

# Design and Behavior of Multilayer Stack-Based Spaceplates

Yaryna Mamchur

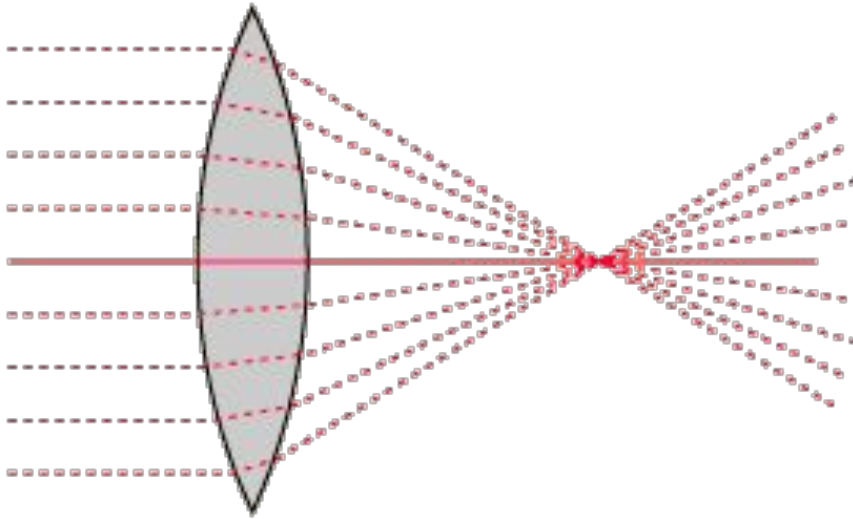
# Optics 101

You have my respect

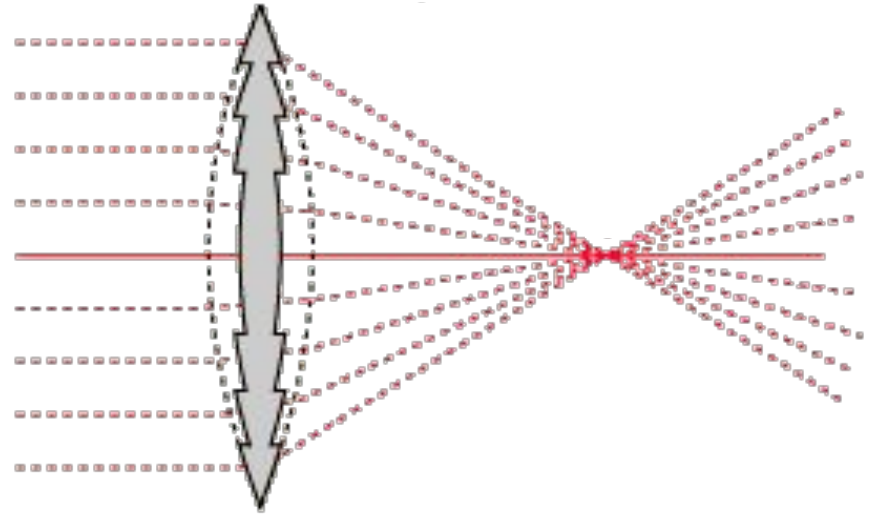
# Local optics

## Local optics

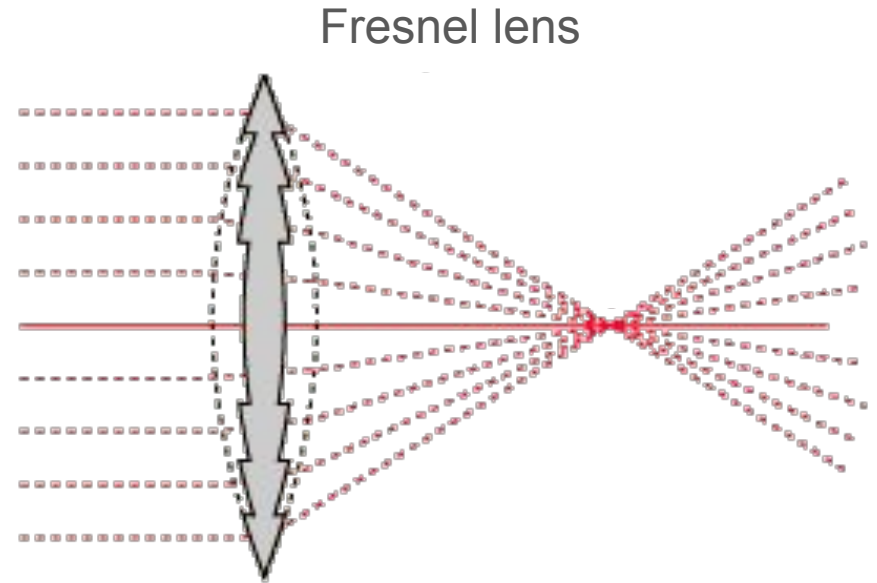
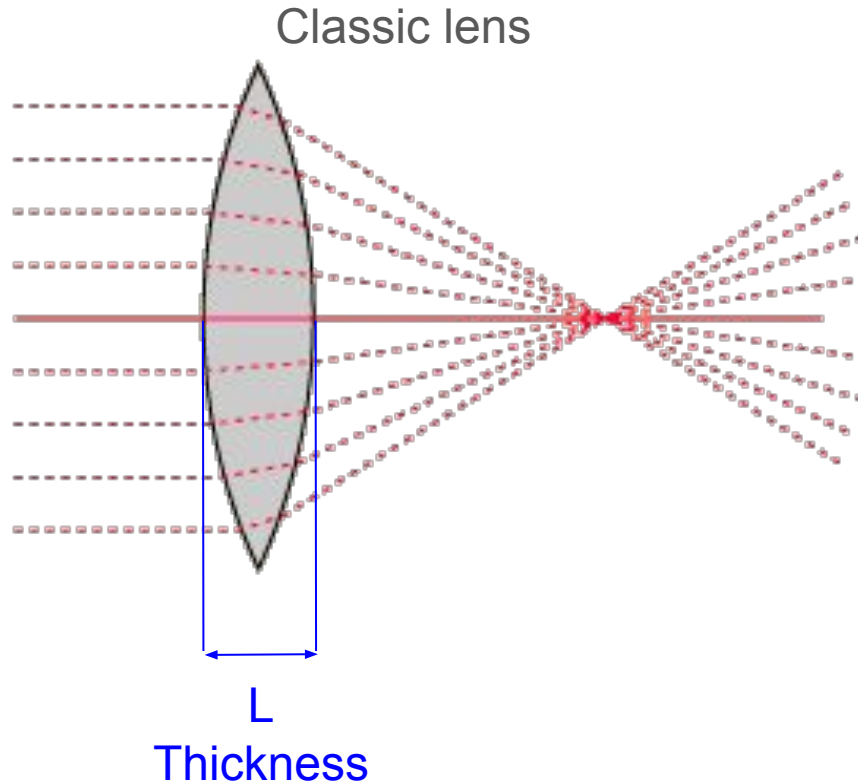
Classic lens



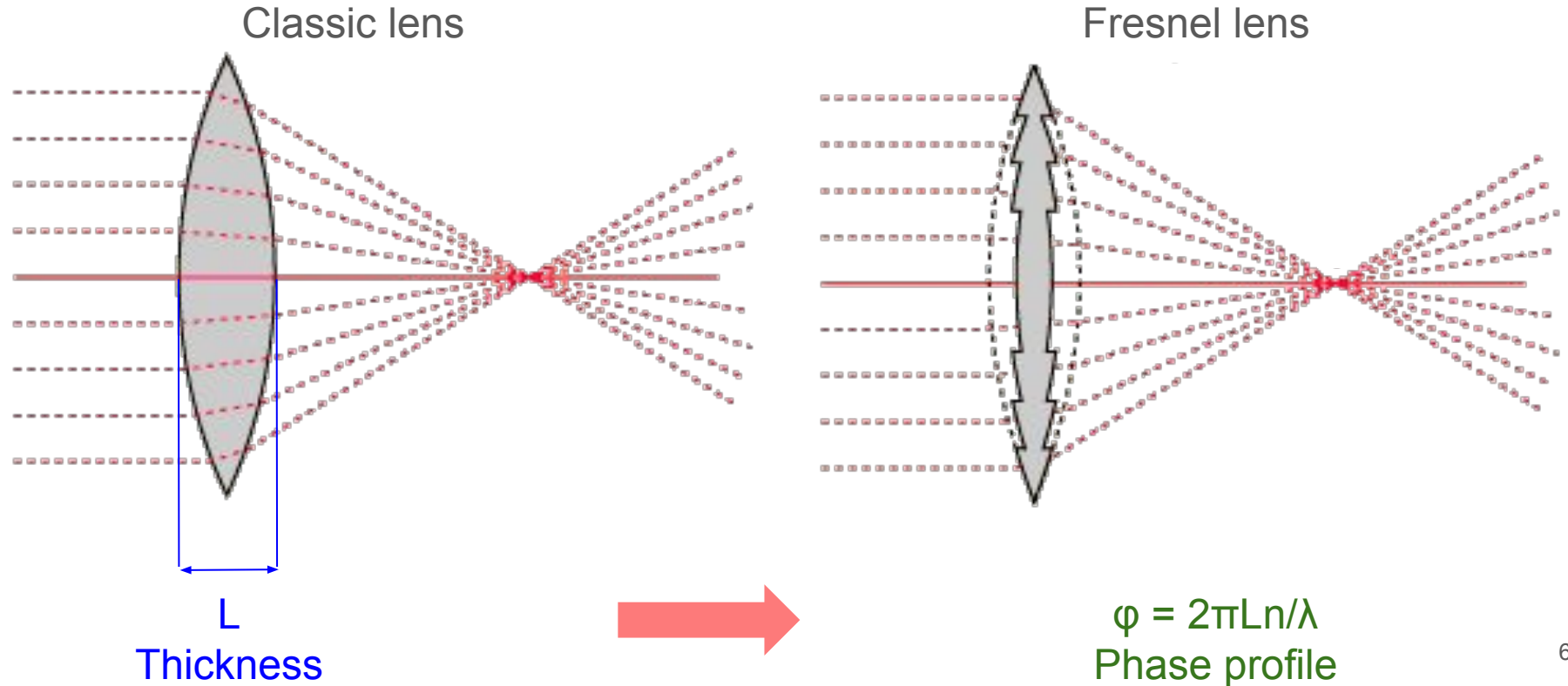
Fresnel lens



## Local optics



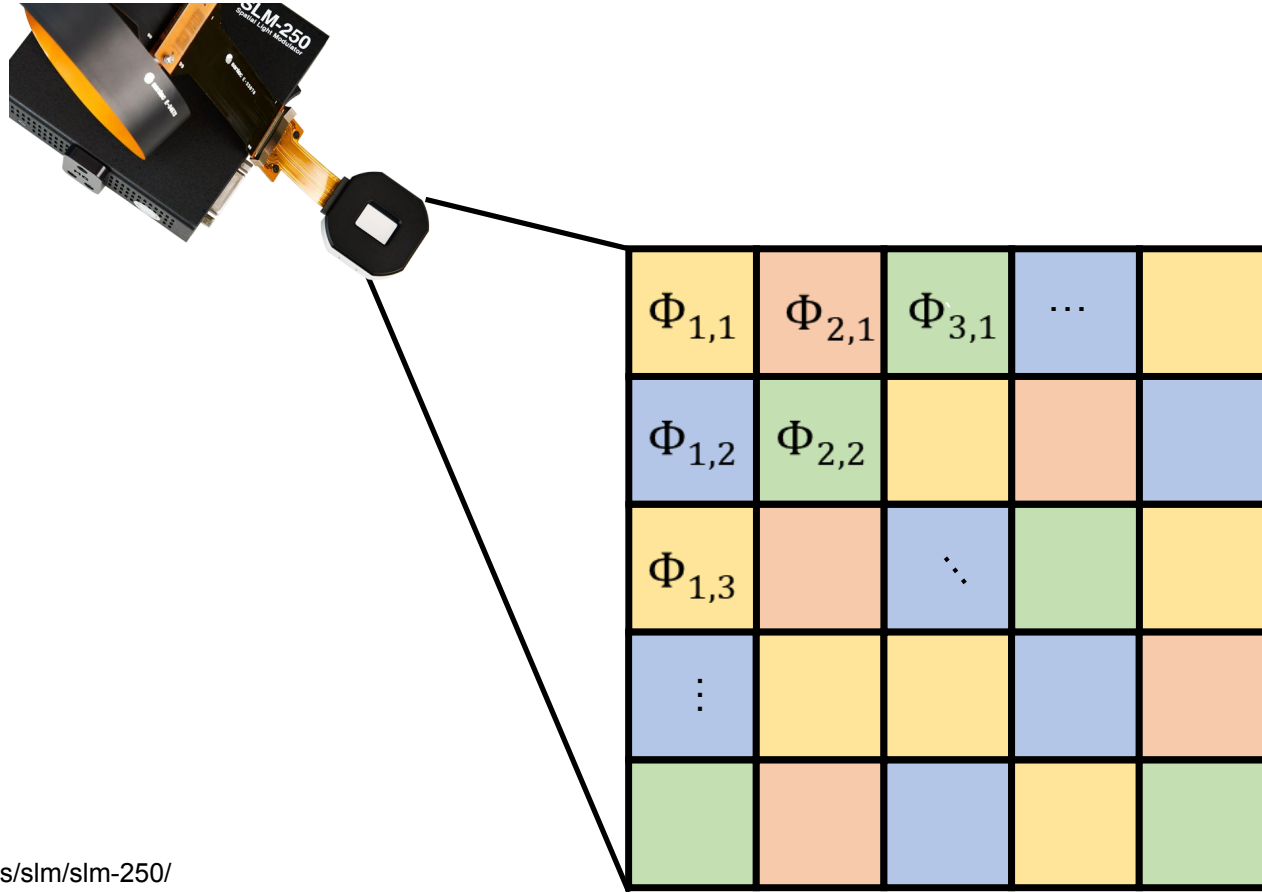
## Local optics



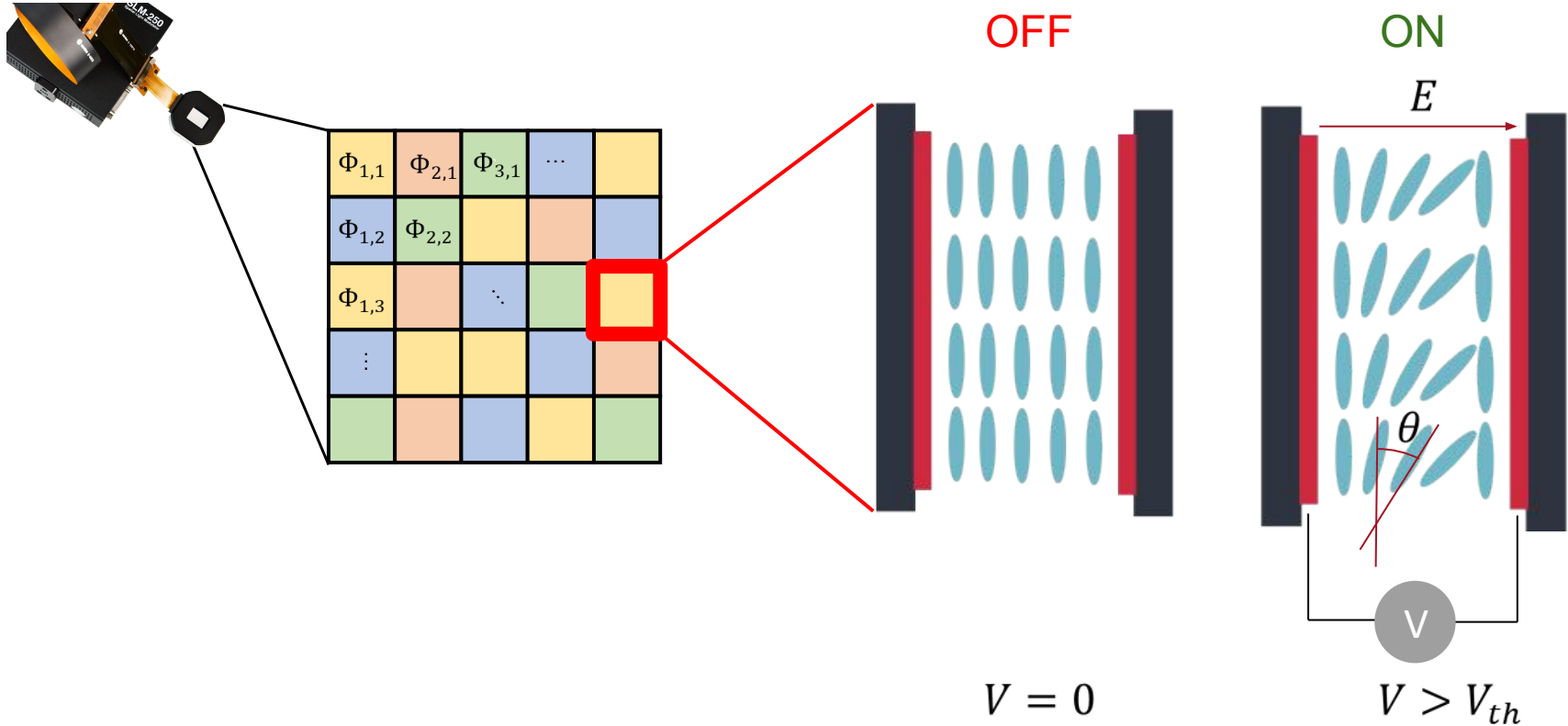
# Spatial light modulators



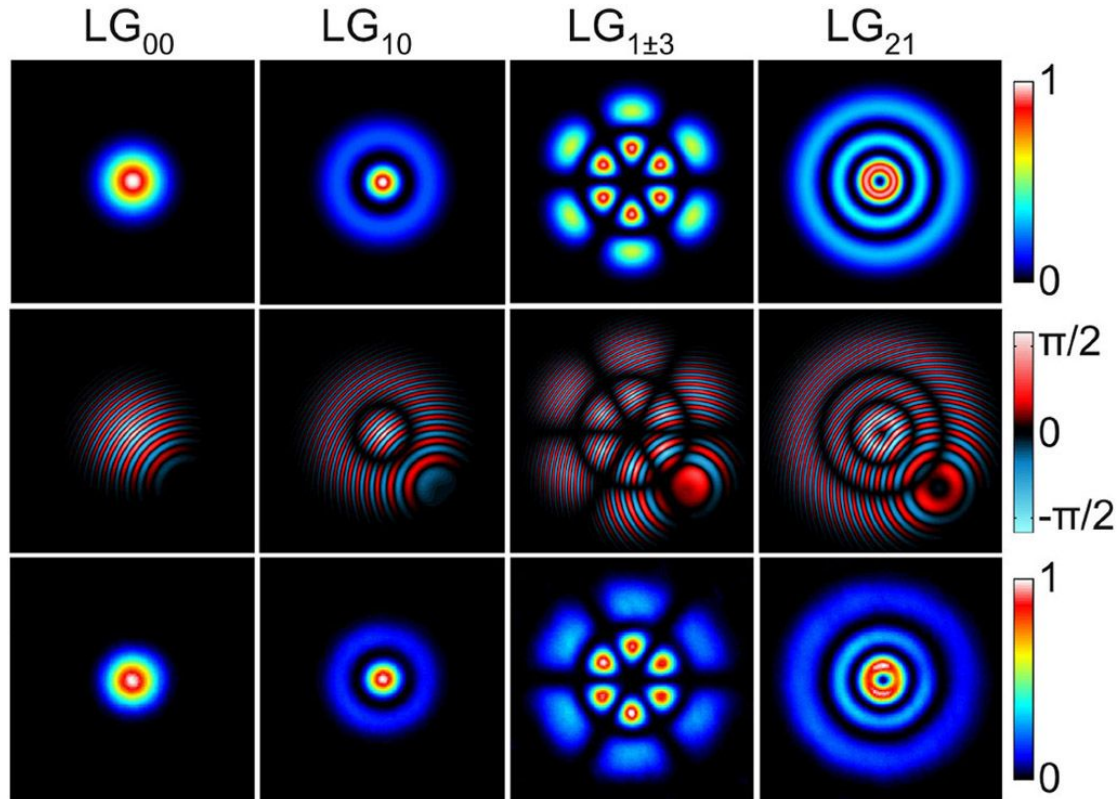
# Spatial light modulators



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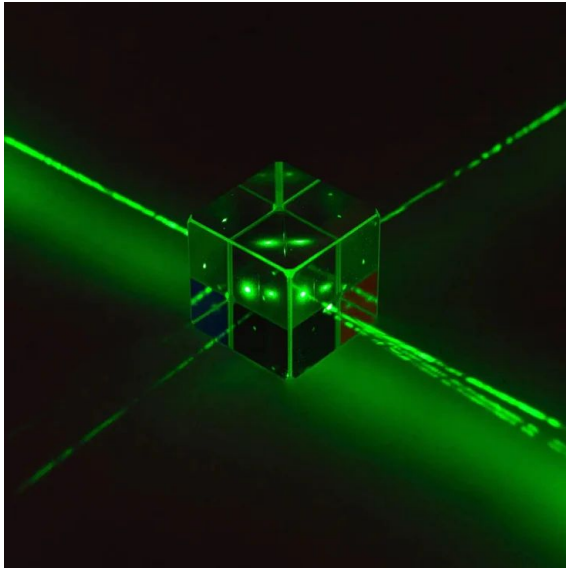


Can we create any transformation with local optics?

No

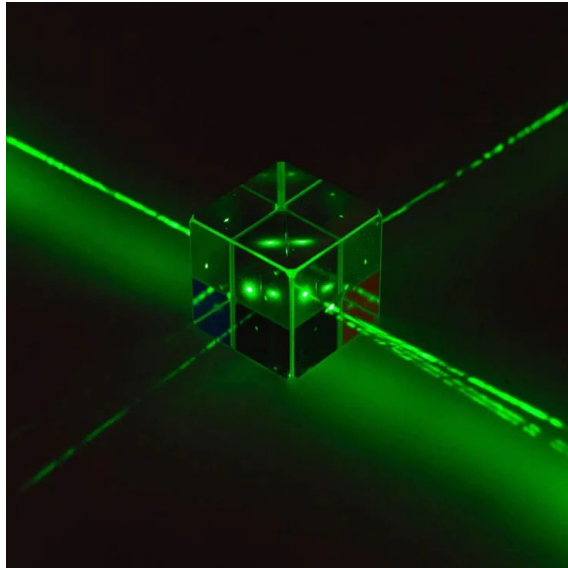
No

## Beamsplitter

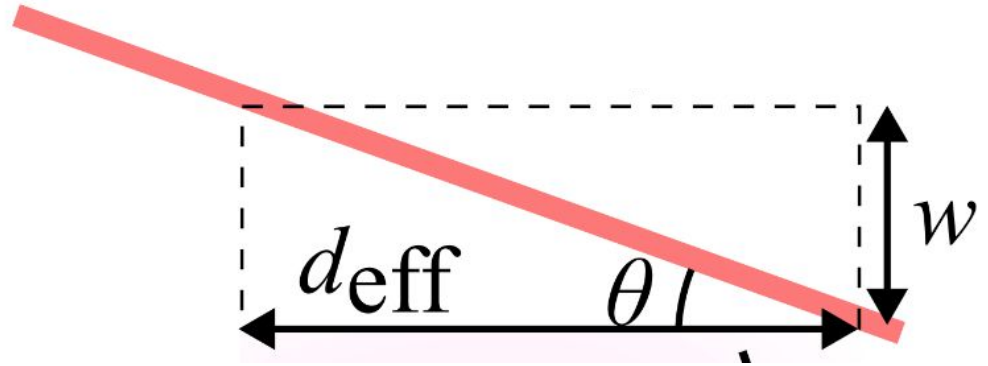


No

Beamsplitter

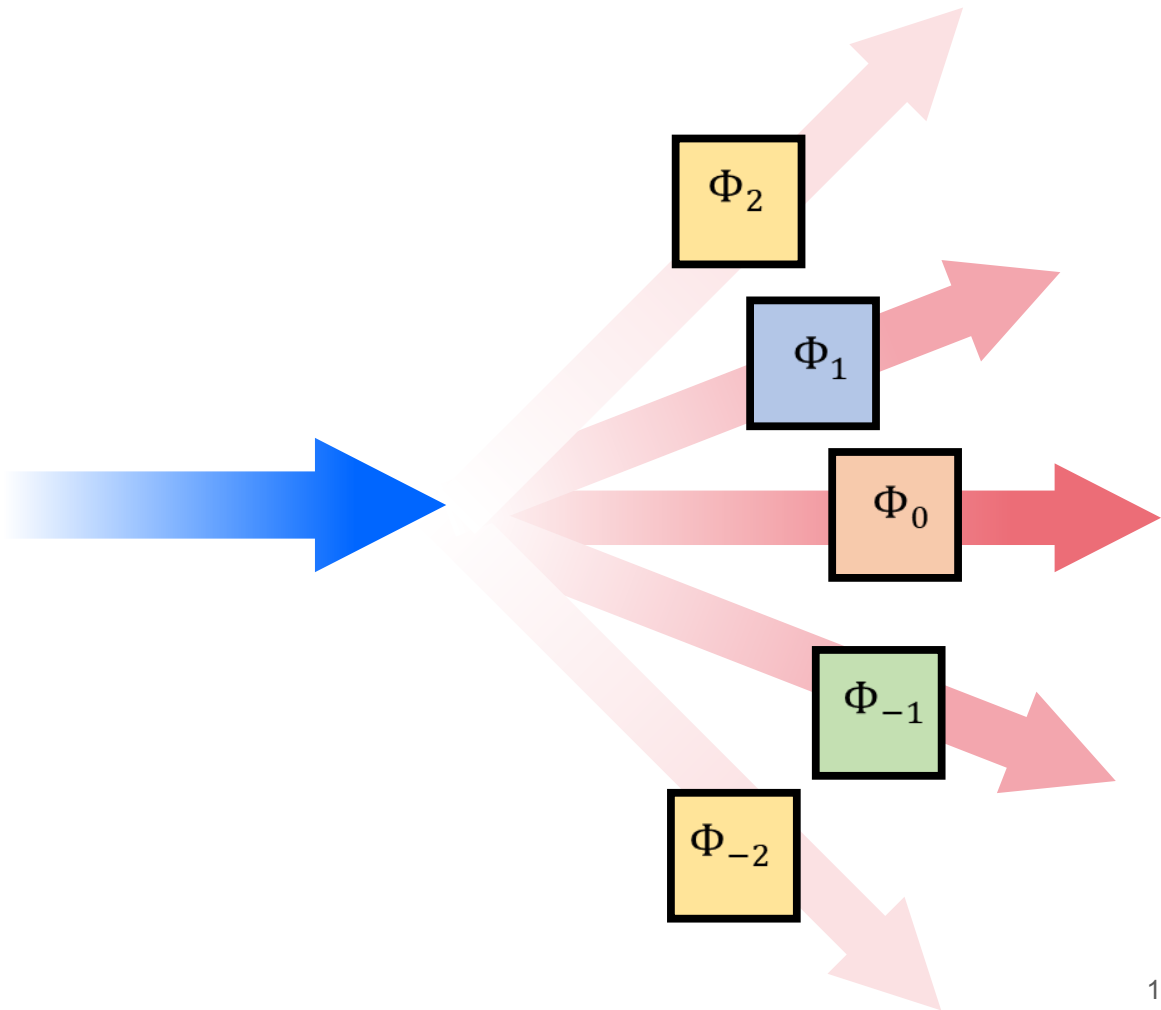
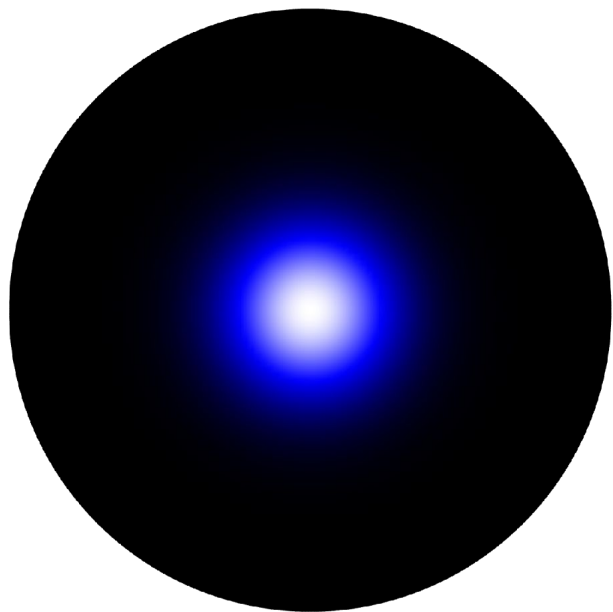


Free space propagation

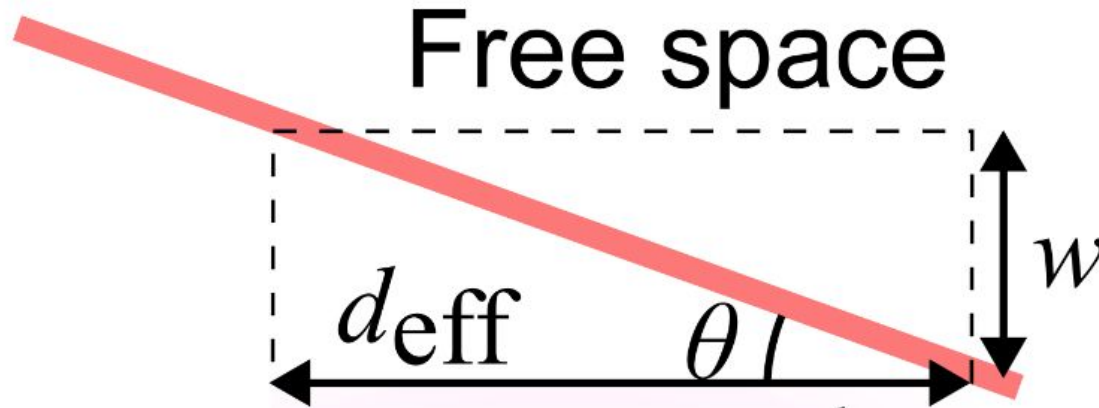


# Non-local optics

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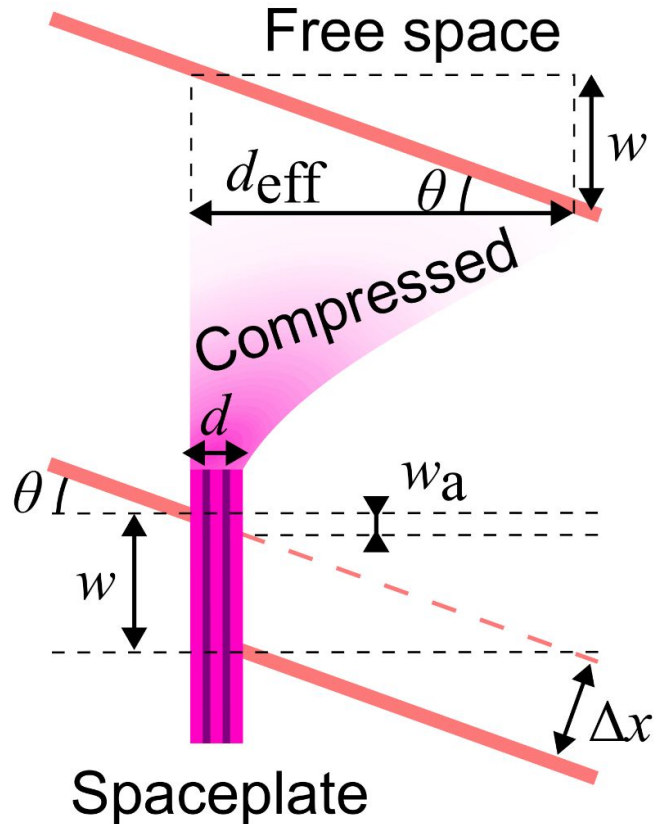


What is a spaceplate?



$d_{\text{eff}}$  - propagation length  
 $w$  - beam shift

# What is a spaceplate?



$d_{\text{eff}}$  - propagation length

$w$  - beam shift in free space over  $d_{\text{eff}}$

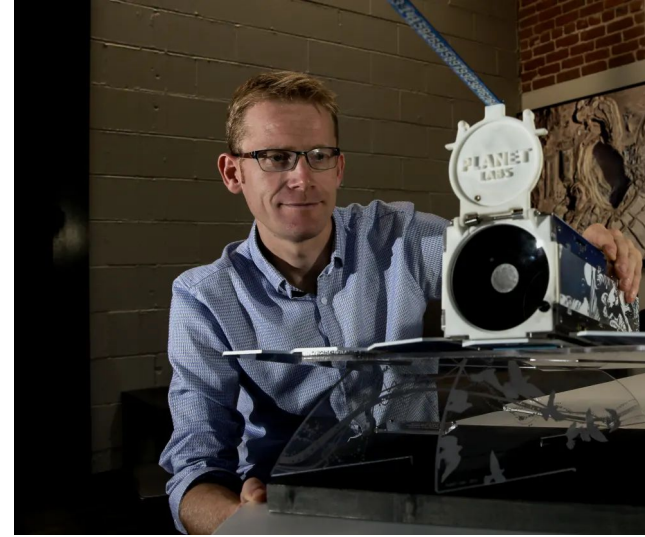
$d$  - thickness of the spaceplate

$w_a$  - beam shift over  $d$

$\Delta x$  - lateral beam shift

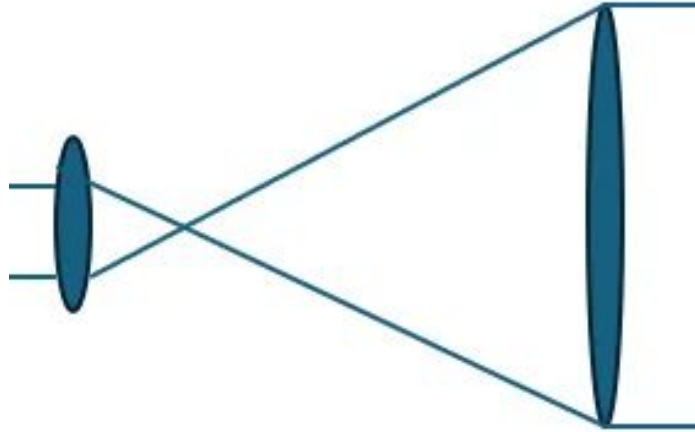
Why do we need the spaceplate?

# To minimize optical systems

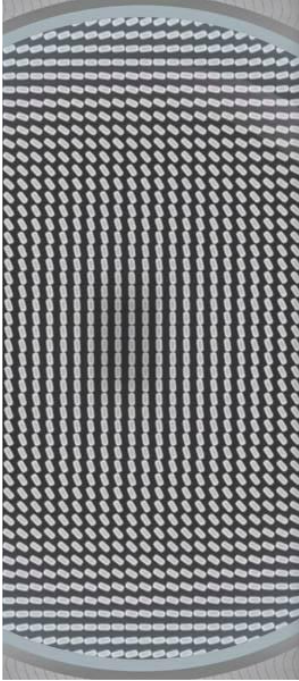


# To minimize optical systems

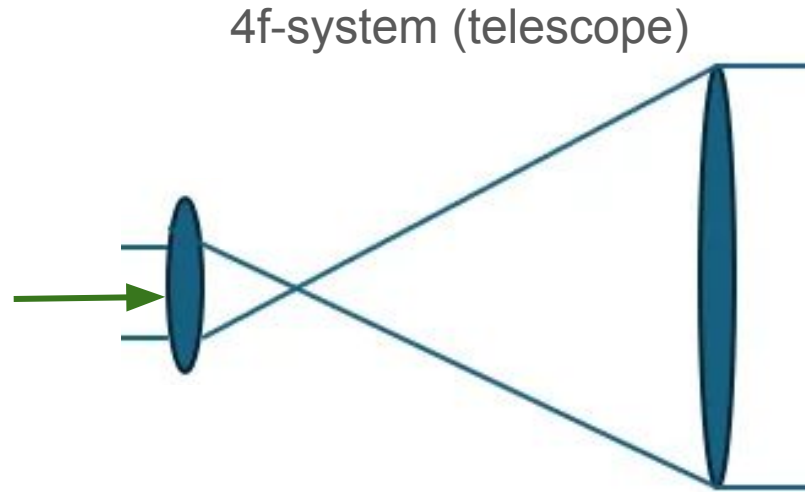
4f-system (telescope)



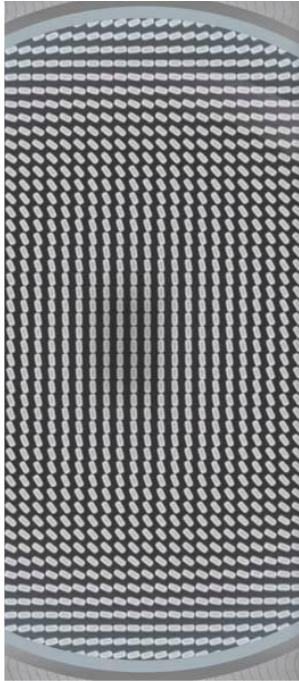
# To minimize optical systems



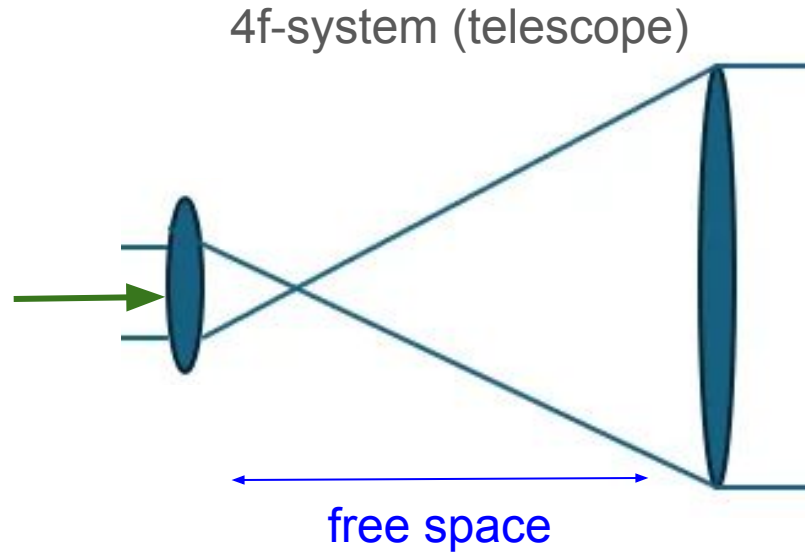
metalenses



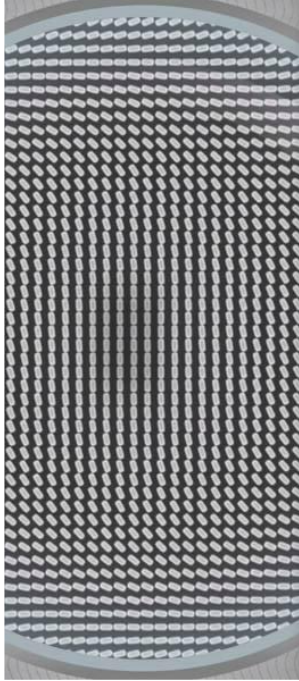
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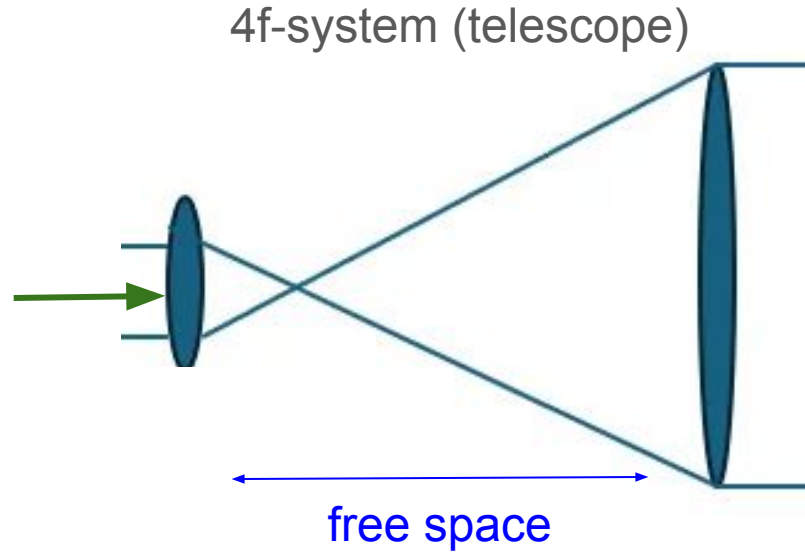
metalenses



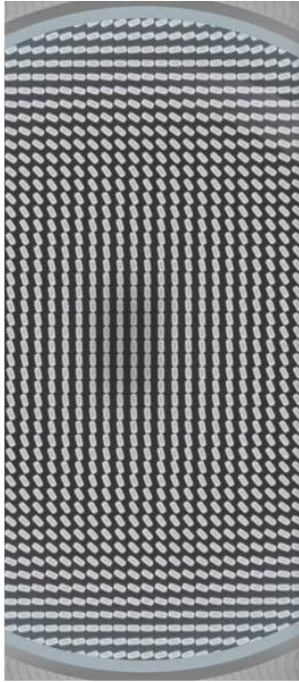
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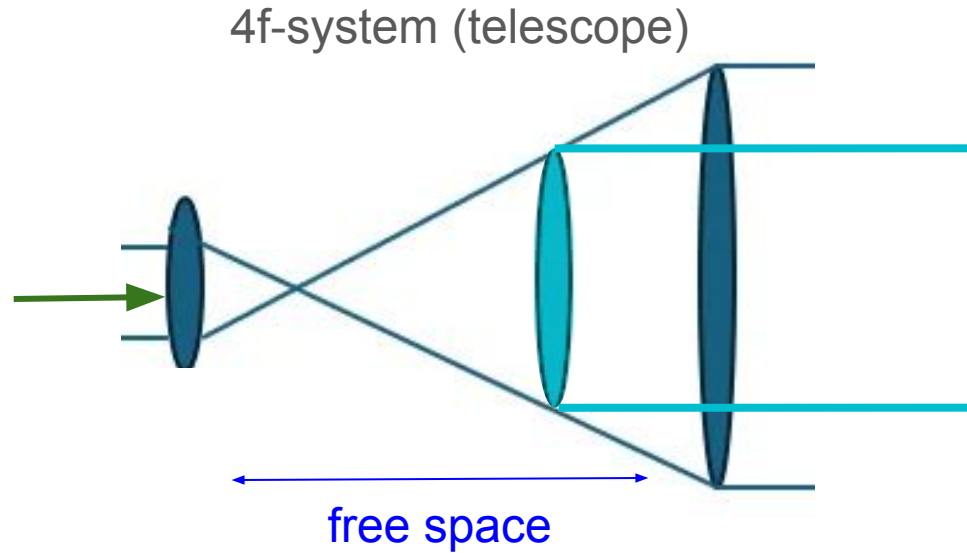
metalenses



# To minimize optical systems

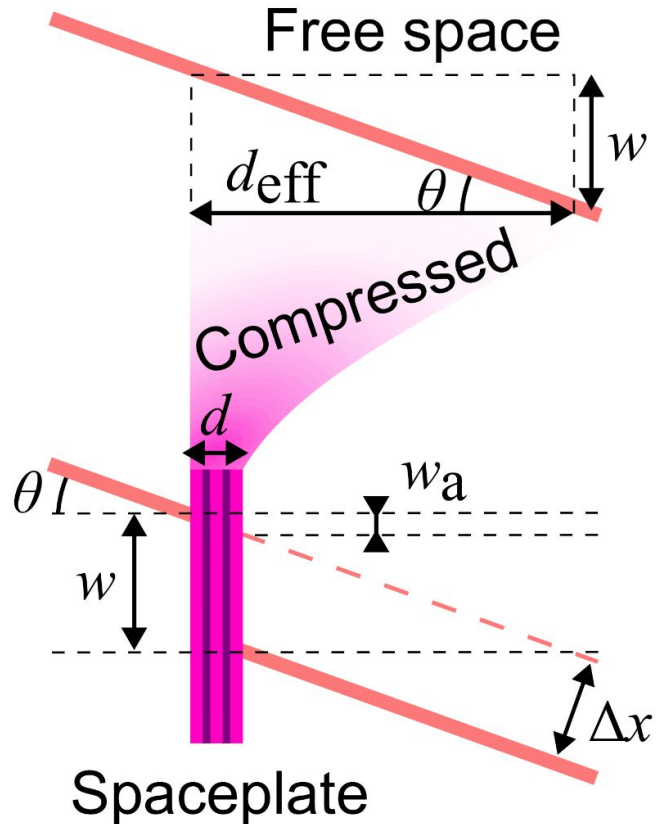


metalenses



How to design a spaceplate?

# Compression factor R

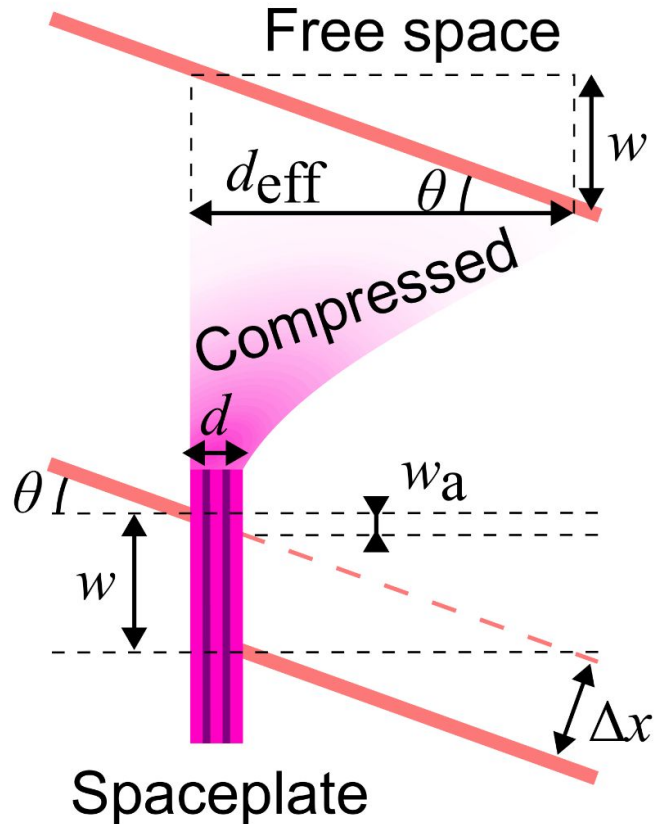


$d_{\text{eff}}$  - propagation length

$d$  - thickness of the spaceplate

$$R = d_{\text{eff}} / d$$

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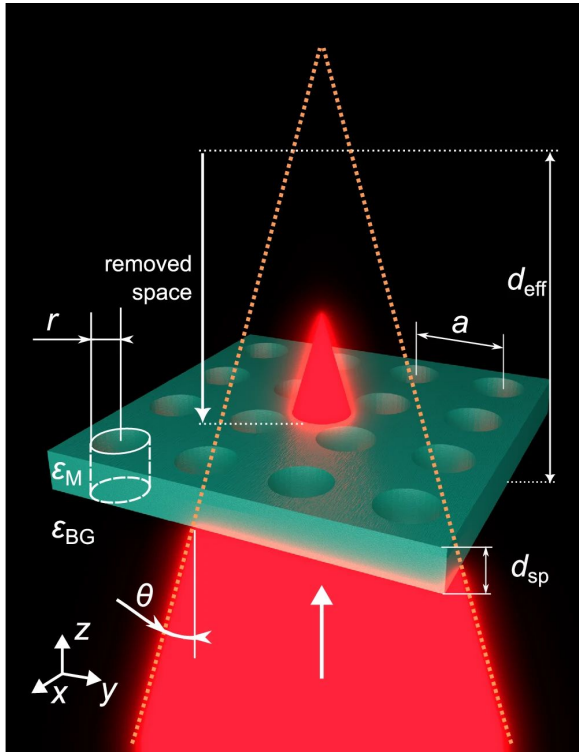
Important characteristics:

- Angular range (numerical aperture)
- wavelength range



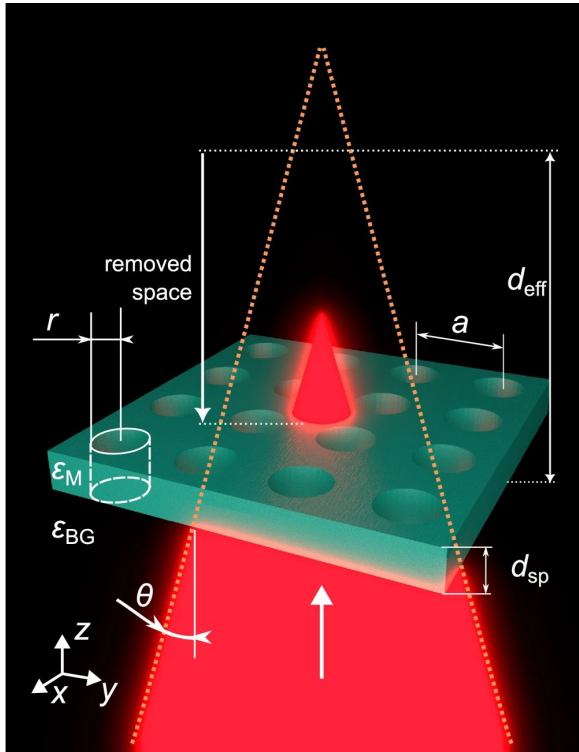
# Spaceplate platforms

# Photonic crystals



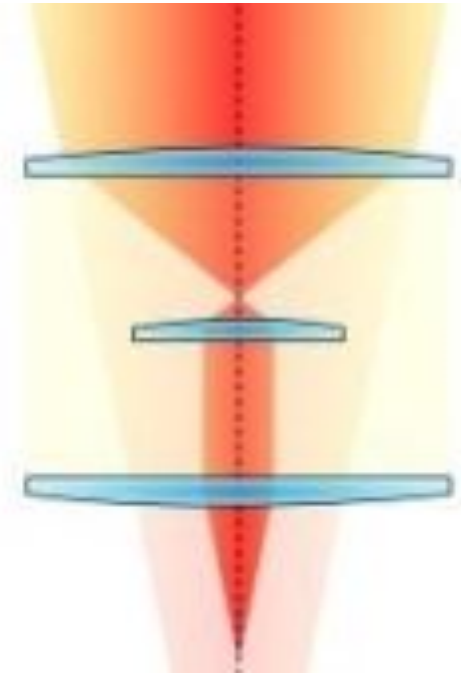
Broadband transparent Huygens' spaceplates. *npj Nanophoton.* **1**, 30 (2024)

## Photonic crystals



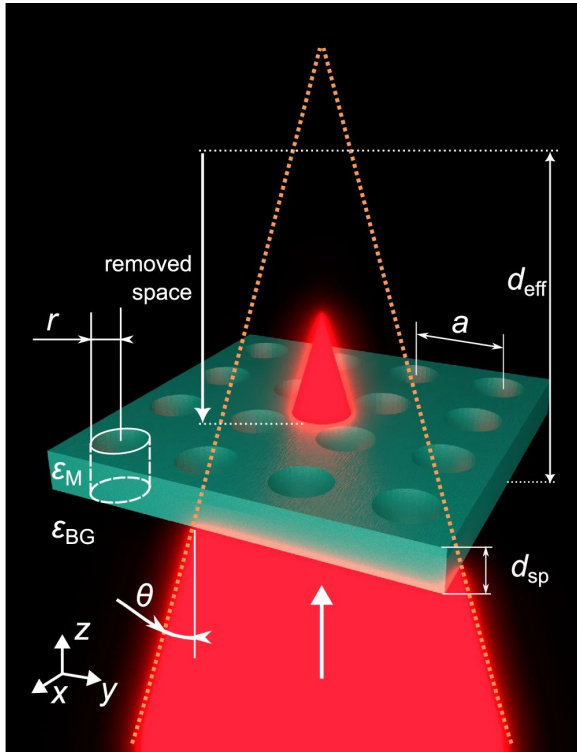
Broadband transparent Huygens' spaceplates. *npj Nanophoton.* **1**, 30 (2024)

## Three-lens systems



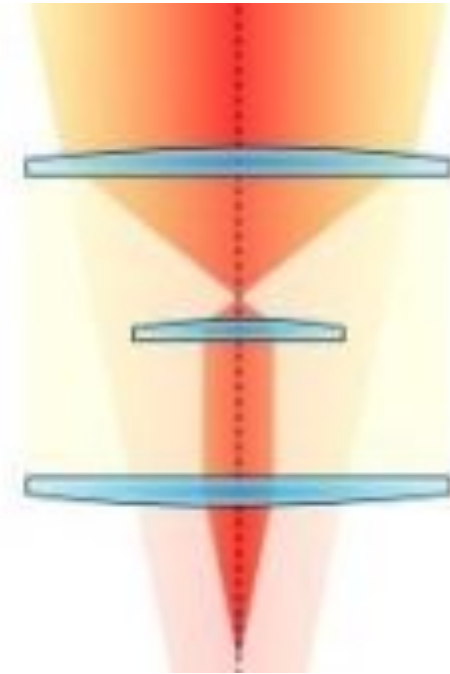
Large-scale optical compression of free-space using an experimental three-lens spaceplate, *Optics Express* Vol. 31, Issue 12, pp. 19766-19776 (2023)

## Photonic crystals



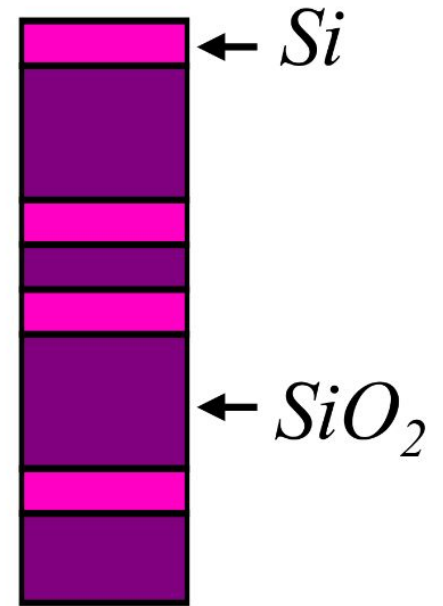
Broadband transparent Huygens' spaceplates. *npj Nanophoton.* **1**, 30 (2024)

## Three-lens systems



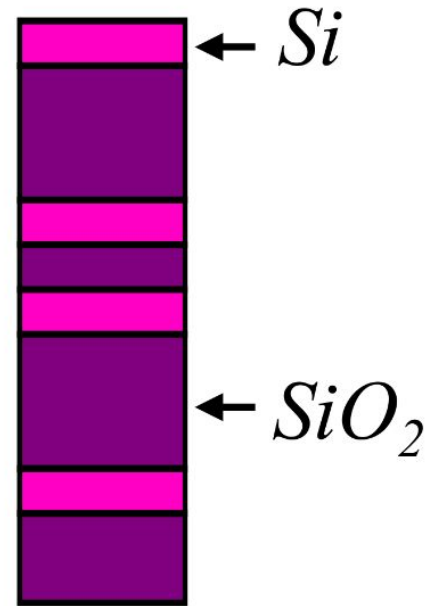
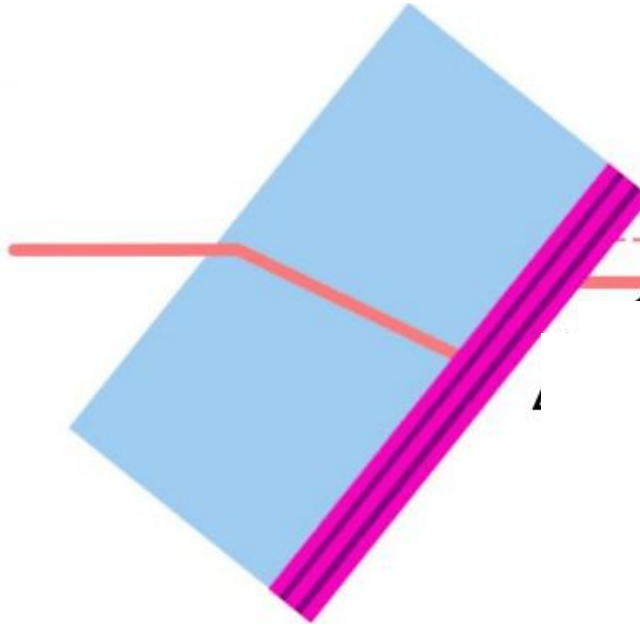
Large-scale optical compression of free-space using an experimental three-lens spaceplate, *Optics Express* Vol. 31, Issue 12, pp. 19766-19776 (2023)

## Multilayer stacks



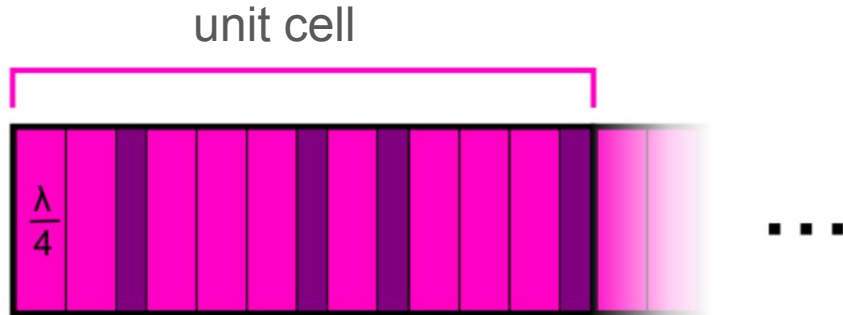
Experimental demonstration of high space compression by optical spaceplates. *Nat Commun.* **17**, 3493 (2026)

Designed for 1550 nm

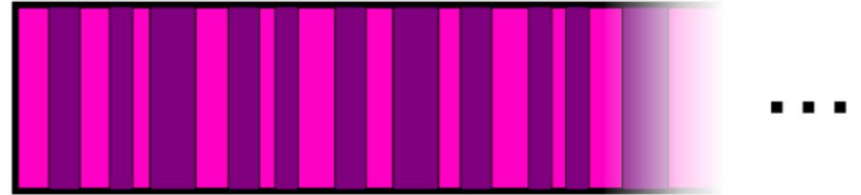


# Design approaches

Coupled Cavity Design (FPC)  
*periodic*

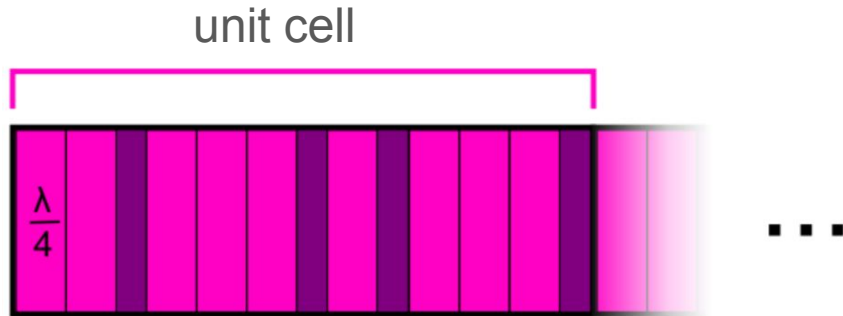


Gradient Descent Algorithm (GD)  
*aperiodic*



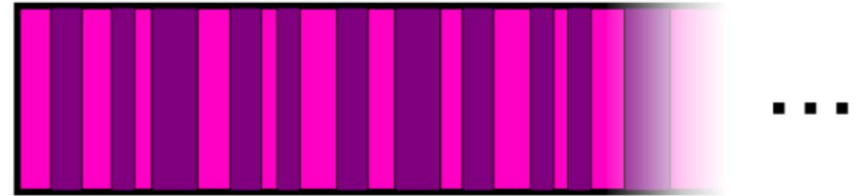
# Design approaches

Coupled Cavity Design (FPC)  
*periodic*



FPC1 -  $3.5^\circ$   
FPC2 -  $1^\circ$

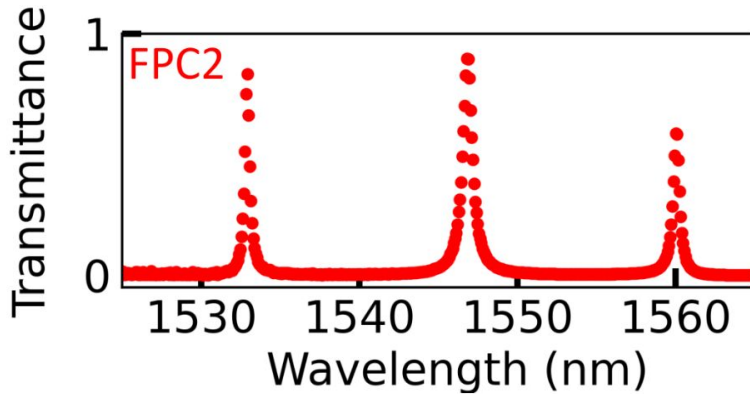
Gradient Descent Algorithm (GD)  
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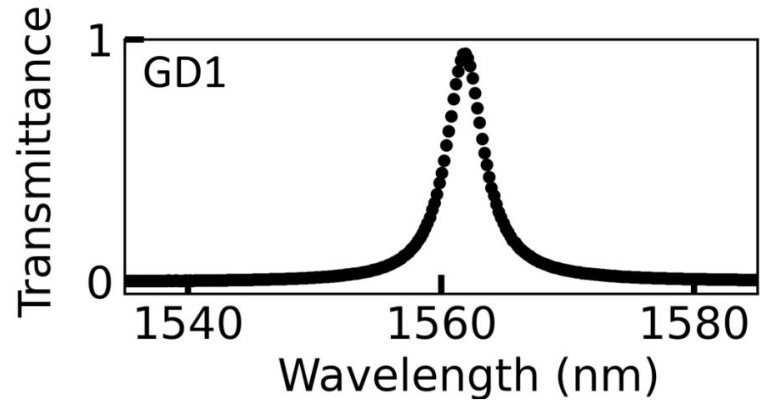
GD1 -  $1^\circ$   
GD2 -  $10^\circ$

# Design approaches

Coupled Cavity Design (FPC)  
*periodic*



Gradient Descent Algorithm (GD)  
*aperiodic*



# Measured Compression Factor R

Device	Thickness ( $\mu\text{m}$ )	Maximum Angle of Incidence $\theta_{\text{max}}$	FWHM Bandwidth (nm)	Wavelength (nm)	Max Compression Ratio $\mathcal{R}$
FPC2	11.51	1°	0.143±0.004	1532.9	96±2
FPC2	11.51	1°	0.282±0.006	1546.85	41.9±0.6
FPC2	11.51	1°	0.147±0.005	1560.1	48.6±1.4
GD1	2.48	10°	2.8±0.3	1561.66	60±4
GD2	13.42	1°	0.055±0.007	1566.06	176±14
FPC1	12.57	3.5°	*	1579.8	3.4±0.3

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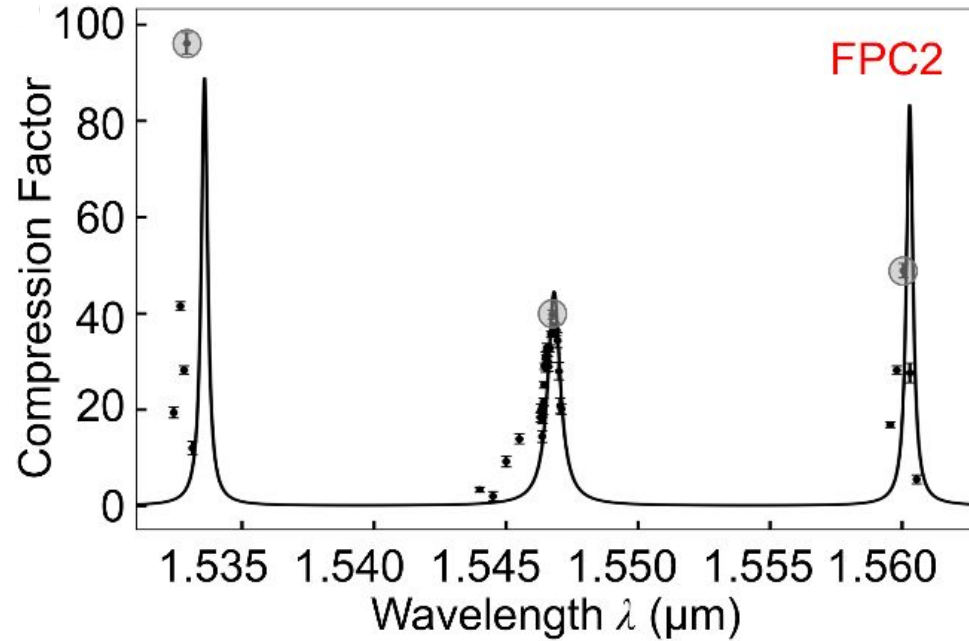
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**The spaceplate of 13.4  $\mu\text{m}$  canceled out 2.4 mm free space propagation**

# Measured Compression Factor R

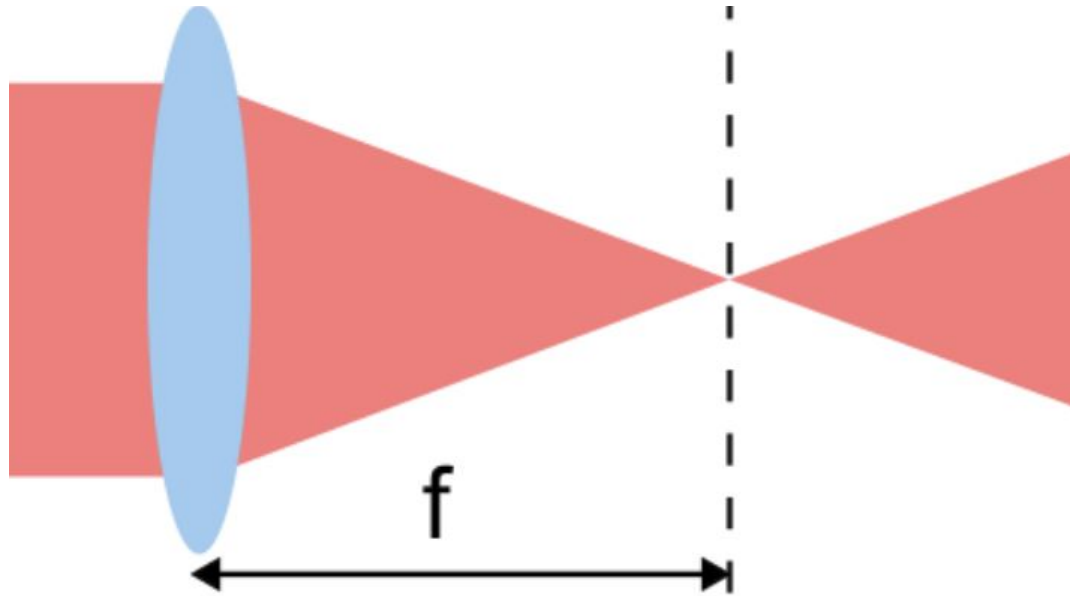
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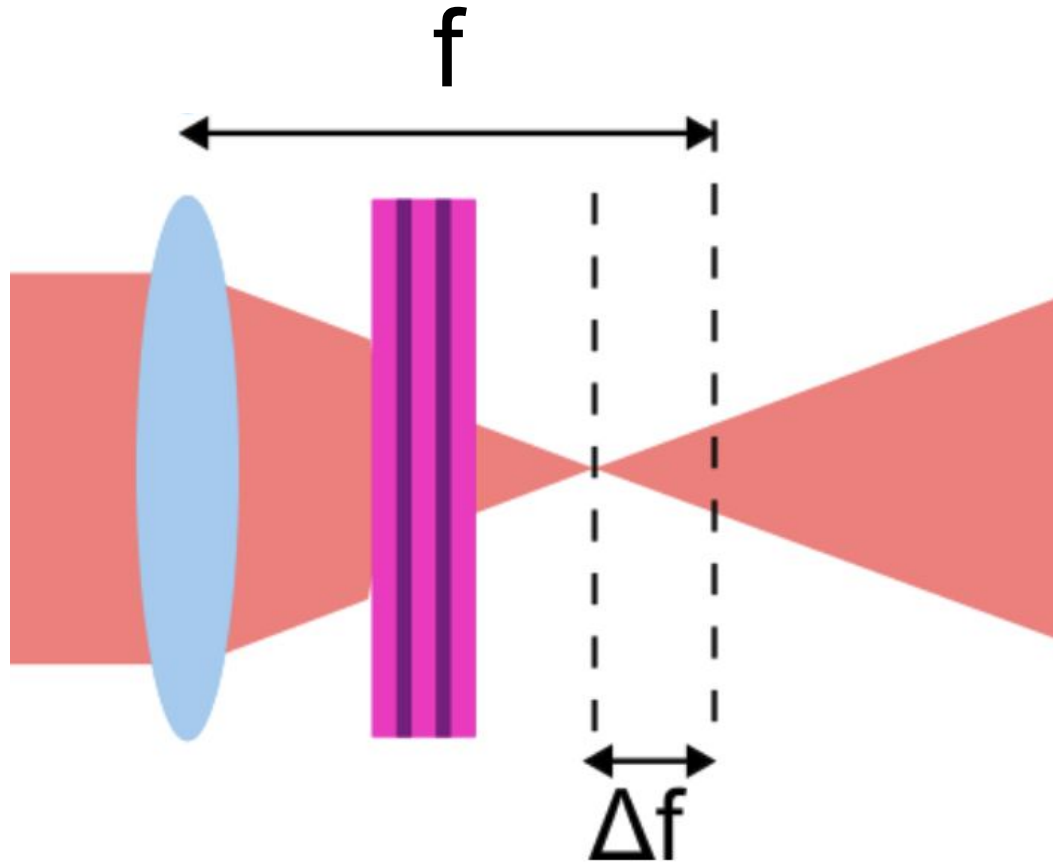


How can we measure this?

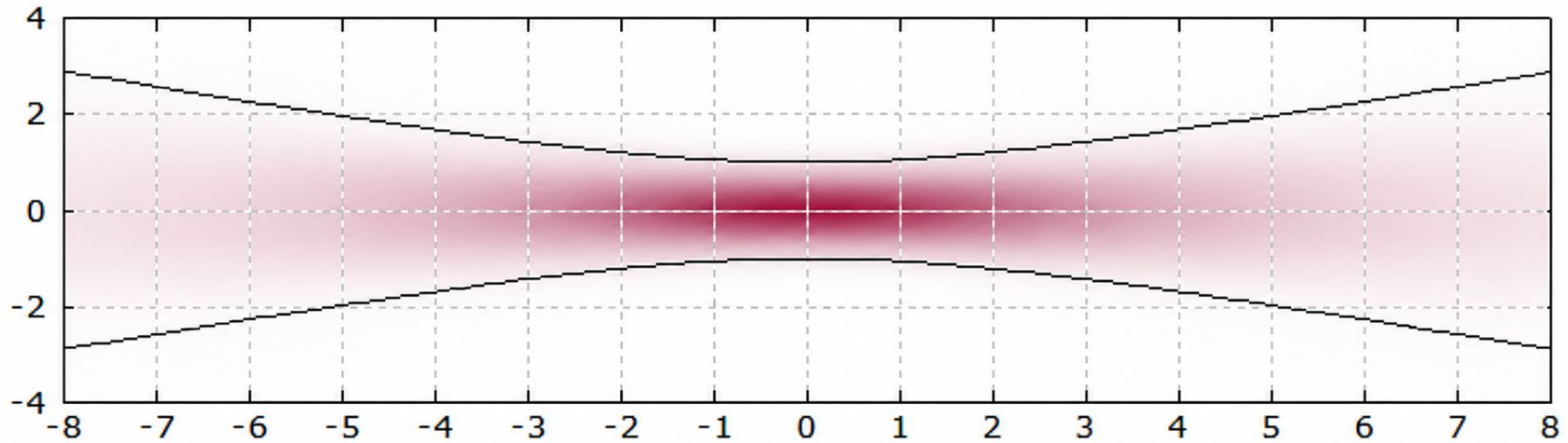
# The action of a spaceplate



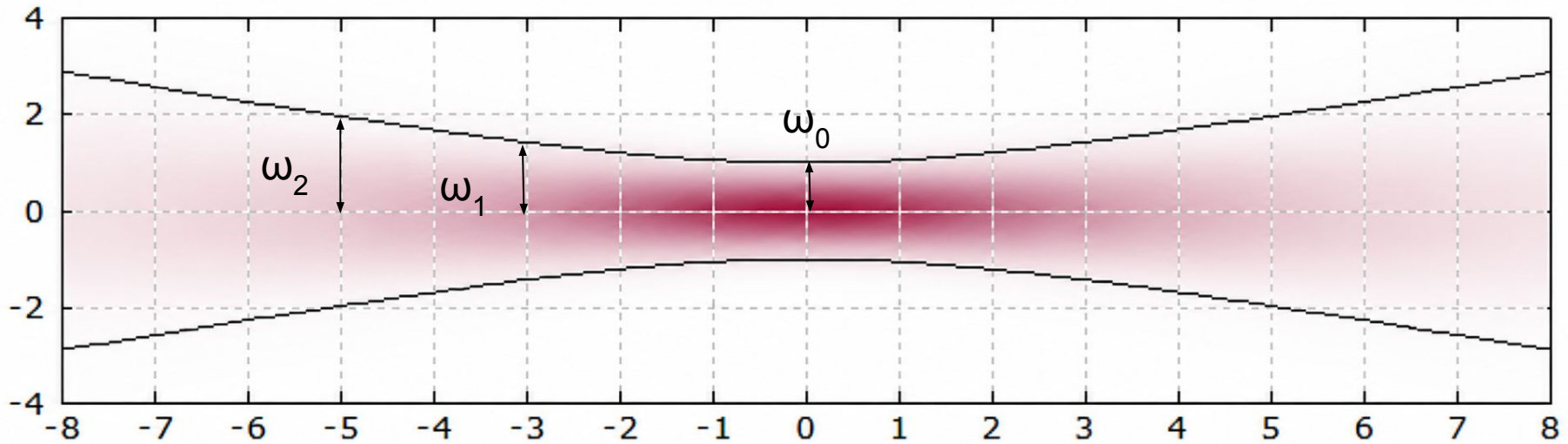
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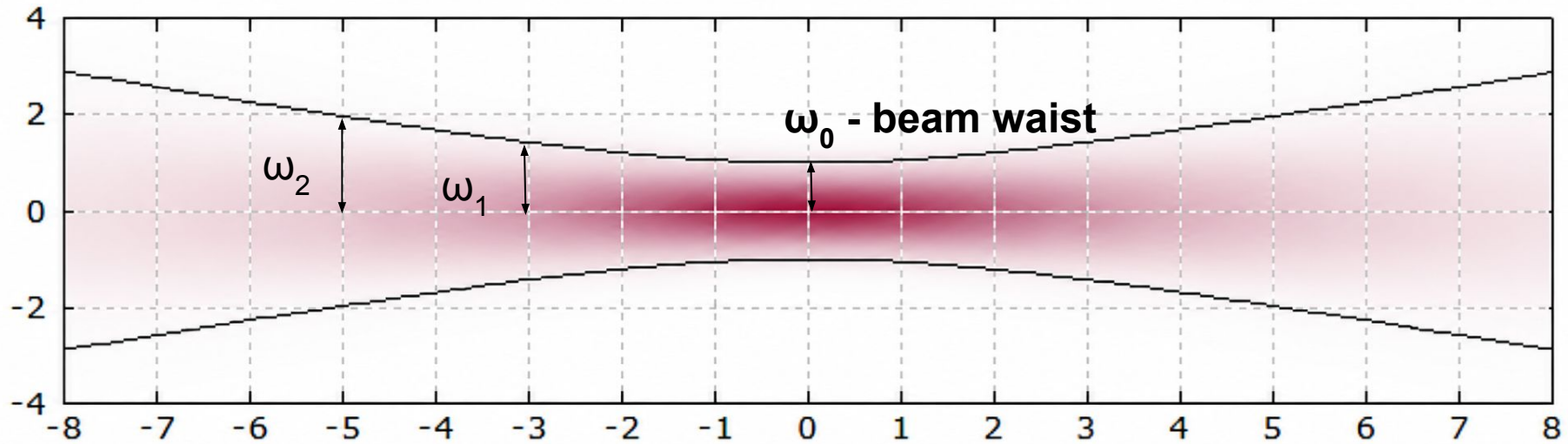
## Measuring the focal shift



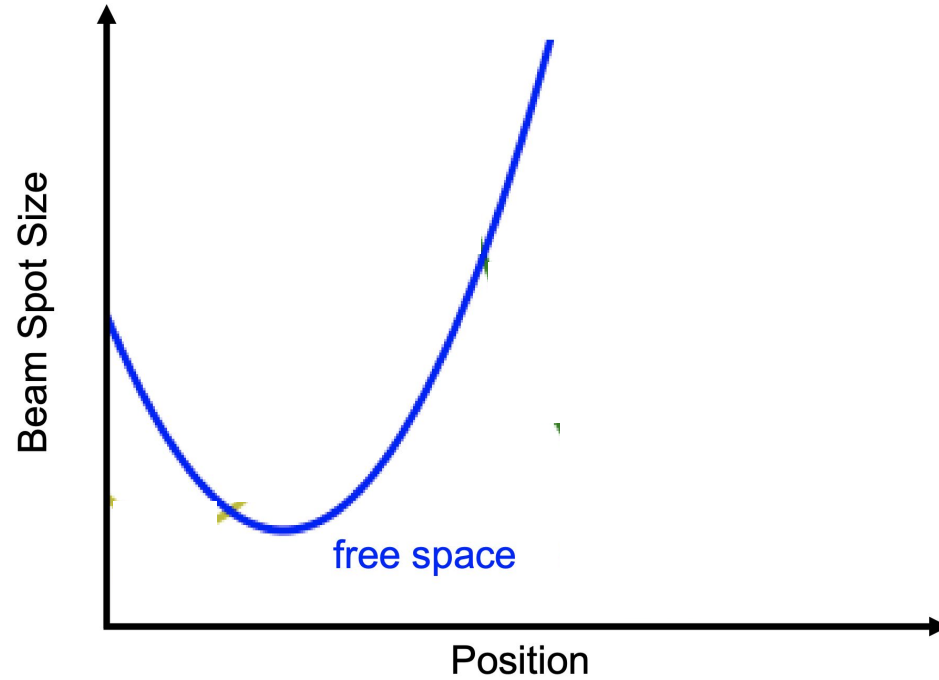
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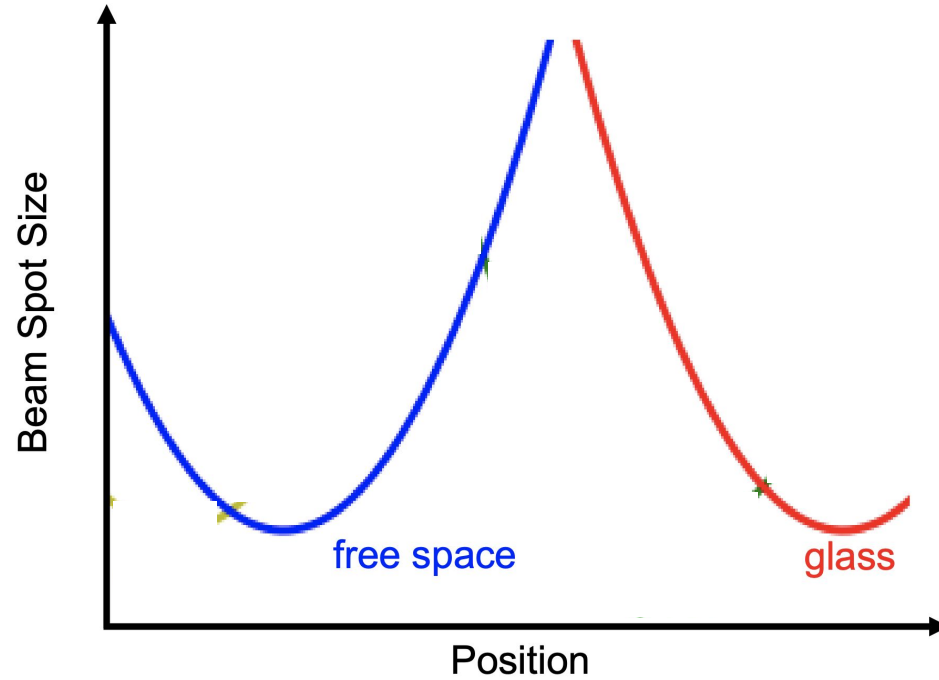
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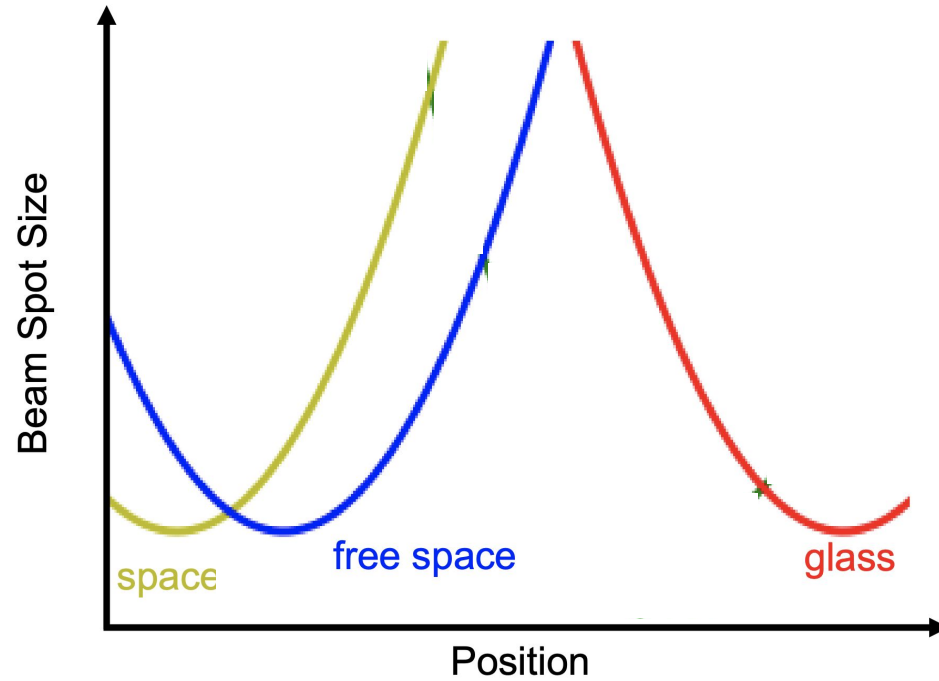
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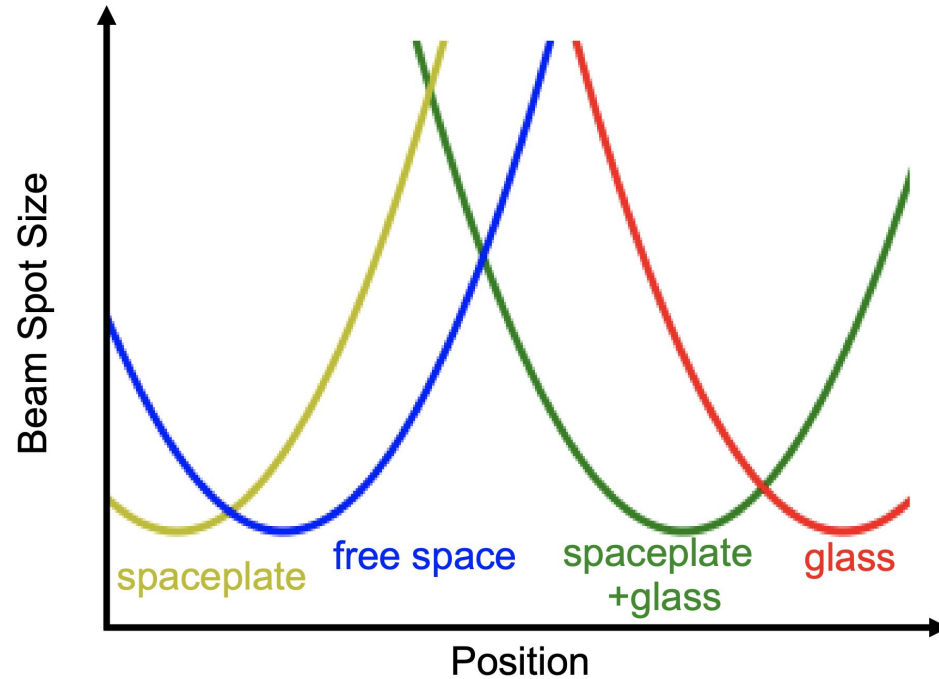
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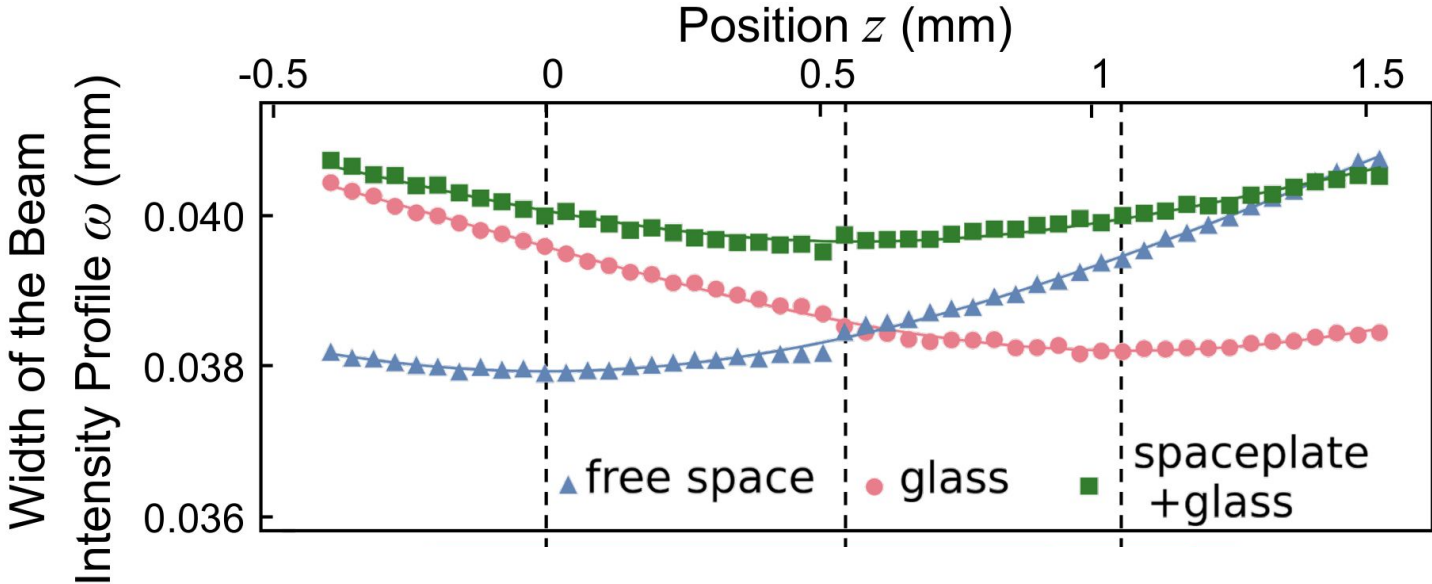
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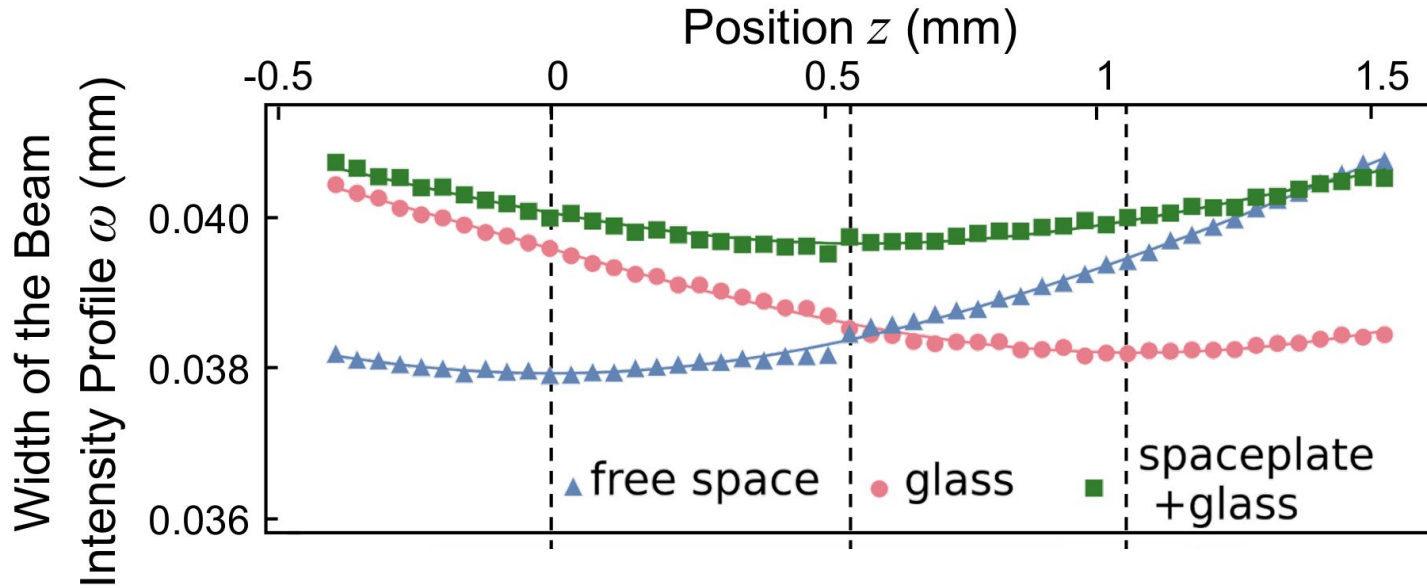
# Measuring the focal shift



# Experimental focal shift - FPC, 1546.9 nm

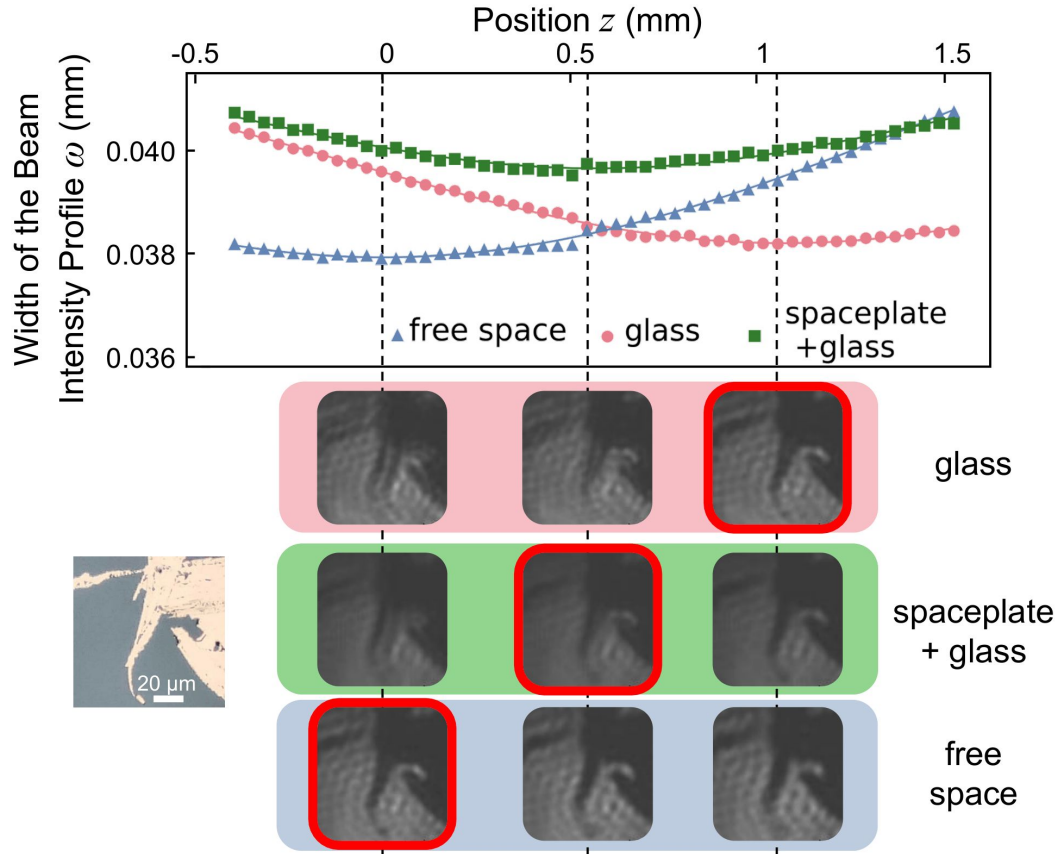


# Experimental focal shift - FPC, 1546.9 nm



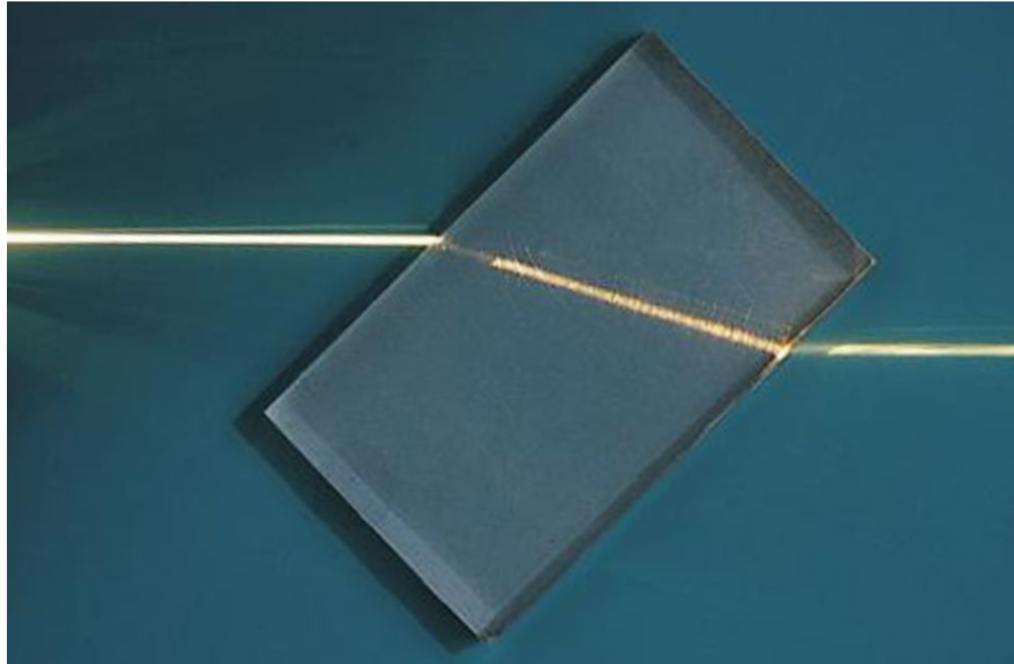
**The spaceplate of 11.5  $\mu\text{m}$  canceled out 0.5 mm of glass**

# Experimental imaging - FPC, 1546.9 nm

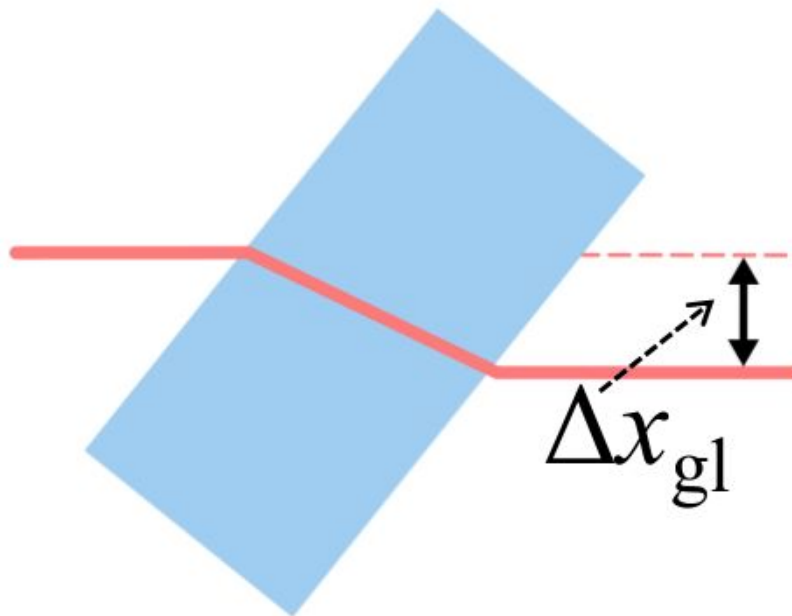


There is an easier way

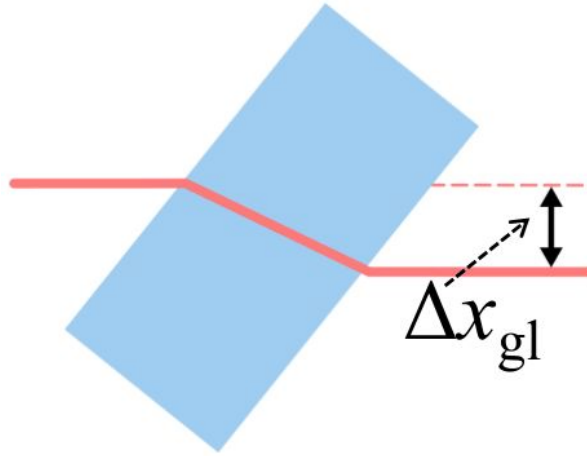
# Lateral Beam Shift



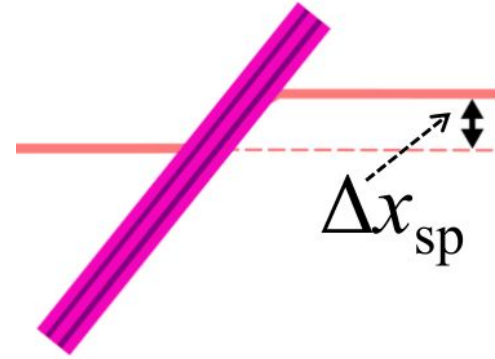
# Lateral Beam Shift



# Lateral Beam Shift

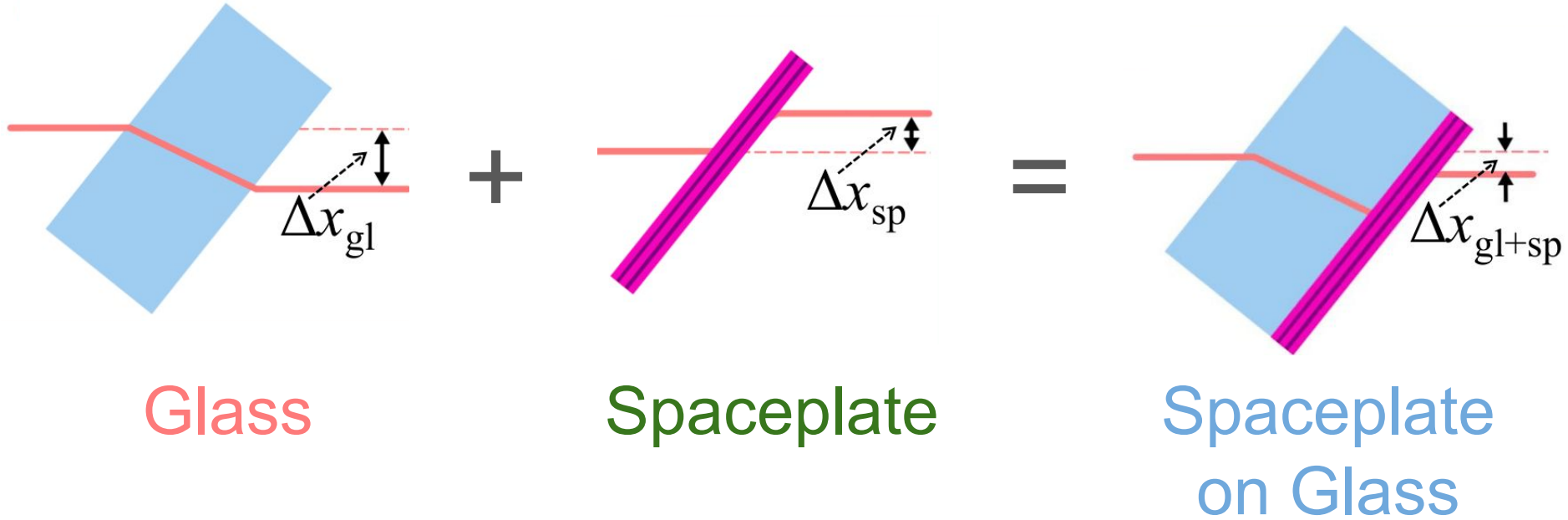


Glass

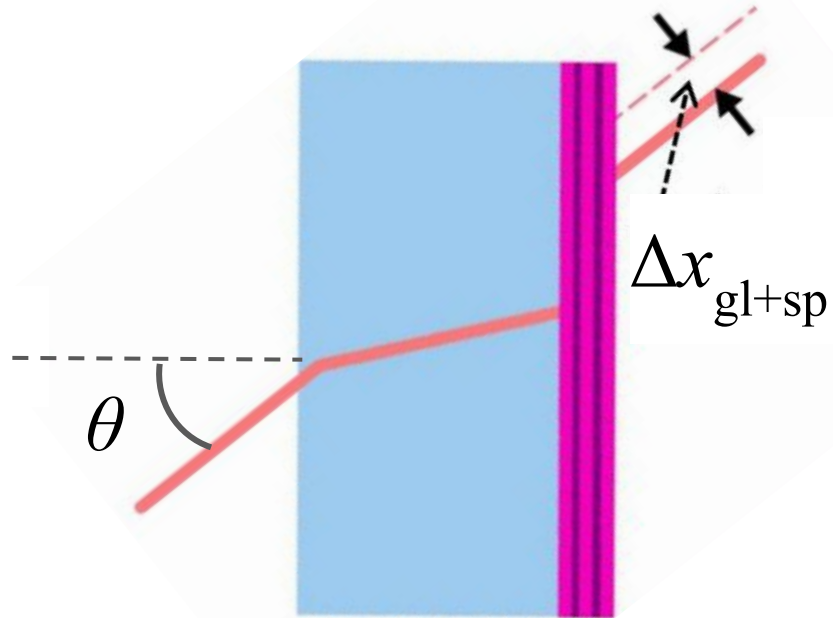


Spaceplate

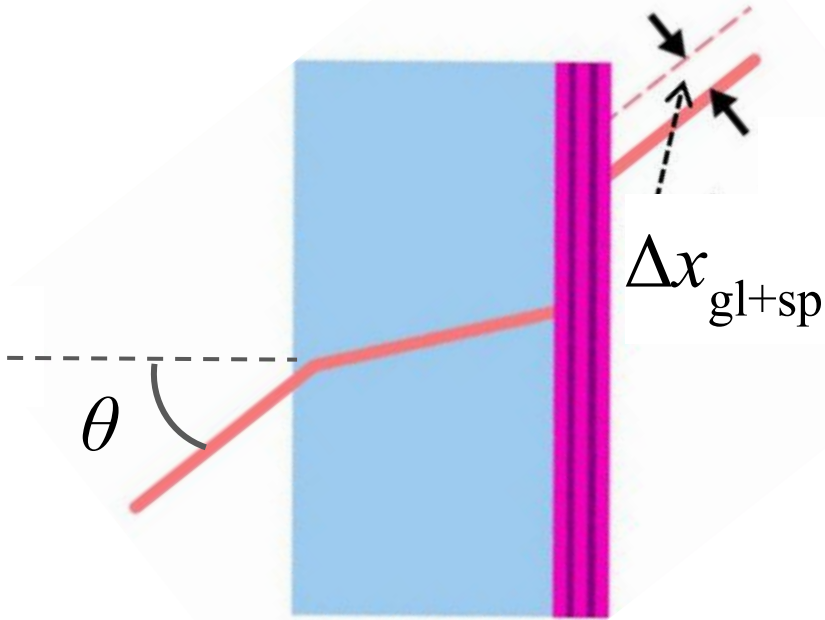
# Fabricated designs



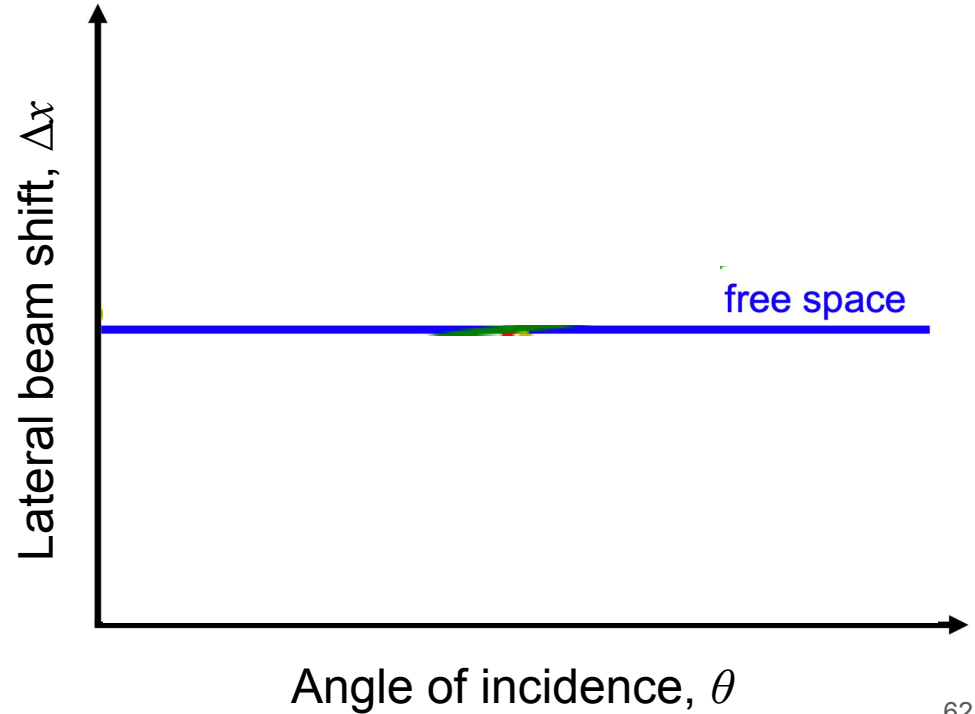
# Measurement technique



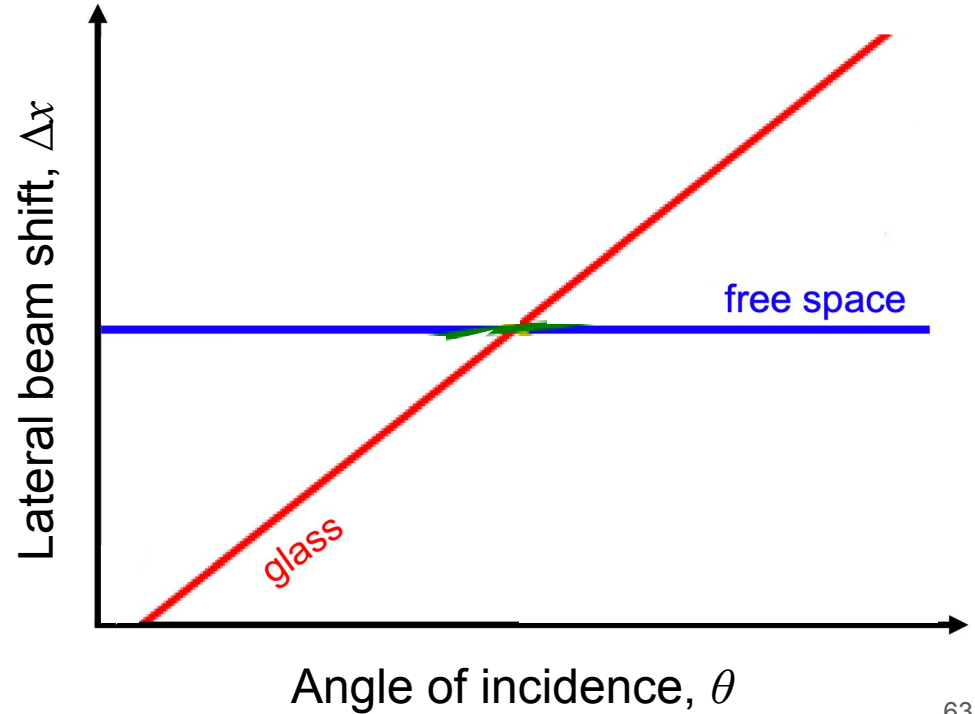
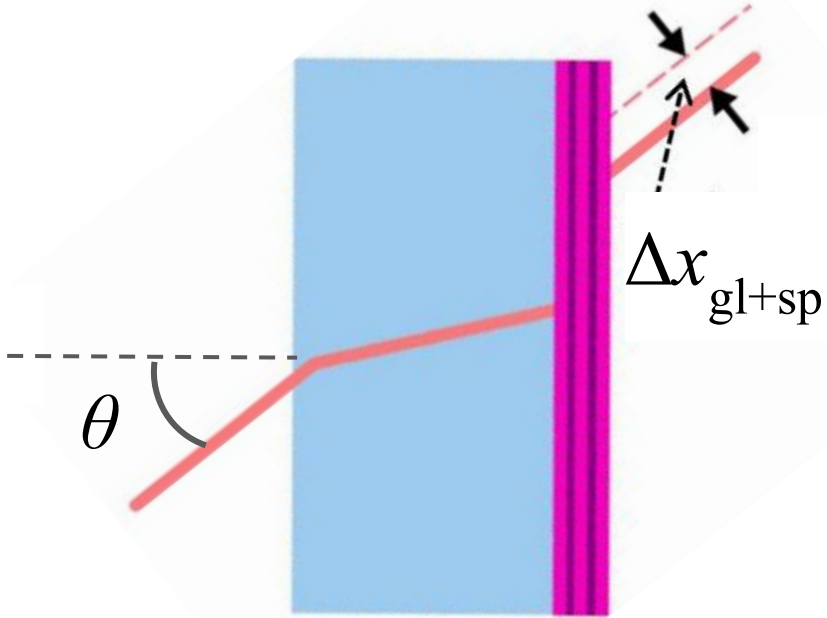
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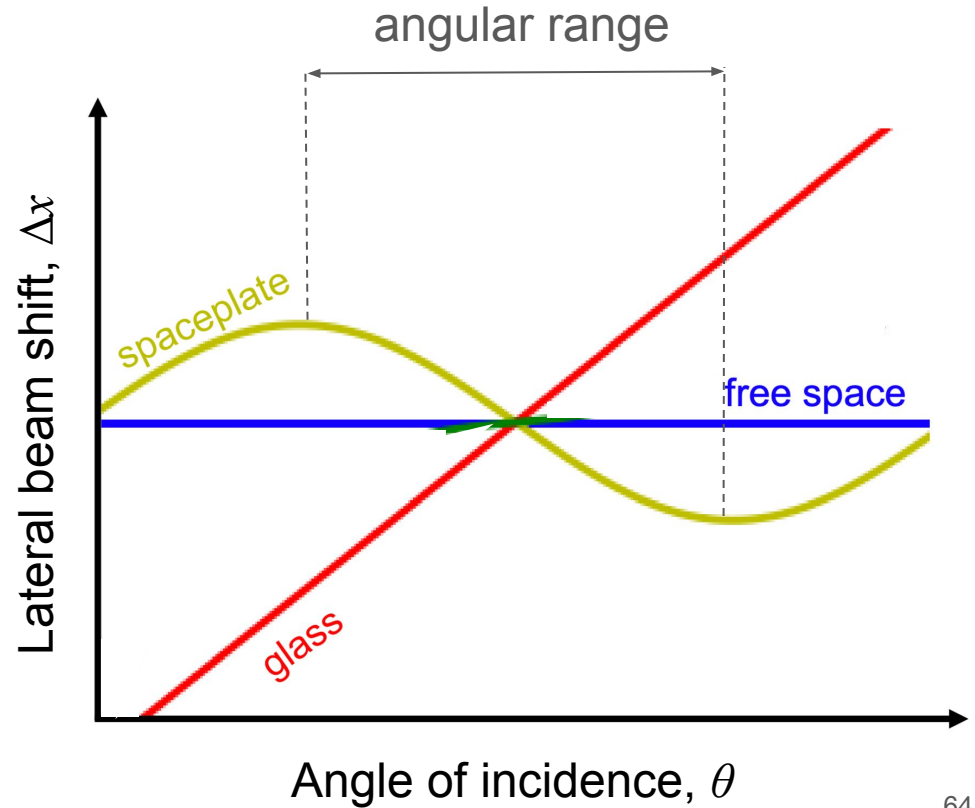
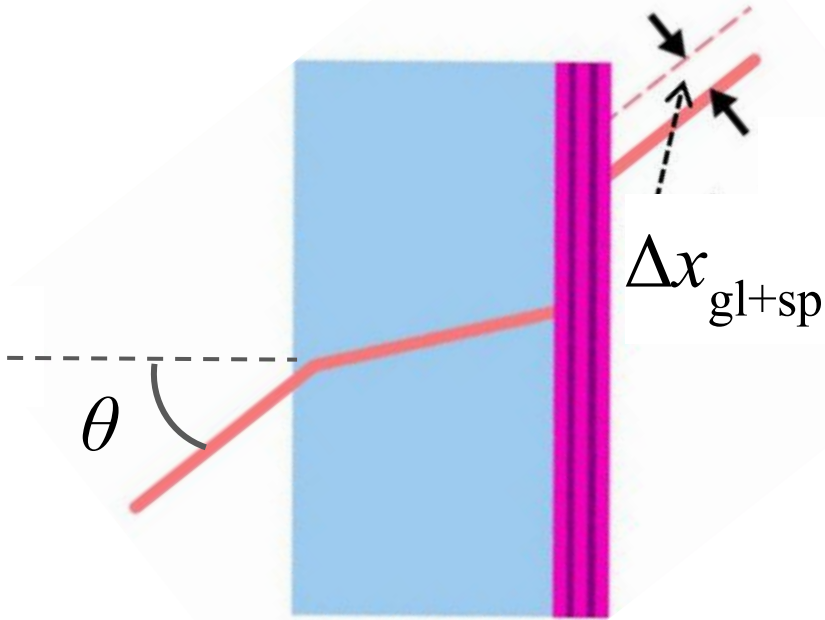
add a back-up slide about the phase



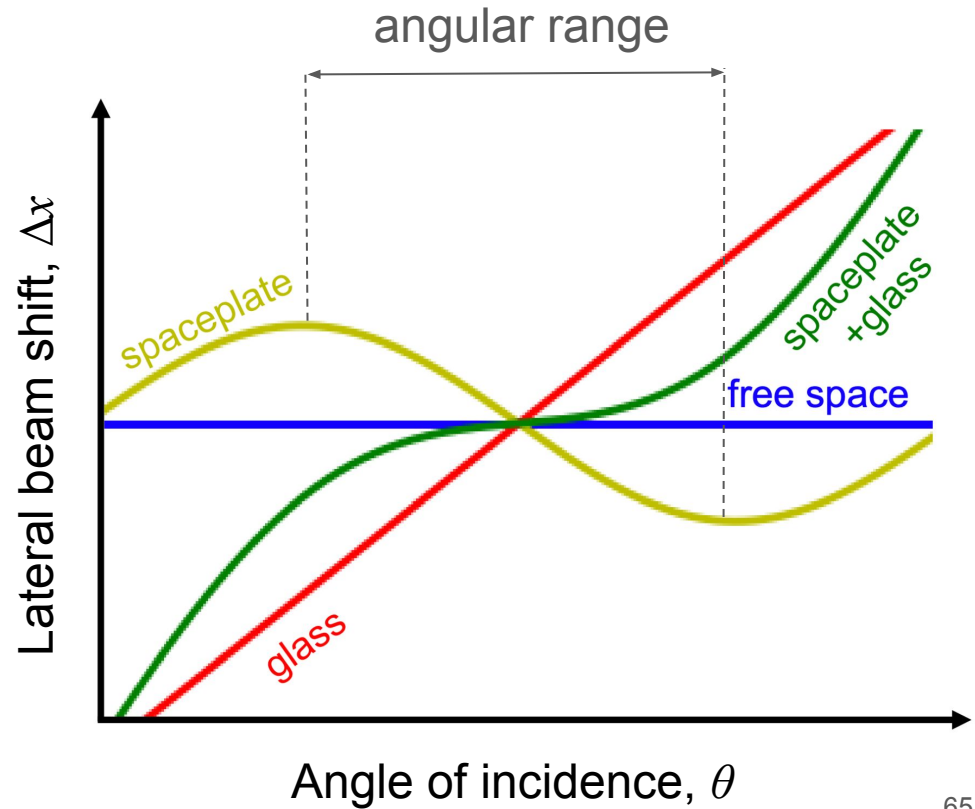
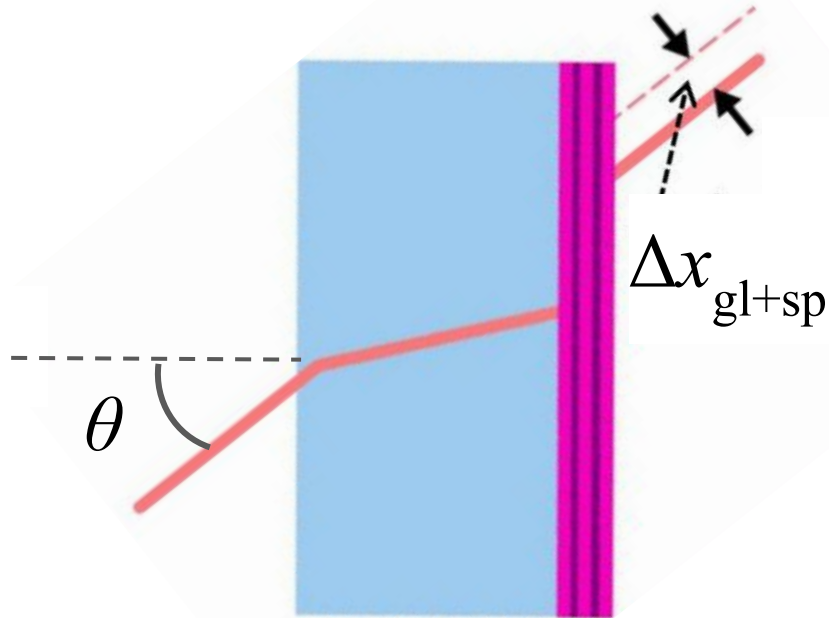
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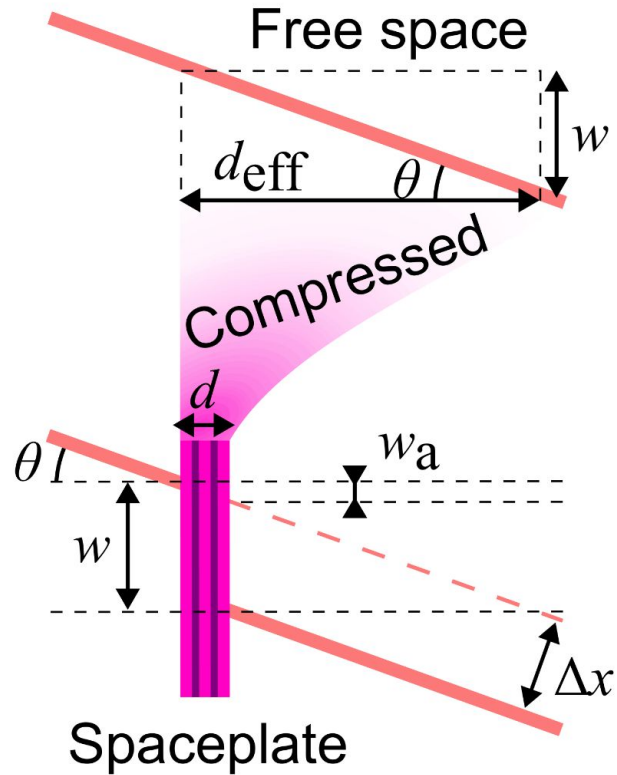
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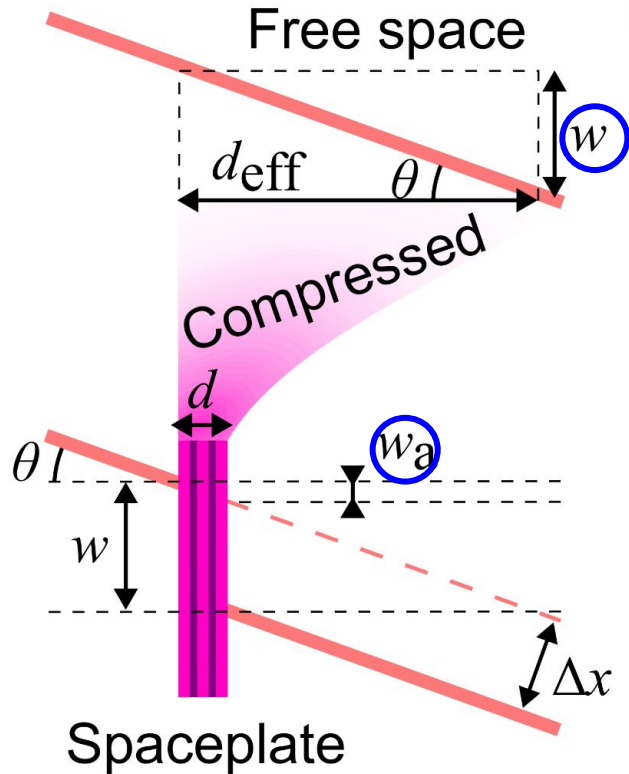
# Measurement technique



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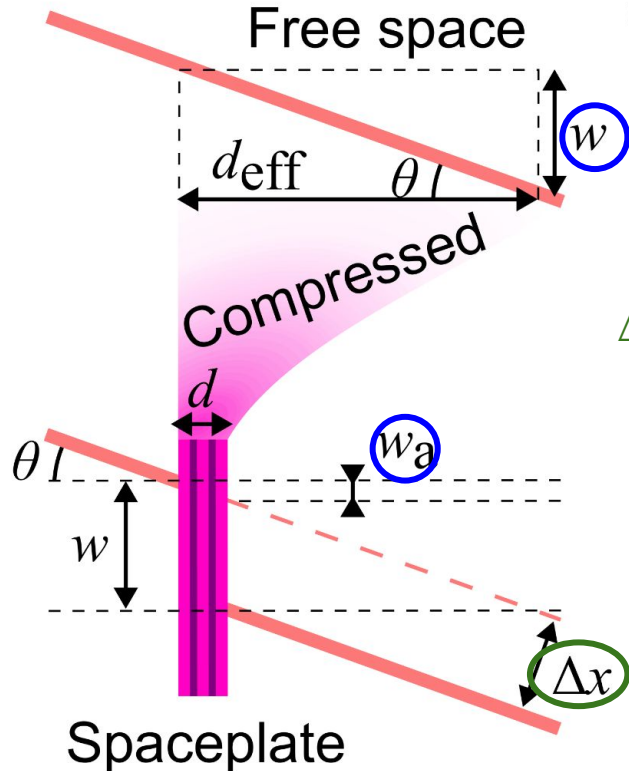
# Measurement technique



$$w = -d_{\text{eff}} \tan \theta$$

$$w_a = d \tan \theta$$

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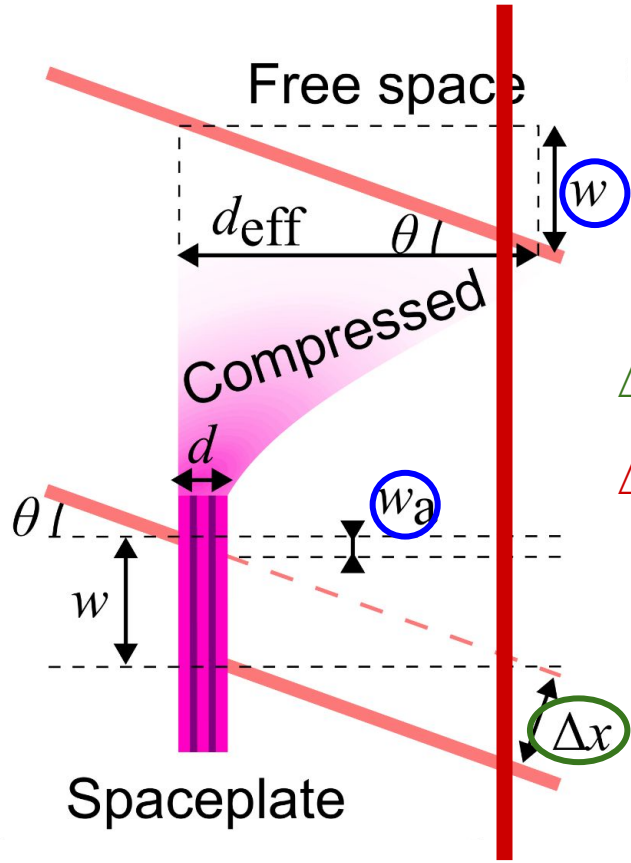


$$w = -d_{\text{eff}} \tan \theta$$

$$w_a = d \tan \theta$$

$$\Delta x = w + w_a = -d_{\text{eff}} \tan \theta + d \tan \theta = -d \tan \theta (R-1)$$

# Measurement technique



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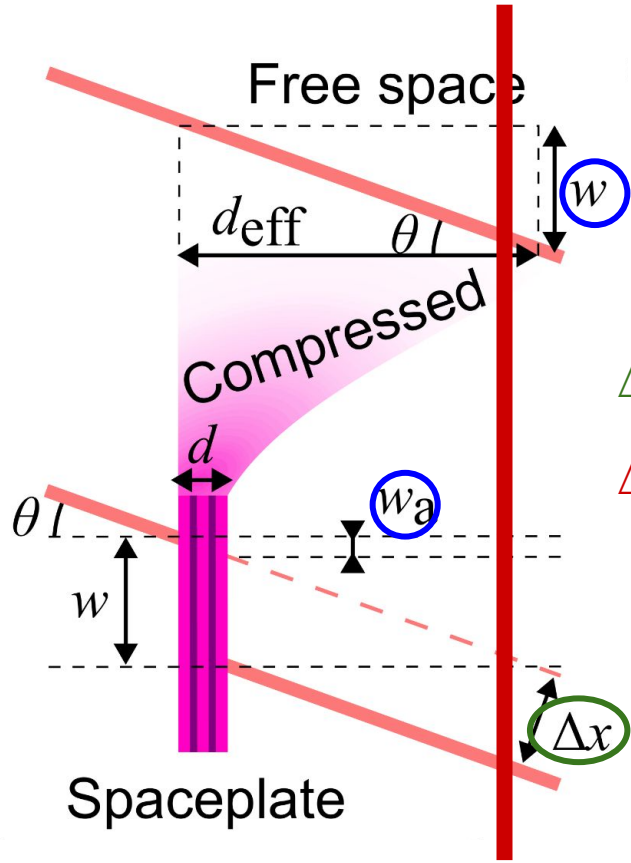
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$$\Delta x_{\text{exp}} = -d \tan\theta (R-1) \cos\theta$$



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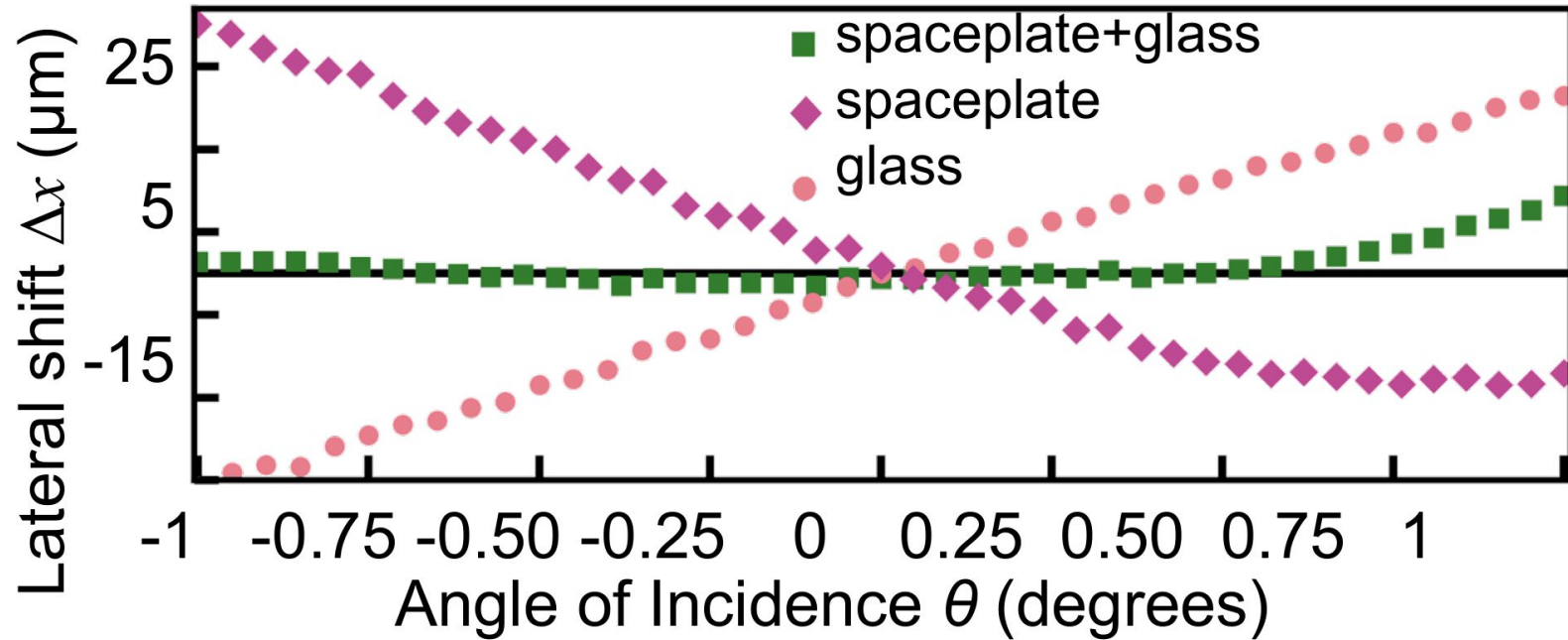
$$w_a = d \tan \theta$$

$$\Delta x = w + w_a = -d_{\text{eff}} \tan \theta + d \tan \theta = -d \tan \theta (R-1)$$

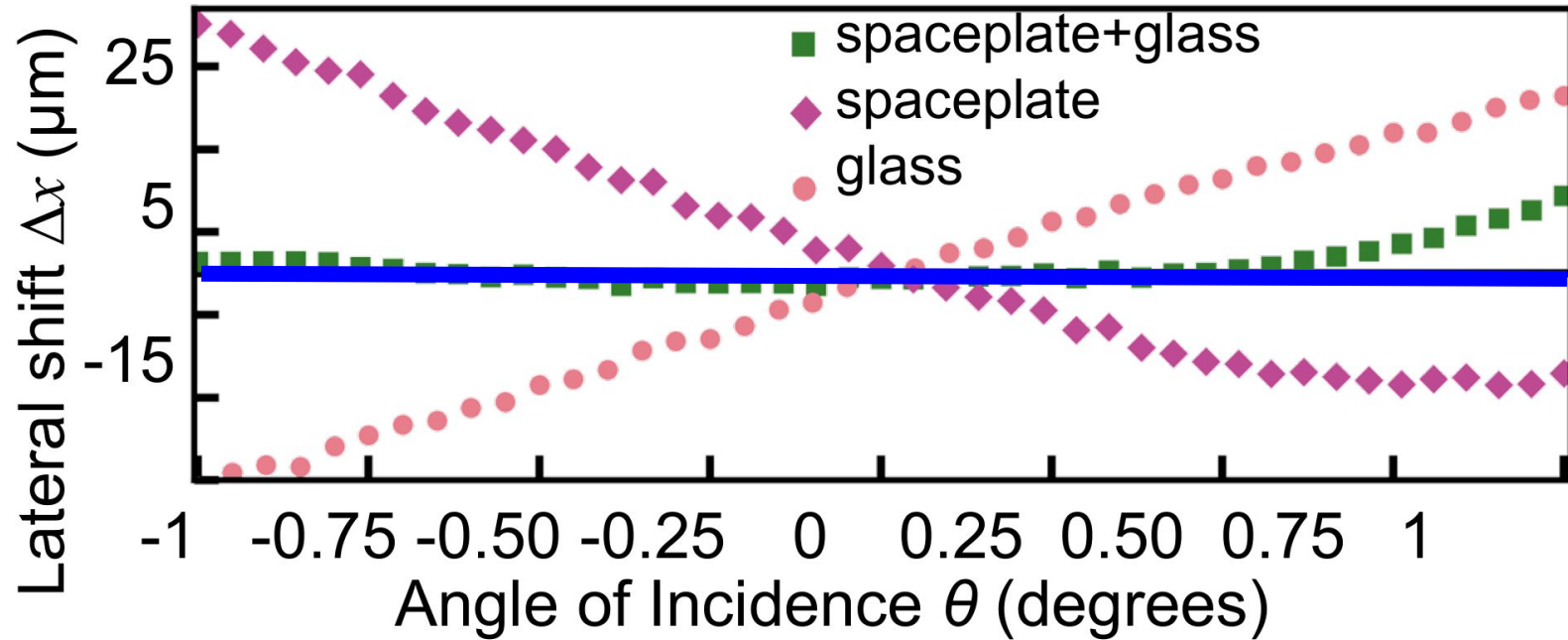
$$\Delta x_{\text{exp}} = -d \tan \theta (R-1) \cos \theta$$

$$\Delta x_{\text{exp}} = -d (R-1) \sin \theta$$

# Lateral shift - FPC, 1532.9 nm



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# Take Away messages

- **Spaceplates** are nonlocal optical devices that mimic free space propagation
- The highest compression factor was measured at 176, which means that the spaceplate of **13.4  $\mu\text{m}$**  canceled out **2.4 mm** free space propagation
- Imaging through spaceplates is possible and opens the possibilities for minimization of **VR-headsets**, **LIDAR systems**, and even **cameras** in the future