Coded Computational Imaging: Light Fields and Applications

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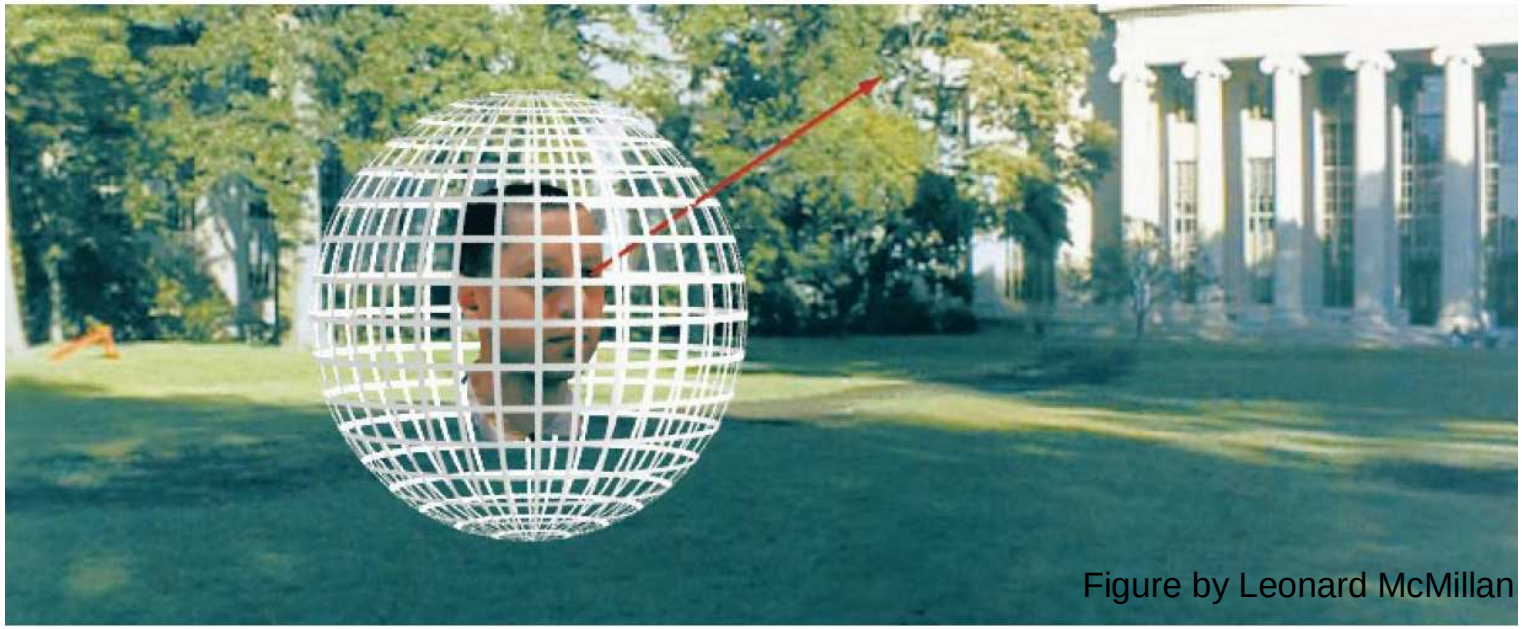
Schedule

Introduction	Srinivasa, 10 mins
Assorted Pixels	Srinivasa, 20 mins
Coding and Modulation in Cameras	Amit, 45 mins
Break	10 min
Light Fields and Applications	Ankit, 60 mins
Break	10 min
Computational Illumination	Srinivasa, 45 mins
Future Trends	Amit, 15 mins
Discussion	

Light Field Basics

The Plenoptic Function



Q: What is the set of all things that we can ever see?
A: The Plenoptic Function [Adelson & Bergen]

Let's start with a stationary person and try to parameterize everything that she can see

Slide adapted from Michael Cohen and Rick Szeliski

Grayscale Snapshot

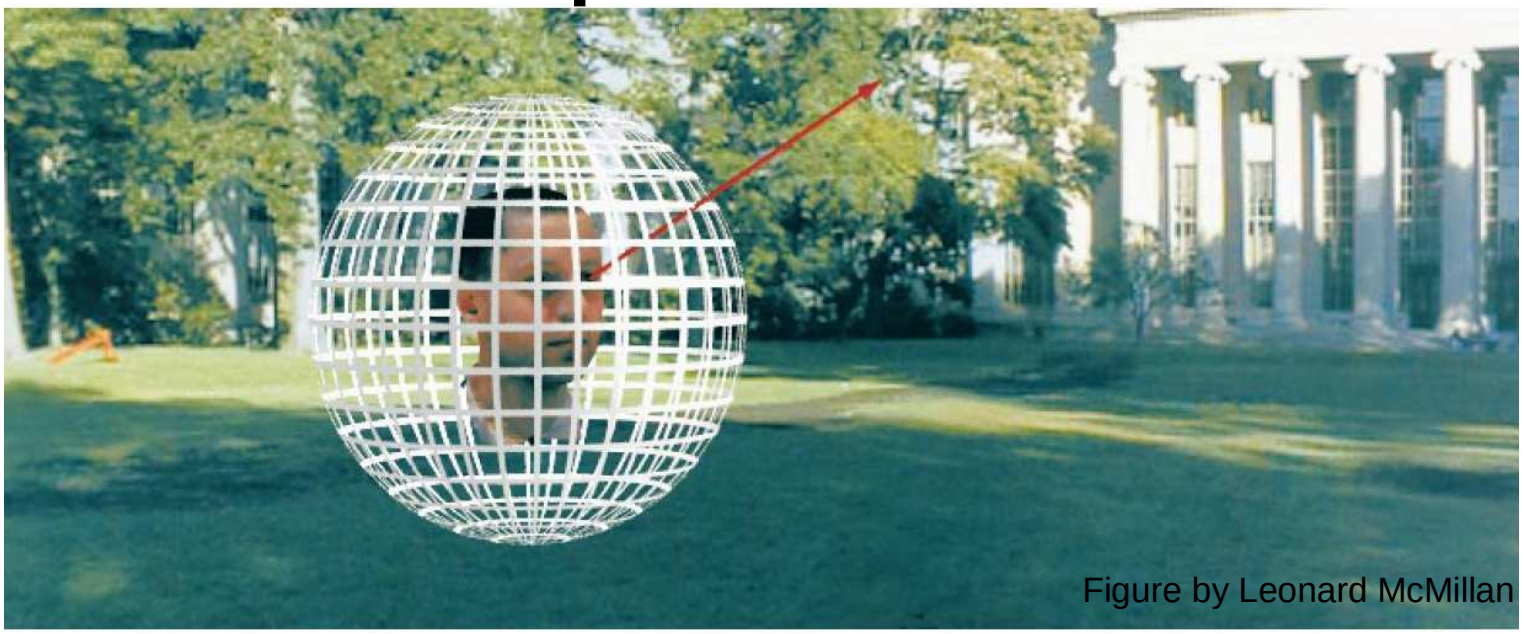
$$P(\theta,\phi)$$

is intensity of light

- Seen from a single view point
- At a single time
- Averaged over the wavelengths of the visible spectrum

Slide adapted from Michael Cohen and Rick Szeliski

Color Snapshot



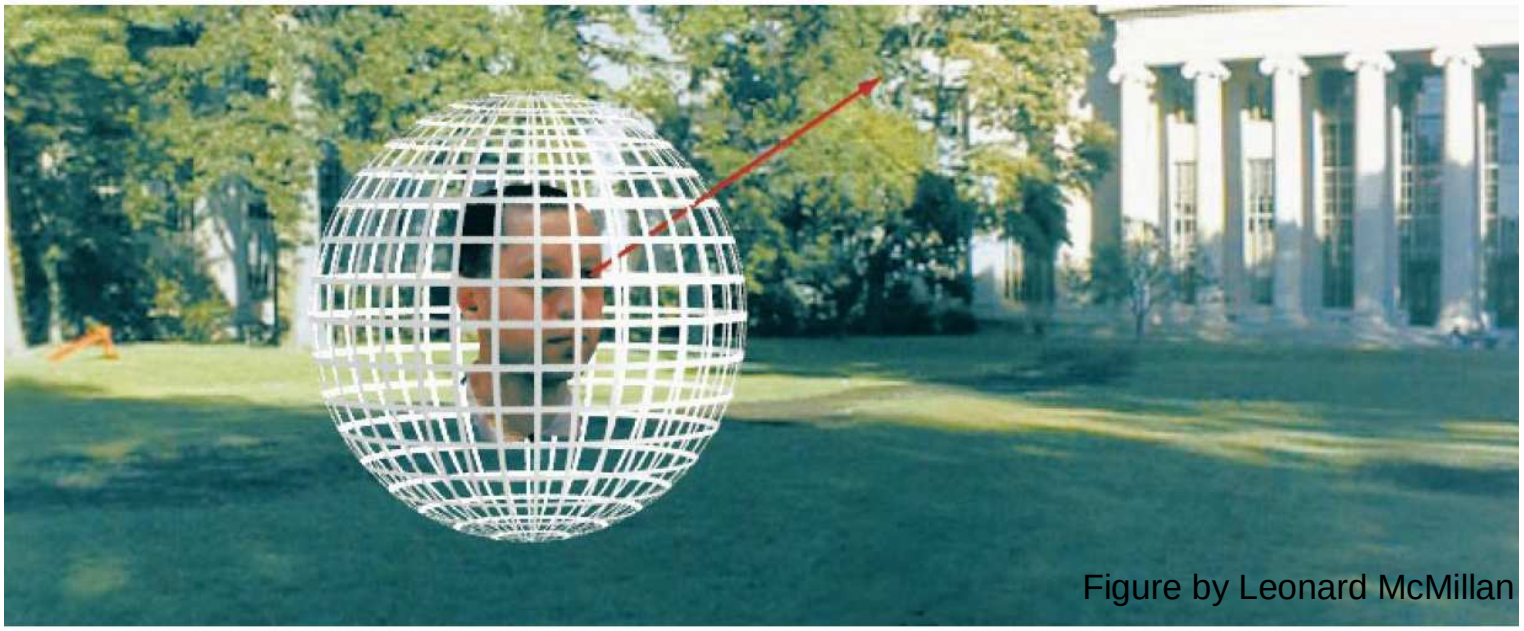
$$P(\theta,\phi,\lambda)$$

is intensity of light

- Seen from a single view point
- At a single time
- As a function of wavelength

Slide adapted from Michael Cohen and Rick Szeliski

A Movie



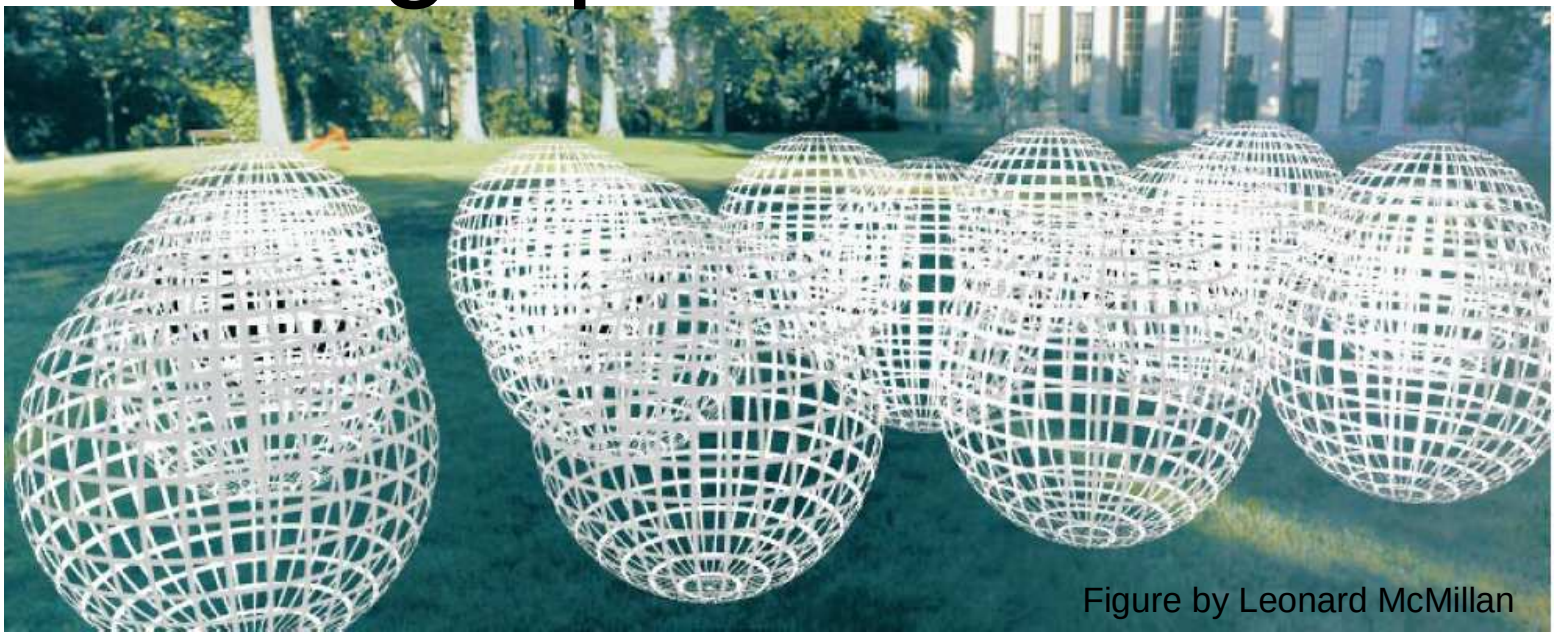
$$P(\theta,\phi,\lambda,t)$$

is intensity of light

- Seen from a single view point
- Over time
- As a function of wavelength

Slide adapted from Michael Cohen and Rick Szeliski

A Holographic Movie



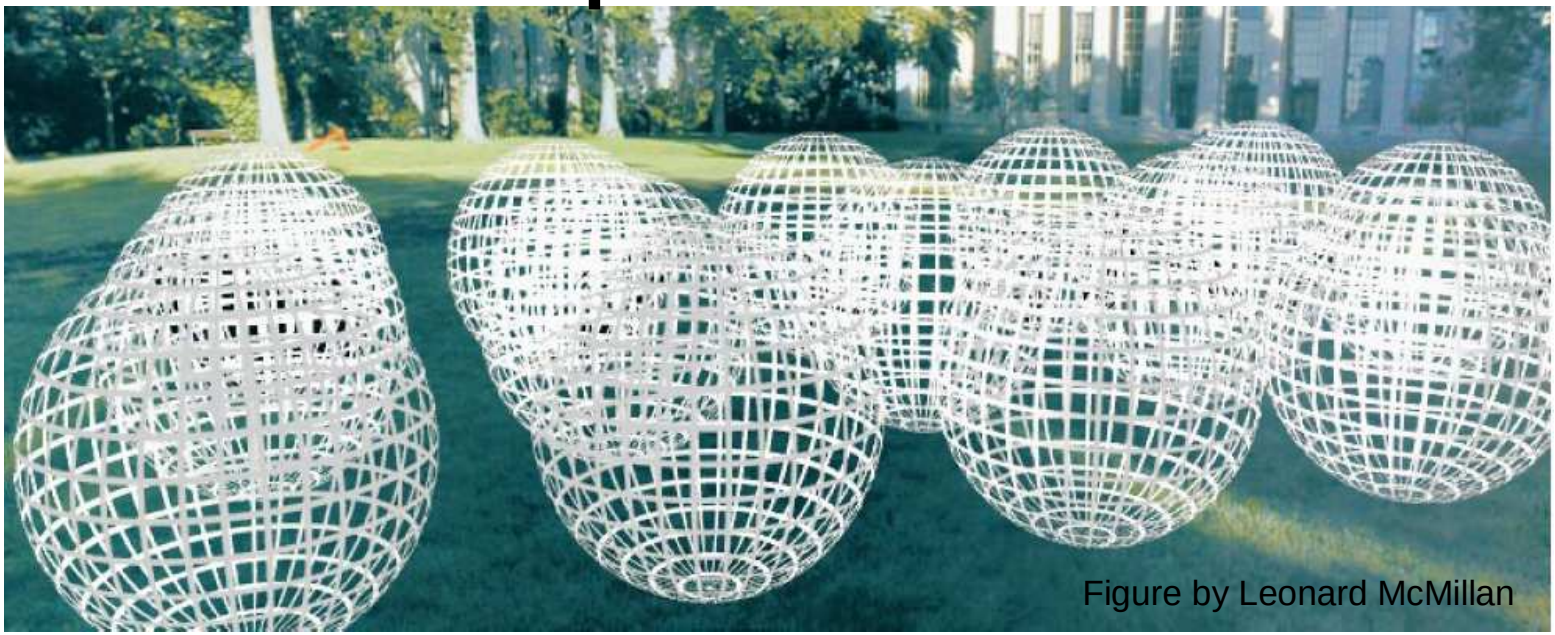
$$P(\theta,\phi,\lambda,,t,V_X,V_Y,V_Z)$$

is intensity of light

- seen from ANY viewpoint
- over time
- as a function of wavelength

Slide adapted from Michael Cohen and Rick Szeliski

The Plenoptic Function



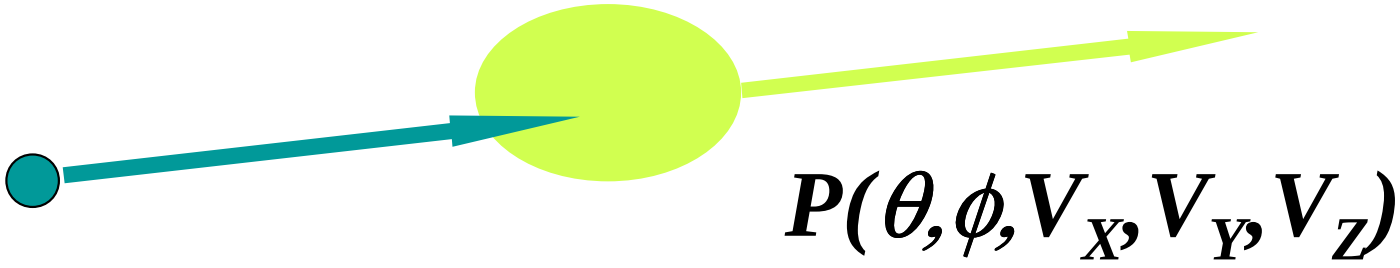
$$P(\theta,\phi,\lambda,,t,V_X,V_Y,V_Z)$$

Can reconstruct every possible view, at every moment, from every position, at every wavelength

Slide adapted from Michael Cohen and Rick Szeliski

Ray of Light

- Let's ignore time and color:

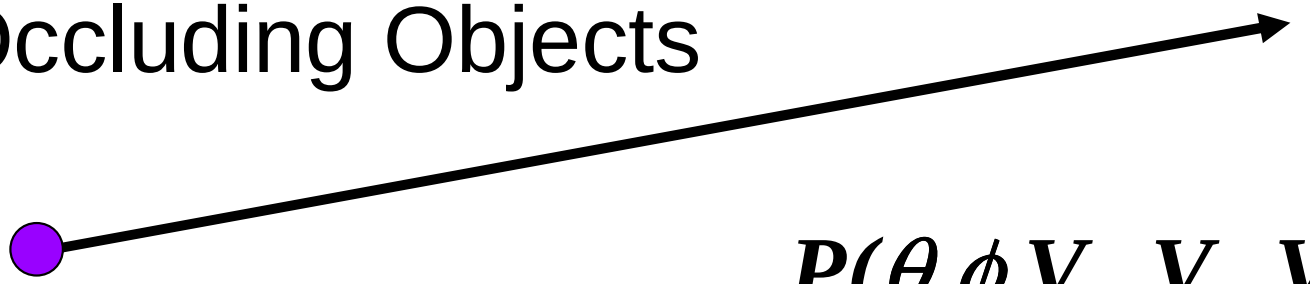


- 5D
  - 3D position
  - 2D direction

Slide adapted from Michael Cohen and Rick Szeliski

Ray of Light in **Free Space**

- No Occluding Objects



$$P(\theta, \phi, V_X, V_Y, V_Z)$$

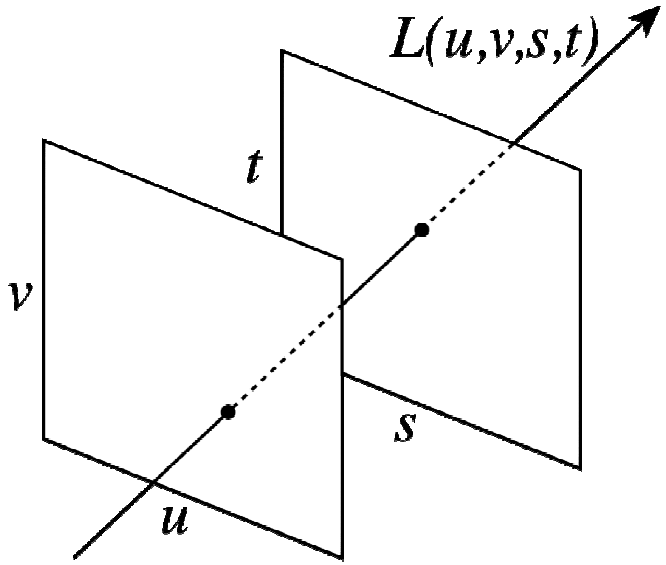
- 4D
  - 2D position
  - 2D direction

Slide adapted from Michael Cohen and Rick Szeliski

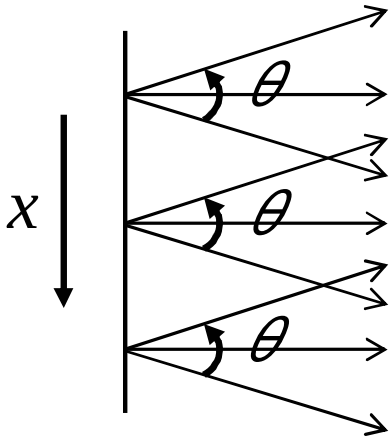
Light Field [Levoy & Hanrahan 1996]

Radiance as a function of position and direction

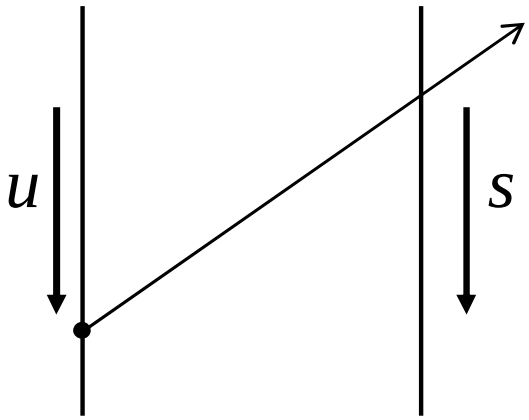
- 4D in 3D free space (*u, v, s, t*)



- 2D in flatland (*u, v, s, t*)



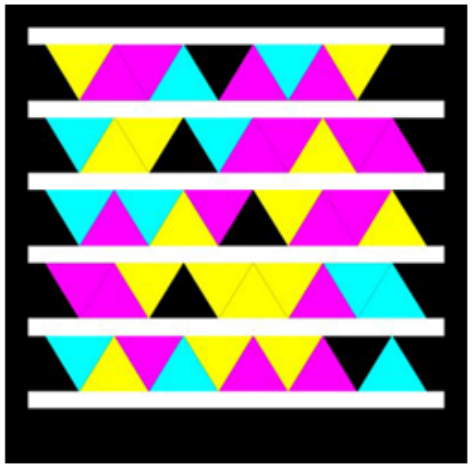
position-angle parameterization

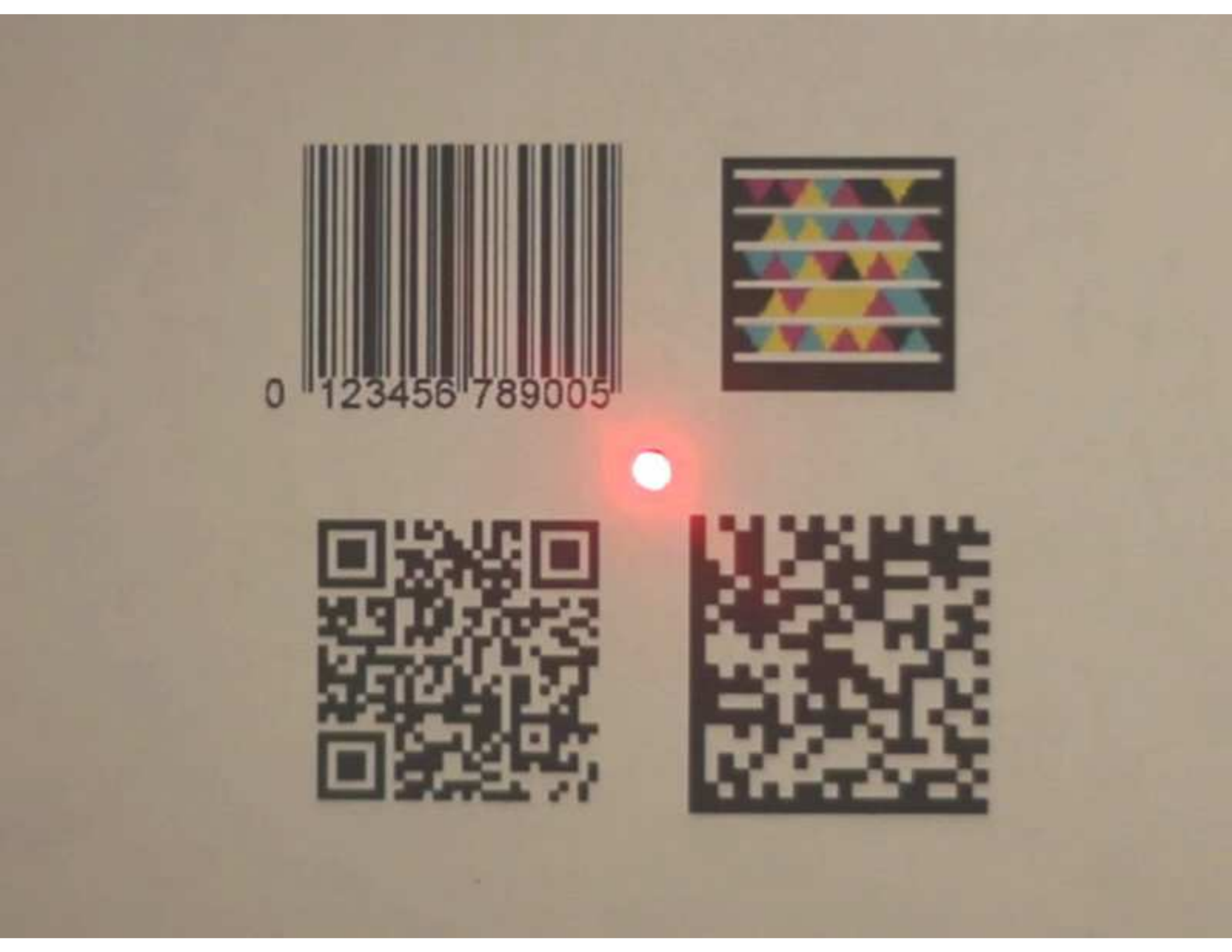


two plane parameterization

Light Field Generation


0 123456 789005




0 123456 789005

visible light barcodes

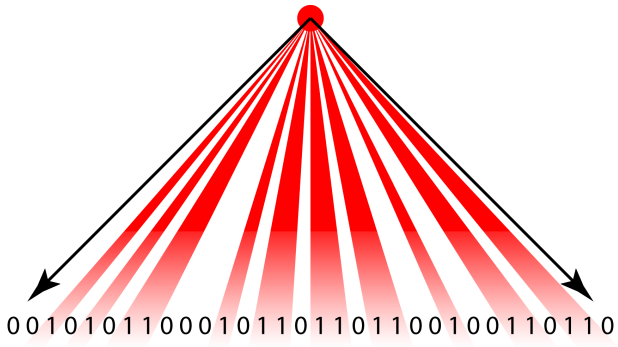
space

[UPC Code, QR Code, Data Matrix Code, Shot Code, Microsoft Tag, …]

time

[IR remote, Sony ID CAM]

angle

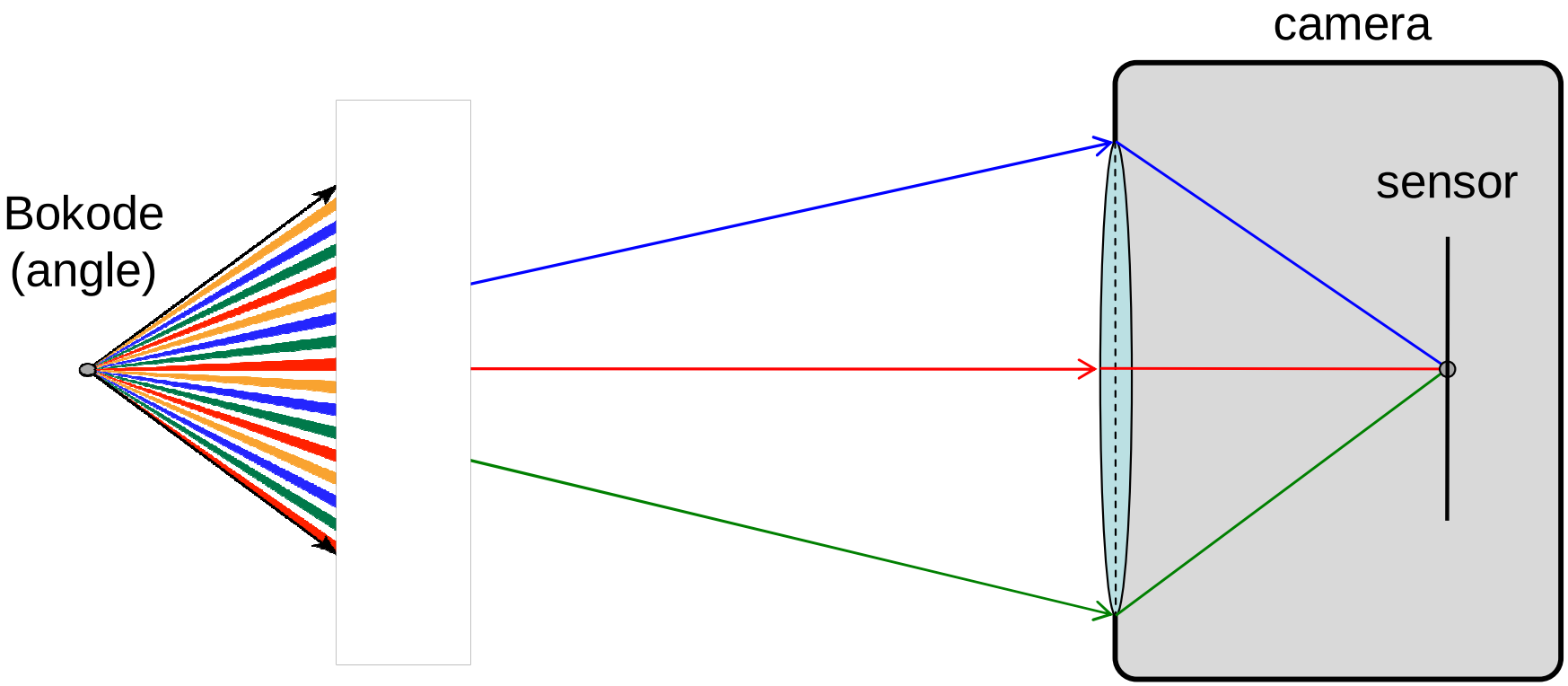


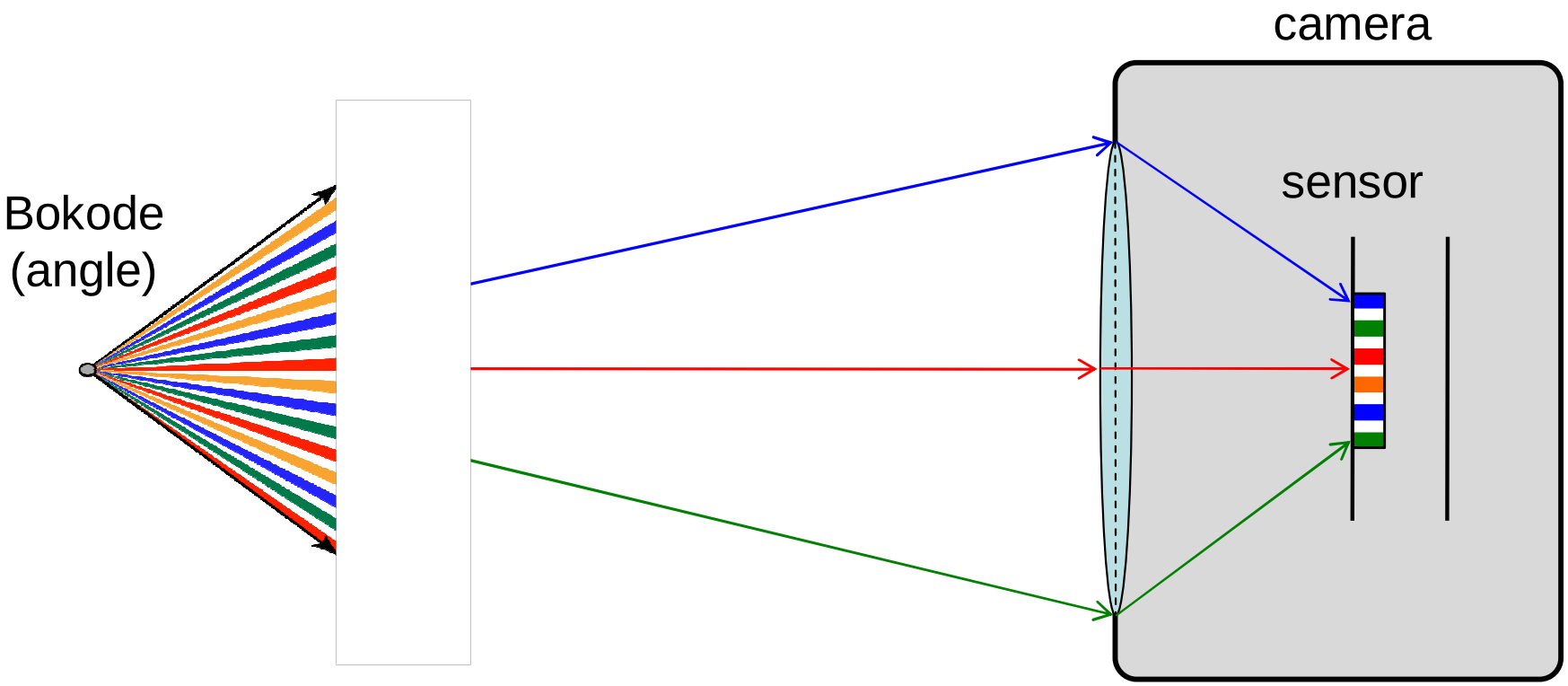
+

standard camera focused at infinity

Bokode

“Bokode: Imperceptible Visual Tags for Camera Based Interaction from a Distance”, Ankit Mohan, Grace Woo, Shinsaku Hiura, Quinn Smithwick and Ramesh Raskar, in **SIGGRAPH 2009**.

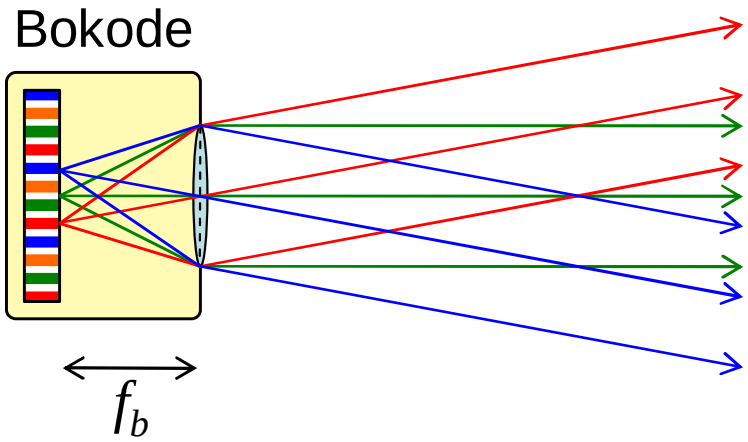

camera
sensor
Bokode
(angle)



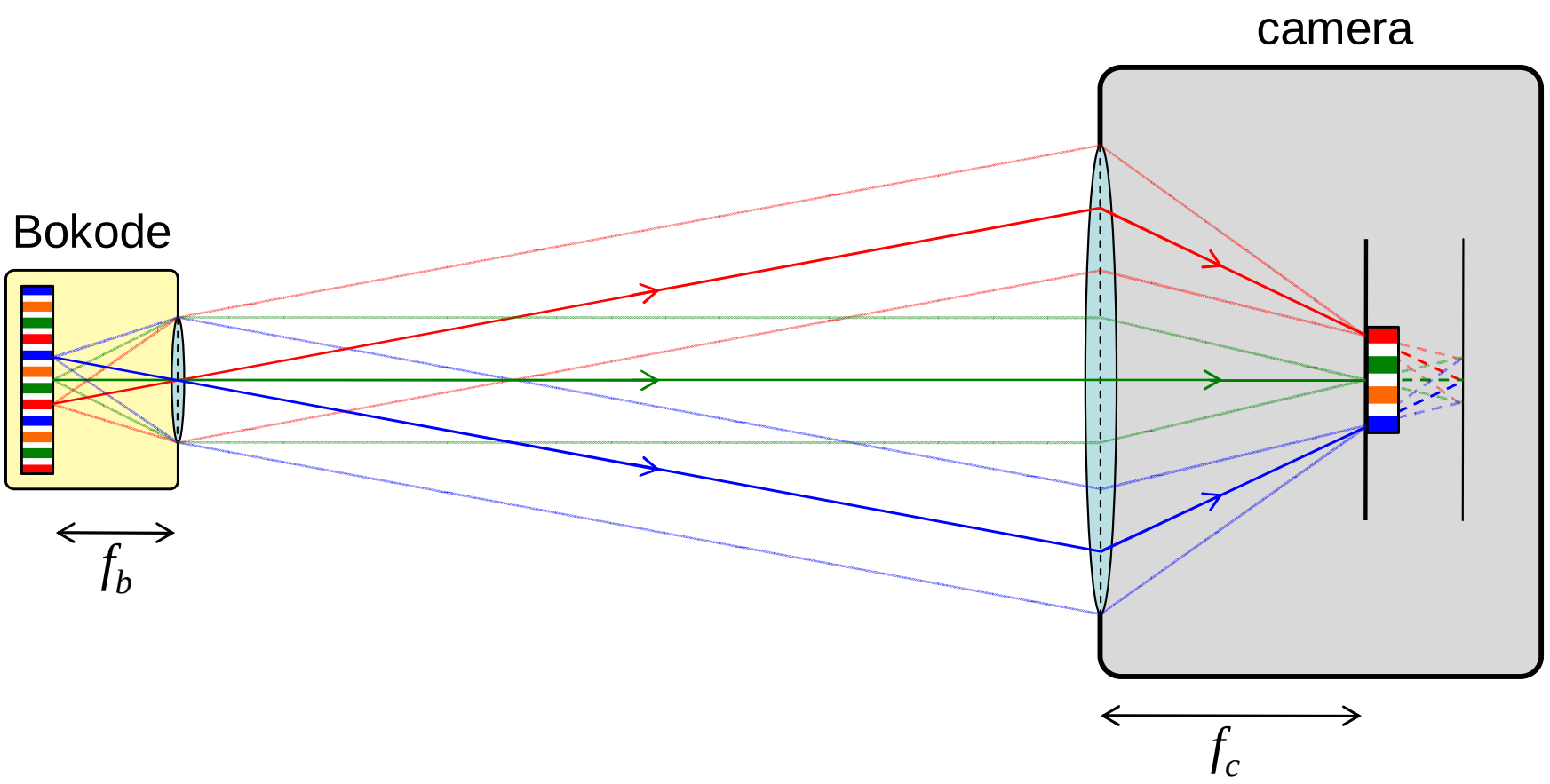
"ahh… circle of confusion → circle of information"

- Kurt Akeley

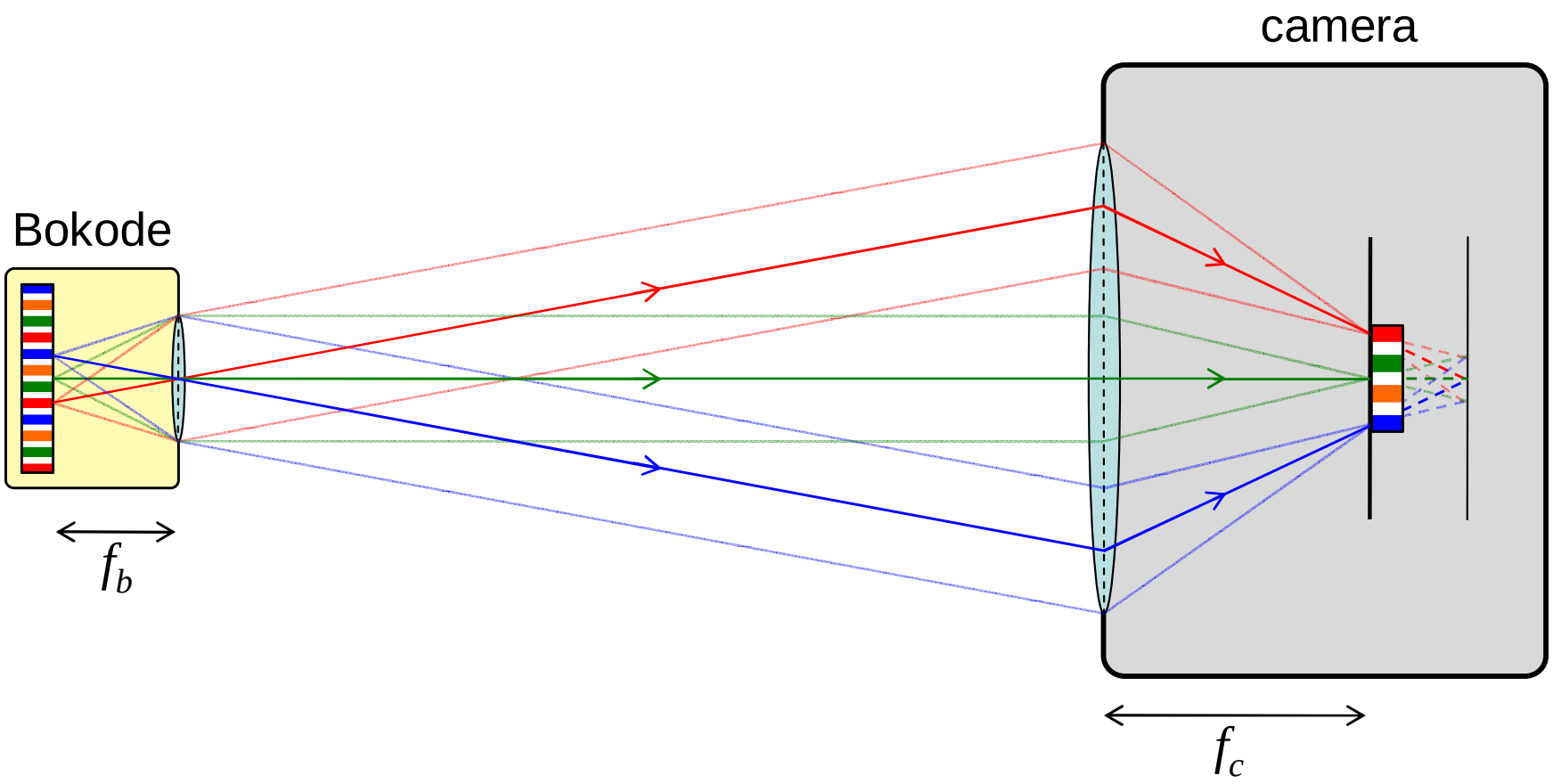
generate directionally encoded information



capture directionally encoded information

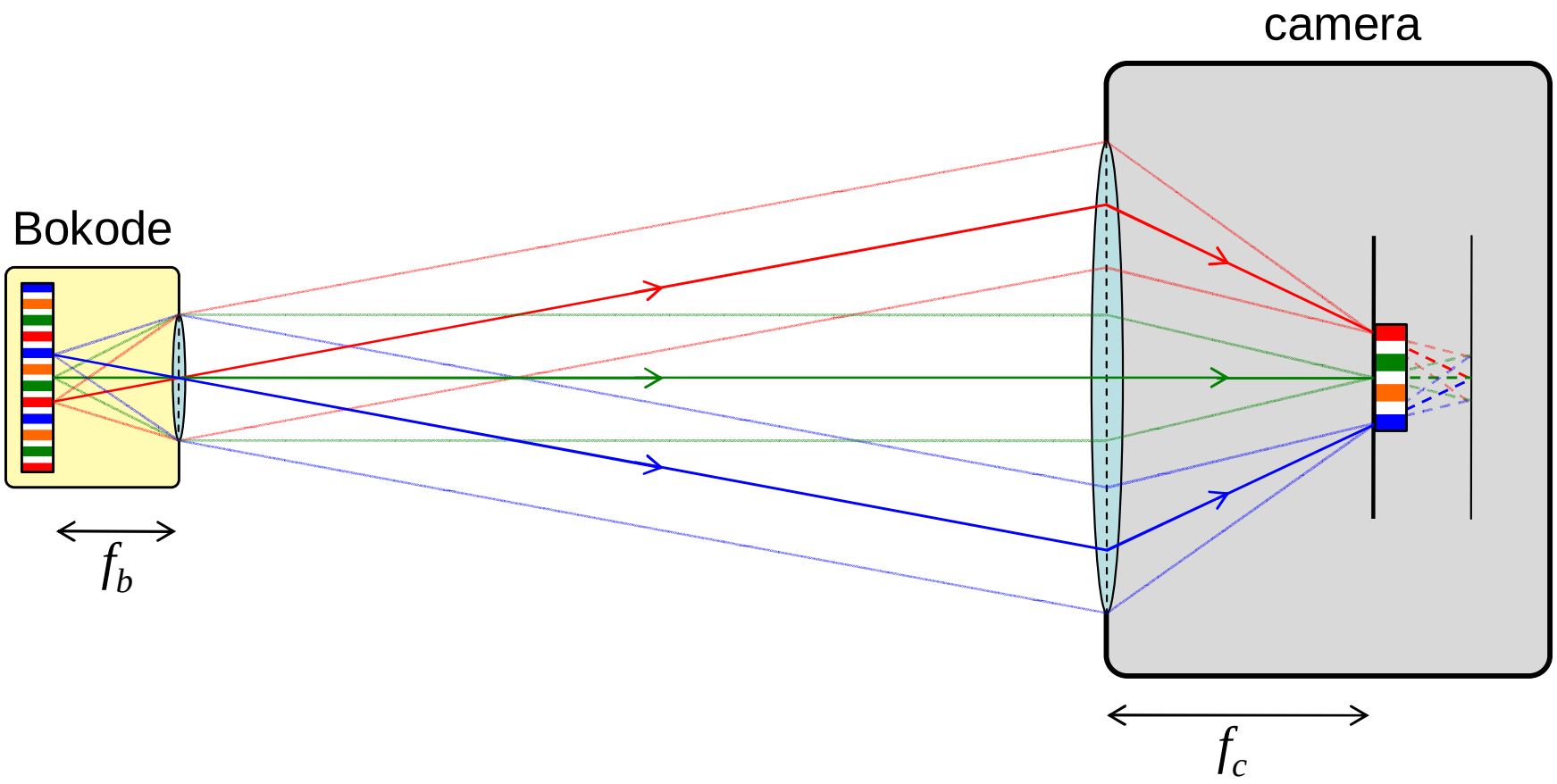


infinity-corrected microscope

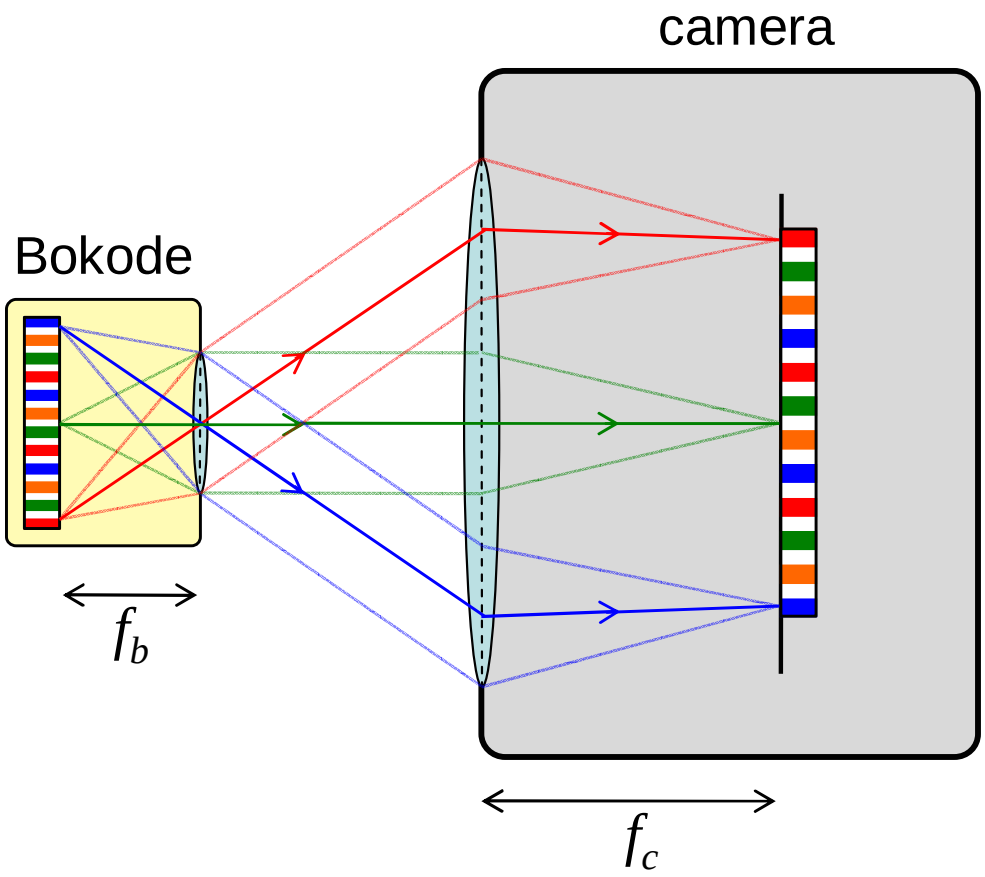


magnification = f_c / f_b (microscope);

focus always at infinity

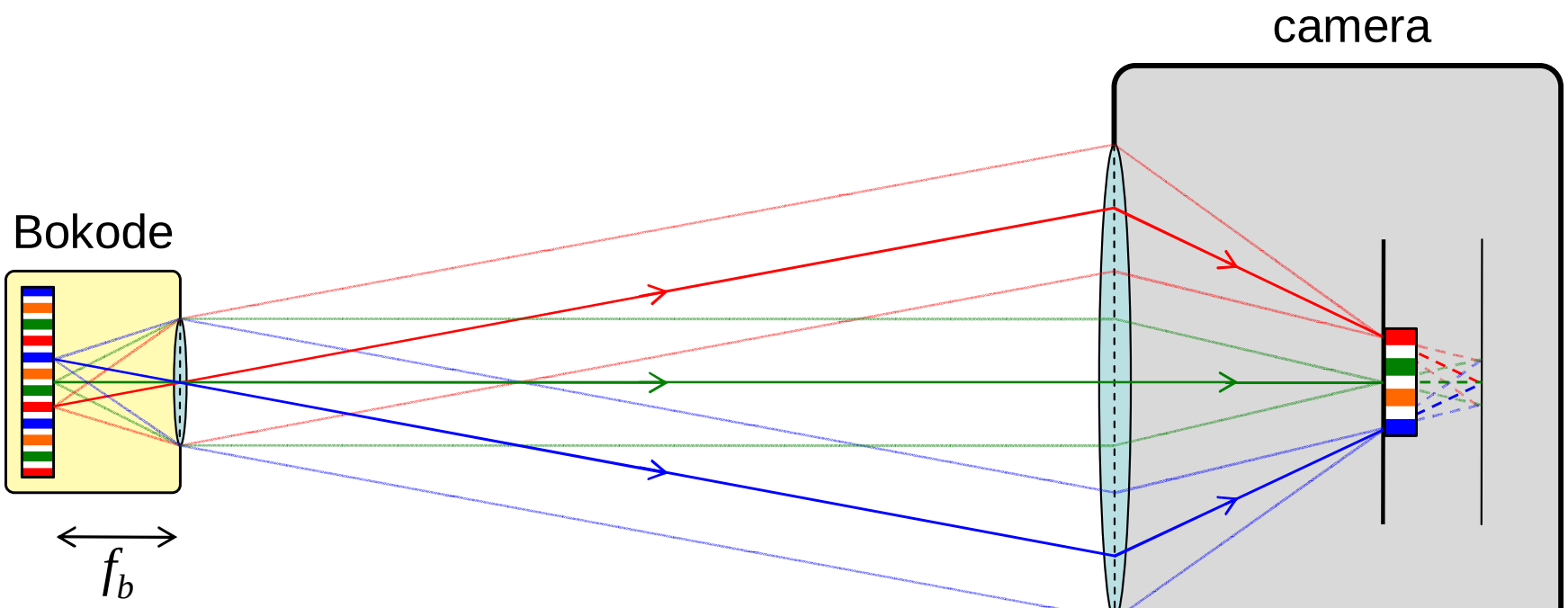


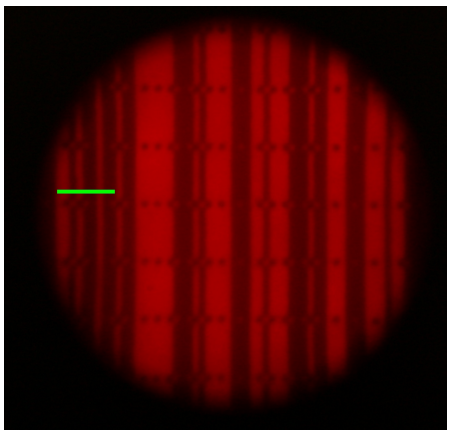
less distance → more of Bokode imaged

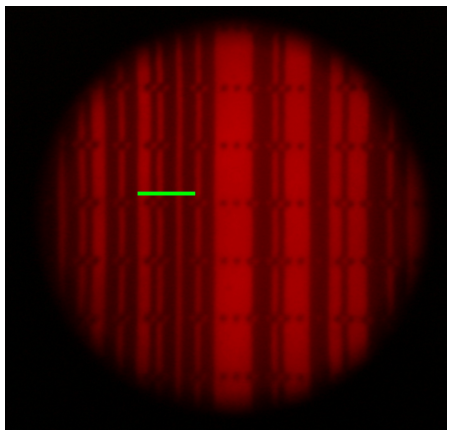


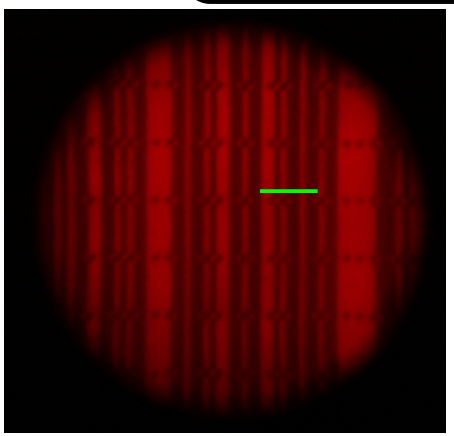
less distance → more of Bokode imaged

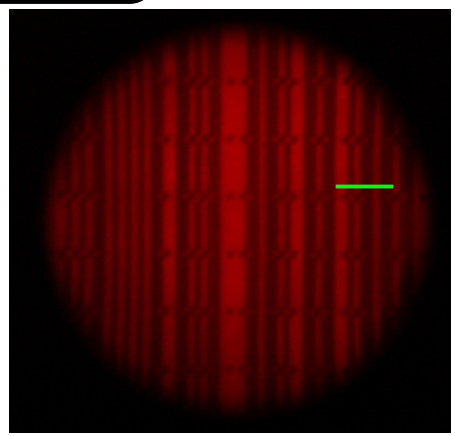
Bokode image depends on camera angle



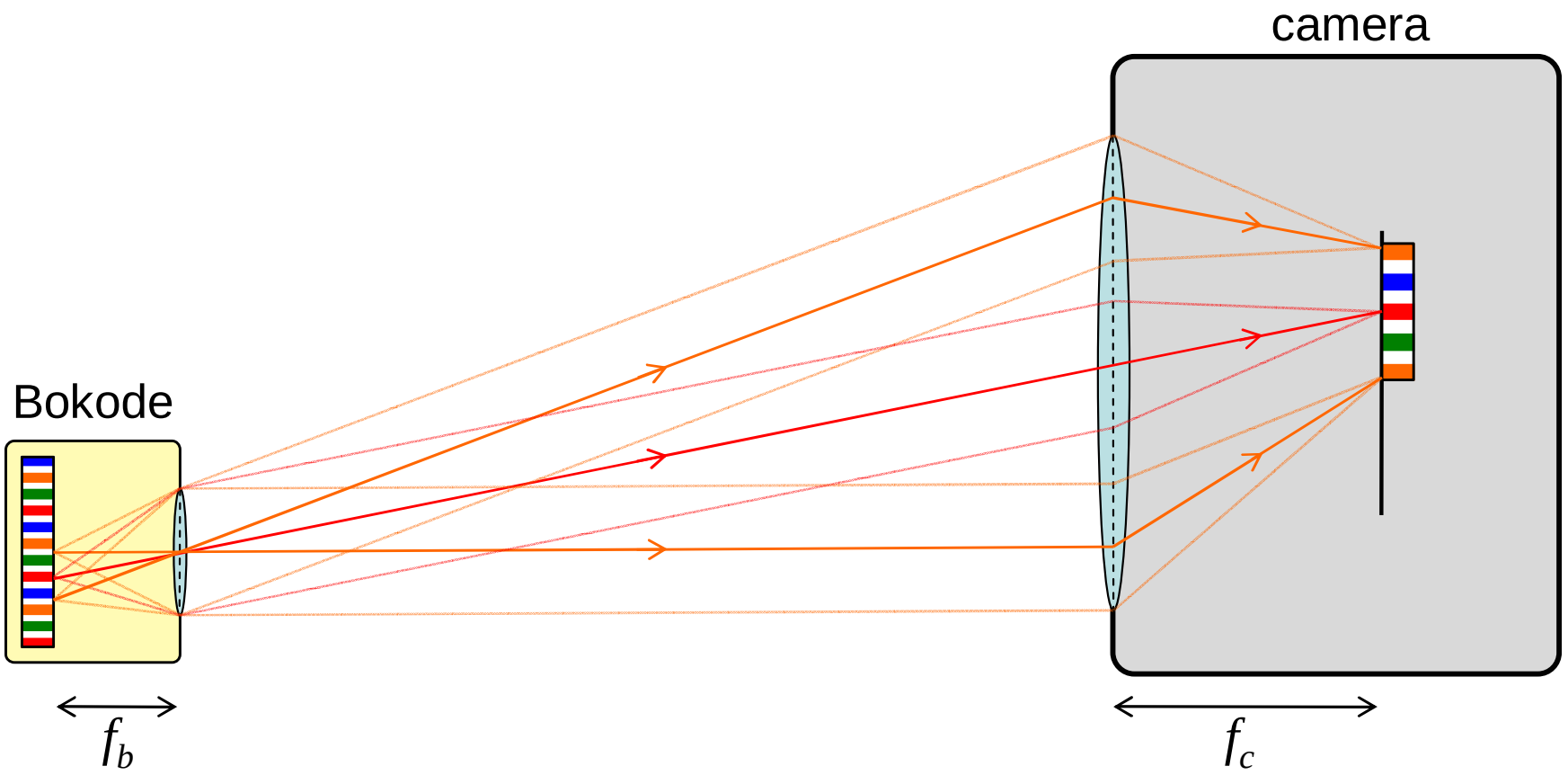


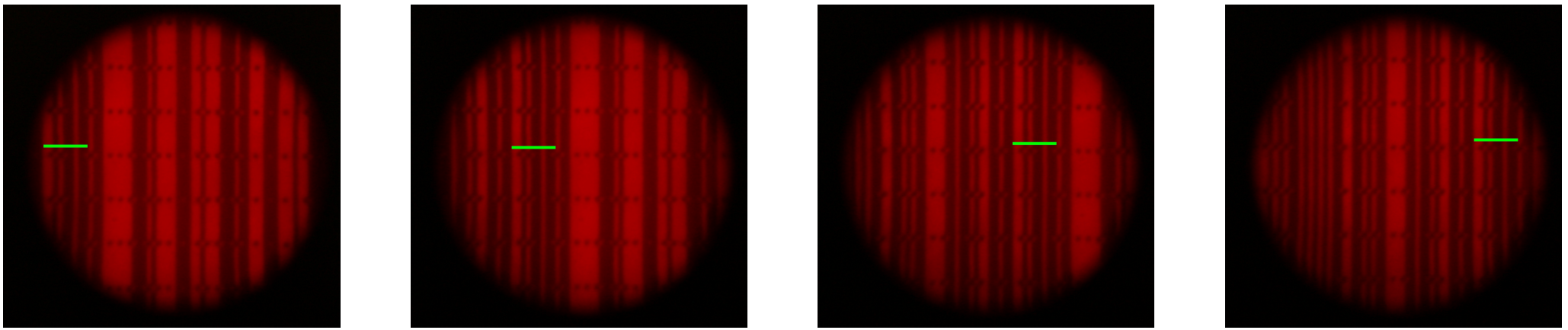


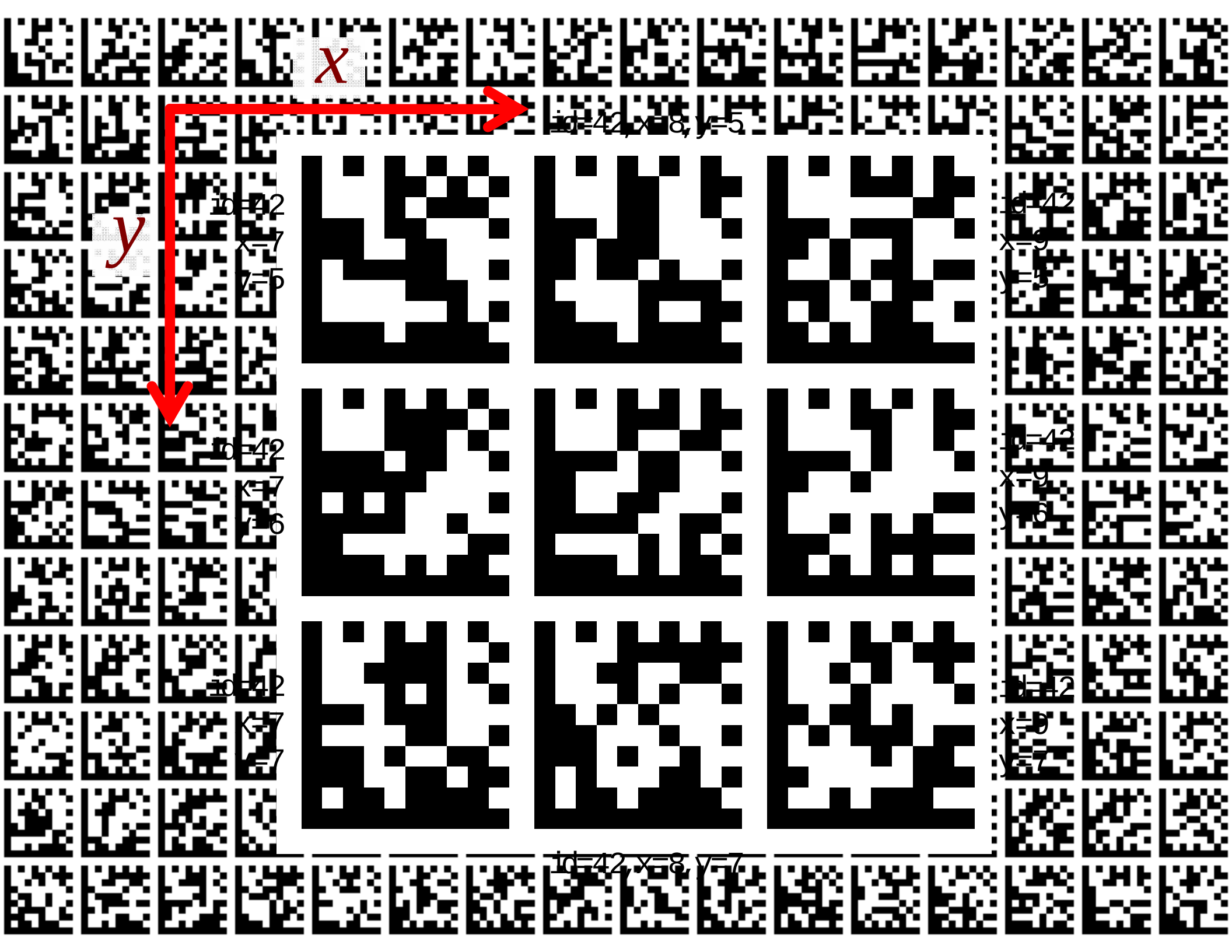




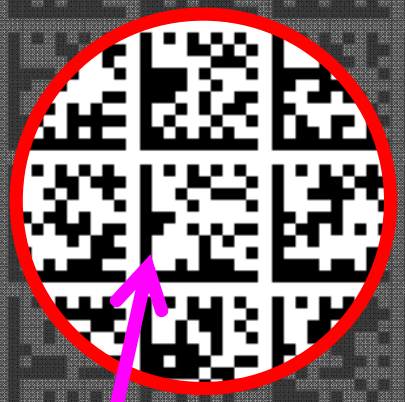
Bokode image depends on camera angle





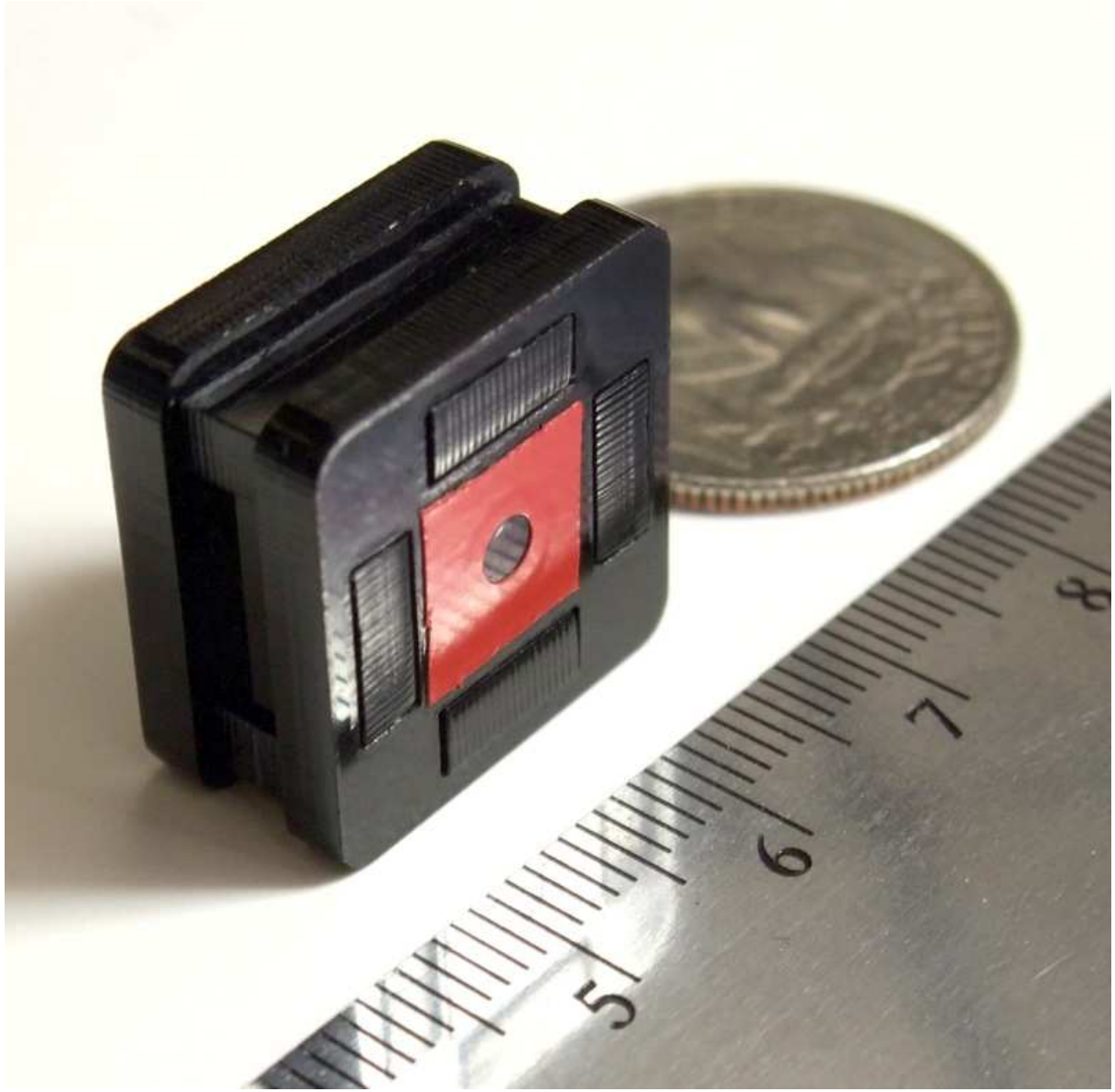

x
y
id=42,x=8,y=5
id=42
x=7
y=5
id=42
x=9
y=5
id=42
x=7
y=6
id=42
x=9
y=6
id=42
x=7
y=7
id=42
x=9
y=7
id=42,x=8,y=7

digital angle from Bokode

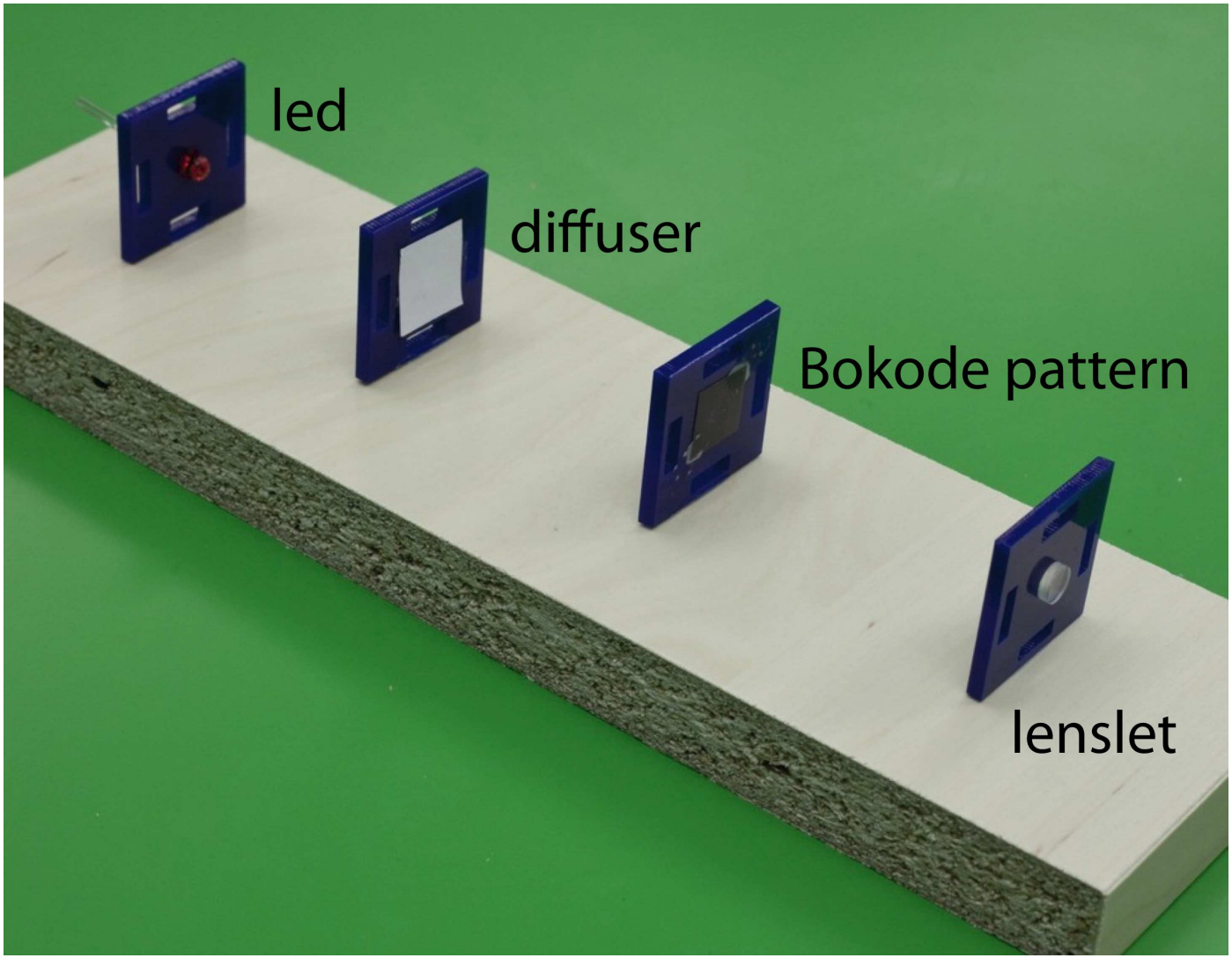


id = (42, 10, 7)

prototype – assembled



prototype – exploded



led: 120˚ view angle, 1350mcd

pattern: 15µm resolution

lenslet: f=8mm, Φ=3mm

cost: ~$5

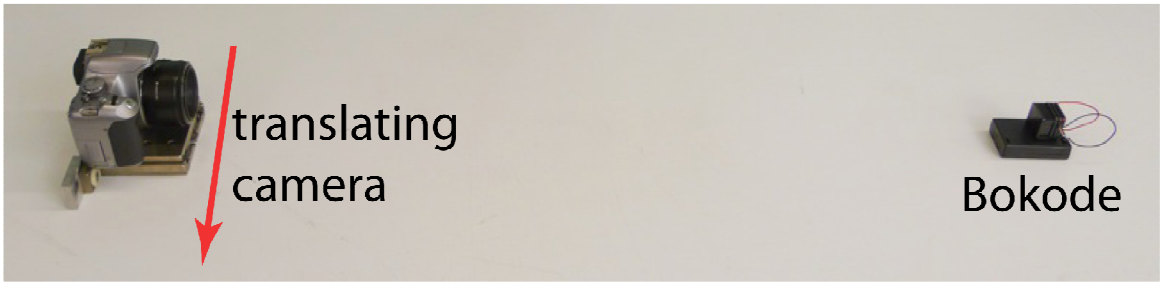
capturing Bokodes

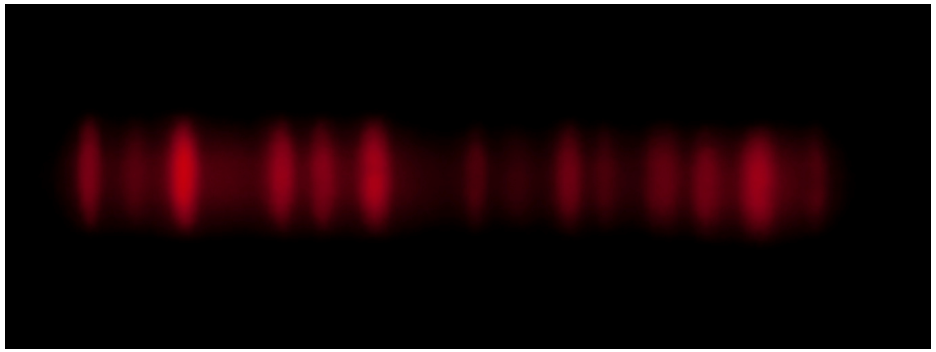
focus blur

(85mm f/1.8;
infinity focus)

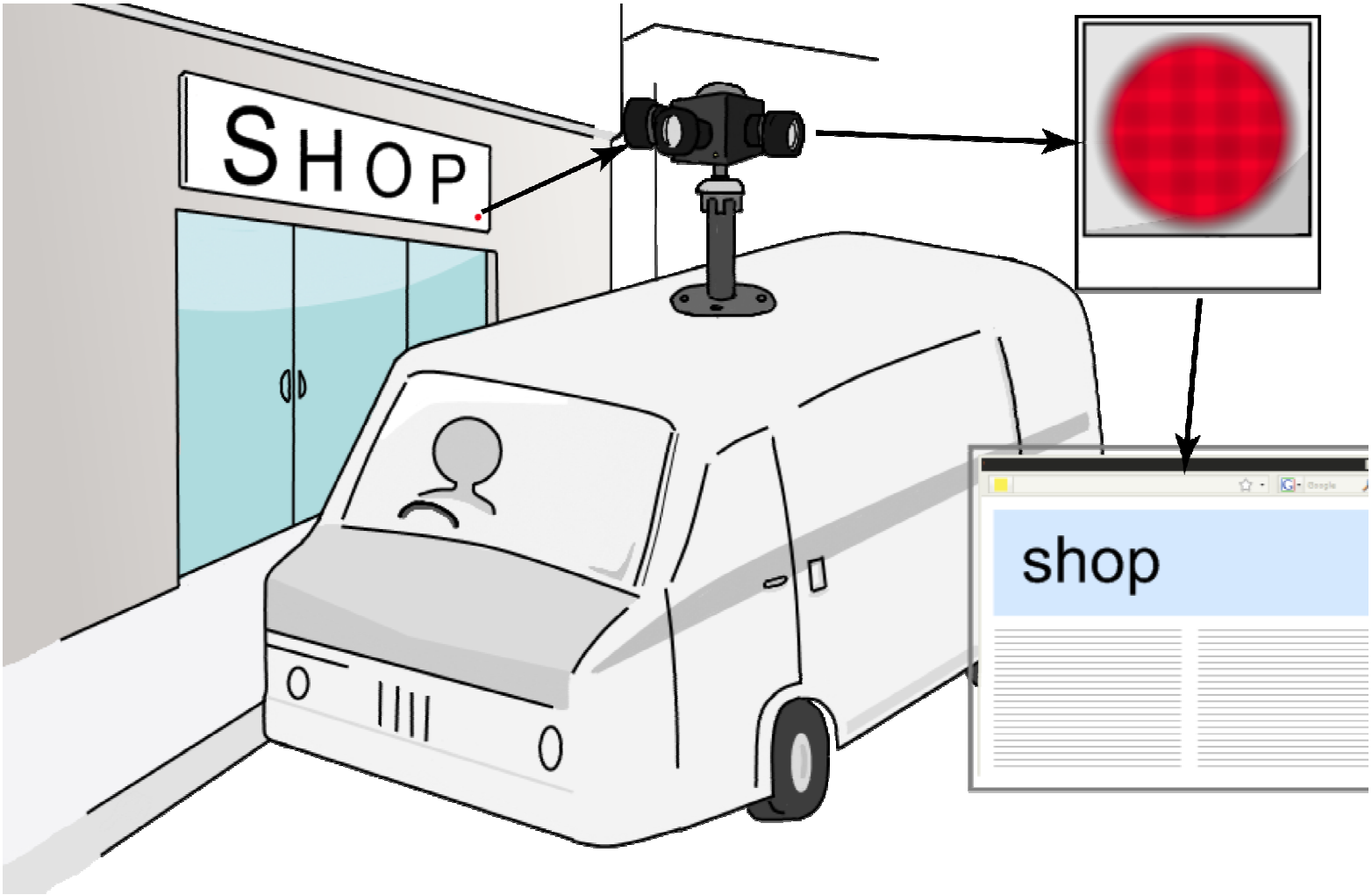
motion blur

(50mm f/8;
~2cm motion)





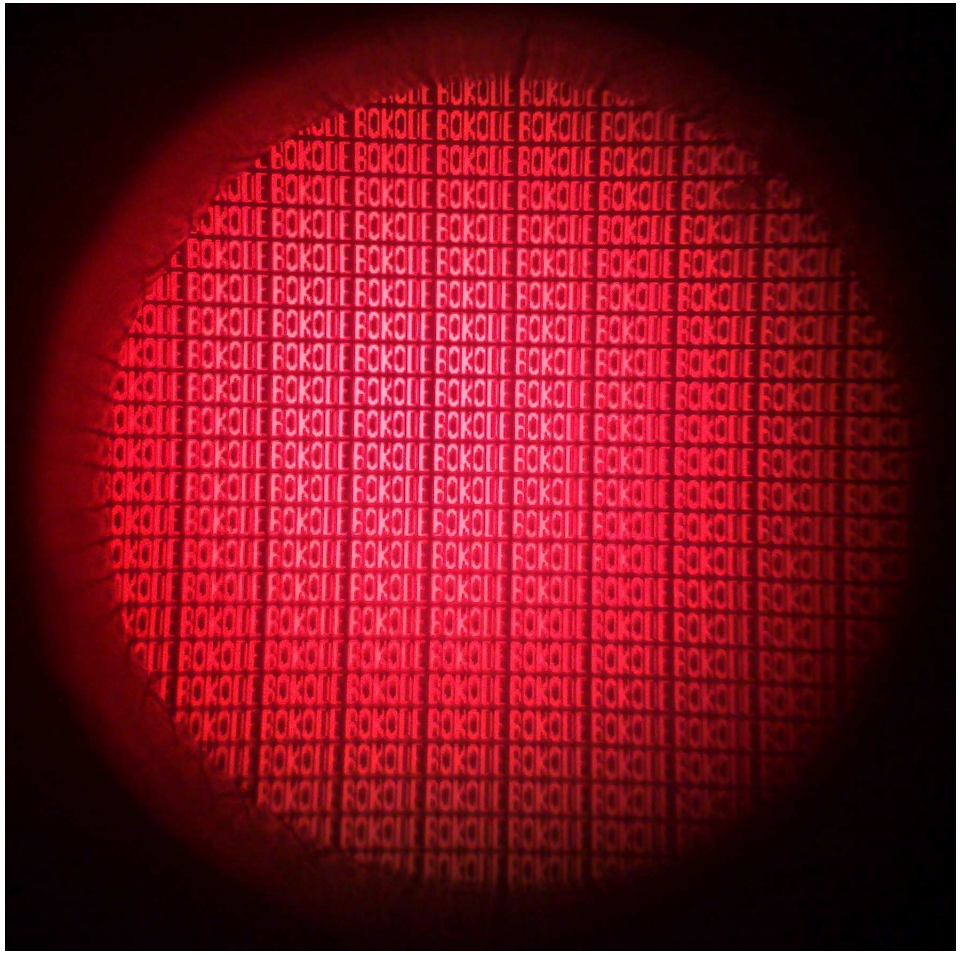
street-view tagging

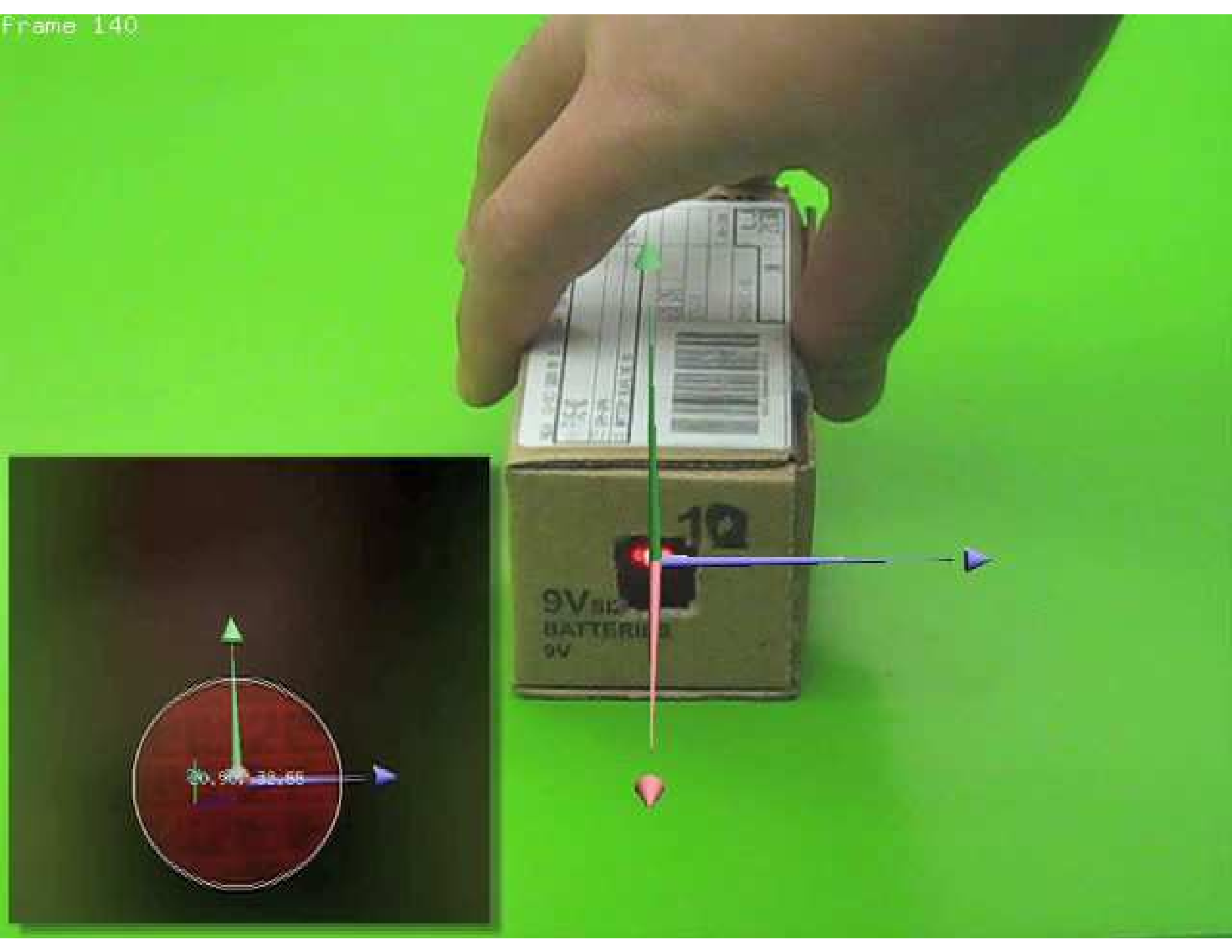


capturing Bokodes

cell-phone camera close to the Bokode

(10,000+ bytes of data)




Frame 140
9V
BATTERY
9V

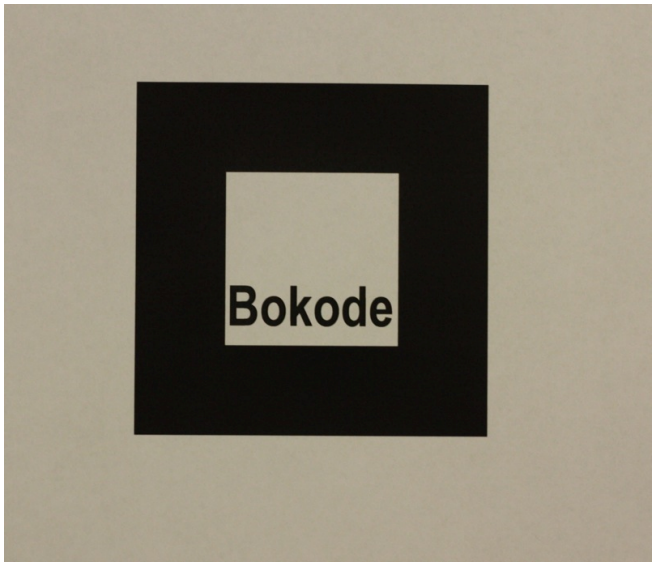
traditional AR markers

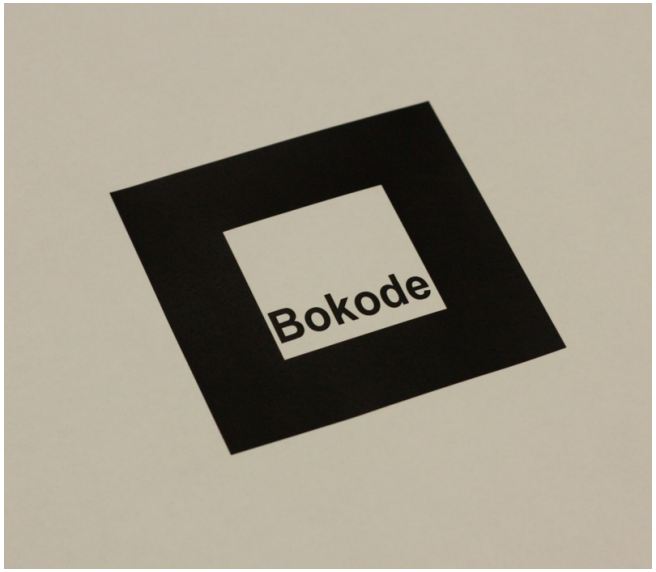
ARToolKit

[Kato and Billinghurst 1999]

ARTag

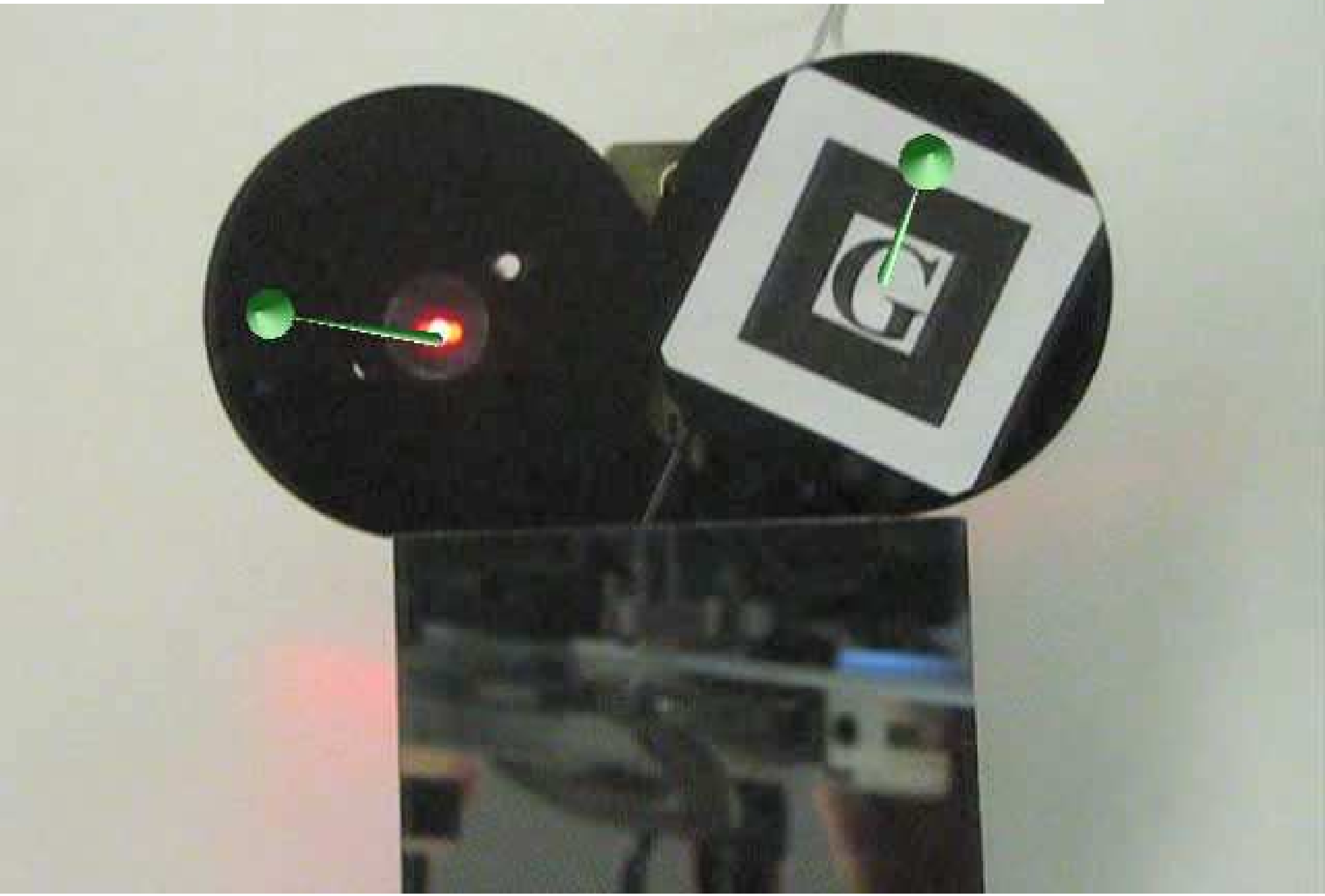
[Fiala 2005]





skew of marker

angle estimation robustness



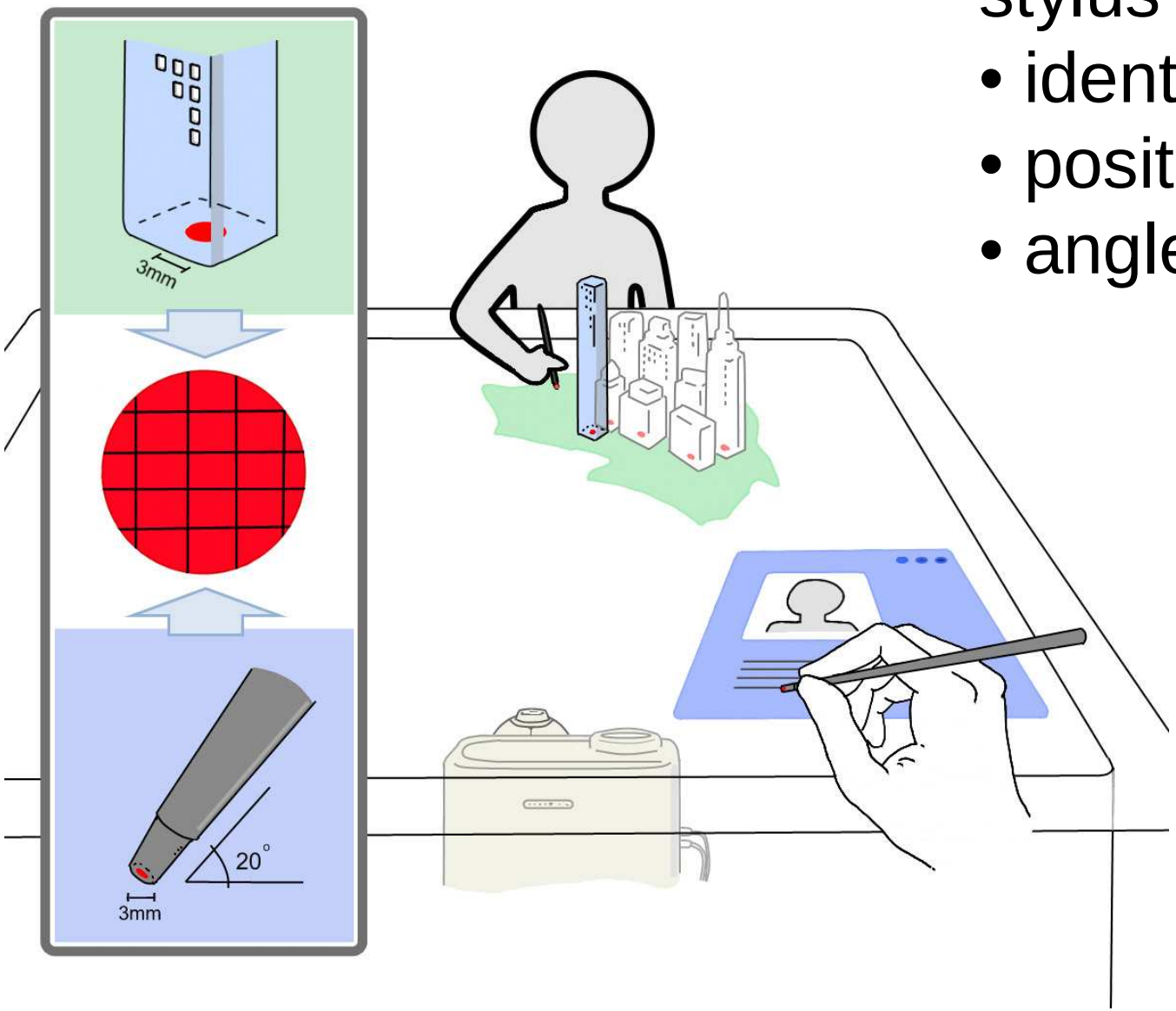
wide field of view Bokode via Krill eye

compound superposition optics

“Krill-eye: Superposition Compound Eye for Wide-Angle Imaging via GRIN Lenses”, Shinsaku Hiura, **Ankit Mohan**, Ramesh Raskar, in **OMNIVIS 2009**.

	barcode	RFID	Bokode
encoding	spatial	rf modulation	angular
decoder	**camera**	dedicated reader	**camera**
geometry	no	no	**yes**
physical size	~ cm	~ cm	**~ mm**
cost	**~ free**	~ $0.05	~ $0.05 (currently $5)
range	~ cm	~ cm	**~ m** (with large aperture lens)
line of sight	yes	no	yes

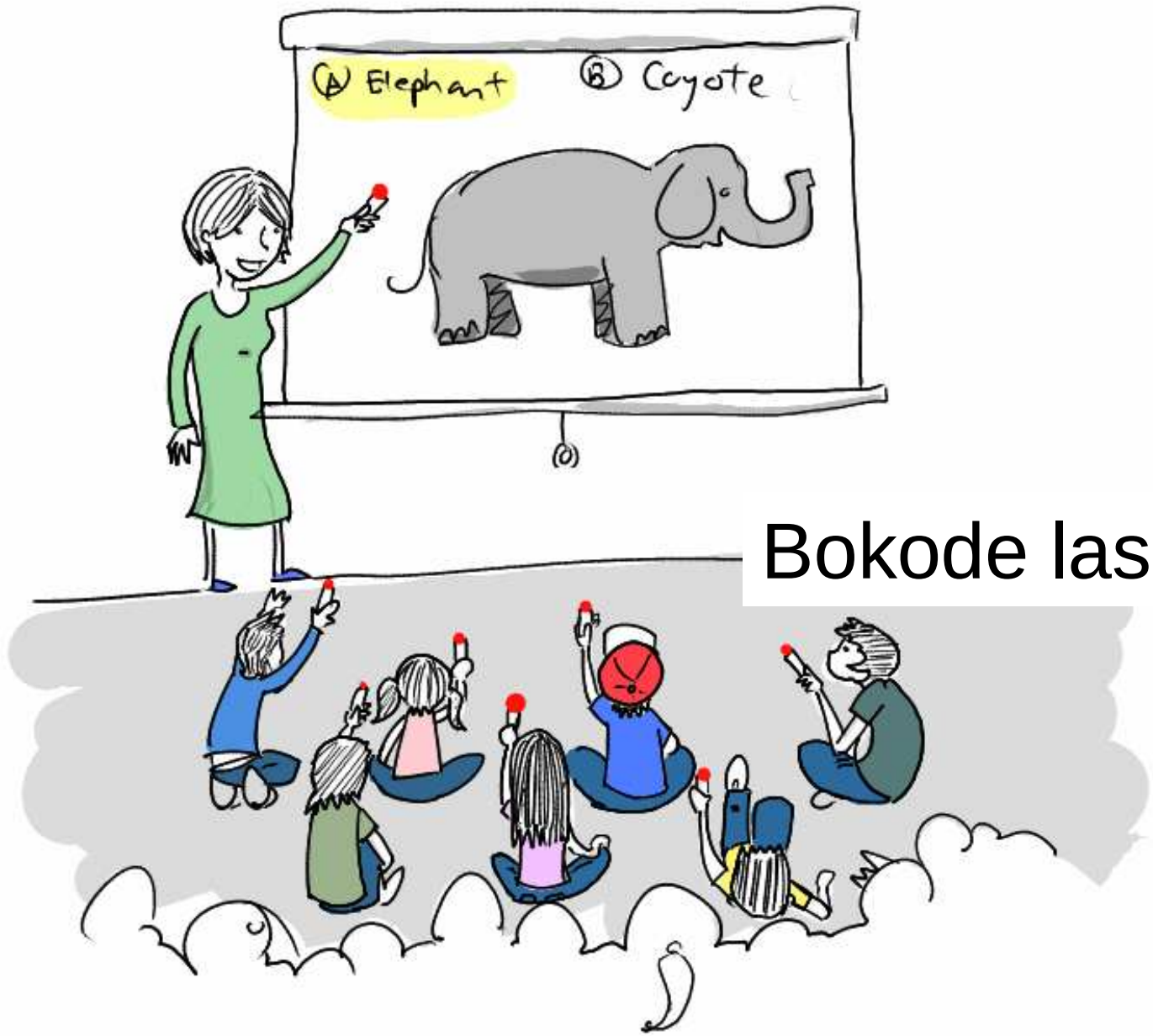
tabletop/surface interaction



stylus based interaction

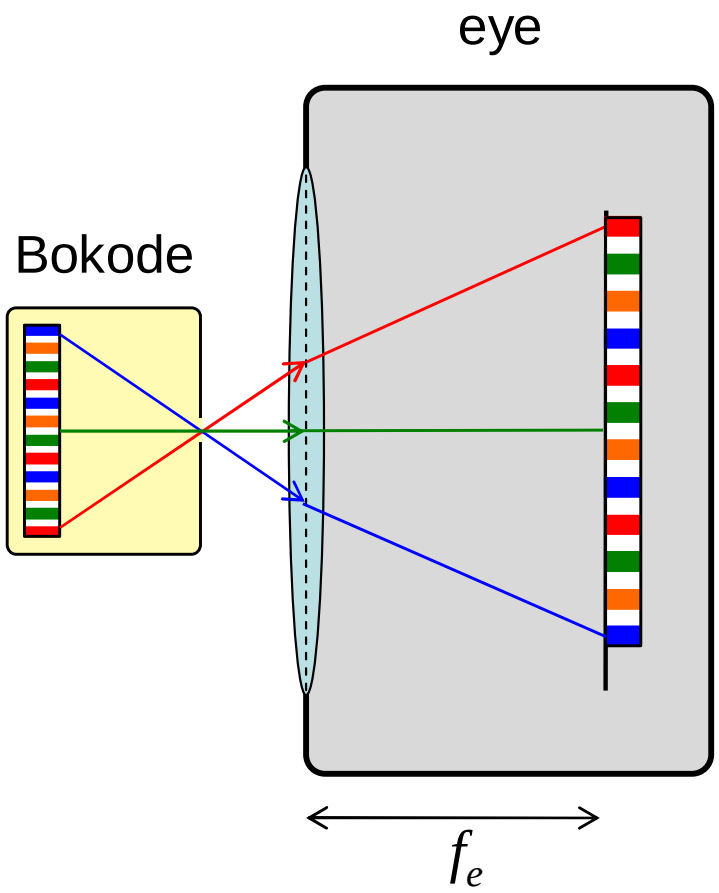
- identity
- position
- angle

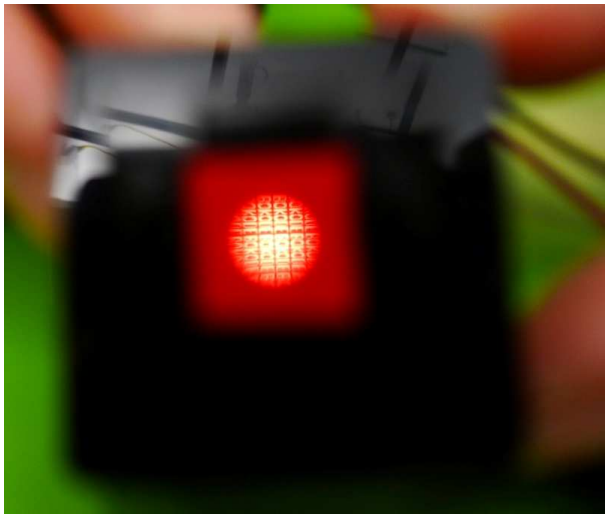
multi-user interaction



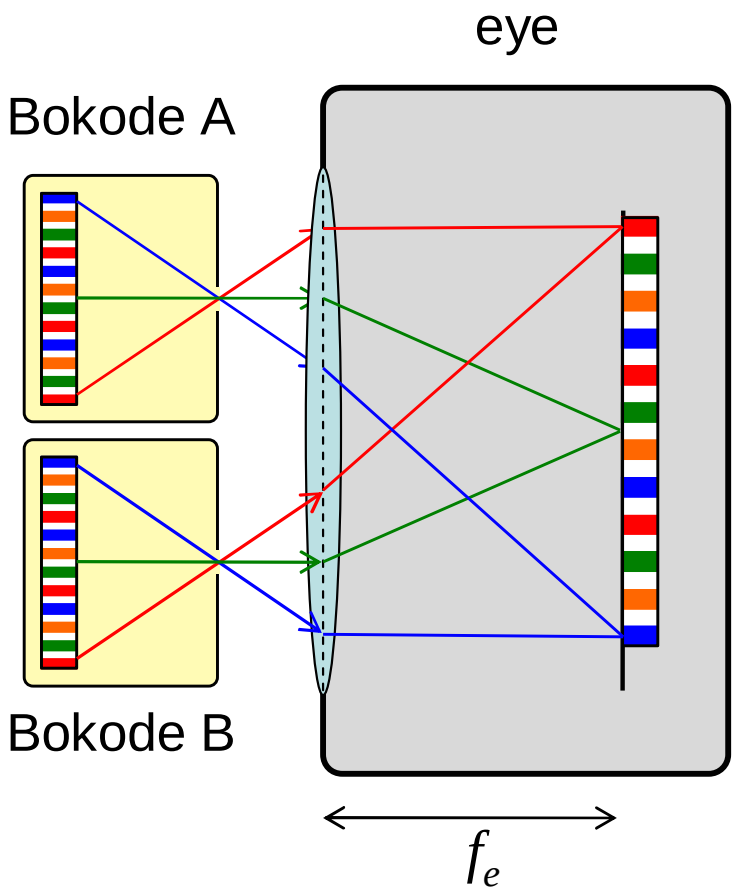
Bokode laser pointers

Bokode next to the eye



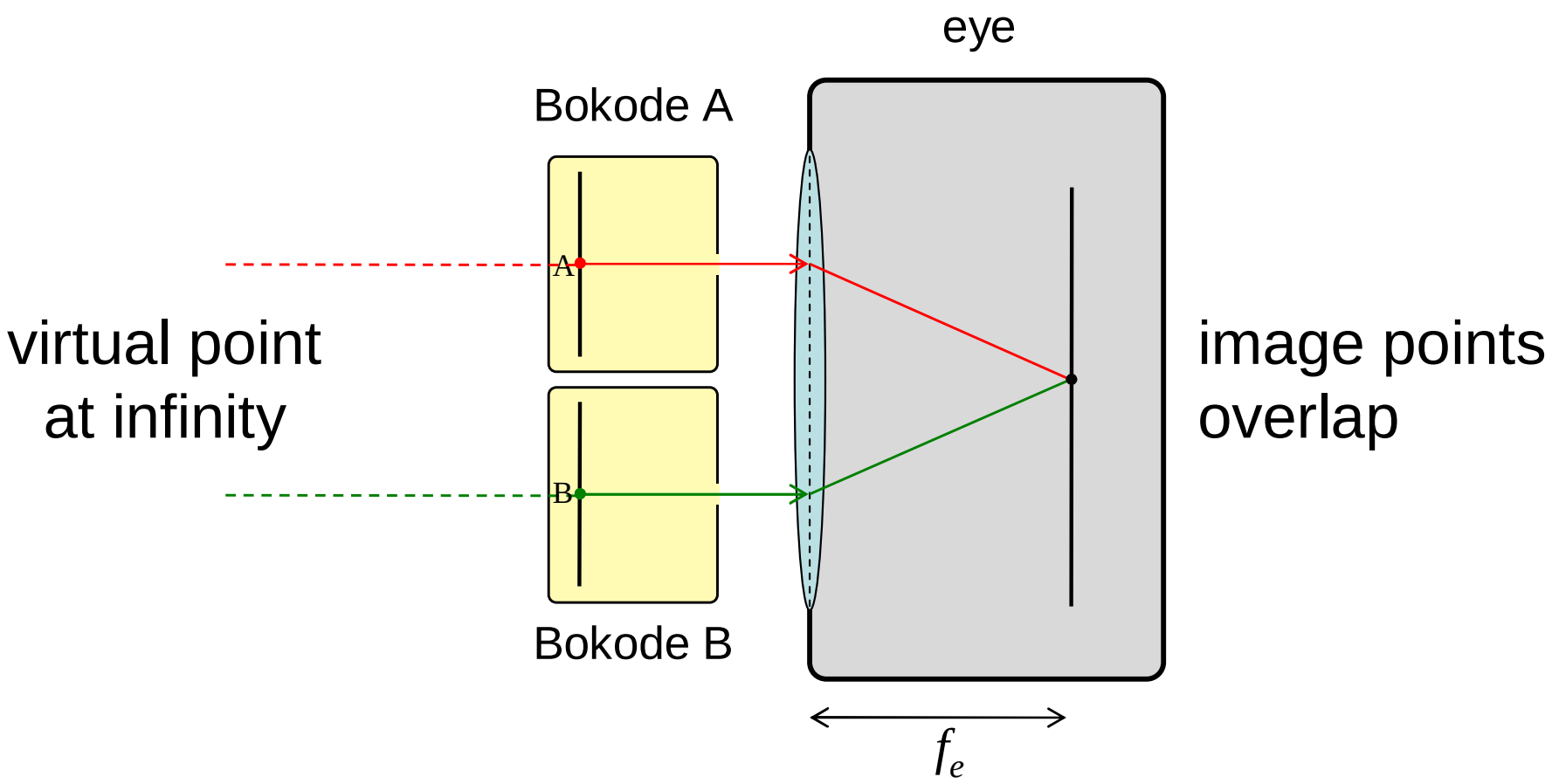


multiple Bokodes next to the eye

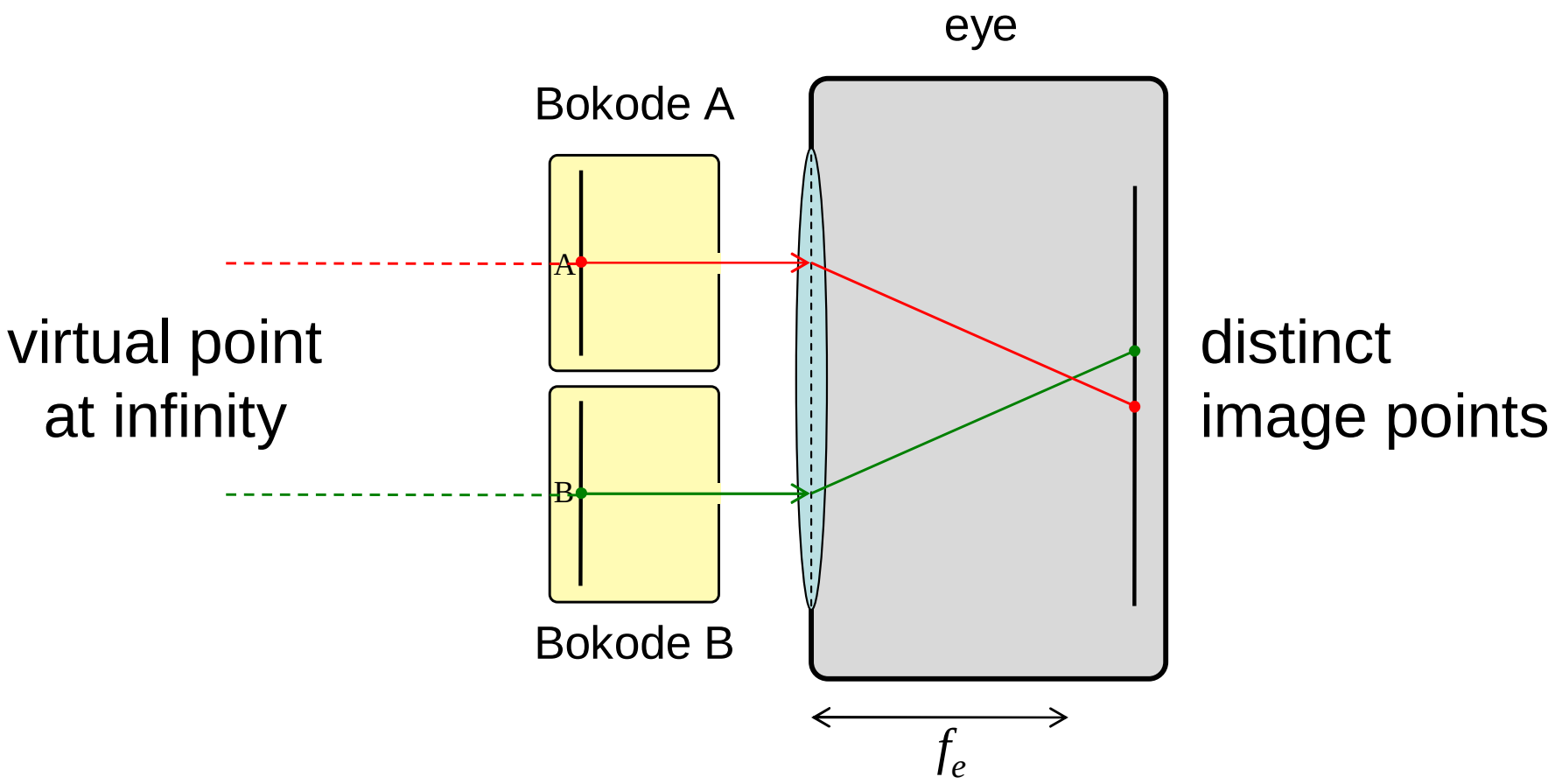


Bokode images **overlap**

relaxed perfect eye focused at infinity

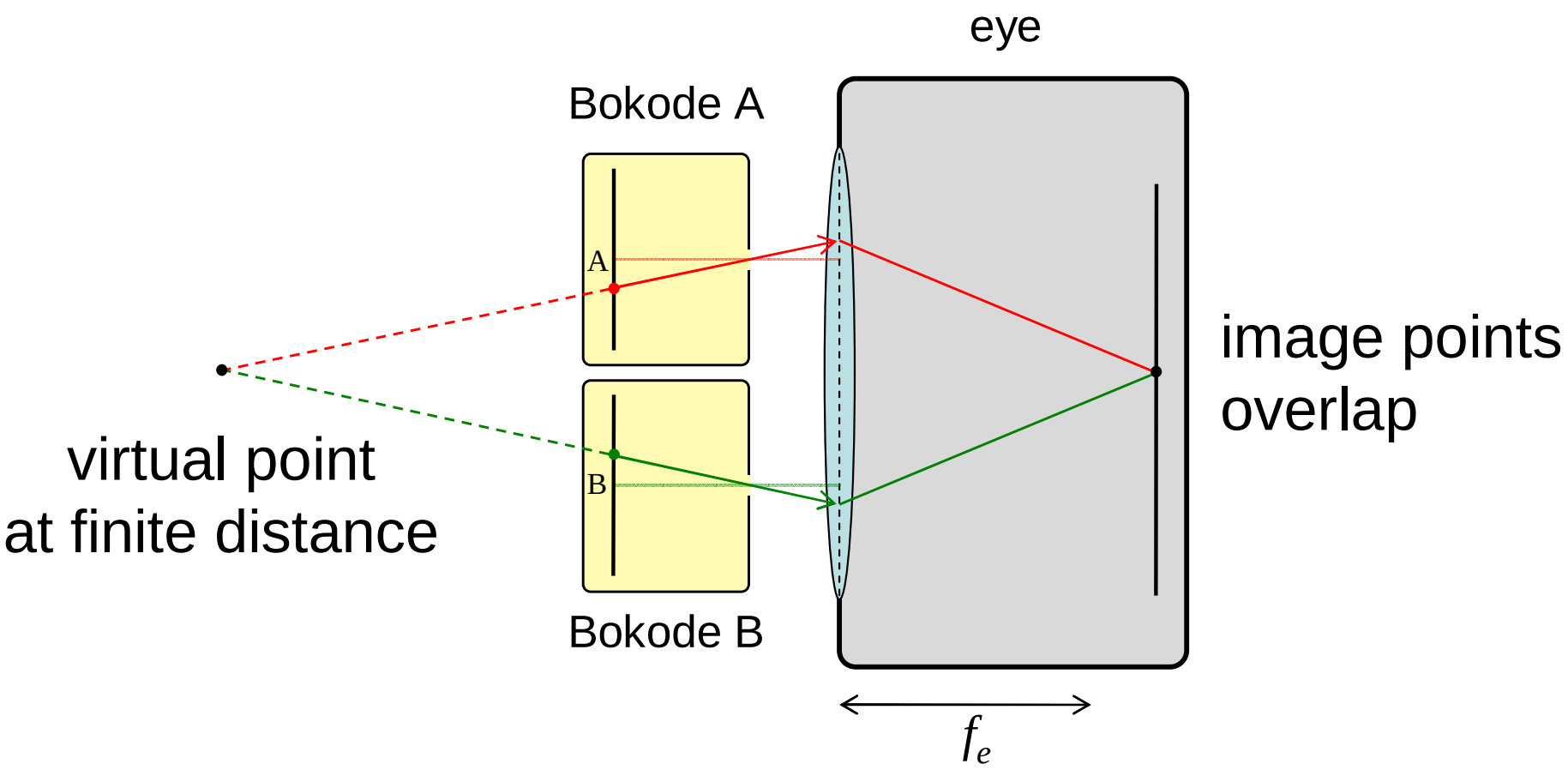


relaxed eye with *myopia*



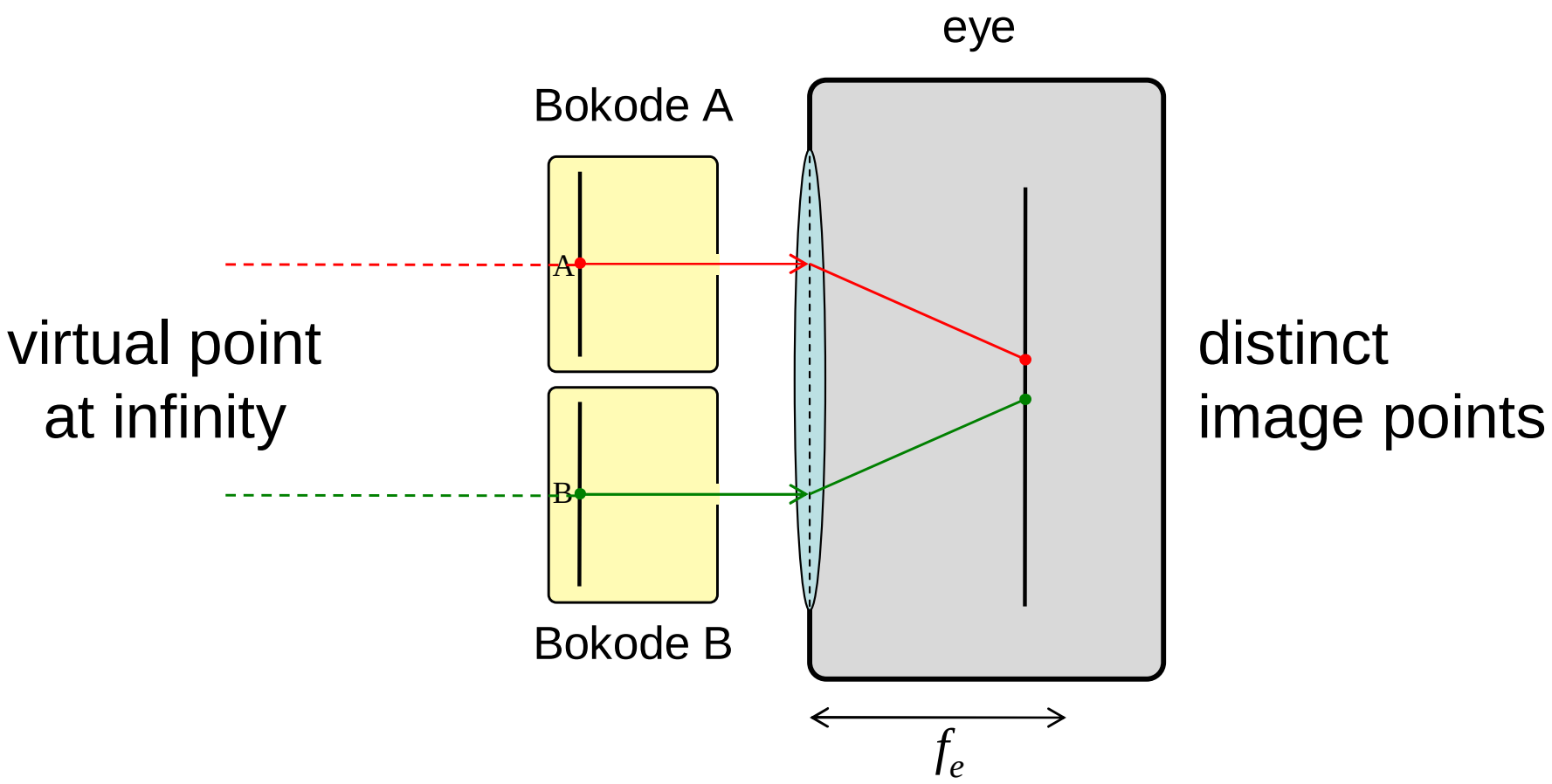
eye unable to focus at infinity

relaxed eye with *myopia*

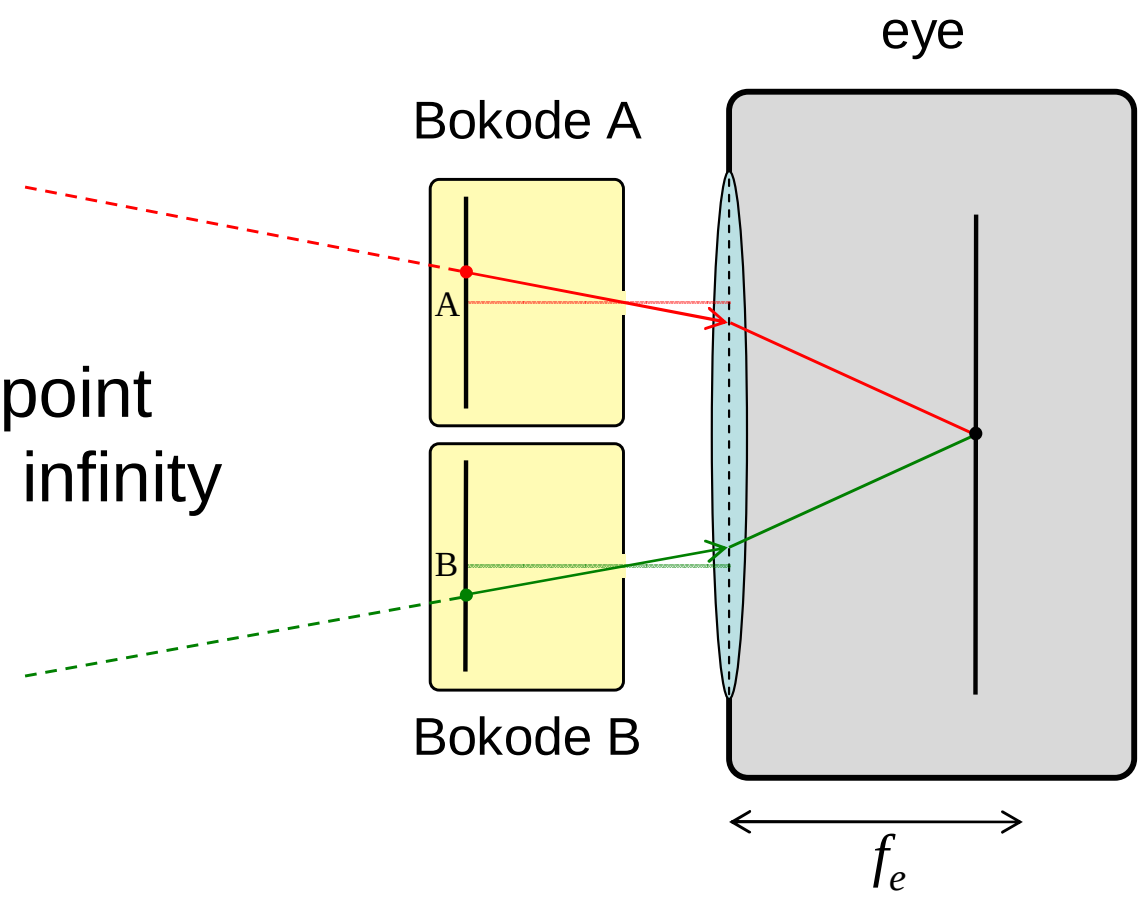


move points **towards** each other

relaxed eye with *hyperopia*



eye with *hyperopia*

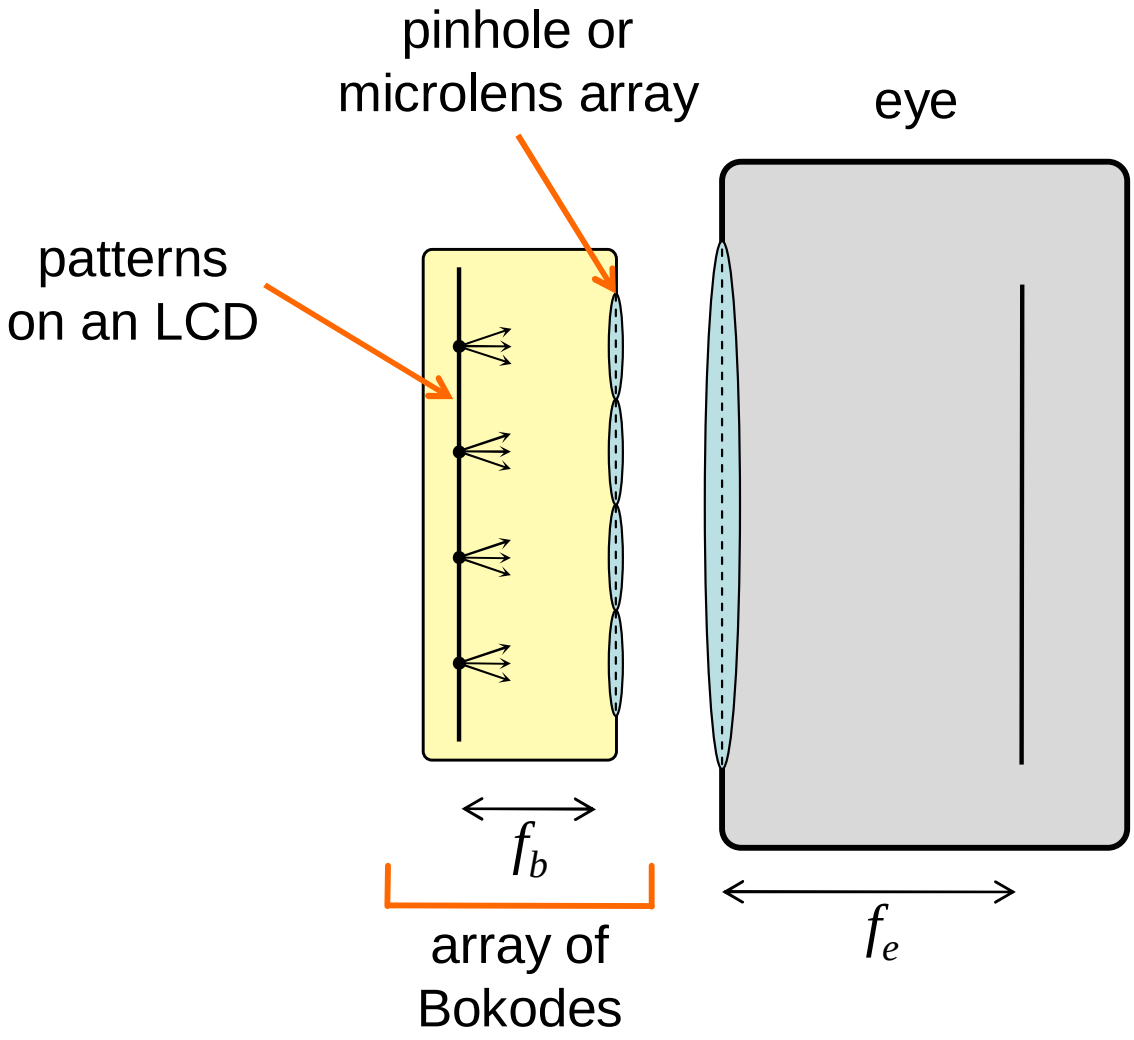


virtual point
“beyond” infinity

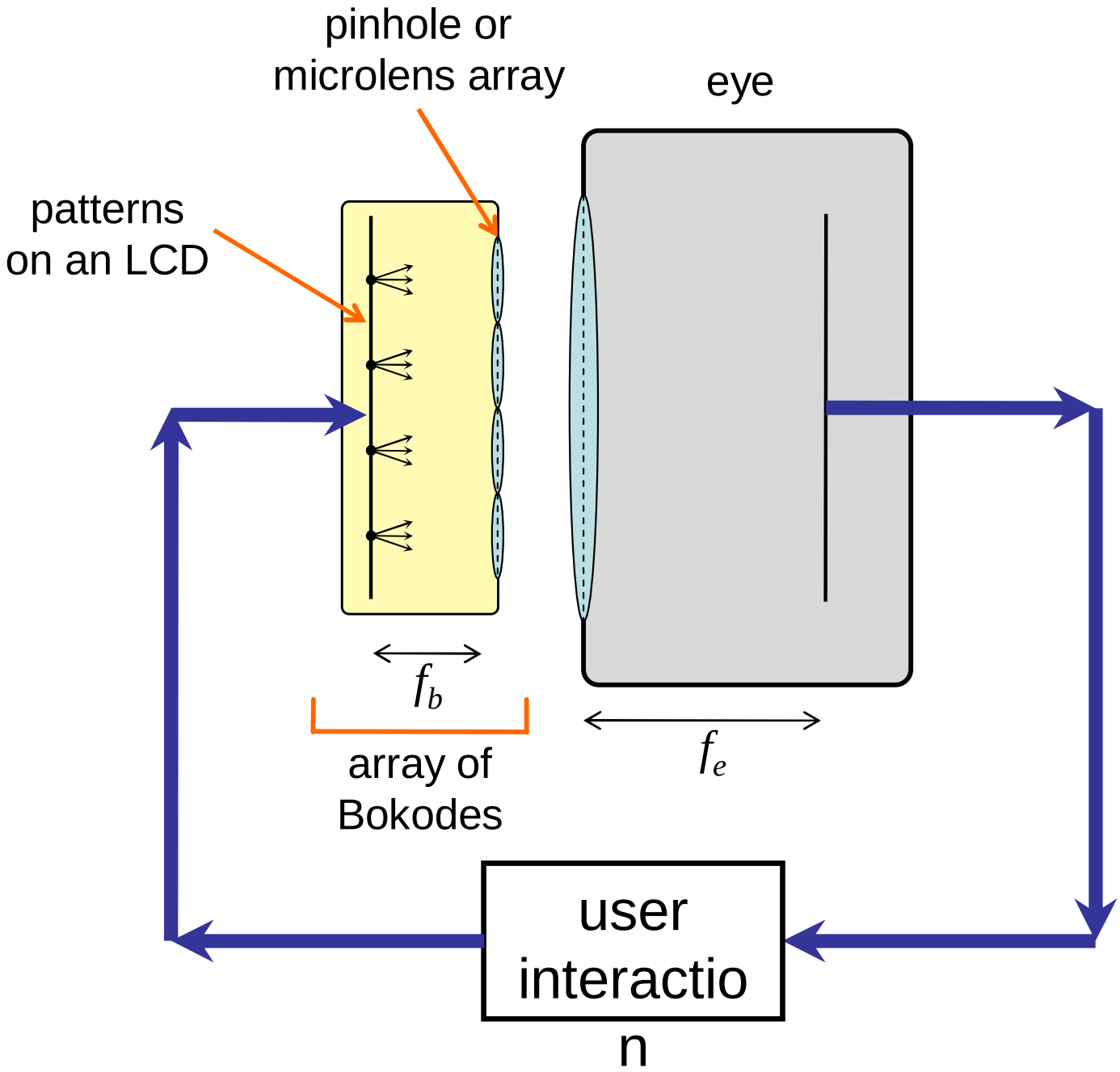
image points
overlap

move points **away** from each other

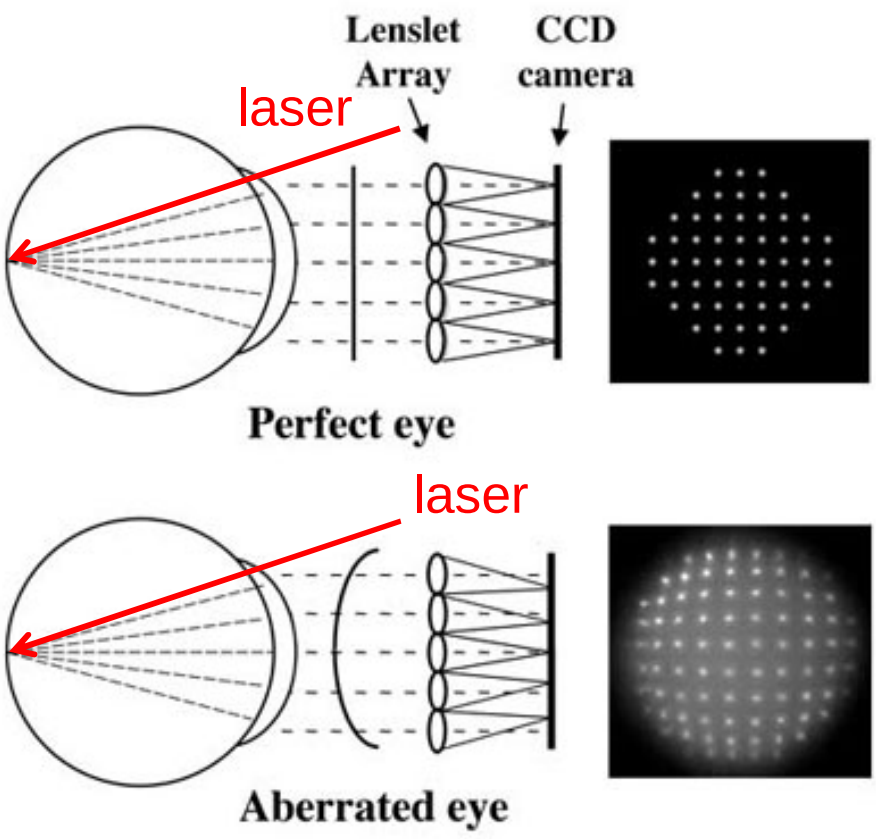
NETRA: interactively measure prescription



NETRA: interactively measure prescription



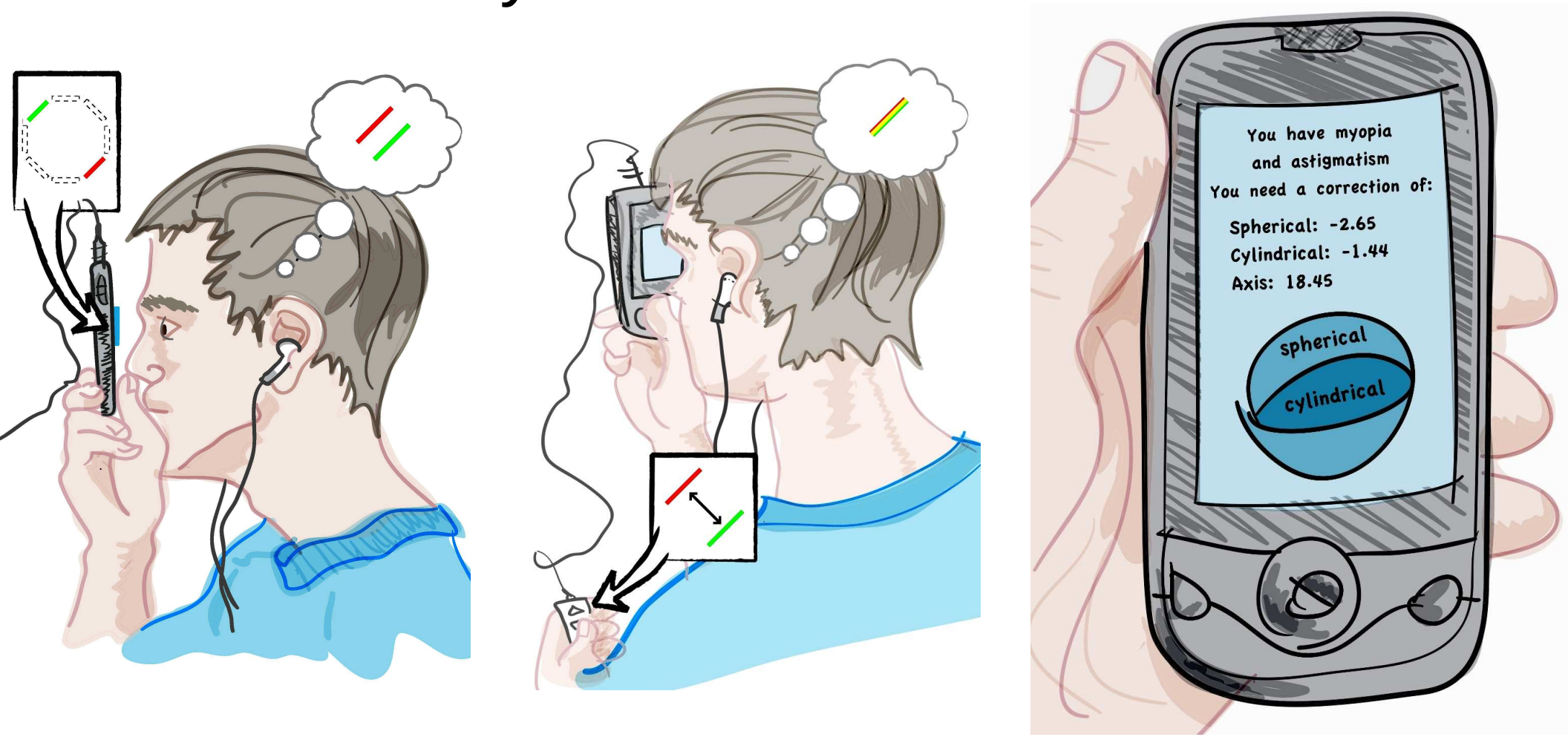
Shack-Hartmann wave-front sensor



wavefront aberroemter

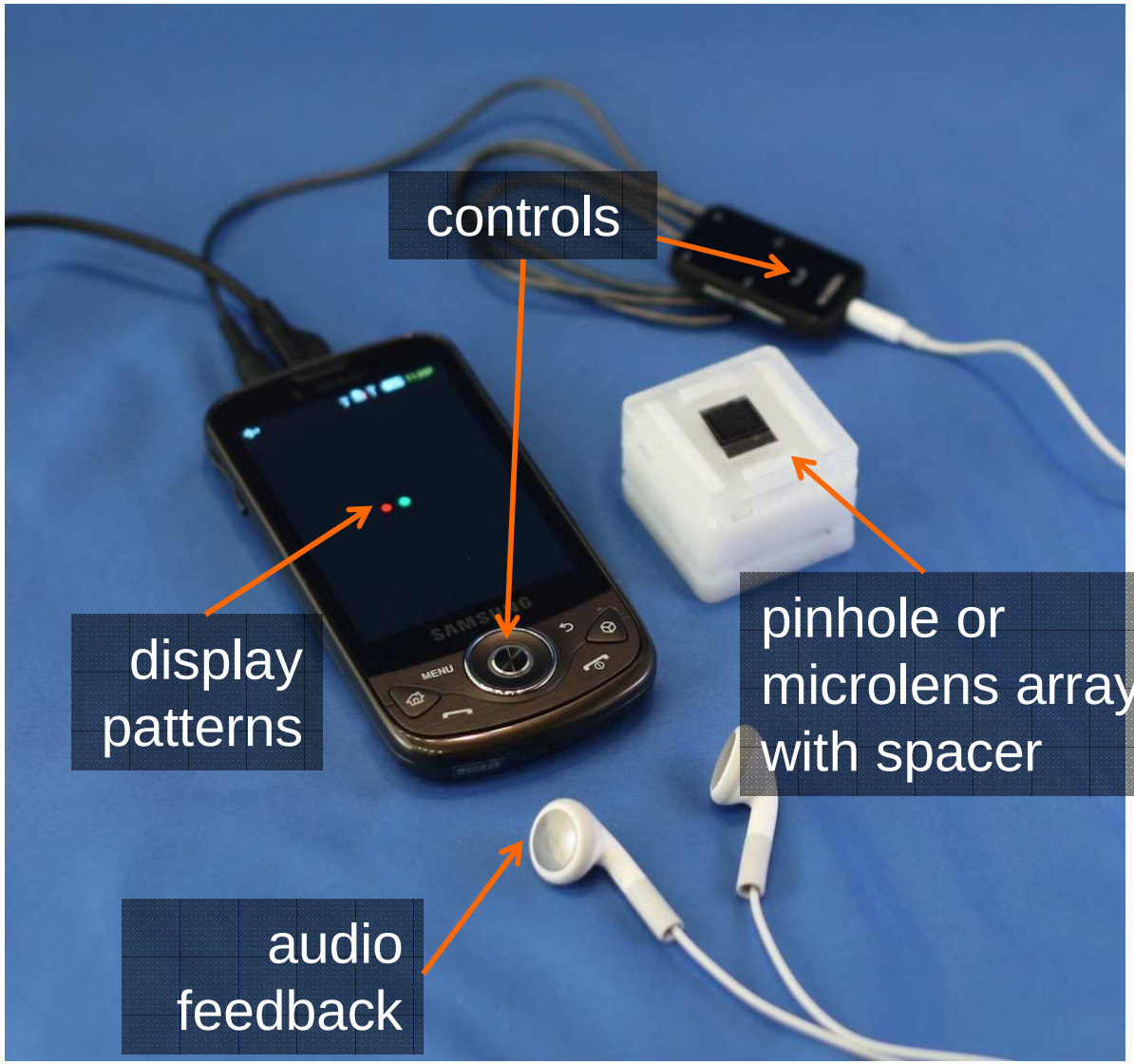
expensive; requires trained professionals

interactive self-evaluation of eye's refractive error



"NETRA: Interactive Display for Estimating Refractive Errors and Focal Range", Vitor Pamplona, Ankit Mohan, Manuel Oliveira, and Ramesh Raskar, in **SIGGRAPH 2010**.

cell phone prototype



lcd: 180dpi

pinhole: a=3mm, Φ~100µm

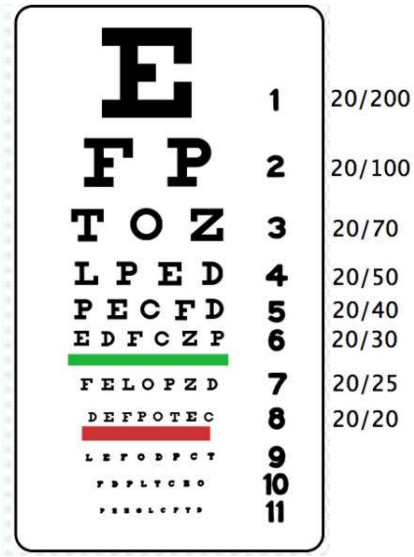
lenslet: f=20mm, a=3mm

resolution: 0.71D

cost: ~$2 (pinhole)

NETRA

vs



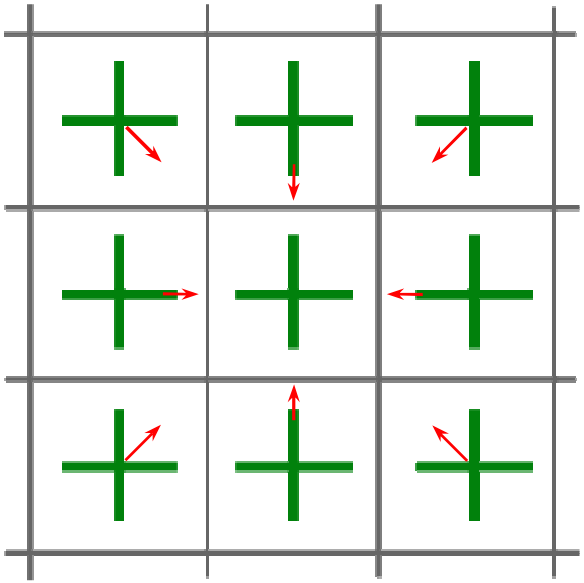
Snellen chart

trial lenses

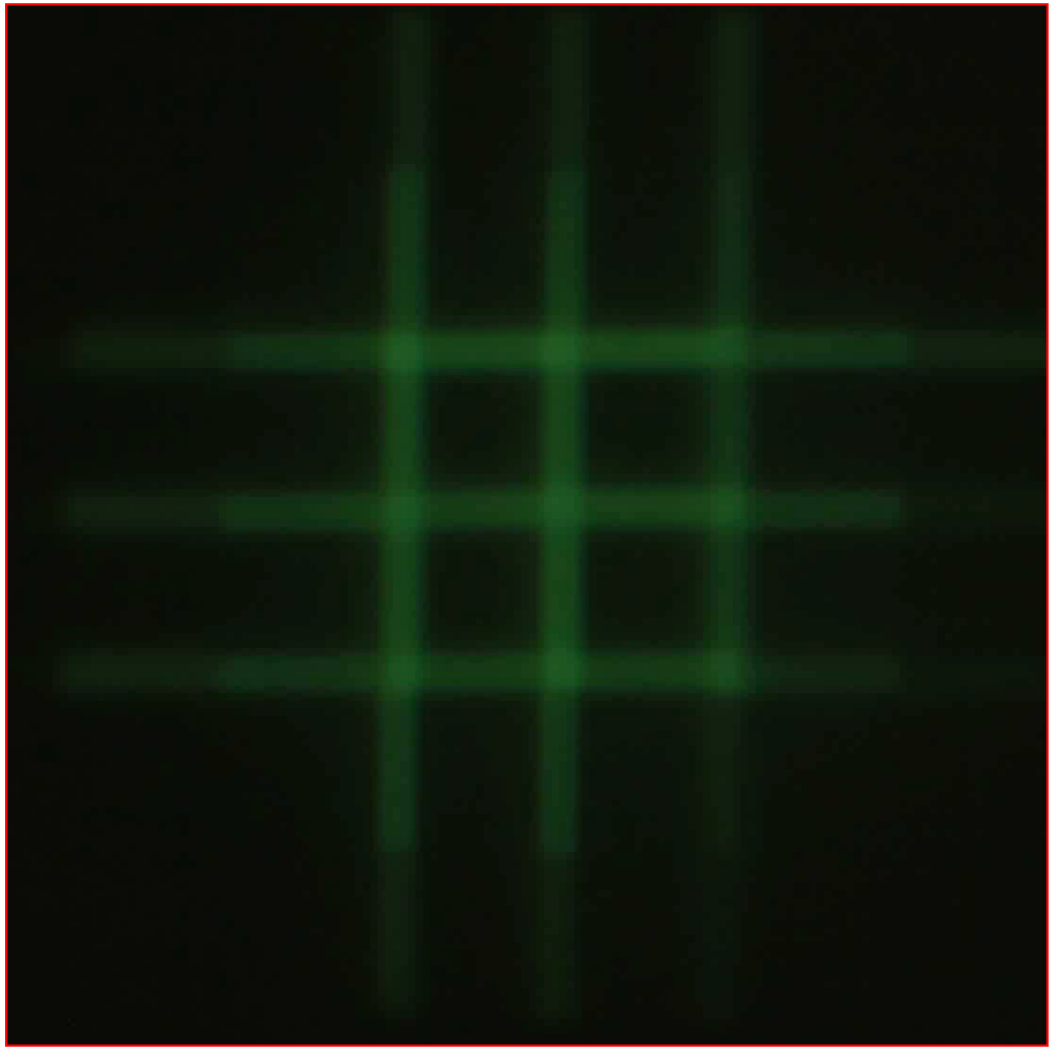
phoropter

- smaller, less bulky, easier to carry
- little no training required
- avoids cycloplegic eye drops
- allows self-evaluation
- cheaper (if phone already exists)

interaction session with camera

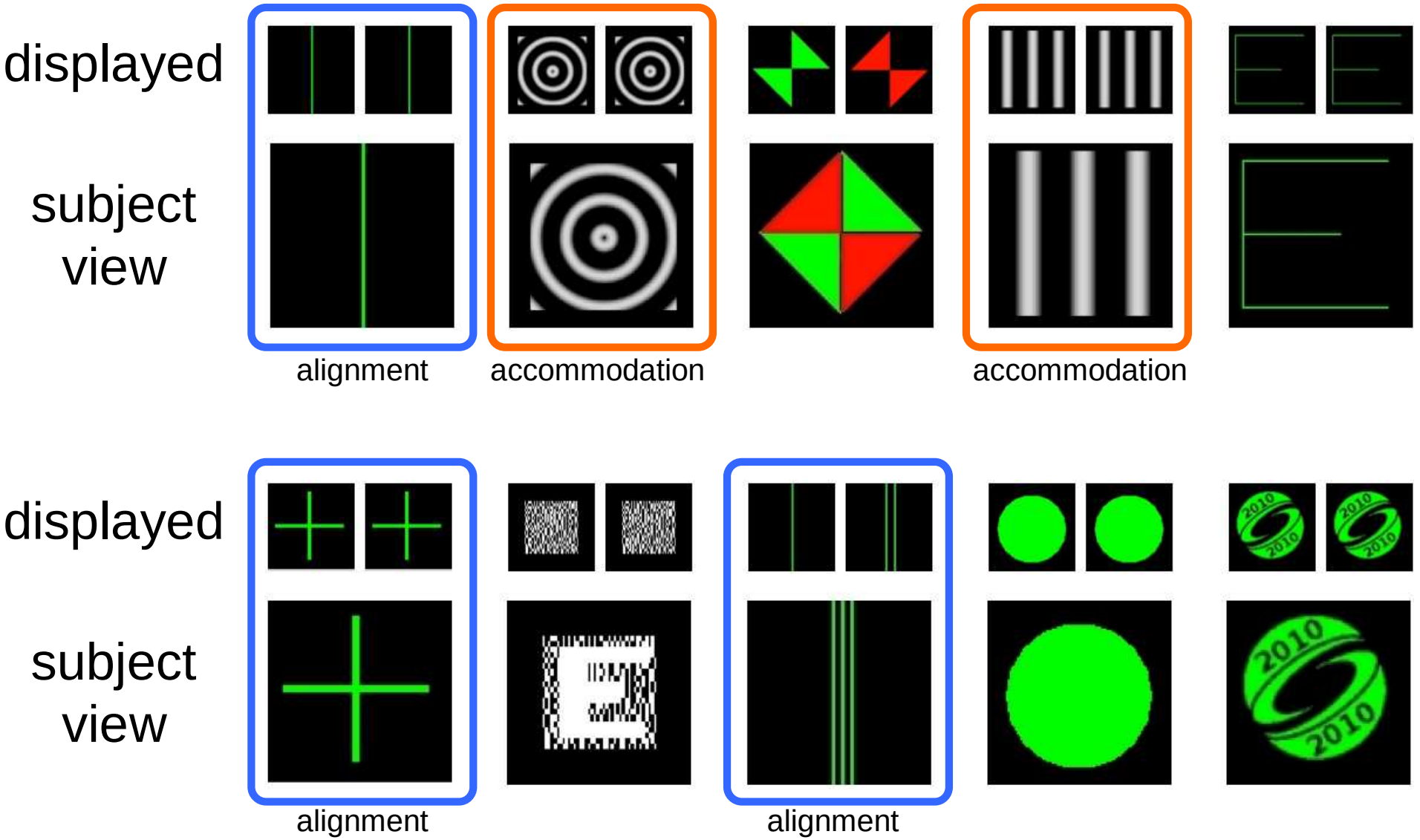


displayed patterns

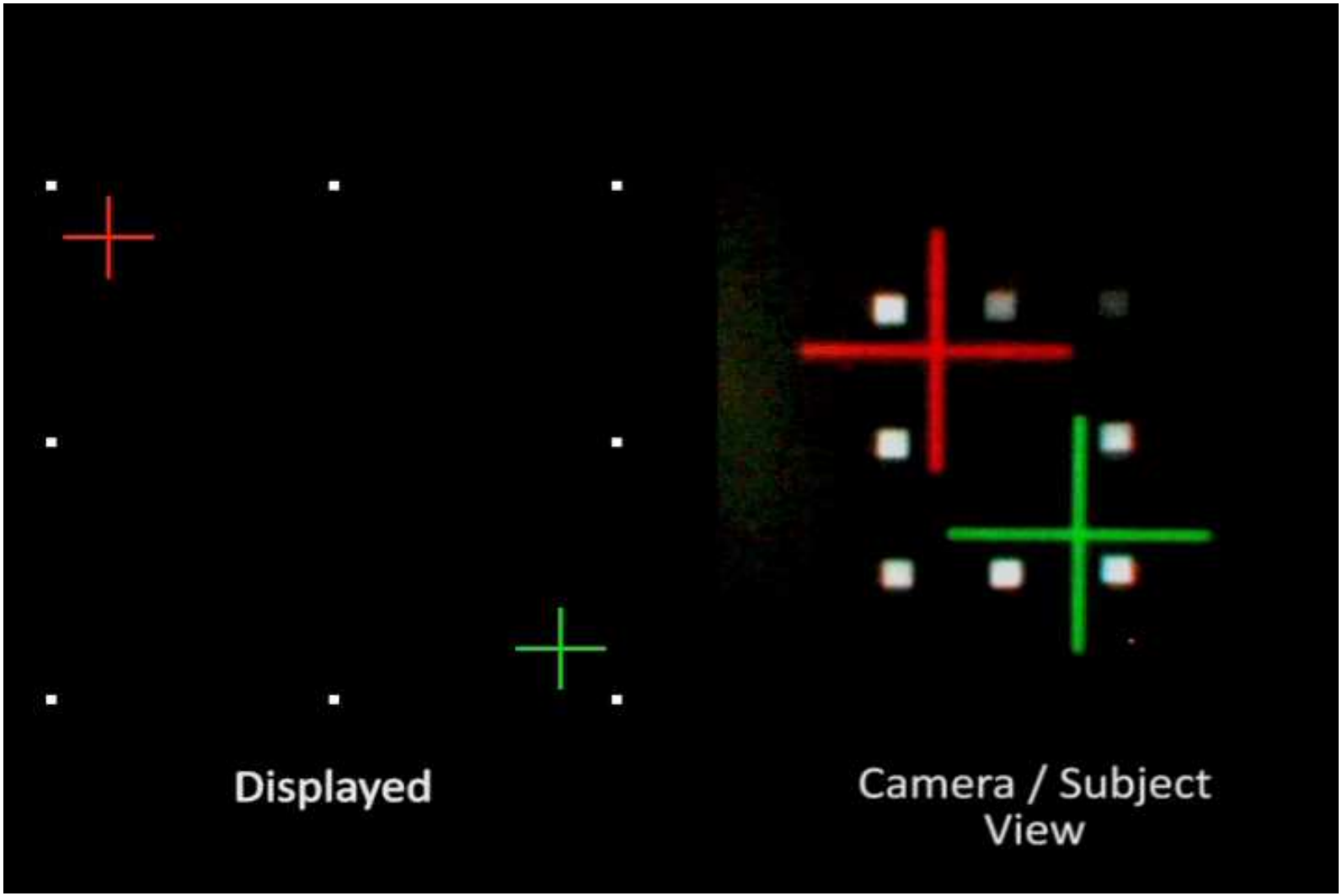


camera/subject view

patterns

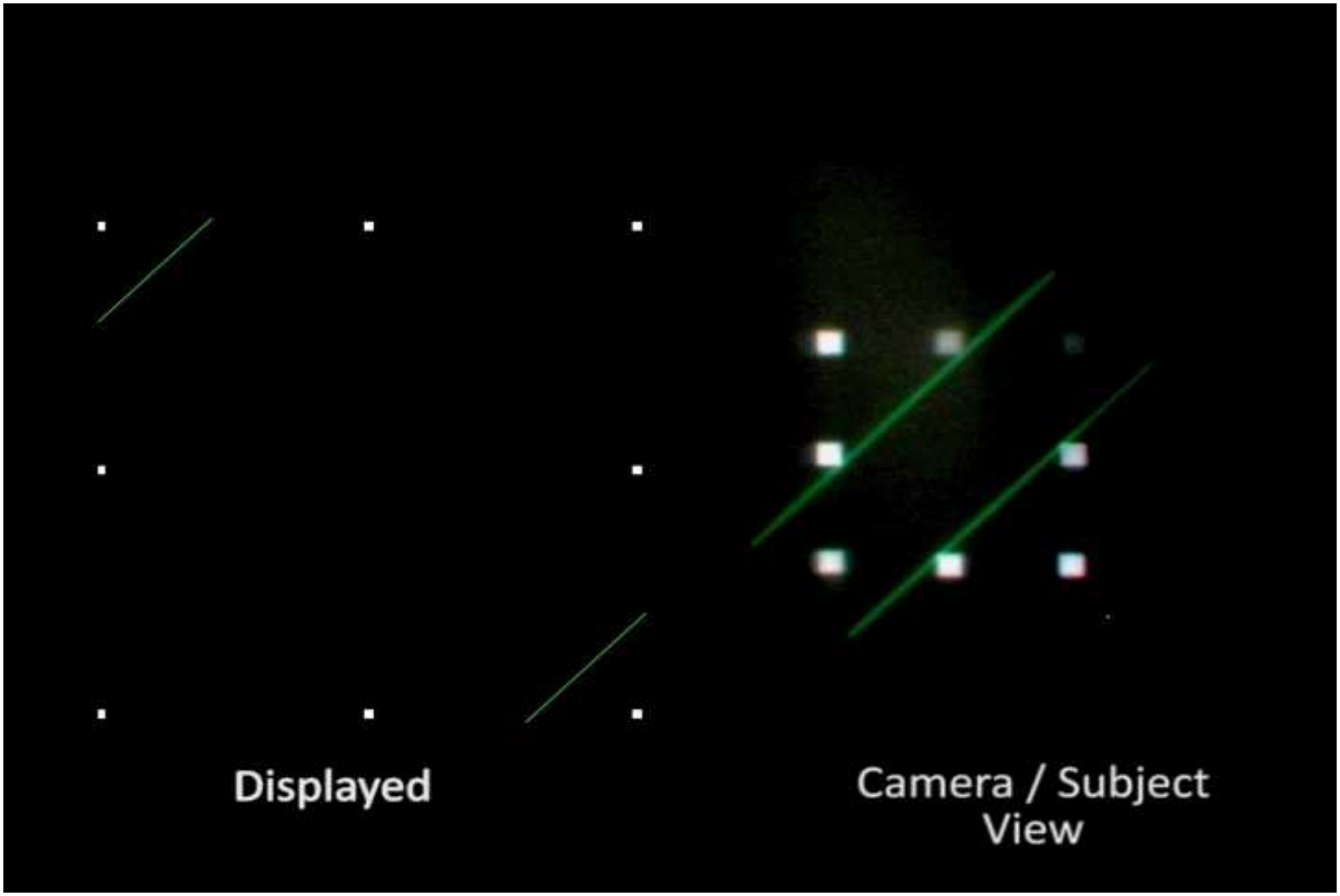

displayed
subject view
alignment
accommodation
accommodation
displayed
subject view
alignment
alignment

astigmatism: radially non-symmetric error



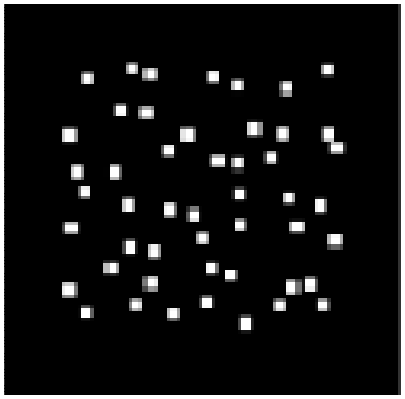
cross or points may never meet with a 1d search

astigmatism

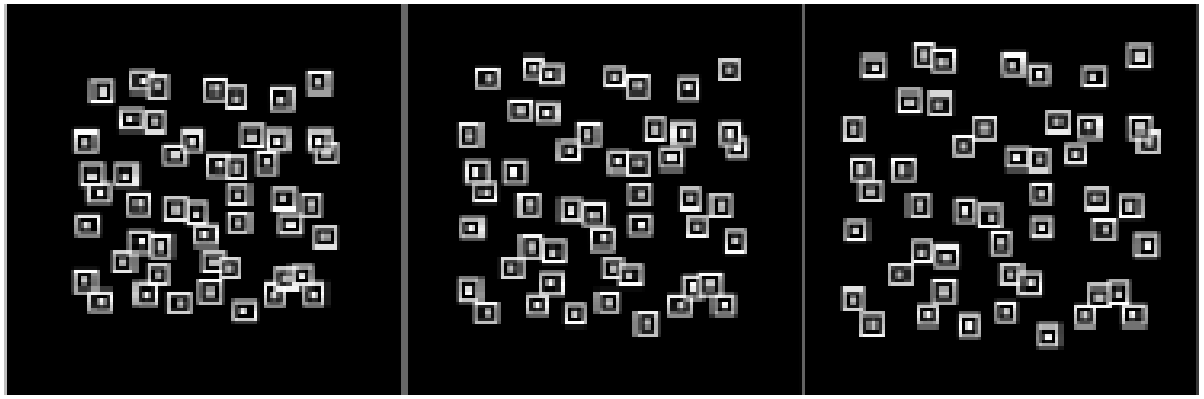


lines reduce the problem to a 1d search

jittered pinholes – reduce crosstalk

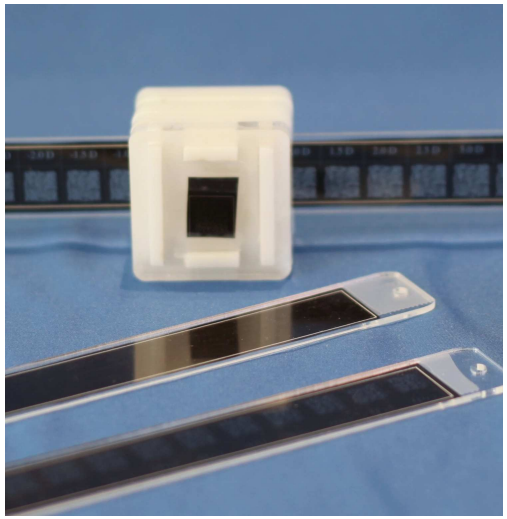


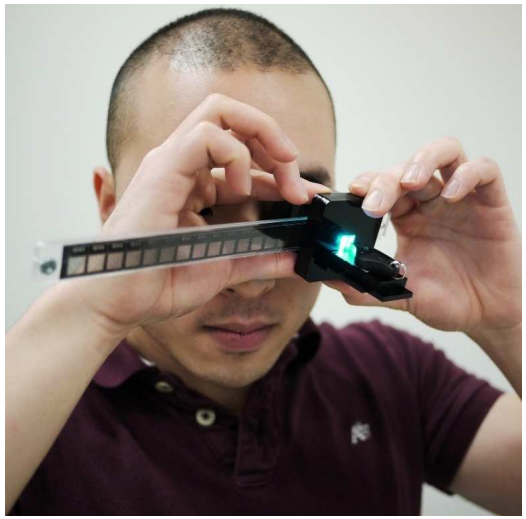
jittered pinholes



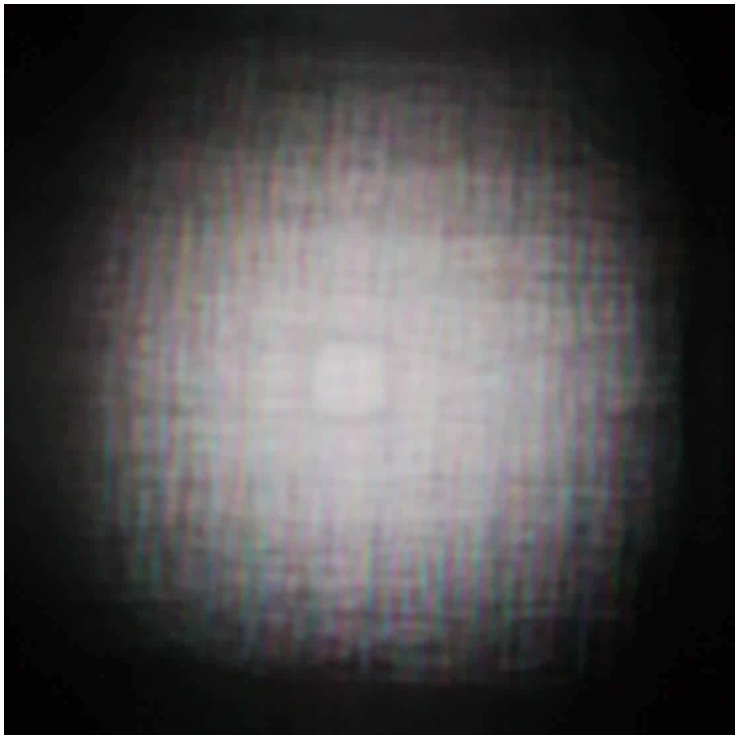
-5D 0D +5D

display patterns



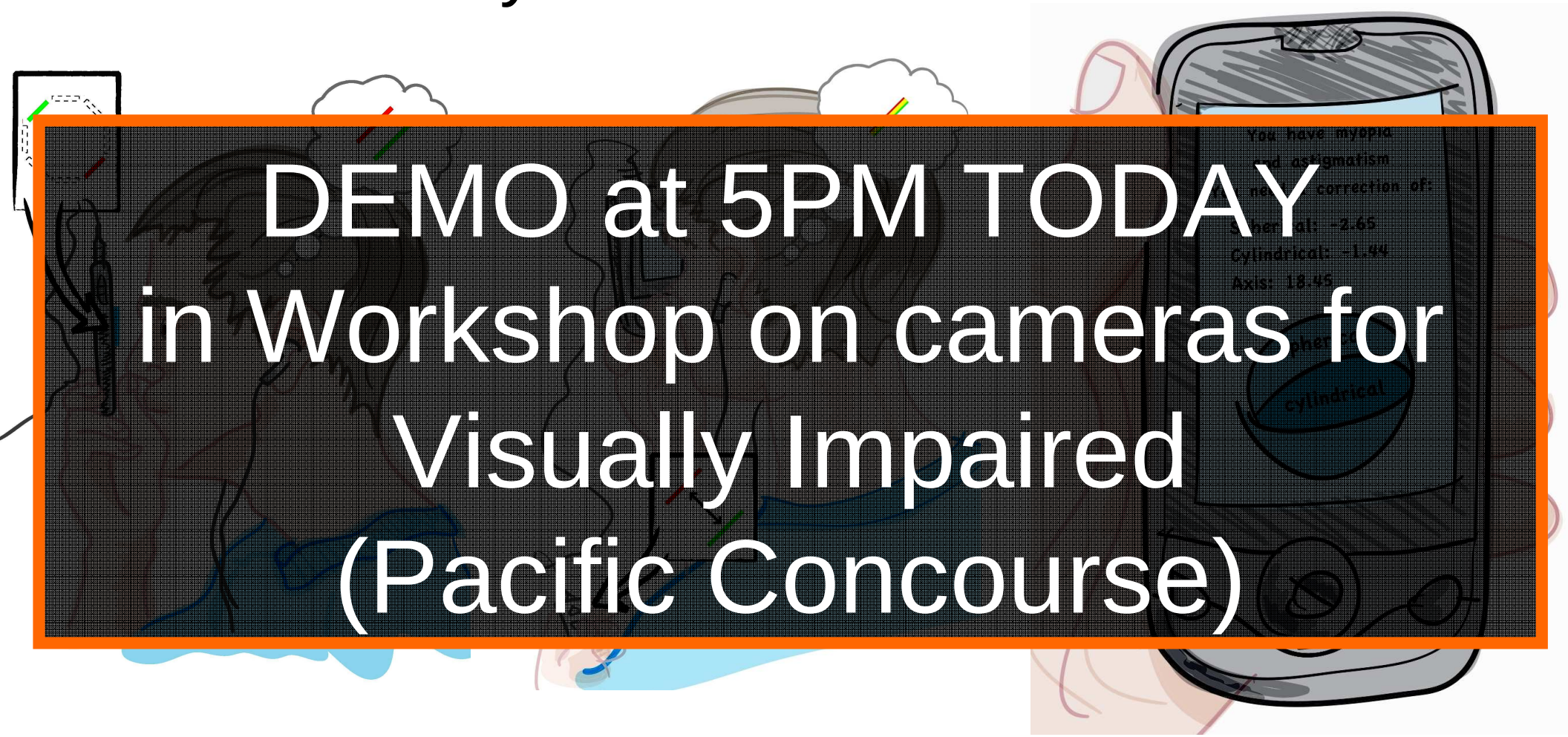


viewmaster inspired prototype



+3D to -5D with accommodation

interactive self-evaluation of eye's refractive error

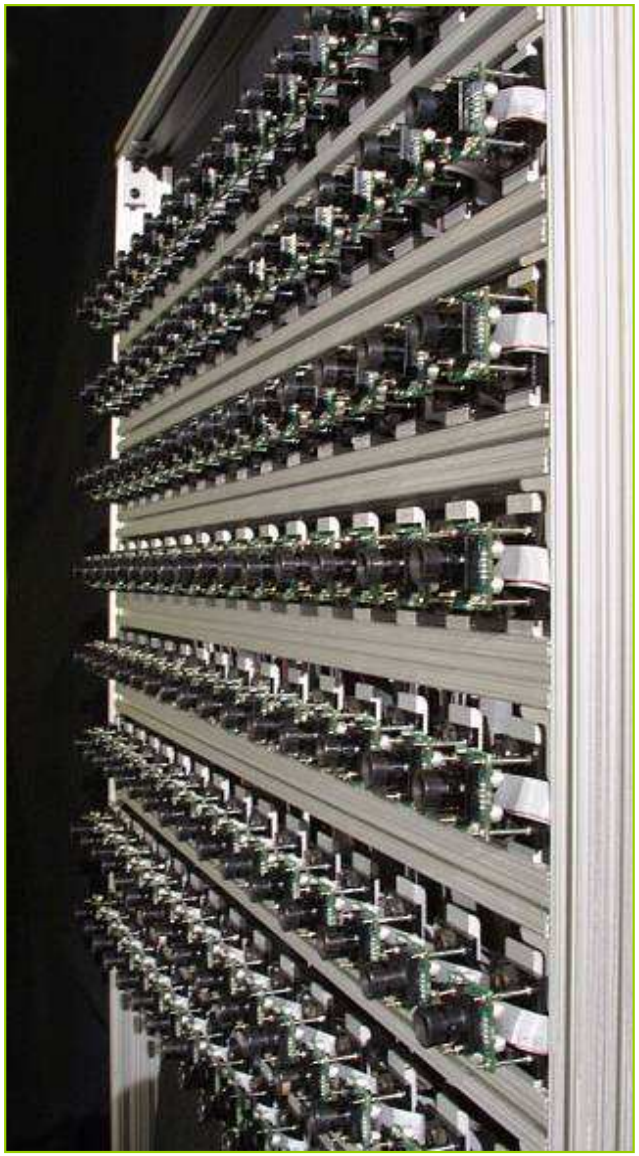


DEMO at 5PM TODAY in Workshop on cameras for Visually Impaired (Pacific Concourse)

"NETRA: Interactive Display for Estimating Refractive Errors and Focal Range", Vitor Pamplona, Ankit Mohan, Manuel Oliveira, and Ramesh Raskar, in **SIGGRAPH 2010**.

Light Field Capture

Camera Arrays [Wilburn 2005]



"High Performance Imaging Using Large Camera Arrays", Bennett Wilburn, Neel Joshi, Vaibhav Vaish, Eino-Ville Talvala, Emilio Antunez, Adam Barth, Andrew Adams, Mark Horowitz, Marc Levoy, in **SIGGRAPH 2005**.

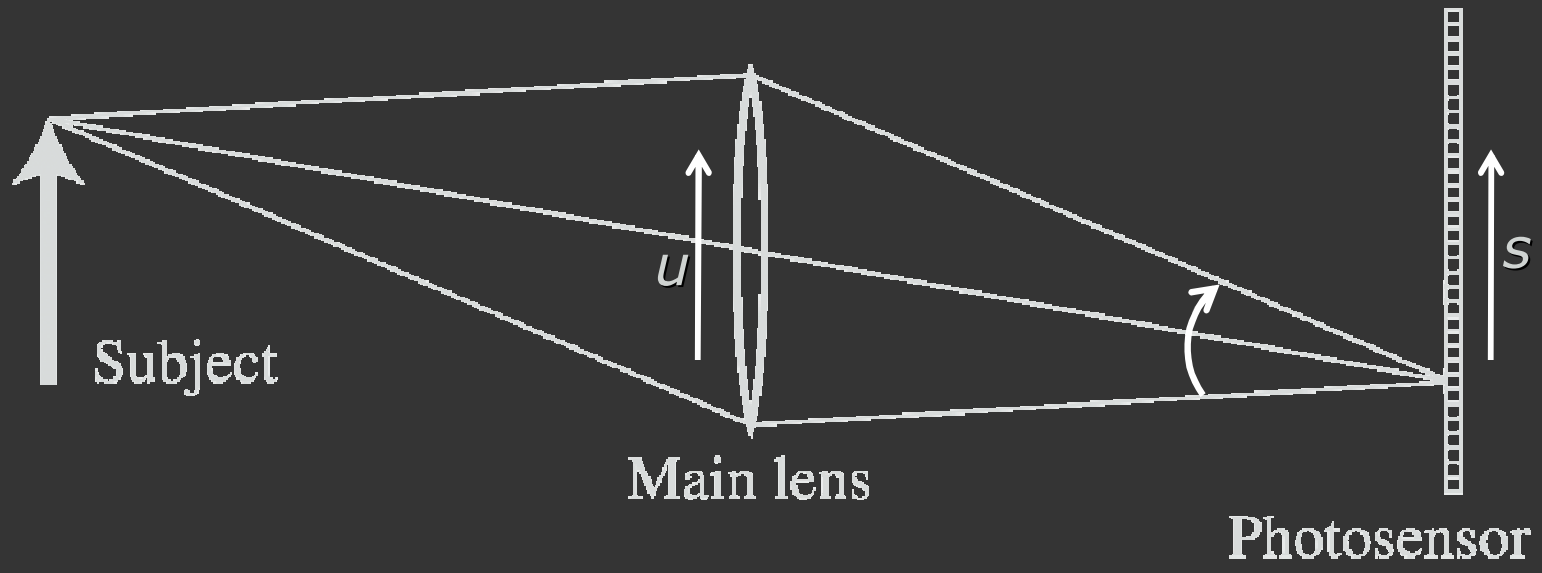
Synthetic aperture photography

Camera array is far away from these bushes, yet it sees…

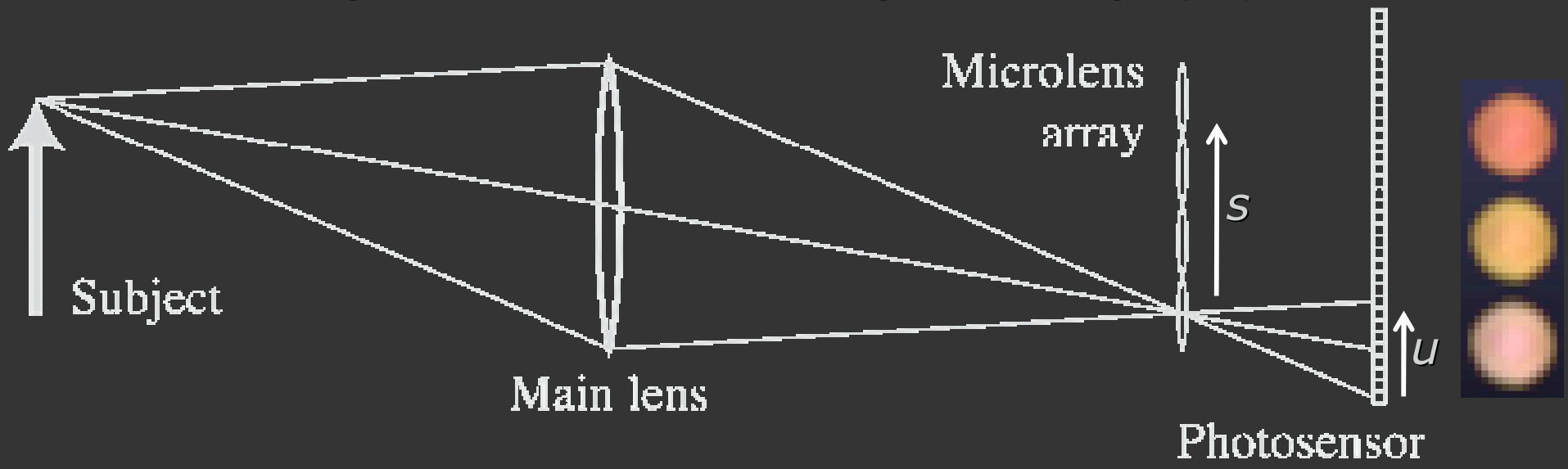
Focus Adjustment: Sum of Bundles

[Vaish et al. 2004]

Light Field Inside a Camera



Lenslet-based Light Field camera / Integral Photography

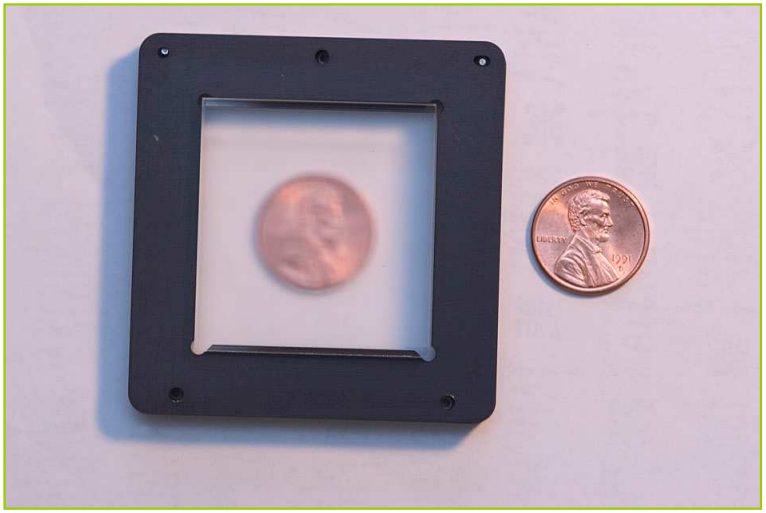


[Lippman 1908, Adelson and Wang, 1992, Ng et al. 2005]

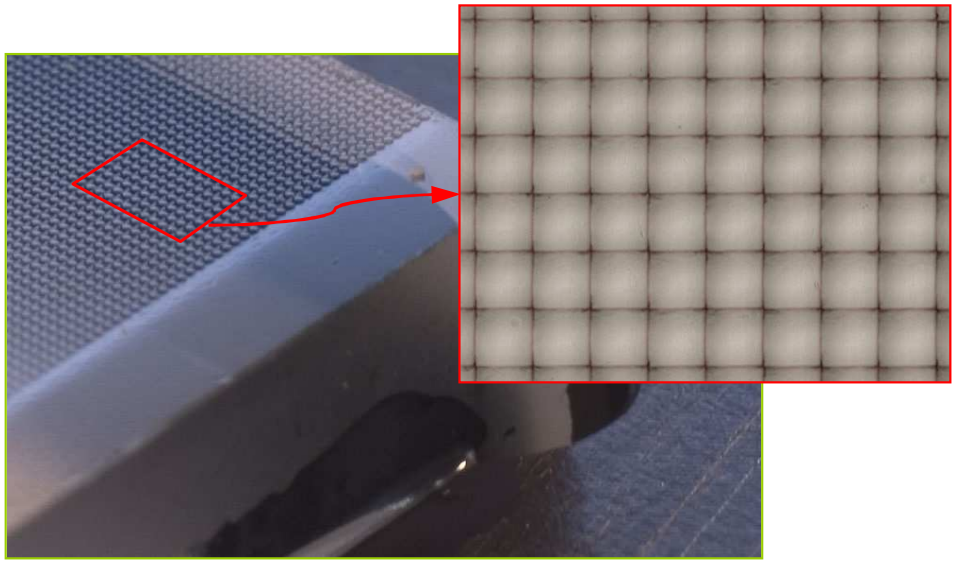
Stanford Plenoptic Camera [Ng et al 2005]

Contax medium format camera

Kodak 16-megapixel sensor



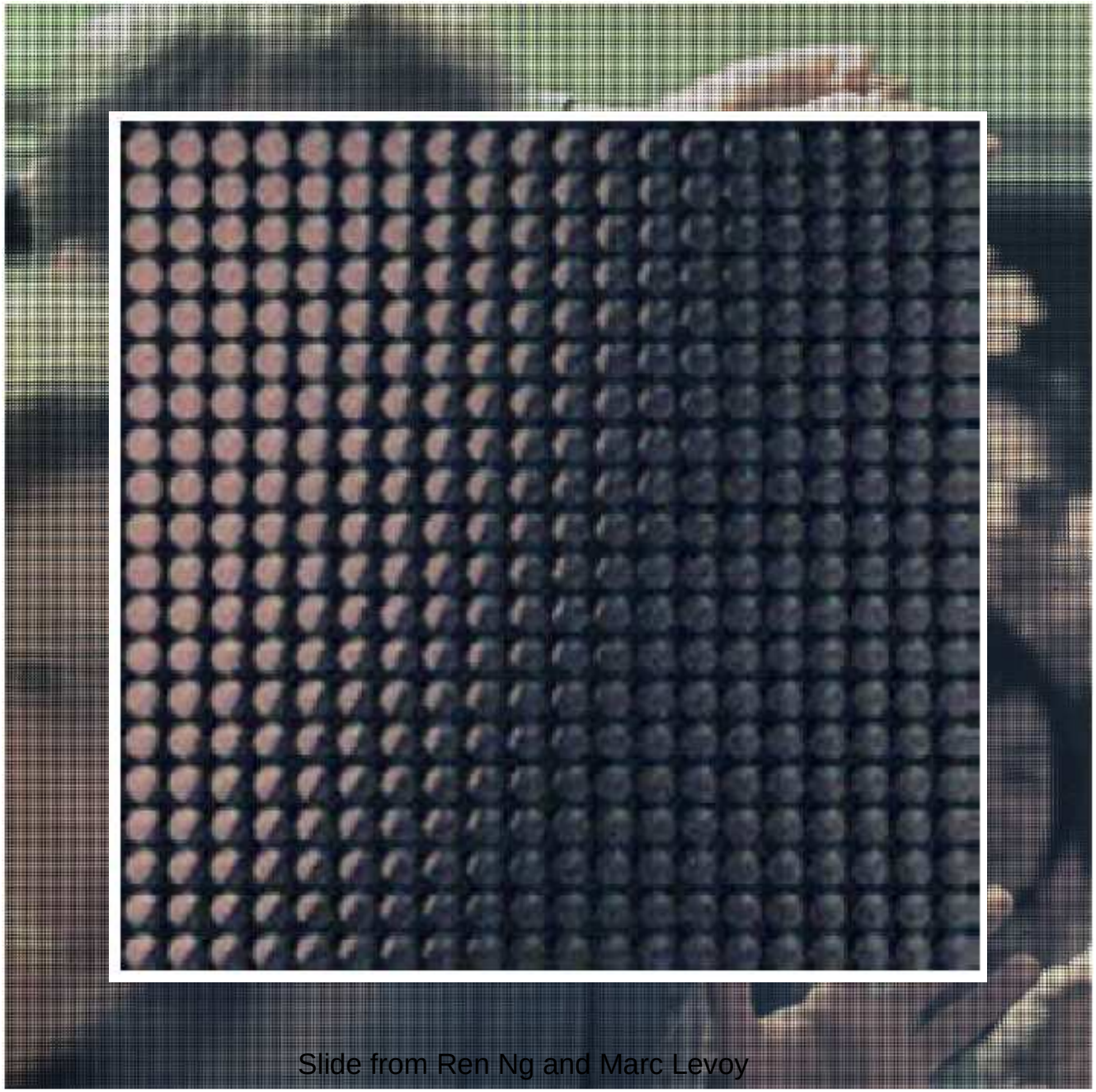
Adaptive Optics microlens array



125 μ square-sided microlenses

4000 × 4000 pixels ÷ 292 × 292 lenses = 14 × 14 pixels per lens

Captured Image Behind Microlens



Slide from Ren Ng and Marc Levoy

Digital Refocusing [Ng et al 2005]

"Light Field Photography with a Hand-Held Plenoptic Camera", Ren Ng, Marc Levoy, Mathieu Bredif, Gene Duval, Mark Horowitz, Pat Hanrahan, in **Stanford Tech Report 2005**.

Extended Depth of Field

Light field

↓

focal stack

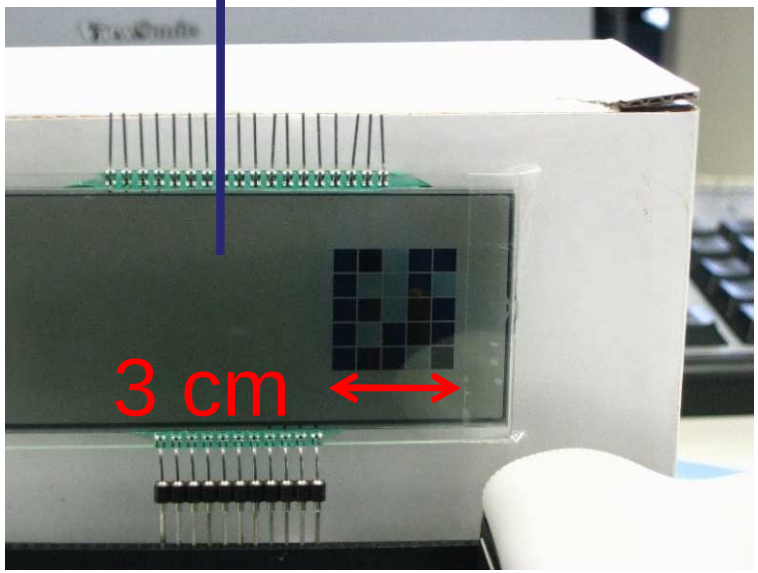
↓

extended DOF

Light Field Capture with a Programmable Aperture

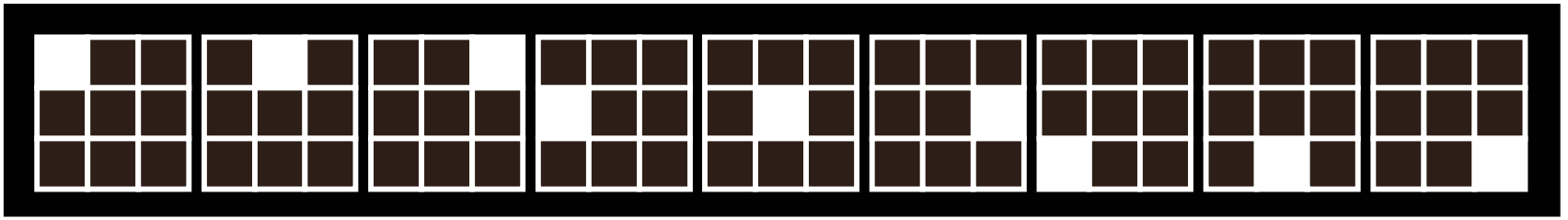
Nikon D70

Liquid crystal array

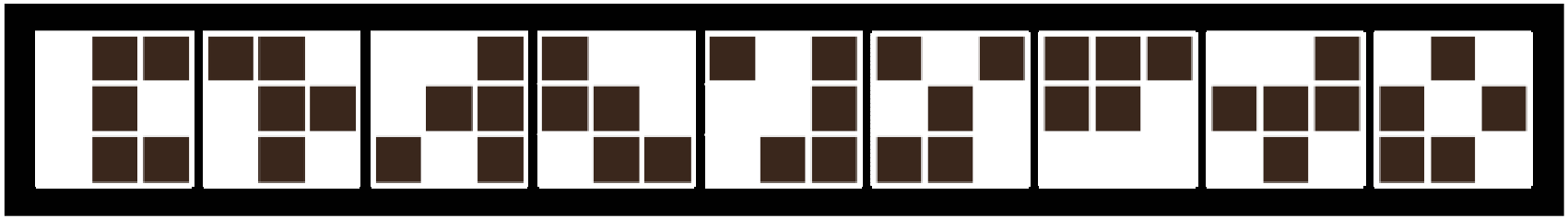


"Programmable Aperture Photography: Multiplexed Light Field Acquisition", Chia-Kai Liang, Tai-Hsu Lin, Bing-Yi Wong, Chi Liu, Homer Chen, in **SIGGRAPH 2008**.

Multiplexing to improve SNR



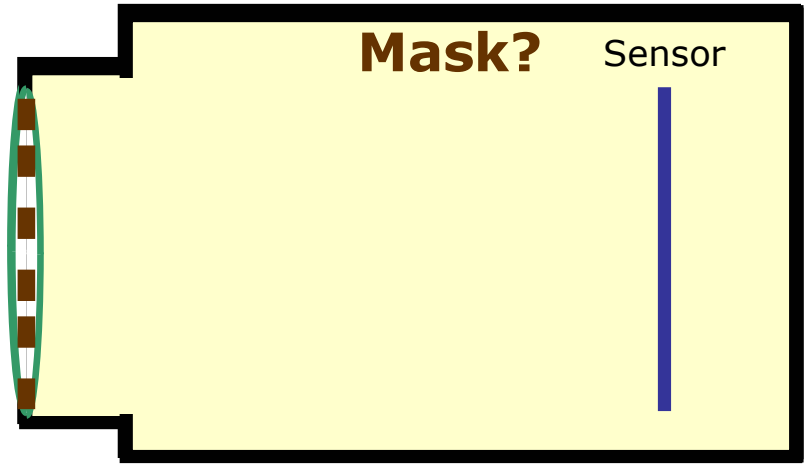
9 aperture patterns for capturing a light field with 3x3 angular resolution

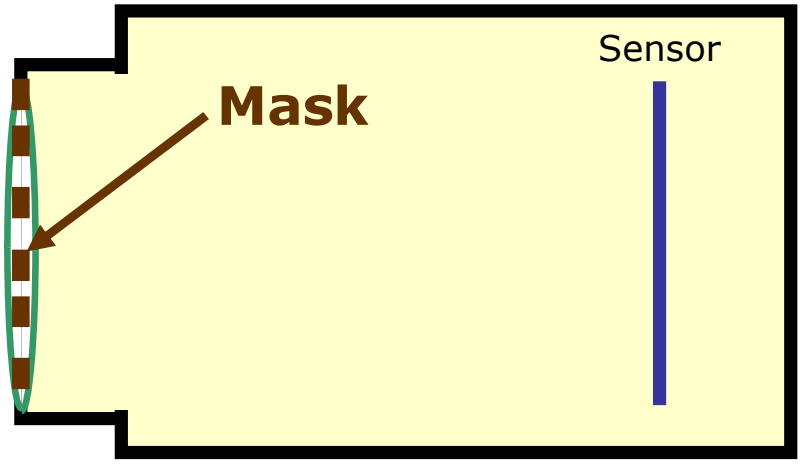


9 multiplexed aperture patterns

- O(*N*) SNR improvement
  - Comparable to previous single-shot light field cameras
- SNR is a function of
  - $\mathbf{W}$ (aperture patterns)
  - The camera noise characteristics

Can we capture the Light-Field using a static mask?





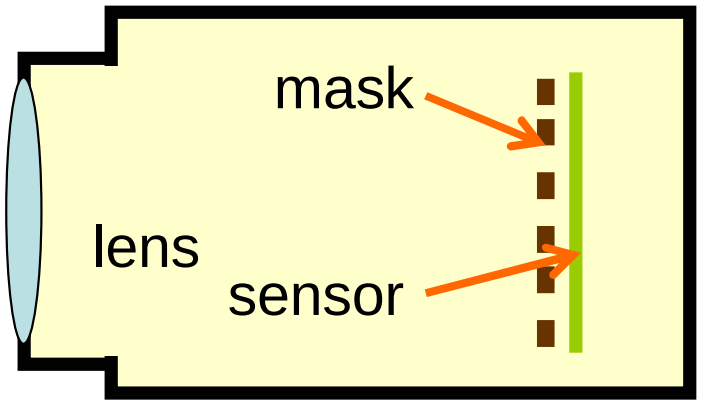
Full Resolution Digital Refocusing:

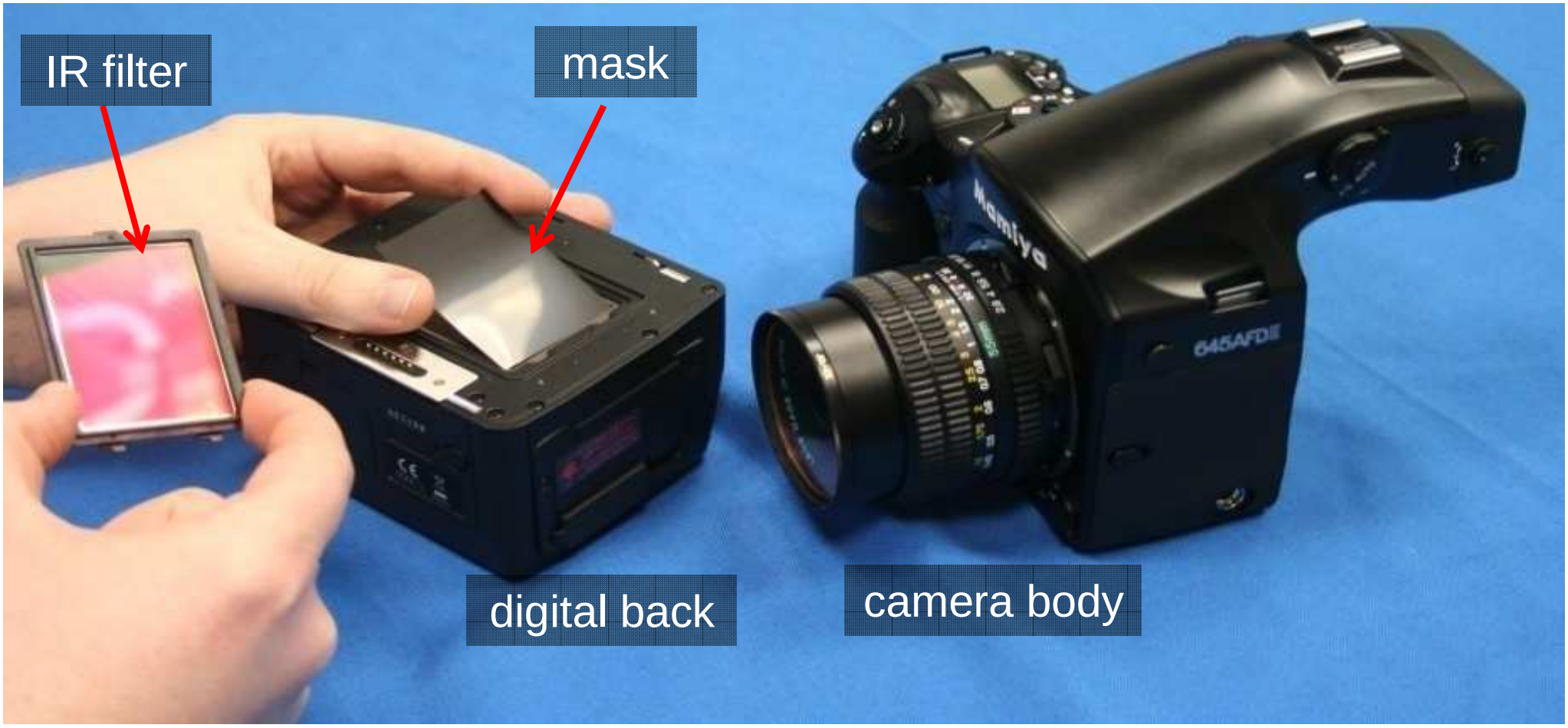
Coded Aperture Camera

4D Light Field from 2D Photo:

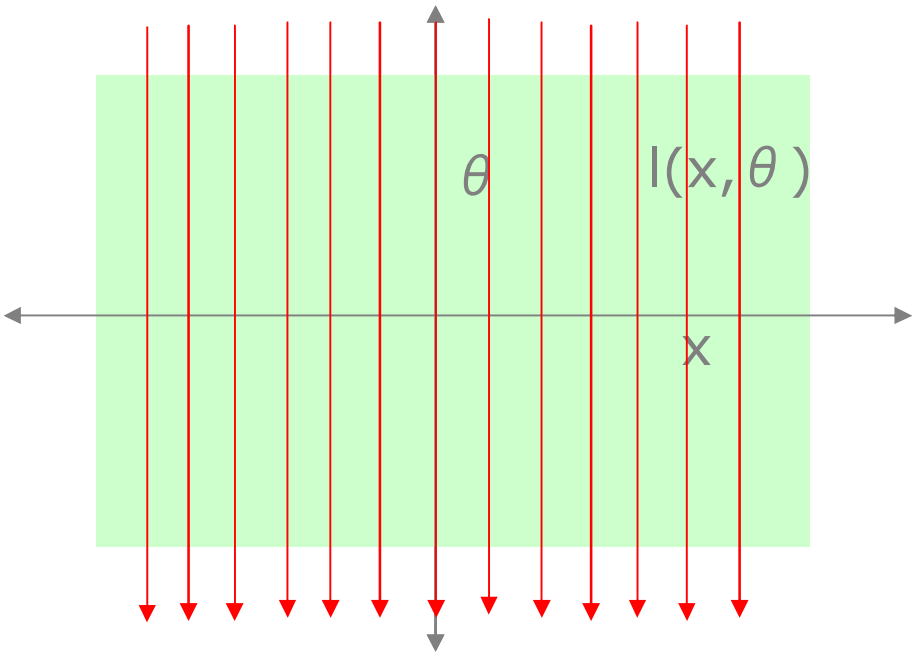
Heterodyne Light Field Camera

mask based light-field camera

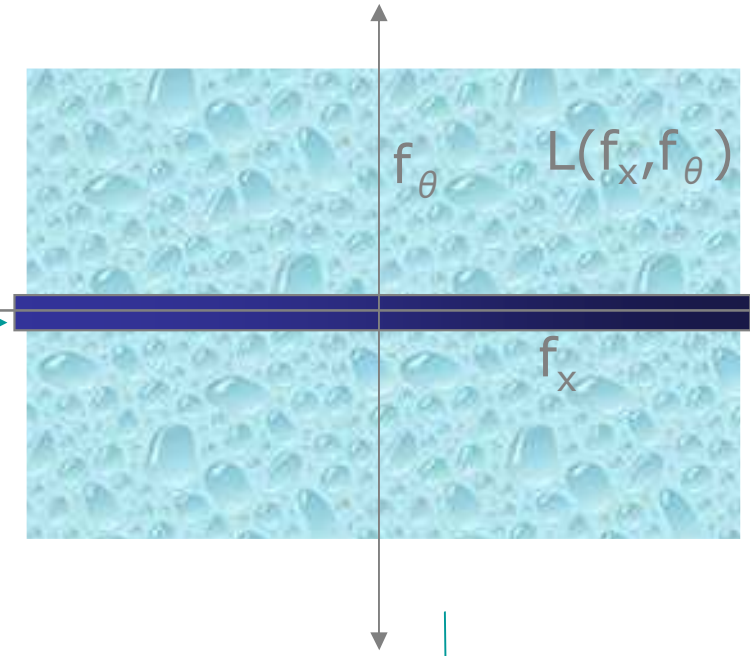




Fourier Slice Theorem



2-D FFT

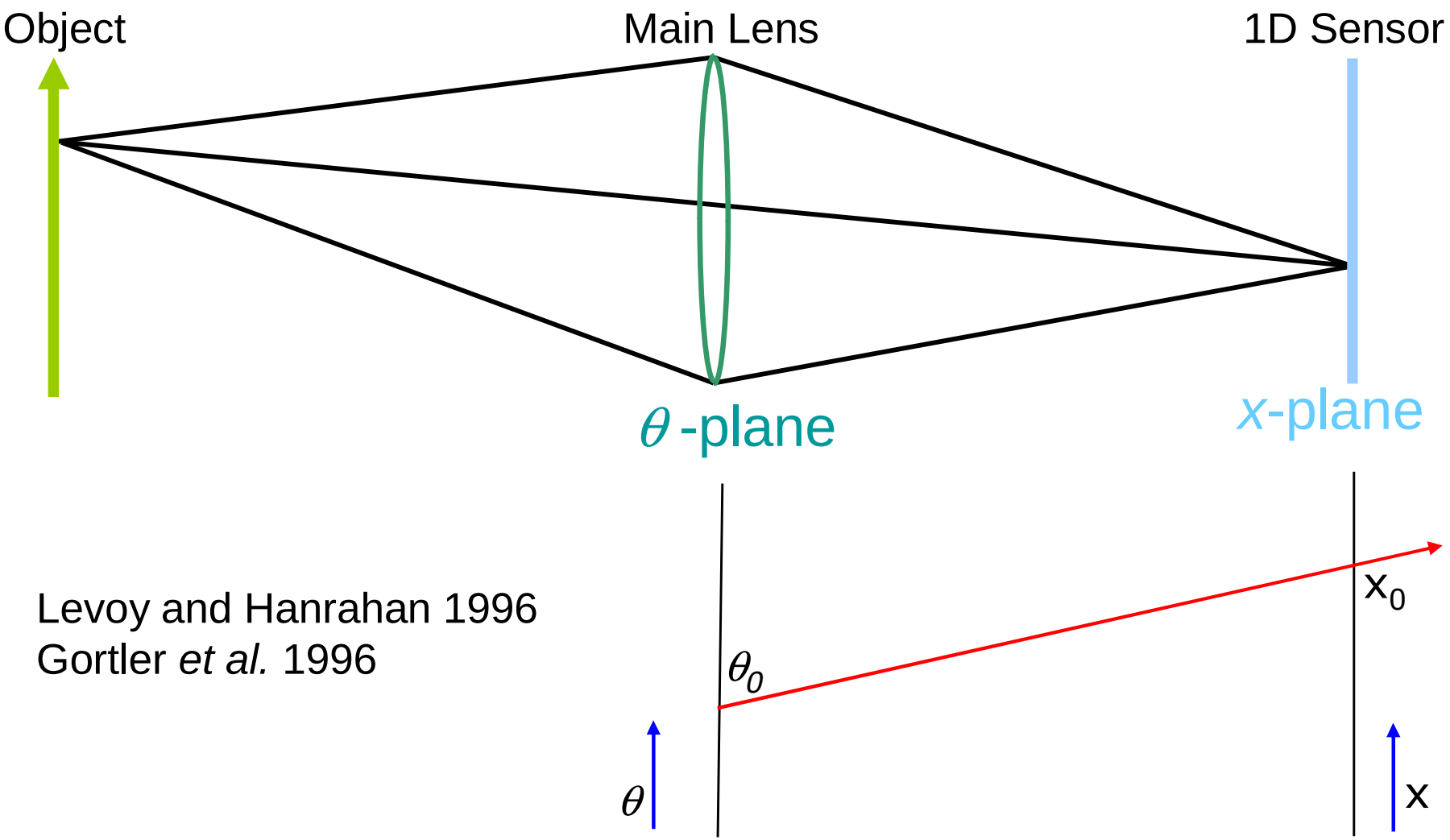


Line Integral

Central Slice

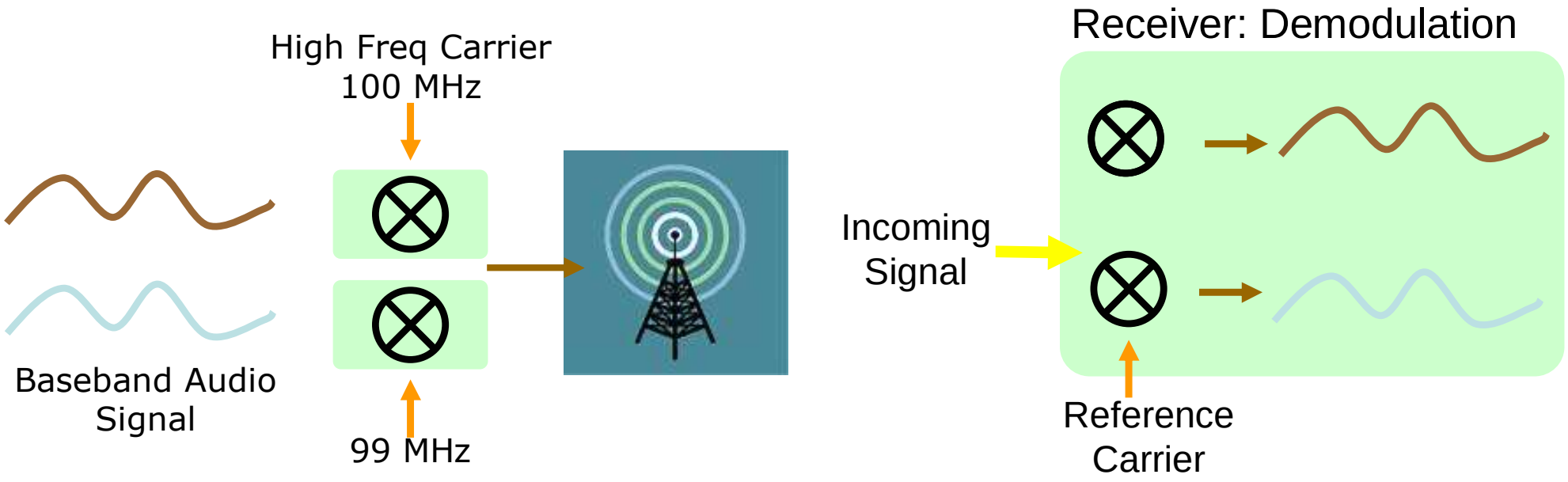
1-D FFT

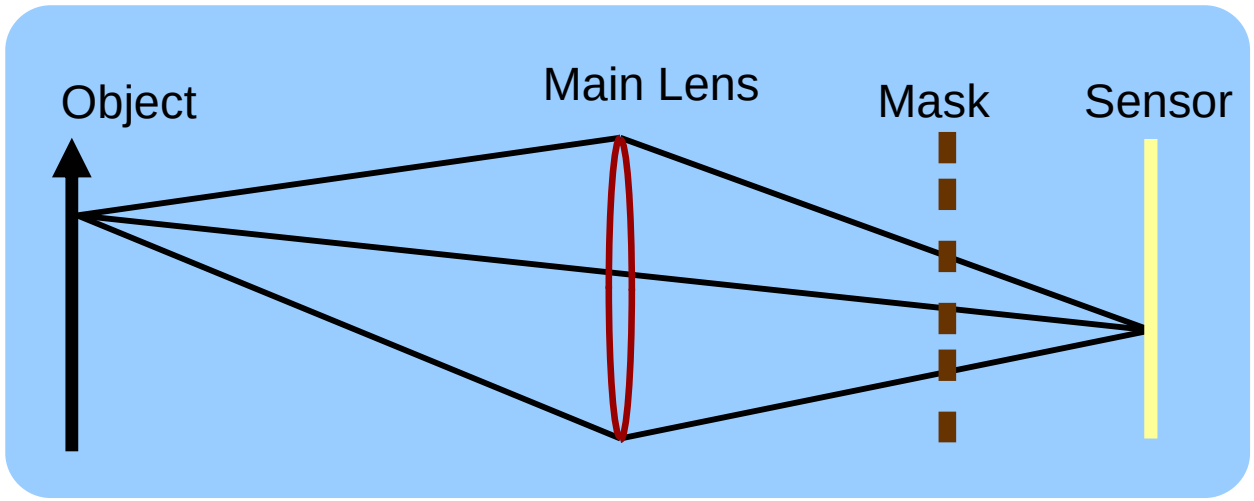
Two-Plane Parameterization of Light Field

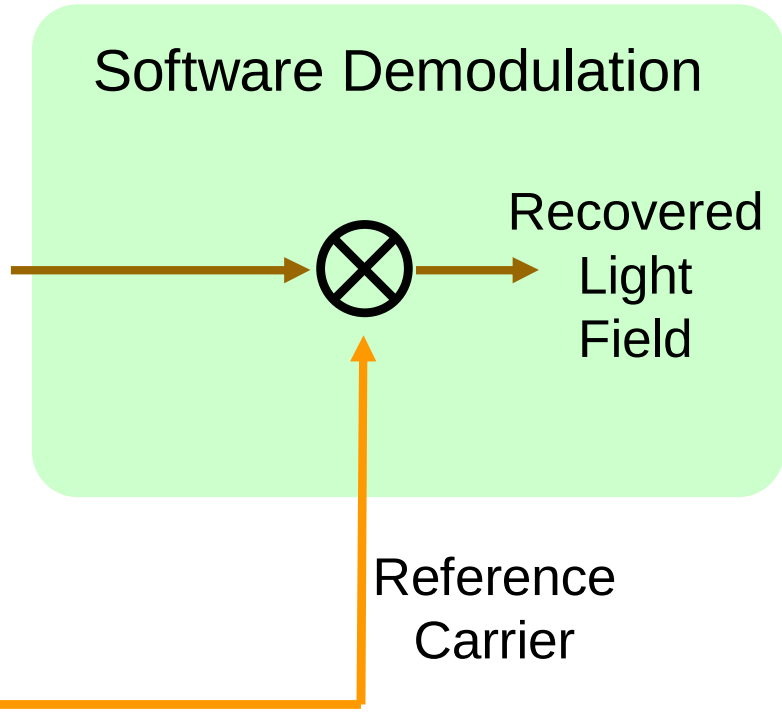


Levoy and Hanrahan 1996
Gortler *et al.* 1996

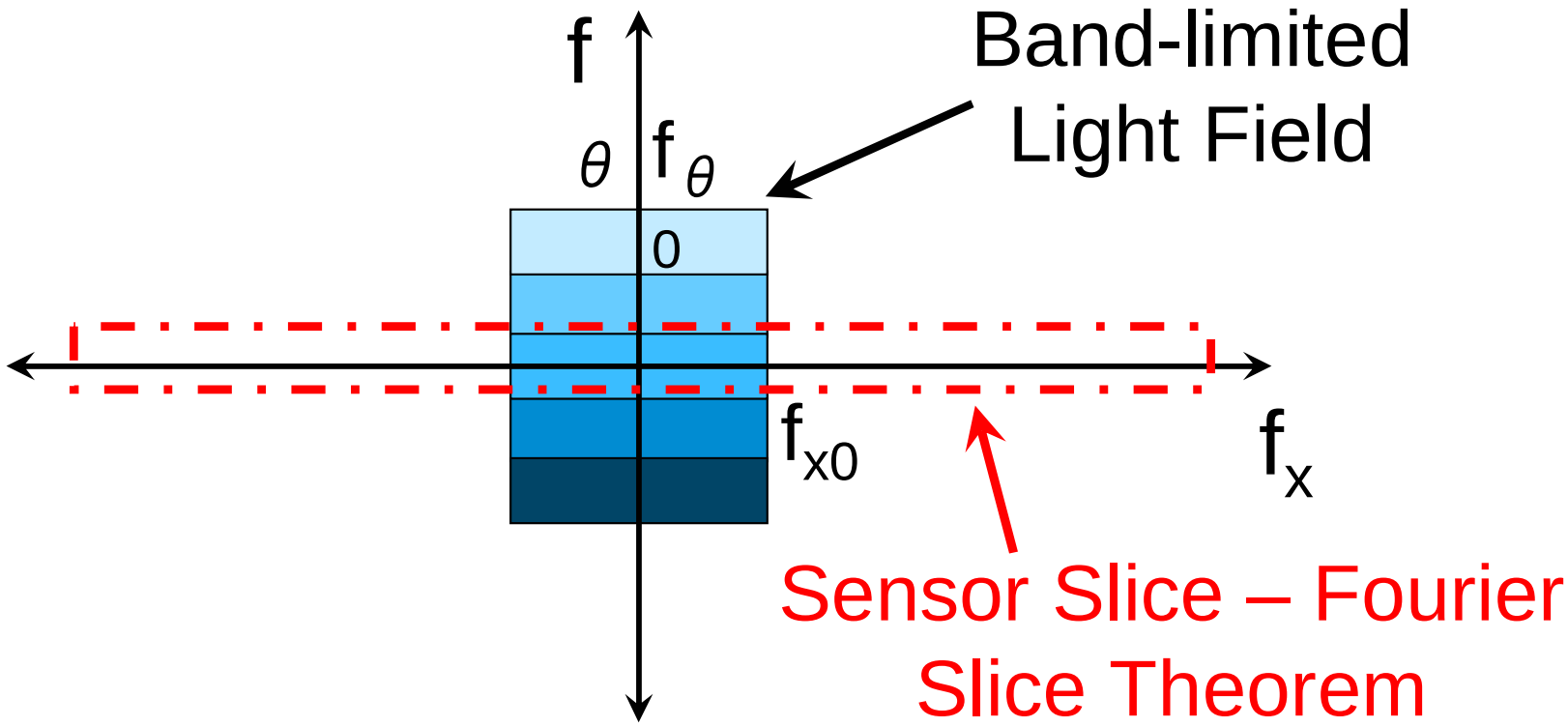
Optical Heterodyning





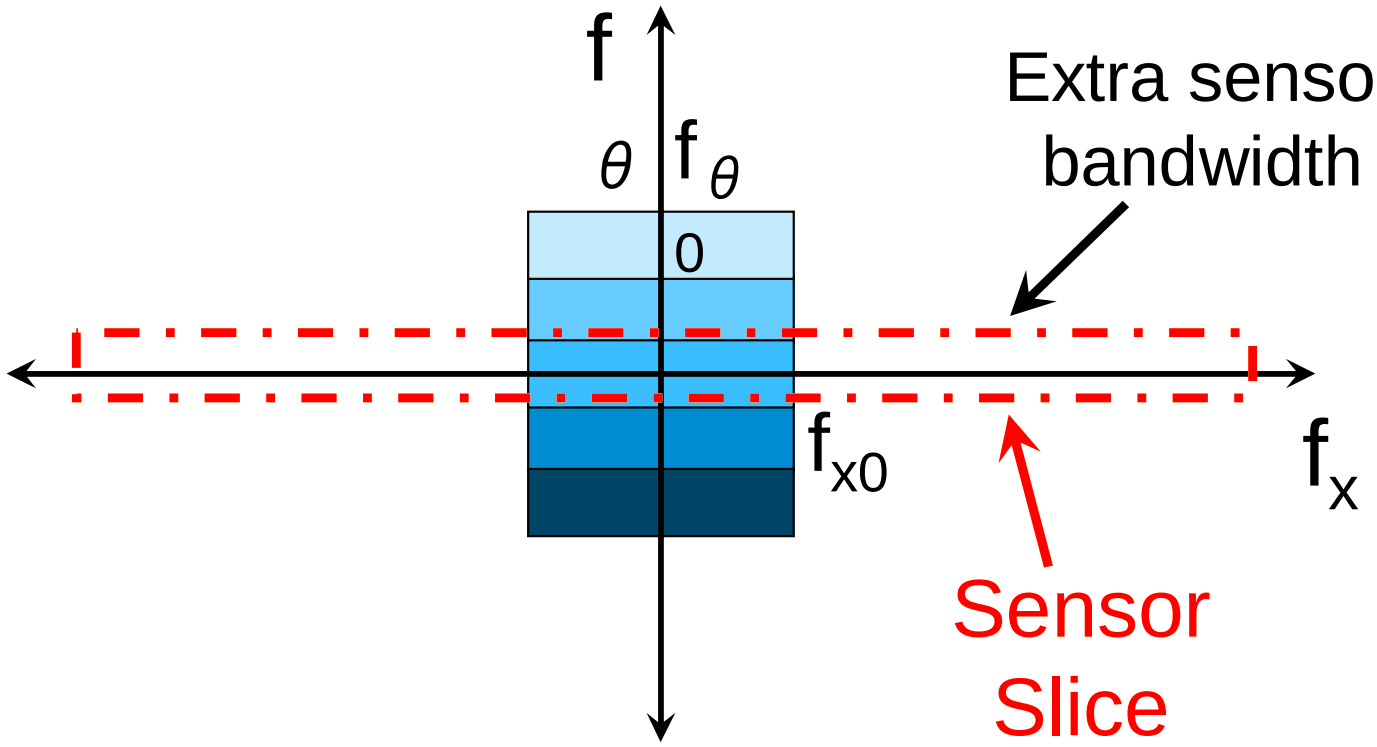


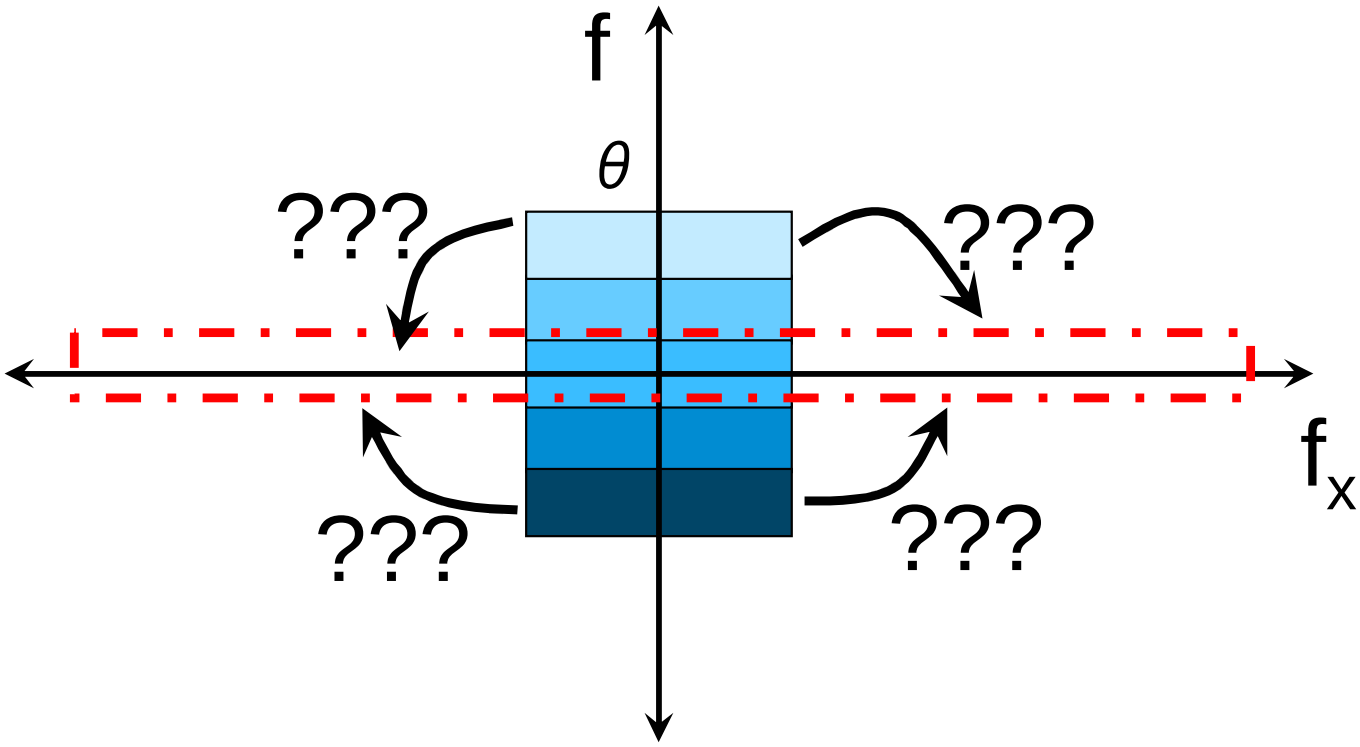
How to Capture 2D Light Field with 1D Sensor ?



Fourier Light Field Space

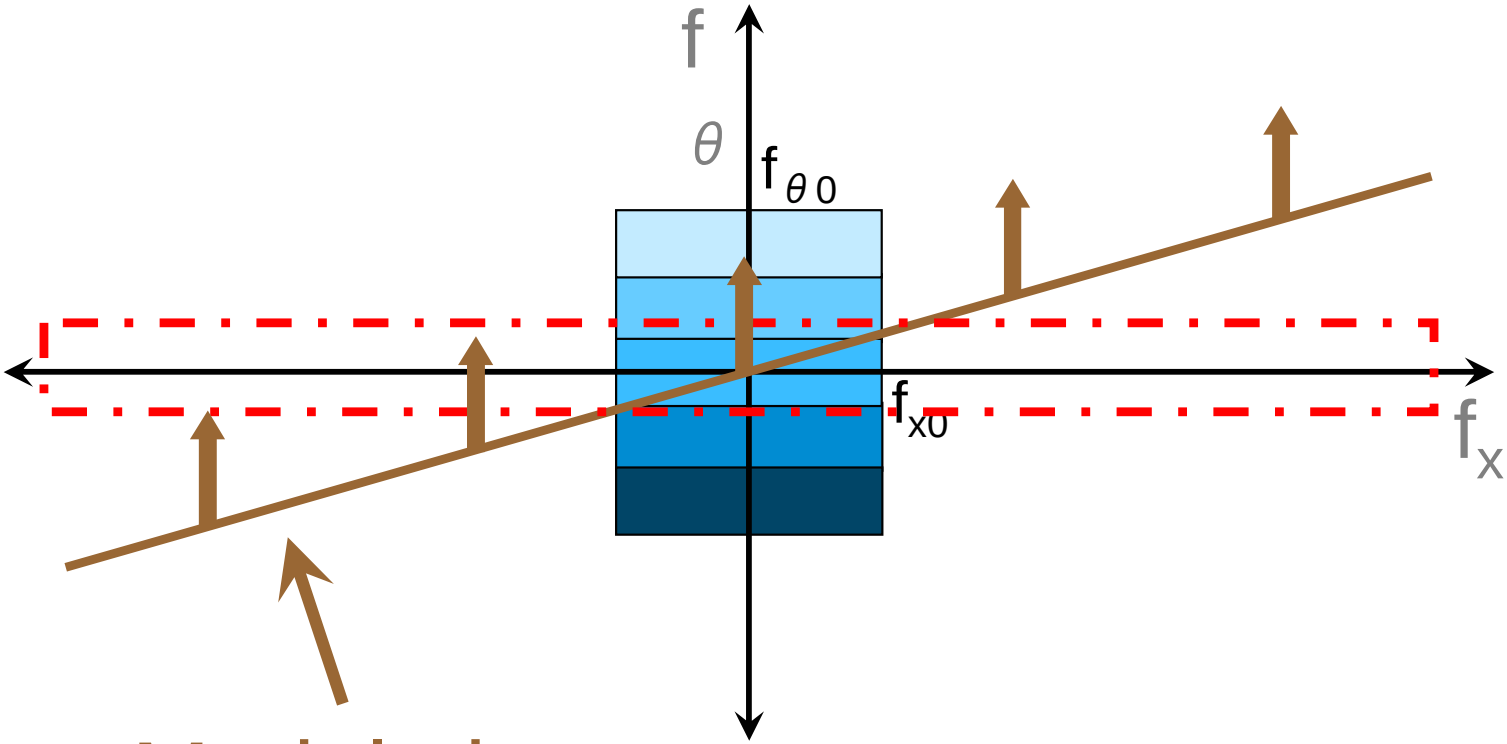
Extra sensor bandwidth cannot capture extra *dimension* of the light field




f
θ
???
???
???
???
f_x

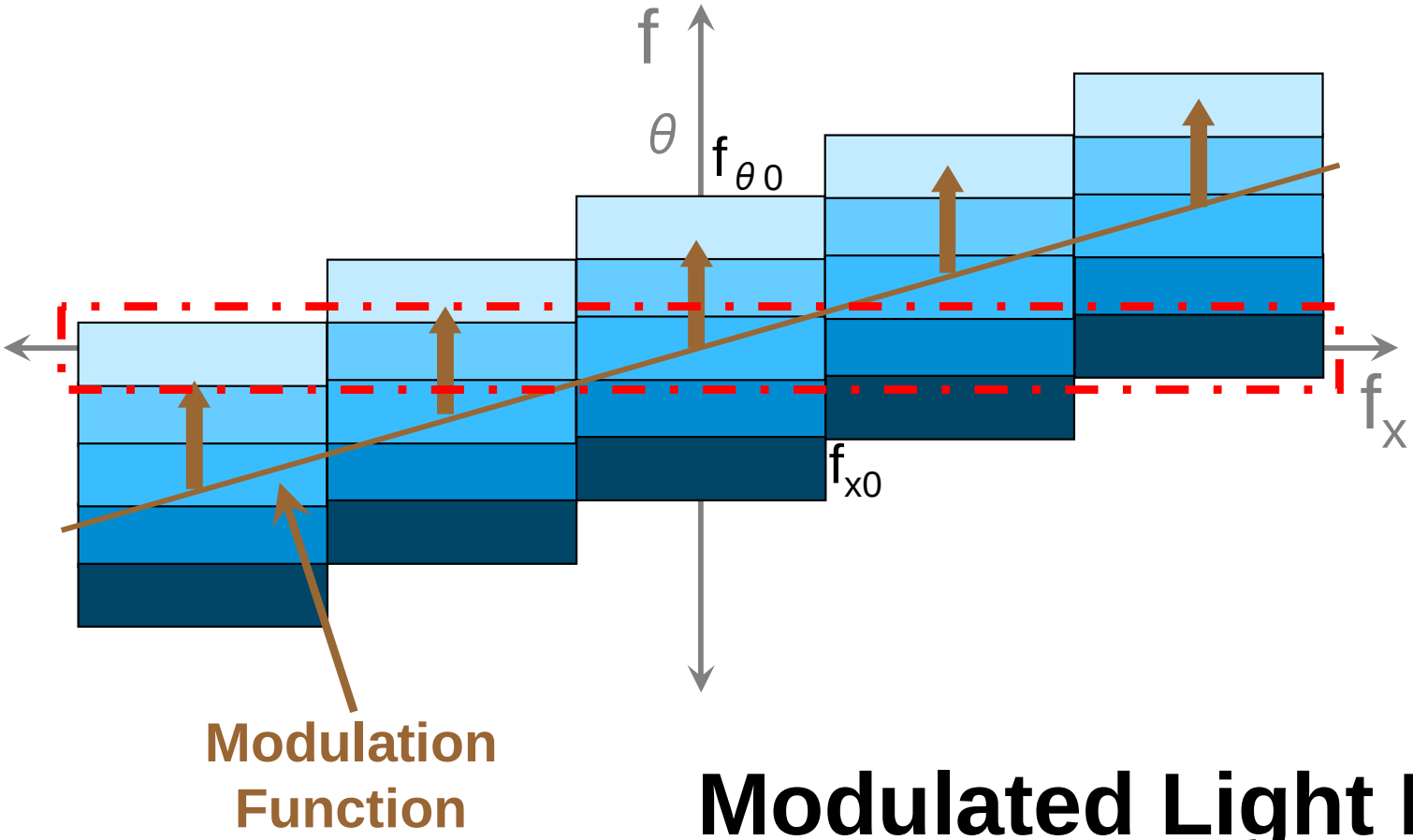
Solution: Modulation Theorem

Make spectral copies of light field



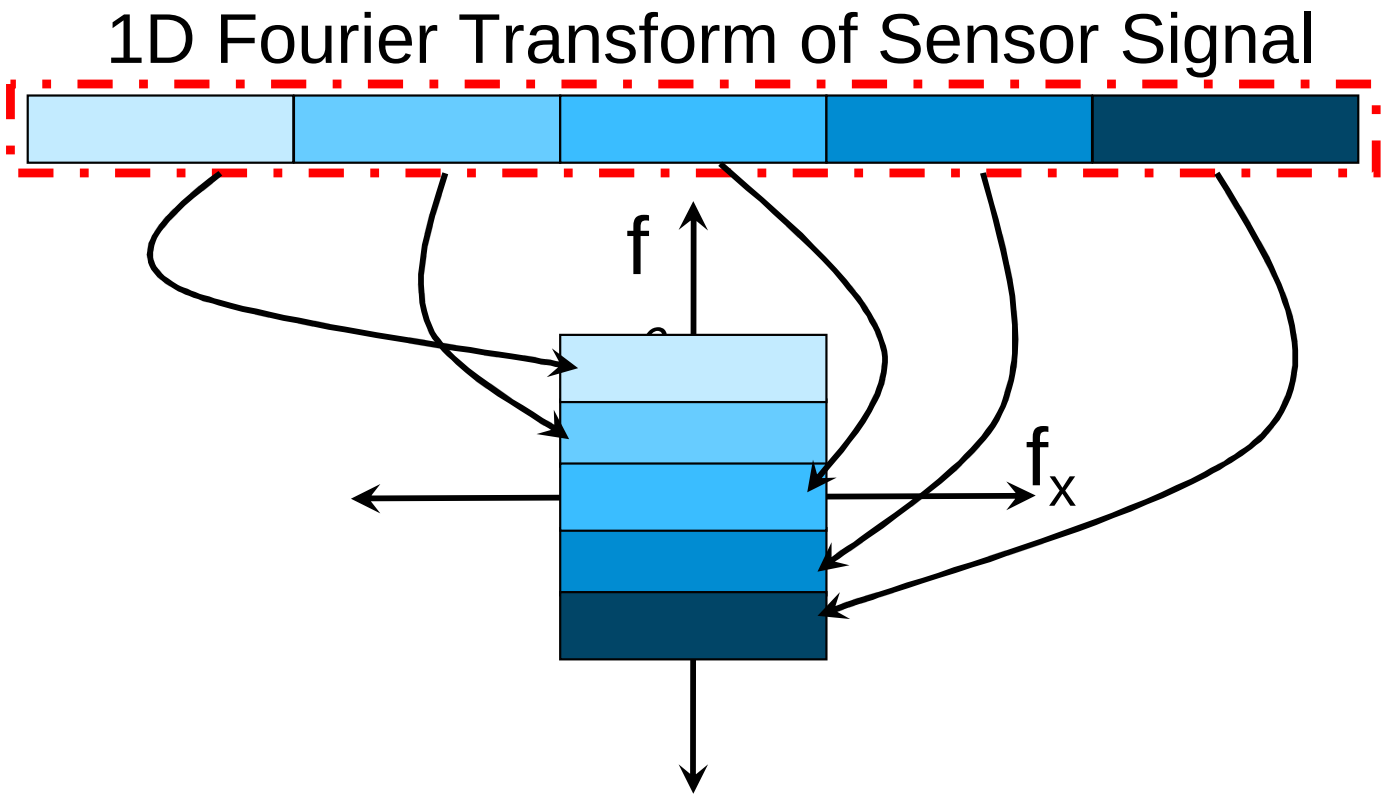
Modulation Function

Sensor Slice captures entire Light Field



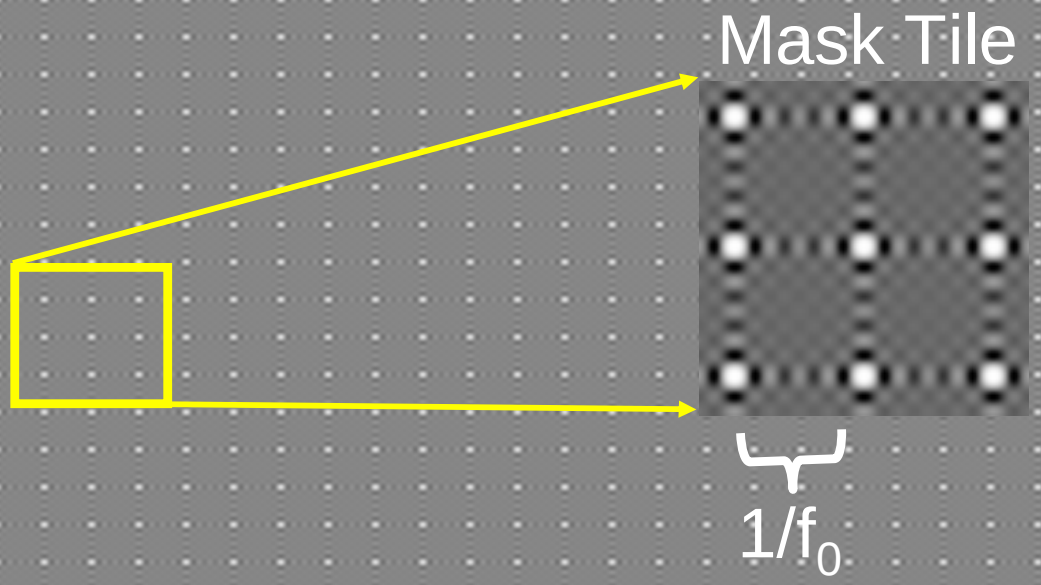
Modulated Light Field

Demodulation to recover Light Field

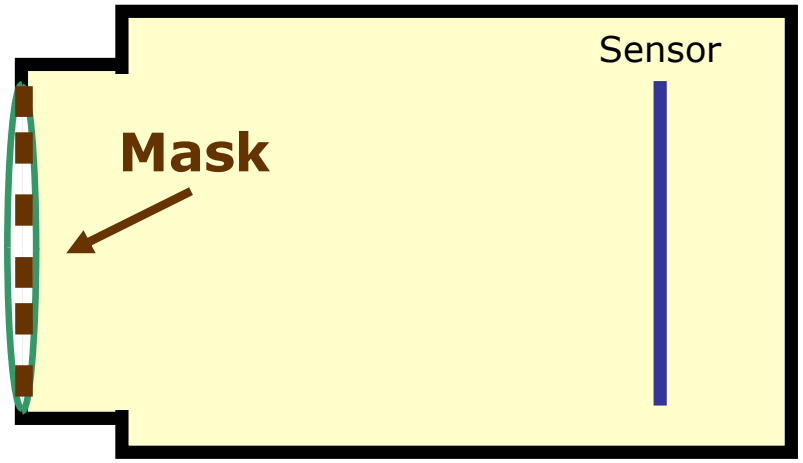


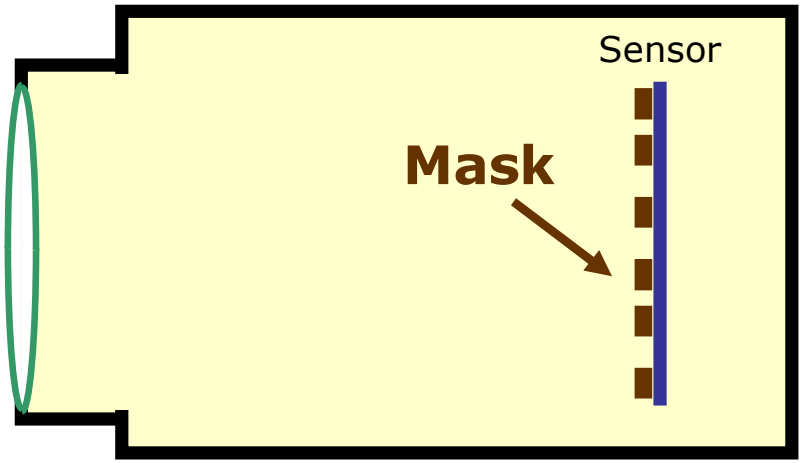
Rearrange 1D Fourier Transform into 2D

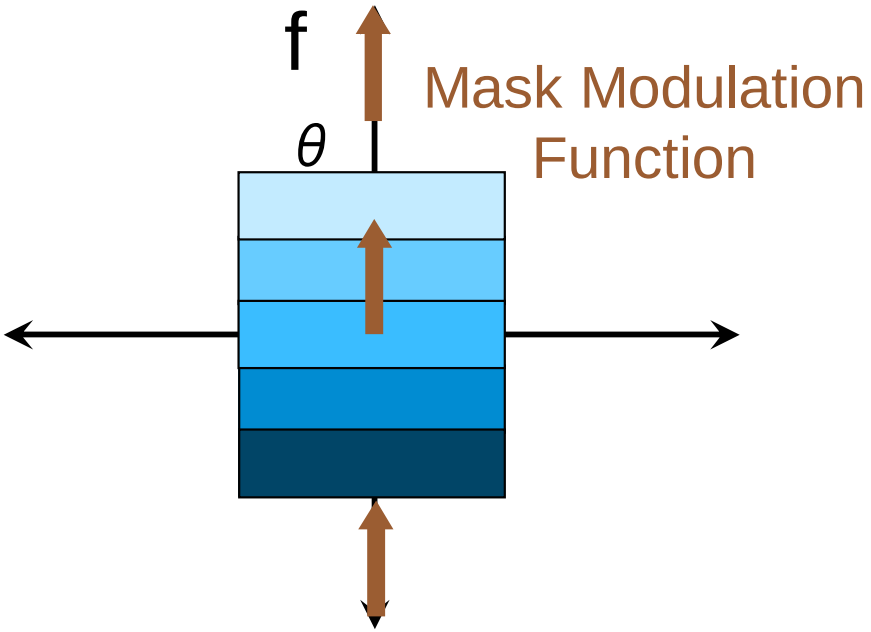
Narrowband Cosine Mask Used

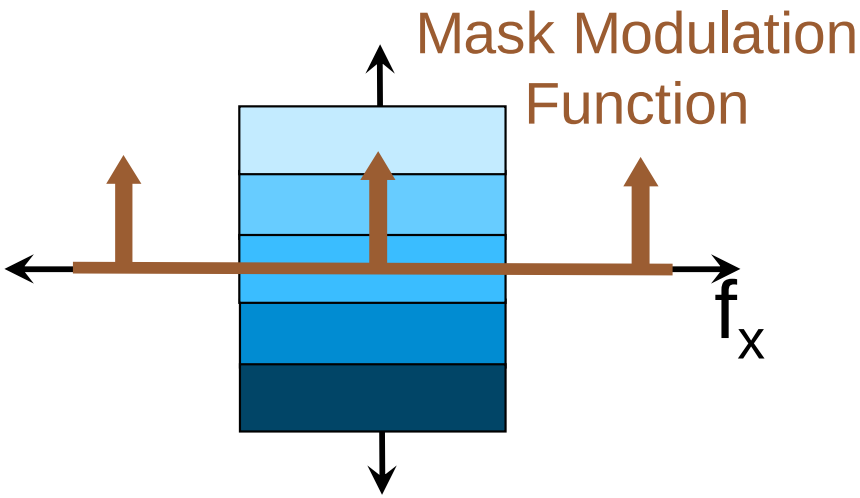


Where to place the Mask?

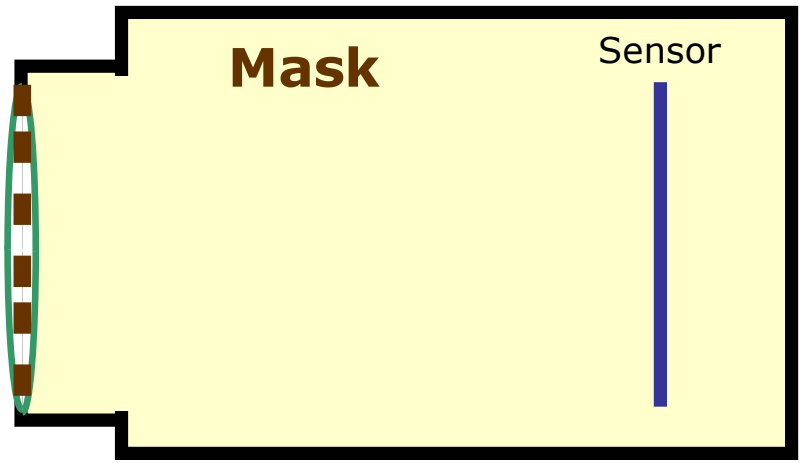


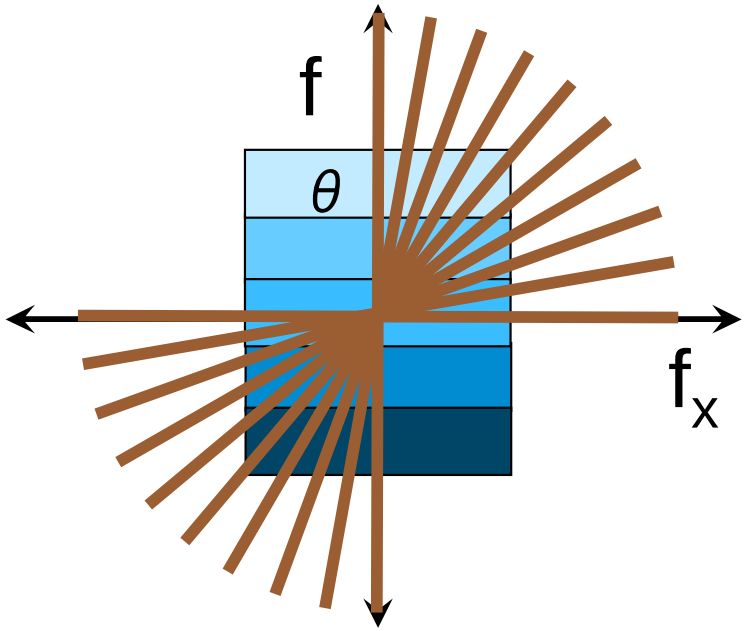






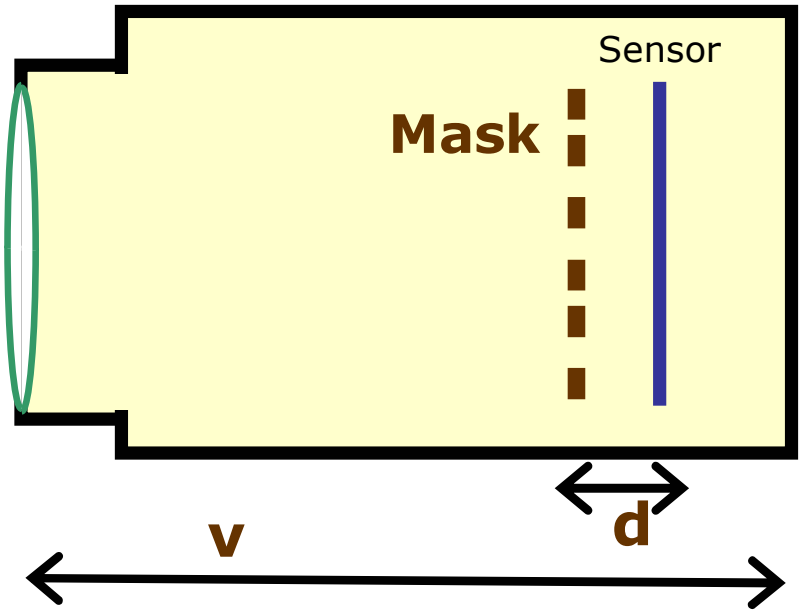
Where to place the Mask?

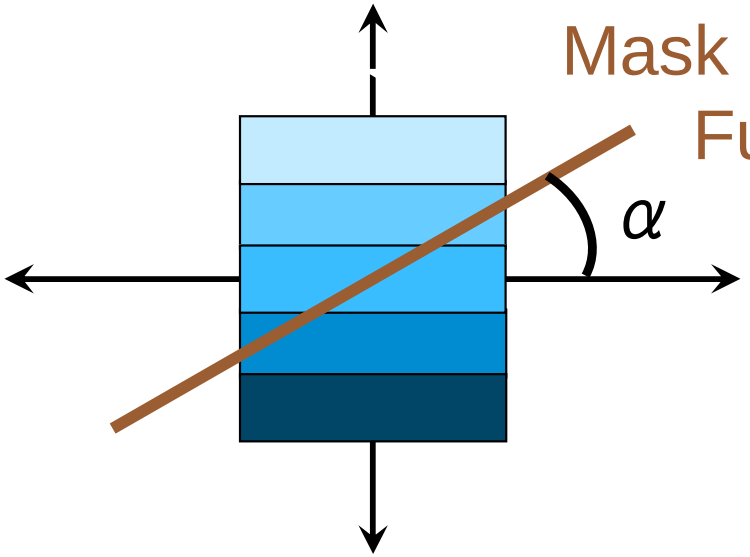




Mask Modulation Function

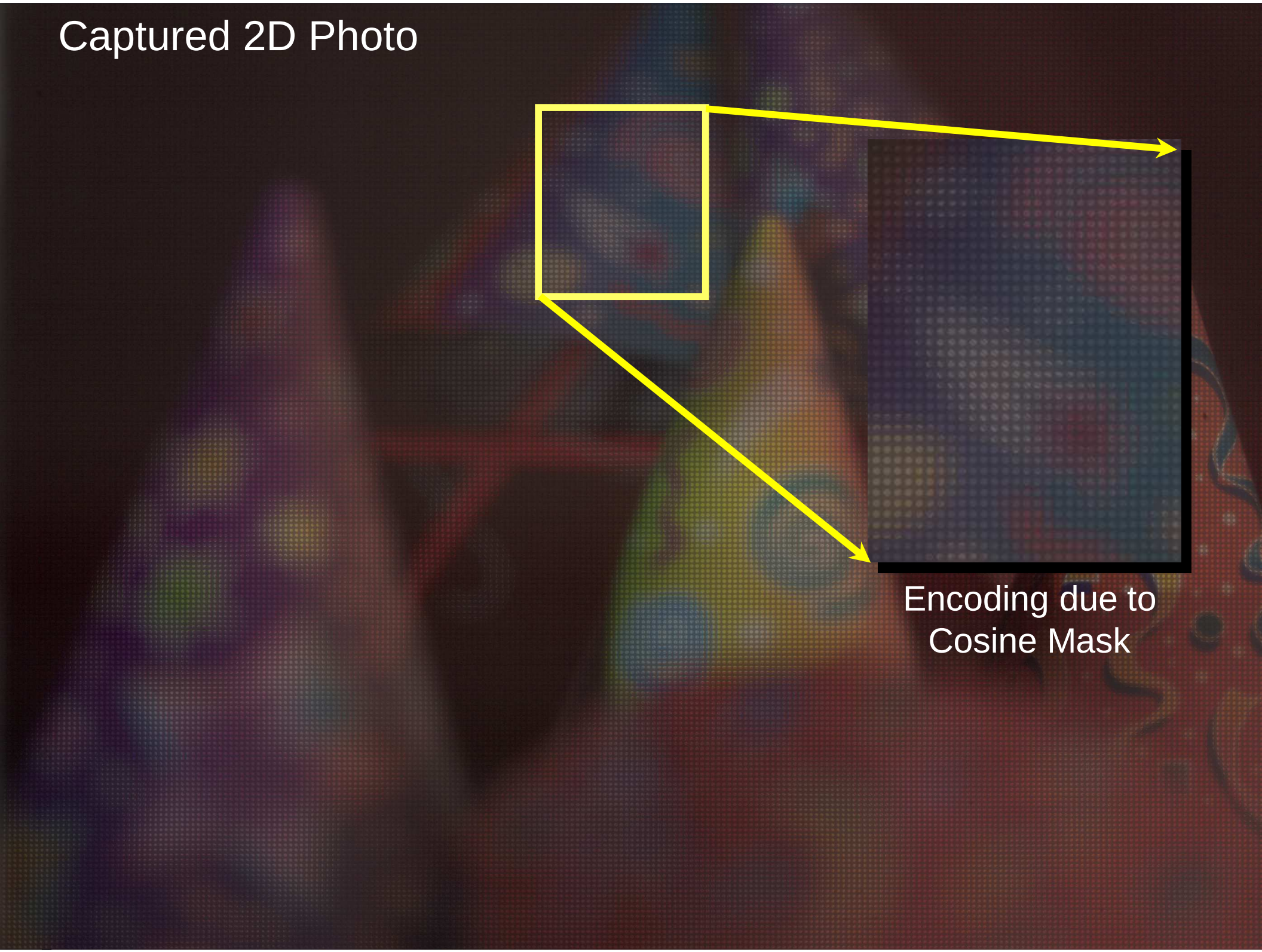
Where to place the Mask?





Mask Modulation Function

$\alpha = (d/v)\,(\pi/2)$

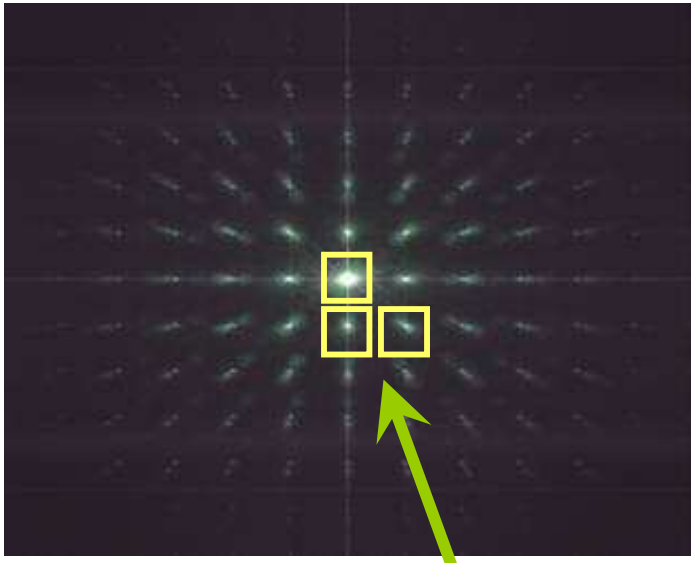

Captured 2D Photo
Encoding due to
Cosine Mask

Computing 4D Light Field

2D Sensor Photo, 1800*1800

2D
FFT

2D Fourier Transform, 1800*1800



9*9=81 spectral copies

Rearrange 2D tiles into 4D planes
200*200*9*9

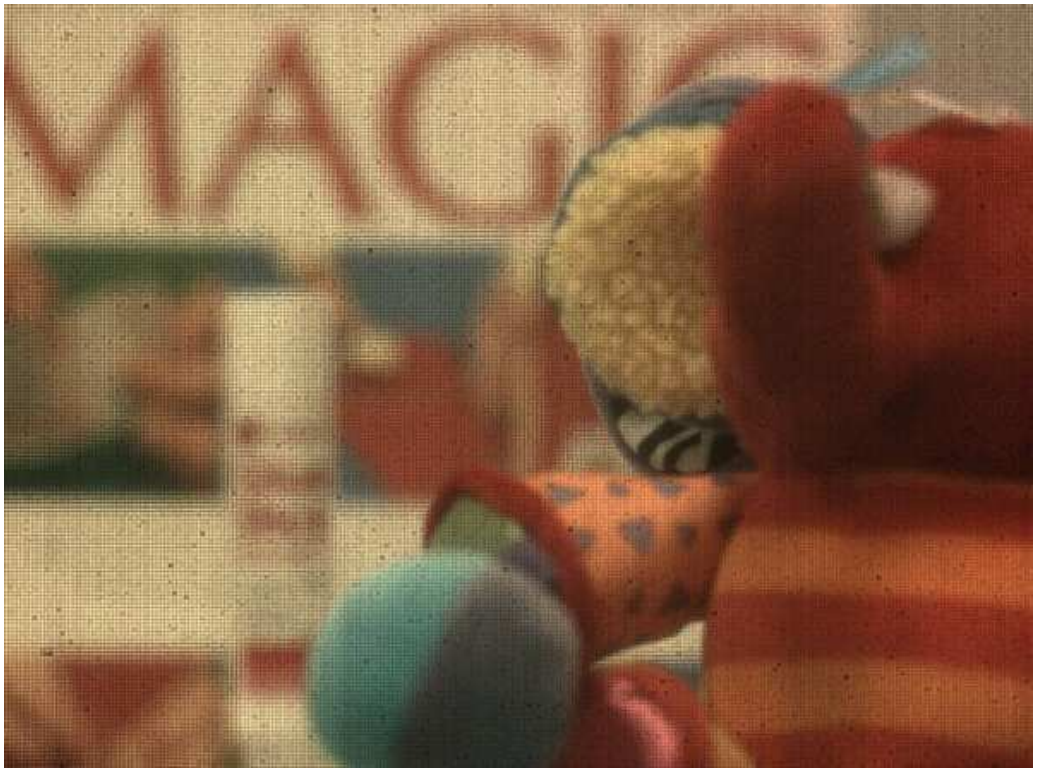
4D IFFT

200*200*9*9

4D Light Field

4d light-field capture results

Captured Photo



Refocusing

Changing Views

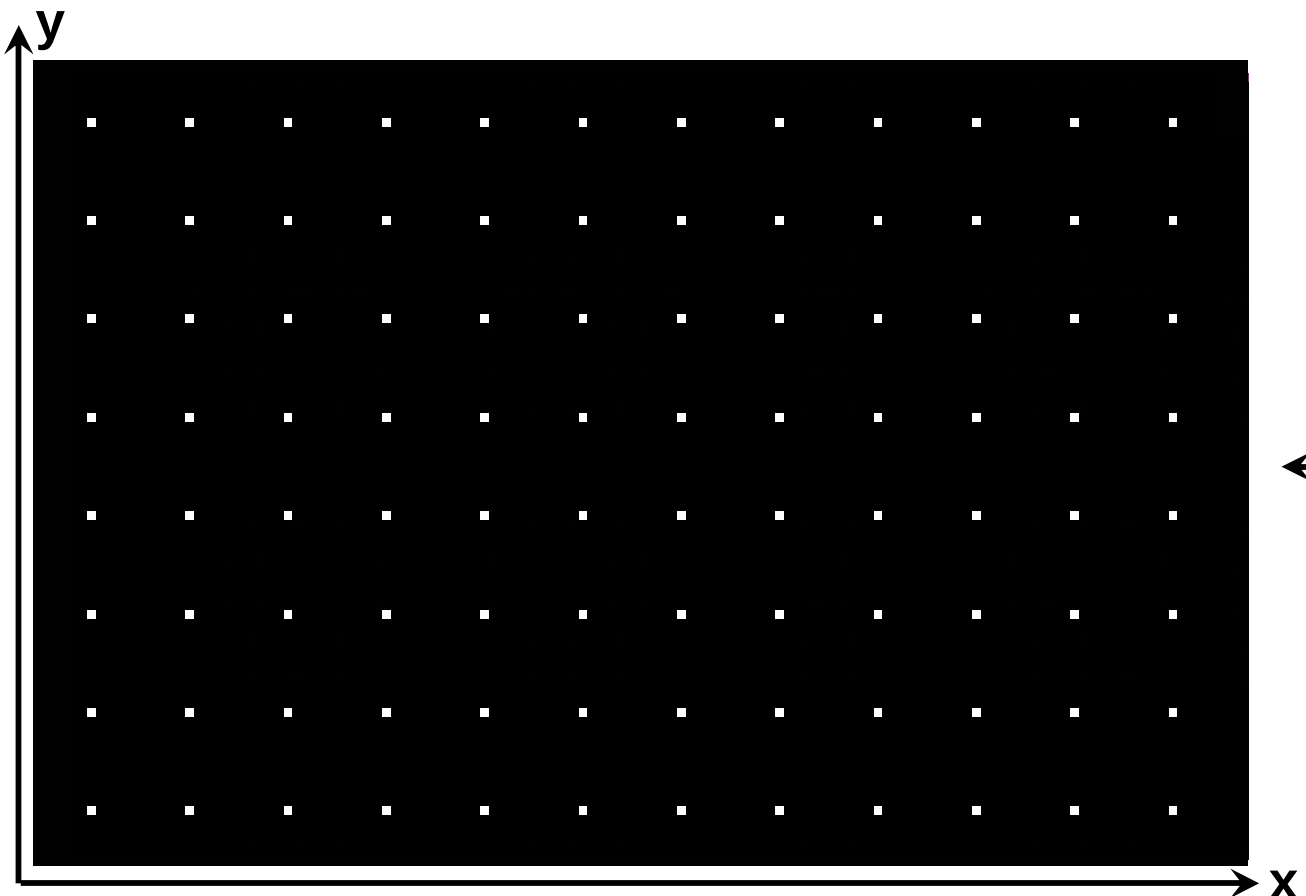
"Dappled Photography: Mask Enhanced Cameras for Heterodyned Light Fields and Coded Aperture Refocusing", Ashok Veeraraghavan, Ramesh Raskar, Amit Agrawal, Ankit Mohan, and Jack Tumblin, in **SIGGRAPH 2007**.

"Non-refractive modulators for encoding and capturing scene appearance and depth", Ashok Veeraraghavan, Ramesh Raskar, Amit Agrawal, Ankit Mohan, and Jack Tumblin, in **IEEE CVPR 2008.**

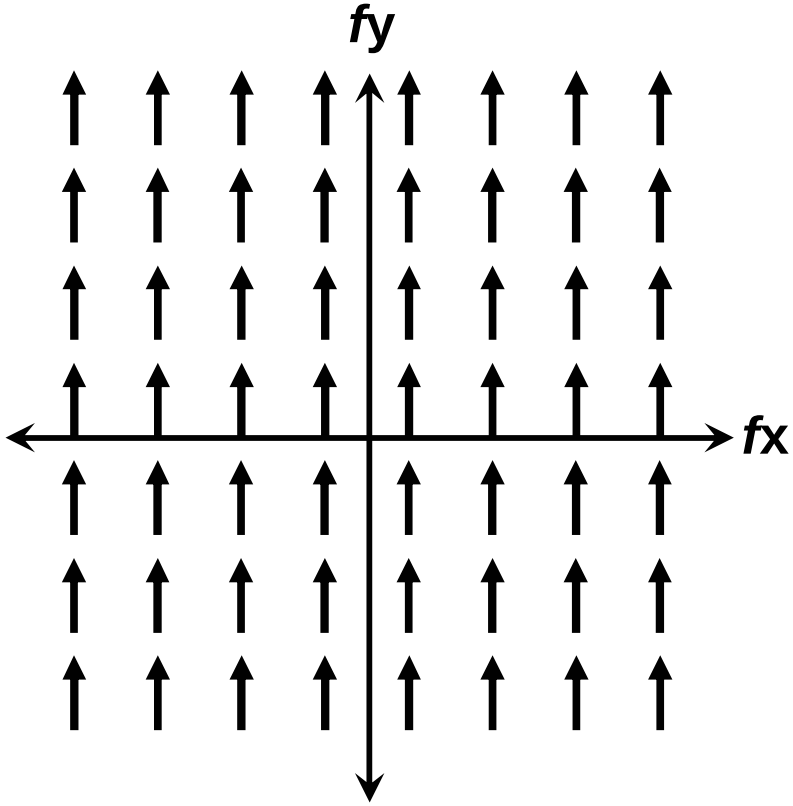

Mamiya
Mamiya
Mamiya
Mamiya
Mask is placed under a glass sheet and slid over the bare sensor.
Camera Body
Digital Back
Bare Sensor
210 mm Lens

Which Heterodyne Mask to Use?

- **Conditions for heterodyne light field detection**
  - Mask spectrum must be a (windowed) 2D impulse train
  - Can be achieved (approximately) with a pinhole array



$m_{pinhole}(x,y)$

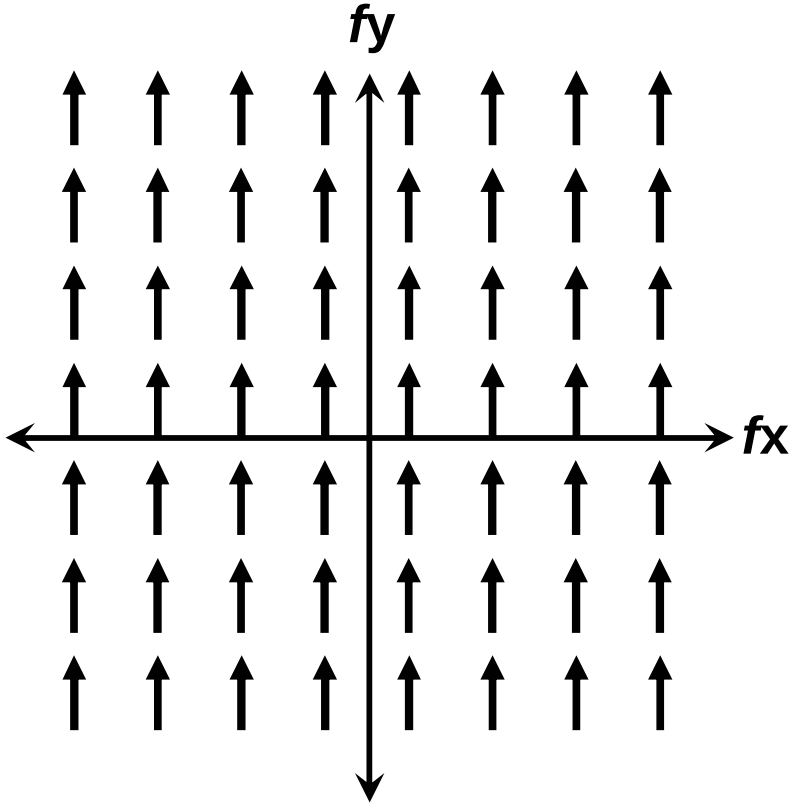


$M_{pinhole}(f_x,f_y)$

Which Heterodyne Mask to Use?

- **Conditions for heterodyne light field detection**
  - Mask spectrum must be a (windowed) 2D impulse train
  - Can be achieved exactly by Sum-of-Sinusoids (SoS) [Veeraraghavan et al. 2007]

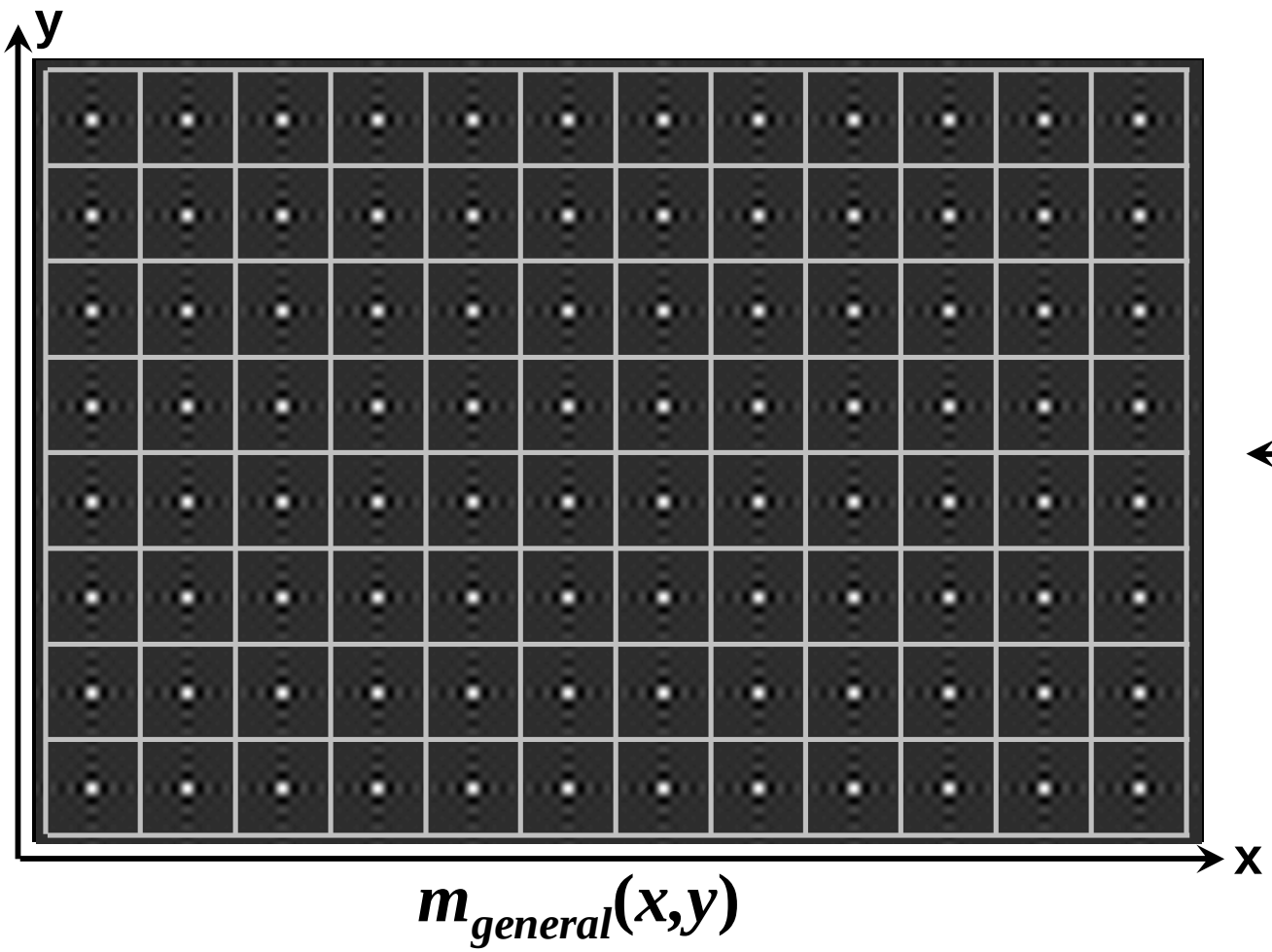
$m_{SoS}(x,y)$

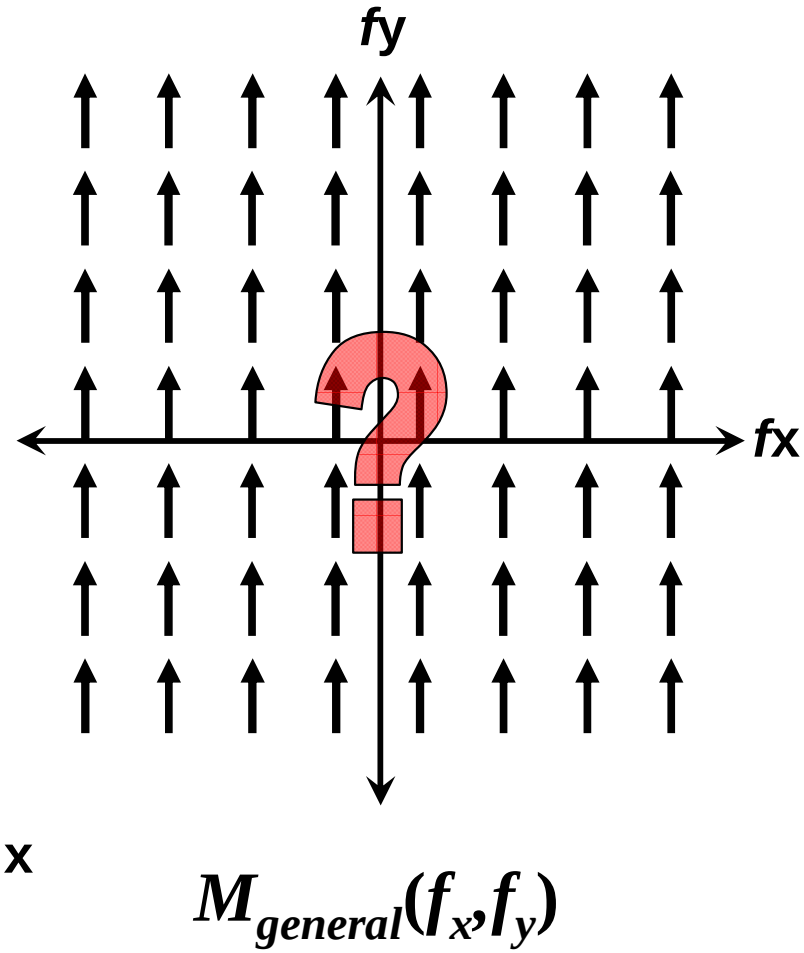


$M_{SoS}(f_x,f_y)$

Which Heterodyne Mask to Use?

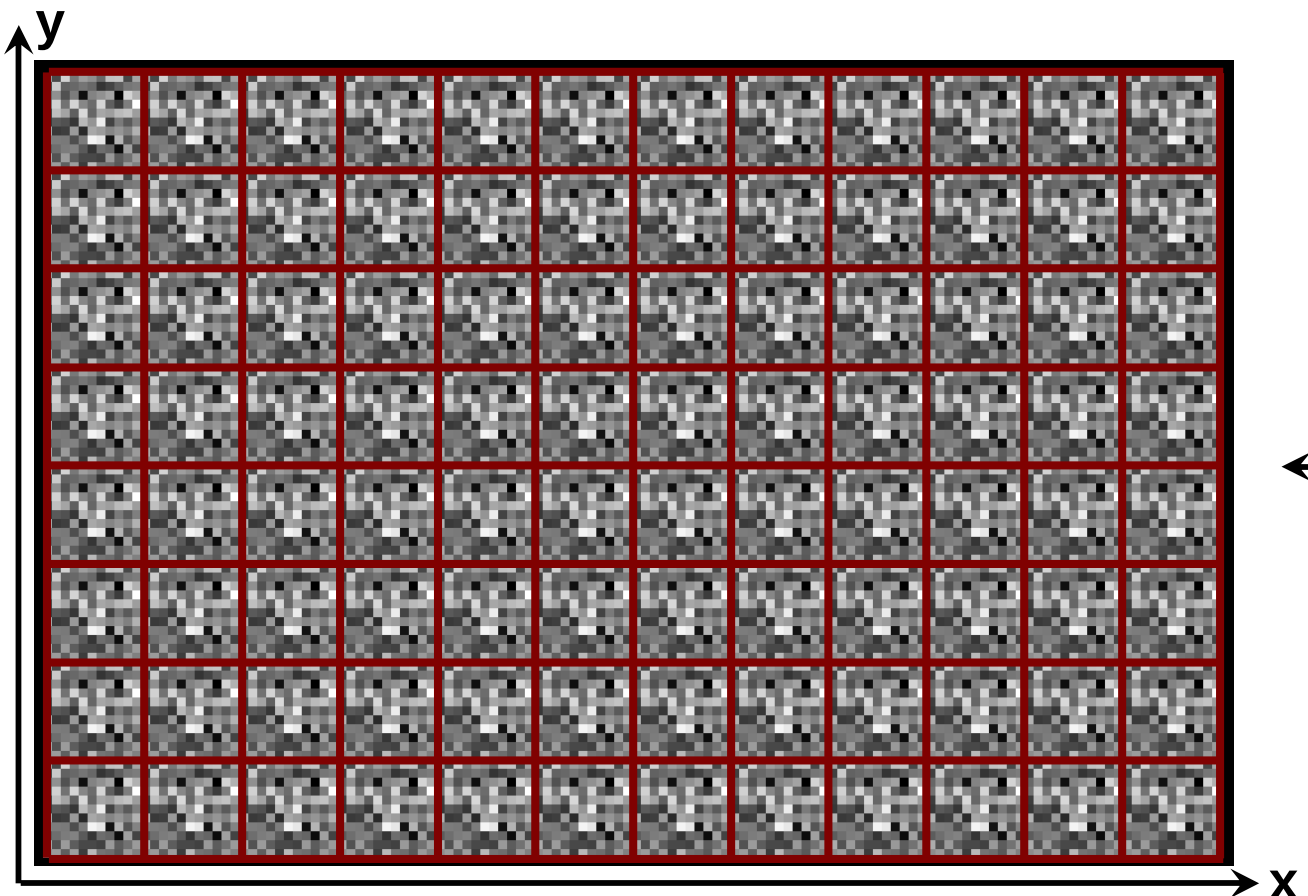
- **Conditions for heterodyne light field detection**
  - Both pinhole array and SoS are *periodic* functions
  - What other tiles lead to impulse trains?



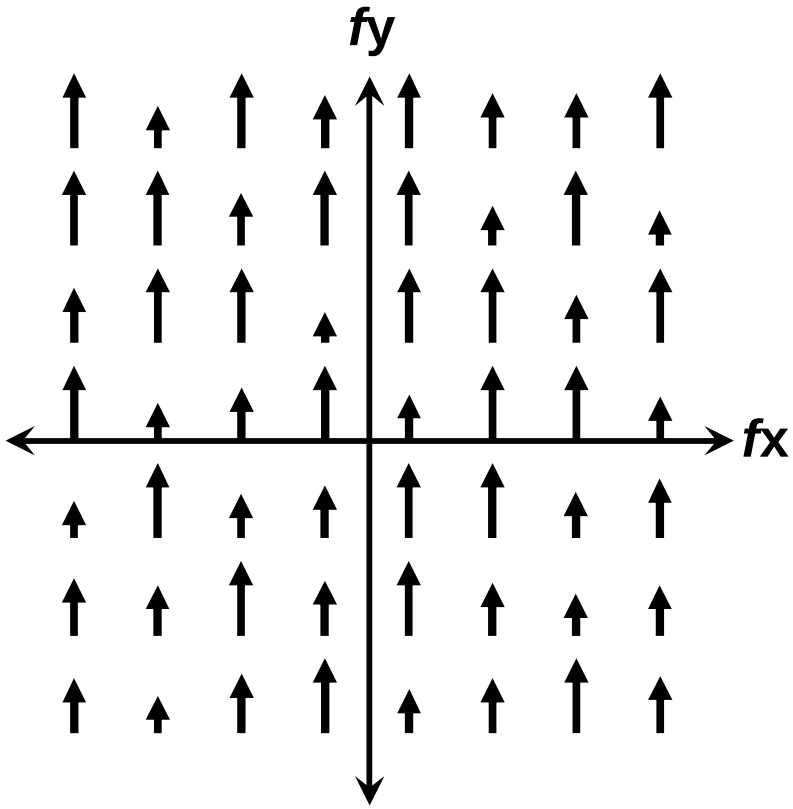


General Tiled-broadband Masks

- **Conditions for heterodyne light field detection**
  - (Almost) any 2D tile can be used (tiling → impulse train)
  - Amplitude of impulses given by Fourier series of tile



$m_{general}(x,y)$



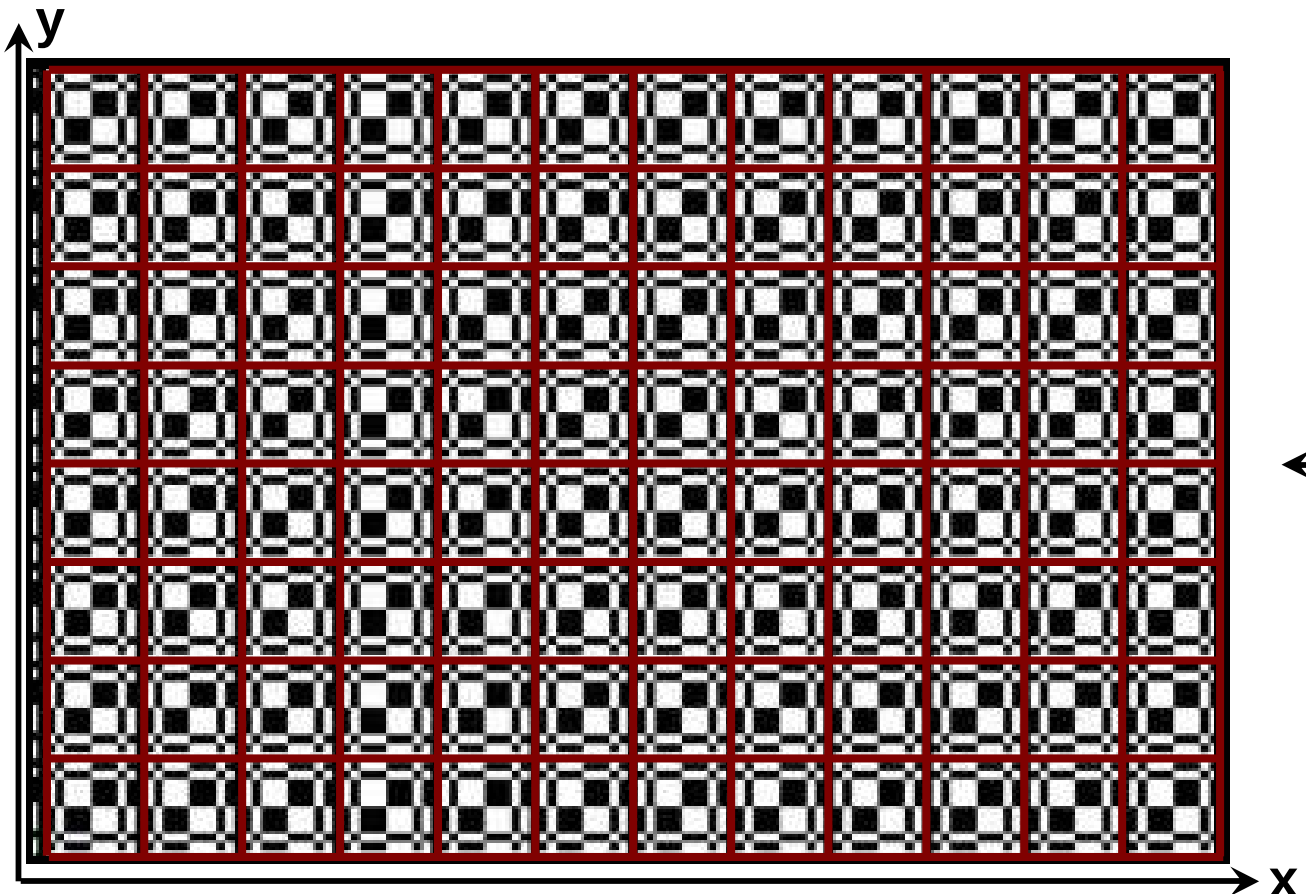
$M_{general}(f_x,f_y)$

Specific Choice: Tiled-MURA

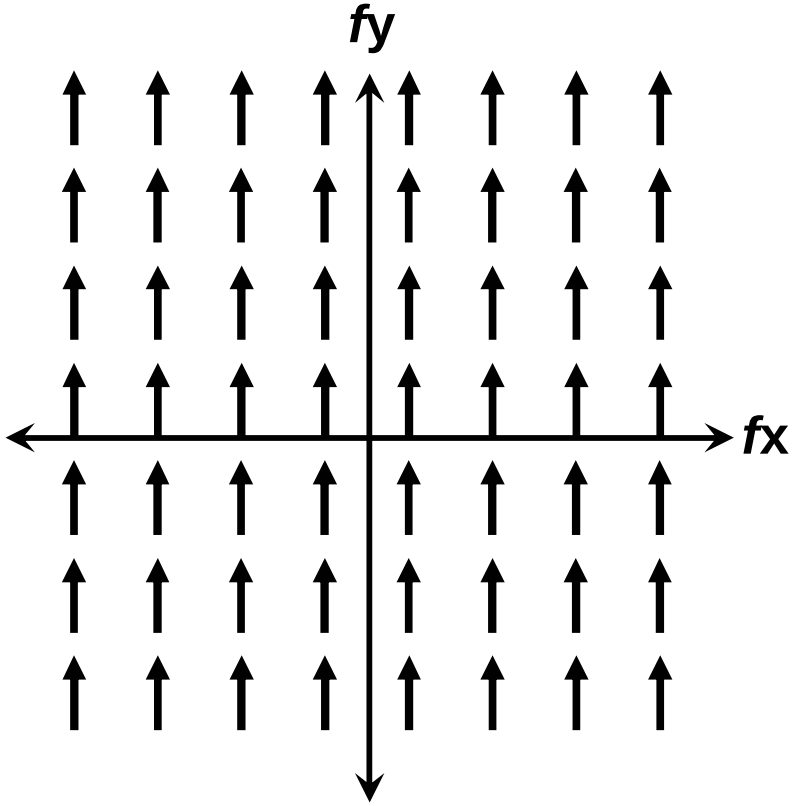
- **Conditions for optimal heterodyne light field detection**

  Modified Uniformly Redundant Array (MURA)

"Shield Fields: Modeling and Capturing 3D Occluders", Douglas Lanman, Ramesh Raskar, Amit Agrawal, Gabriel Taubin, in **SIGGRAPH Asia 2008**.

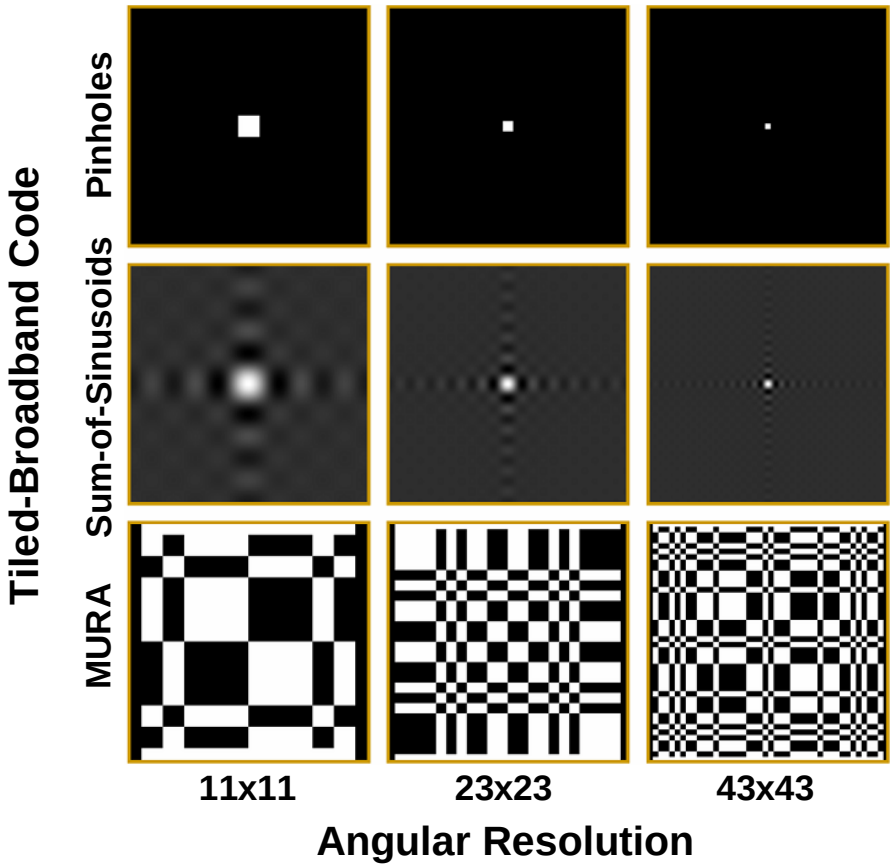


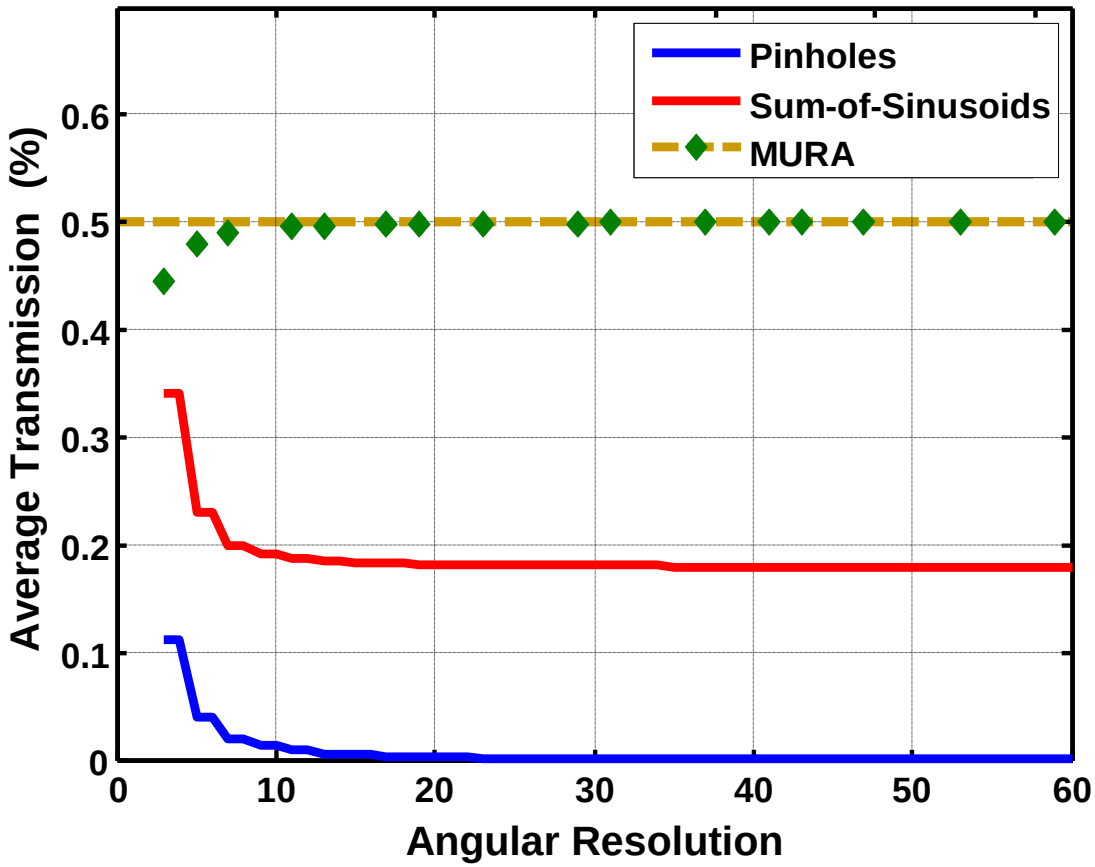
$M_{MURA}(x,y)$



$M_{MURA}(f_x,f_y)$

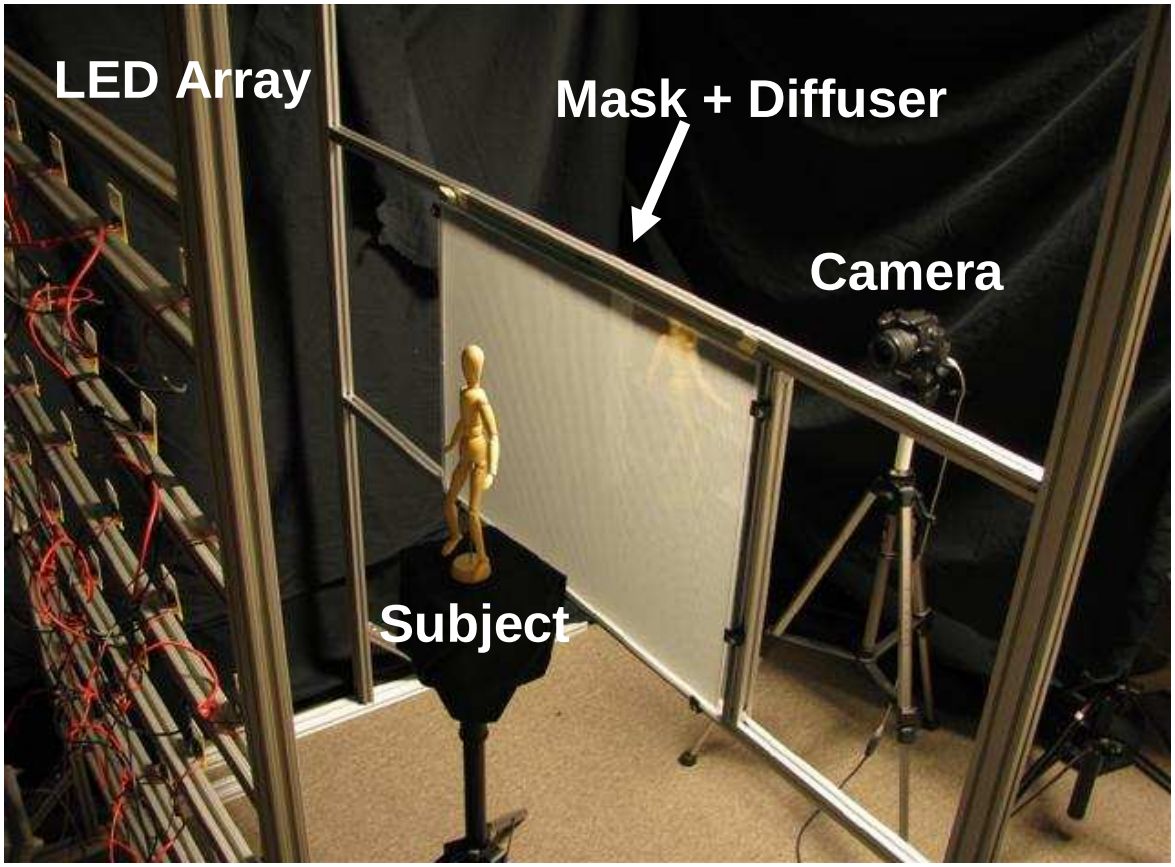
Benefits of New Heterodyne Codes





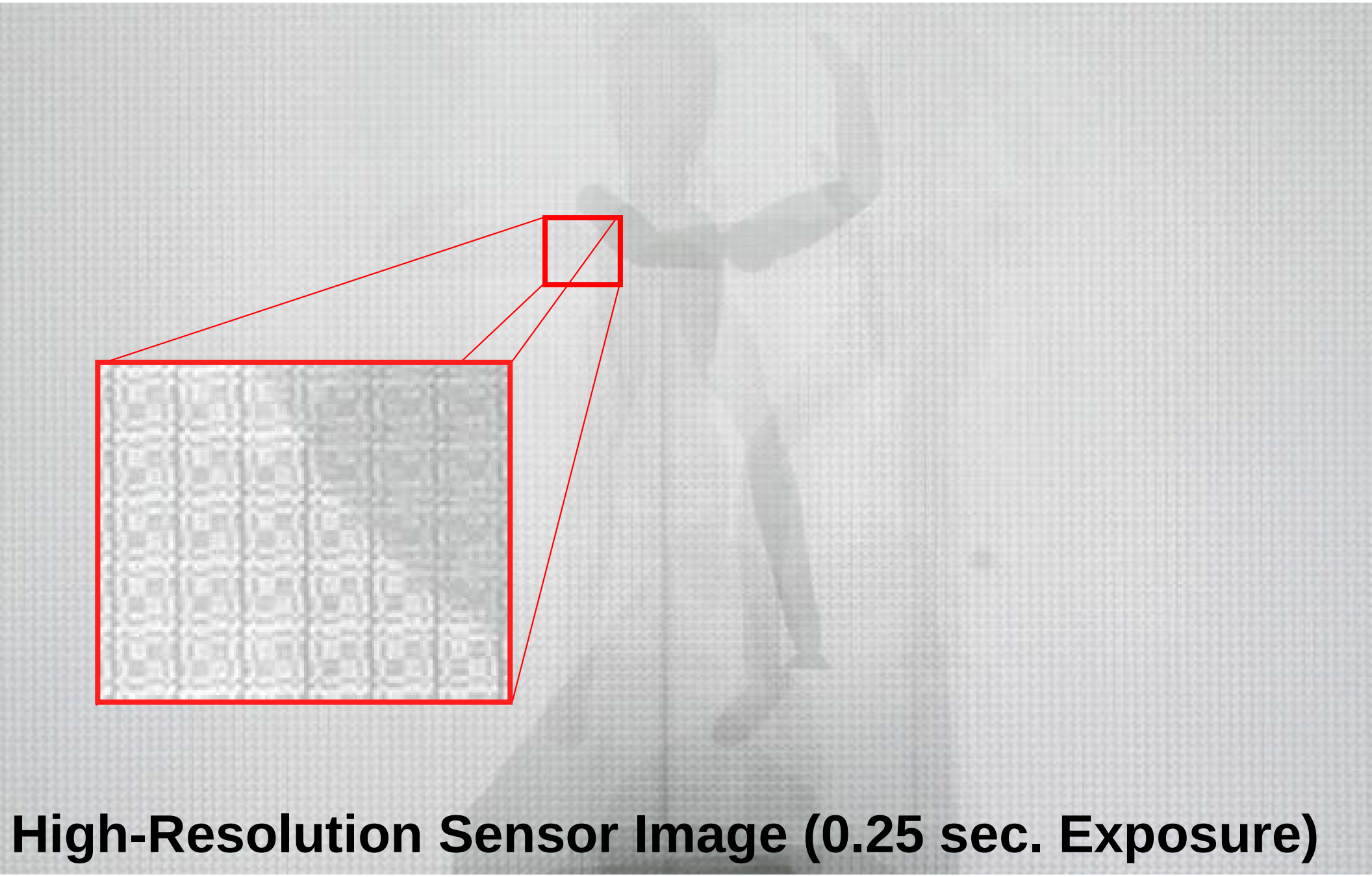
- **Benefits and Limitations**
  - Sum-of-Sinusoids converges to ≈18% transmission
  - Tiled-MURA near 50% (but only for prime-lengths)
  - Binary vs. continuous-tone process (quantization)

Prototype Implementation



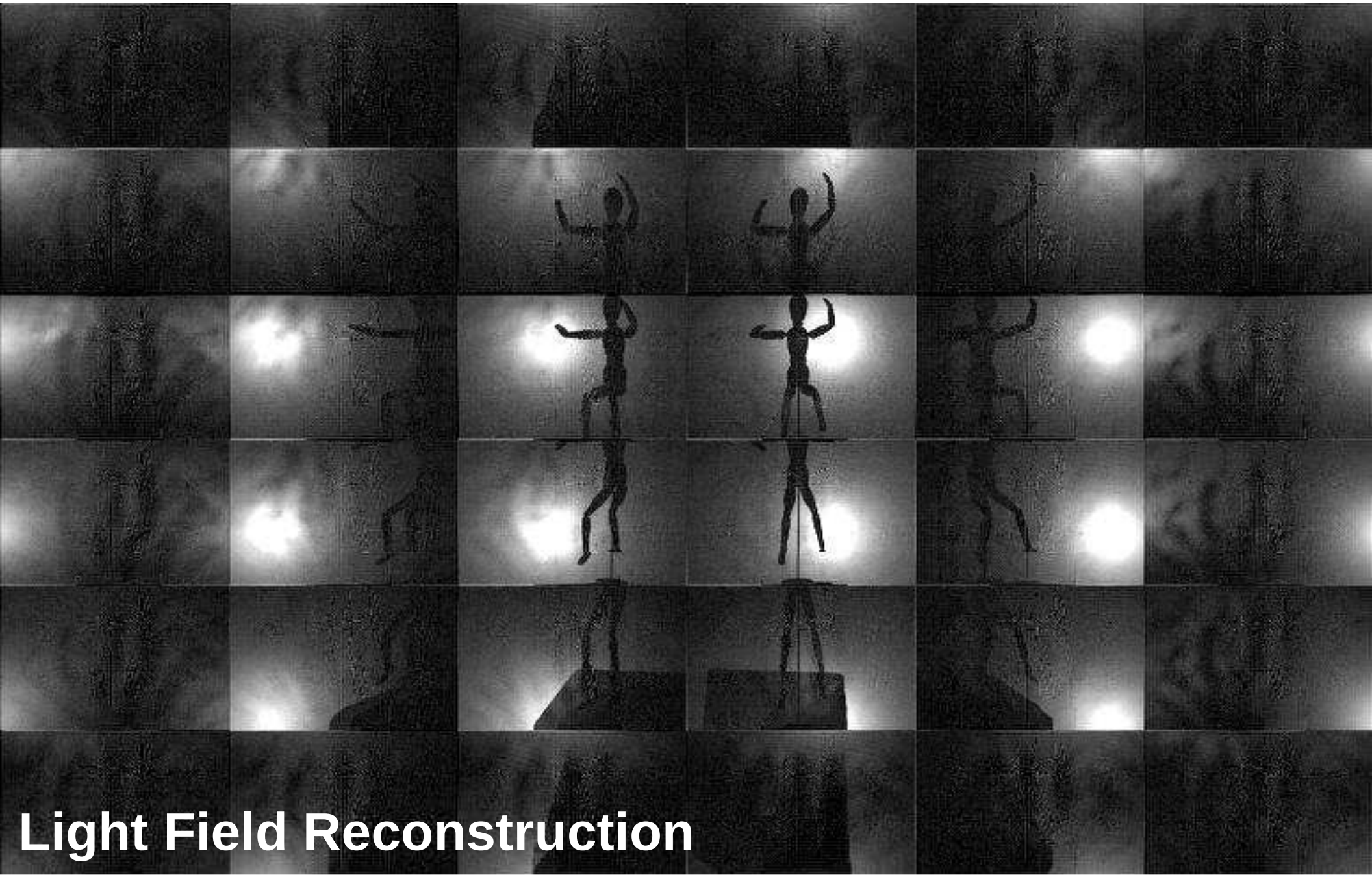
- **Components**
  - 8.0 megapixel Canon EOS Digital Rebel XT
  - 6x6 array of Philips Luxeon Rebel LEDs [1.2x1.2 m]
  - 5,080 DPI mask and a paper vellum diffuser [75x55 cm]

Tiled-MURA Results: Sensor Image

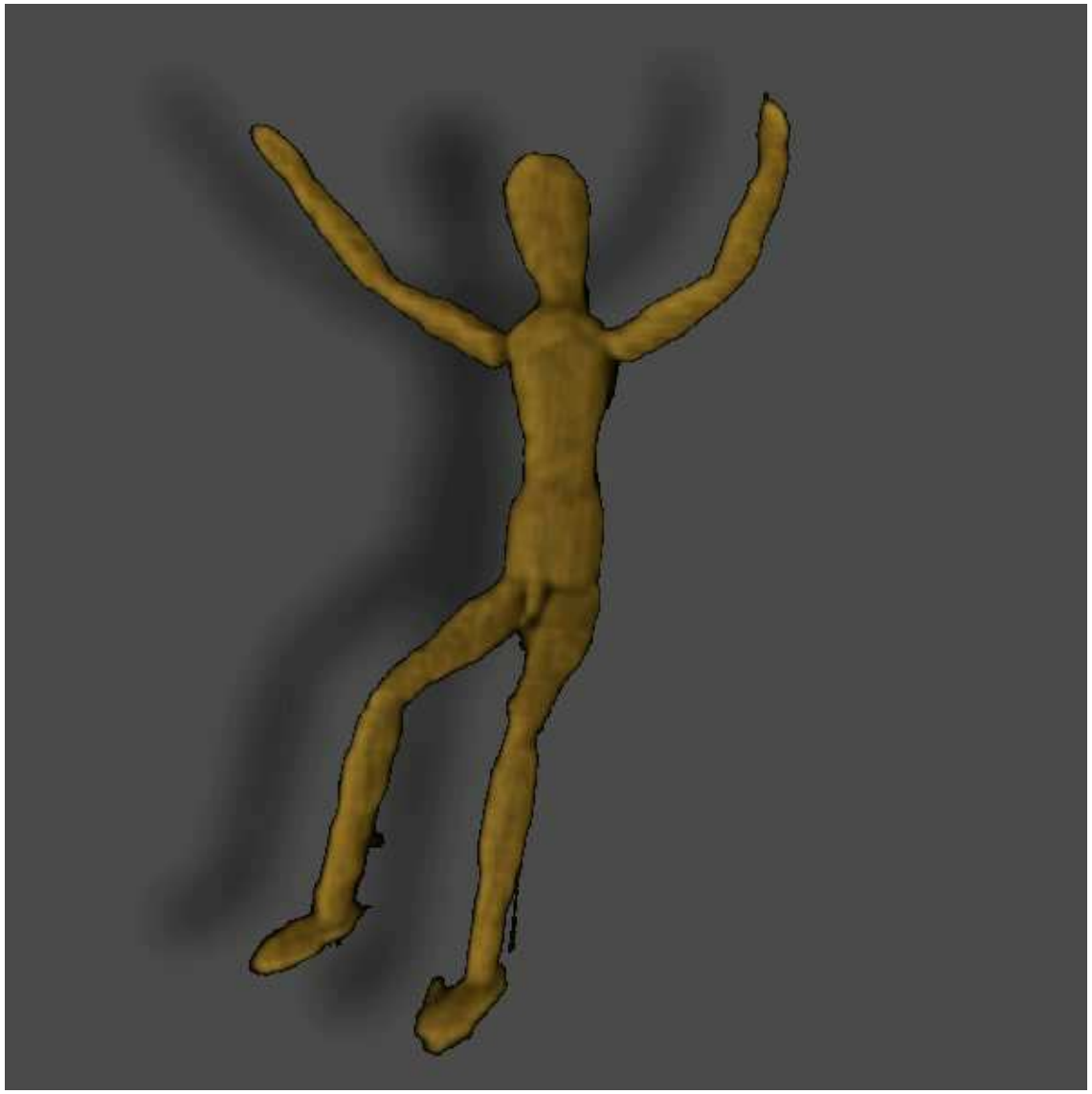


High-Resolution Sensor Image (0.25 sec. Exposure)

Tiled-MURA Results: Shadowgrams

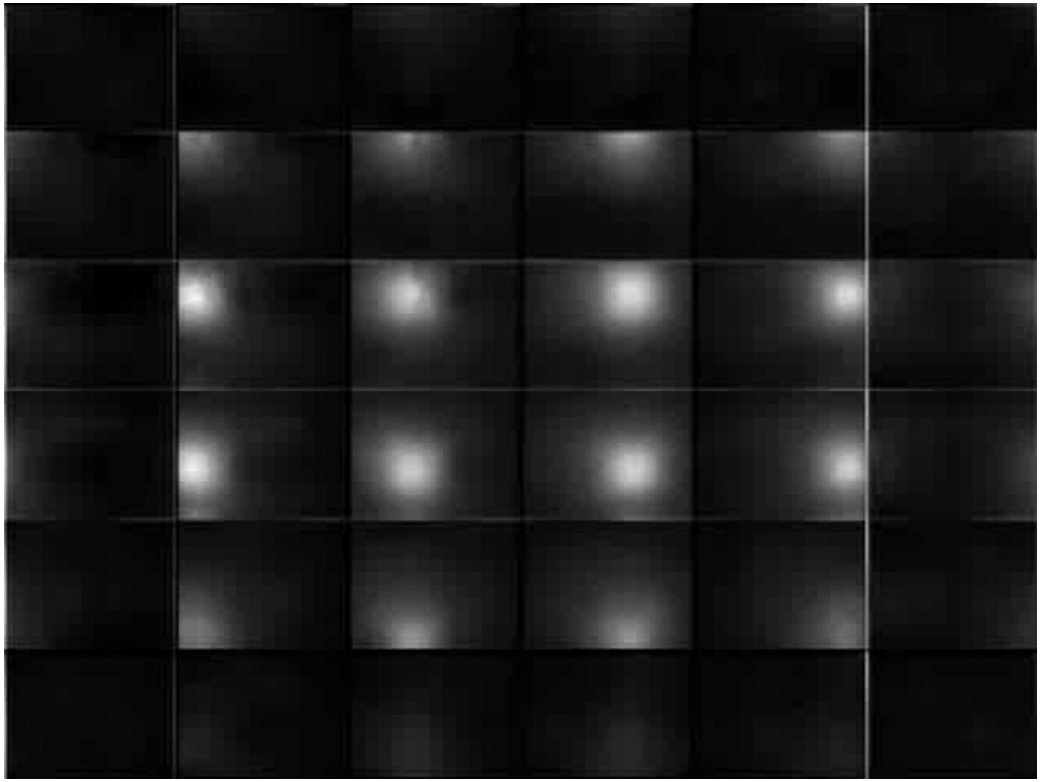


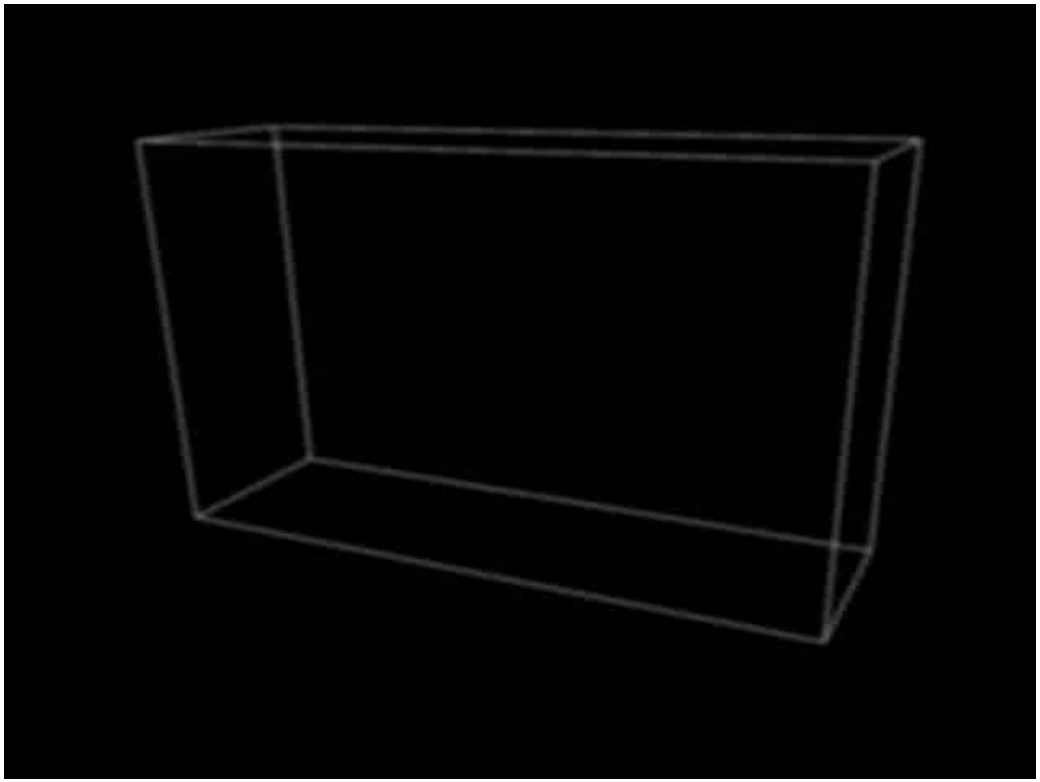
Reconstruction



Visual Hull Reconstruction

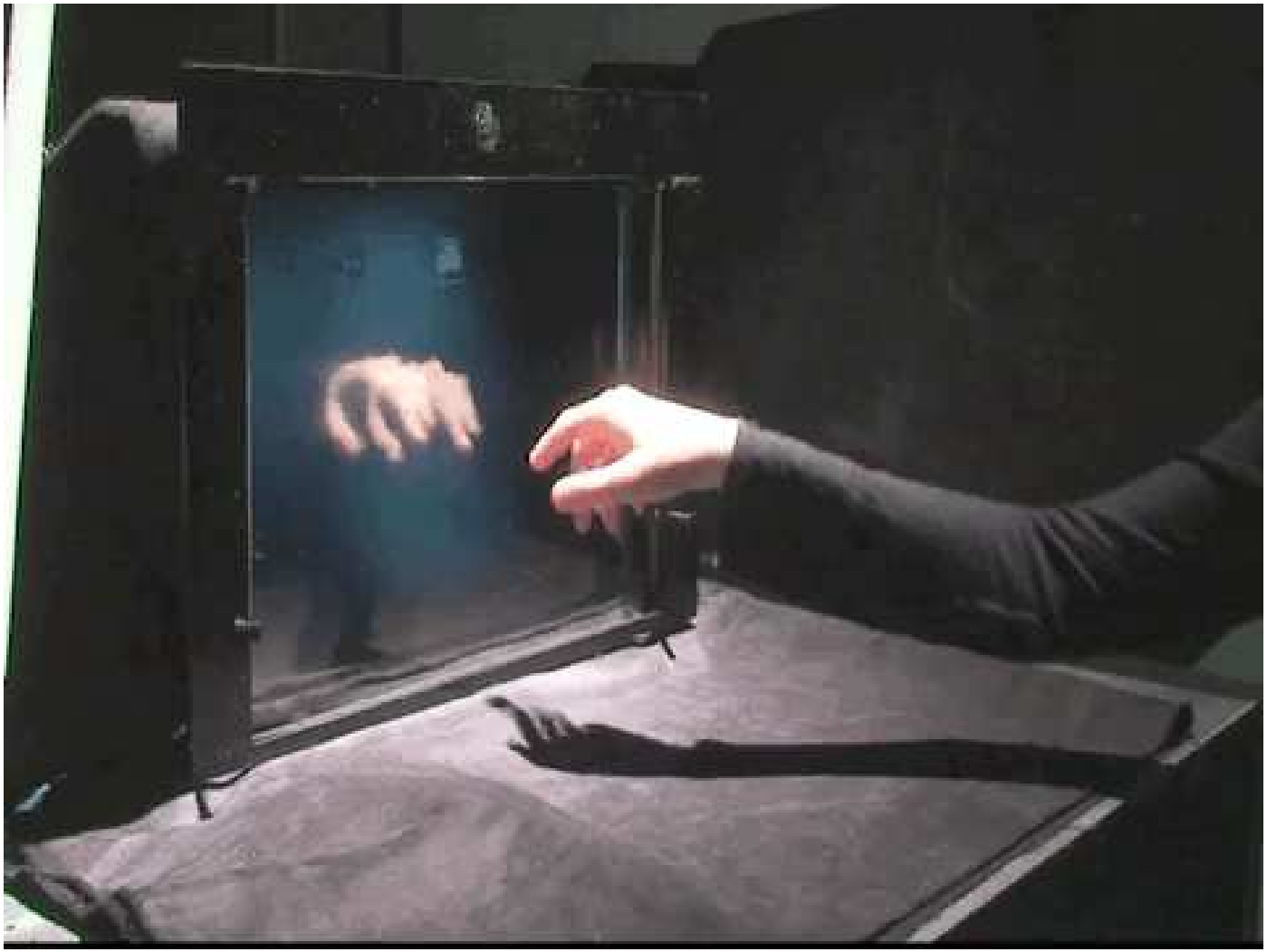
Tiled-MURA Results: Dynamic Scene





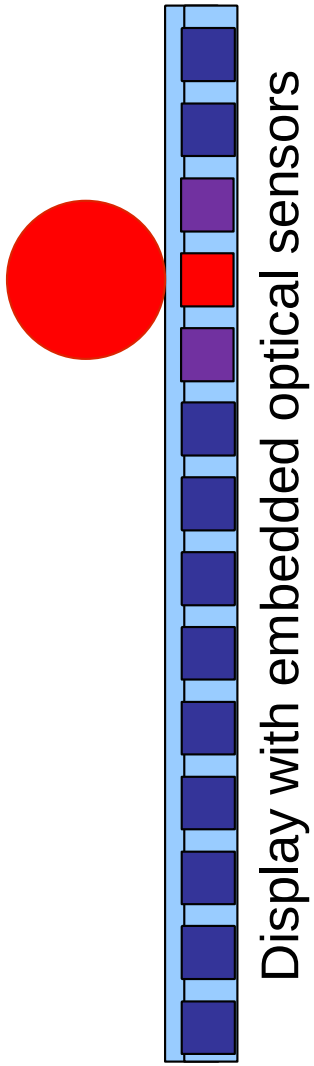
- **Components and Limitations**
  - 1600x1200 15 fps Point Grey Grasshopper camera
  - 6x6 array of Philips Luxeon Rebel LEDs [1.2x1.2 m]
  - 5,080 DPI mask and a paper vellum diffuser [75x55 cm]
  - Individual shadowgrams only 75x50 pixels

Bi-Di Screen: Light Field capture with a flat display for **User Interaction**

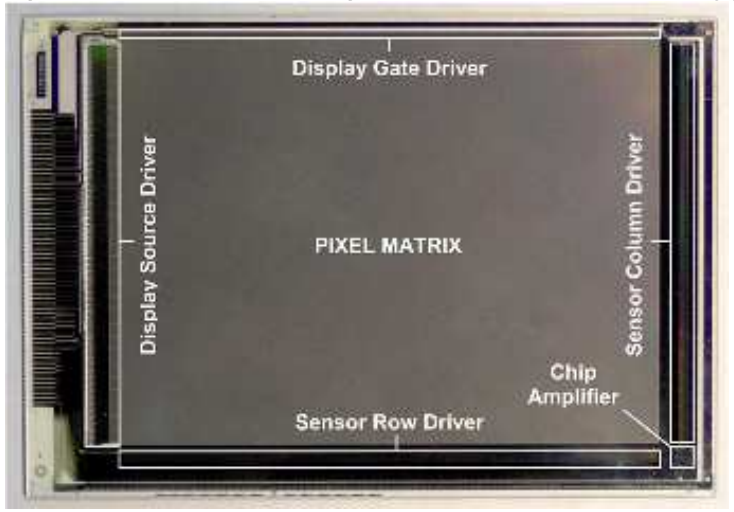


"BiDi Screen: A Thin, Depth-Sensing LCD for 3D Interaction using Light Fields", Matthew Hirsch, Douglas Lanman, Henry Holtzman, Ramesh Raskar, in **SIGGRAPH Asia 2009**.

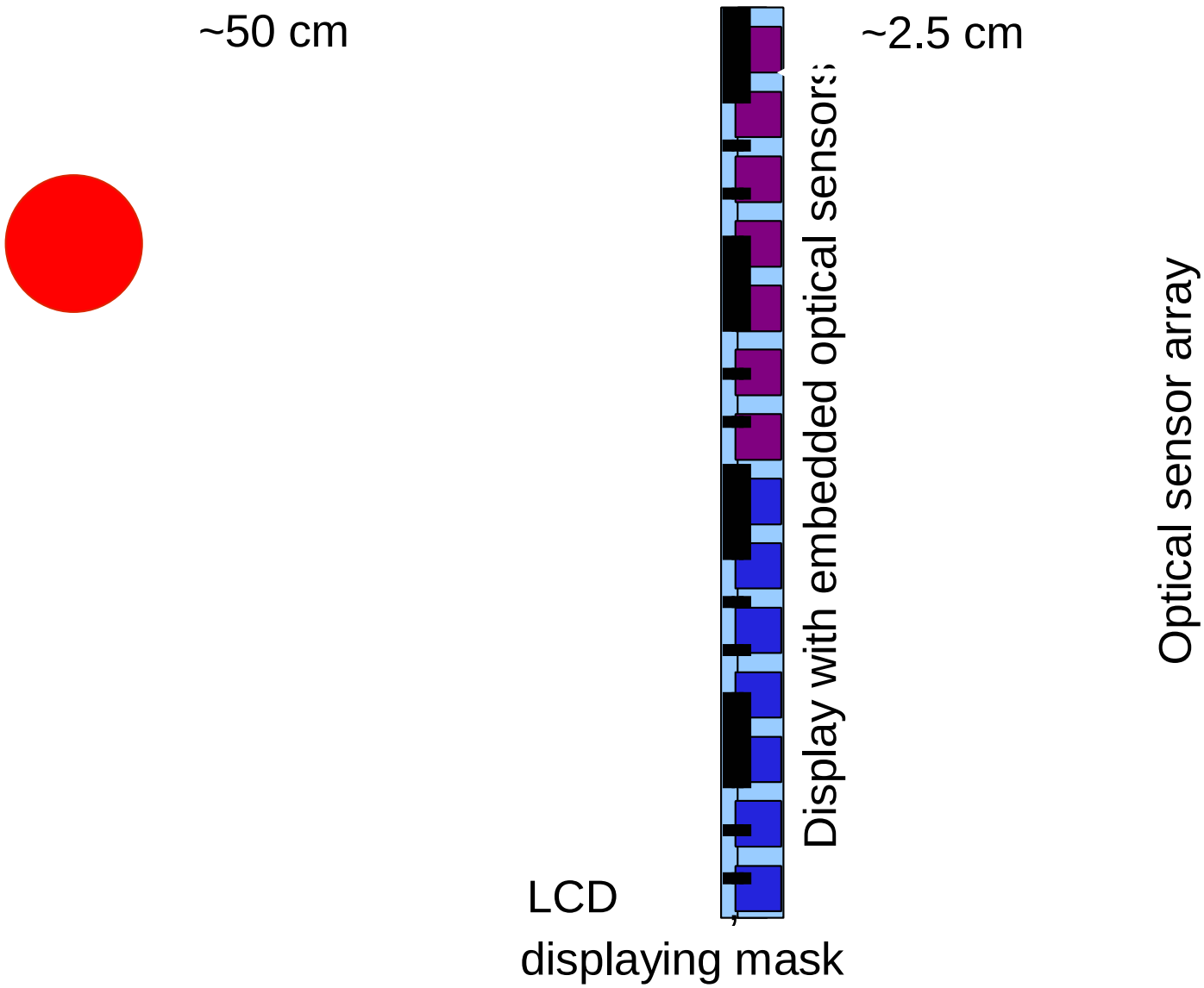
BiDi Screen



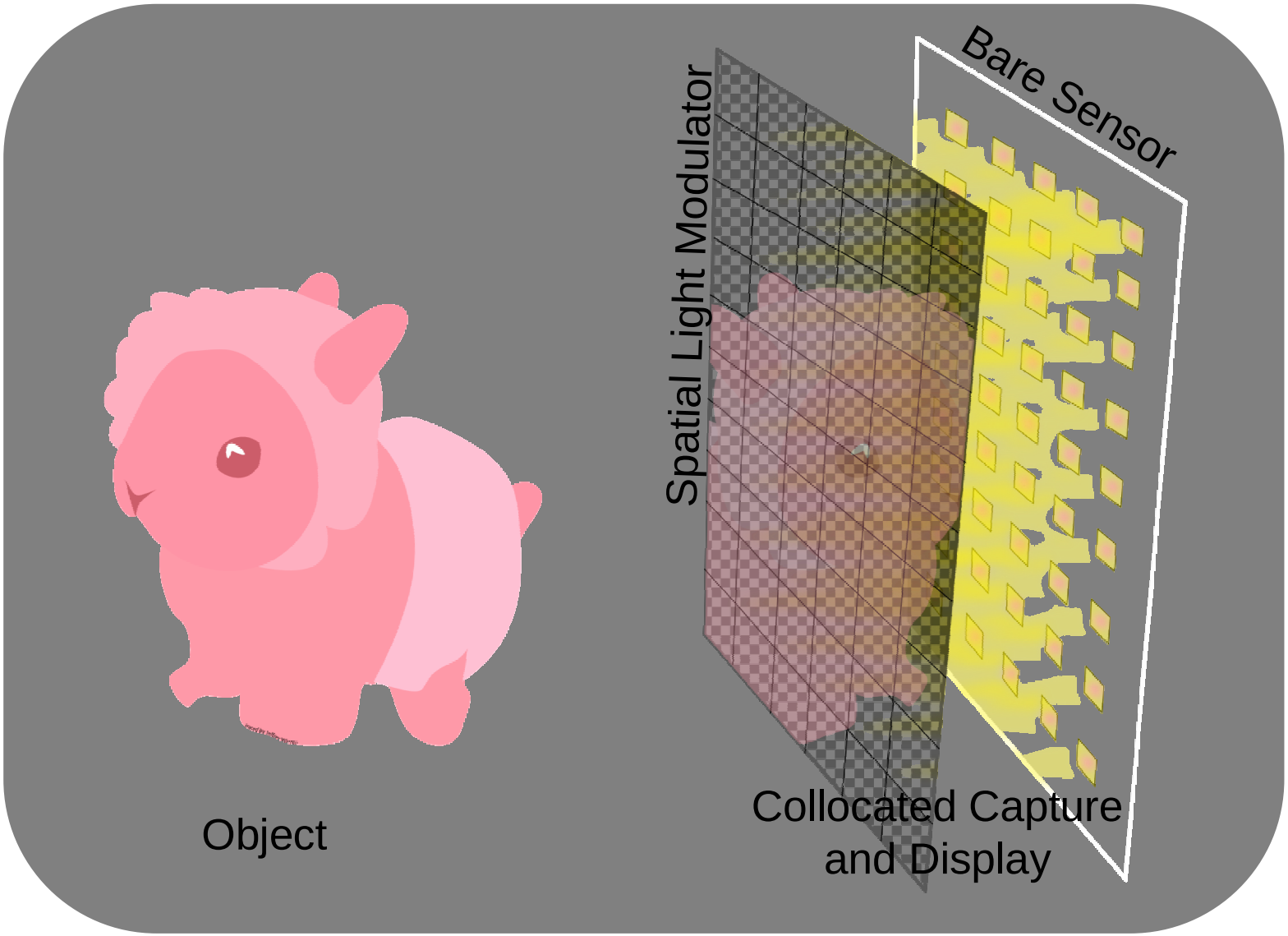
Sharp Microelectronics Optical Multi-touch Prototype



BiDi Screen: Design Overview

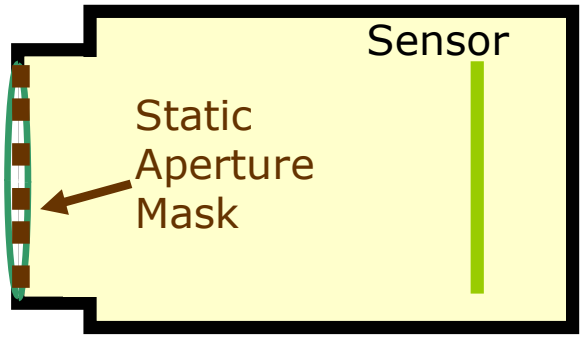


BiDi Screen: Design Vision



Reinterpretable Imaging

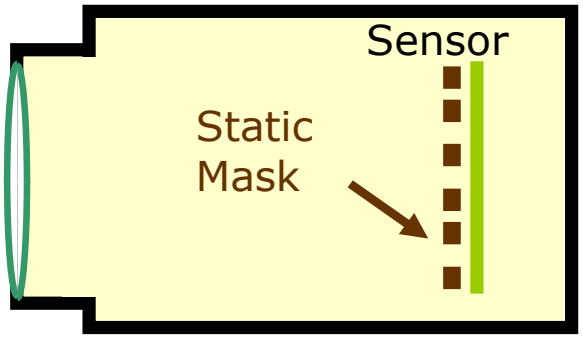
Coded Aperture



Veeraraghavan et al.
SIGGRAPH 2007

Digital
Refocusing

Optical Heterodyning

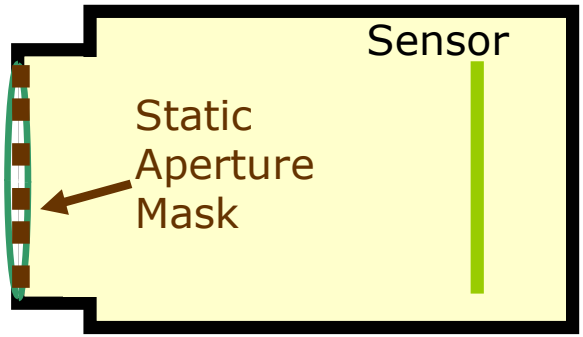


Veeraraghavan et al.
SIGGRAPH 2007

Light Field
Capture

Reinterpretable Imager

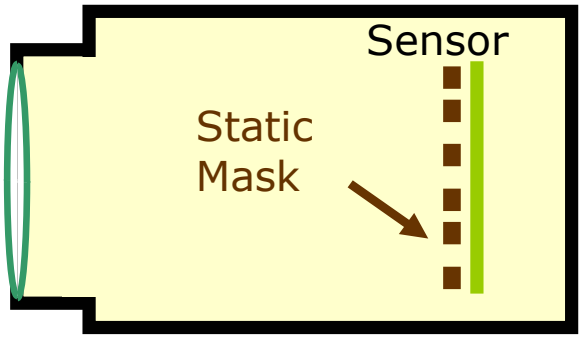
Coded Aperture



Veeraraghavan et al.
SIGGRAPH 2007

Digital
Refocusing

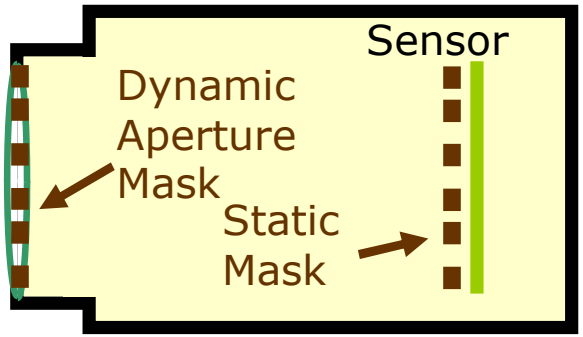
Optical Heterodyning



Veeraraghavan et al.
SIGGRAPH 2007

Light Field
Capture

Reinterpretable Imager

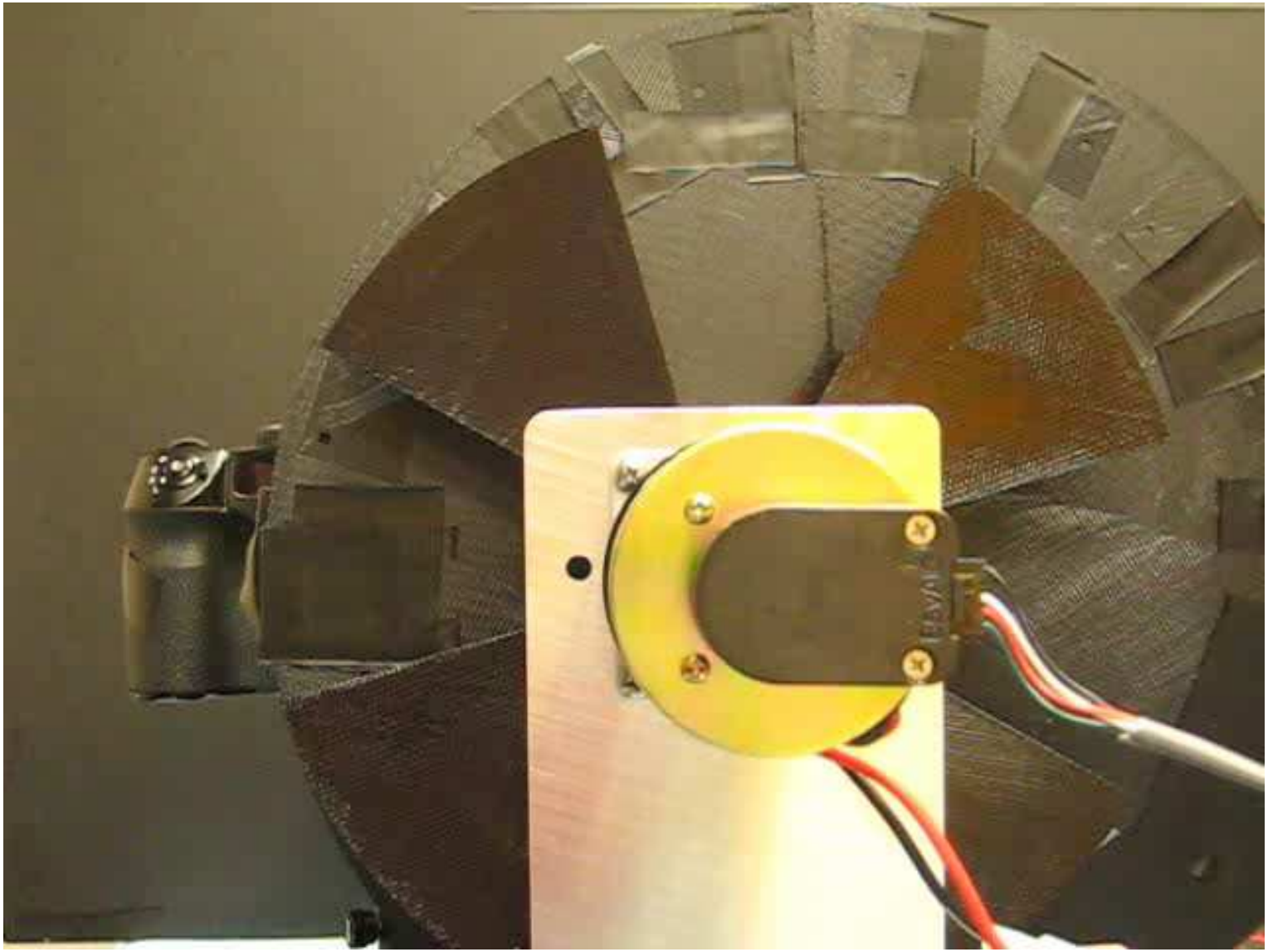


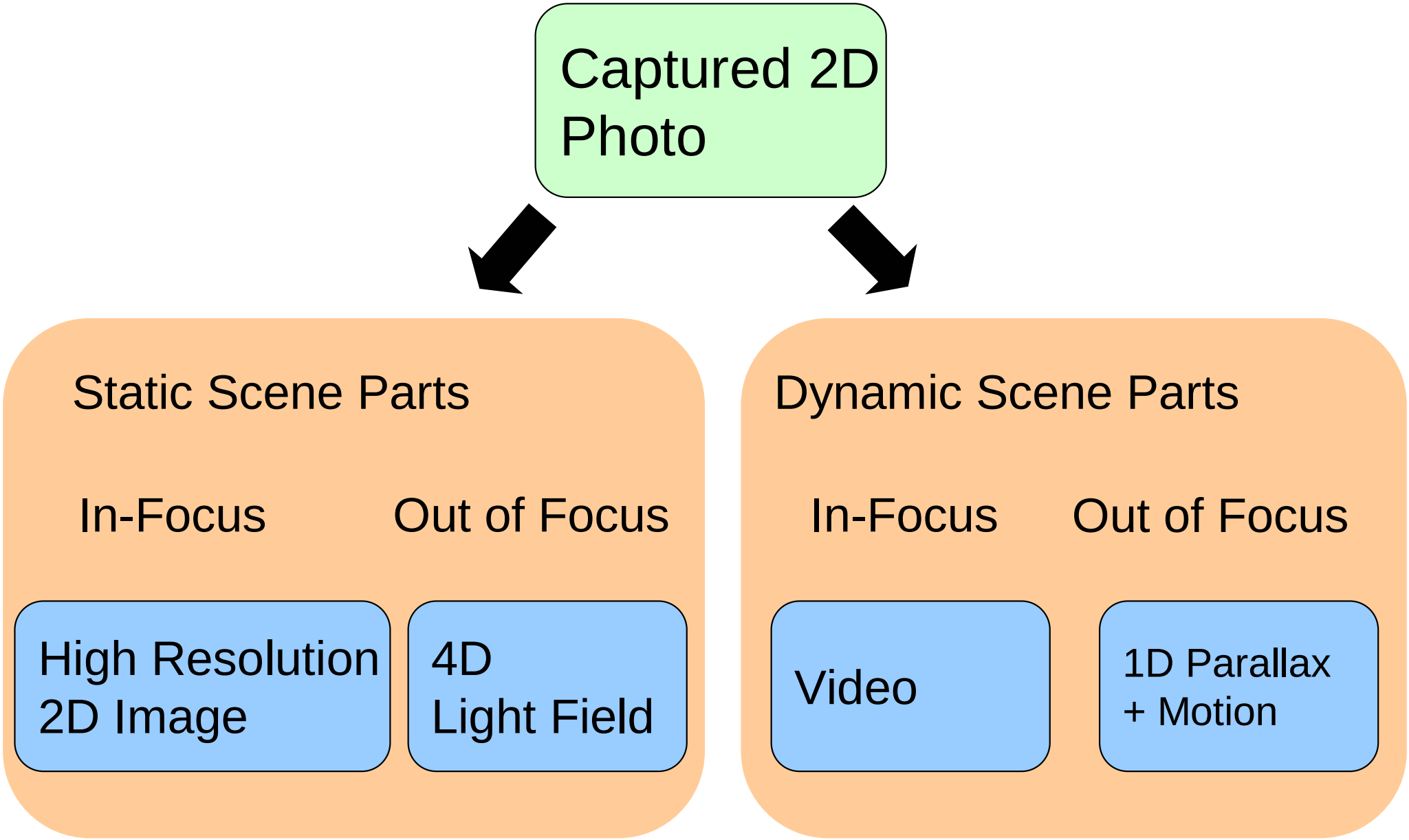
Agrawal et al.
Eurographics 2009

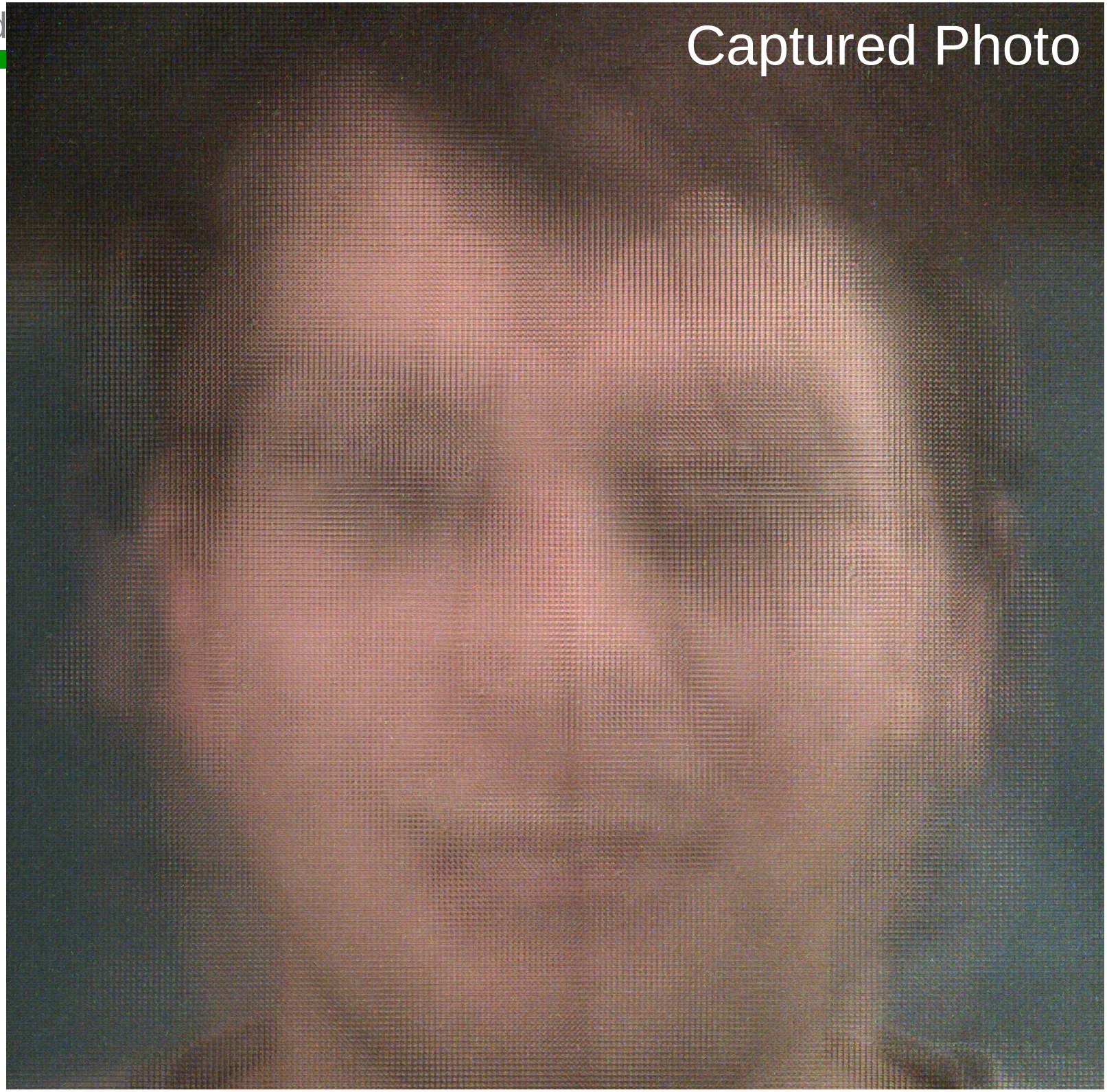
Post-Capture
Resolution Control

"Reinterpretable Imager: Towards Variable Post-Capture Space, Angle and Time Resolution in Photography", Amit Agrawal, Ashok Veeraraghavan, Ramesh Raskar, in **Eurographics 2010**.

Temporally changing mask in Aperture

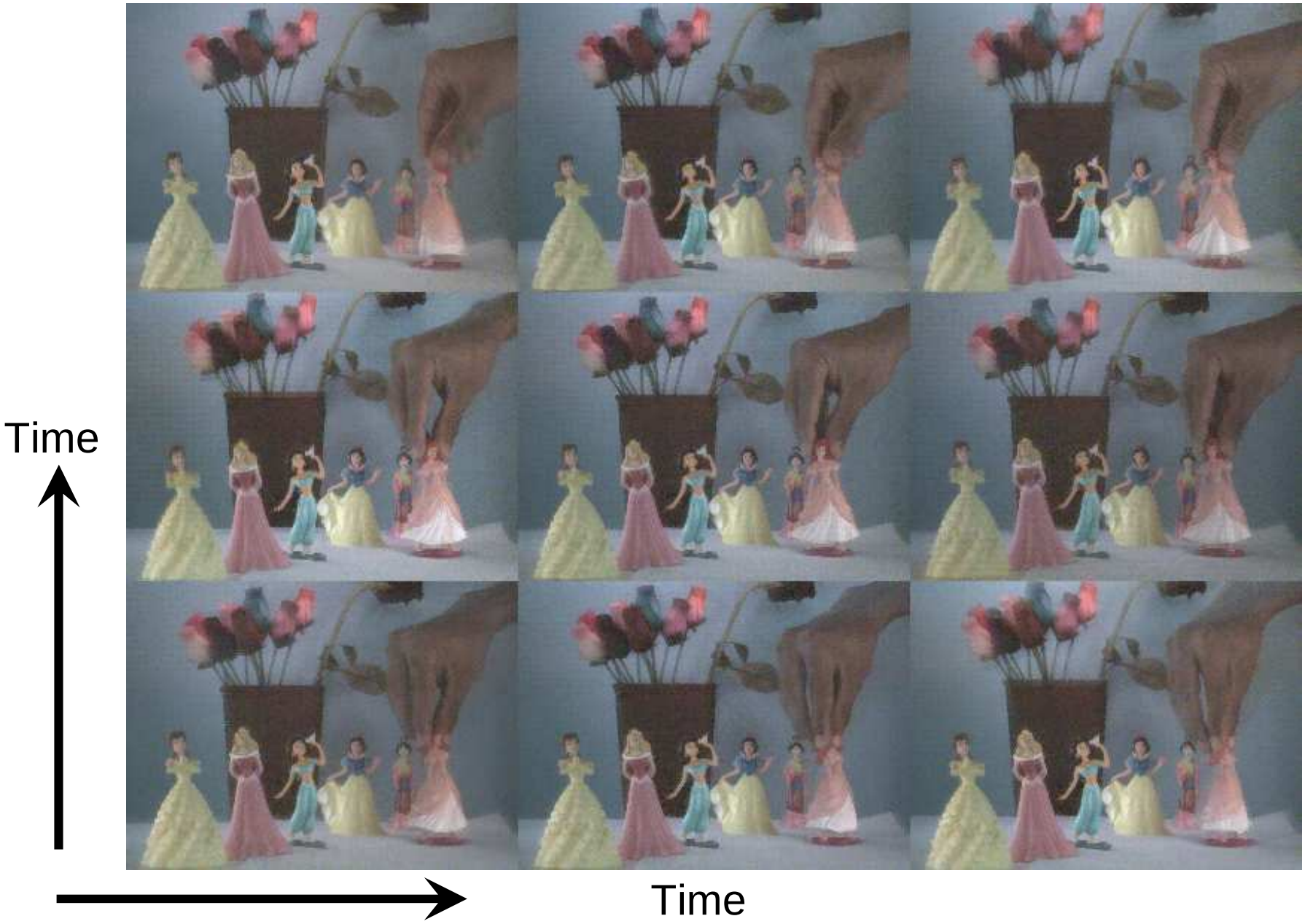



Captured 2D Photo
Static Scene Parts
In-Focus
Out of Focus
High Resolution 2D Image
4D Light Field
Dynamic Scene Parts
In-Focus
Out of Focus
Video
1D Parallax + Motion

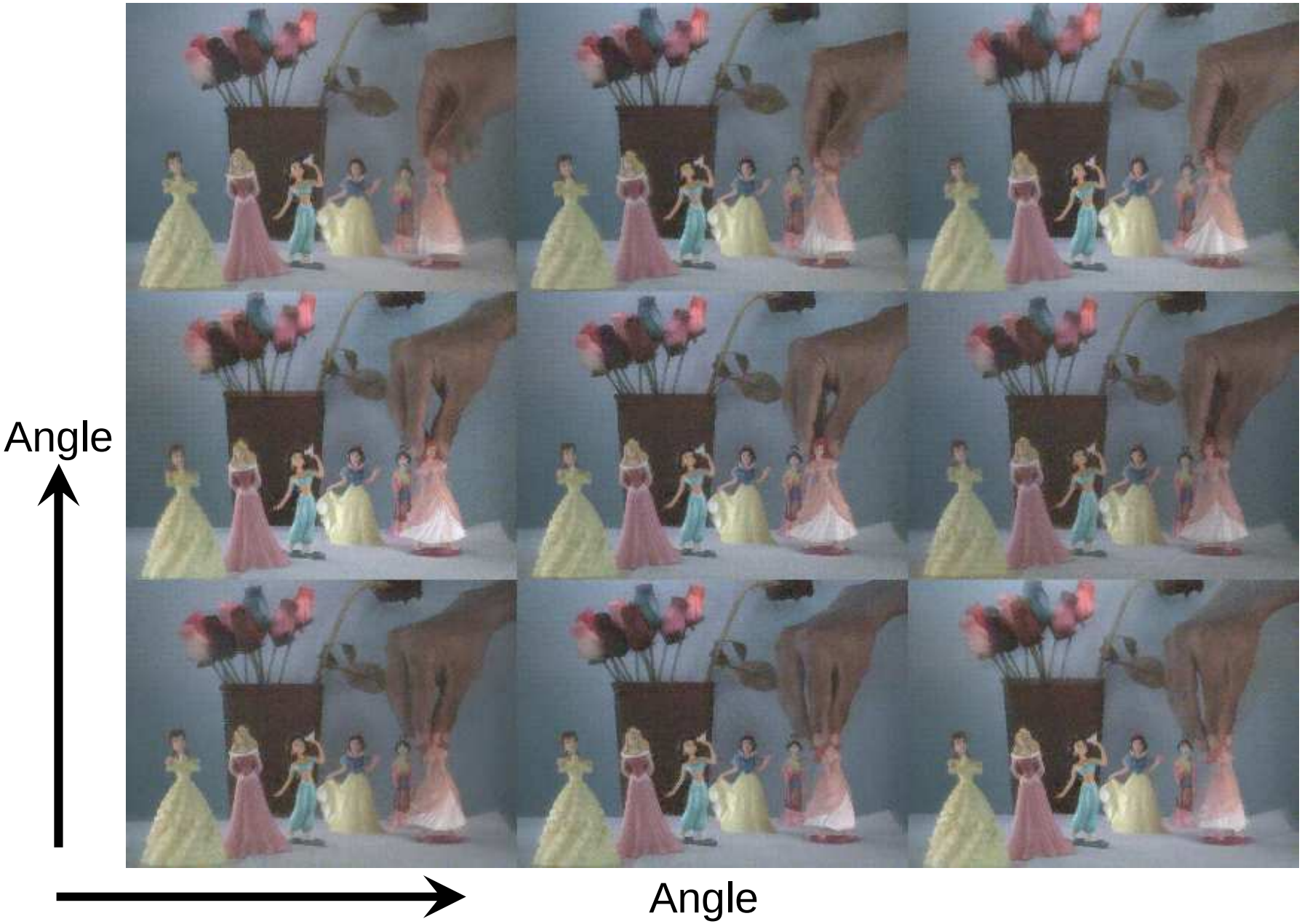

Captured Photo

Video from Single-Shot (Temporal Frames)

Reconstructed Sub-Aperture Views (3 by 3 Light Field)



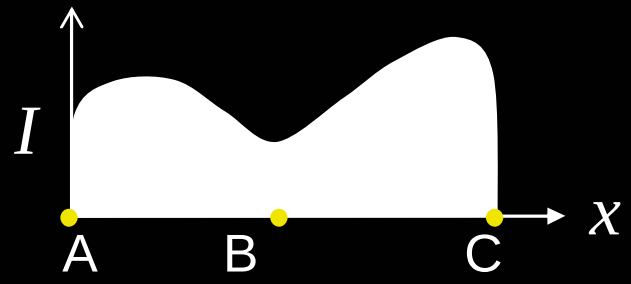
For Rotating Doll

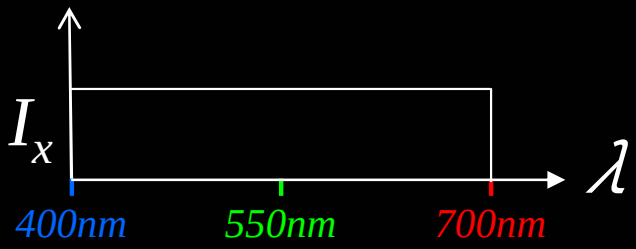


For Static Scene Parts

Light Field Modulation

Agile Spectrum Imaging

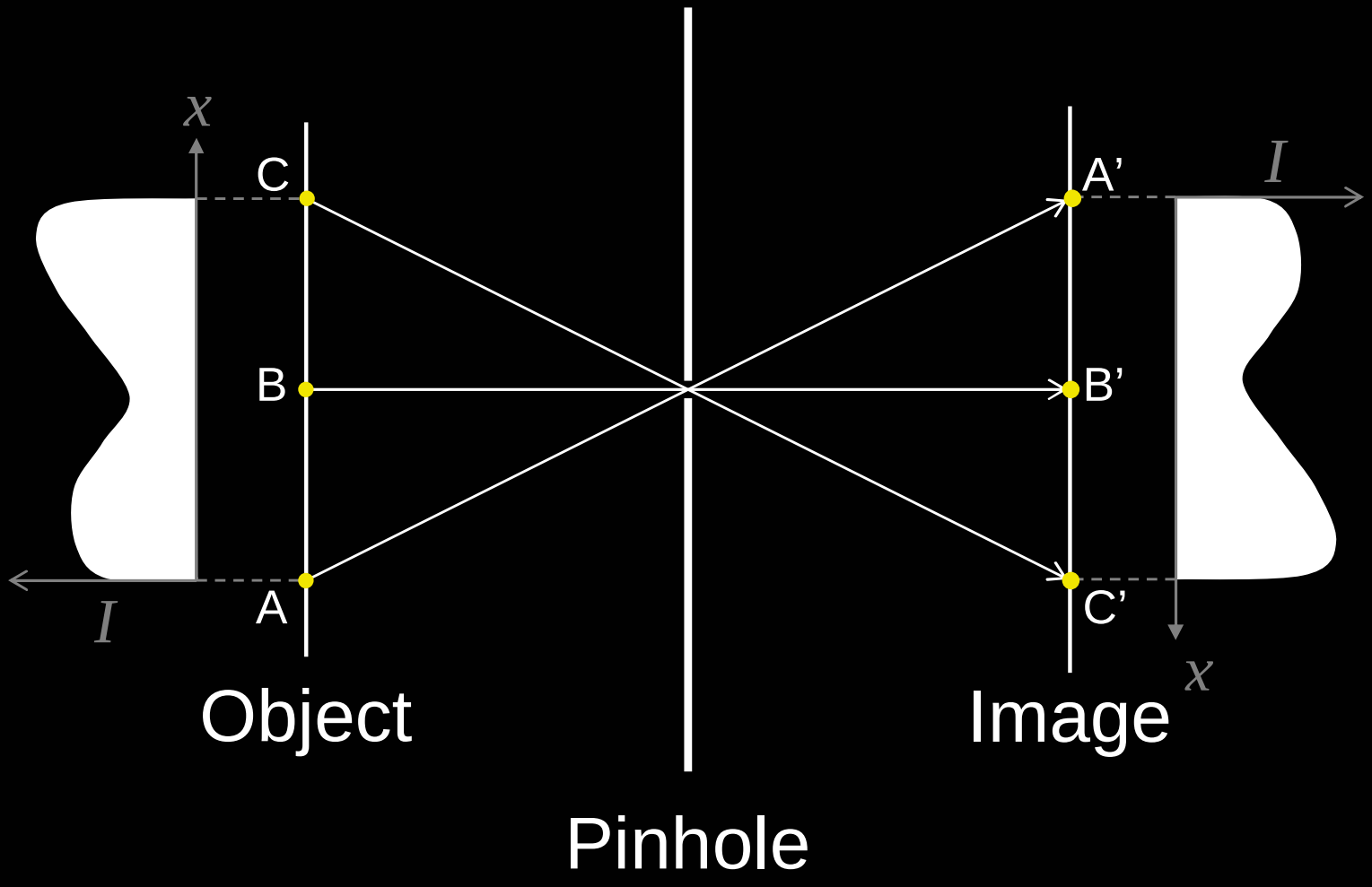


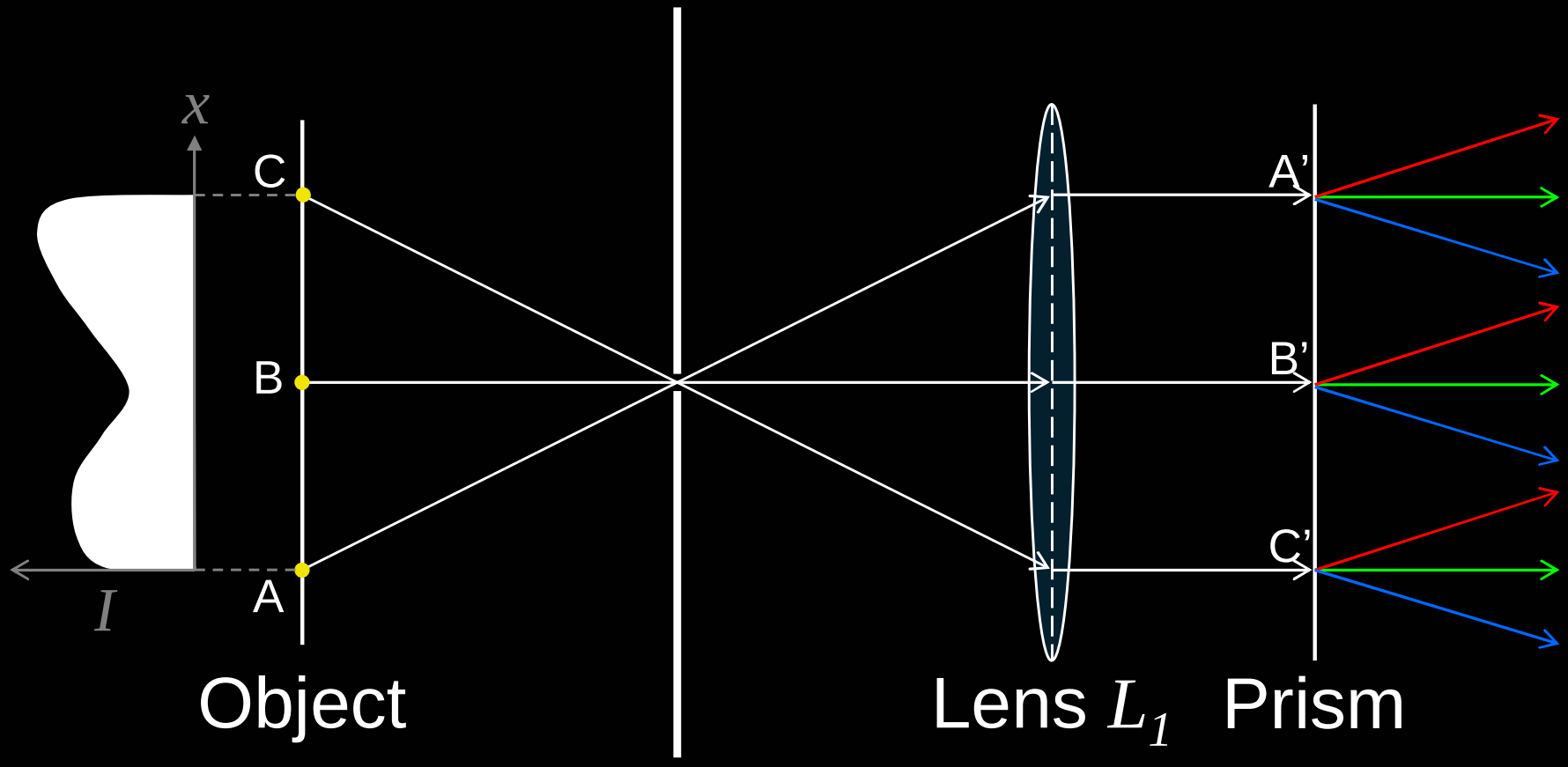


Arbitrary *white* 1D signal

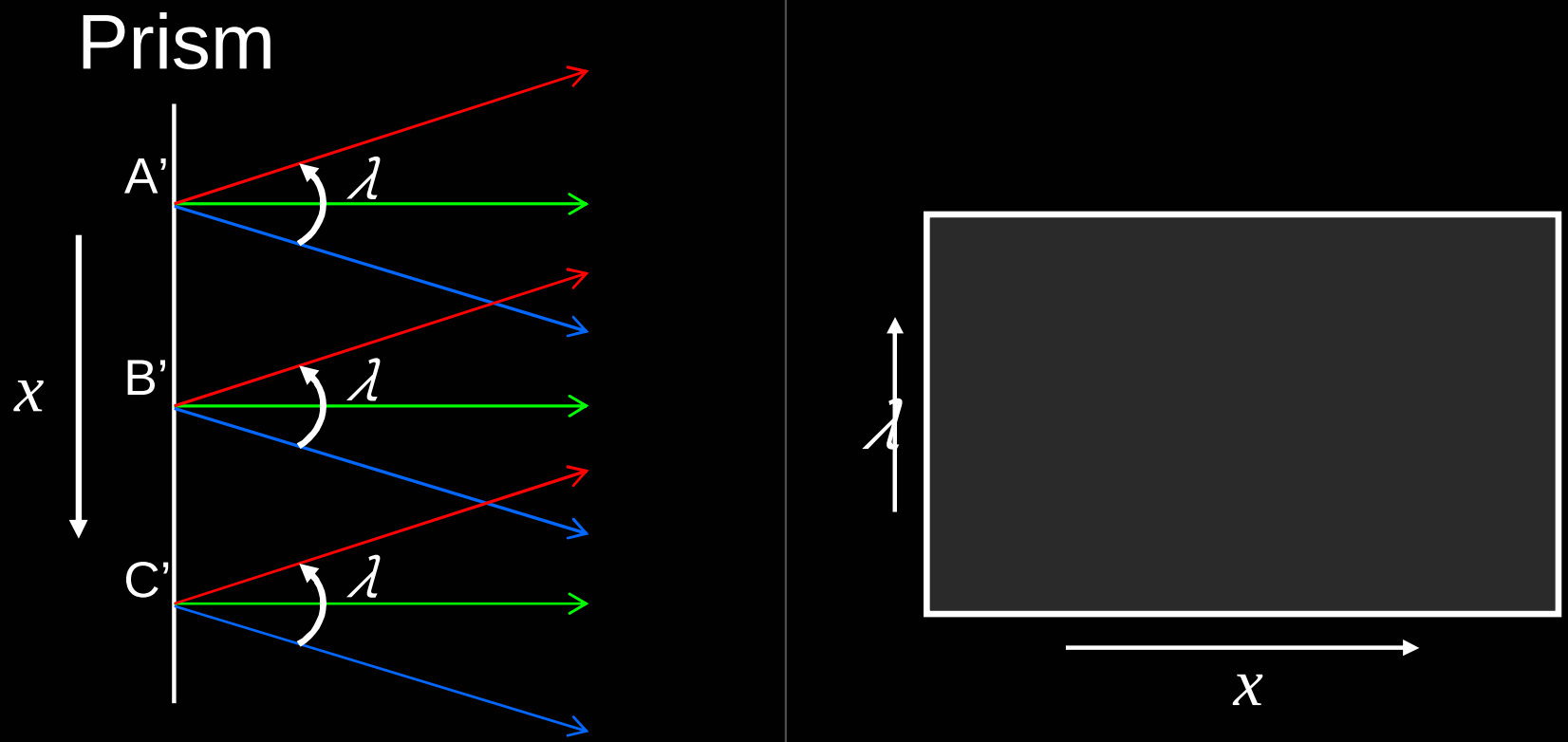
"Agile Spectrum Imaging: Programmable Wavelength Modulation for Cameras and Projectors", Ankit Mohan, Ramesh Raskar and Jack Tumblin, in **Eurographics 2008**.

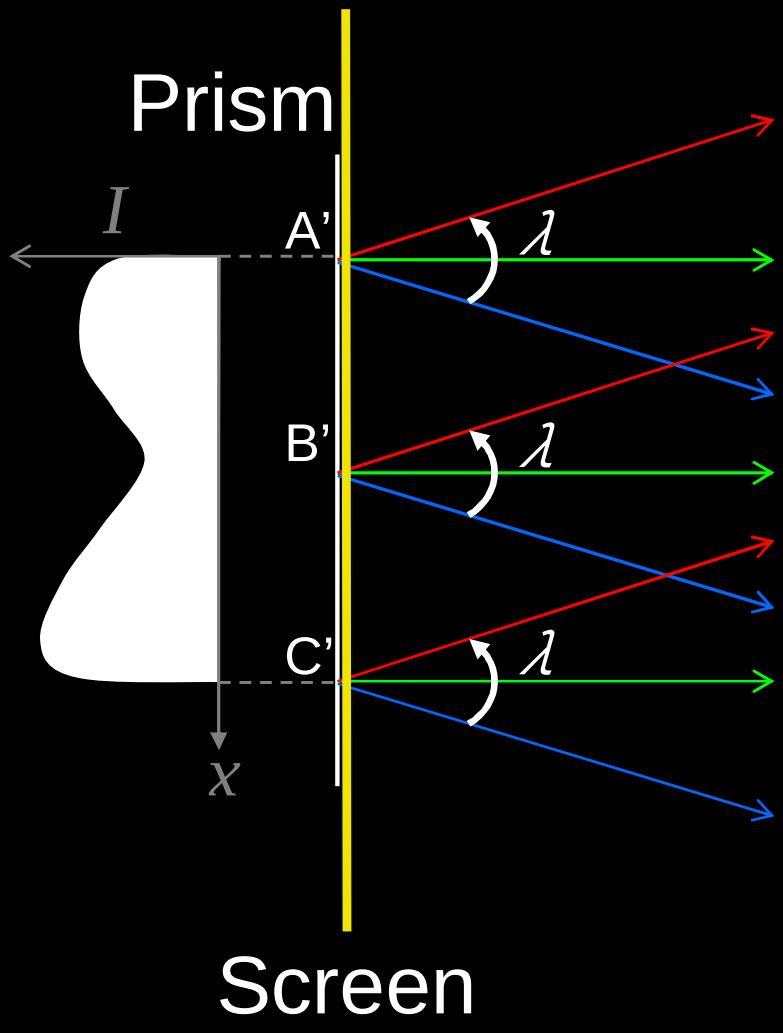
Pinhole Camera

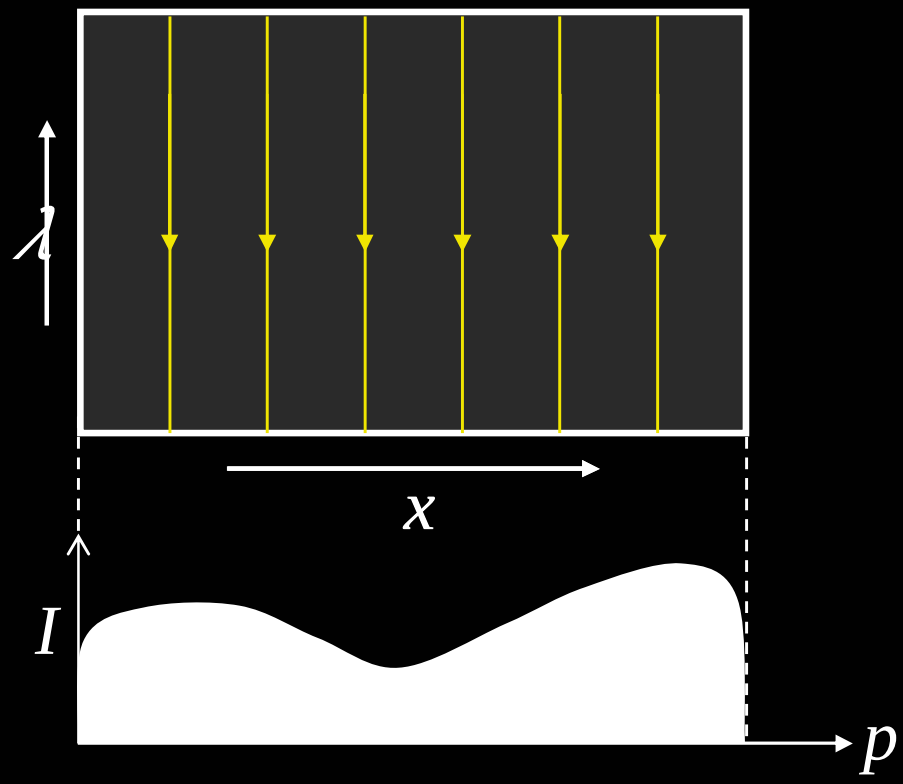



x
C
B
A
I
A'
B'
C'
Object
Pinhole
Lens L_1
Prism

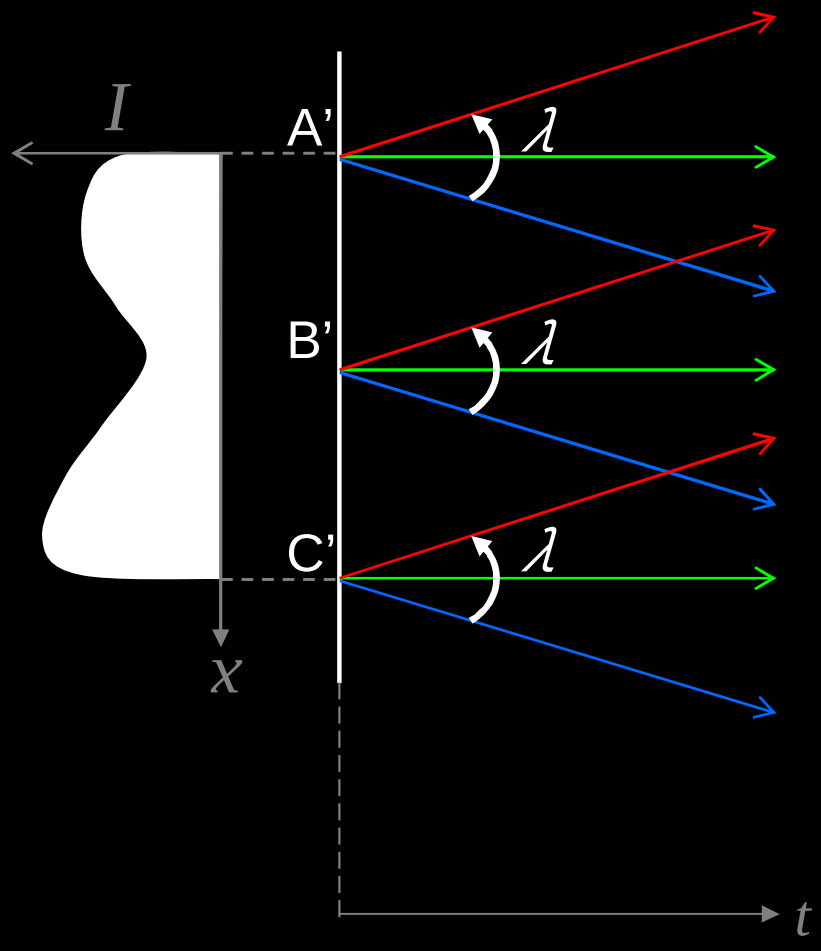
Spectral Light-Field



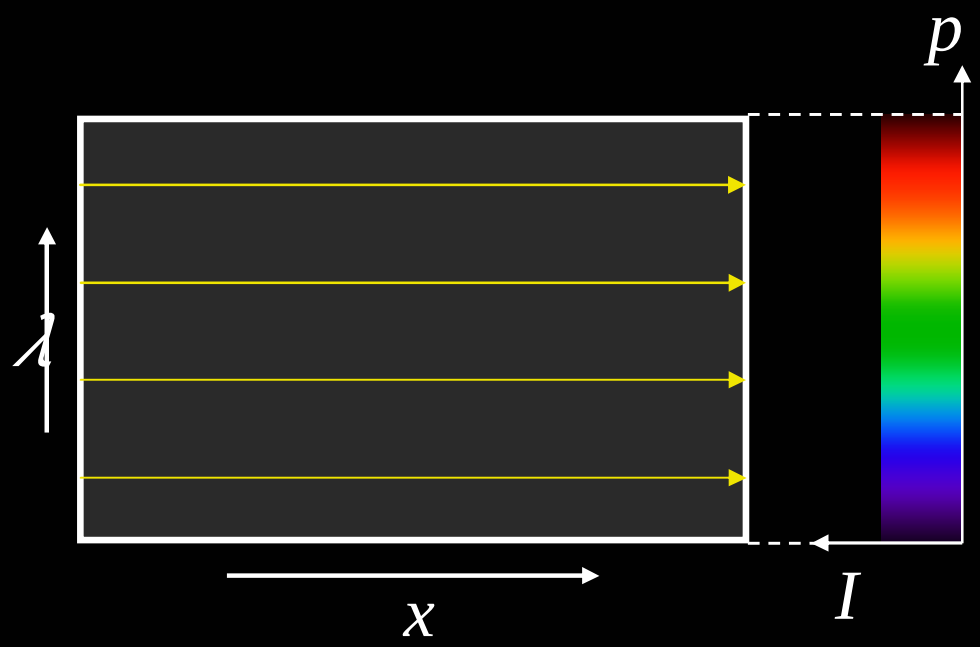

Prism
I
A’
B’
C’
λ
λ
λ
x
Screen

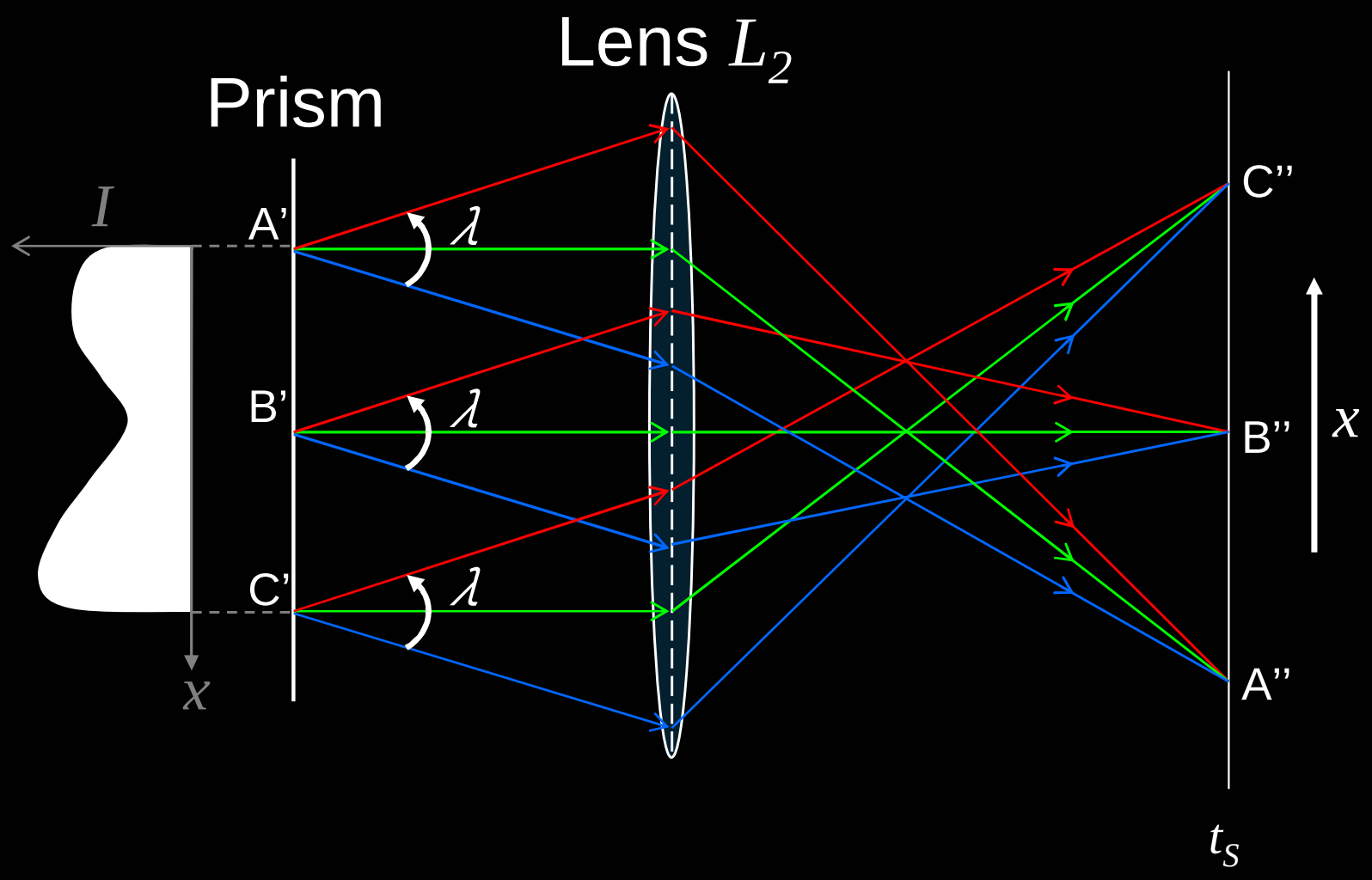

λ
x
I
p

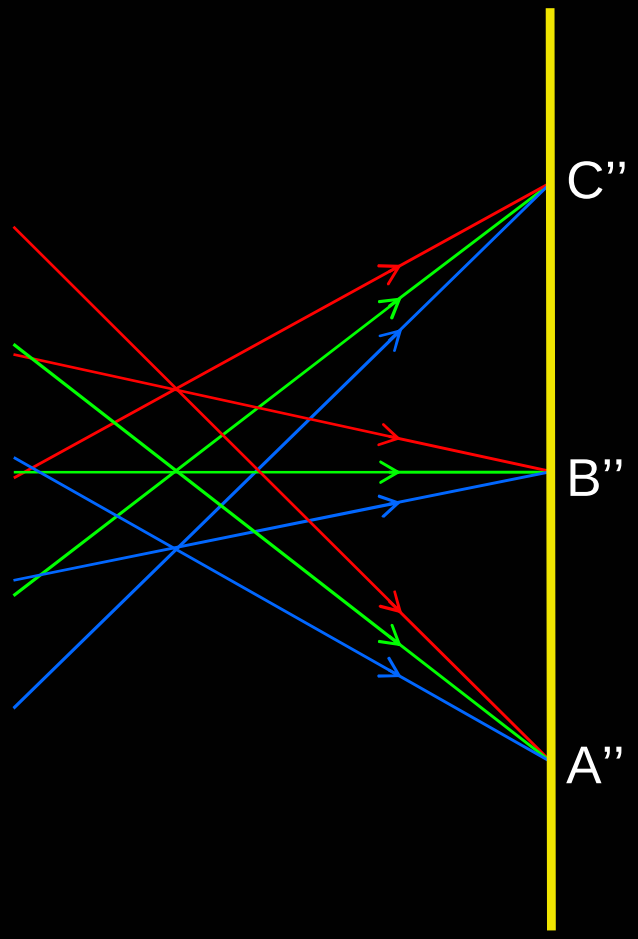
Prism



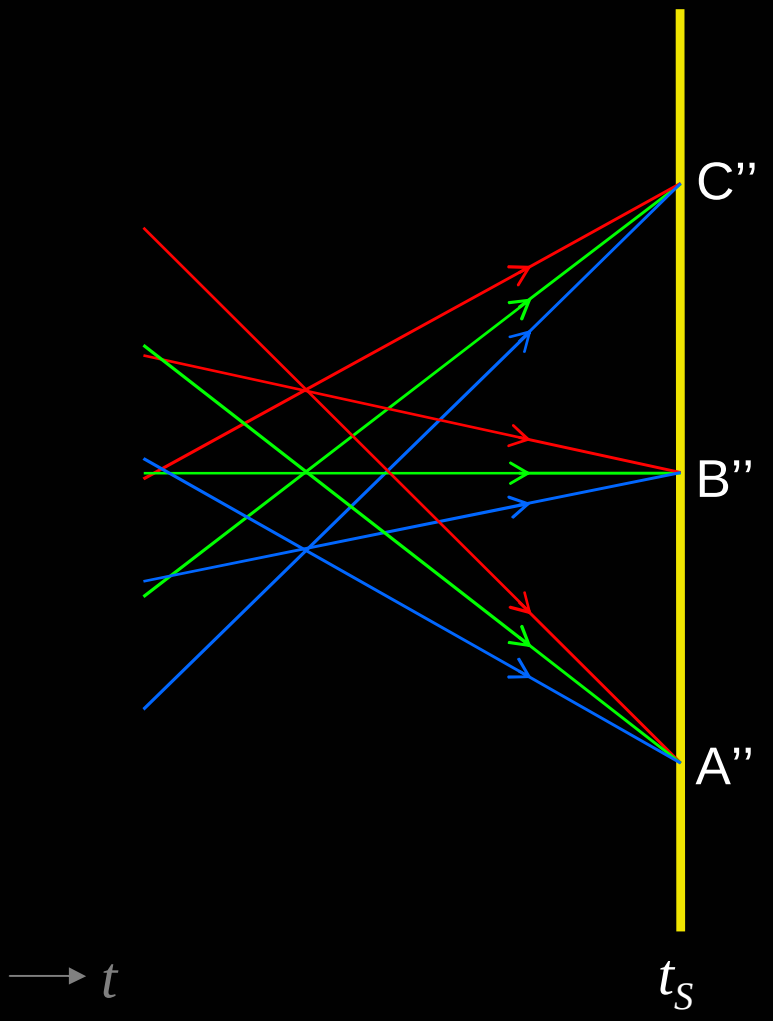
$t = \infty$

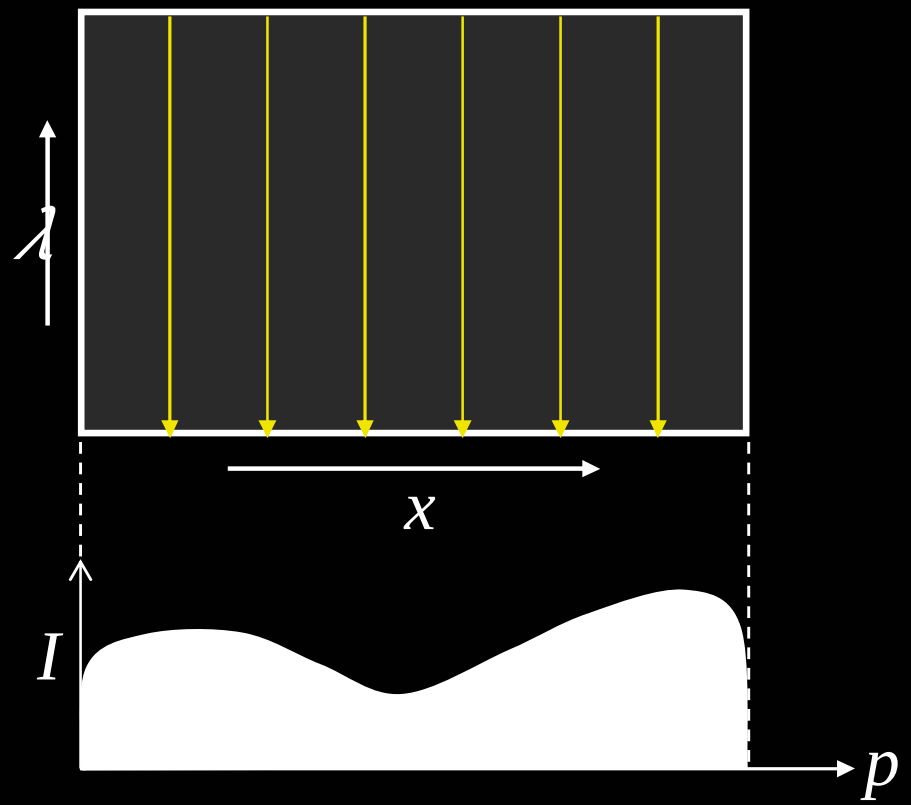



Lens L_2
Prism
I
A'
B'
C'
λ
λ
λ
x
C''
B''
A''
x
t_S

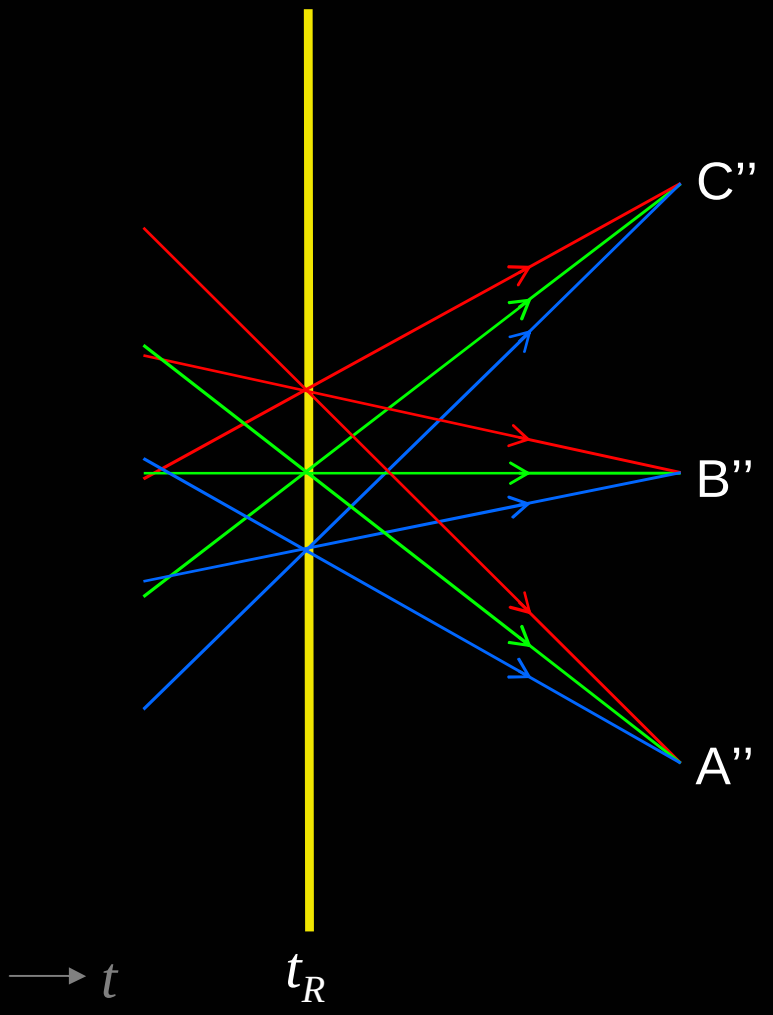

C”
B”
A”

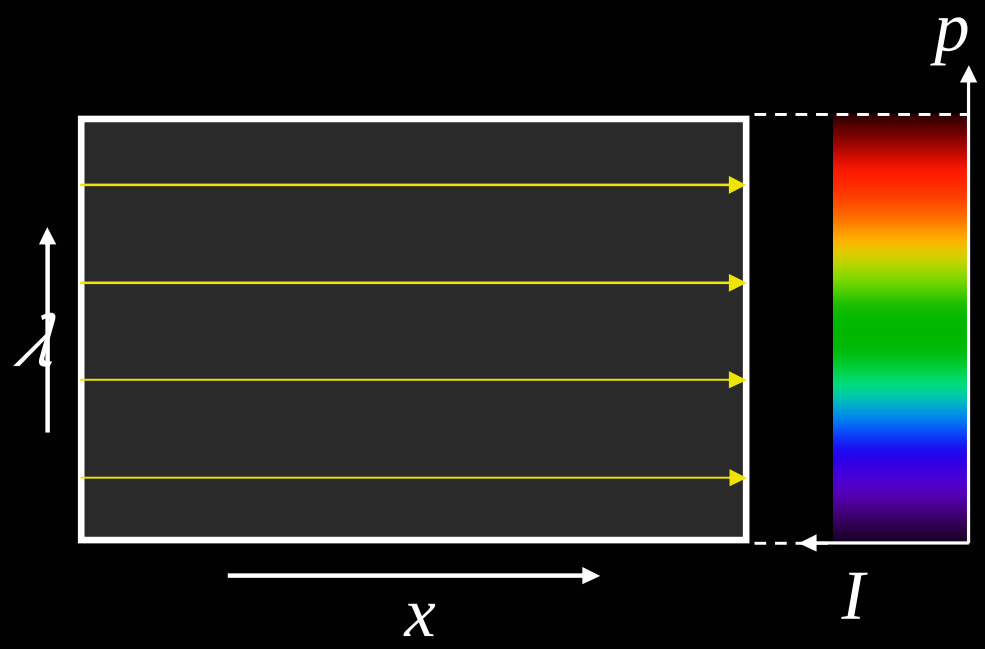
Sensor plane ($t=t_s$)



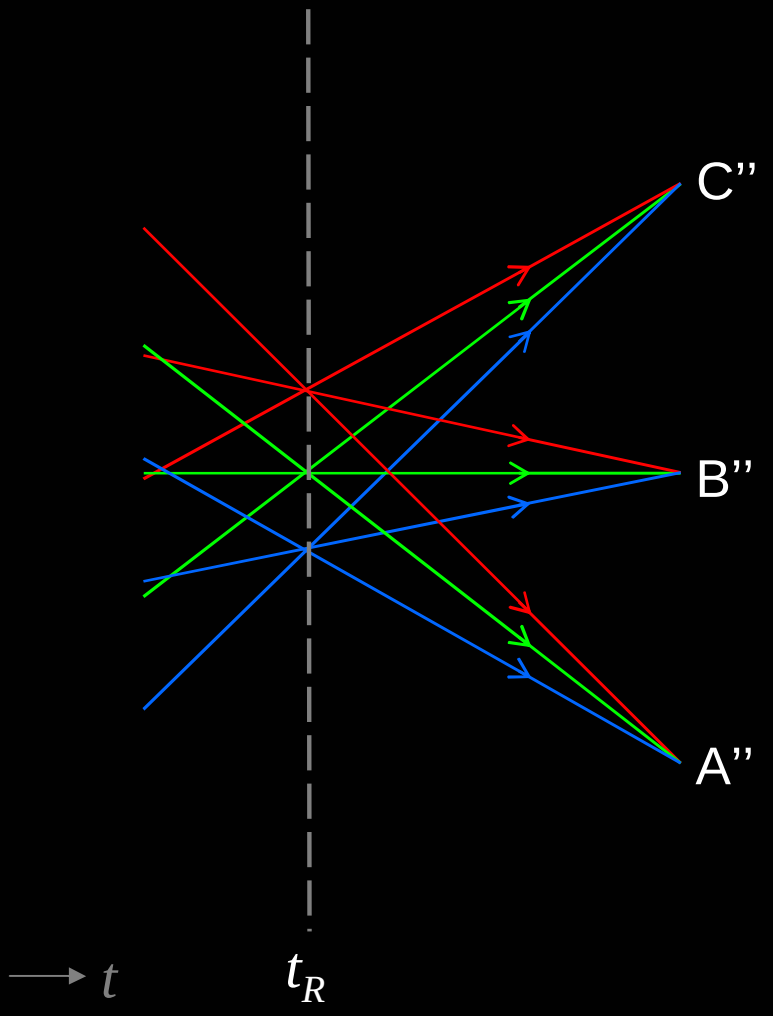


Rainbow plane ($t=t_R$)





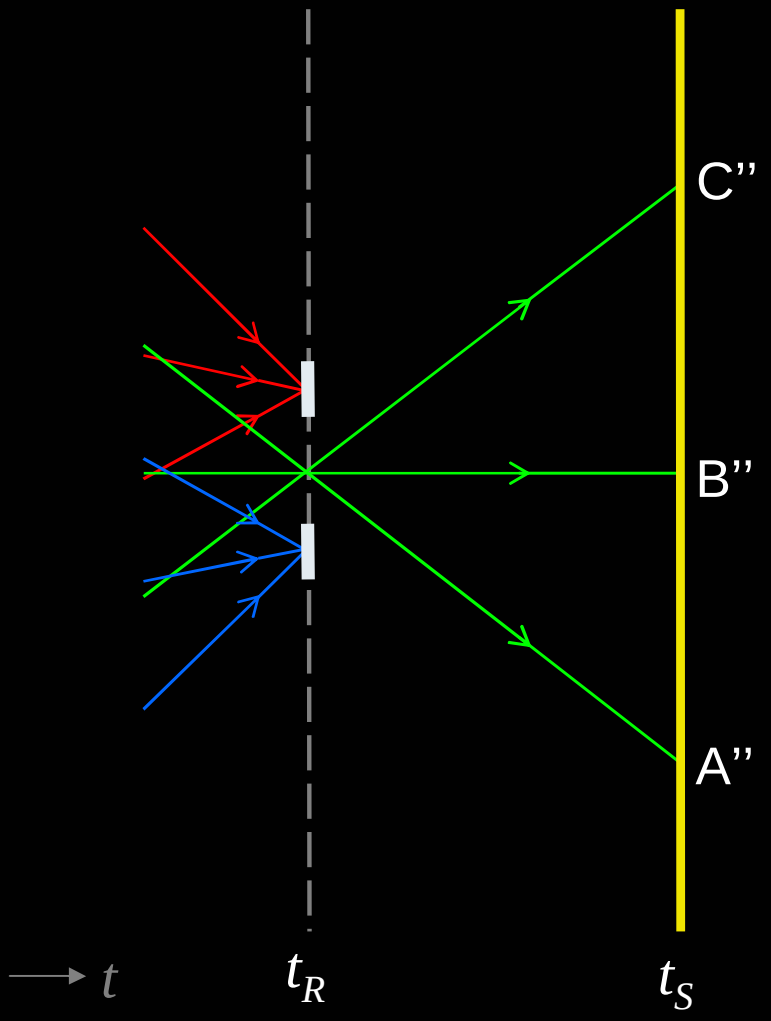
Rainbow plane (t=t_R)

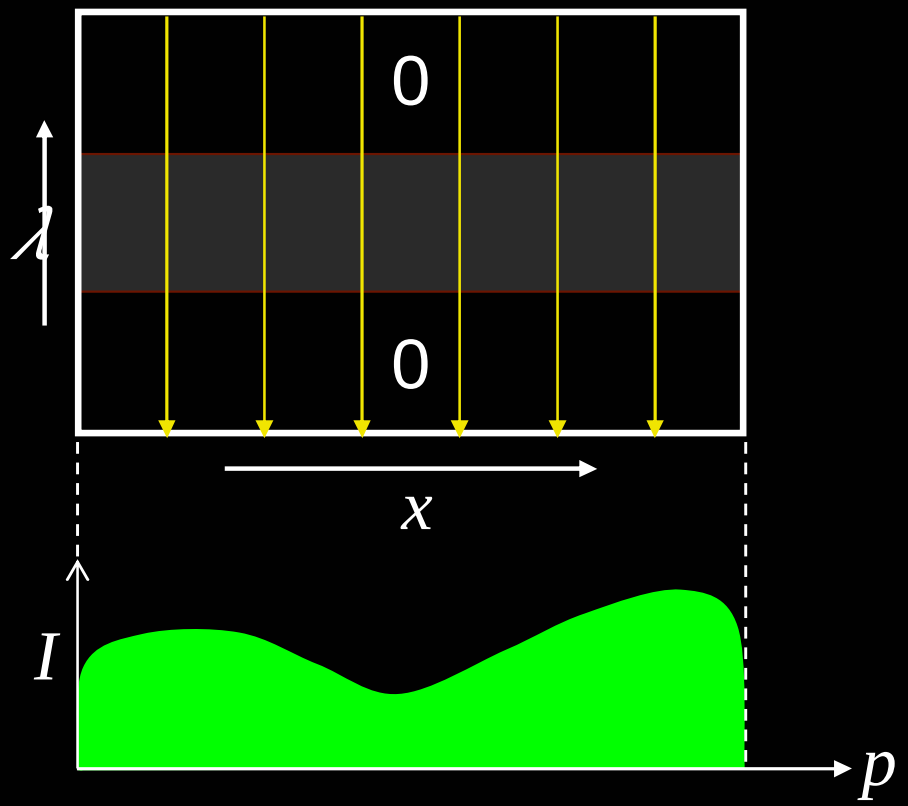


$\lambda \leftarrow\rightarrow$

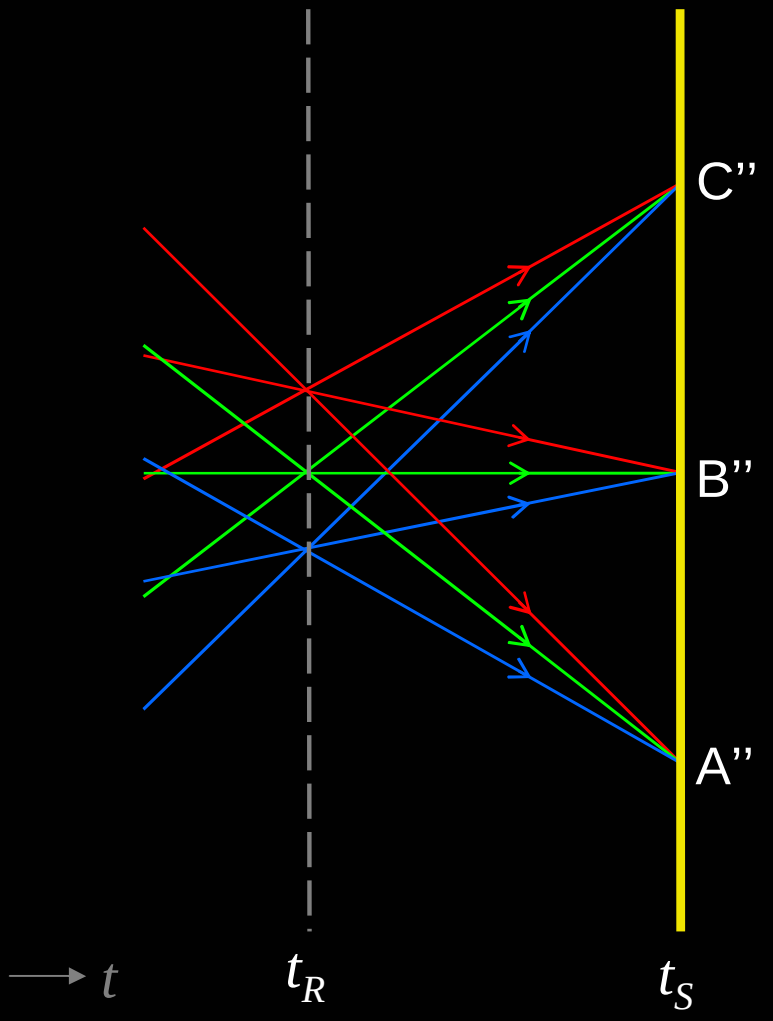
position

Mask in the Rainbow plane

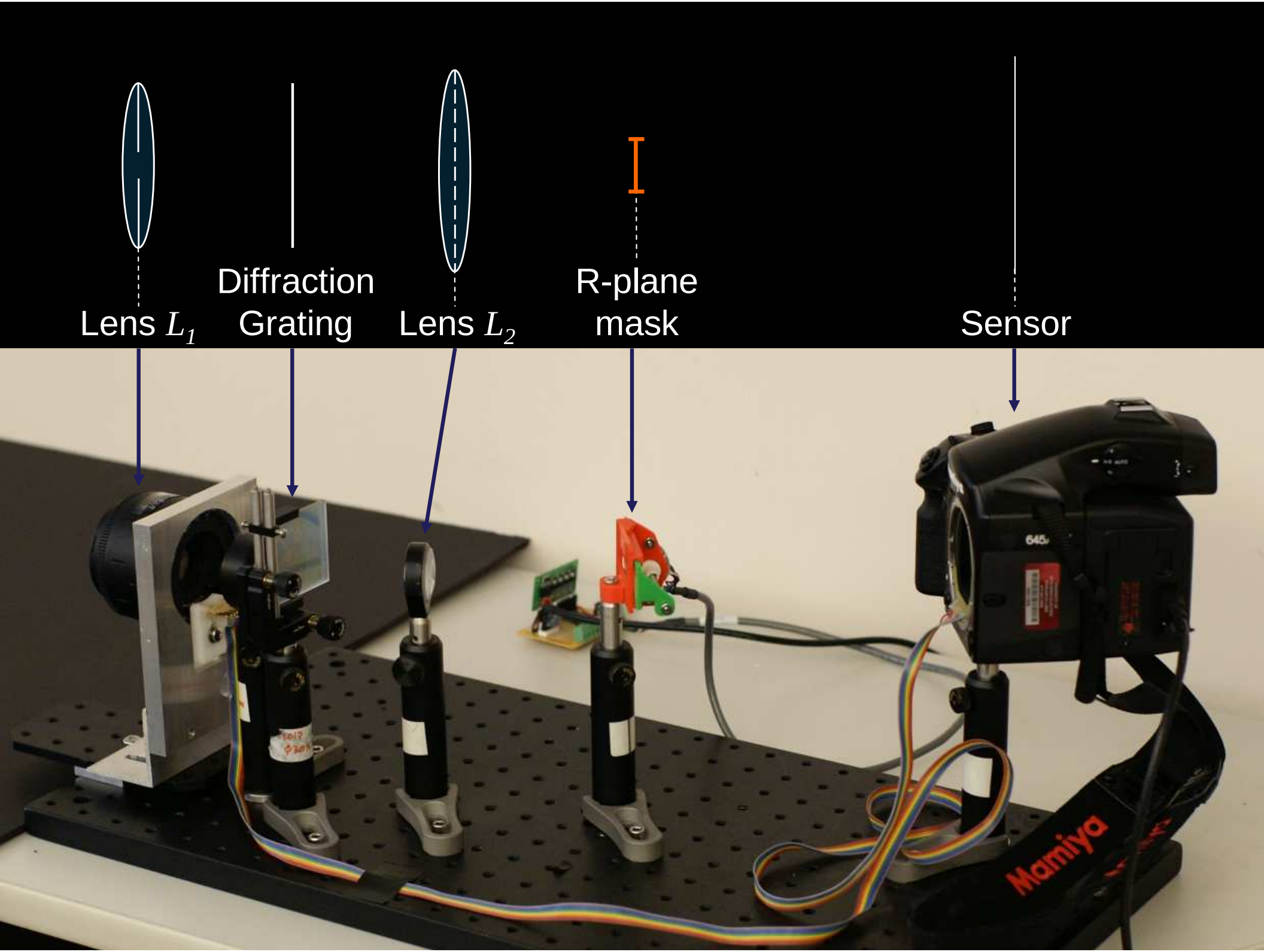


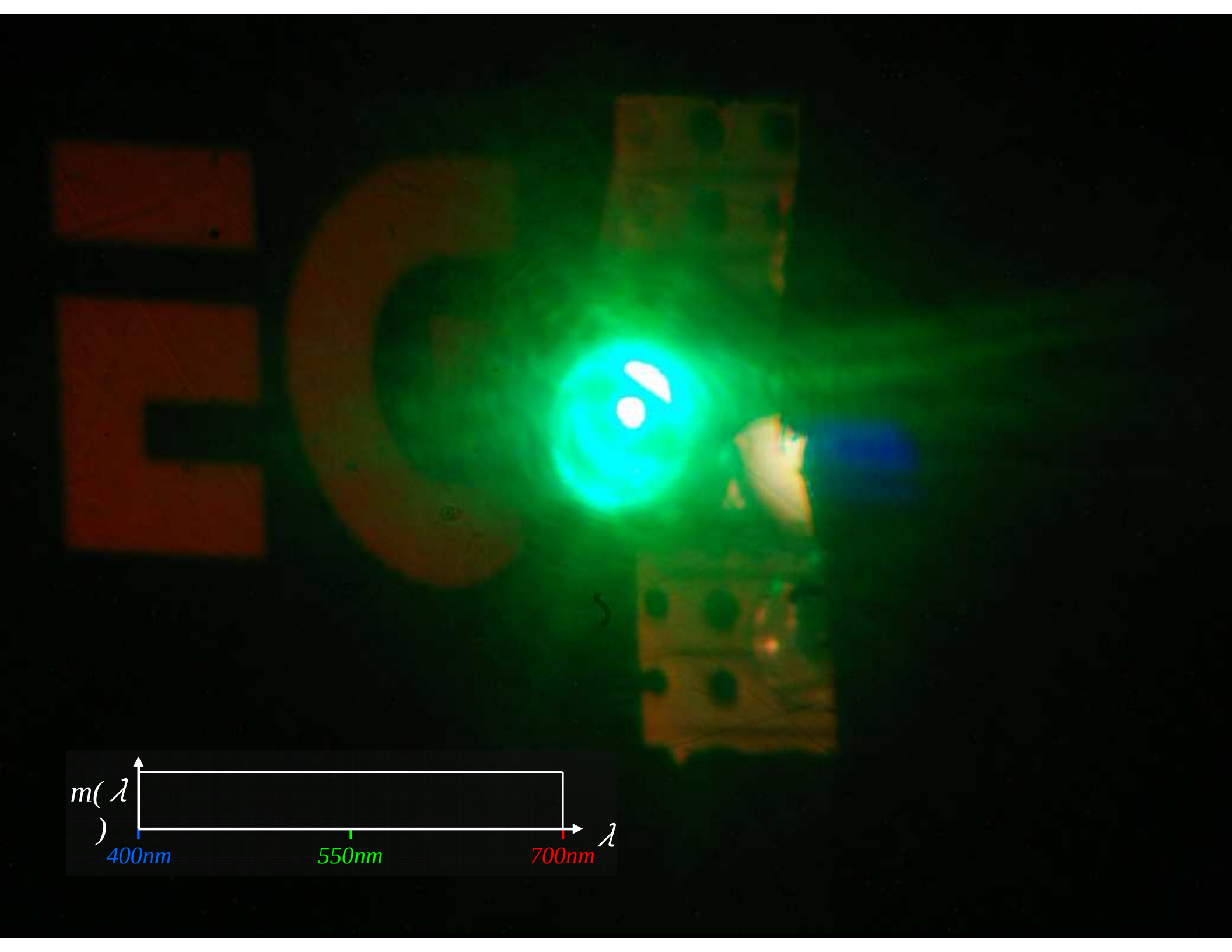


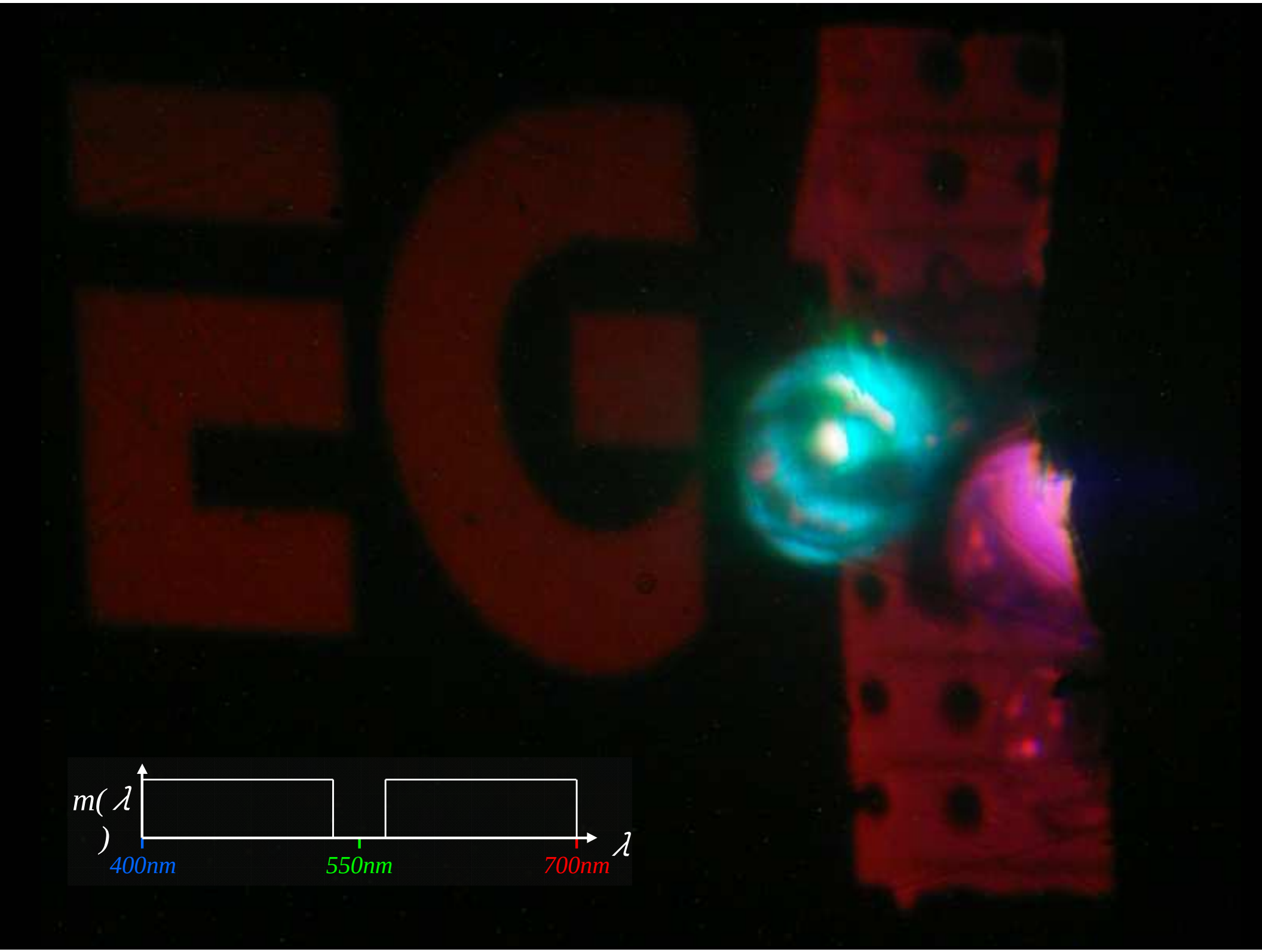
Rainbow plane ($t=t_R$)



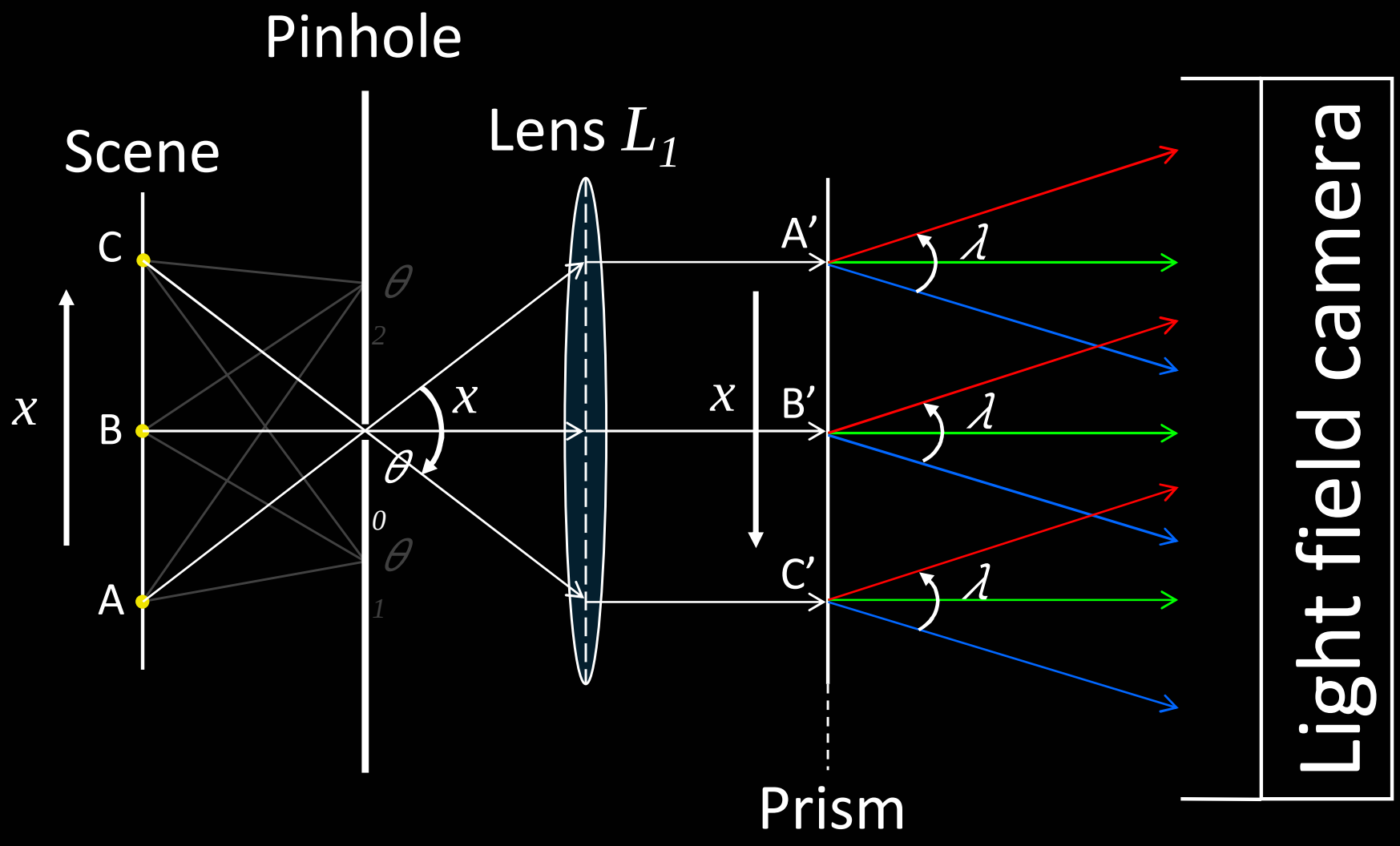
Control the *spectral sensitivity* of the sensor by placing an appropriate *grayscale masks* in the R-plane.


Lens L_1
Diffraction Grating
Lens L_2
R-plane mask
Sensor
Mamiya

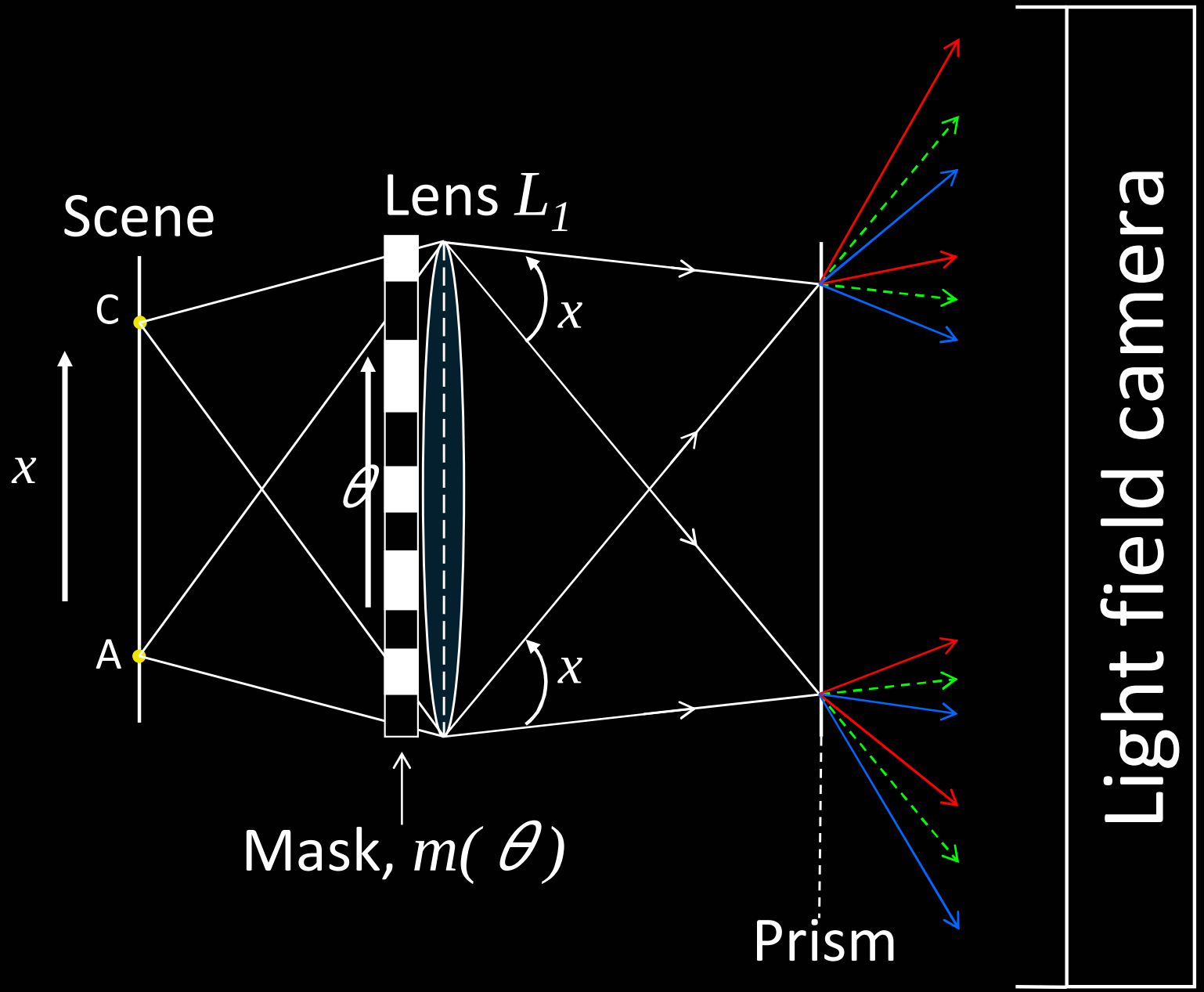

m(λ)
λ
400nm
550nm
700nm


m(λ)
400nm
550nm
700nm
λ

Pinhole multi-spectral camera



Mask based multi-spectral camera

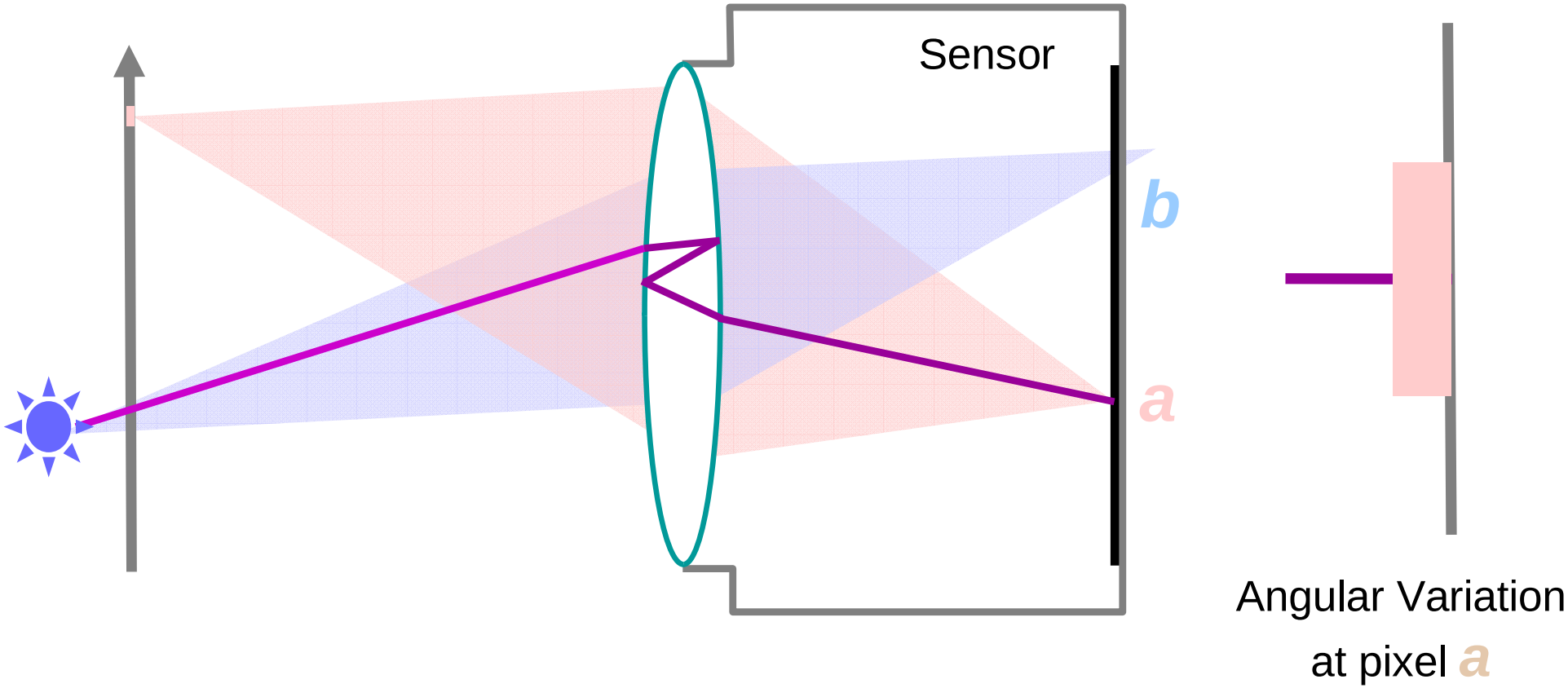


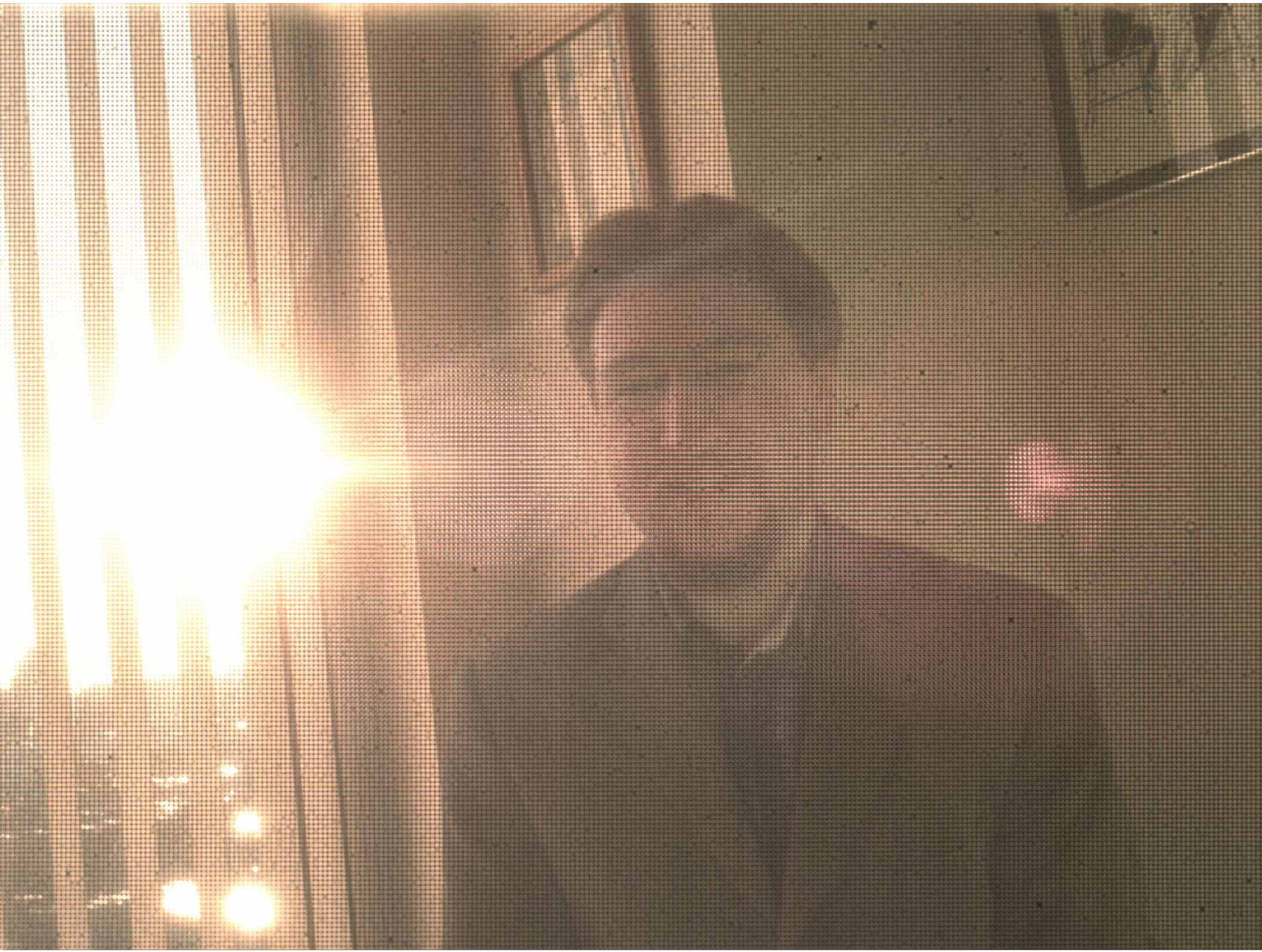
Glare separation camera

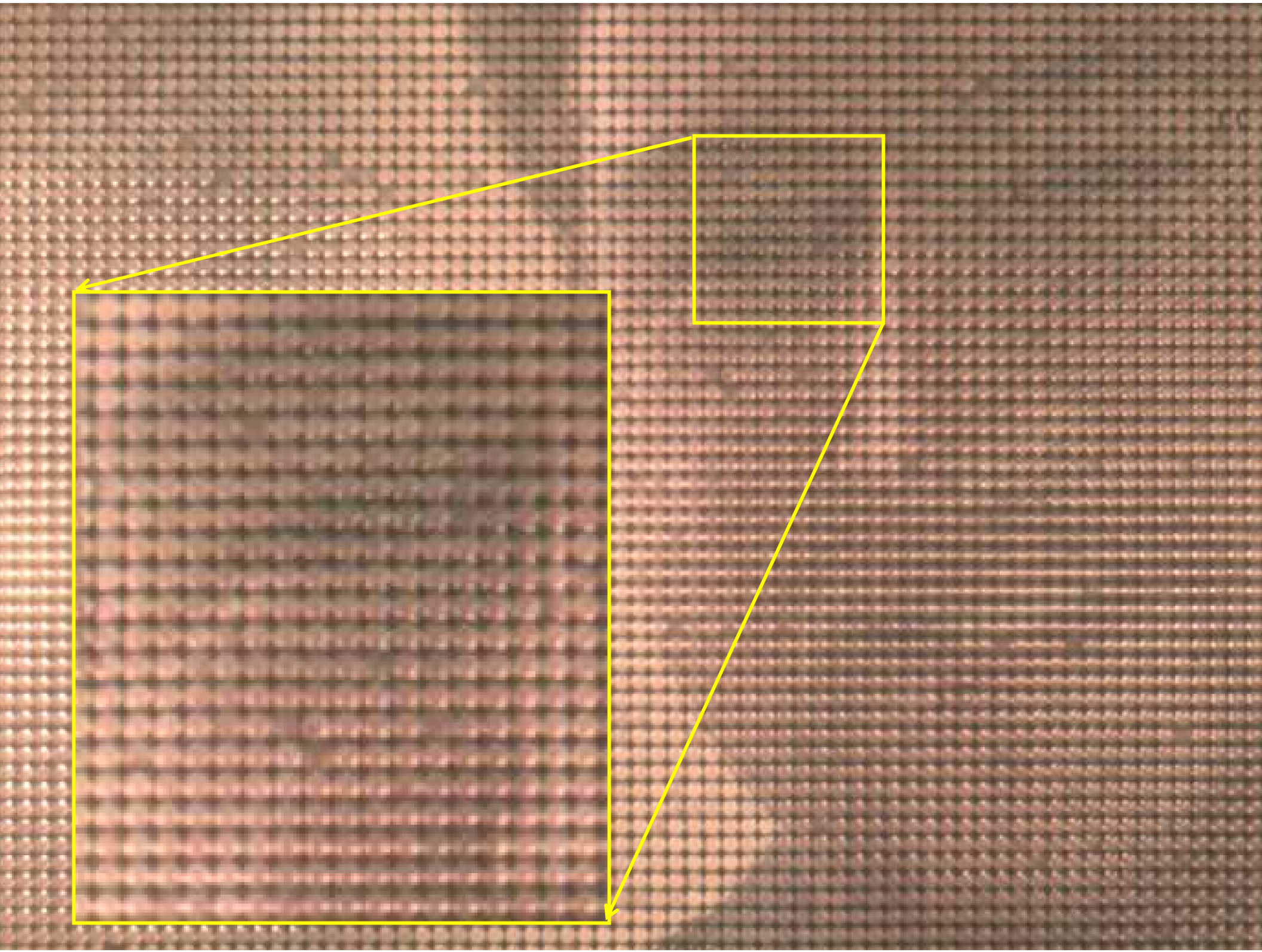
“Glare Aware Photography: 4D Ray Sampling for Reducing Glare Effects of Camera Lenses”, Ramesh Raskar, Amit Agrawal, Cyrus Wilson and Ashok Veeraraghavan, in **SIGGRAPH 2008**.

Effects of Glare on Image

- Hard to model, Low Frequency in 2D
- But reflection glare is outlier in 4D ray-space
- Glare coherence to recover full resolution







Reducing Glare

Conventional Photo

After removing outliers

Glare Reduced Image

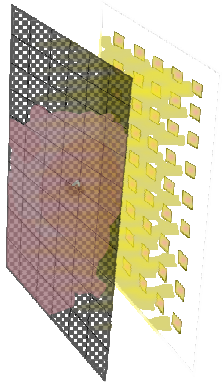
Enhancing Glare

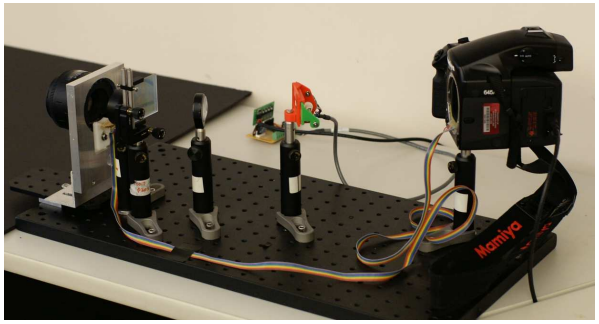
Conventional Photo

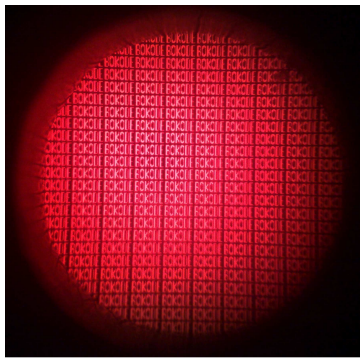
Glare Enhanced Image

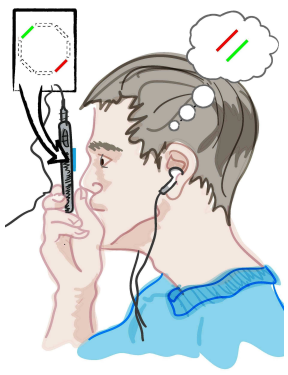
Conclusions

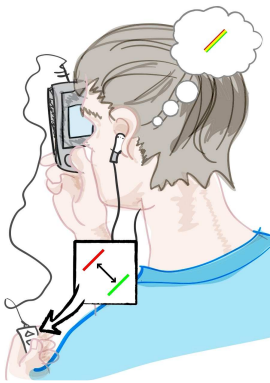
- Light Field Capture
  - Heterodyne Camera
  - Shield Fields
  - BiDi Screen
  - Reinterpretable Imager
- Light Field Modulation
  - Spectral Light Fields
  - Glare Camera
- Light Field Generation
  - Bokode
  - NETRA











Massachusetts Institute of Technology

Post-doc Position at MIT
Camera Culture group

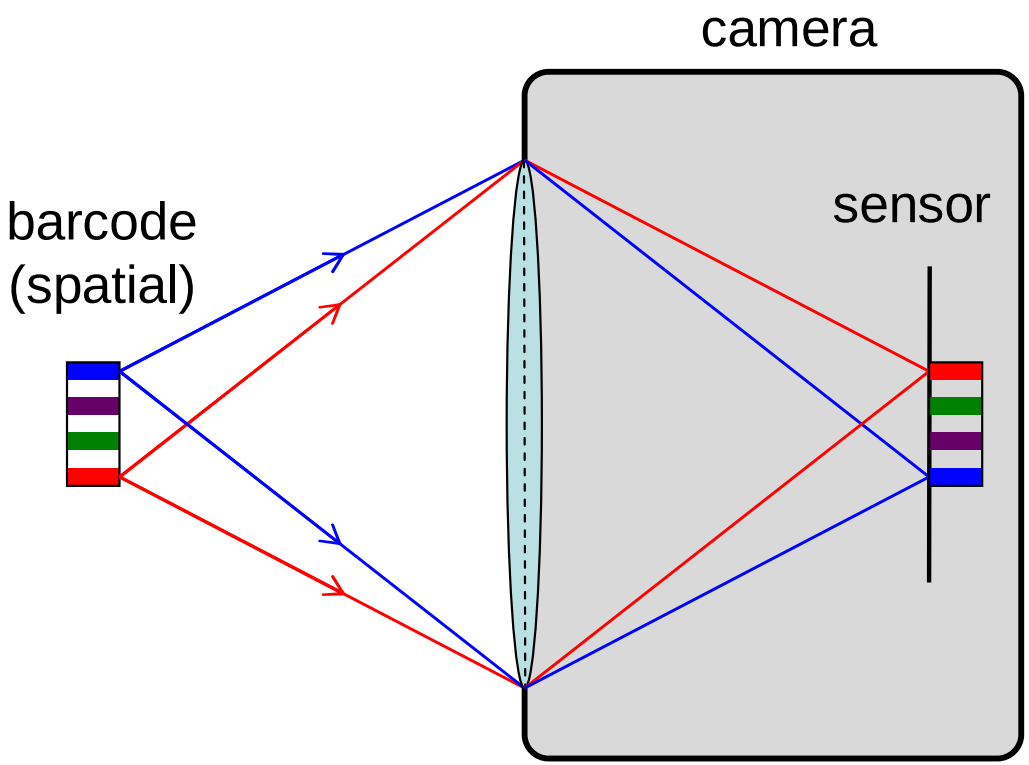
Start Date: Immediately
Duration: 1-2 years

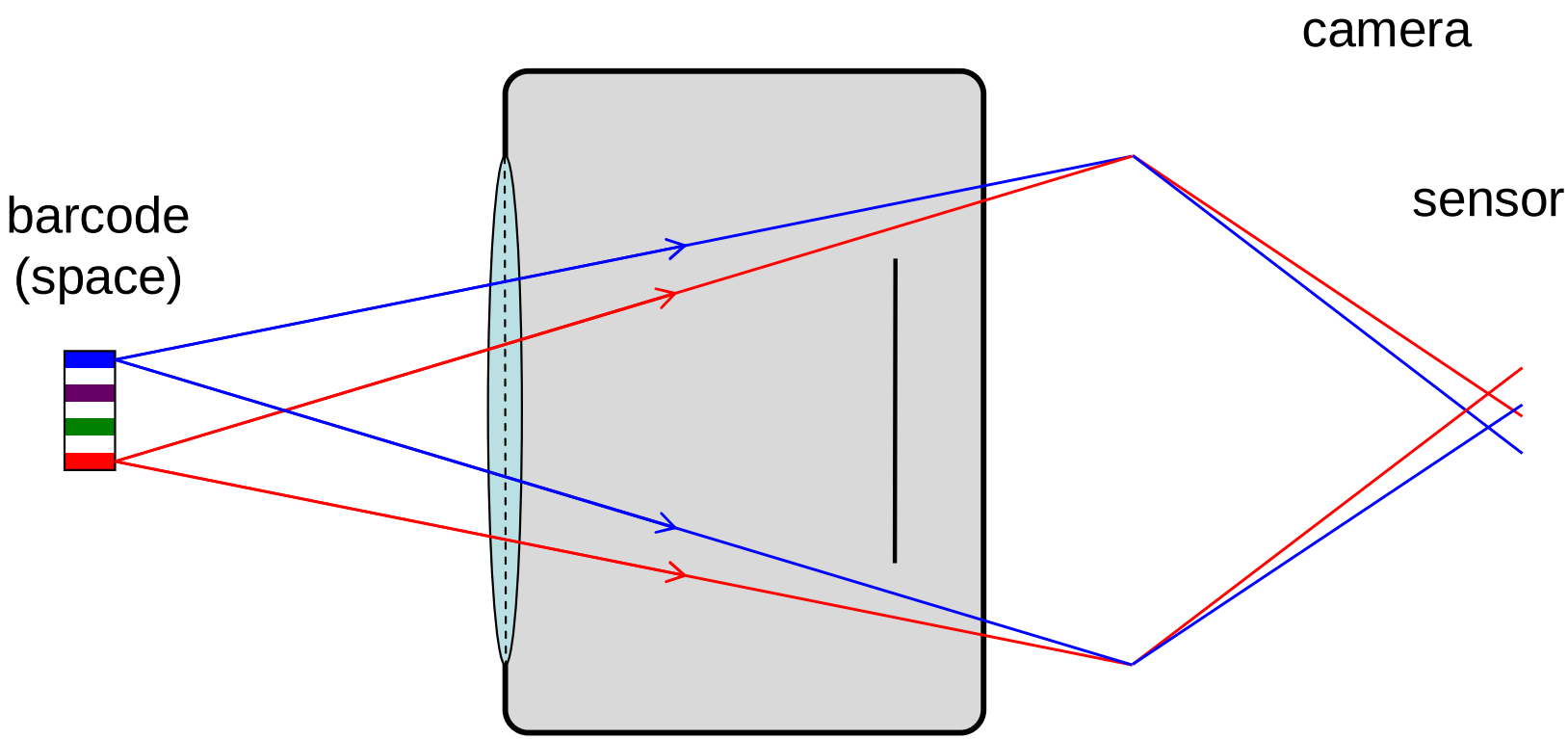
We are seeking a talented and highly motivated Postdoctoral Fellow with a strong background in computer graphics, vision, HCI and/or applied optics.

Camera Culture Group conducts multi-disciplinary research in computational imaging, modern optics, sensors, illumination, actuators, probes and software processing. This work ranges from creating novel feature-revealing computational cameras and new lightweight medical imaging mechanisms, to facilitating positive social impact via the next billion personalized cameras.

Please refer to the group webpage for instructions on how to apply. http://cameraculture.media.mit.edu/join

Keywords: Computational photography and imaging, Displays, Signal processing, Applied optics, Computer graphics and vision, Medical Imaging, Thermal and ultrasound sensing, Electronic hardware, Art, Online photo collections, Internet Vision, Visual social computing.


camera
barcode
(spatial)
sensor


camera
barcode
(space)
sensor

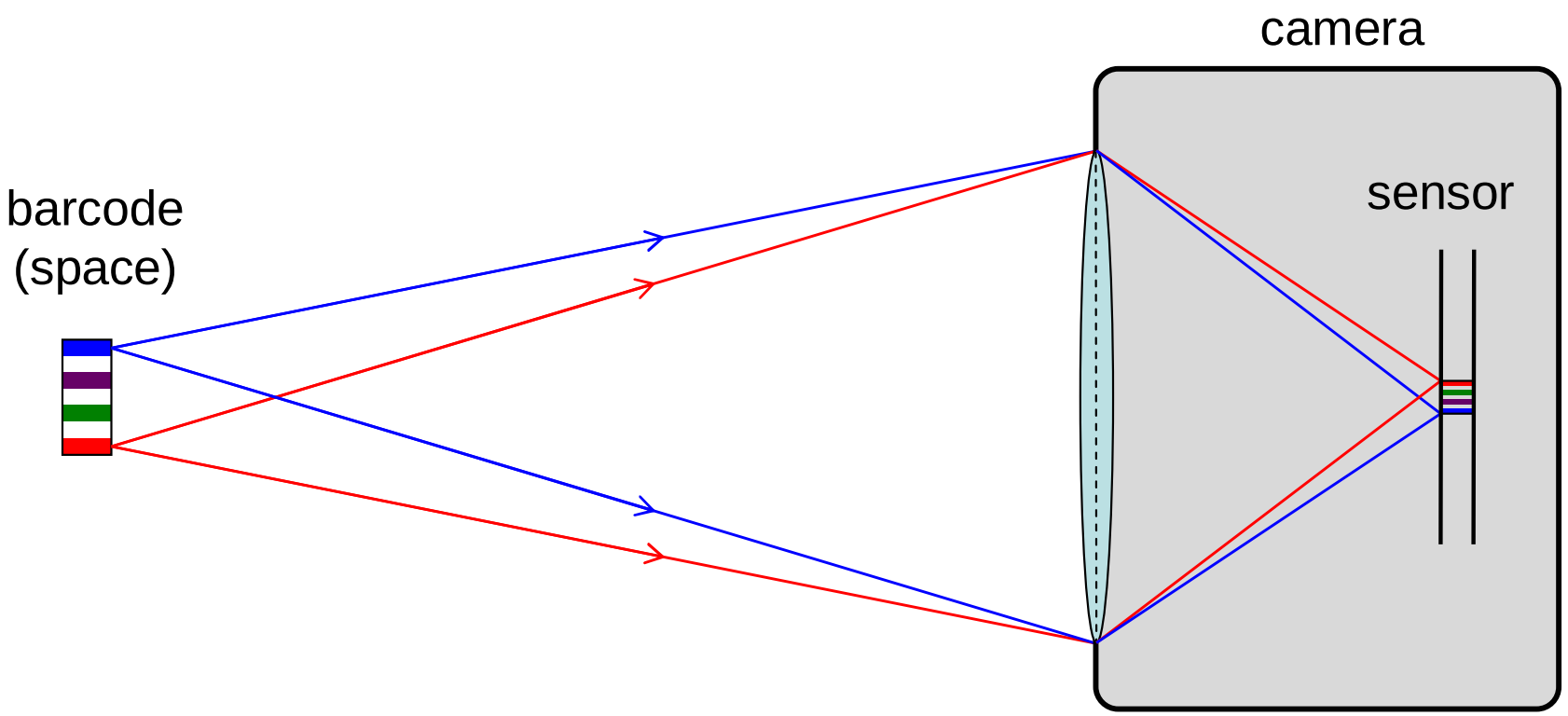
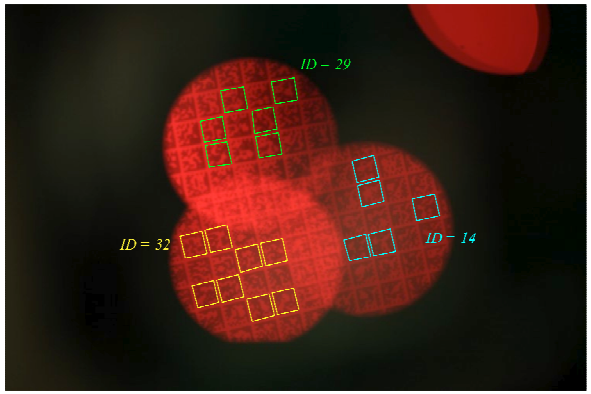


image much smaller;

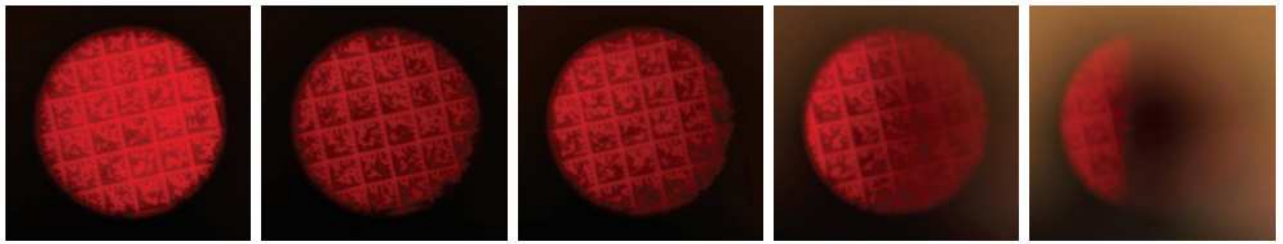
refocus if distance changes

limitations

- overlapping Bokodes

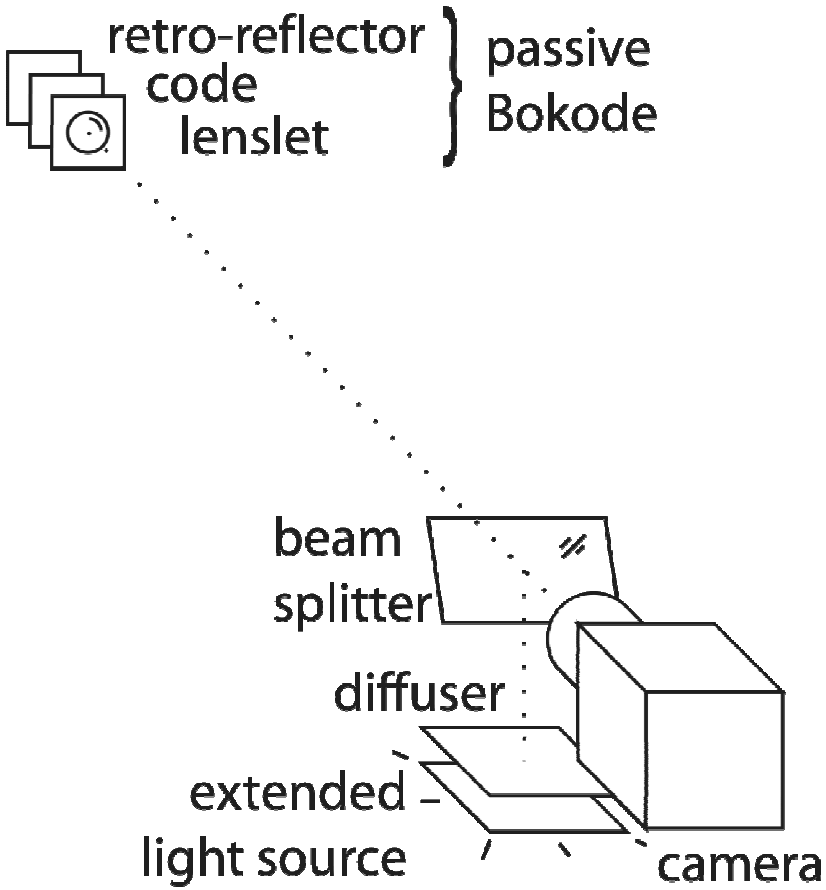


- auto-exposure / motion blur
- angular range (+/-20°)



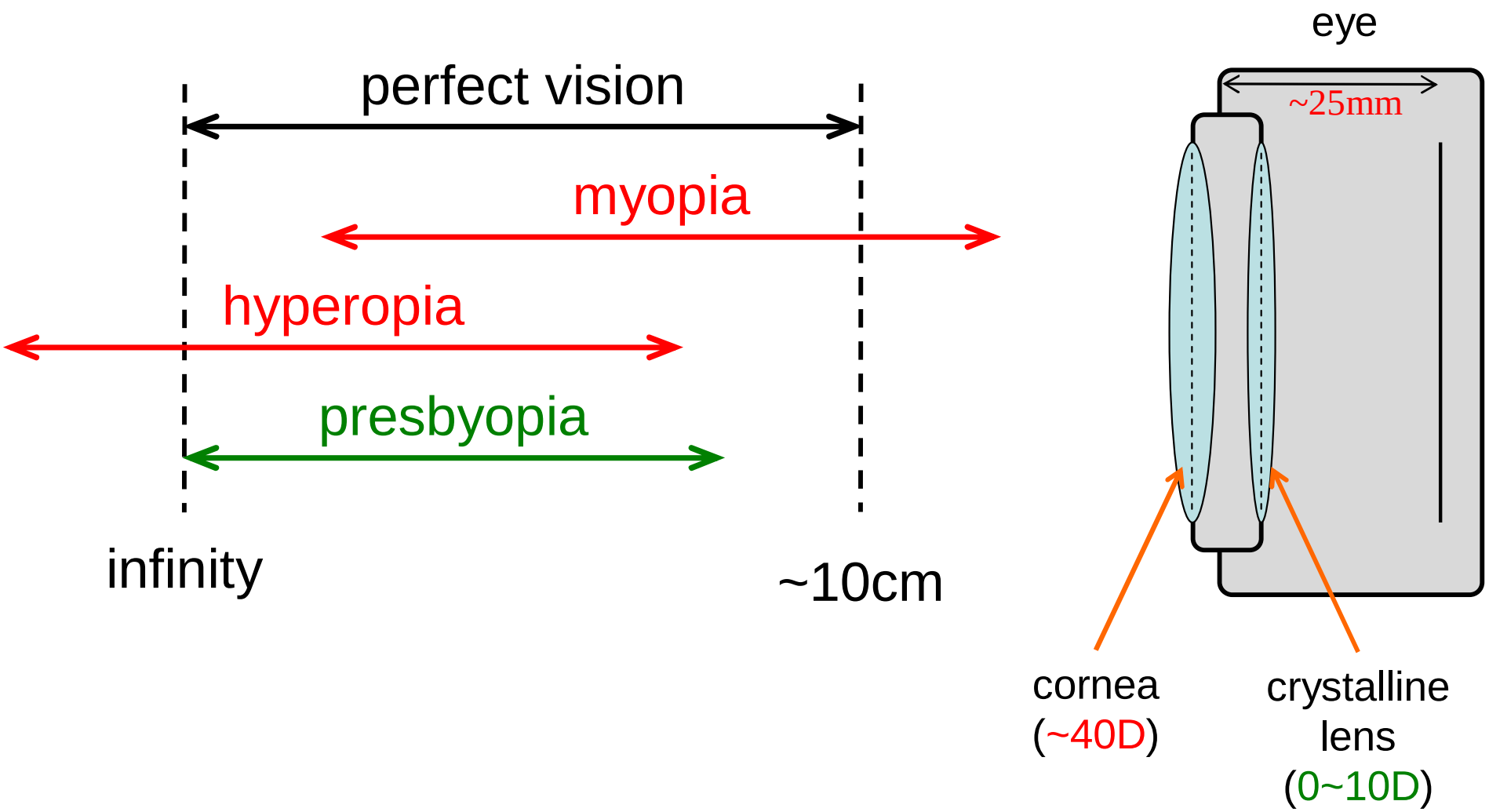
- thickness → holographic Bokode

retro-reflector for passive Bokode

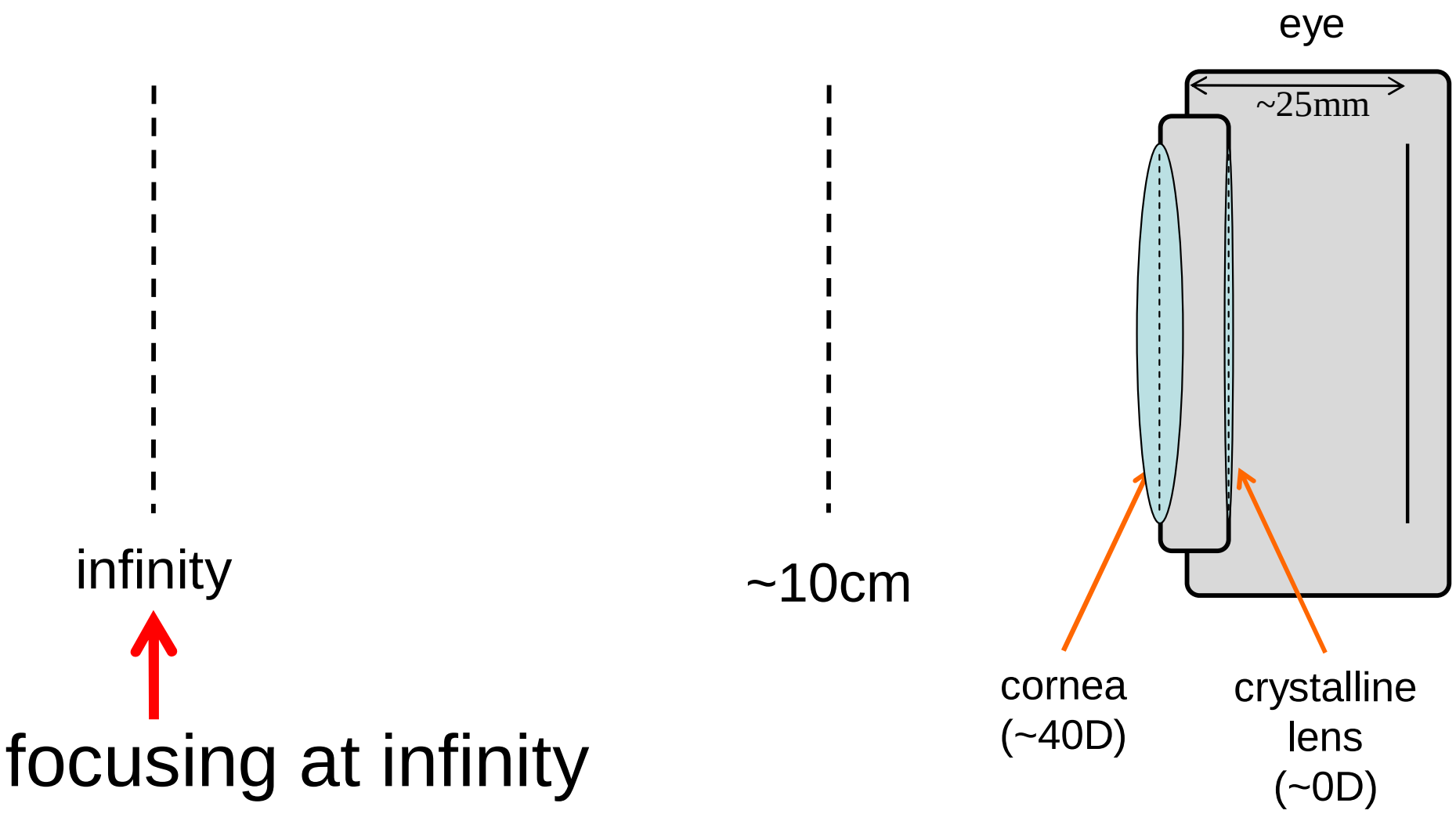


beam-splitter passive Bokode

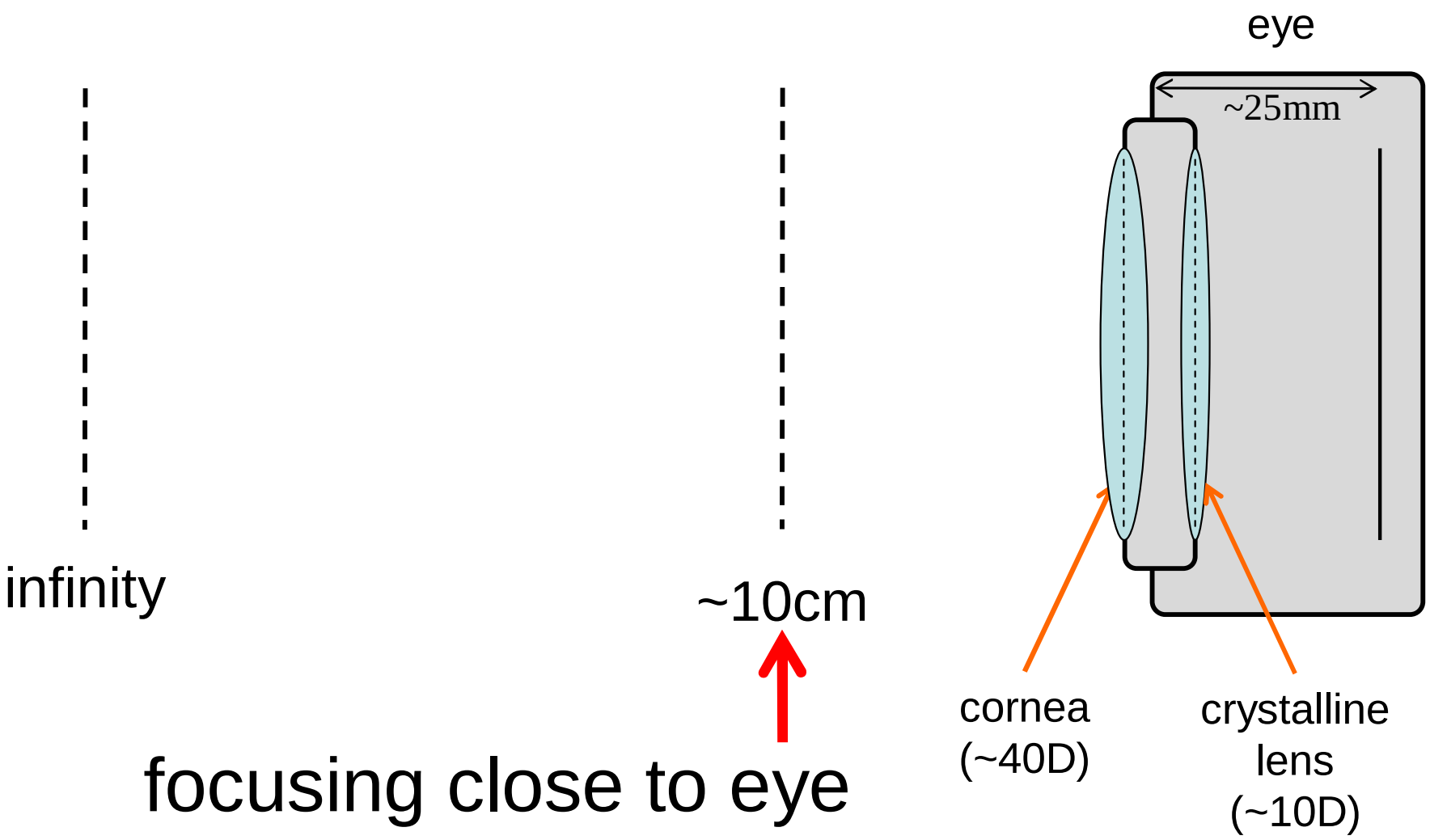
focusing range and refractive errors



accommodation



accommodation



Impact / PerfectSight

MIT IDEAS award to deploy in Mwanda, Malawi

LVPEI
So that all may see
L V Prasad Eye Institute

sending 4 prototypes over the summer

D'AMBROSIO Eye Care

local testing

CliCk Diagnostics

VisionSpring

cureblindness.org
HIMALAYAN CATARACT PROJECT