Proposal for a CVPR 2011 Tutorial

1 Course Title

Light Fields in Computational Photography

2 Type

Advanced, 3 hours

3 Abstract

Computational photography involves optical processing as well as digital image processing. The concepts are often represented via higher dimensional data structures. The ray–based 4D lightfield representation, based on simple 3D geometric principles, has led to a range of new algorithms and applications in Computer Vision and Graphics. They include digital refocusing, depth estimation, synthetic aperture, image stabilization and glare reduction within a camera or using an array of cameras. The lightfield representation is, however, inadequate to describe interactions with diffractive or phase–sensitive optical elements. Fourier optics principles are used to represent wavefronts with additional phase information. This course reviews the current and future directions in exploiting higher dimensional representation of light transport. We hope the course will inspire researchers in computer vision comfortable with ray–based analysis to develop new tools and algorithms based on joint exploration of geometric and wave optics concepts. The notes are aimed at readers familiar with the basics of computer vision and computational photography.

4 Motivation

Computational photography techniques involve a range of concepts in higher dimensional representation for image capture and processing. This course focuses on 4D light fields which are highly suited for analyzing light transport involving optics, illumination, sensors and digital processing. The topics include digital refocusing, depth estimation, synthetic aperture, image stabilization and glare reduction within a camera or using an array of cameras. In addition, newer concepts in using lightfield for wave-effects will also be covered.

5 Target Audience

The course is suitable anyone interested in modern topics in computational photography and their applications in computer vision or graphics.

6 Interest for Computer Vision community

CVPR and other vision conferences now have sessions on computational photography. In addition, there are several papers in active illumination and optical processing. The CVPR workshops for beyond visible spectrum and computer vision for HCI also have overlapping interests. With Xbox Kinect devices that will provide real time 3D information, there is growing interest in higher dimensional capture and processing.

7 Topics

Course syllabus

(Please see Slides for a sample of the material)

1. Introduction to Light Fields in Computer Vision (Raskar, 10 mins)
    a. Examples: Defocus, Multi-baseline stereo and Visual Hull
2. Light Fields and Computational Photography (Raskar, 35 mins)
    a. Scalar versus Vector light fields
    b. Radiance fields versus Irradiance fields
    c. Representations and Parameterizations
    d. Higher-dimensional Fields: BRDFs, BSSRDFs, Transport Matrices
    e. Line space dualities, Fourier representation
    f. Vision algorithms interpreted as operations on Light Fields
3. Light Field Propagation and Scene Interaction (Horstmeyer,, 35 mins)
    a. Capturing and Analyzing Light Fields
    b. Shield Fields and Visual Hulls
    c. Fourier Domain Applications of Light Fields
    d. Relationship between Rays and Wavefronts in Light Fields
4. Q and A (10 mins)
5. Wavefront Representation in Computer Vision and Imaging (Horstmeyer, 45 mins)
    a. Introduction to Wigner distribution function
    b. Light Fields upgraded using Wigner distribution function
    c. Propagation, Attenuation, Scattering, Diffraction and Holography
6. Applications in Computer vision and Imaging (Raskar, 35 mins)
7. Q and A (10 mins)

8 Relationship to previous short courses/tutorials, if any

2009 CVPR: This course presented by Raskar, Oh, Zhang two years ago. Please see evaluation and recommendation by 2009 Course organizer, Yanxi Liu. The course has generated a lot of interest. See the Wiki for the course at http://scripts.mit.edu/~raskar/lightfields/

2010 CVPRP: Coded Computational Photography was presented by Narasimhan, Agrawal, Mohan. Our course will emphasize the theory and application of higher dimensional representation.

9 Instructors' bios:

Ramesh Raskar

Ramesh Raskar is an Associate Professor at the MIT Media Lab and heads the Camera Culture research group. The group focuses on creating a new class for imaging platforms to better capture and share the visual experience. This research involves developing novel cameras with unusual optical elements, programmable illumination, digital wavelength control, and femtosecond analysis of light transport, as well as tools to decompose pixels into perceptually meaningful components. Raskar's research also involves creating a universal platform for the sharing and consumption of visual media.
Raskar received his PhD from the University of North Carolina at Chapel Hill, where he introduced "Shader Lamps," a novel method for seamlessly merging synthetic elements into the real world using projector-camera based spatial augmented reality. In 2004, Raskar received the TR100 Award from Technology Review, which recognizes top young innovators under the age of 35, and in 2003, the Global Indus Technovator Award, instituted at MIT to recognize the top 20 Indian technology innovators

worldwide. He holds 35 US patents and has received four Mitsubishi Electric Invention Awards. He is currently co-authoring, with Jack Tumblin, a book on computational photography.

Roarke Horstmeyer

Roarke Horstmeyer is currently a graduate student with the camera culture group at the MIT Media Lab. His research interests fall into the broad category of computational imaging and display, with a focus on developing novel models of light propagation. His interest in the intersection of wave optics with ray optics has led to several publications on the subject. Before joining the Media Lab, he performed research in optics at the MITRE Corporation and with the Duke Imaging and Spectroscopy Program. He received a BS degree in Physics from Duke University.

Contact Information
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http://web.media.mit.edu/~roarkeh/

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10 Planned Material

Please see sample material on the website for a similar course two years ago.
http://scripts.mit.edu/~raskar/lightfields/
The courses notes in form of slides and text notes will be made available to attendees via this continuously updated website.

Wed. Feb 17, 2010

Dear CVPR Course Reviewer

Re: CVPR 2009 Tutorial on 'Light Field: Present and Future' by Raskar et al.

I was the tutorials chair for CVPR 2009 where I invited Ramesh Raskar to present a curated course. I am able to report that this course was very well attended (fulfilled two connected rooms), received, and was also one of the most popular topics. We collected informal feedback from the audience and the speakers were given high scores for presentation.

The course was at a good introductory level. The details were sufficient but at a higher abstraction level to maintain audience interest. I dropped by during their presentation and can confirm from my own impression that the course was both interesting and well delivered.

Given the high degree of interest in light fields and wave phenomenon in computational photography and rendering, this is a relevant topic at CVPR and computer graphics events. I would have no hesitation in recommending this tutorial again for a future CVPR event. If you need more information in making a decision, please feel free to email me.

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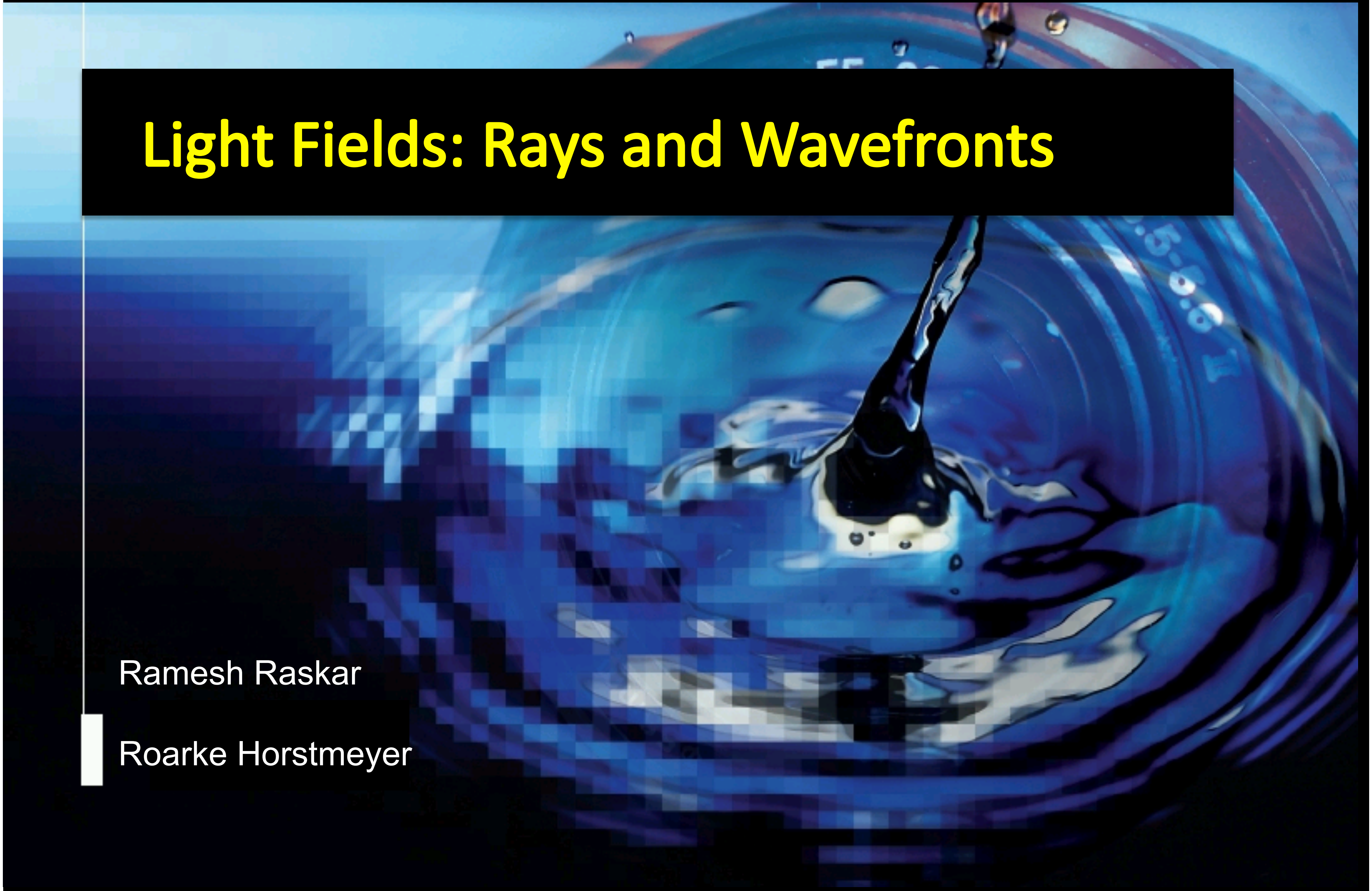
CVPR 2011 Tutorial



Light Fields: Rays and Wavefronts

Ramesh Raskar

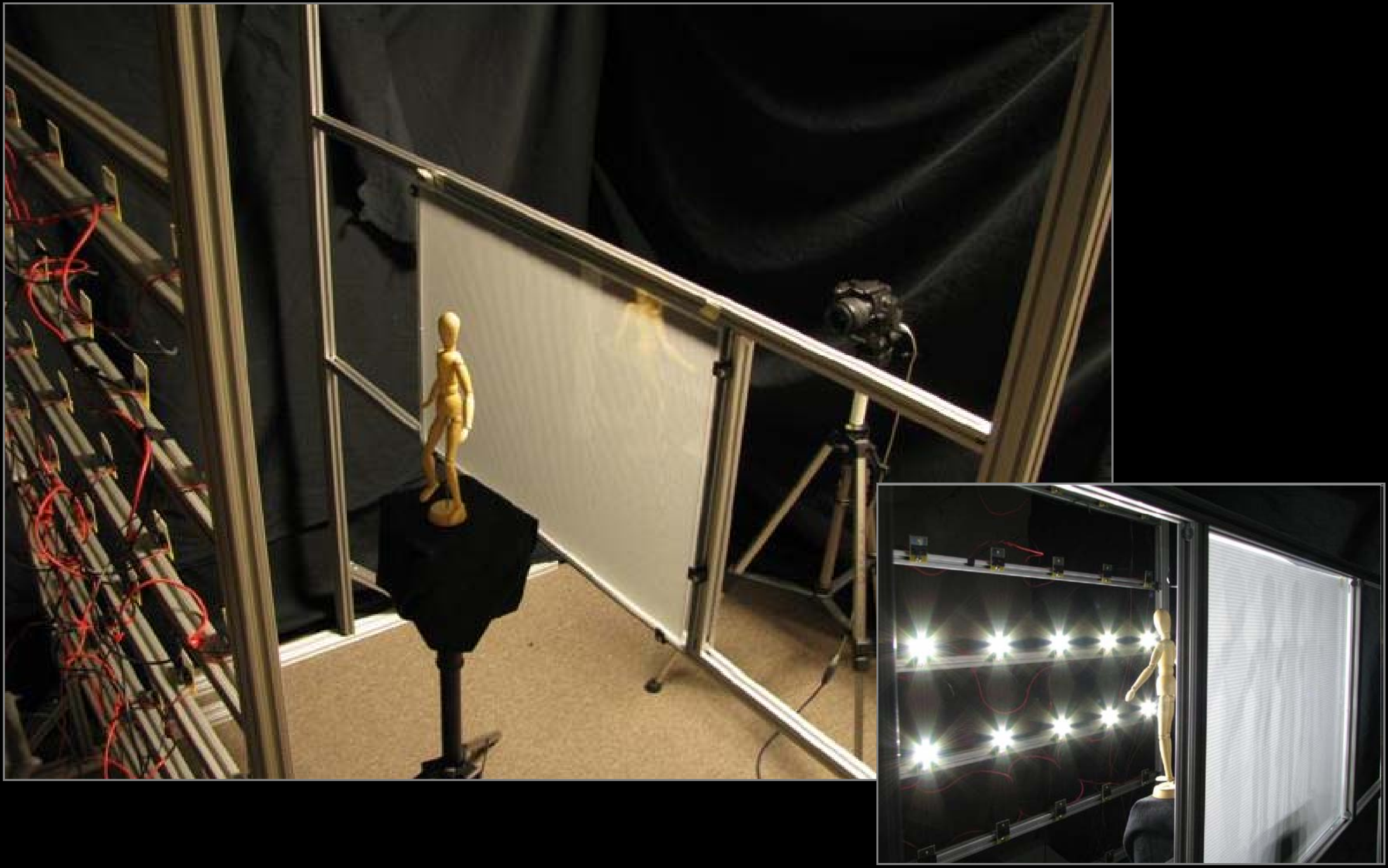
Roarke Horstmeyer

Light Fields

Outline

- Light Fields in Computer Vision
- Light Fields and Computational Photography
- Light Field Propagation and Scene Interaction
- Representation in Computer Vision and Imaging

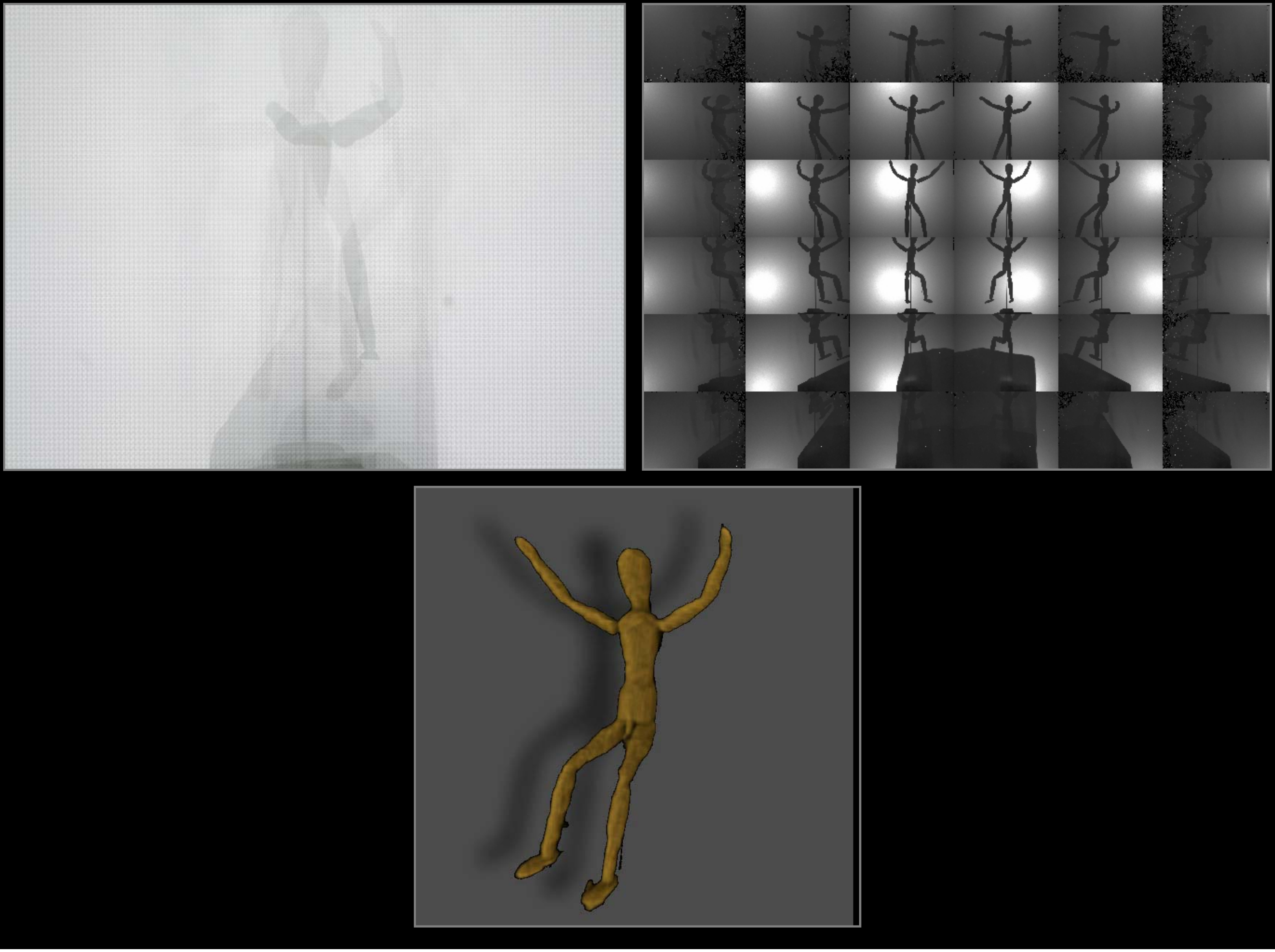
Single shot visual hull using Light Fields



Lanman, Raskar, agrawal, Tumblin, 2008

Single shot Visual Hulls:

Shield Field: Simultaneous Projections using Masks

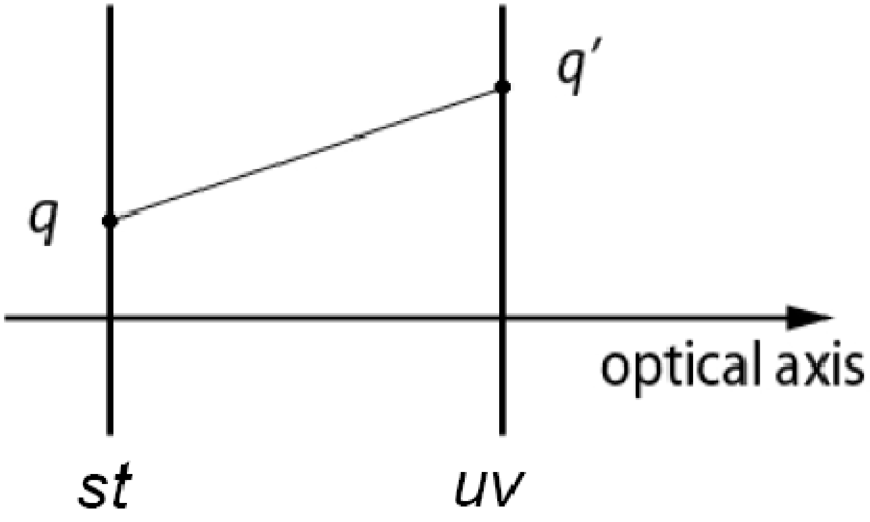


Light Fields

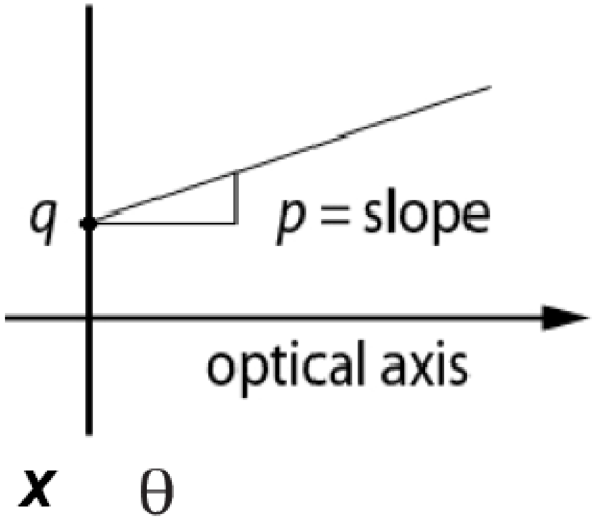
- What are they?
- What are the properties?
- How to capture?
- What are the applications?

Two parameterization of rays

“Two plane”



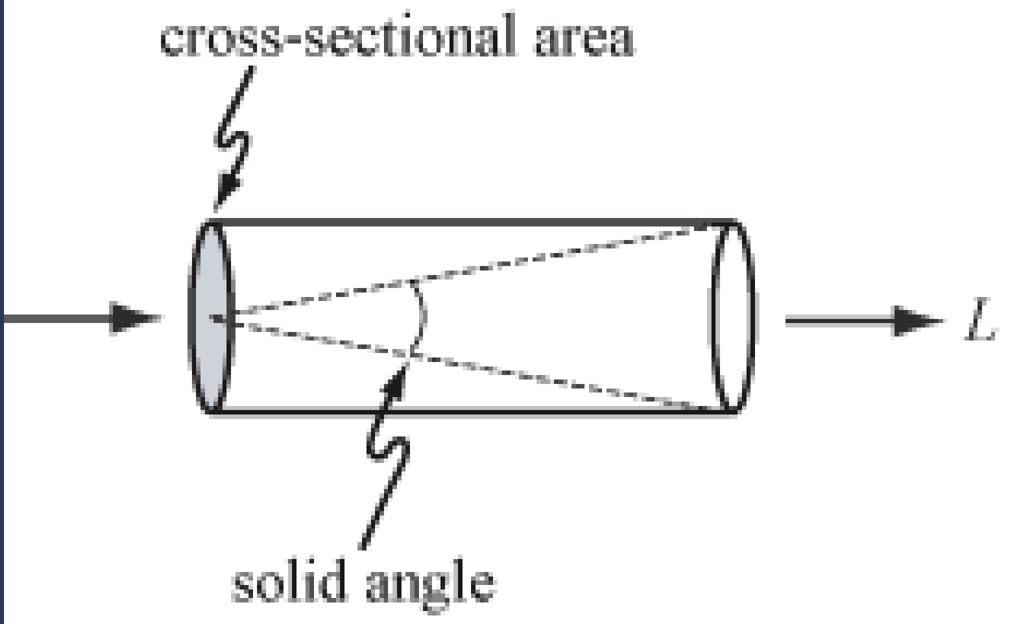
“Location-angle”



Express radiance as ***r(q,p)***

Slides by Todor Georgiev

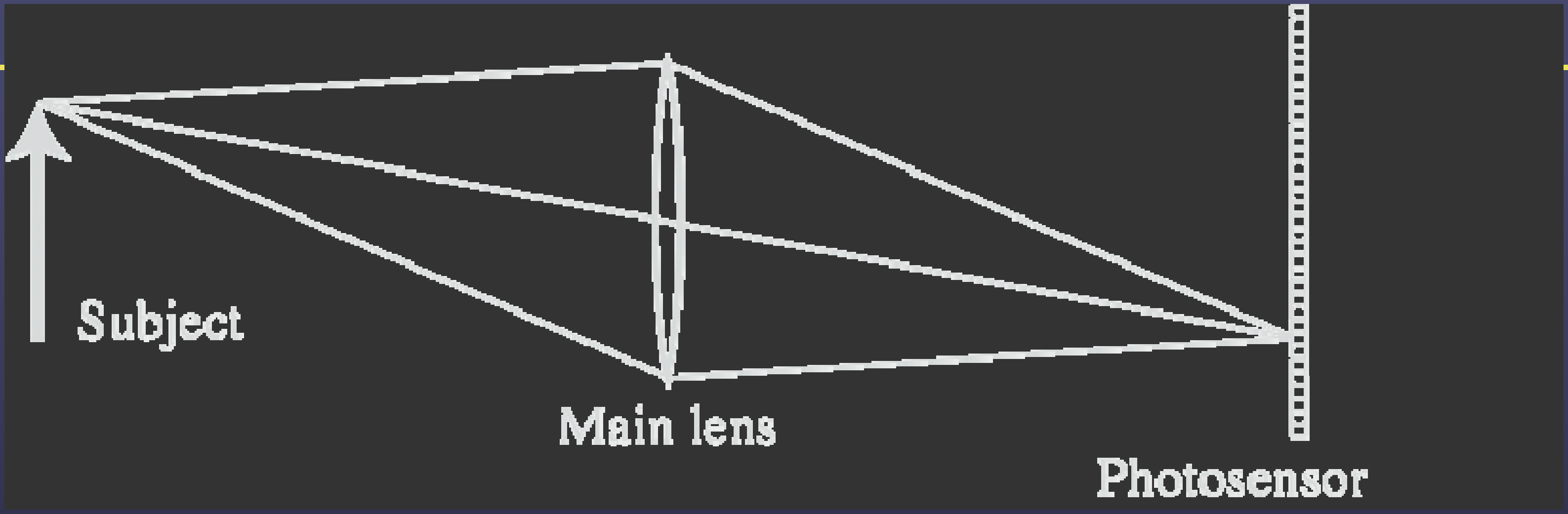
Radiance ‘along a ray’



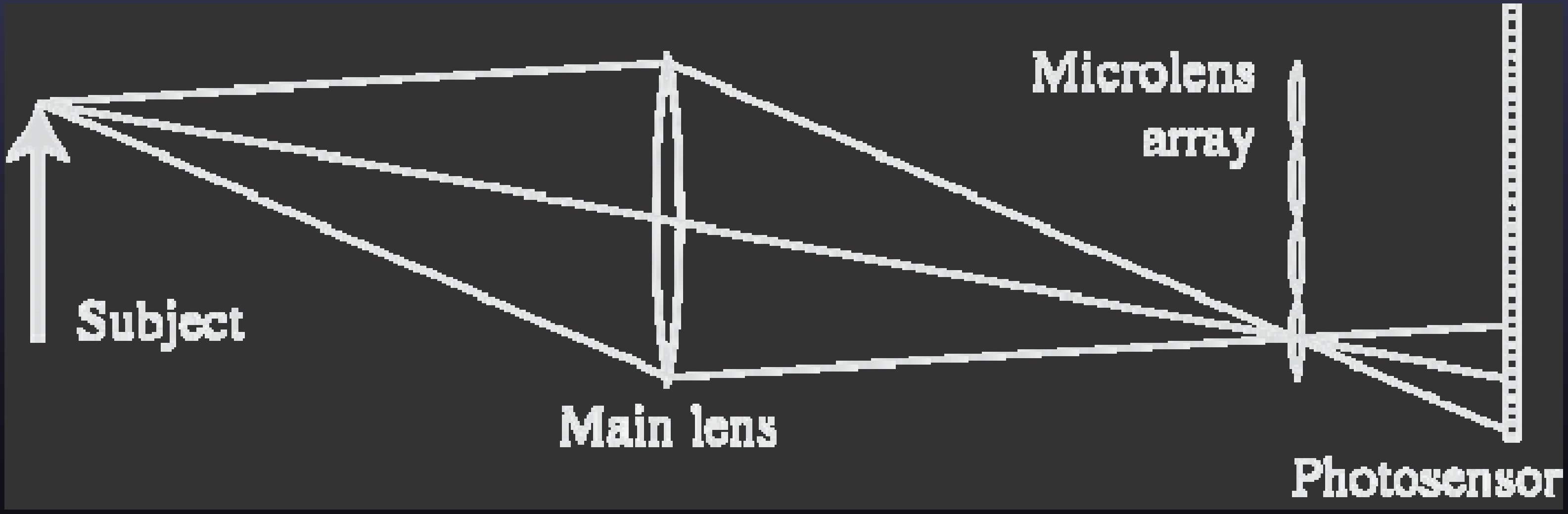
Radiance *L* along a ray can be thought of as the amount of light traveling along all possible straight lines through a tube whose size is determined by its solid angle and cross-sectional area.

measured in watts (W) per steradian (sr) per meter squared (m2).

Light Field Inside a Camera

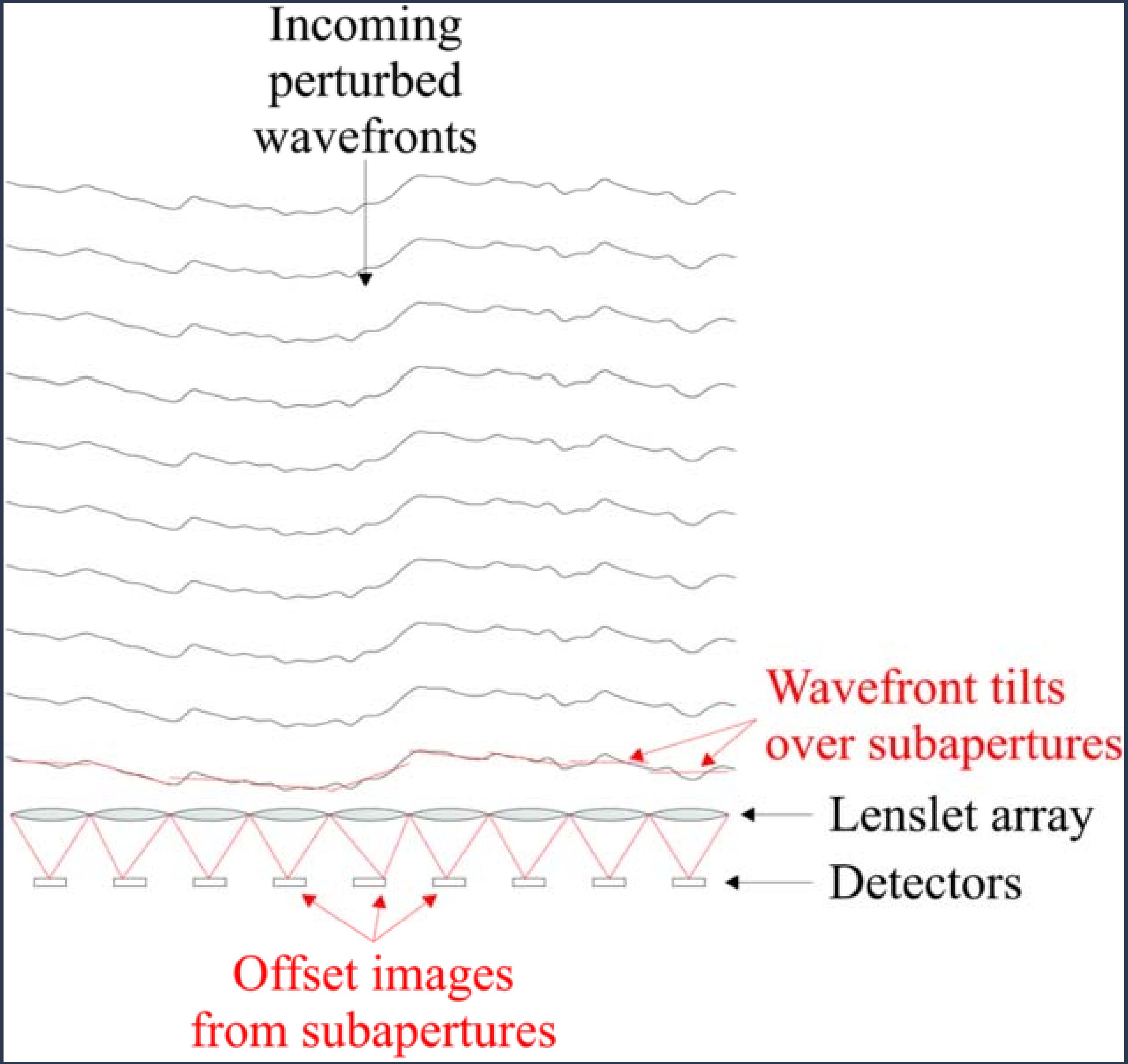


Lenslet-based Light Field camera



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

Shack Hartmann wavefront sensor (commonly used in Adaptive optics)



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

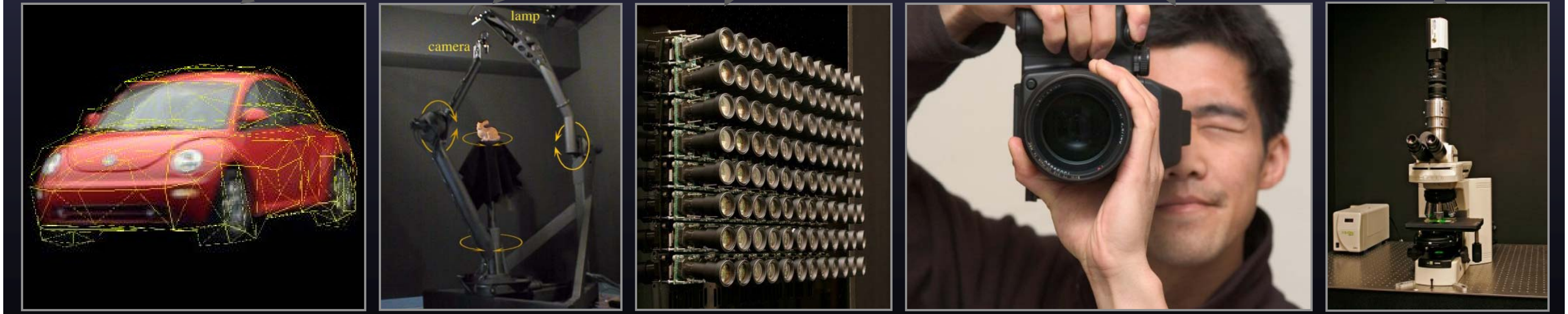
Devices for recording light fields
(using geometrical optics)

big
baseline

↕

small
baseline

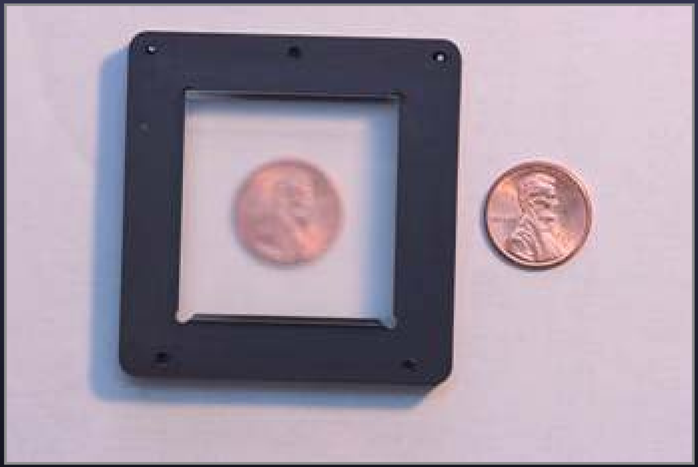
	• handheld camera	[Buehler 2001]
	• camera gantry	[Stanford 2002]
→	• array of cameras	[Wilburn 2005]
→	• plenoptic camera	[Ng 2005]
→	• light field microscope	[Levoy 2006]



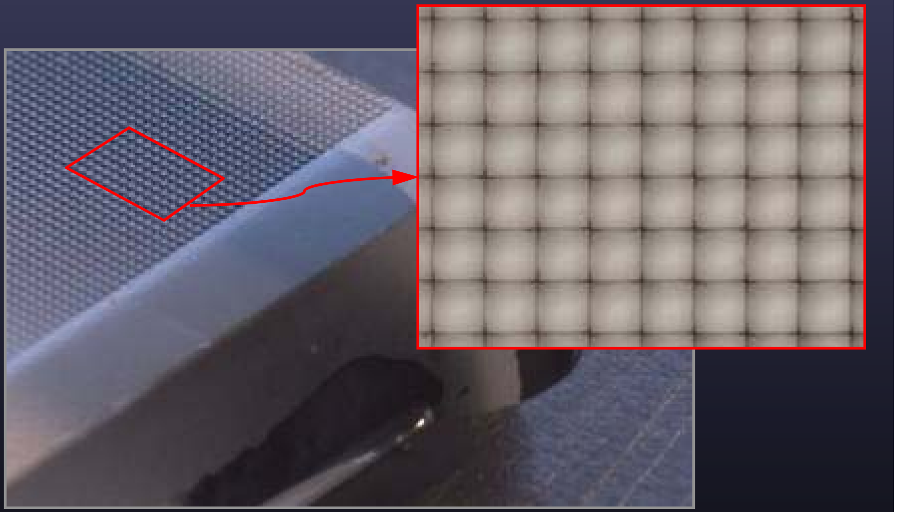
Stanford Plenoptic Camera [Ng et al 2005]

Contax medium format camera

Kodak 16-megapixel sensor



Adaptive Optics microlens array



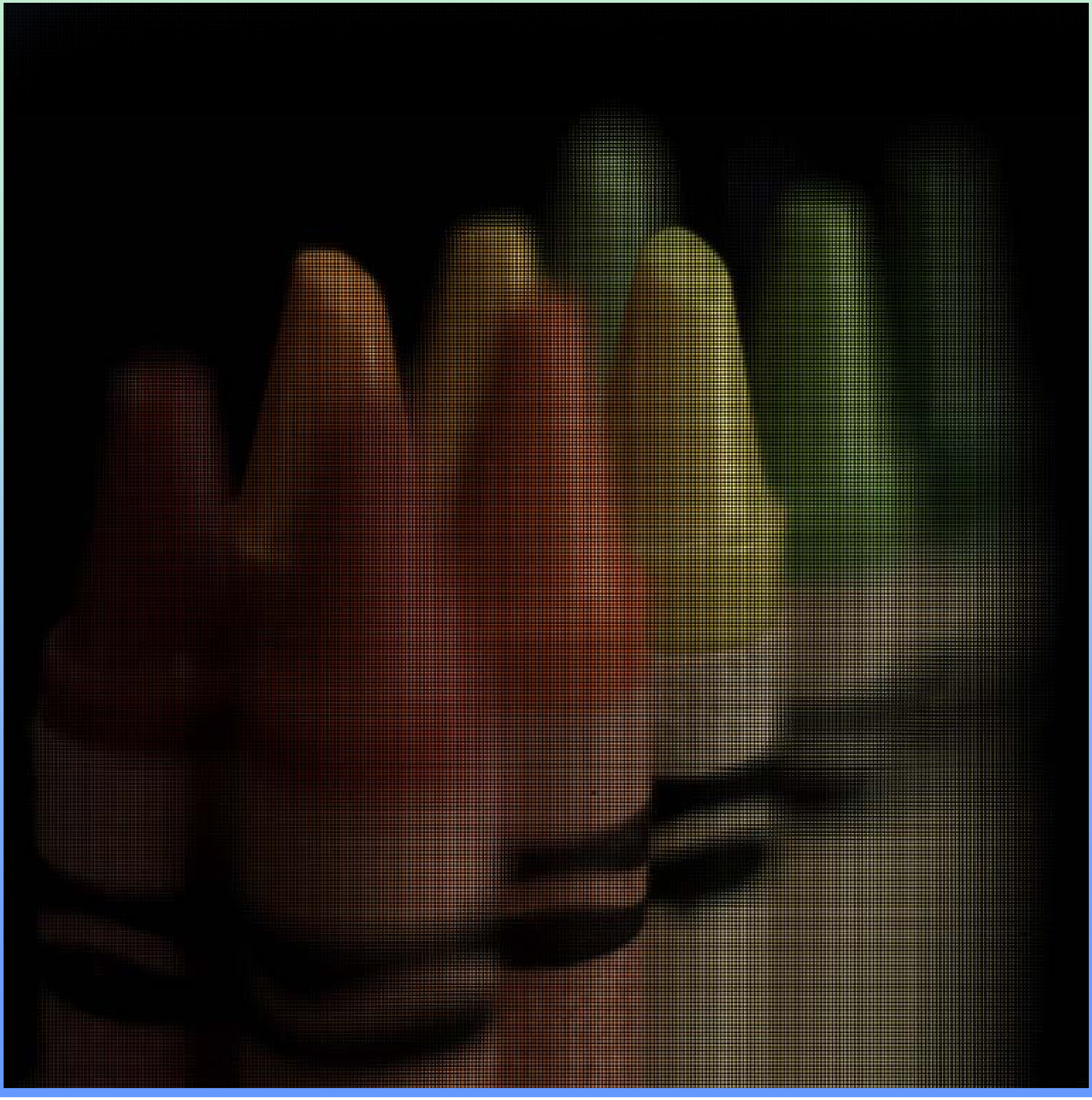
125μ square-sided microlenses

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

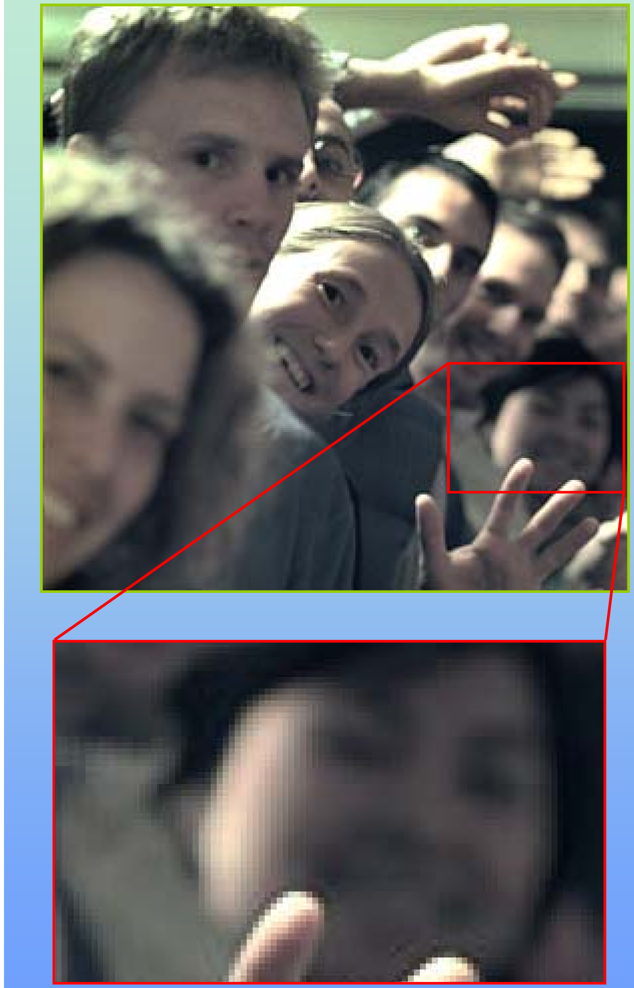
Digital Refocusing

[Ng et al 2005]

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



Extending the depth of field

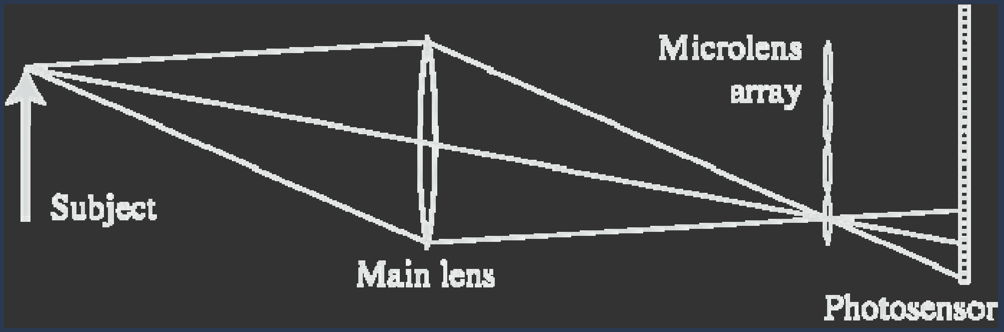


conventional photograph,
main lens at f / 4

conventional photograph,
main lens at f / 22

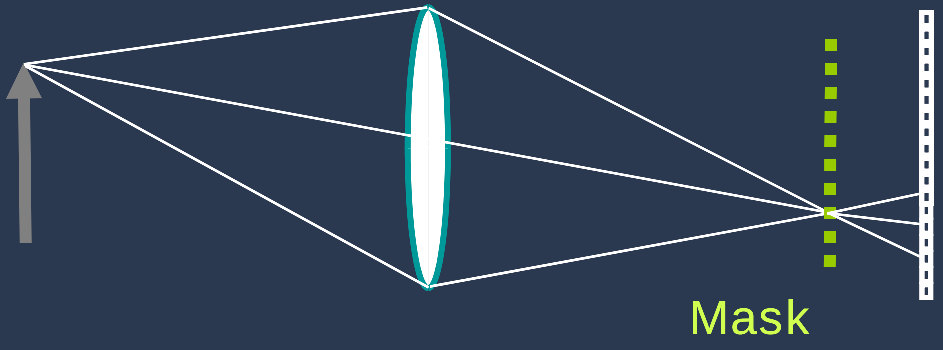
light field, main lens at f / 4,
after all-focus algorithm
[Agarwala 2004]

Single Shot Light Field Cameras



Adelson and Wang, 1992, Ng et al. 2005

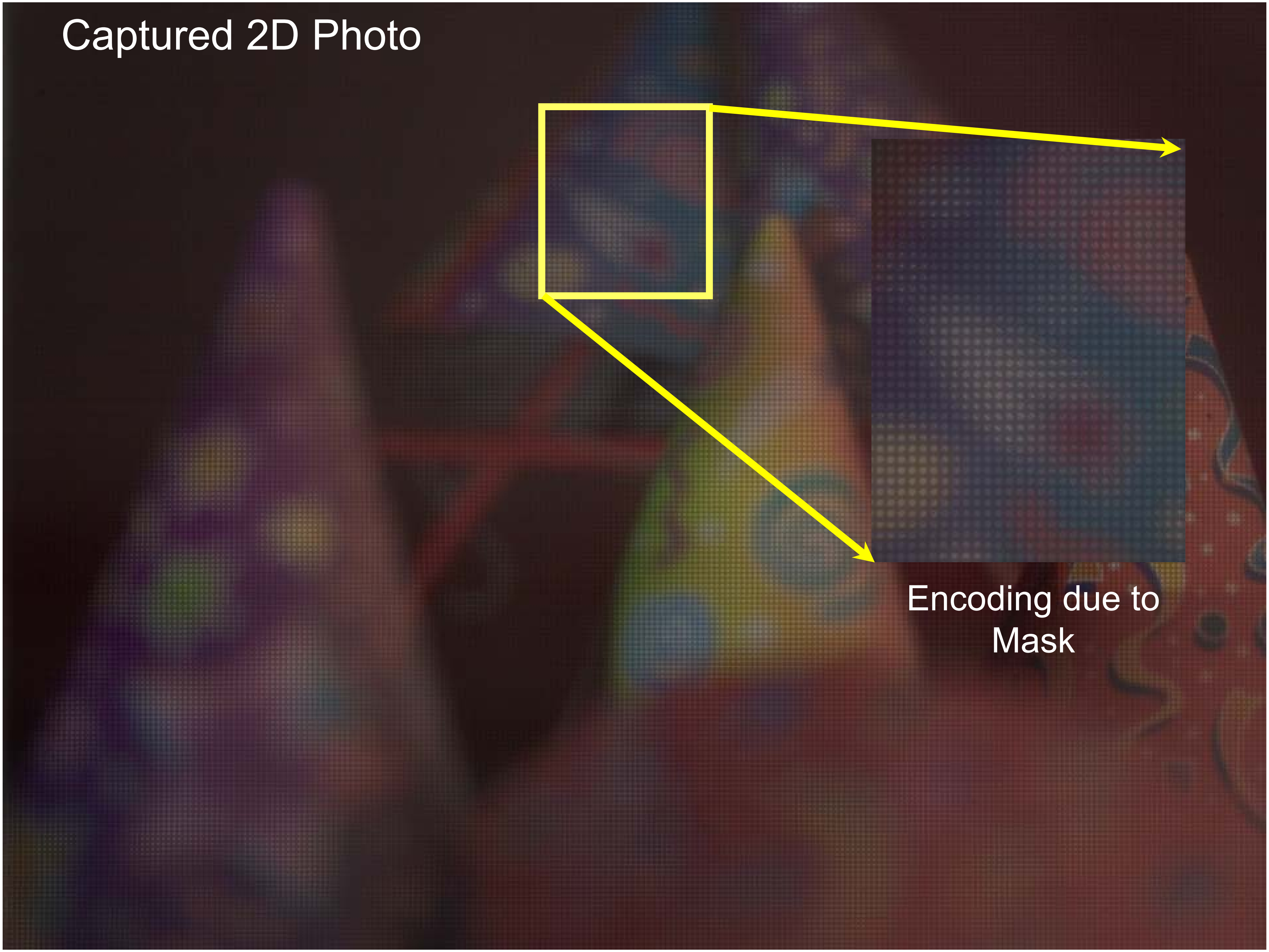
Using Lenslets, Ng et al. 2005



Kanolt 1933, Veeraraghavan et al. 2007

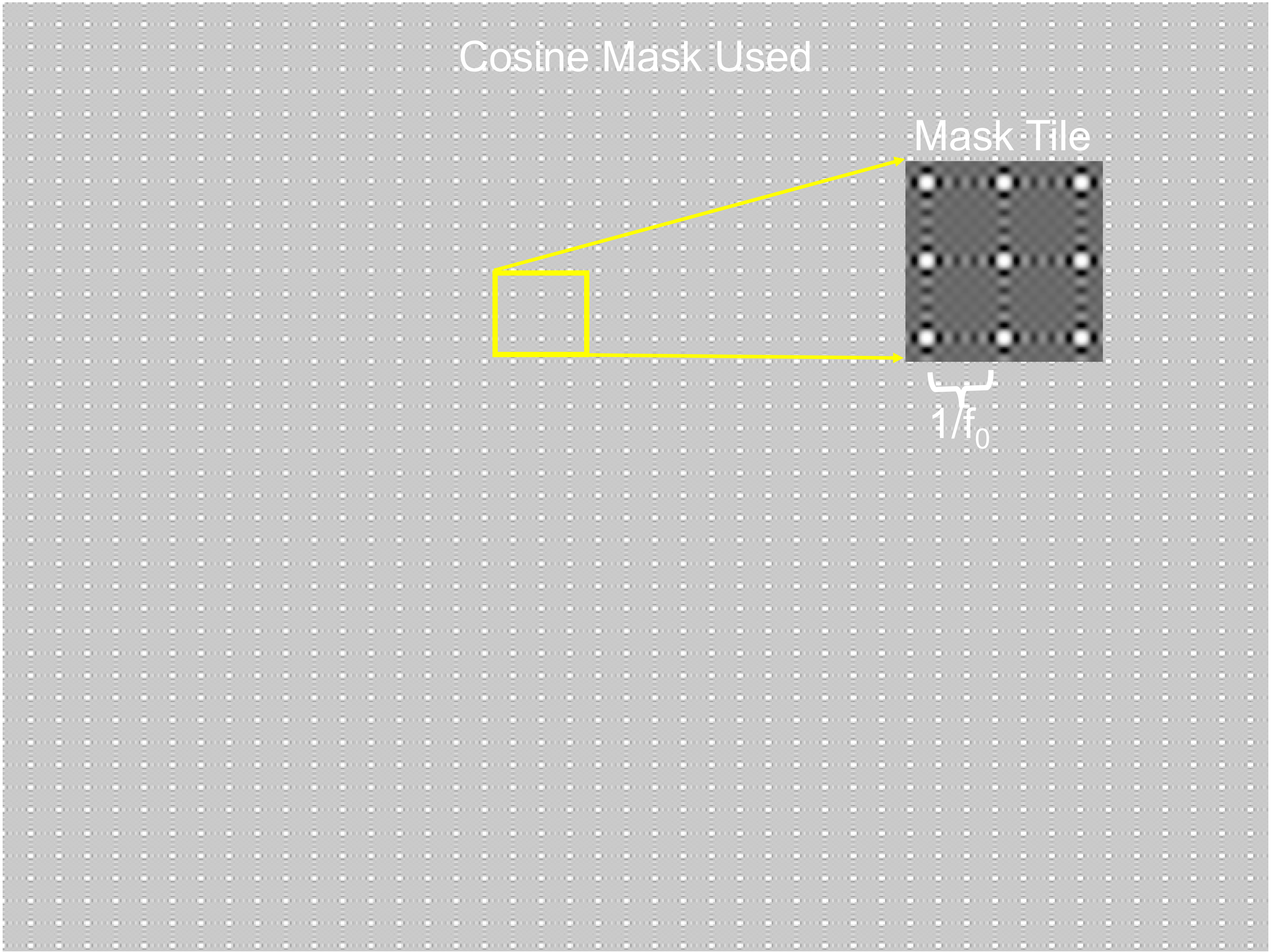
Using Mask

Captured 2D Photo

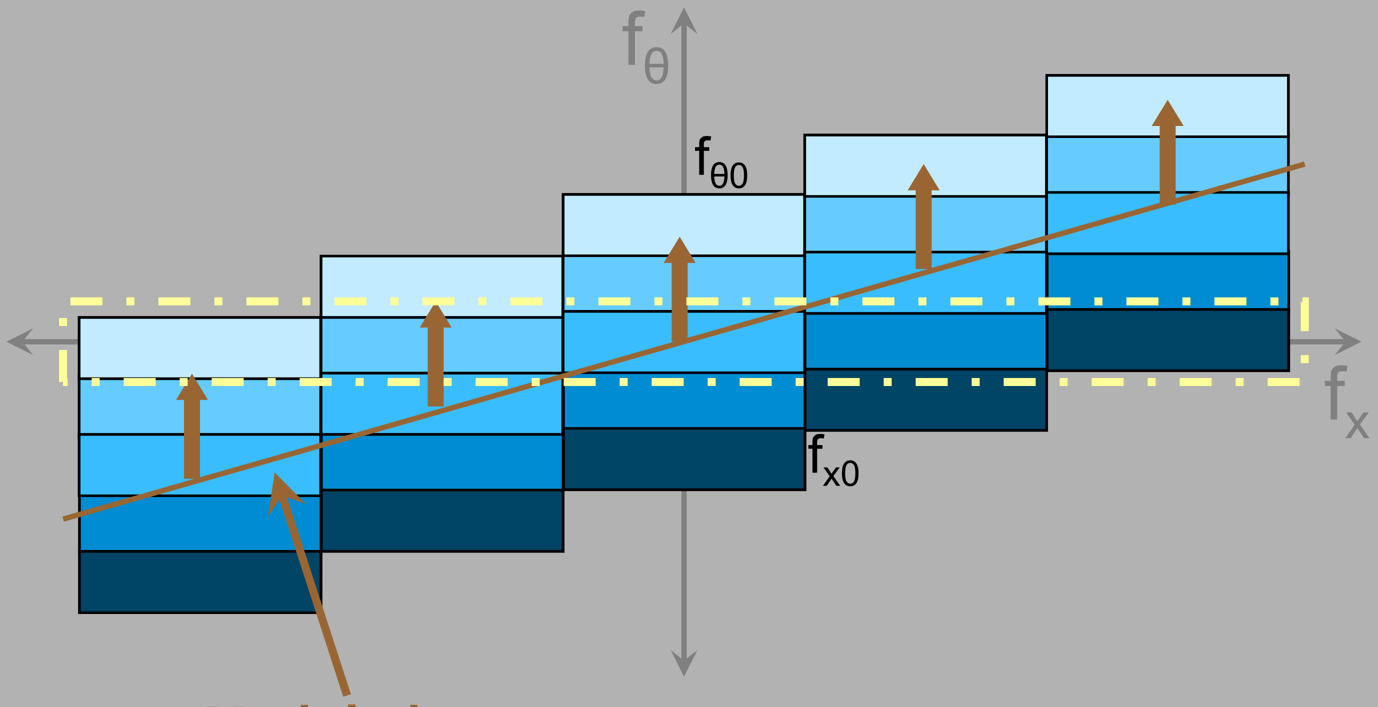


Encoding due to Mask

Cosine Mask Used



Sensor Slice captures entire Light Field



Modulation Function

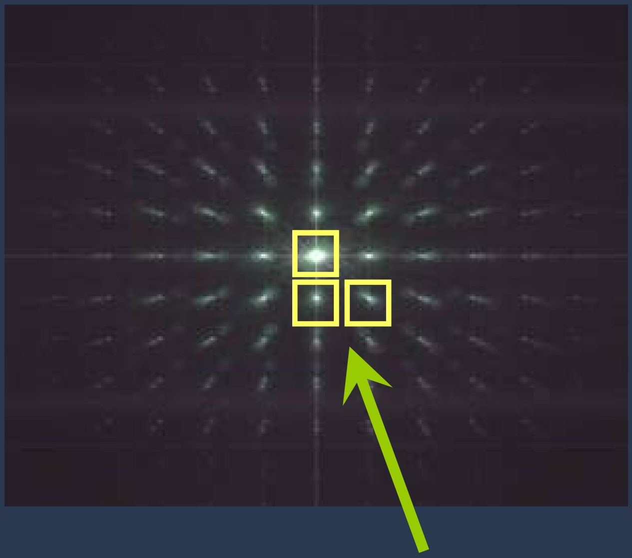
Modulated Light Field

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

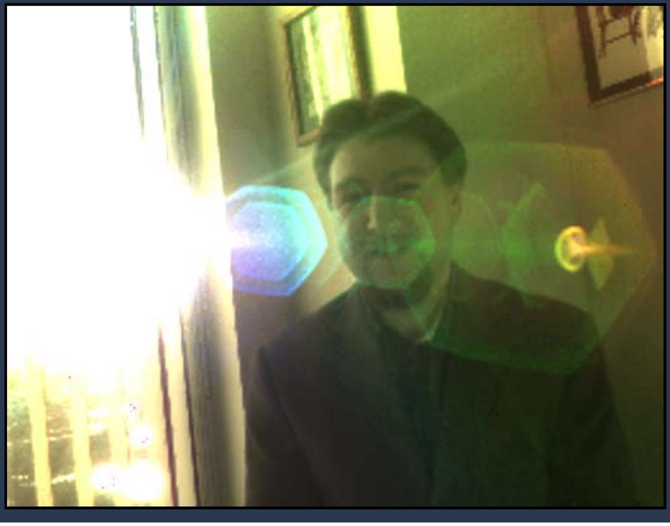
4D Light Field
200*200*9*9

Lens Glare Reduction

[Raskar, Agrawal, Wilson, Veeraraghavan SIGGRAPH 2008]

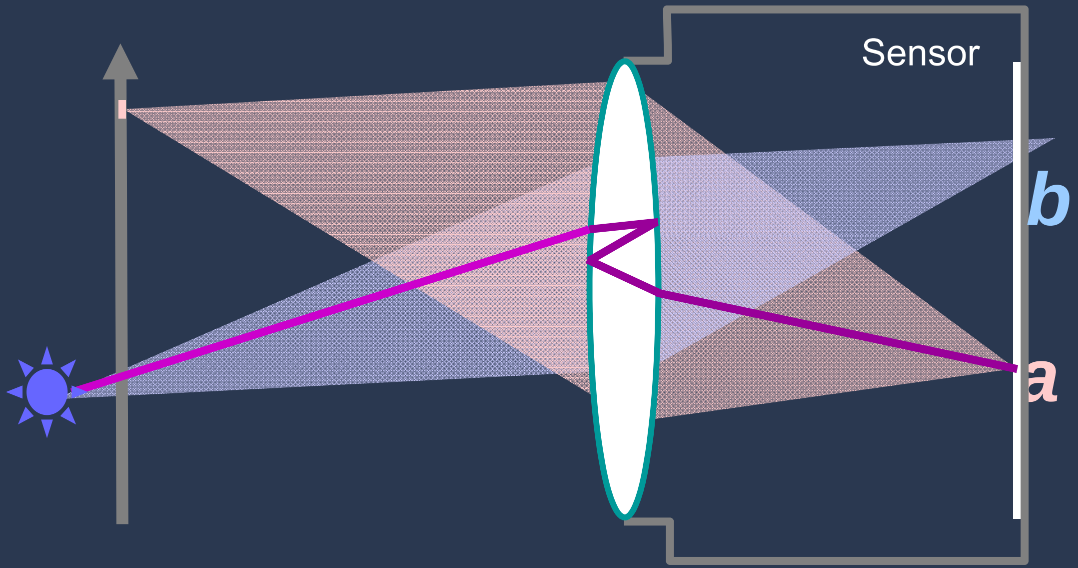
reducing

enhancing



Key Idea

- Lens Glare manifests as low frequency in 2D Image
- But Glare is highly view dependent
  - manifests as outliers in 4D ray-space
- Reducing Glare == Remove outliers among rays



Light Field Applications

- Geometric
  - Estimate depth
  - Create new views
  - Synthetic aperture (Foreground/background)
  - Estimate Shape (visual hull or deconvolution based)
  - Insert synthetic objects

- Lens effects
  - Refocussing
  - New aperture setting
  - All in focus image

- Statistical
  - Lens glare
  - Specular-diffuse separation

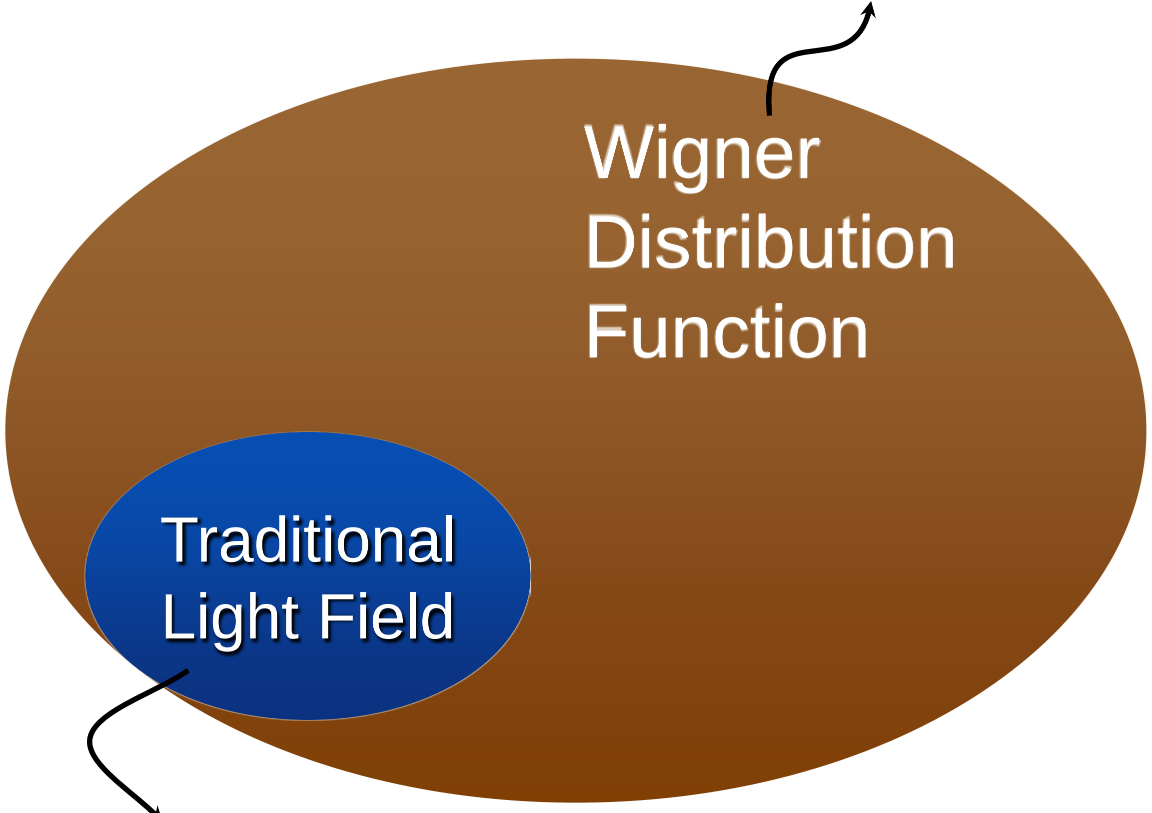
- Note:
  - In many cased, LF not required, 4D sampling sufficient
  - Similar higher-dimensional analysis also works for motion, wavelength, displays

Wavefront Representation in Computer Vision

- Introduction to Wigner distribution function
- Light Fields upgraded using Wigner distribution function
- Phenomenon
  - Propagation, Attenuation, Scattering, Diffraction and Holography
- Applications in Computer vision and Imaging

Introduction

rigorous but cumbersome
wave optics based



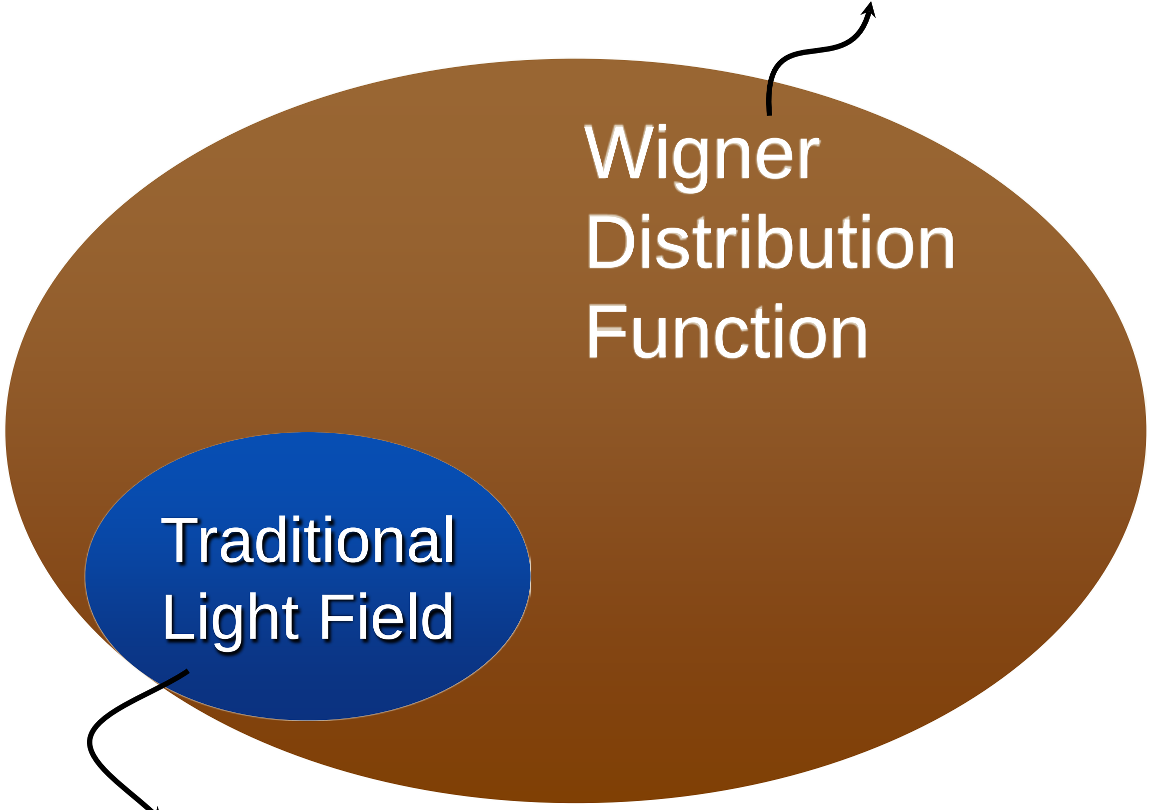
Wigner
Distribution
Function

Traditional
Light Field

ray optics based
simple and powerful
limited in diffraction & interference

Introduction

rigorous but cumbersome
wave optics based



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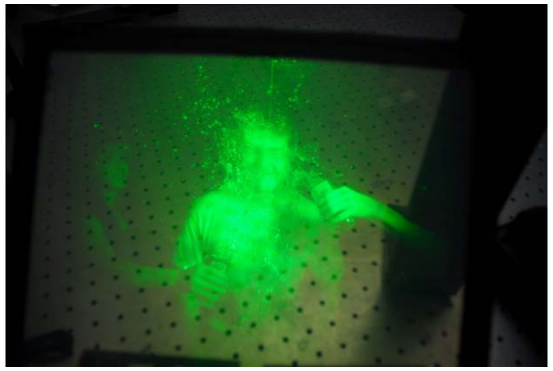
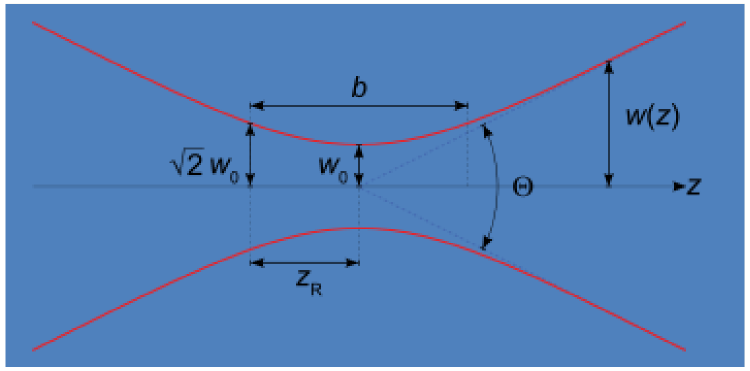
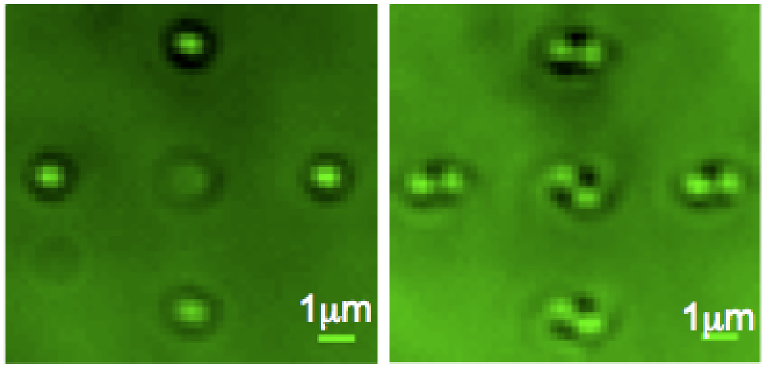


holograms

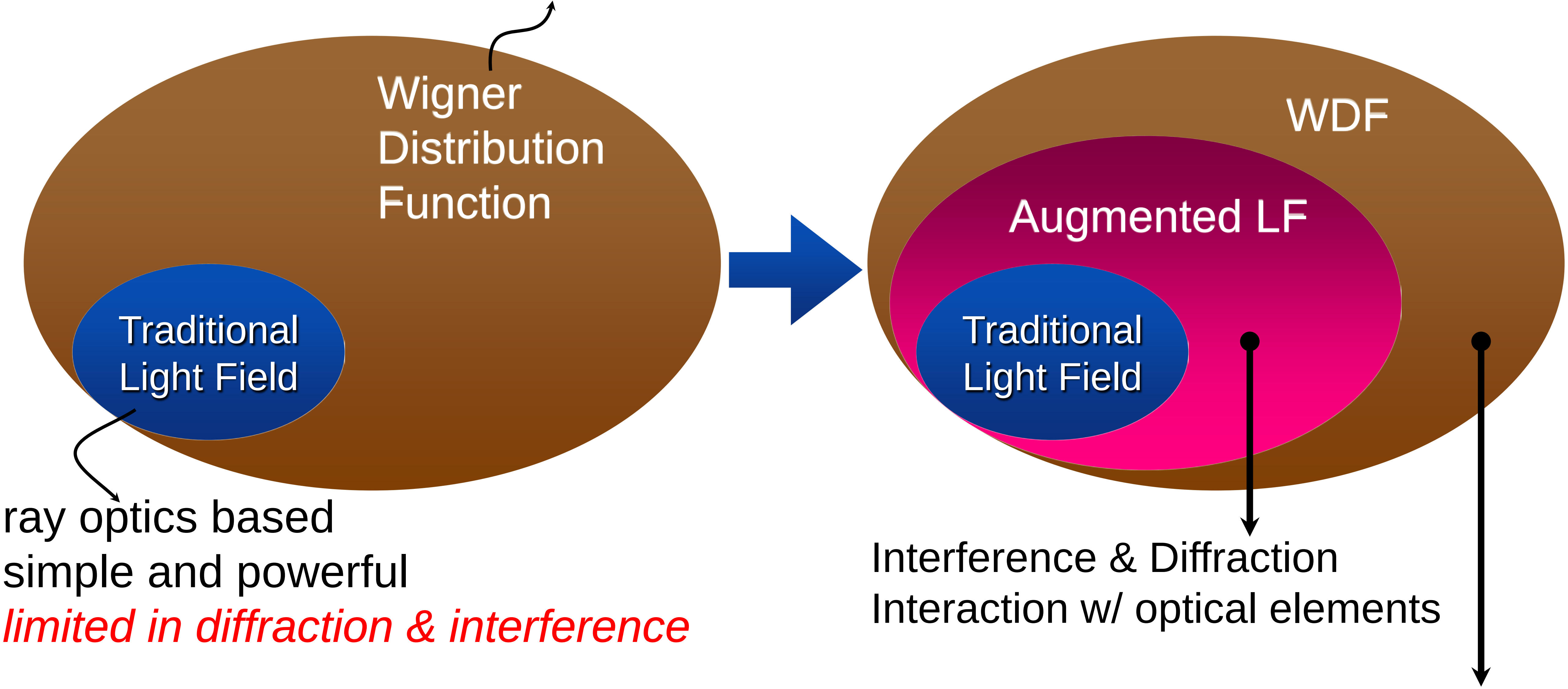


beam shaping



rotational PSF

Augmented LF



rigorous but cumbersome
wave optics based

Wigner
Distribution
Function

Traditional
Light Field

ray optics based
simple and powerful
limited in diffraction & interference

WDF

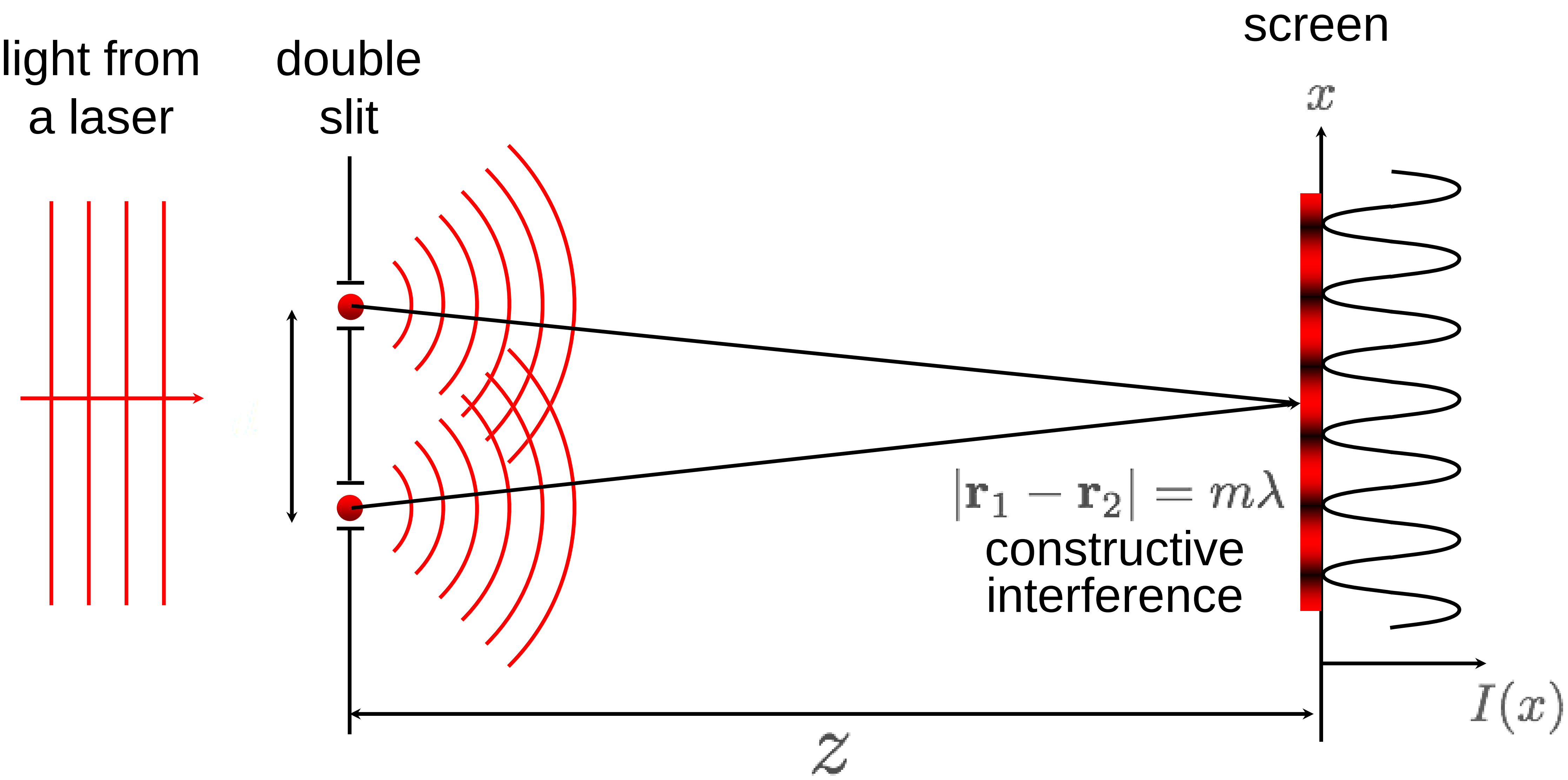
Augmented LF

Traditional
Light Field

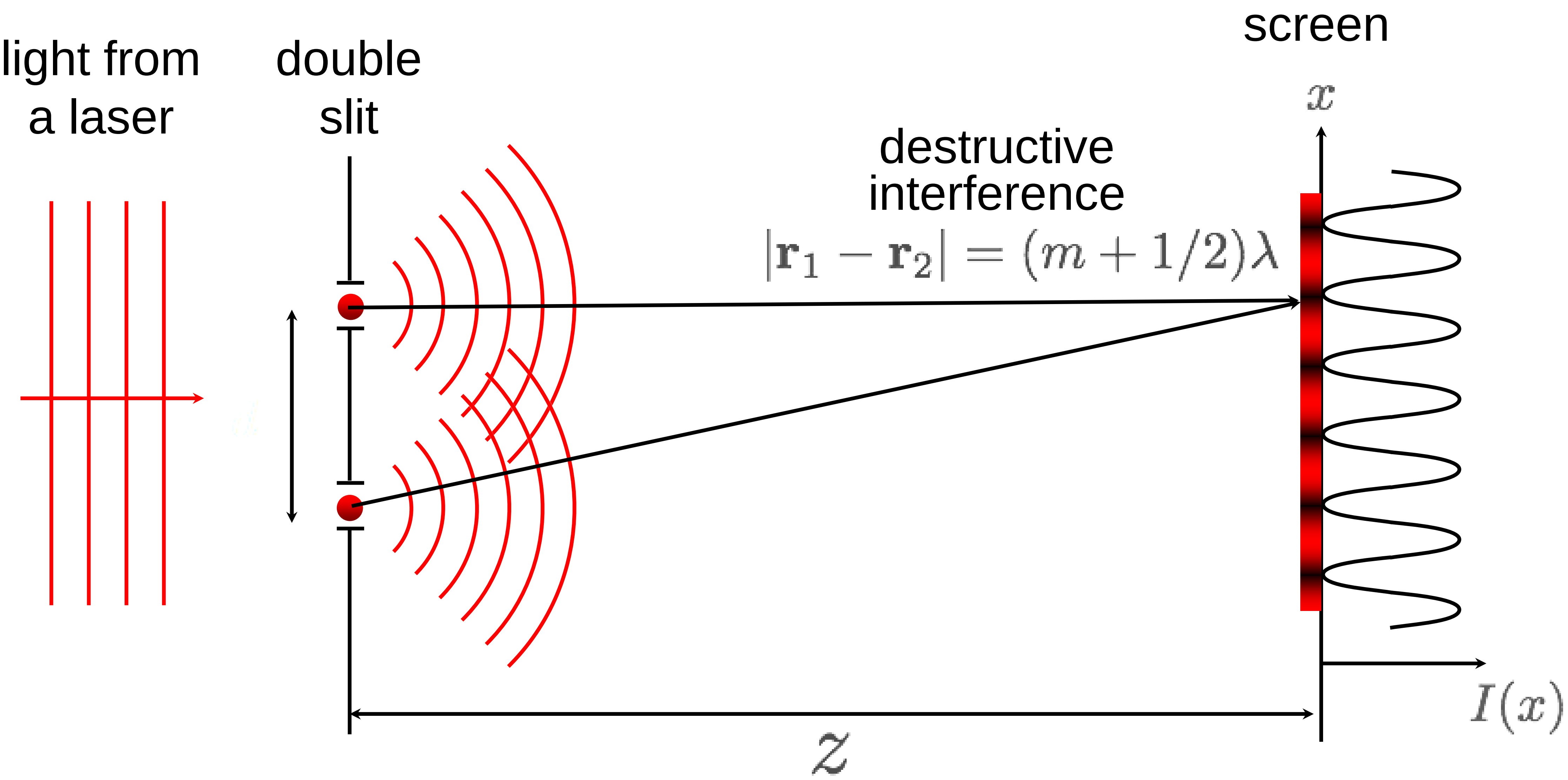
Interference & Diffraction
Interaction w/ optical elements

Non-paraxial propagation

Young’s experiment



Young's experiment



light from a laser

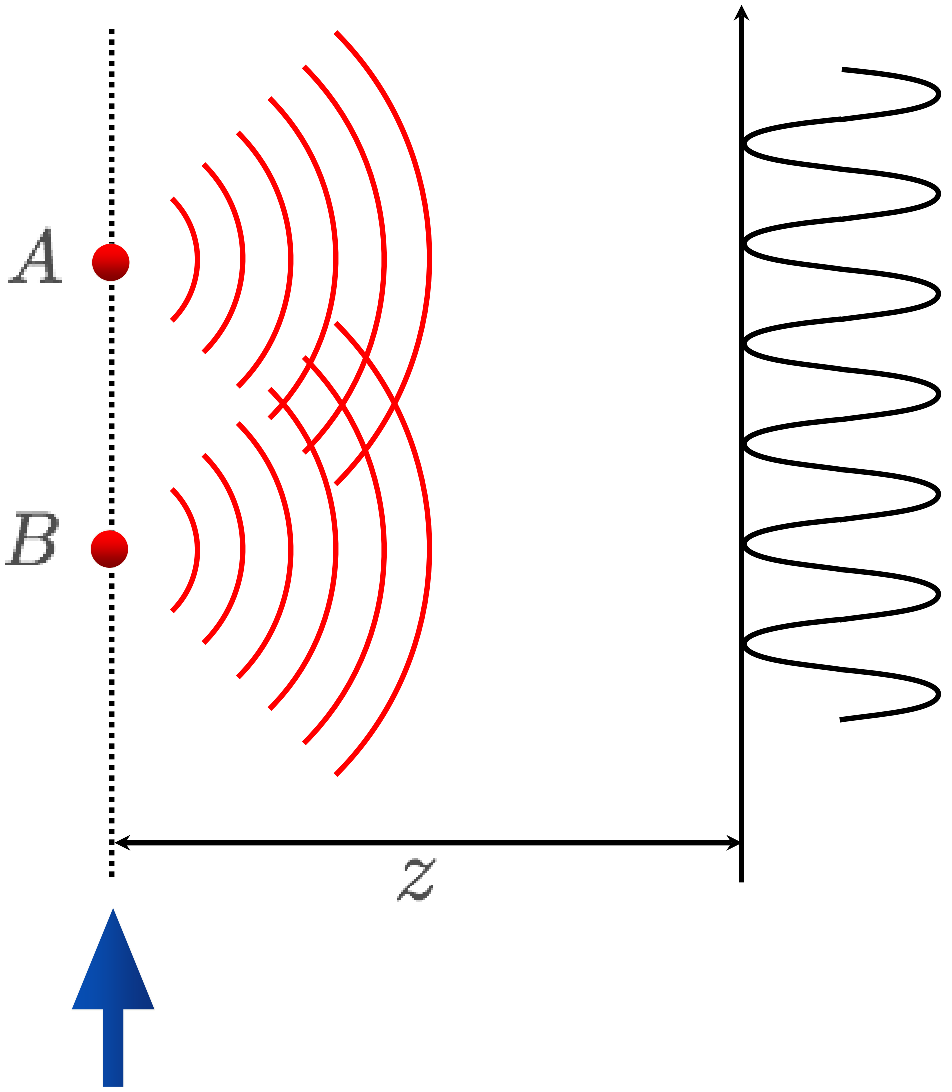
double slit

screen

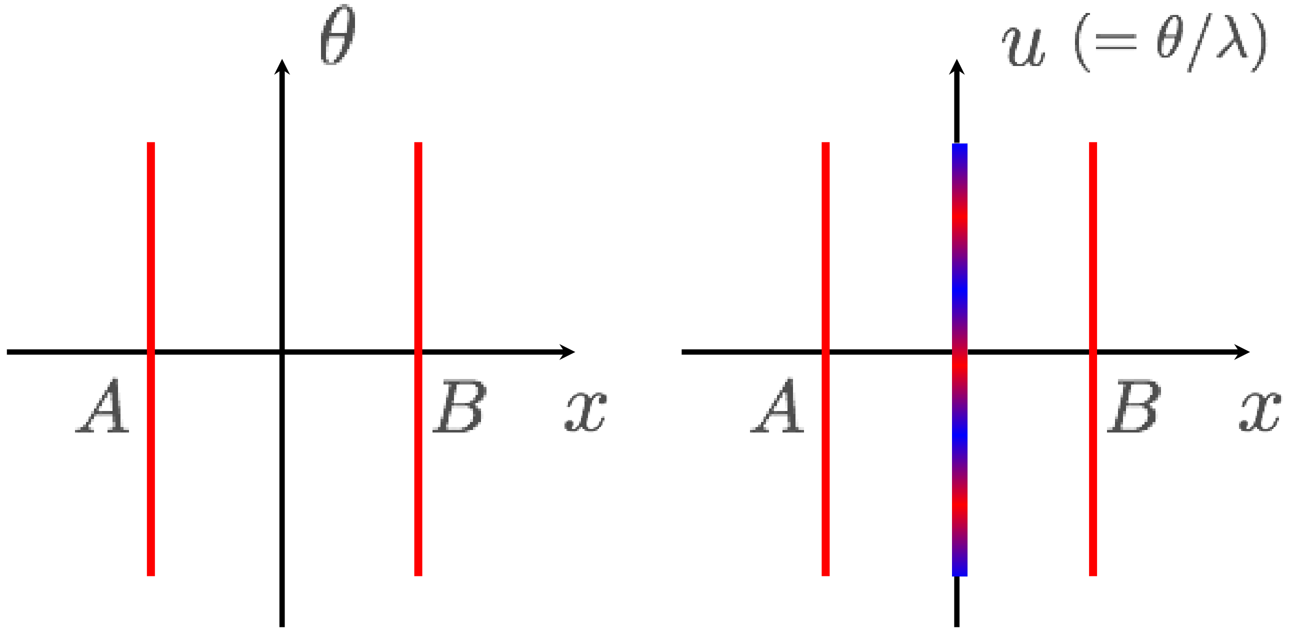
destructive interference

$$|\mathbf{r}_1 - \mathbf{r}_2| = (m + 1/2)\lambda$$

Young's experiment



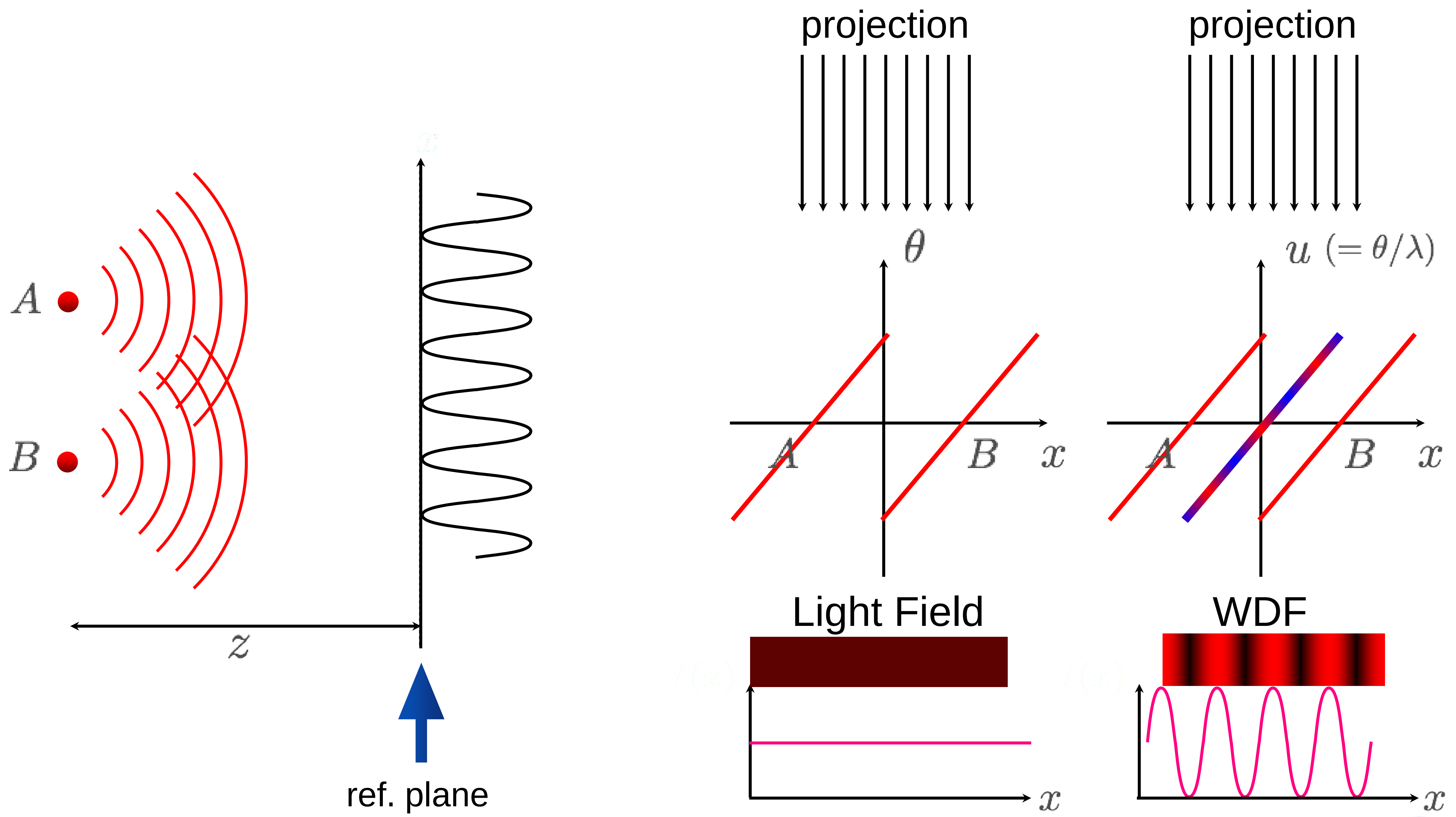
ref. plane



Light Field

WDF

Young’s experiment



projection

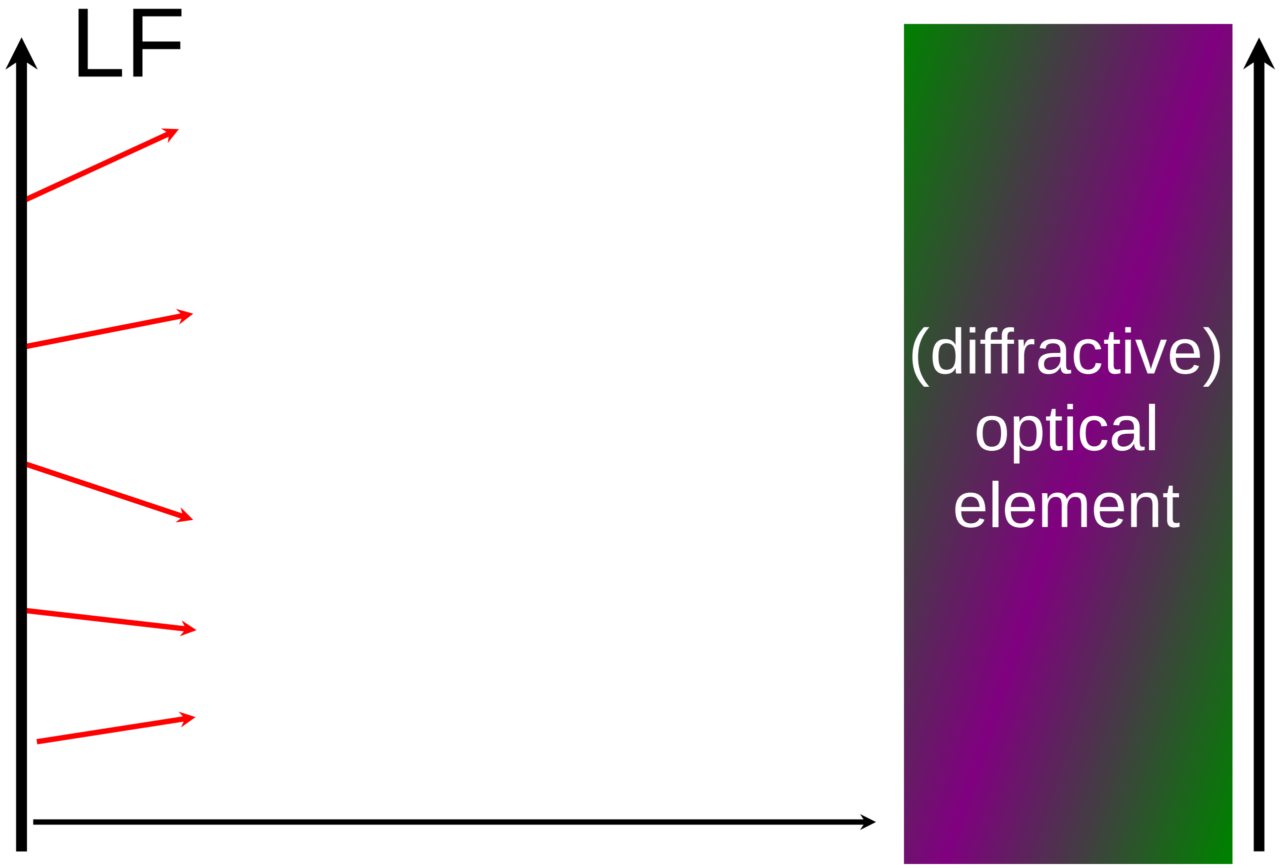
projection

Light Field

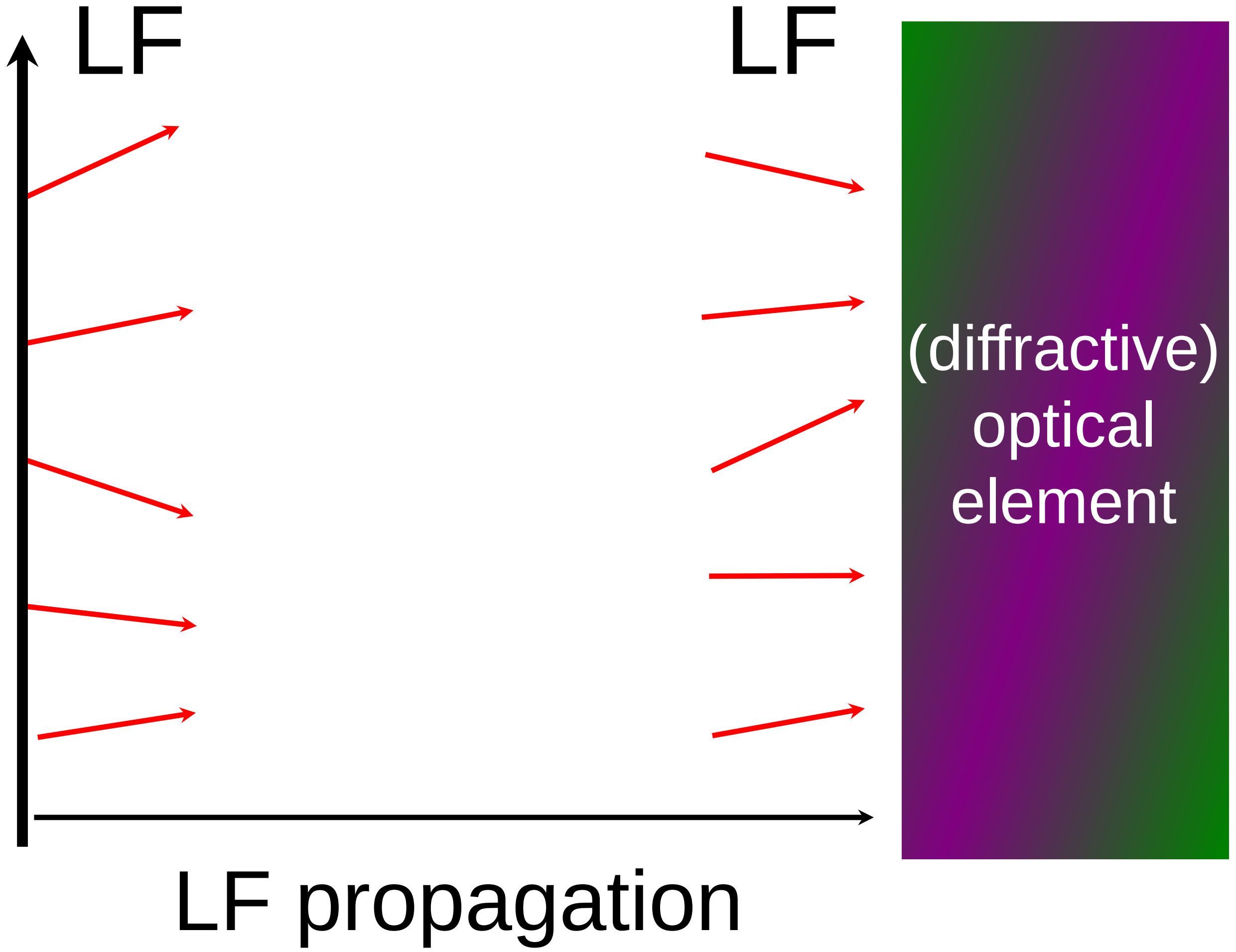
WDF

ref. plane

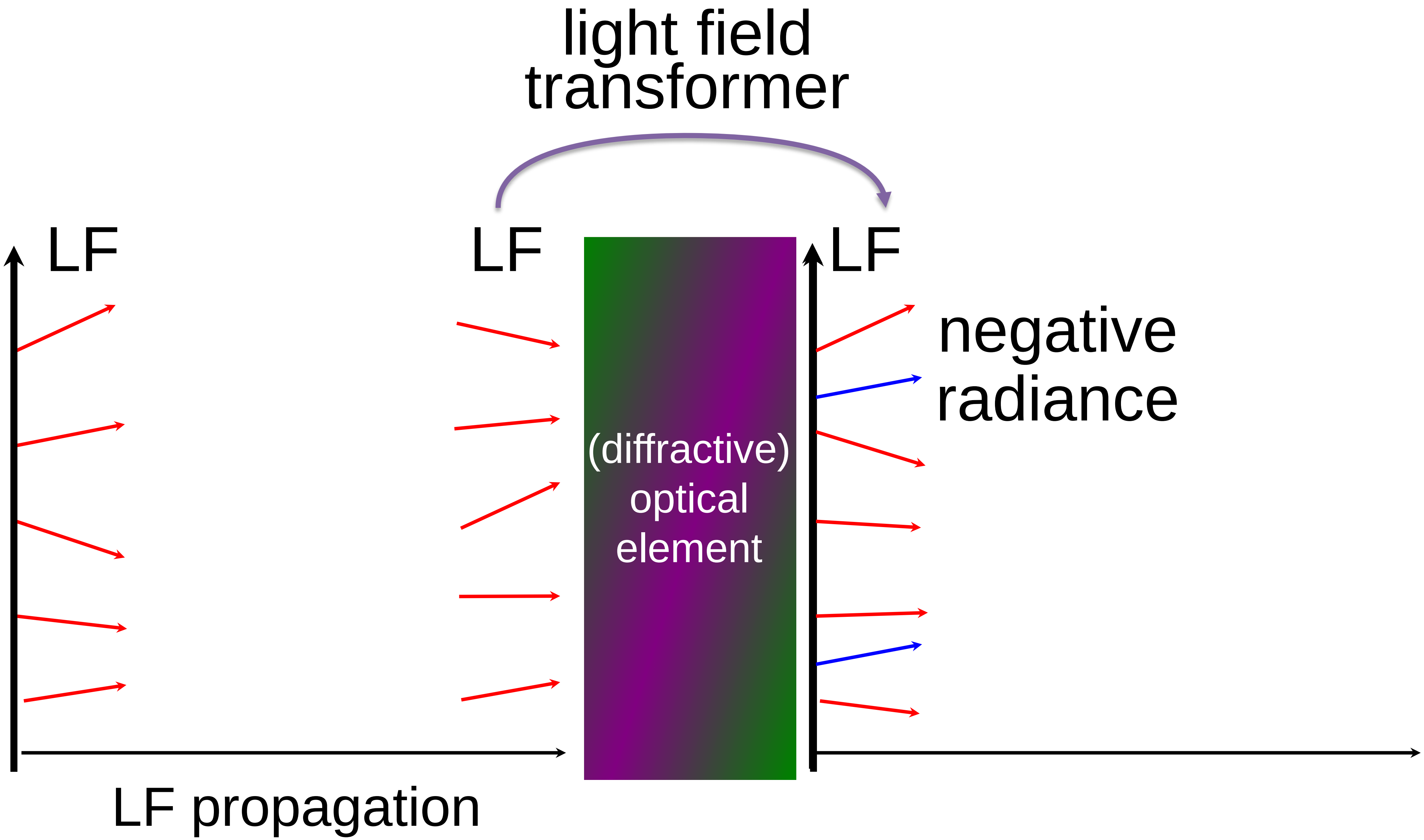
Augmented LF framework



Augmented LF framework



Augmented LF framework



light field
transformer

LF

LF

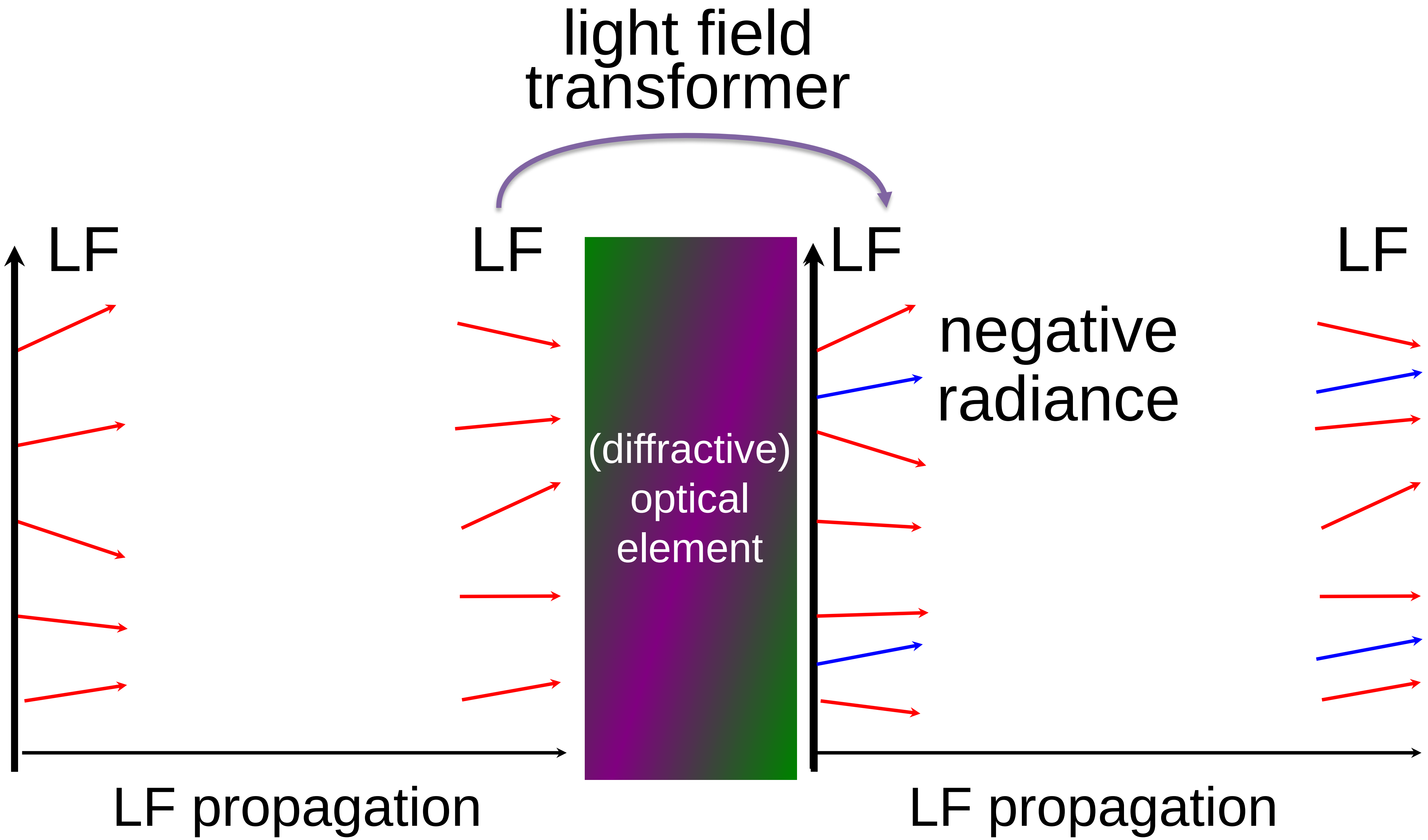
(diffractive)
optical
element

LF

negative
radiance

LF propagation

Augmented LF framework



Diffraction can be included in the light field framework!

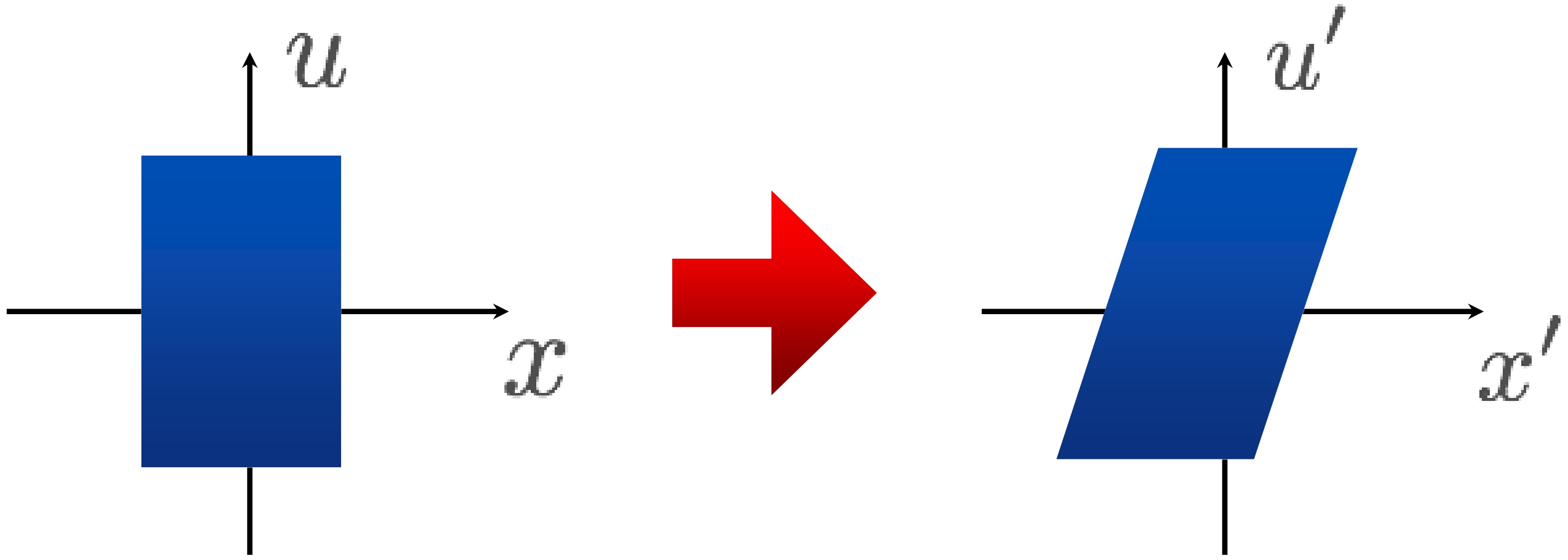
Tech report, S. B. Oh et al.

Outline

- Limitations of Light Field analysis
  - Ignore wave phenomena
  - Only positive ray -> no interference

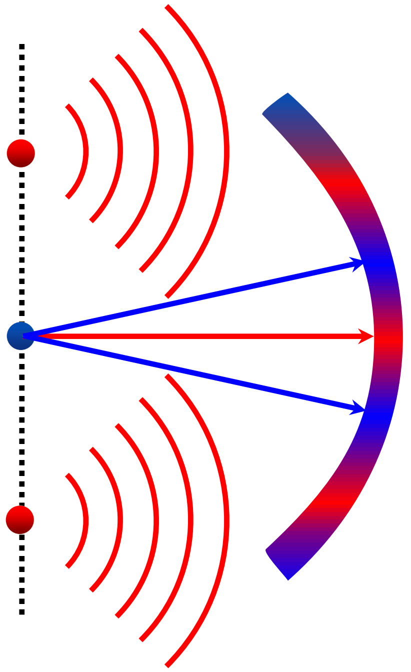
Outline

- Limitations of Light Field analysis
- Augmented Light Field
  - – free-space propagation



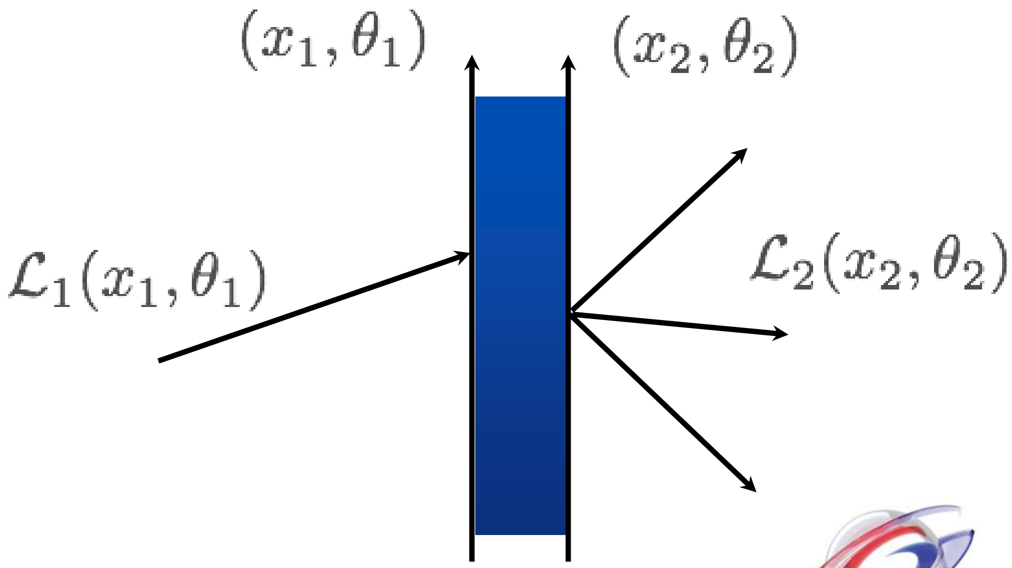
Outline

- Limitations of Light Field analysis
- Augmented Light Field
  - free-space propagation
  - virtual light projector in the ALF
    - Possible negative
    - Coherence



Outline

- Limitations of Light Field analysis
- Augmented Light Field
  - free-space propagation
  - virtual light projector in the ALF
    - Possible negative
    - Coherence
  - light field transformer



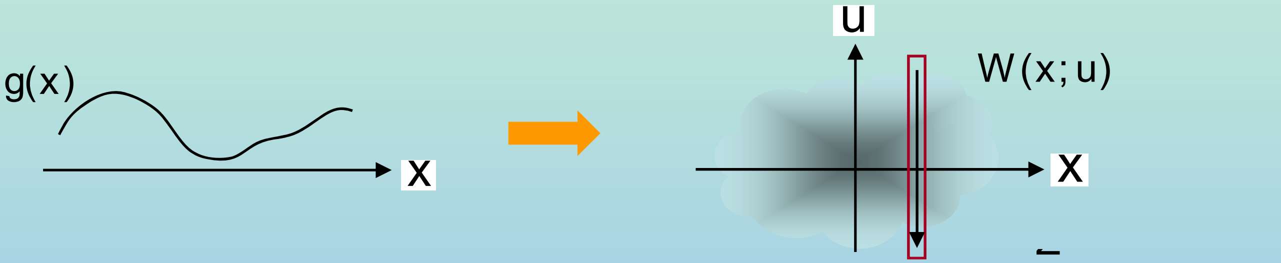
Assumptions

- **monochromatic** (= temporally coherent)
  - can be extended into polychromatic
- **flatland** (= 1D observation plane)
  - can be extended to the real world
- **scalar field and diffraction** (= one polarization)
  - can be extended into polarized light
- **no non-linear effect** (two-photon, SHG, loss, absorption, etc)

Introduction

- Wigner distribution function

$$W(x;u) = \int g(x+\lambda/2)\,g^{*}(x-\lambda/2)\,e^{-i2\pi u\lambda}\,d\lambda = WDF\,[g(x)]$$



$$I(x) = \int W(x;u)\,du$$

  - Local spatial frequency spectrum
  - Spatial frequency ⇔ propagation angle of plane waves
    - Local spatial frequency ⇔ Direction of rays in geometrical optics
    - *LIGHT FIELD* concept in computer vision/graphics
  - Intensity: $I(x) = \int W(x;u)\,du$
  - ***Signal & transform as geometrical representation***
    - Digital holography
    - Generalized sampling problems
    - Integral imaging/3D display

E. Wigner, Phy. Rev. **40**:749-759, (1932)

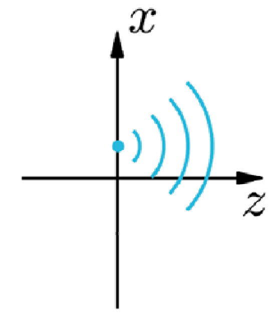
WDF of various Light Fields

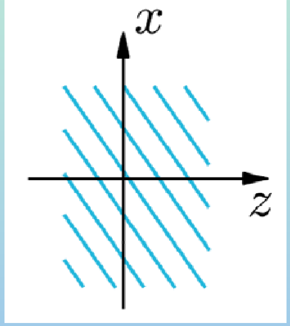
point source

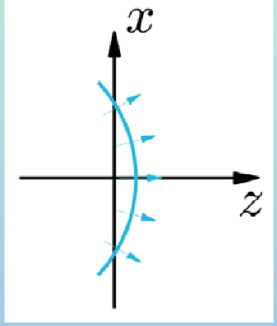
plane wave

spherical wave

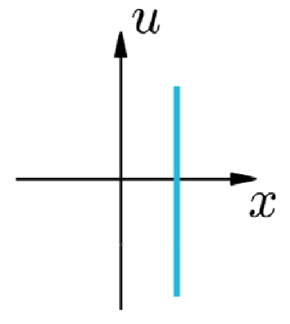
E-field
In space

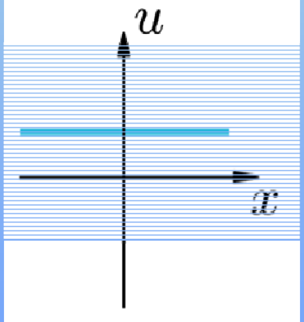


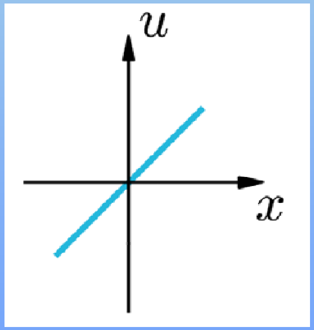




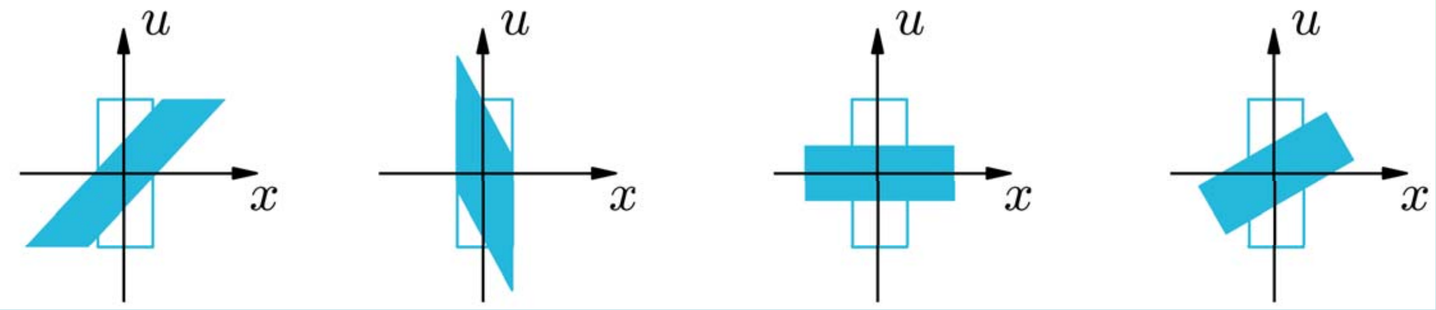
Wigner







WDF of Propagation and Transforms

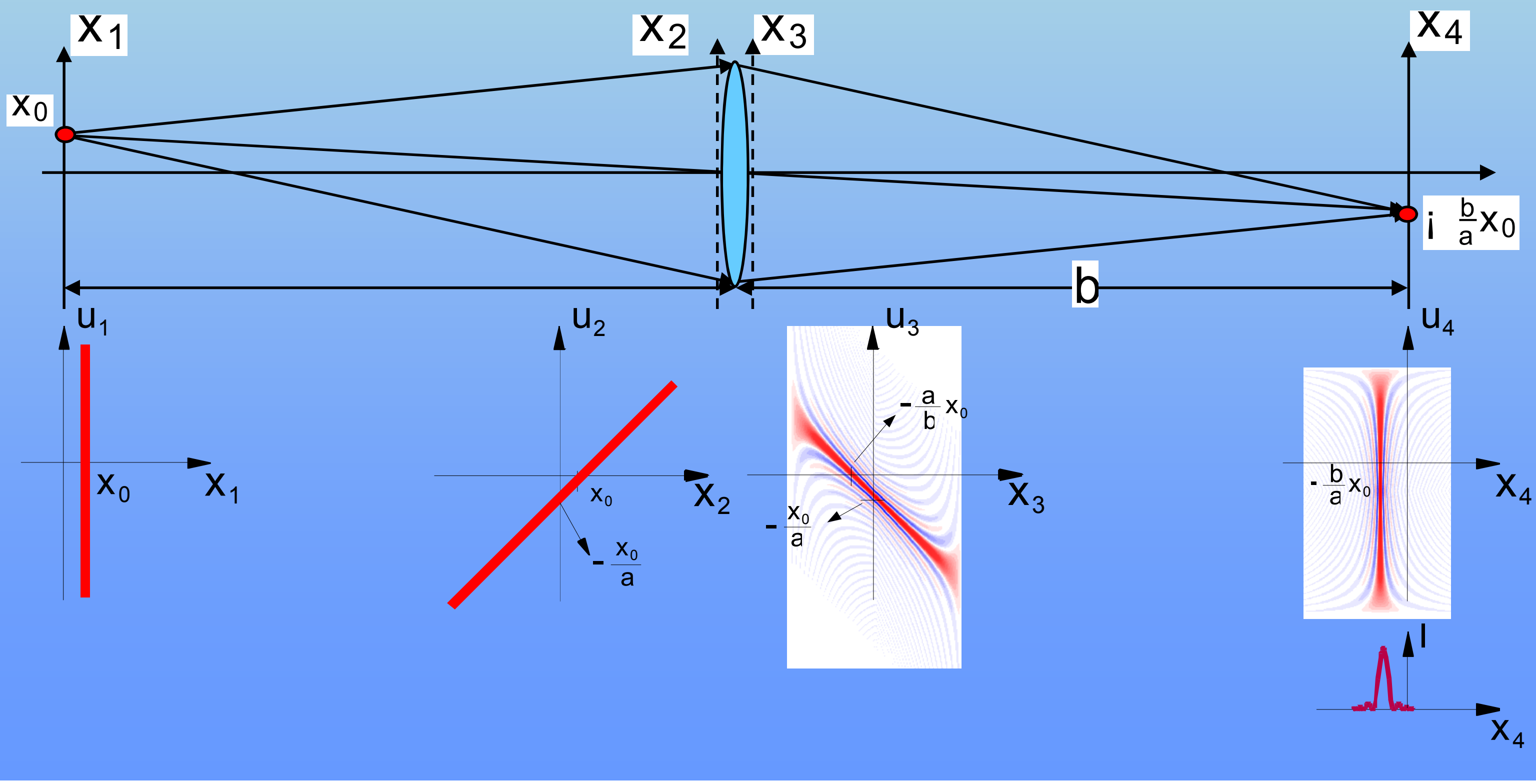


Fresnel propagation

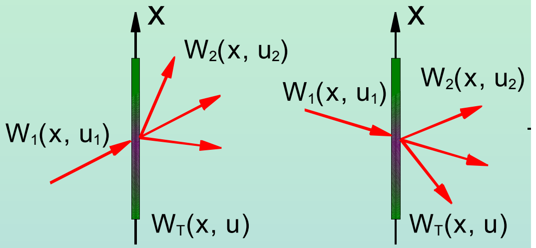
Chirp (Lens)

Fourier transform

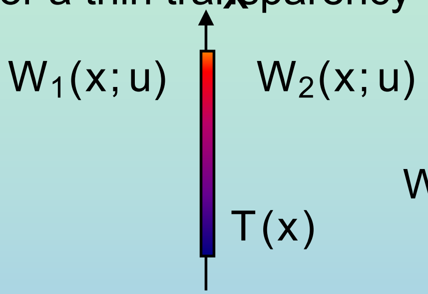
Fractional Fourier transform



Wigner representation of Optical Elements



- For a thin transparency T(x)



$$W_2(x;u) = \int W_1(x;u - u')W_T(x;u')du'$$

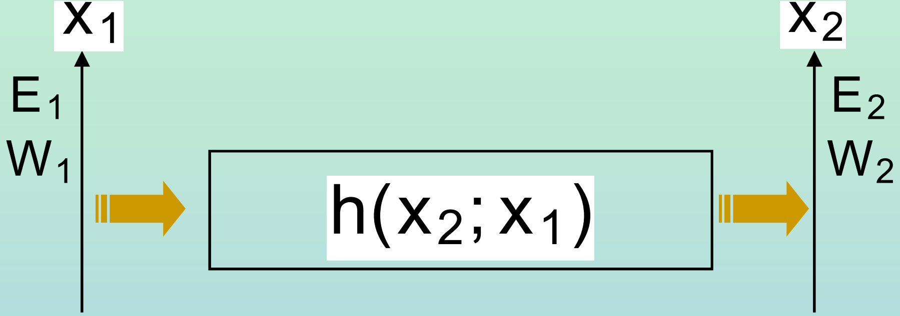
$$W_T(x;u) = WDF\,[T(x)]$$

  - Lens: u-shear
  - Circular aperture
    - M. J. Bastiaans and P.G.J. van de Mortel, *JOSA A*, 13 (1996)
  - Phase grating
    - V. Arrizon and J. Ojeda-Castaneda, *JOSA A*, 9 (1992)
  - Phase mask (slowly varying phase) $\phi(x)$

$$W_2(x;u) = W_1\left[x; u - \frac{1}{2\pi}\frac{\partial\phi}{\partial x}\right]$$

- Volume hologram?
  - Not a thin transparency

Linear system approach in Wigner space


x_1

E_1

W_1

$h(x_2;x_1)$

x_2

E_2

W_2

$$E_2(x_2) = \int h(x_2;x_1)E_1(x_1)dx_1$$

$$W(x;u) = \int E(x+\xi/2)E^*(x-\xi/2)\exp\{-j2\pi u\xi\}d\xi$$

$$W_2(x_2;u_2) = \iint \underbrace{K_h(x_2;u_2;x_1;u_1)}W_1(x_1;u_1)dx_1du_1$$

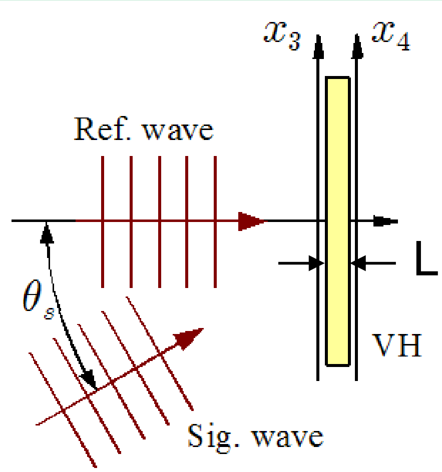
Double Wigner distribution function of impulse response*

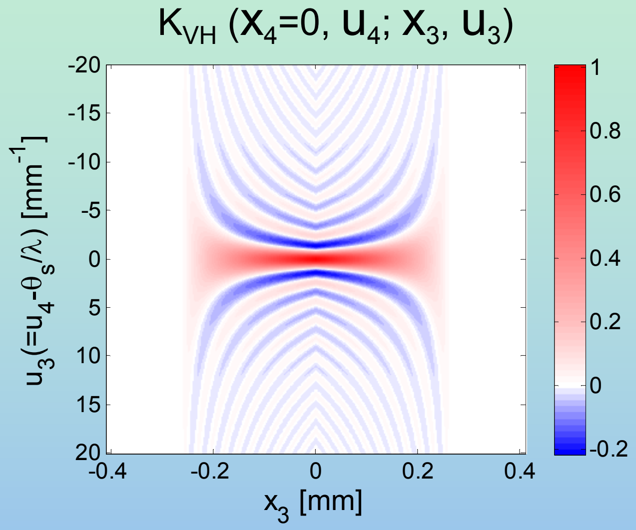
$$K_h(x_2;u_2;x_1;u_1) = \iint h\left[x_2+\frac{x_2'}{2};x_1+\frac{x_1'}{2}\right]h^*\left[x_2-\frac{x_2'}{2};x_1-\frac{x_1'}{2}\right]\exp\{-j2\pi(x_2'u_2-x_1'u_1)\}dx_2'dx_1'$$

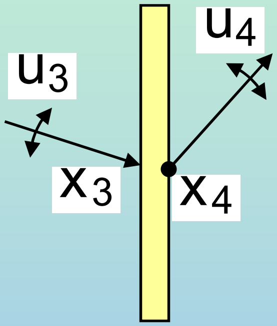
$$= WDF^{2D}[h(x_2;x_1)]$$

Pan *et al*. *Appl. Opt*. **47**(1):45-51, (2008)

Plane wave reference volume hologram (2D:x-z)







$$\boxed{K_{VH}(x_4;u_4;x_3;u_3) = \left(\frac{2}{L\theta_s}\right)\delta\left(u_4 - u_3 - \frac{\theta_s}{\lambda}\right) * \left(\frac{x_3 - x_4}{L\theta_s/2}\right)\mathrm{sinc}\{2(L\theta_s - 2|x_3 - x_4|)u_3\}}$$

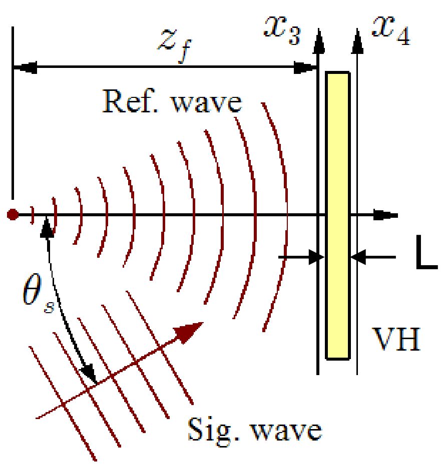
Derivation: $h(x_2;x_1) \approx \delta(x_1 + x_2 - f\theta_s)\,\mathrm{sinc}\left(\frac{L}{2\lambda f^2}\left[x_1^2 - x_2^2 + f^2\theta_s^2\right]\right)$

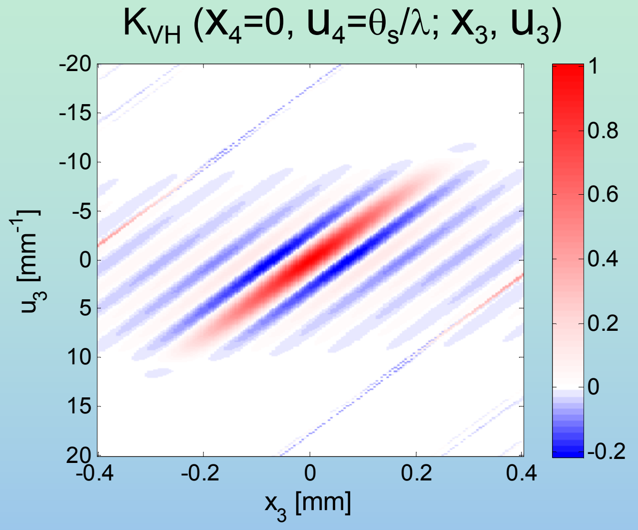
$K_{VHI}(x_2;u_2;x_1;u_1)$

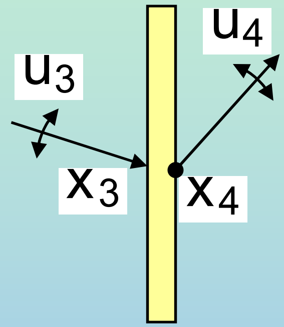
$K_{VH}(x_4;u_4;x_3;u_3)$

Parameters:
λ = 0.5 μm
θ_s= 30°
L = 1 mm

Spherical wave reference volume hologram (2D:x-z)







$$K_{VH}(x_4;u_4;x_3;u_3)=\iint dx_3^0dx_4^0e^{-i2\pi(u_4^0x_4-u_3^0x_3)}\exp\left\{-i2\pi\lambda z_f\,(u_3^0+u_4^0)\left(-u_3+u_4-\frac{\theta_s}{\lambda}\right)\right\}$$
$$\times\,\mathrm{sinc}\left\{L\lambda\left(-u_3+u_4+\frac{u_3^0+u_4^0}{2}\right)\left(u_4+\frac{u_4^0}{2}-\frac{\theta_s}{\lambda}\right)\right\}\mathrm{sinc}\left\{L\lambda\left(-u_3+u_4-\frac{u_3^0+u_4^0}{2}\right)\left(u_4-\frac{u_4^0}{2}-\frac{\theta_s}{\lambda}\right)\right\}$$

Derivation: $h(x_2;x_1)=\exp\left\{-i\frac{\pi z_f}{\lambda f^2}(x_1+x_2-f\theta_s)^2\right\}\mathrm{sinc}\left\{\frac{L}{\lambda f^2}(x_1+x_2)(x_2-f\theta_s)\right\}$

$K_{VHI}(x_2;u_2;x_1;u_1)$

$K_{VH}(x_4;u_4;x_3;u_3)$

Parameters:
λ = 0.5 μm
θ_s= 30°
L = 1 mm
z_f = 50 mm

Part 5
Applications in rendering

Simulation methods

- **Diffraction Shaders**

Stam 1999

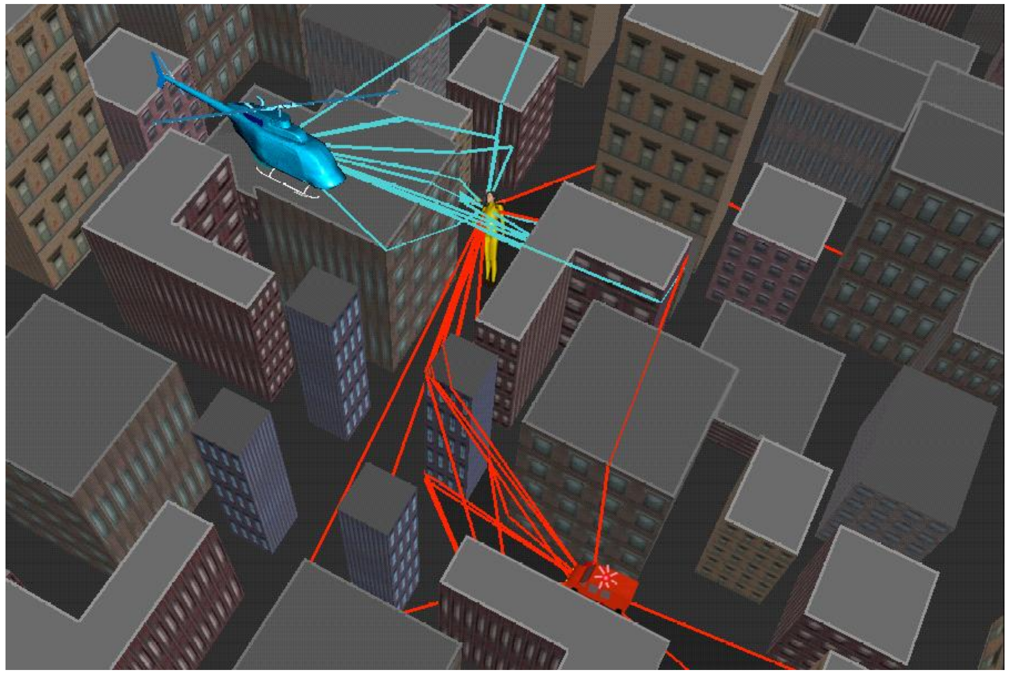
Simulation methods

- **Diffraction Shaders**
- **Phase Tracking**

Ziegler 2008

Simulation methods

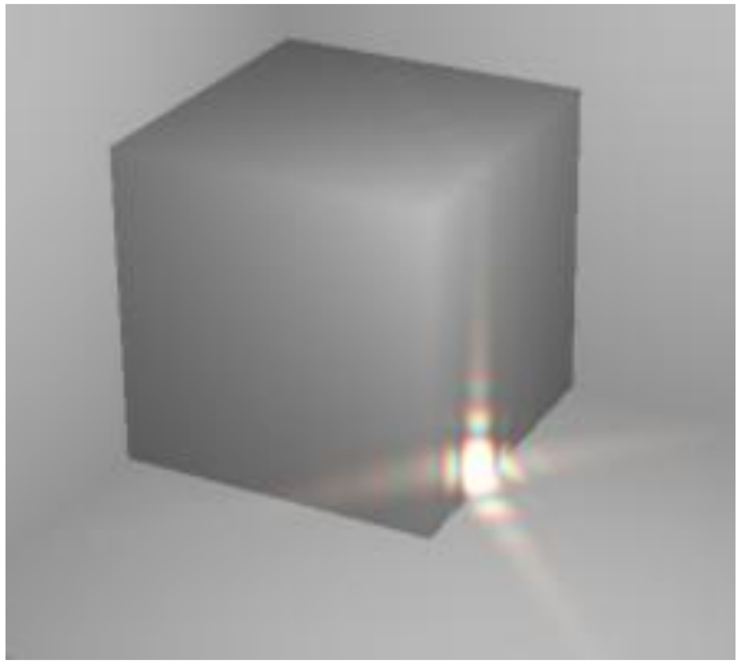
- **Diffraction Shaders**
- **Phase Tracking**
- **Edge diffraction**



Tsingos 2001

Simulation methods

- **Diffraction Shaders**
- **Phase Tracking**
- **Edge diffraction**
- **Augmented Light Fields**



Oh 2010

	Edge Diffraction	**Phase Tracking**	**Diffraction Shaders**	**ALF**
Strategy	Edge-only diffraction OPD for interference	Create new wavefronts with phase computation	Instantaneous diffraction and interference	Two plane lightfield parameterization
Examples	Tsingos2001	Ziegler2007, Moravec1981	Stam1999	Oh2010
Diffraction	Yes (at edges)	Yes	Yes	Yes
Interference	At receiver	At receiver	Single point-single direction	At receiver
Near vs far field	Near field: approximated; Far field accurate	Both	Far field	Both
Local vs directional source	Both	Both	Directional only	Both
Phase vs amplitude grating	Typically for binary amplitude	Both	Phase shown Amplitude possible	Amplitude show Phase possible
Light/Audio	Typically for audio	Both	Light, Audio (very far field)	Light Audio possible
Convenience	---	---	+++	++
Phase representation	Yes	Yes	Not required	Not required
Scatter / gather operations	Deferred diffraction and interference	Deferred diffraction and interference	Instantaneous diffraction and interference	Deferred diffraction and interference
Statistical vs explicit micro geometry	Explicit only	Explicit only	Both	Explicit only

Light Fields

Outline

- Light Fields in Computer Vision
- Light Fields and Computational Photography
- Light Field Propagation and Scene Interaction
- Representation in Computer Vision and Imaging