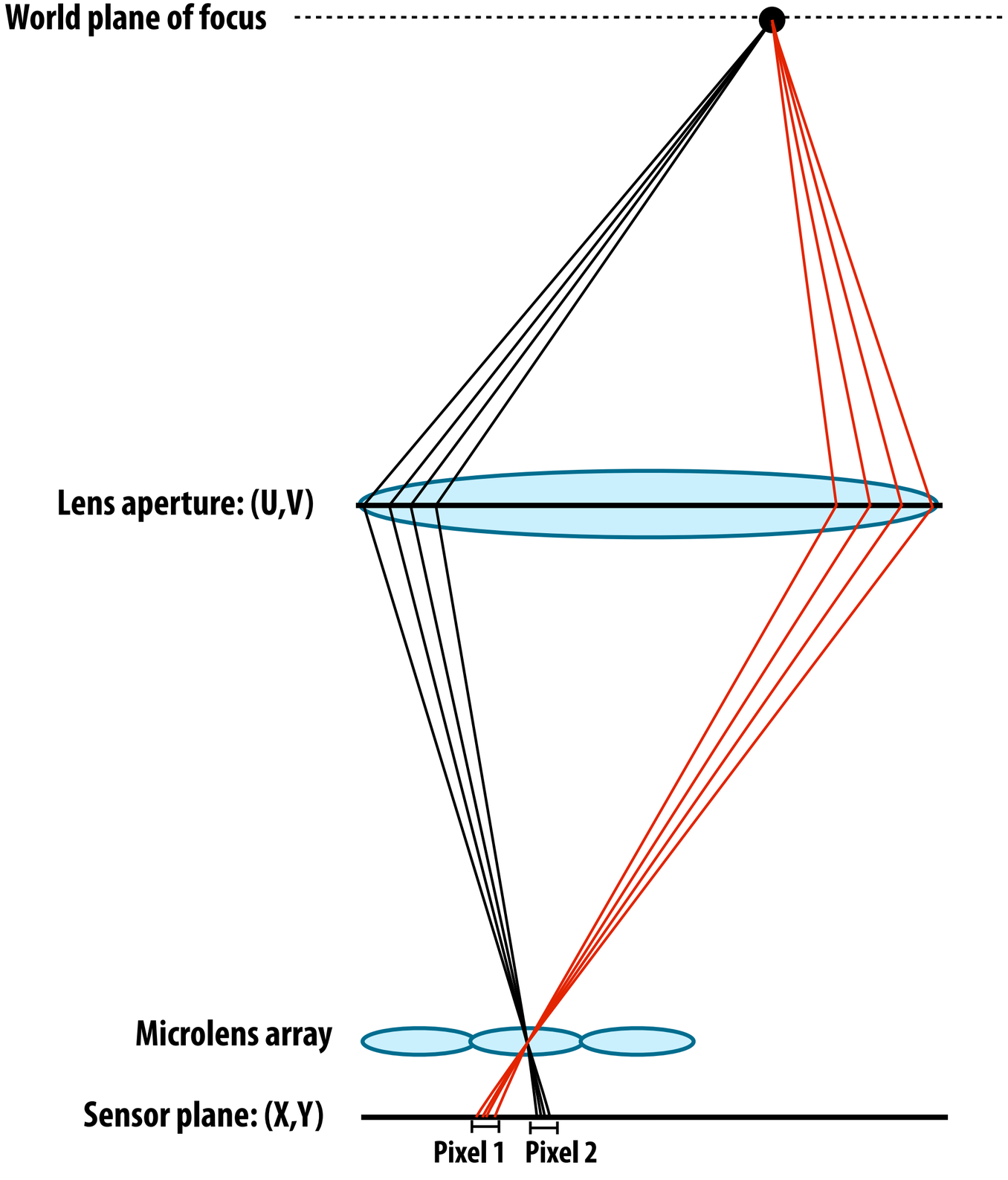


# Plenoptic camera [Adelson and Wang, 1992]

## Measure plenoptic function for single lens stereo applications

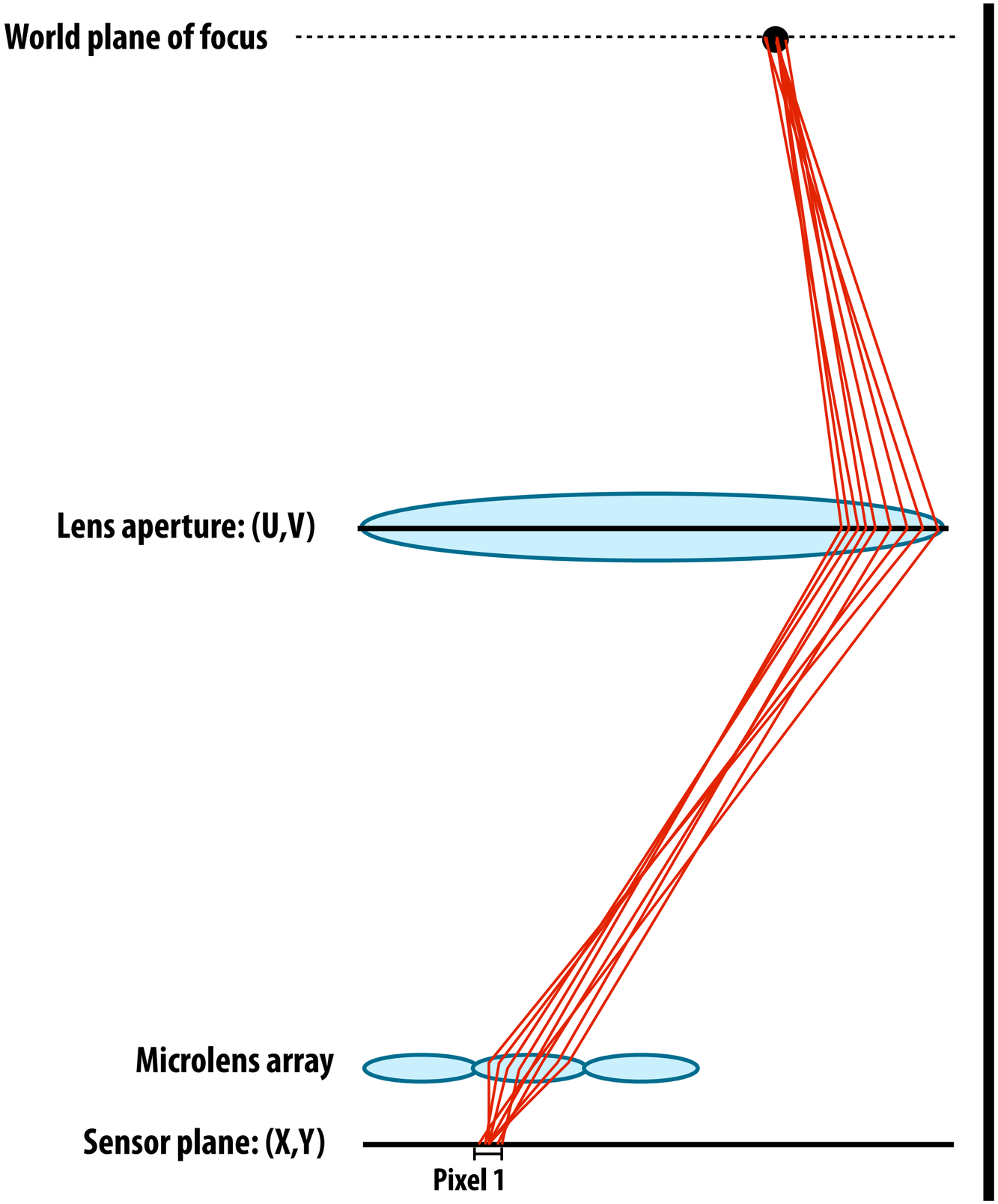


# Handheld light field camera

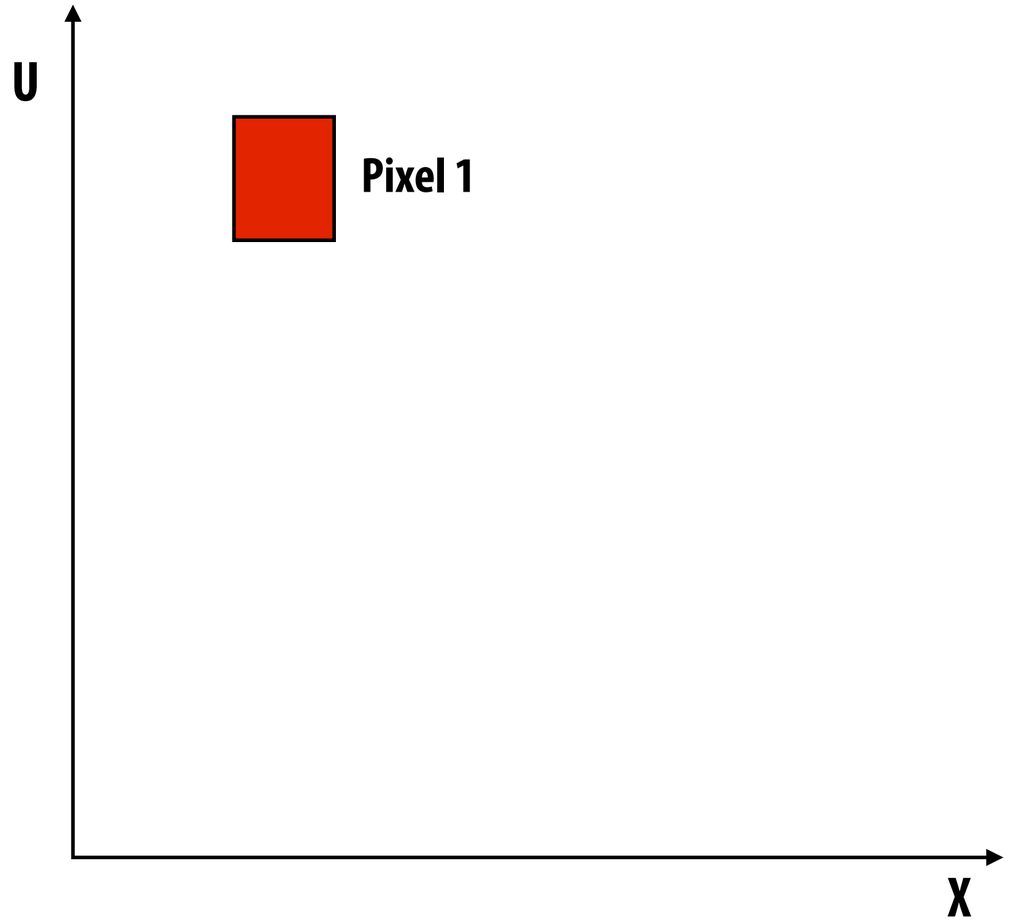


Ng et al. 2005

# Each sensor pixel records a beam of light




Ray space plot



# Captured light field

16 MP sensor
296 x 296 micolens array
12 x 12 pixels per microlens

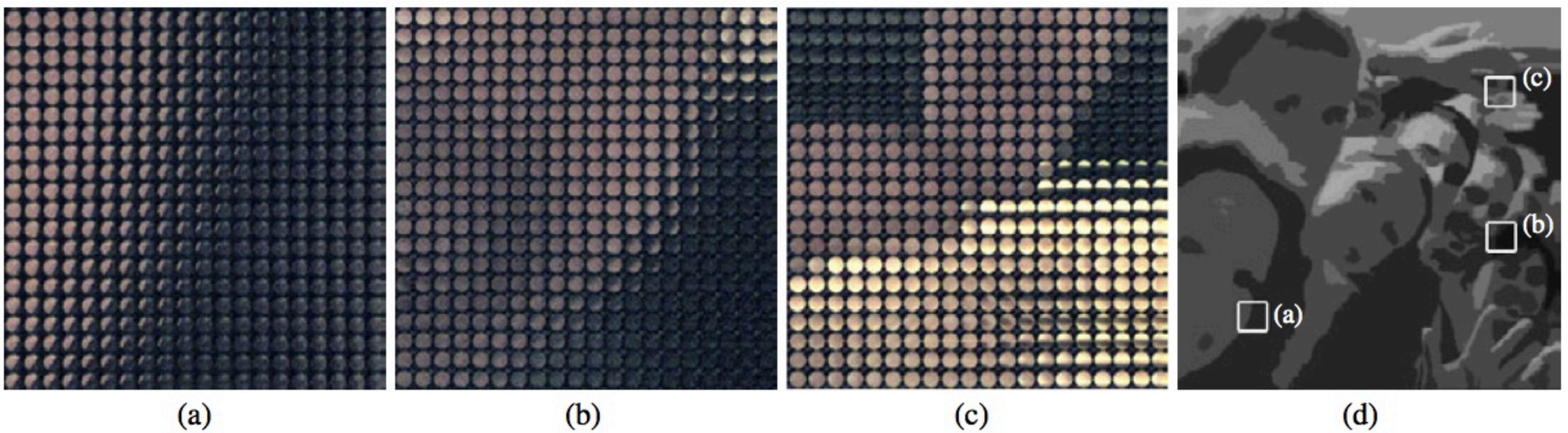
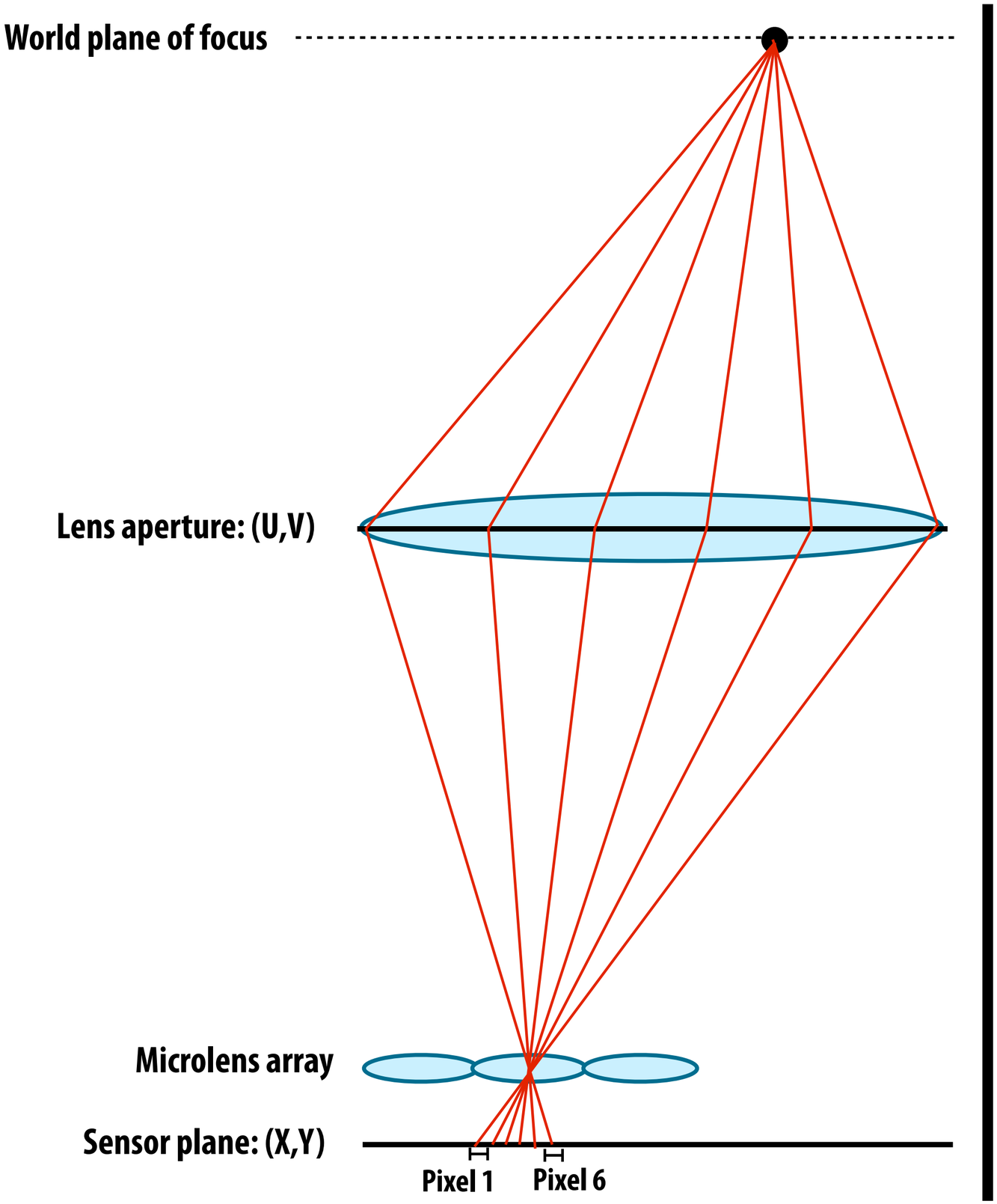
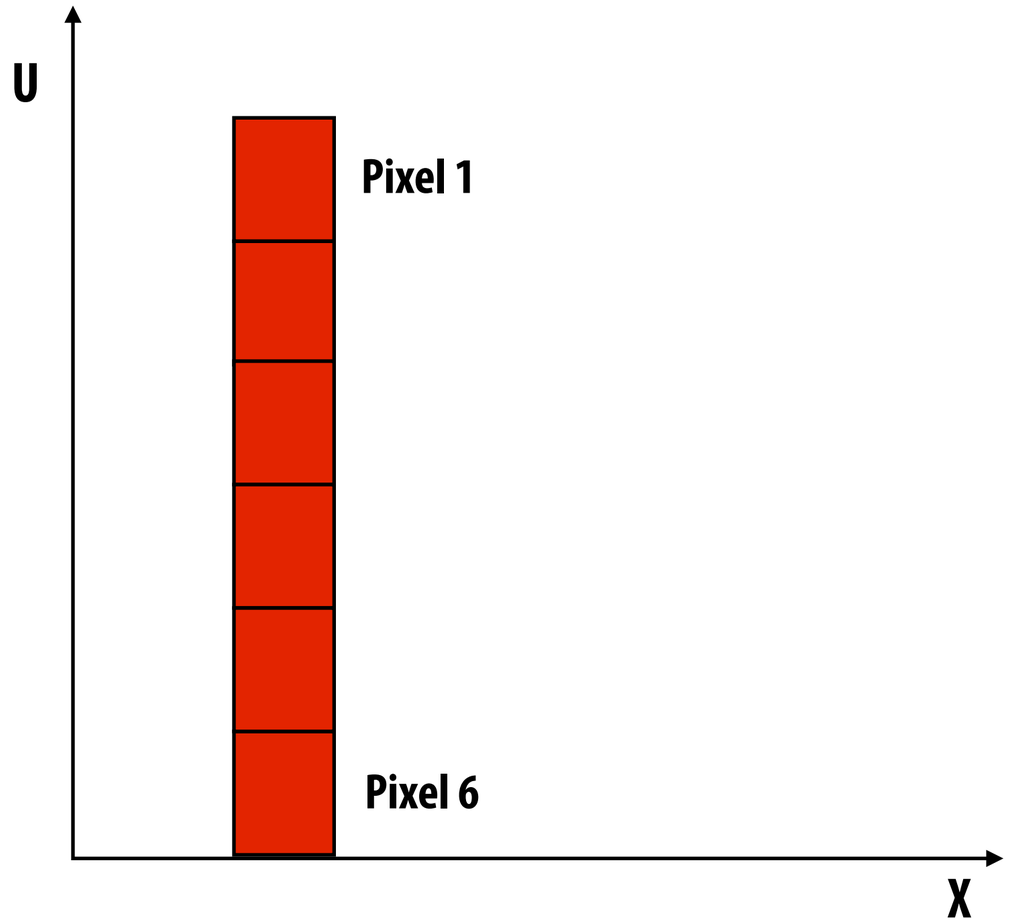



Image: Ng et al. 2006

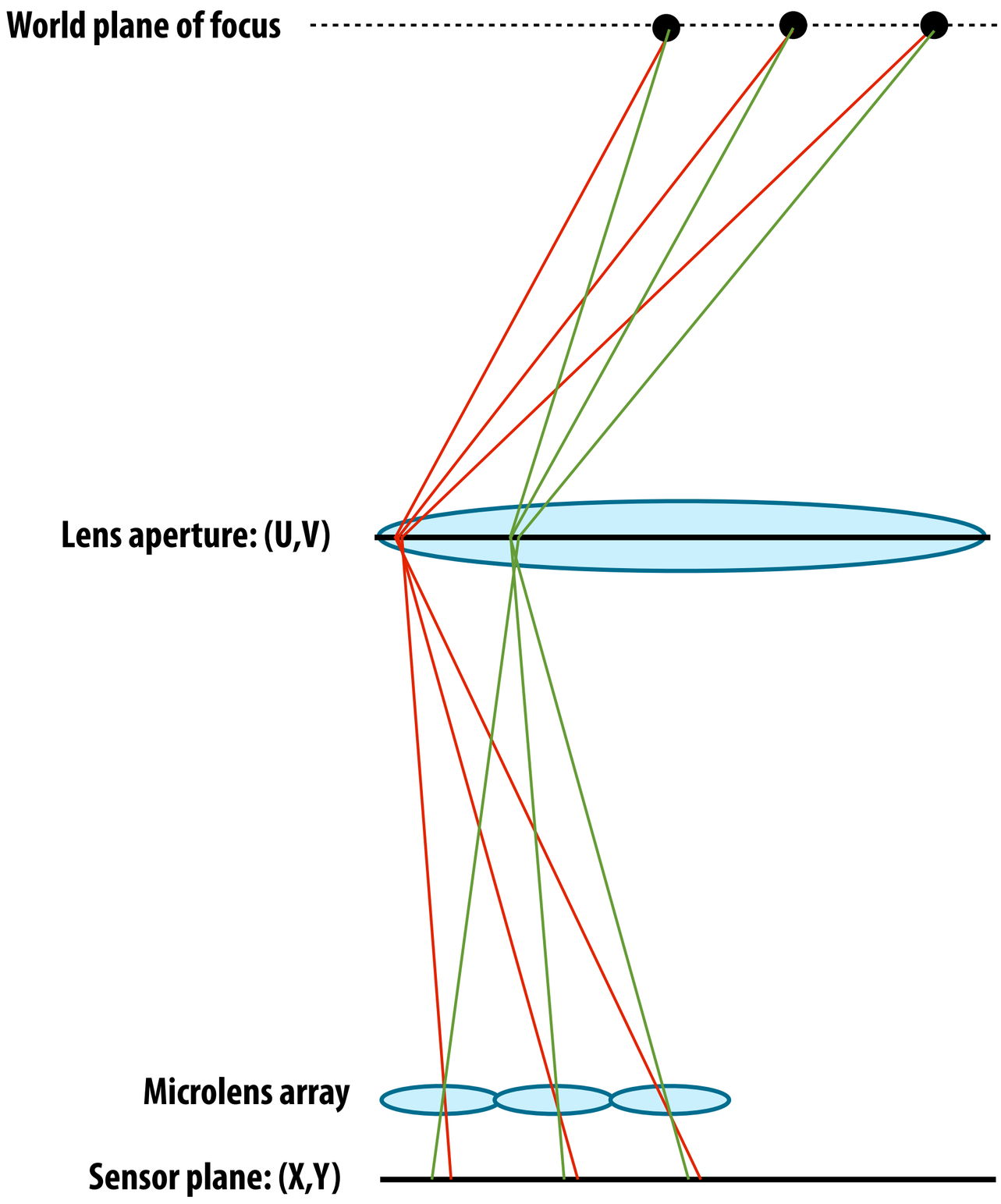
# Computing a photograph




## Ray space plot

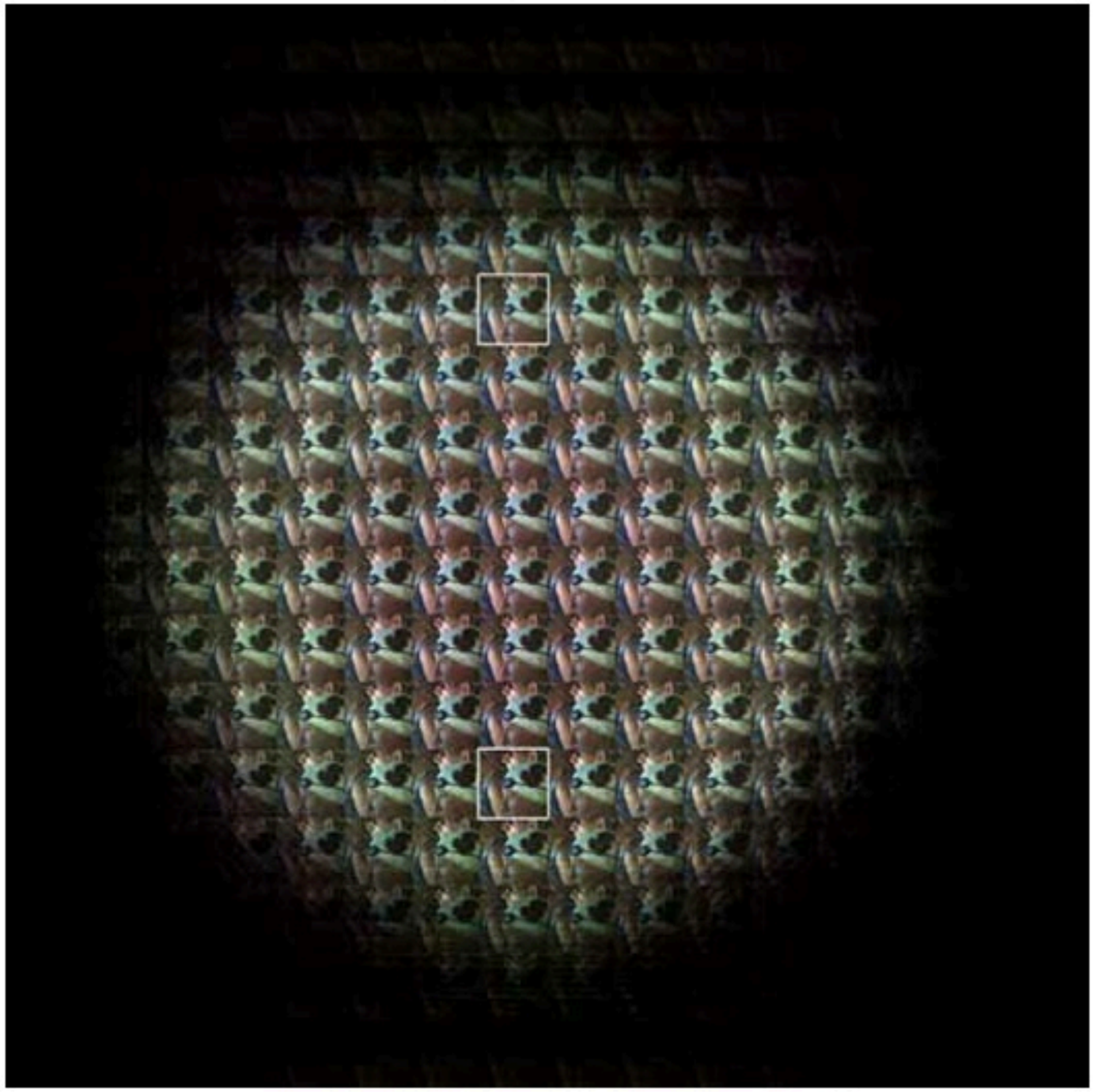


# Sub-aperture image

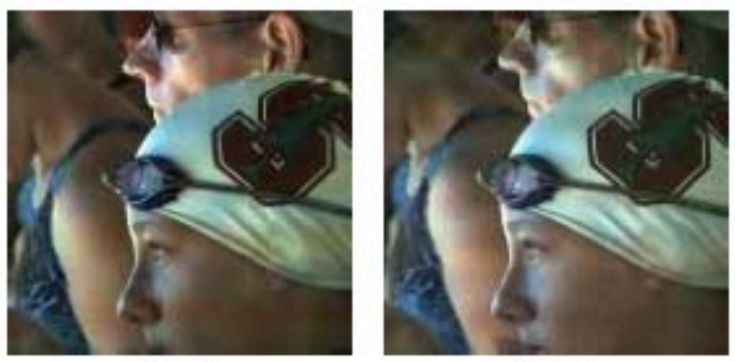


# Sub-aperture images

**Each image displays light incident on sensor from a small region of aperture**



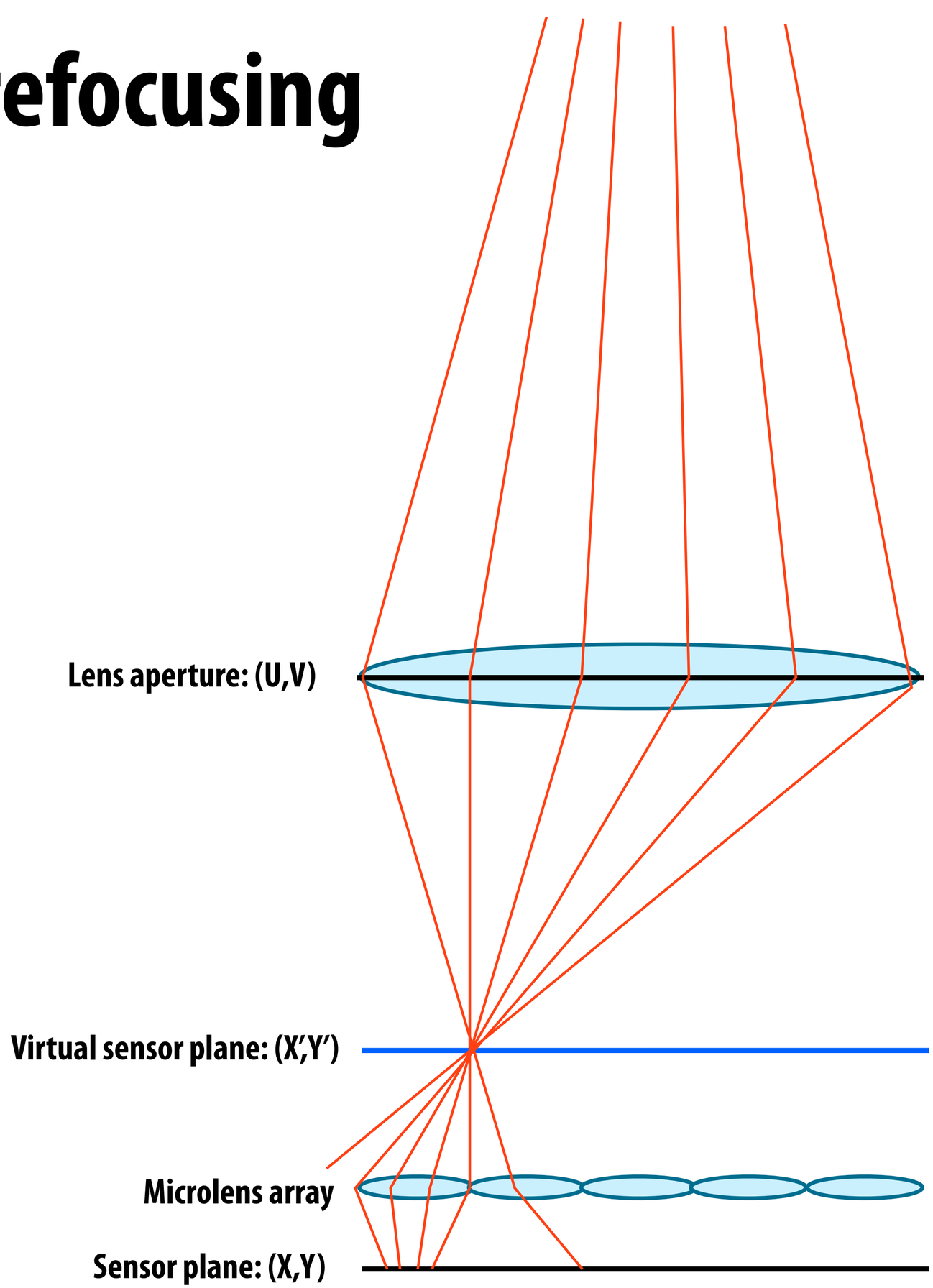
**Note slight shift in perspective**



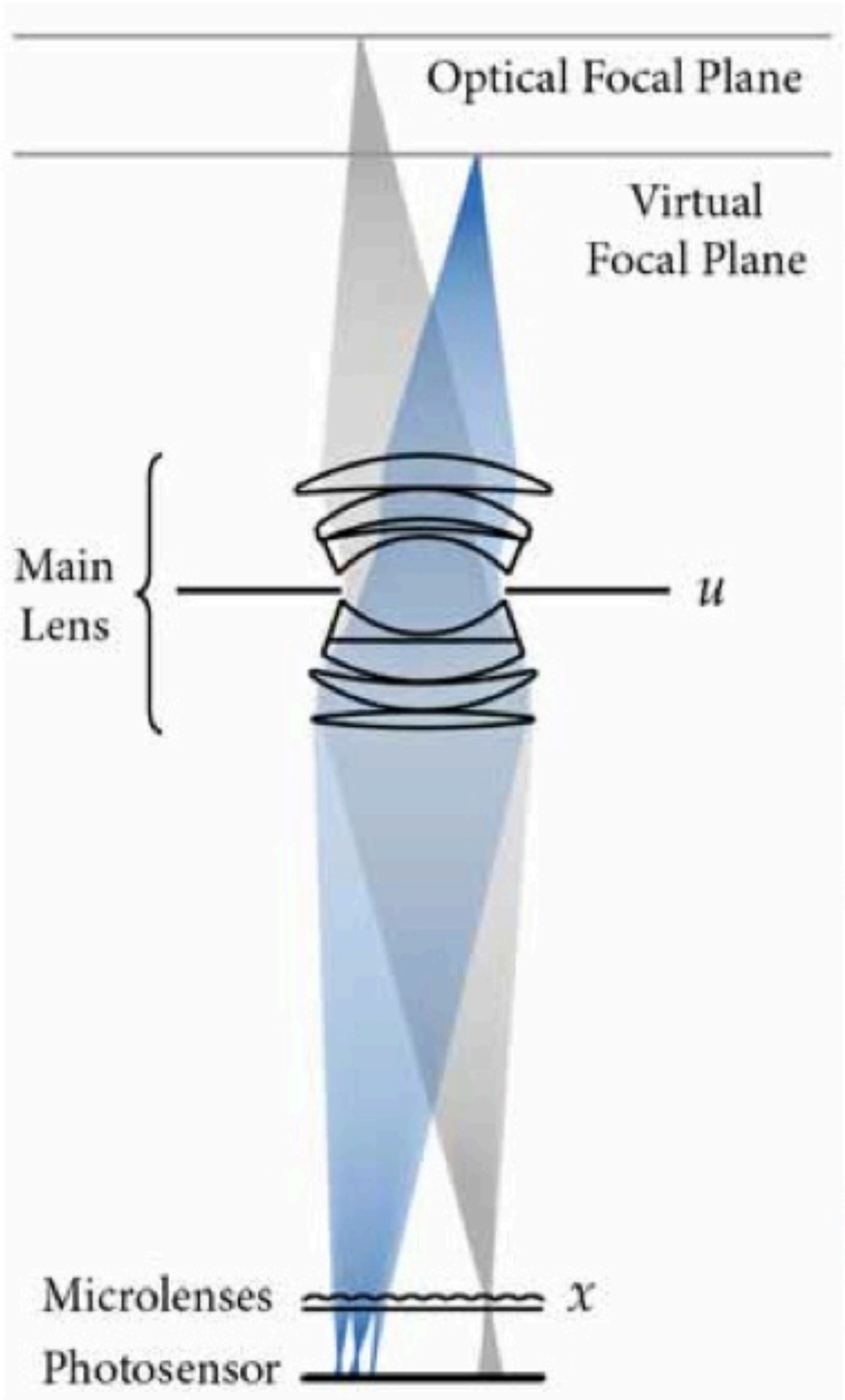
(z1) (z2)

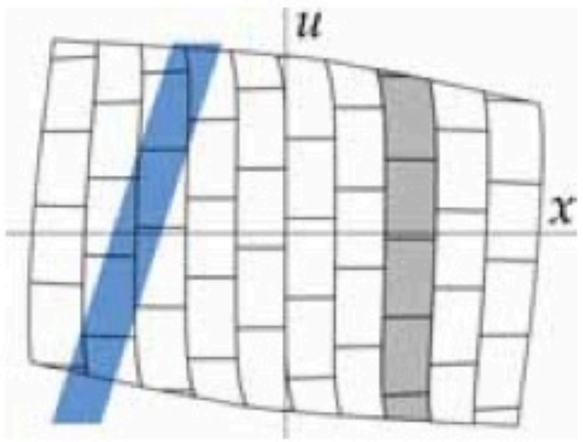
**Image: Ng et al. 2006**

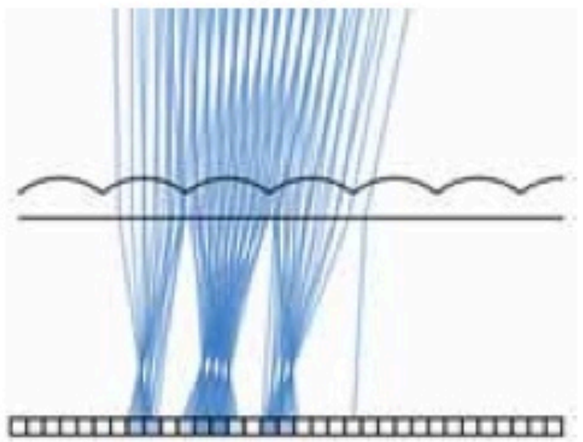
# Digital refocusing



# Digital refocusing



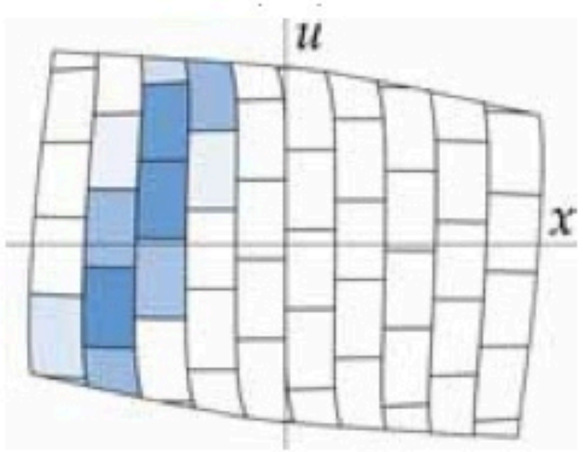
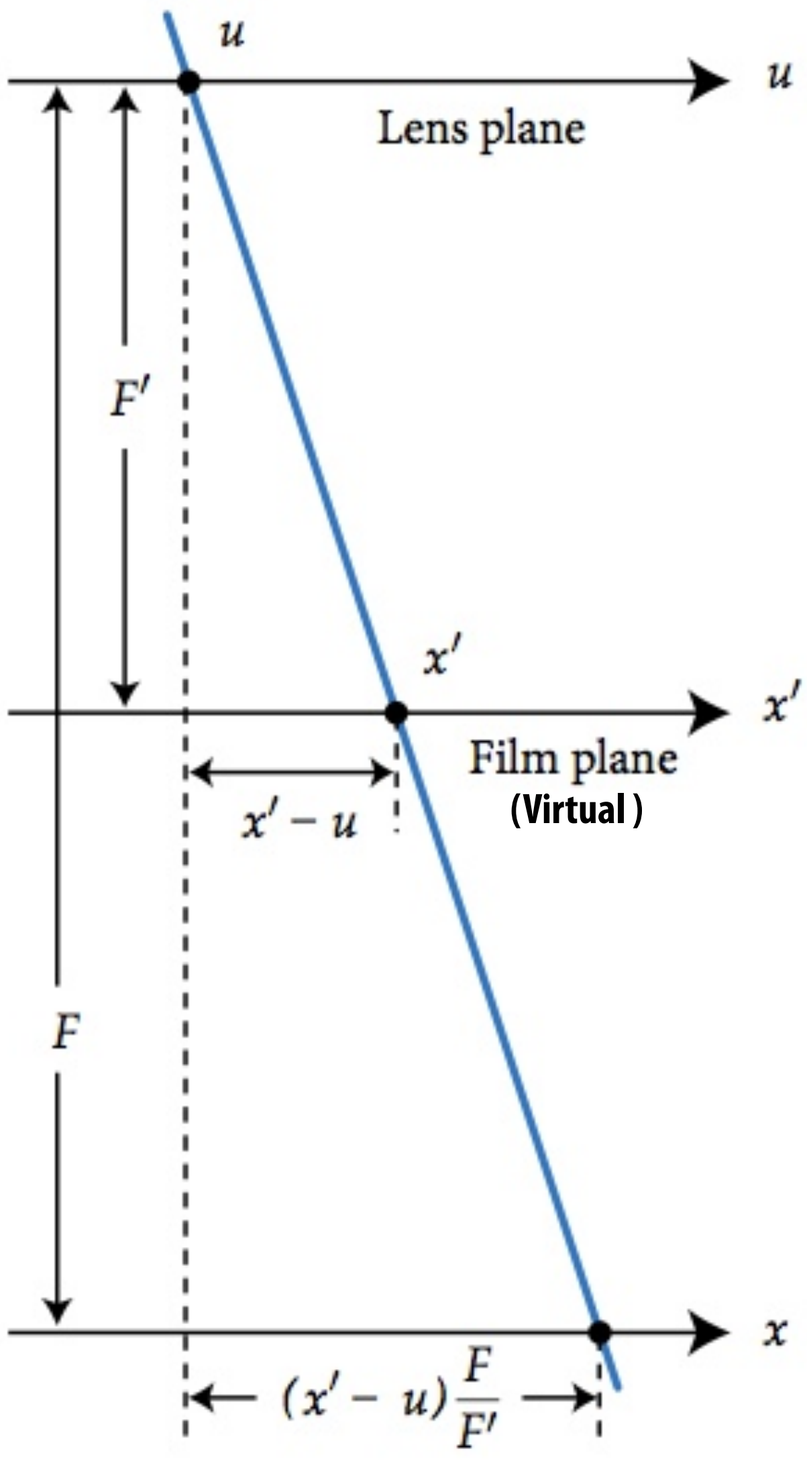



Image: Ng et al. 2006

# Reparameterization




F plane: plane of microlens array
F′ plane: virtual plane of focus

$L_F$ = light field parameterized by lens and F plane
$L_{F'}$ = light field parameterized by lens and F′ planes

Can define $L_{F'}$ using $L_F$

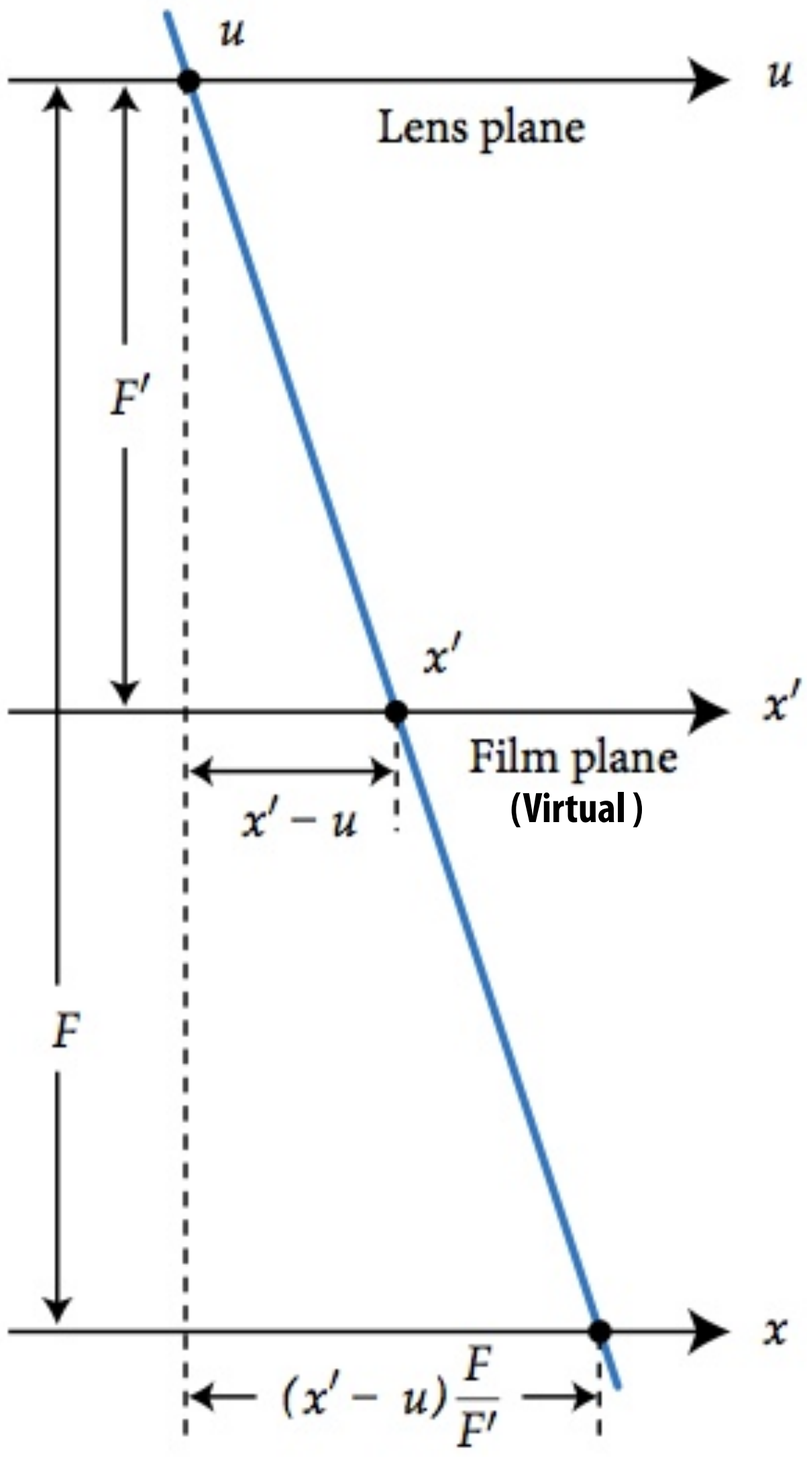
$$\alpha = F'/F$$

$$L_{F'}(x',y',u,v) = L_F\left(u + \frac{x'-u}{\alpha},\ v + \frac{y'-v}{\alpha},\ u,\ v\right)$$

$$= L_F\left(u\left(1-\frac{1}{\alpha}\right) + \frac{x'}{\alpha},\ v\left(1-\frac{1}{\alpha}\right) + \frac{y'}{\alpha},\ u,\ v\right)$$

Image: Ng et al. 2006

# Refocused photograph




**Integrate all light arriving at point (x′,y′) on F′ plane**

$$E_{(\alpha \cdot F)}(x', y') = \frac{1}{\alpha^2 F^2} \iint L_F \left(u(1-1/\alpha) + x'/\alpha,\ v(1-1/\alpha) + y'/\alpha,\ u,\ v\right) du\, dv$$

**Define $L_F^{(u,v)}$ to be sub-aperture image from lens region (u,v)**

$$E_{(\alpha \cdot F)}(x', y') = \frac{1}{\alpha^2 F^2} \iint L_F^{(u,v)} \left(u(1-1/\alpha) + x'/\alpha,\ v(1-1/\alpha) + y'/\alpha\right) du\, dv$$

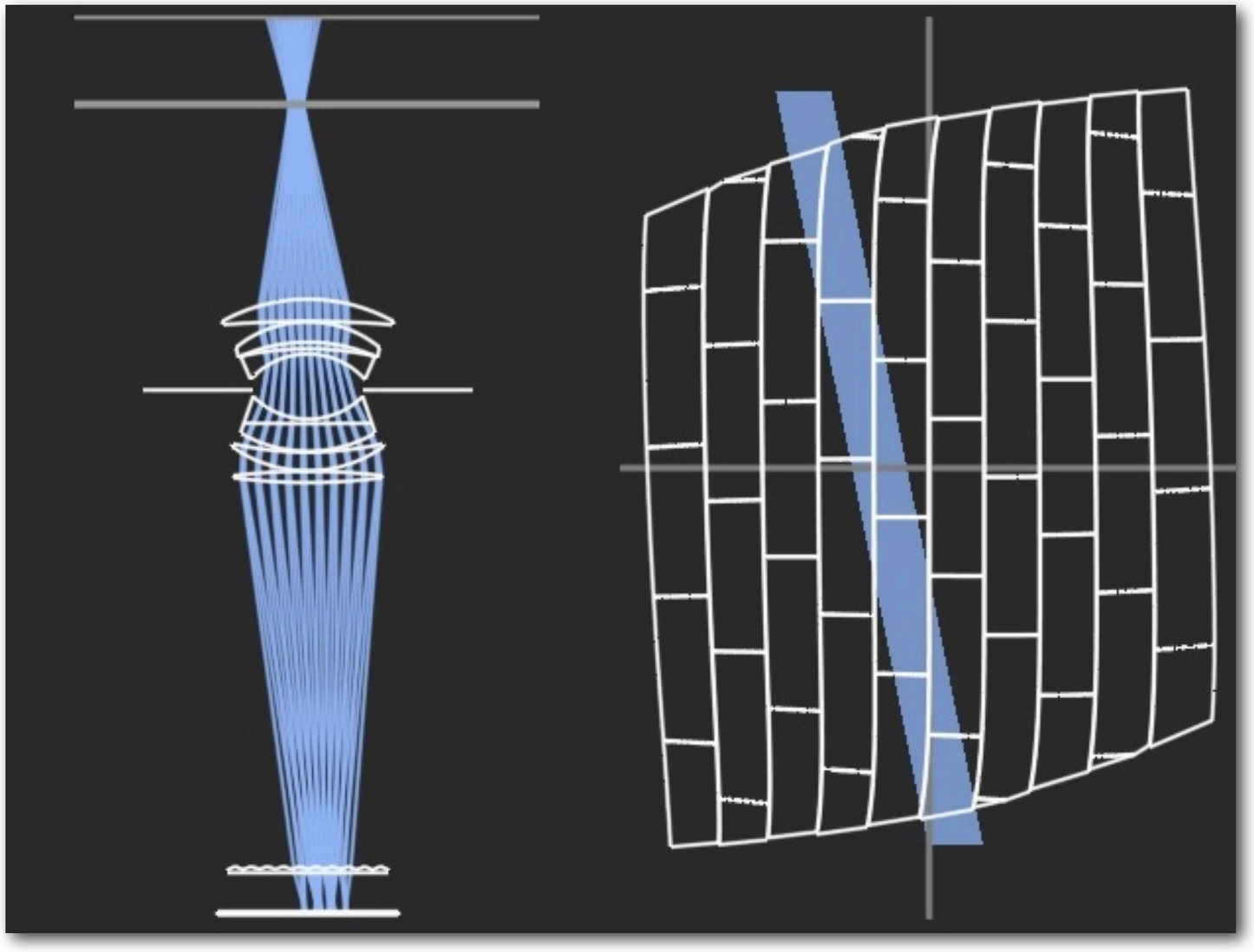
**Sum of shifted, scaled sub-aperture images**

**Scale image by $\alpha$ an ignore, invariant of lens position)**

**Shift image by ( $u(1-1/\alpha)$, $v(1-1/\alpha)$)**

**Image: Ng et al. 2006**

# Video



# Potential advantages of light-field cameras

## (For traditional photography)

- Remove (or significantly simplify) auto-focus
  - Diminished shutter lag
- Better low-light shooting
  - Shoot with aperture wide open (traditional camera has shallow depth of field = high possibility of misfocus)
    - Can digitally refocus after the shot
    - Can digitally extend depth of field
- New lens form factors, capabilities
  - Correct for aberrations digitally

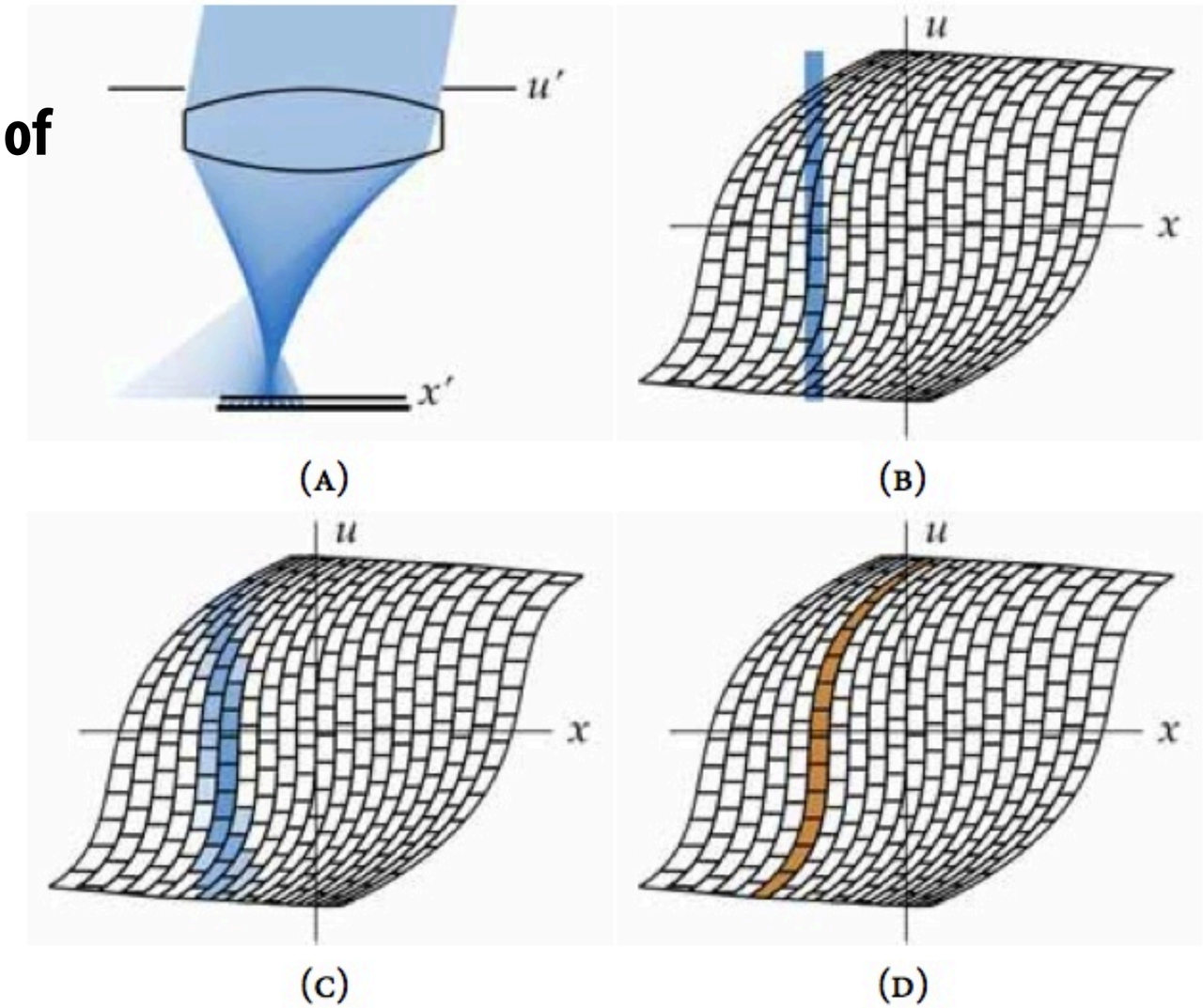



Image: Ng et al. 2006

# New photography applications

- Interactive pictures (single shot captures information that can be used to generate many different pictures)
  - Digital (post shot) refocusing
  - Parallax
- Stereo images
- Extended depth of field (put entire image in focus)

# Lytro light field camera

**11 megapixel (“megaray”) sensor**

**F/2 8x zoom lens**

# More computational cameras

Pelican Imaging

Raytrix Plenoptic Camera

# Computational challenges?

- What are computational challenges of light field photography?

# Trends

- No free lunch: measure directional information at cost of spatial resolution
  - Ng's original prototype: 16 MP sensor, but output 300x300 images
  - 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
  - Recall: few motivations high-pixel-count sensors for traditional cameras today

- High resolution cameras introduce computational challenges
  - Processing challenges
  - Storage challenges
  - Data transfer challenges

# Modern photography: capture-process-communicate

**Where to perform computation?**

**What representation to transmit? Full light field? Single image?**

**Future consumer light field camera ~ 50-100 MP**

**Cloud Storage/ Processing**

**Personal Computer**

# Summary

- Light field photography
  - From user's perspective, very much like traditional photography
  - Main idea: capture light field in a single exposure
  - Perform (large amounts of) computation to compute desired final image