Introduction to Light Fields

Ramesh Raskar

MIT Media Lab

http://cameraculture.media.mit.edu/

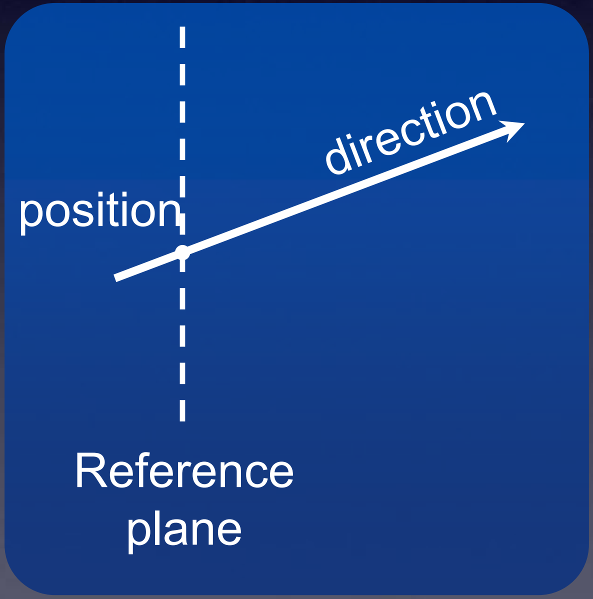
Introduction to Light Fields

- Ray Concepts for 4D and 5D Functions
- Propagation of Light Fields
- Interaction with Occluders
- Fourier Domain Analysis and Relationship to Fourier Optics
- Coded Photography: Modern Methods to Capture Light Field
- Wigner and Ambiguity Function for Light Field in Wave Optics
- New Results in Augmenting Light Fields

Light Fields

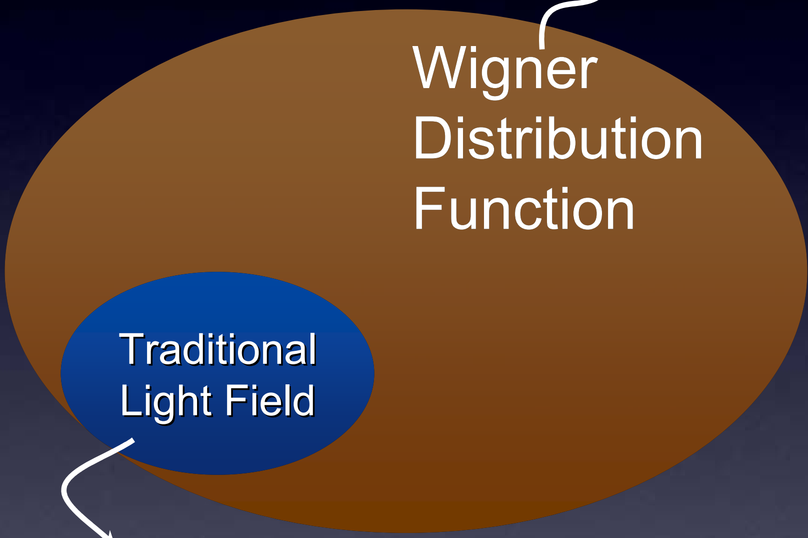
Goal: Representing propagation, interaction and image formation of light using purely position and angle parameters

- Radiance per ray
- Ray parameterization:
  - Position : s, x, r
  - Direction : u, θ, s



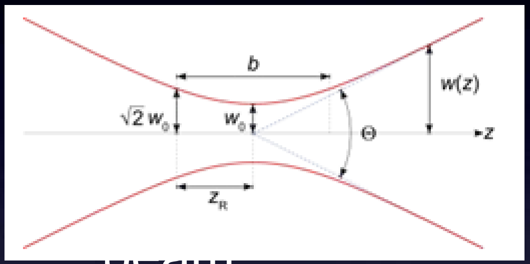
Limitations of Traditional Lightfields

rigorous but cumbersome
wave optics based

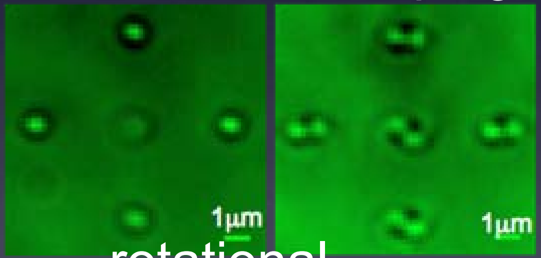


ray optics based
simple and powerful
limited in diffraction & interference

hologram
s

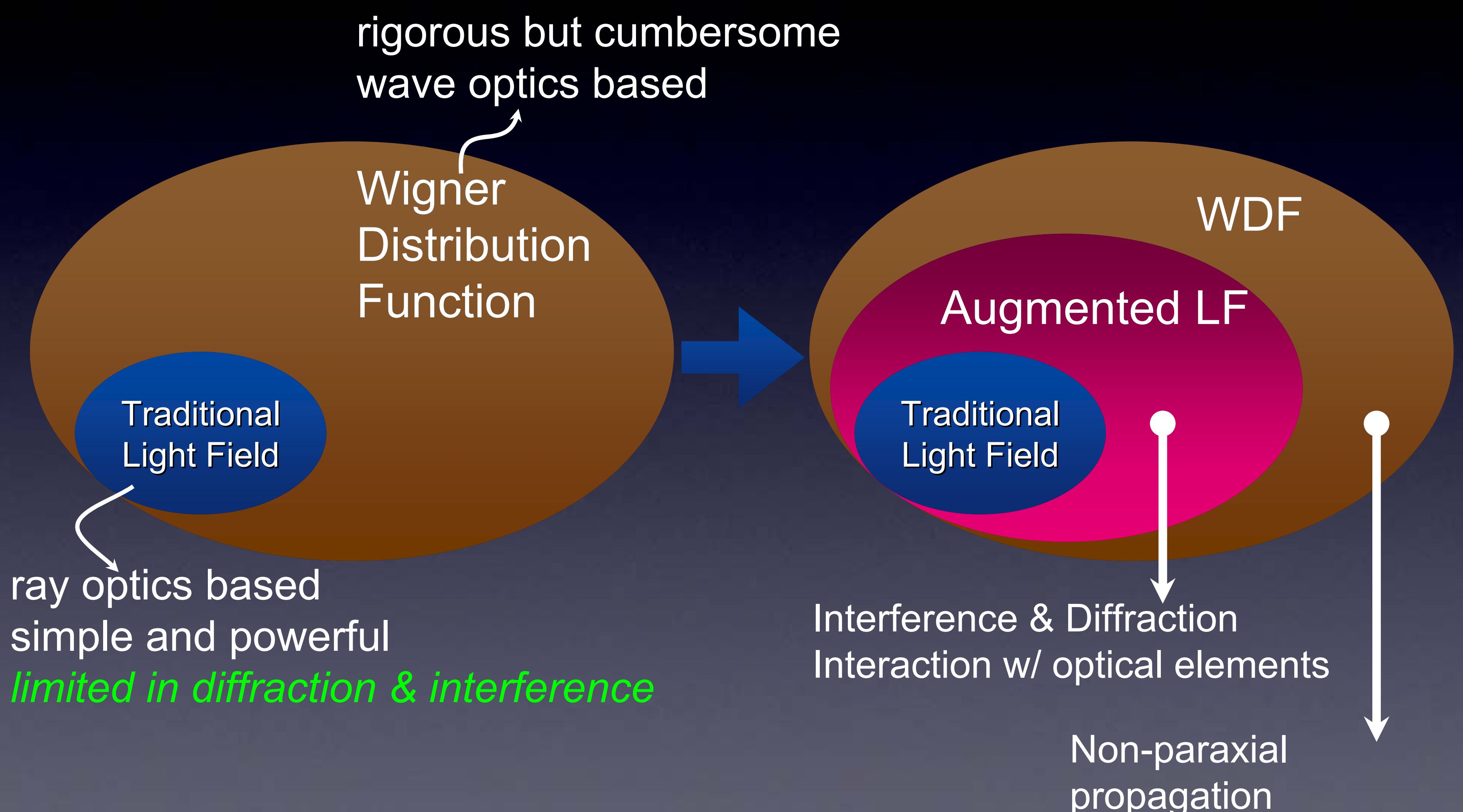


beam
shaping



rotational
PSF

Example: New Representations Augmented Lightfields



The Plenoptic Function

Figure removed due to copyright restrictions.

- 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 <u>everything</u> that he can see…

Grayscale snapshot

Figure removed due to copyright restrictions.

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

- is intensity of light
  - Seen from a single view point
  - At a single time
  - Averaged over the wavelengths of the visible spectrum
- (can also do *P(x,y)*, but spherical coordinate are nicer)

Color snapshot

Figure removed due to copyright restrictions.

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

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

A movie

Figure removed due to copyright restrictions.

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

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

Holographic movie

Figure removed due to copyright restrictions.

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

- is intensity of light
  - Seen from ANY viewpoint
  - Over time
  - As a function of wavelength

The Plenoptic Function

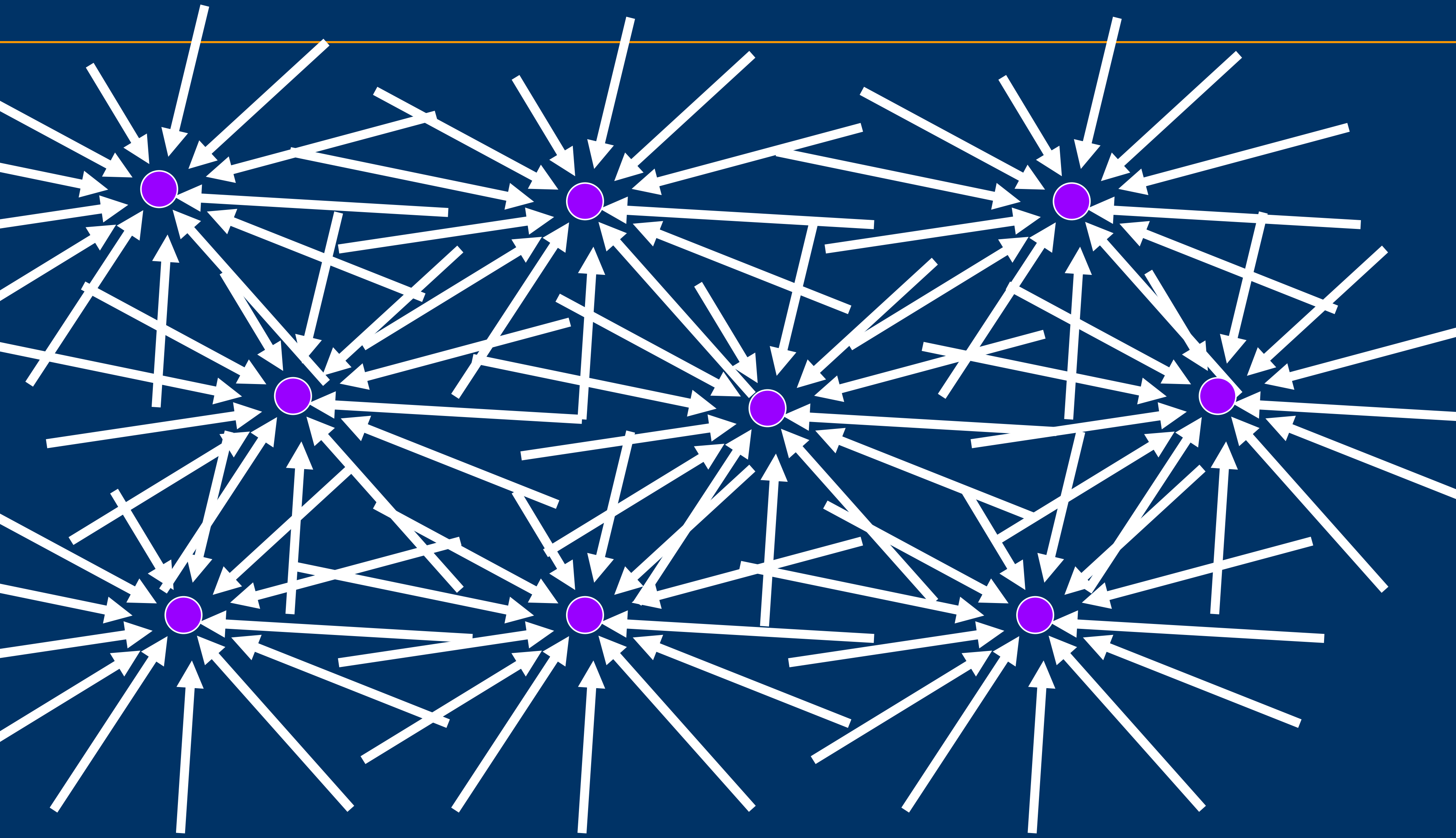
Figure removed due to copyright restrictions.

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

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

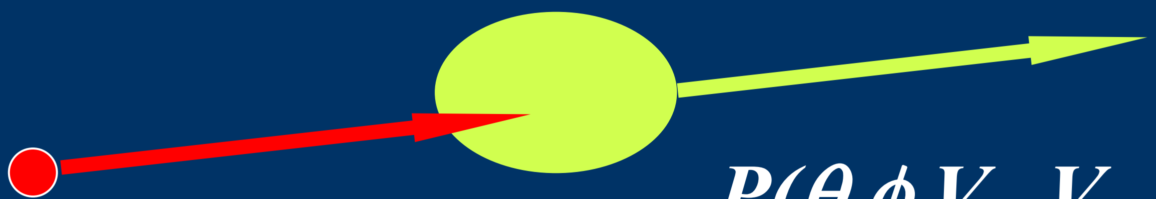
– Contains every photograph, every movie, everything that anyone has ever seen.

Sampling Plenoptic Function (top view)



Ray

- Let's not worry about time and color:



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

- 5D
  - 3D position
  - 2D direction

Ray

- No Occluding Objects

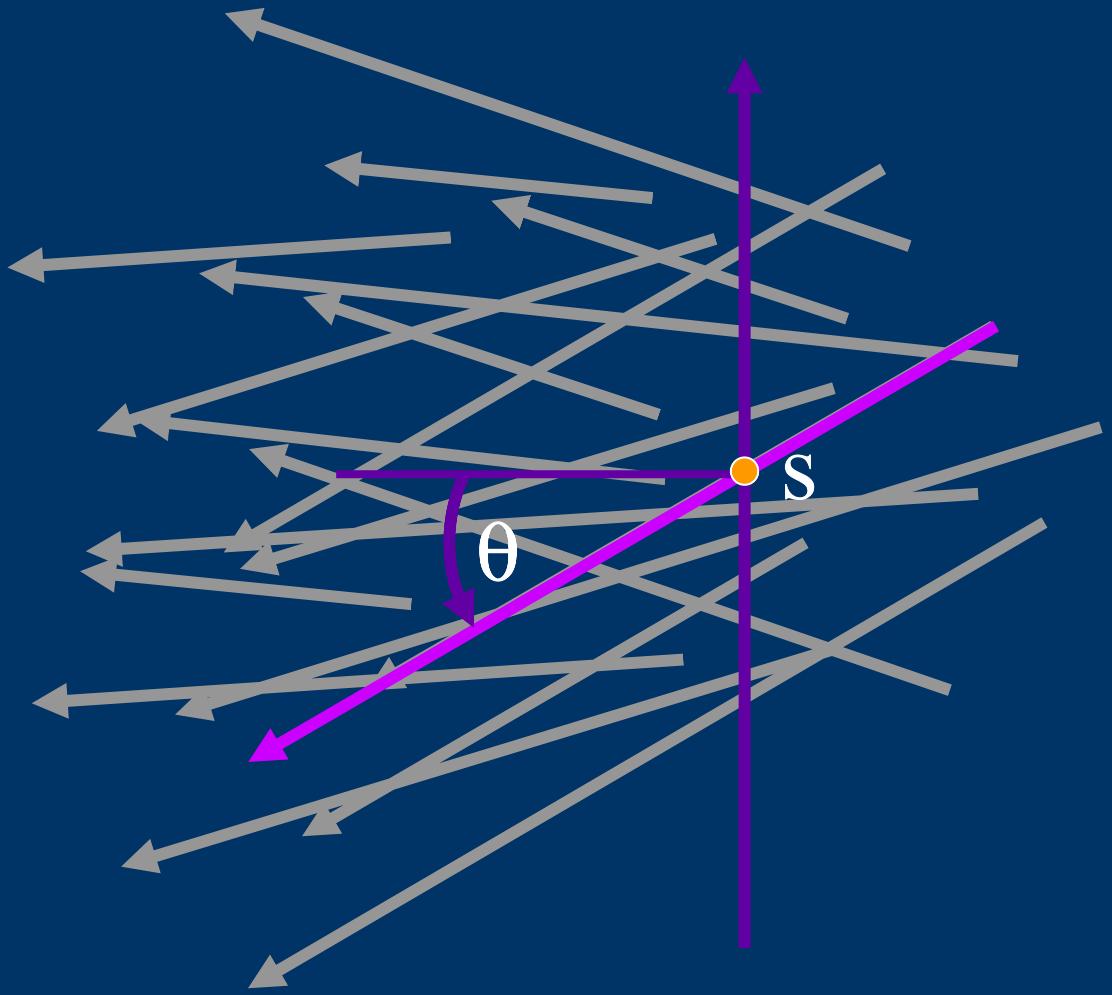
$$P(\theta,\phi,V_X,V_Y,V_Z)$$

- 4D
  - 2D position
  - 2D direction

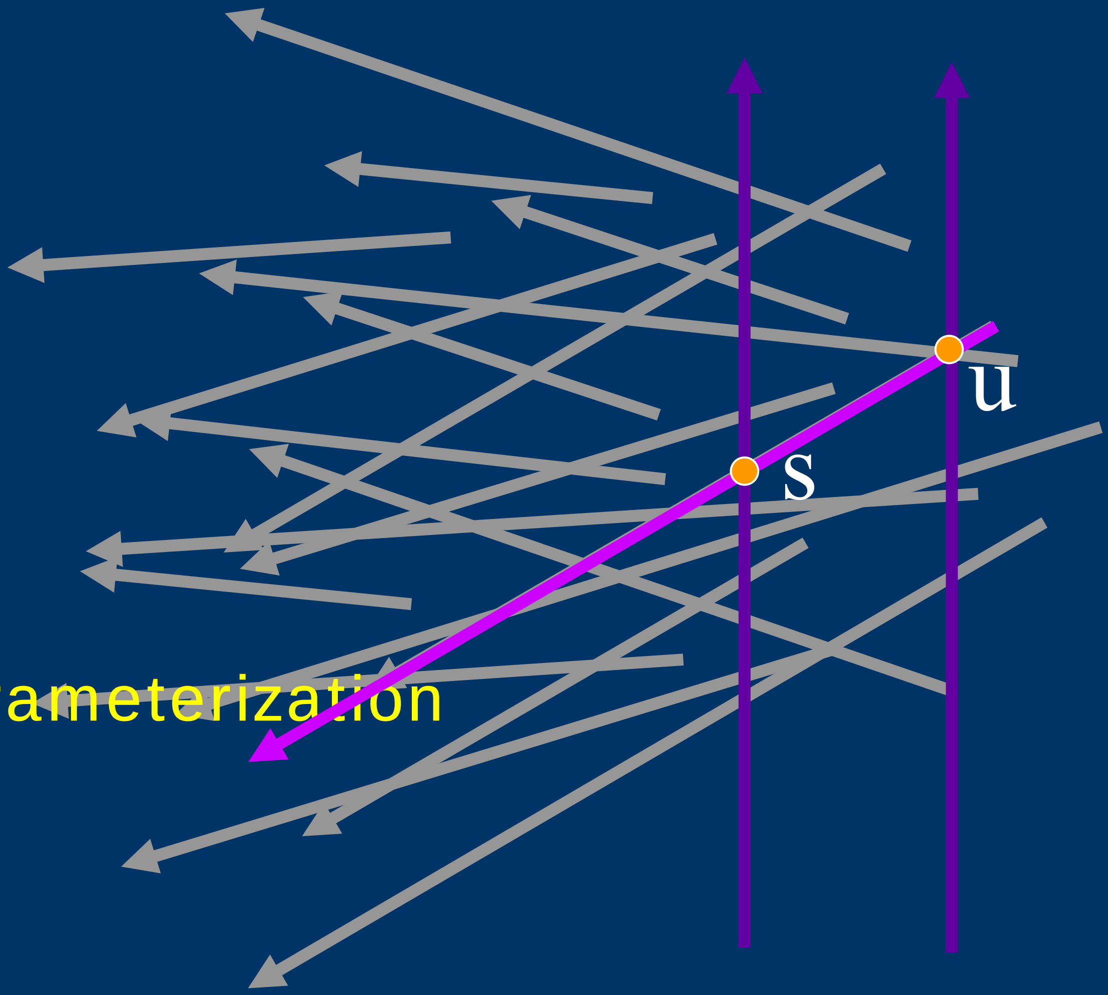
- The space of all lines in 3-D space is 4D.

Lumigraph/Lightfield - Organization

- 2D position
- 2D direction



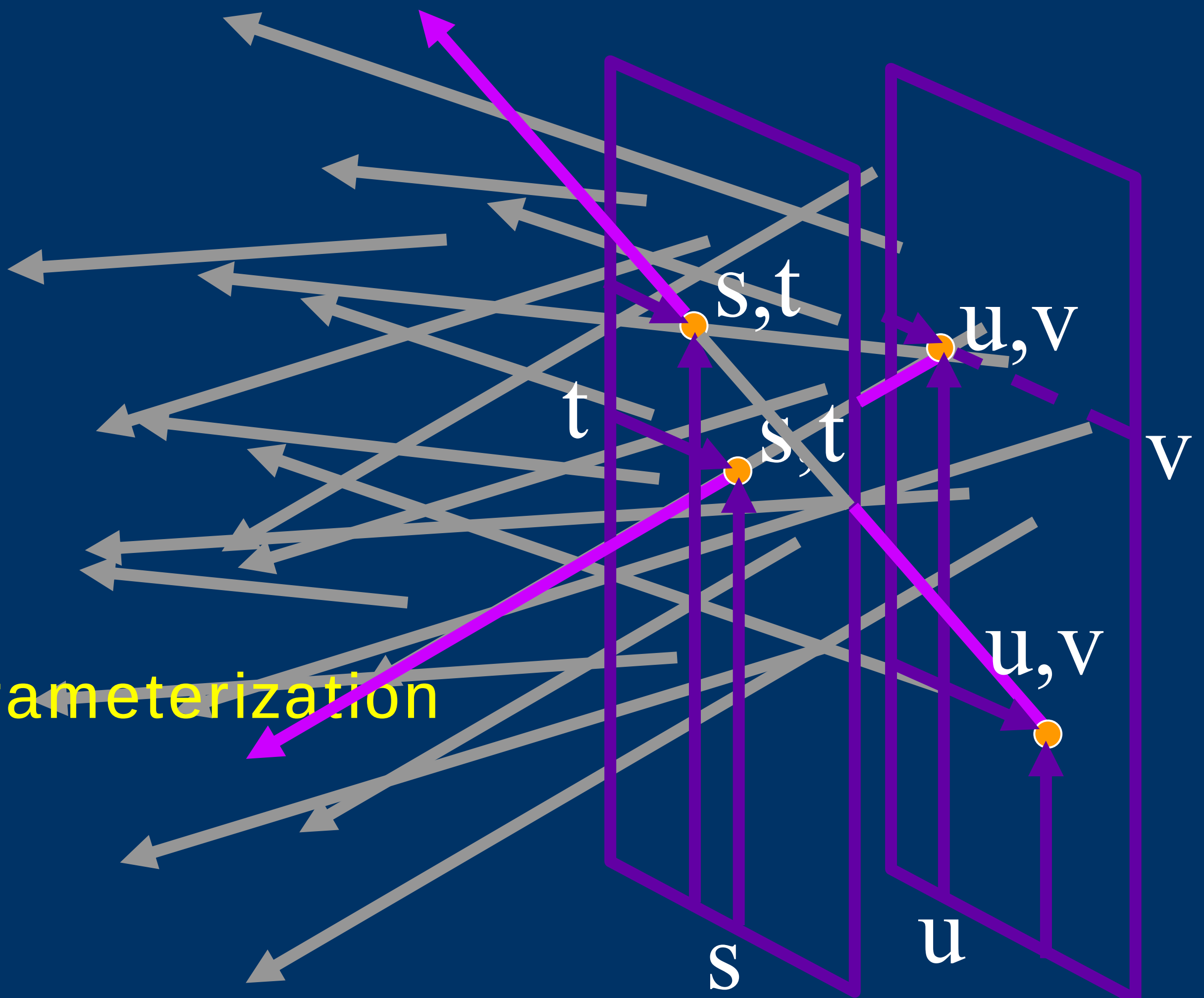
- 2D position
- 2D position



- 2 plane parameterization

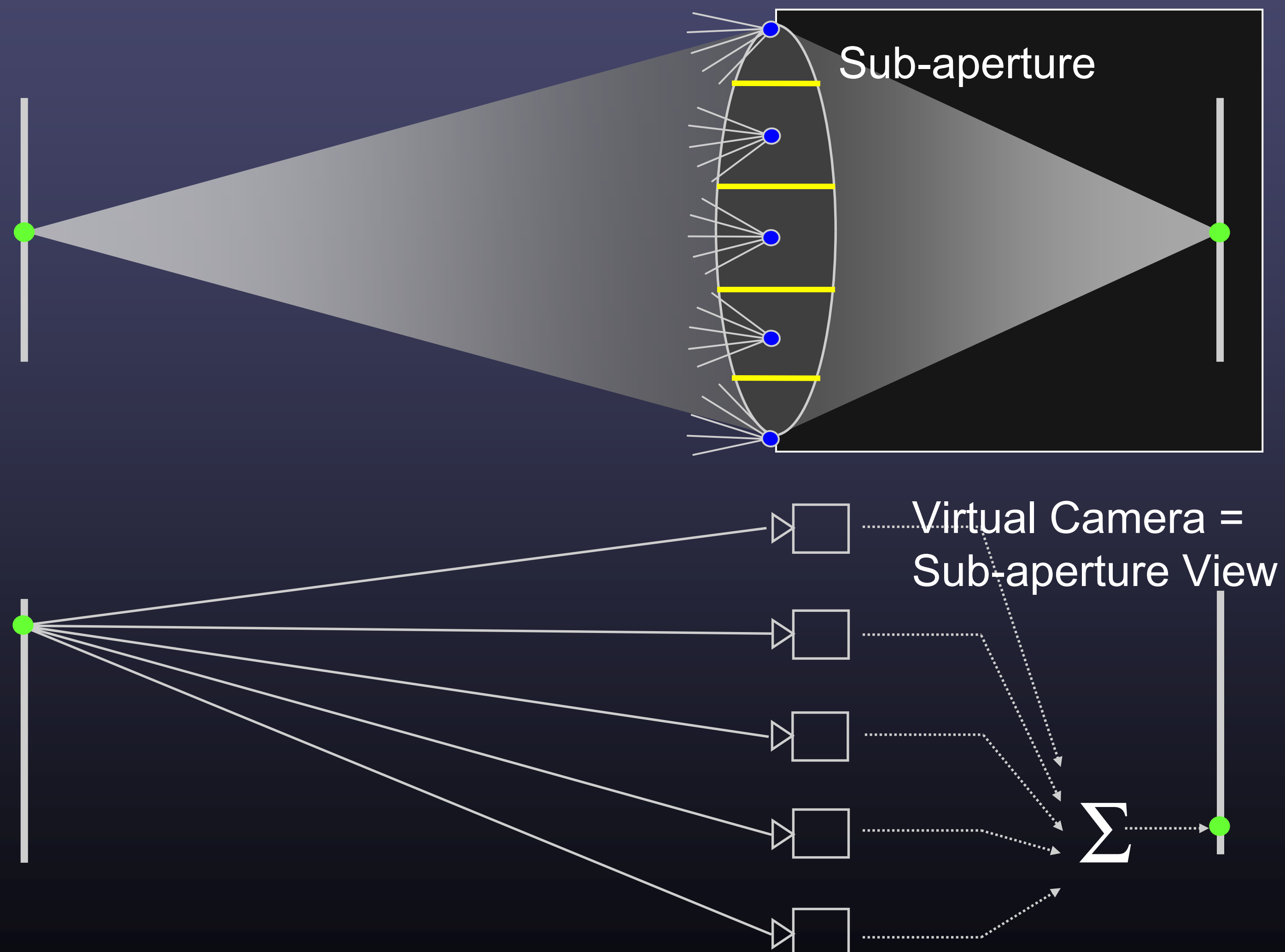
Slide by Rick Szeliski and Michael Cohen

- 2D position
- 2D position
- 2 plane parameterization



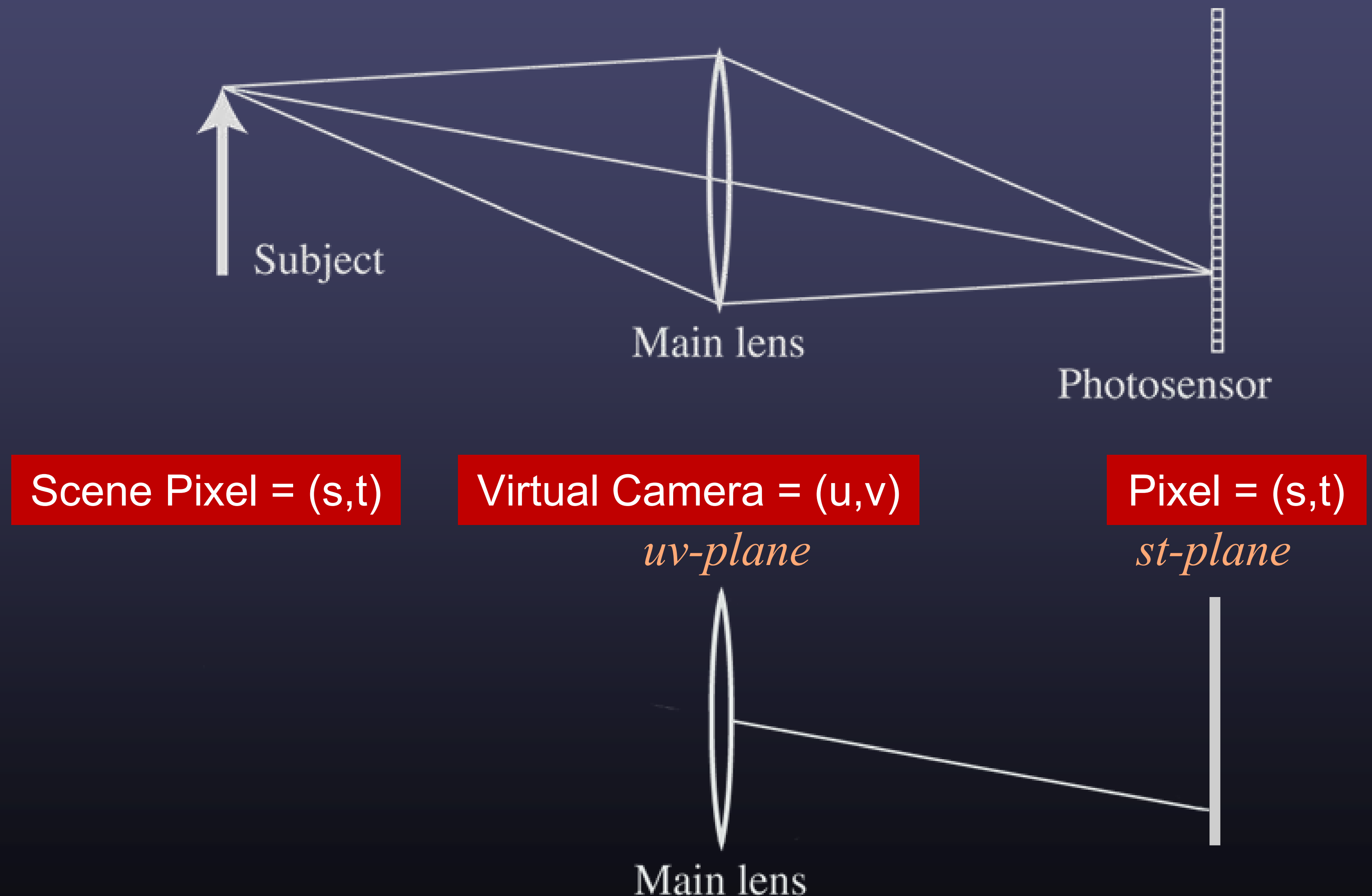
Slide by Rick Szeliski and Michael Cohen

Light Field = Array of (virtual) Cameras



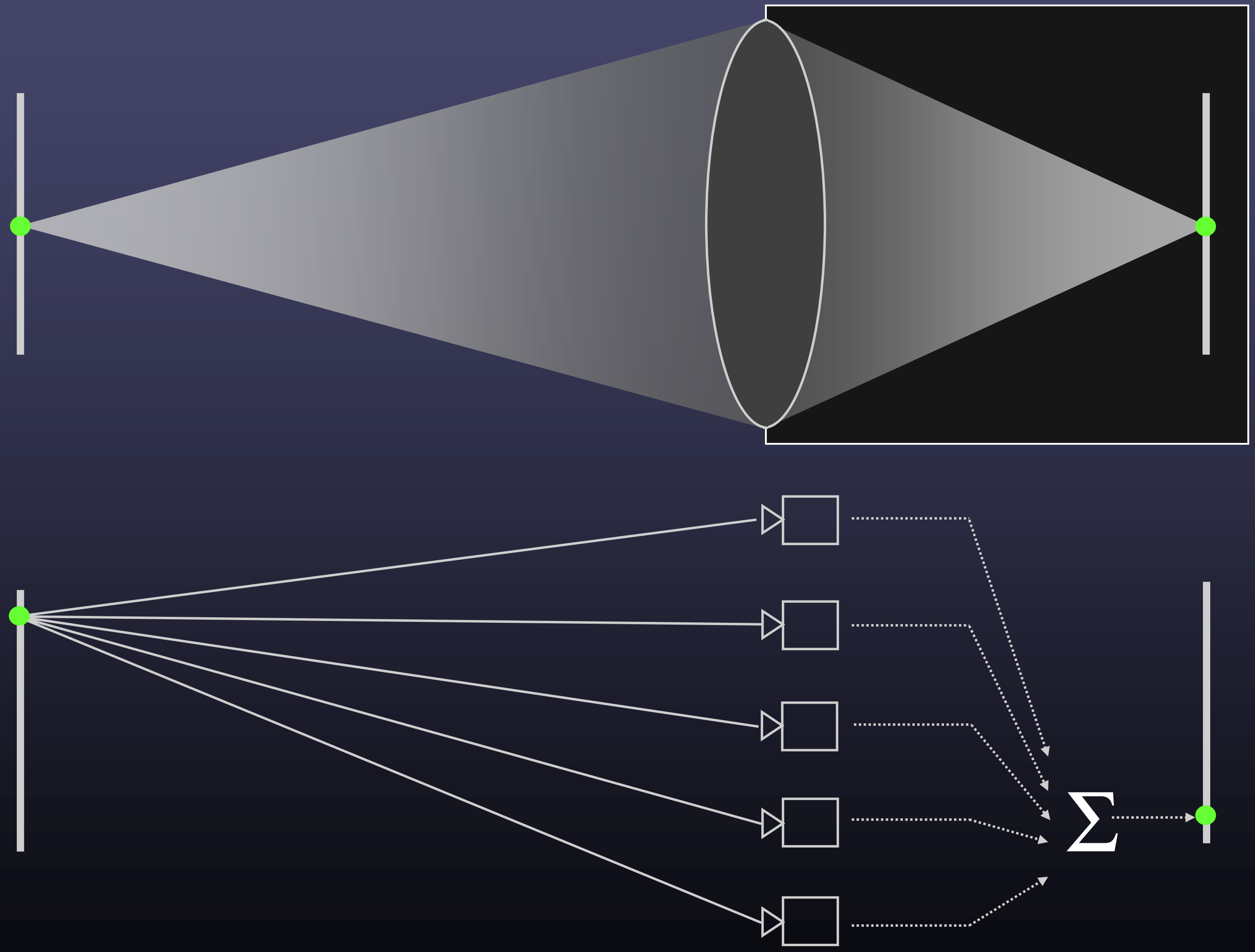
Based on original slide by Marc Levoy. Used with permission.

Conventional versus plenoptic camera



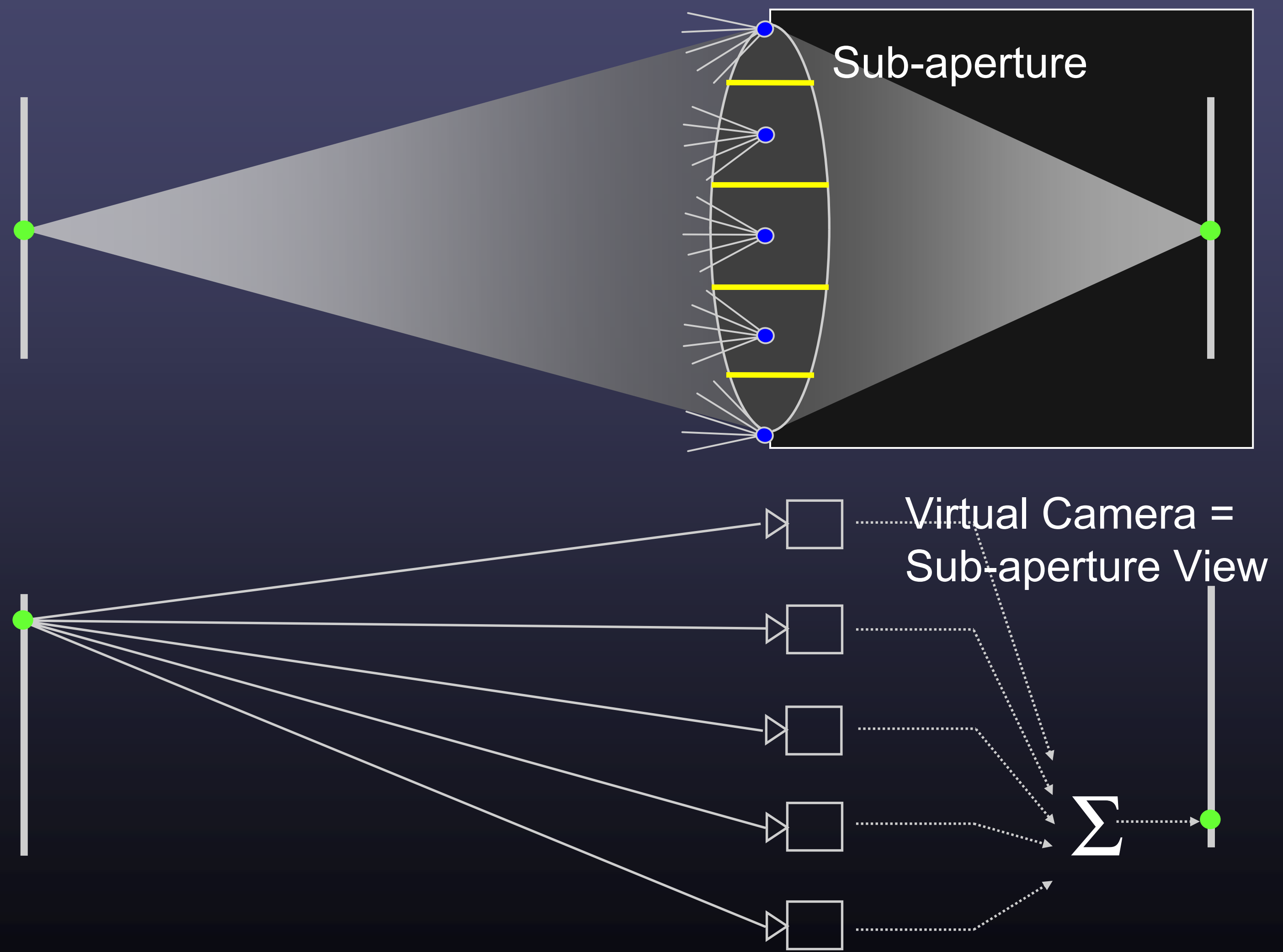
Based on original slide by Marc Levoy. Used with permission.

Light Field = Array of (virtual) Cameras

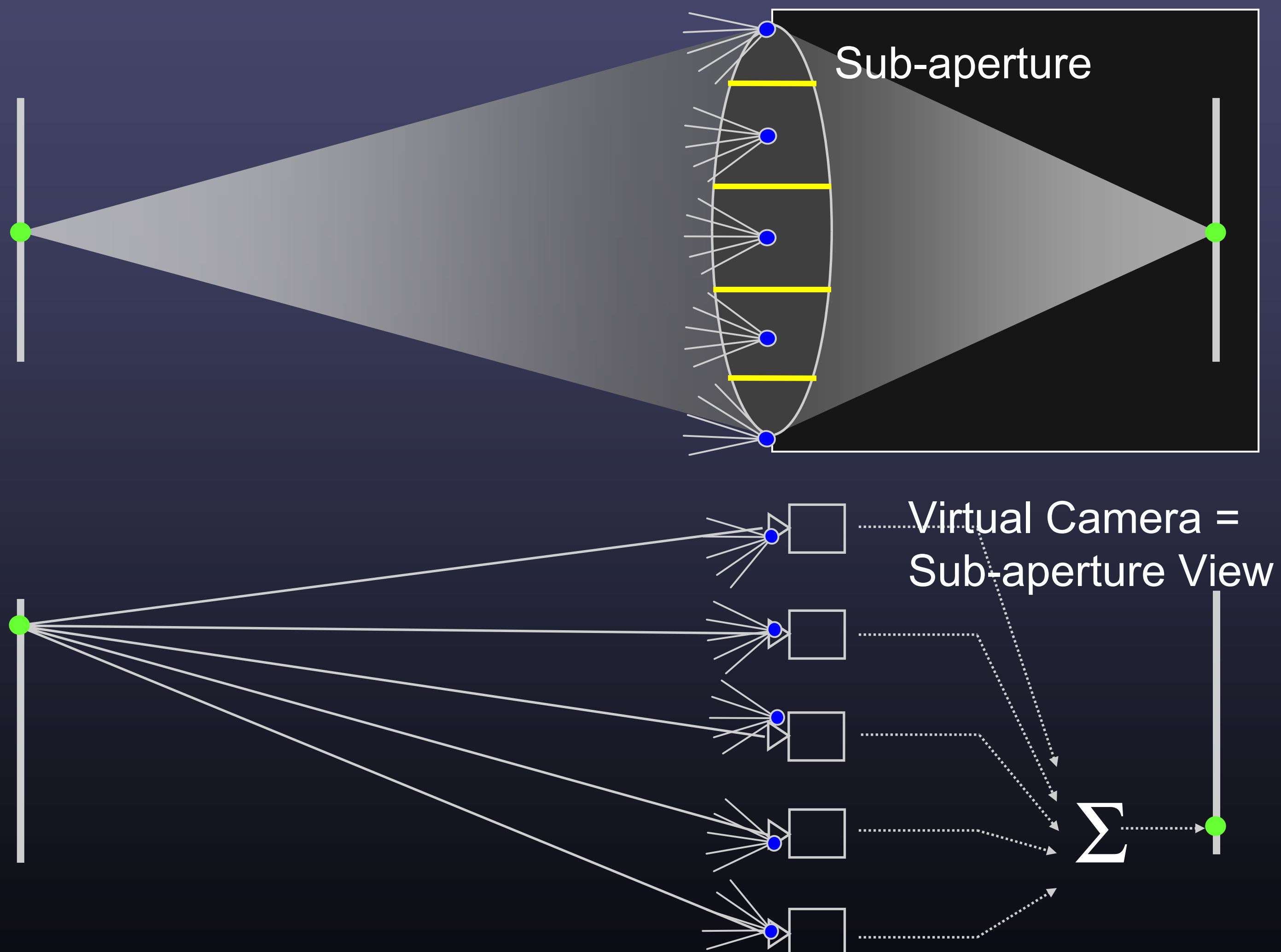


Based on original slide by Marc Levoy. Used with permission.

Light Field = Array of (virtual) Cameras

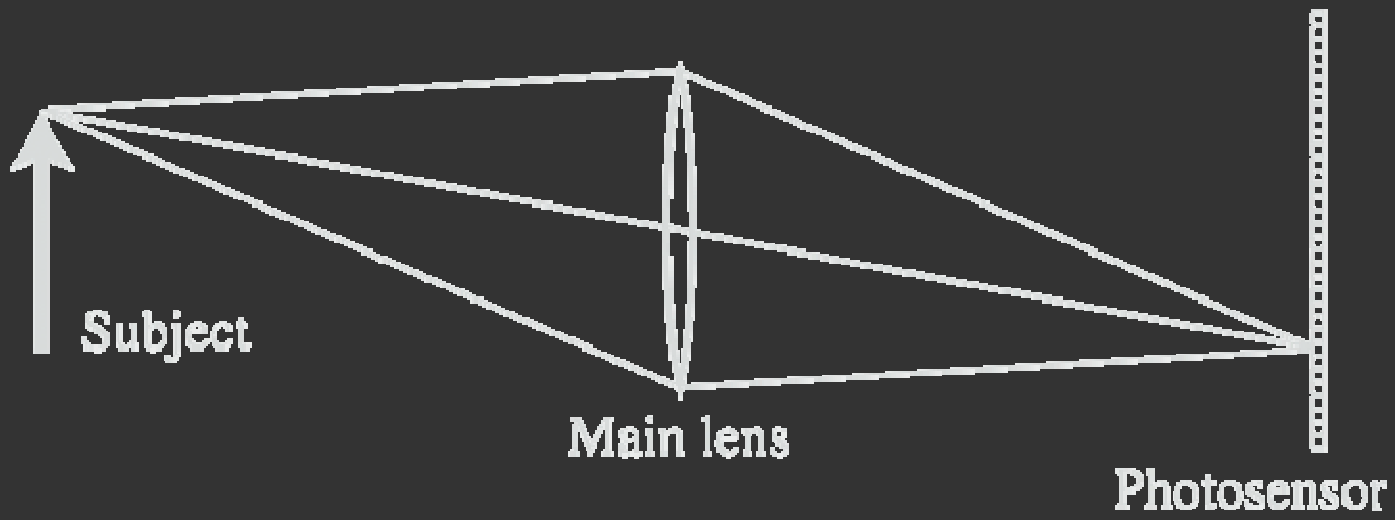


Light Field = Array of (virtual) Cameras



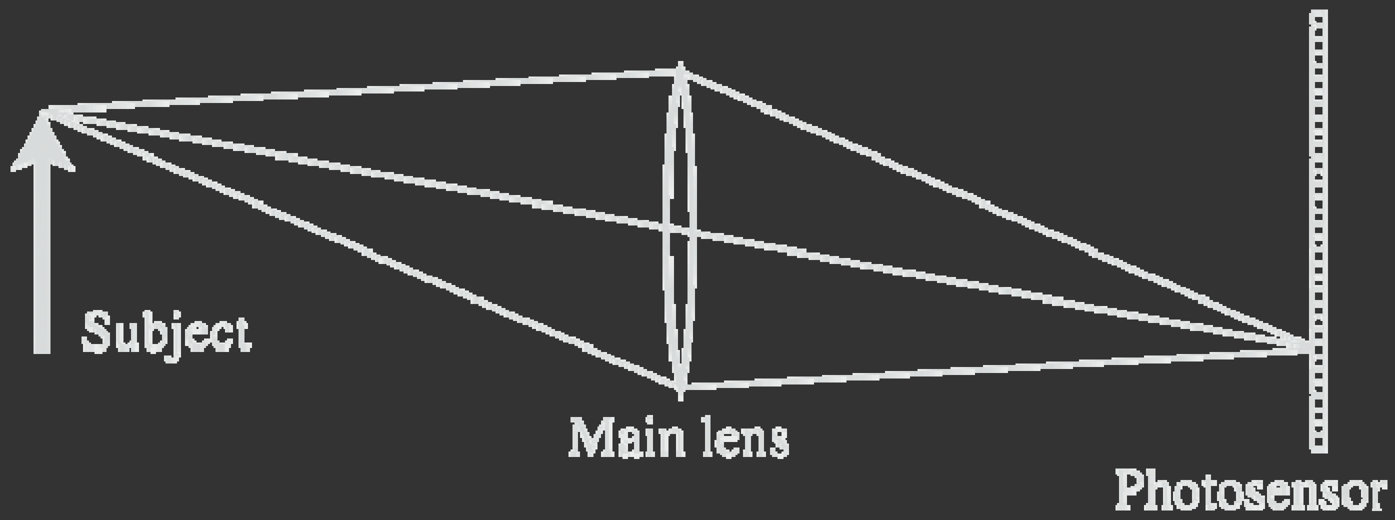
Based on original slide by Marc Levoy. Used with permission.

Light Field Inside a Camera

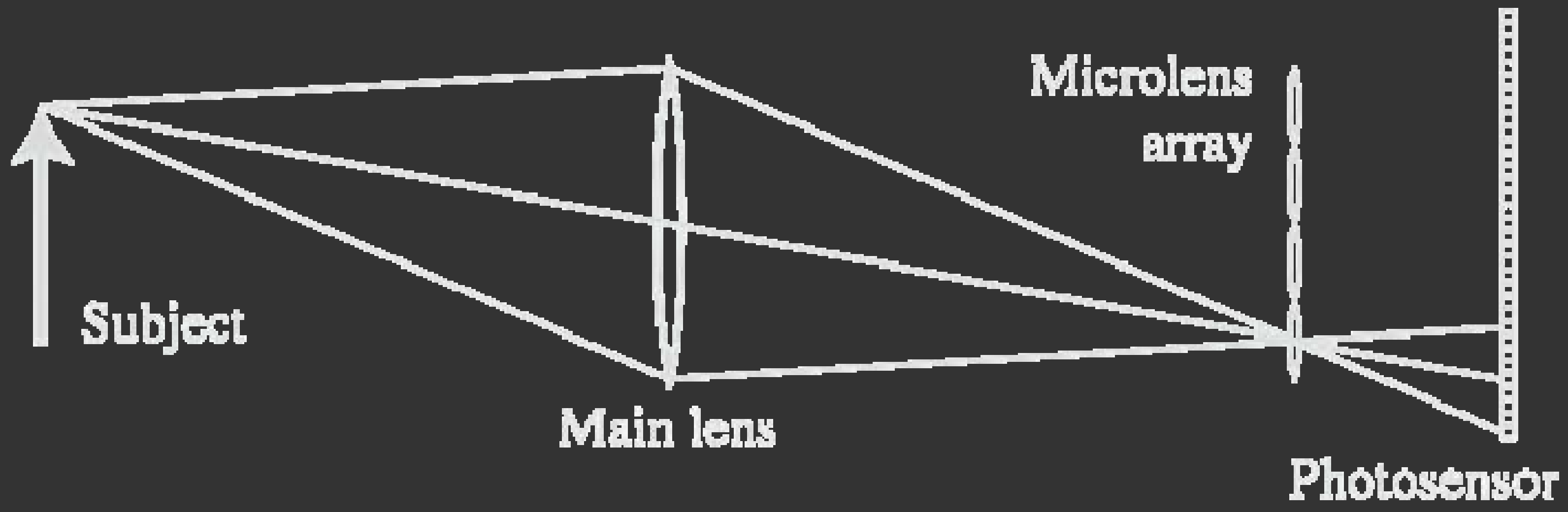


Courtesy of Ren Ng. Used with permission.

Light Field Inside a Camera



Lenslet-based Light Field camera



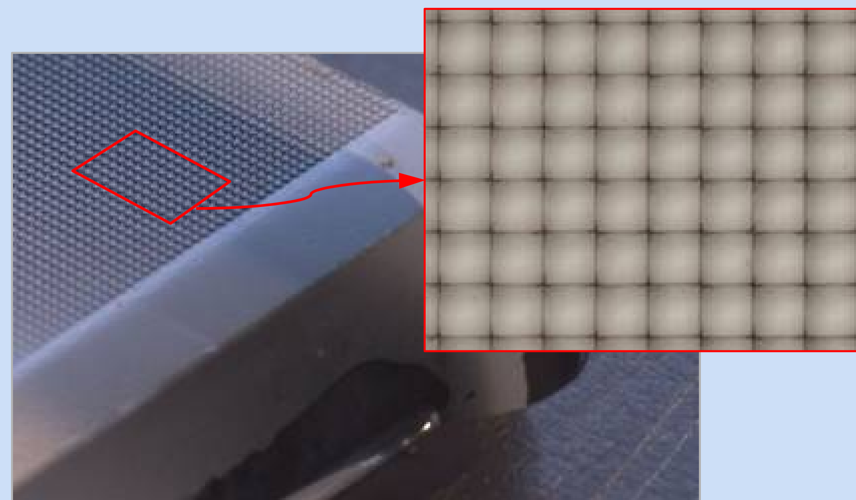
[Adelson and Wang, 1992, Ng et al. 2005]

Stanford Plenoptic Camera [Ng et al 2005]

Contax medium format camera

Kodak 16-megapixel sensor

Adaptive Optics microlens array



125μ square-sided microlenses

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

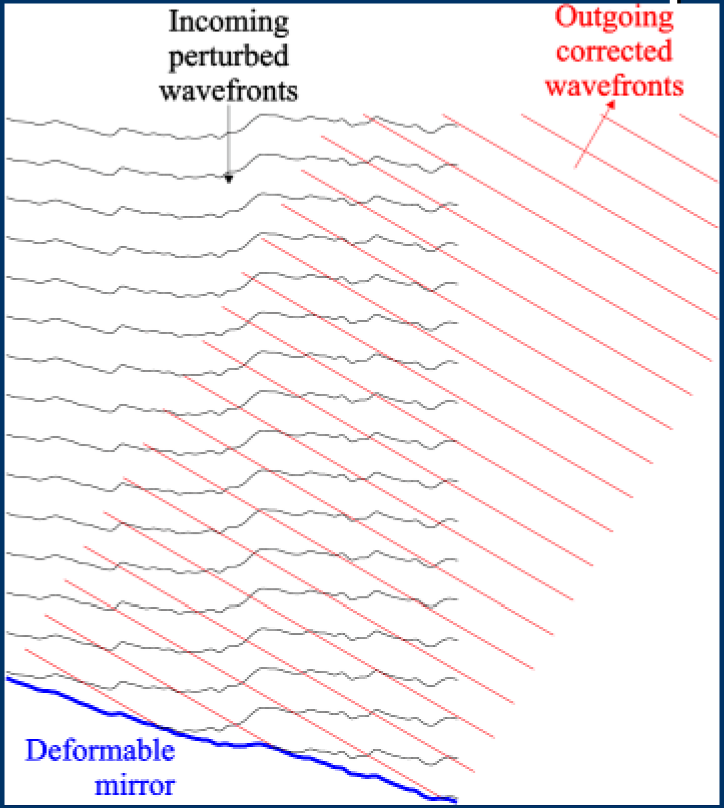
Digital Refocusing

Courtesy of Ren Ng. Used with permission.

[Ng et al 2005]

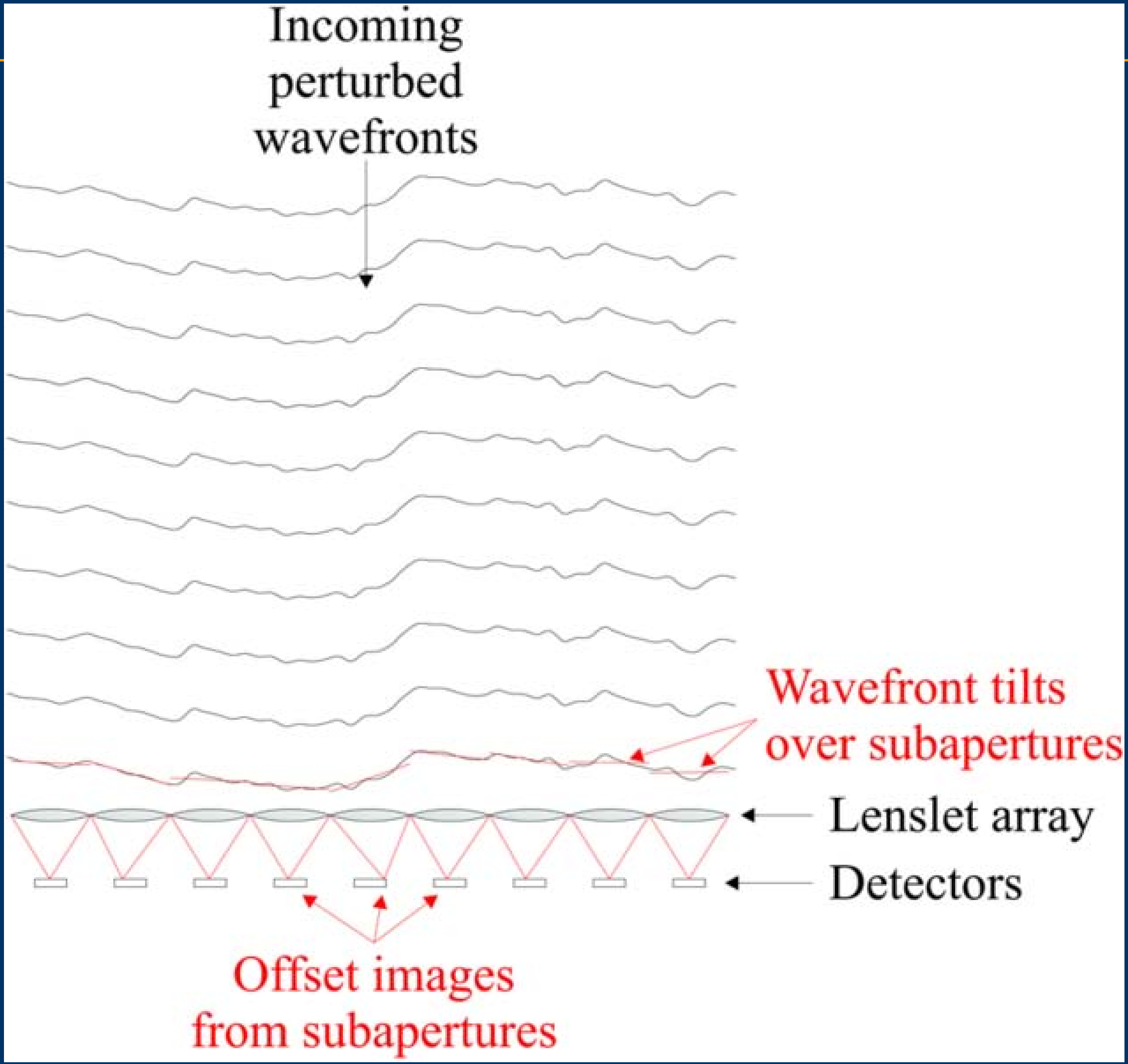
Adaptive Optics

- A deformable mirror can be used to correct wavefront errors in an astronomical telescope



http://en.wikipedia.org/wiki/Image:Adaptive_optics_correct.png

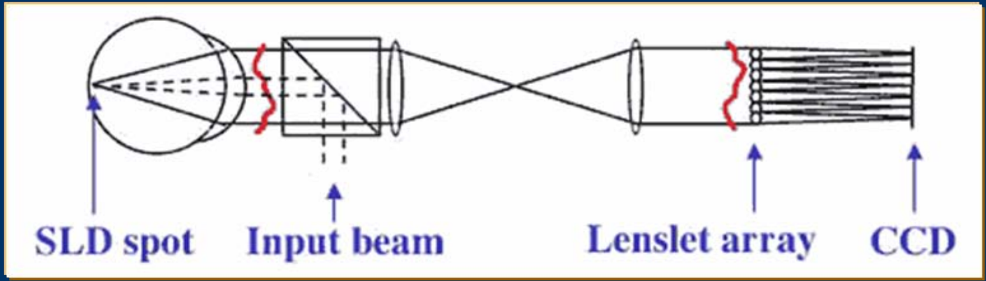
Shack Hartmann wavefront sensor (commonly used in Adaptive optics).



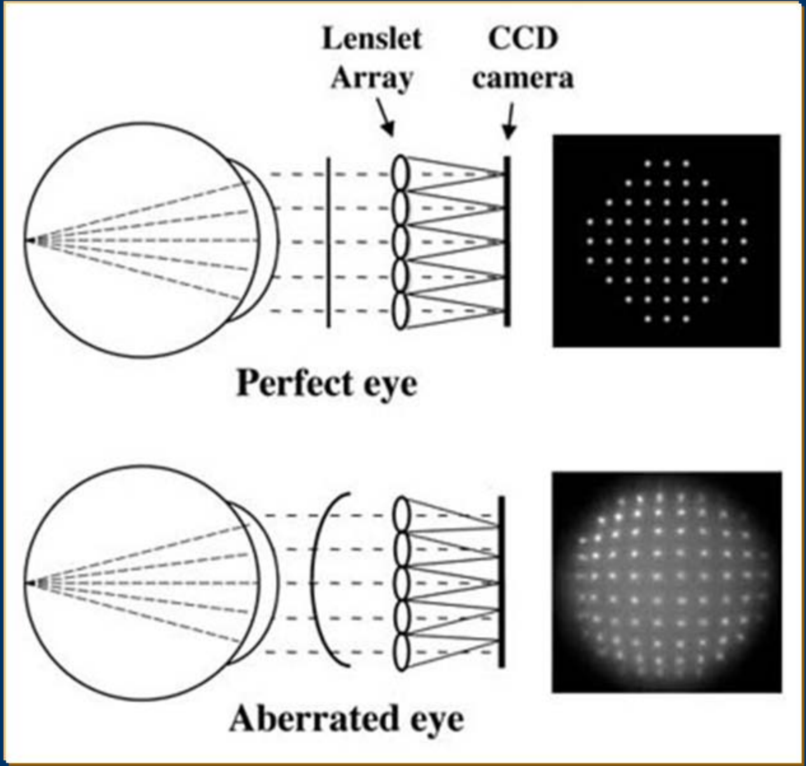
http://en.wikipedia.org/wiki/Image:Shack_hartmann.png

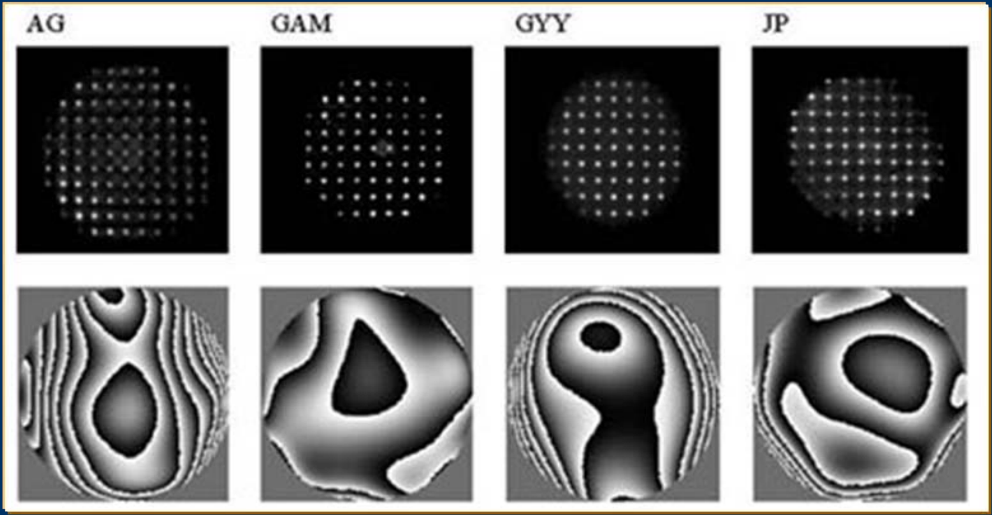
Measuring shape of wavefront = Lightfield Capture

- http://www.cvs.rochester.edu/williamslab/r_shackhartmann.html



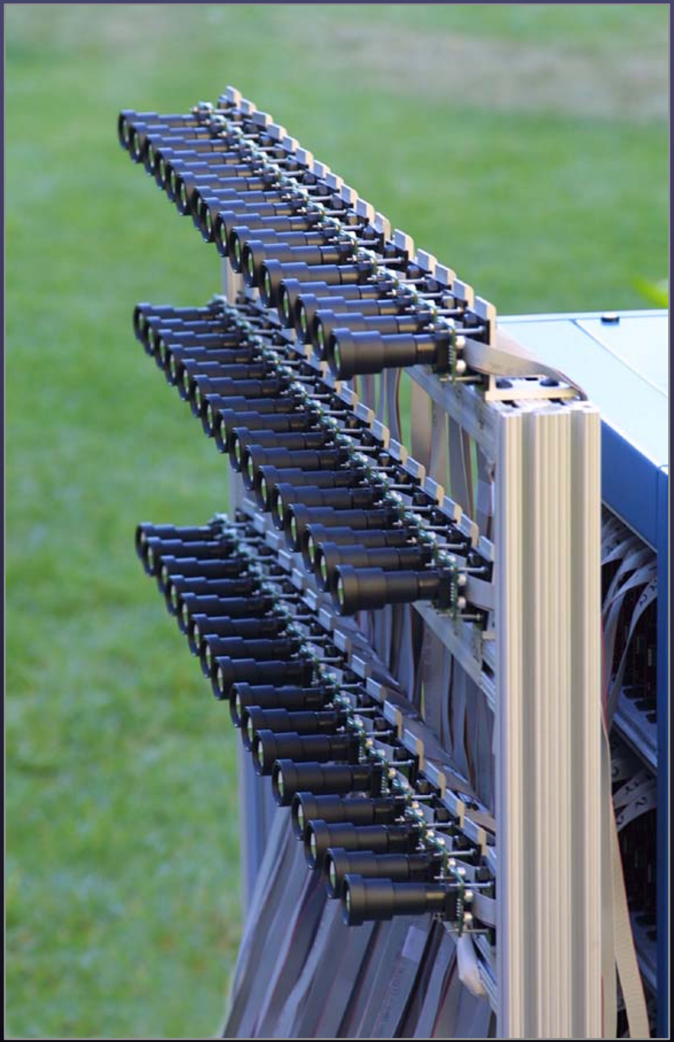
Courtesy of David Williams Lab @ the Center for Visual Science, University of Rochester. Used with permission.



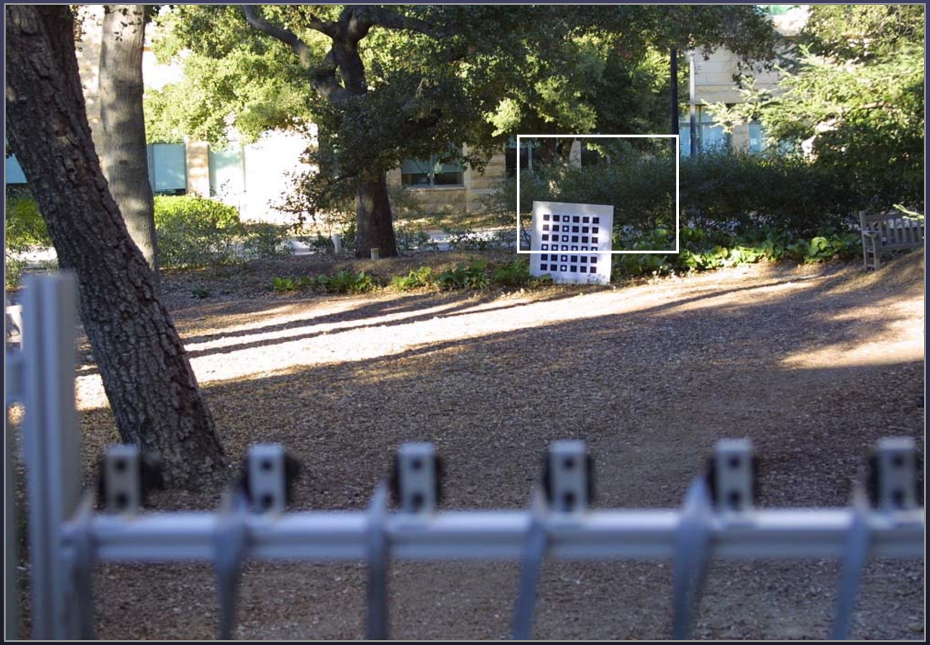


The spots formed on the CCD chip for the eye will be displaced because the wavefront will hit each lenslet at an angle rather than straight on.

Example using 45 cameras
[Vaish CVPR 2004]



Courtesy of Marc Levoy. Used with permission.

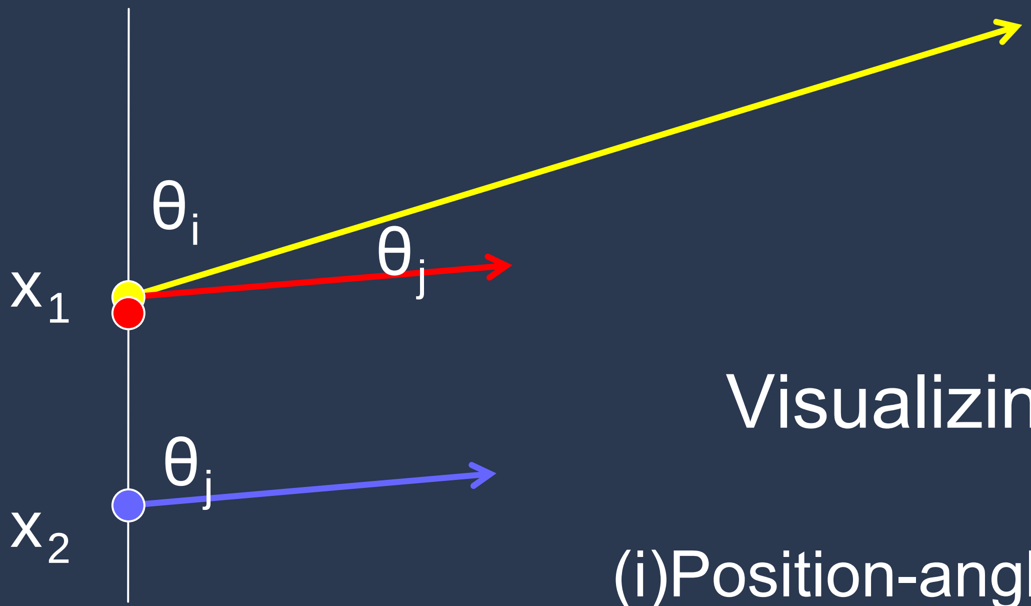


Vaish, V., et al. "Using Plane + Parallax for Calibrating Dense Camera Arrays." *Proceedings of CVPR 2004*.
Courtesy of IEEE. Used with permission. © 2004 IEEE.

Synthetic aperture videography

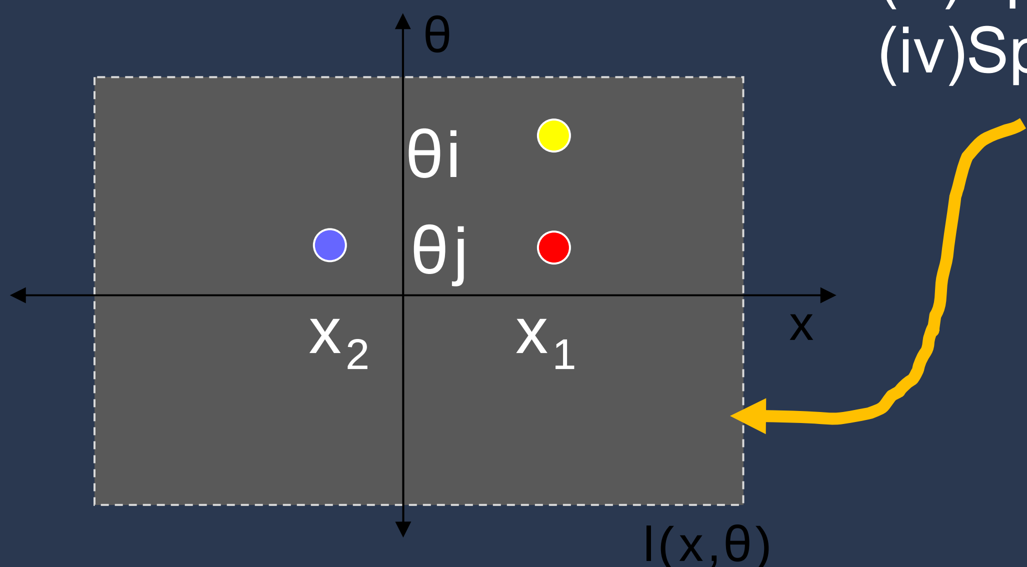
Image removed due to copyright restrictions.

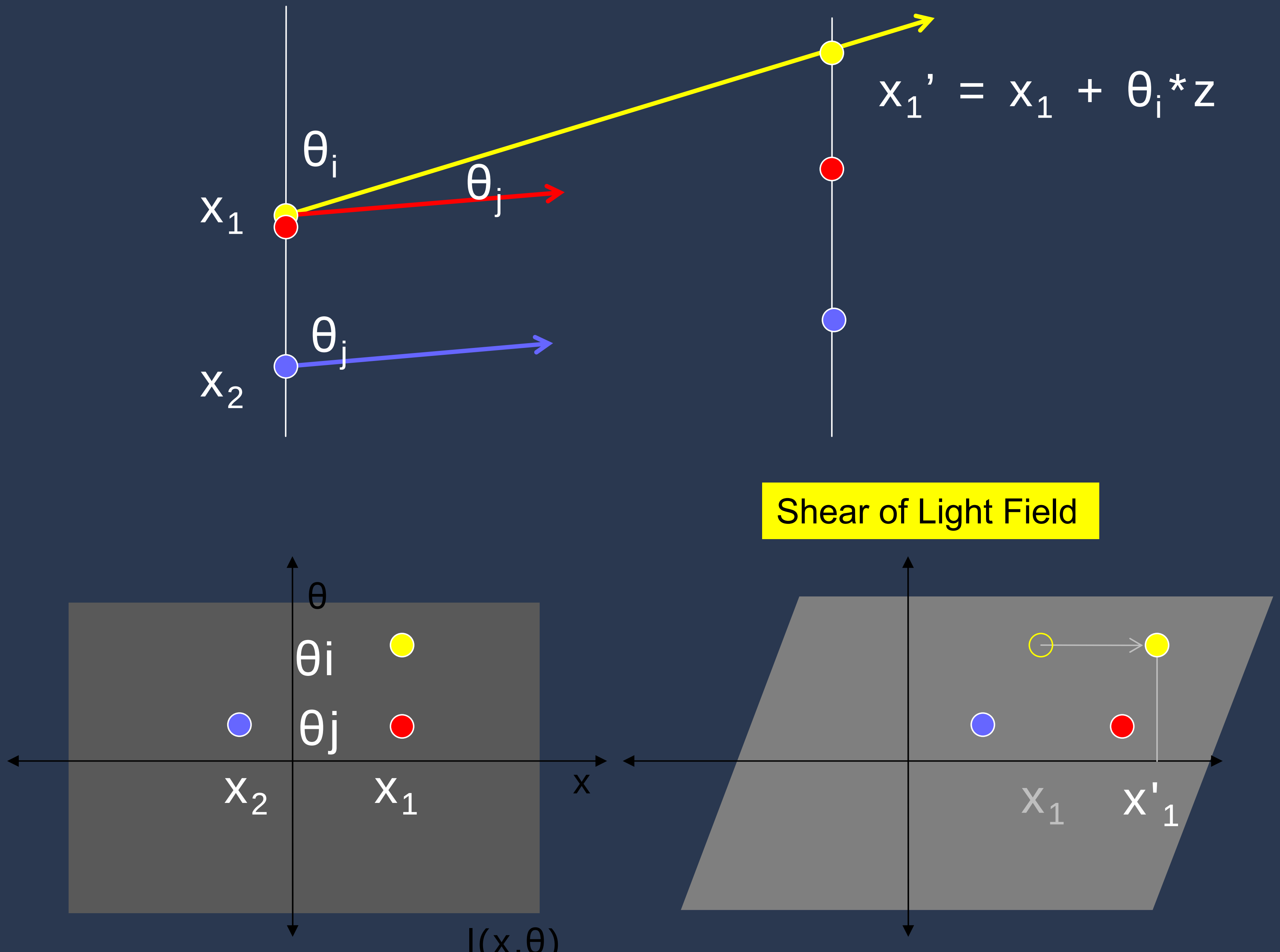

Vaish, V., et al. "Using Plane + Parallax for Calibrating Dense Camera Arrays." *Proceedings of CVPR 2004*.



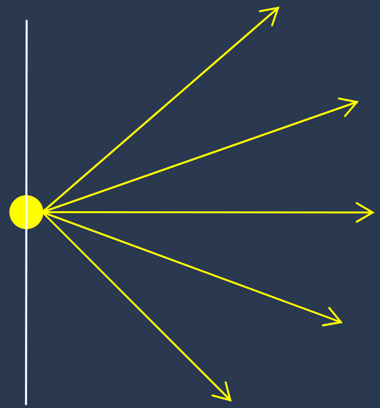
Visualizing Lightfield

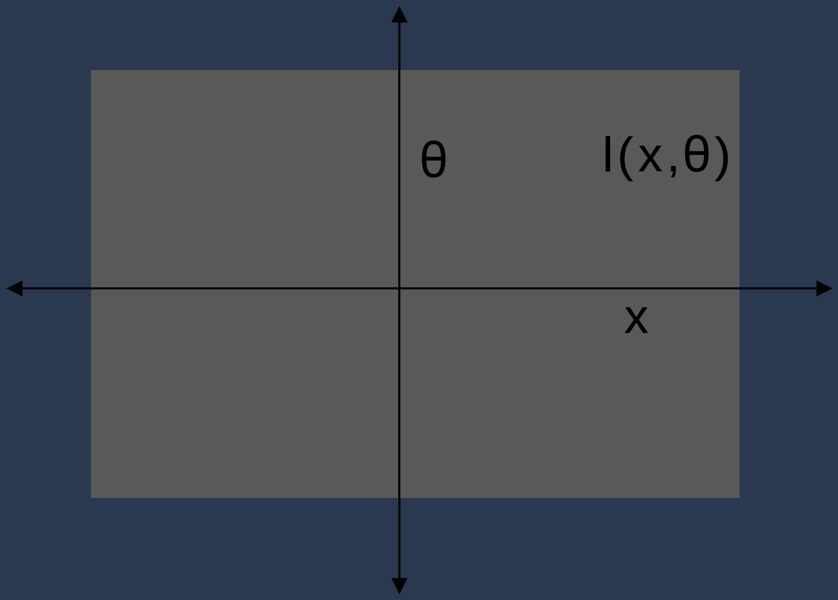
(i)Position-angle space
(ii)Phase-space
(iii)Space- Spatial Frequency
(iv)Spectrogram

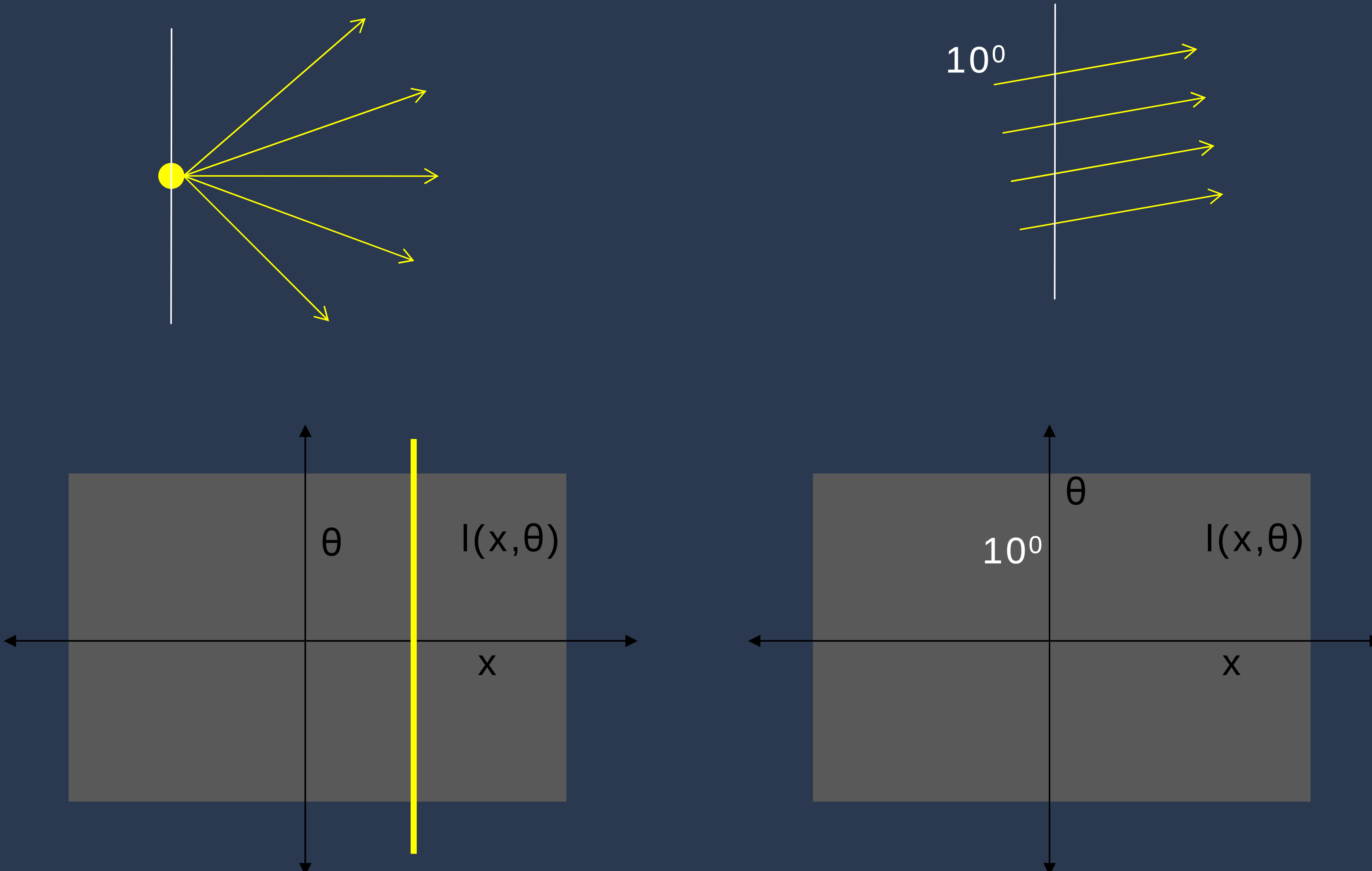


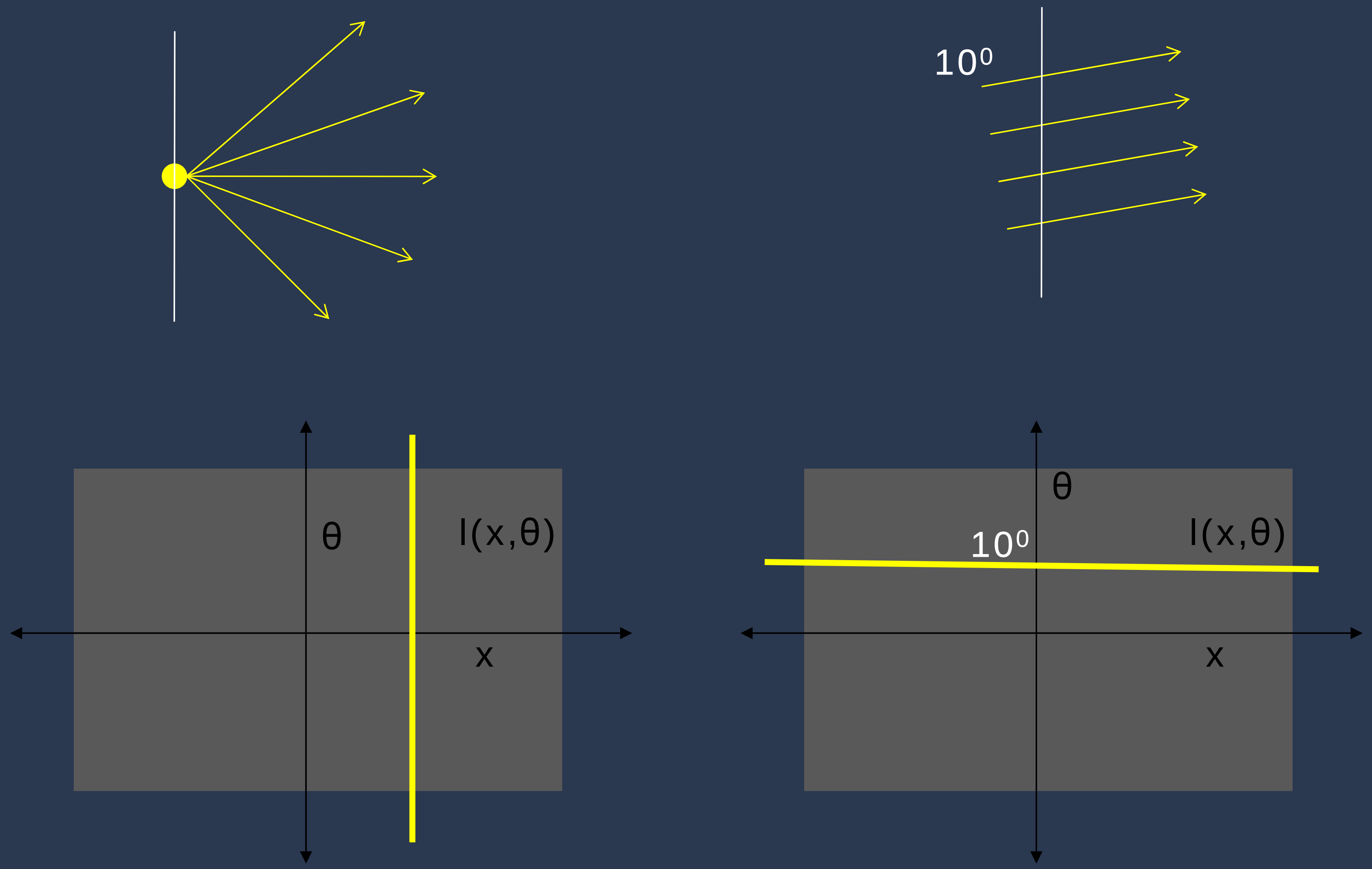


$x_1' = x_1 + \theta_i * z$
θ_i
θ_j
x_1
x_2
Shear of Light Field
θ
θi
θj
x_2
x_1
x
I(x,θ)
x_1
x'_1



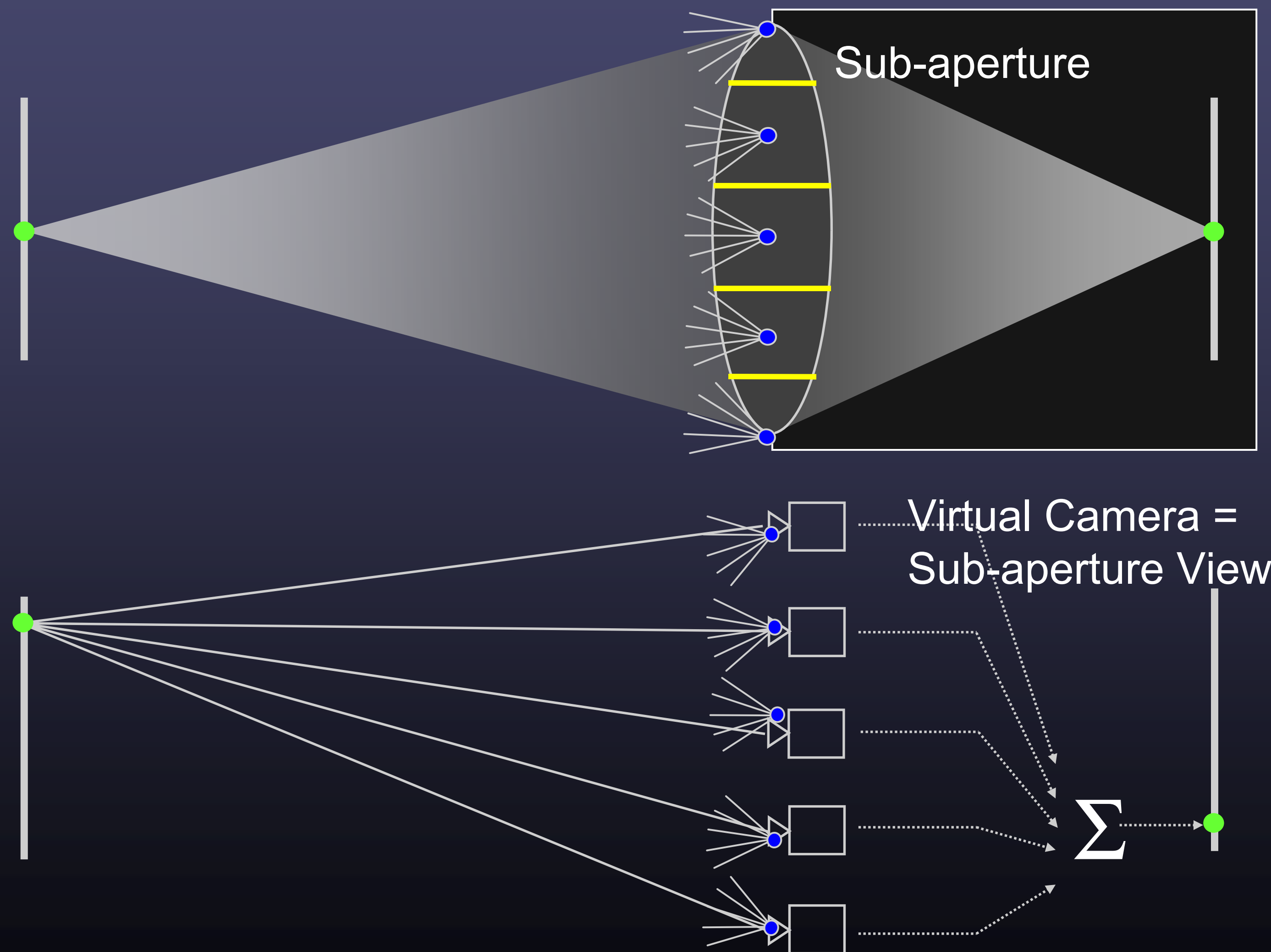

θ
I(x,θ)
x


10^0
θ
I(x,θ)
x
θ
10^0
I(x,θ)
x



10^0
θ
I(x,θ)
x
θ
10^0
I(x,θ)
x

Light Field = Array of (virtual) Cameras



Three ways to capture LF inside a camera

- Shadows using pin-hole array
- Refraction using lenslet array
- Heterodyning using masks

Sub-Aperture = Pin-hole + Prism

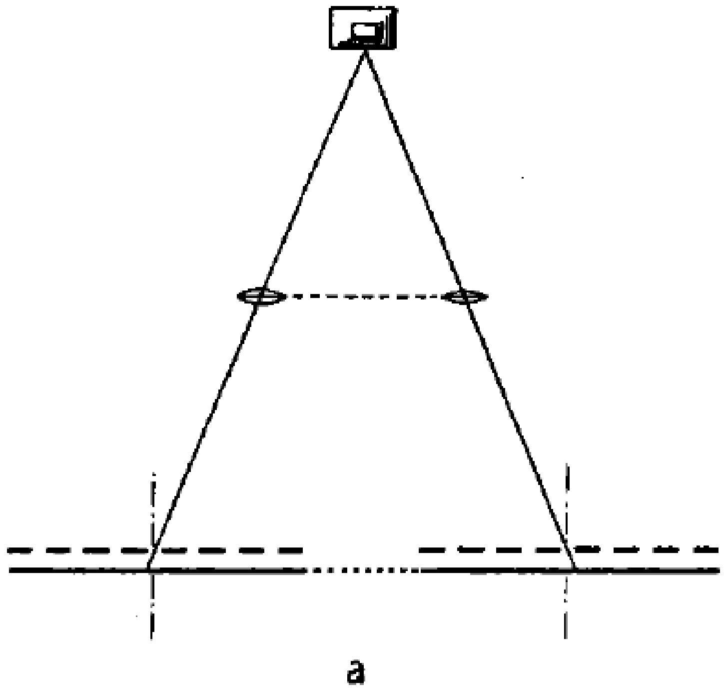


FIG. 1. *Two methods of making parallax panoramagram negatives. (a) A moving lens exposing a sensitive plate behind a grating slightly separated from it; lens, grating and plate being maintained in line during the exposure. (b) A large stationary lens, projecting an image on a stationary plate through a grating slightly separated from it.*

Ives 1933

vertical axis than is called for by the simple formula above developed. This correction, which is roughly proportional to the cosine of the angle between *ww'* and the sensitive surface, and so is of importance only for

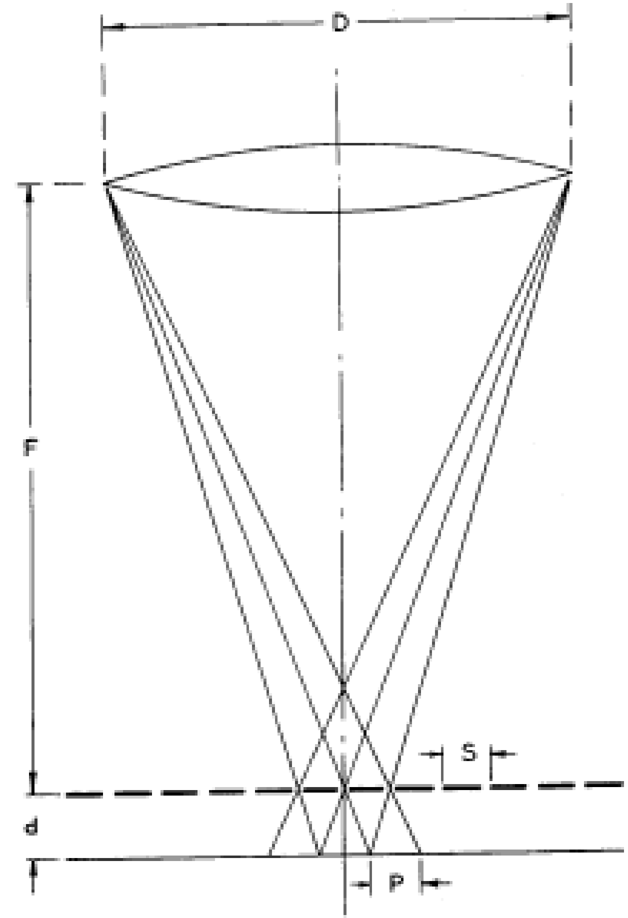
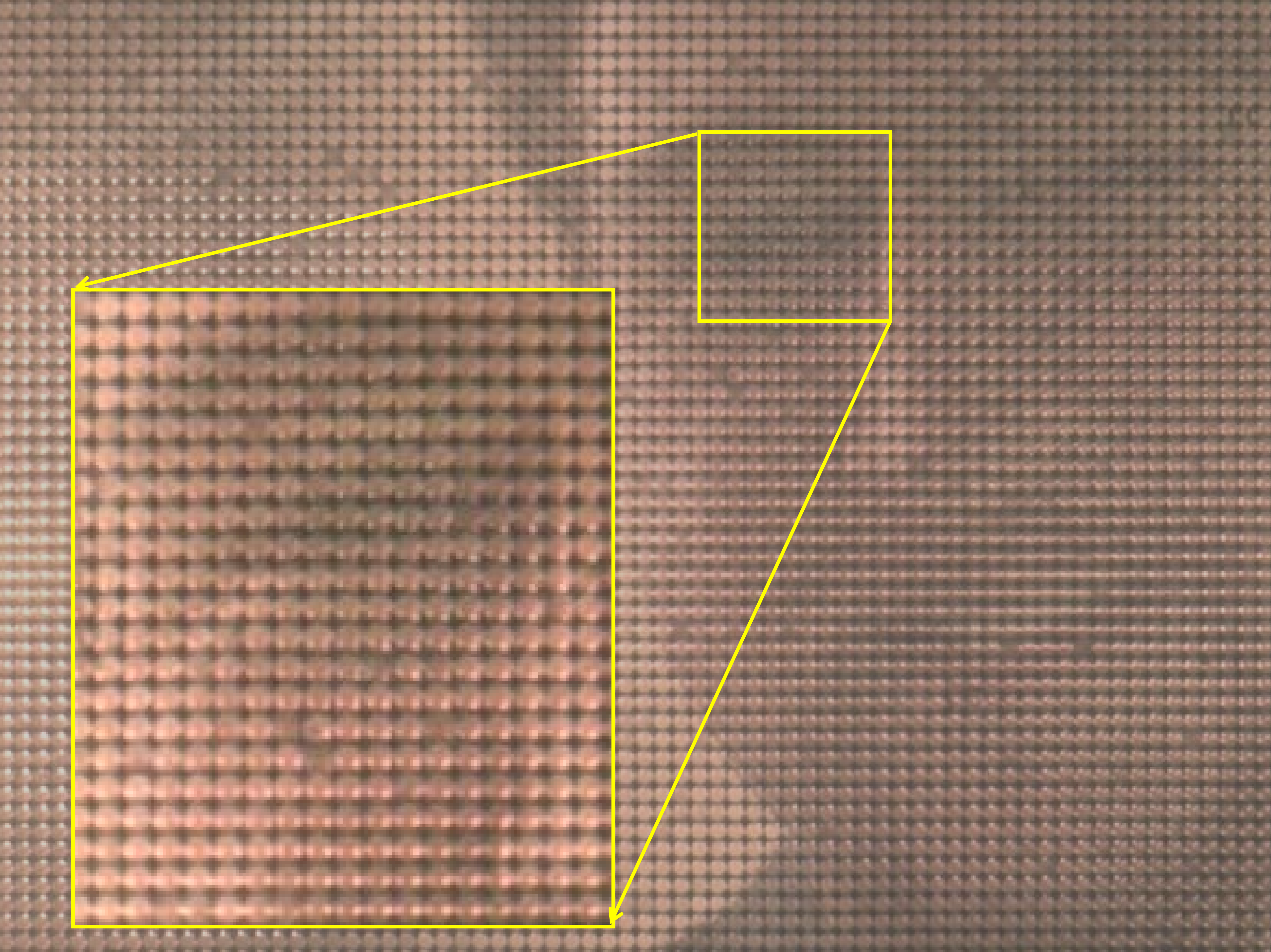


FIG. 4. *Determination of separation of grating and plate as function of grating spacing, lens diameter and focal distance.*

large angles, also varies with the angle of observation. A diameter of taking lens and size of picture can theoretically be attained such that this second order correction will fail. The slightly greater magnification of the viewing grating called for over the amount given by the



Lens Glare Reduction

[Raskar, Agrawal, Wilson, Veeraraghavan SIGGRAPH 2008]

Glare/Flare due to camera lenses reduces contrast

Reducing Glare

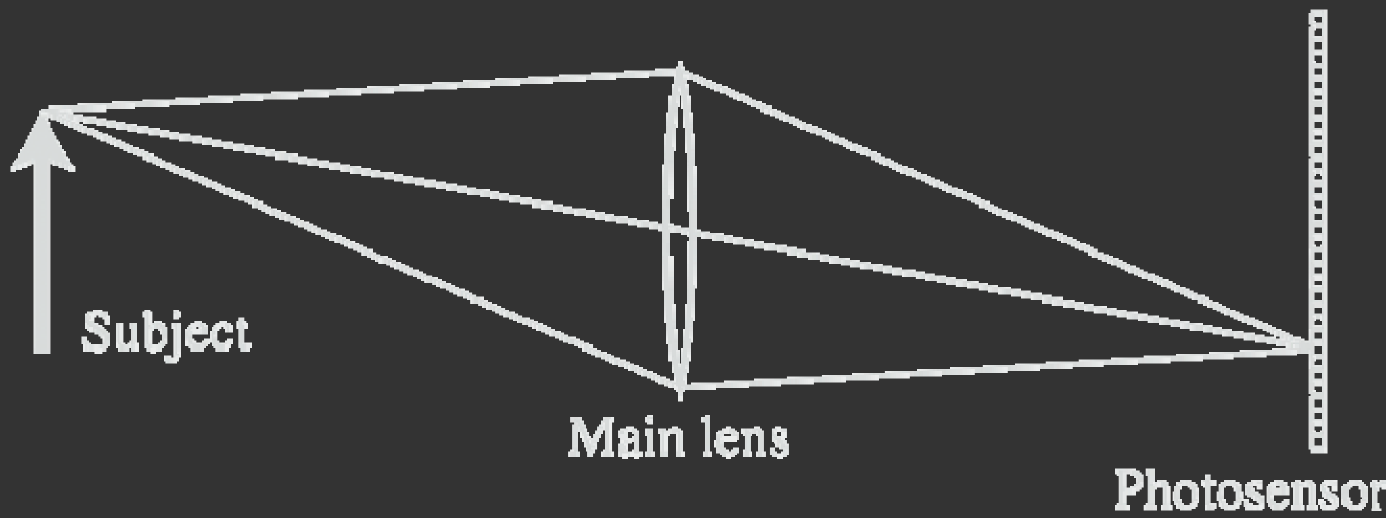
Conventional Photo

After removing outliers

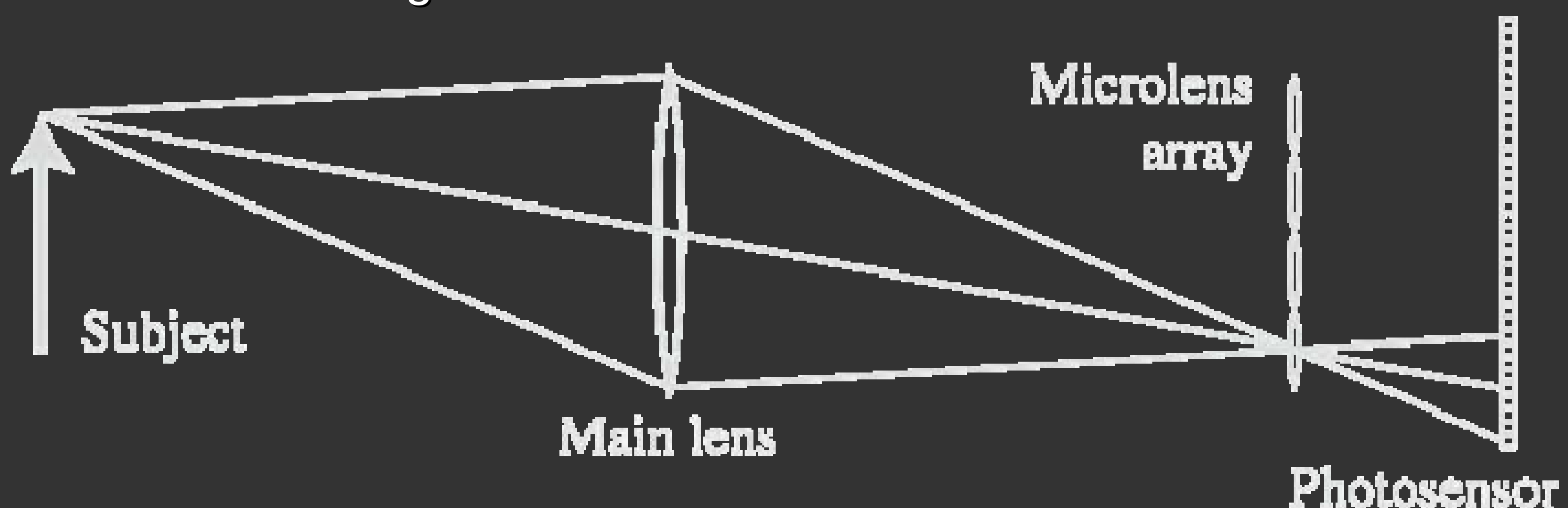
Glare Reduced Image

Raskar, R., et al. "Glare Aware Photography: 4D Ray Sampling for Reducing Glare Effects of Camera Lenses." *Proceedings of SIGGRAPH 2008*.

Light Field Inside a Camera



Lenslet-based Light Field camera

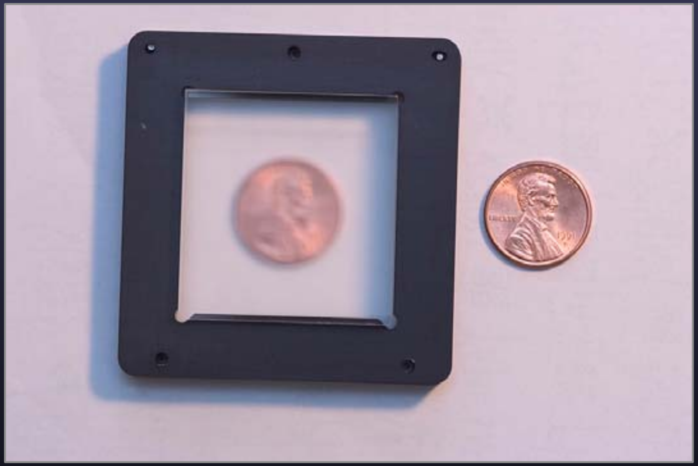


[Adelson and Wang, 1992, Ng et al. 2005]

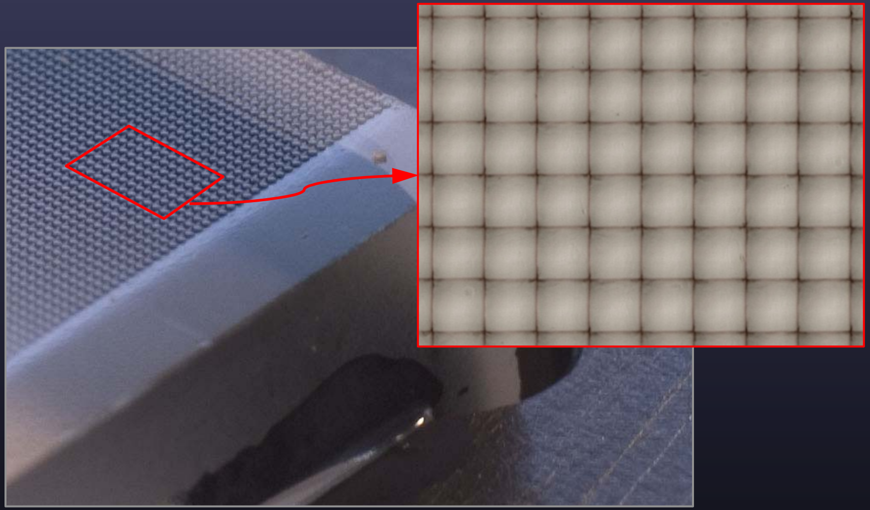
Prototype camera

Contax medium format camera

Kodak 16-megapixel sensor



Adaptive Optics microlens array

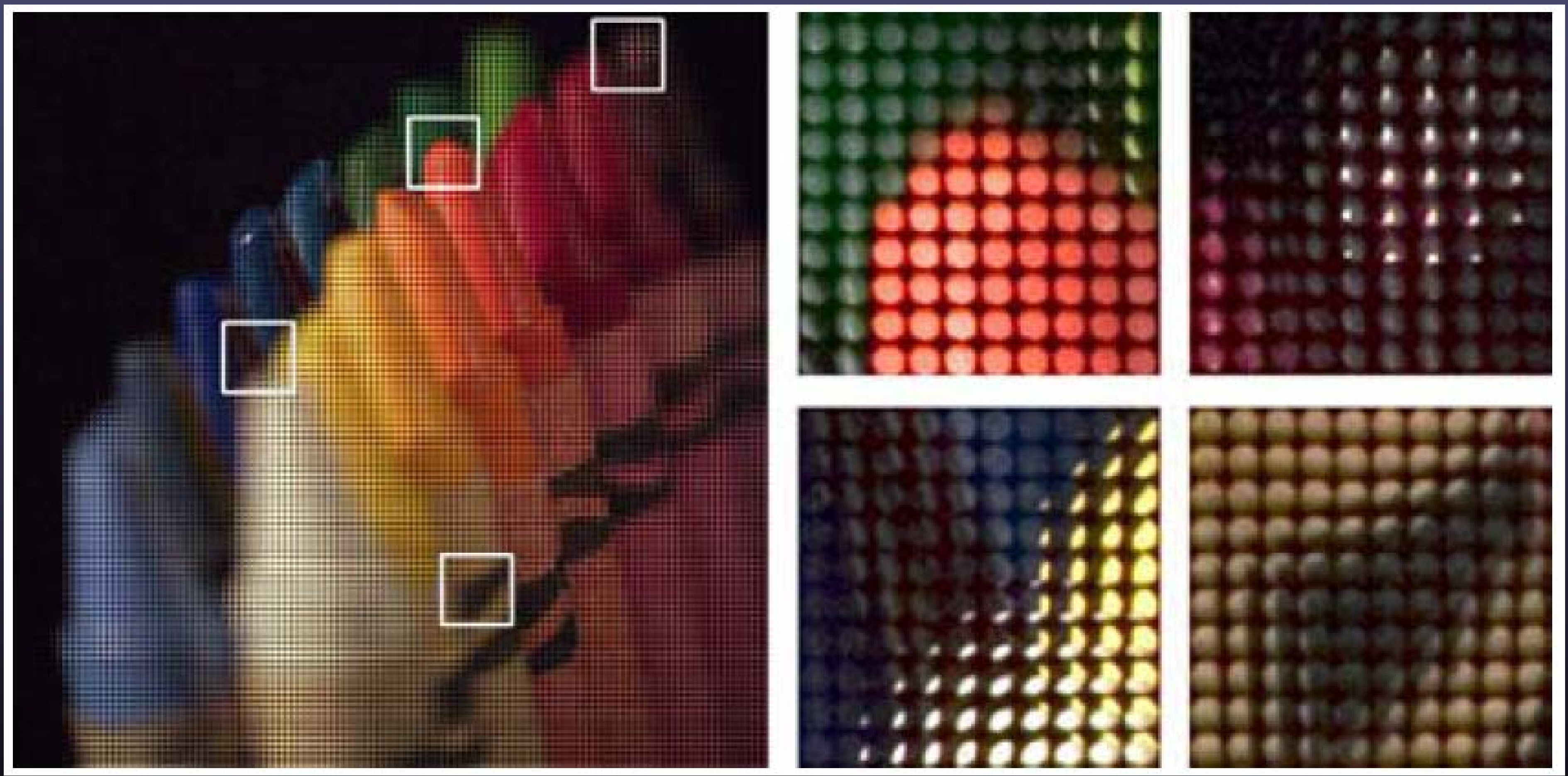


125µ square-sided microlenses

Courtesy of Ren Ng. Used with permission.

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

Zooming into the raw photo



Courtesy of Ren Ng. Used with permission.

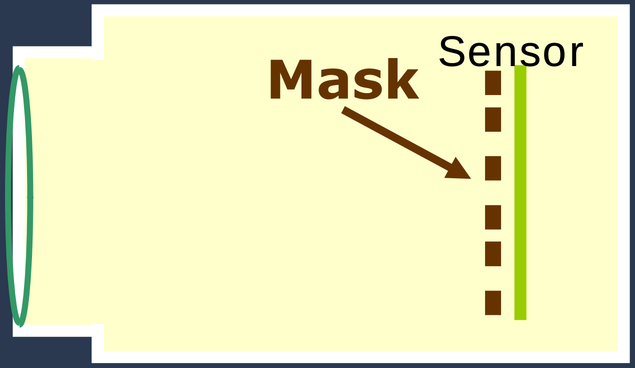
Digital Refocusing

Courtesy of Ren Ng. Used with permission.

[Ng et al 2005]

Can we achieve this with a <u>Mask</u> alone?

Mask based Light Field Camera

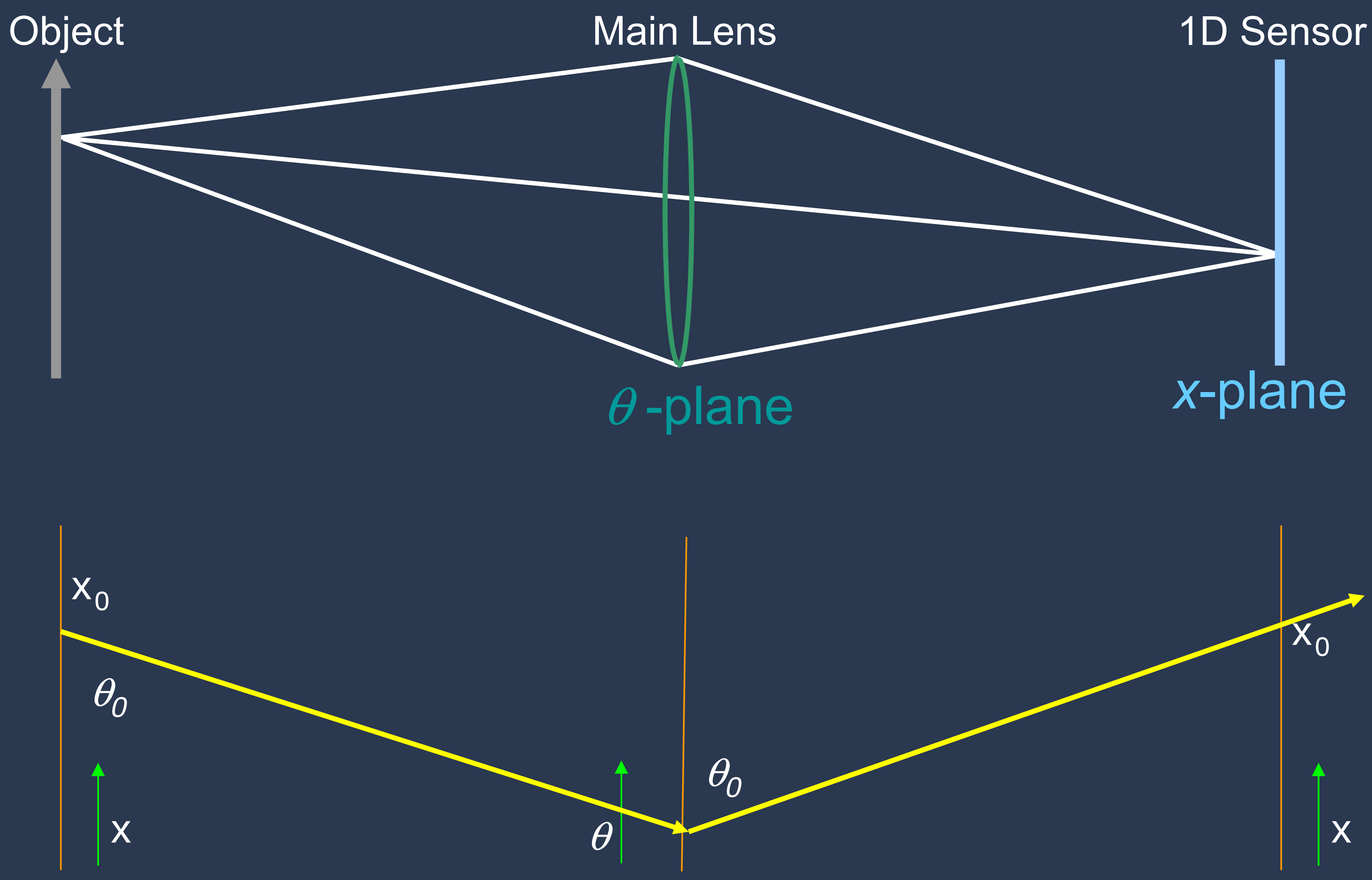


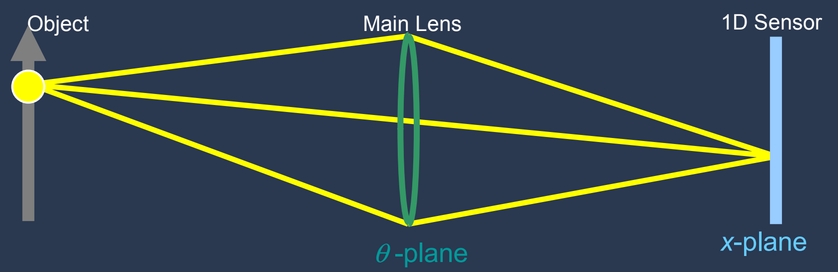
[Veeraraghavan, Raskar, Agrawal, Tumblin, Mohan, Siggraph 2007]

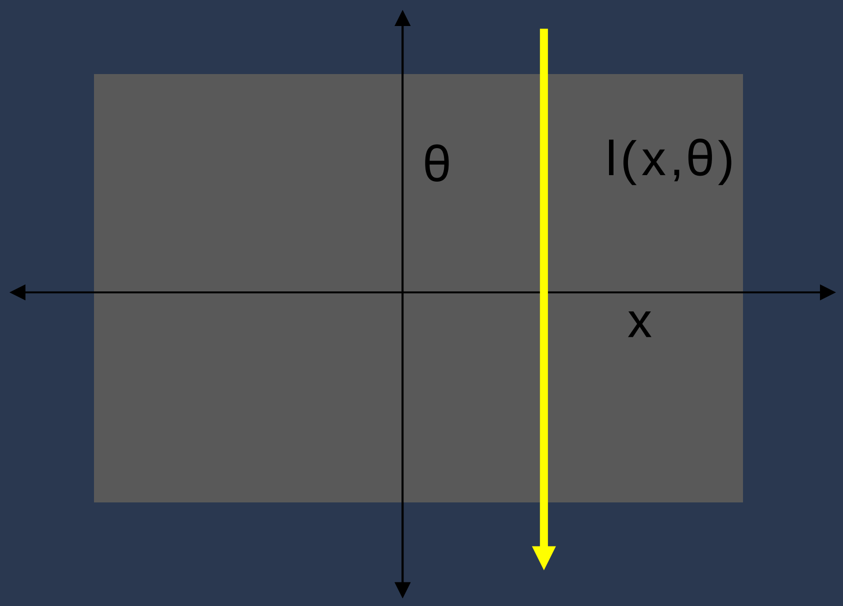
How to Capture 4D Light Field with 2D Sensor ?

What should be the pattern of the mask ?

Lens Copies the Lightfield of Conjugate Plane

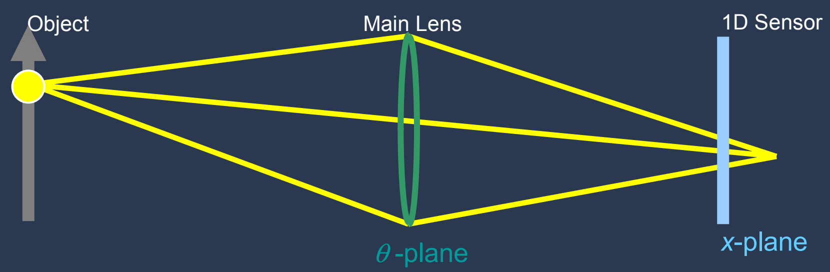


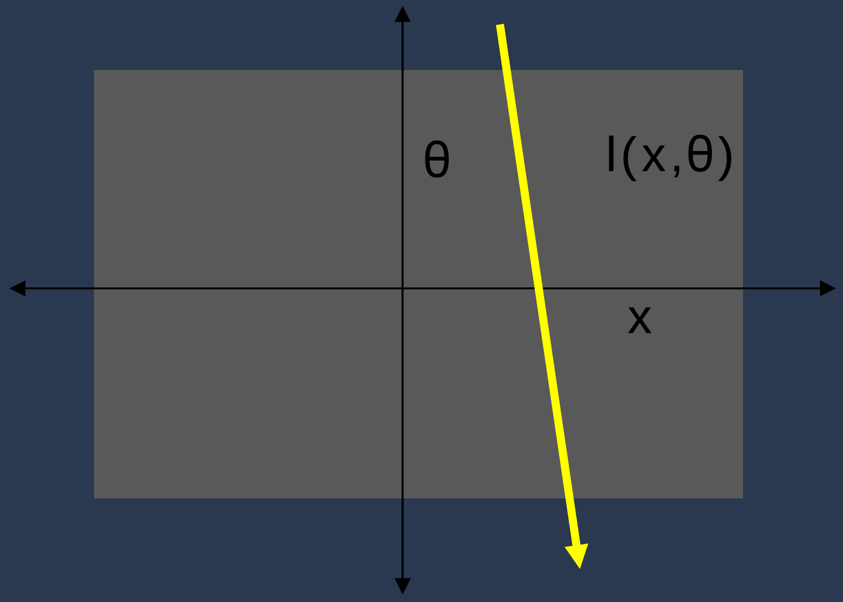




Line Integral

Captured Photo

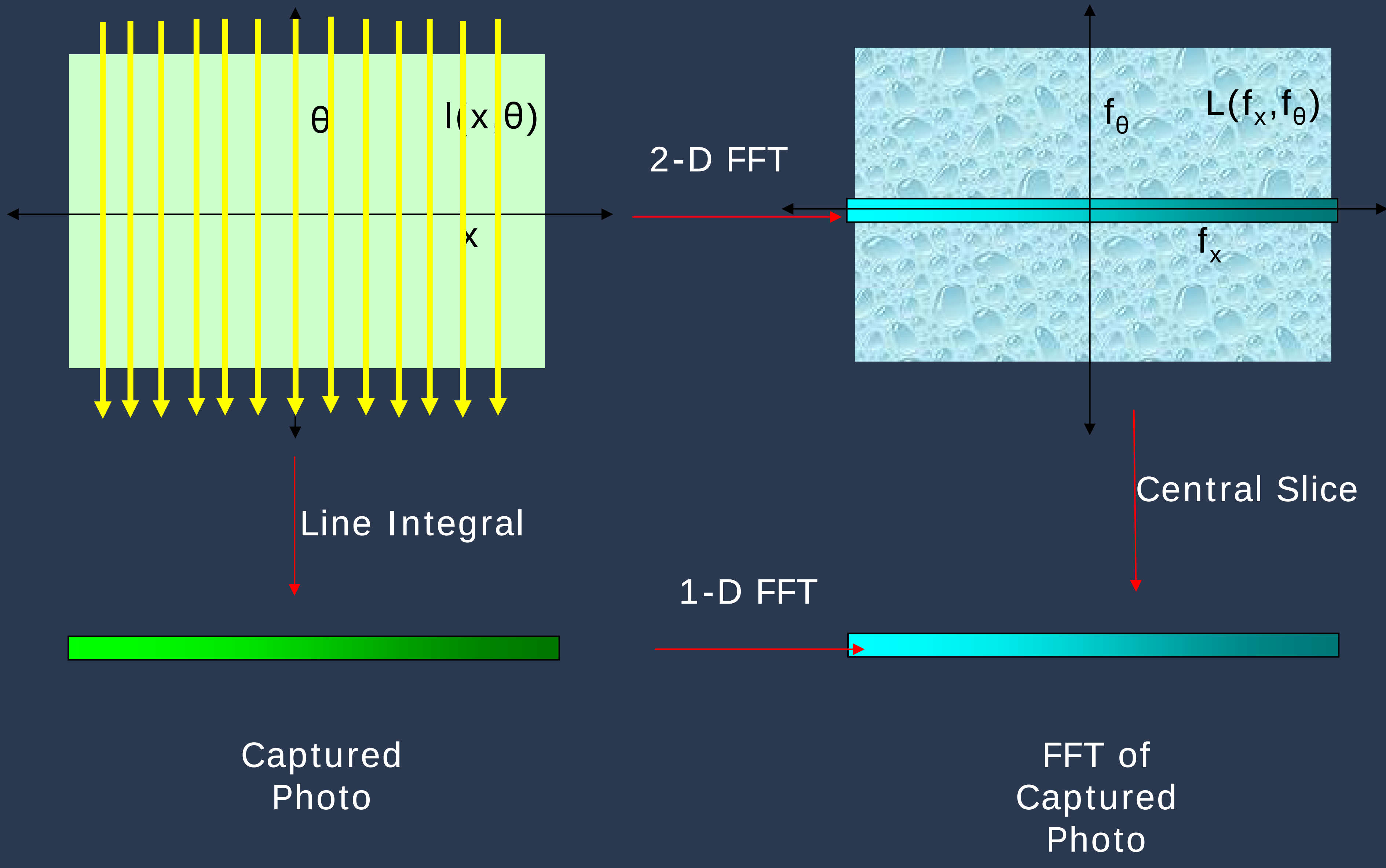




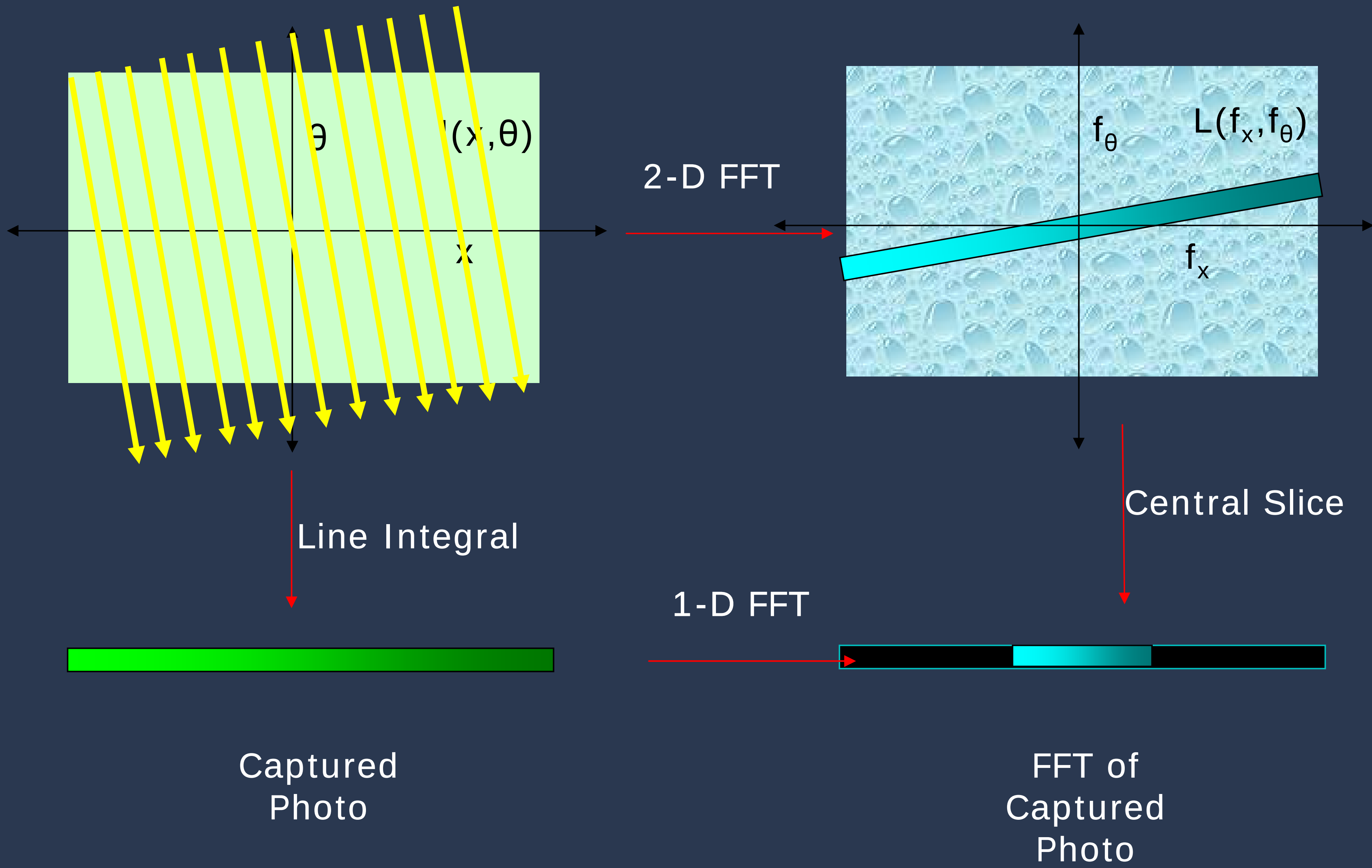
Line Integral

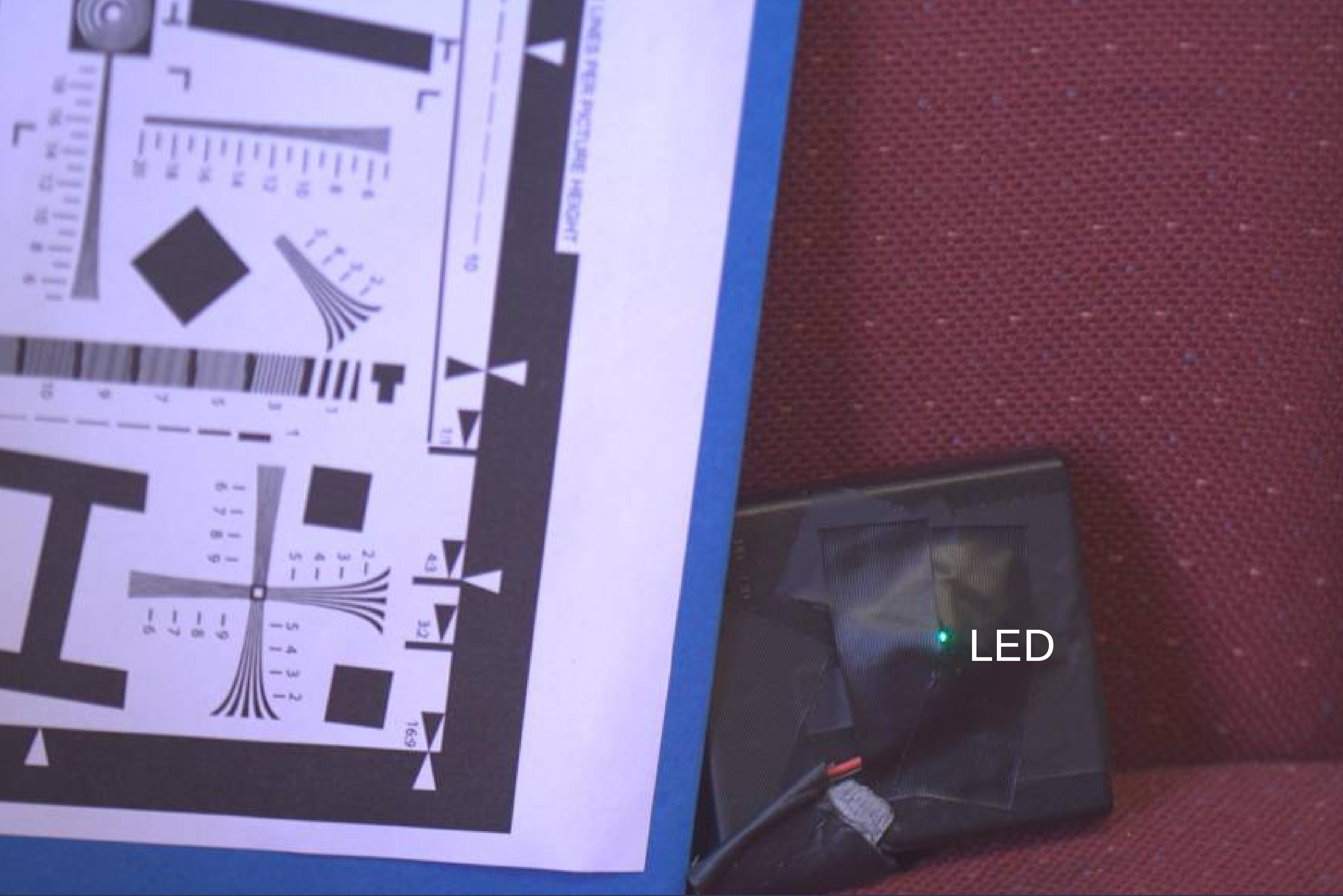
Captured Photo

Fourier Slice Theorem



Light Propagation (Defocus Blur)





In Focus Photo

Out of Focus Photo: Open Aperture

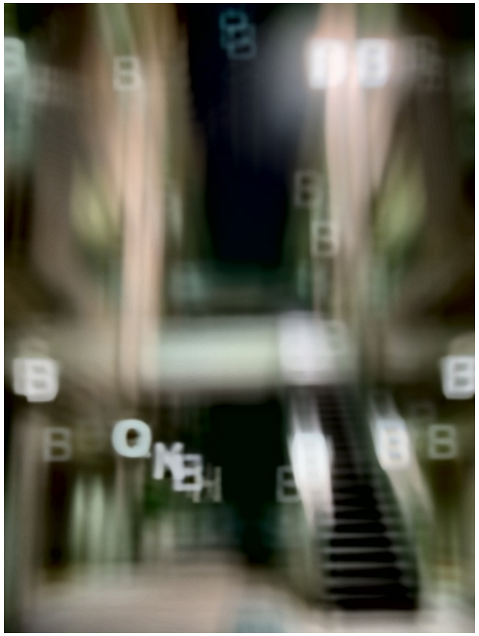
Coded Aperture Camera

The aperture of a 100 mm lens is modified

Insert a coded mask with chosen binary pattern

Rest of the camera is unmodified

Out of Focus Photo: Coded Aperture



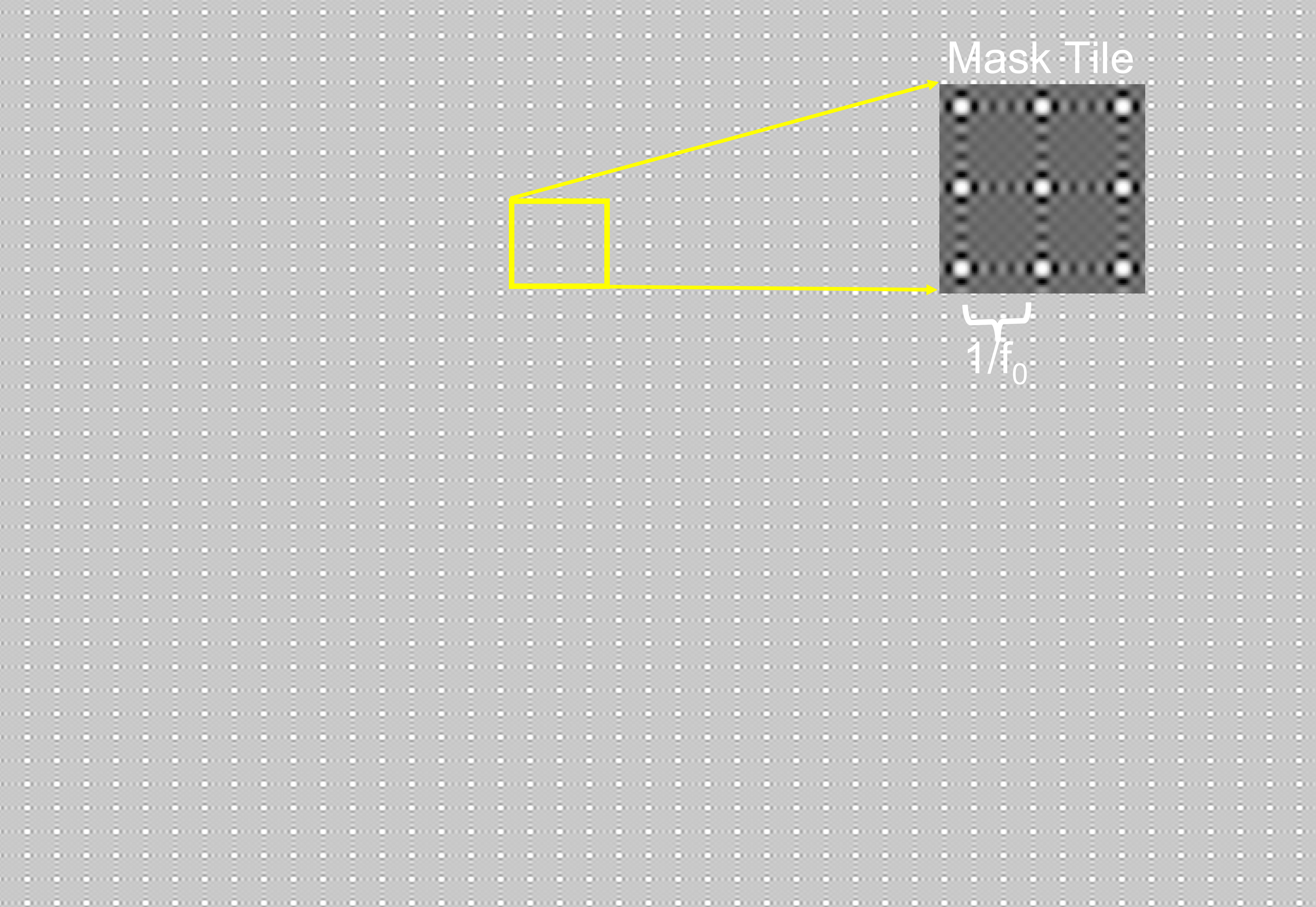
Modeling and Synthesis of Aperture Effects in Cameras

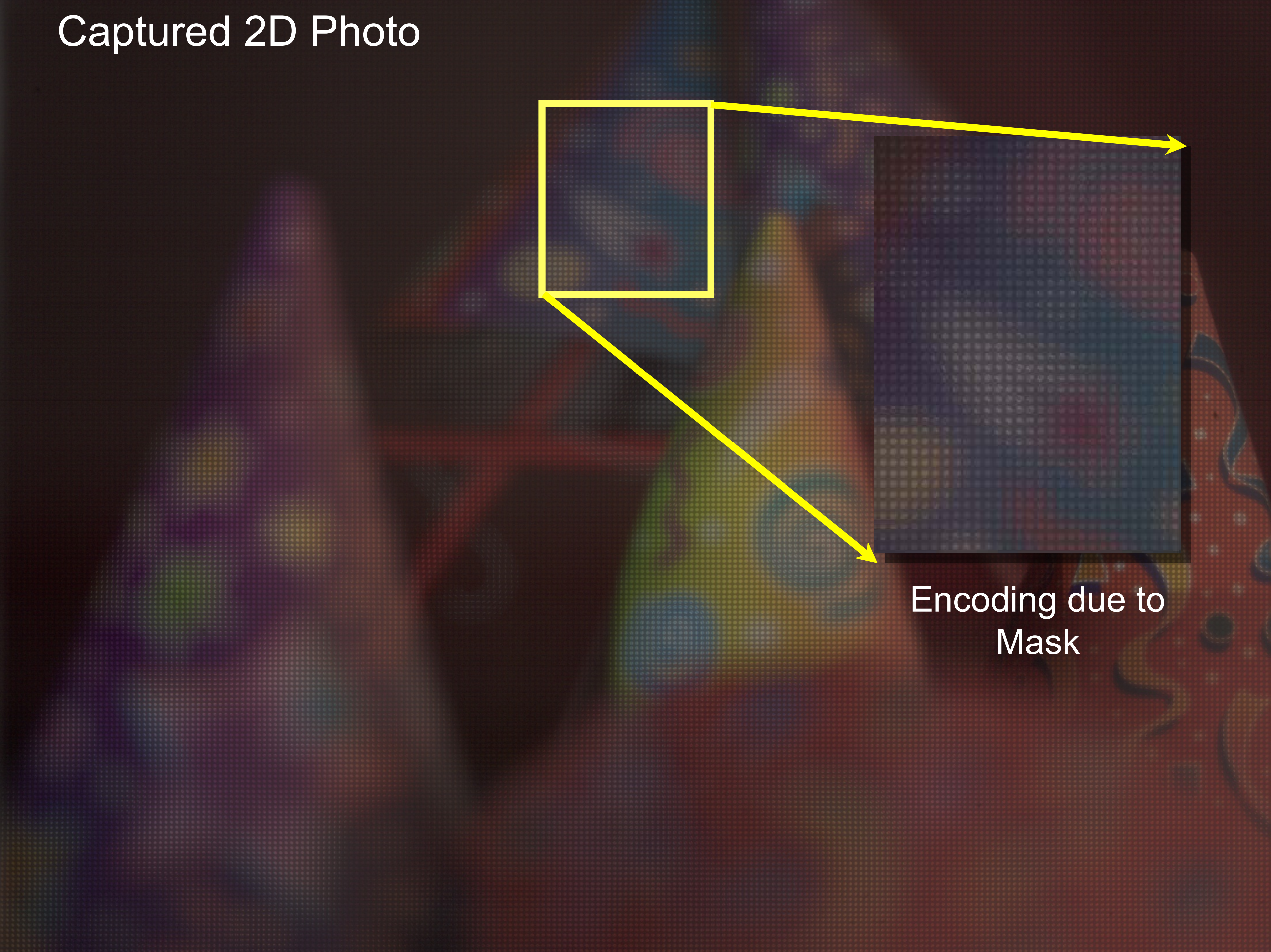
Douglas Lanman, Ramesh Raskar, and Gabriel Taubin

Computational Aesthetics 2008
20 June, 2008

Slides removed due to copyright restrictions.
See this paper and associated presentation at
http://mesh.brown.edu/dlanman/research.html

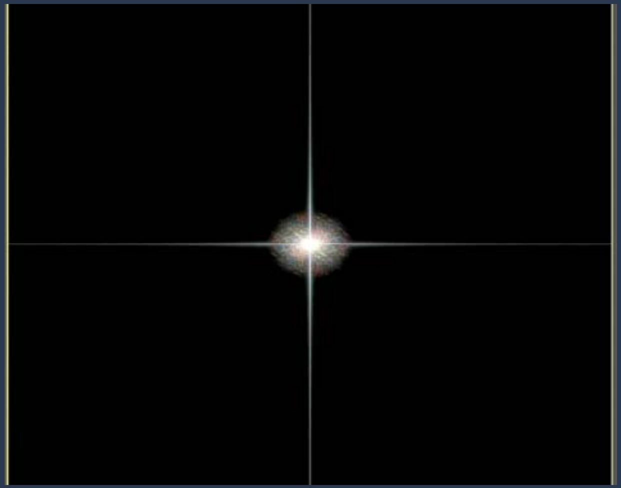
Cosine Mask Used




Captured 2D Photo
Encoding due to
Mask

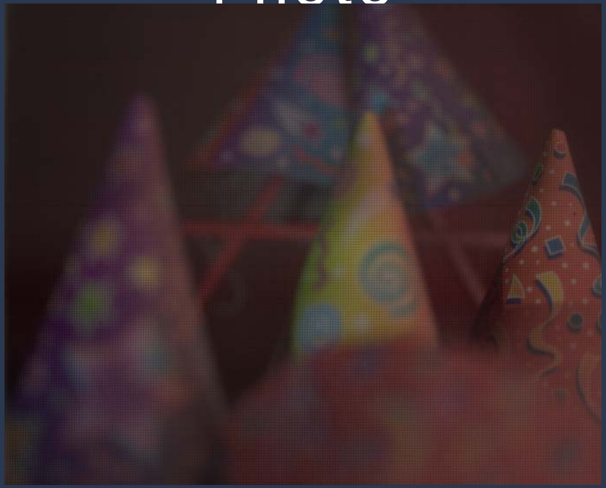
Veraraghavan, Raskar, Agrawal, Mohan, Tumblin. "**Dappled Photography: Mask Enhanced Cameras for Heterodyned Light Fields and Coded Aperture Refocusing.**" ***Proceedings of SIGGRAPH 2007*.**

2D FFT →

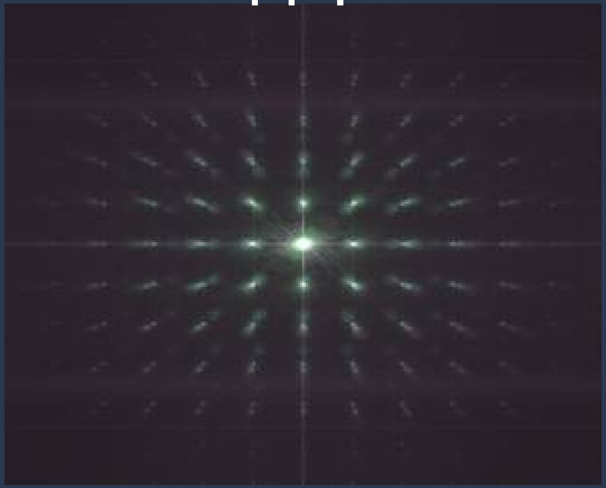


Traditional Camera Photo

Magnitude of 2D FFT



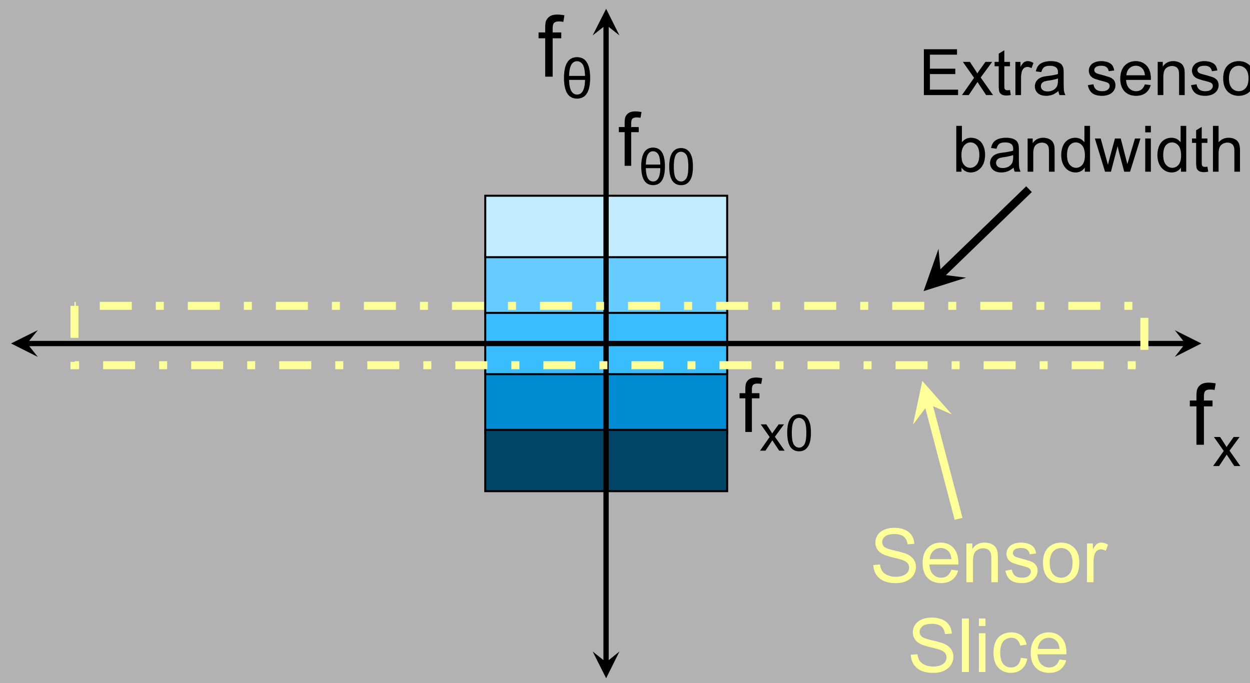
2D FFT →



Heterodyne Camera Photo

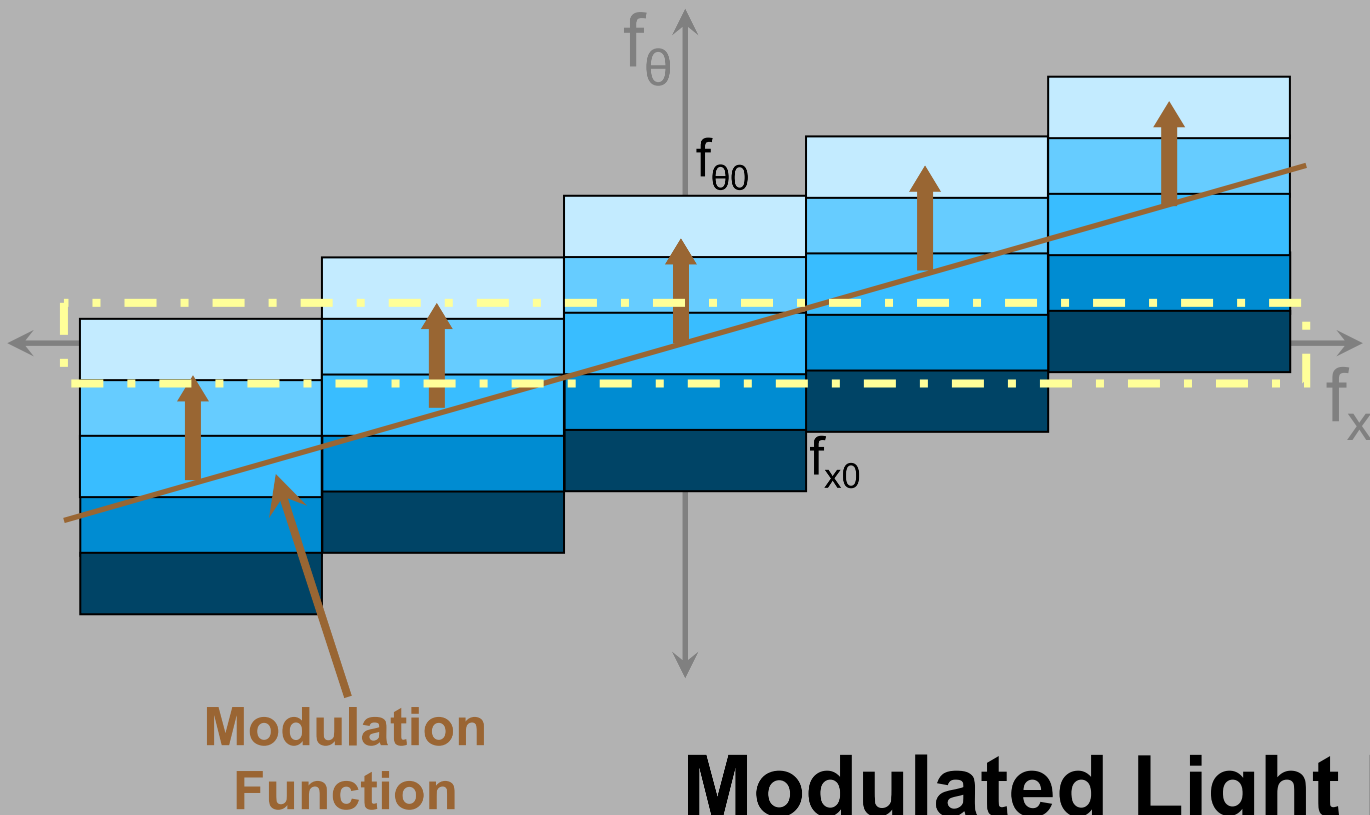
Magnitude of 2D FFT

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



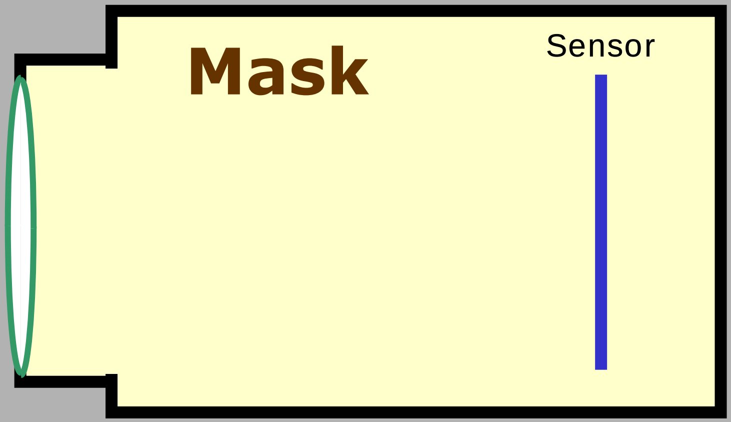
Fourier Light Field Space (Wigner Transform)

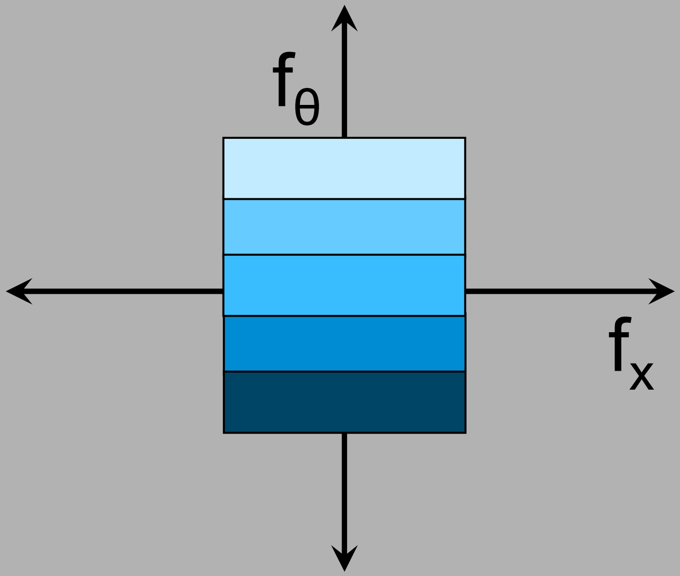
Sensor Slice captures entire Light Field



Modulated Light Field

Where to place the Mask?





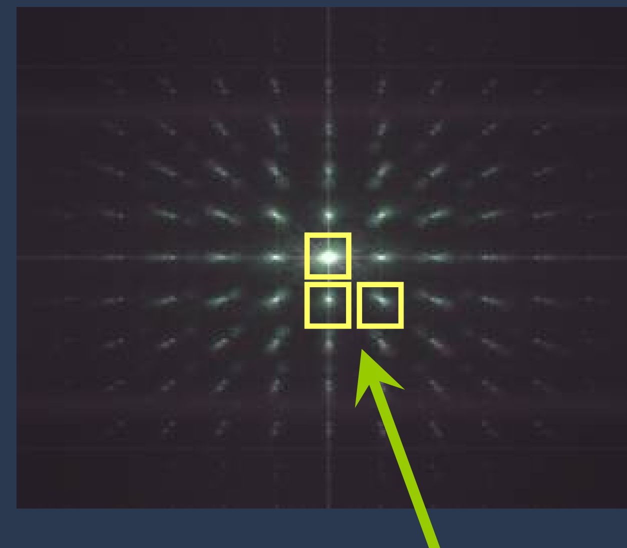
Mask Modulation Function

Computing 4D Light Field

2D Sensor Photo, 1800*1800

2D FFT

2D Fourier Transform, 1800*1800

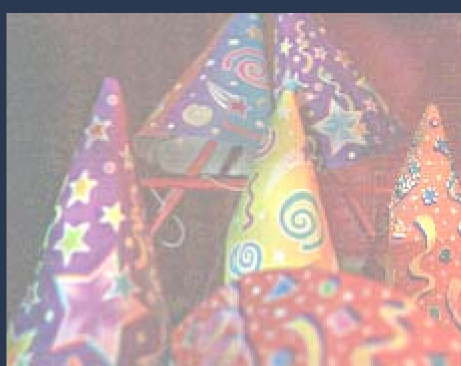


9*9=81 spectral copies

Rearrange 2D tiles into 4D planes

200*200*9*9

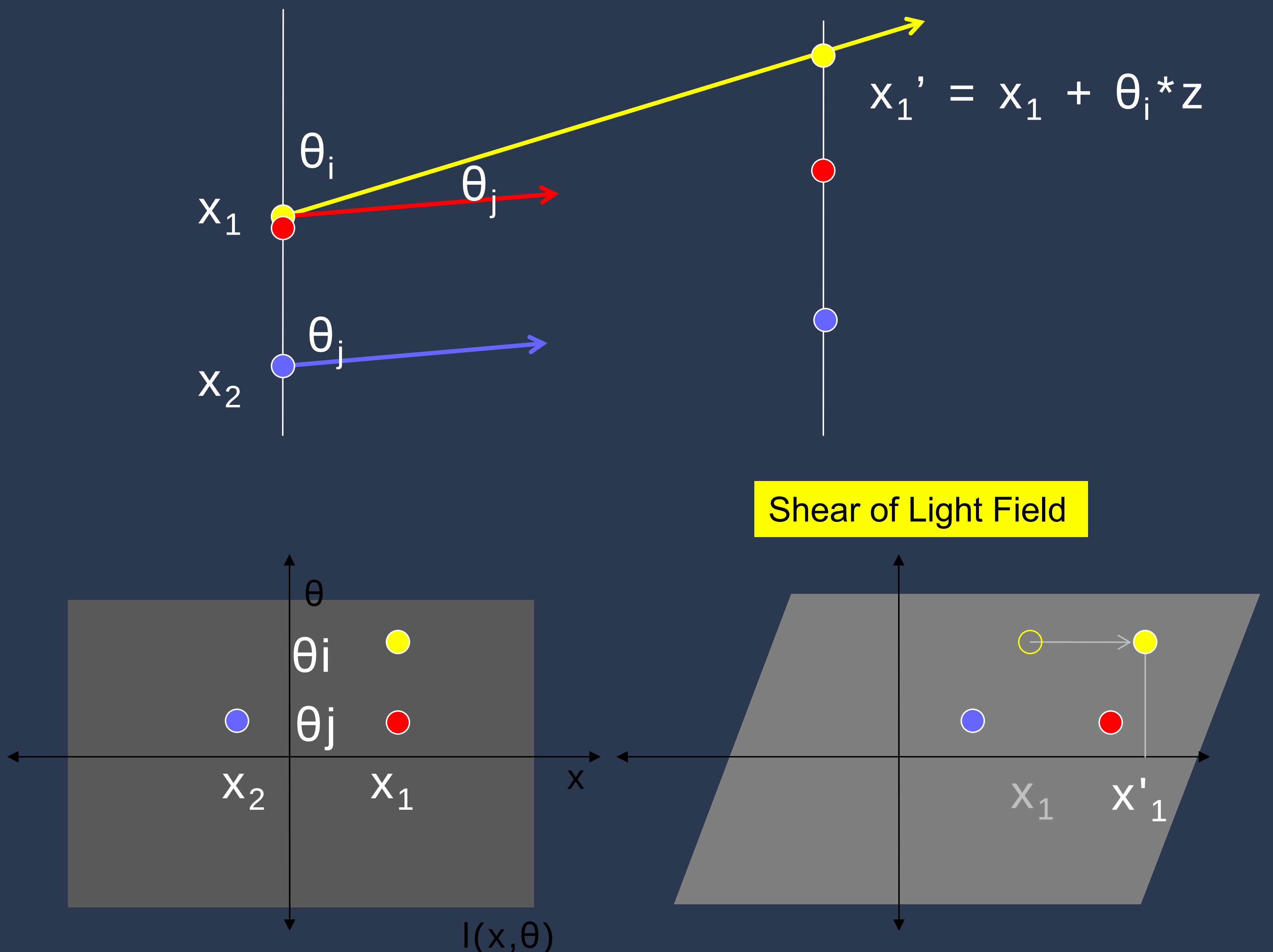
4D IFFT



4D Light Field

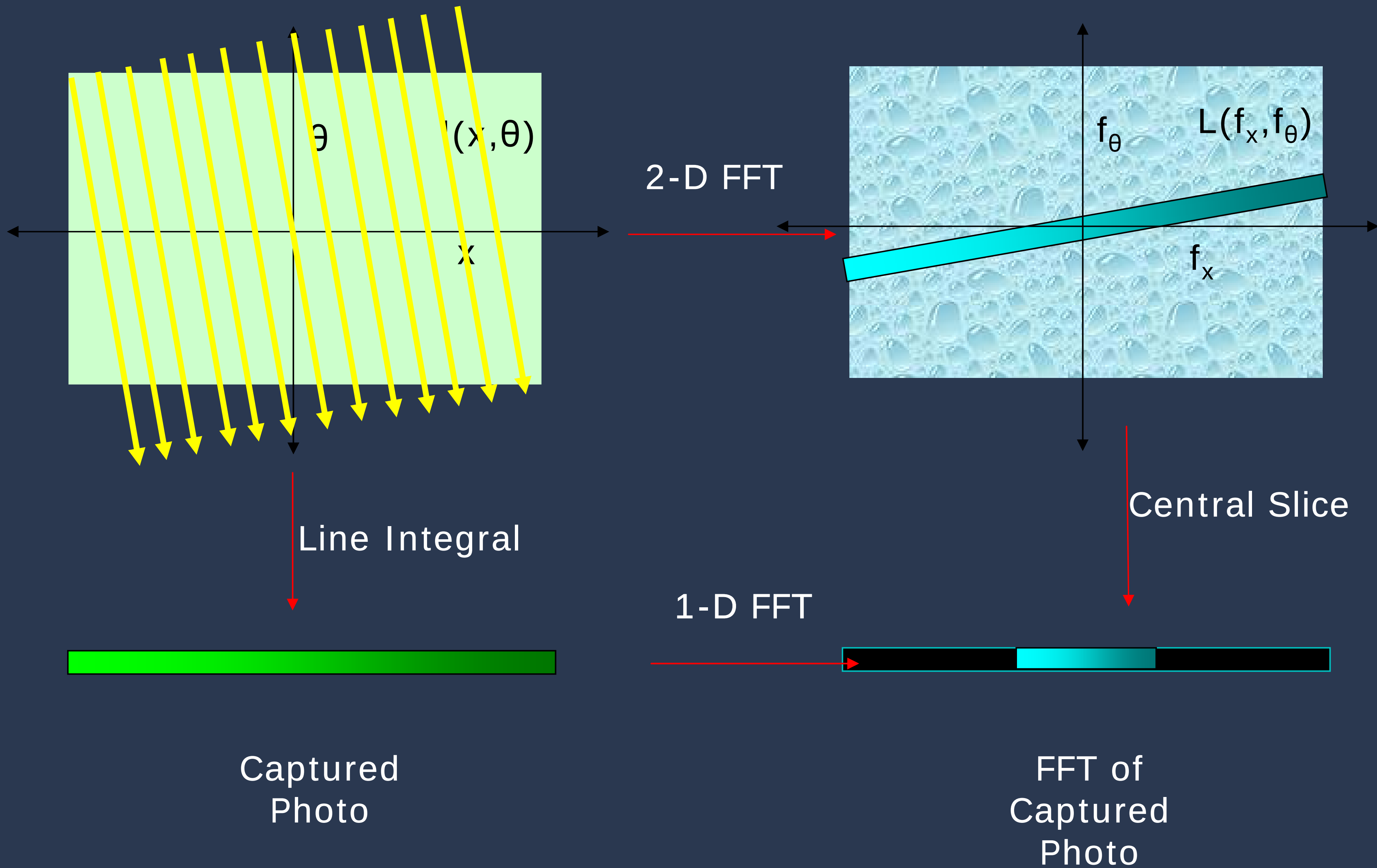
200*200*9*9

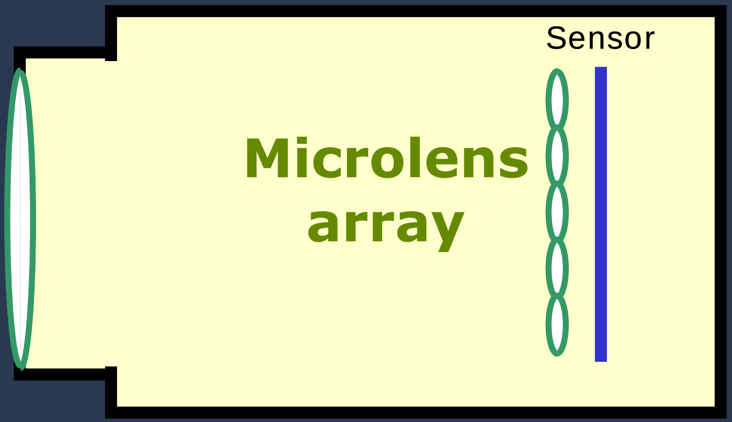
Veraraghavan, Raskar, Agrawal, Mohan, Tumblin. “**Dappled Photography: Mask Enhanced Cameras for Heterodyned Light Fields and Coded Aperture Refocusing.**” ***Proceedings of SIGGRAPH 2007.***



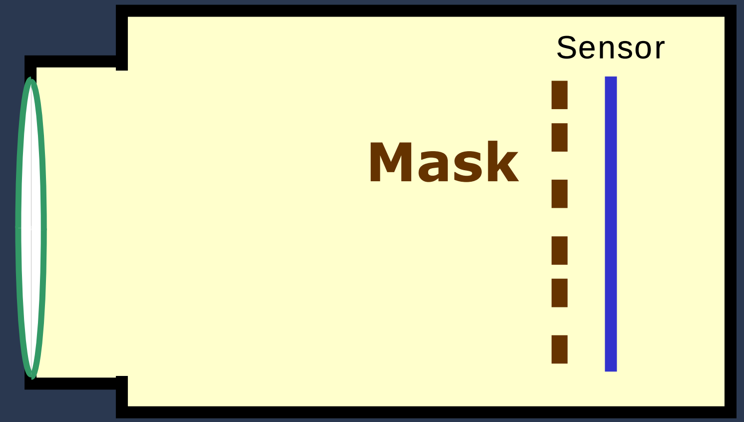
x1' = x1 + θi*z
θi
θj
x1
θj
x2
Shear of Light Field
θ
θi
θj
x2
x1
x
I(x,θ)
x1
x'1

Light Propagation (Defocus Blur)





Plenoptic Camera

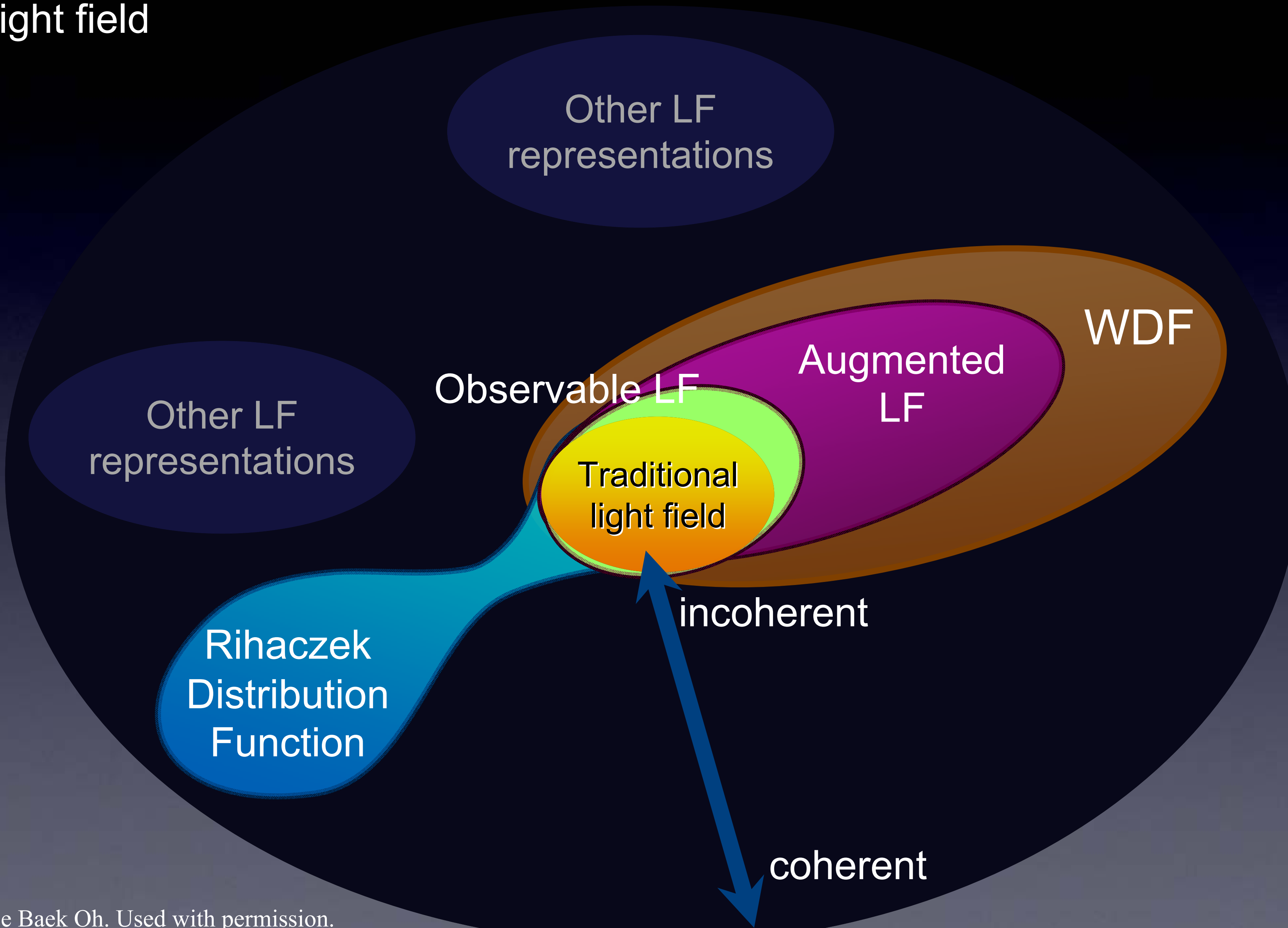


Heterodyne Camera

- Samples individual rays
- Predefined spectrum for lenses
- Chromatic abberration
- High alignment precision
- Peripheral pixels wasted pixels
- Negligible Light Loss

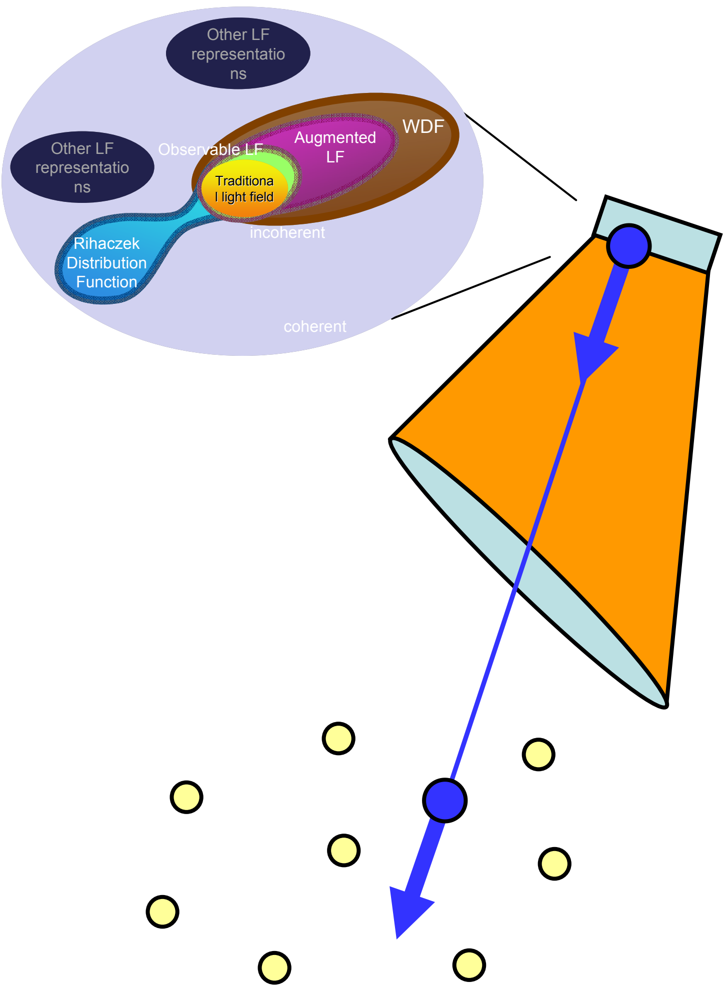
- Samples coded combination of rays
- Supports any wavelength
- Reconfigurable f/#, Easier alignment
- No wastage
- High resolution image for parts of scene in focus
- 50 % Light Loss due to mask

Space of LF representations
Time-frequency representations
Phase space representations
Quasi light field



Quasi light fields

the utility of light fields, the versatility of Maxwell



We form coherent images by

formulating,

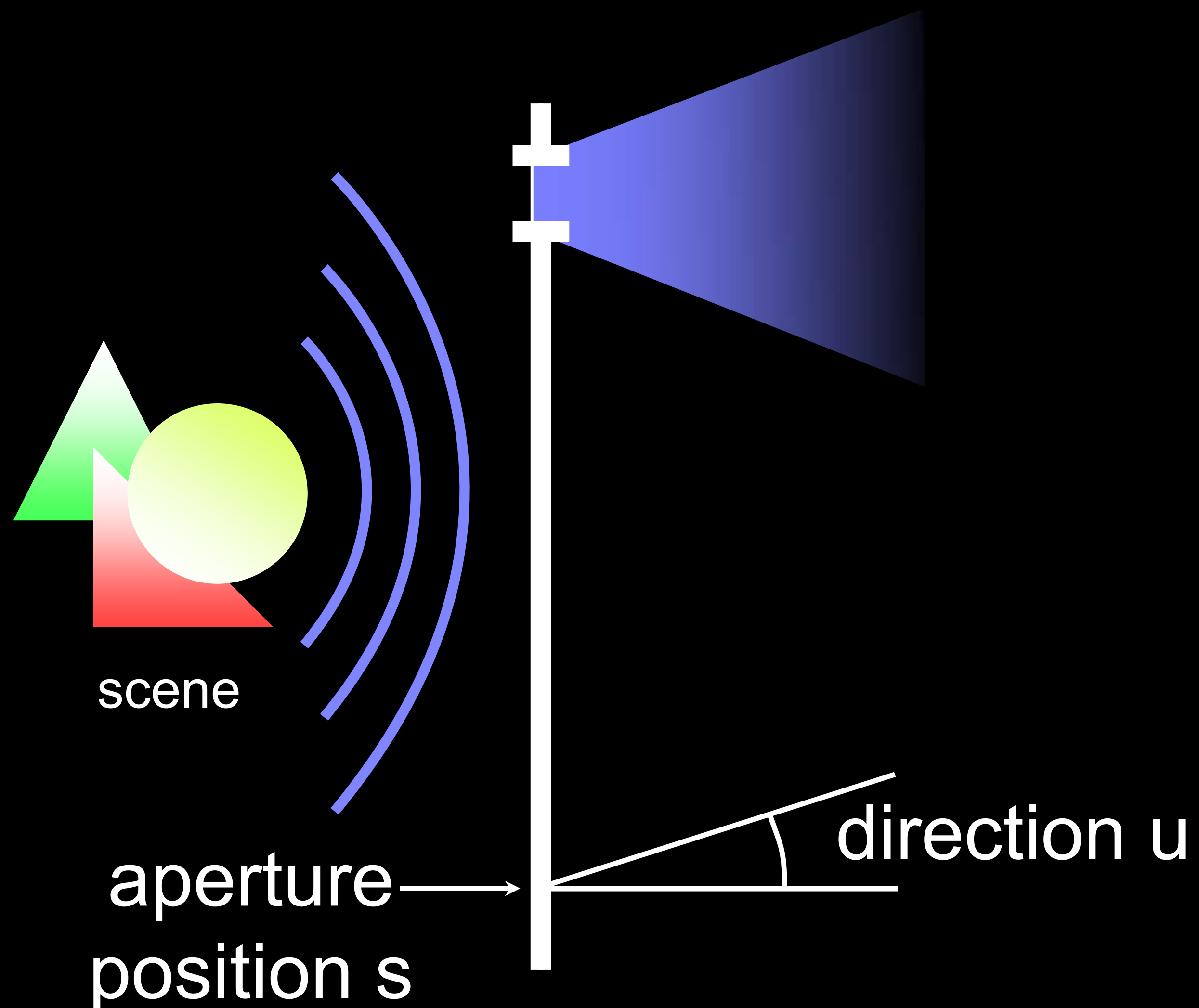
capturing,

and integrating

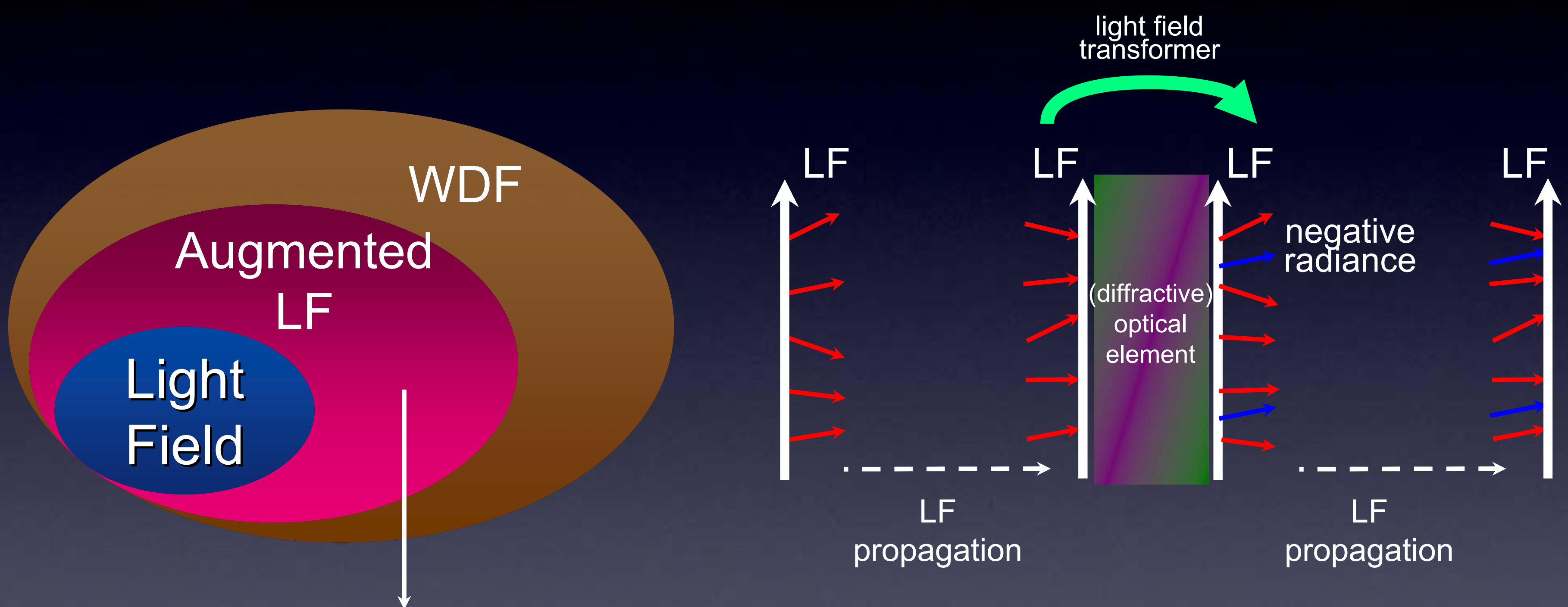
quasi light fields.

(i) Observable Light Field

- move aperture across plane
- look at directional spread
- continuous form of plenoptic camera

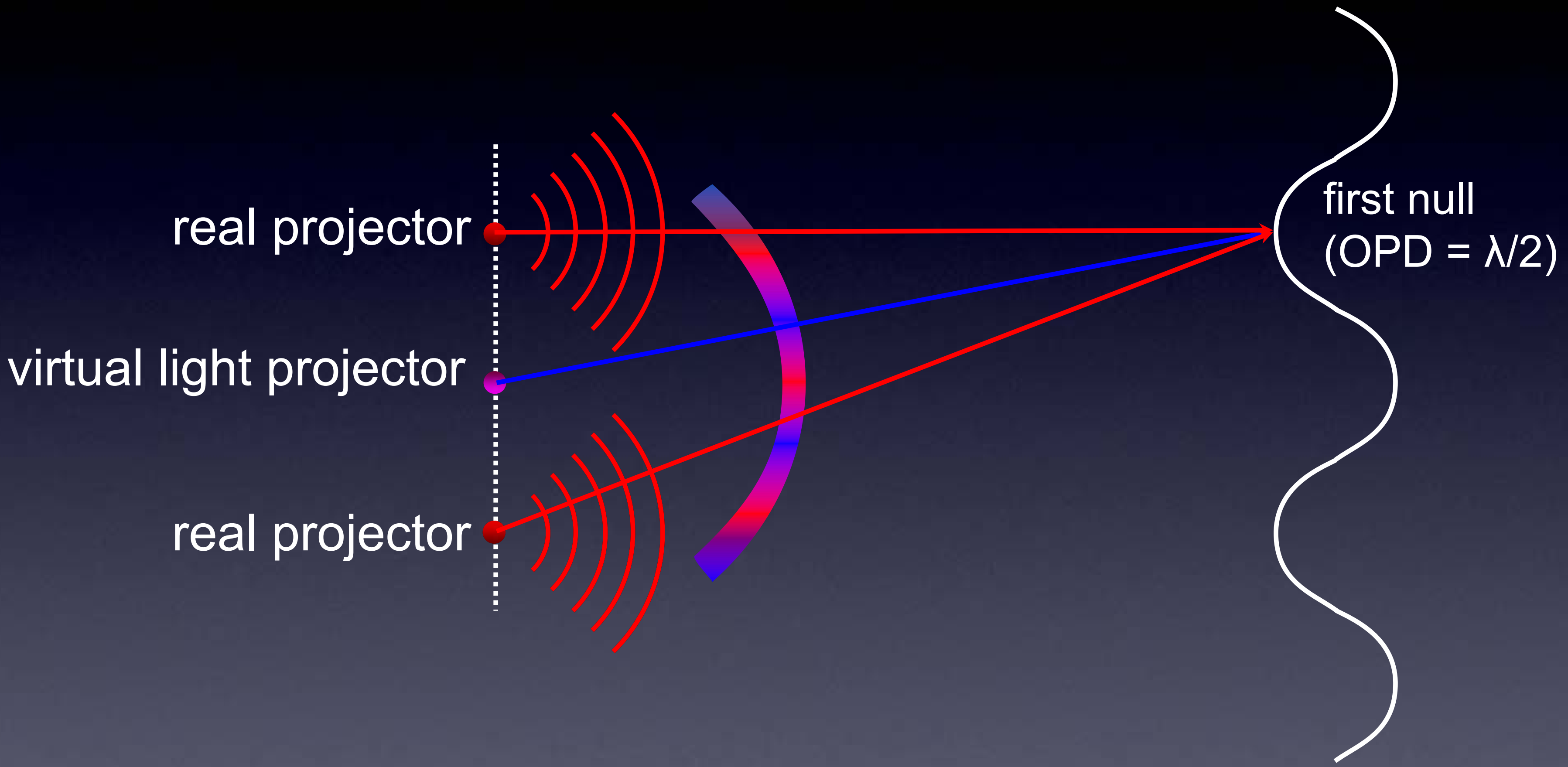


(ii) Augmented Light Field with LF Transformer

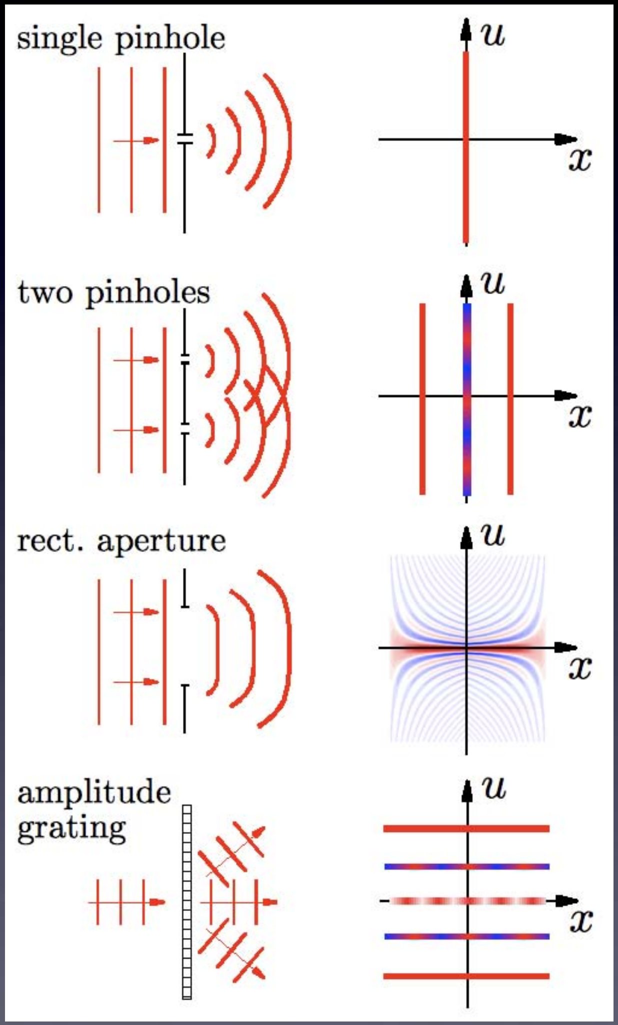


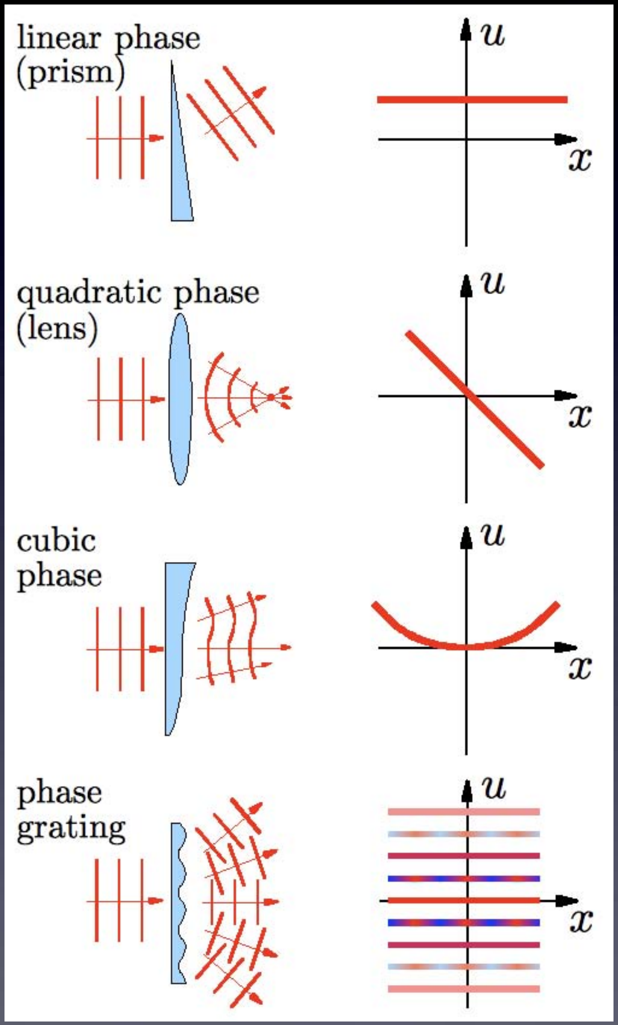
Interaction at the optical elements

Virtual light projector with real valued (possibly <u>negative</u> radiance) along a ray

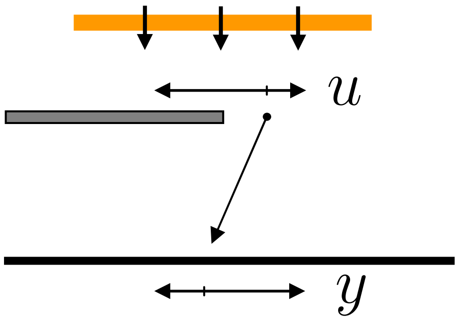


(ii) ALF with LF Transformer





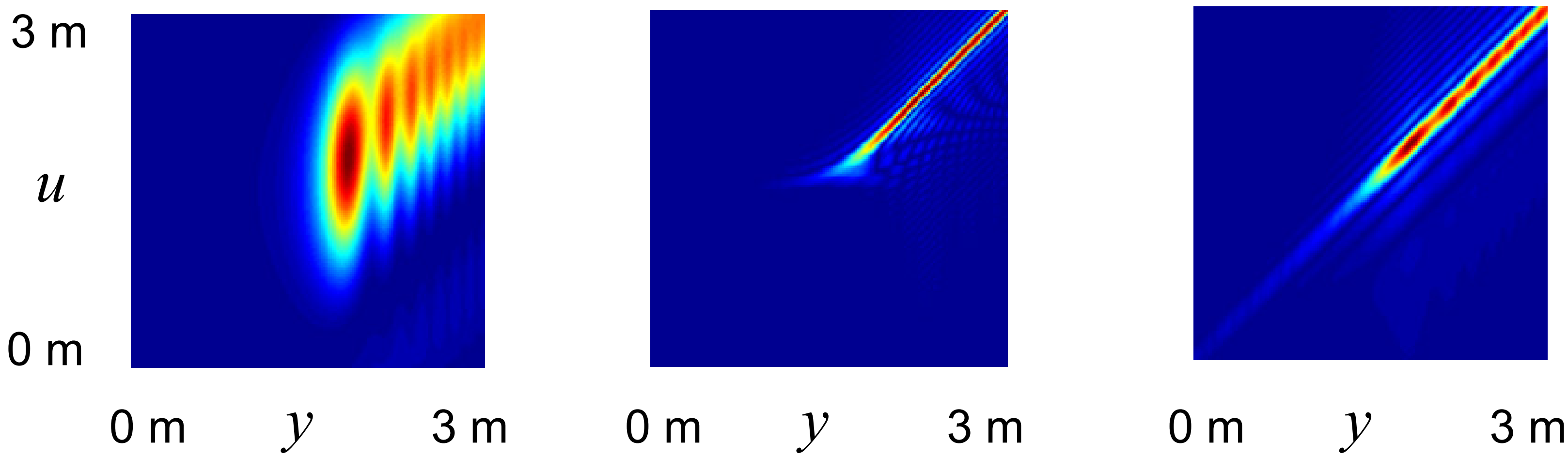
Tradeoff between cross-interference terms and localization



(i) Spectrogram
non-negative
localization

(ii) Wigner
localization
cross terms

(iii) Rihaczek
localization
complex



Property of the Representation

	Constant along rays	Non-negativity	Coherence	Wavelength	Interference Cross term
Traditional LF	always constant	always positive	only incoherent	zero	no
Observable LF	nearly constant	always positive	any coherence state	any	yes
Augmented LF	only in the paraxial region	positive and negative	any	any	yes
WDF	only in the paraxial region	positive and negative	any	any	yes
Rihaczek DF	no; linear drift	complex	any	any	reduced

Benefits & Limitations of the Representation

	Ability to propagate	Modeling wave optics	Simplicity of computation	Adaptability to current pipe line	Near Field	Far Field
Traditional LF	x-shear	no	very simple	high	no	yes
Observable LF	not x-shear	yes	modest	low	yes	yes
Augmented LF	x-shear	yes	modest	high	no	yes
WDF	x-shear	yes	modest	low	yes	yes
Rihaczek DF	x-shear	yes	better than WDF, not as simple as LF	low	no	yes

Motivation

- What is the difference between a hologram and a lenticular screen?
- How they capture ‘phase’ of a wavefront for telescope applications?
- What is ‘wavefront coding’ lens for extended depth of field imaging?

Acknowledgements

- Dartmouth
  - Marcus Testorf,
- MIT
  - Ankit Mohan, Ahmed Kirmani, Jaewon Kim
  - George Barbastathis
- Stanford
  - Marc Levoy, Ren Ng, Andrew Adams
- Adobe
  - Todor Georgiev,
- MERL
  - Ashok Veeraraghavan, Amit Agrawal

Light Fields

Ramesh Raskar

MIT Media Lab

http:// CameraCulture . info/