EUV High-NA Wavefront Sensing

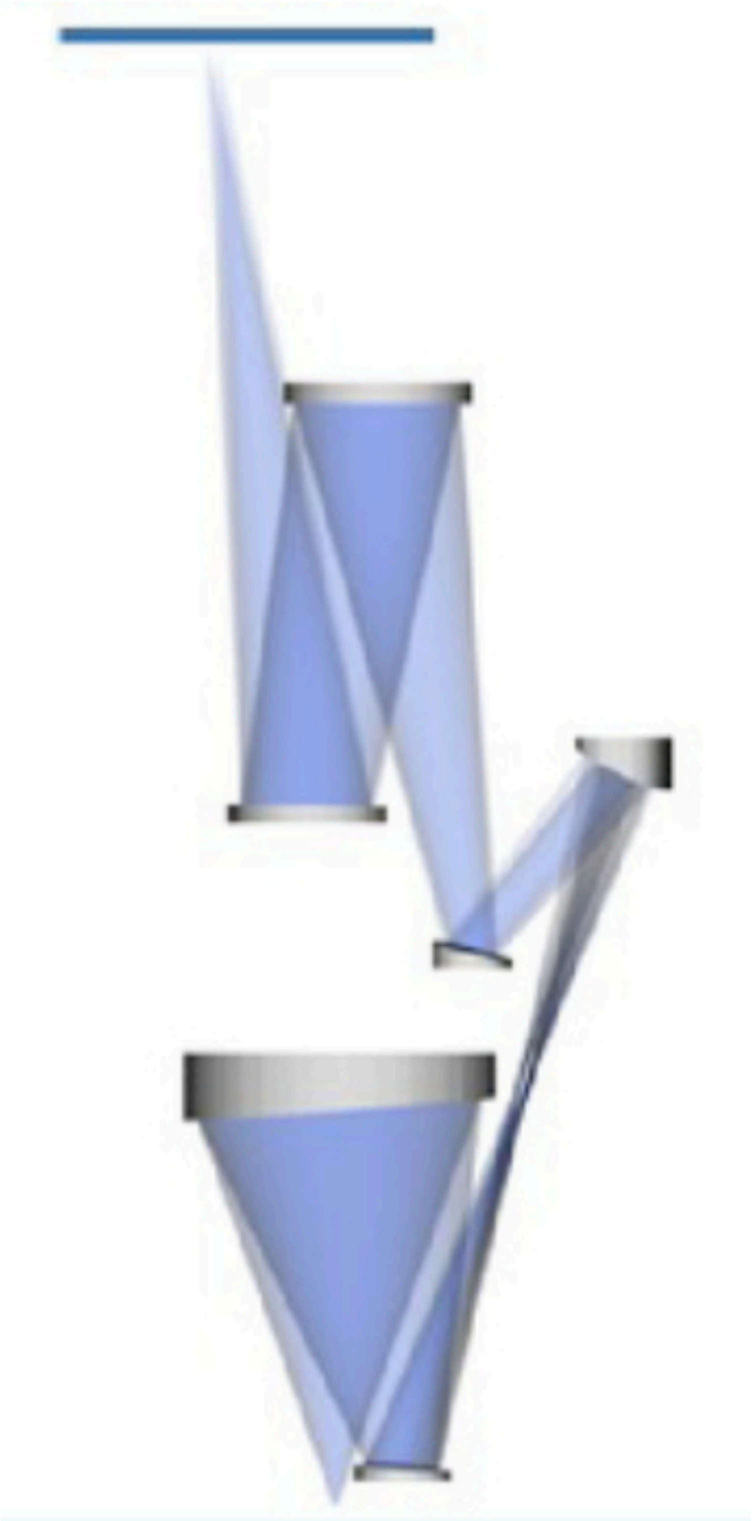
Ryan Miyakawa, Chris Anderson, Wenhua Zhu, Geoff Gaines, Carl Cork, Jeff Gamsby, Gideon Jones, Michael Dickenson, Daniel Zehm, Brandon Volmer, Seno Rekawa, and Patrick Naulleau

CXRO
THE CENTER FOR X-RAY OPTICS

1st GEN EUV

NA: 0.33

(ISOMORPHIC)



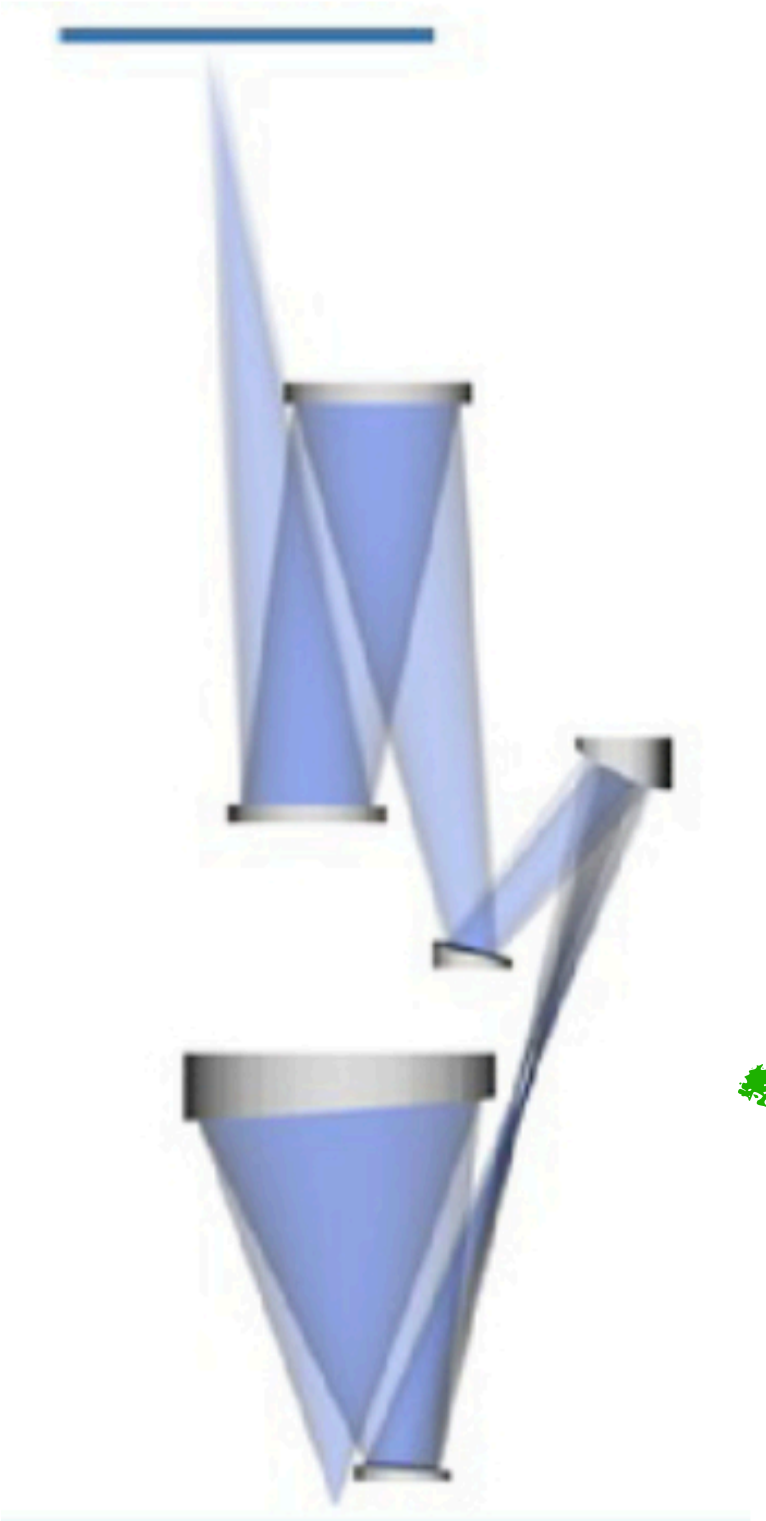
Sascha Migura et al.,Proc. SPIE 9661, 31st European Mask and Lithography Conference, 96610T (4 September 2015);

1st GEN EUV

2nd GEN EUV

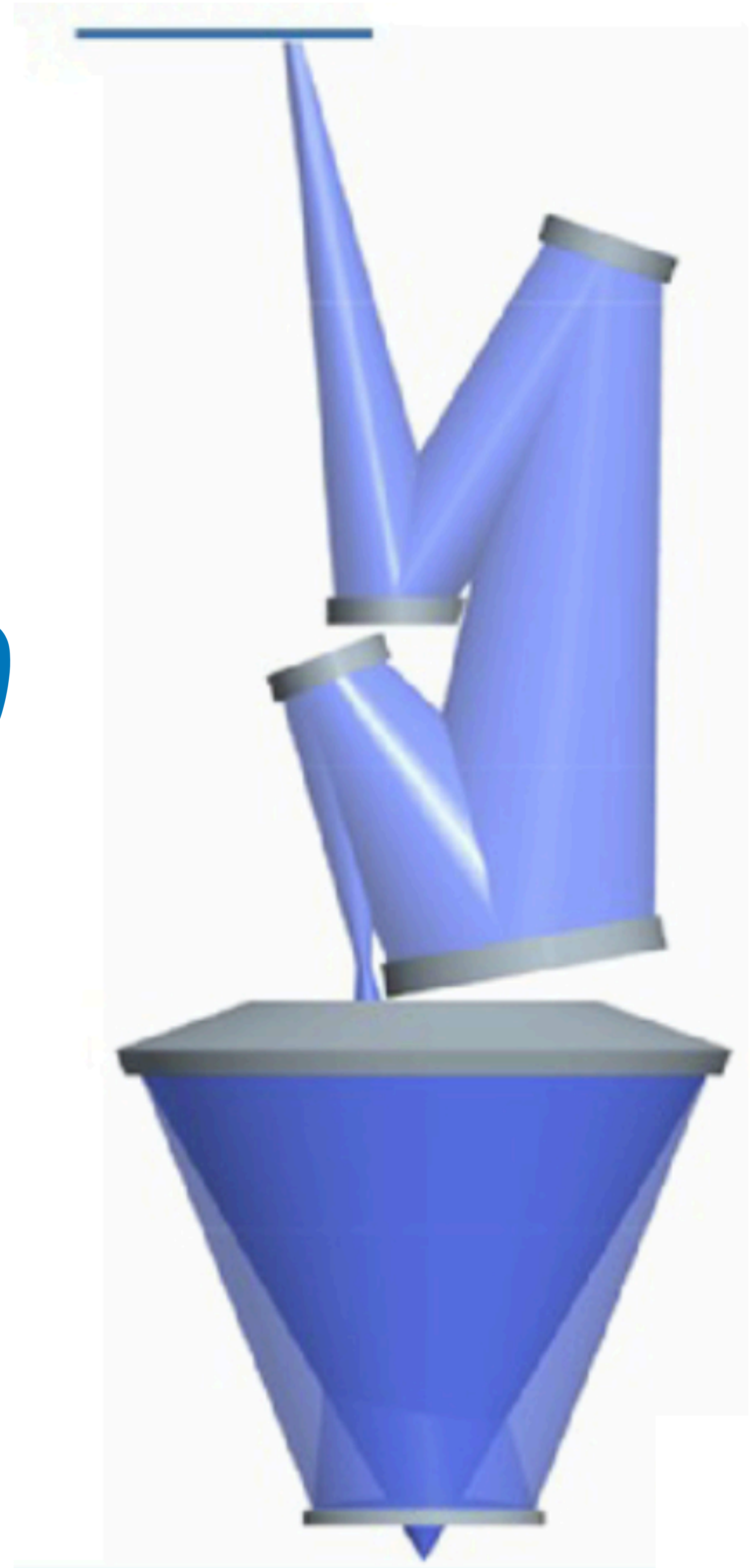
NA: 0.33

(ISOMORPHIC)



NA: 0.55

(ANAMORPHIC)



Sascha Migura et al.,Proc. SPIE 9661, 31st European Mask and Lithography Conference, 96610T (4 September 2015);

CXRO EUV Program Overview

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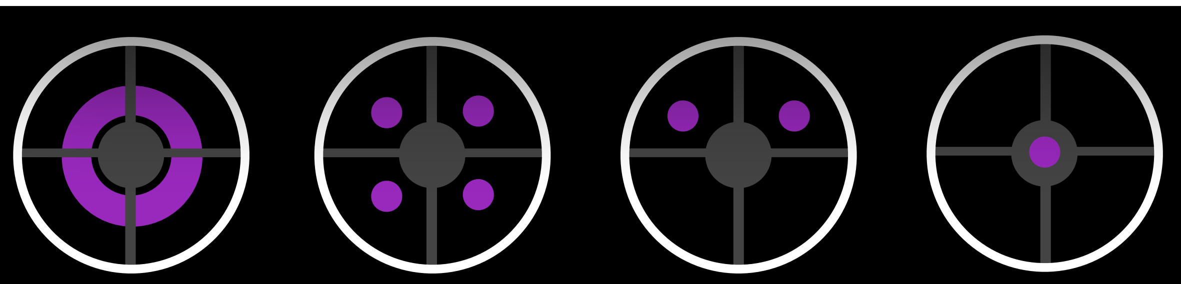
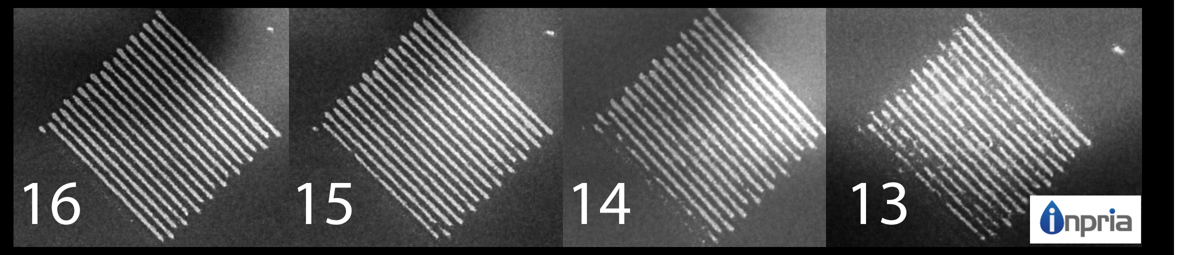
EUV Lithography tools



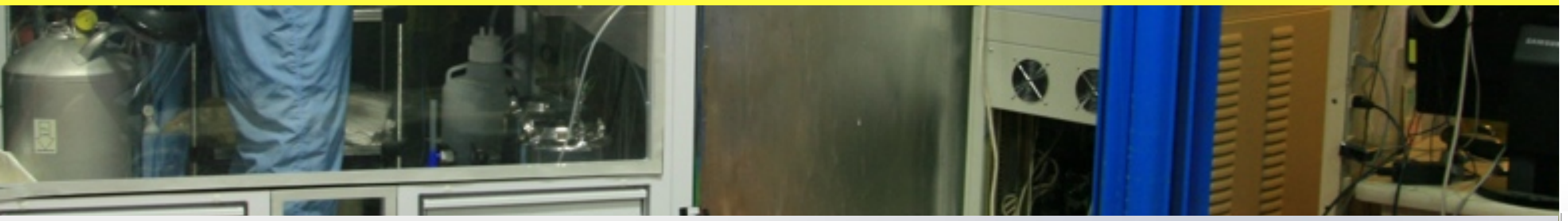
Engineered coherence

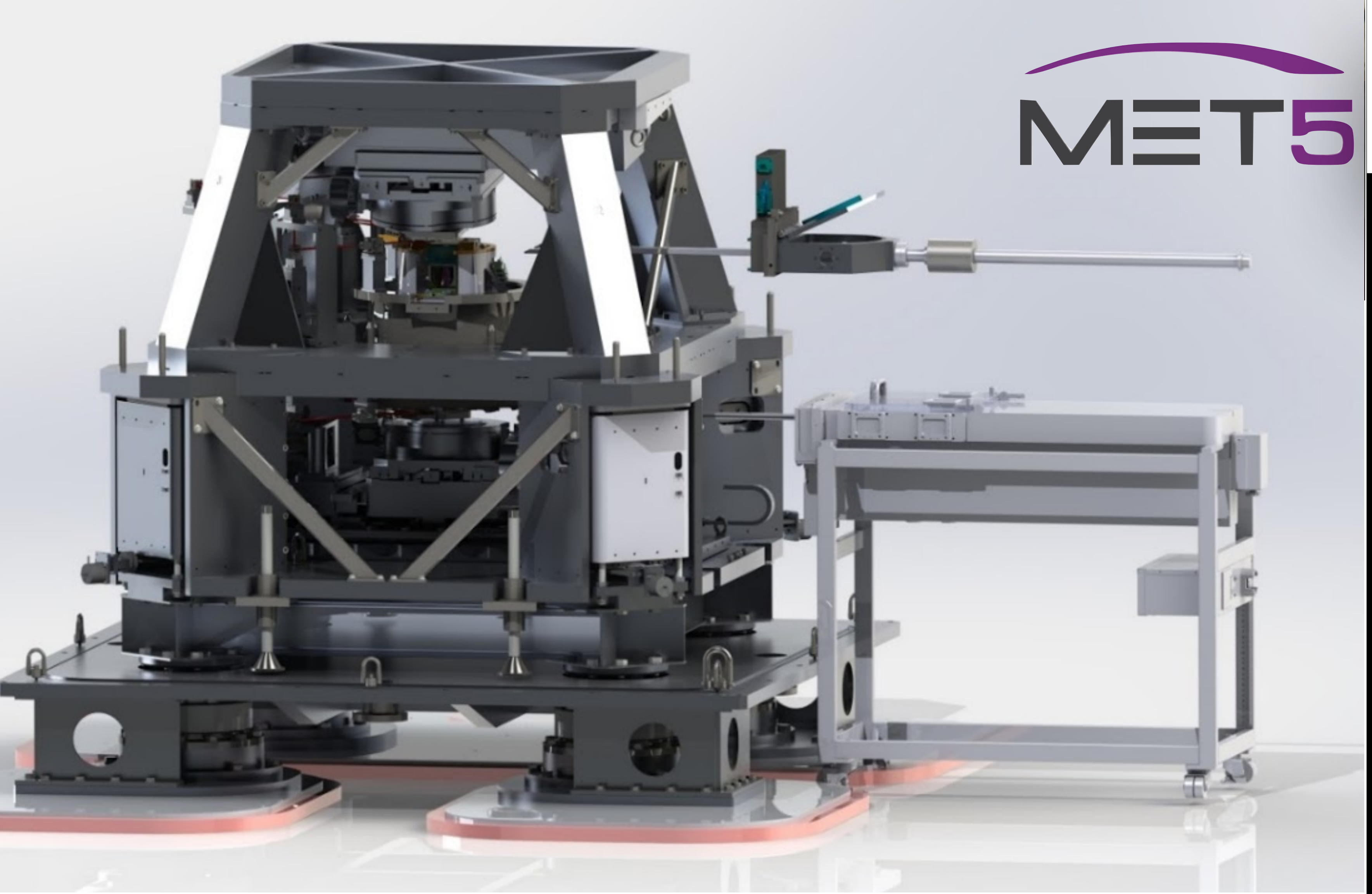
Demonstration of 15-nm half-pitch

Naulleau, et. al. EUVLS 2010



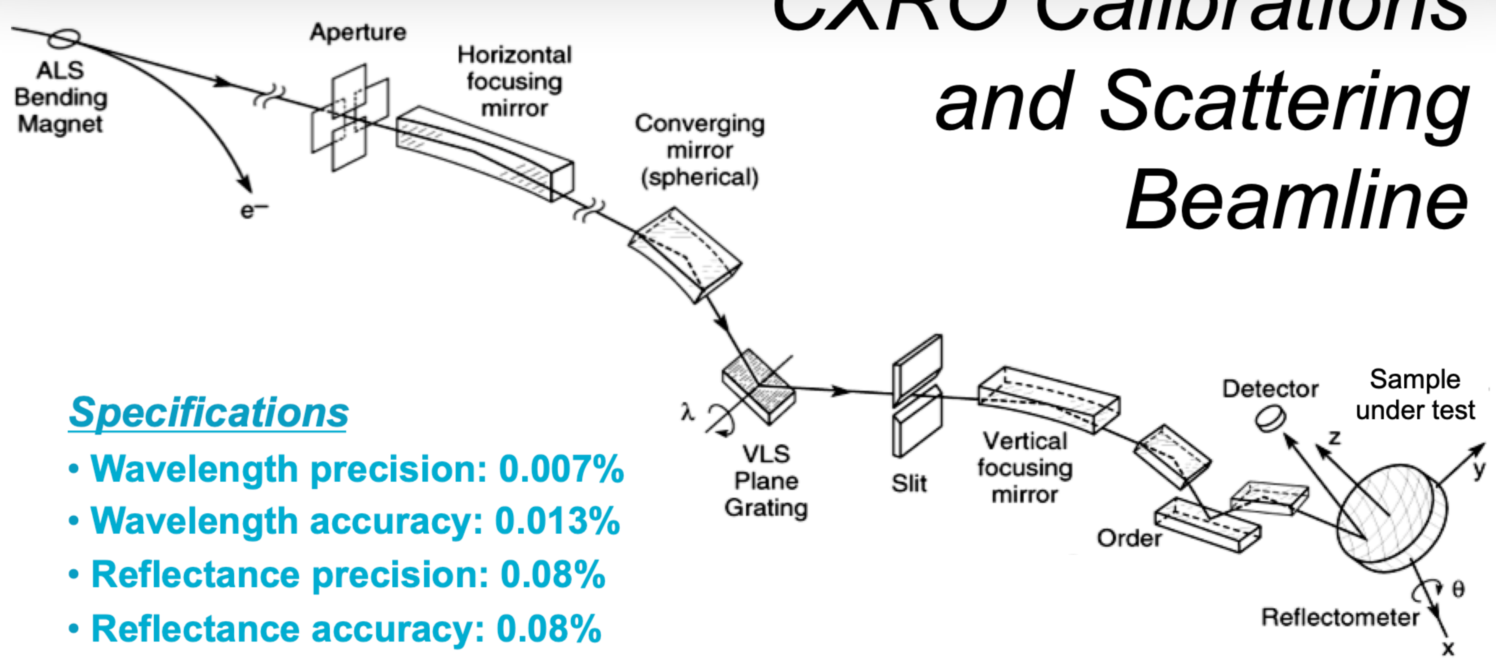
11,400 resist + UL + dev combinations tested to date.





Scatterometry and coating characterization

CXRO Calibrations and Scattering Beamline



Specifications

- **Wavelength precision: 0.007%**
- **Wavelength accuracy: 0.013%**
- **Reflectance precision: 0.08%**
- **Reflectance accuracy: 0.08%**
- **Spectral purity: 99.98%**
- **Dynamic range: 10^{10}**

EUV Mask Inspection

λ = 13.5 nm

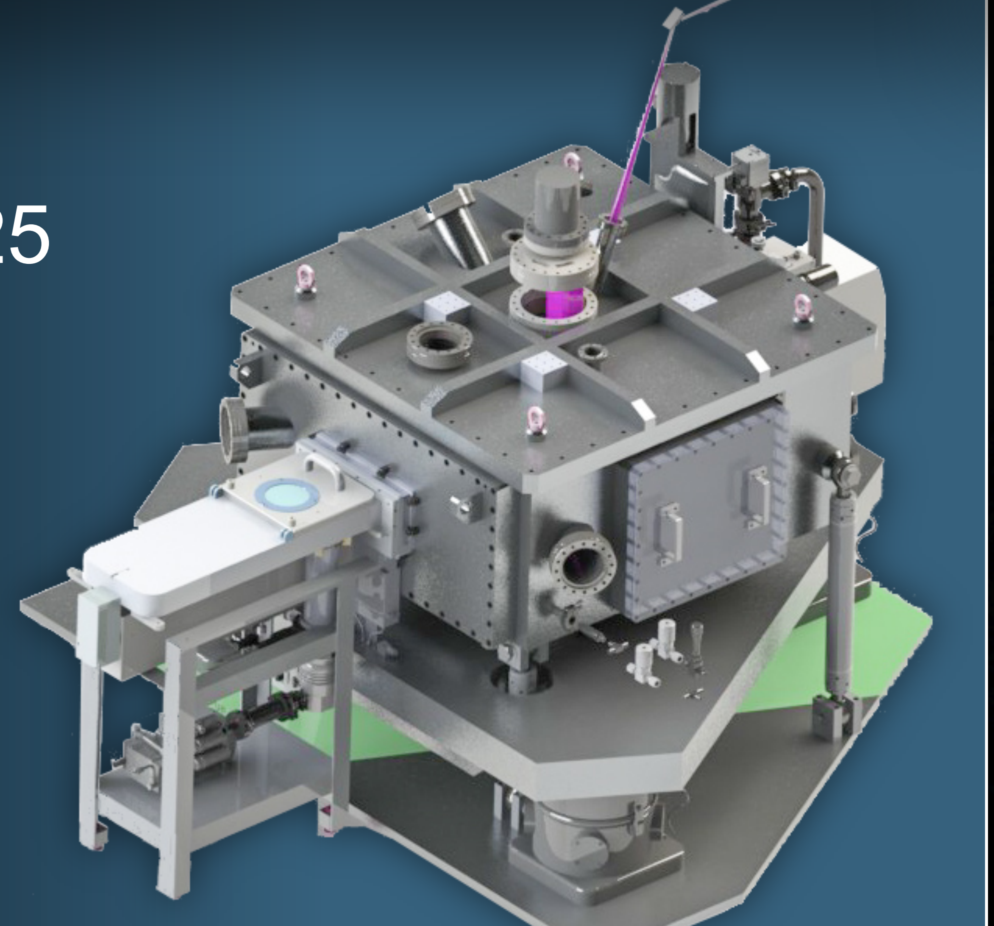
4×NA: 0.25–0.625

Programmable σ

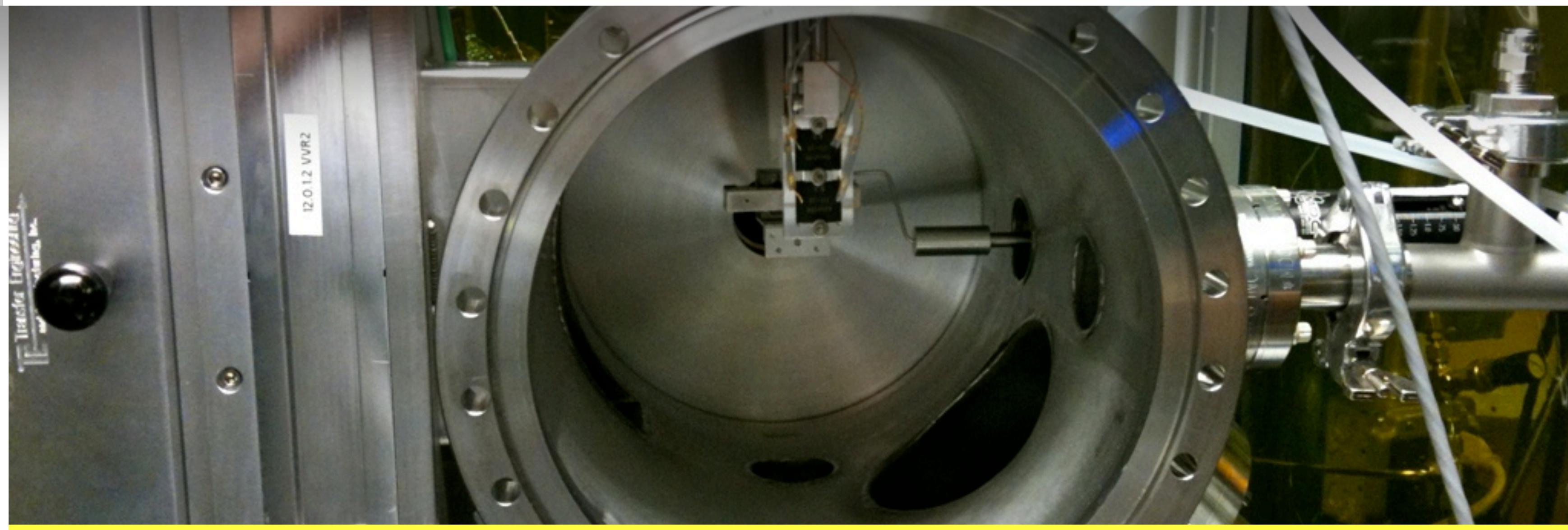
Full-mask Nav

5–10 sec/image

sharp.lbl.gov



Resist characterization



4400 resist + UL + dev combinations tested since 2011

Sensitivity & contrast of EUV resists

Dose Calibration Tool (DCT)

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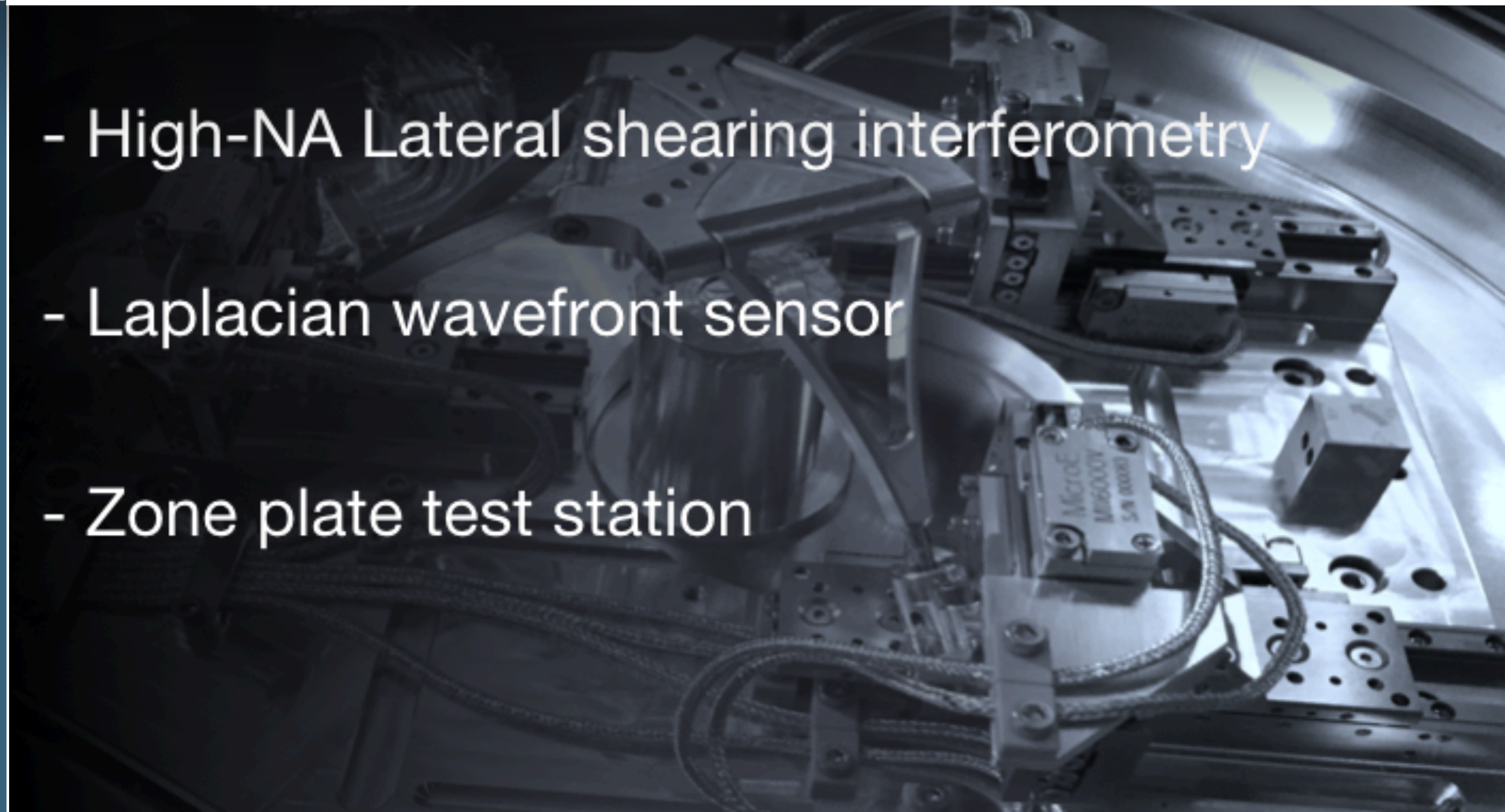
Wavefront sensor development



- High-NA Lateral shearing interferometry
- Laplacian wavefront sensor
- Zone plate test station

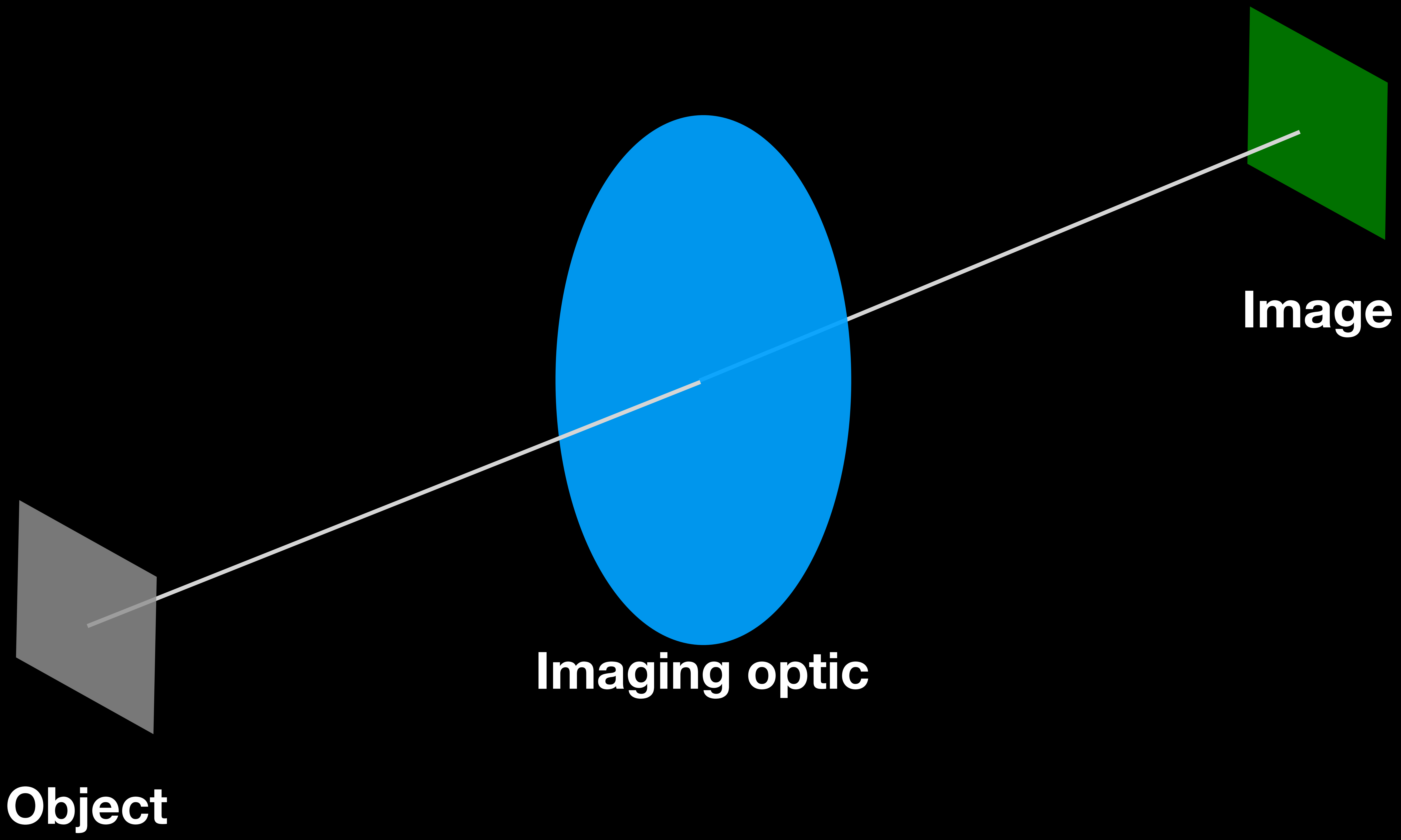
WHY DO WE NEED WAVEFRONT SENSING?

$$d_{\min} \geq k_1 \frac{\lambda}{NA}$$

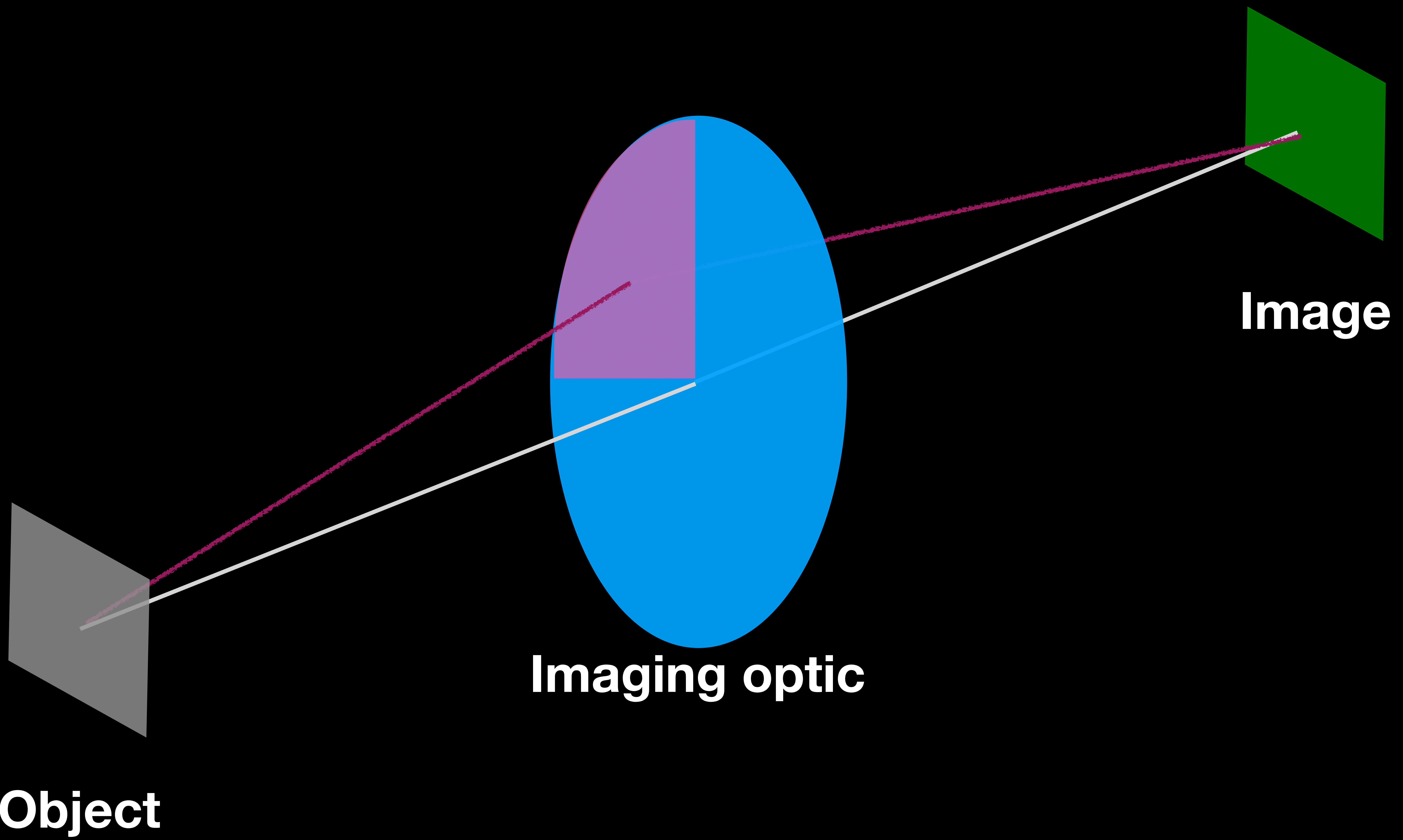
WHY DO WE NEED WAVEFRONT SENSING?

ANSWER: TO CHARACTERIZE AND MINIMIZE ABERRATIONS FOR OPTIMAL IMAGING

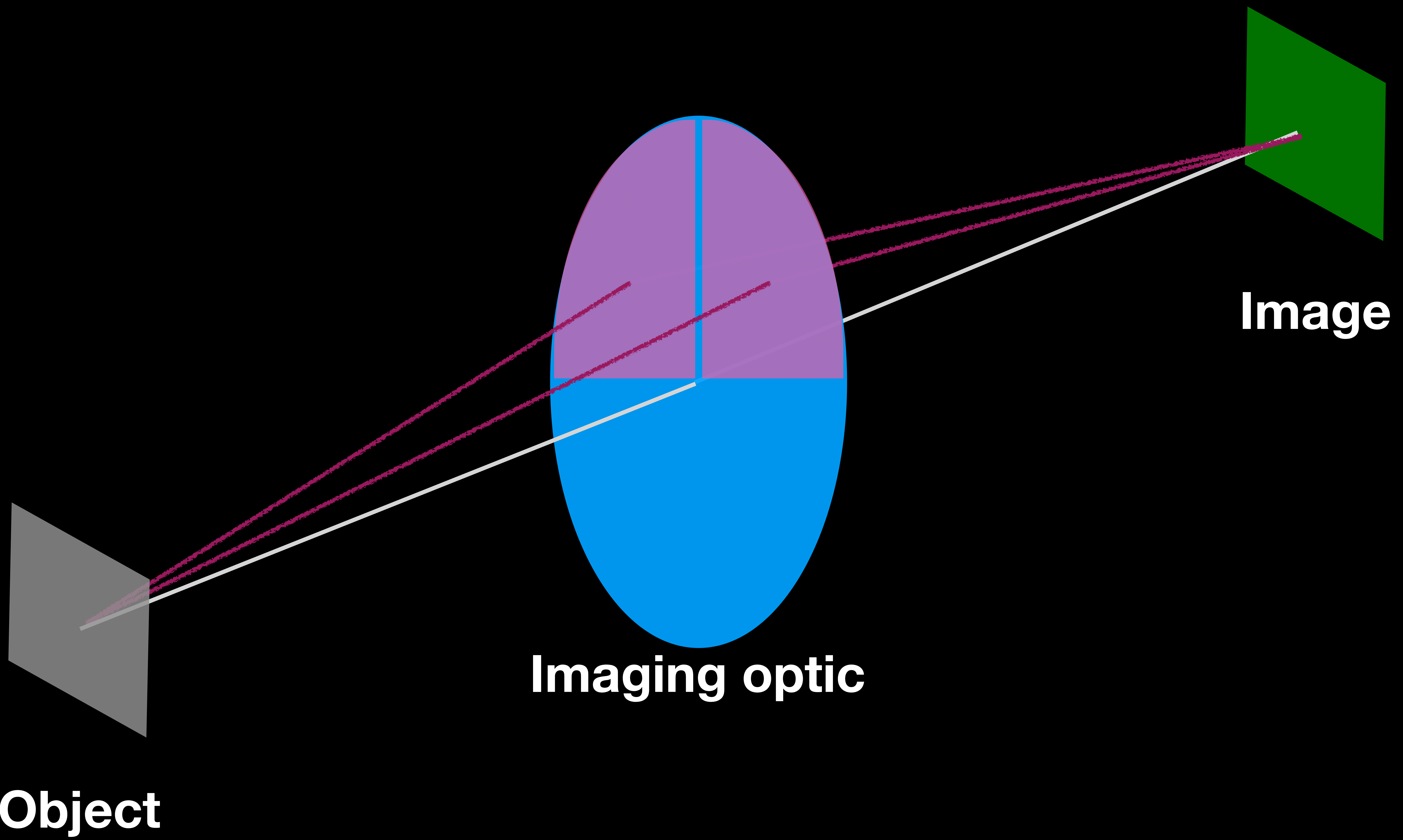
IDEAL OPTICAL SYSTEM



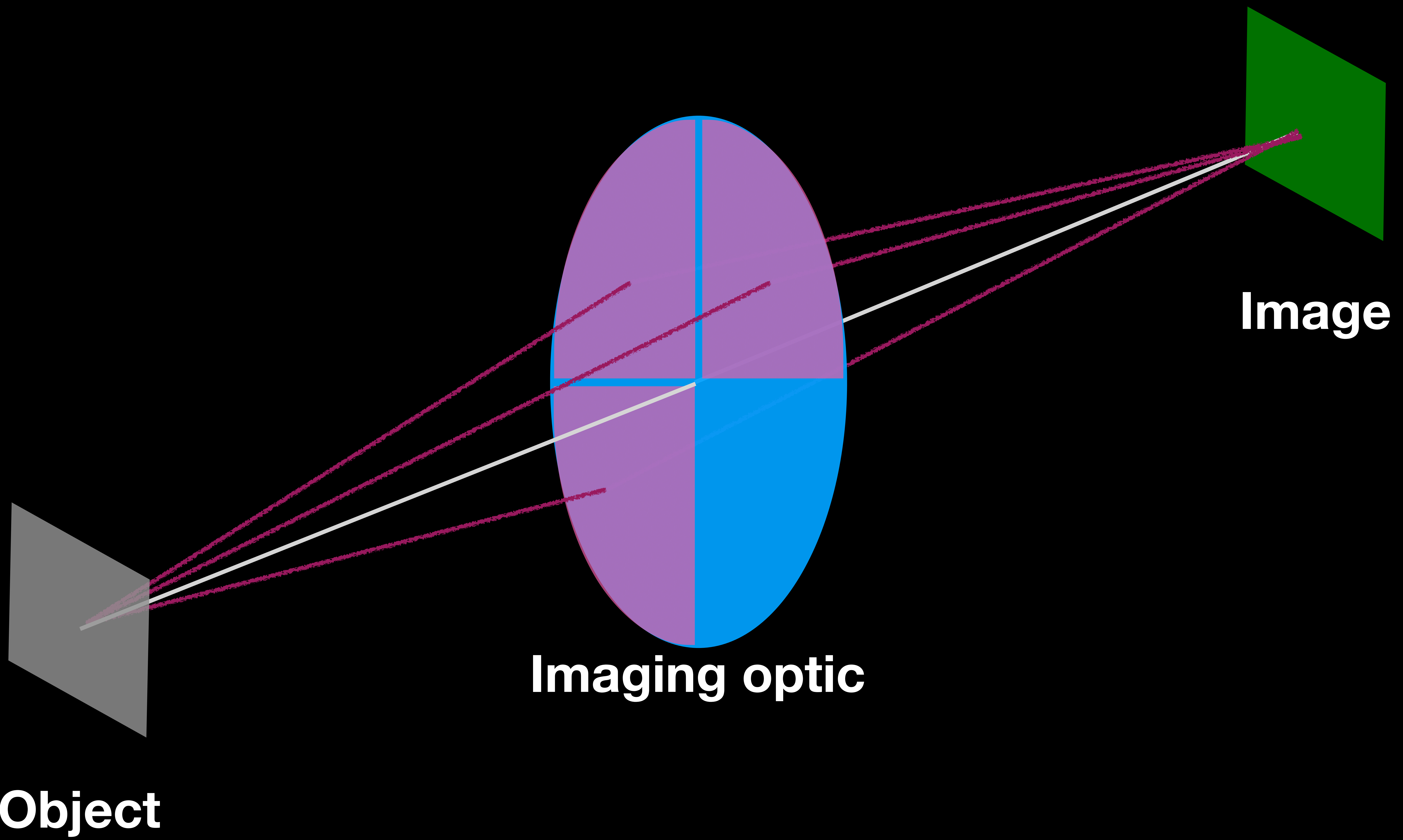
IDEAL OPTICAL SYSTEM



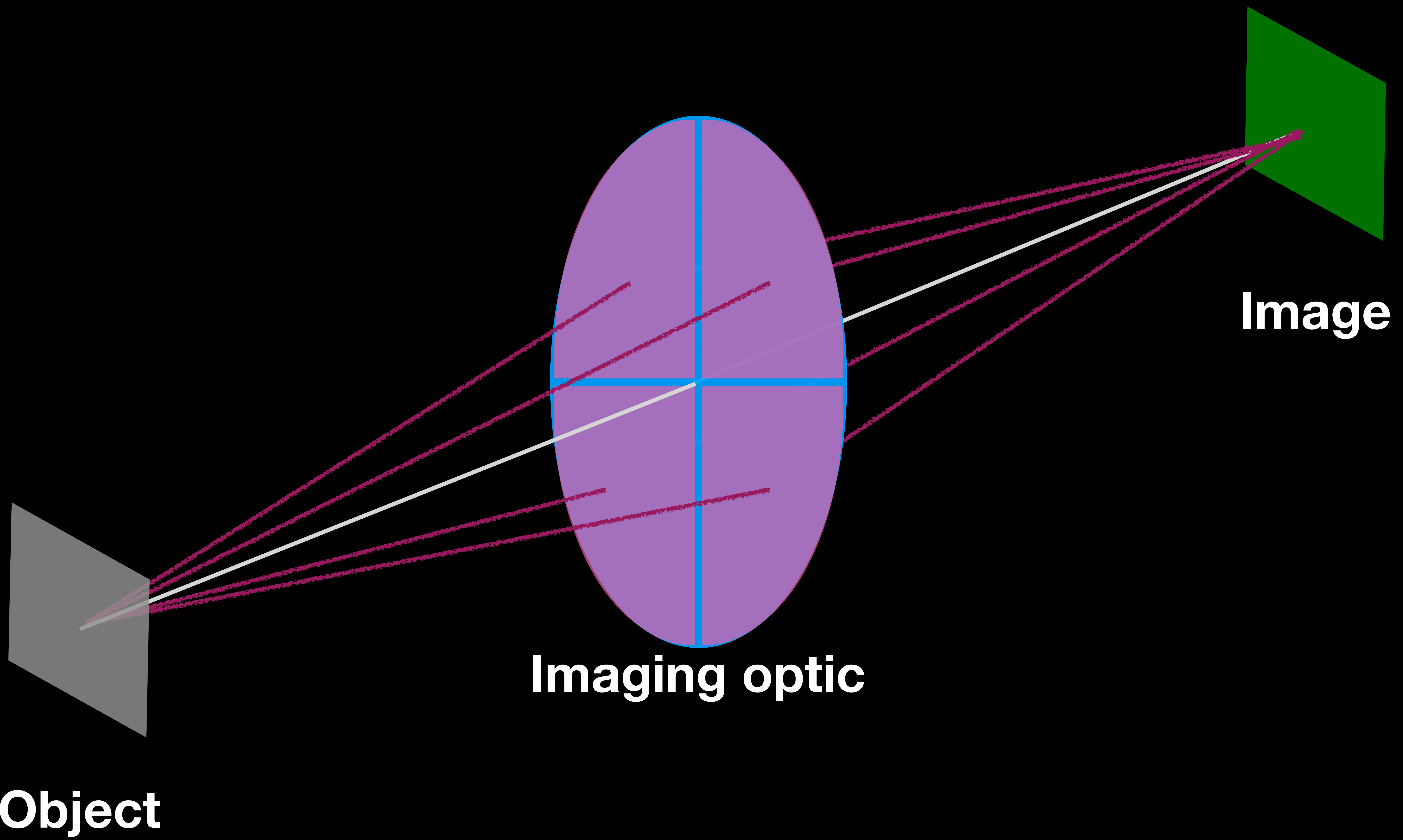
IDEAL OPTICAL SYSTEM



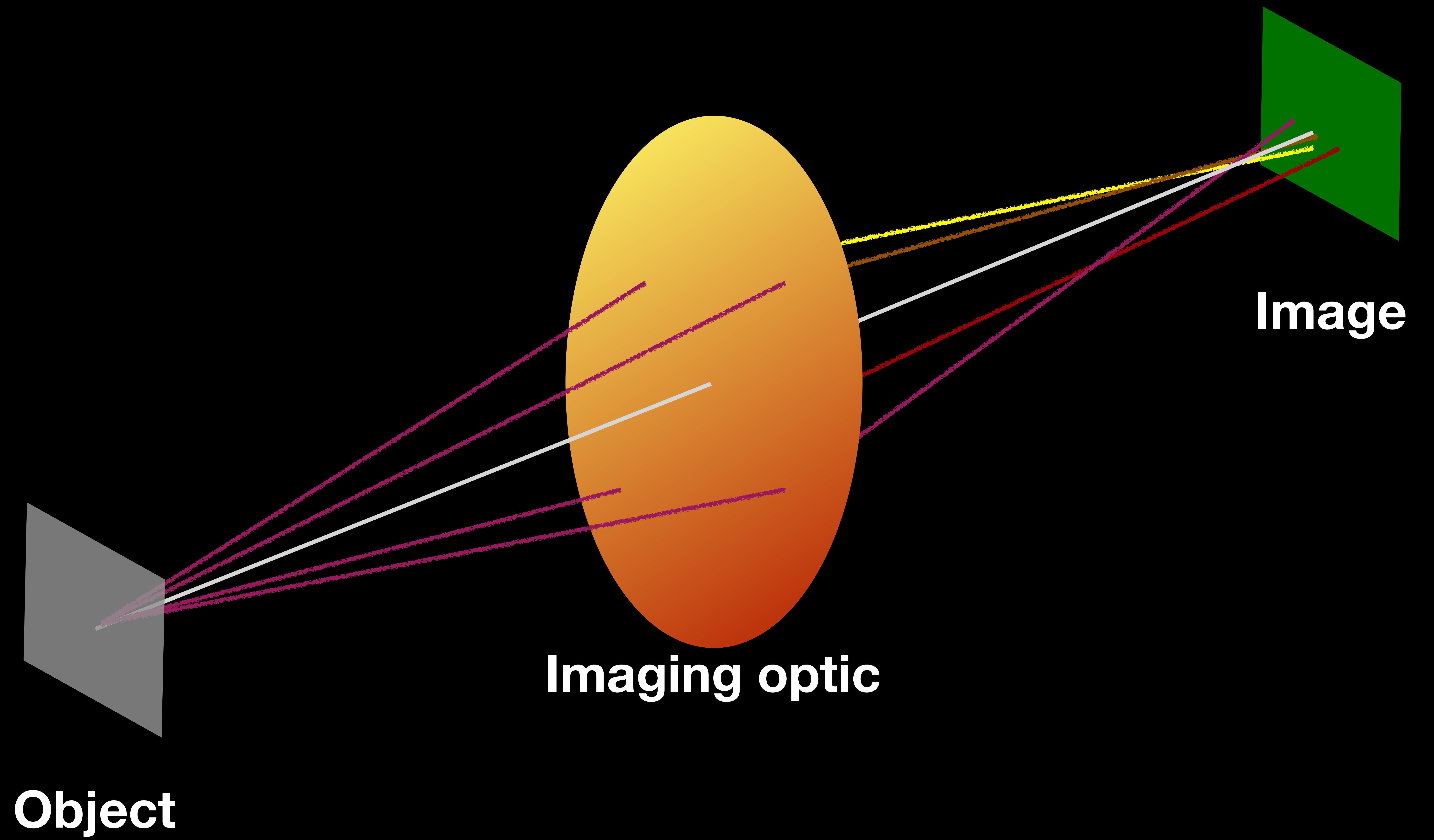
IDEAL OPTICAL SYSTEM



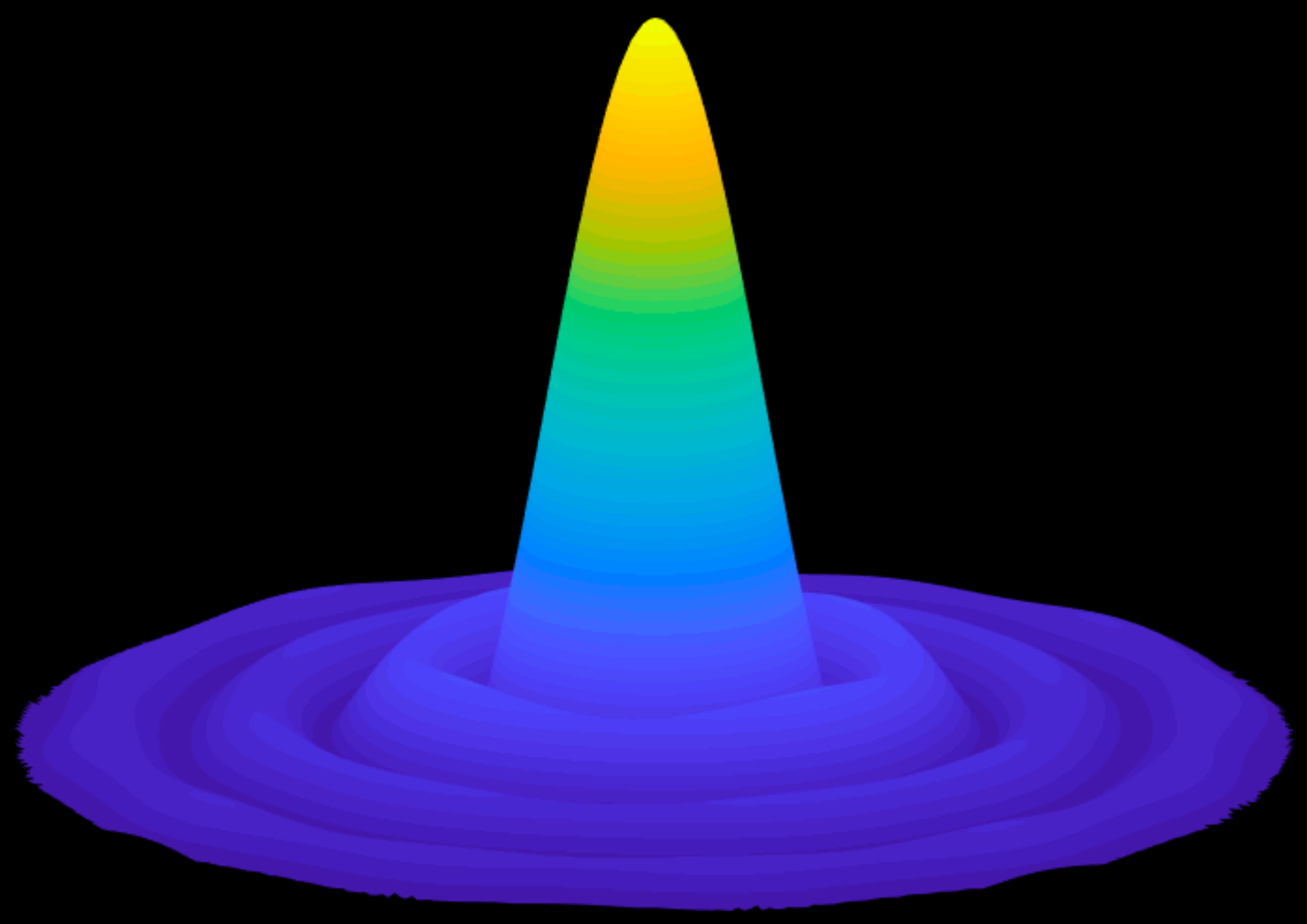
IDEAL OPTICAL SYSTEM



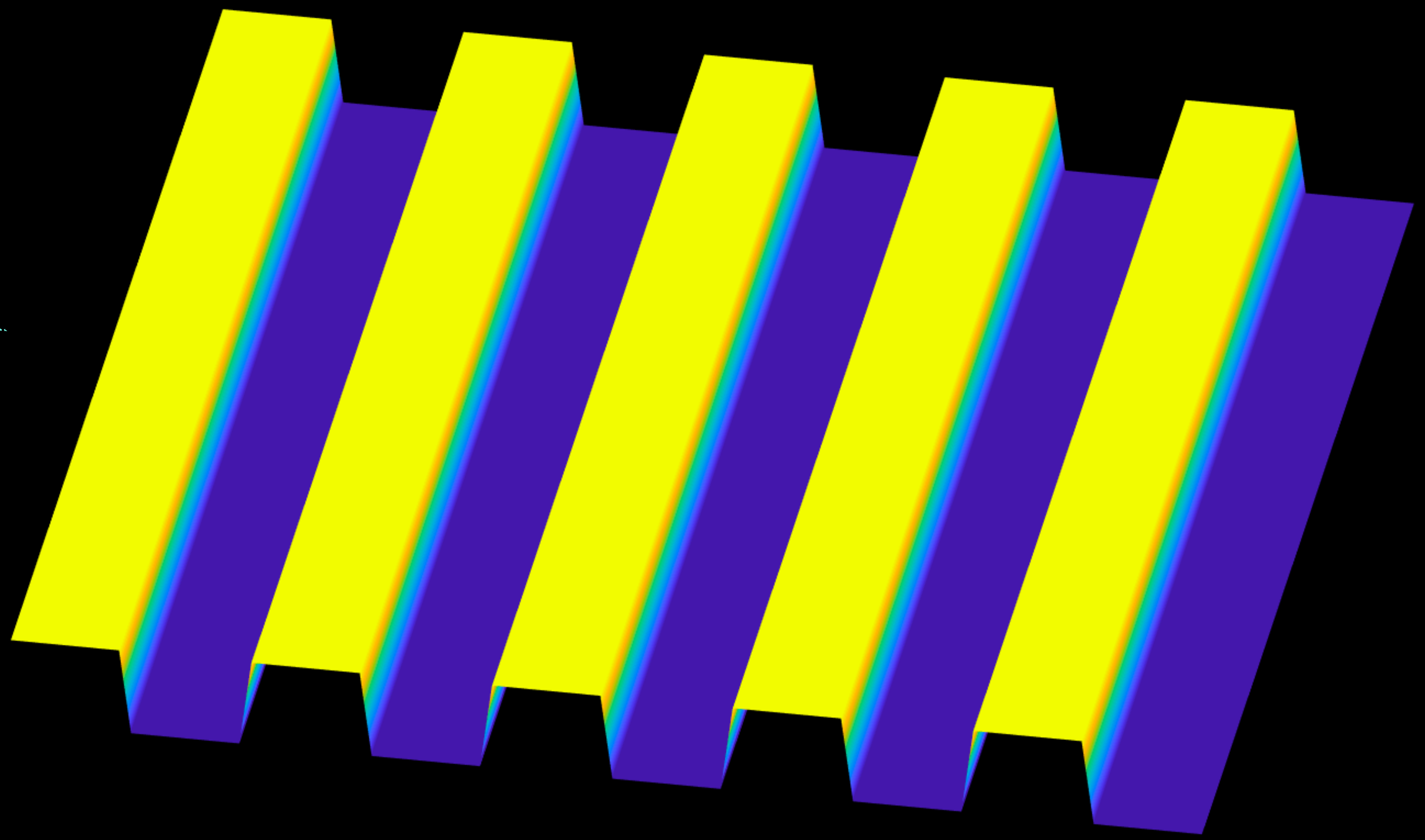
ABERRATED OPTICAL SYSTEM



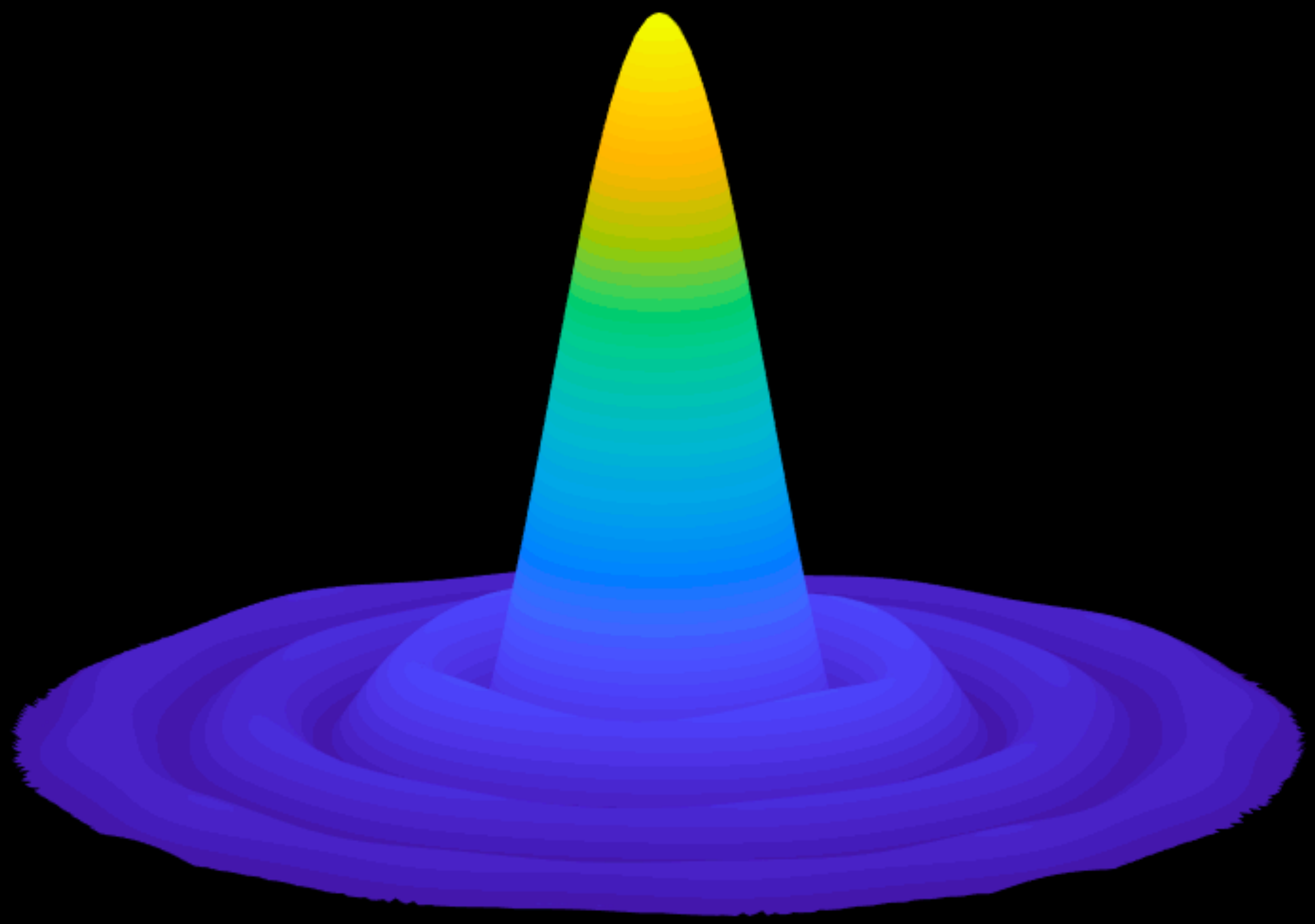
POINT SPREAD FUNCTION (BLUR)

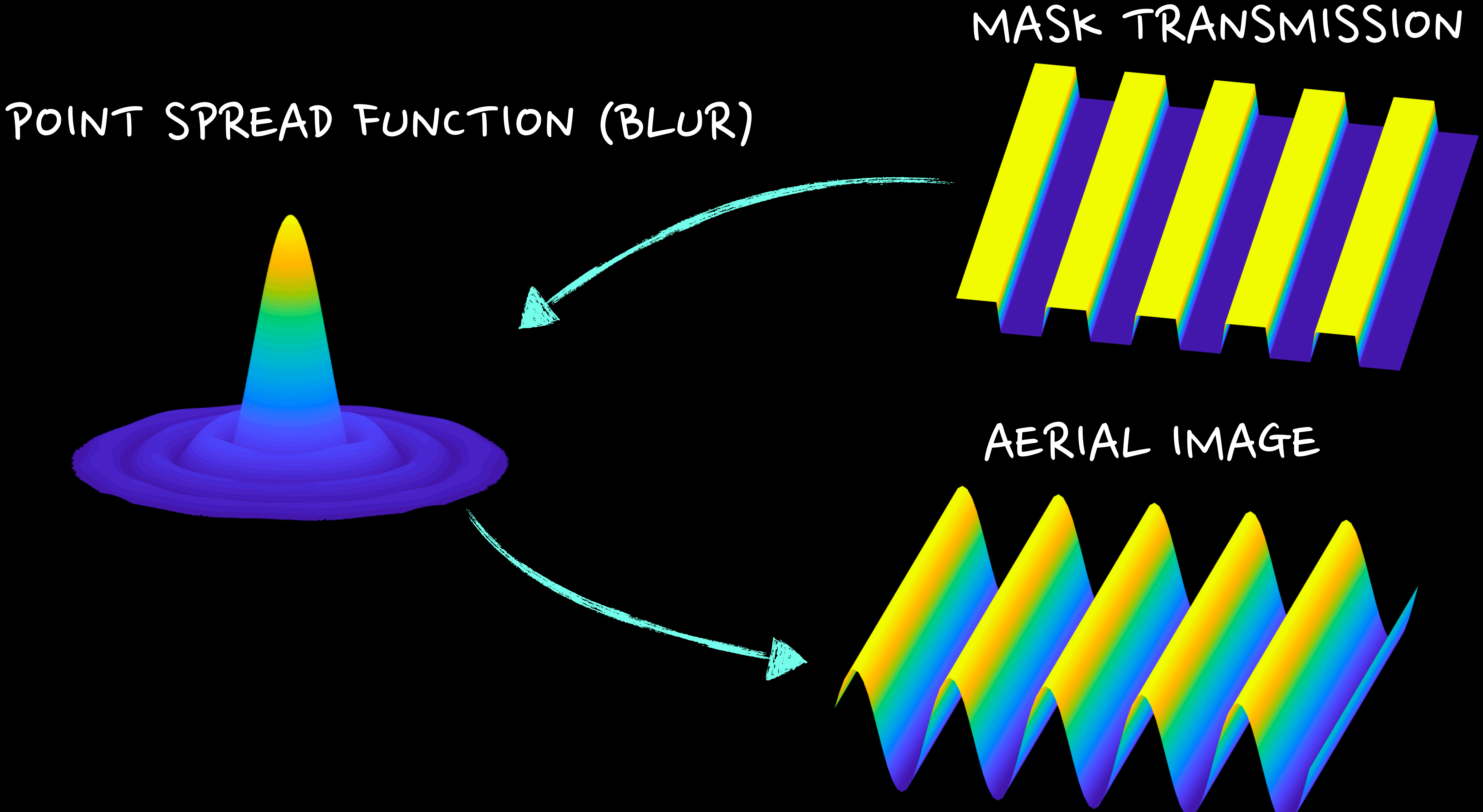


MASK TRANSMISSION

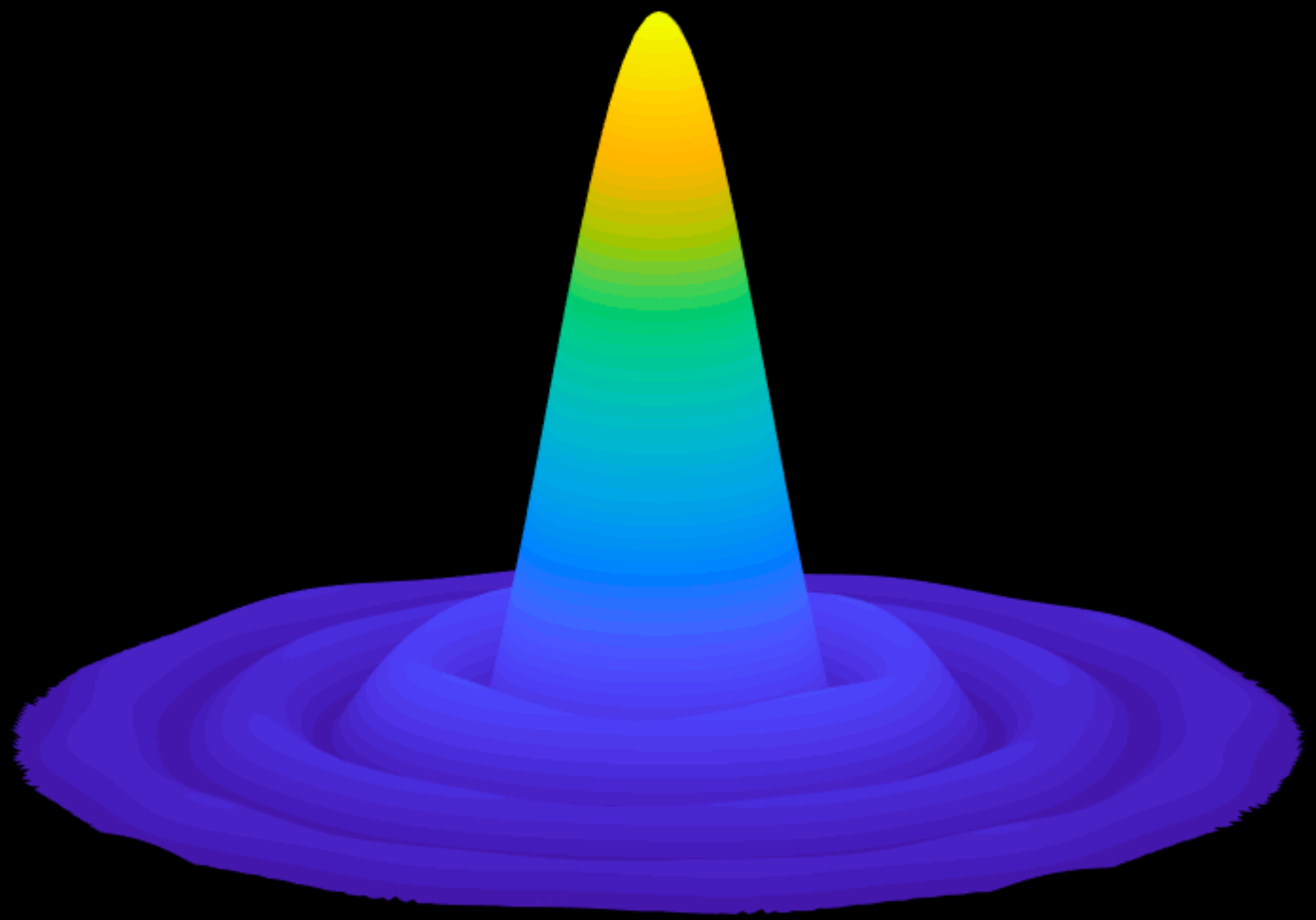


POINT SPREAD FUNCTION (BLUR)



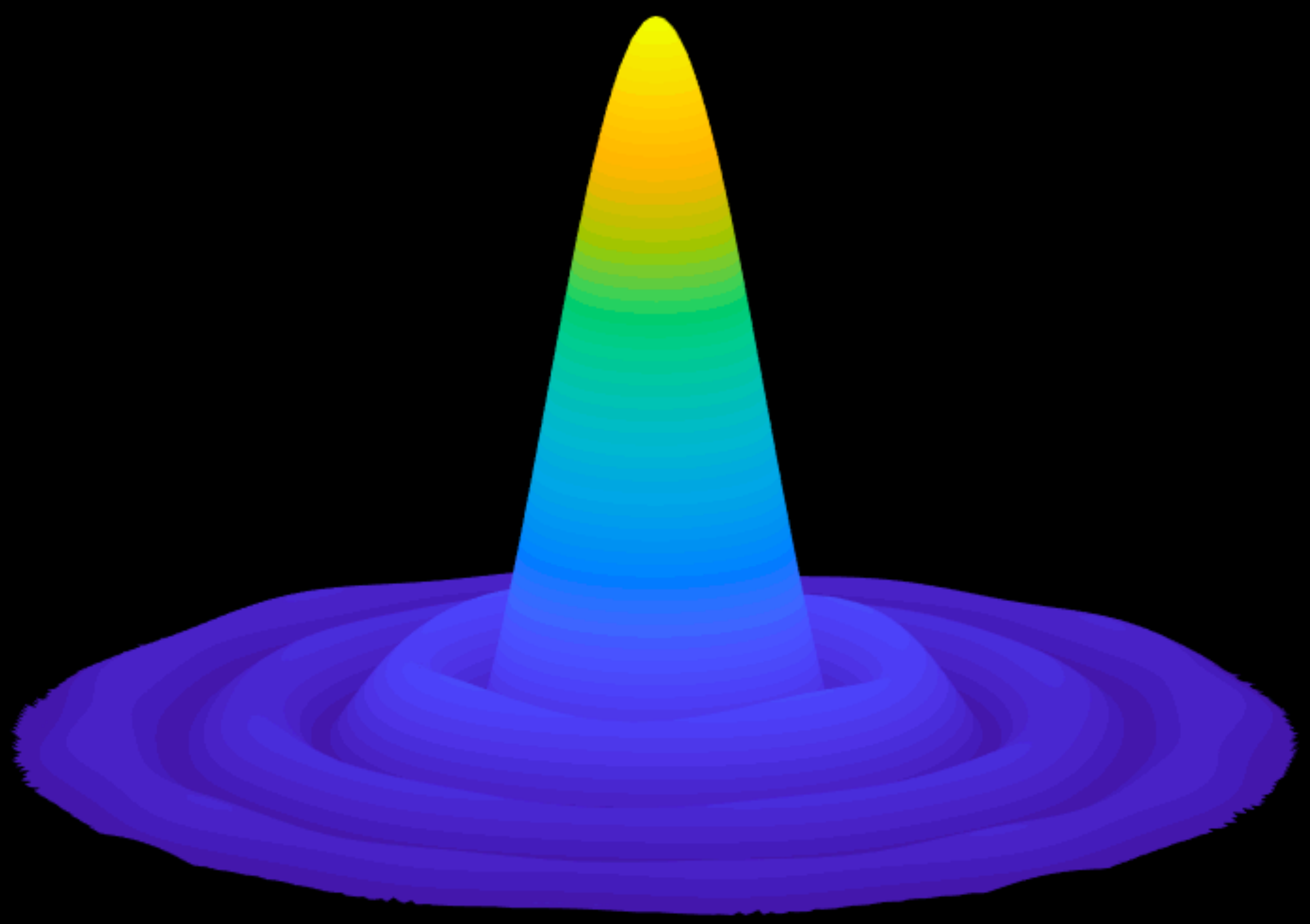

MASK TRANSMISSION
POINT SPREAD FUNCTION (BLUR)
AERIAL IMAGE

DIFFRACTION LIMITED



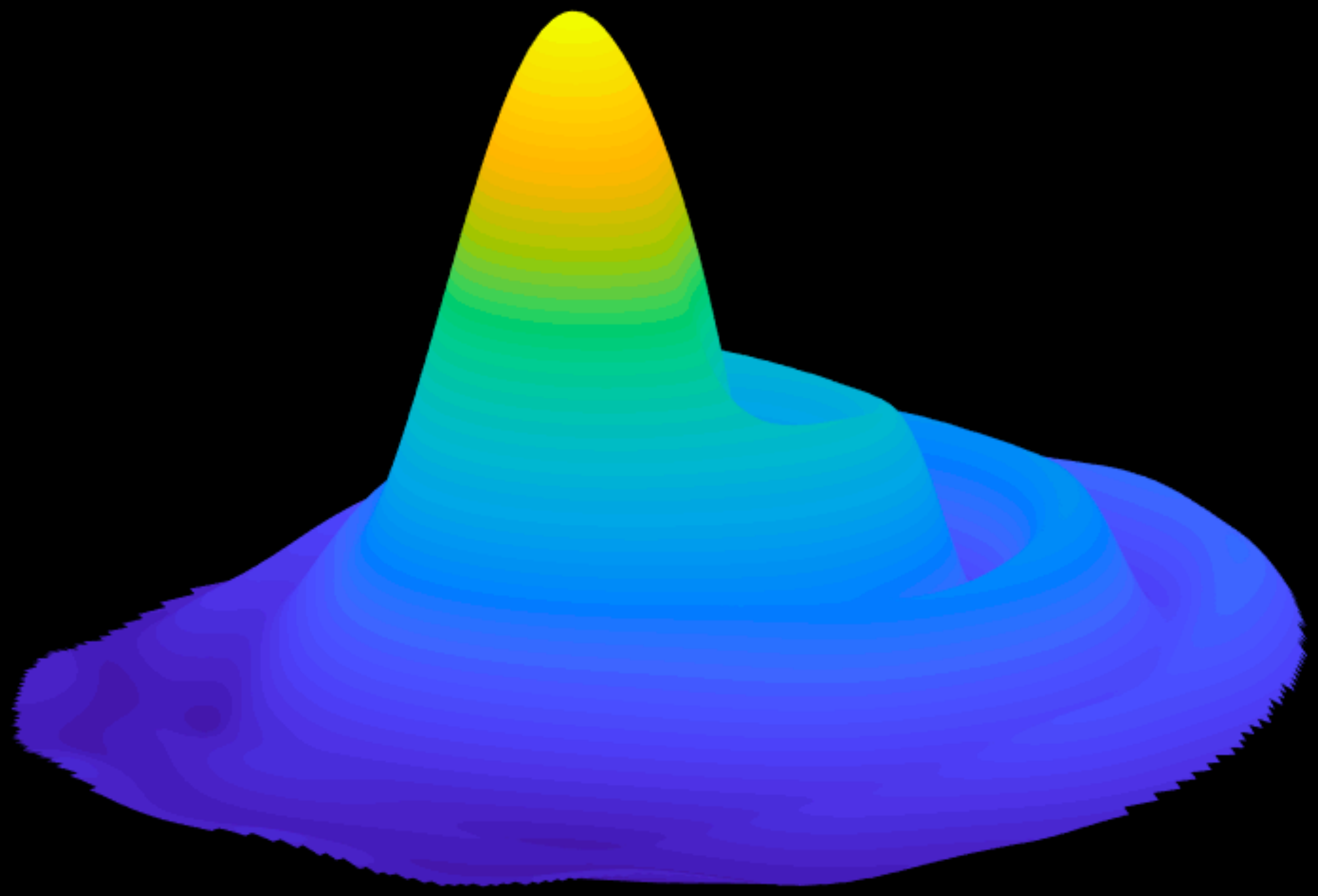
$$d_{\min} = k_1 \frac{\lambda}{NA}$$

DIFFRACTION LIMITED



$$d_{\min} = k_1 \frac{\lambda}{NA}$$

ABERRATION LIMITED



$$d_{\min} \geq k_1 \frac{\lambda}{NA}$$

High-NA EUV wavefront sensos

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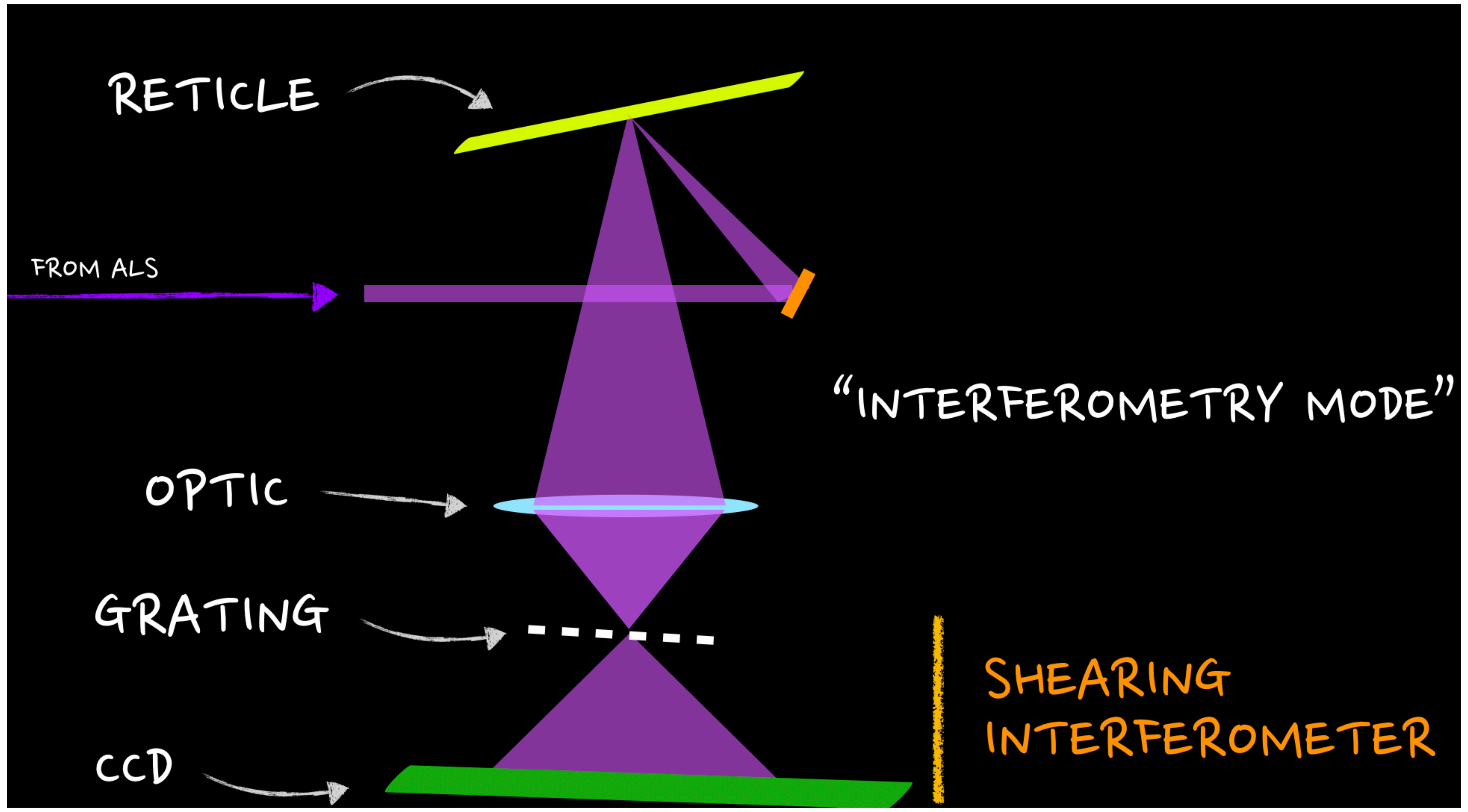
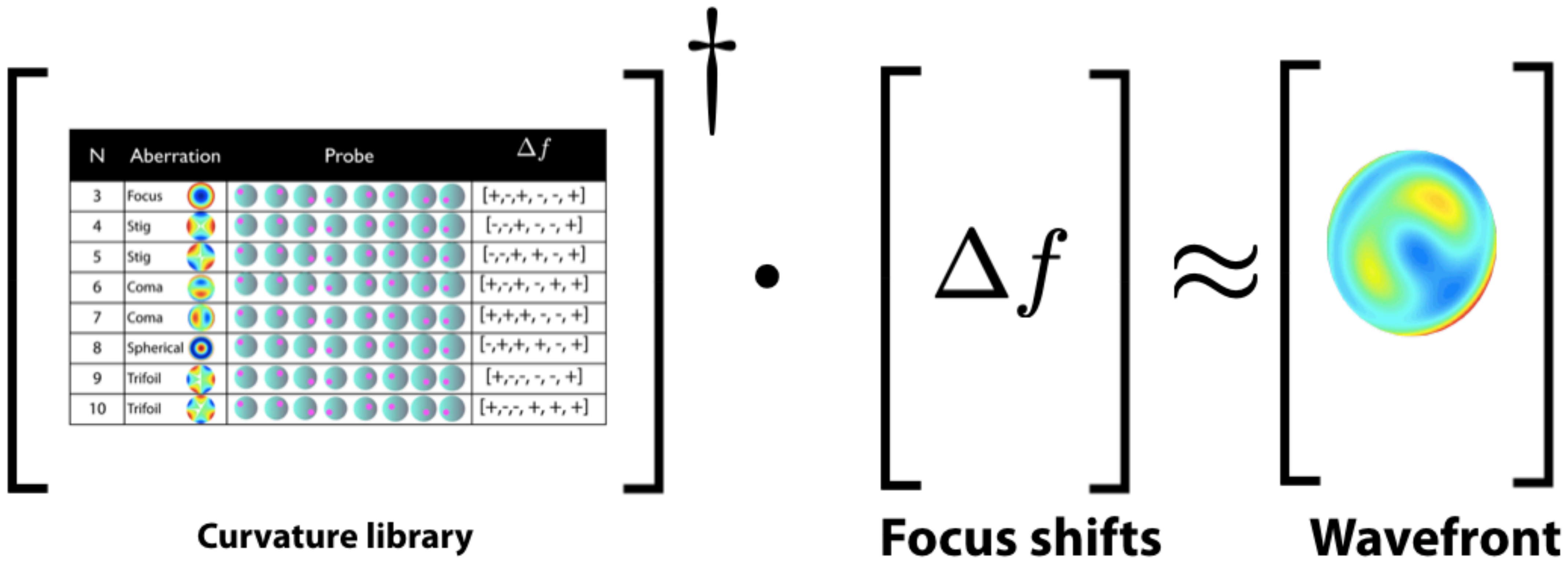
LATERAL SHEARING INTERFEROMETRY (LSI)



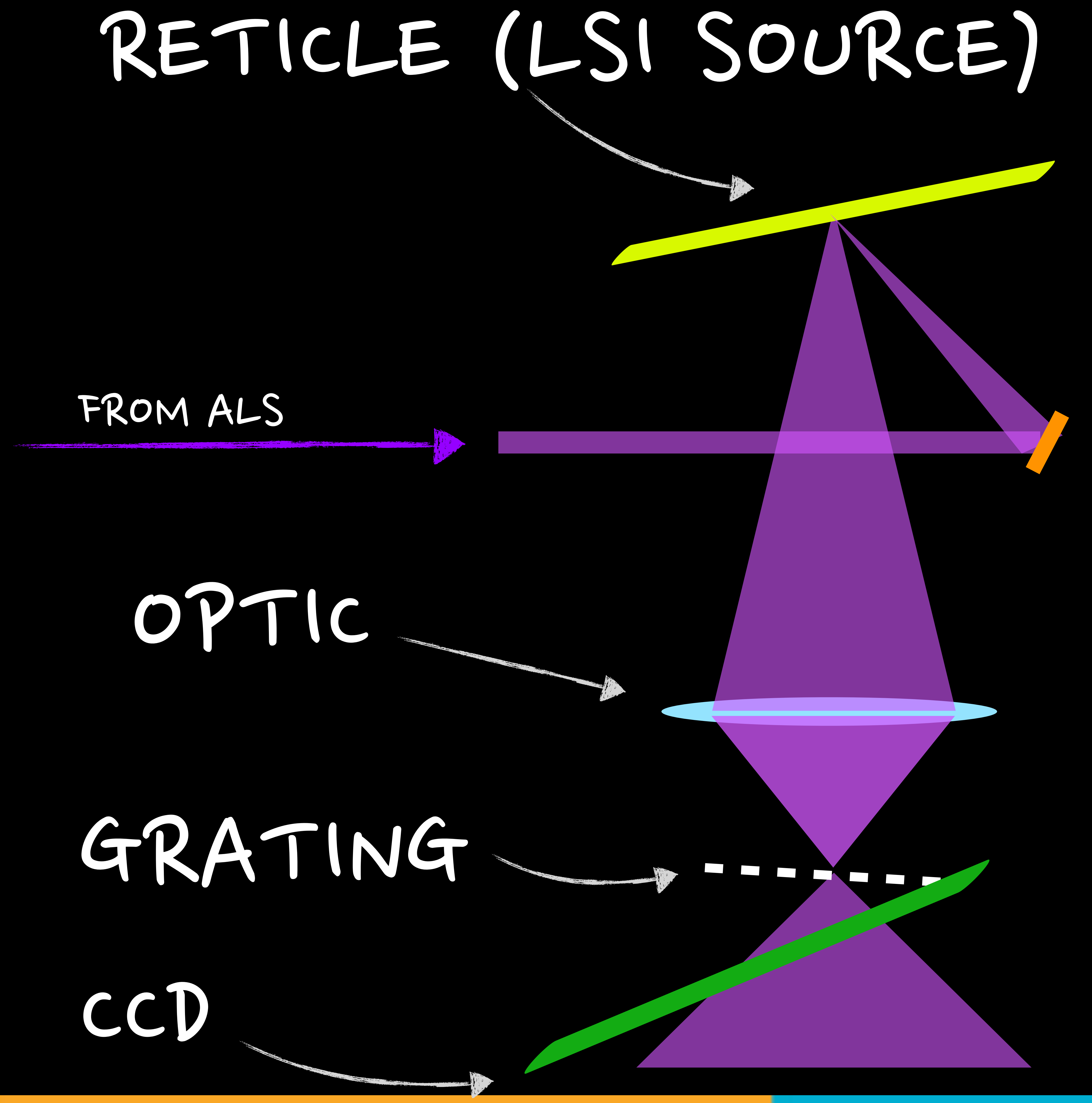
LAPLACIAN WAVEFRONT SENSOR (LWS)



LATERAL SHEARING INTERFEROMETRY

LSI working principle

THE CENTER FOR X-RAY OPTICS



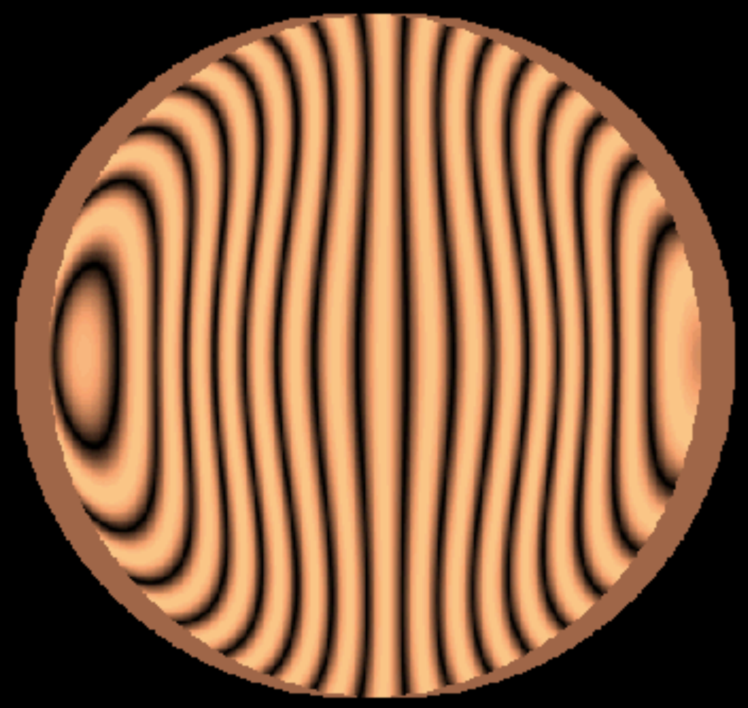
SHEARING INTERFEROMETER

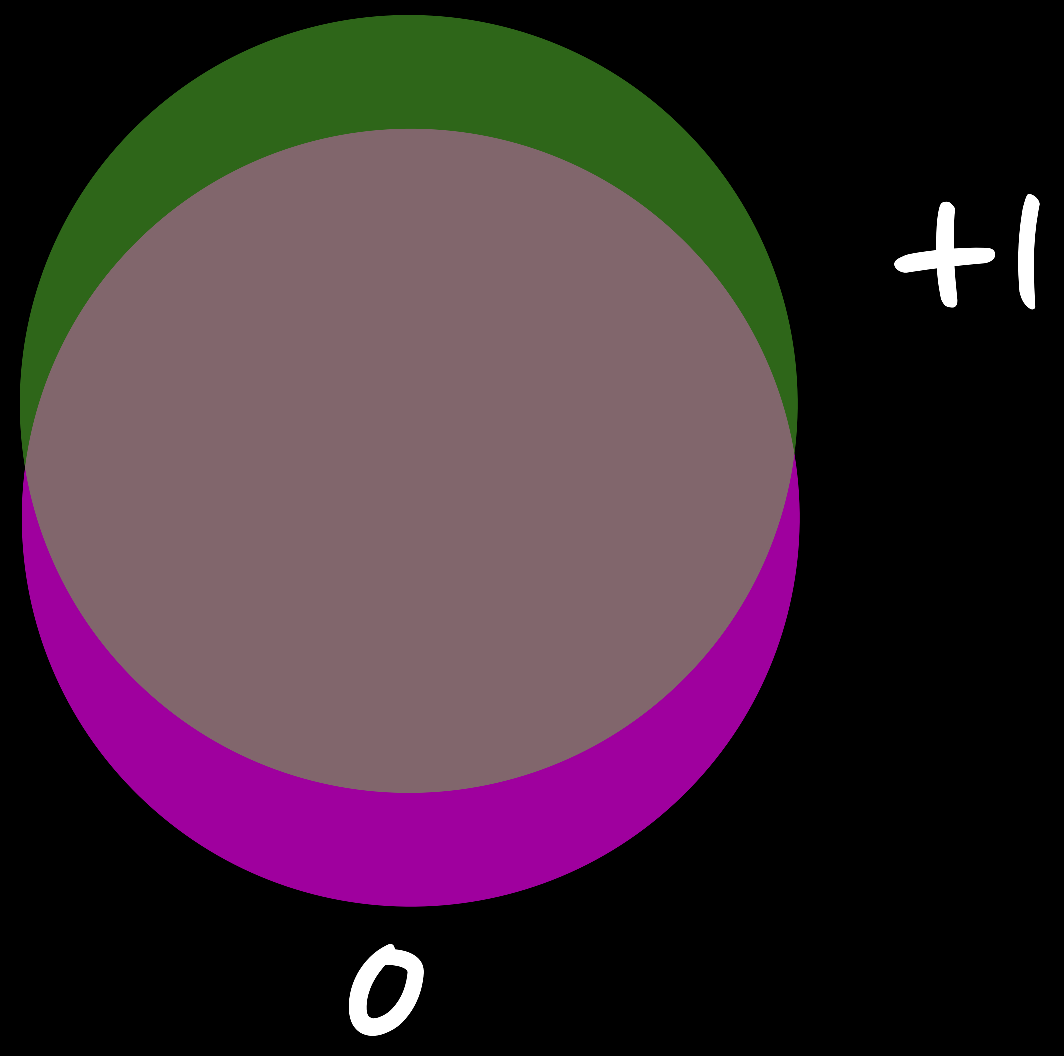
MET5

LSI working principle

$$\phi_x = w(x + s, y) - w(x, y)$$

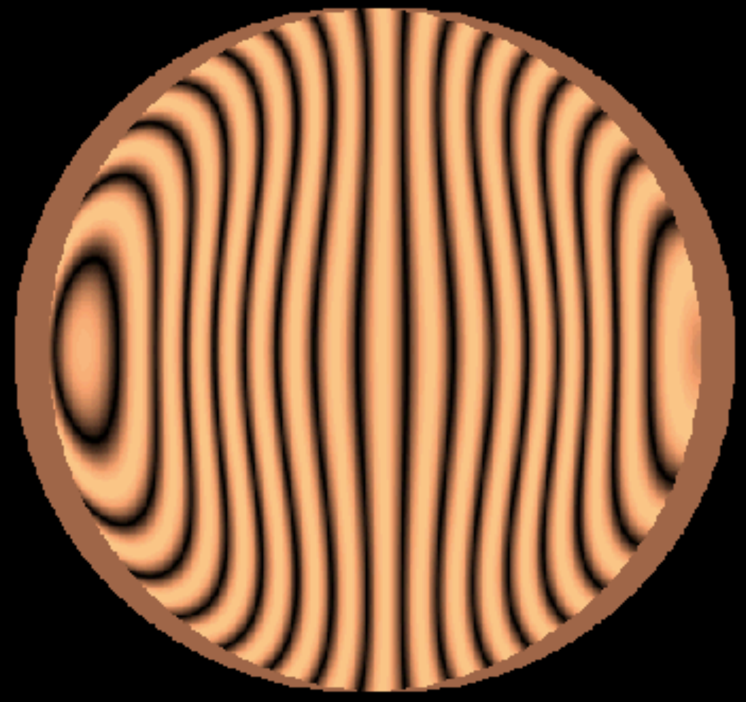
$$\phi_Y = w(x, y + s) - w(x, y)$$



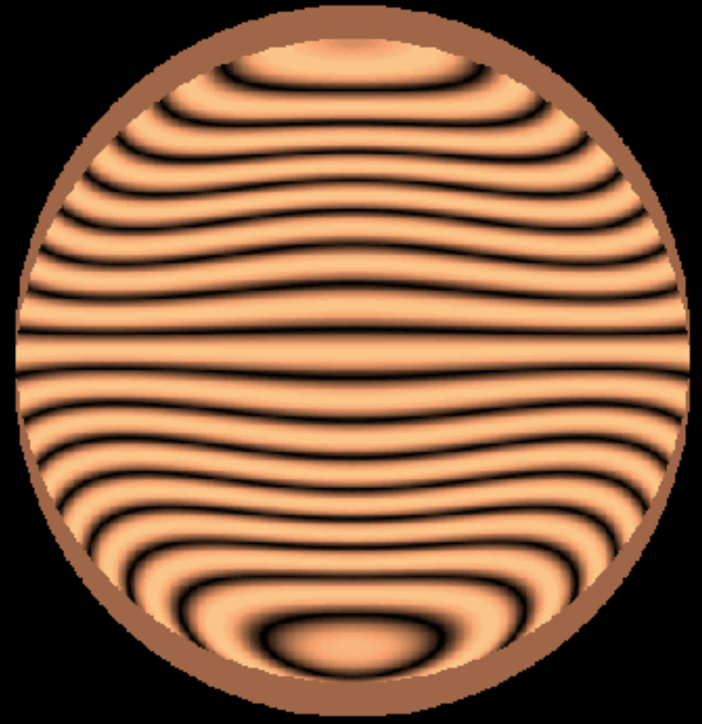


LSI working principle

$\phi_X = W(x + s, y) - W(x, y)$



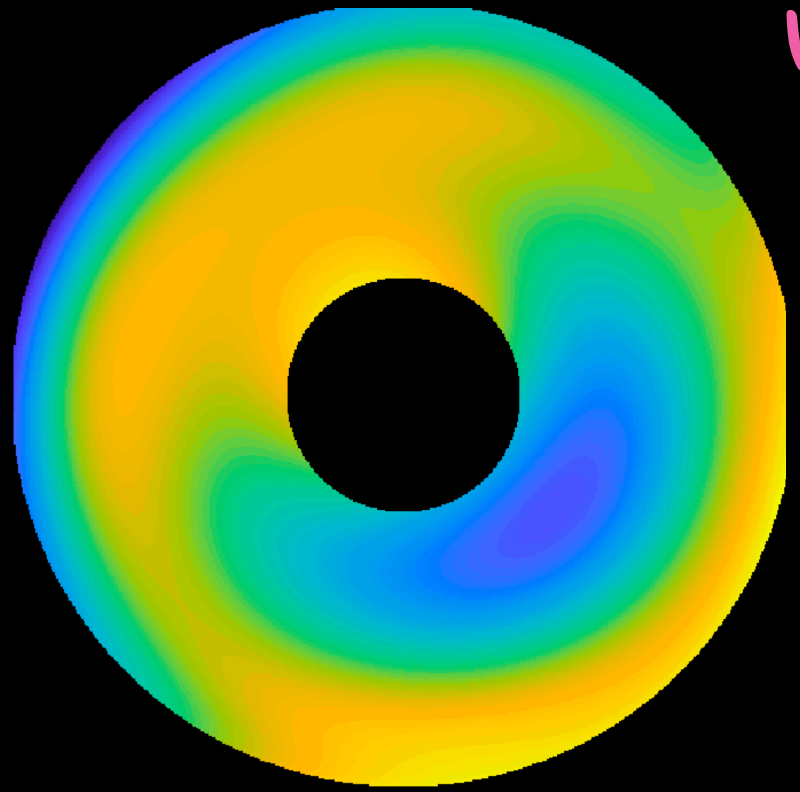
$\phi_Y = W(x, y + s) - W(x, y)$



LEAST SQUARES ALGORITHM

(High-NA or low-NA)

RECONSTRUCTED WAVEFRONT



Adapting LSI to high NA

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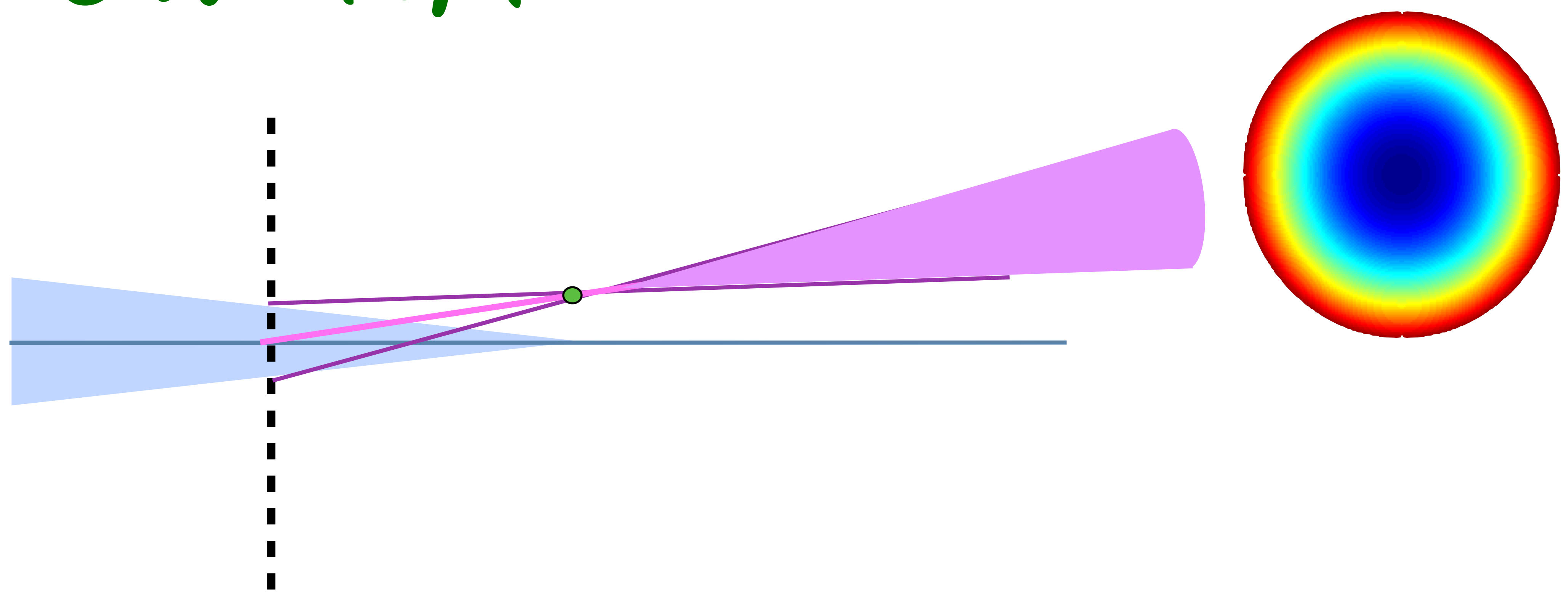
Low-NA



$$w(x + s, y) - w(x, y) \approx s \cdot dw/dx$$

Adapting LSI to high NA

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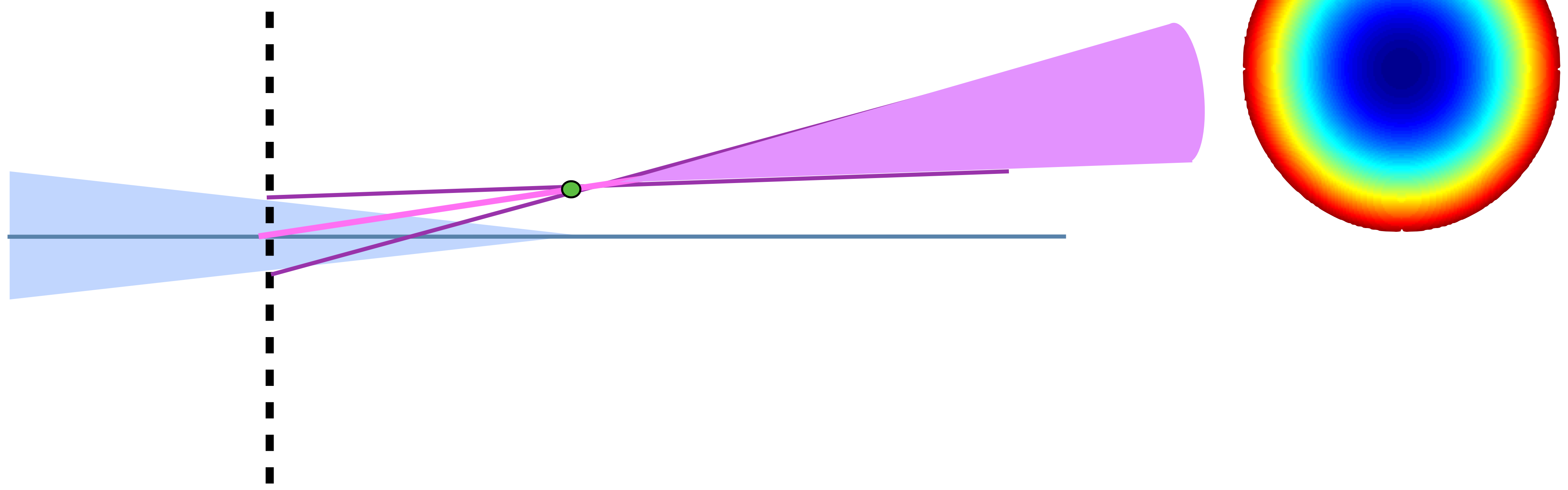
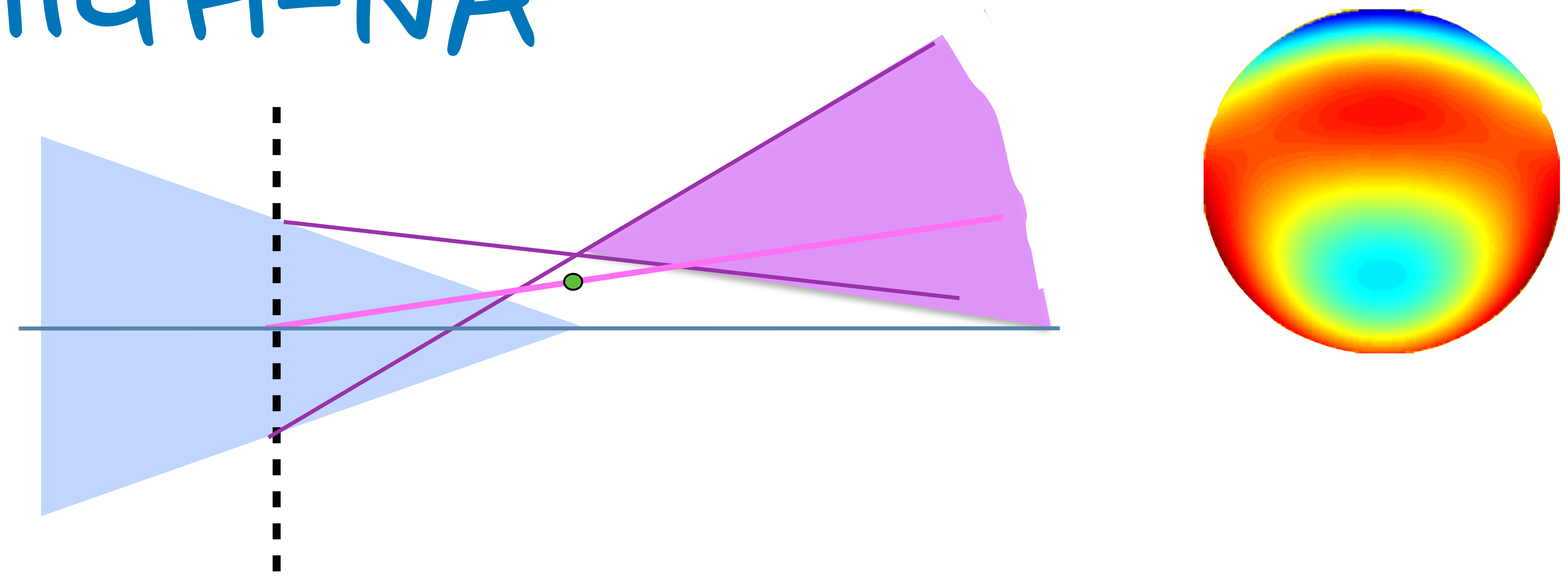
LOW-NA



$$w(x + s, y) - w(x, y) \approx s \cdot dw/dx$$

HIGH-NA



$$w(x + s, y) - w(x, y) \neq s \cdot dw/dx$$

Multiplexed source requirements

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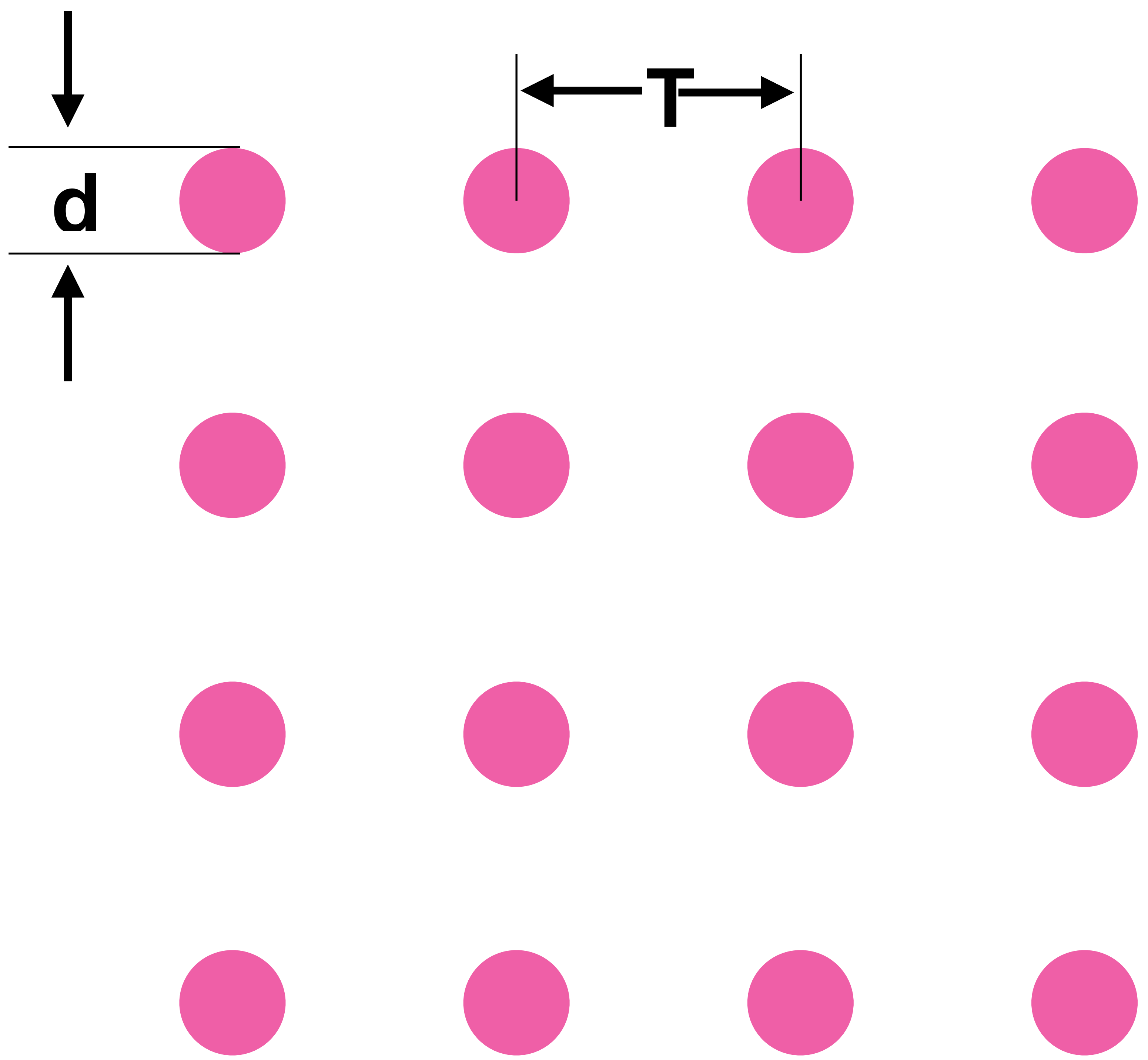
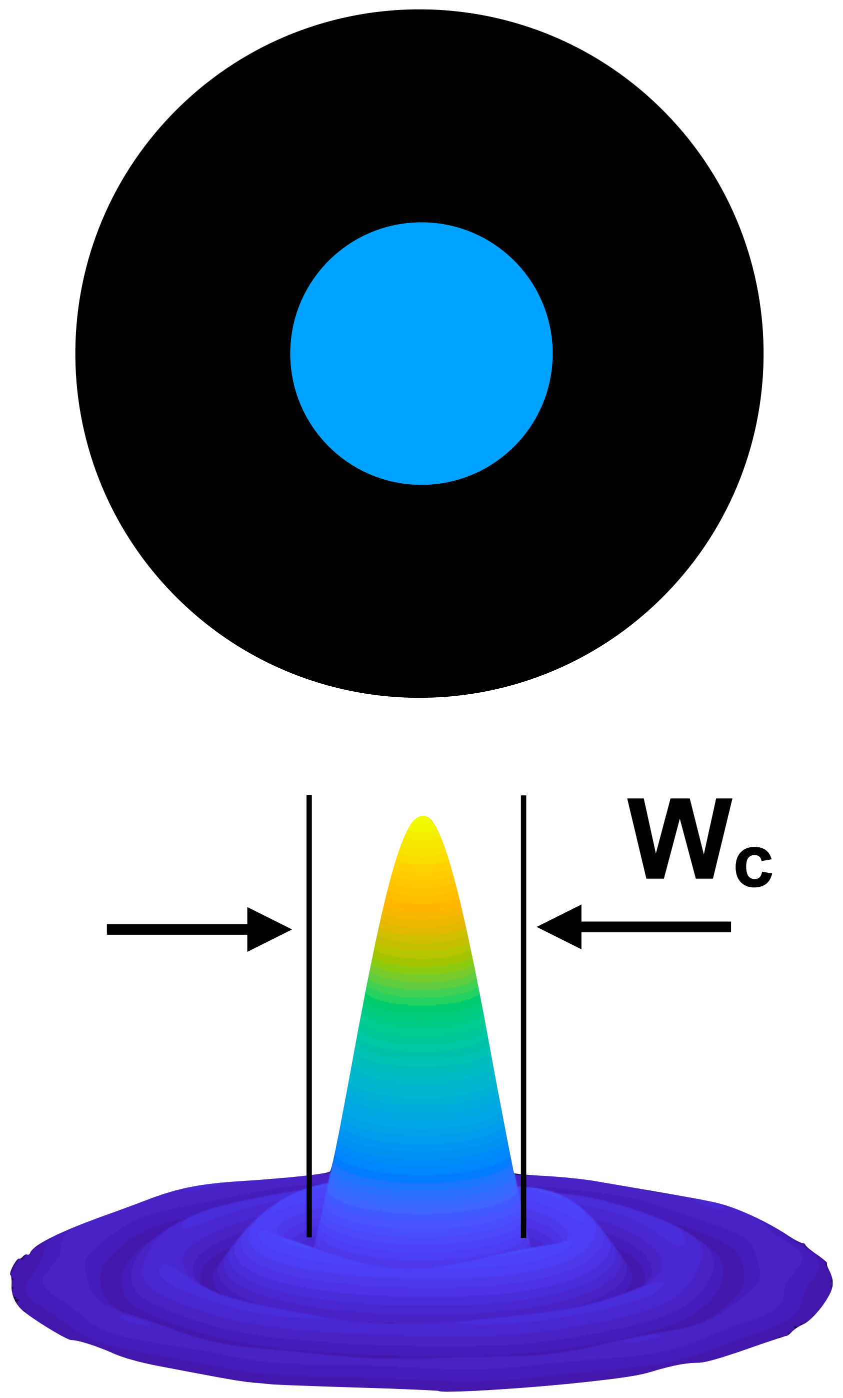
Reticle multiplexed point source field

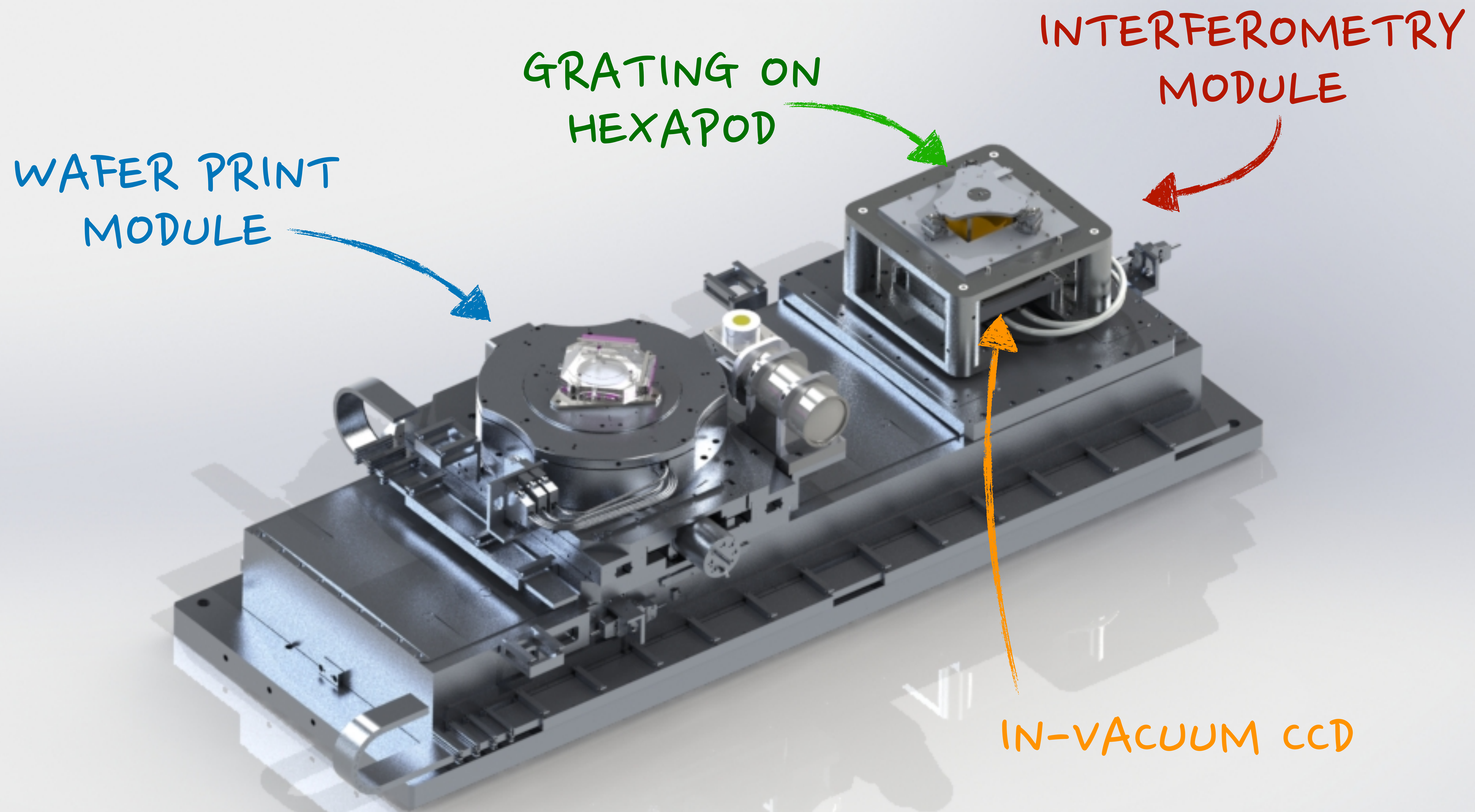


Disk illumination (0.3 σ)



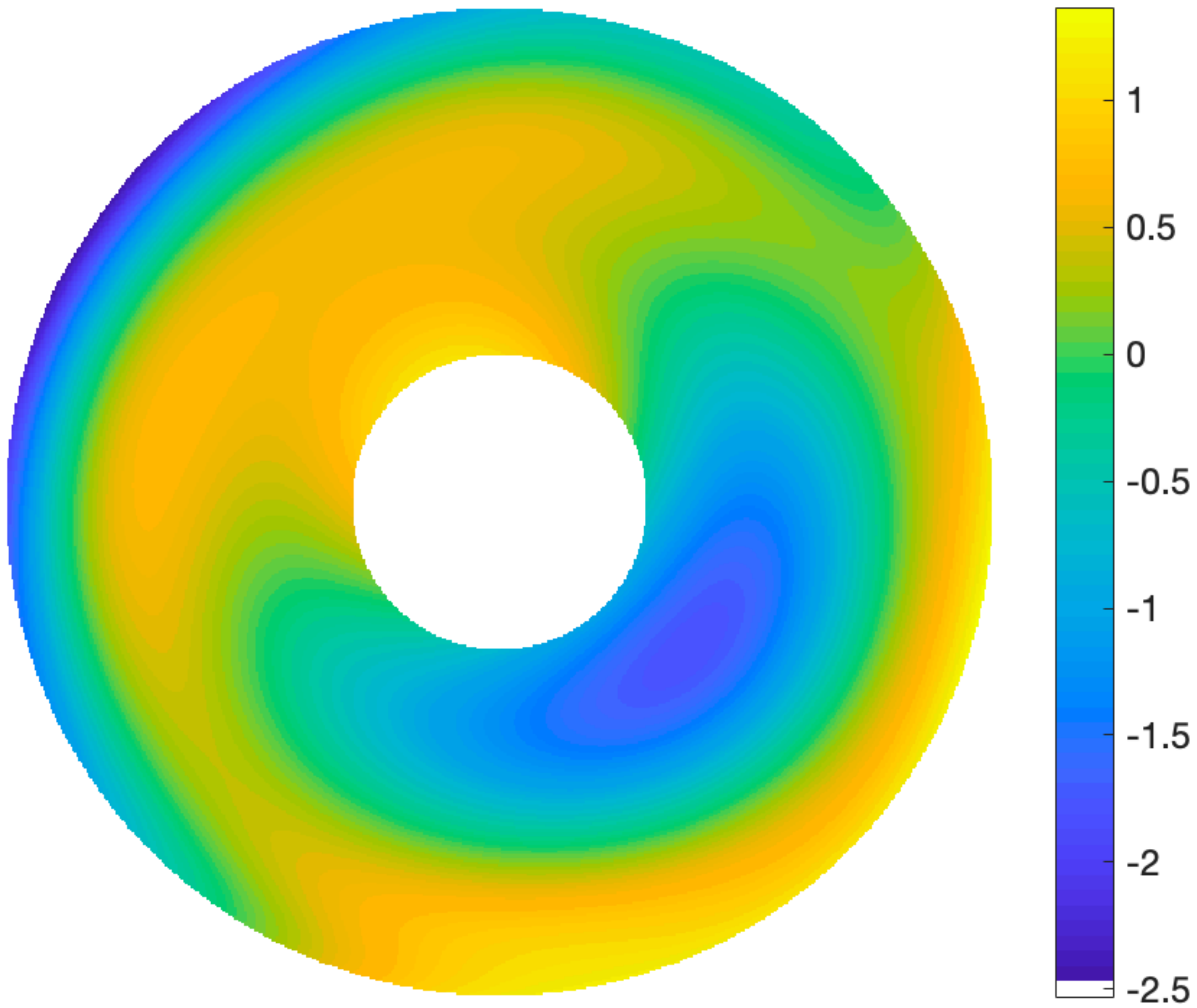
Source constraints:

- Reticle and wafer grating periods obey: $T = mT_w$
- Coherence function of illumination: $w_c < T$
- Point source diffraction + illumination NA fill pupil NA


WAFER PRINT MODULE
GRATING ON HEXAPOD
INTERFEROMETRY MODULE
IN-VACUUM CCD

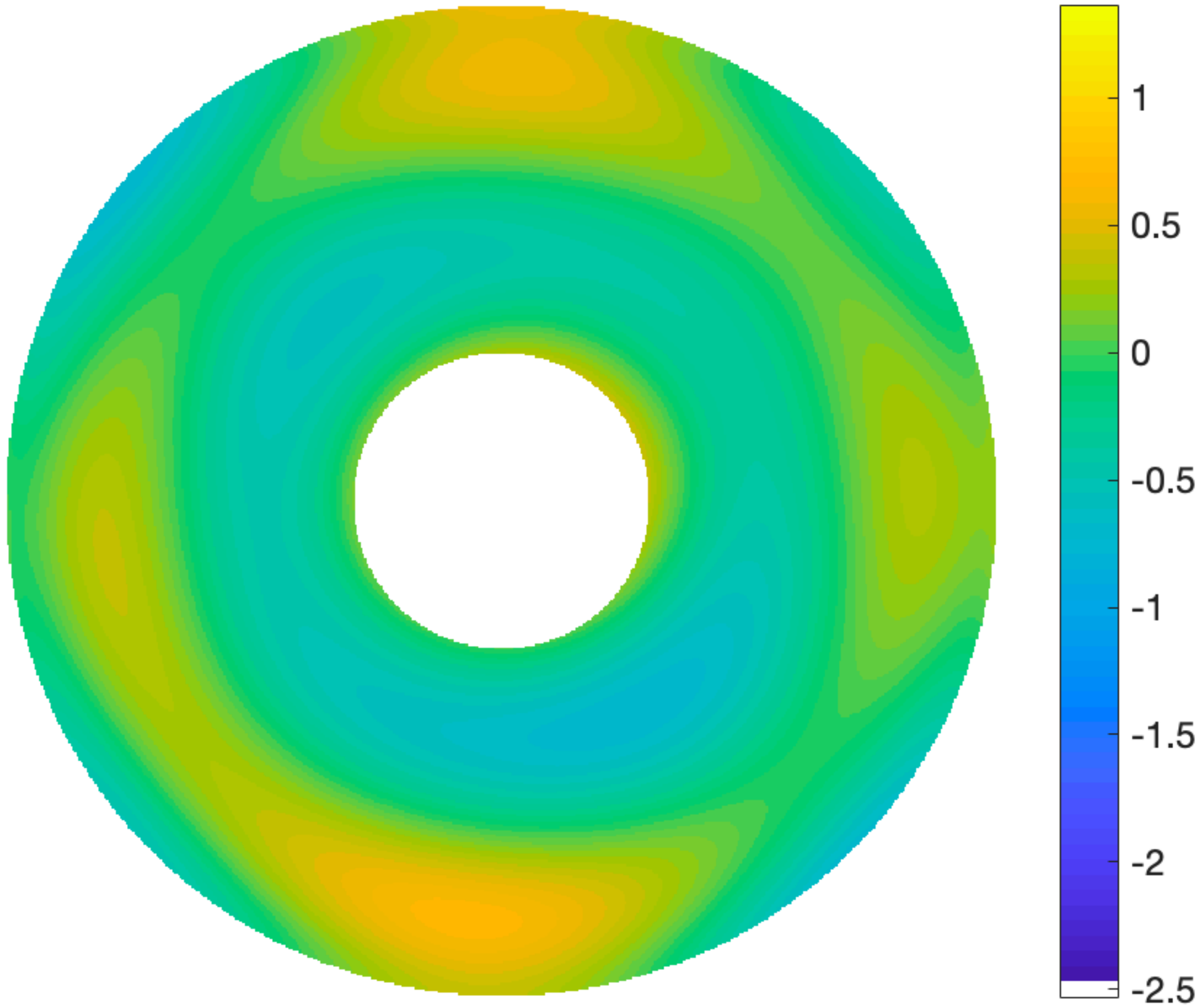
Optical alignment 10/31/18

Pre-alignment



RMS WFE: 0.69 nm

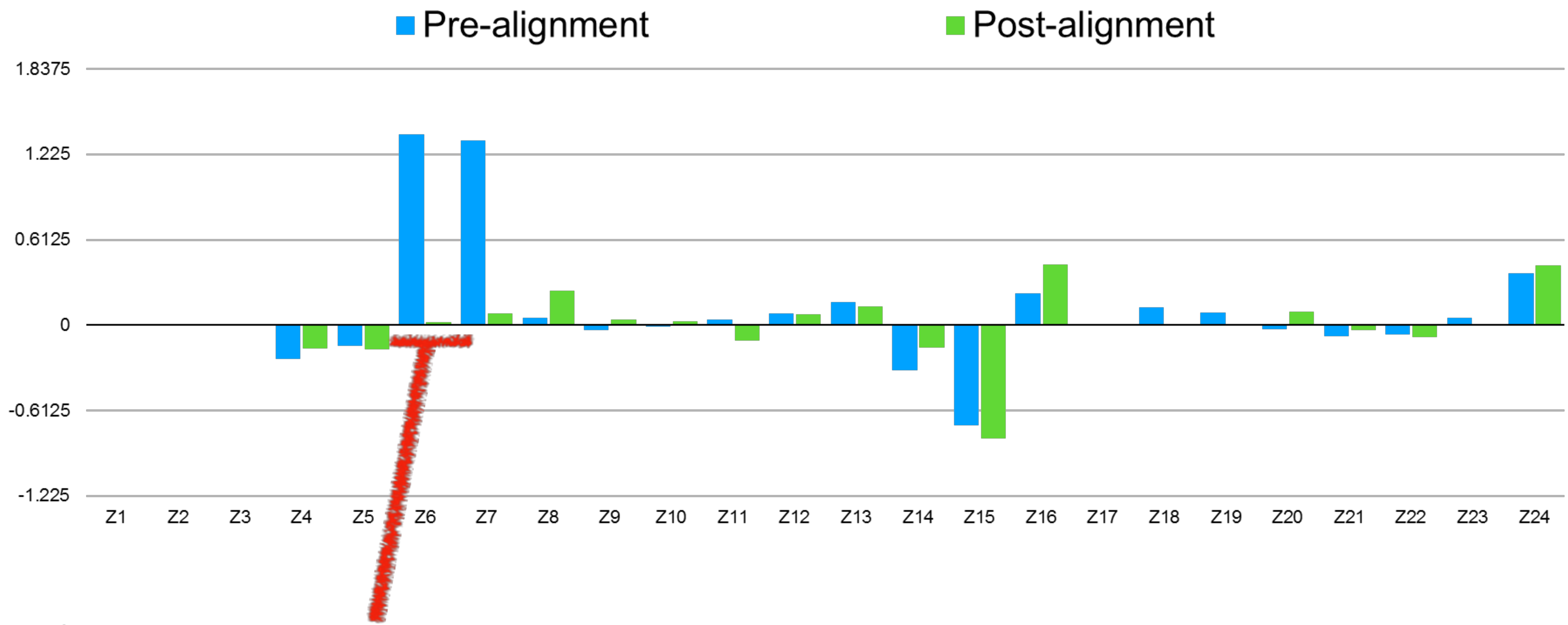
Post-alignment



RMS WFE: 0.31 nm

Measurements taken at field center. Specification is 0.50 nm

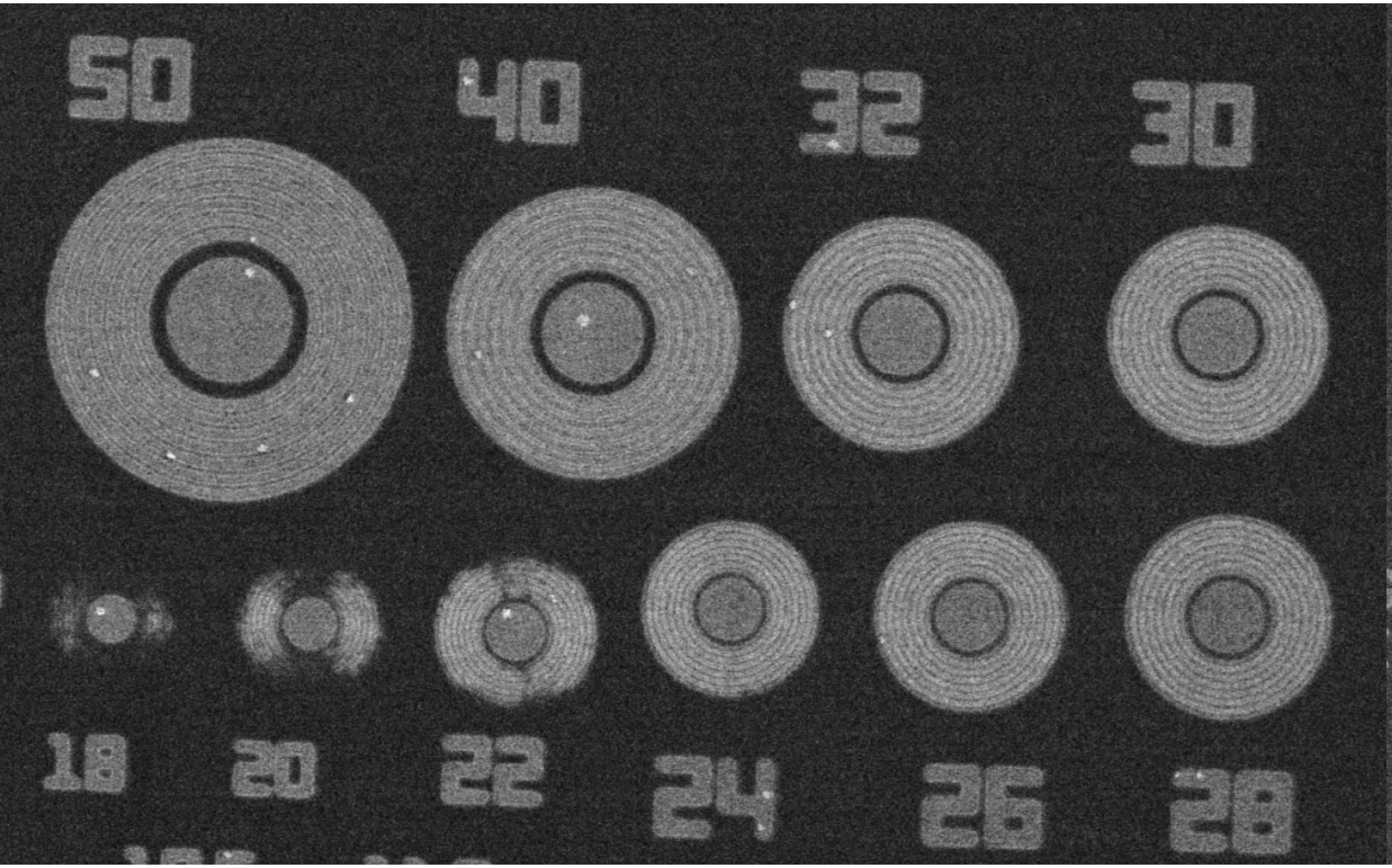
Zernike decomposition of optical aberrations



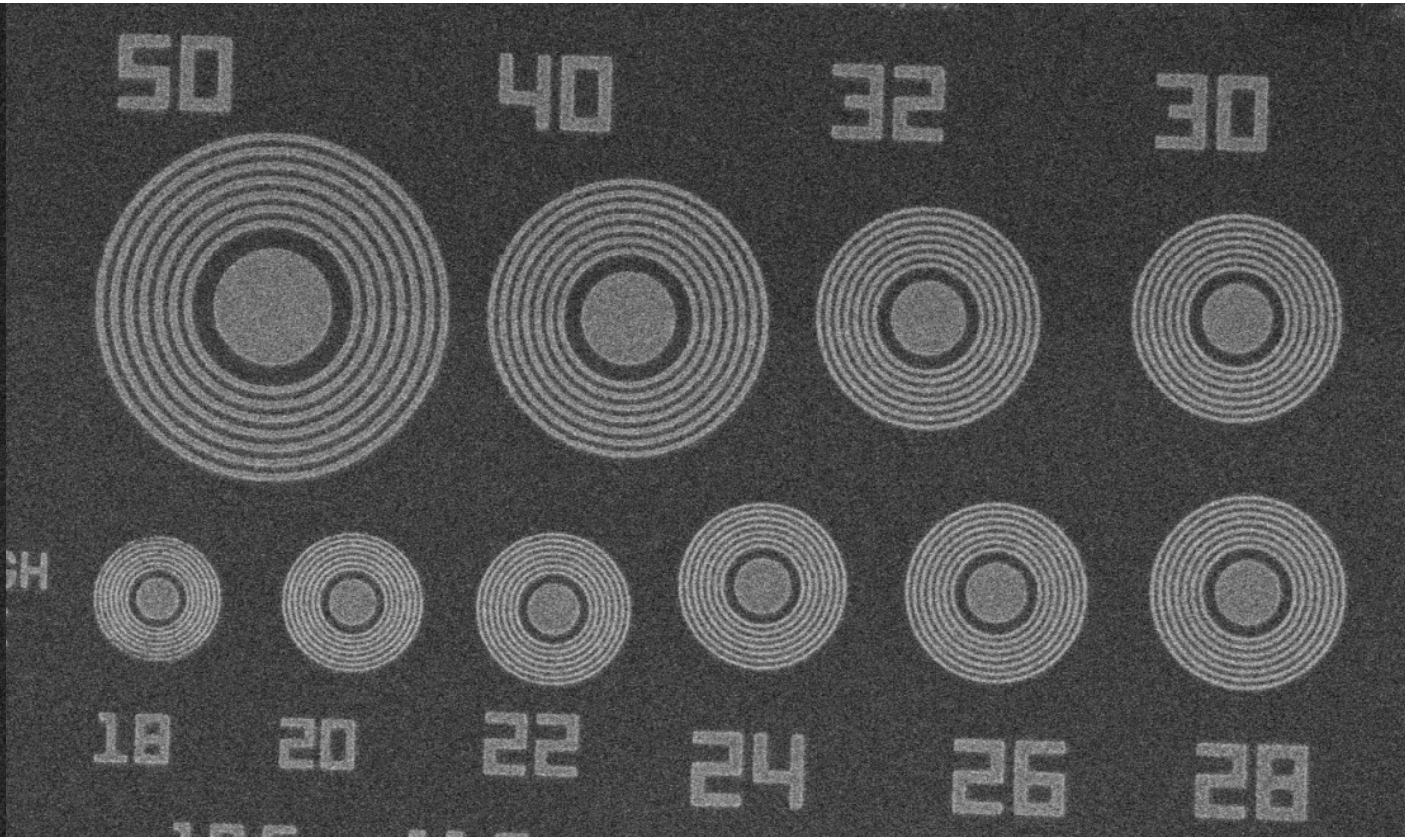
Optic movement was to correct primary X and Y coma

Printing improvement

Before alignment



After alignment



LAPACIAN WAVEFRONT SENSOR

Laplacian Wavefront Sensor (LWS)

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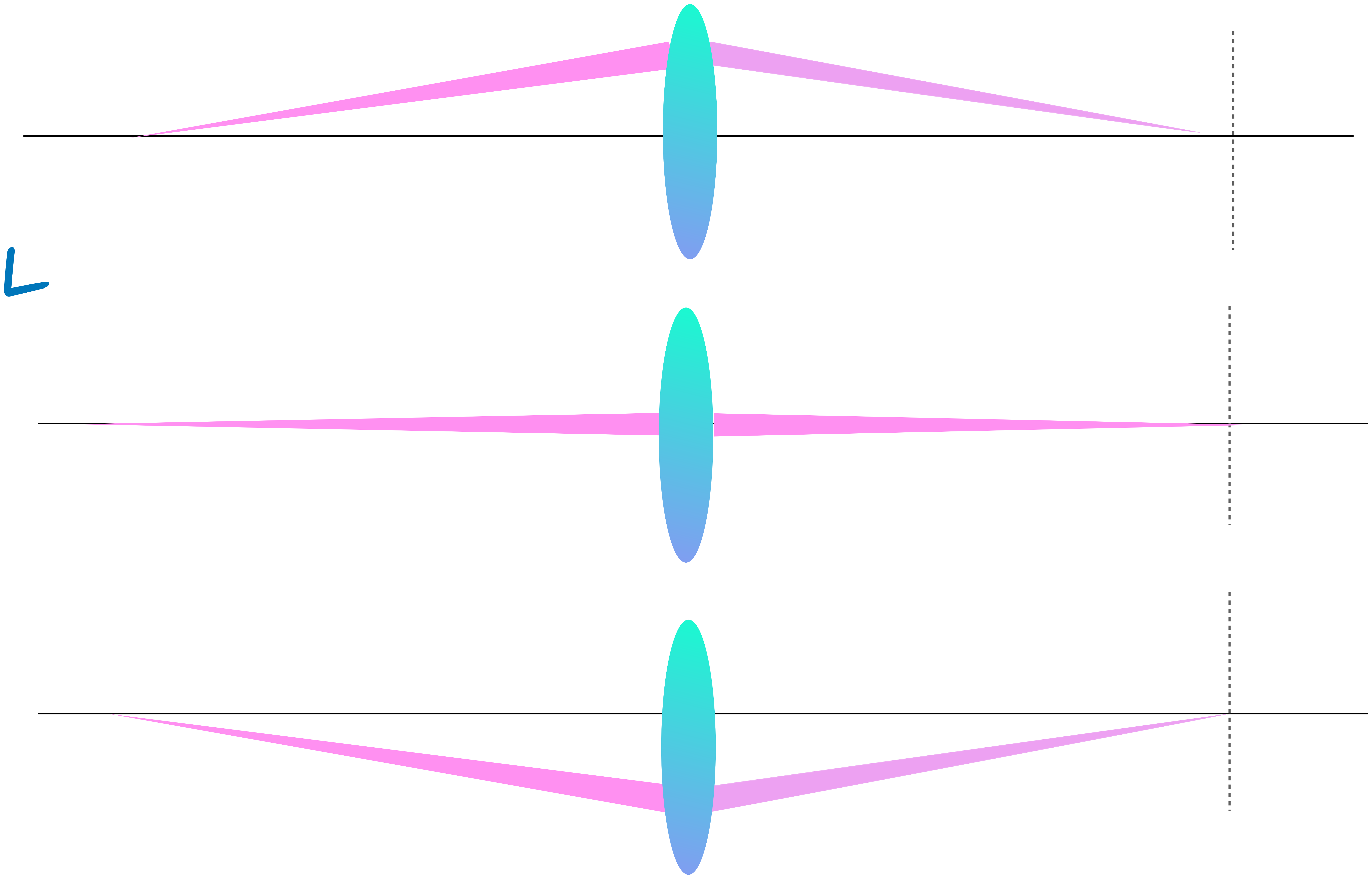
IDEAL OPTICAL SYSTEM



Laplacian Wavefront Sensor (LWS)

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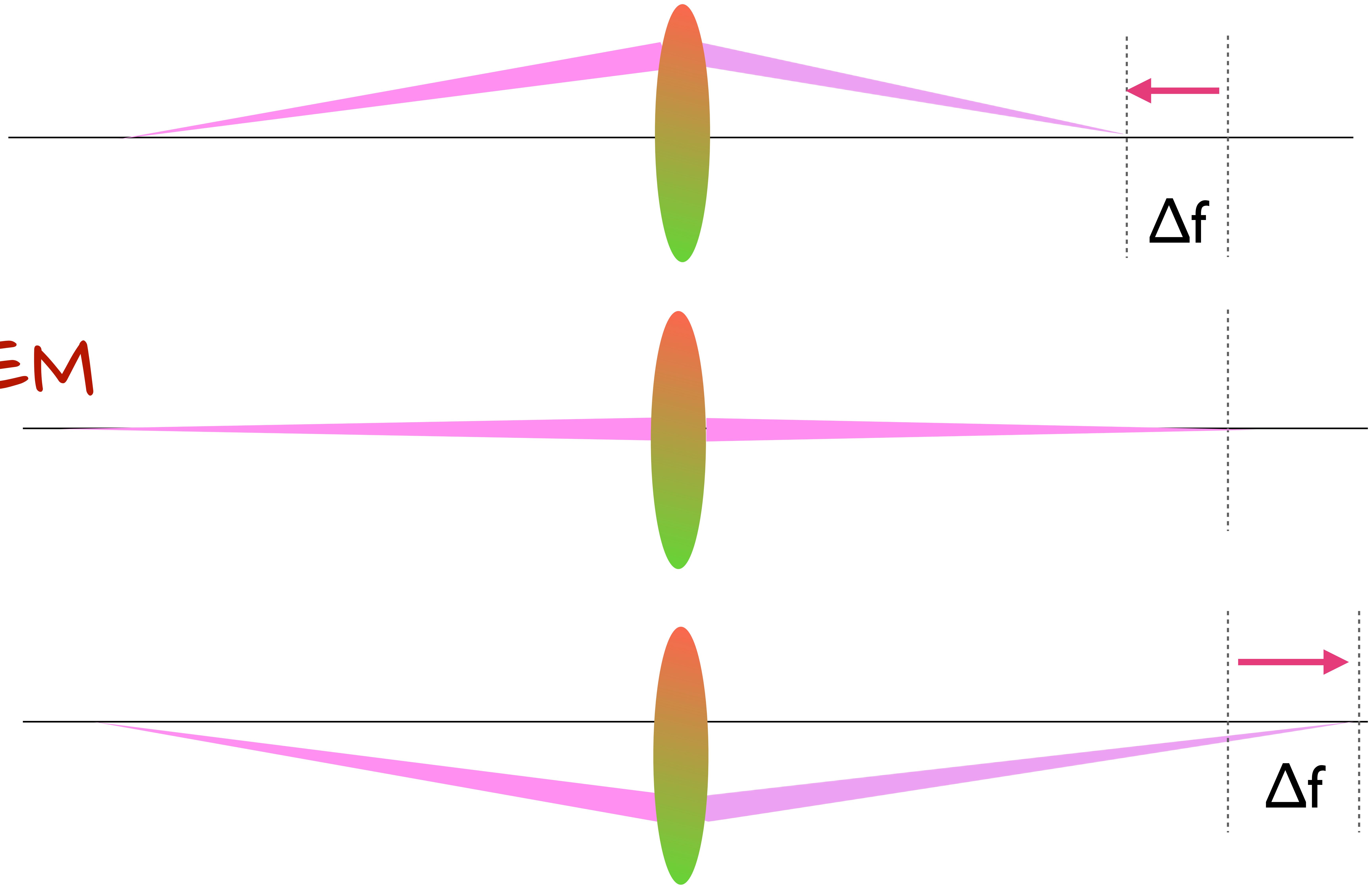
ABERRATED OPTICAL SYSTEM



Laplacian Wavefront Sensor (LWS)

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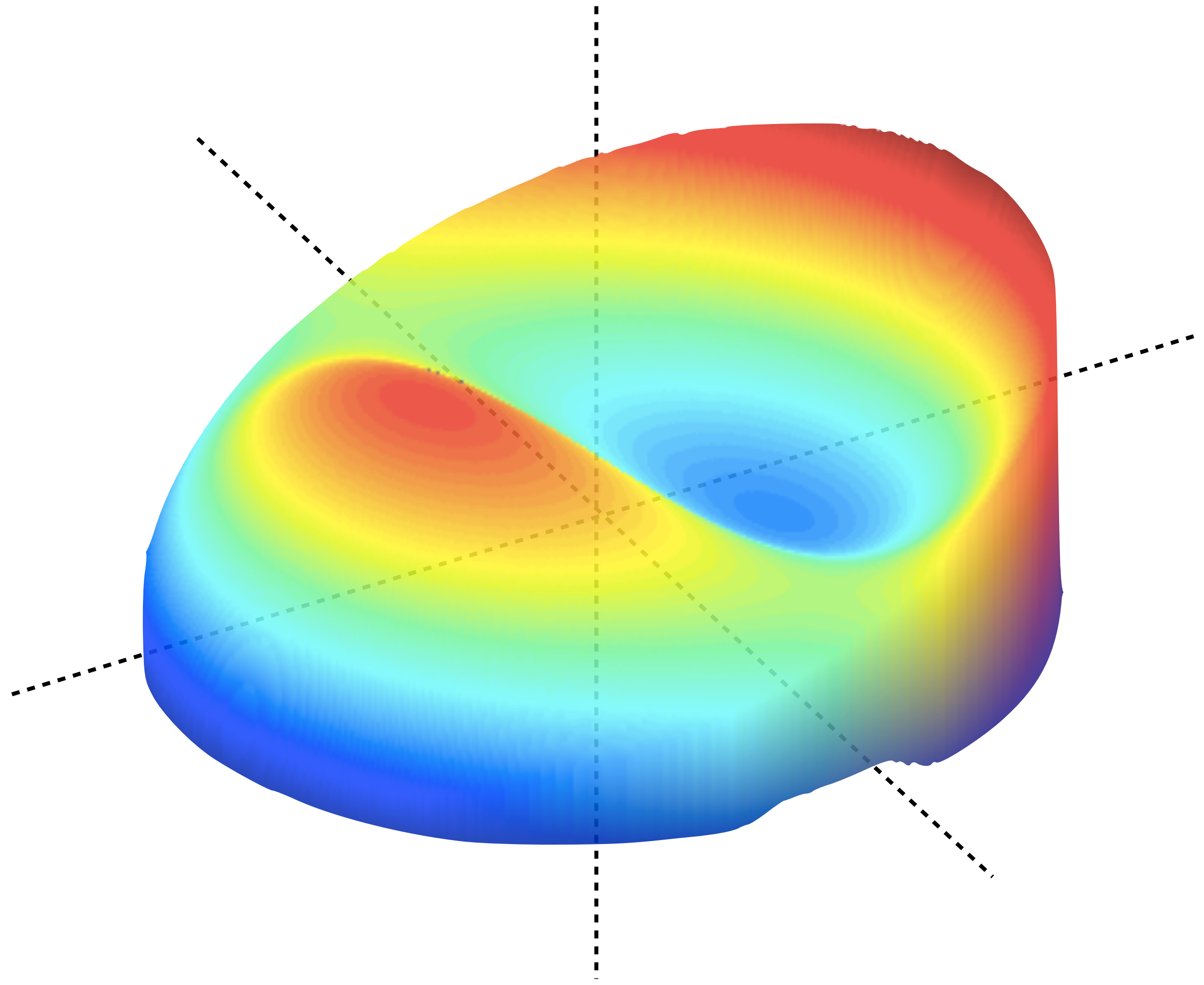
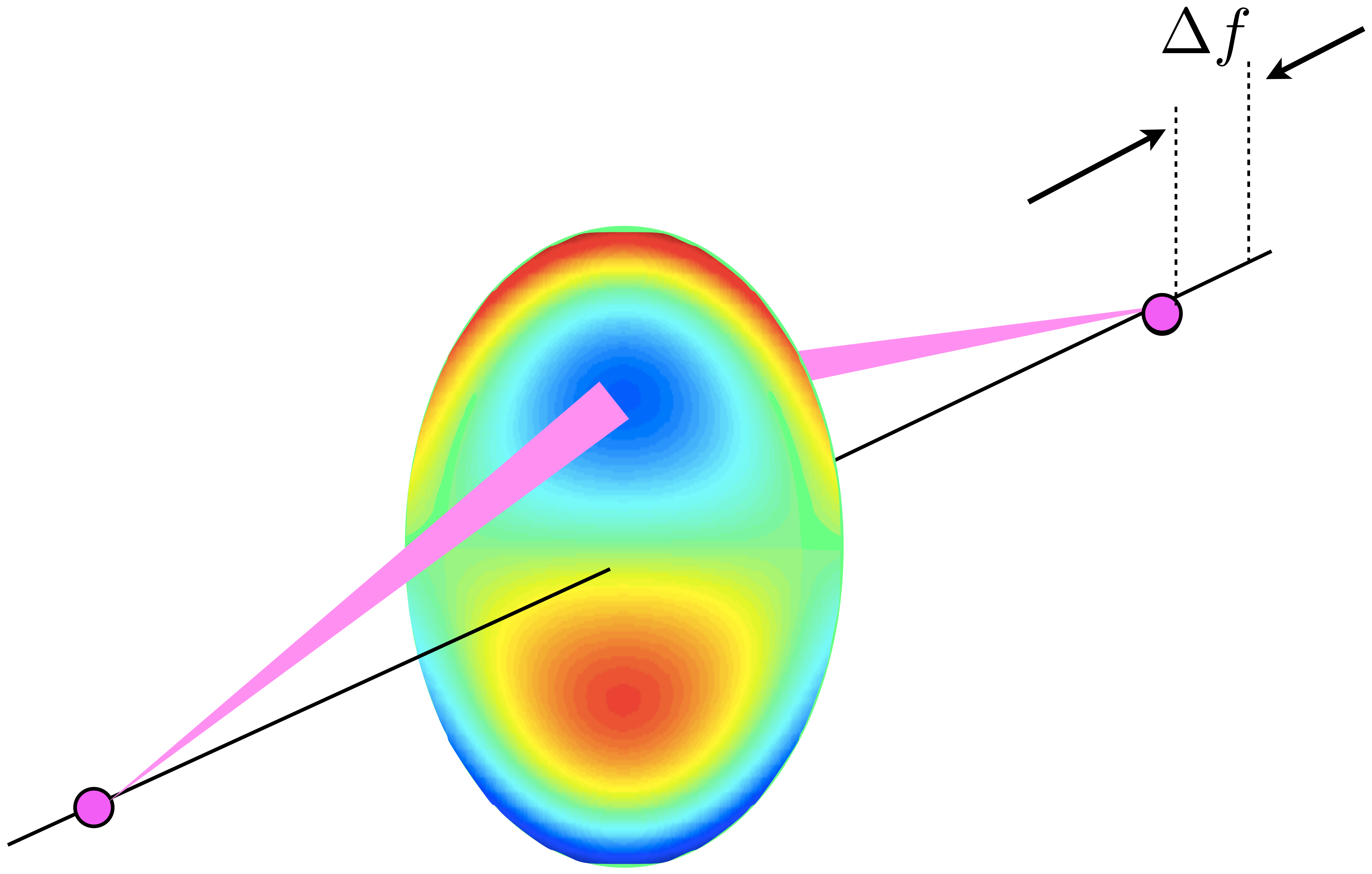
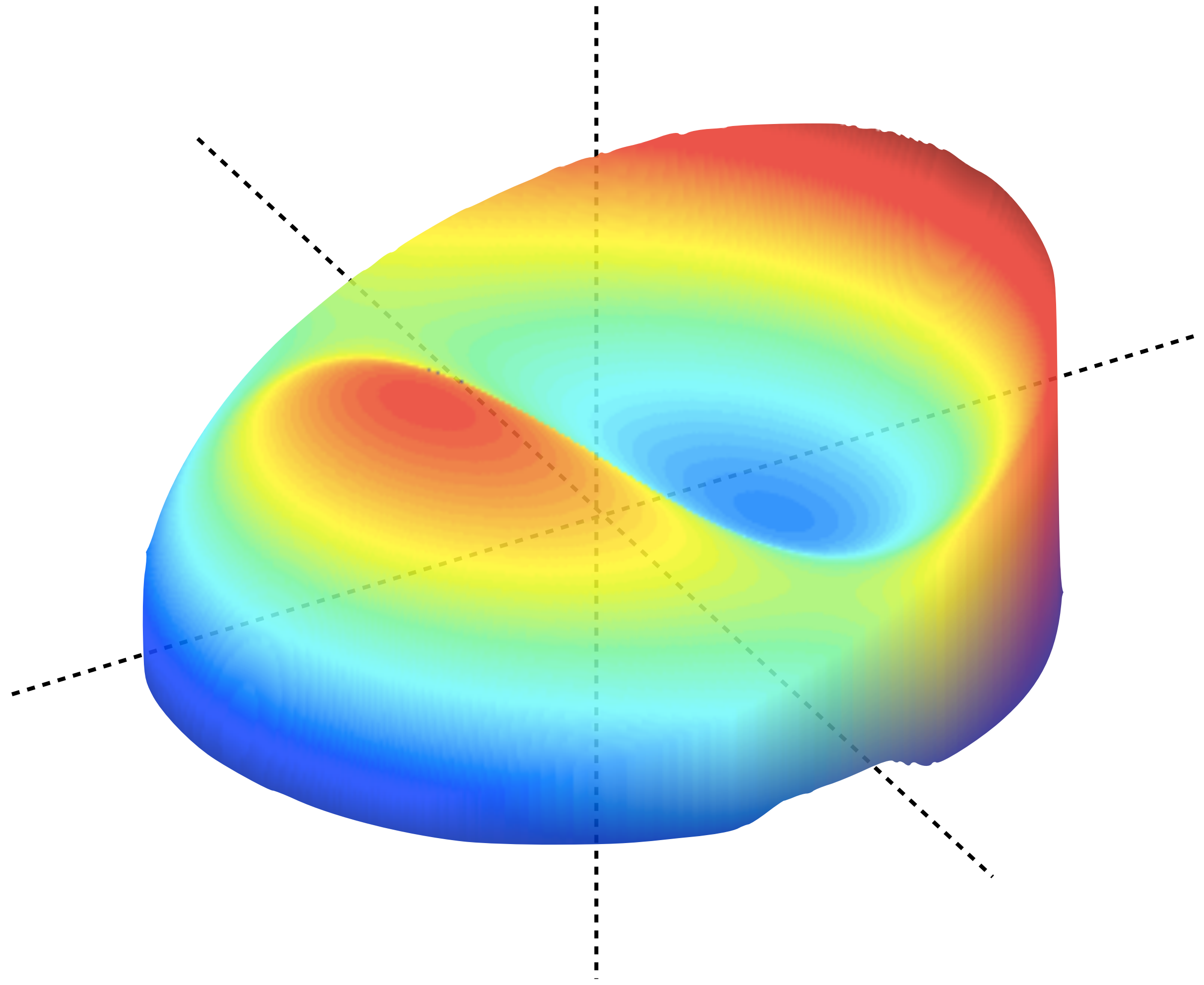
EXAMPLE: X-COMA

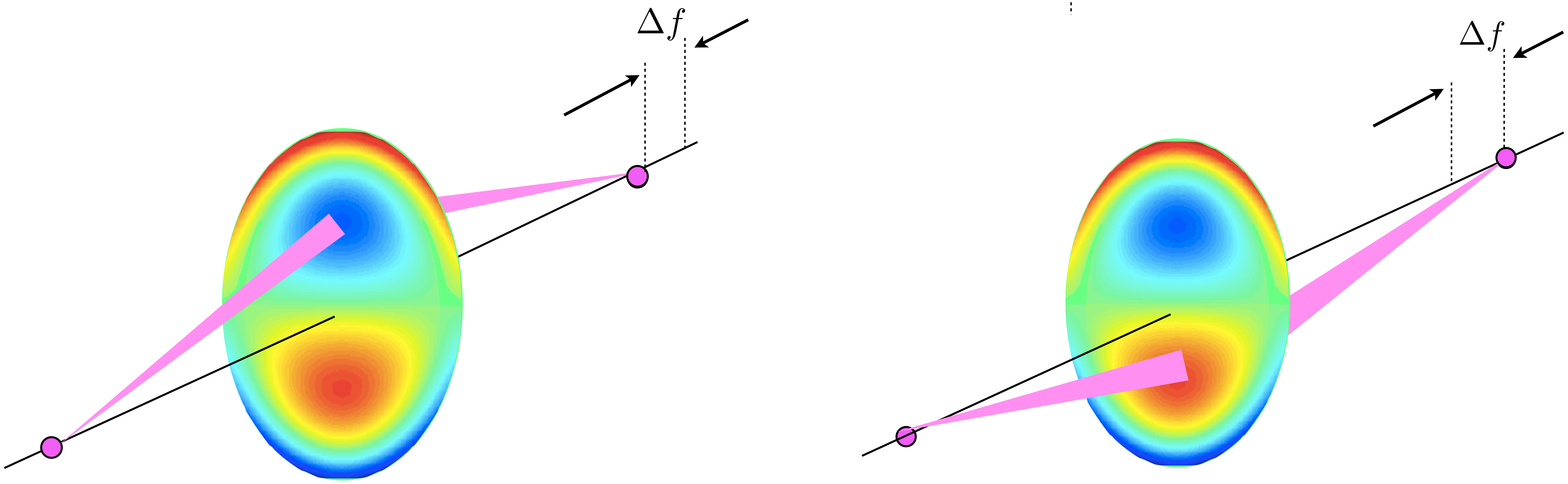




Laplacian Wavefront Sensor (LWS)

EXAMPLE: X-COMA





Curvature library

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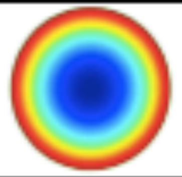
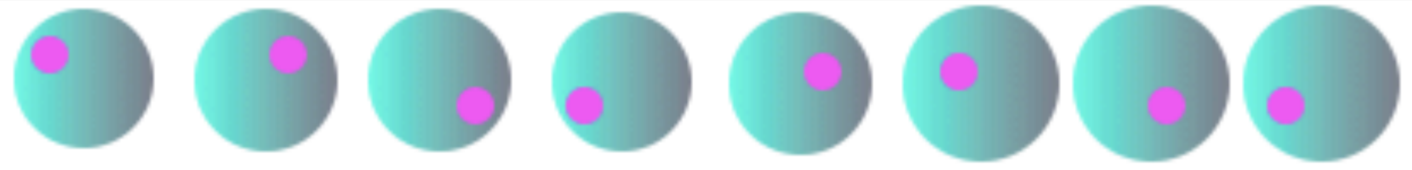
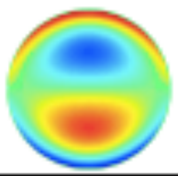
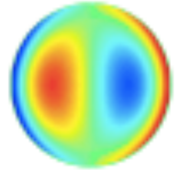
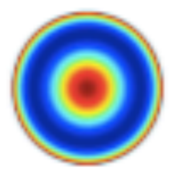
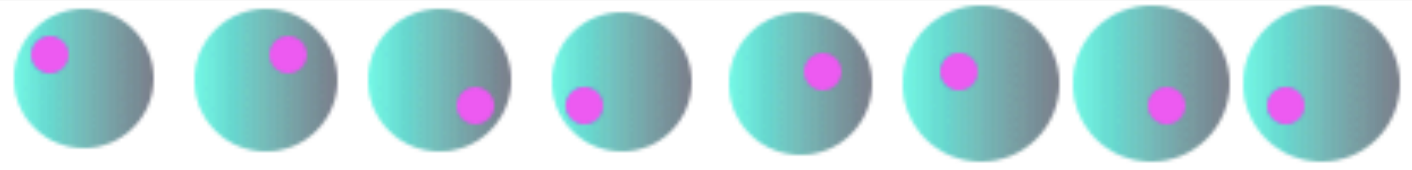
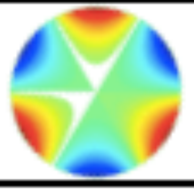
BUILD A CURVATURE LIBRARY FOR SET OF ZERNIKE TERMS

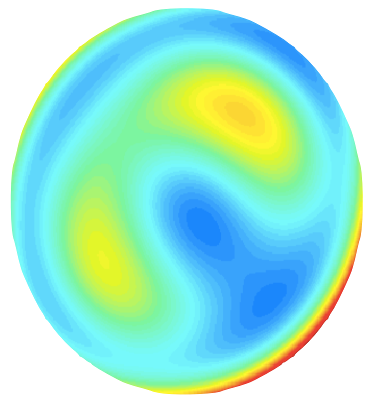
N	Aberration	Probe	Δf
3	Focus 		[+,-,+, -, -, +]
4	Stig 		[-,-,+, -, -, +]
5	Stig 		[-,-,+, +, -, +]
6	Coma 		[+,-,+, -, +, +]
7	Coma 		[+,+,+, -, -, +]
8	Spherical 		[-,+,+, +, -, +]
9	Trifoil 		[+,-,-, -, -, +]
10	Trifoil 		[+,-,-, +, +, +]

LWS reconstruction

Curvature library · **Wavefront** = **Focus shifts**

N	Aberration	Probe	Δf
3	Focus		[+,-,+, -, -, +]
4	Stig		[-,-,+, -, -, +]
5	Stig		[-,-,+, +, -, +]
6	Coma		[+,-,+, -, +, +]
7	Coma		[+,+,+, -, -, +]
8	Spherical		[-,+,+, +, -, +]
9	Trifoil		[+,-,-, -, -, +]
10	Trifoil		[+,-,-, +, +, +]

$\bullet$



$$= \left[\Delta f \right]$$

LWS reconstruction

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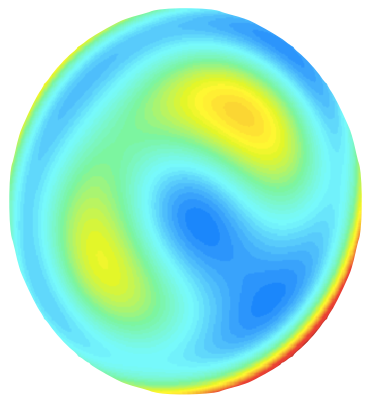
Curvature library · **Wavefront** = **Focus shifts**

N	Aberration	Probe	Δf
3	Focus		[+,-,+, -, -, +]
4	Stig		[-,-,+, -, -, +]
5	Stig		[-,-,+, +, -, +]
6	Coma		[+,-,+, -, +, +]
7	Coma		[+,+,+, -, -, +]
8	Spherical		[-,+,+, +, -, +]
9	Trifoil		[+,-,-, -, -, +]
10	Trifoil		[+,-,-, +, +, +]

$\cdot$

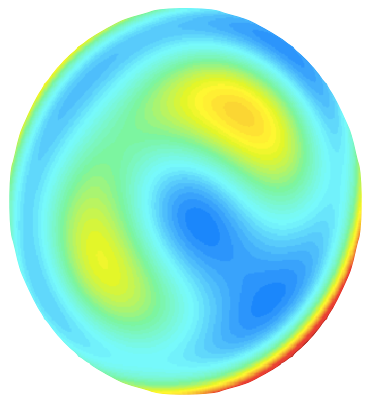


$=$ Δf

Curvature library† · **Focus shifts** $\approx$ **Wavefront**

N	Aberration	Probe	Δf
3	Focus		[+,-,+, -, -, +]
4	Stig		[-,-,+, -, -, +]
5	Stig		[-,-,+, +, -, +]
6	Coma		[+,-,+, -, +, +]
7	Coma		[+,+,+, -, -, +]
8	Spherical		[-,+,+, +, -, +]
9	Trifoil		[+,-,-, -, -, +]
10	Trifoil		[+,-,-, +, +, +]

$\cdot$ Δf $\approx$



Laplacian Wavefront Sensor (LWS)

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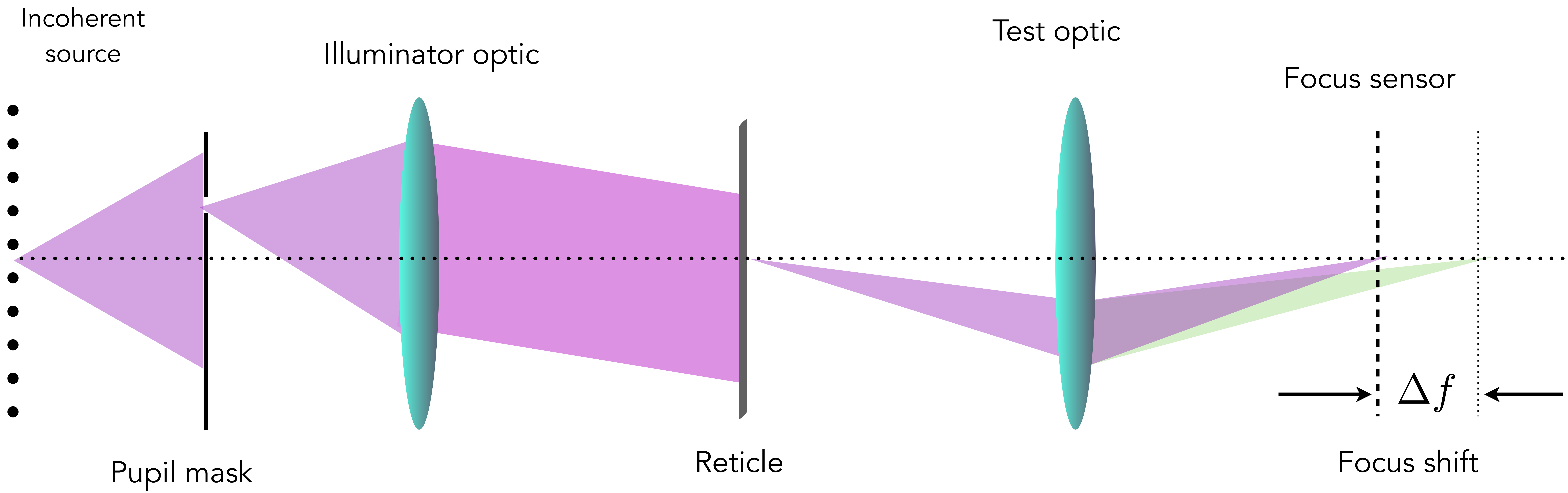
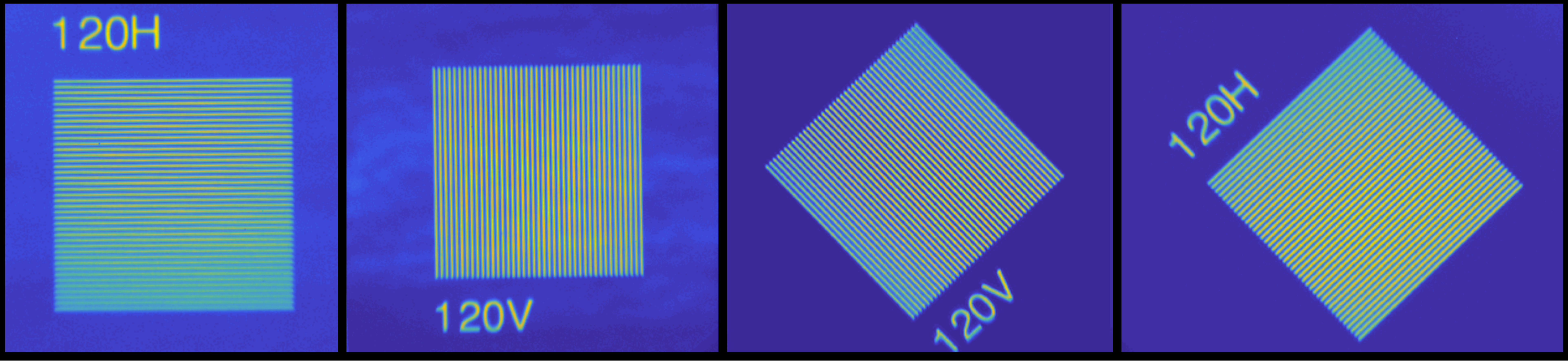


LWS experiment on SHARP



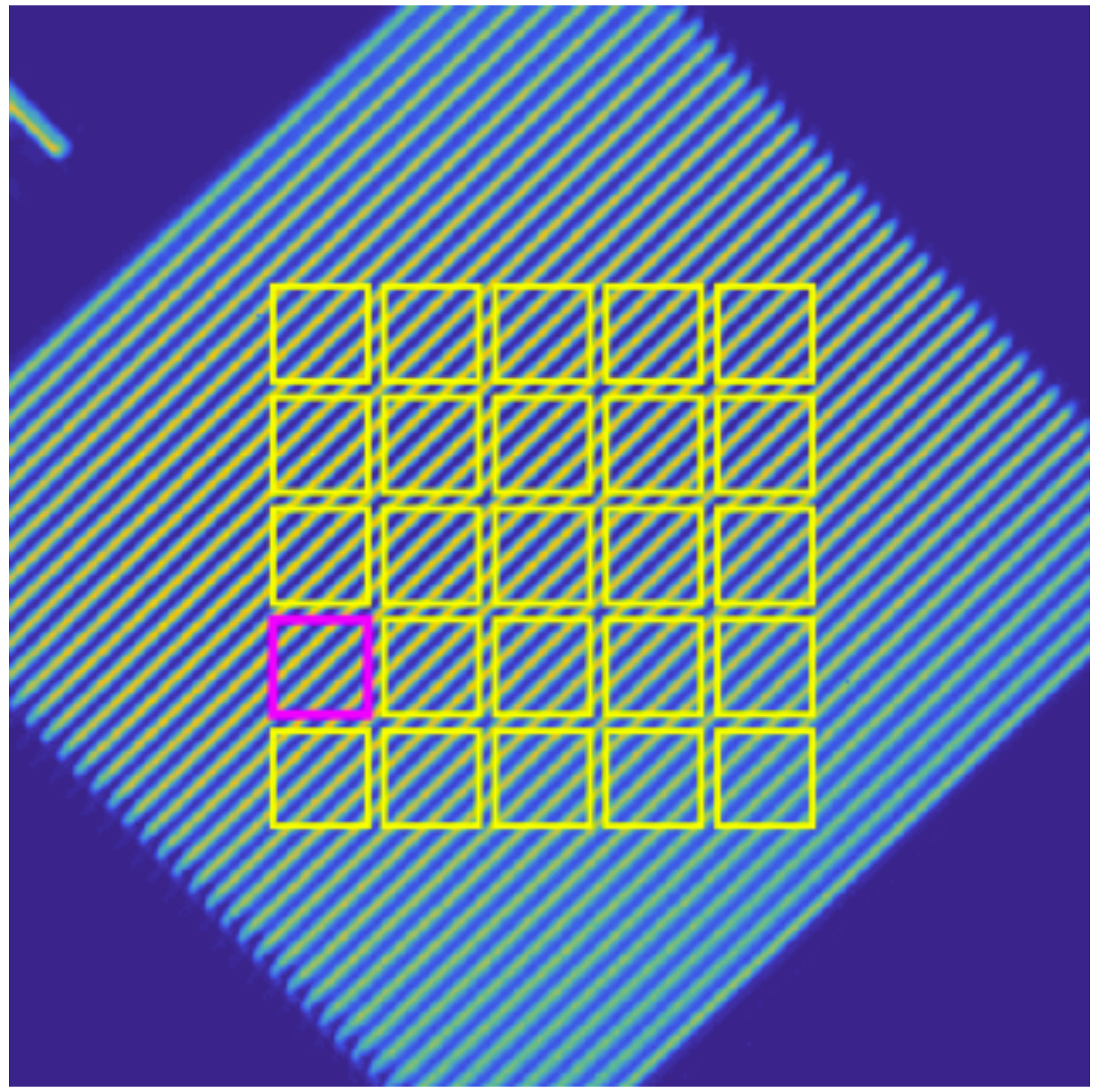
NA: **0.33 / 4**

lambda: **13.5 nm**

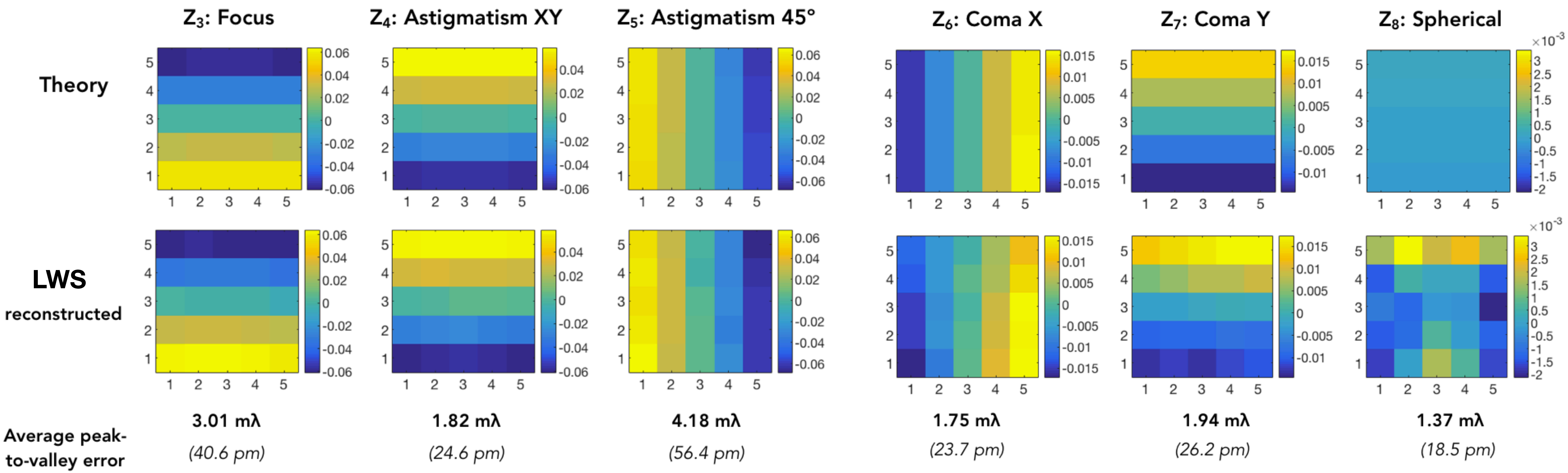
Data sets: **13 (4 gratings)**

Focus steps: **17 @ Δz = 300 nm**

Field locations: **25**



LWS experiment on SHARP



Zernike	Average peak-to-valley error mλ (pm)	Average peak-to-valley error λ/x
Focus (Z_3)	**3.01** *(40.6)*	λ/331
Astigmatism XY (Z_4)	**1.82** *(24.6)*	λ/549
Astigmatism 45° (Z_5)	**4.18** *(56.4)*	λ/238
Coma X (Z_6)	**1.75** *(23.7)*	λ/571
Coma Y (Z_7)	**1.94** *(26.2)*	λ/514
Spherical (Z_8)	**1.37** *(18.5)*	λ/726
Total RMS error	**2.78** *(37.5)*	**λ/359**

Single aberration peak-to-valley error better than **λ/238** Total RMS aberration **λ/359**

Summary of high-NA wavefront sensors

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Lateral Shearing Interferometry (LSI)

- Works by measuring wavefront derivative
- Interferometric method (requires integration of diffraction grating and CCD)
- Good sensitivity to all figure Zernike terms
- Fast measurement (between 1 and 36 data points)
- High accuracy demonstrated (λ/100)

Laplacian Wavefront Sensor (LWS)

- Works by measuring wavefront curvature (focus shifts)
- Image-based method
- Ideal for measuring primary Zernikes terms (Z_4 - Z_9)
- Lots of data required (> 100 images)
- Extremely high accuracy demonstrated (λ/230)

EUREKA

intel

SAMSUNG

IBM

inpria

JSR

APPLIED MATERIALS

ZEISS

euvtech

astrileux
ACCELERATING THE FUTURE

CYMER
An ASML company