*2015 Advanced Lithography :*

# Measuring Aberrations using EUV Mask Roughness

**Rene Claus**

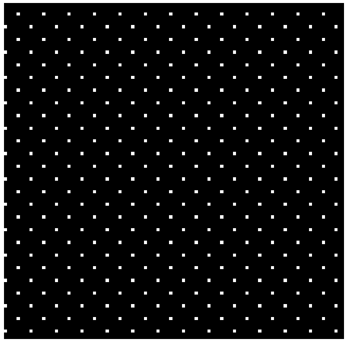
Markus Benk, Antoine Wojdyla, Alex Donoghue,
David Johnson, Kenneth Goldberg, Andrew Neureuther,
Patrick Naulleau, and Laura Waller

Berkeley
UNIVERSITY OF CALIFORNIA

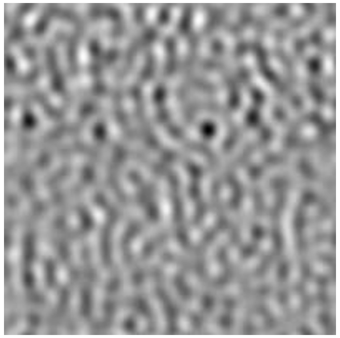
# Measuring Aberrations with Roughness

- Aberrations change the results from an EUV actinic inspection system
  - Want to measure aberrations
  - Want to measure from images directly
- Could use a programmed object (ex: contact array)
- We present a way to use existing mask roughness
  - Aberrations can be measured on any mask

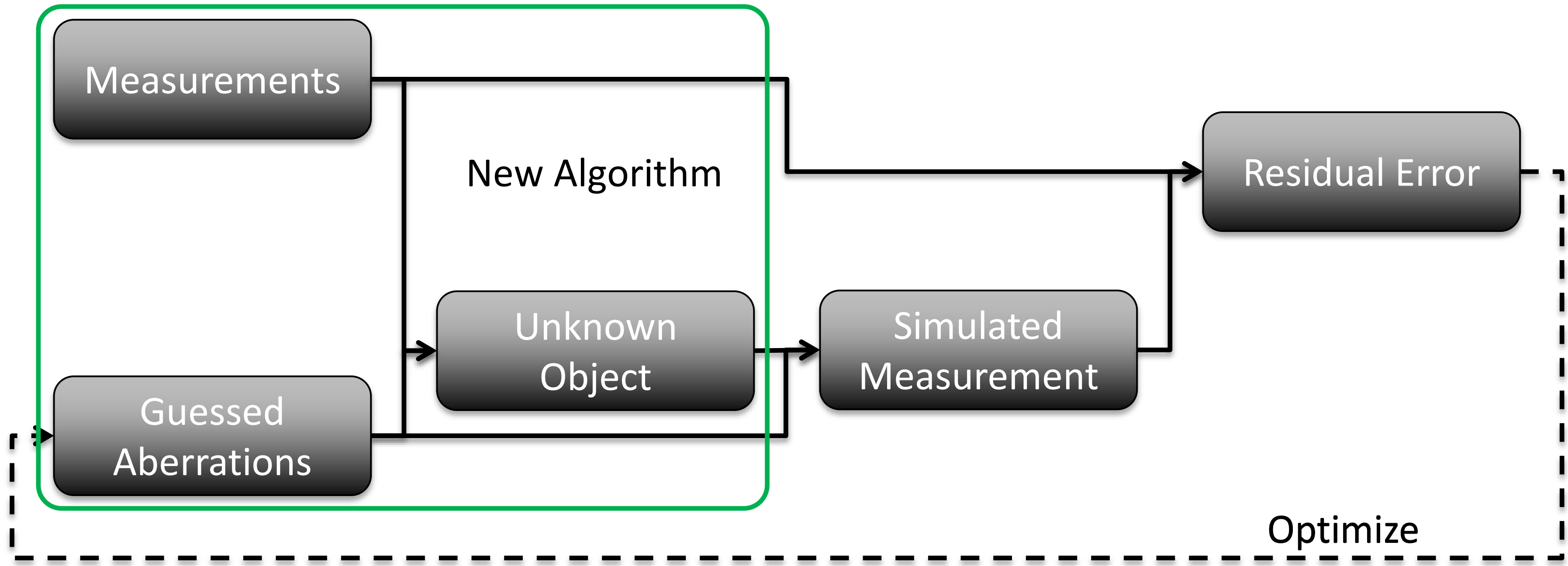
Programmed Test Object



Existing Mask Roughness



# Measuring Aberrations




- Unknown test object
  - Calculate object from model + measurements
- Unknown aberrations
- Minimize residual error by guessing different aberrations

# New Phase Retrieval Algorithm

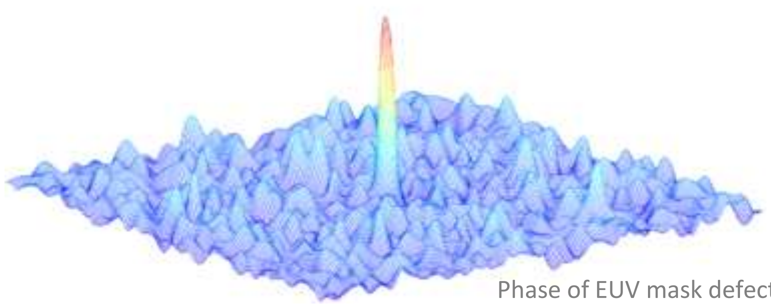
Arbitrary Pupil (Aberrations) + Arbitrary Source (partial coherence)

↓

Aerial Image Measurements (focus series)

↓

Quantitative Phase & Amplitude

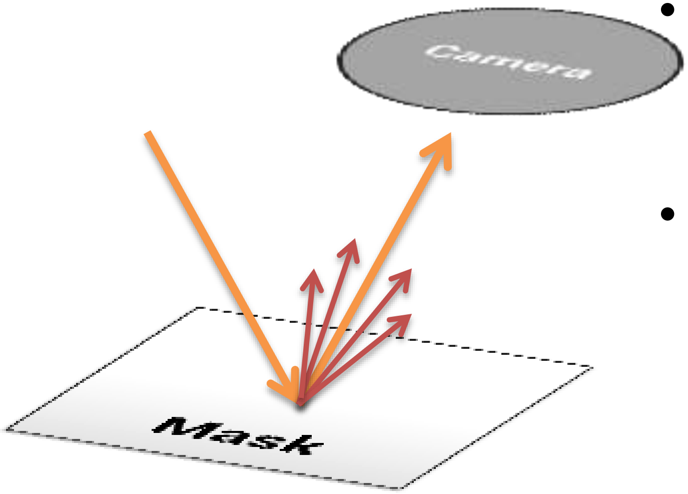


Phase of EUV mask defect

More details in:

**R. Claus, "Phase Measurements of EUV Masks," SPIE Advanced Lithography (2015).**

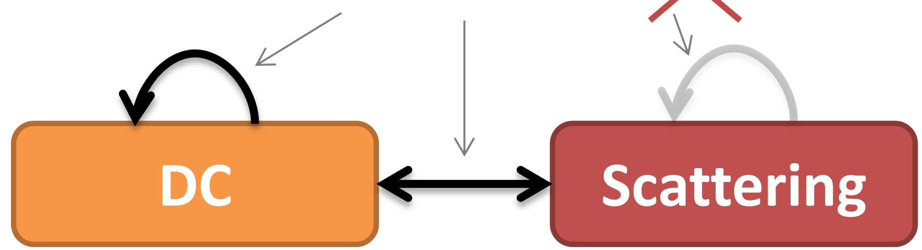
# Weak Object Assumption




- Consider a rough mirror (or mask)
  - Most of the light is reflected
  - Some of the light is scattered
- The electric field leaving the mask can be expressed as the sum of these components

$$E = 1 + E_s$$

$$I = |1 + E_s|^2 = 1 + 2Re\{E_s\} + |\cancel{E_s}|^2$$




- For most objects *Scattering* ≪ *DC*
  - We can ignore *Scattering-Scattering*

# Recovering the Field

Write the intensity as a sum of convolutions:

$$I = 1 + E_{re} * K_{re} + E_{im} * K_{im} + O(|E_s|^2)$$

$$\downarrow$$

$$\tilde{I} = 1 + \widetilde{E_{re}} \cdot \widetilde{K_{re}} + \widetilde{E_{im}} \cdot \widetilde{K_{im}}$$

$$\downarrow$$

$$\begin{bmatrix} \tilde{I}_1\,(f_i) \\ \vdots \\ \tilde{I}_n\,(f_i) \end{bmatrix} = \begin{bmatrix} \widetilde{K_{re}^{1}}(f_i) & \widetilde{K_{im}^{1}}(f_i) \\ \vdots & \vdots \\ \widetilde{K_{re}^{n}}(f_i) & \widetilde{K_{im}^{n}}(f_i) \end{bmatrix} \begin{bmatrix} \widetilde{E_{re}}(f_i) \\ \widetilde{E_{im}}(f_i) \end{bmatrix}$$

Linear system of equations → solve with least squares

Transfer functions:

$$\widetilde{K_{re}} = (P \cdot L) \star P + P \star (P \cdot L)$$
$$\widetilde{K_{im}} = (P \cdot L) \star P - P \star (P \cdot L)$$

$P$: pupil function, $L$: source shape

consider aberrations

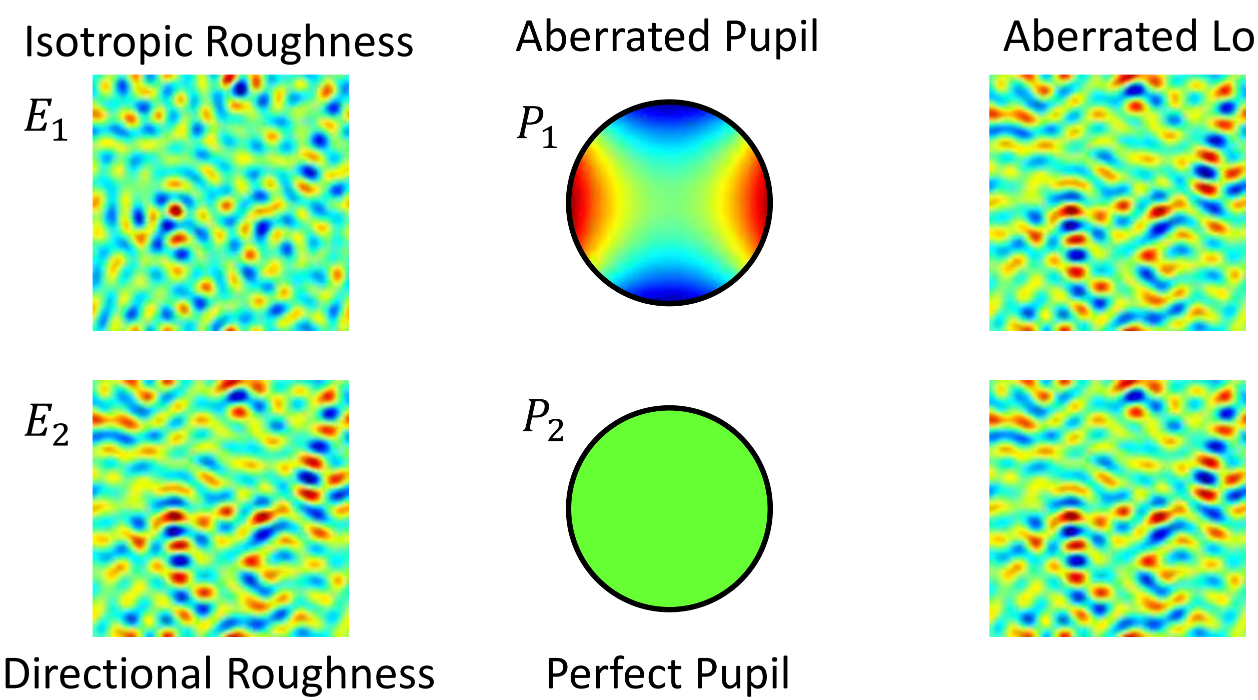
use partial coherence

Berkeley UNIVERSITY OF CALIFORNIA

More details in:
R. Claus, "Phase Measurements of EUV Masks," SPIE Advanced Lithography (2015).

# Aberration and Coherent Imaging

- Under coherent illumination, the object & aberrations are not linearly independent
- Partial coherence can solve the problem

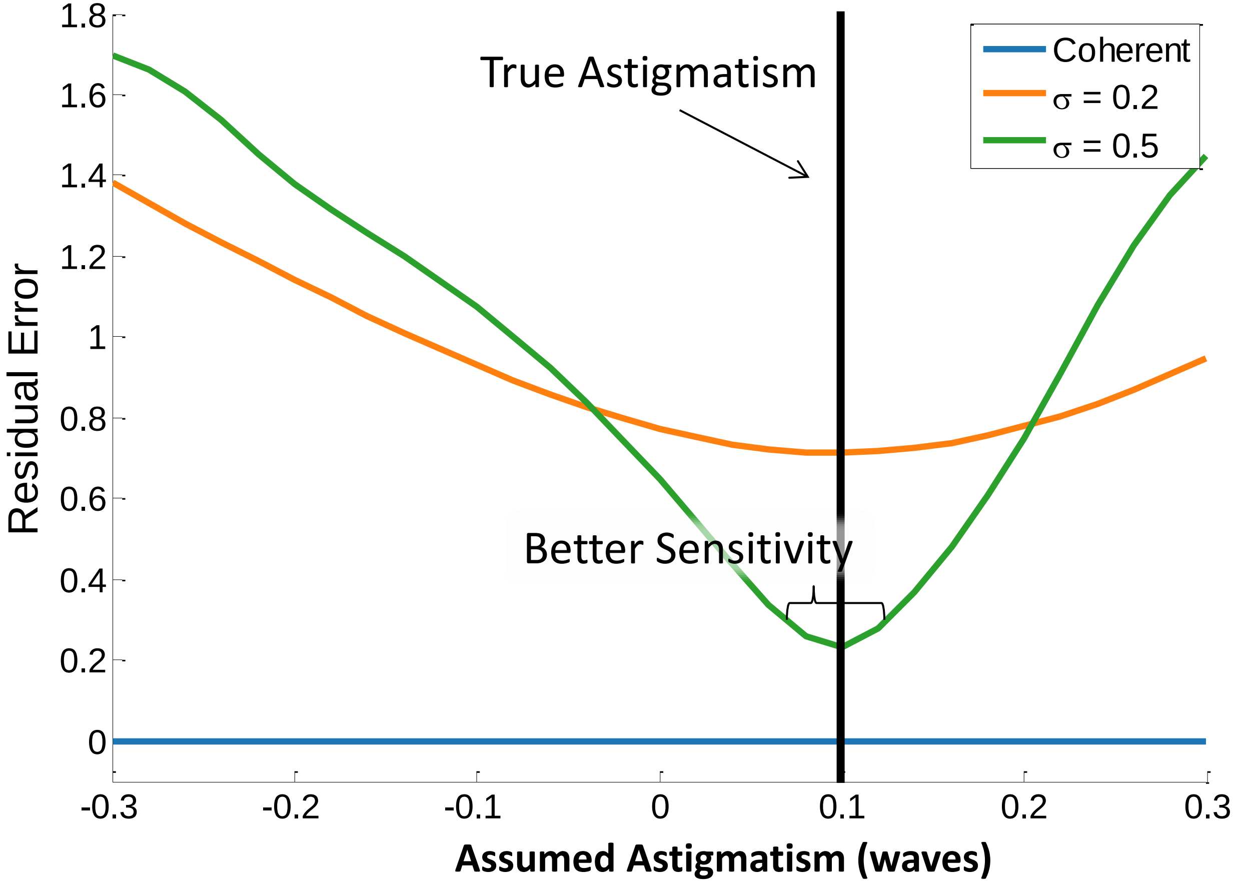



$$I = |E_1 * P_1|^2$$

$$I = |E_2 * P_2|^2$$

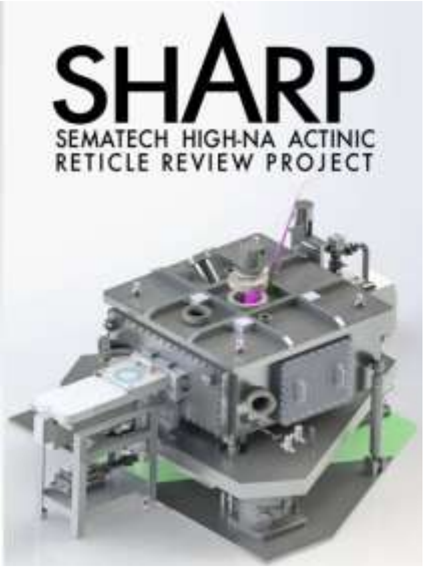
# Partial Coherence Improves Sensitivity

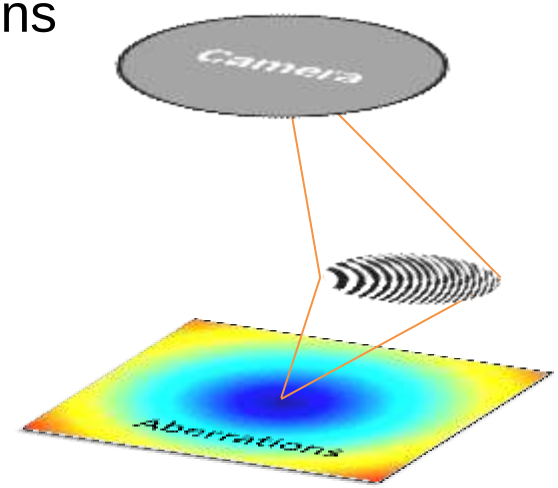
Simulated 21 through-focus images of speckle with astigmatism:



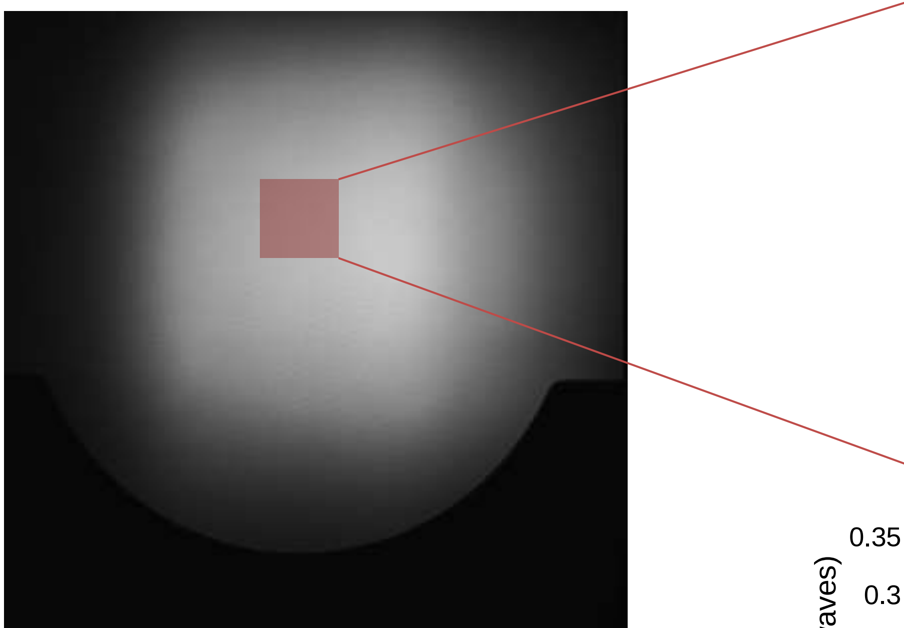
# SEMATECH Berkeley SHARP

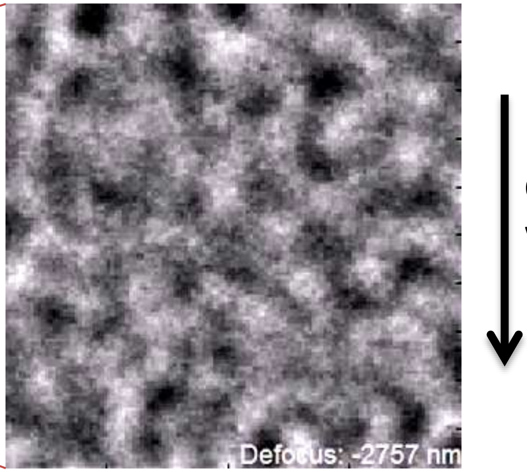
- Actinic mask inspection system at LBNL
- Zone plate lens as objective
  - + Less expensive than multilayer optics
  - + Easy to test different lenses
  - – Single lens system
  - – Strong field dependent aberrations
  - – Aberrations vary with focus



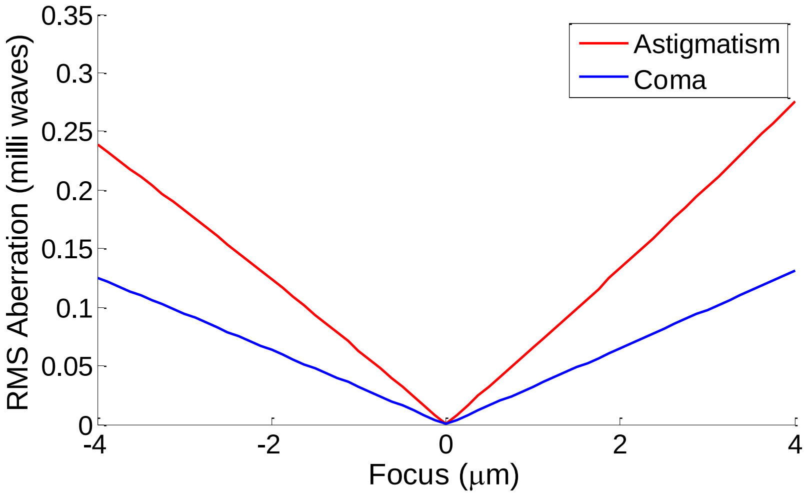
# Aberrations Vary With Focus





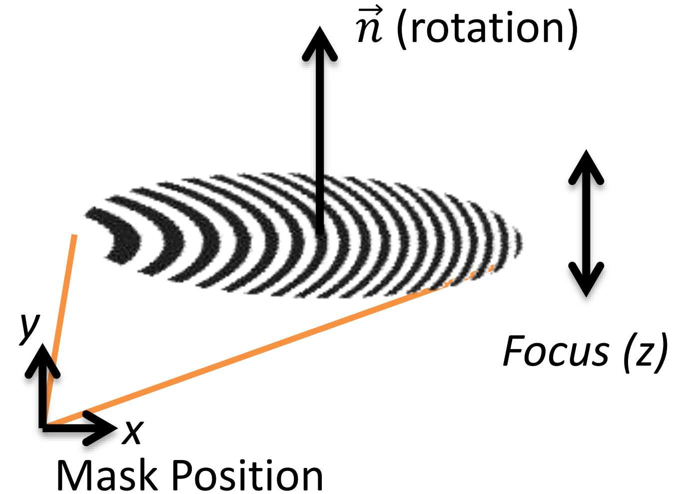

Object moves with focus

Aberration is not constant with focus

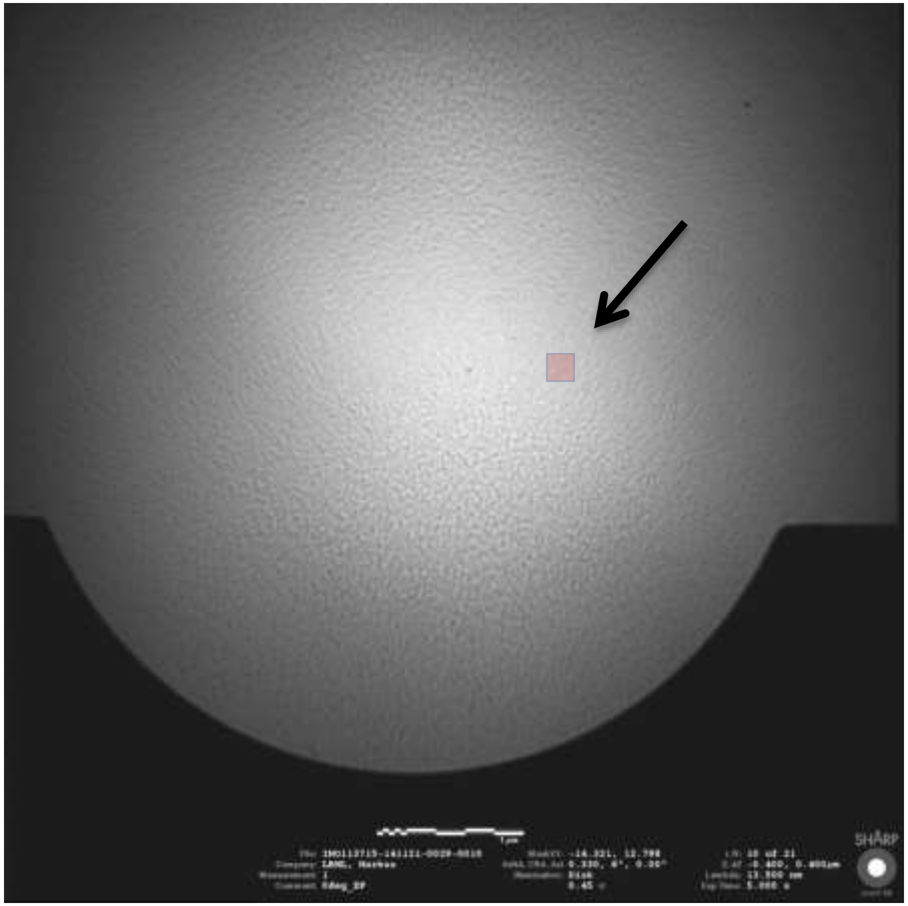


# Modeling the Zone Plate

- Instead of modeling aberrations at each position we model the zone plate
  - rotation of zone plate
  - position of zone plate
  - illumination angle
- Calculate aberrations using ray tracing
- Consider physical measurement
  - "Zone plate was moved 500nm up per image"
  - Captures how aberrations change in each image
  - Captures how object moves
- Fewer parameters to optimize



# Calibrating the Zone Plate



Illumination: $\sigma = 0.25$, monopole

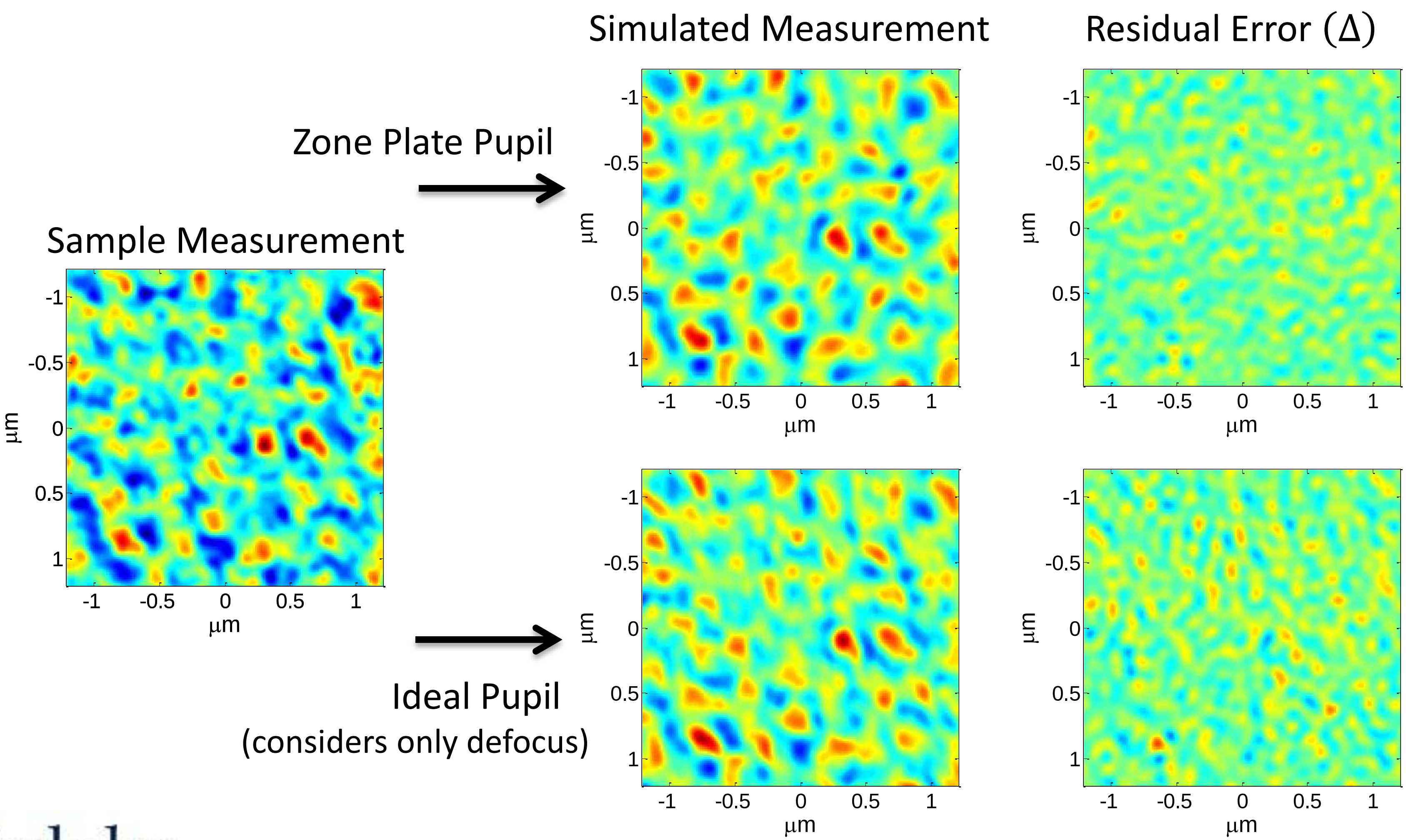
Examine small areas →
aberrations are approx constant

- Where is the center of the field?
- What is the tip/tilt of the zone plate?

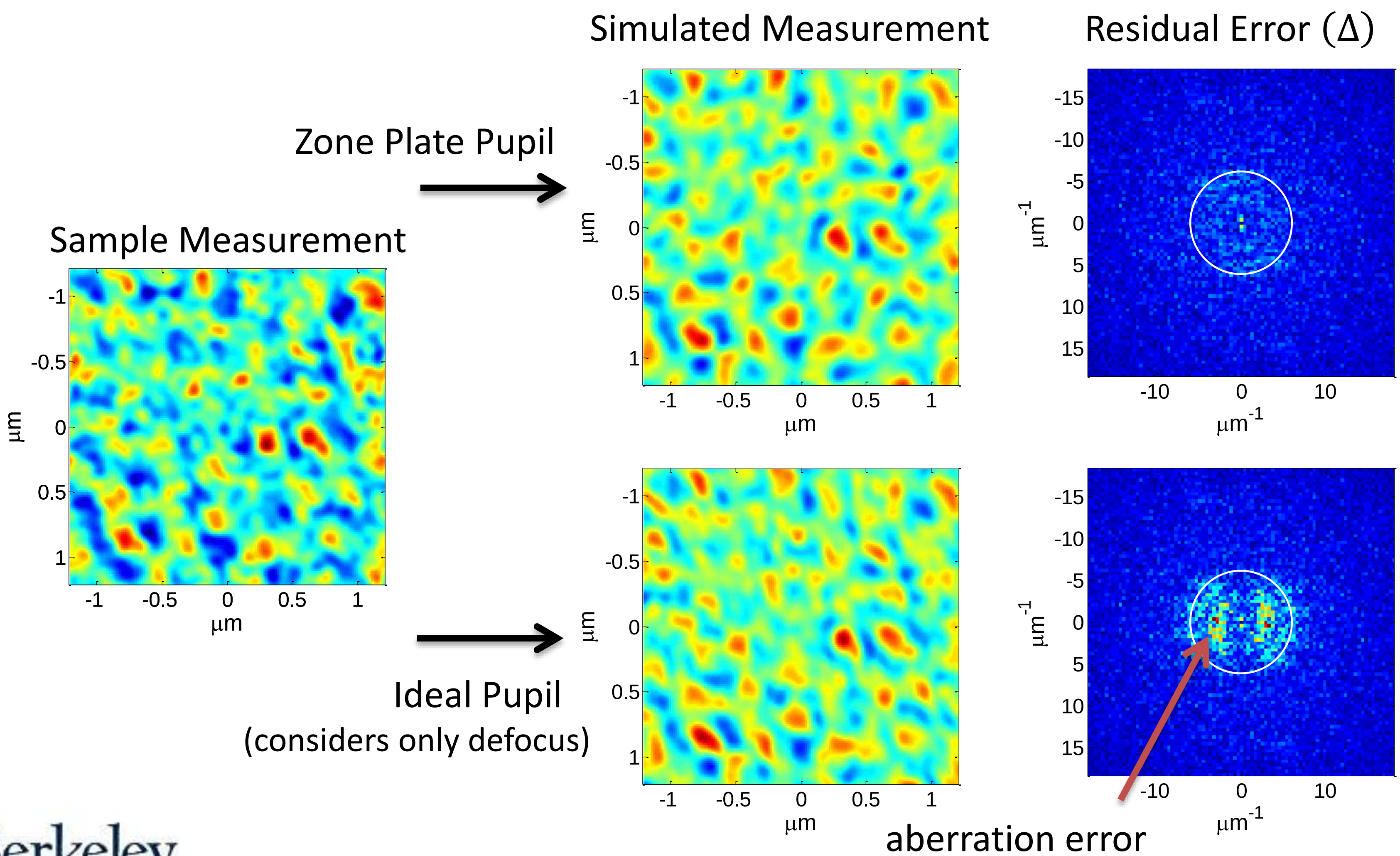
Wasn't able to automatically optimize the parameters
  - Small stage drift
  - Field dependent illumination

Guessed good parameters

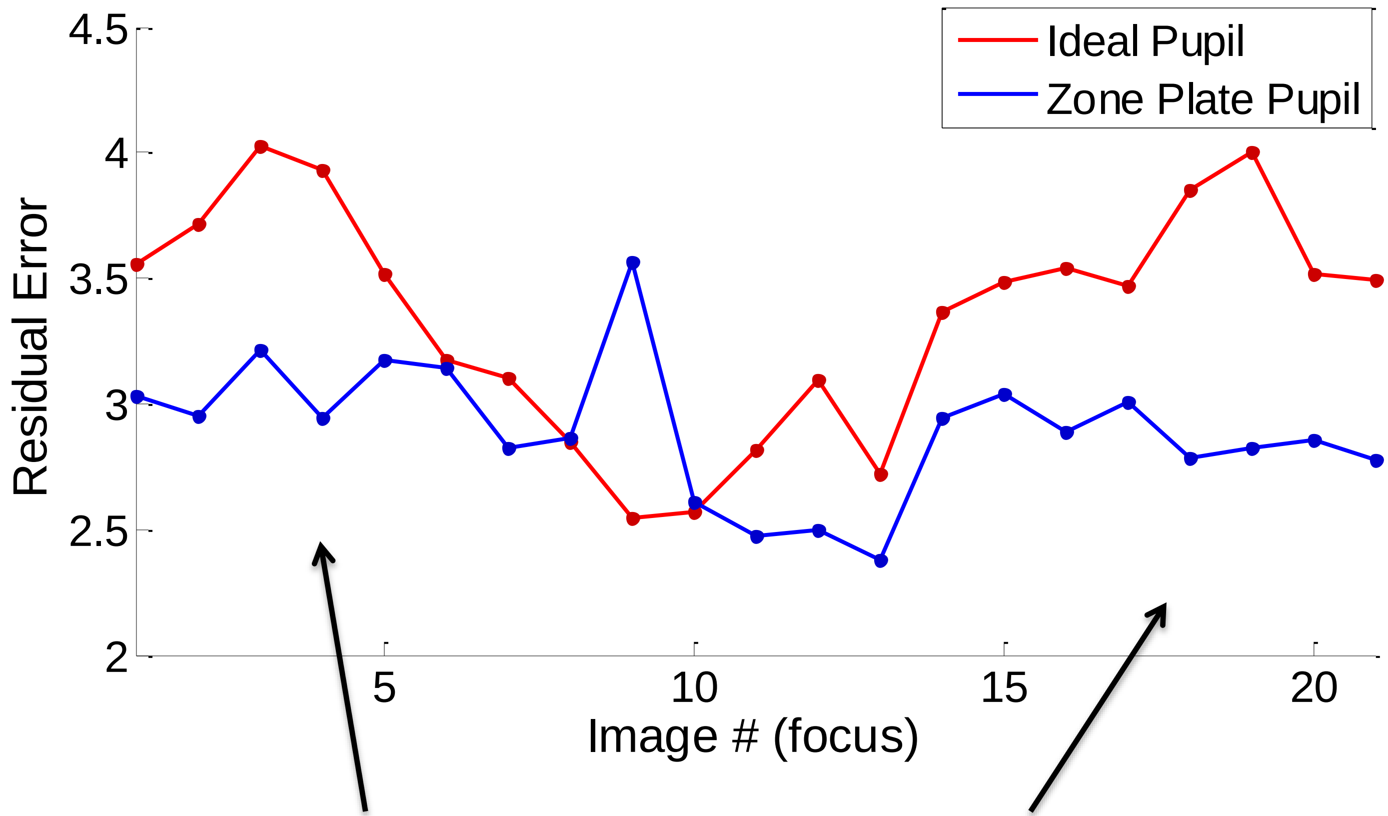
# Reduced Residual



# Reduced Residual



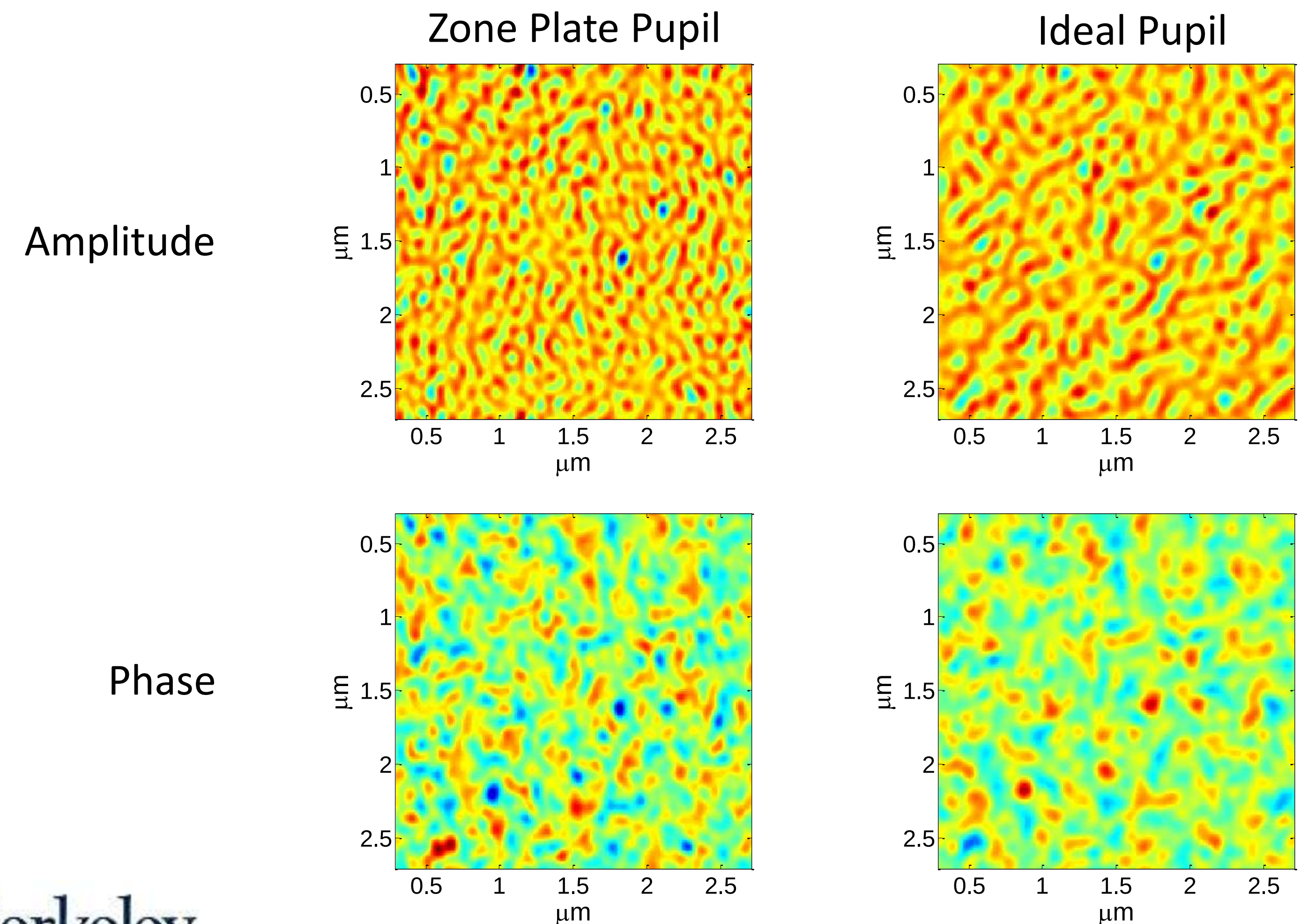
# Improved Results with ZP Model




Ideal pupil fits “average aberration” → fits best at center of the stack

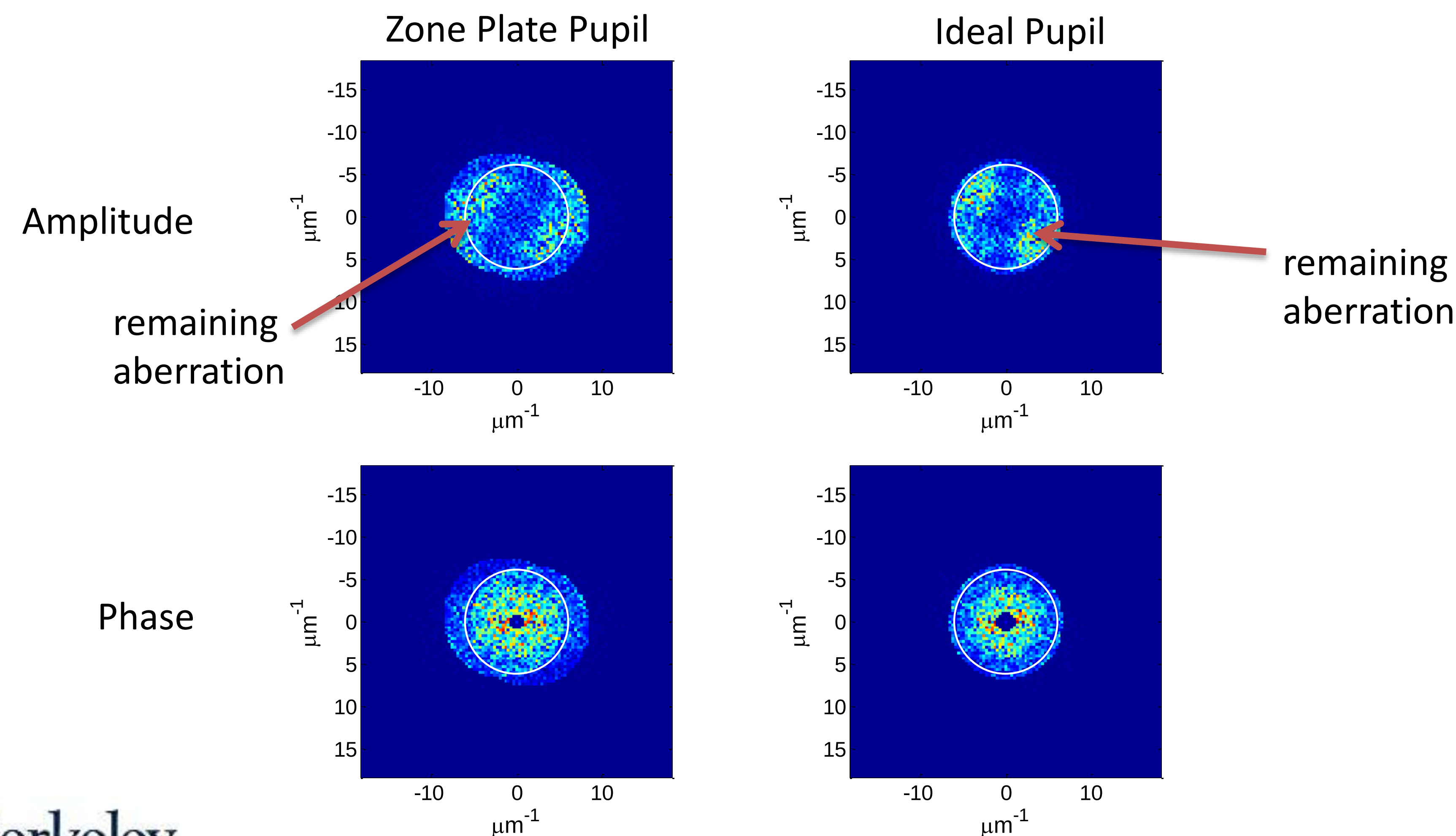
# Uncorrected Aberrations Affect the Object

**Recovered Object:**



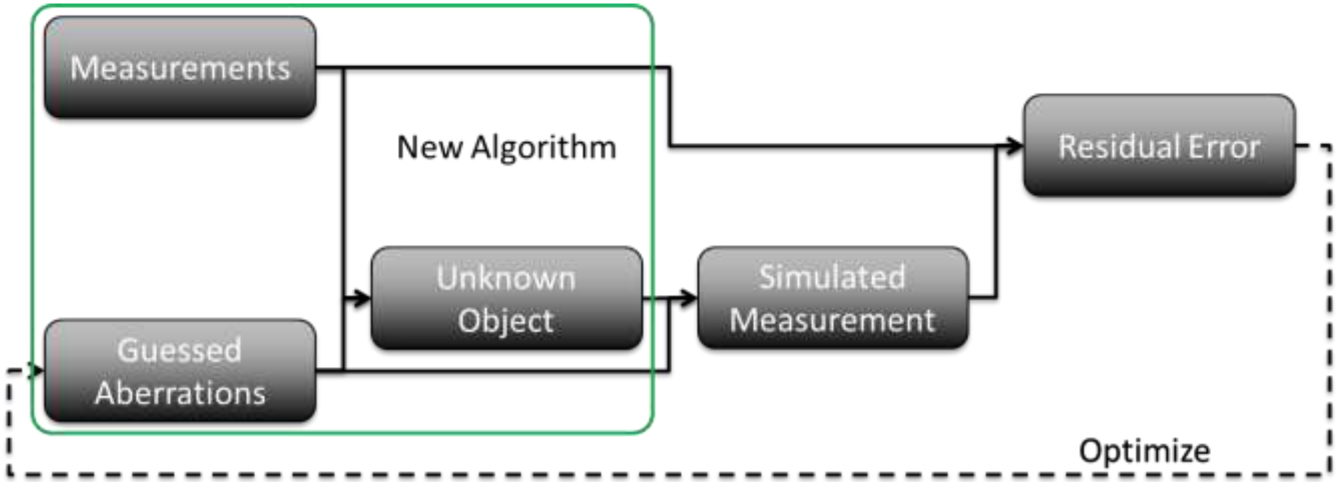
# Uncorrected Aberrations Affect the Object

**Recovered Object:**



# Conclusion

- Presented new algorithm to measure aberrations
  - Unknown test object (ex: EUV mask roughness)
  - Use partial coherence to improve sensitivity
- Used a physical model for the zone plate on SHARP
  - Removed zone plate aberrations
  - Recovered field from aberrated images



# Acknowledgement

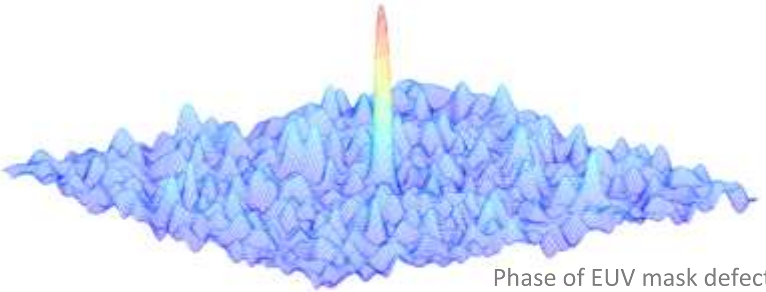
IMPACT+
integrated modeling process and computation for technology

CXRO
THE CENTER FOR X-RAY OPTICS

BERKELEY LAB

Berkeley
UNIVERSITY OF CALIFORNIA

SPIE. ADVANCED LITHOGRAPHY

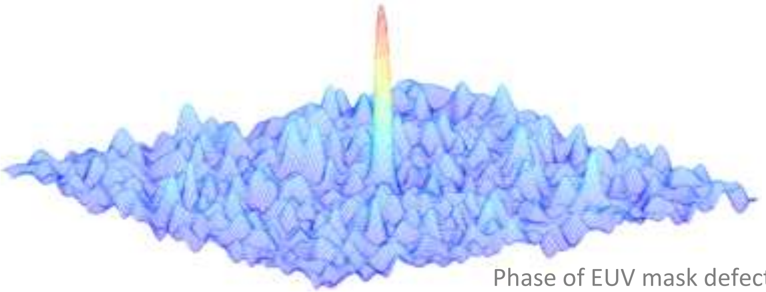


Phase of EUV mask defect

# Thank you for your attention!

**reneclaus@gmail.com**

Berkeley
UNIVERSITY OF CALIFORNIA


Phase of EUV mask defect

# Questions?

**reneclaus@gmail.com**