Quantitative phase imaging for EUV masks

Stuart Sherwin[a], Laura Waller[a], Andrew Neureuther[a], Patrick Naulleau[b]
[a]: UC Berkeley, Electrical Engineering and Computer Science
[b]: LBNL, Center for X-Ray Optics

EUVL Workshop 2019

Quantitative phase imaging for EUV masks

1. **Problem**: optical phase of absorber affects imaging for EUV masks

2. **Objective**: image EUV mask complex reflection function on SHARP

3. **Measurements**: defocus (conventional) or coded apertures (new)

4. **Algorithm**: PhaseLift convex solver for phase retrieval

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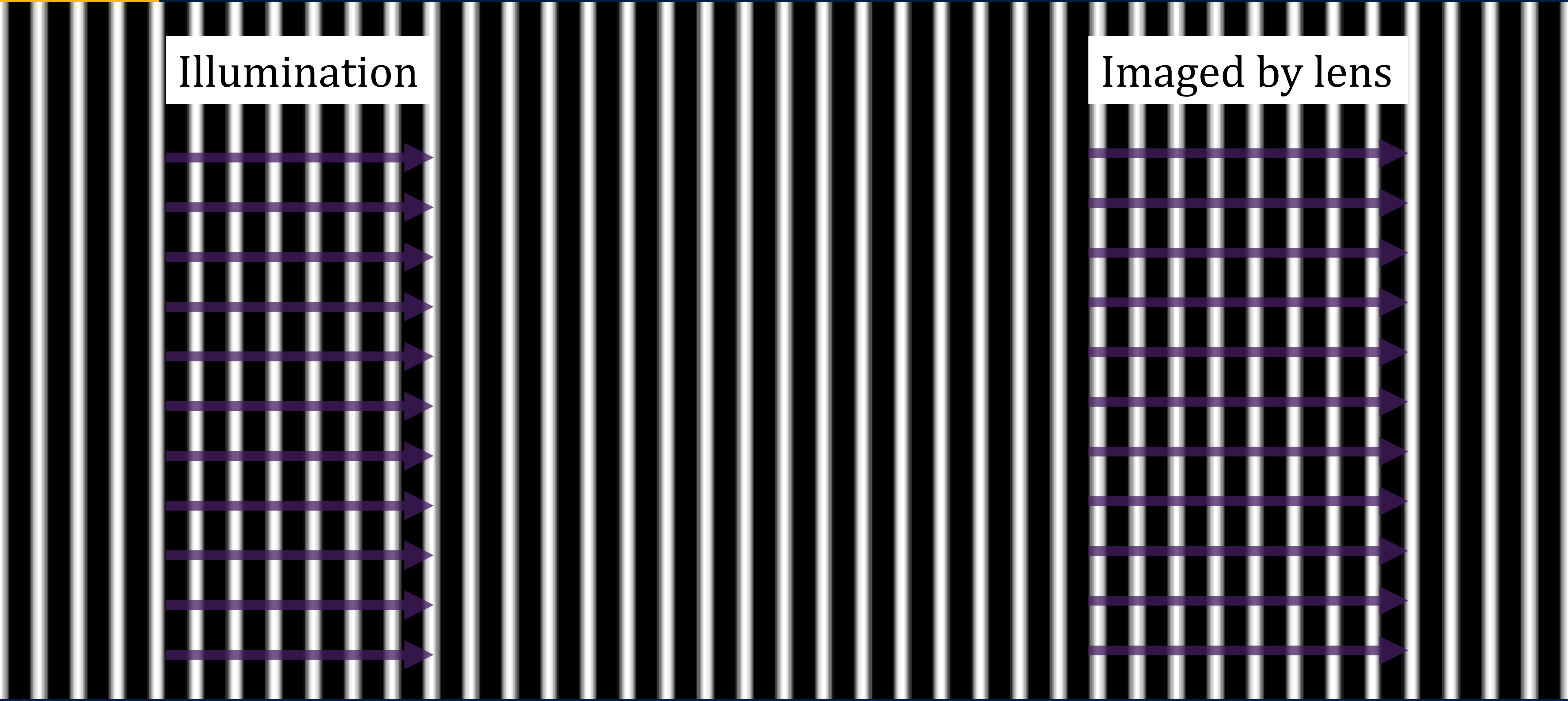
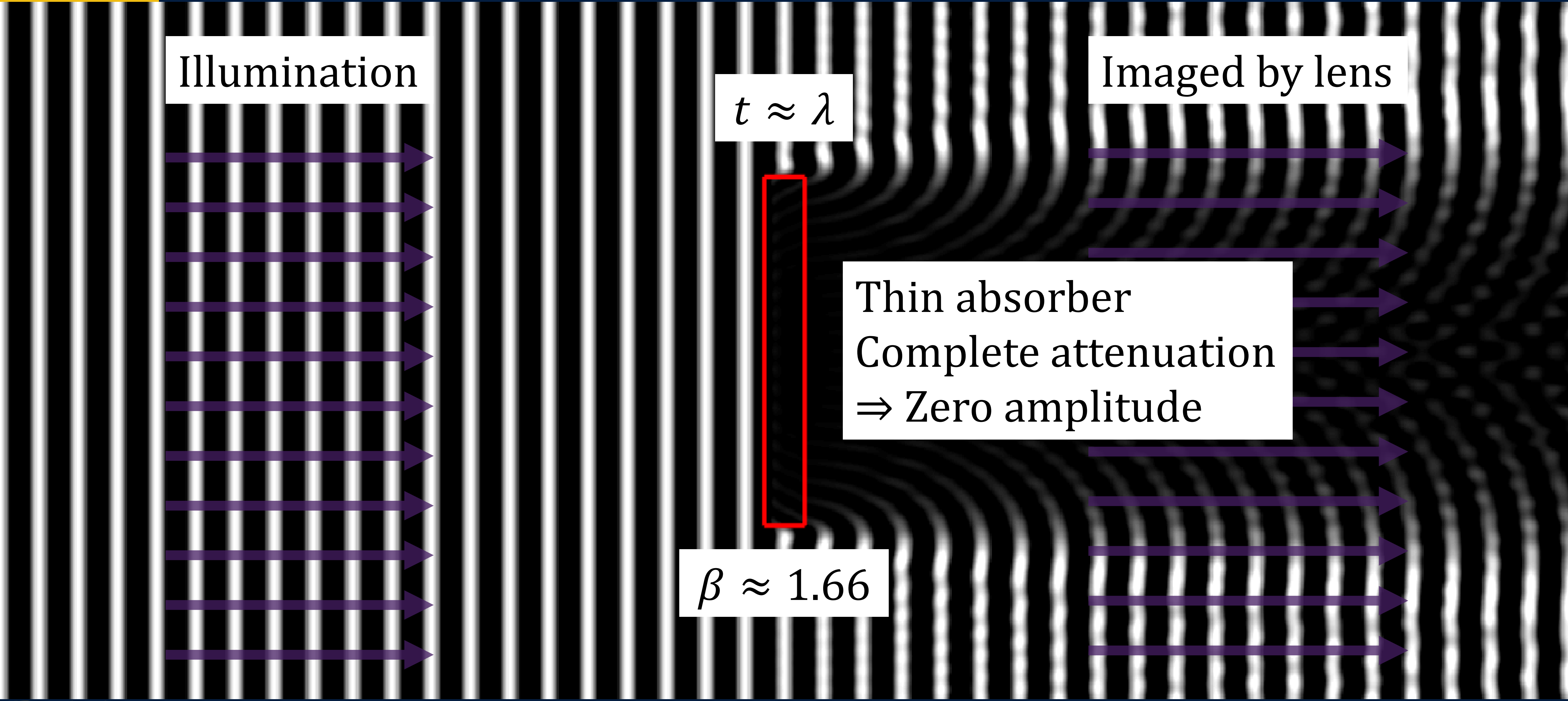
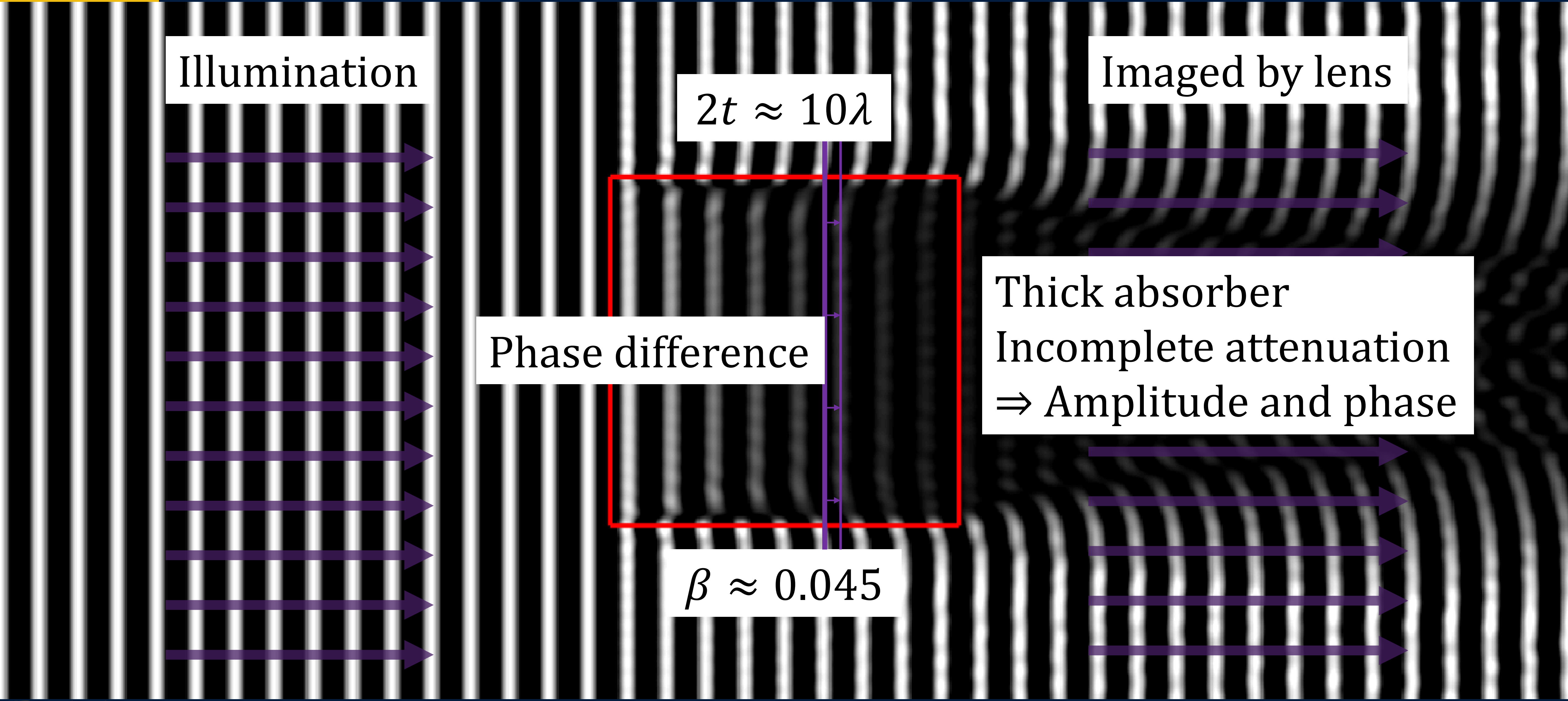
Plane wave



DUV absorber: Complete attenuation



EUV absorber: Attenuation and phase



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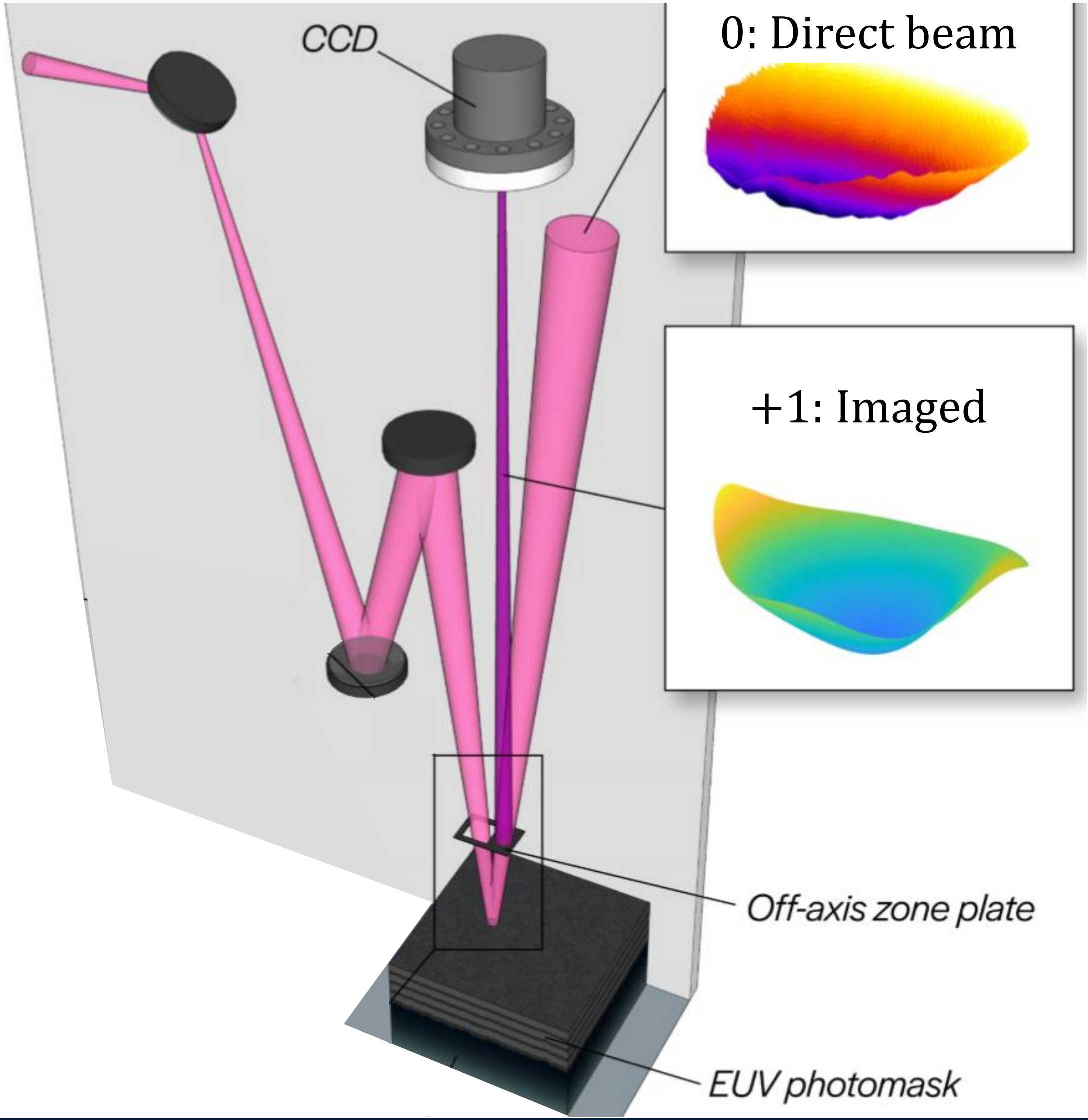
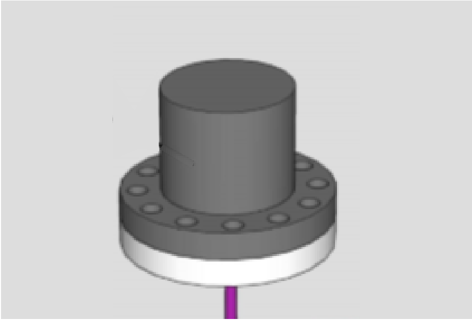
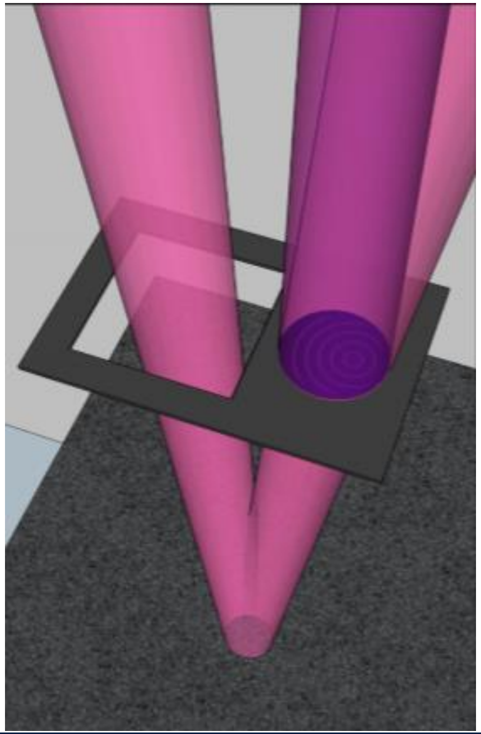
Imaging the mask reflection function





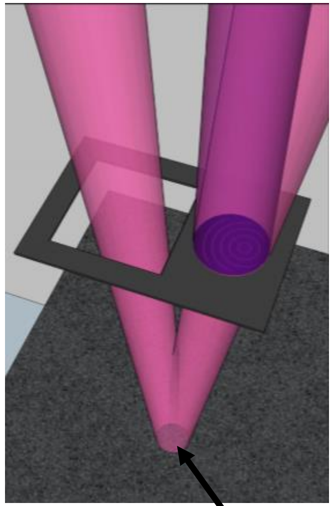
CCD (Multiple images)



Zone plate (objective)

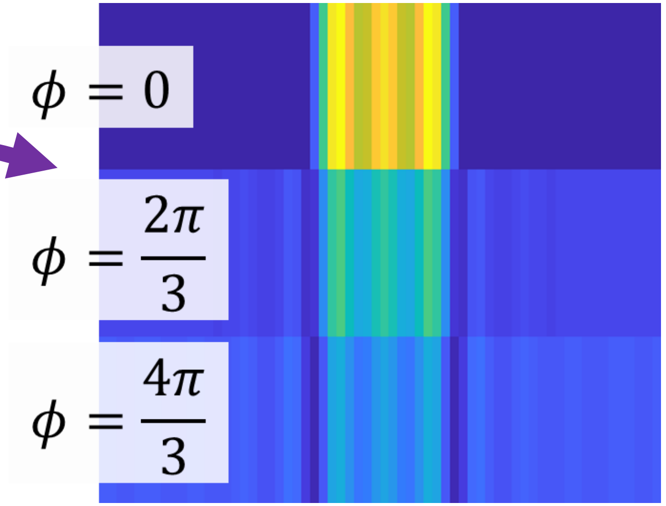
EUV Photomask
(reflection function)

Imaging the mask reflection function



$$f: E \mapsto I$$

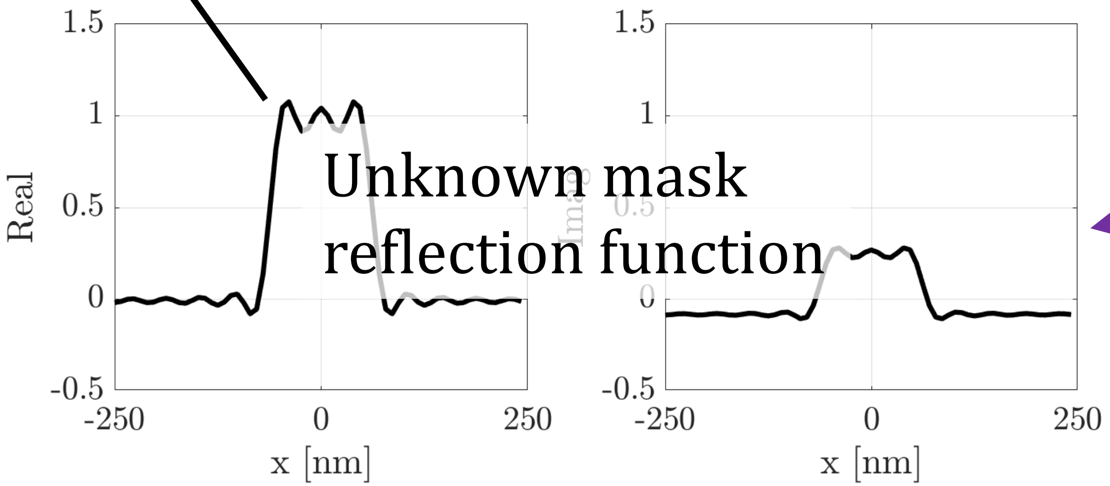
Known physics



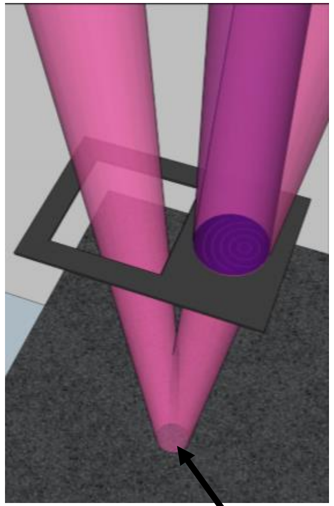
$$f^{-1}: I \mapsto E_{fit}$$

Computational recovery

Unknown mask reflection function

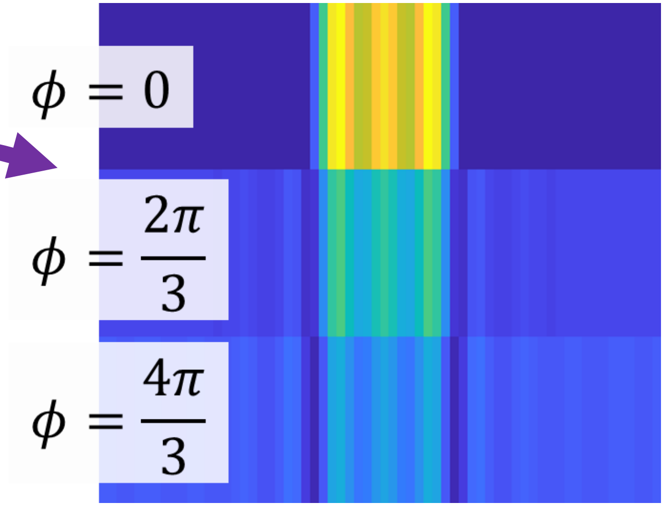


Imaging the mask reflection function



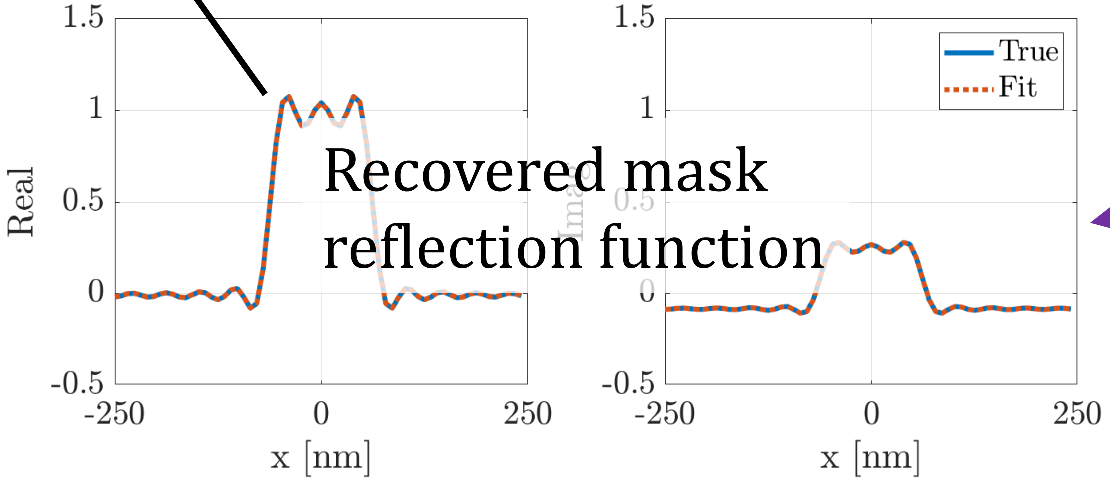
$$f : E \mapsto I$$

Known physics



$$f^{-1} : I \mapsto E_{fit}$$

Computational recovery



Recovered mask reflection function

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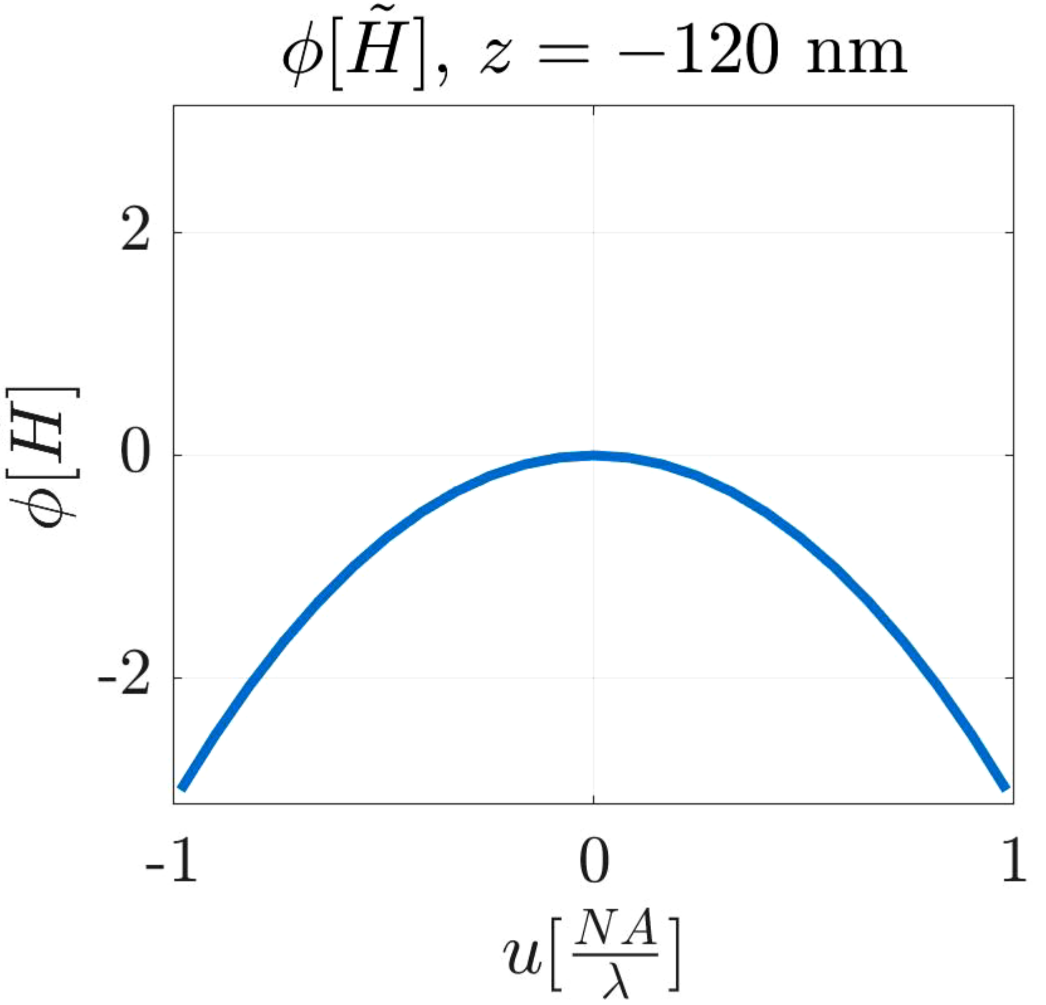
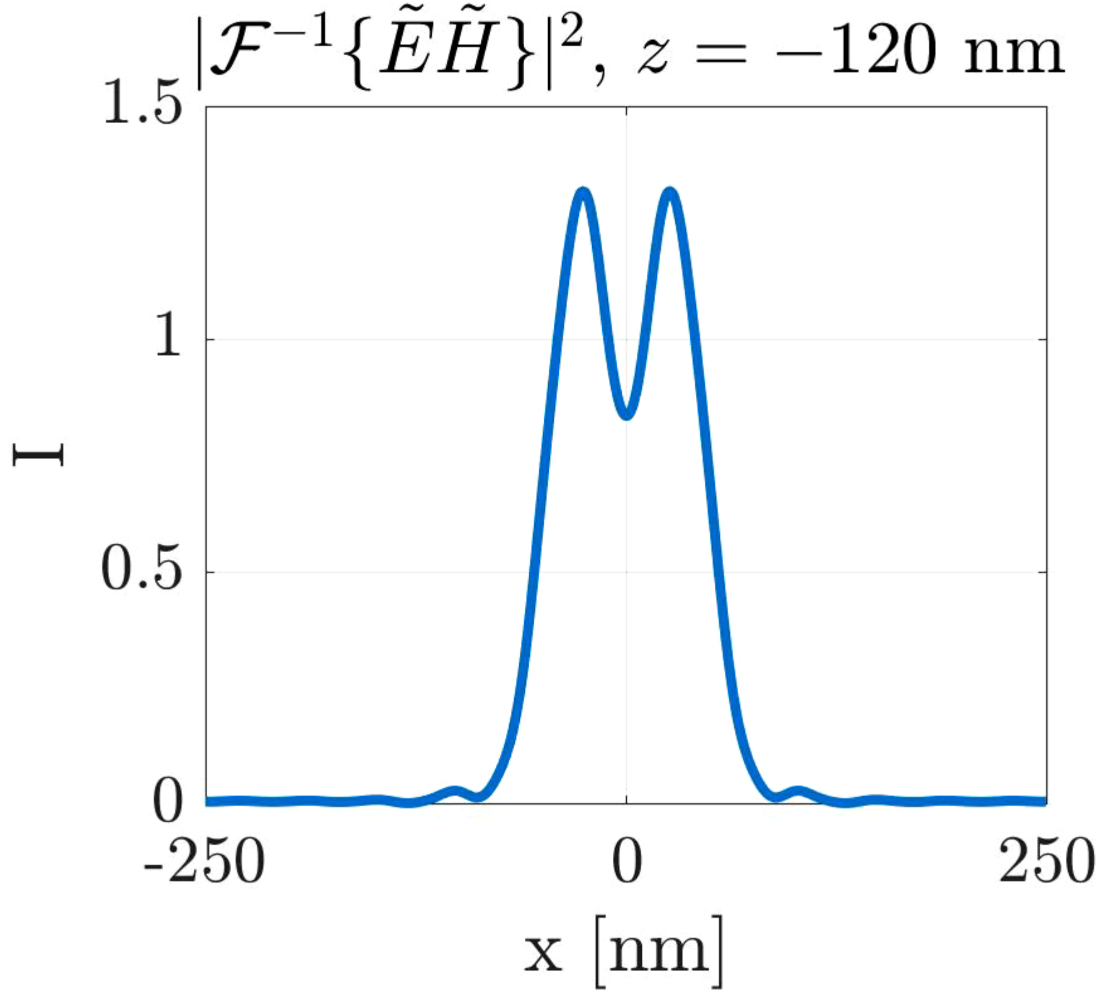
Through-focus coherent imaging





Phase sensitivity decreases for large features

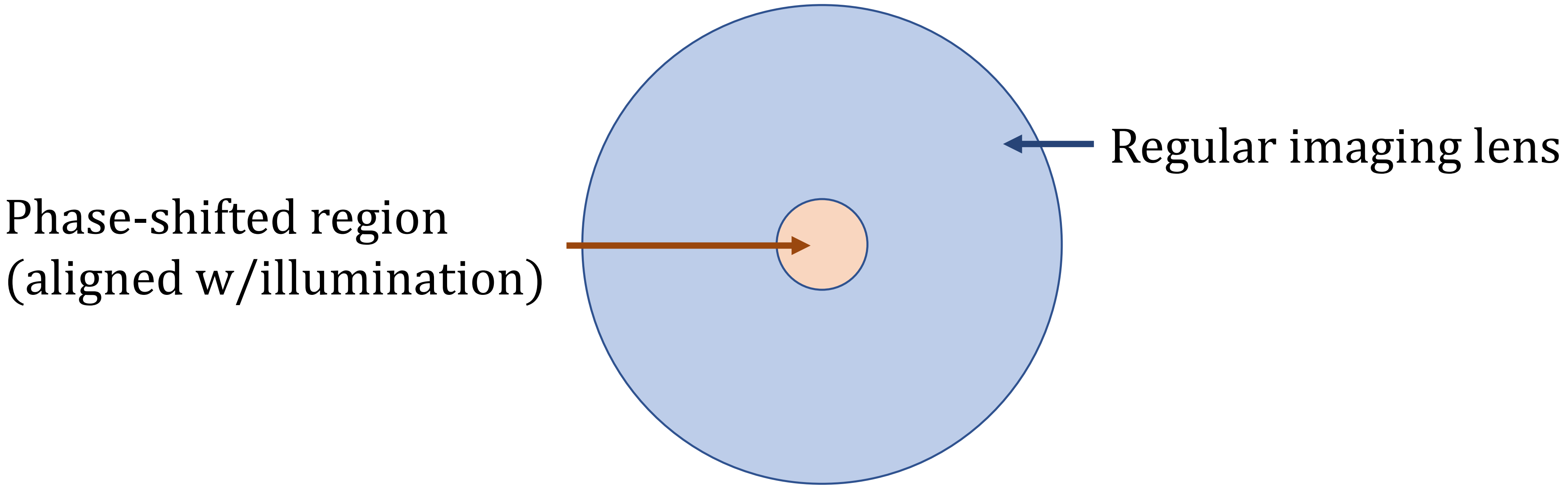
- Phase difference between 0 order and 1st order goes as $\frac{\Delta z \lambda}{p^2}$
  - For fixed Δz, λ:

$$\Delta\phi_{0,1} \propto \frac{1}{p^2}$$

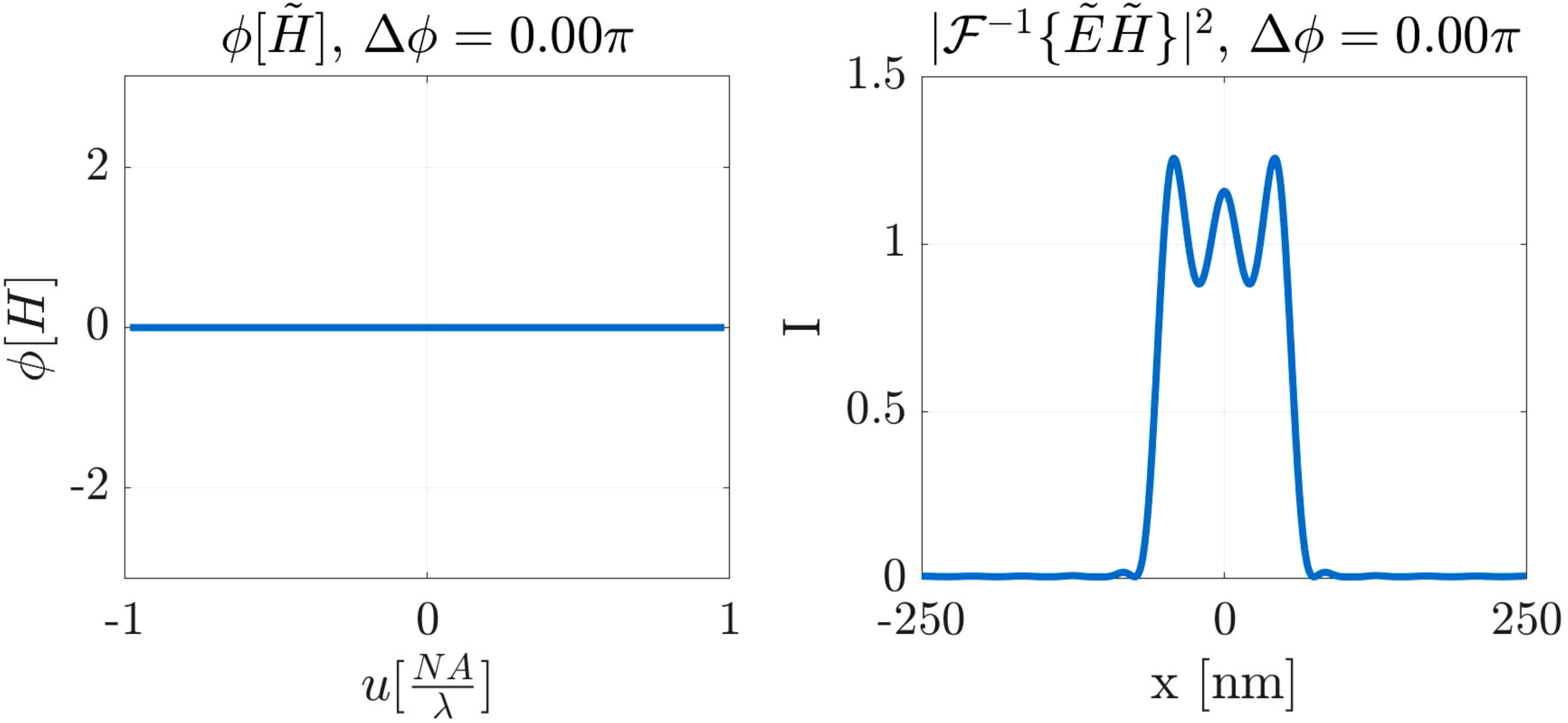
- $\Rightarrow$ Defocus is not good for measuring low frequencies
  - (including isolated features)

Improved detection with coded aperture

- How to introduce a large phase-shift between 0 order and 1^{st} order?
  - Zernike phase-contrast inspired coded aperture
  - Impart arbitrary phase shift on 0 order, image all other orders normally
  - Fabrication: set of zone-plates with different phase shifts on 0 order

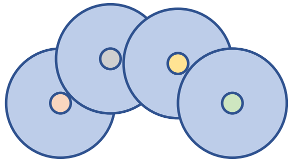


Improved detection with coded aperture

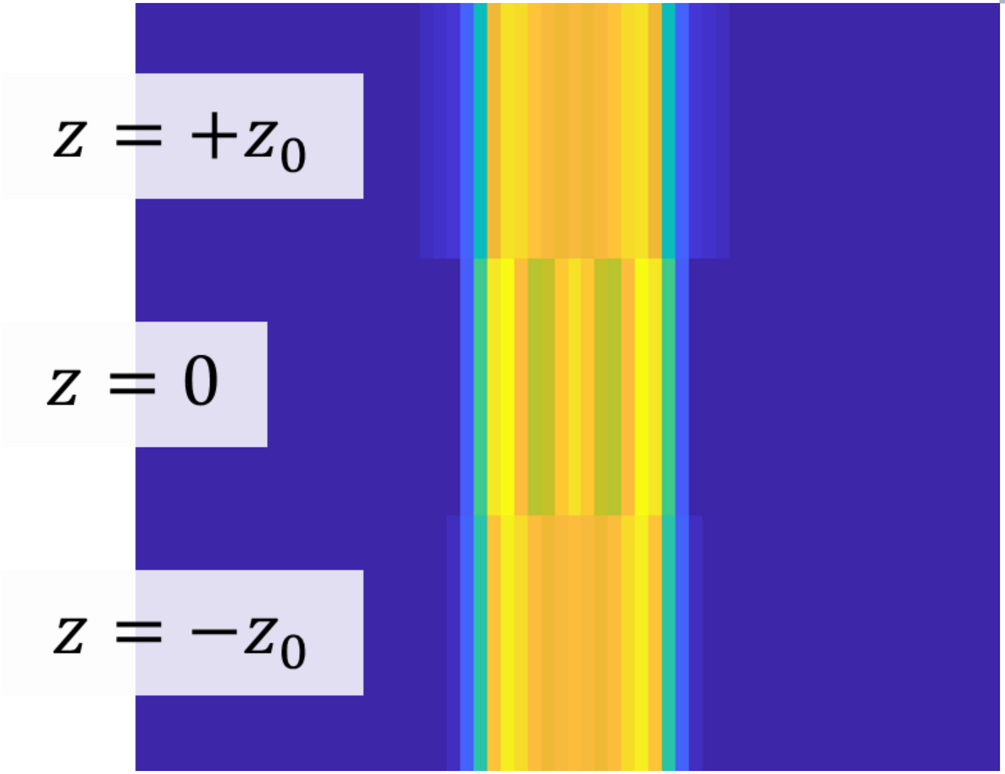


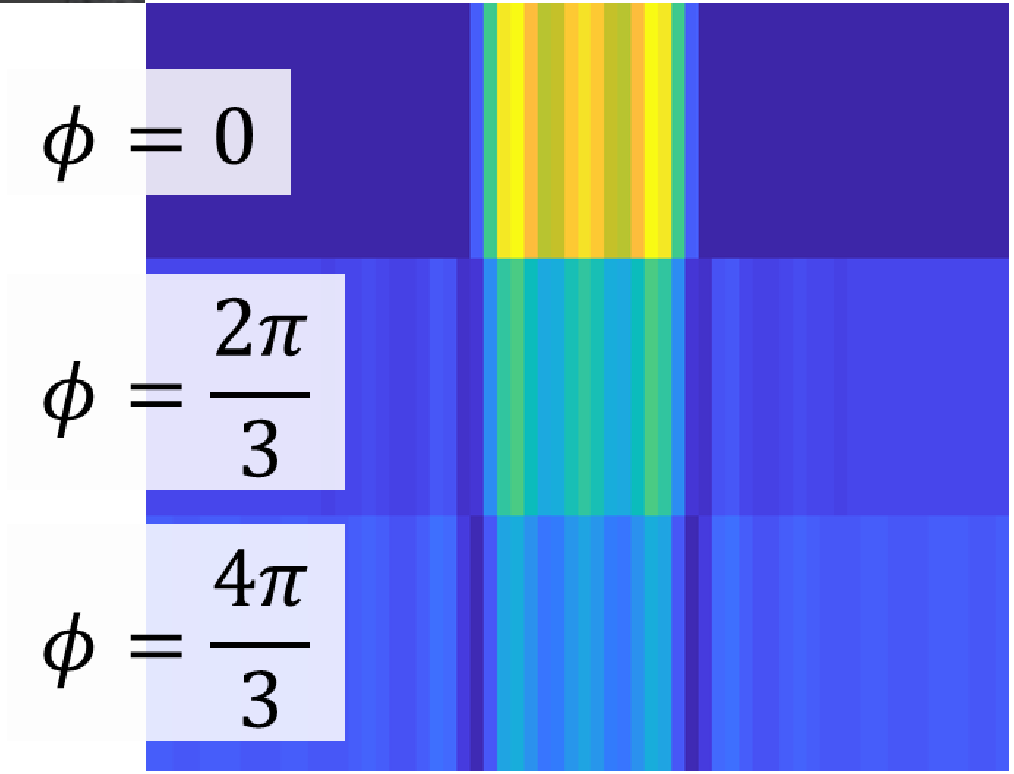
Comparison: Raw data

Through-focus



Coded aperture





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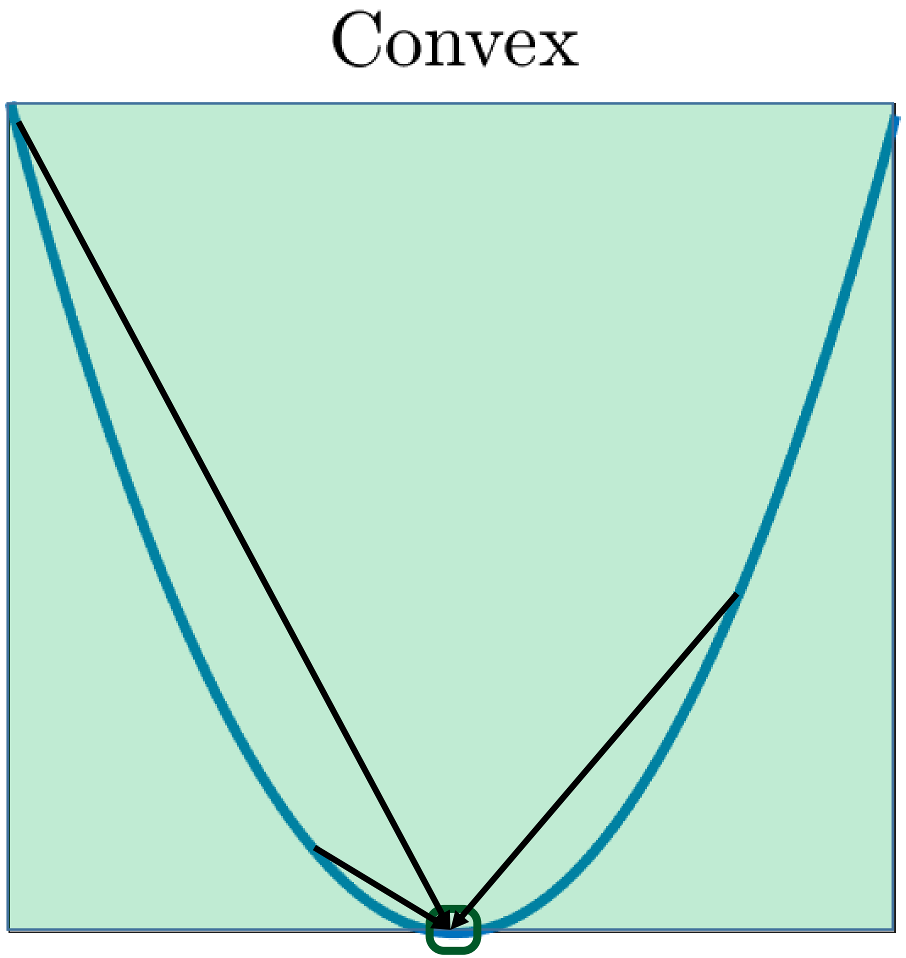
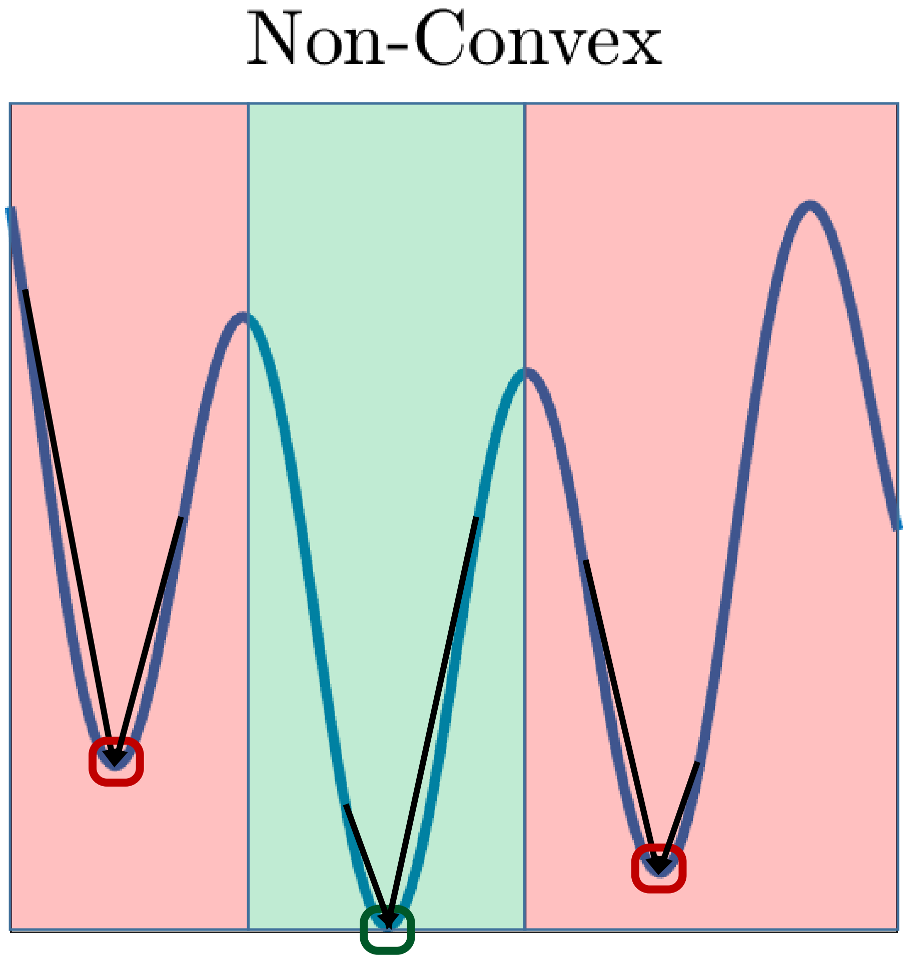
Convex problem: any initial guess works





PhaseLift: Robustness ≫ speed

- Nonlinear, nonconvex formulation (traditional):

Fast

No guarantees

$$I = \left|\mathcal{F}^{-1}\{\tilde{E}\widetilde{H}\}\right|^2$$

Nonlinear imaging model

$$\min_{\tilde{E}} \sum_i \left\| \sqrt{I_i} - \left|\mathcal{F}^{-1}\{\tilde{E}\widetilde{H}_i\}\right| \right\|_2^2$$

Nonconvex problem

- Linear, convex formulation (PhaseLift):

Slow

Guarantees

$$I_i = \mathcal{L}_i\{\tilde{E}\tilde{E}^*\} = \mathcal{L}_i\{\mathrm{X}\}$$

Linear imaging model

$$\min_{\mathrm{X}} \alpha \mathrm{Trace}[\mathrm{X}] + \sum_i \|I_i - \mathcal{L}_i\{\mathrm{X}\}\|_2^2$$

Convex problem

Ref: Candes, E. J., Strohmer, T., & Voroninski, V. (2013). Phaselift: Exact and stable signal recovery from magnitude measurements via convex programming. Communications on Pure and Applied Mathematics, 66(8), 1241-1274.

Understanding the PhaseLift problem

Recover complex autocorrelation matrix with iterative solver

I_i: Measured image i

$\mathcal{L}_i$: Known linear operator i

- Underdetermined ⇒ nullspace

$$\min_{X} \alpha \mathrm{Trace}[X] + \sum_i \| I_i - \mathcal{L}_i\{X\} \|_2^2$$

Trace minimization promotes low-rank solutions

$$X = \tilde{E}\tilde{E}^*$$

⇒ True solution is rank-1

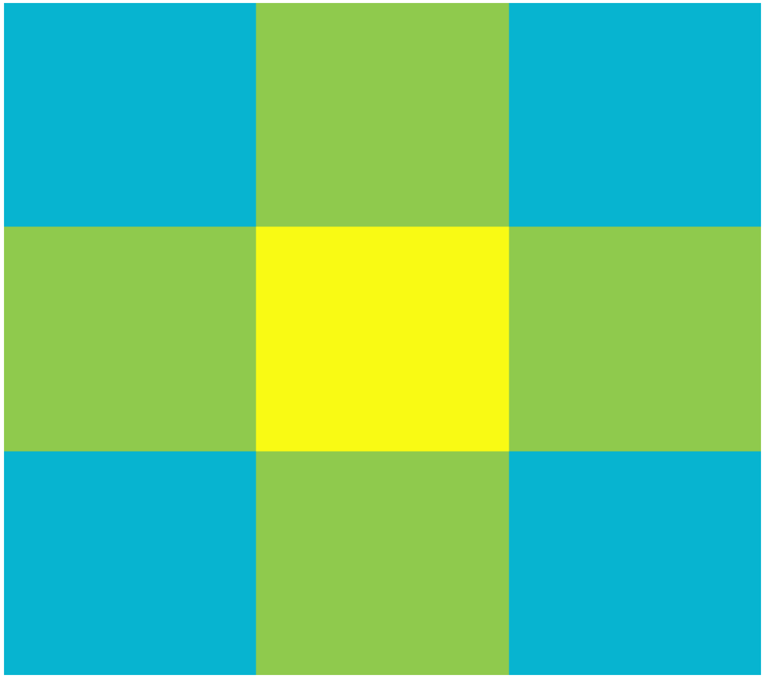
X: Unknown complex autocorrelation matrix

$$X = \tilde{E}\tilde{E}^*$$

⇒ Dimension is *squared*

PhaseLift walkthrough: 3-beam imaging

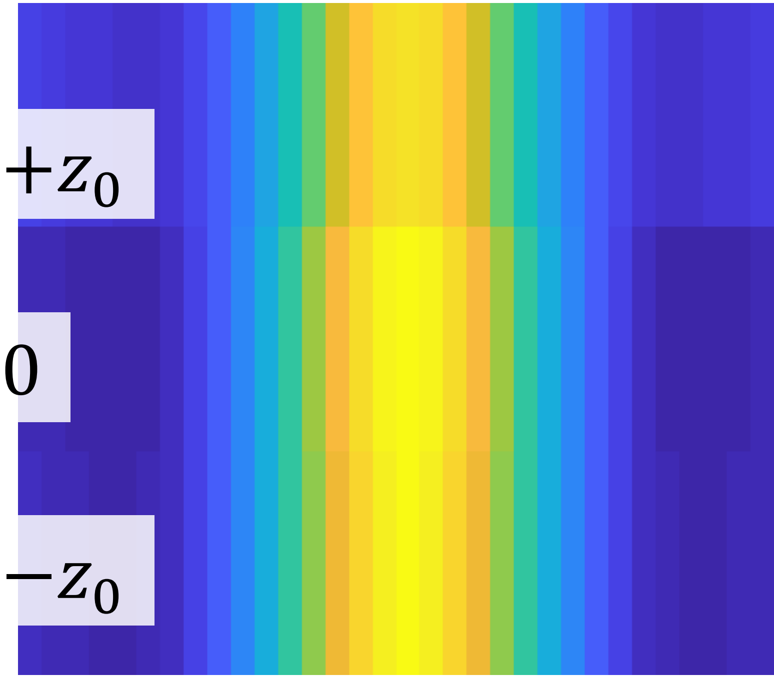
True $X = \tilde{E}\tilde{E}^*$



3 Diffraction orders
3 Focus steps

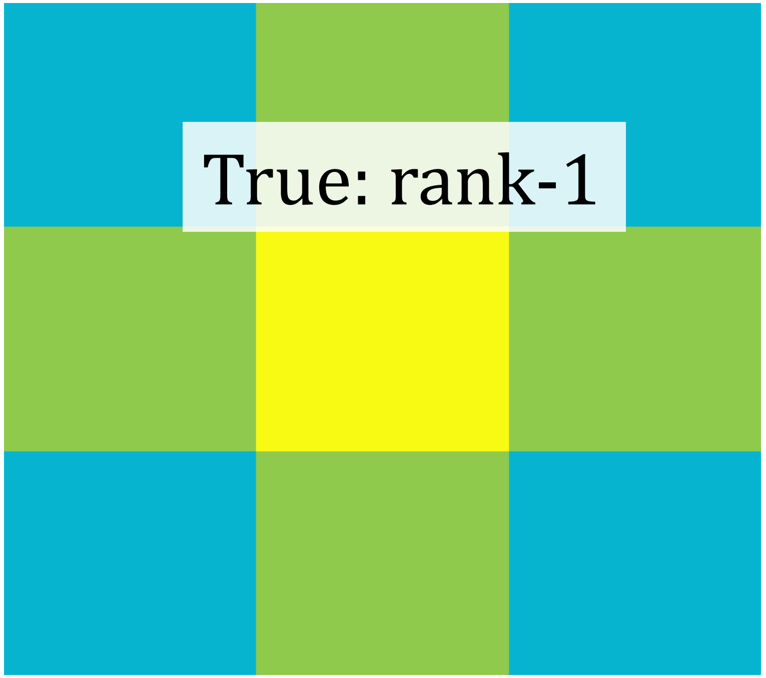
Linear operator
$\mathcal{L}: X \mapsto I$

Measured I

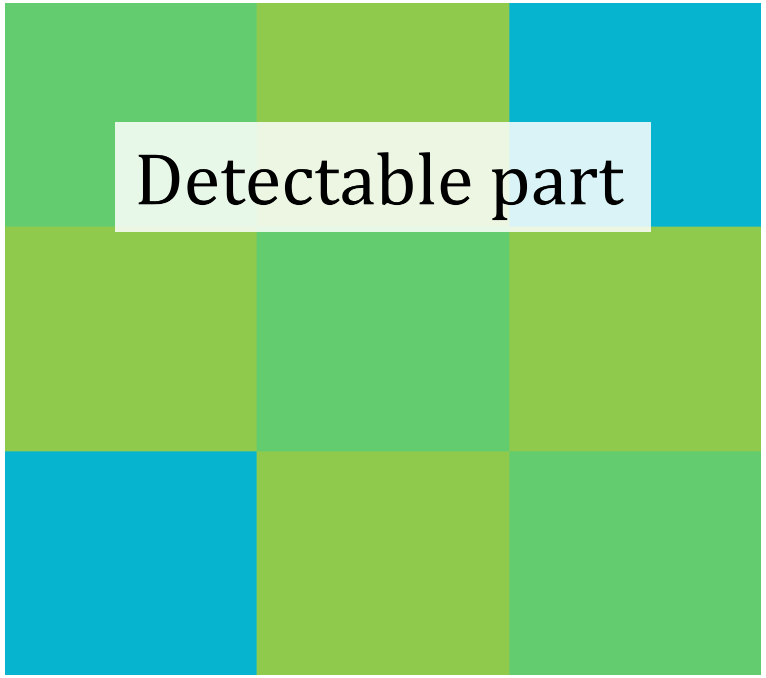


PhaseLift walkthrough: 3-beam imaging

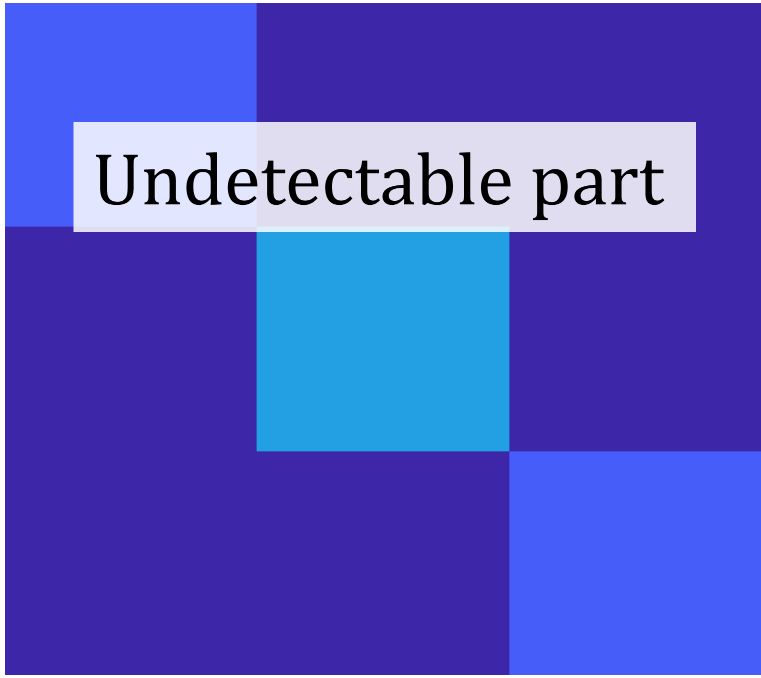
True $X = \tilde{E}\tilde{E}^*$



X projected to range$\{\mathcal{L}\}$



$X - \mathcal{P}X \in \text{null}\{\mathcal{L}\}$



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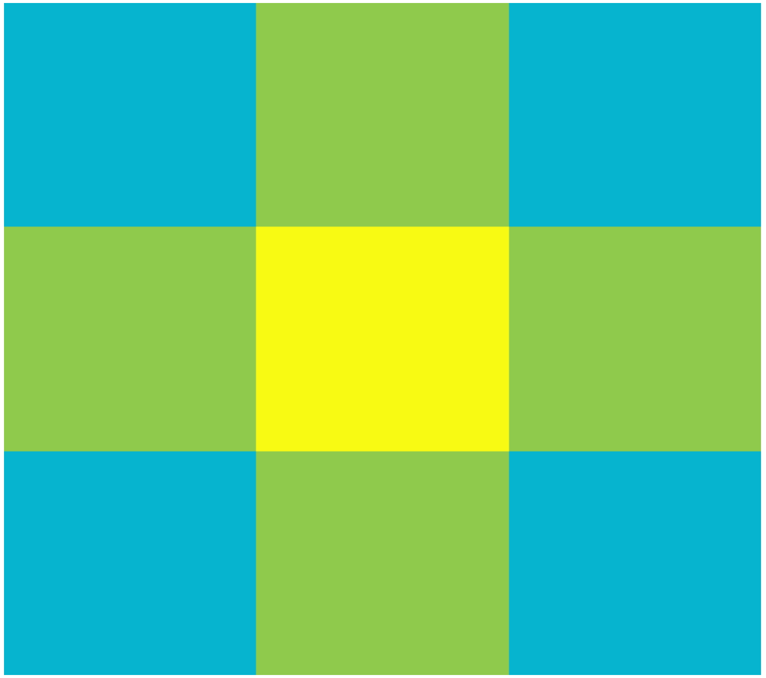
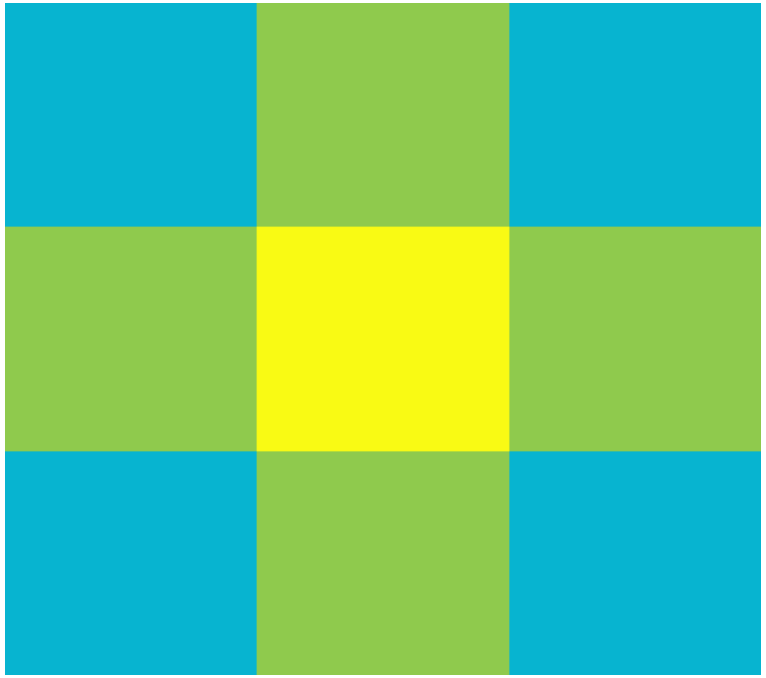
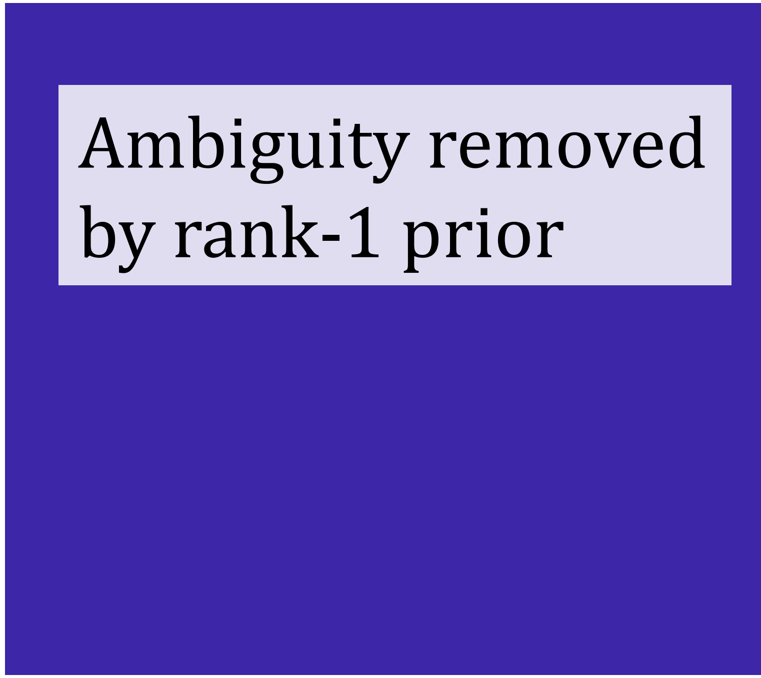


Solution from PhaseLift



Error, 10x



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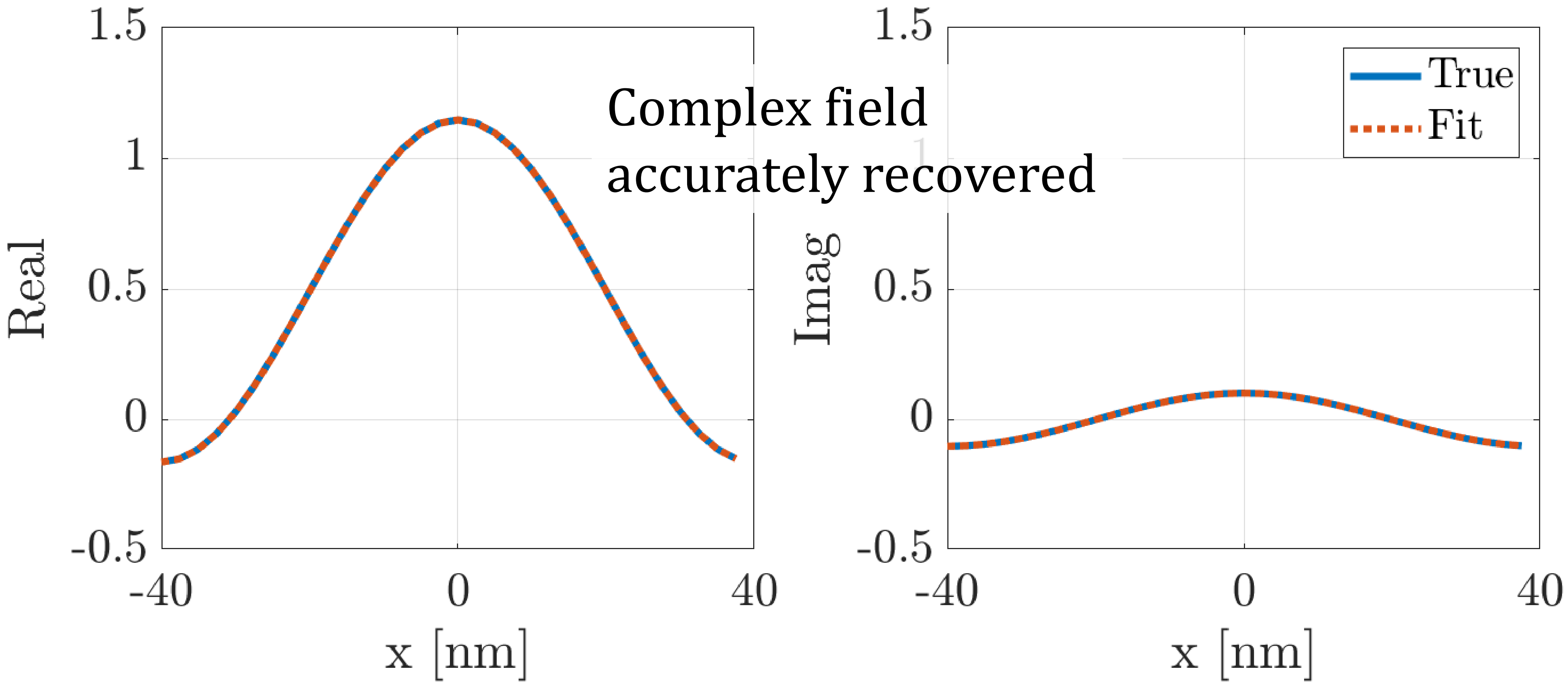
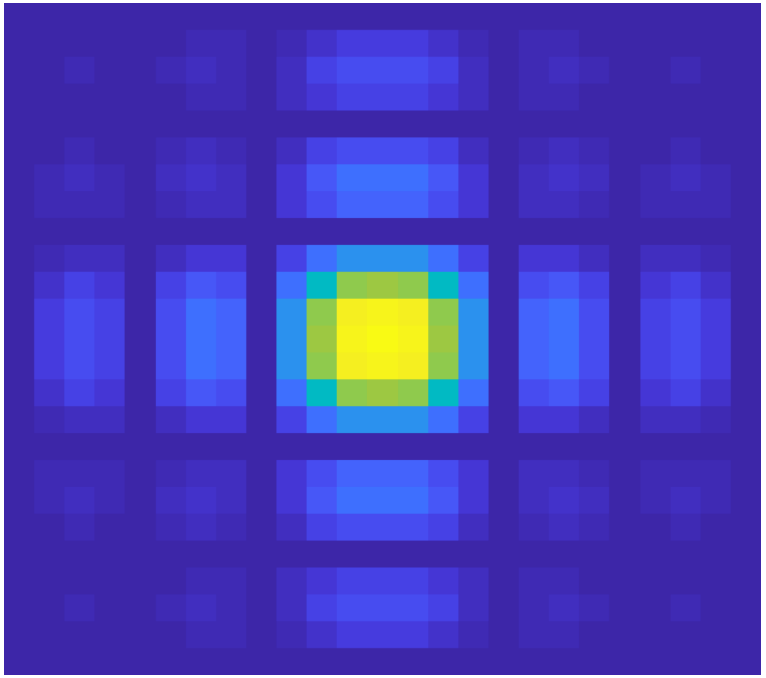


Complex field
accurately recovered

PhaseLift walkthrough: larger pitch

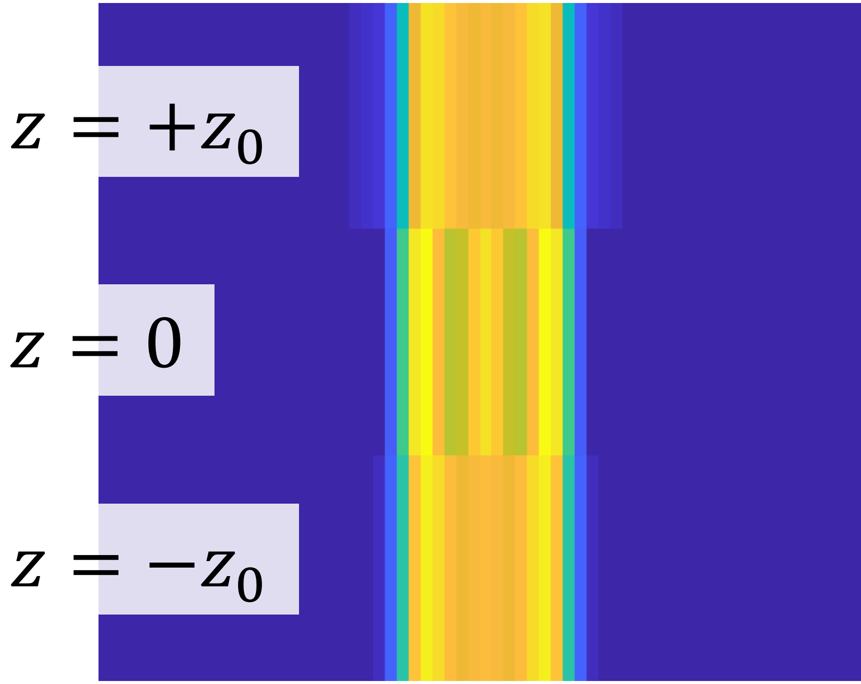
True $X = \tilde{E}\tilde{E}^*$



25 Diffraction orders
3 Focus steps

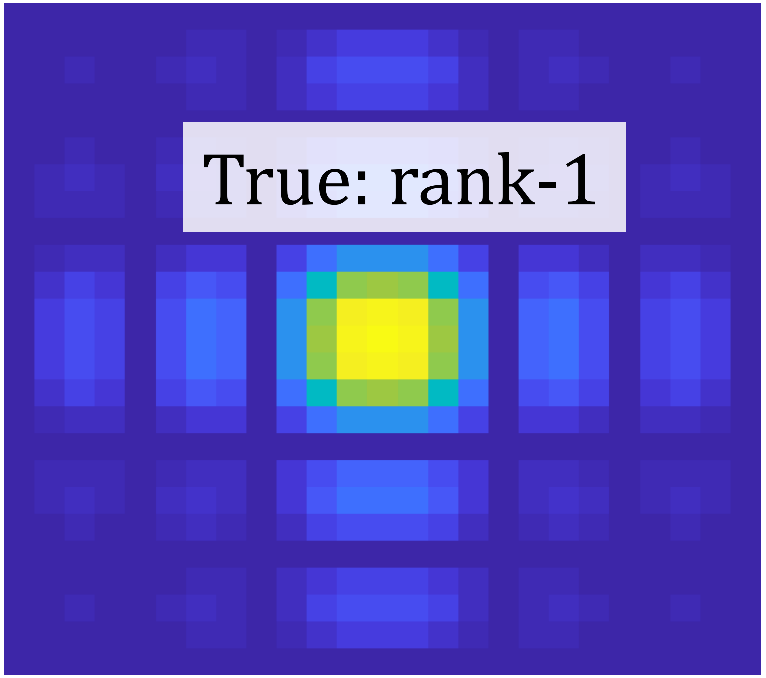
Linear operator
$\mathcal{L}: X \mapsto I$

Measured I



PhaseLift walkthrough: larger pitch

True $X = \tilde{E}\tilde{E}^*$



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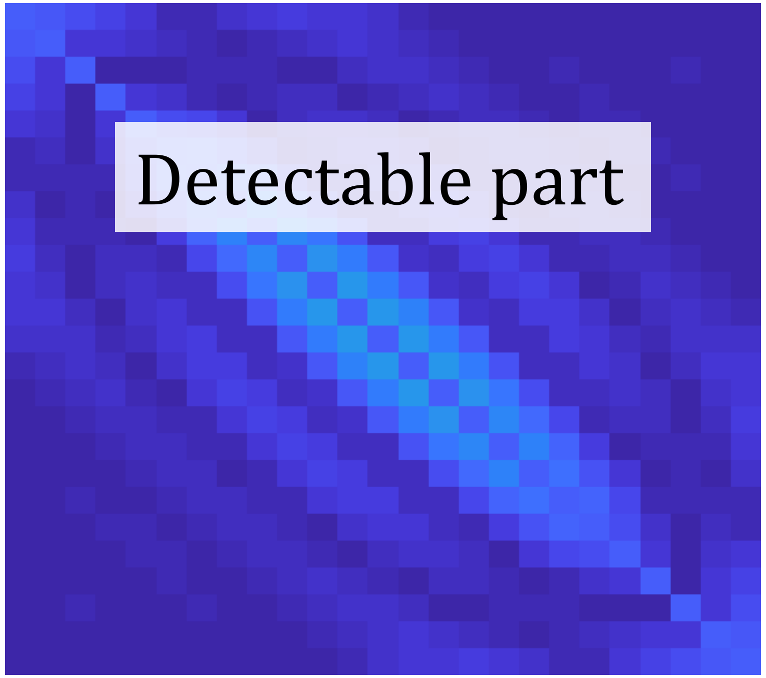

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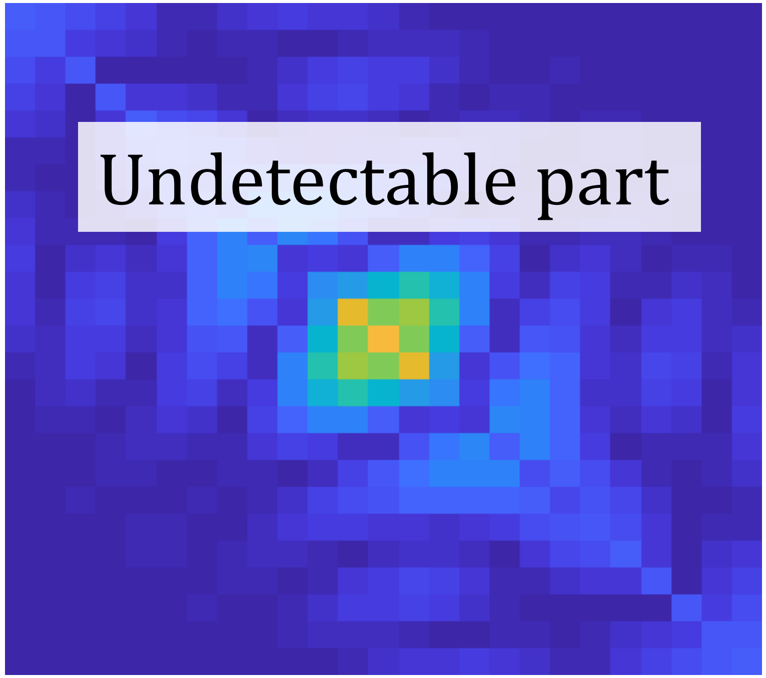
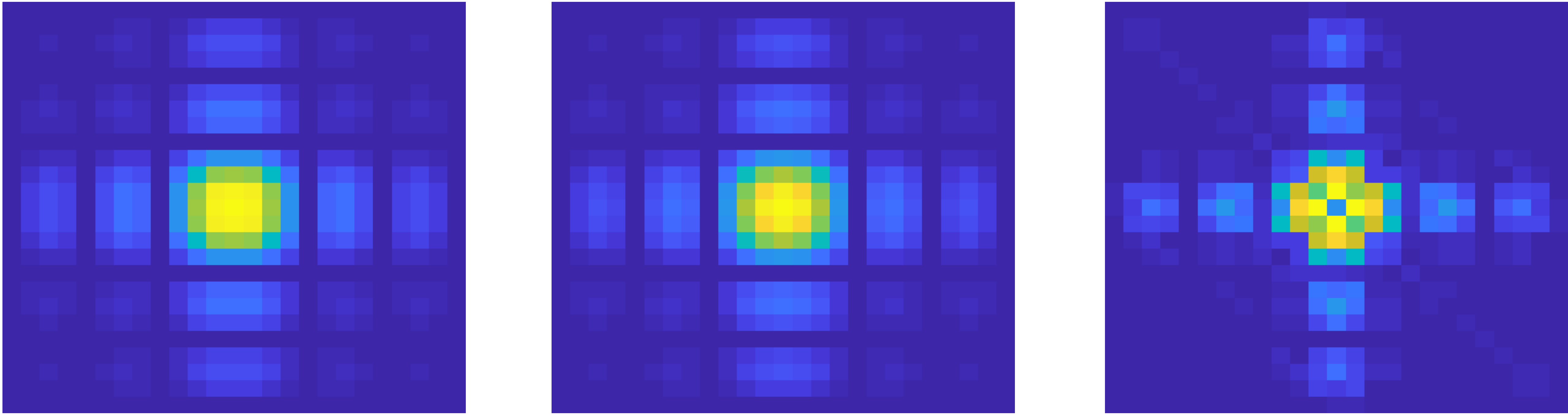


PhaseLift walkthrough: larger pitch

True $X = \tilde{E}\tilde{E}^*$ | $\hat{X}$: solution from PhaseLift | Error, 10x



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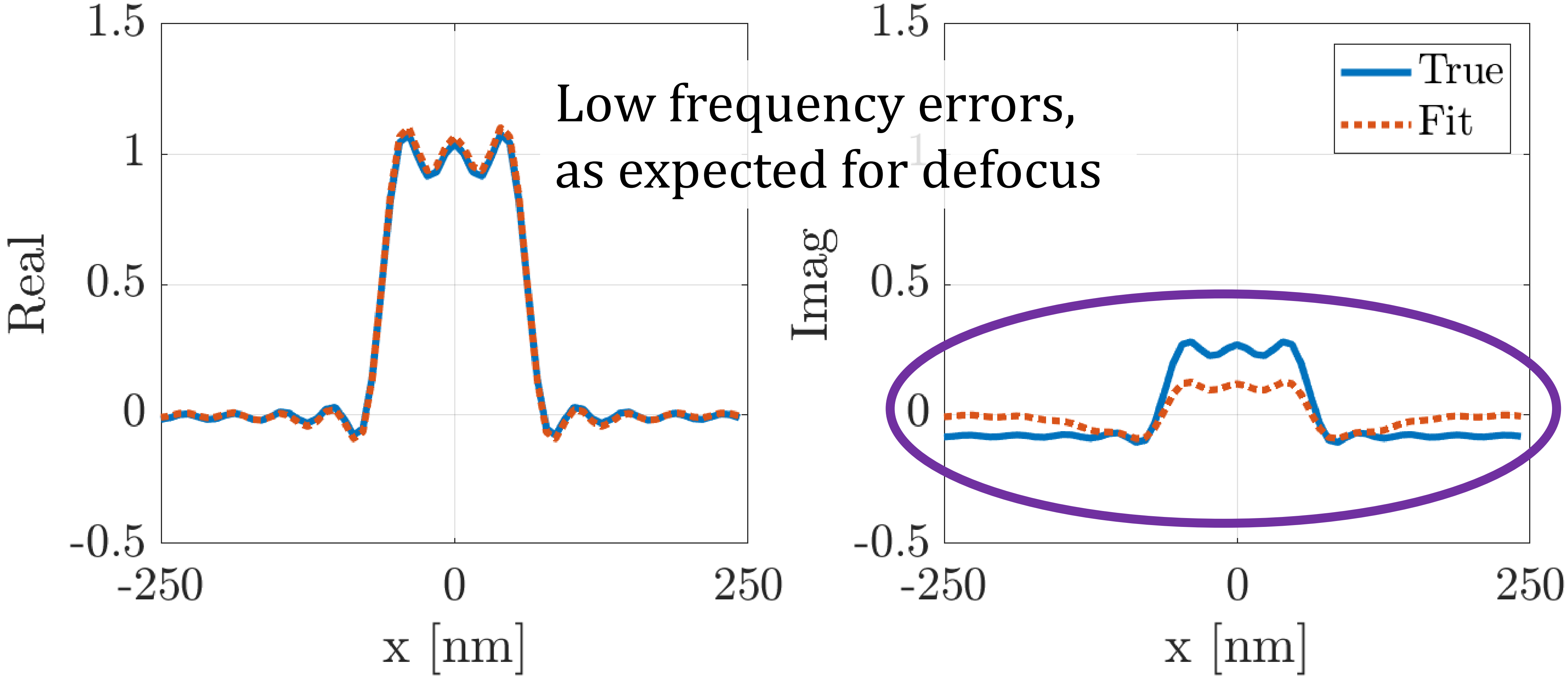
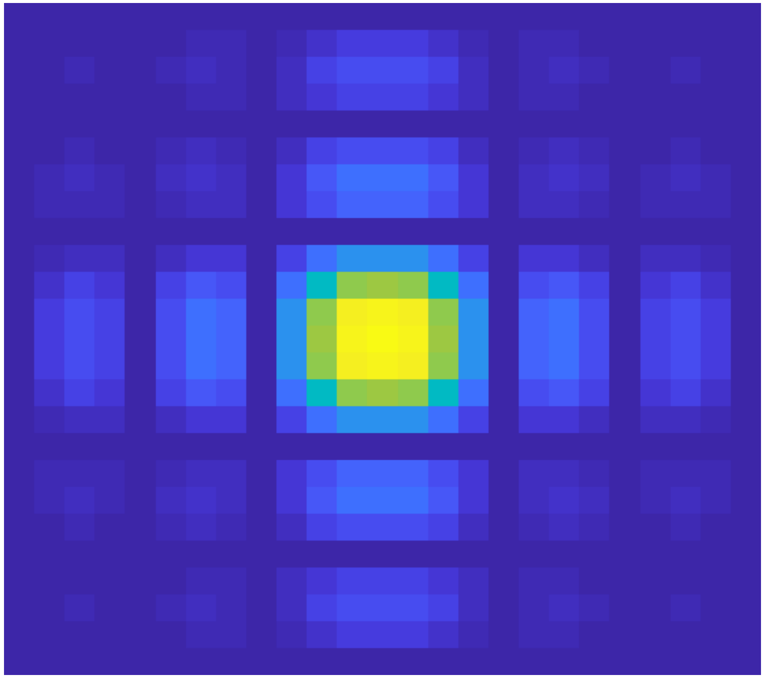


Low frequency errors,
as expected for defocus

PhaseLift walkthrough: coded aperture

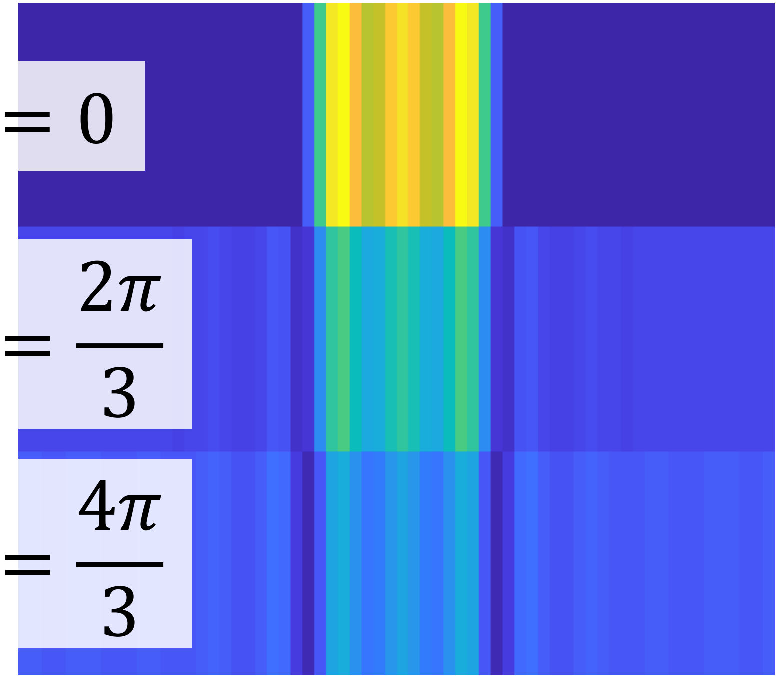
True $X = \tilde{E}\tilde{E}^*$



25 Diffraction orders
3 Coded apertures

Linear operator
$\mathcal{L}: X \mapsto I$

Measured I



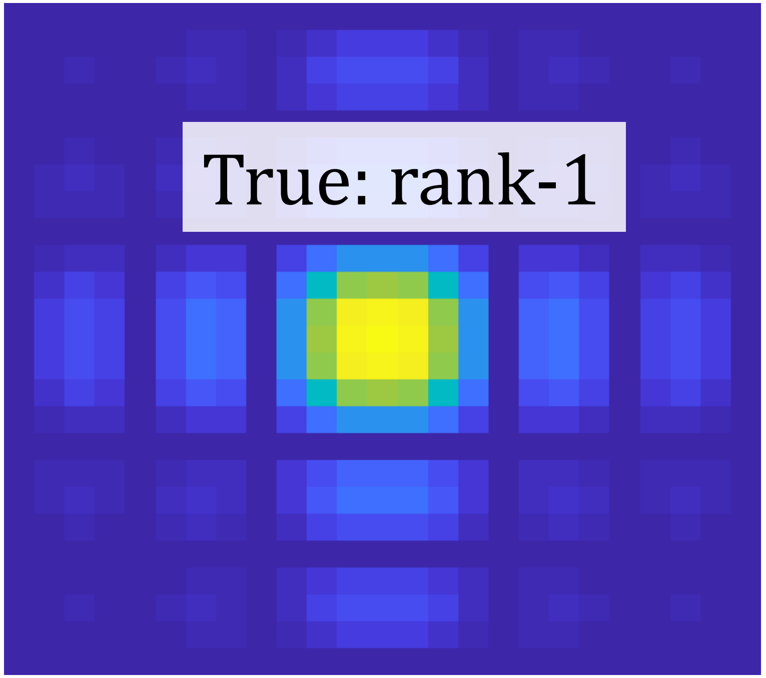
$\phi = 0$

$\phi = \frac{2\pi}{3}$

$\phi = \frac{4\pi}{3}$

PhaseLift walkthrough: coded aperture

True $X = \tilde{E}\tilde{E}^*$



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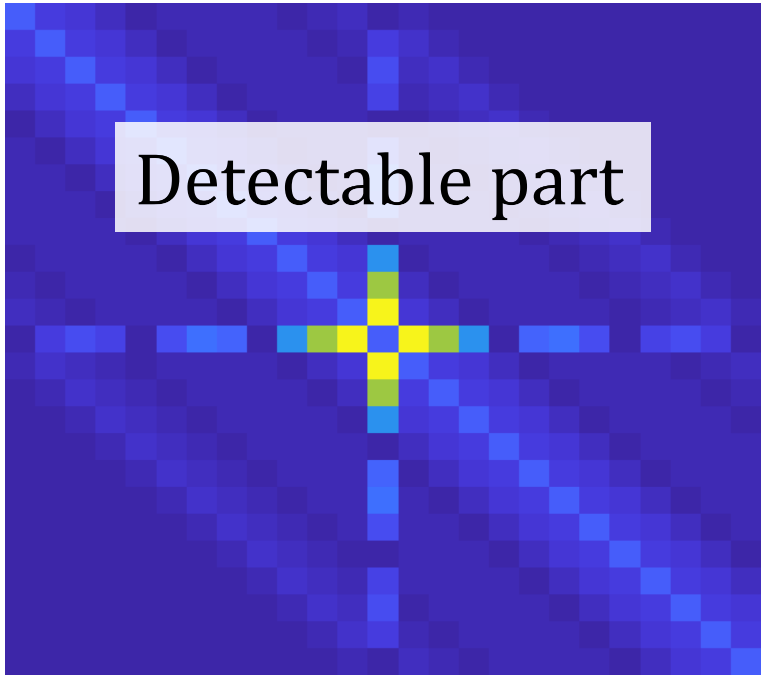

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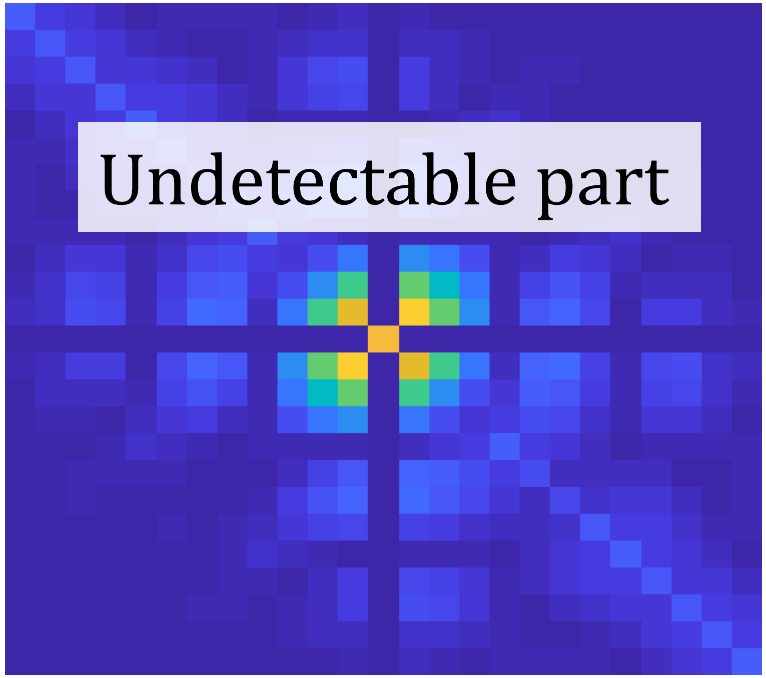
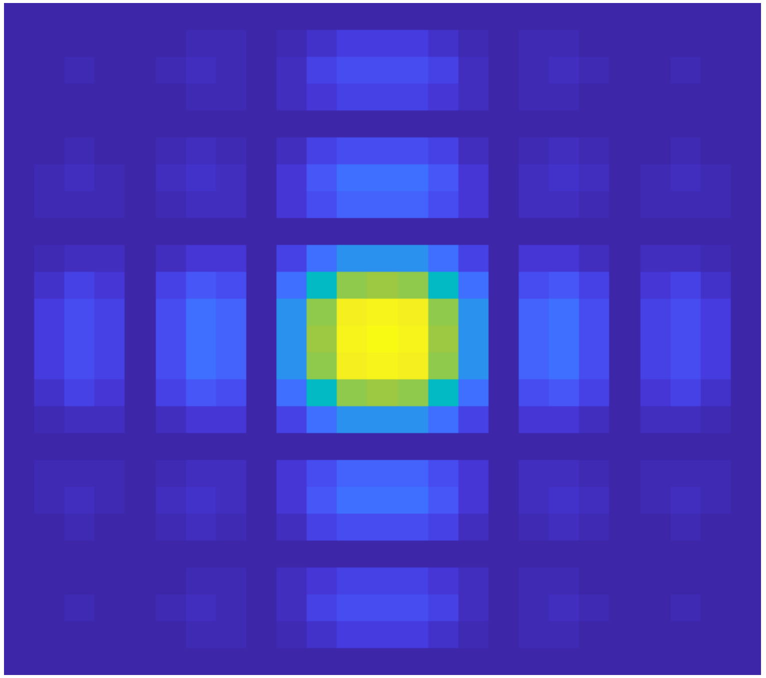
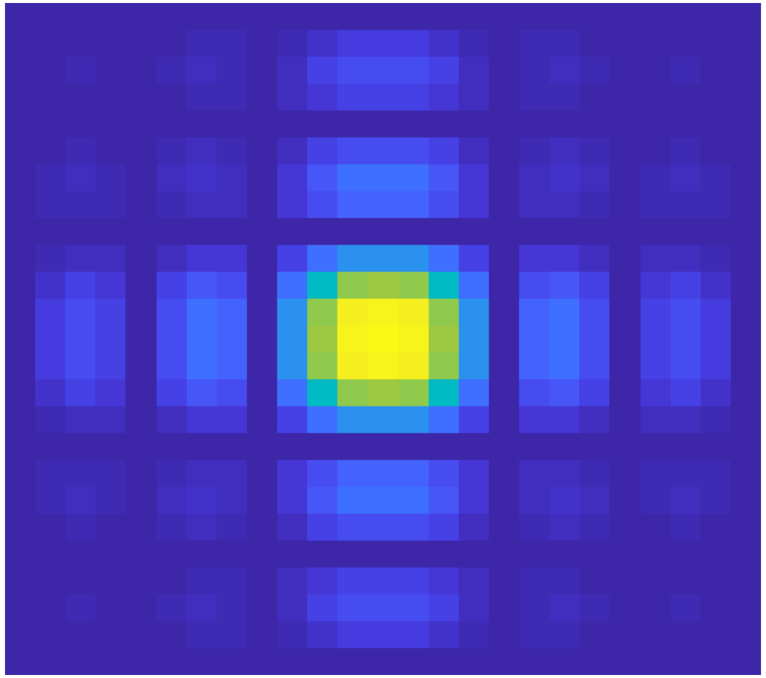


PhaseLift walkthrough: coded aperture

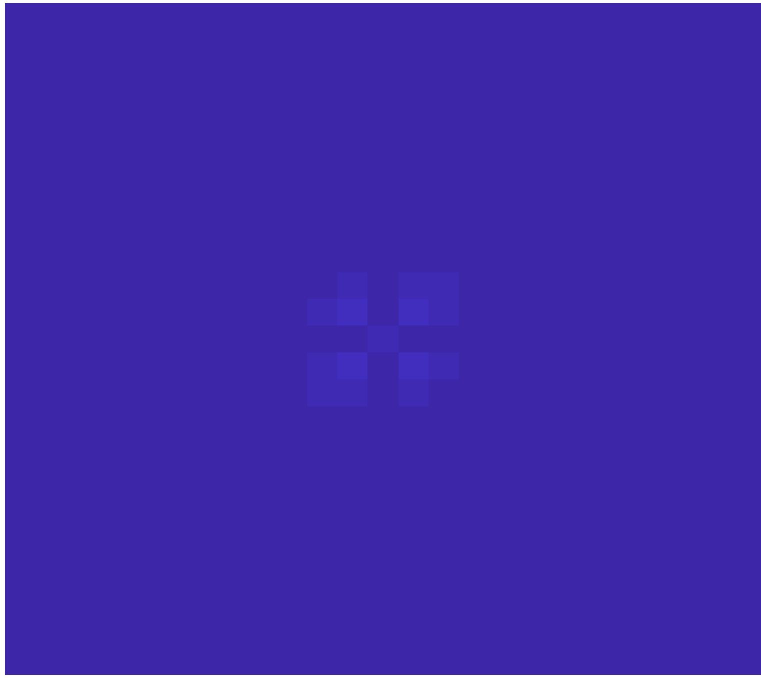
True $X = \tilde{E}\tilde{E}^*$



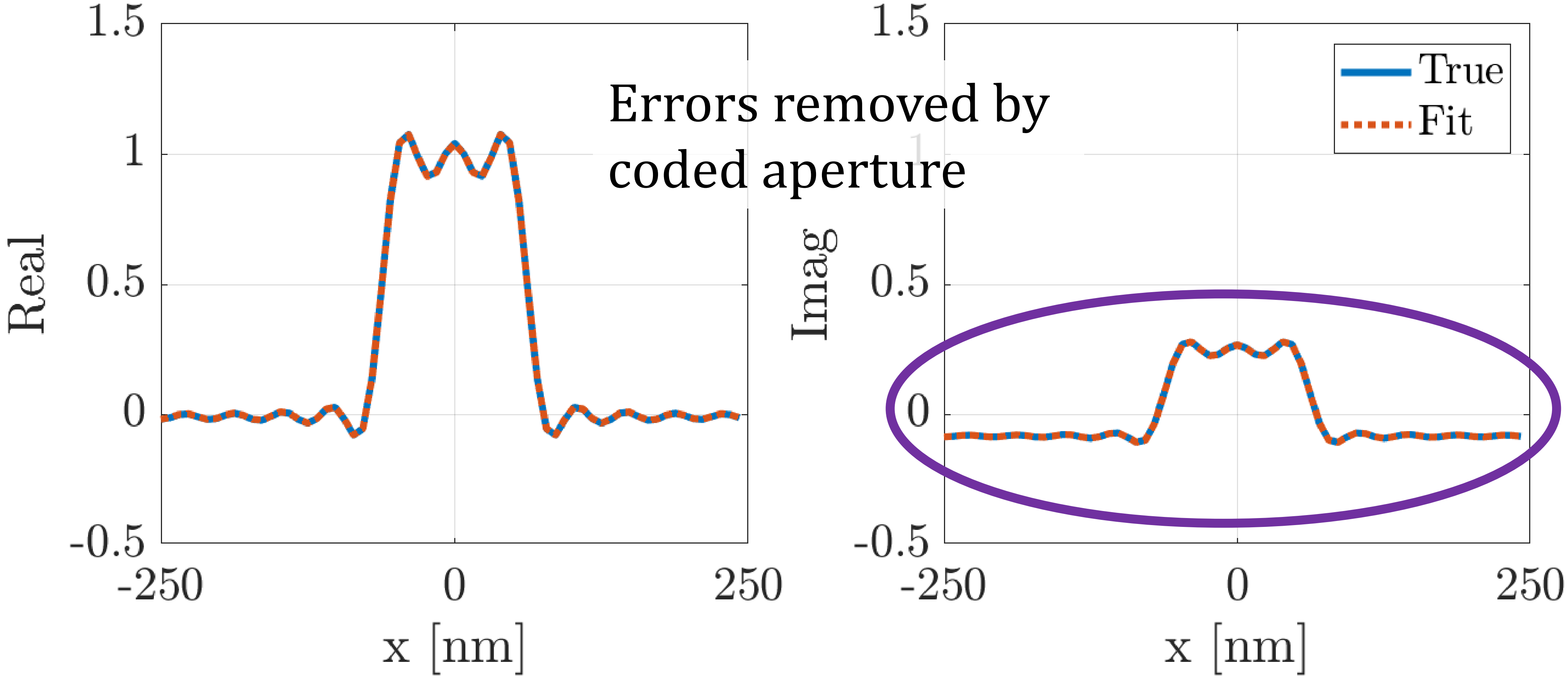
$\hat{X}$: solution from PhaseLift



Error, 10x



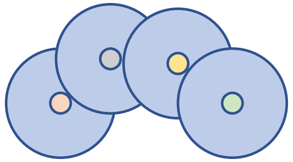
PhaseLift walkthrough: coded aperture



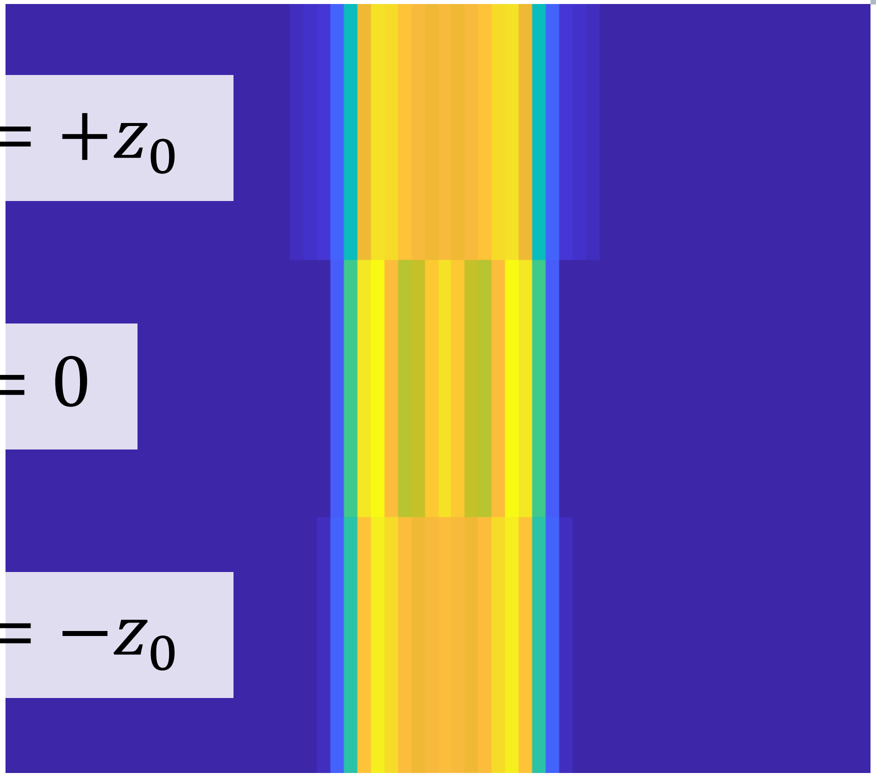
Errors removed by coded aperture

Comparison: Raw data

Through-focus



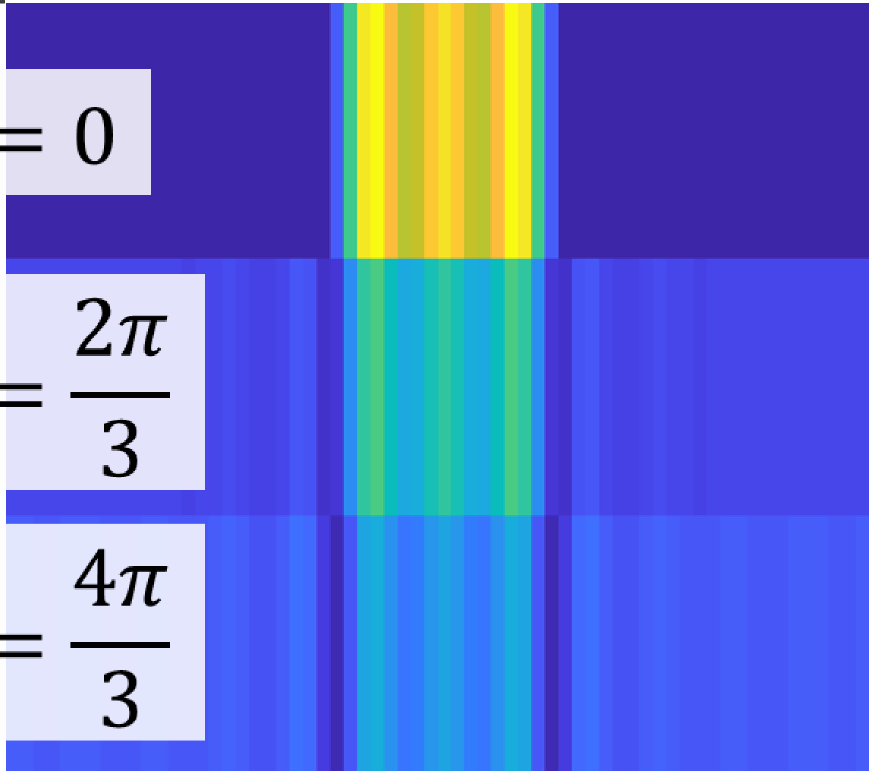
Coded aperture



$z = +z_0$

$z = 0$

$z = -z_0$



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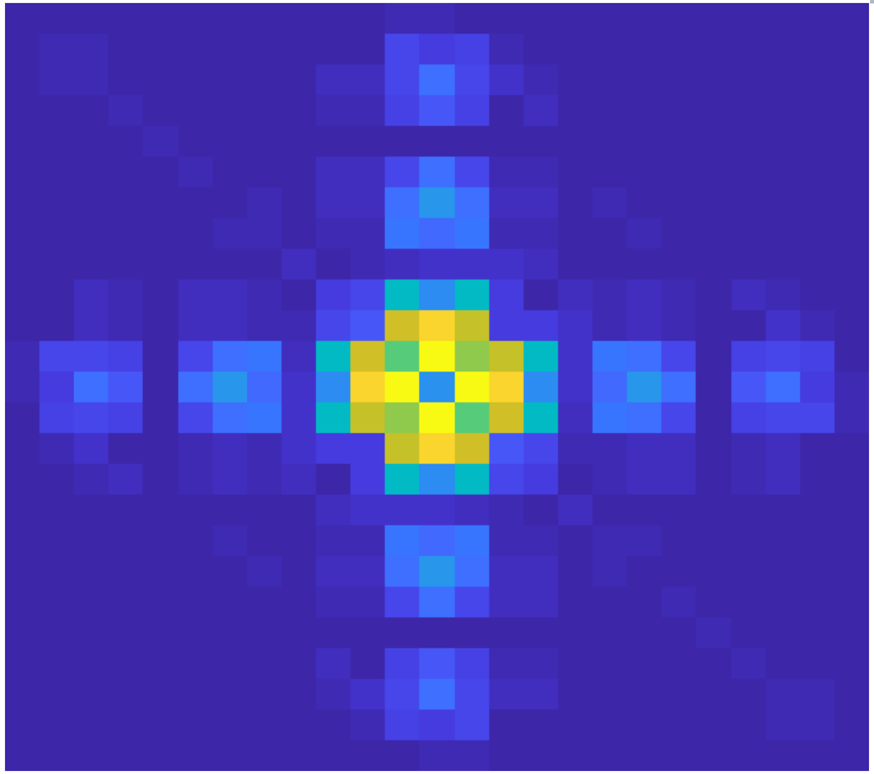
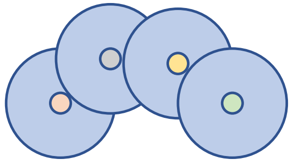
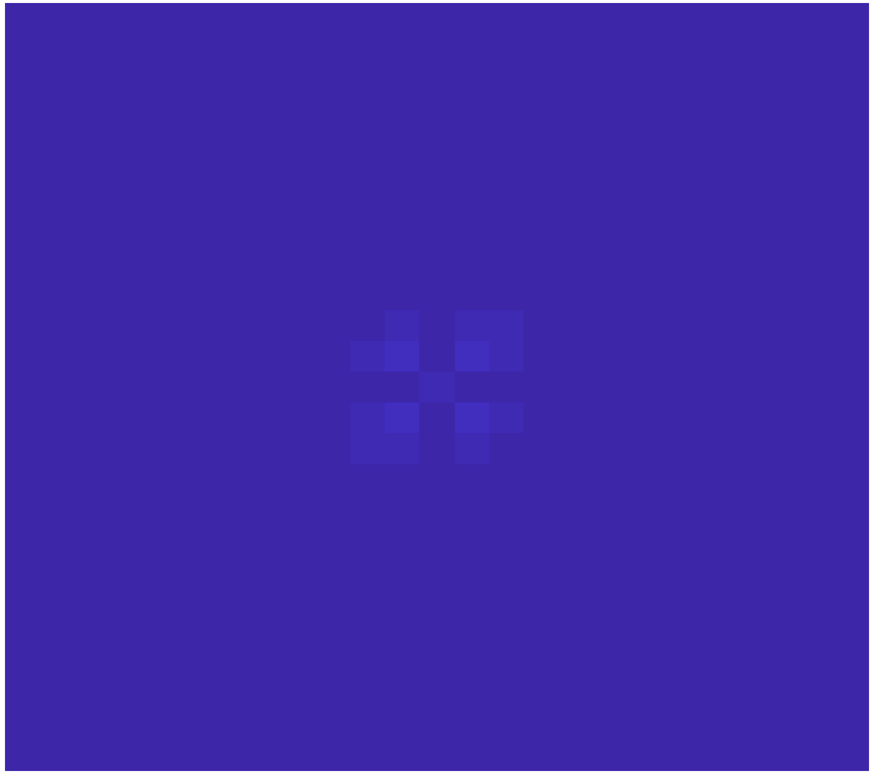
Comparison: Error, 10x

Through-focus

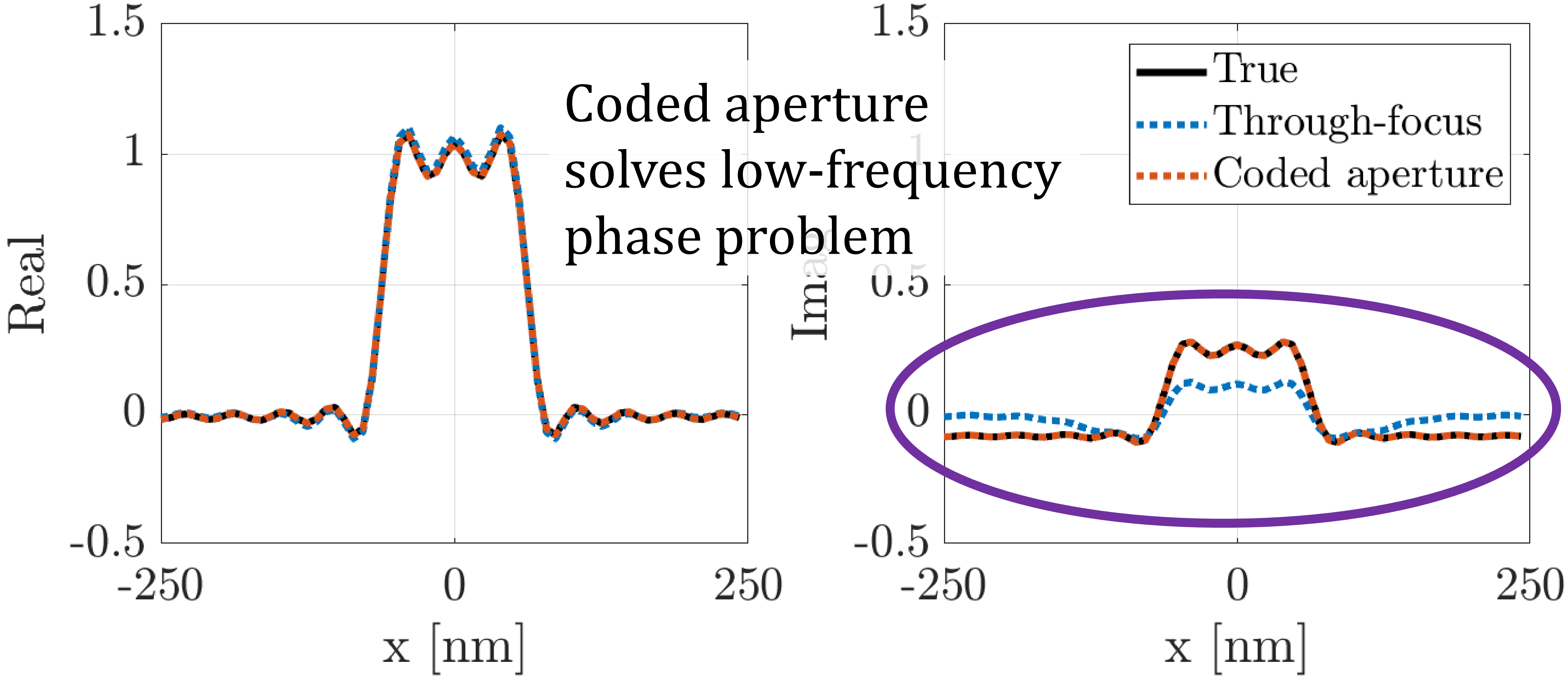


Coded aperture





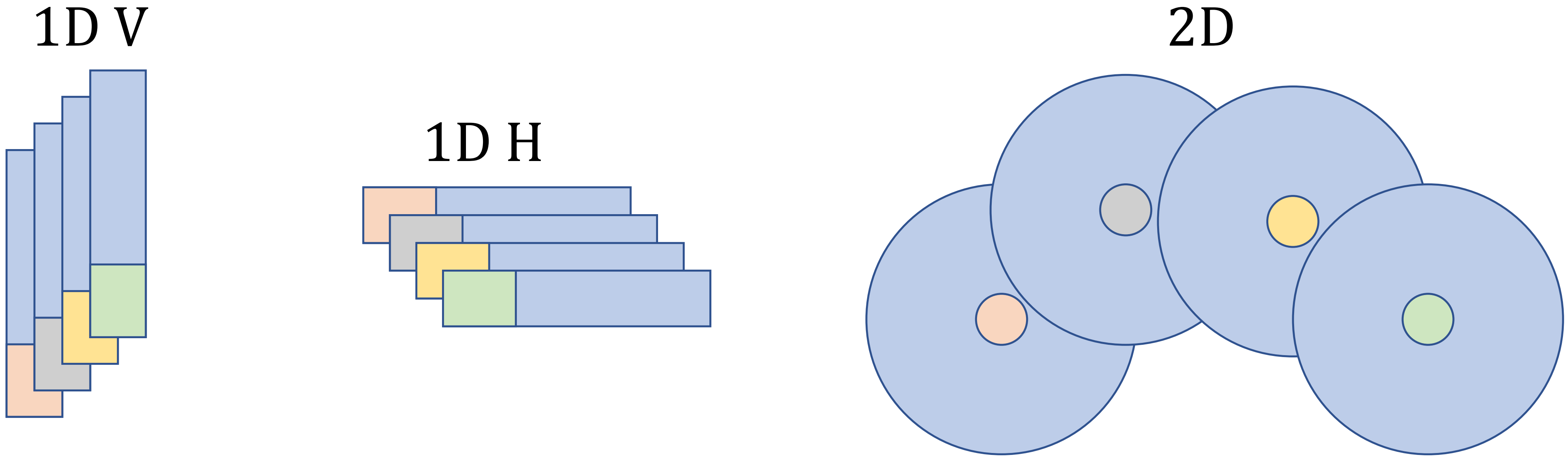
Comparison: Complex field



Coded aperture solves low-frequency phase problem

What's next?

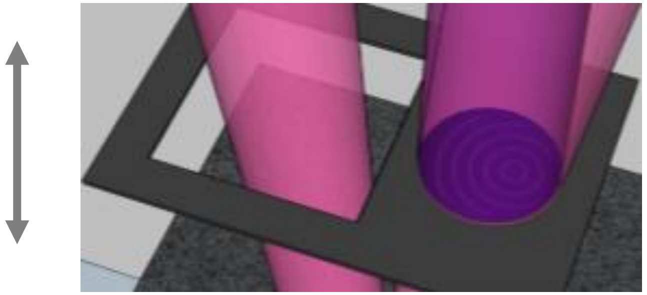
- Fabricate coded zone plates for 1D H/V and 2D samples

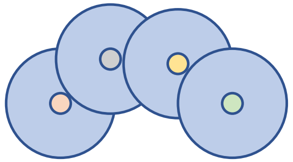


What's next?

- Fabricate coded zone plates for 1D H/V and 2D samples
- Experimental comparison of coded aperture vs through-focus

Through-focus





Coded aperture

What's next?

- Fabricate coded zone plates for 1D H/V and 2D samples
- Experimental comparison of coded aperture vs through-focus
- Comparison of image-based vs scatterometry-based phase retrieval
  - Mask at CXRO, scatterometry measurements already performed

Thank you!