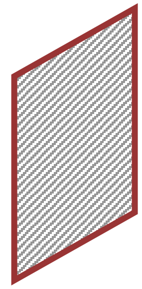
3D Optics

2D Optics

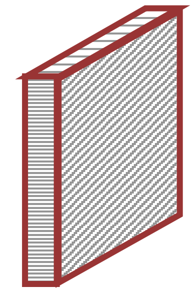
lenses



gratings

Light interacts with medium
on a sequence of
discrete surfaces

3D Optics

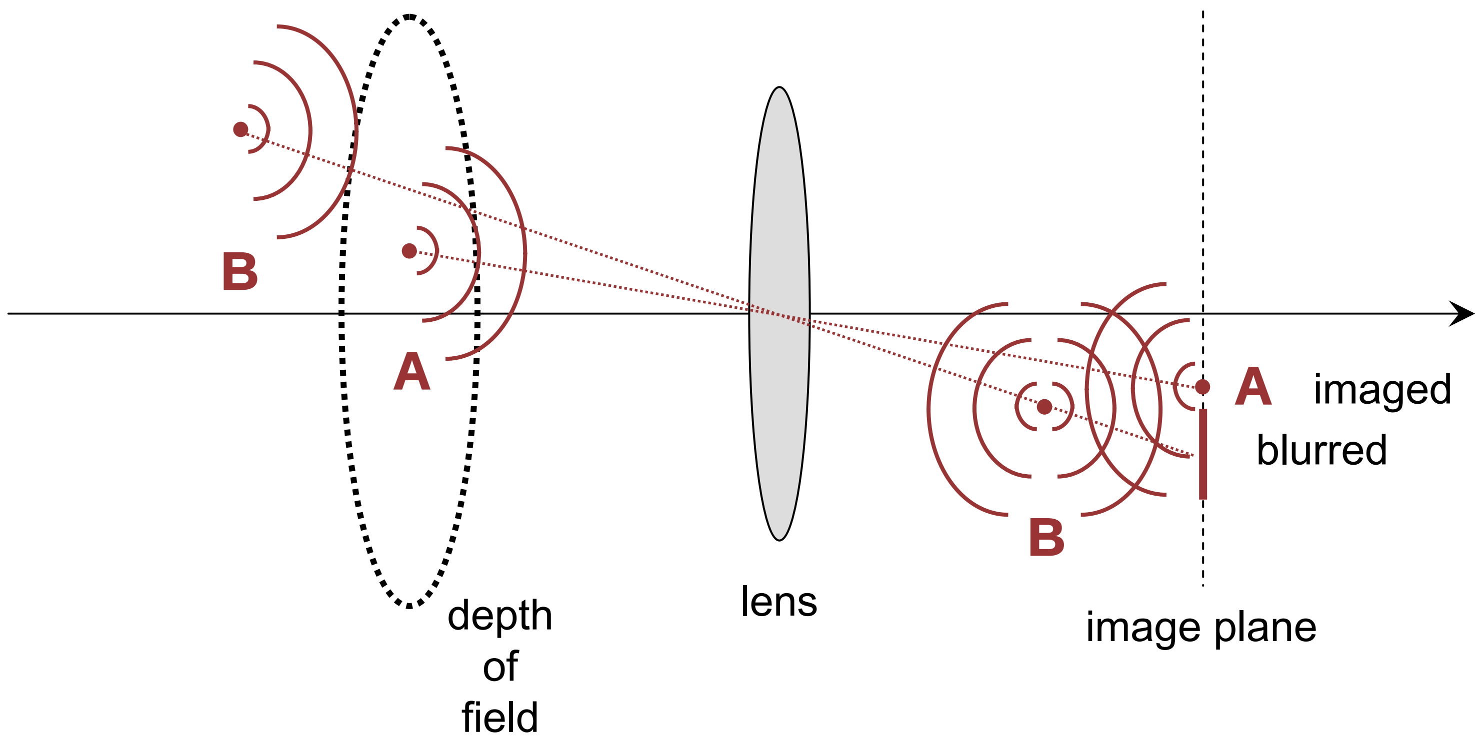


GRadient INdex optics
(GRIN)

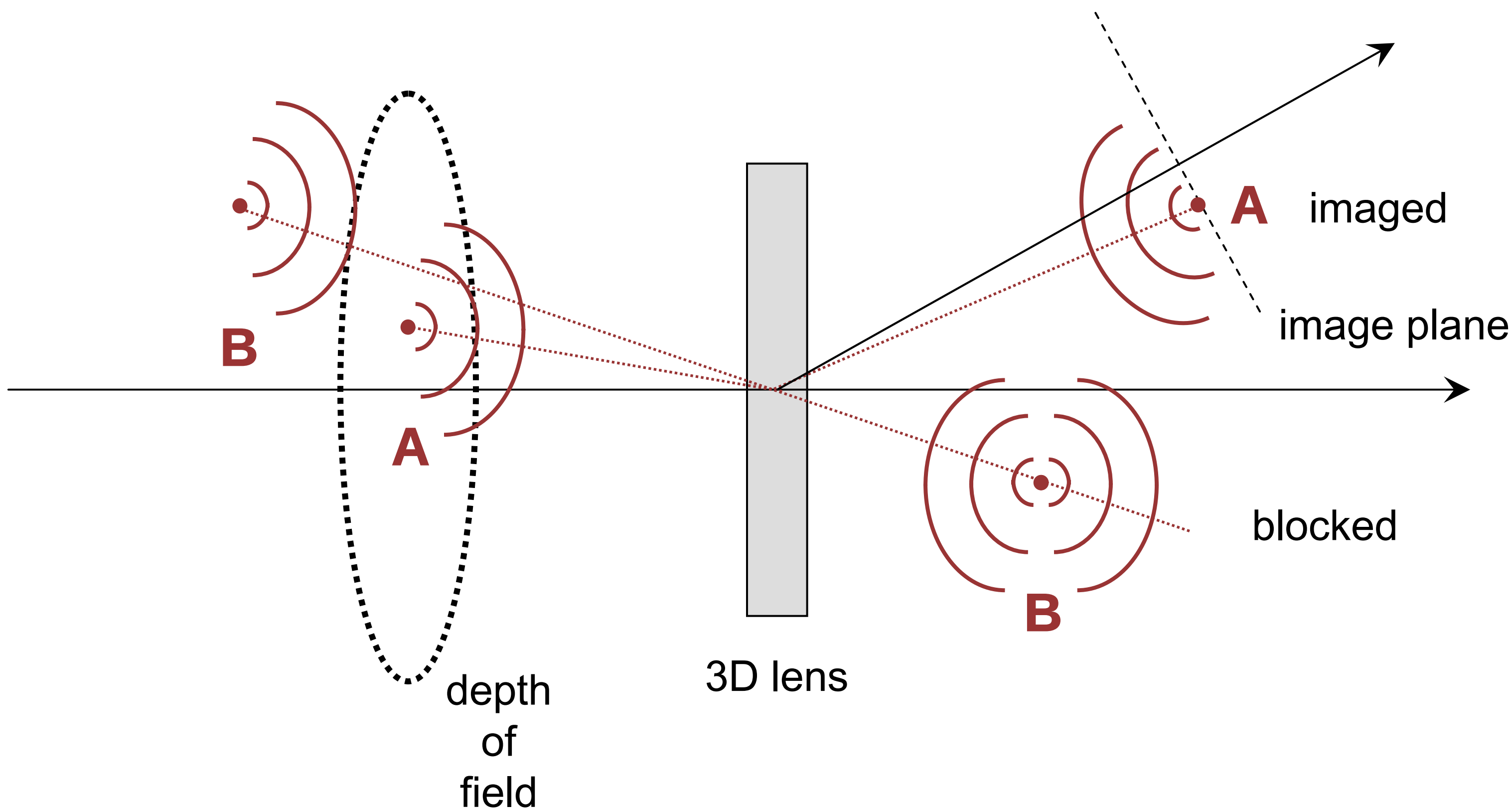
Volume
Holograms

Light interacts with medium
throughout a volume

Imaging with traditional lenses

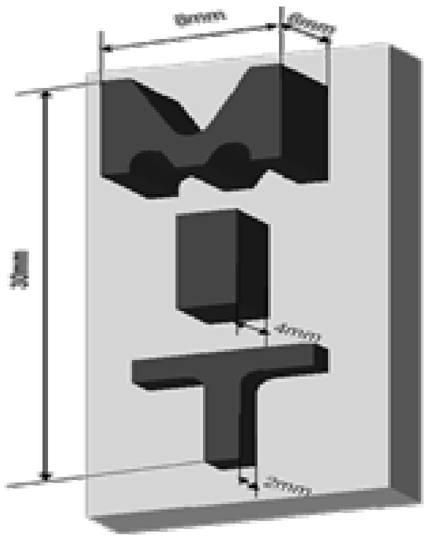


Imaging with 3D lenses



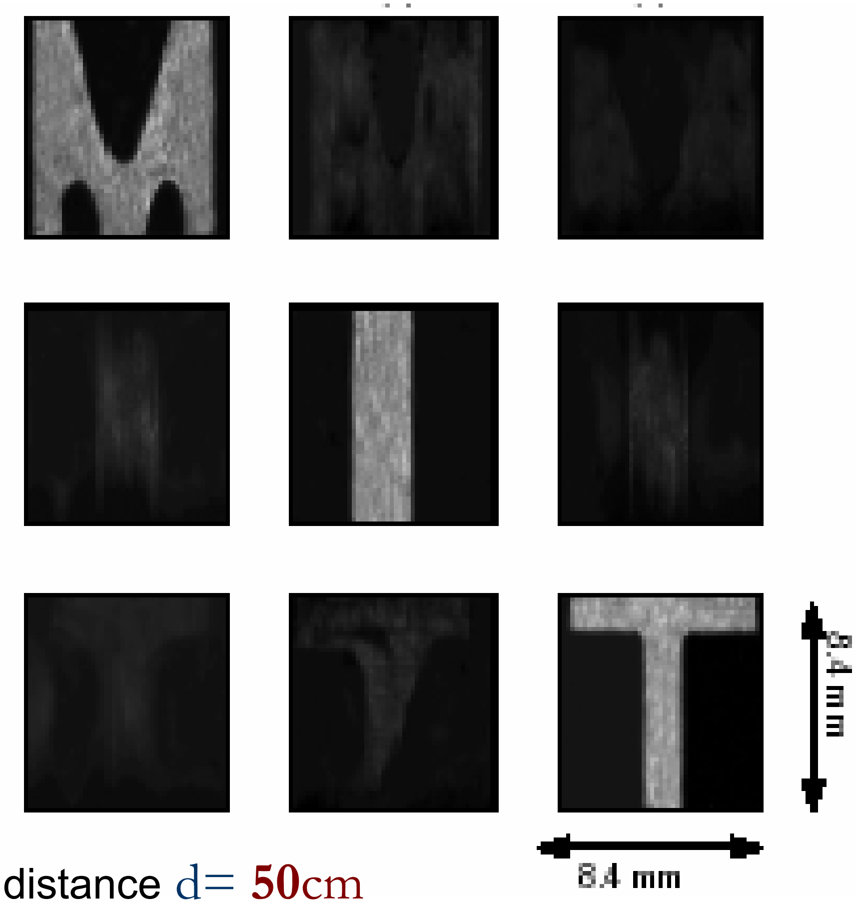
Defocus ⇔ Contrast

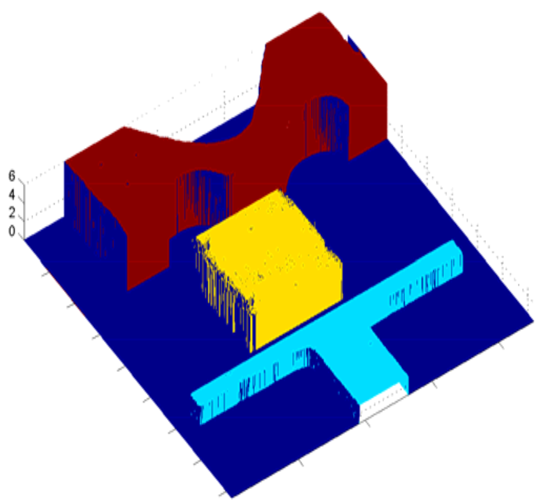
Shape recovery ("profilometry") with 3D lenses



Line scan method: 2D scanning
longitudinal + one lateral dimension

raw images
on CCD camera





2½D shape
("profile")
in digital form

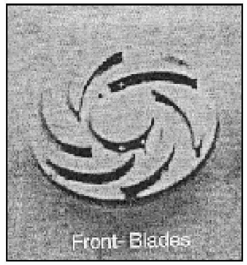
Working distance $d = \mathbf{50}\text{cm}$

Longitudinal resolution $\Delta z_{FWHM} < 1\text{mm}$

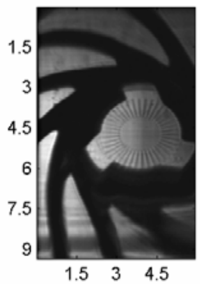
Shape recovery ("profilometry") with 3D lenses

Arnab Sinha, George Barbastathis
MIT 3D Optical Systems group
Optics Express **11**:3202, 2003

original object

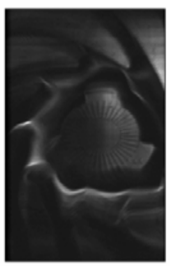


raw images

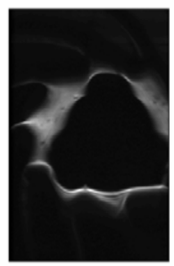


z=0 µm

z=50 µm



z=200 µm

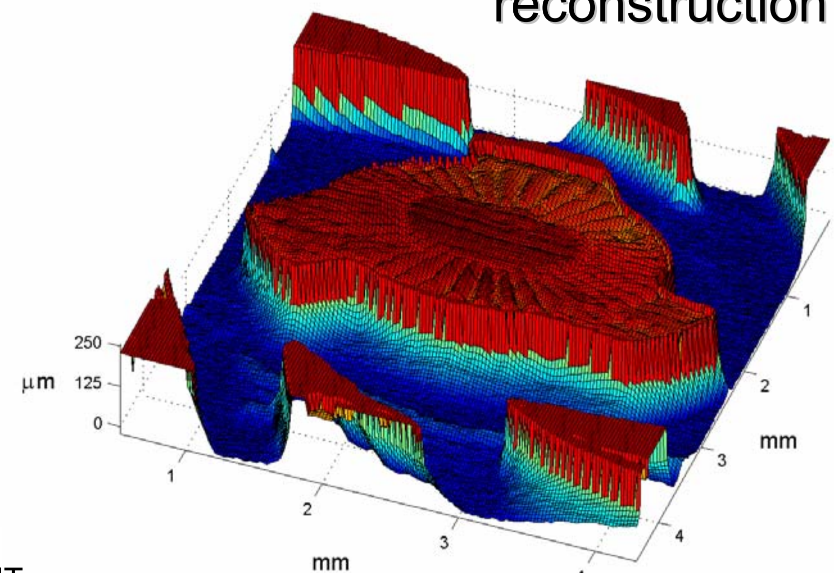


z=250 µm

Object Distance = 46 cm

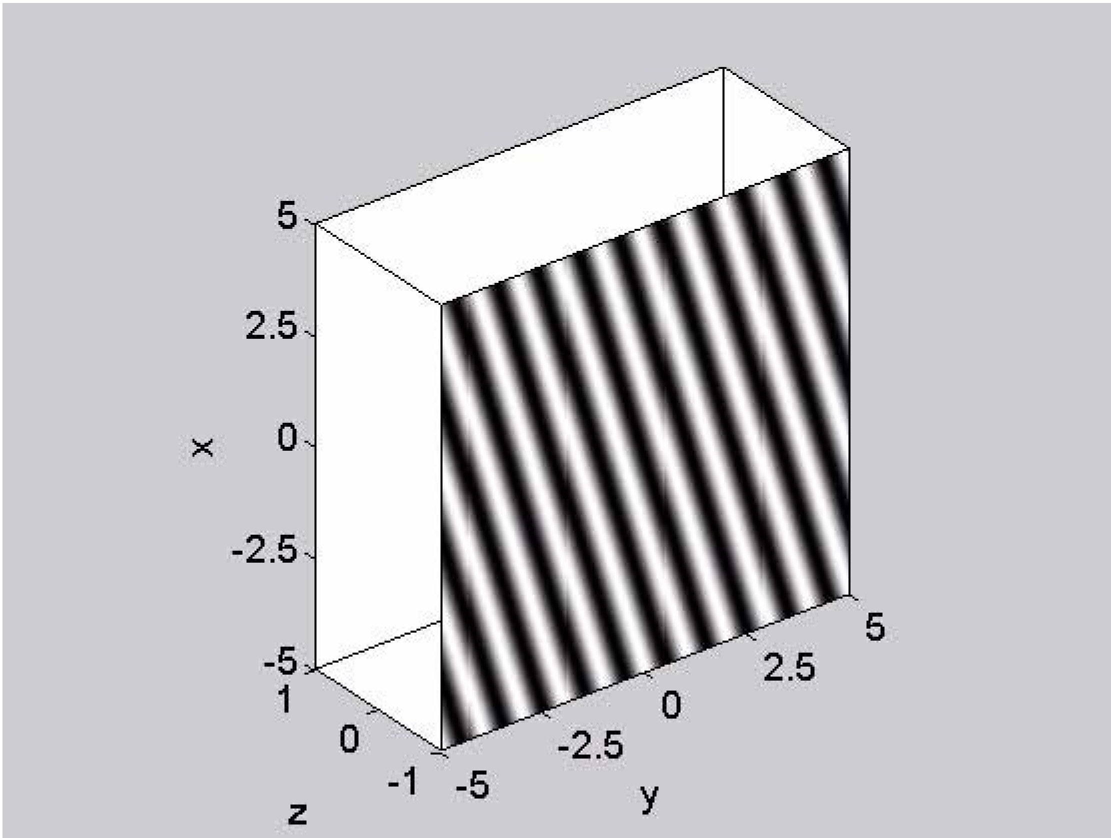
Resolution accomplished ≤ 100 µm

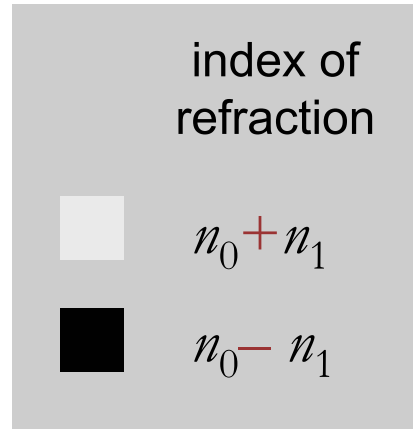
profile reconstruction



Microturbine provided by Chee Wei Wong, Alan Epstein, MIT

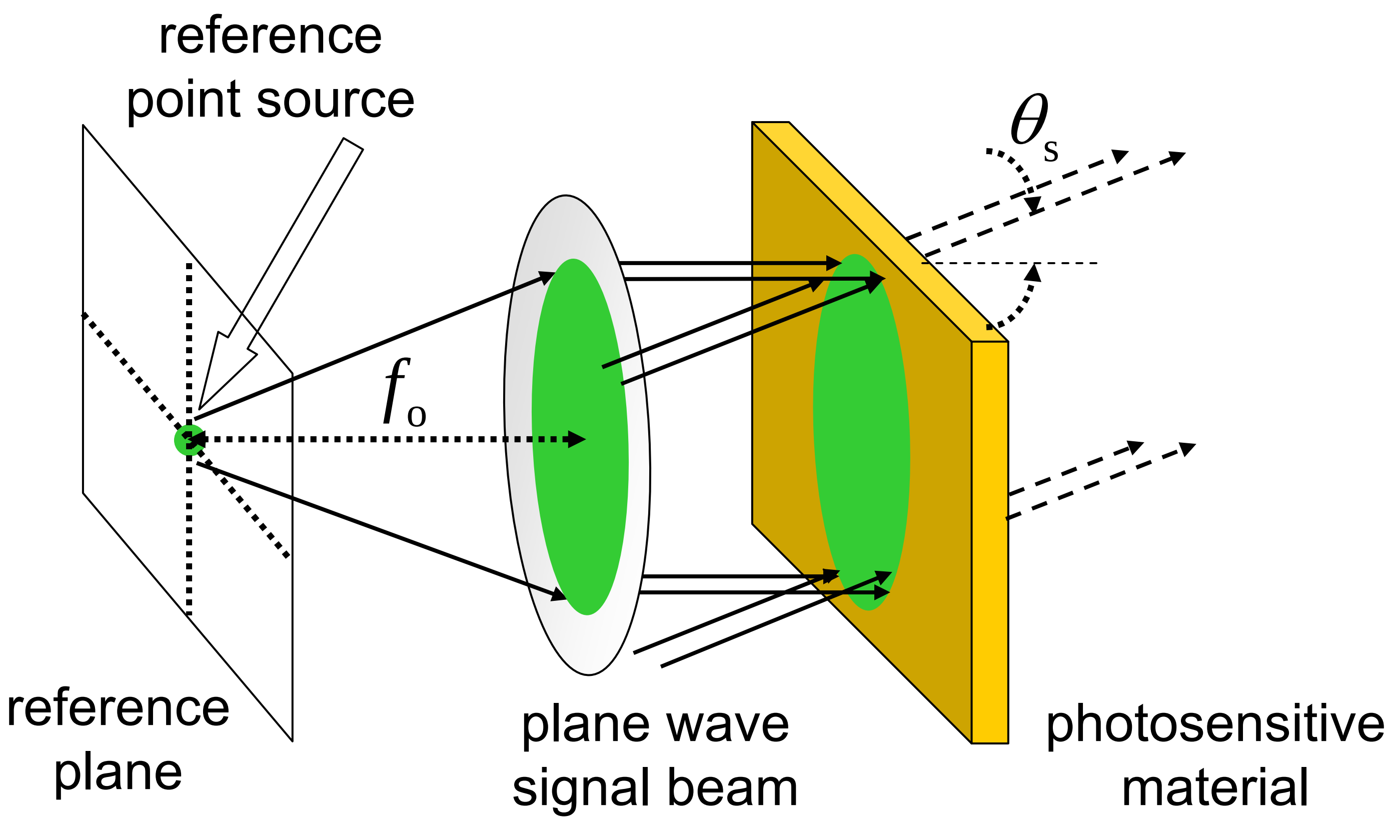
3D lens: plane-to-plane wave volume hologram





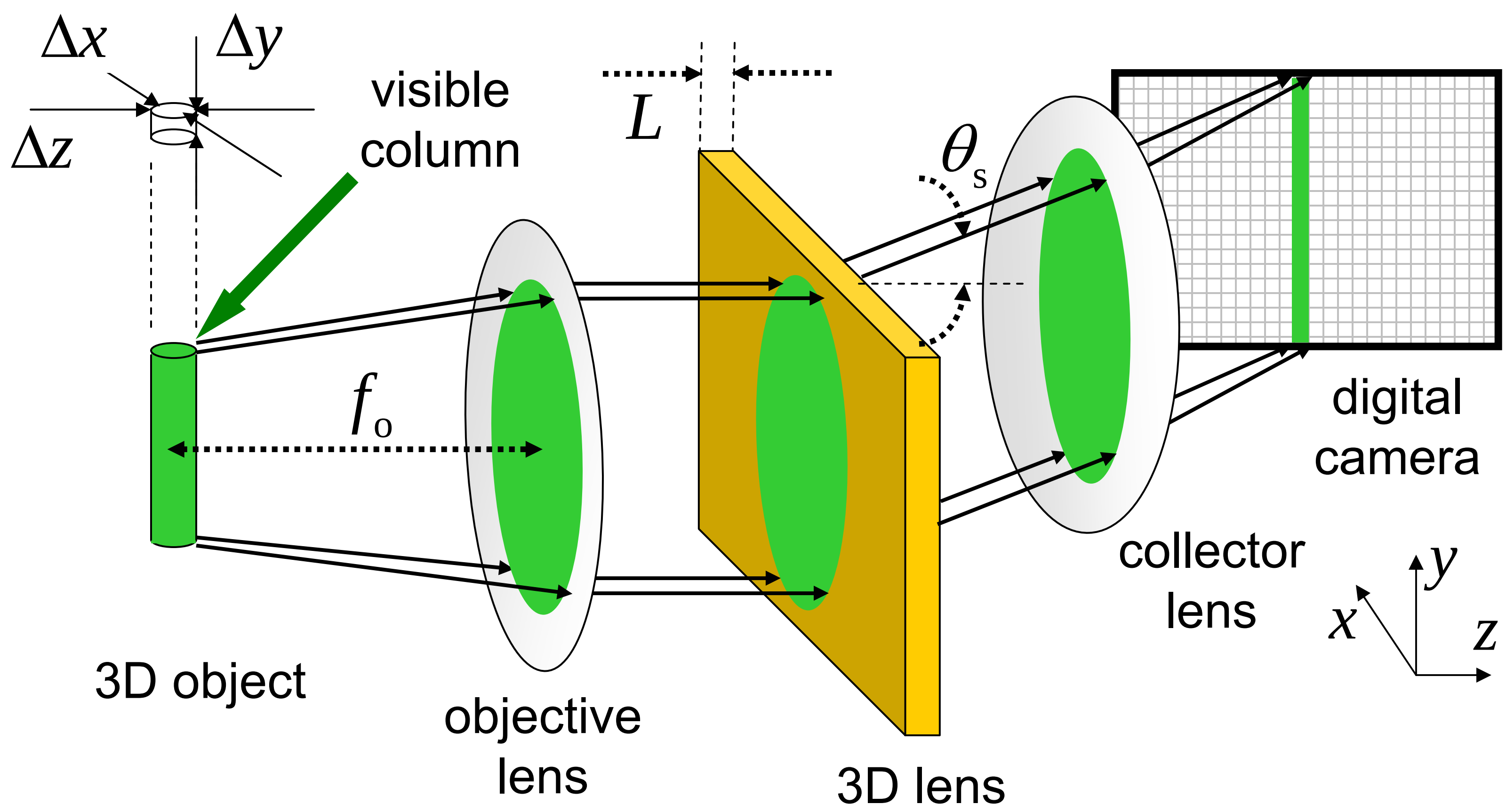
Making the (simplest) 3D lens

after exposure $n(\mathbf{r}) = n_0 + n_1 \cos\left[\left(\mathbf{k}_s - \mathbf{k}_r\right)\cdot\mathbf{r}\right]$

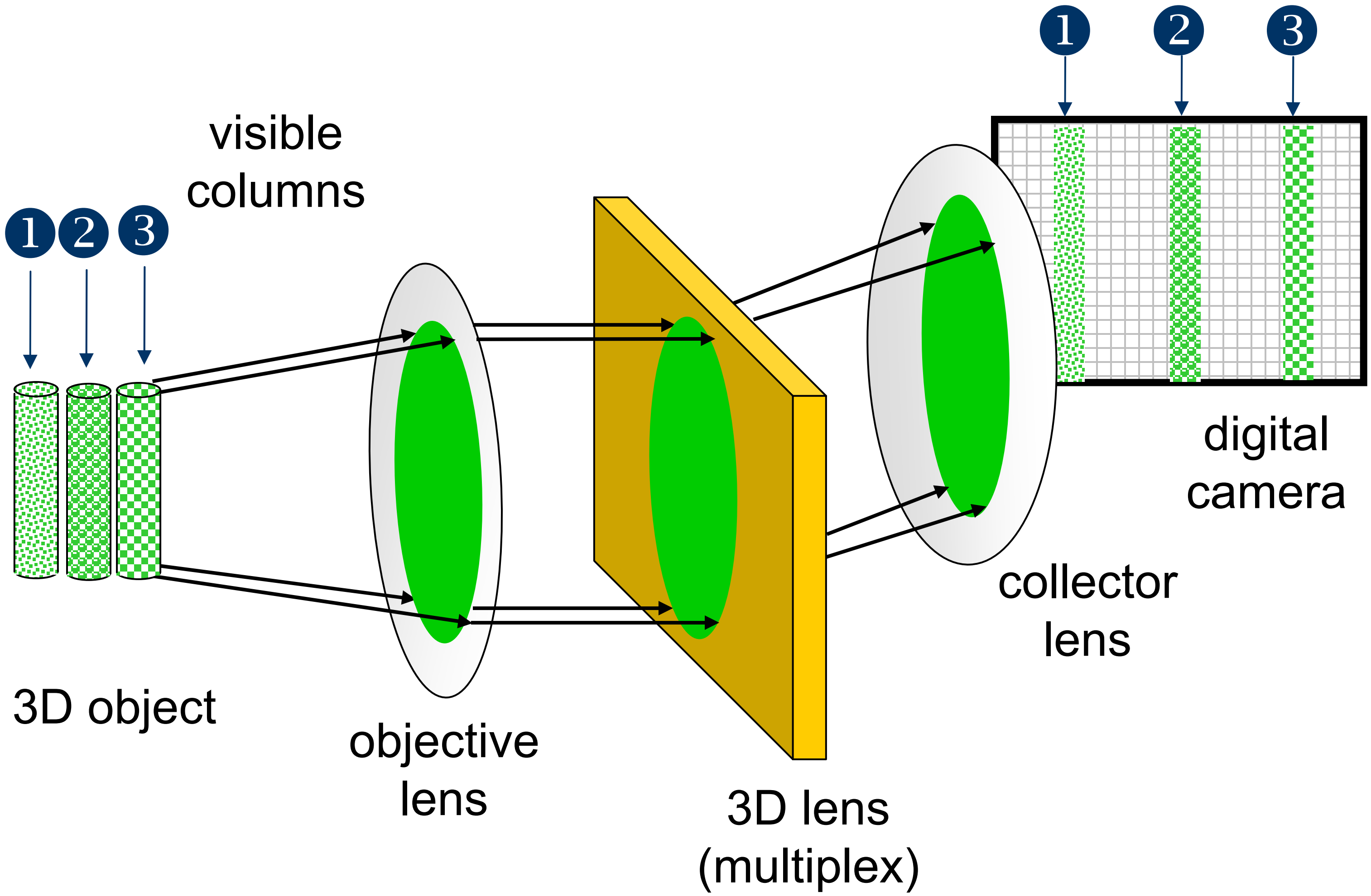


Operating the (simplest) 3D lens

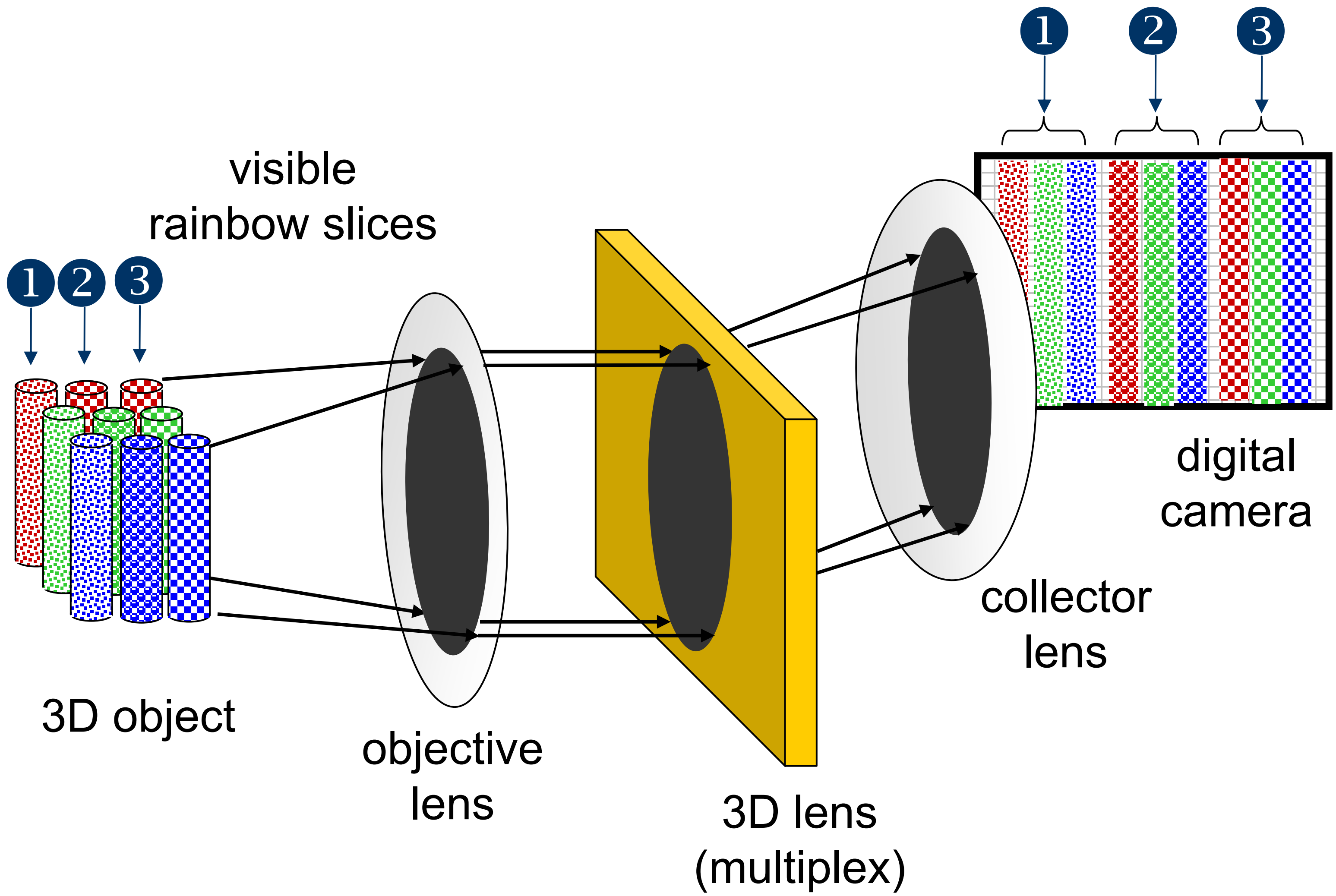
$$L \sim 100\,\mu\text{m} \div 1\text{mm}$$



Operating a multiplex 3D lens



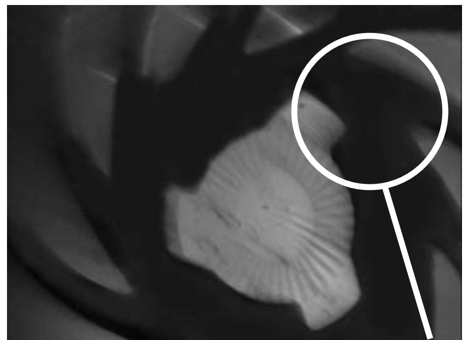
Operating a hyperspectral multiplex 3D lens



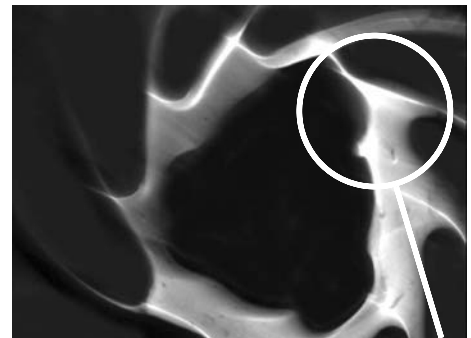
Rainbow volume holographic imaging

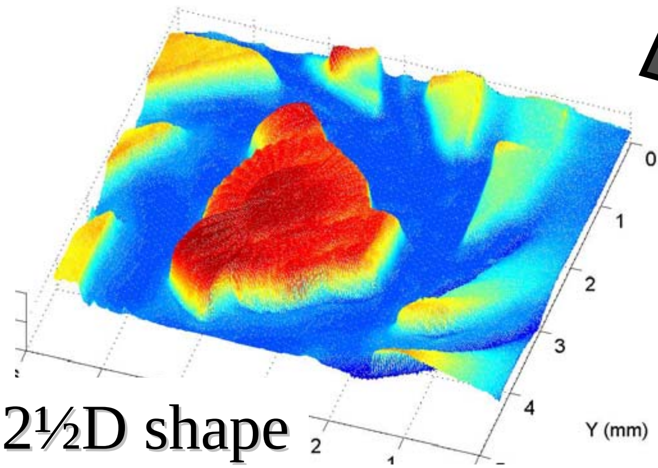
Wenyang Sun, George Barbastathis
MIT 3D Optical Systems group
Optics Letters **30**:976, 2005

slice #1

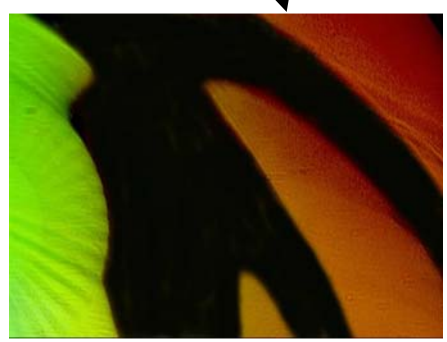


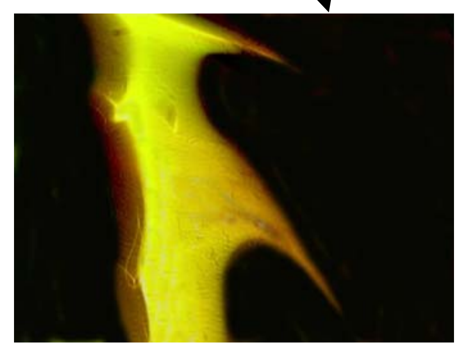
slice #2





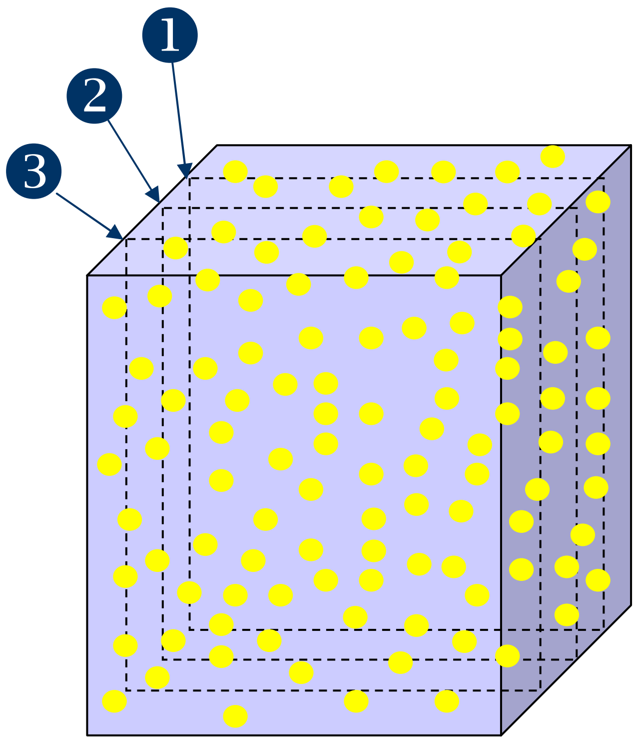
2½D shape



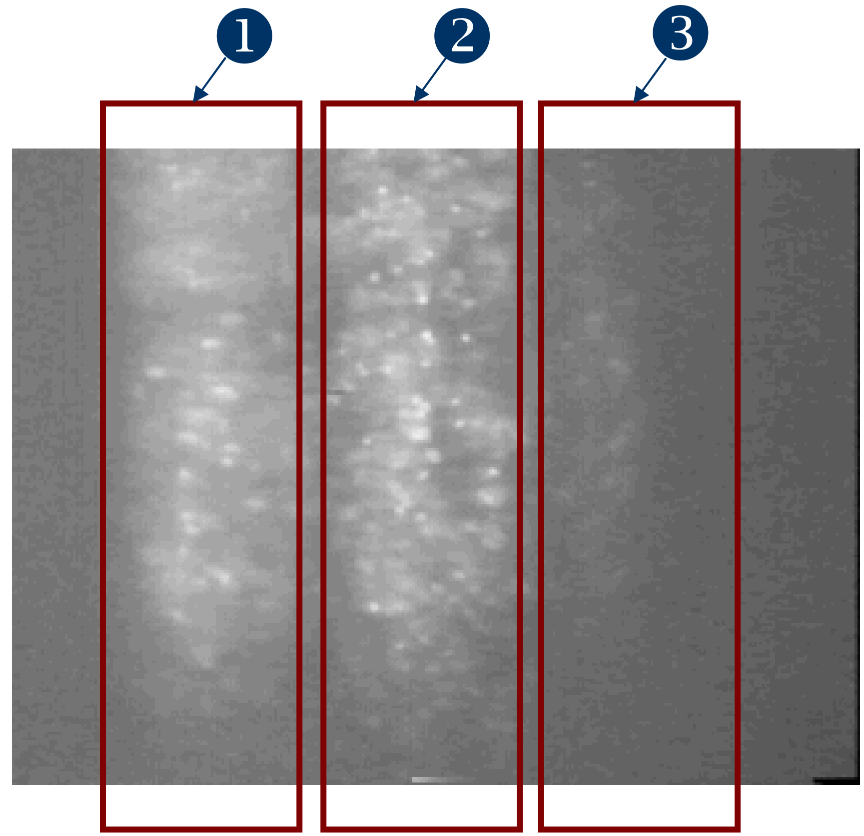


Multiplex imaging of 3D fluorescent object

three "slices" through fluorescent (3D) object, stacked along **longitudinal** direction …



… are viewed **simultaneously** and **side-by-side** on the digital camera



3D object:

fluorescent beads in water

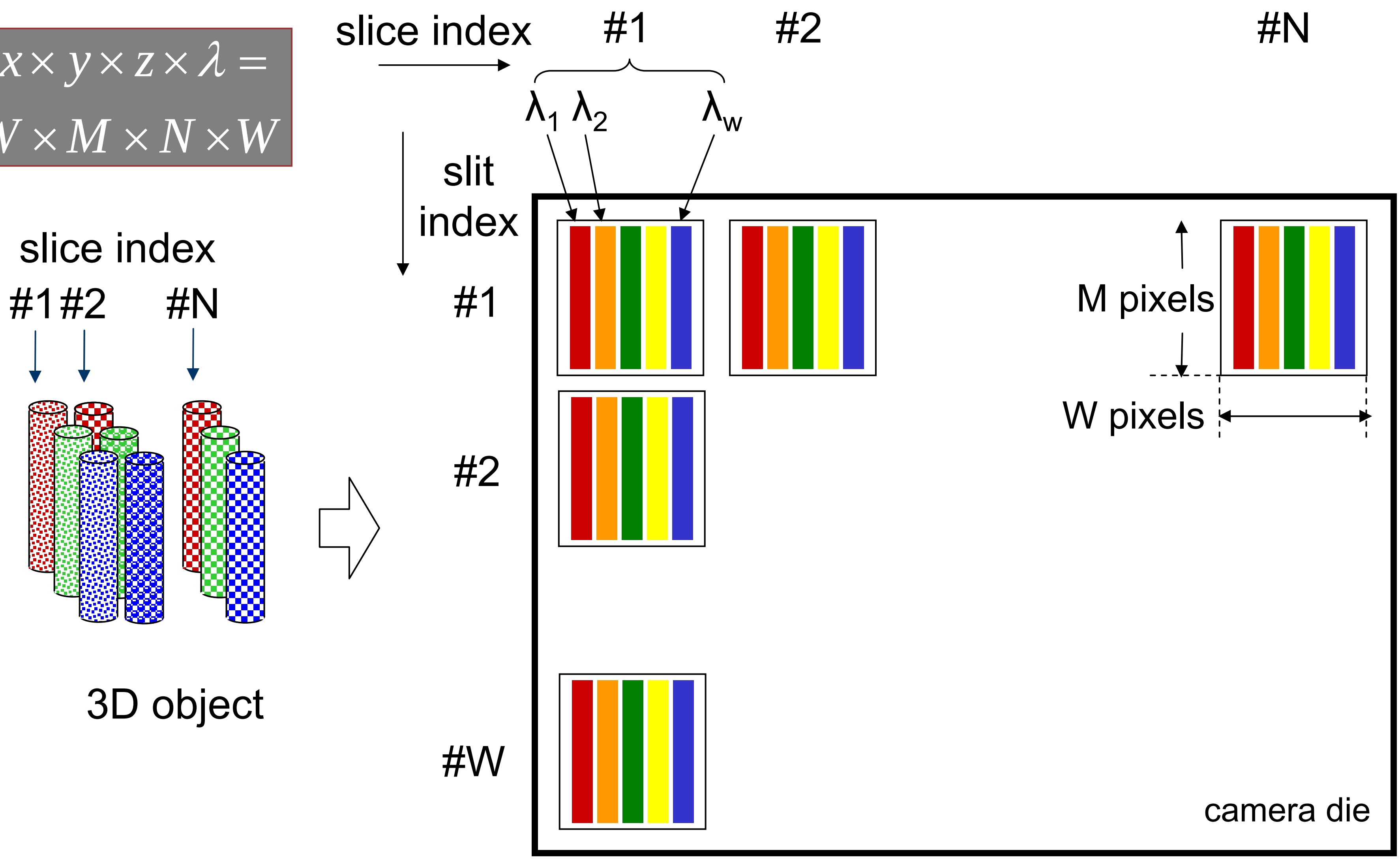
Wenhai Liu,* Demetri Psaltis,* George Barbastathis**

*Caltech Optical Info. Proc. group **MIT 3D Optical Systems group

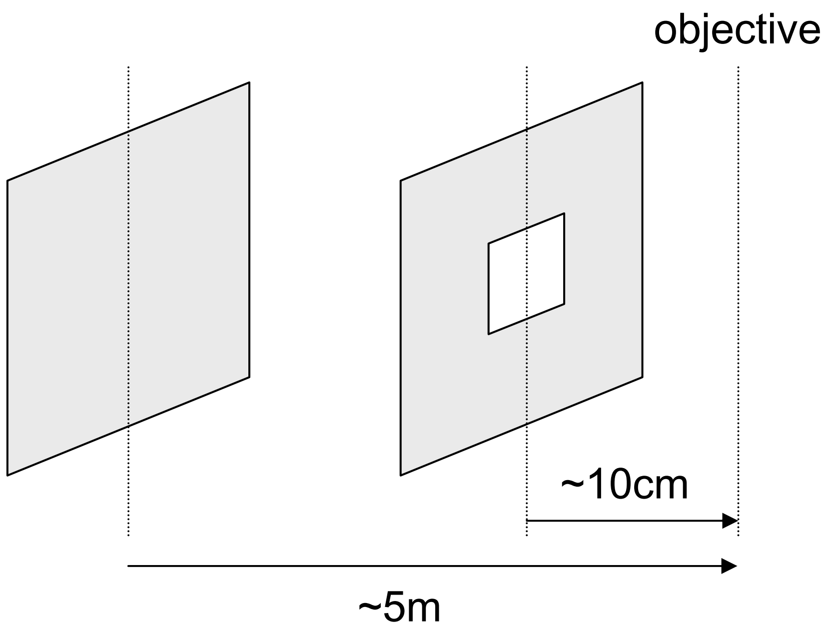
Optics Letters **27**:854, 2002

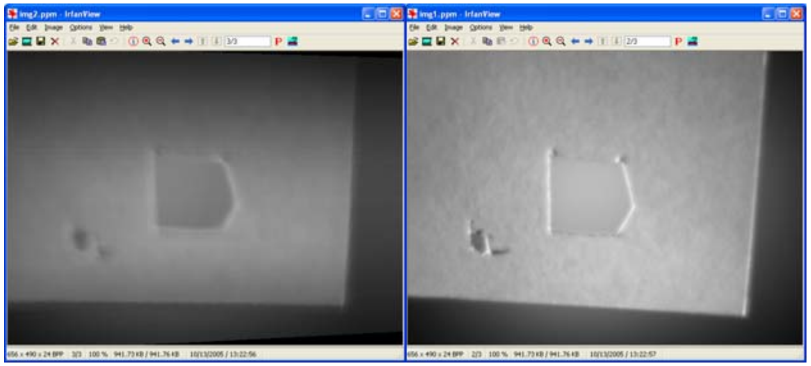
Camera pixel layout for 4D (3D spatial + spectral) imaging

$$x \times y \times z \times \lambda = W \times M \times N \times W$$



Sun Light (completely passive) illumination

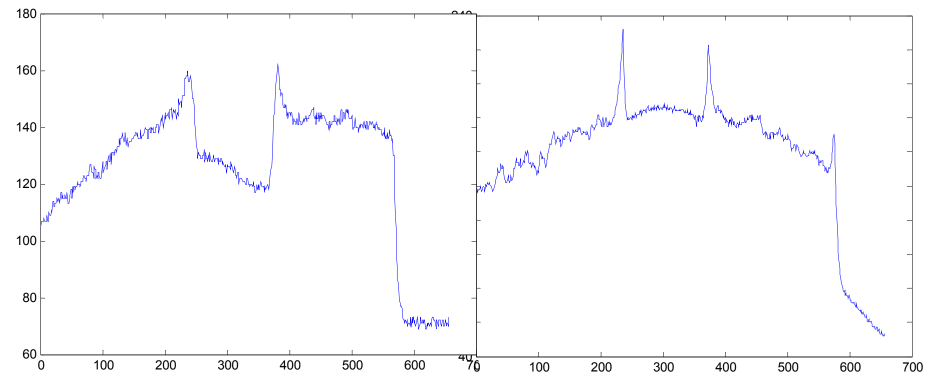




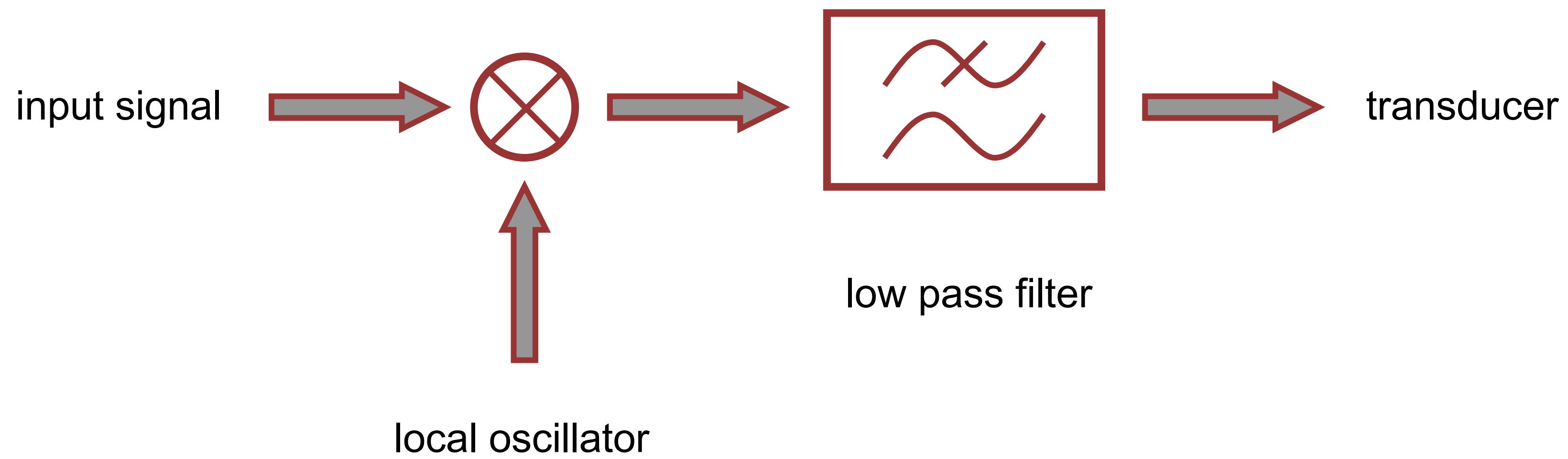
3D optical image

traditional camera

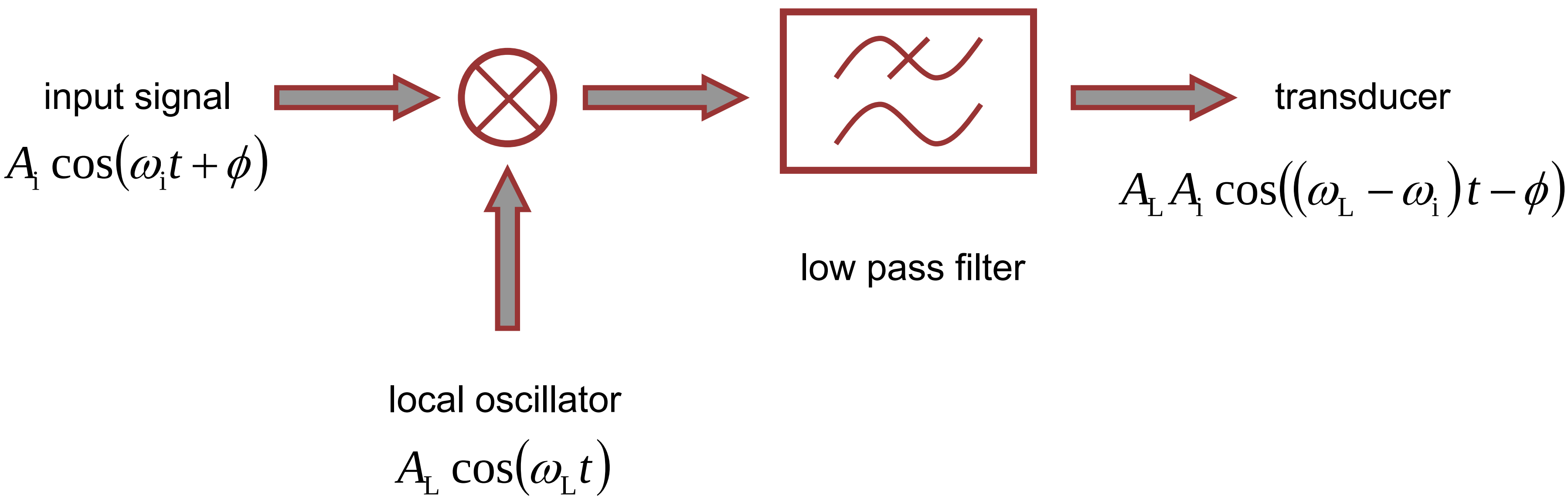
irradiance across image cross-section



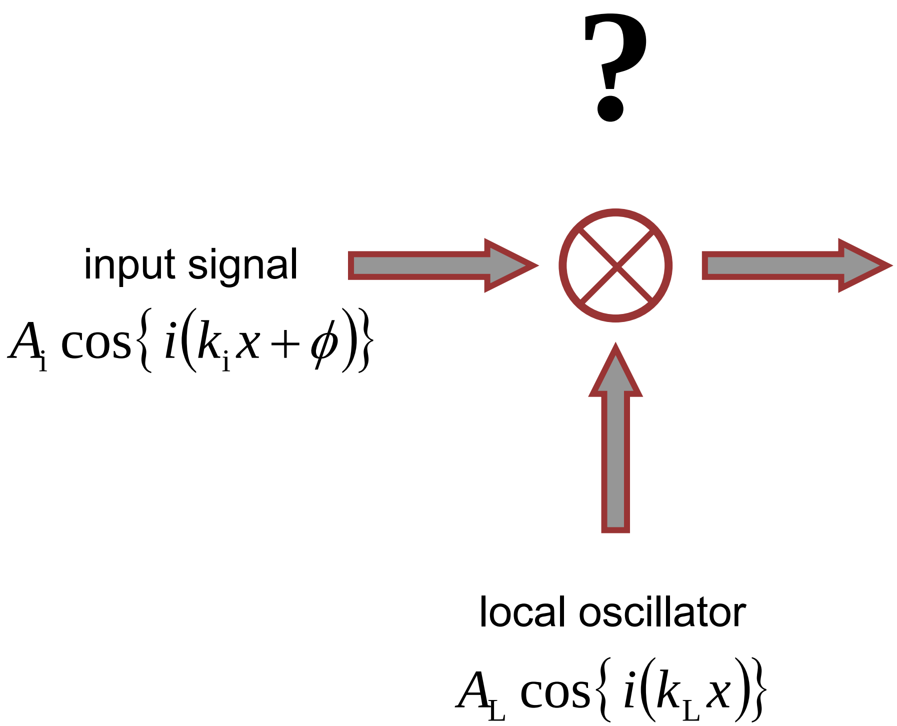
Temporal Heterodyning



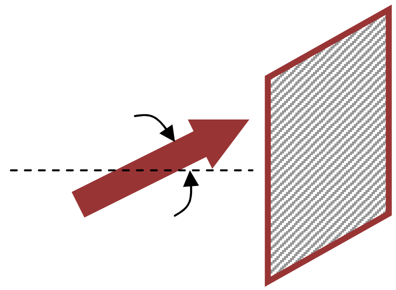
Temporal Heterodyning



1D Spatial Heterodyning

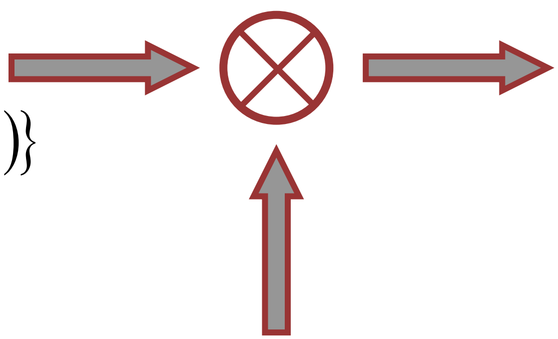


1D Spatial Heterodyning



input signal

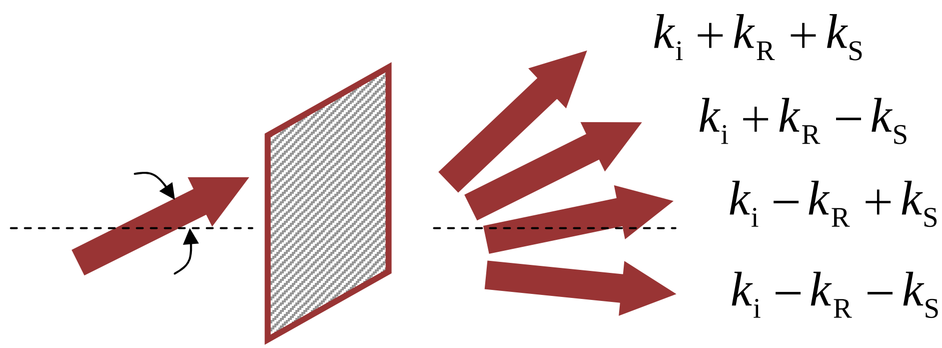
$$A_{\mathrm{i}} \exp\left\{ i\left(k_{\mathrm{i}} x + \phi\right)\right\}$$



local oscillator

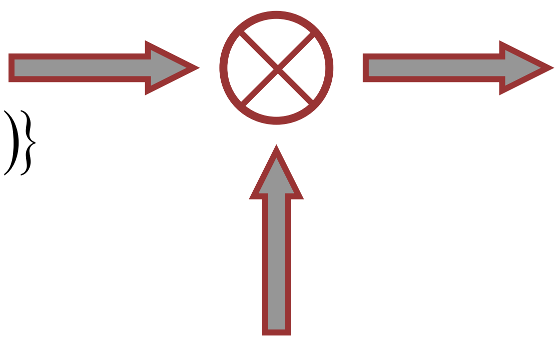
$$\left| A_{\mathrm{R}} \exp\left(i k_{\mathrm{R}} x\right) + A_{\mathrm{S}} \exp\left(i k_{\mathrm{S}} x + \phi_{\mathrm{S}}\right)\right|^2$$

1D Spatial Heterodyning



input signal

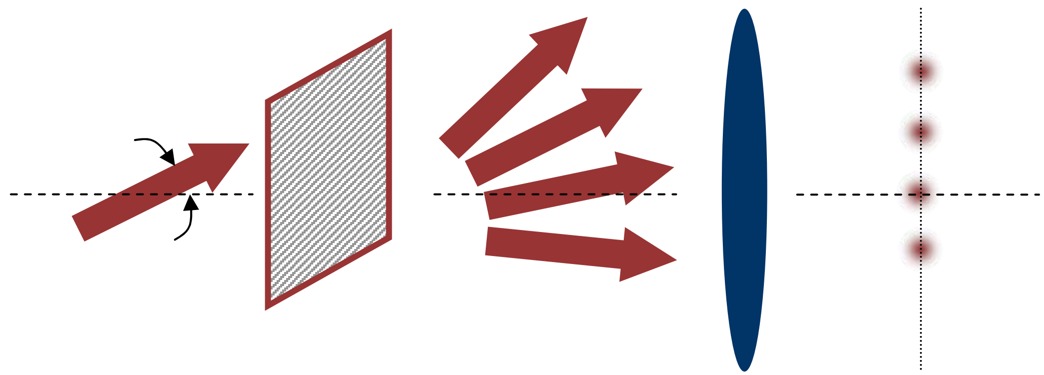
$A_i \exp\{ i(k_i x + \phi)\}$

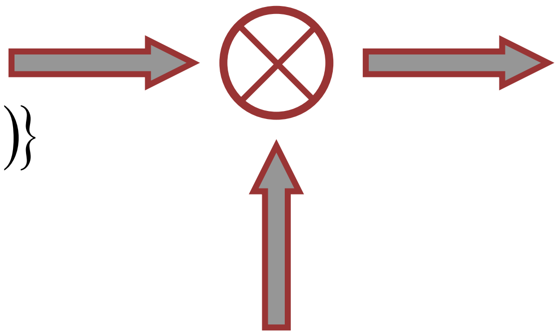


local oscillator

$\left| A_R \exp(ik_R x) + A_S \exp(ik_S x + \phi_S) \right|^2$

1D Spatial Heterodyning





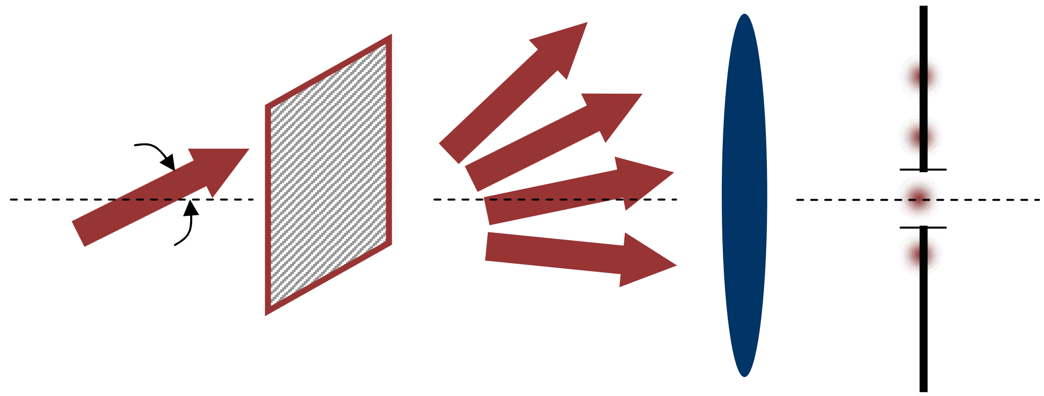
input signal

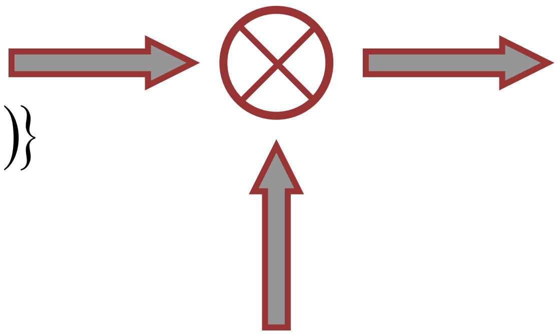
$$A_\mathrm{i}\exp\{i(k_\mathrm{i}x+\phi)\}$$

local oscillator

$$\left|A_\mathrm{R}\exp(ik_\mathrm{R}x)+A_\mathrm{S}\exp(ik_\mathrm{S}x+\phi_\mathrm{S})\right|^2$$

1D Spatial Heterodyning





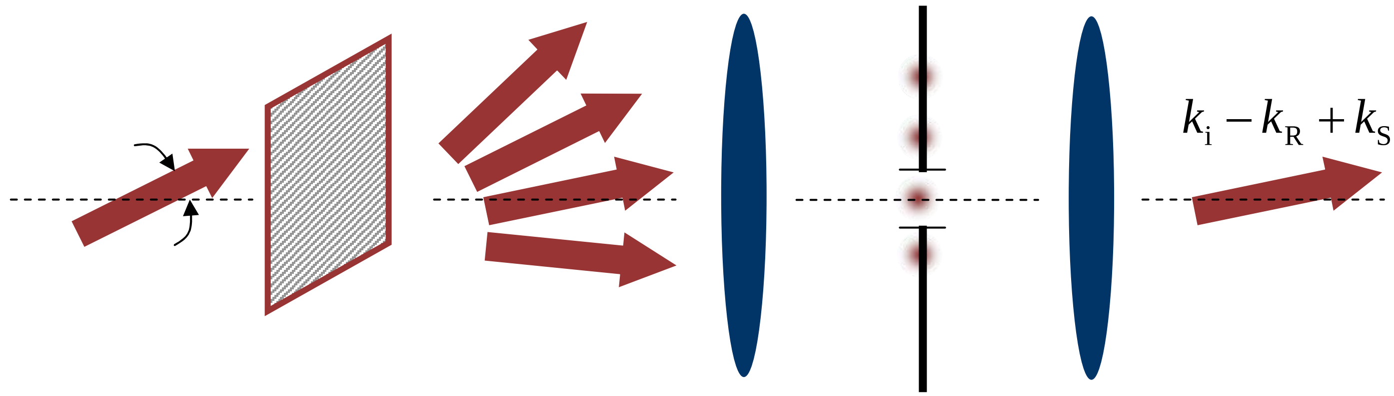
input signal

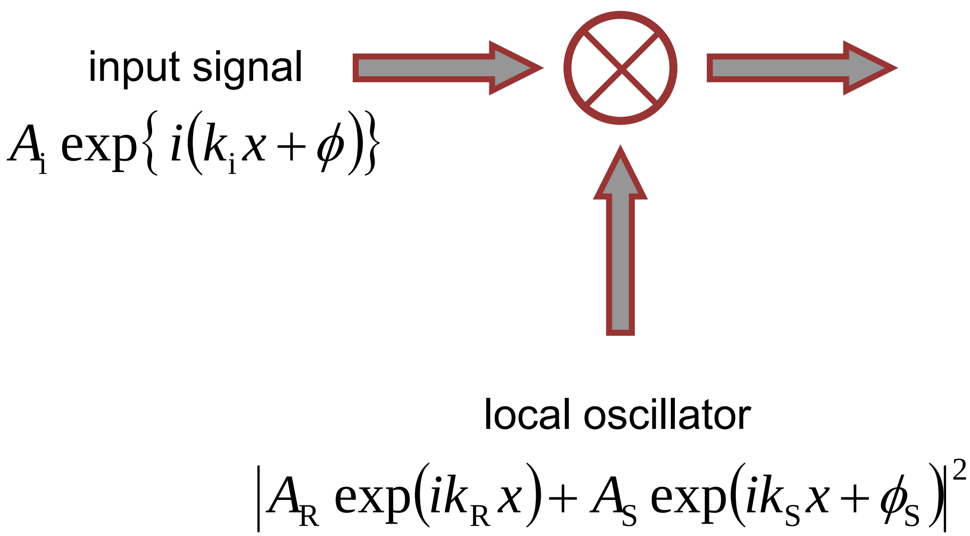
$$A_{\mathrm{i}} \exp\left\{ i\left(k_{\mathrm{i}} x + \phi\right)\right\}$$

local oscillator

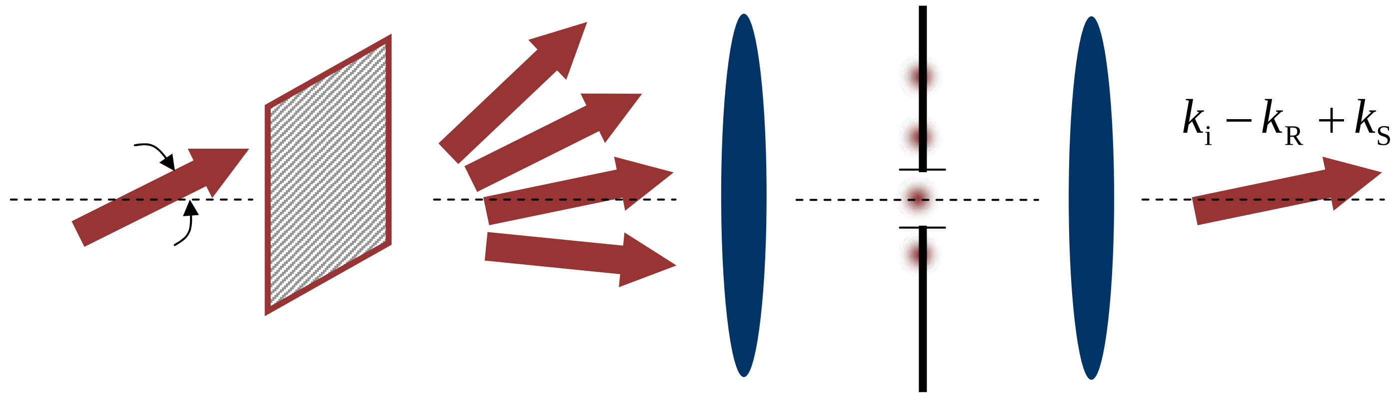
$$\left|A_{\mathrm{R}} \exp\left(ik_{\mathrm{R}} x\right) + A_{\mathrm{S}} \exp\left(ik_{\mathrm{S}} x + \phi_{\mathrm{S}}\right)\right|^2$$

1D Spatial Heterodyning



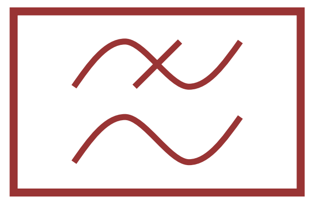


1D Spatial Heterodyning



input signal

$$A_i \exp\{ i(k_i x + \phi)\}$$



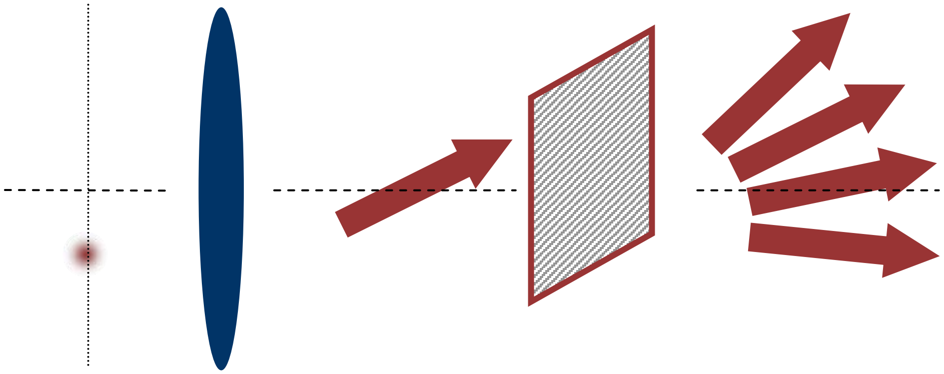
low pass filter

local oscillator

$$\left| A_R \exp(ik_R x) + A_S \exp(ik_S x + \phi_S) \right|^2$$

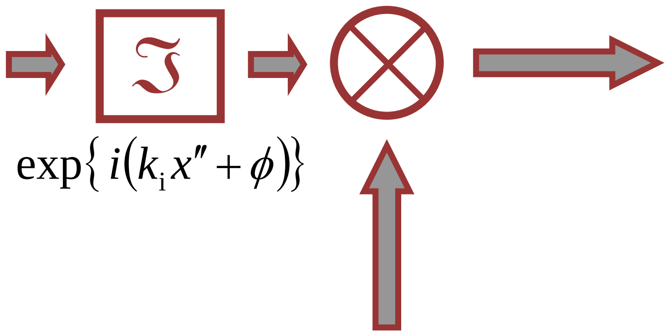
$$A_i A_R A_S \exp\left\{ i \begin{bmatrix} (k_i - k_R + k_S)x' \\ +(\phi + \phi_S) \end{bmatrix} \right\}$$

1D Spatial Heterodyning in the Fourier domain



input signal

$$\delta\left(x-\frac{\lambda f k_{\mathrm{i}}}{2\pi}\right)$$

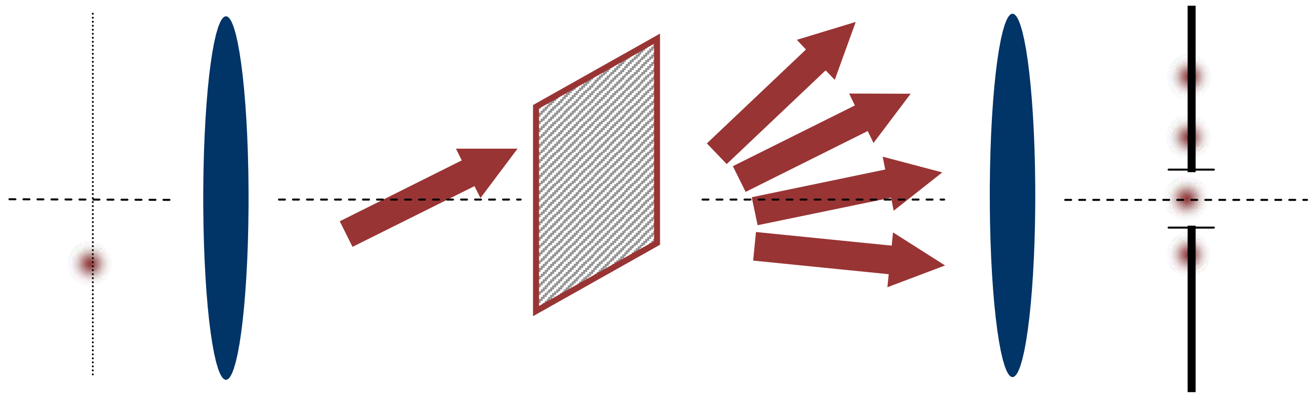


$$\exp\left\{i\left(k_{\mathrm{i}}x''+\phi\right)\right\}$$

local oscillator

$$\left|A_{\mathrm{R}}\exp\left(ik_{\mathrm{R}}x''\right)+A_{\mathrm{S}}\exp\left(ik_{\mathrm{S}}x''+\phi_{\mathrm{S}}\right)\right|^2$$

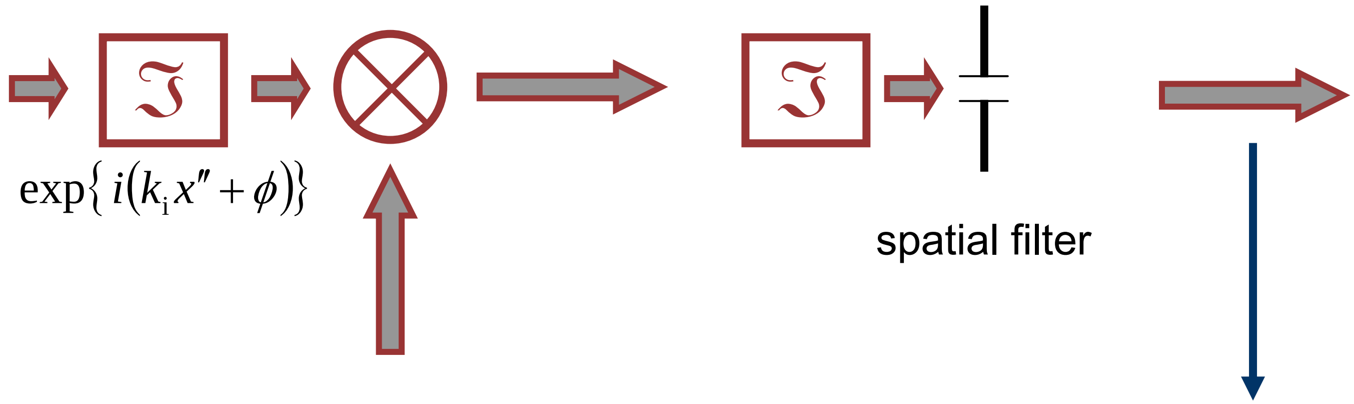
1D Spatial Heterodyning in the Fourier domain



input signal

$$\delta\left(x - \frac{\lambda f k_i}{2\pi}\right)$$

$$\exp\{i(k_i x'' + \phi)\}$$



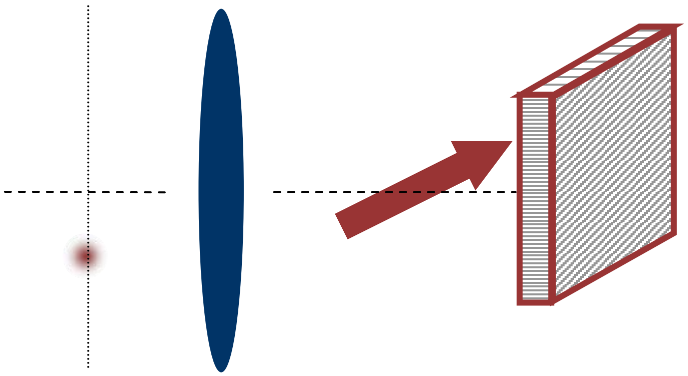
spatial filter

local oscillator

$$\left|A_R \exp(ik_R x'') + A_S \exp(ik_S x'' + \phi_S)\right|^2$$

$$\delta\left[x' - \frac{\lambda f\left(k_i - k_R + k_S\right)}{2\pi}\right]$$

3D Spatial Heterodyning in the Fourier domain



input signal $\rightarrow \boxed{\mathfrak{I}} \rightarrow$ **?** $\longrightarrow$

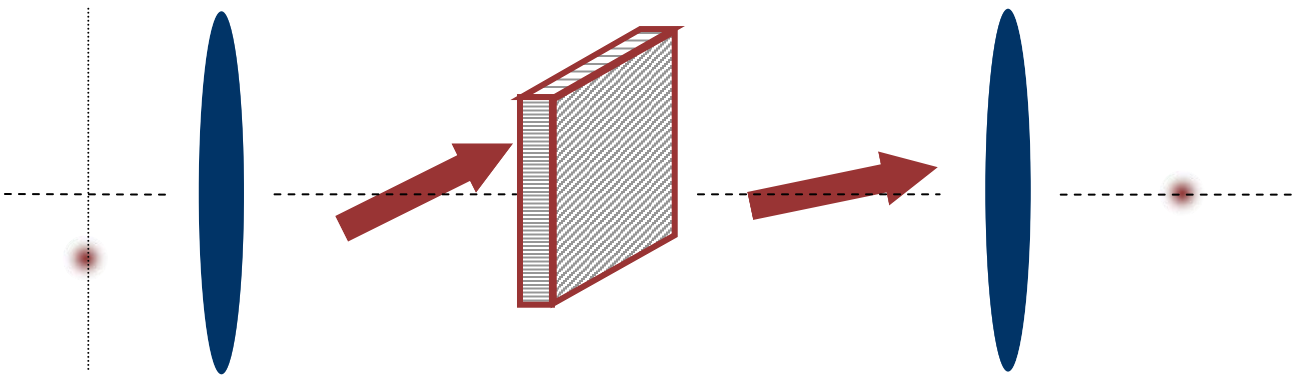
$\delta\left(x-\dfrac{\lambda f k_{\mathrm{i}}}{2\pi}\right)$ $\exp\left\{i\left(\mathbf{k}_{\mathrm{i}}\cdot\mathbf{r}''+\phi\right)\right\}$

$\uparrow$

local oscillator

$$\left|A_{\mathrm{R}}\exp\left(i\mathbf{k}_{\mathrm{R}}\cdot\mathbf{r}''\right)+A_{\mathrm{S}}\exp\left(i\mathbf{k}_{\mathrm{S}}\cdot\mathbf{r}''+\phi_{\mathrm{S}}\right)\right|^{2}$$

3D Spatial Heterodyning in the Fourier domain



input signal $\rightarrow \boxed{\mathfrak{I}} \rightarrow$? $\rightarrow$

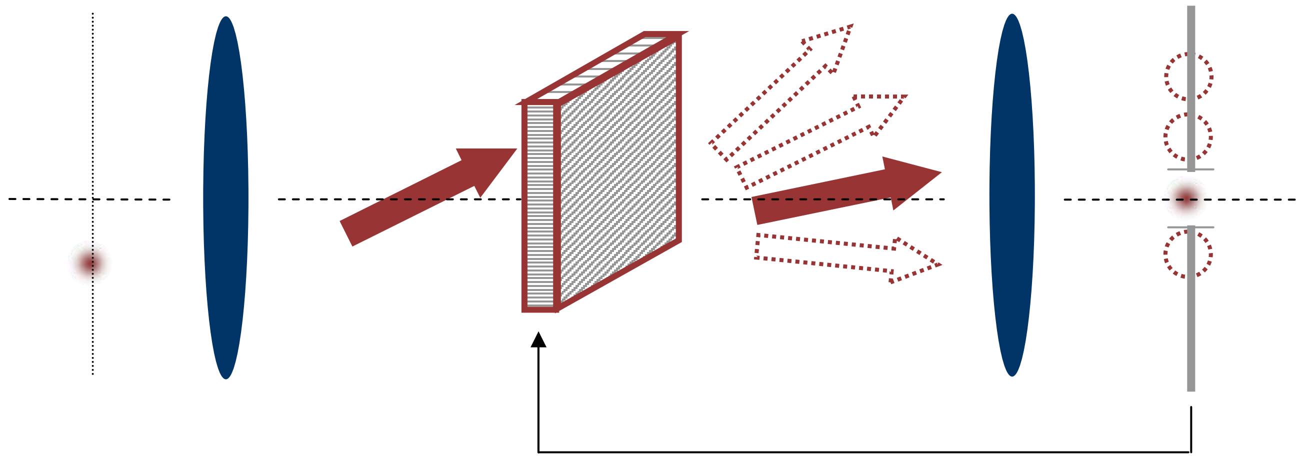
$$\delta\left(x-\frac{\lambda f k_{\mathrm{i}}}{2\pi}\right) \qquad \exp\left\{i\left(\mathbf{k}_{\mathrm{i}}\cdot\mathbf{r}''+\phi\right)\right\}$$

local oscillator

$$\left|A_{\mathrm{R}}\exp\left(i\mathbf{k}_{\mathrm{R}}\cdot\mathbf{r}''\right)+A_{\mathrm{S}}\exp\left(i\mathbf{k}_{\mathrm{S}}\cdot\mathbf{r}''+\phi_{\mathrm{S}}\right)\right|^{2}$$

$$\delta\left[x'-\frac{\lambda f\left(k_{\mathrm{i}}-k_{\mathrm{R}}+k_{\mathrm{S}}\right)}{2\pi}\right]$$

3D Spatial Heterodyning in the Fourier domain



input signal $\rightarrow \boxed{\mathfrak{I}} \rightarrow$ **?** $\rightarrow$ $\rightarrow$

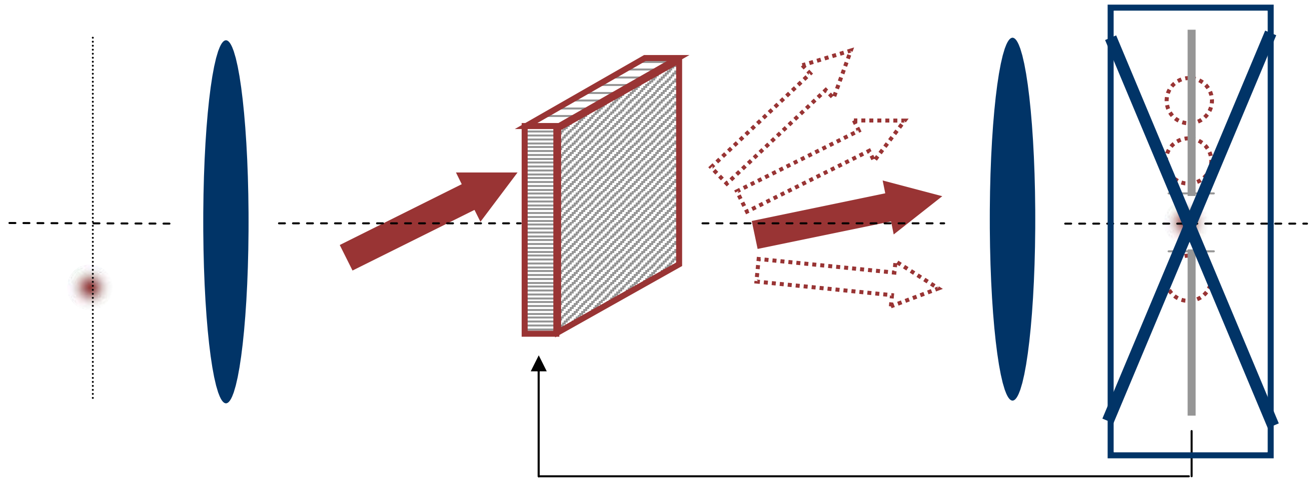
$$\delta\left(x - \frac{\lambda f k_{\mathrm{i}}}{2\pi}\right) \qquad \exp\left\{i\left(\mathbf{k}_{\mathrm{i}} \cdot \mathbf{r}'' + \phi\right)\right\}$$

local oscillator

$$\left|A_{\mathrm{R}} \exp\left(i\mathbf{k}_{\mathrm{R}} \cdot \mathbf{r}''\right) + A_{\mathrm{S}} \exp\left(i\mathbf{k}_{\mathrm{S}} \cdot \mathbf{r}'' + \phi_{\mathrm{S}}\right)\right|^2$$

$$\delta\left[x' - \frac{\lambda f\left(k_{\mathrm{i}} - k_{\mathrm{R}} + k_{\mathrm{S}}\right)}{2\pi}\right]$$

3D Spatial Heterodyning in the Fourier domain



input signal $\boxed{\mathfrak{I}}$?

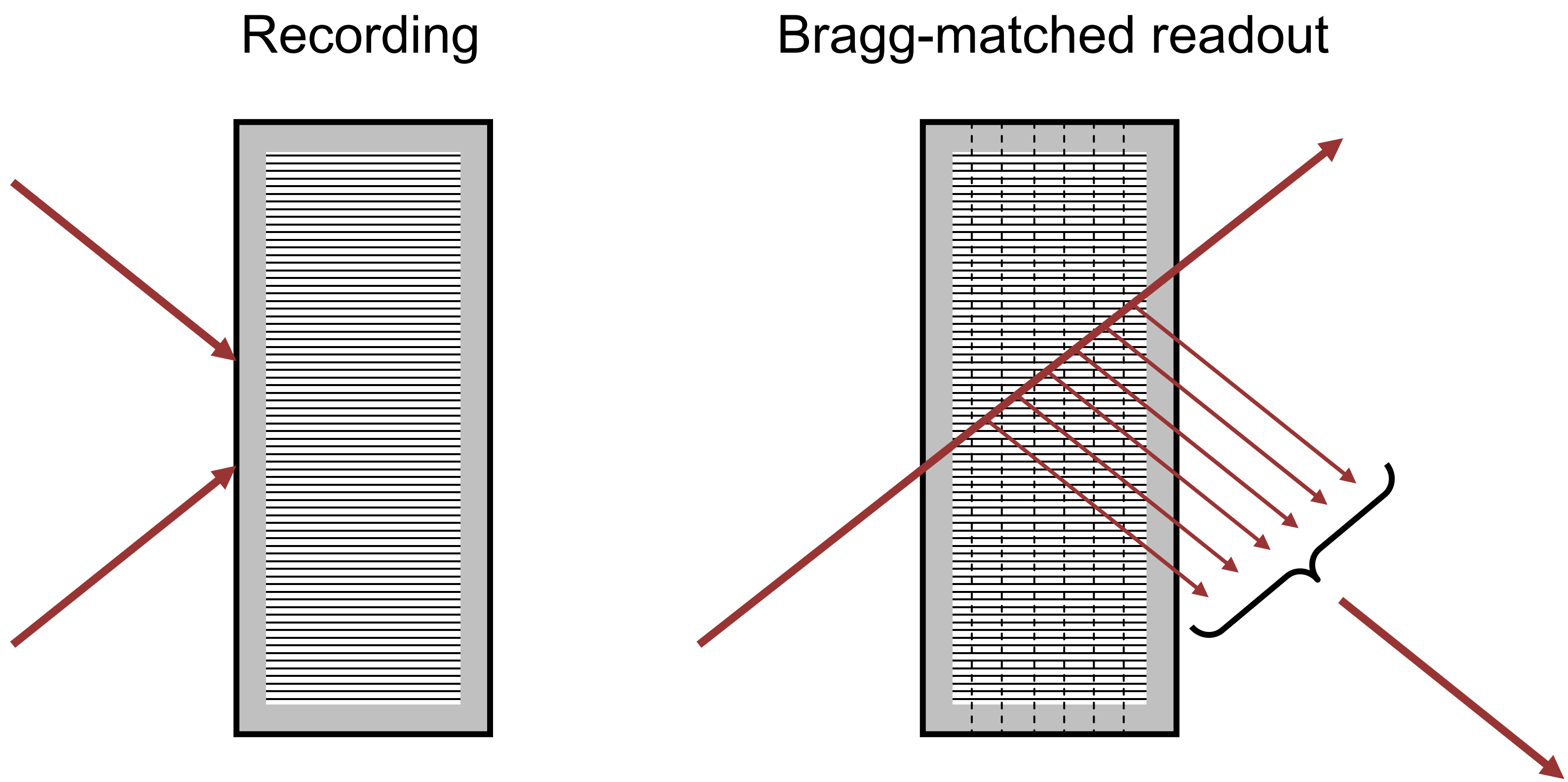
$$\delta\left(x - \frac{\lambda f k_{\mathrm{i}}}{2\pi}\right) \qquad \exp\left\{ i\left(\mathbf{k}_{\mathrm{i}} \cdot \mathbf{r}'' + \phi\right)\right\}$$

local oscillator

$$\left| A_{\mathrm{R}} \exp\left(i\mathbf{k}_{\mathrm{R}} \cdot \mathbf{r}''\right) + A_{\mathrm{S}} \exp\left(i\mathbf{k}_{\mathrm{S}} \cdot \mathbf{r}'' + \phi_{\mathrm{S}}\right)\right|^2$$

$$\delta\left[x' - \frac{\lambda f\left(k_{\mathrm{i}} - k_{\mathrm{R}} + k_{\mathrm{S}}\right)}{2\pi}\right]$$

Phase matching as a filter for 3D spatial heterodyning

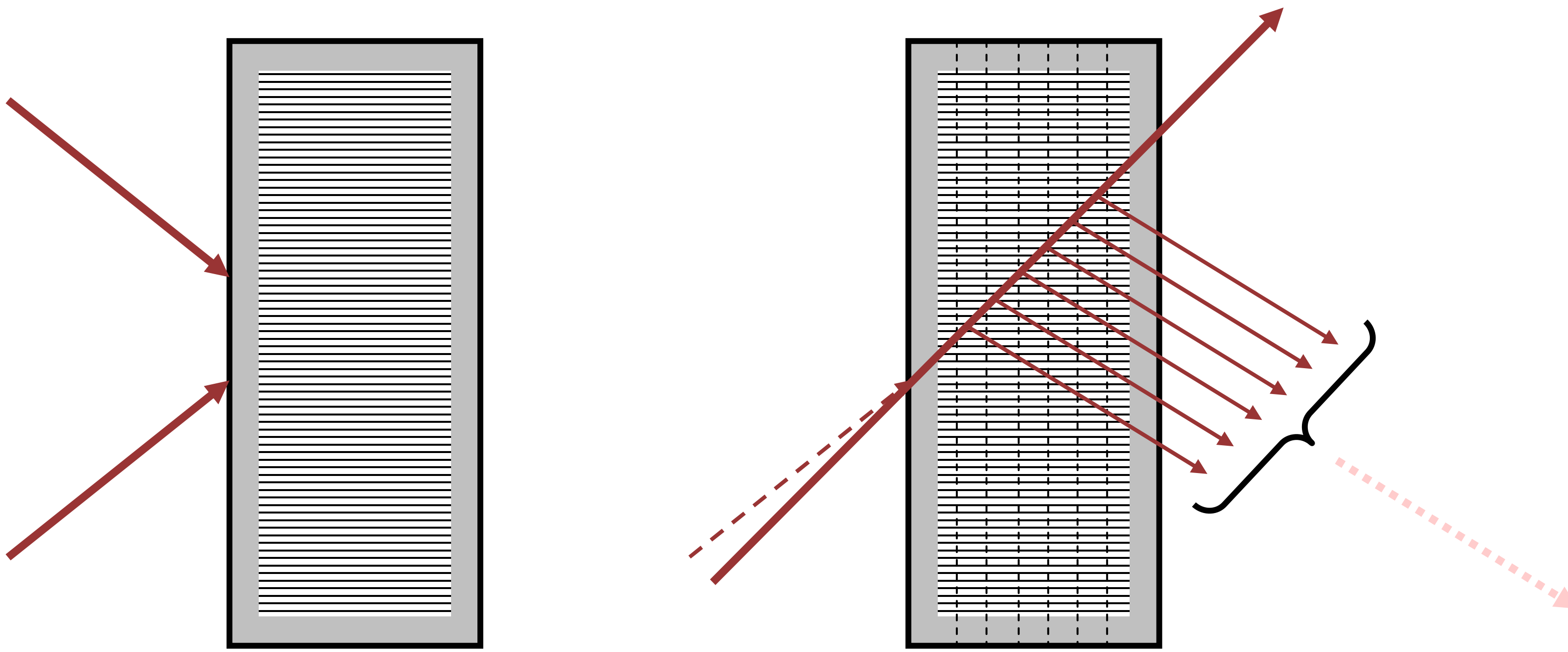


Diffracted beams from elemental thin slices are all **in phase** → strong diffraction

Phase matching as a filter for 3D spatial heterodyning

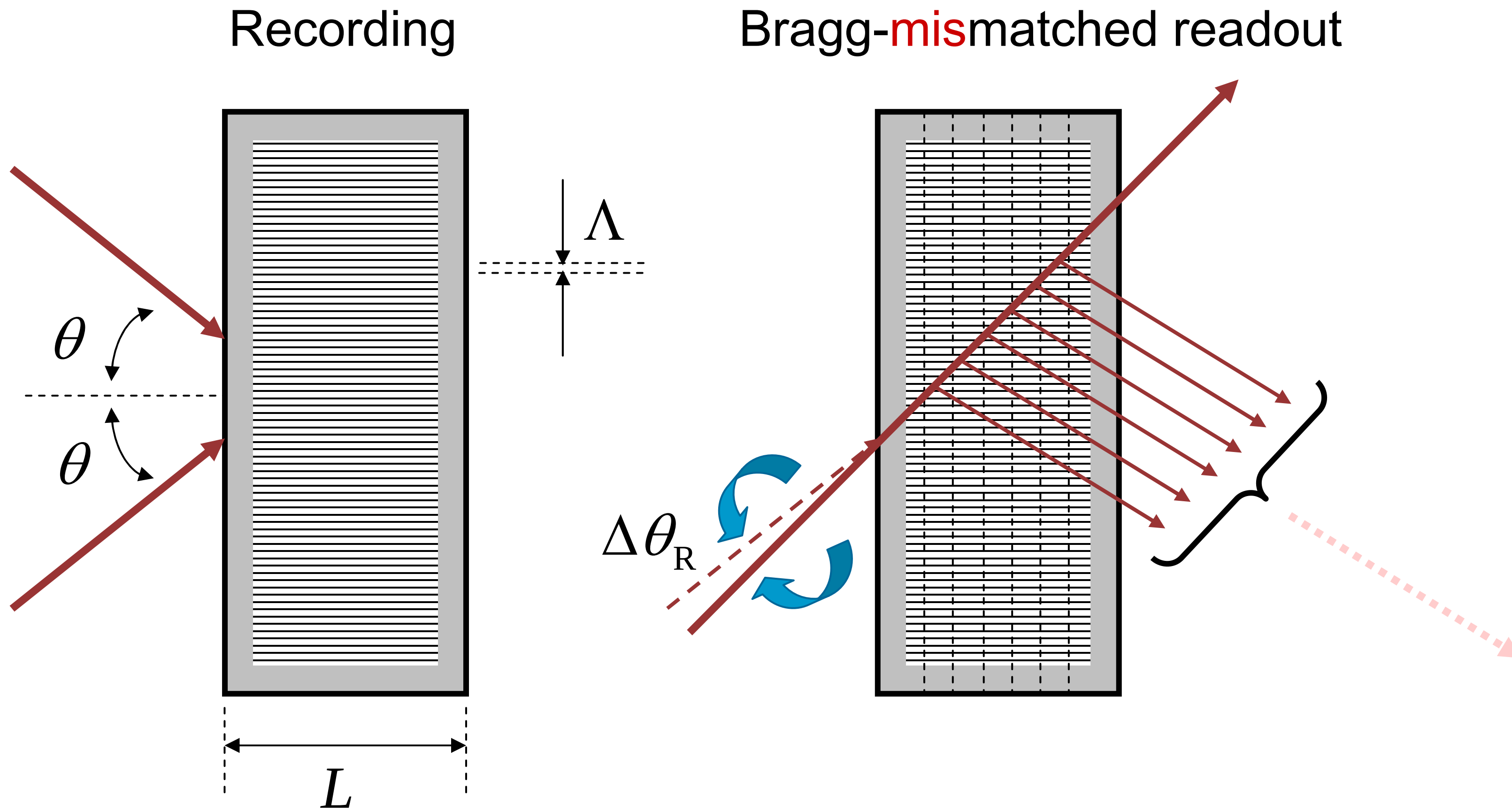
Recording

Bragg-mismatched readout



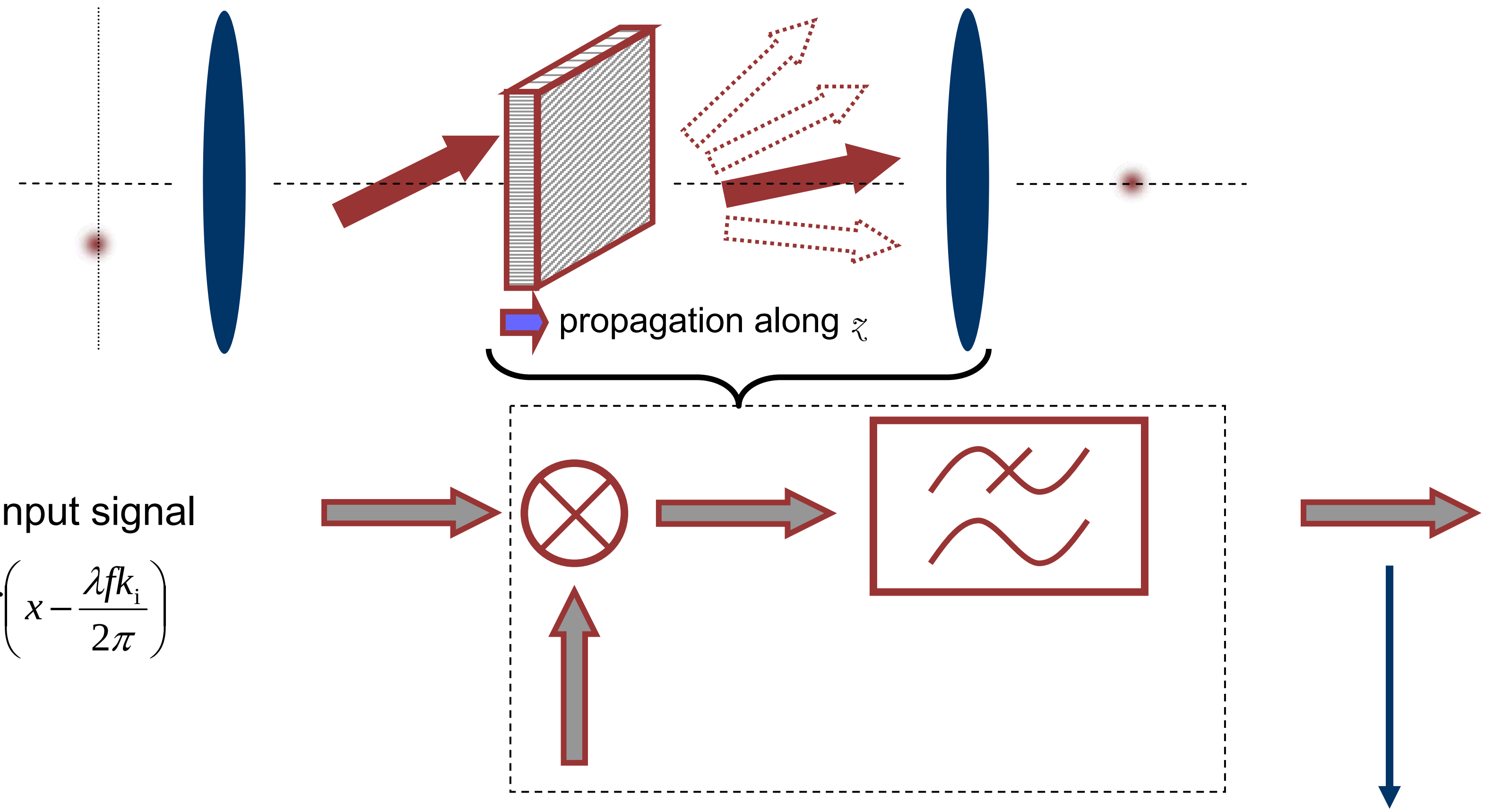
Diffracted beams from elemental thin slices
are **out of phase** → no diffraction

Phase matching as a filter for 3D spatial heterodyning



Angle Bragg selectivity $$\Delta\theta_R = \frac{\Lambda}{L} = \frac{\lambda}{2L\sin\theta}$$

3D Spatial Heterodyning in the Fourier domain



Input signal:

$$\delta\left(x-\frac{\lambda f k_{\mathrm{i}}}{2\pi}\right)$$

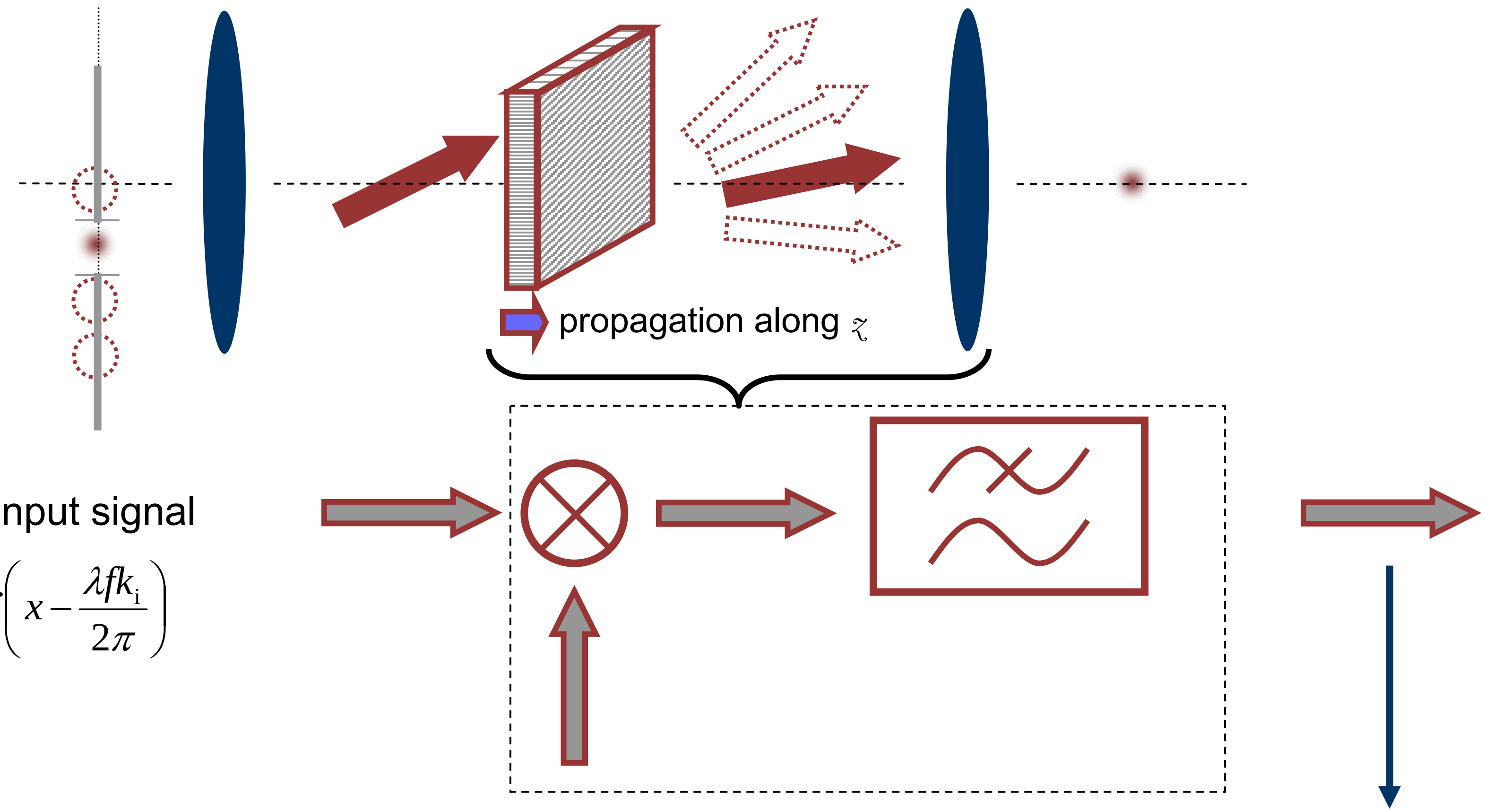
Local oscillator:

$$\left|A_{\mathrm{R}}\exp\left(i\mathbf{k}_{\mathrm{R}}\cdot\mathbf{r}''\right)+A_{\mathrm{S}}\exp\left(i\mathbf{k}_{\mathrm{S}}\cdot\mathbf{r}''+\phi_{\mathrm{S}}\right)\right|^{2}$$

Output:

$$\delta\left[x'-\frac{\lambda f\left(k_{\mathrm{i}}-k_{\mathrm{R}}+k_{\mathrm{S}}\right)}{2\pi}\right]$$

3D Spatial Heterodyning in the Fourier domain



input signal

$$\delta\left(x-\frac{\lambda f k_{\mathrm{i}}}{2\pi}\right)$$

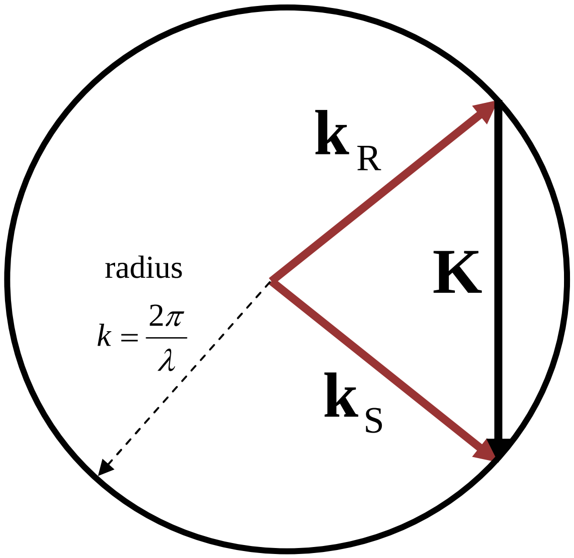
local oscillator

$$\left|A_{\mathrm{R}}\exp\left(i\mathbf{k}_{\mathrm{R}}\cdot\mathbf{r}''\right)+A_{\mathrm{S}}\exp\left(i\mathbf{k}_{\mathrm{S}}\cdot\mathbf{r}''+\phi_{\mathrm{S}}\right)\right|^{2}$$

$$\delta\left[x'-\frac{\lambda f\left(k_{\mathrm{i}}-k_{\mathrm{R}}+k_{\mathrm{S}}\right)}{2\pi}\right]$$

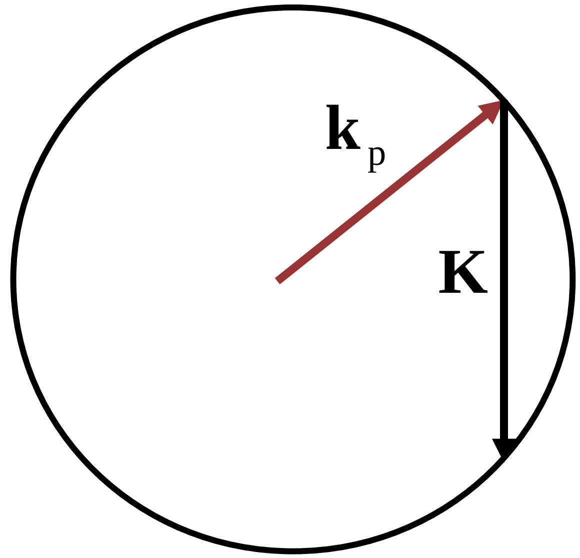
3D Spatial Heterodyning in *k*-space

Recording



$$\mathbf{K} = \mathbf{k}_S - \mathbf{k}_R$$

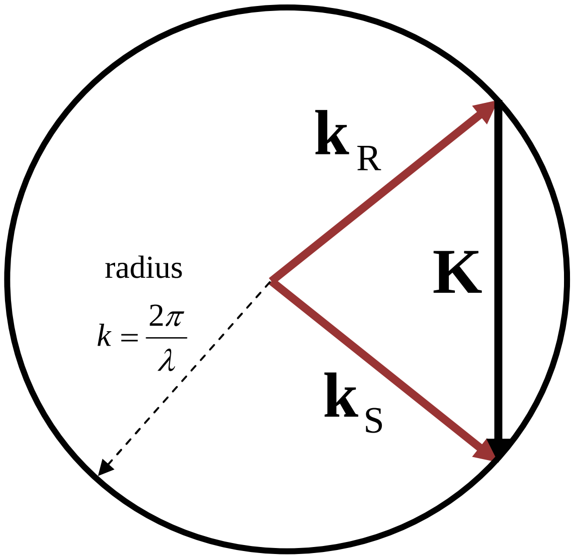
Bragg-matched readout

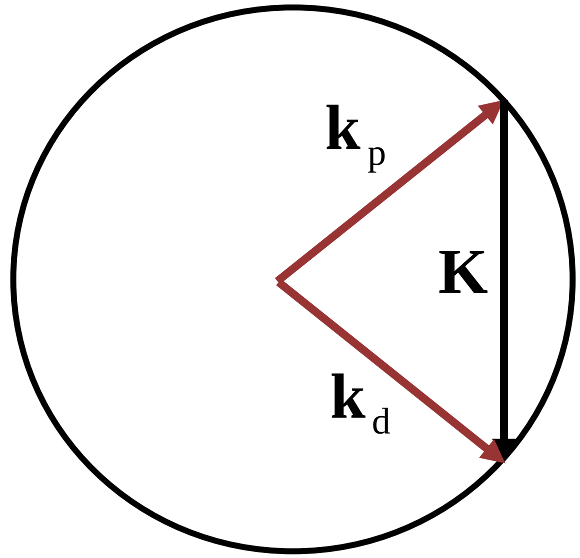


3D Spatial Heterodyning in *k*-space

Recording

Bragg-matched readout

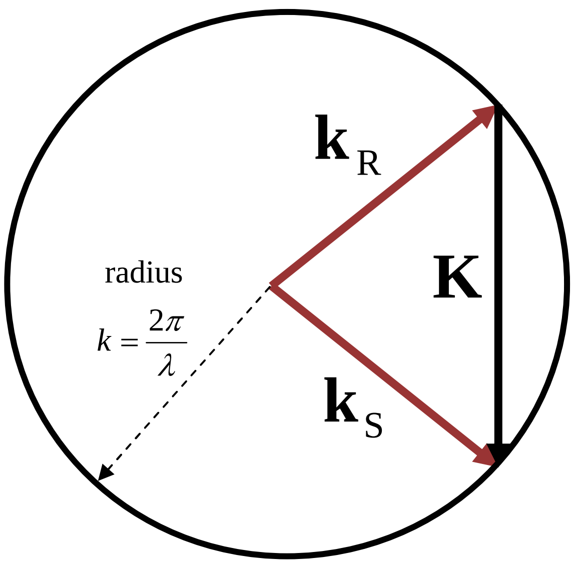




$$\mathbf{K} = \mathbf{k}_S - \mathbf{k}_R \qquad \mathbf{k}_d = \mathbf{k}_R + \mathbf{K}$$

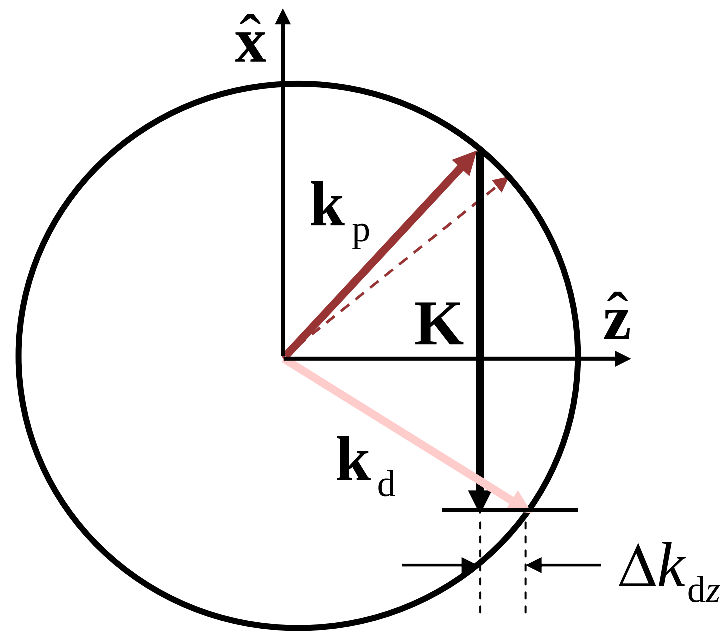
3D Spatial Heterodyning in *k*-space

Recording



$$\mathbf{K}=\mathbf{k}_S-\mathbf{k}_R$$

Bragg-mismatched readout

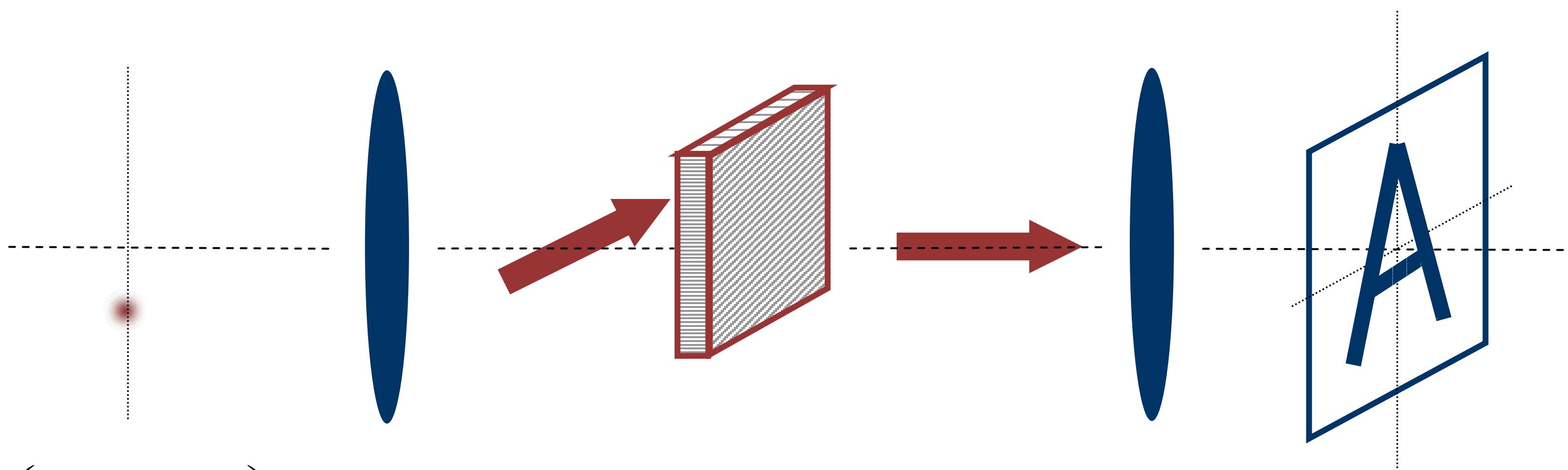


$$\mathbf{k}_d=\left[\left(\mathbf{k}_R+\mathbf{K}\right)\cdot\hat{\mathbf{x}}\right]\hat{\mathbf{x}}+k_{dz}\hat{\mathbf{z}}$$

$$\left\|\mathbf{k}_d\right\|=k$$

$$I_{\text{diffracted}}=I_{\text{Bragg-matched}}\operatorname{sinc}^2\left(\frac{1}{2}\Delta k_{dz}L\right)$$

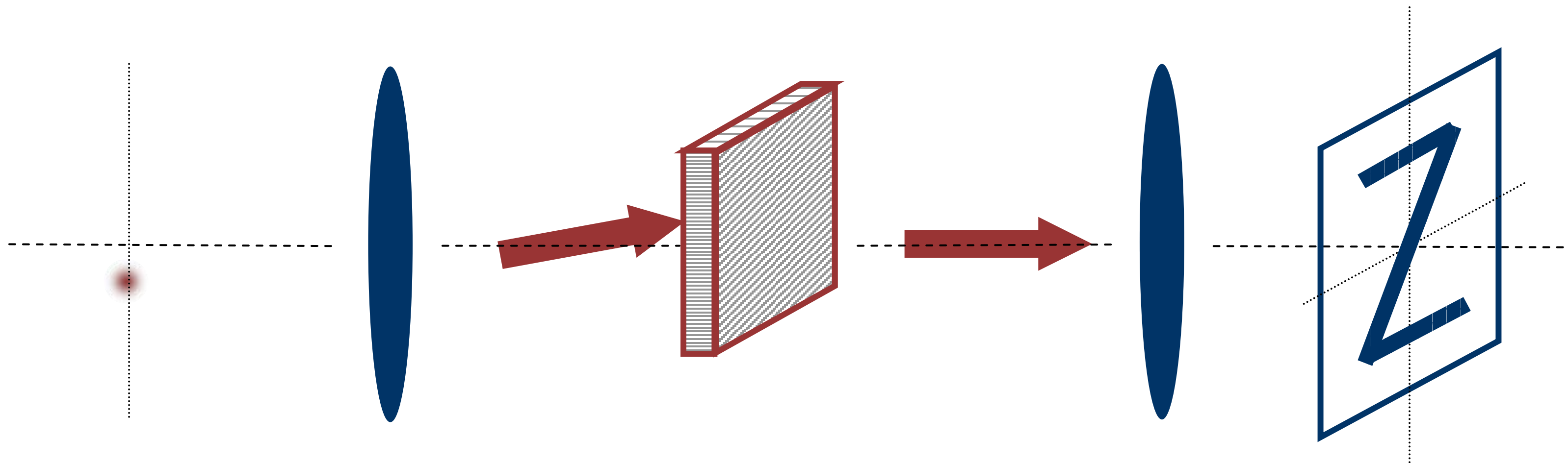
Applications: 3D holographic data storage



$$\delta\left(x-\frac{\lambda f k_{\mathrm{i},m}}{2\pi}\right)$$

$$g_m(x',y')$$

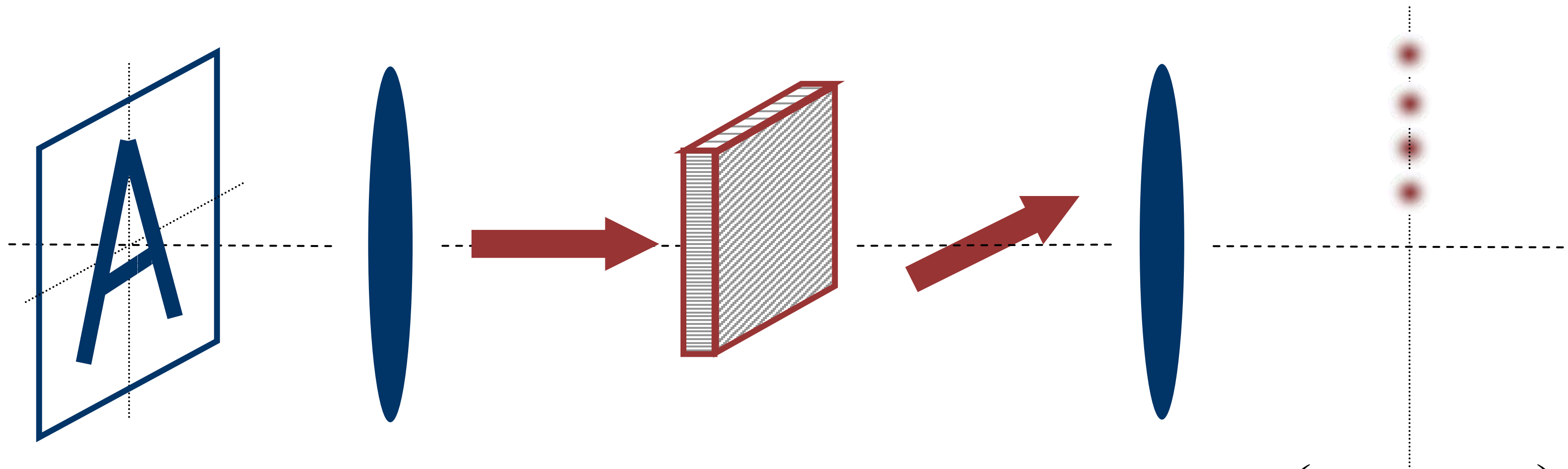
Applications: 3D holographic data storage



$$\delta\left(x-\frac{\lambda f k_{\mathrm{i},n}}{2\pi}\right)$$

$$g_n(x', y')$$

Applications: 3D holographic optical correlators

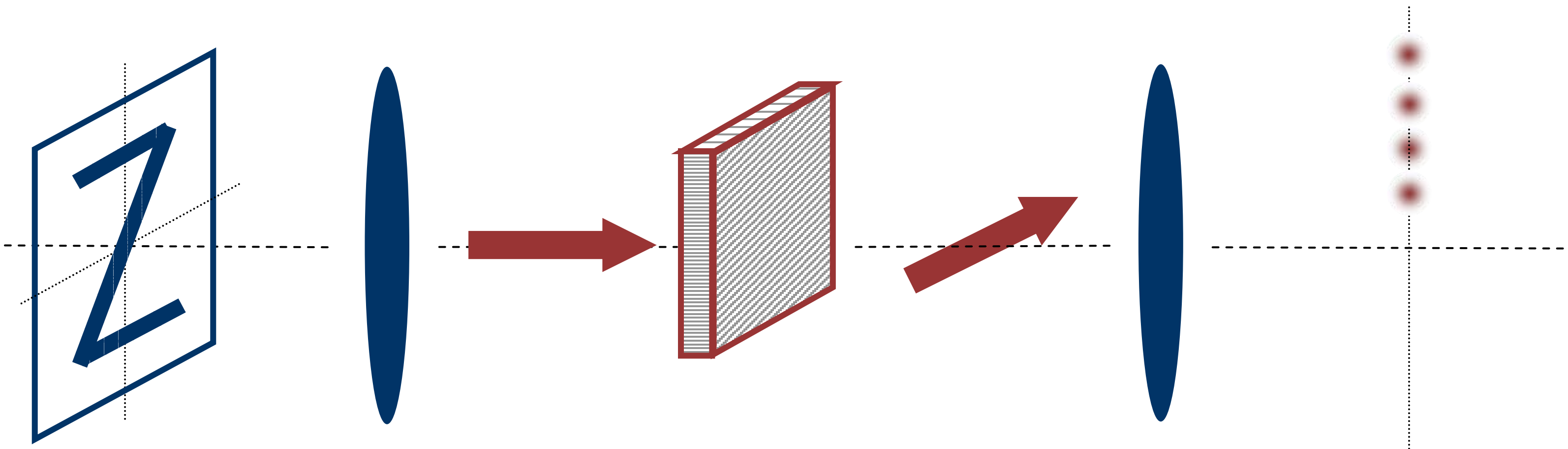


$g_m(x, y)$

$$\delta\left(x' - \frac{\lambda f k_{\mathrm{i},m}}{2\pi}\right)$$

strongest

Applications: 3D holographic optical correlators

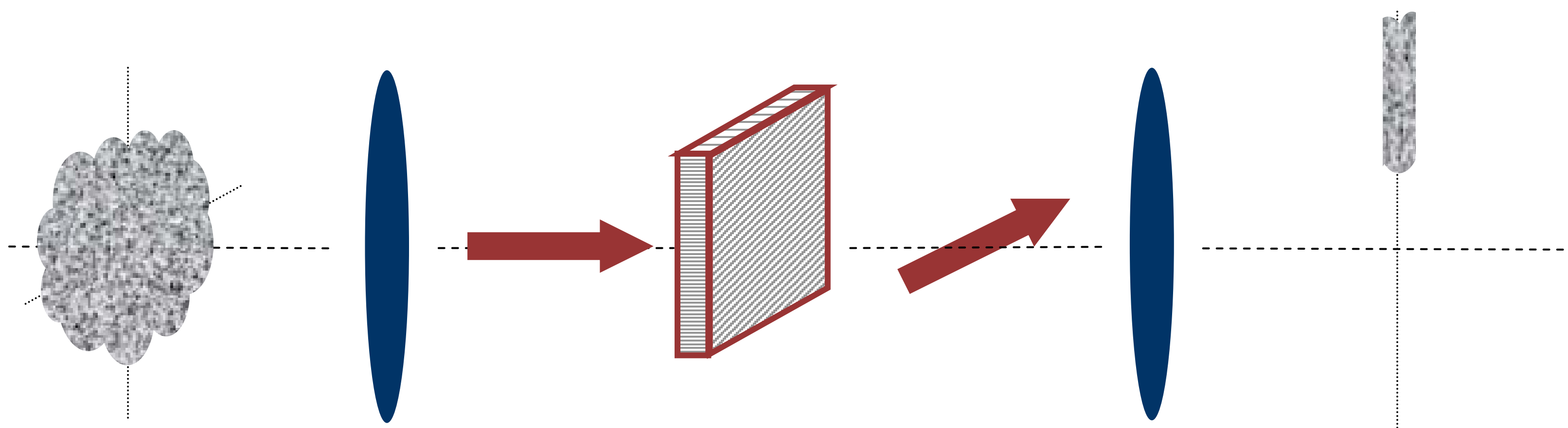


$g_n(x, y)$

$\delta\left(x' - \frac{\lambda f k_{i,n}}{2\pi}\right)$

strongest

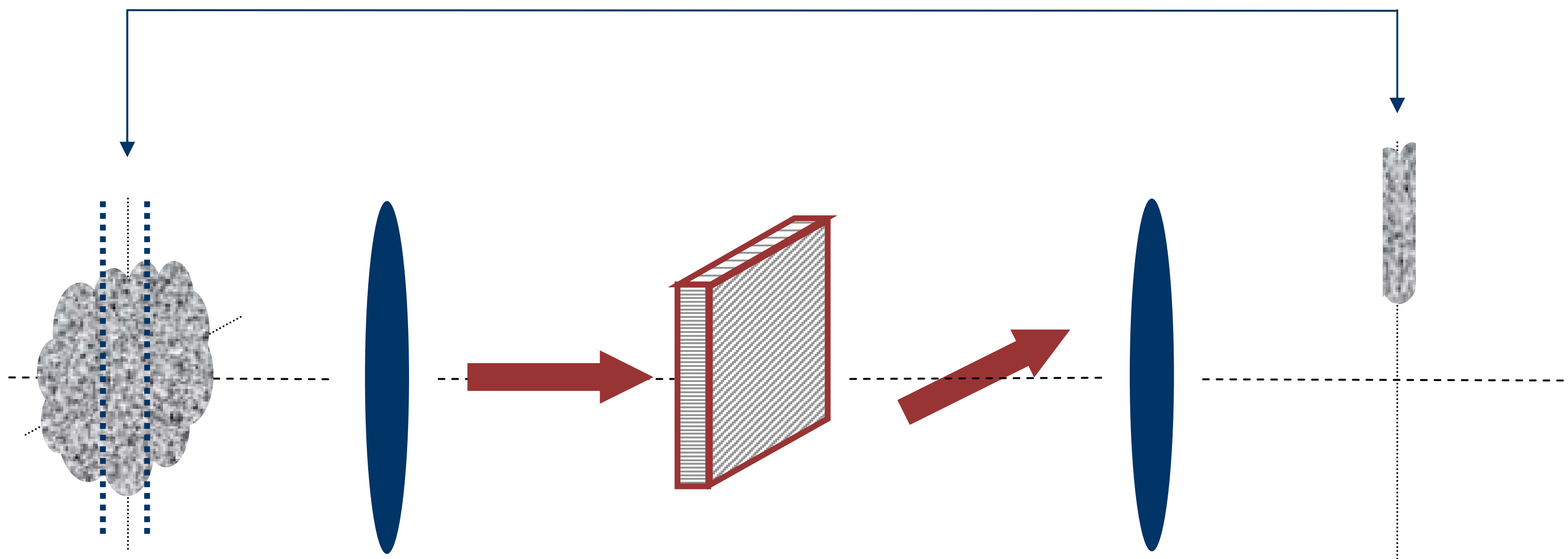
Applications: 3D holographic optical imaging



$$f(x,y,z)$$

$$f\left(x' - \frac{\lambda f k_0}{2\pi}, y', z\right) \times$$
$$\times\, \mathrm{slit}\left(\frac{x'}{\Delta x'}\right) \times \mathrm{slice}\left(\frac{z}{\Delta z}\right)$$

Applications: 3D holographic optical imaging

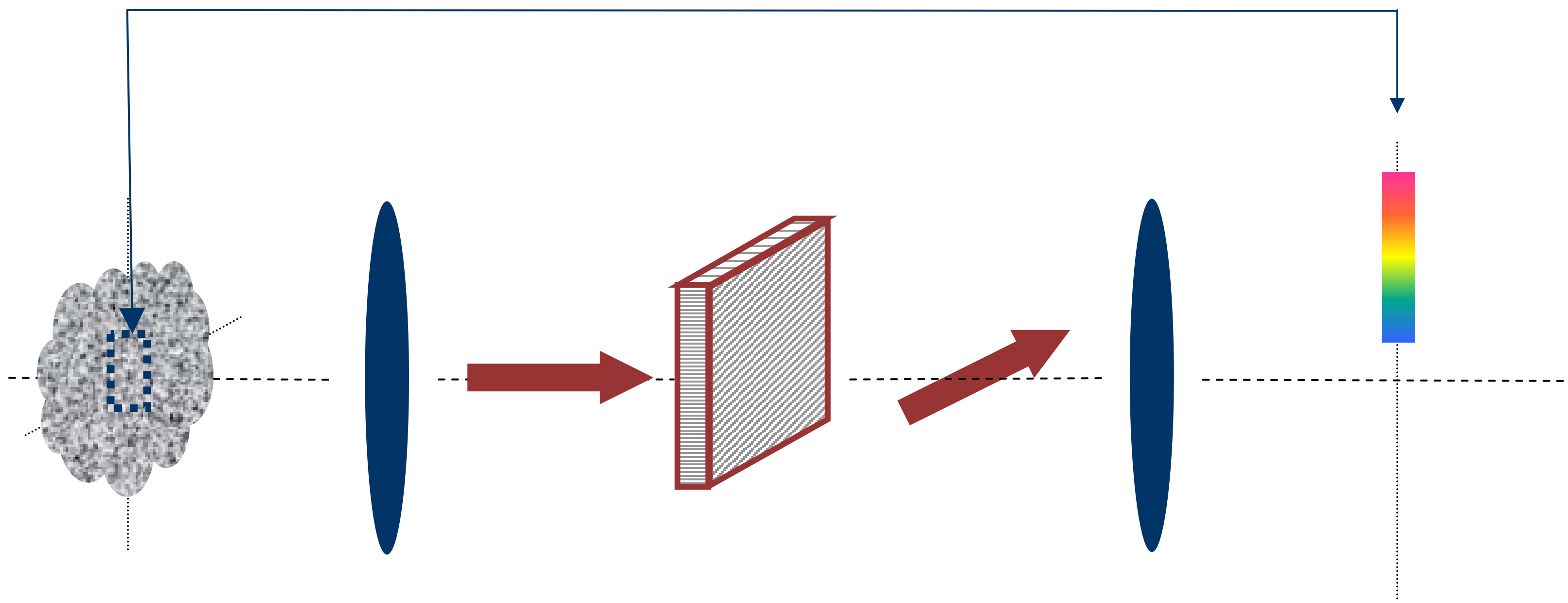


$$f\left(x,y,z\right)$$

$$f\left(x'-\frac{\lambda f k_0}{2\pi},y',z\right)\times$$

$$\times\mathrm{slit}\left(\frac{x'}{\Delta x'}\right)\times\mathrm{slice}\left(\frac{z}{\Delta z}\right)$$

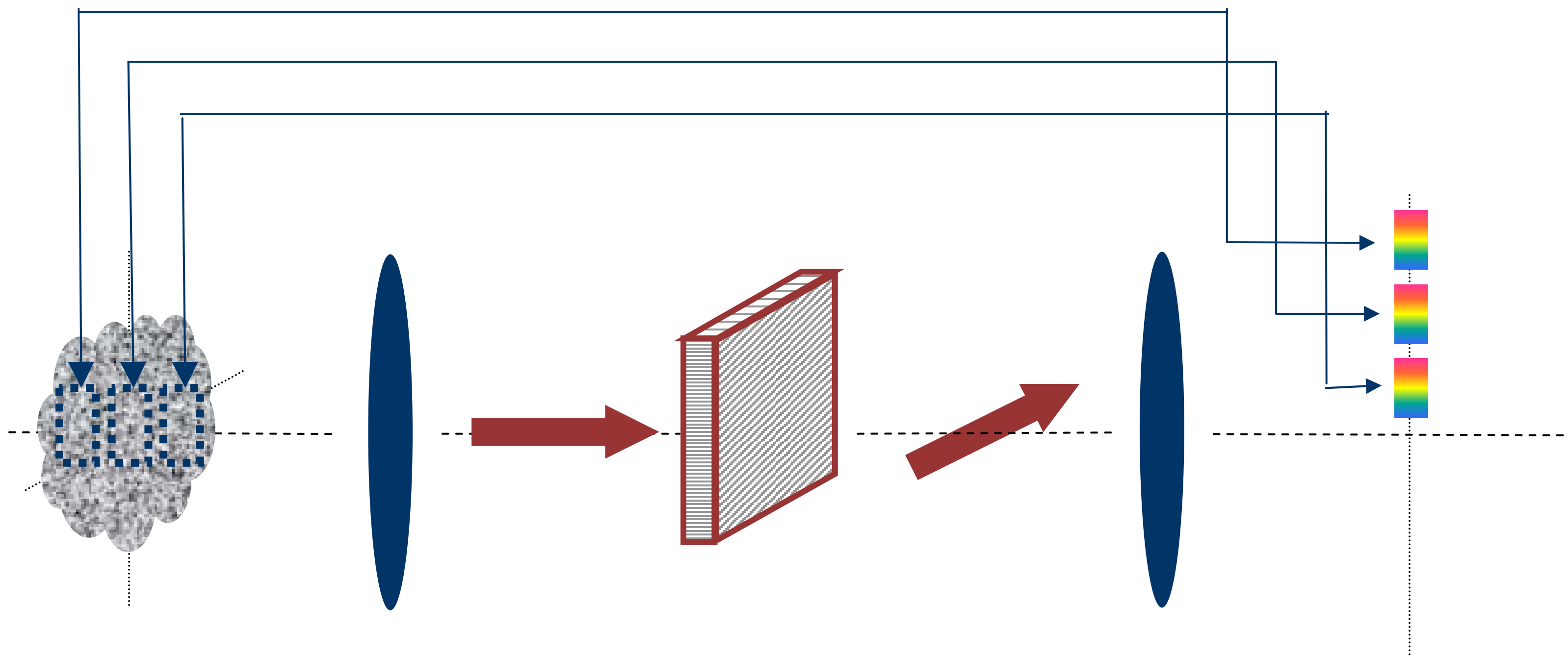
Applications: 3D holographic hyperspectral imaging



$f(x, y, z, \lambda)$

spectral components of
selected voxel are spread
out on detector plane

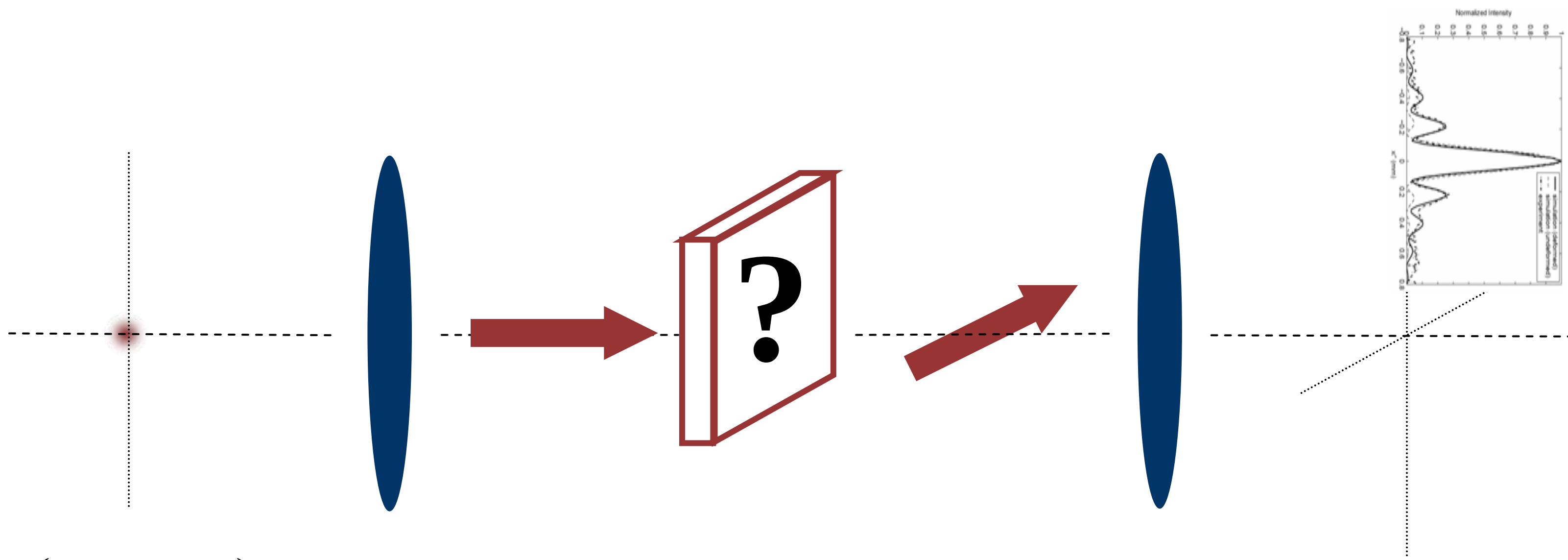
Applications: 3D multiplex hyperspectral imaging



$f(x, y, z, \lambda)$

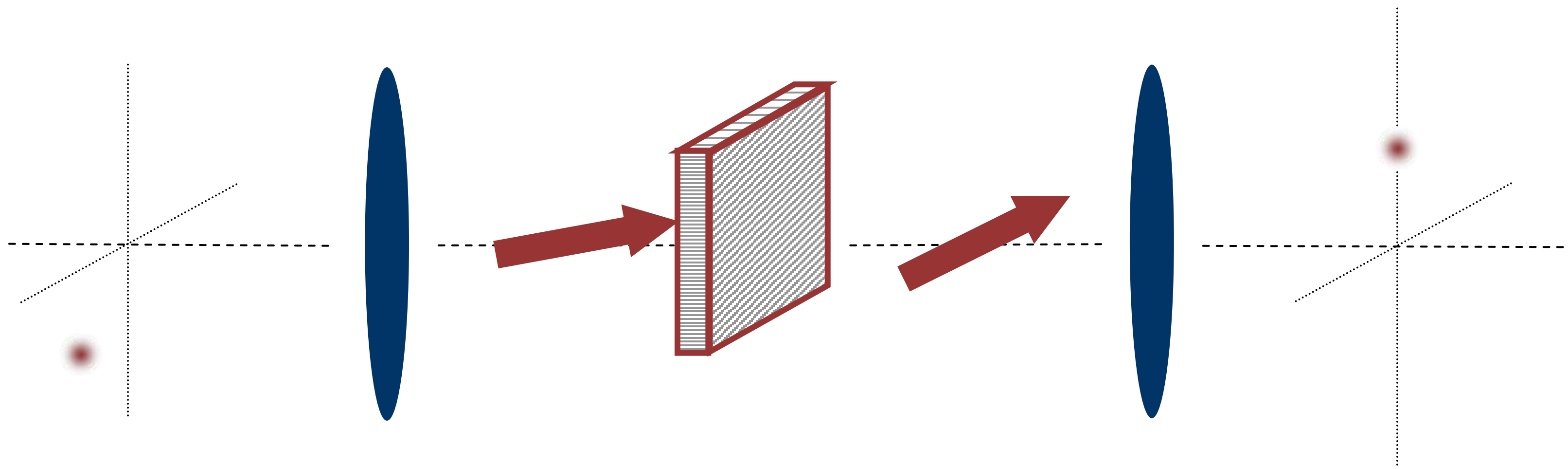
spectral components of
multiple voxels are spread
out on non-overlapping locations
in detector plane

Applications: probing unknown 3D holograms



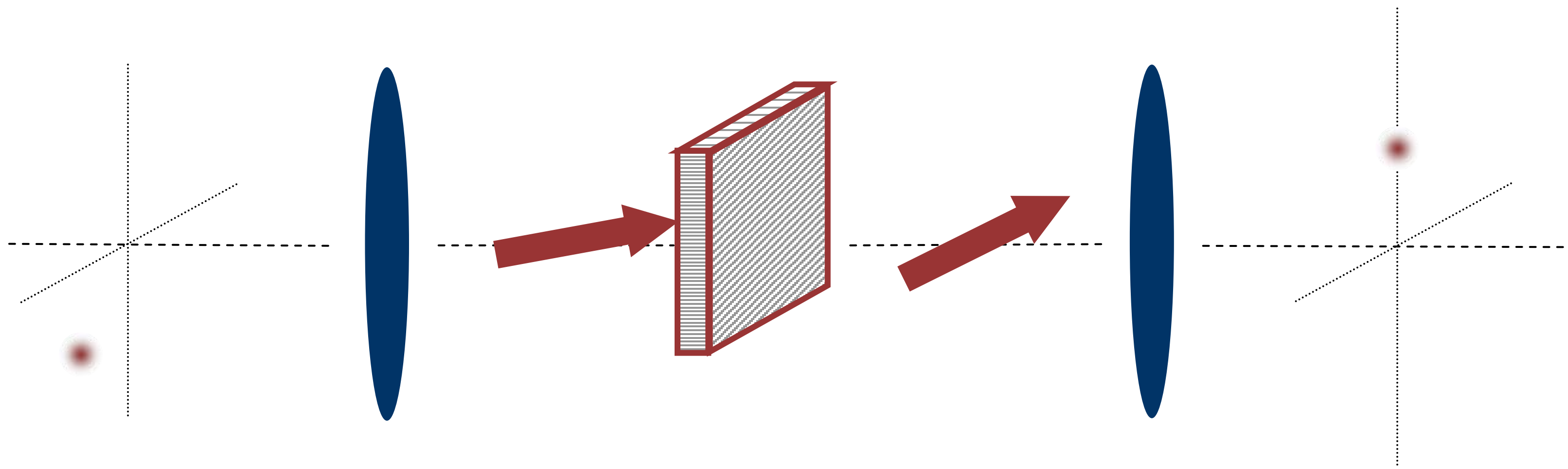
$$\delta\left(x-\frac{\lambda f k_0}{2\pi}\right) \qquad \varepsilon\left(x'',y'',z''\right) \qquad I\left(x',y'\right)$$

Optical imaging with 3D pupil



$$\delta(x - x_0, y - y_0) \qquad \varepsilon(x'', y'', z'') \qquad h(x', y'; x_0, y_0)$$

Optical imaging with 3D pupil



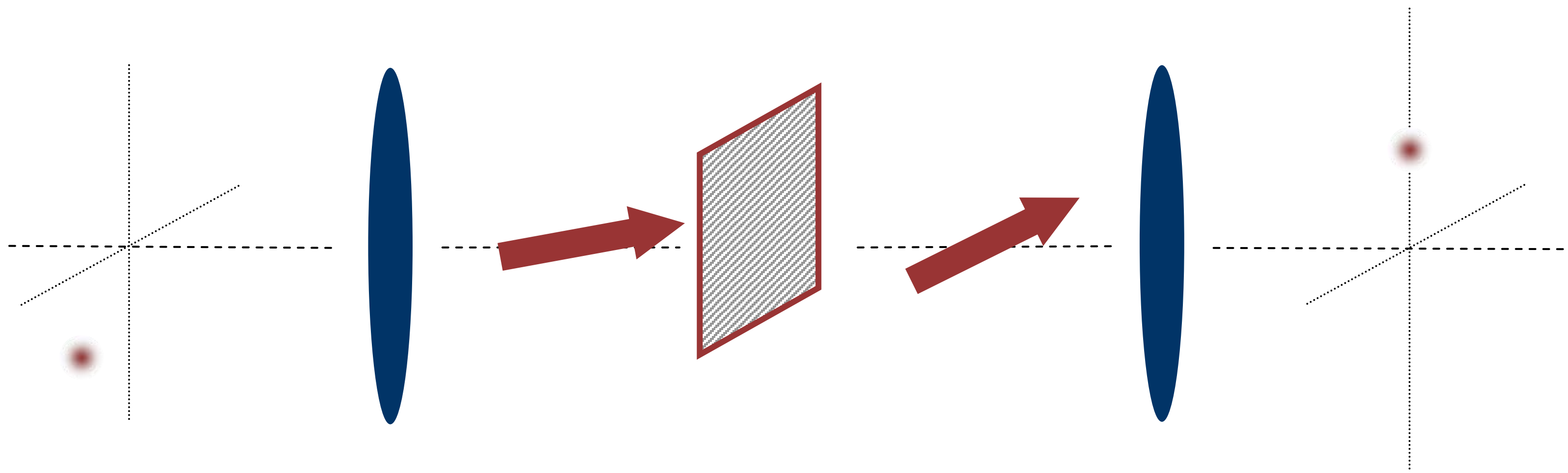
$\delta(x - x_0, y - y_0)$

$\varepsilon(x'', y'', z'')$

$h(x', y'; x_0, y_0)$

$$h(x', y'; x_0, y_0) = \Im\{\varepsilon\}\left[\frac{1}{\lambda}\left(\frac{x_0}{f_1} + \frac{x'}{f_2}\right), \frac{1}{\lambda}\left(\frac{y_0}{f_1} + \frac{y'}{f_2}\right), \frac{1}{\lambda}\left(\frac{x_0^2 + y_0^2}{2 f_1^2} - \frac{x'^2 + y'^2}{2 f_2^2}\right)\right]$$

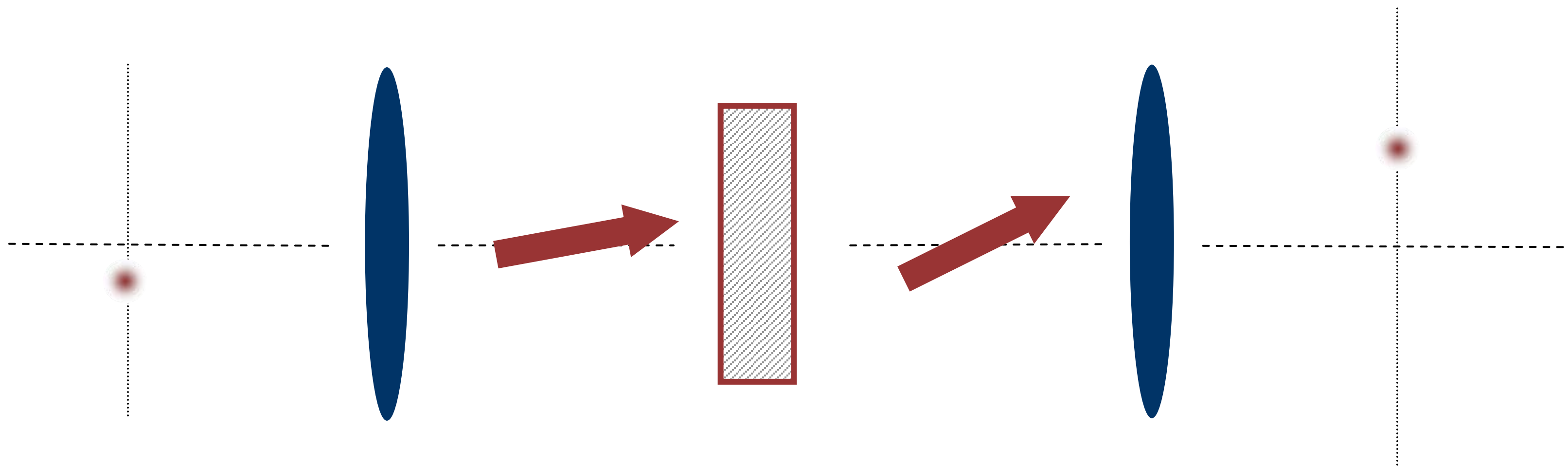
Optical imaging with 2D pupil



$$\delta(x-x_0, y-y_0) \qquad \varepsilon(x'', y'', \;) \qquad h(x', y'; x_0, y_0)$$

$$h(x', y'; x_0, y_0) = \Im\{\varepsilon\}\left[\frac{1}{\lambda}\left(\frac{x_0}{f_1}+\frac{x'}{f_2}\right), \frac{1}{\lambda}\left(\frac{y_0}{f_1}+\frac{y'}{f_2}\right), \qquad \right]$$

Optical imaging with 3D pupil

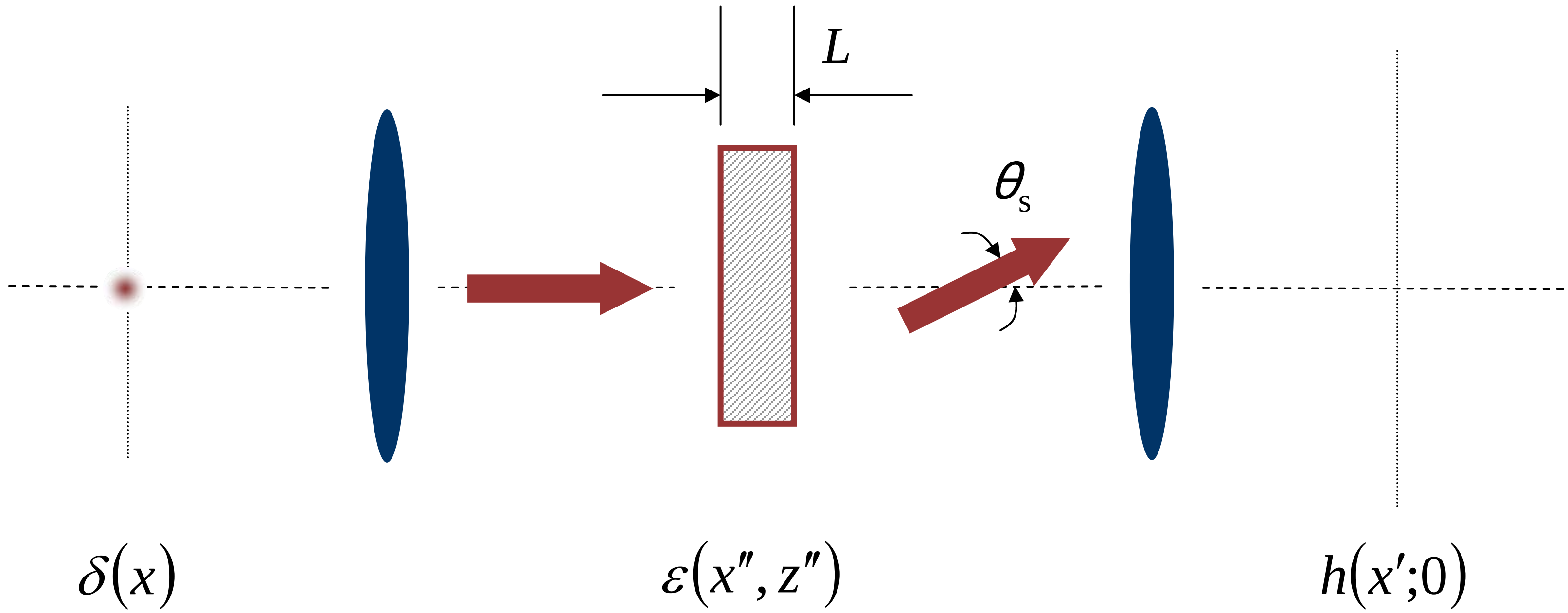


$\delta(x - x_0)$ $\varepsilon(x'', z'')$ $h(x'; x_0)$

$$h(x'; x_0) = \Im\{\varepsilon\}\left[\frac{1}{\lambda}\left(\frac{x_0}{f_1} + \frac{x'}{f_2}\right), \frac{1}{\lambda}\left(\frac{x_0^2}{2f_1^2} - \frac{x'^2}{2f_2^2}\right)\right]$$

simplify to 1D lateral dimension + longitudinal dimension

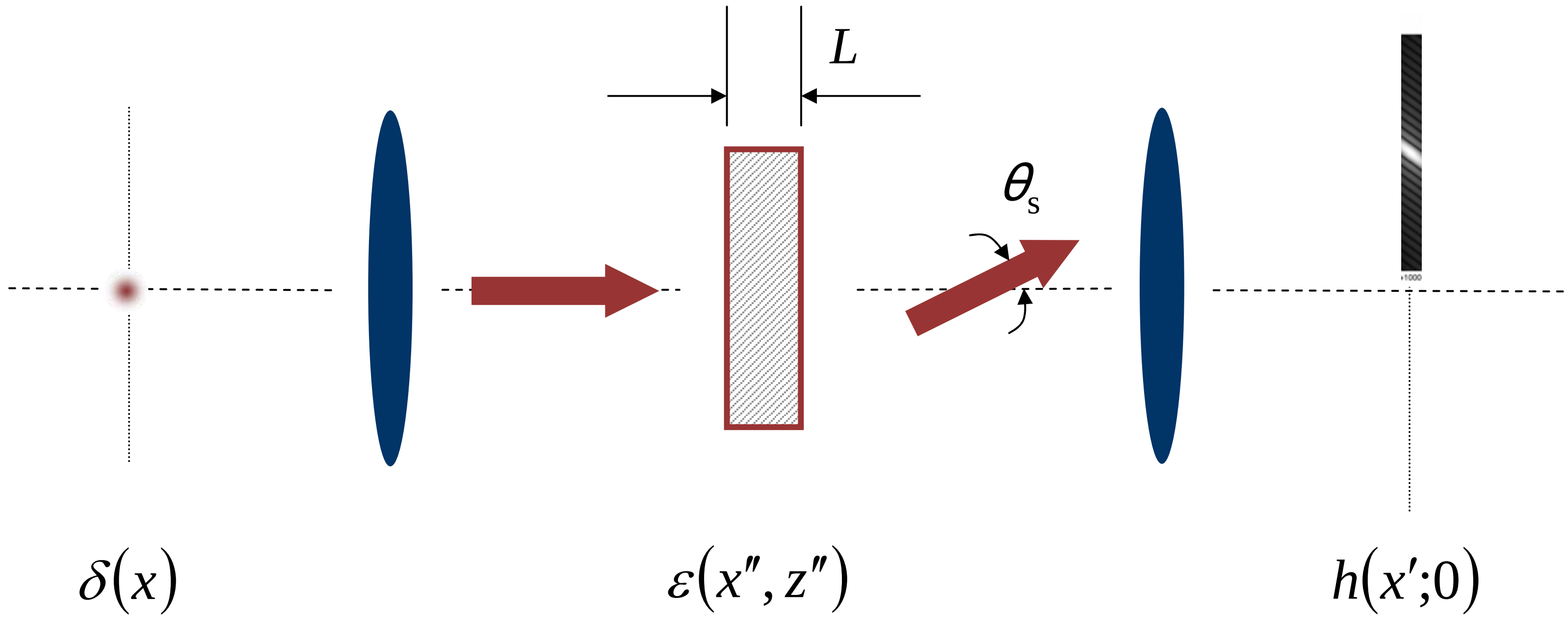
Optical imaging with 3D pupil: building the Hopkins matrix



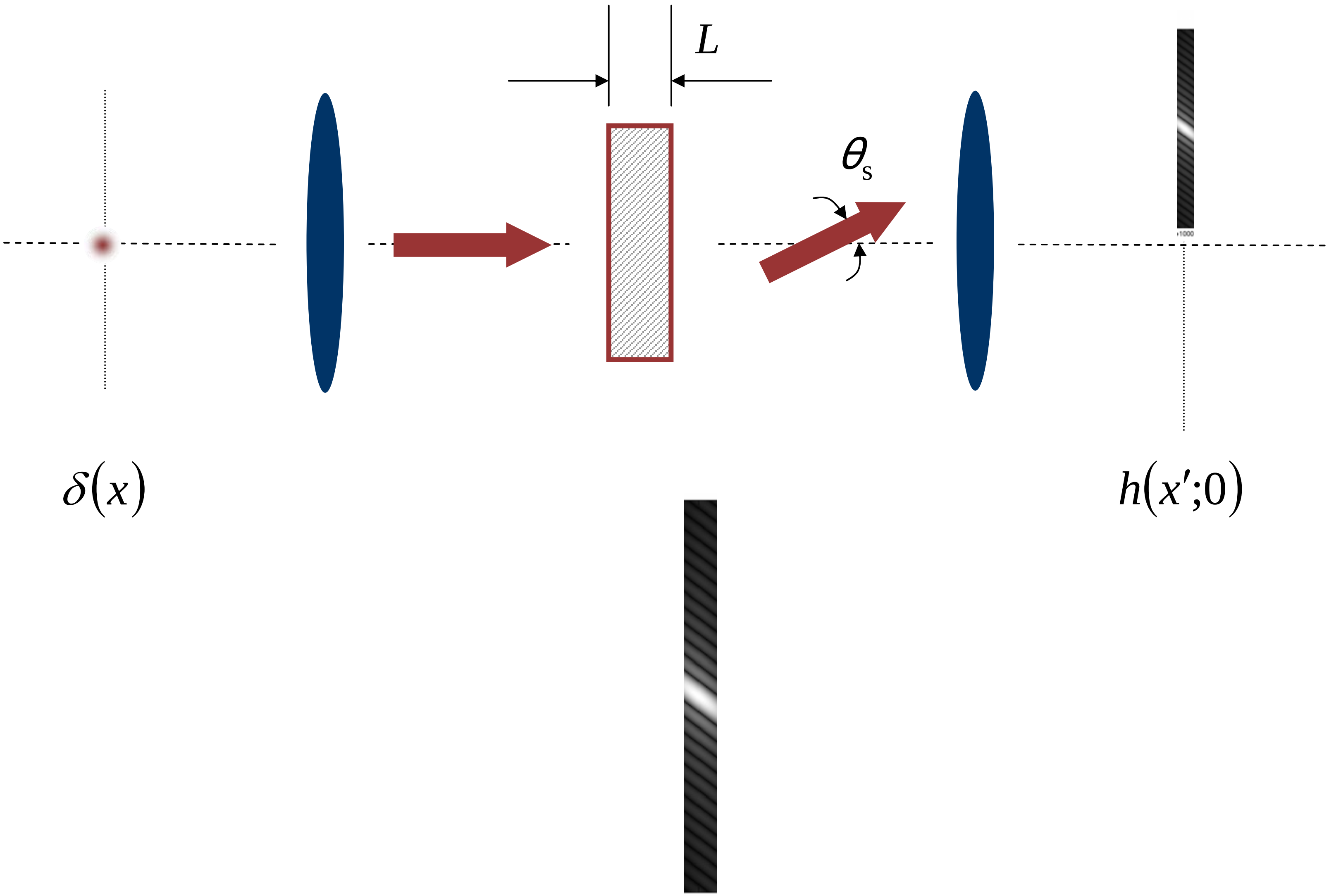
Plane-to-plane wave hologram
On-axis reference

$$\varepsilon(x'', z'') = \left|\exp(ikz) + \exp\left(ik\left[x\sin\theta_s + z\cos\theta_s\right]\right)\right|^2$$

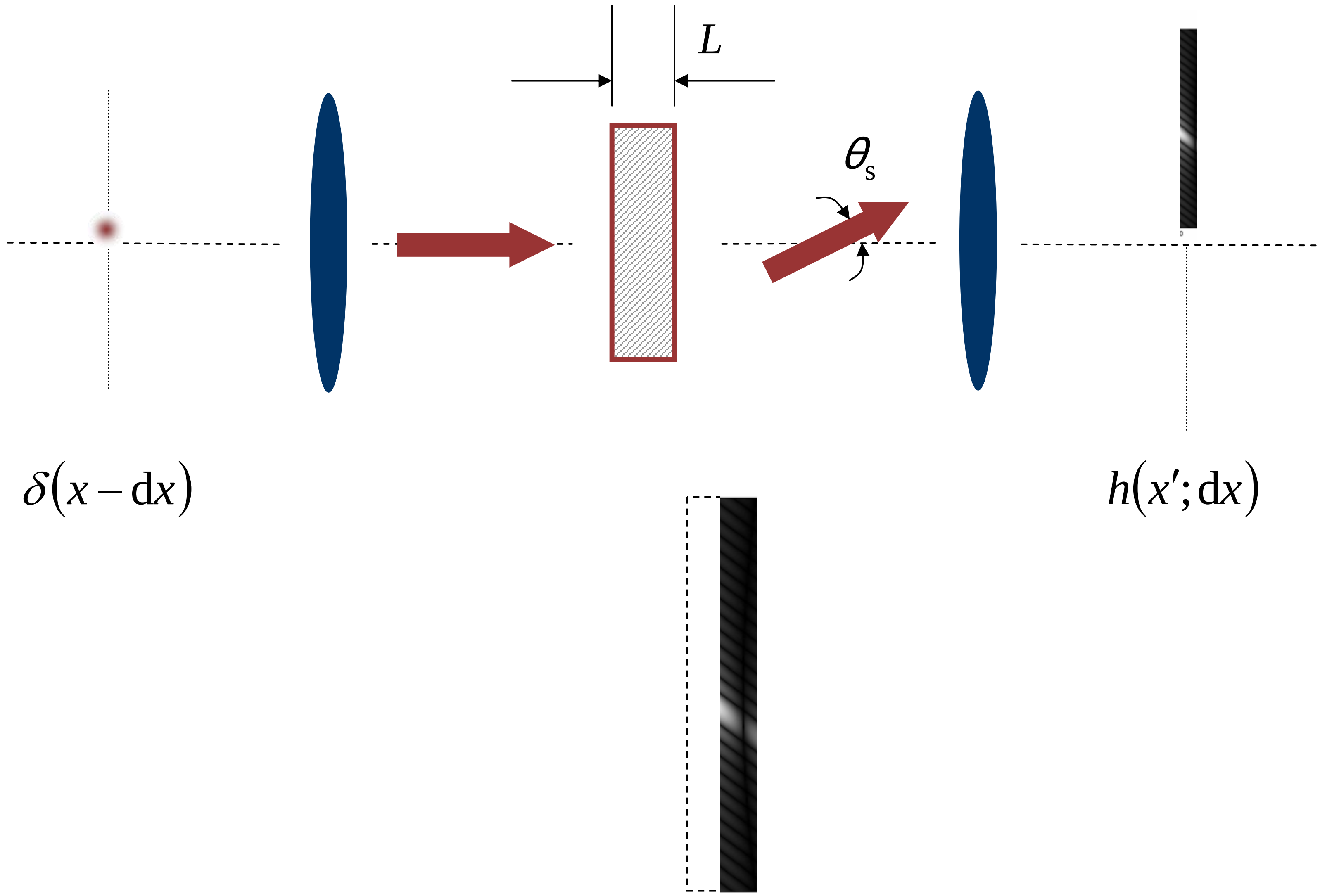
Optical imaging with 3D pupil: building the Hopkins matrix



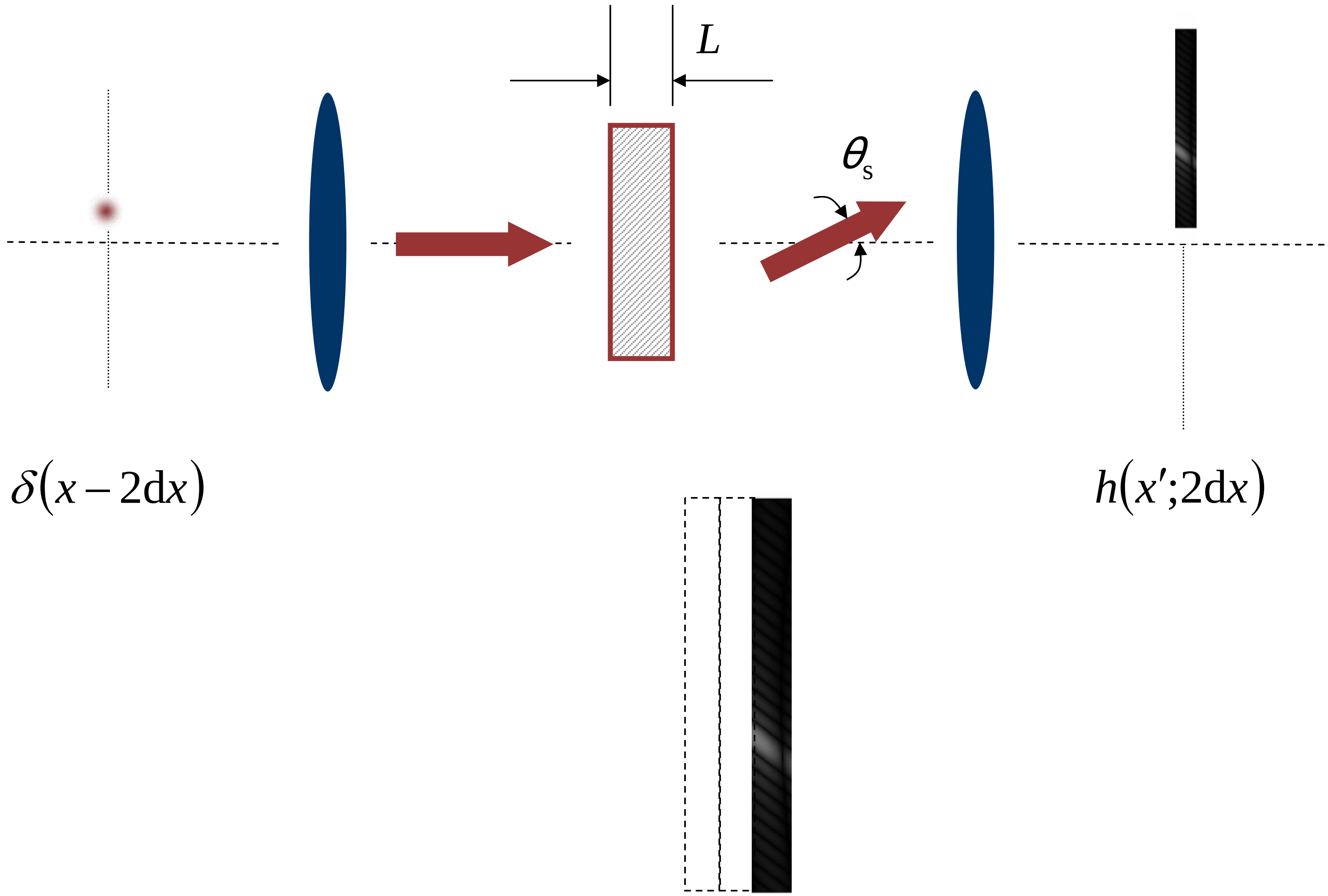
Optical imaging with 3D pupil: building the Hopkins matrix



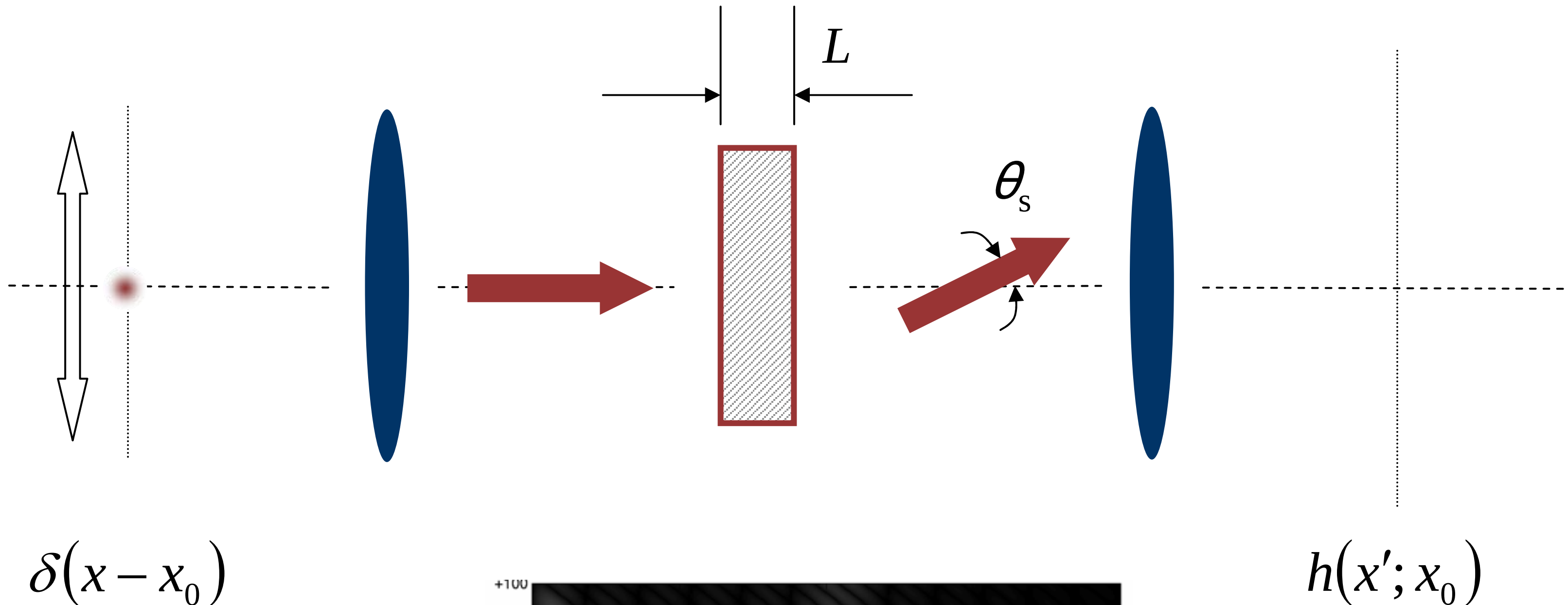
Optical imaging with 3D pupil: building the Hopkins matrix

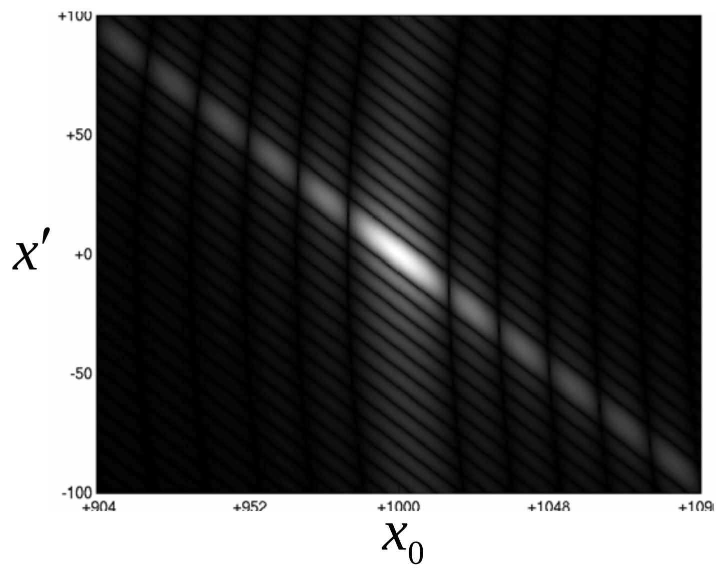


Optical imaging with 3D pupil: building the Hopkins matrix

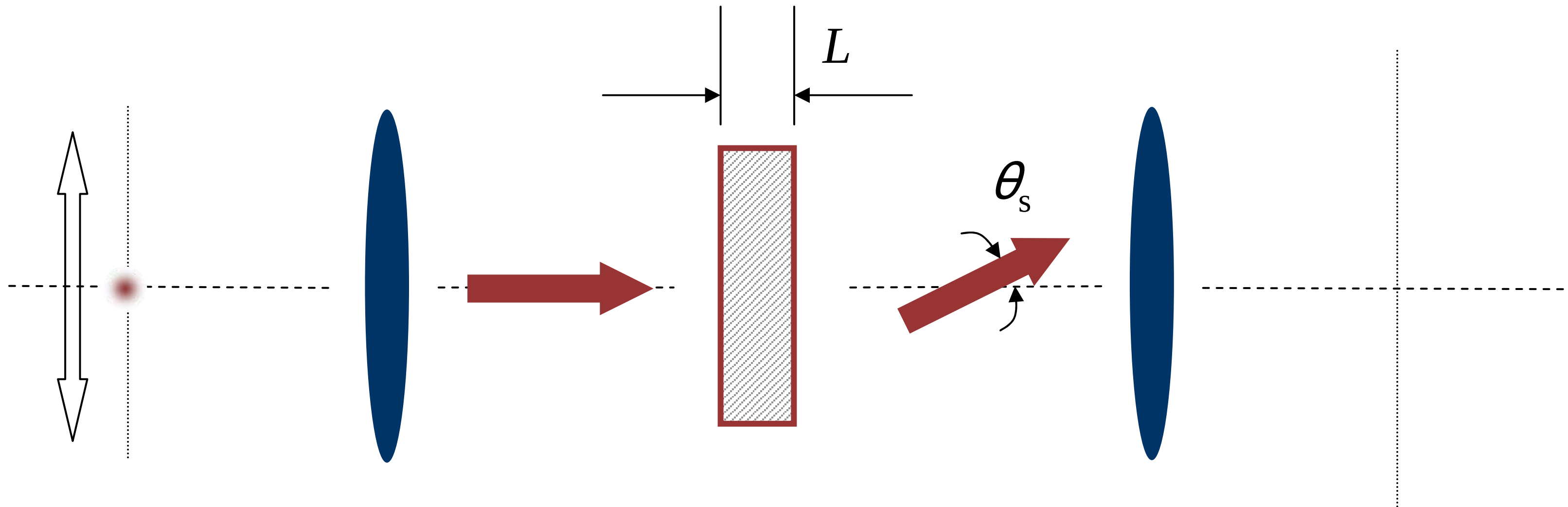


Optical imaging with 3D pupil: building the Hopkins matrix



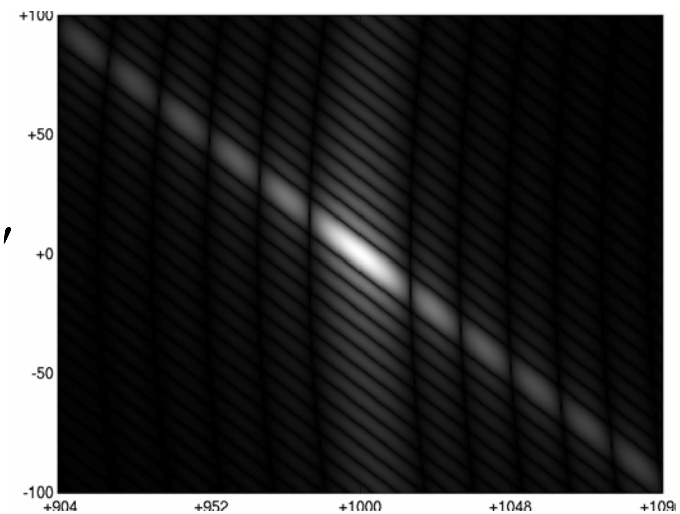


Optical imaging with 3D pupil: building the Hopkins matrix



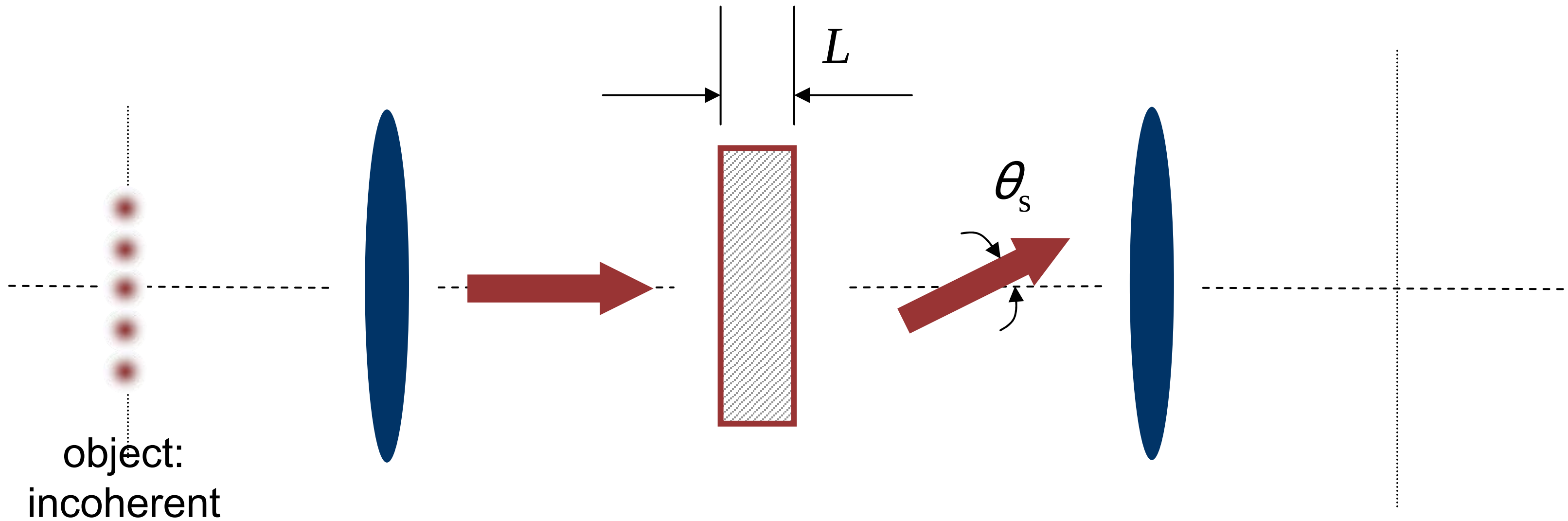
$\delta(x-x_0)$

$h(x';x_0)$



Hopkins matrix

Incoherent imaging with 3D pupil

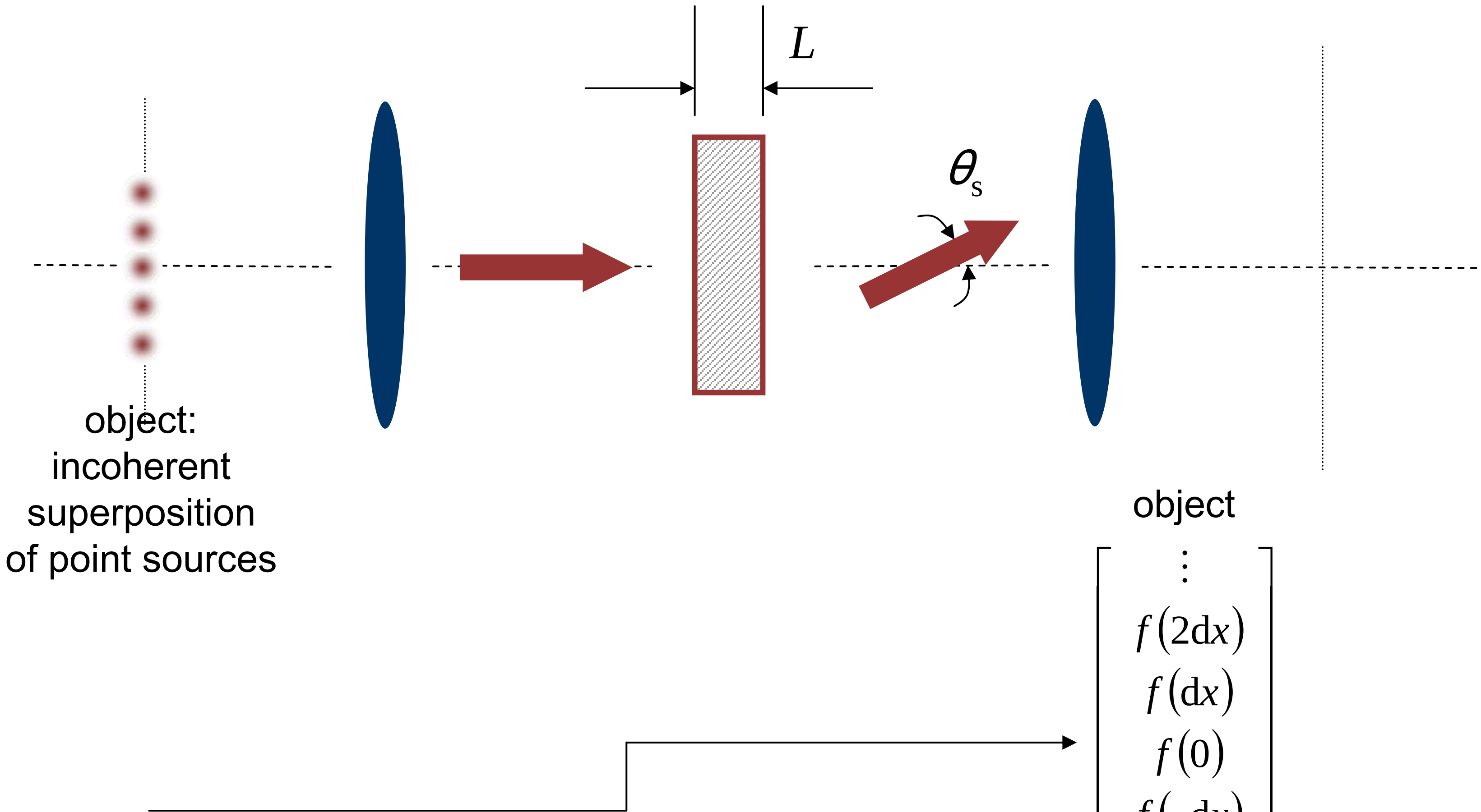


object:
incoherent
superposition
of point sources

image

$$\begin{bmatrix} \vdots \\ f(2\mathrm{d}x) \\ f(\mathrm{d}x) \\ f(0) \\ f(-\mathrm{d}x) \\ f(-2\mathrm{d}x) \\ \vdots \end{bmatrix} \qquad \begin{bmatrix} \vdots \\ g(2\mathrm{d}x') \\ g(\mathrm{d}x') \\ g(0) \\ g(-\mathrm{d}x') \\ g(-2\mathrm{d}x') \\ \vdots \end{bmatrix} = ?$$

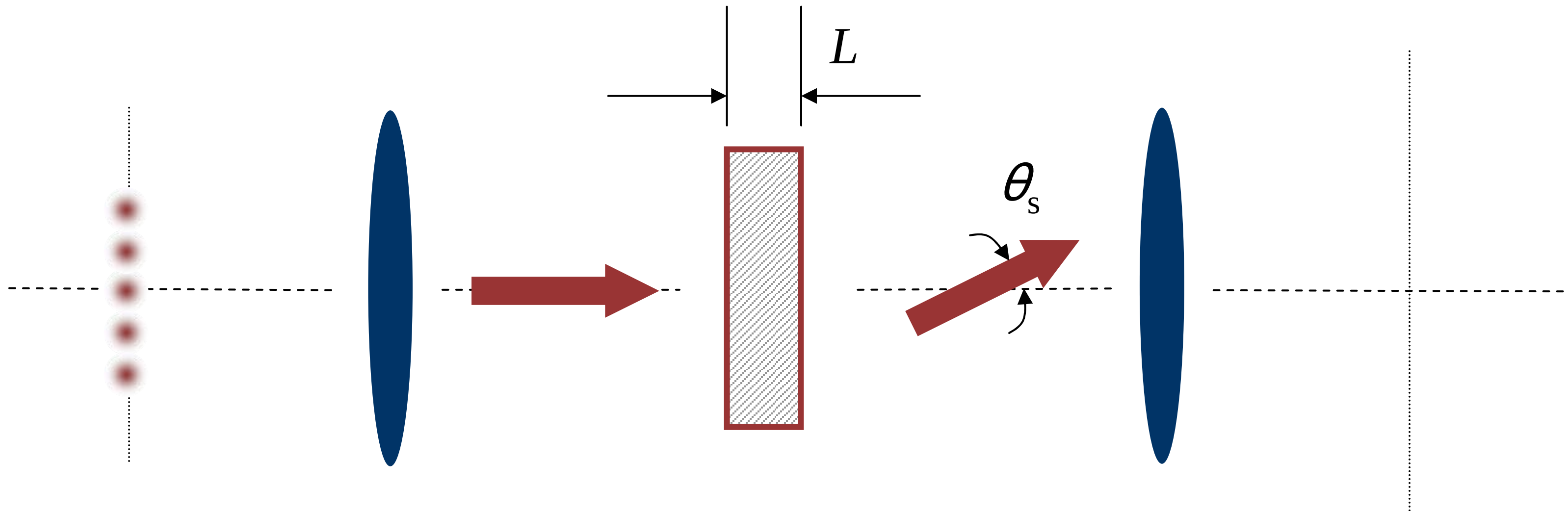
Incoherent imaging with 3D pupil



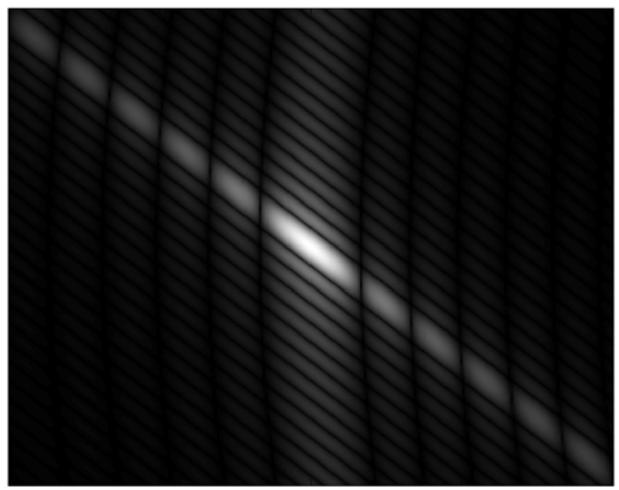
object

$$\begin{bmatrix} \vdots \\ f(2\mathrm{d}x) \\ f(\mathrm{d}x) \\ f(0) \\ f(-\mathrm{d}x) \\ f(-2\mathrm{d}x) \\ \vdots \end{bmatrix}$$

Incoherent imaging with 3D pupil



Hopkins matrix



object

$$\begin{bmatrix} \vdots \\ f(2\mathrm{d}x) \\ f(\mathrm{d}x) \\ f(0) \\ f(-\mathrm{d}x) \\ f(-2\mathrm{d}x) \\ \vdots \end{bmatrix}$$

Incoherent imaging with 3D pupil

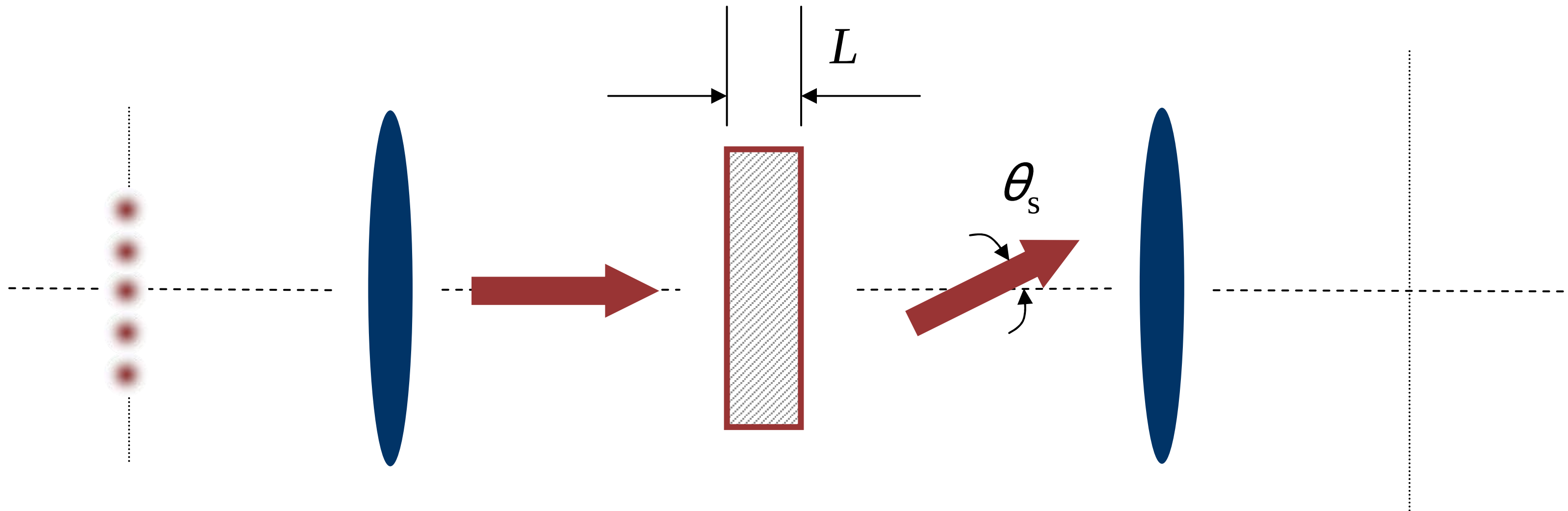
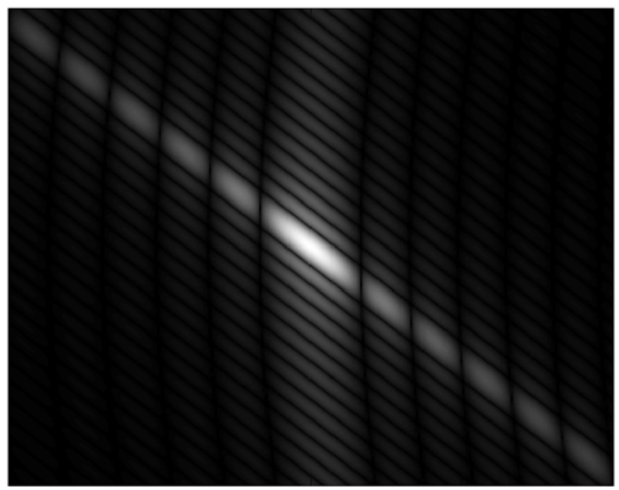


image — Hopkins matrix — object

$$\begin{bmatrix}\vdots\\ g(2\mathrm{d}x')\\ g(\mathrm{d}x')\\ g(0)\\ g(-\mathrm{d}x')\\ g(-2\mathrm{d}x')\\ \vdots\end{bmatrix} =$$



$$\begin{bmatrix}\vdots\\ f(2\mathrm{d}x)\\ f(\mathrm{d}x)\\ f(0)\\ f(-\mathrm{d}x)\\ f(-2\mathrm{d}x)\\ \vdots\end{bmatrix}$$

Incoherent imaging with clear (2D) pupil

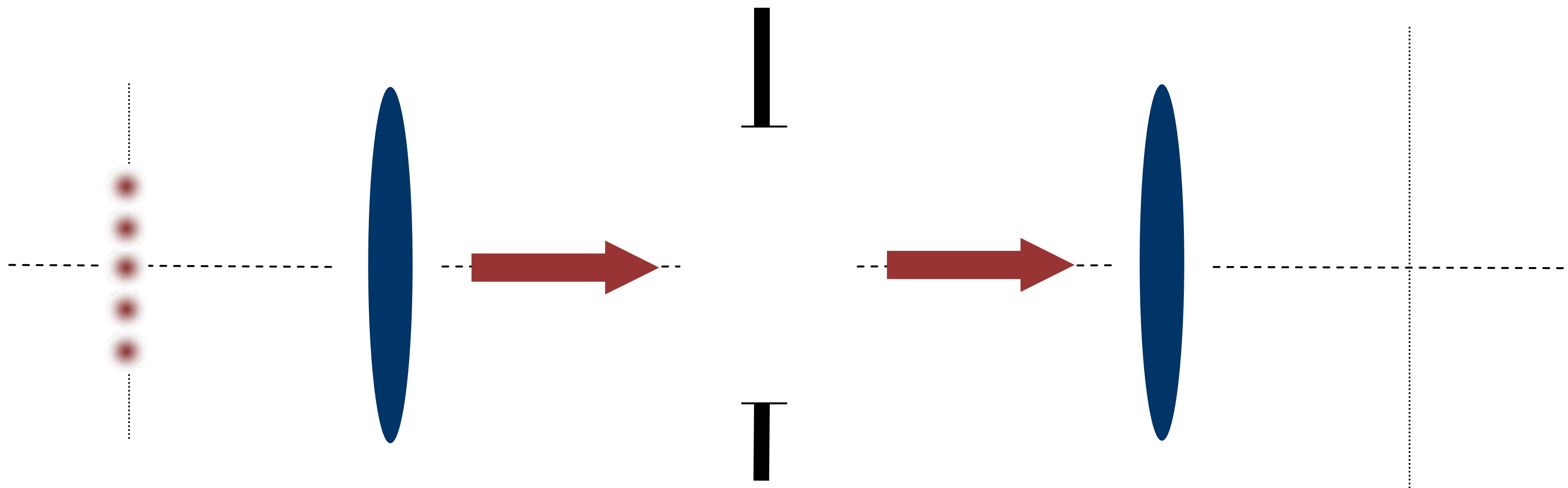
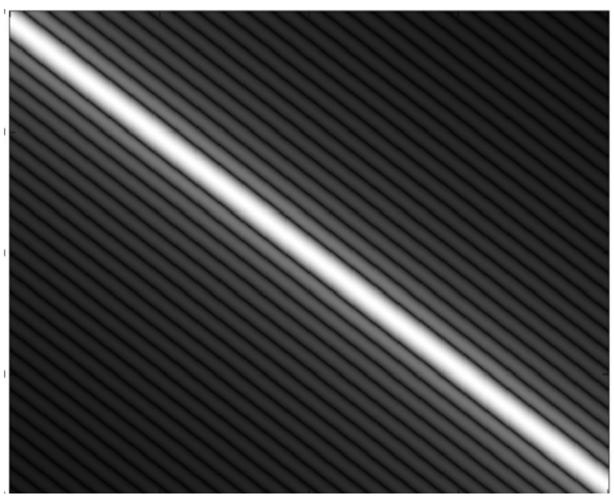


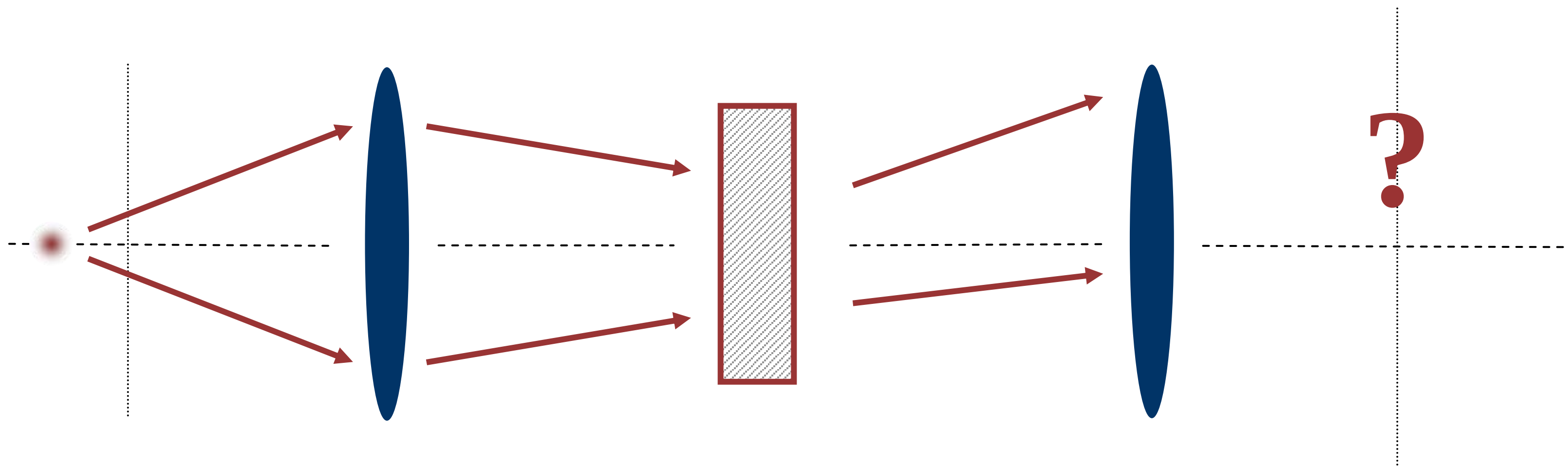
image — Hopkins matrix — object

$$\begin{bmatrix} \vdots \\ g(2\mathrm{d}x') \\ g(\mathrm{d}x') \\ g(0) \\ g(-\mathrm{d}x') \\ g(-2\mathrm{d}x') \\ \vdots \end{bmatrix} =$$



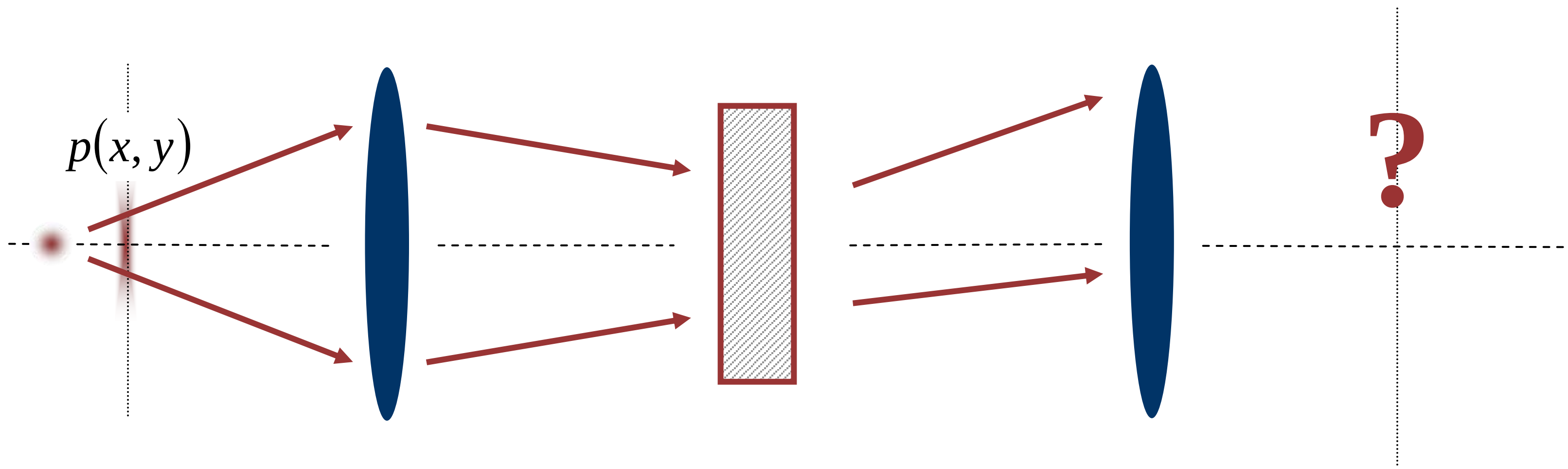
$$\begin{bmatrix} \vdots \\ f(2\mathrm{d}x) \\ f(\mathrm{d}x) \\ f(0) \\ f(-\mathrm{d}x) \\ f(-2\mathrm{d}x) \\ \vdots \end{bmatrix}$$

Defocused response of 3D pupils



$$\delta(x - x_0, y, z - z_0) \qquad \varepsilon(x'', y'', z'') \qquad q(x', y'; x_0, z_0)$$

Defocused response of 3D pupils



$\delta(x-x_0, y, z-z_0)$ $\qquad$ $\varepsilon(x'', y'', z'')$ $\qquad$ $q(x', y'; x_0, z_0)$

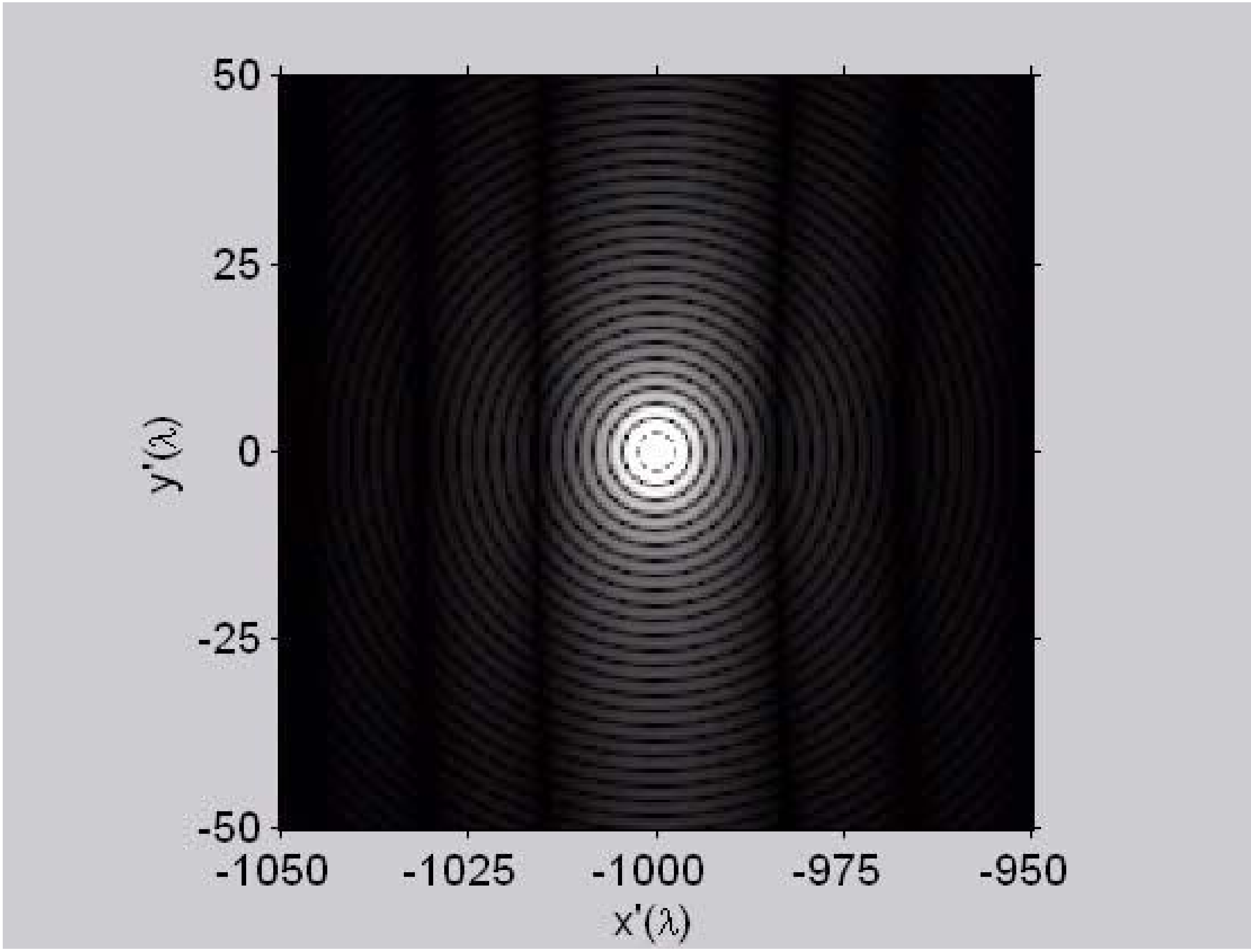
$$p(x,y) = \text{Fresnel}(z_0)$$

$$P(x'',y'',z'') = \exp\left\{i2\pi\frac{z}{\lambda}\right\}\iint \mathrm{d}x\mathrm{d}y\, p(x,y)\exp\left\{i2\pi\frac{xx''+yy''}{\lambda f_1}\right\}\times\exp\left\{-i\pi\frac{(x^2+y^2)z''}{\lambda f_1^2}\right\}$$

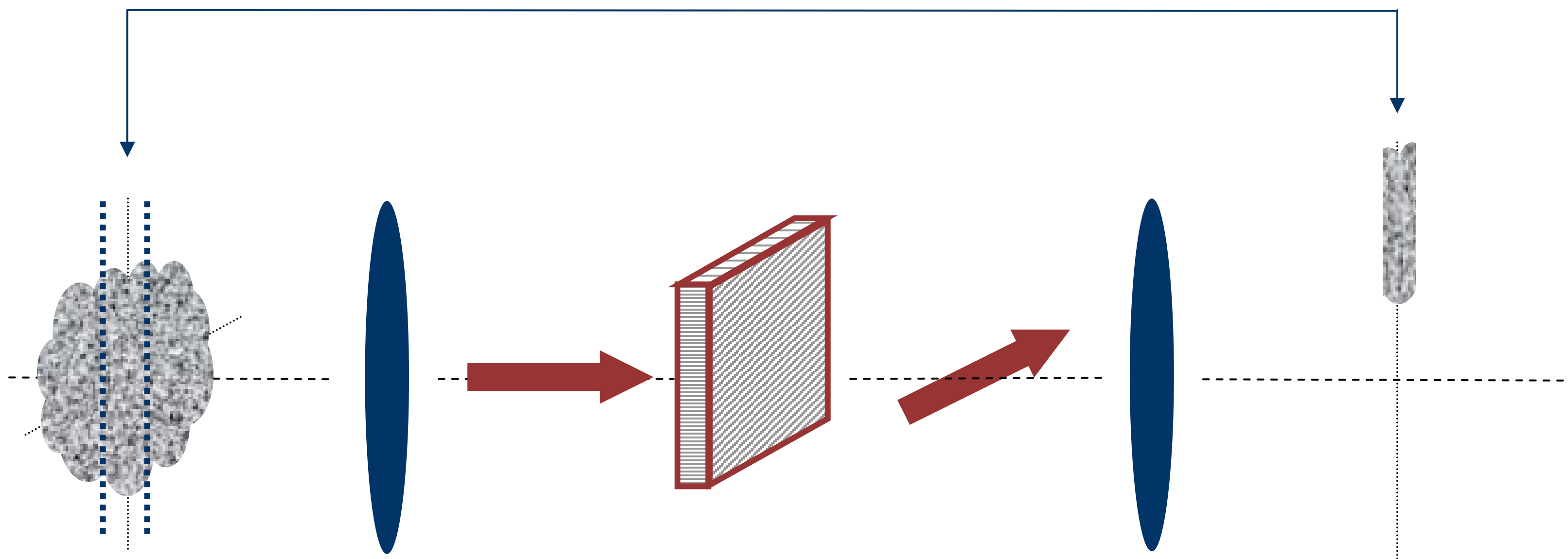
$$g(x'',y'',z'') = \varepsilon(x'',y'',z'')\times P(x'',y'',z'')$$

$$q(x',y') = G\left[\frac{x'}{\lambda f_2}, \frac{y'}{\lambda f_2}, \frac{1}{\lambda}\left(1-\frac{x'^2+y'^2}{2f_2^2}\right)\right]$$

Blinking spot of 3D pupil



Applications: 3D holographic optical imaging

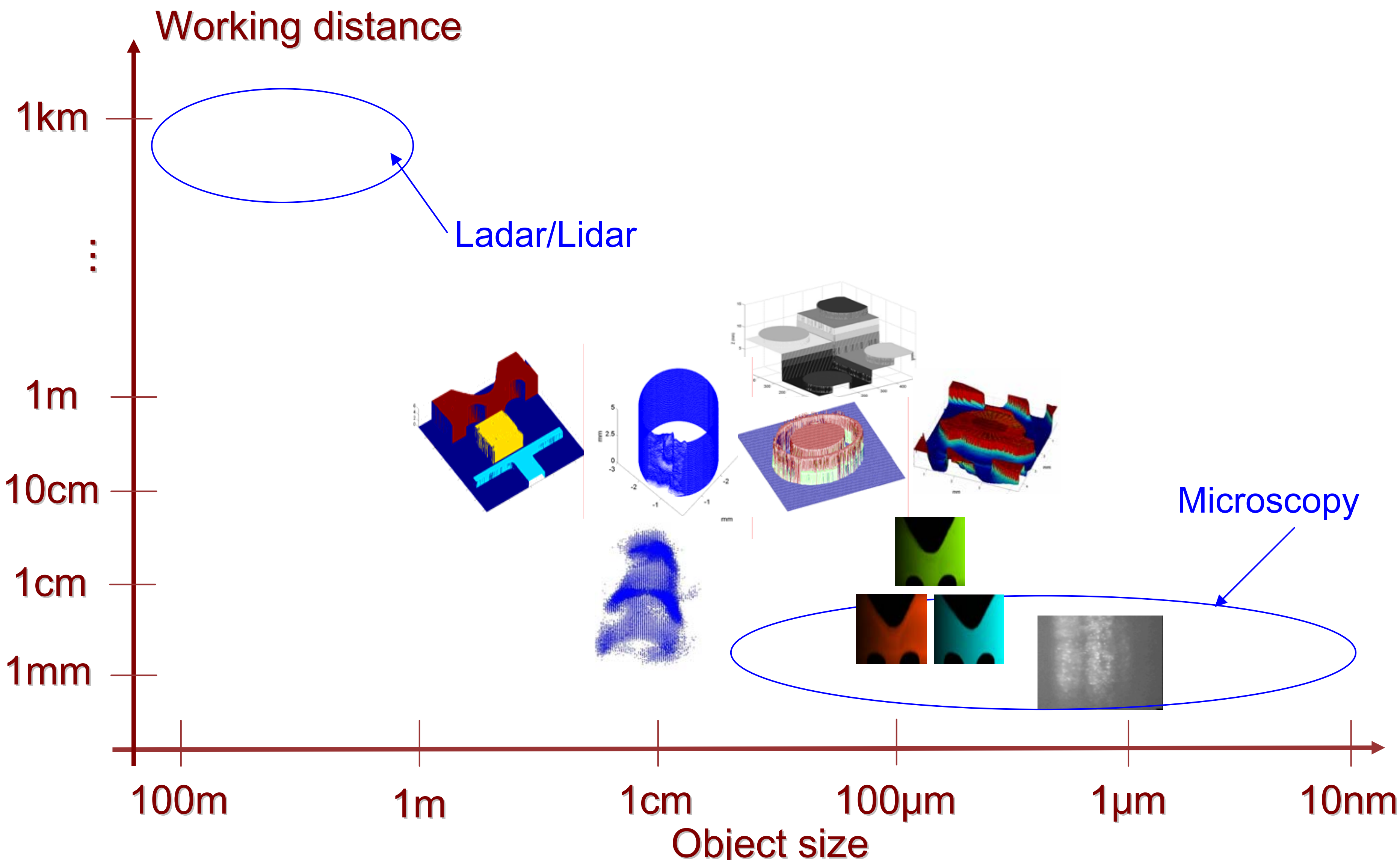


$$f\left(x, y, z\right)$$

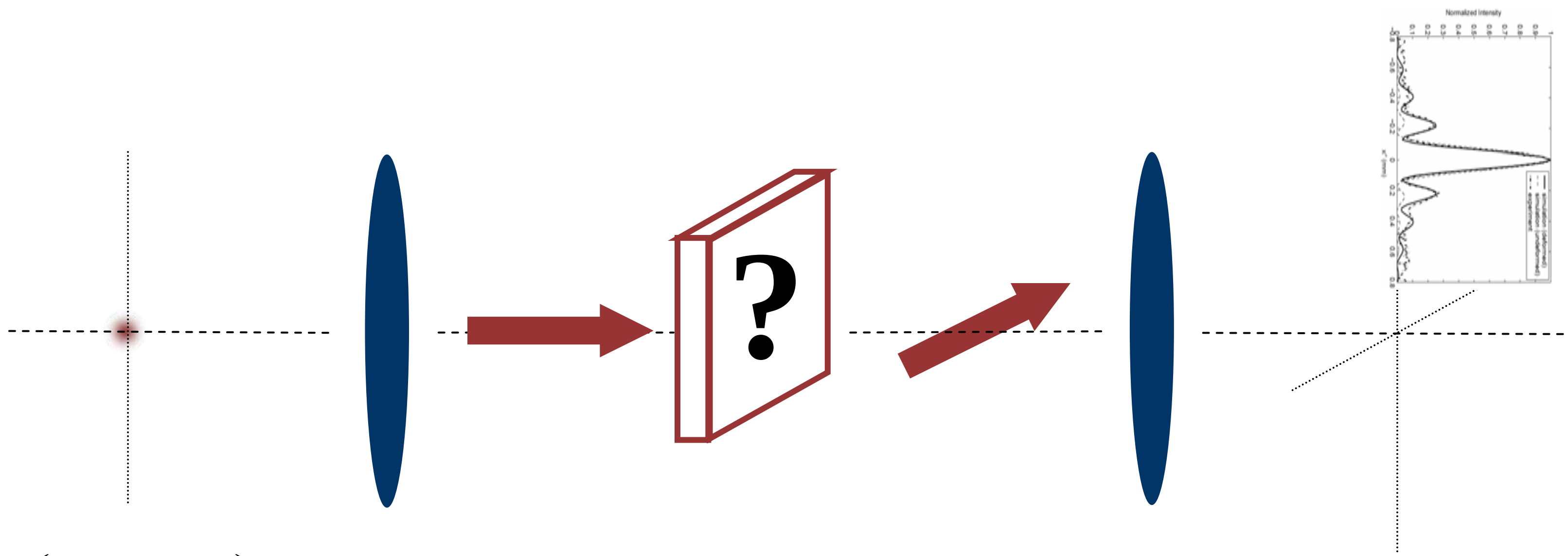
3D pupil

$$f\left(x' - \frac{\lambda f k_0}{2\pi}, y', z\right) \times$$
$$\times \mathrm{slit}\left(\frac{x'}{\Delta x'}\right) \times \mathrm{slice}\left(\frac{z}{\Delta z}\right)$$

3D optics for imaging: summary

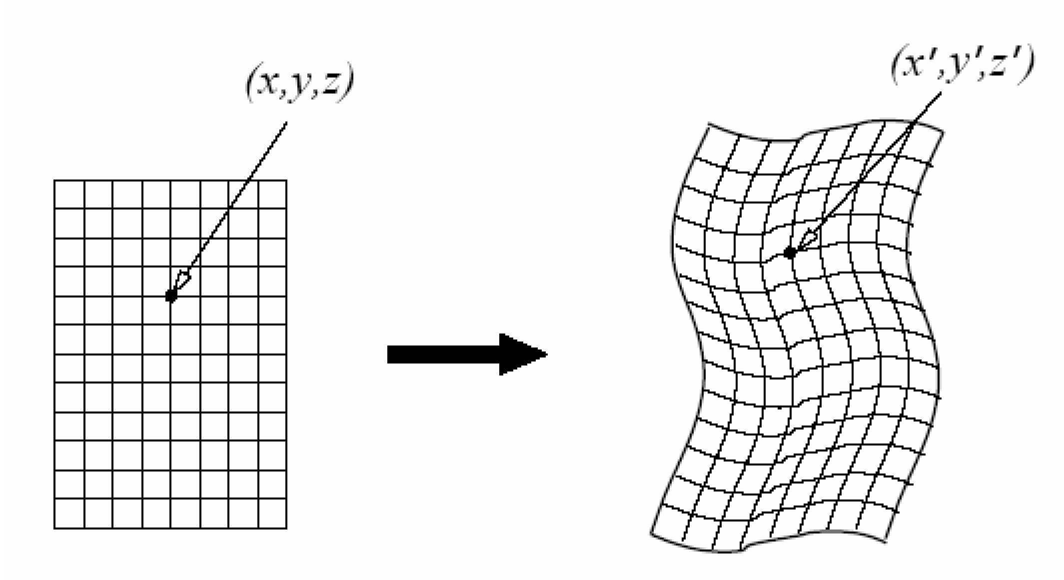


Probing unknown 3D holograms

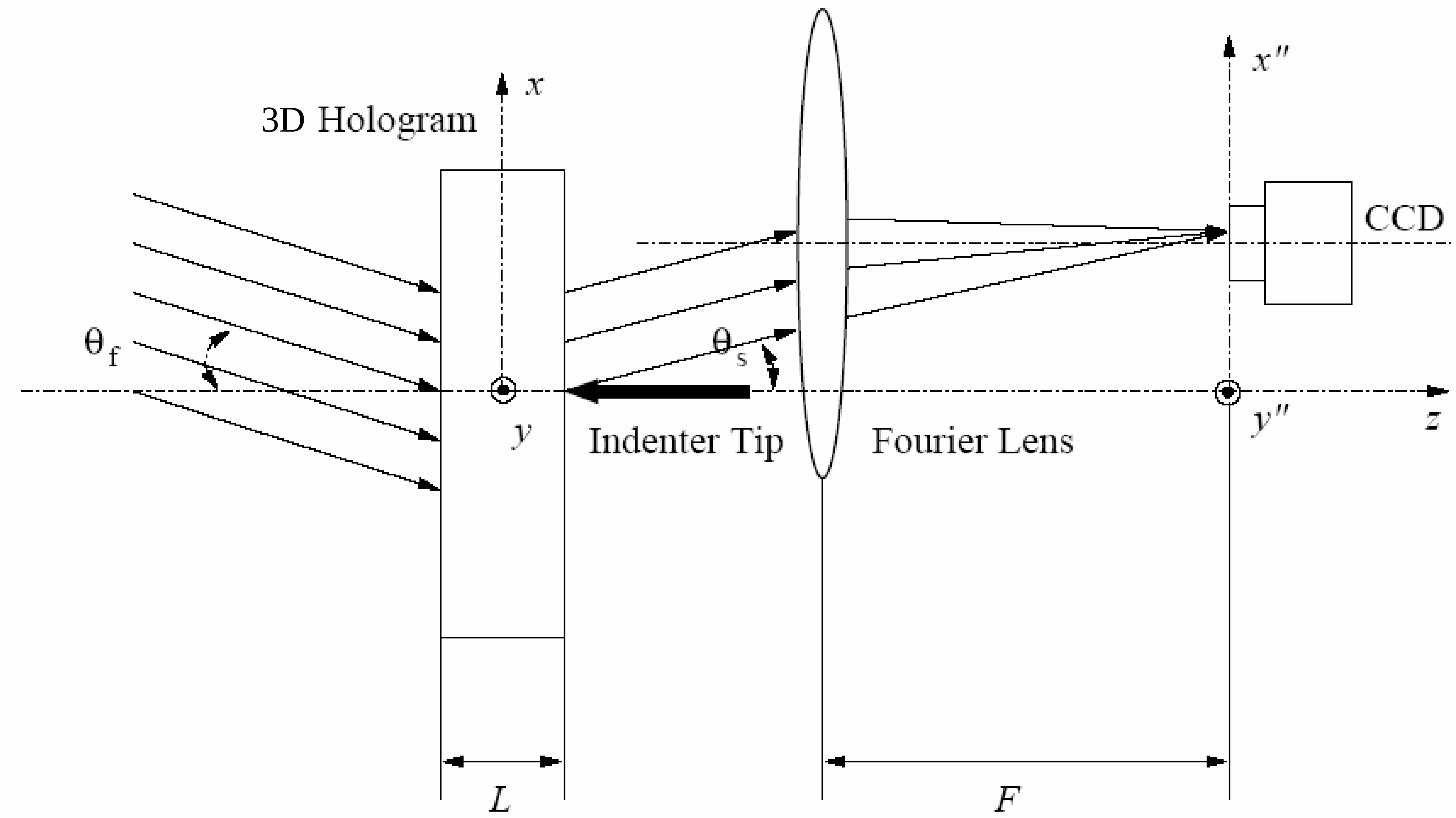


$$\delta\left(x - \frac{\lambda f k_0}{2\pi}\right) \qquad \varepsilon(x'', y'', z'') \qquad I(x', y')$$

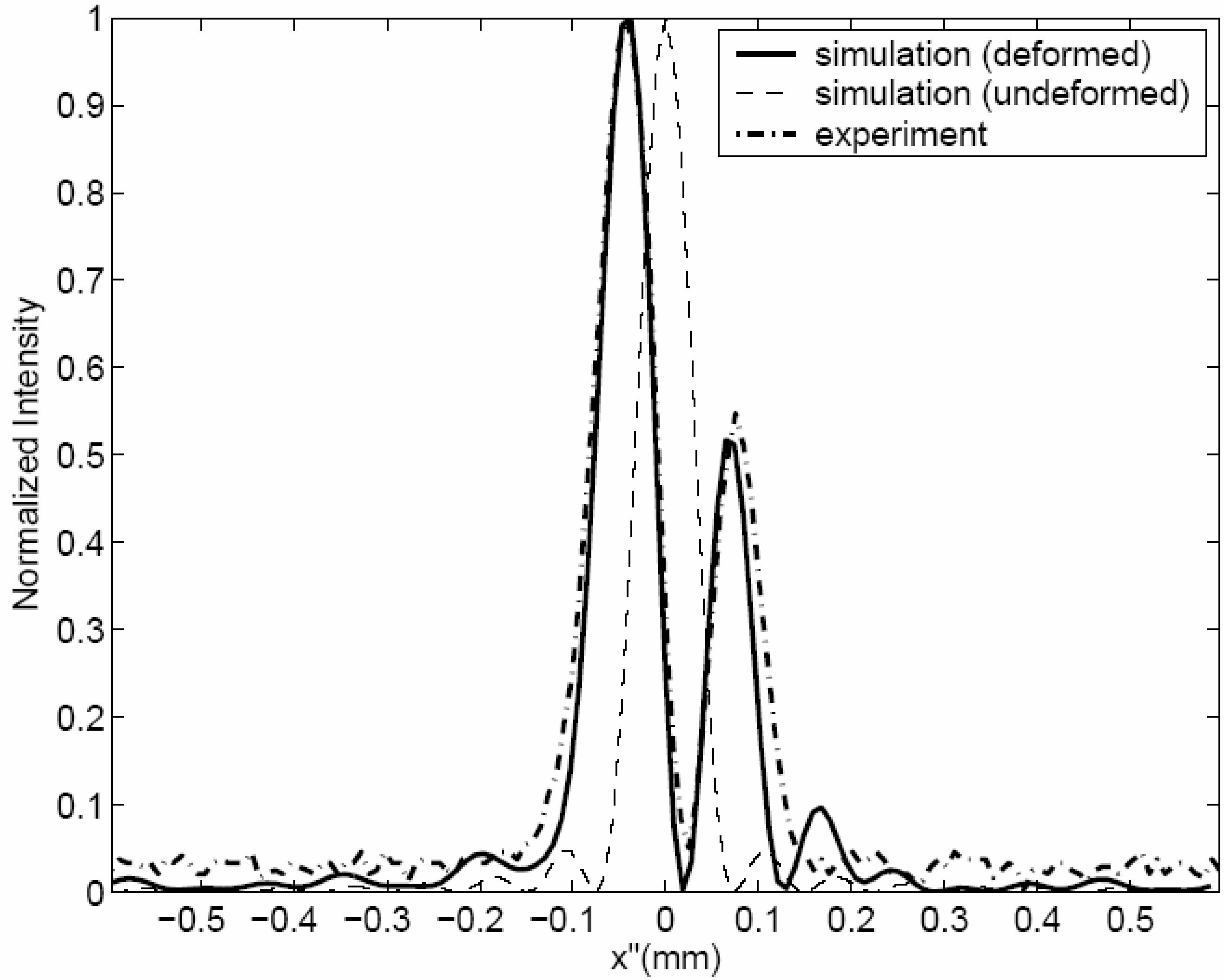
Diffraction from deformed 3D holograms



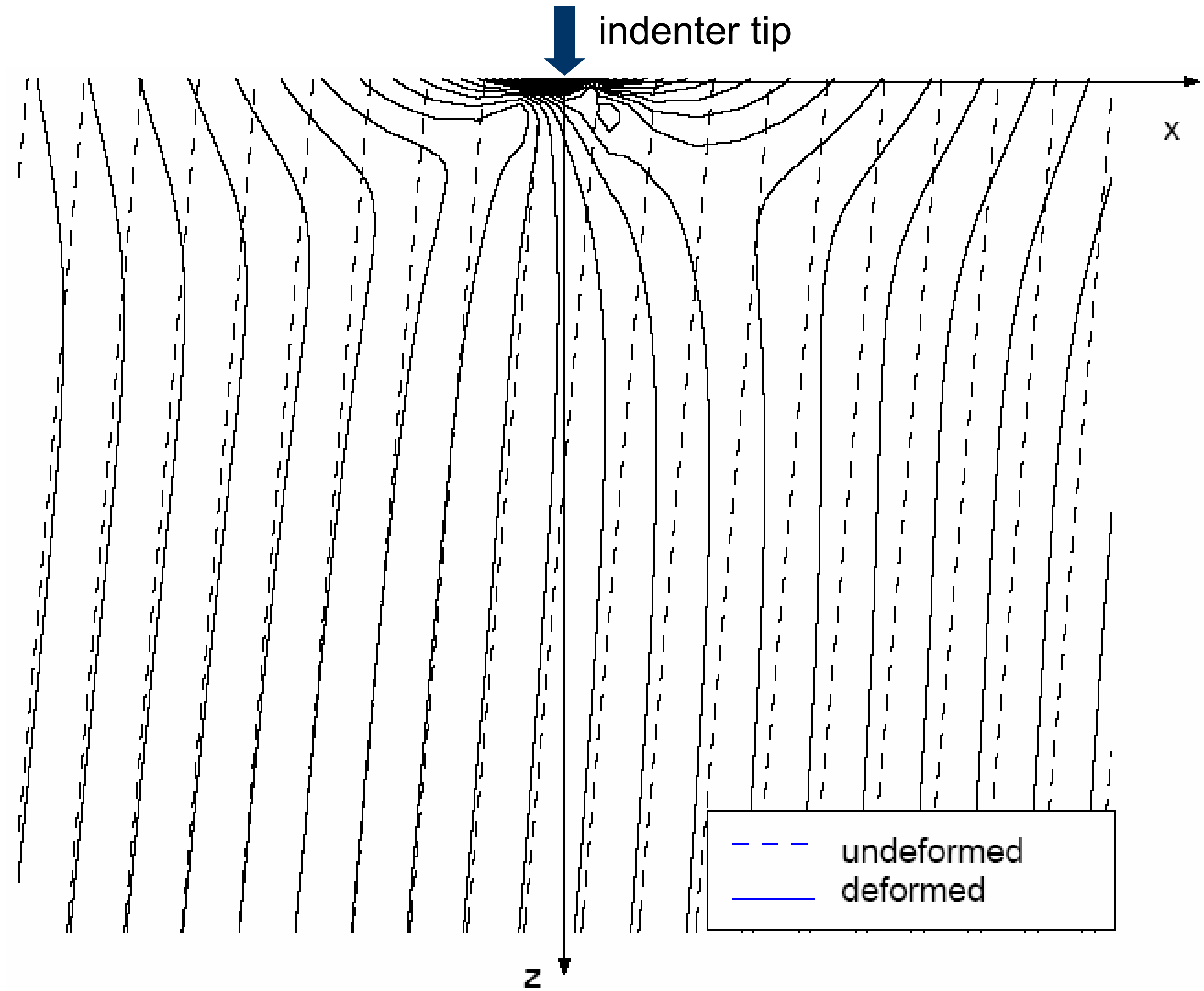
Experimental arrangement: transmission geometry



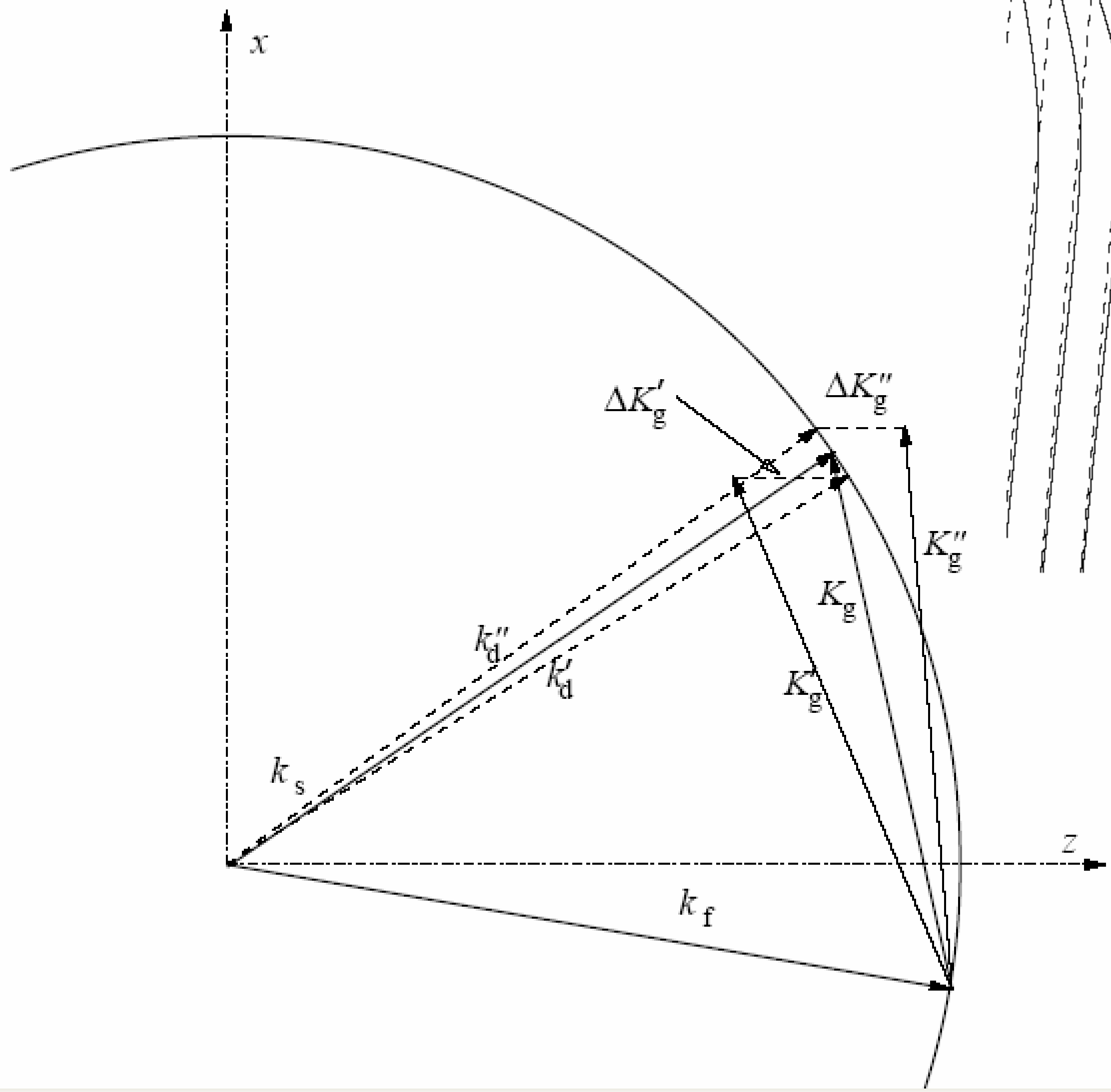
Experiment: diffraction from indented 3D hologram

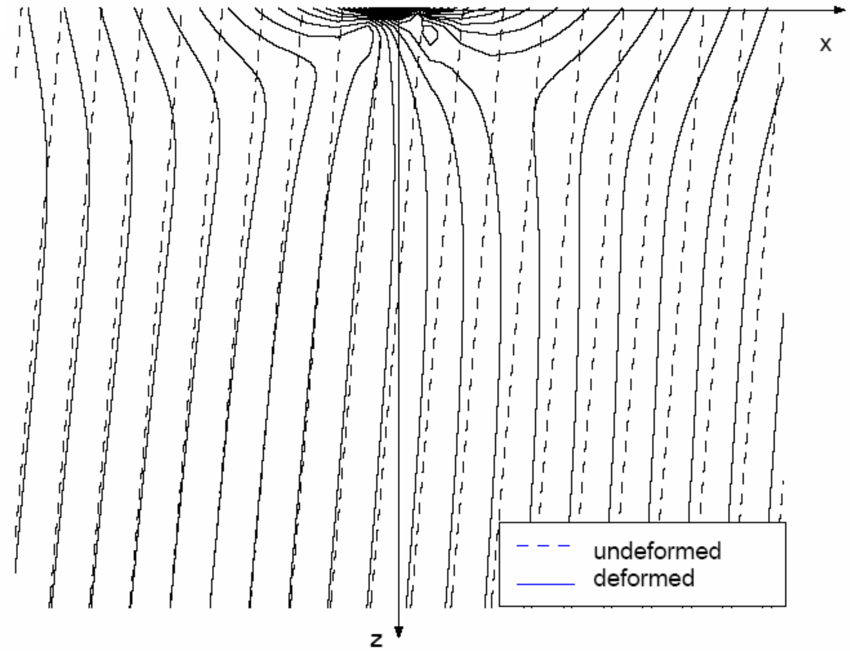


Fringe deformation due to indenter (transmission)

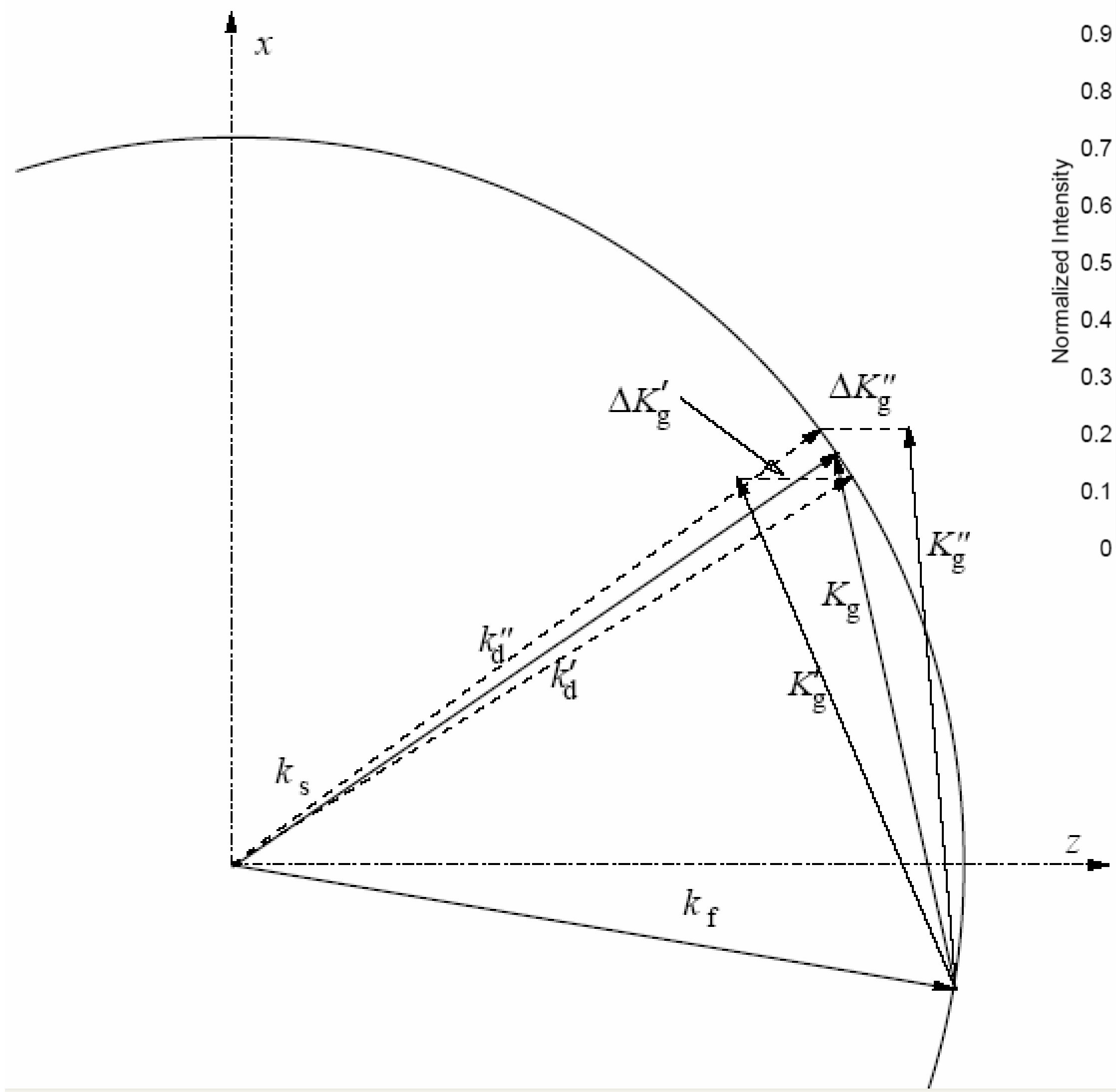


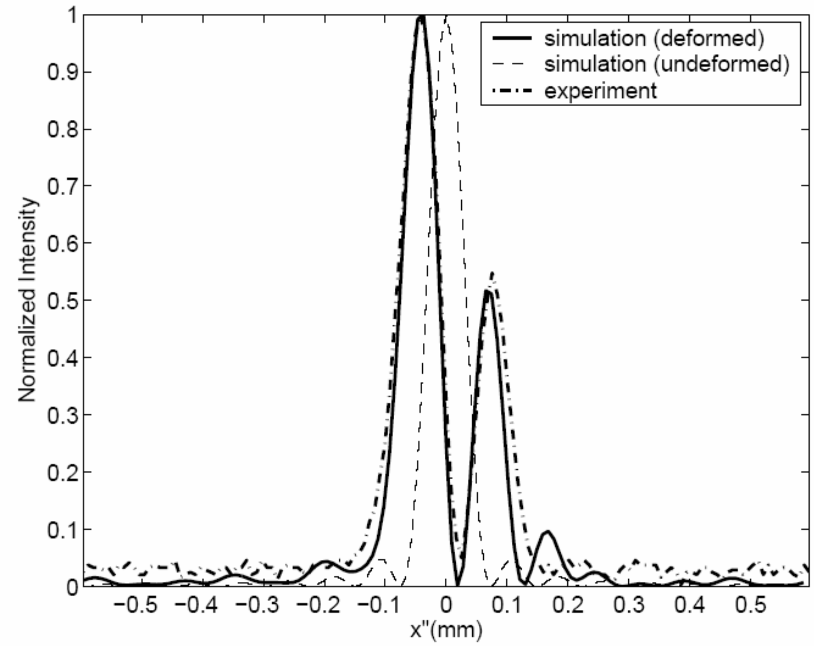
Deformed transmission 3D hologram in *k*-space



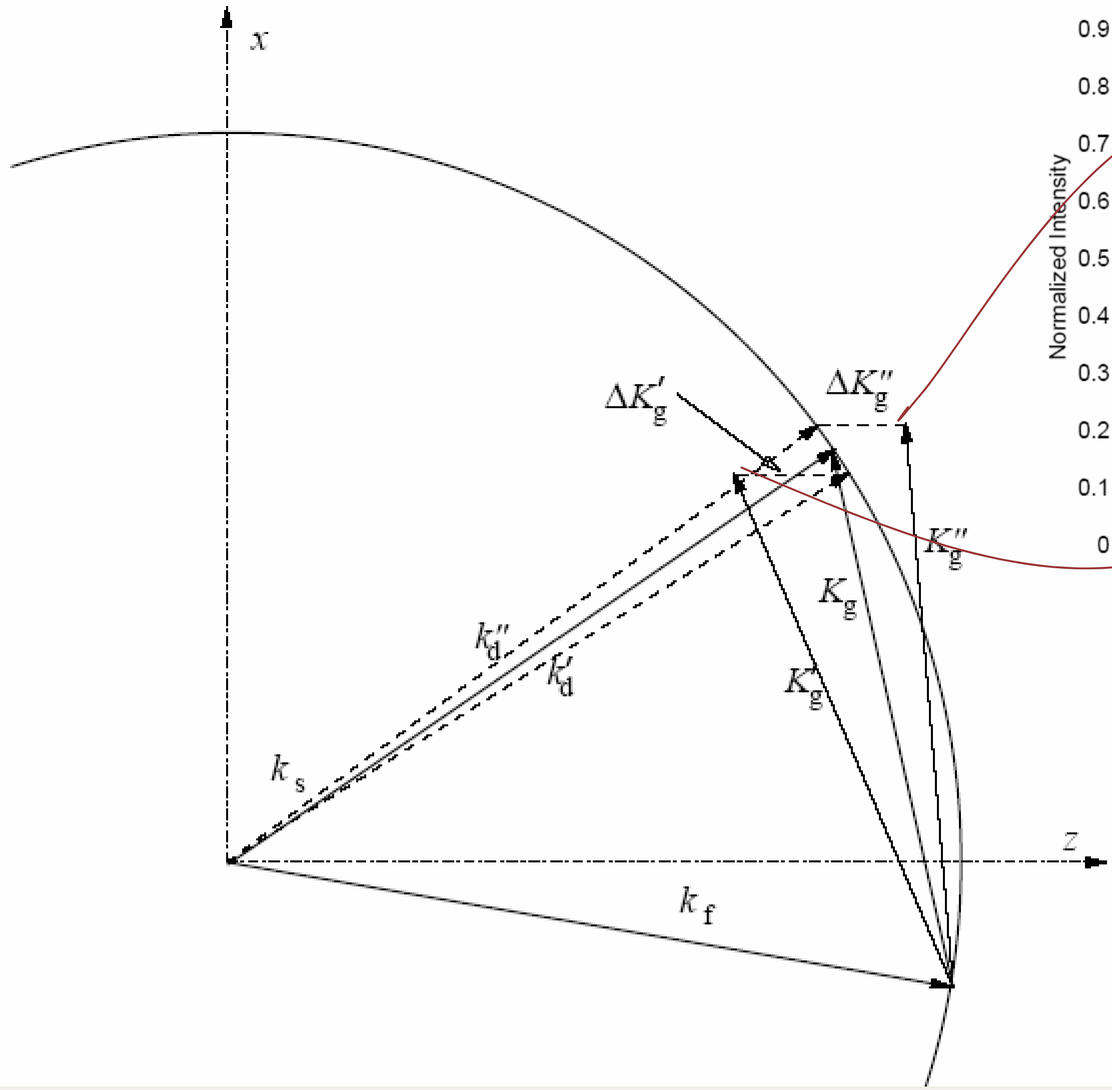


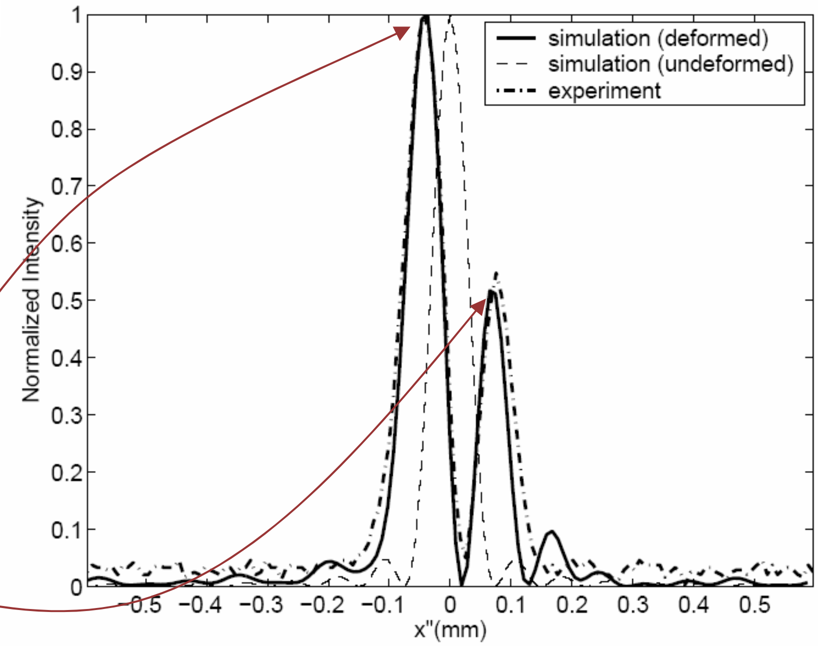
Deformed transmission 3D hologram in *k*-space



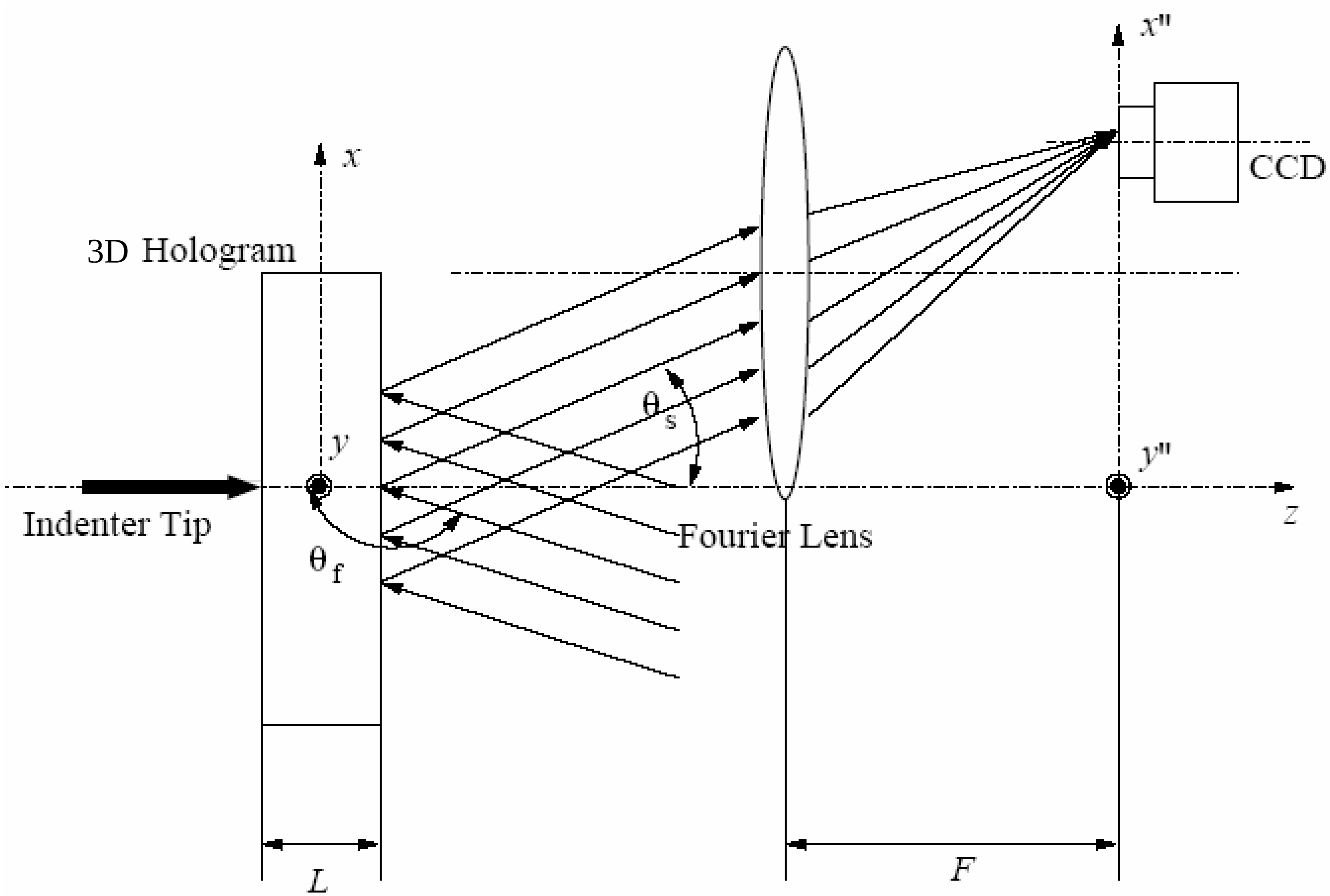


Deformed transmission 3D hologram in *k*-space

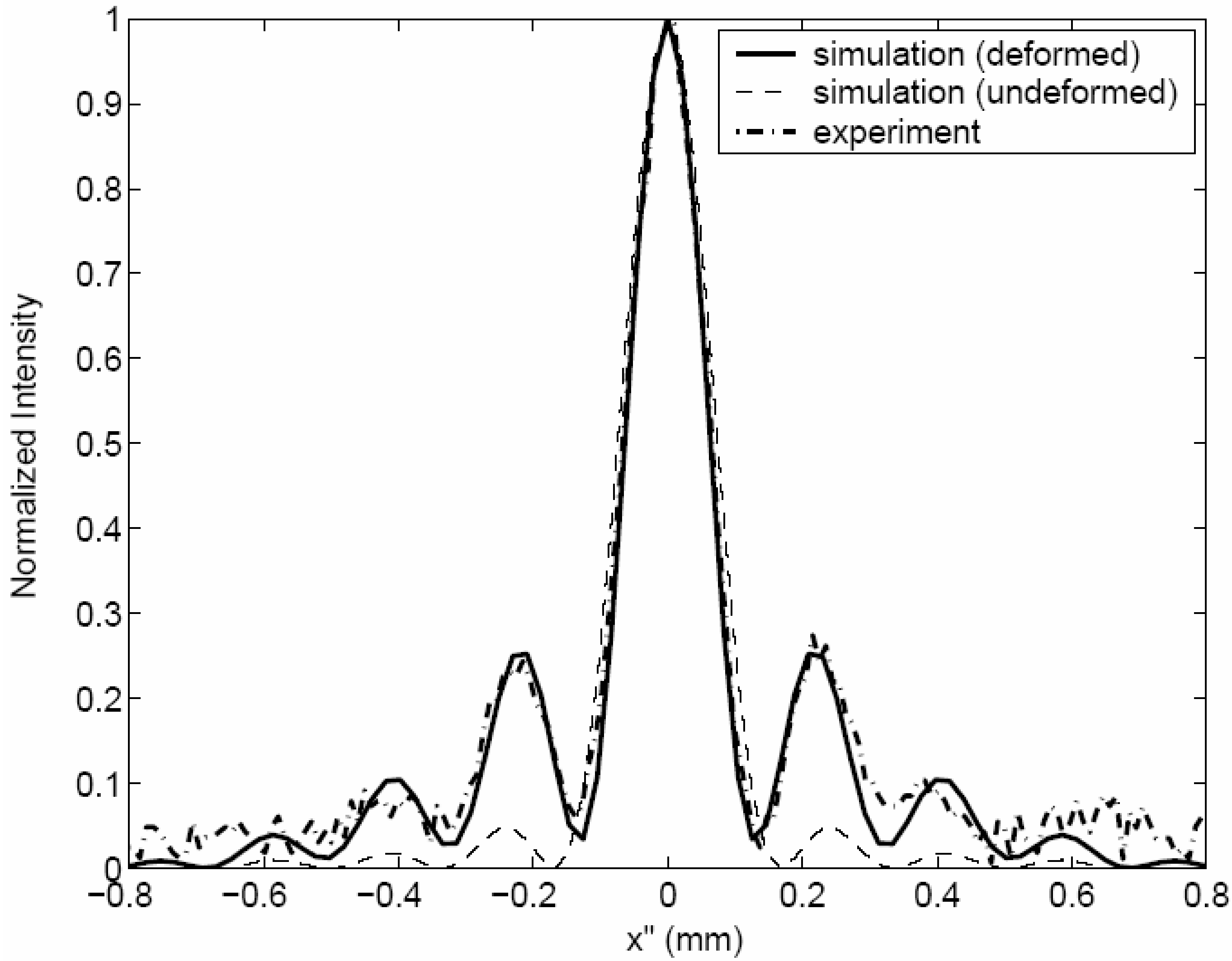




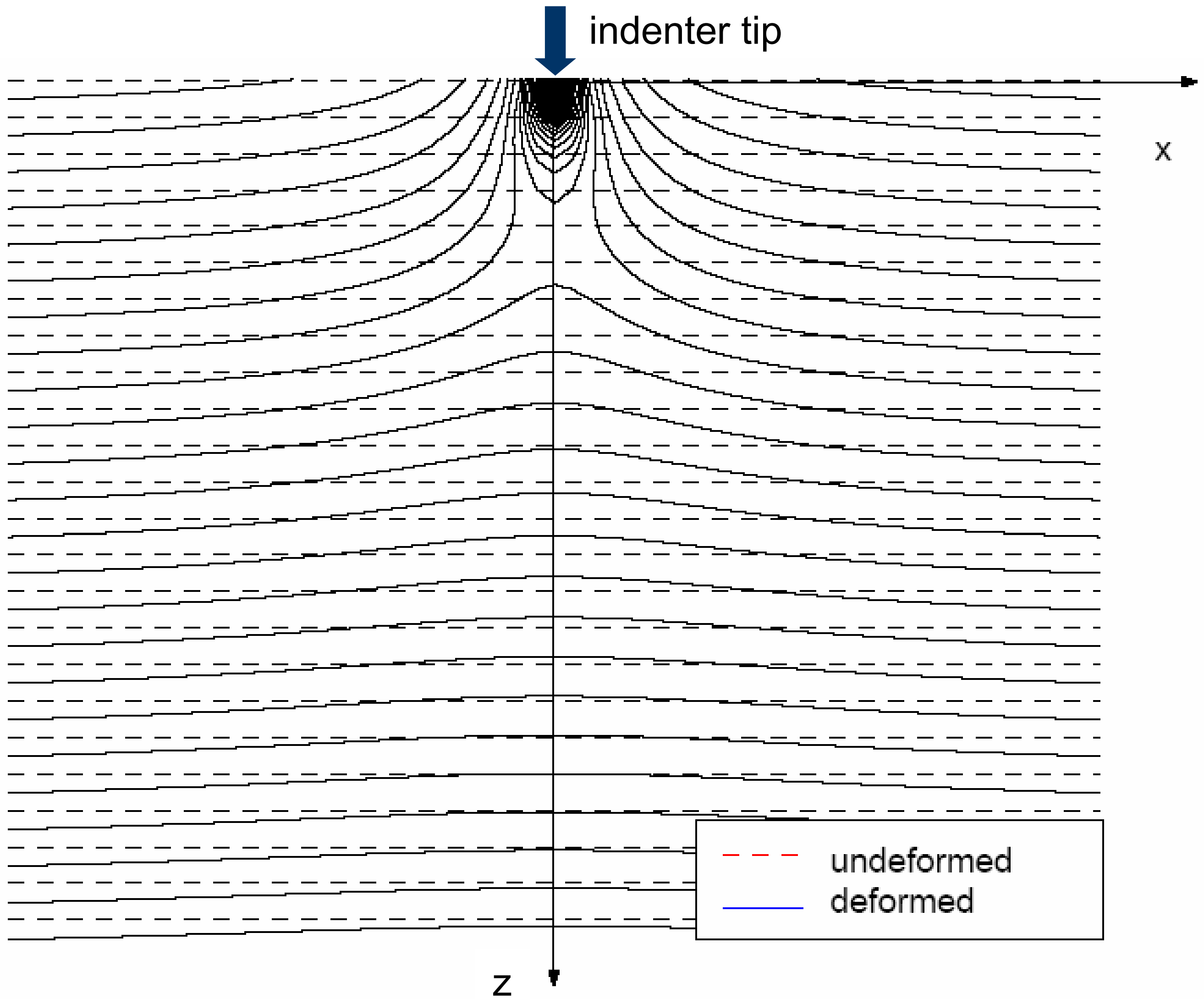
Experimental arrangement: reflection geometry



Experiment: diffraction from indented 3D hologram



Fringe deformation due to indenter (reflection)



Deformed reflection 3D hologram in *k*-space