The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA International Atomic Energy Agency

2223-23

Winter College on Optics in Imaging Science

31 January - 11 February, 2011

On breaking the Abbe diffraction limit in Optical Nanopatterning & Nanoscopy

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USA

On breaking the Abbé diffraction limit in Optical Nanopatterning & Nanoscopy

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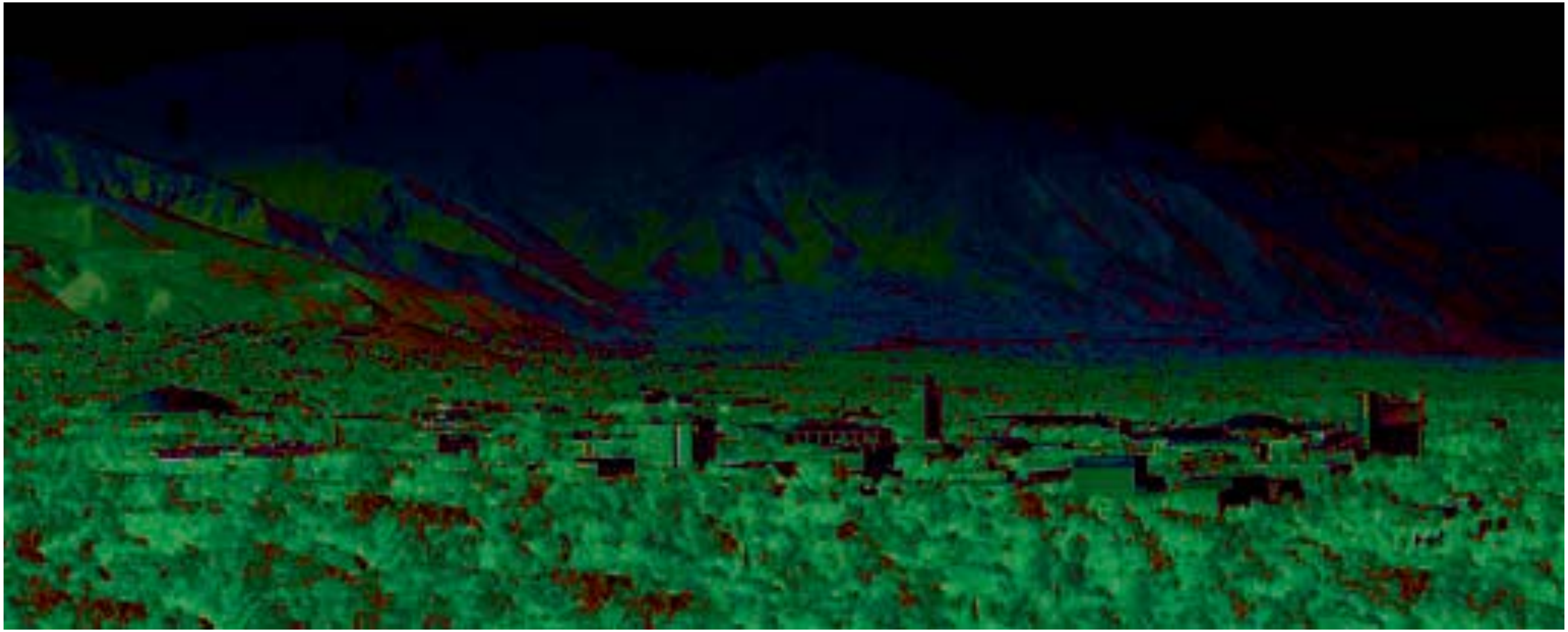

- 1st year fellowship open to the best PhD students (including international students)
- Infra-structures & facilities
- Highly inter-disciplinary research
- Entrepreneurship opportunities


New Hampshire
Vermont
Massachusetts
Maine
Washington
Montana
North Dakota
Minnesota
Oregon
Wisconsin
South Dakota
Idaho
Wyoming
Michigan
New York
Rhode Island
Nebraska
Iowa
Pennsylvania
Connecticut
Nevada
Utah
Ohio
Illinois
Indiana
New Jersey
Colorado
Delaware
Kansas
Missouri
Virginia
Maryland
California
Kentucky
West Virginia
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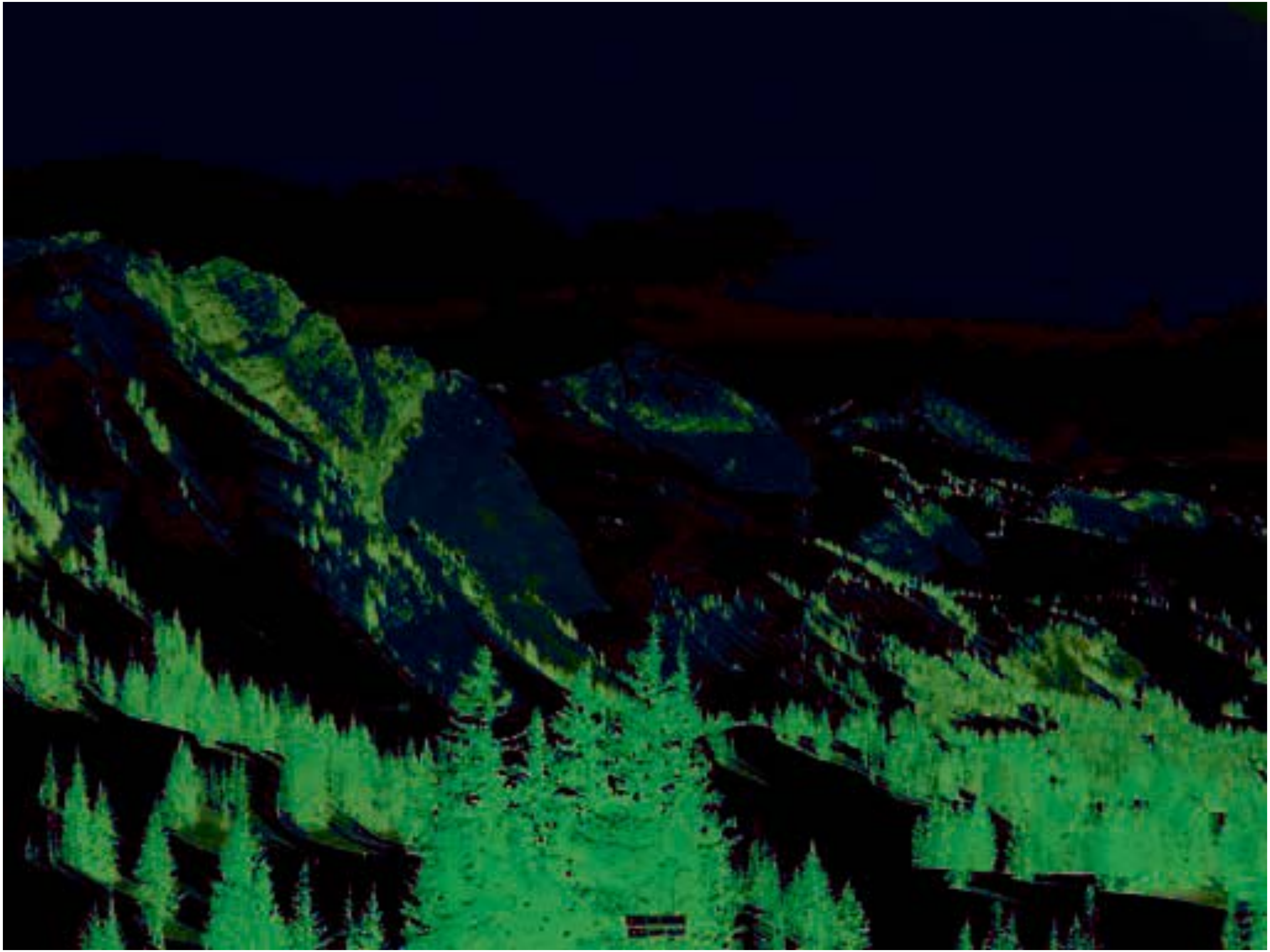
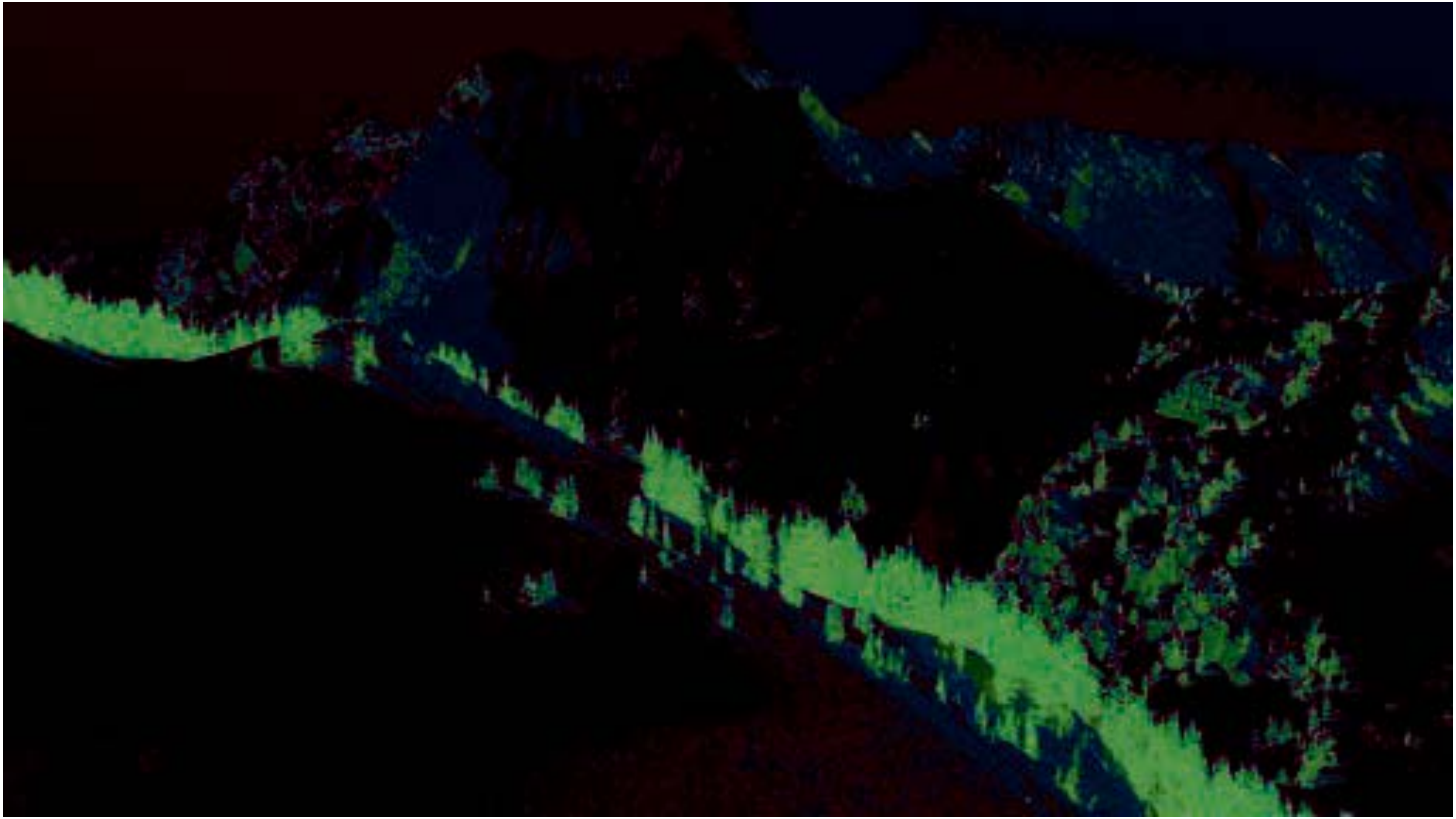
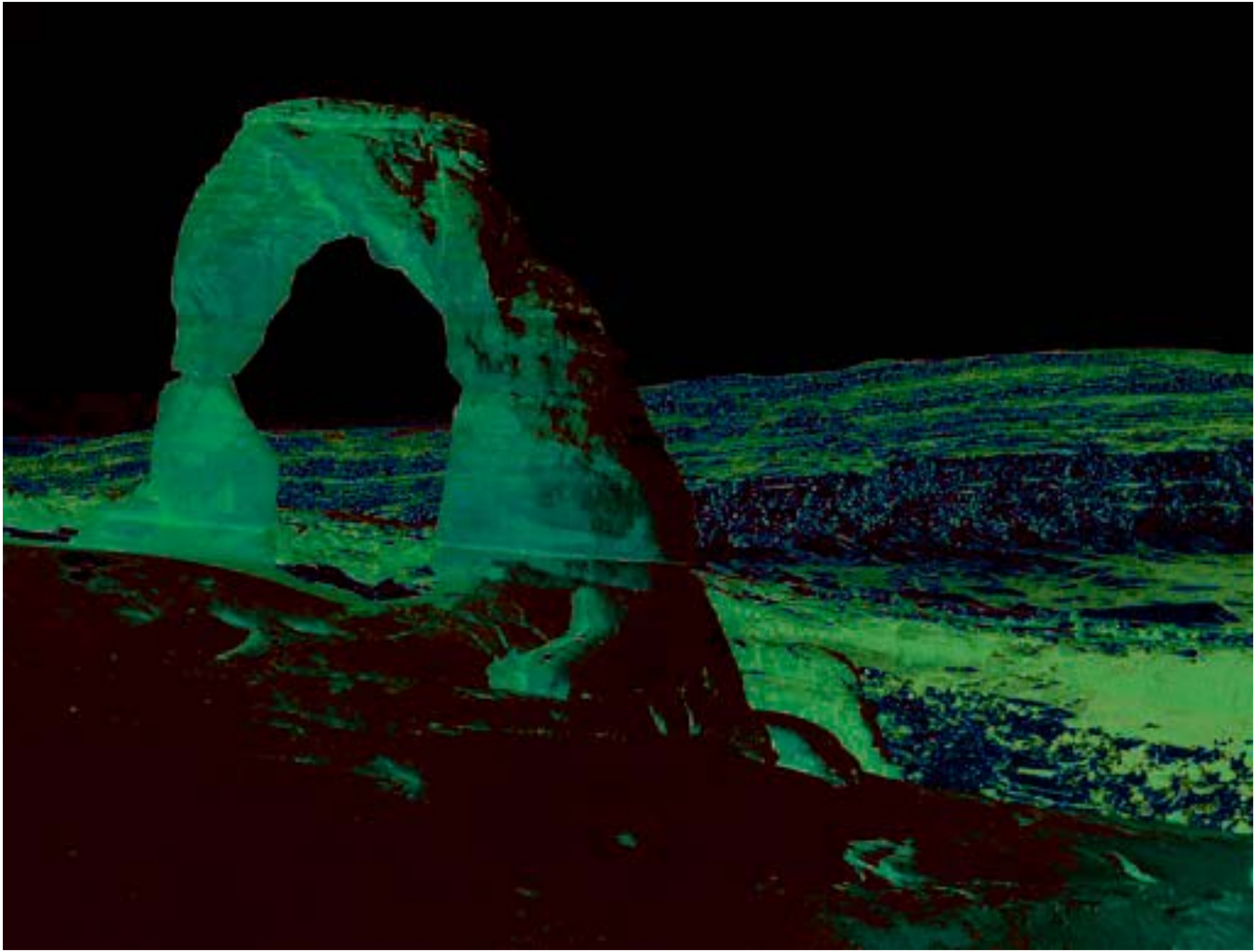
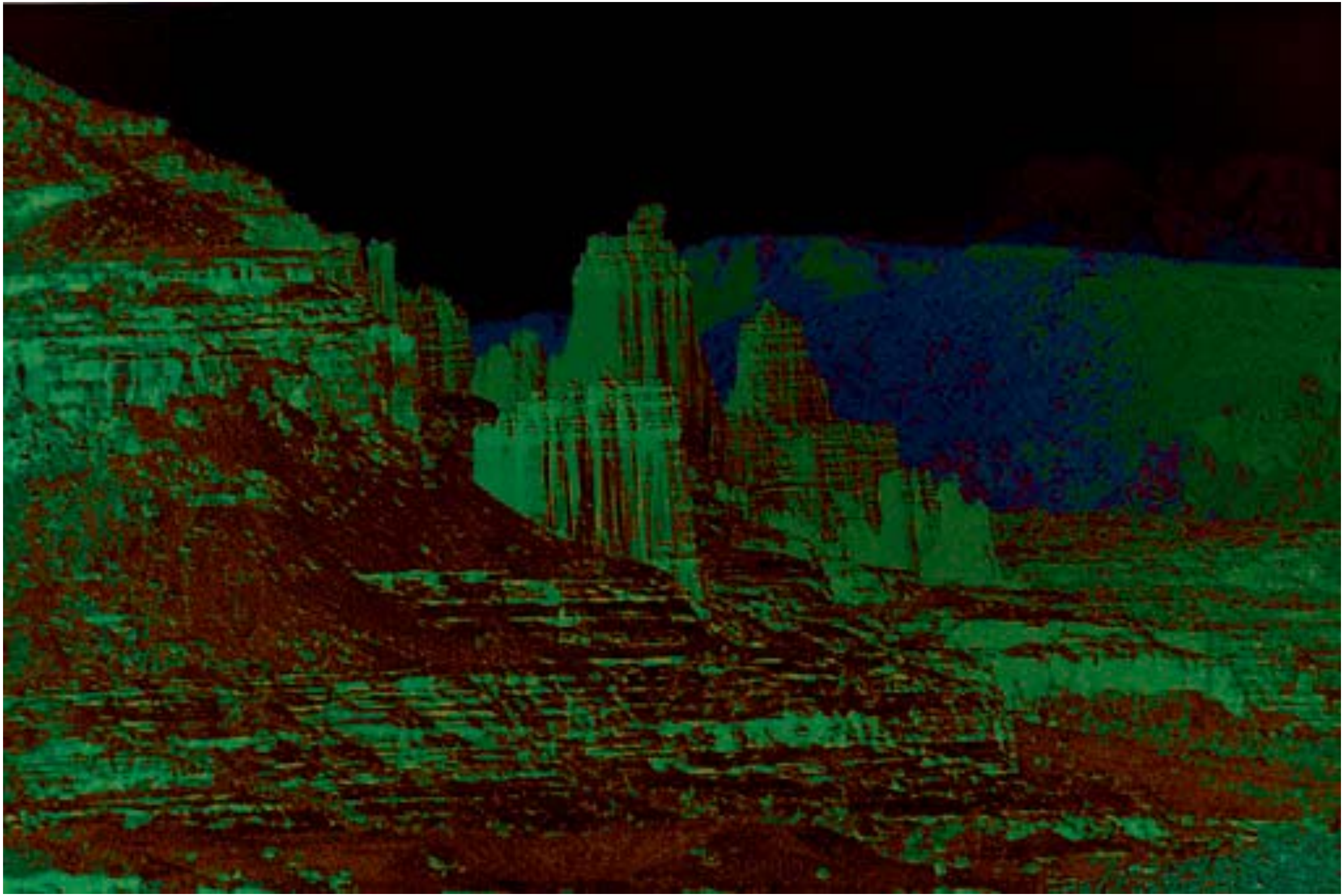
Hawaii



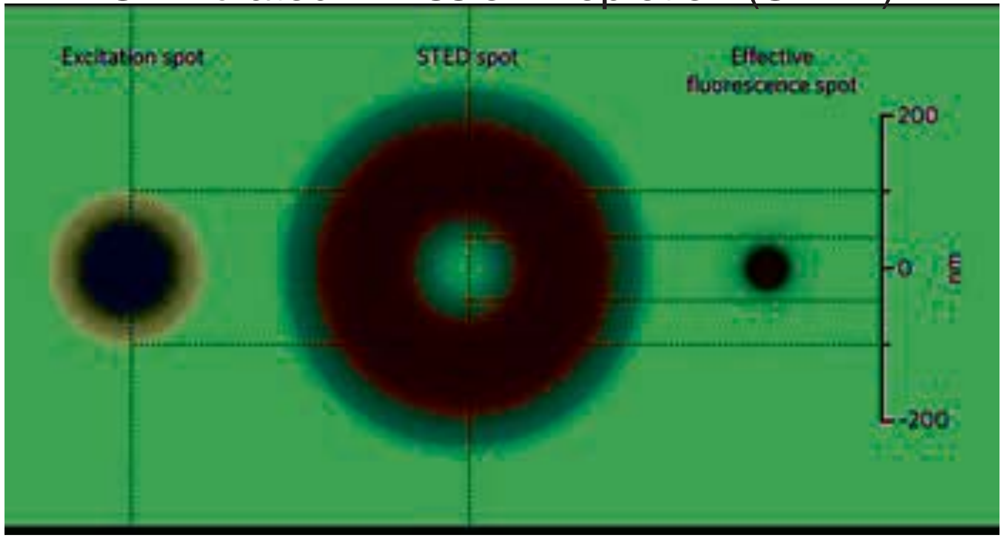




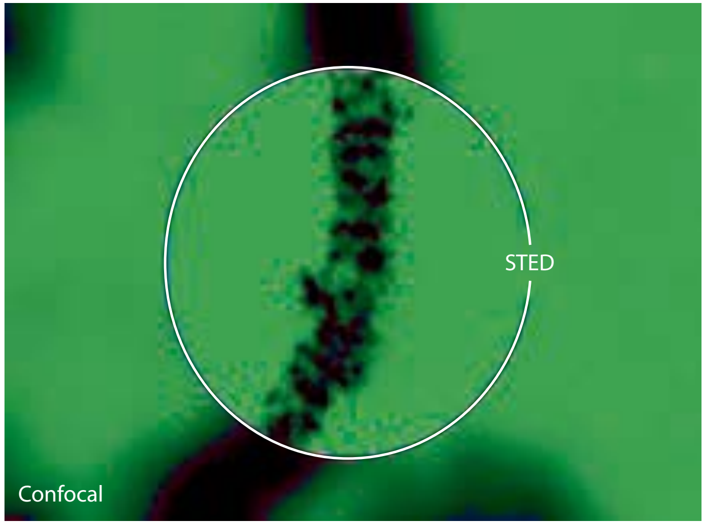


Superresolution using Fluorescence

STimulated Emission Depletion (STED)

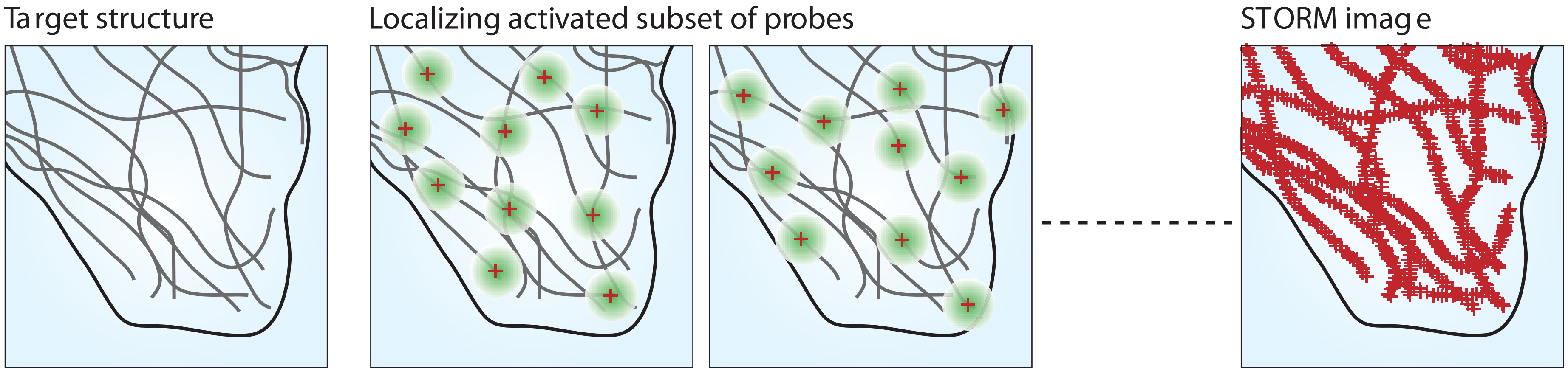


Folds of the mitochondrial inner membrane



T. A. Klar, *et. al, PNAS* 97, 8206 (2000).

STochastic Optical Reconstruction Microscopy (STORM)

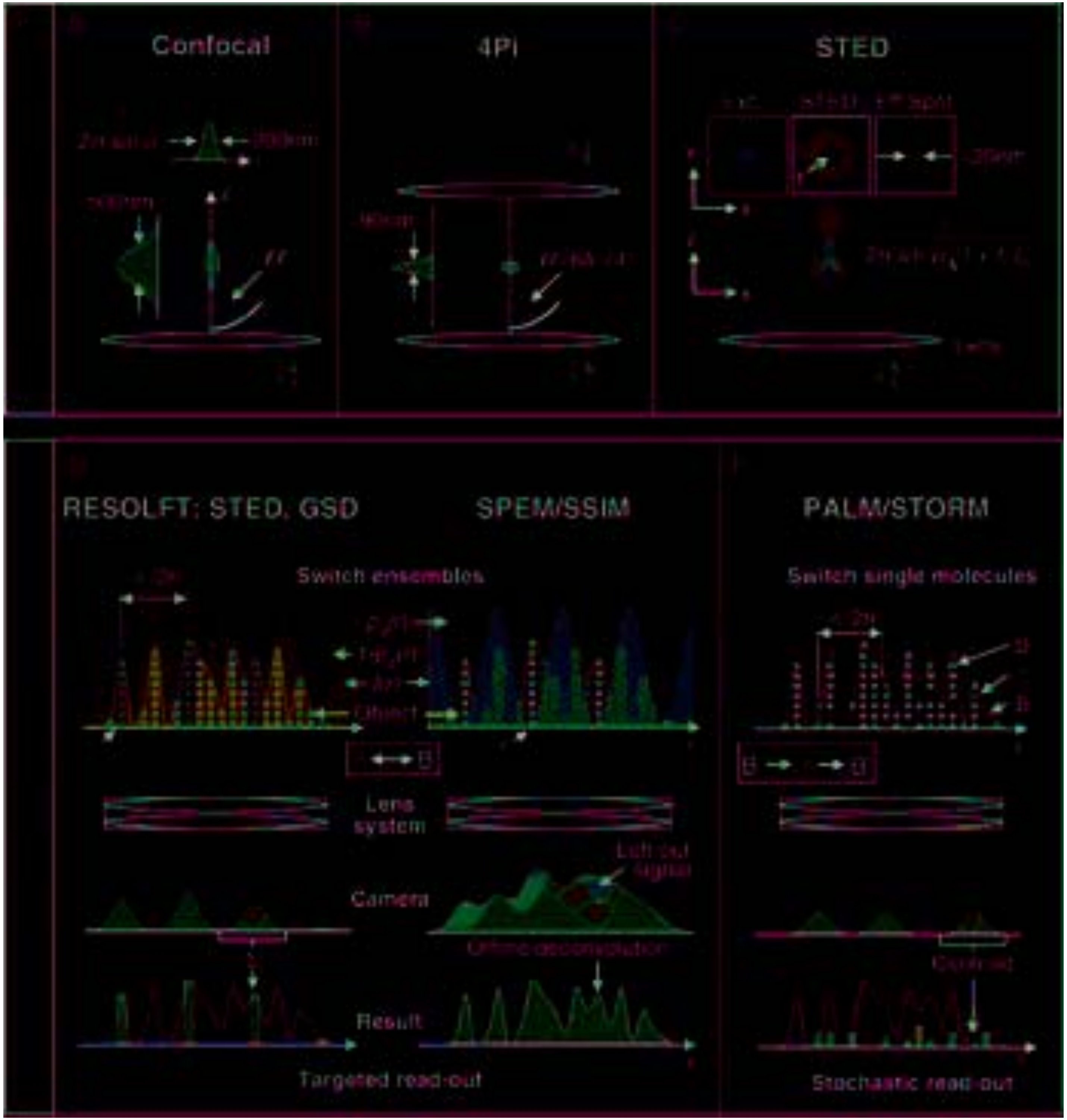


X. Zhuang, *Nat. Photonics*, 3, 365 (2009).

Acronyms

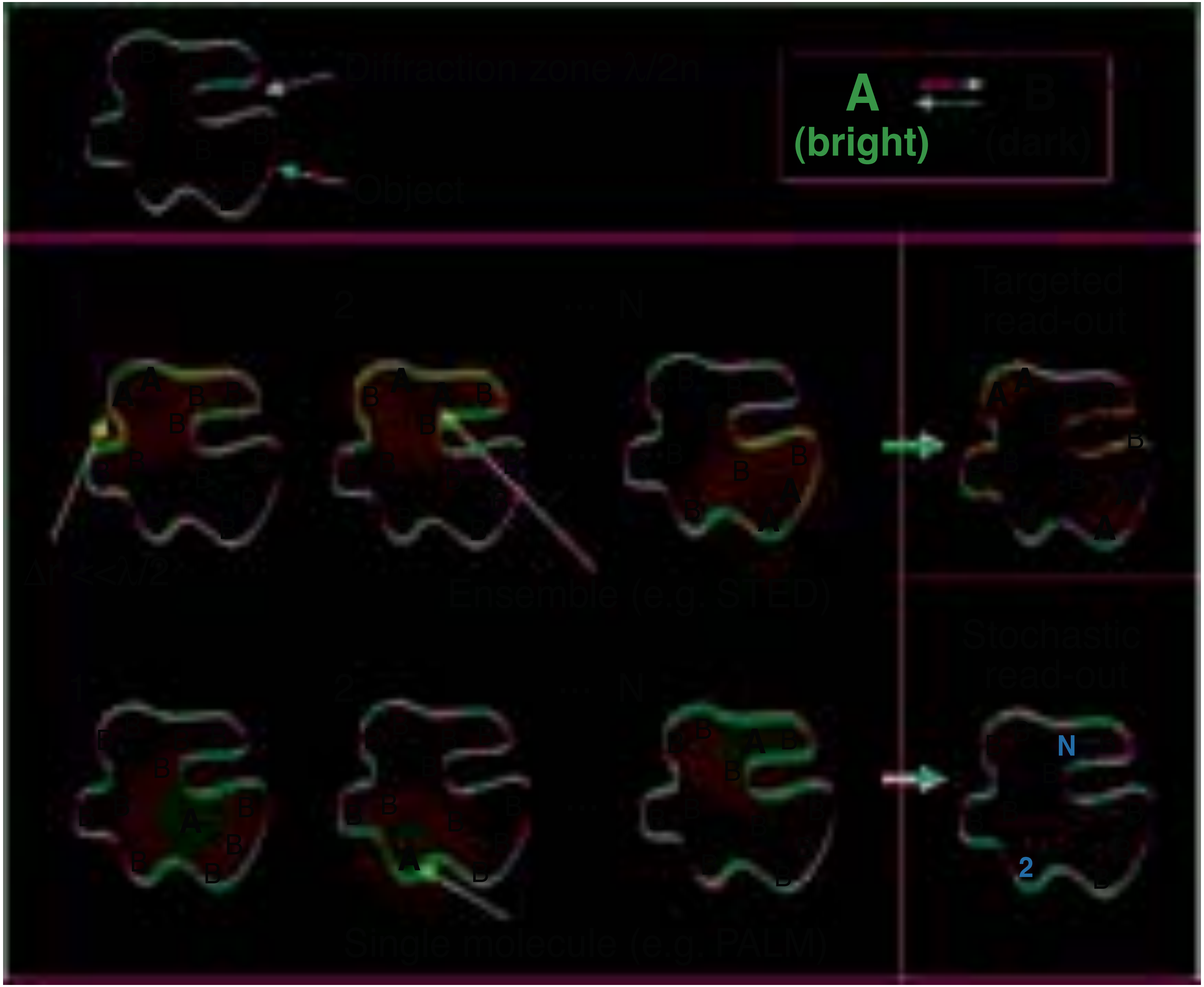
STED = stimulated emission depletion
GSD = ground state depletion
RESOLFT = reversible saturable optically linear fluorescence transitions
SPEM = saturated pattern excitation microscopy
SSIM = saturated structured illumination microscopy

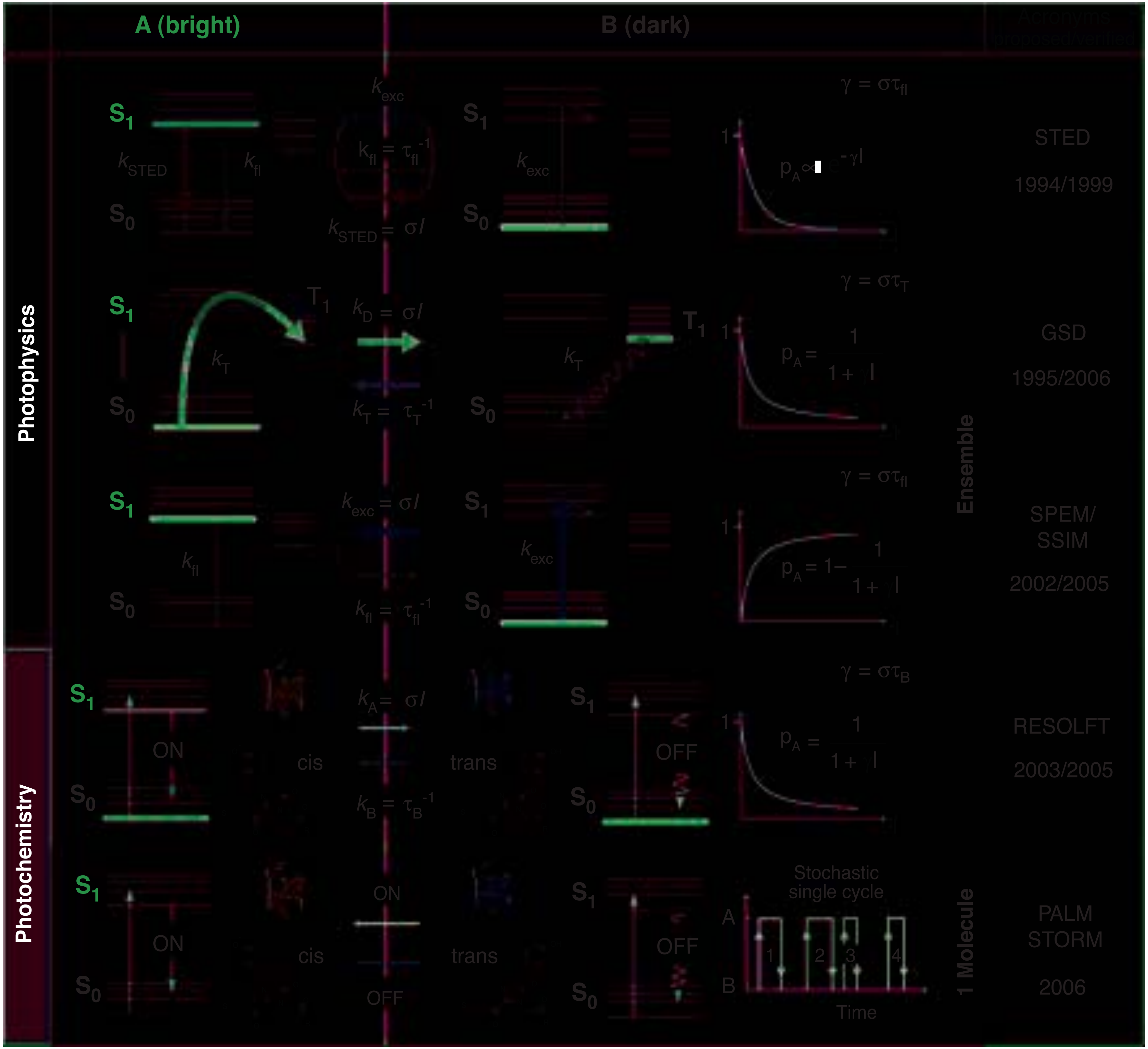
PALM = photoactivatable localization microscopy
STORM = stochastic optical reconstruction microscopy



S. W. Hell, Science, 316, 1153 (2007)

Scanning vs non-scanning: STED vs PALM





$\tau_{fl} \approx 10^{-9}$ s

$\sigma \approx 10^{-16}$ cm^2

Is = $(\sigma\tau_{fl})^{-1}$
~ 10MW/cm^2
sub-ns, not femtosecond

$\tau_T \approx 10^3$ to 10^6 ns
(T_1 is meta-stable)

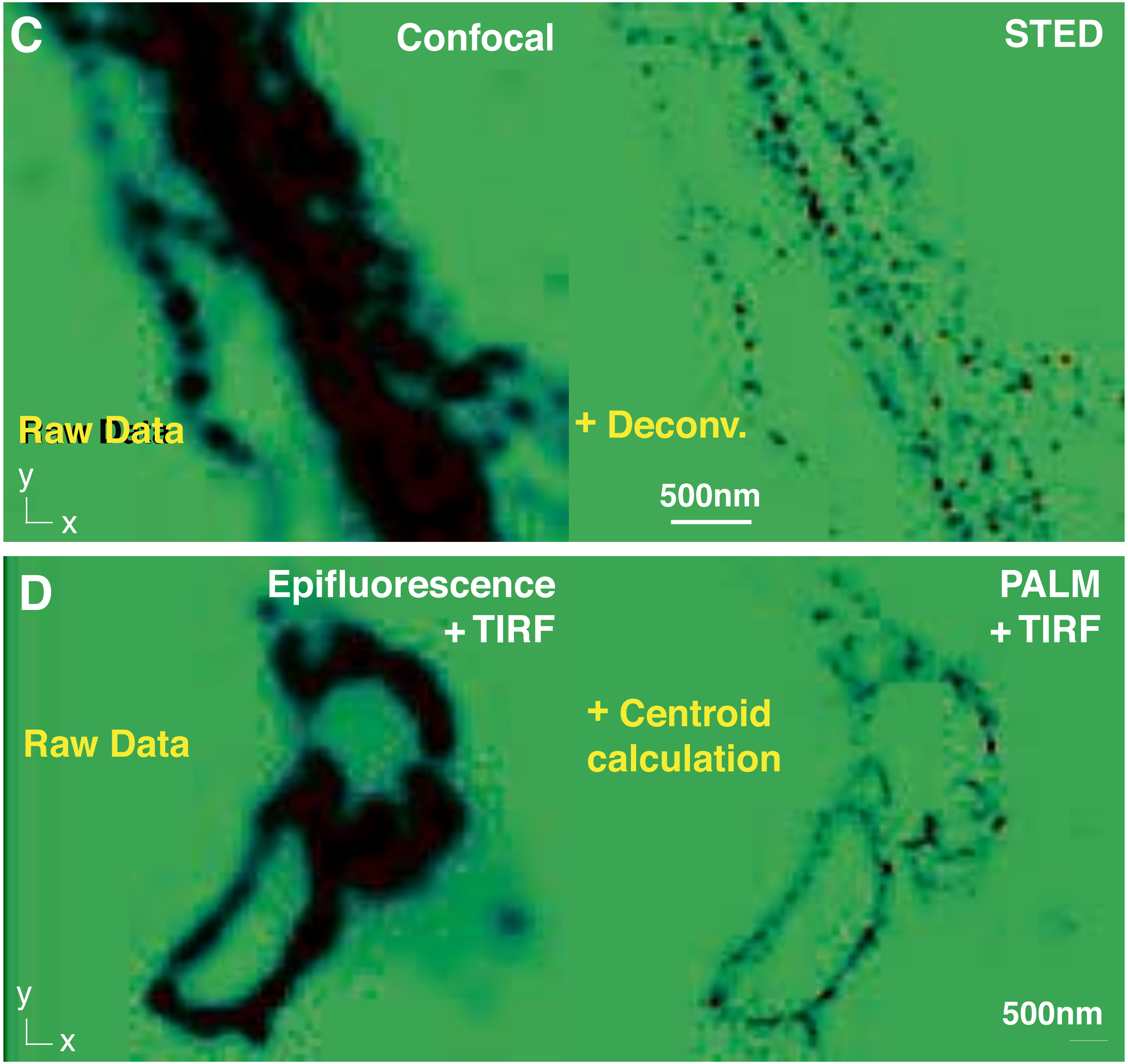
~100 kW/cm^2 (CW)

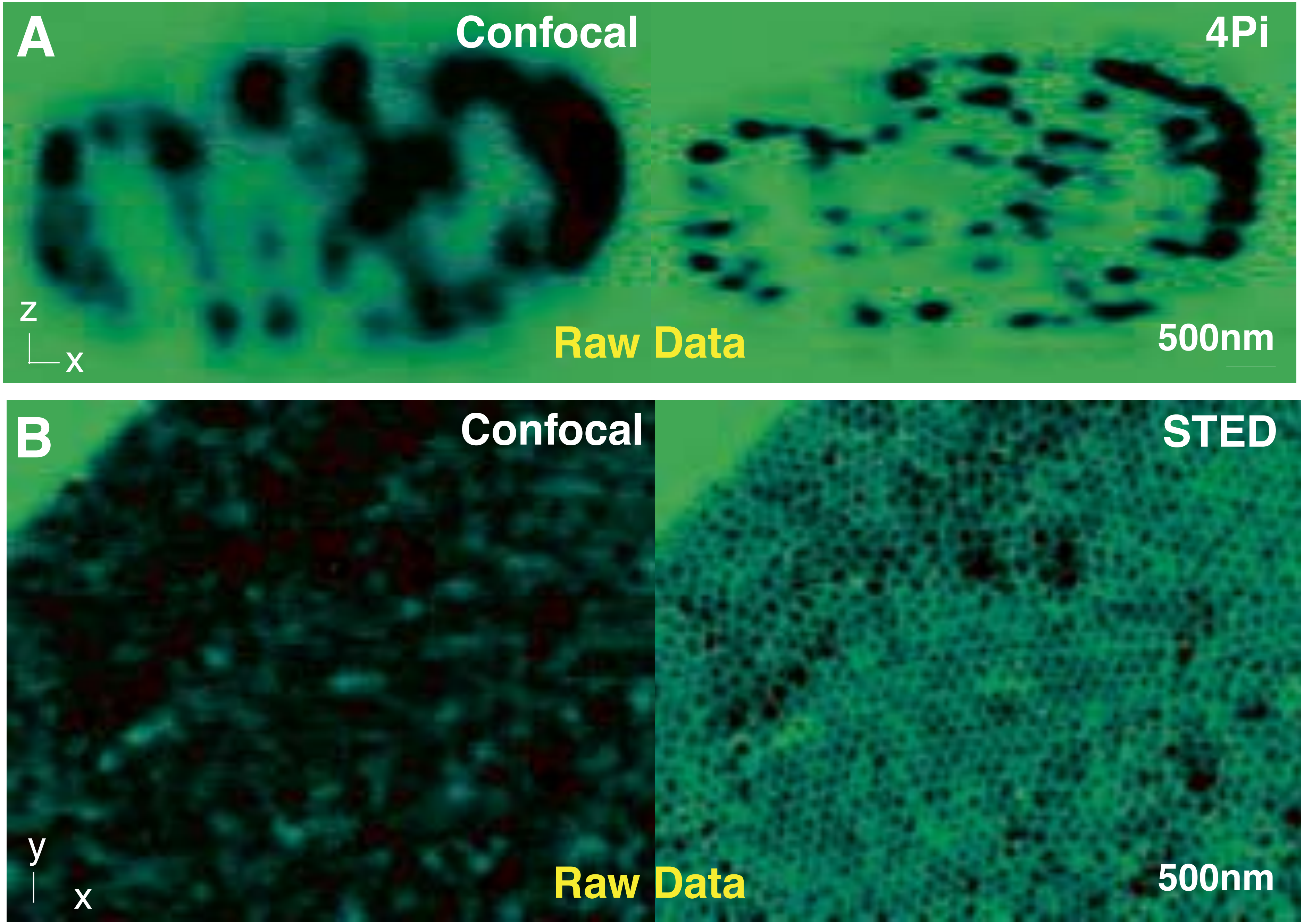
Higher SNR requiremen

10 W/cm^2

Photostability ?

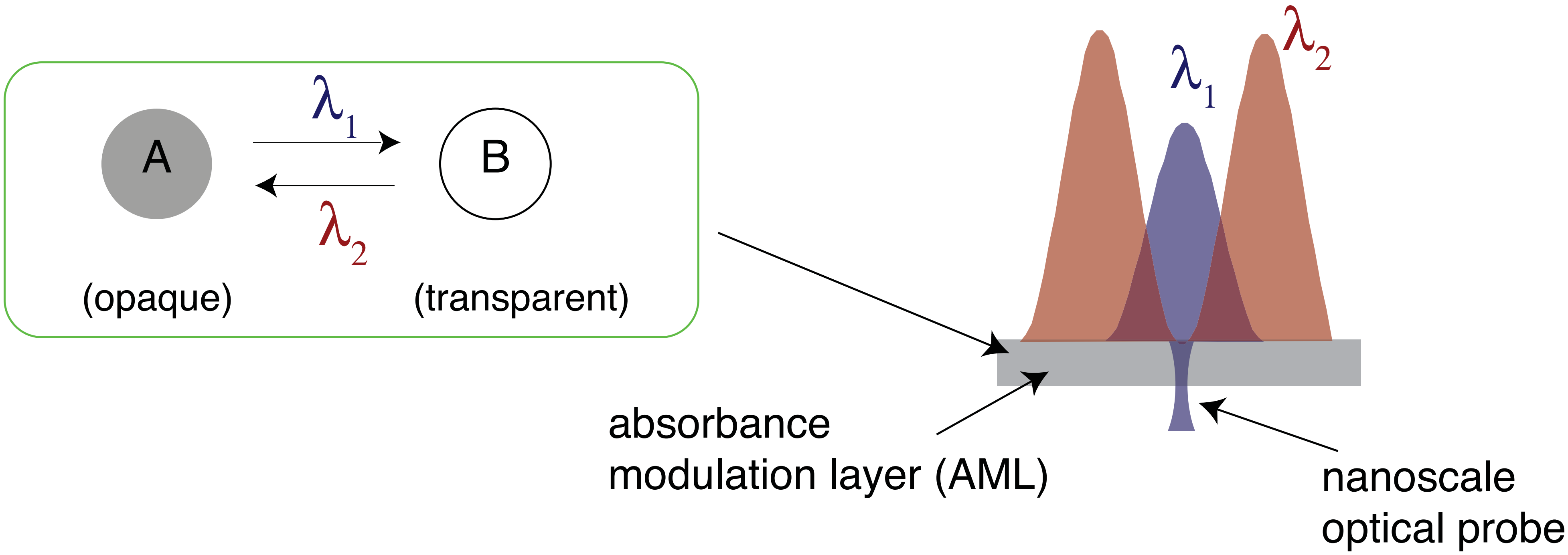
computation
long recording times


C
Confocal
STED
Raw Data
+ Deconv.
500nm
y
x
D
Epifluorescence
+ TIRF
PALM
+ TIRF
Raw Data
+ Centroid
calculation
500nm
y
x



A
Confocal
4Pi
z
x
Raw Data
500nm
B
Confocal
STED
y
x
Raw Data
500nm

Absorbance Modulation: Exploiting Wavelength-selective chemistry to overcome the Diffraction limit

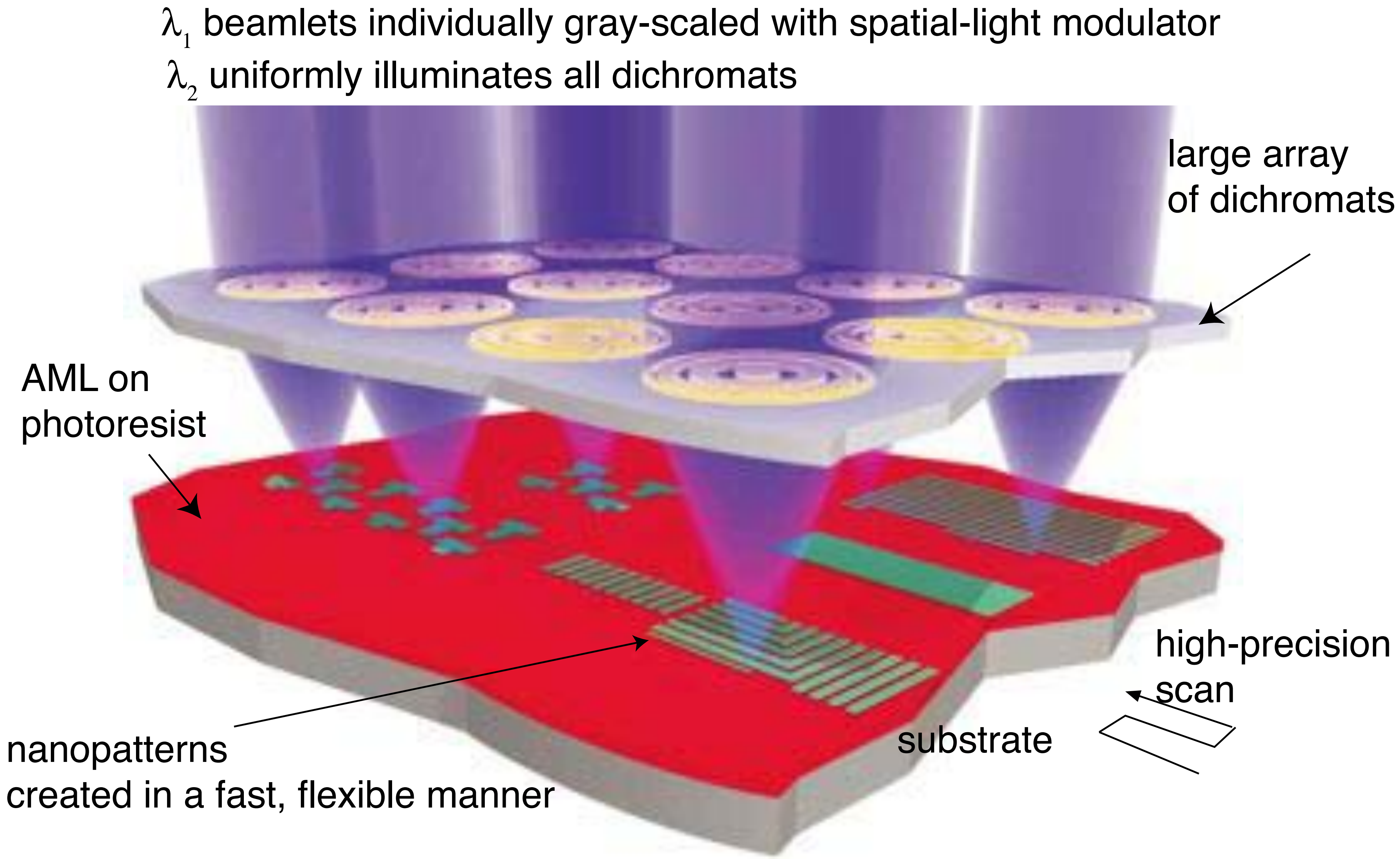


Focal ring at λ_2 in competition with round spot at λ_1 creates a localized sub-wavelength aperture.

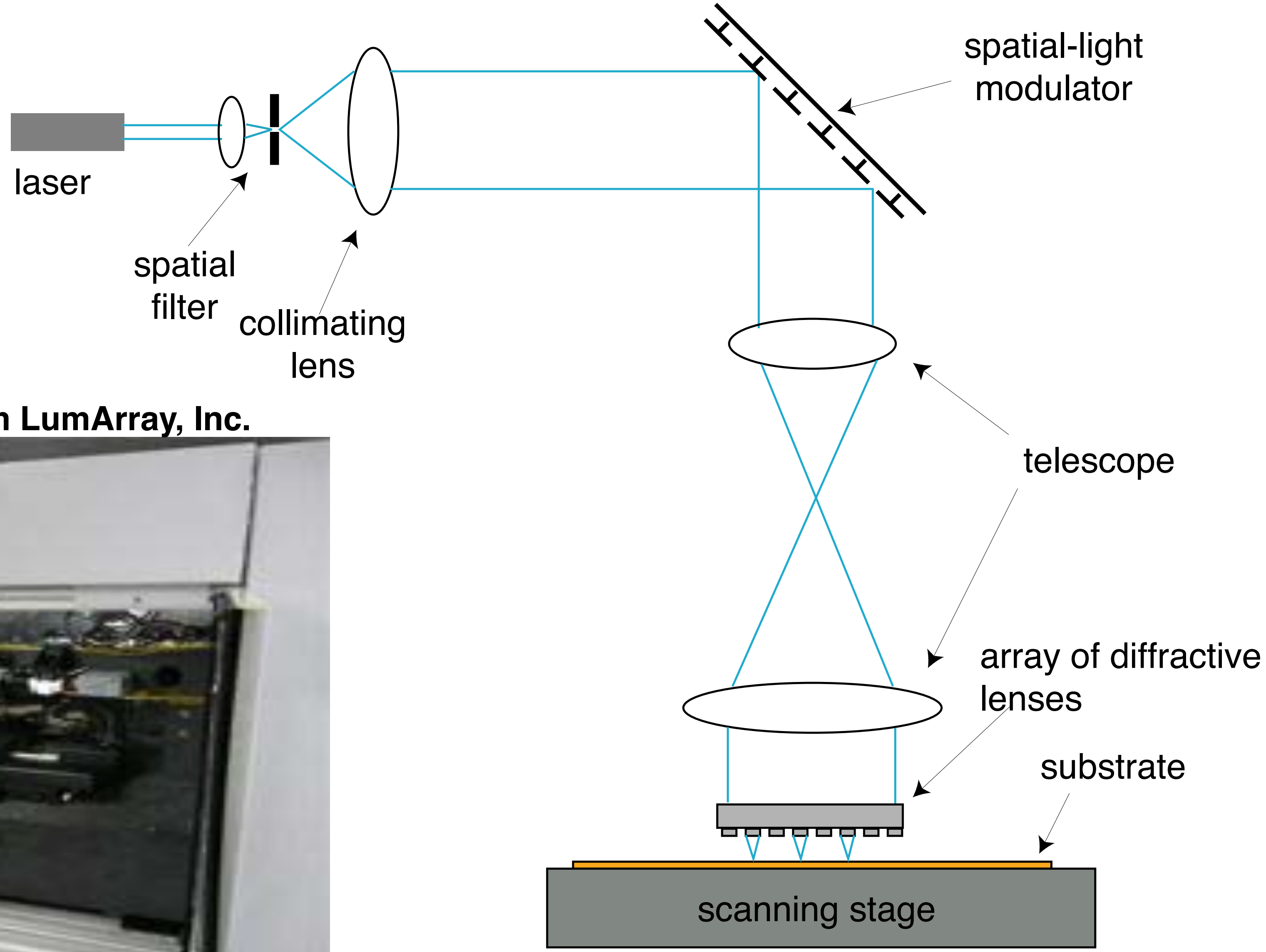
Light at λ_1 penetrates through this aperture forming a nanoscale probe

T. L. Andrew, H-Y. Tsai, **R. Menon**, Science, 324, 917 (2009),
H-Y. Tsai, G. W. Wallraff, **R.Menon**, Appl. Phys. Lett. 91(9), 094103 (2007)
R. Menon, H-Y. Tsai & S. W. Thomas, III, Phys. Rev. Lett. 98, 043905 (2007).
R. Menon, H. I. Smith, JOSA A, 23, 2290 (2006).

Vision: Massively parallel, independently controllable nanoscale optical probes



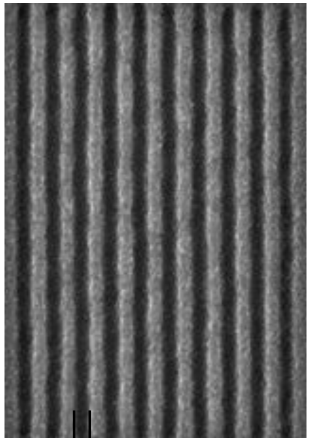
Architecture for massively parallel patterning



Commercial tool from LumArray, Inc.

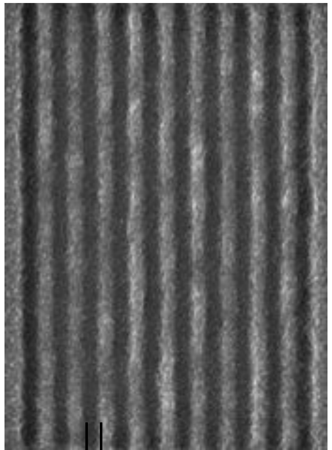
Examples of ZPAL Patterns

$k_1 = 0.38$



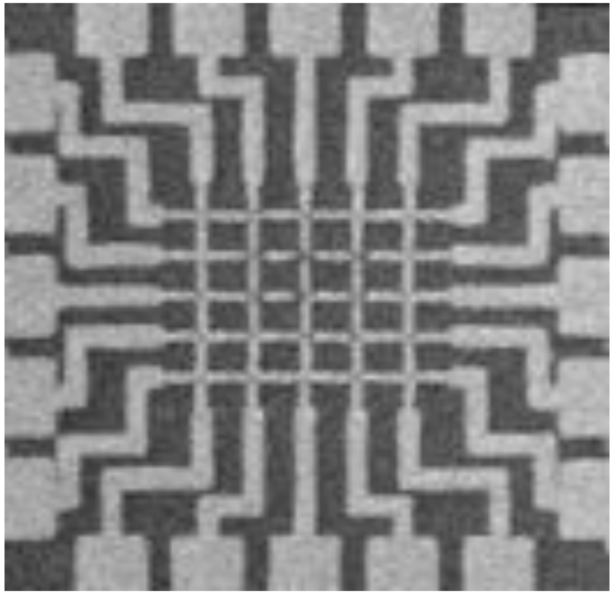
180nm

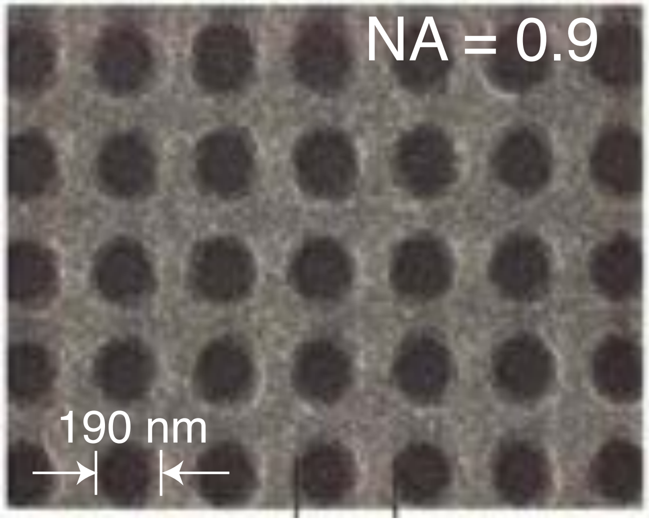
$k_1 = 0.32$



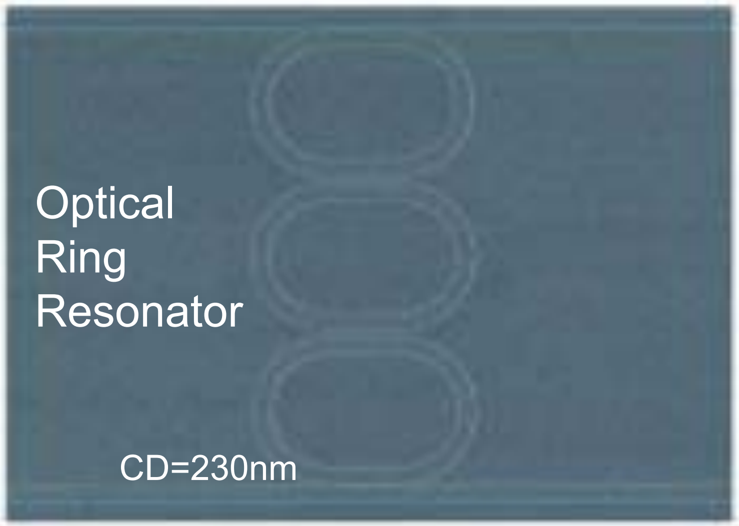
150nm

Prototype MRAM memory



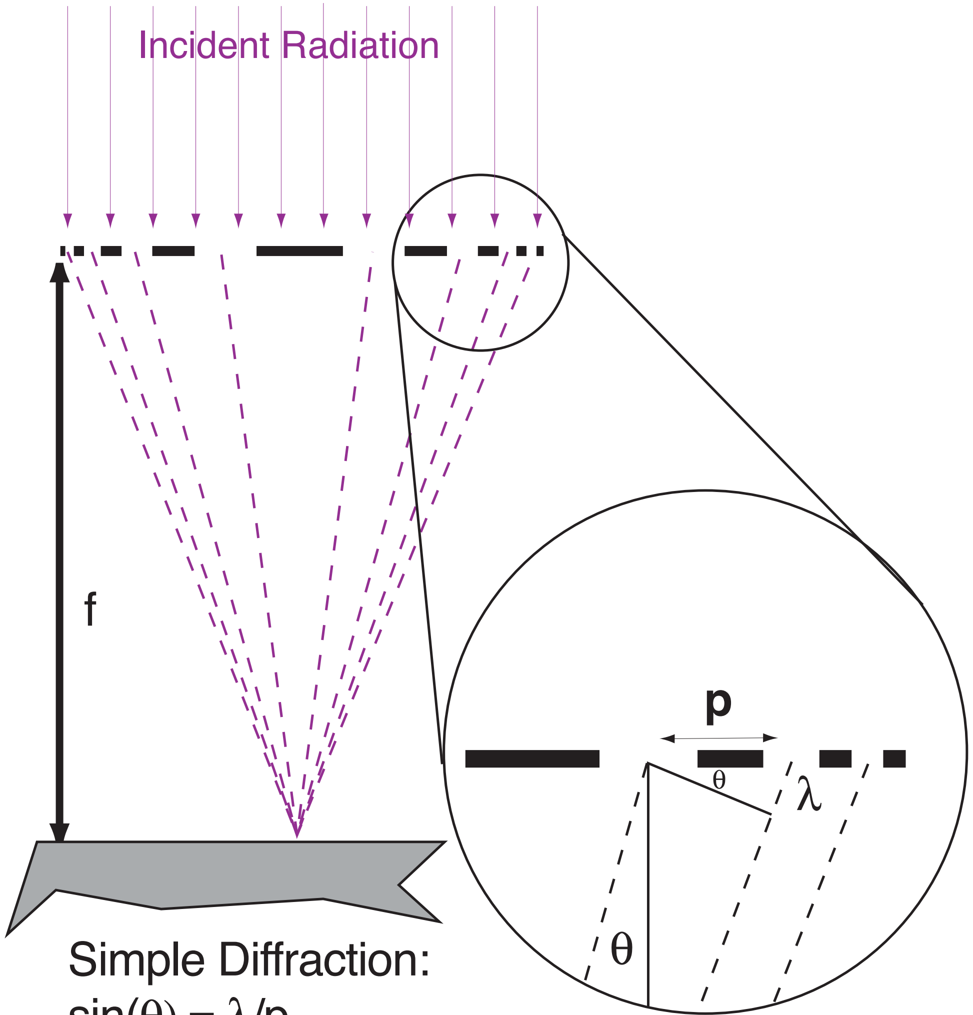


Array of contact holes



SPIE Advanced Lithography 2009

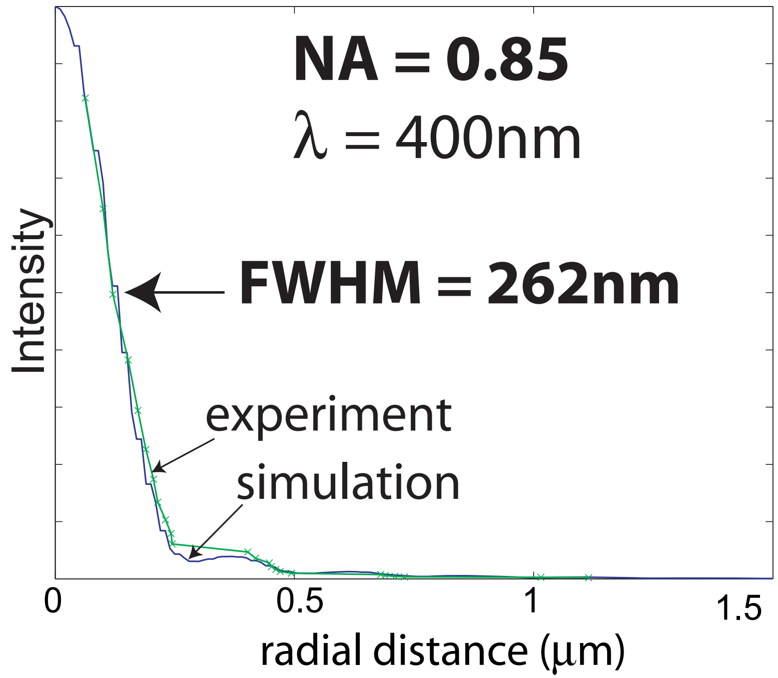
Zone Plate: A Simple Diffractive Lens



Simple Diffraction:
$\sin(\theta) = \lambda/p$

Why diffractive optics?

- Abberation-free on-axis.
- High-NA at low cost.
- Fabricated with planar process.
- Focus uniformity across array.
- Wavefront engineering.

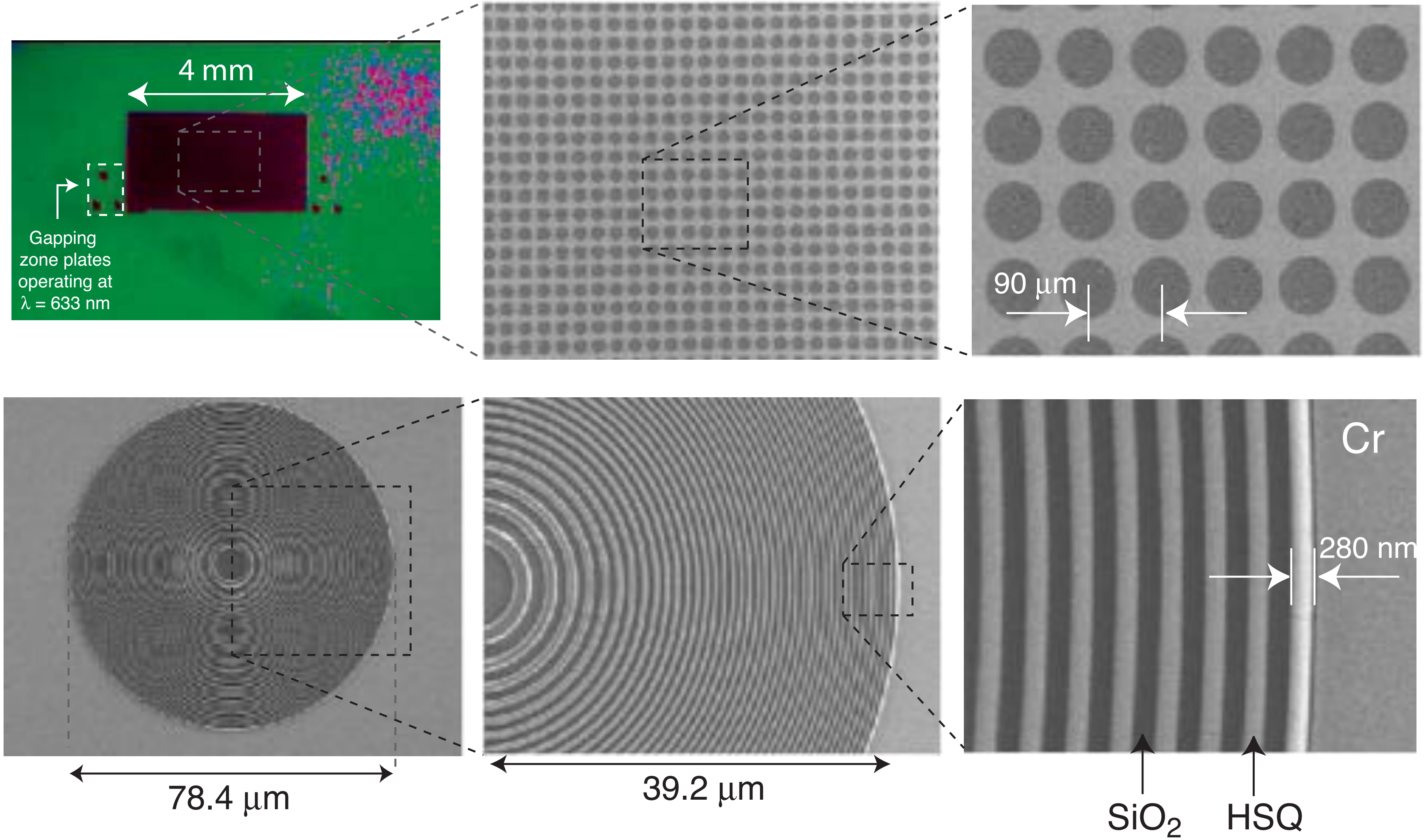


D. Gil, et al. 'The Case for Diffractive Optics in Maskless LIthography,' J. Vac. Sci. Technol B 21(6) 2003

Large Zone-Plate Arrays Possible

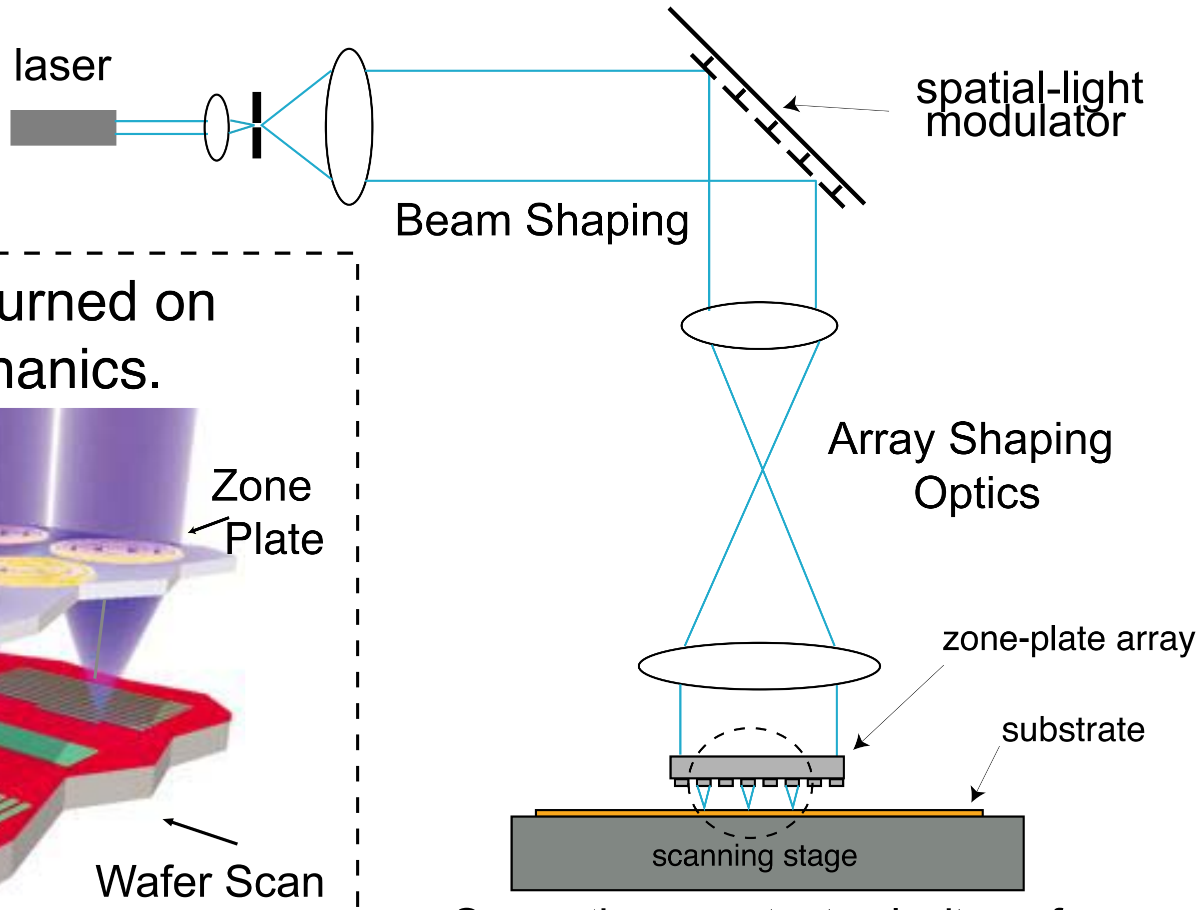
1000 Zone Plates for λ = 400 nm, with NA = 0.7 and Focal Length = 40 μm

Areal Coverage ~ 9 mm^2



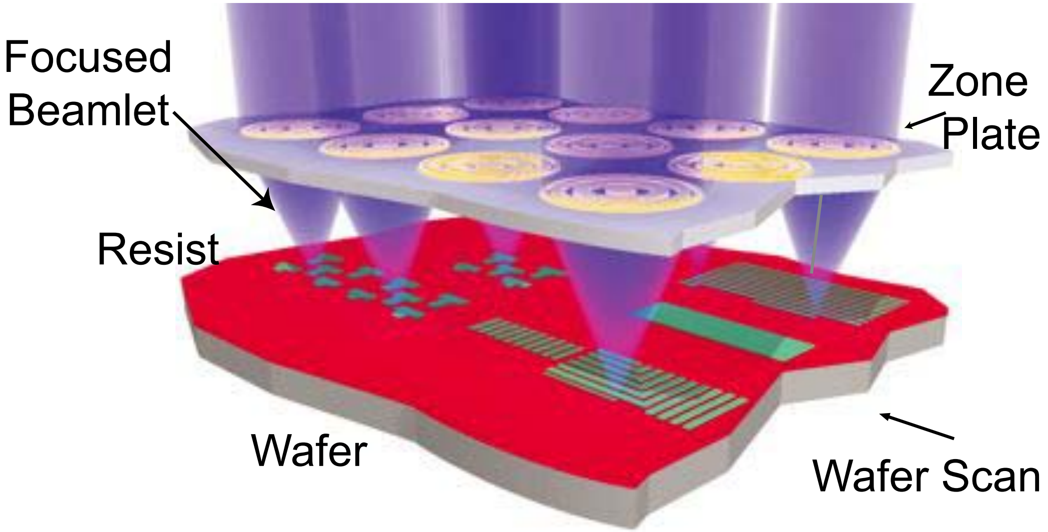
Zone-Plate-Array Lithography

Arbitrary patterns in a dot-matrix fashion as substrates are scanned beneath a fixed array of diffractive microlenses known as zone-plates.



Serpentine, constant-velocity wafer scan.

Beamlets individually turned on and off with micromechanics.



Each ZP focuses radiation to a spot.

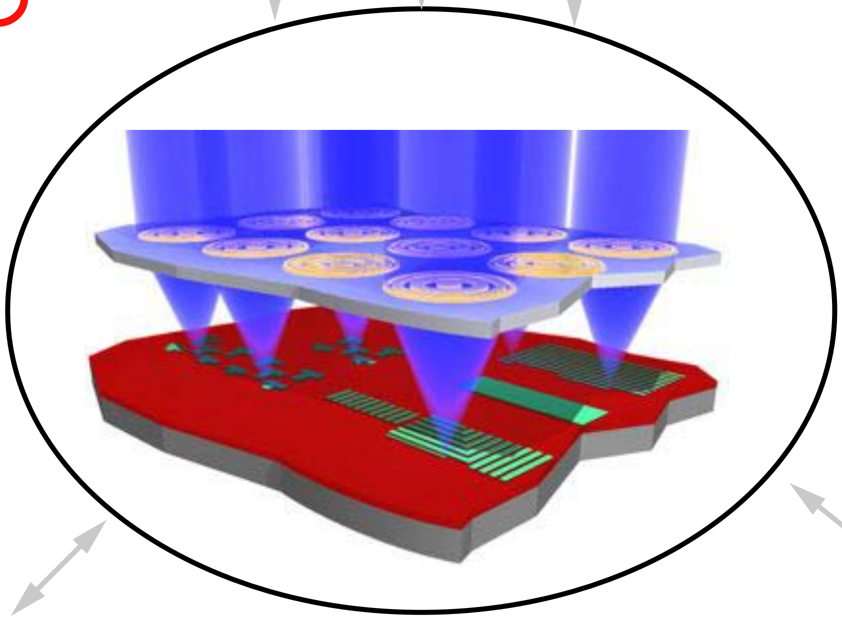
ZP-150A System Overview

Data Delivery Electronics
Custom FPGA design.
Synchronizes data with motion.
Position-clocked laser trigger.

Spatial Light Modulator
Silicon Light Machines Grating Light Valve,
1088 Pixels, 290 kHz, 8-bit grayscale.

Optics
405nm GaN Laser.
Beam Mapped to GLV.
GLV mapped to ZPA.

Data Preparation
GDSII Pattern.
PEC & Fracturing.
Optimized bitmap.
~4 Tb /150mm wafe.r



ZPA Fabrication
e-beam lithography
HSQ on Fused Silica
1000 lens monolithic array
0.85NA, ~135µm diameter

1nm position
@ 20MHz

Precision Metrology
Direct ZPA-Wafer Measurement
minimizes Abbe error, drift.
2D Grid Encoder, min res 0.3nm.
3-5nm repeatability, 50nm global

Scanning Air Bearing & Position Control System
6“ x6” Hi-res travel
~3nm RMS Error
20mm/sec velocity

ISPI Gapping & Overlay
Direct Measurement of
ZPA to Wafer Distance.
Overlay Detection <1nm

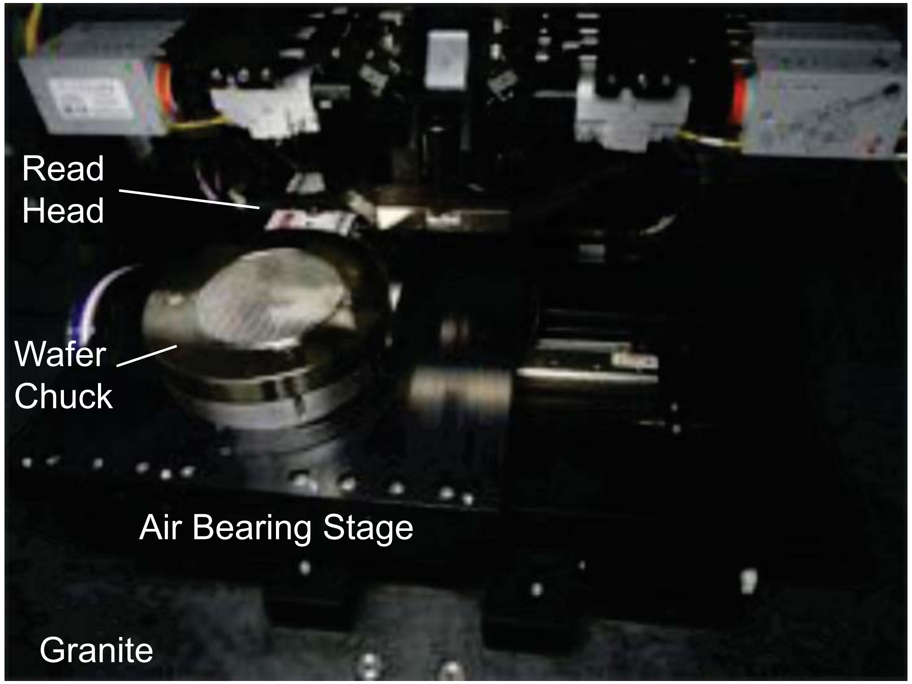
Design for Accuracy

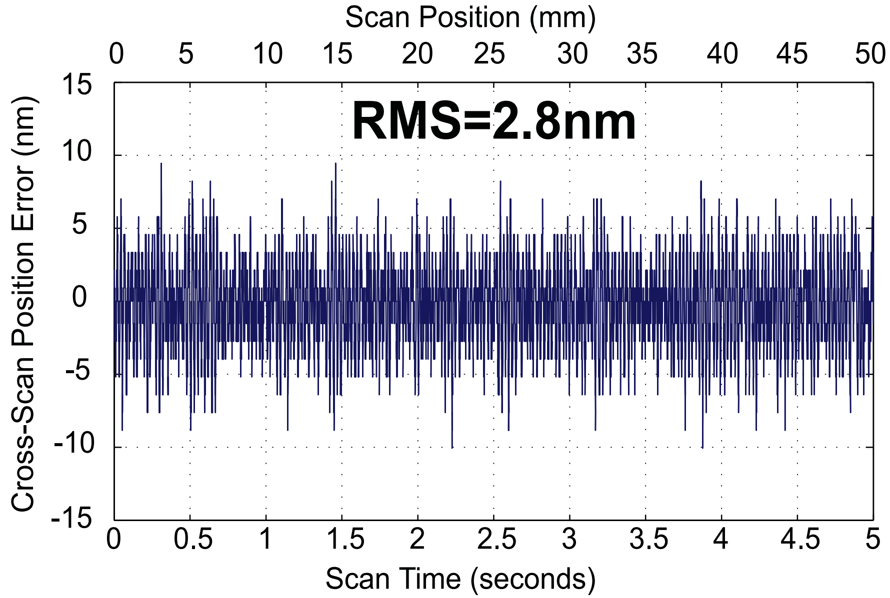
Design	Benefit
Static Lens Array Monolithic zone-plate array fixes relative positions of all beams on wafer.	★ Accurate Stitching ★ Loose Tolerances for beams to ZPA. ★ Location of beams on wafer determined only by stage position relative to ZPA.
Position-clocked data Timing of exposure determines location of exposed pixels on wafer	★ Only errors normal to scan are printed. ★ Position and velocity errors along scan compensated by exposure timing.
Direct Metrology ZPA, wafer chuck integrated in metrology frame with 2D encoder.	★ Directly measures ZPA relative to wafer, not to machine frame ★ Reduces Abbe error, simplifies overall system. ★ More robust than laser interferometer

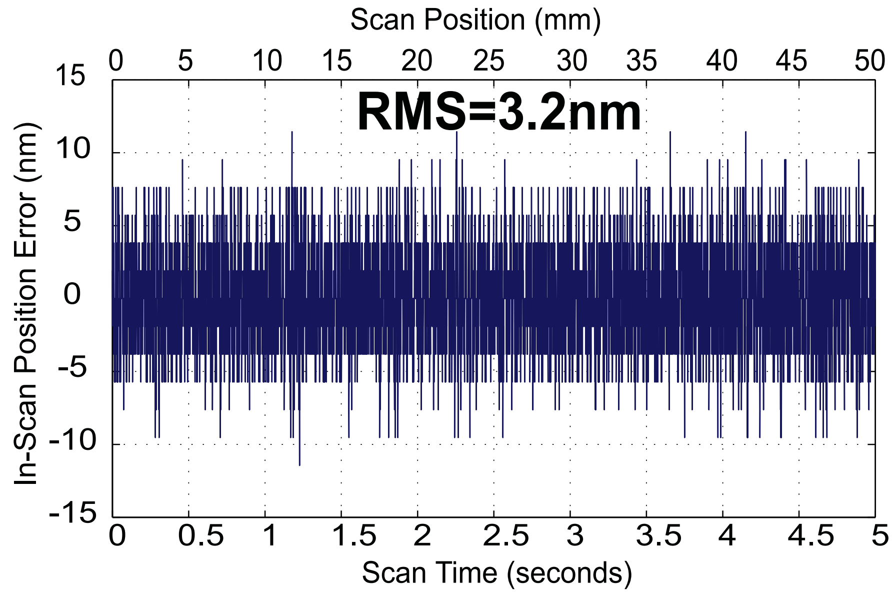
Scanning System

Only Cross-Scan error, not along scan,contributes to pattern error

- Custom XY Air Bearing onGranite Base
- 1nm resolution at 20MHz
- 2kHz Control Loop



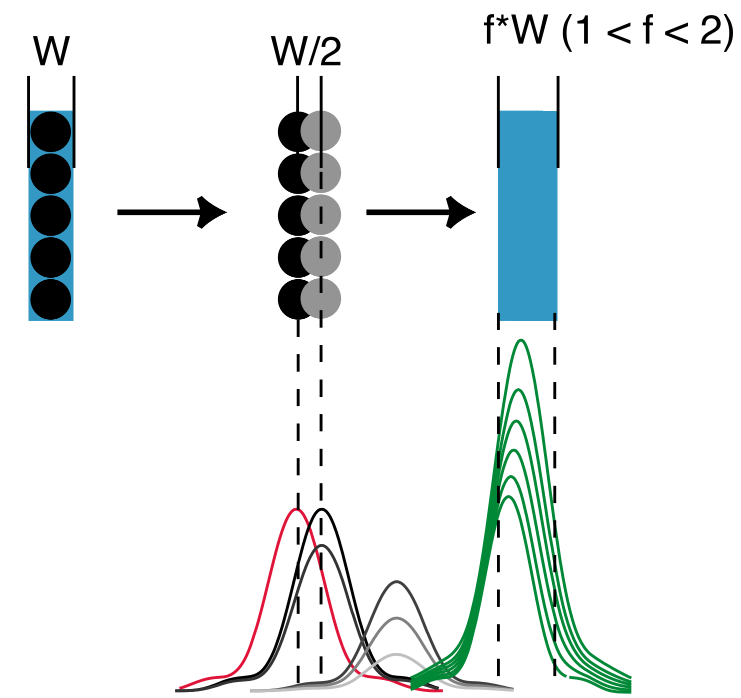




Pattern Optimization

Proprietary software ensures pattern fidelity, CD linearity by optimizing dose level to every pixel. Also corrects illumination inhomogeneity.

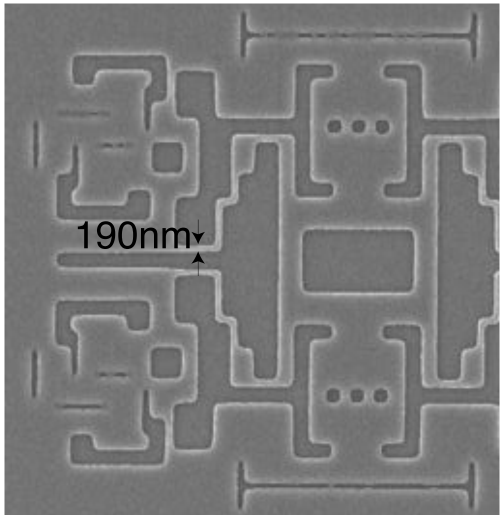
Line-Edge Control



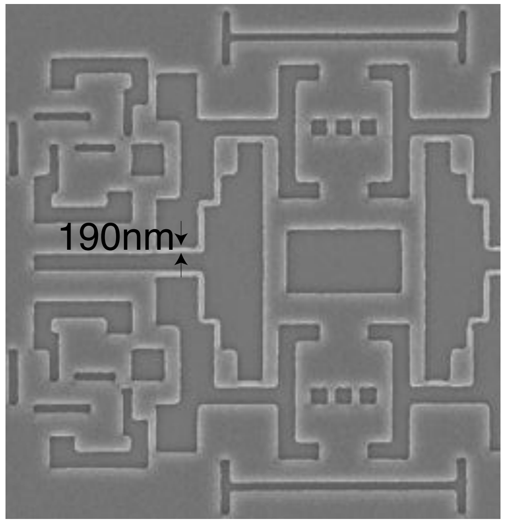
~200 gray-levels for every exposure pixel allows sub-pixel line control

Proximity-Effect Correction

Uncorrected



Corrected

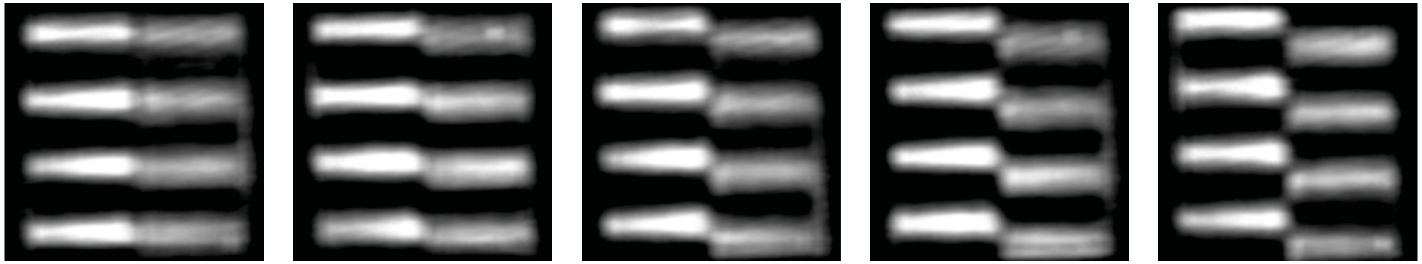


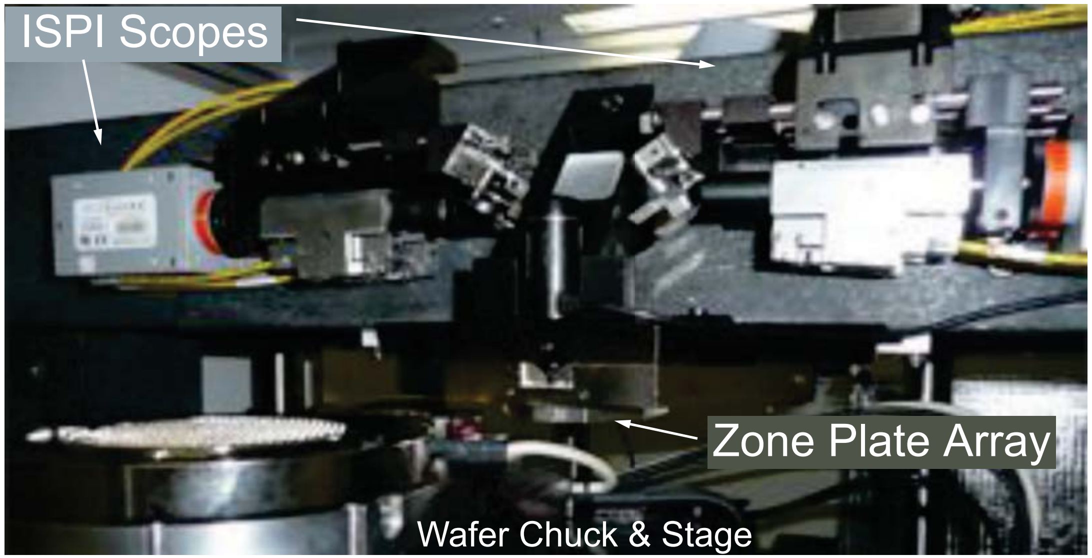
PEC is computationally easier for ZPAL (incoherent) than coherent imaging (e.g. projection litho).

Interferometric Spatial-Phase Imaging

ISPI encodes position in the spatial-phase disparity between a matched pair of interferometric moiré patterns that magnify displacement.

sub-1 nm via phase-analysis





Benefits of ISPI

Directly measure working distance.

Direct ZPA-wafer overlay.

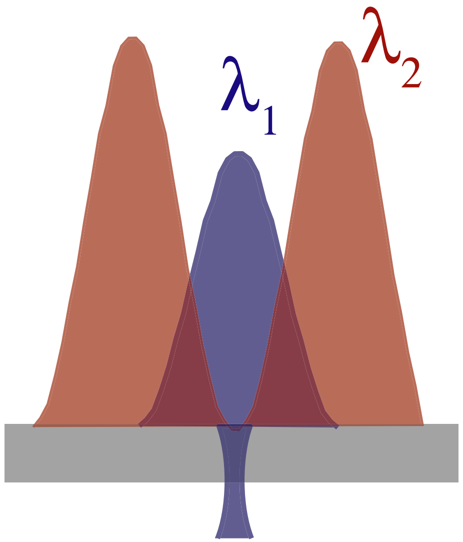
Dark Field Imaging for High-SNR.

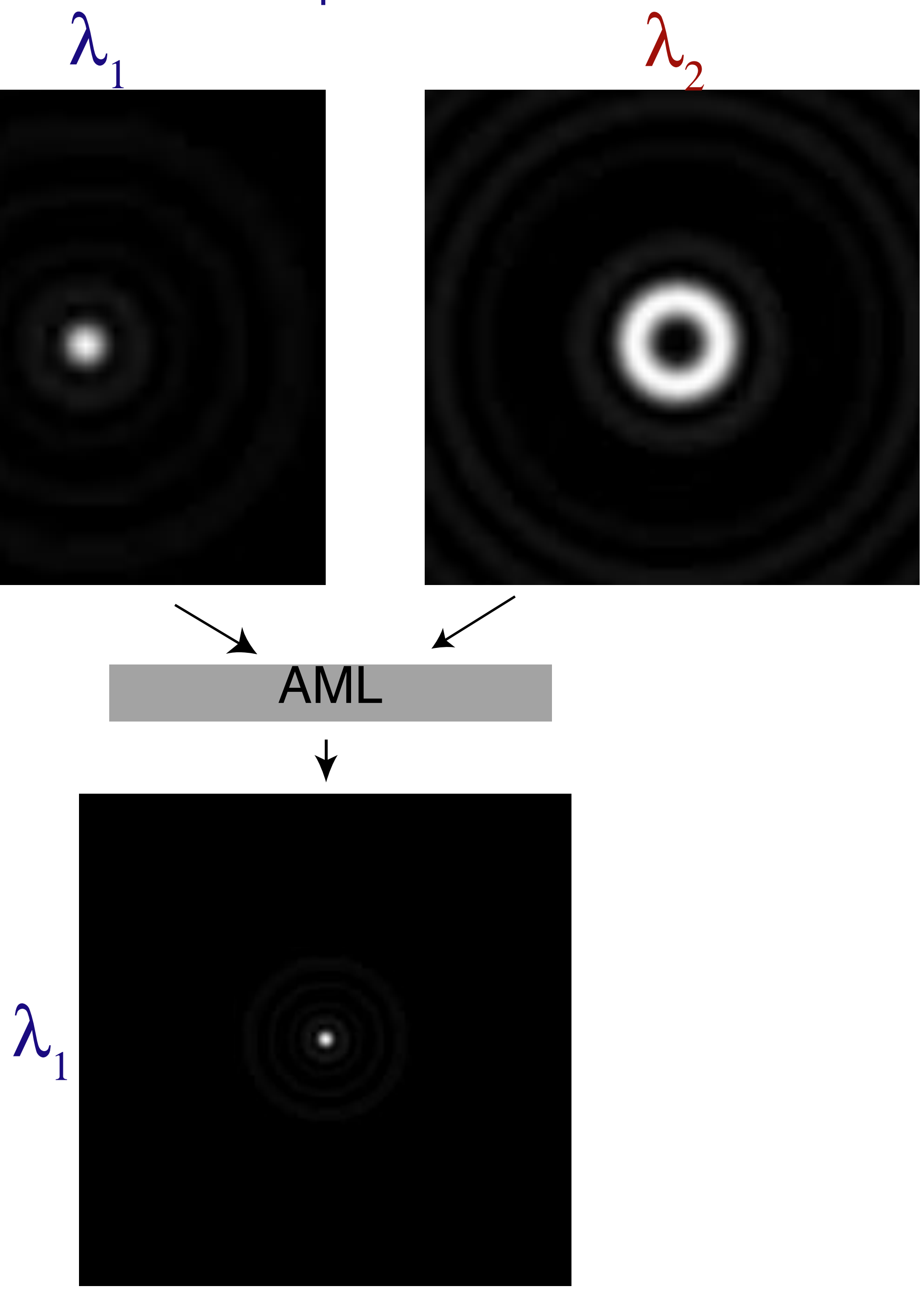
Low-NA (0.06) optics.

Robust through multiple layers.

E.E. Moon et al, *J. Vac Sci. Technol. B* 21(6) 3112 (2003)

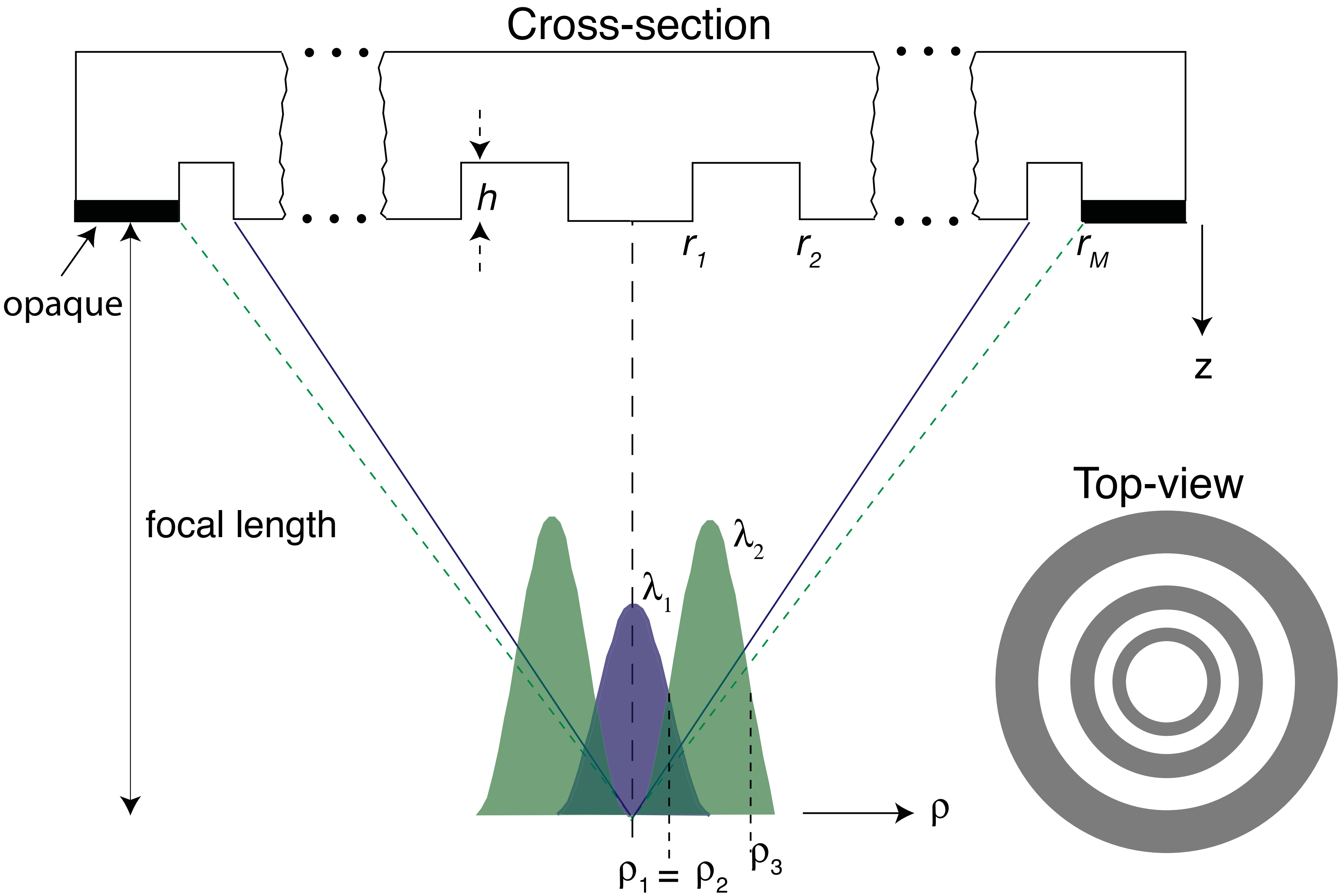
Extension to 2-D requires Ring-shaped spot @ λ_2 & Round spot @ λ_1



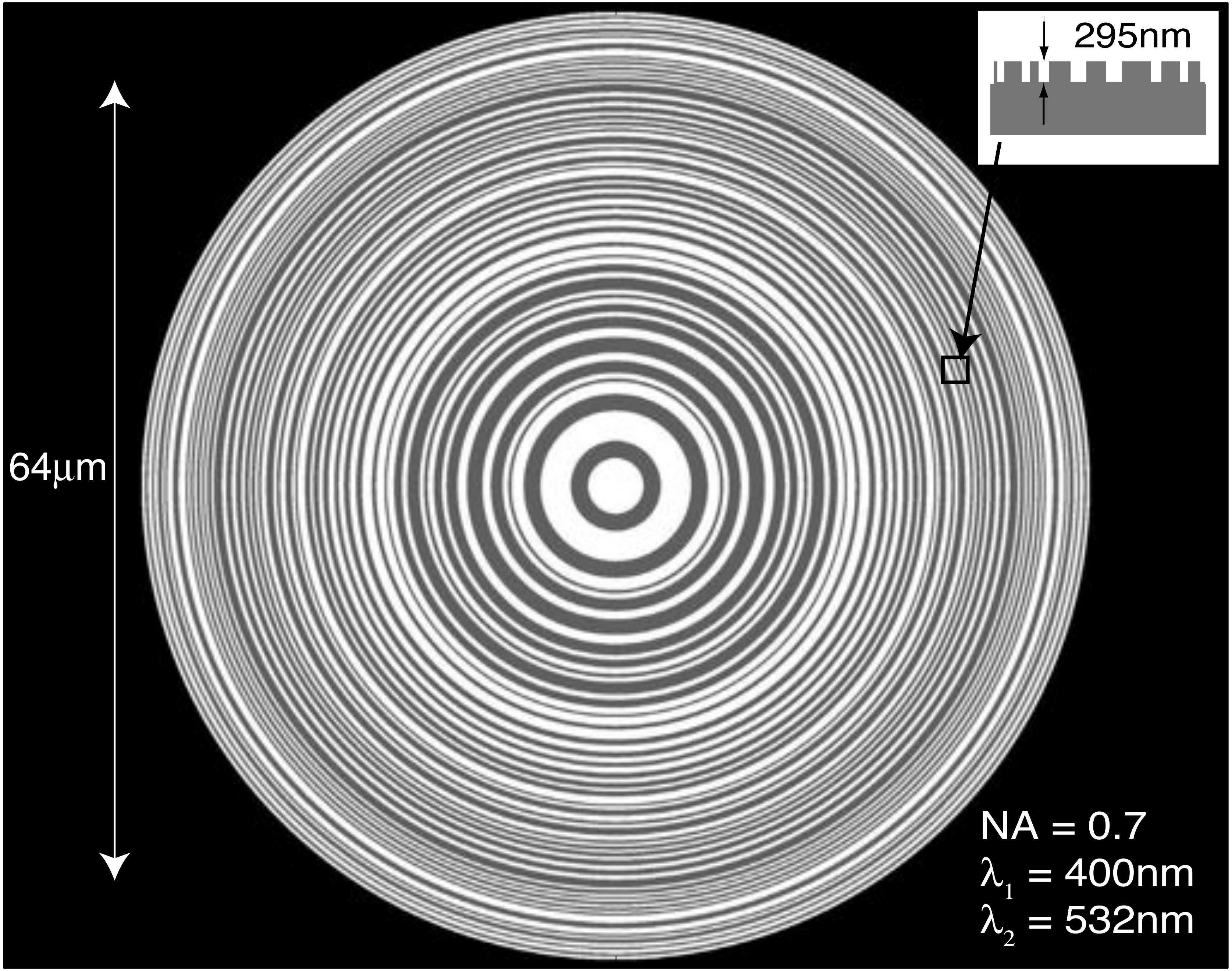


Can we design a single lens for both wavelengths?

Ease of fabrication → binary phase, circular symmetric, diffraction-limited

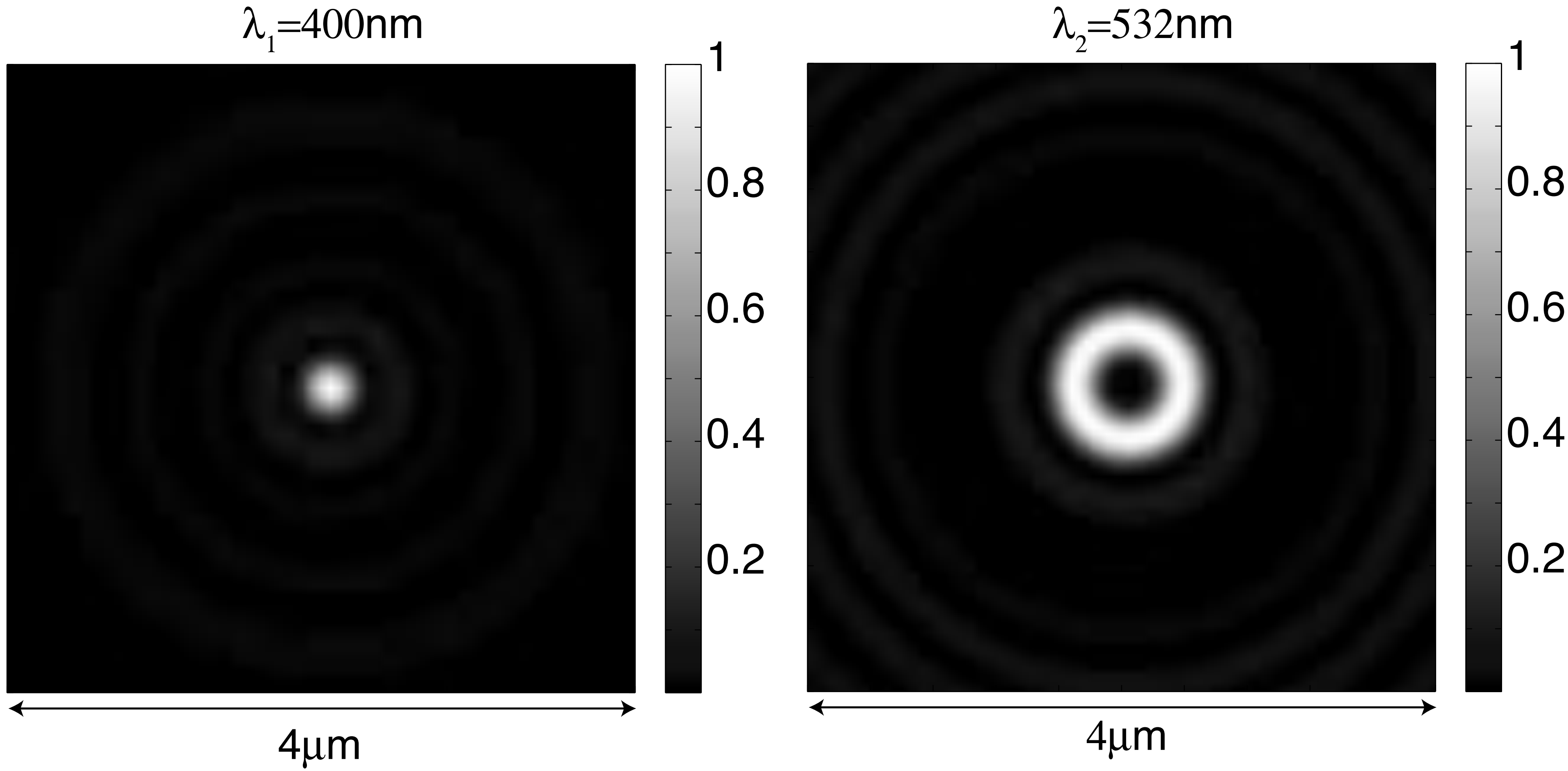


Dichromat: A dual-wavelength phase diffractive lens



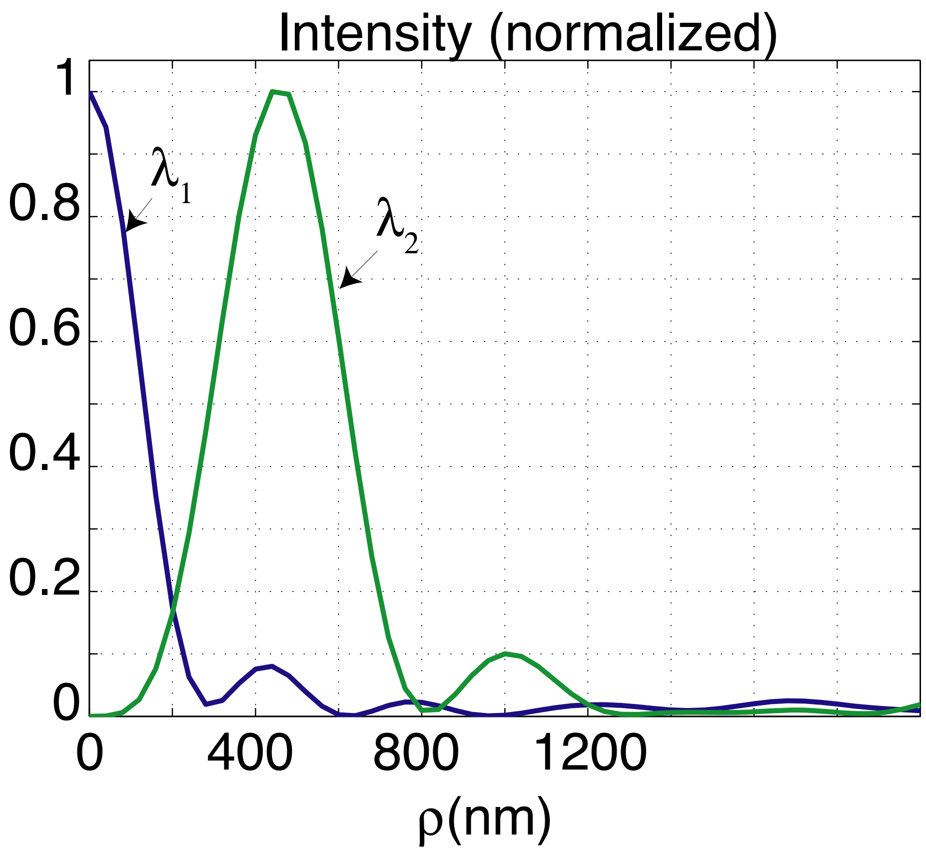
R. Menon, P. Rogge, & H-Y Tsai, *J. Opt. Soc. Am. A*, 26 (2), 297 (2009).

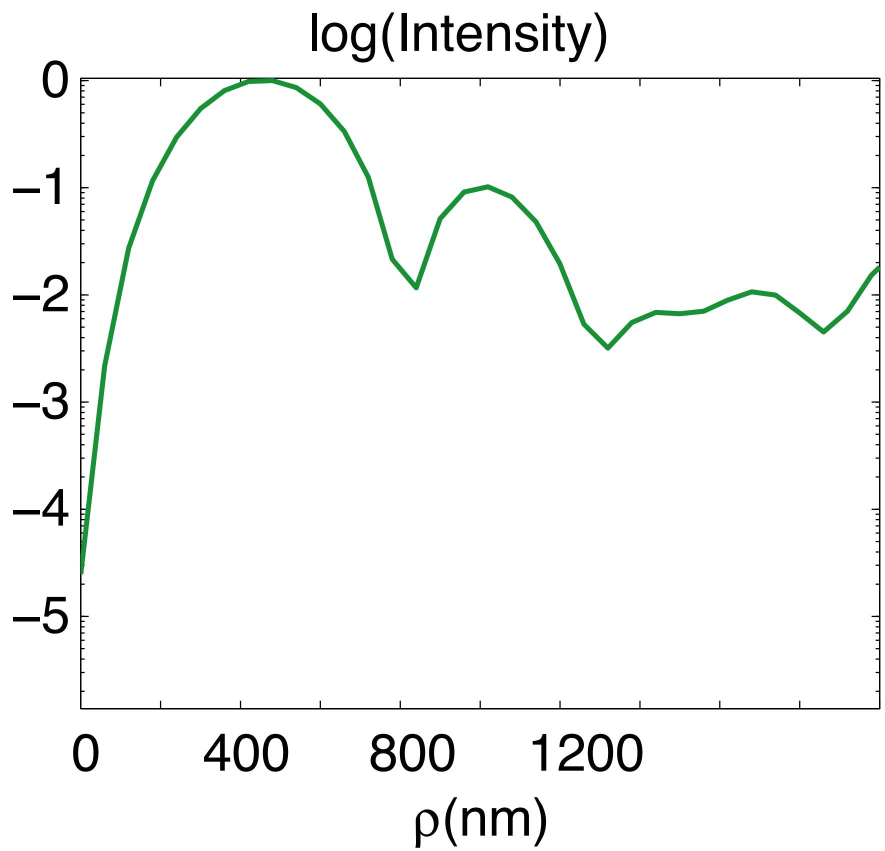
Simulated Focal Spots of the Dichromat



Simulated Focal Spots of the Dichromat

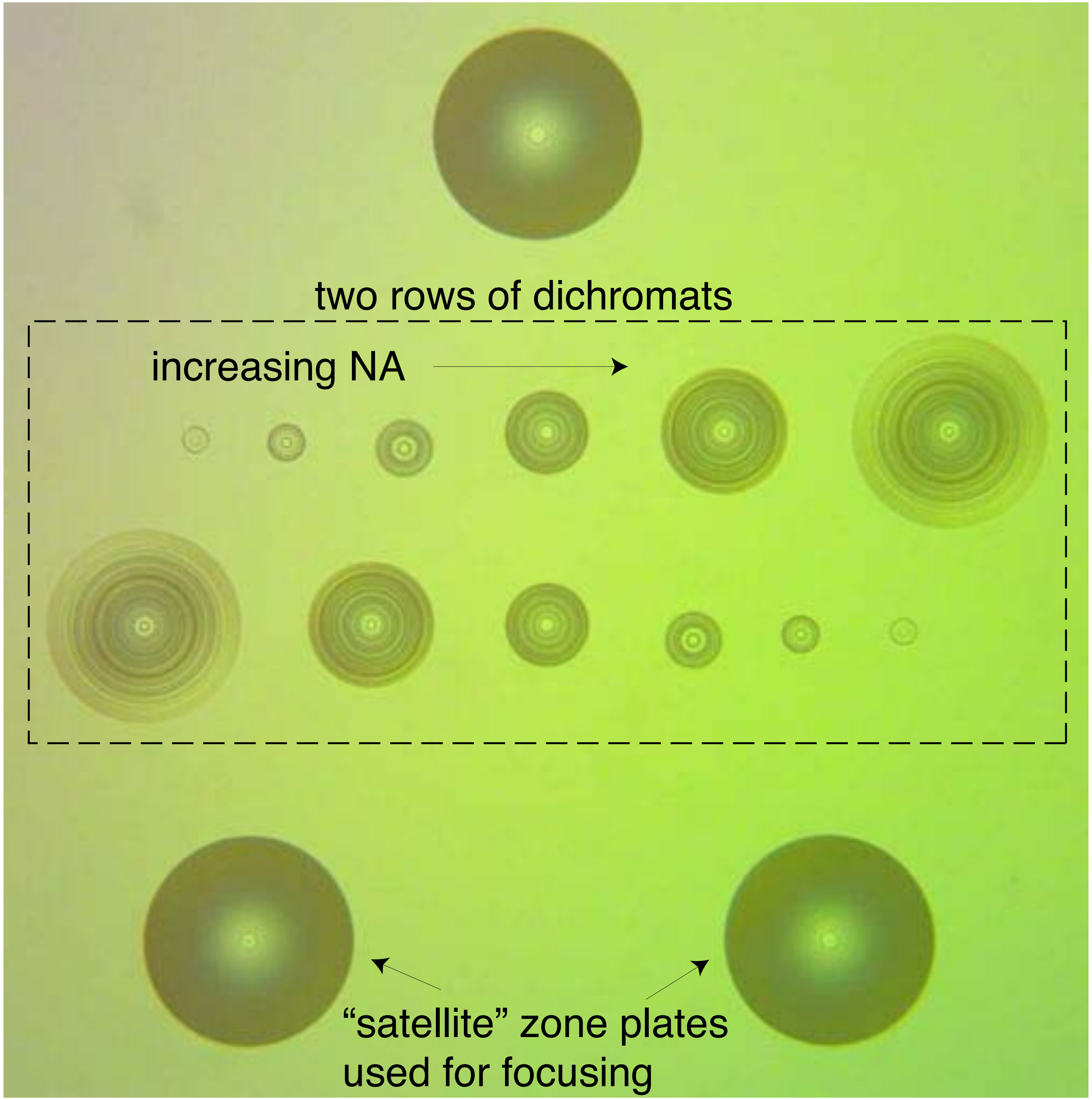
Radial cross-sections



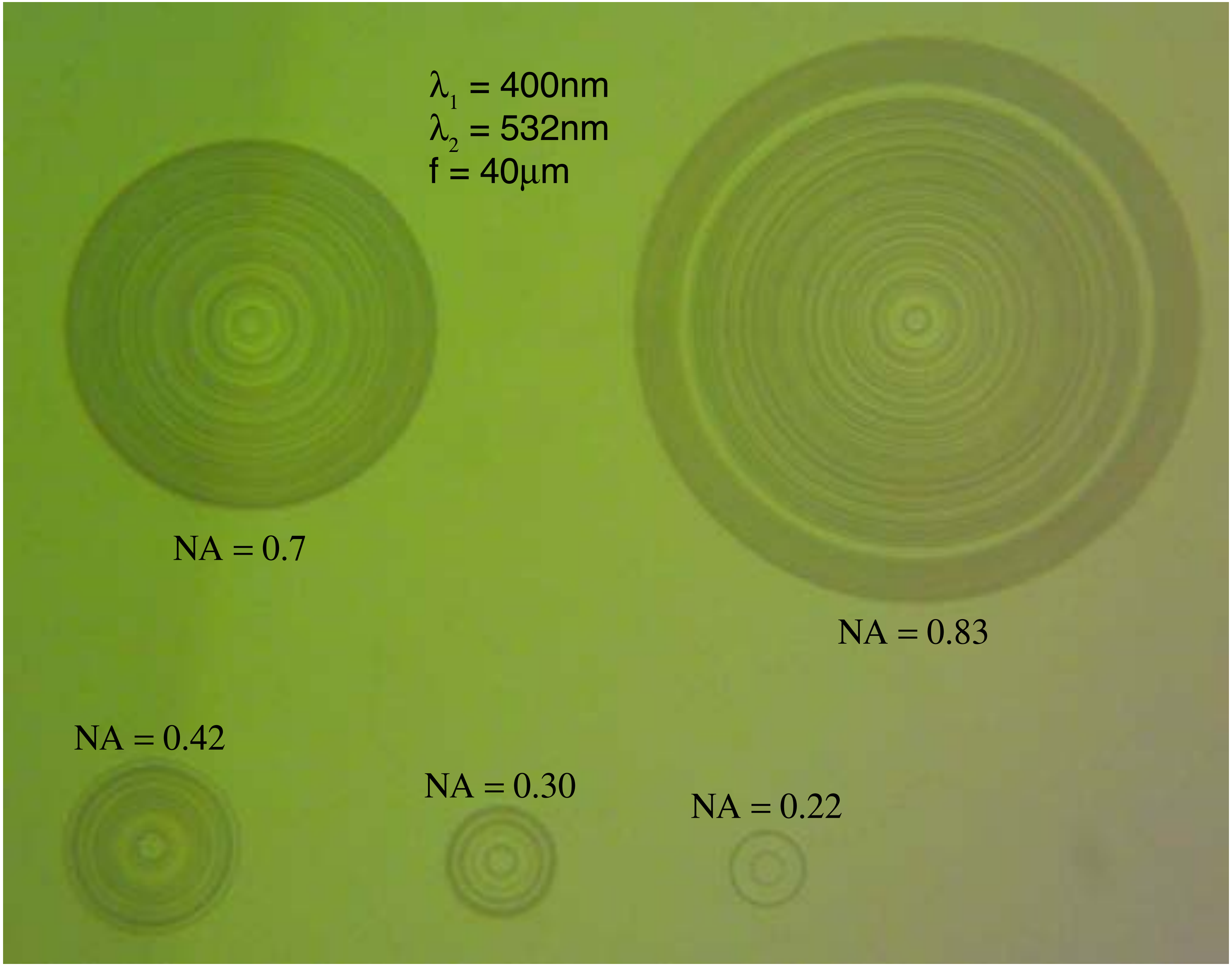


R. Menon, *et. al., Opt. Lett.*, (submitted)

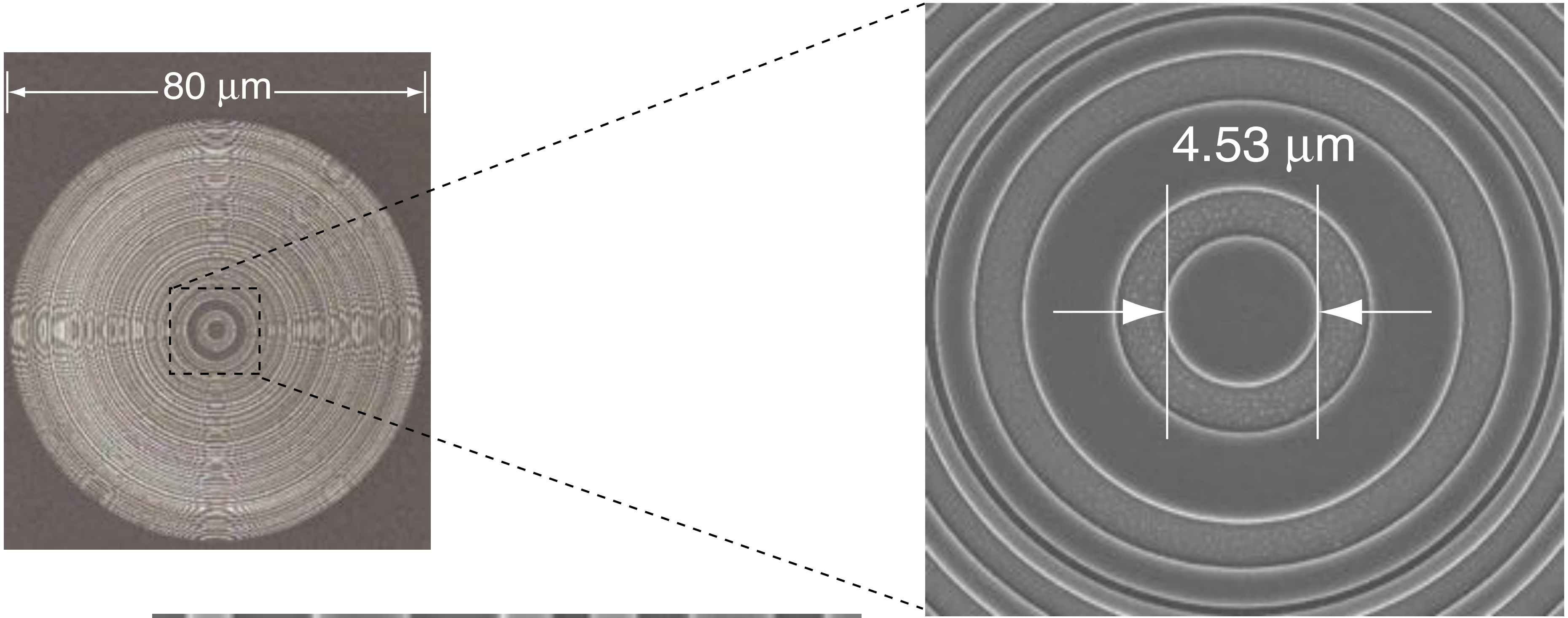
Fabricated Dichromats

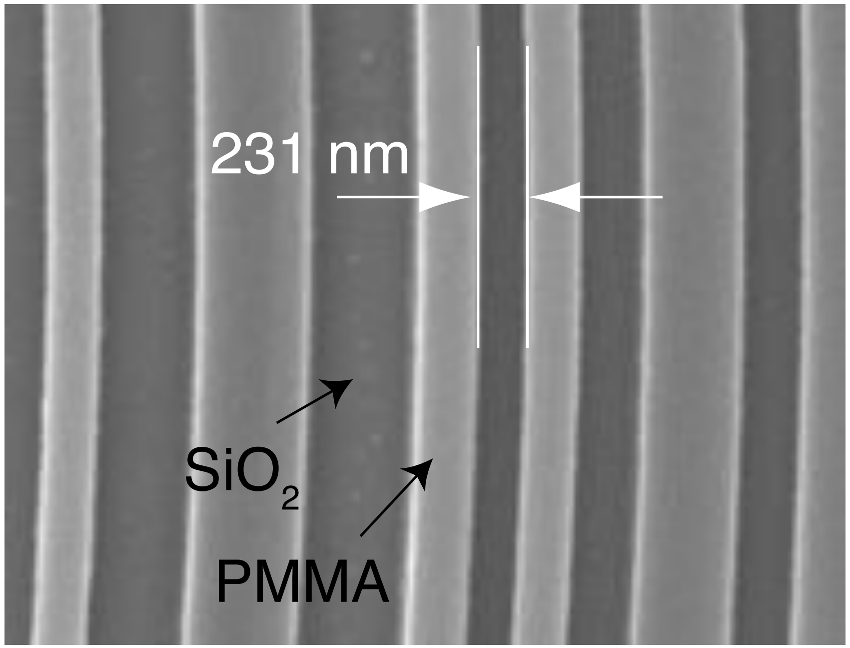


Fabricated Dichromats



Fabricated Dichromat

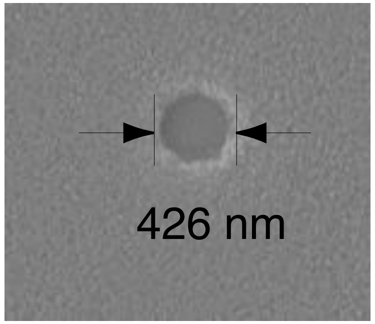




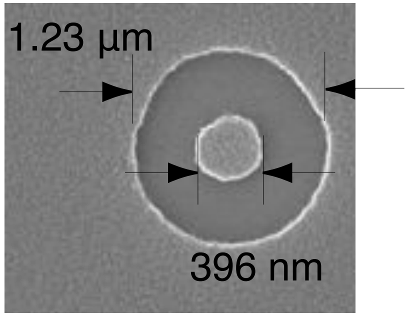
- Patterned with scanning-electron-beam lithgraphy (SEBL)
- PMMA on glass substrate
- λ_1 = 400nm, λ_2 = 532nm, NA = 0.7

Characterizing the Dichromats

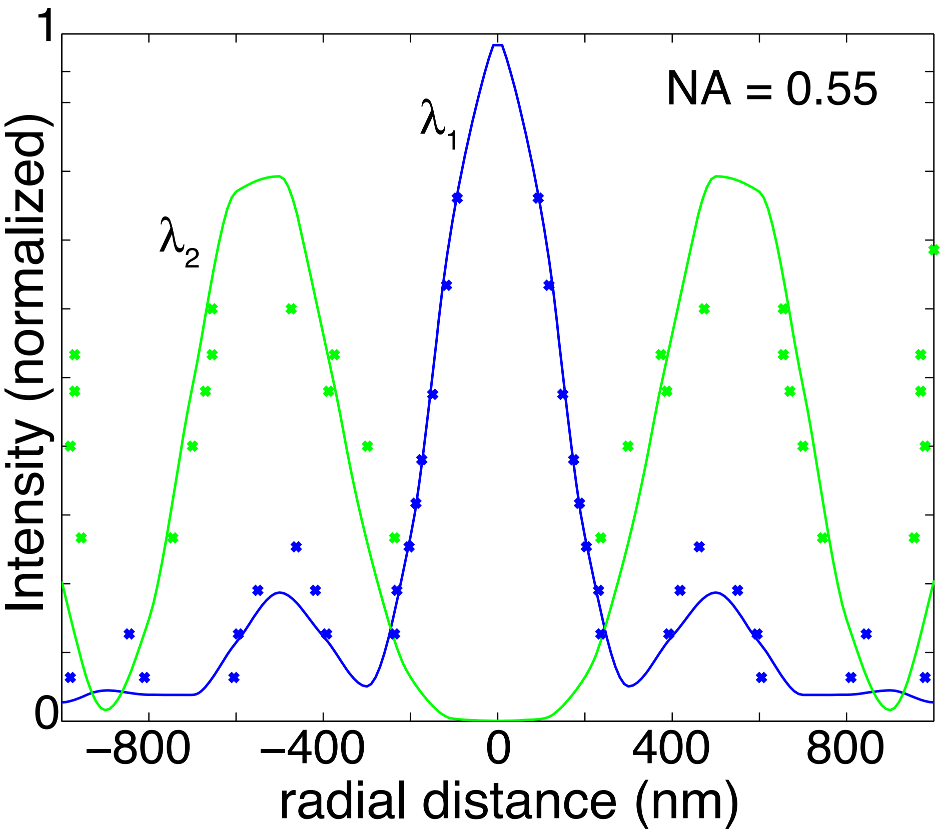
Focal spot at λ_1

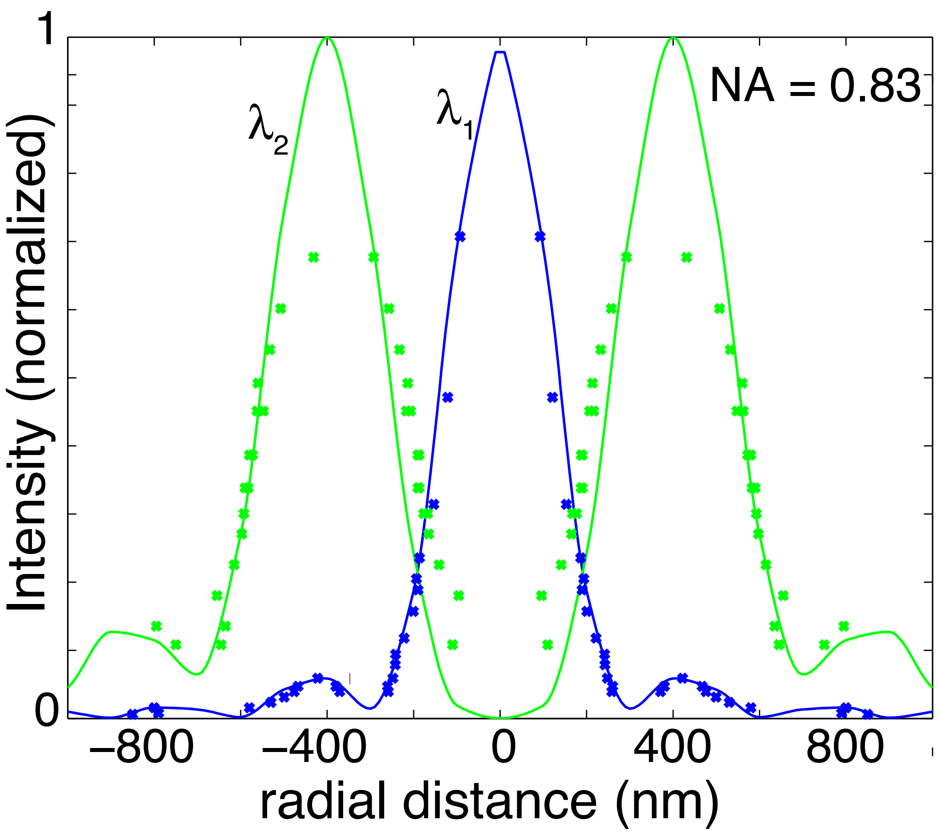


Focal ring at λ_2



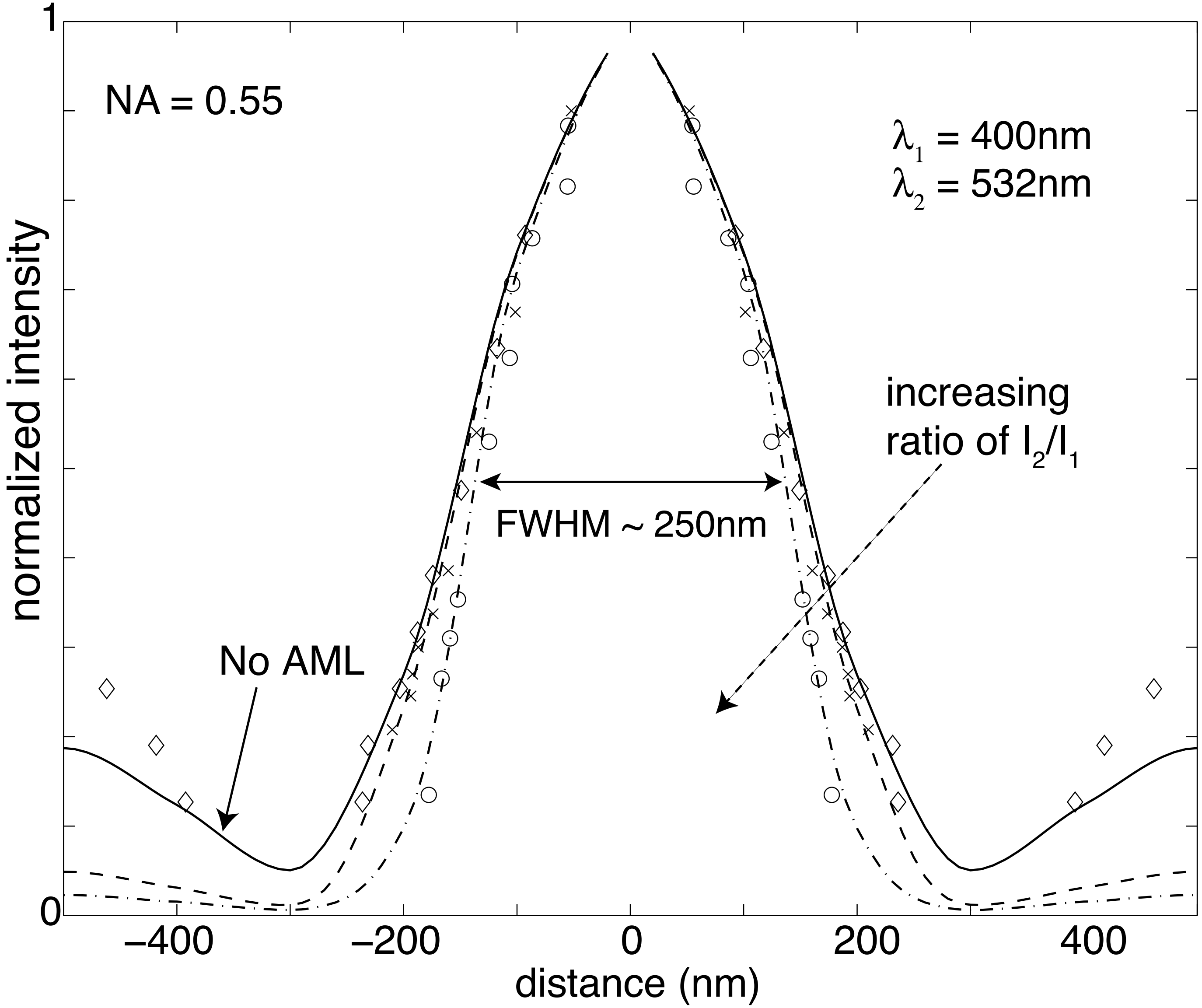
Measured Point-Spread Functions





H-Y. Tsai, H. I. Smith, R. Menon, *Opt. Lett.* 33(24), 2916 (2008).

“Squeezed” spot with Dichromat

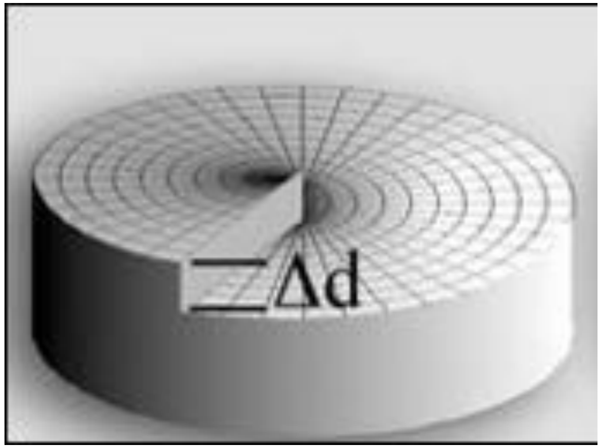


AML = 200nm of azobenzene polymer

Thermal instability of the azobenzene & the sensitivity of the photoresist to λ_2 limit “squeezing.”

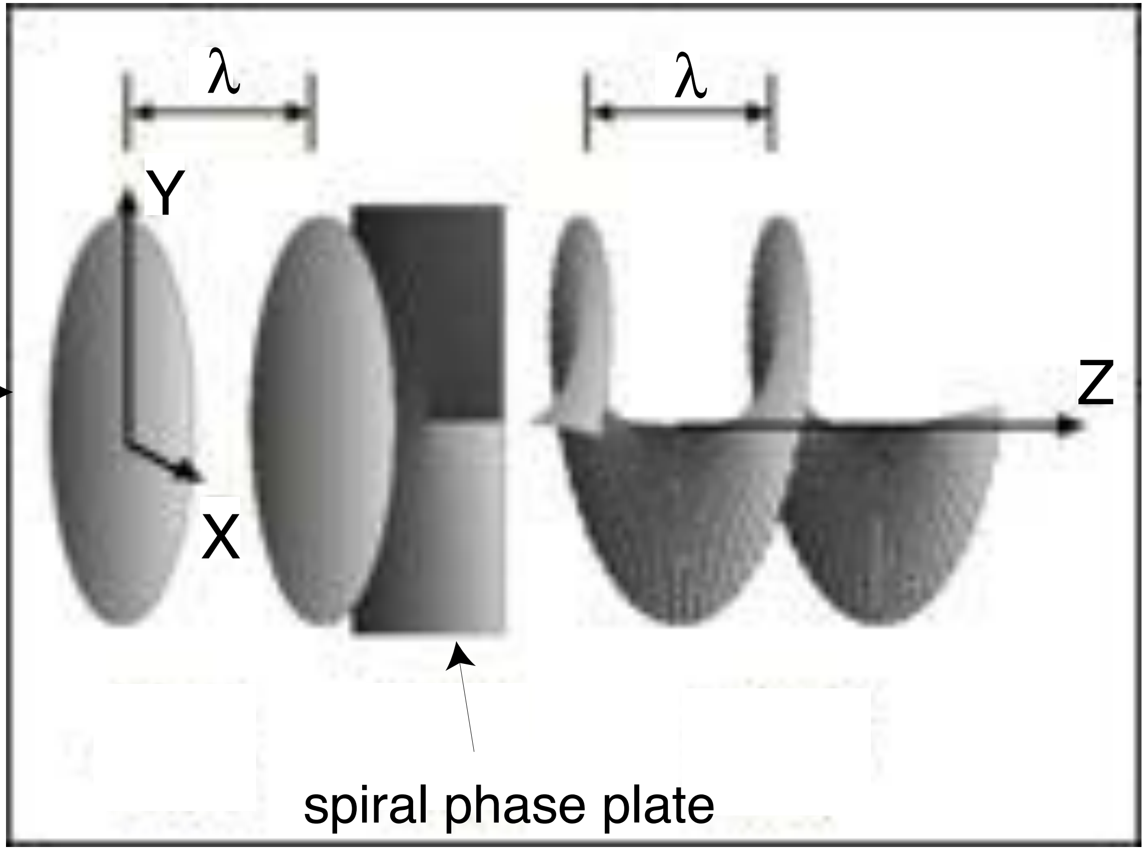
H-Y. Tsai, H. I. Smith, R. Menon, *Opt. Lett.* 33(24), 2916 (2008).

Phase singularities (optical vortices) generate dark beams



Spiral Phase Plate of topological charge 1

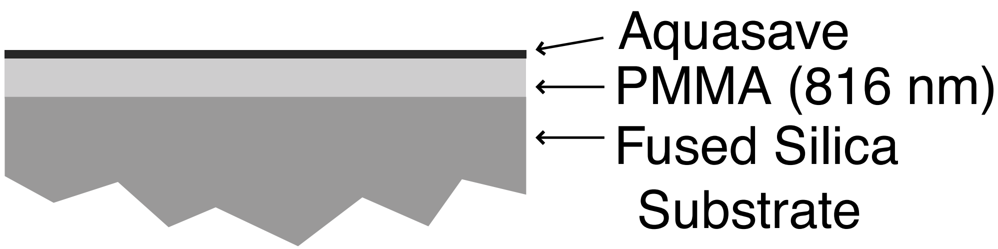
incident plane wave



output helical wave

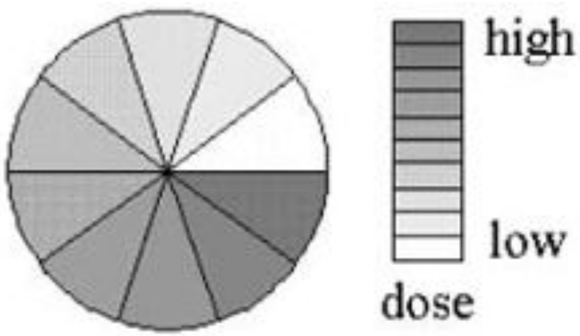
G. A. Swartzlander, *OPN*, 40 (2006)

Spiral-Phase Plates (SPPs) are hard to fabricate



↓

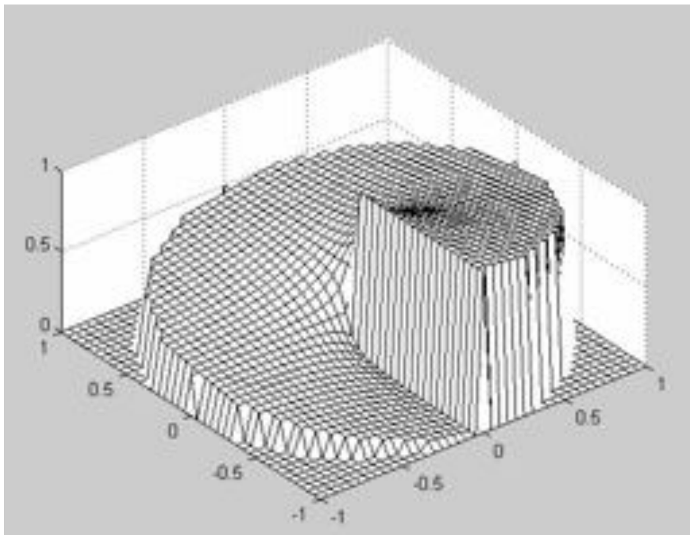
Grayscale E-beam exposure



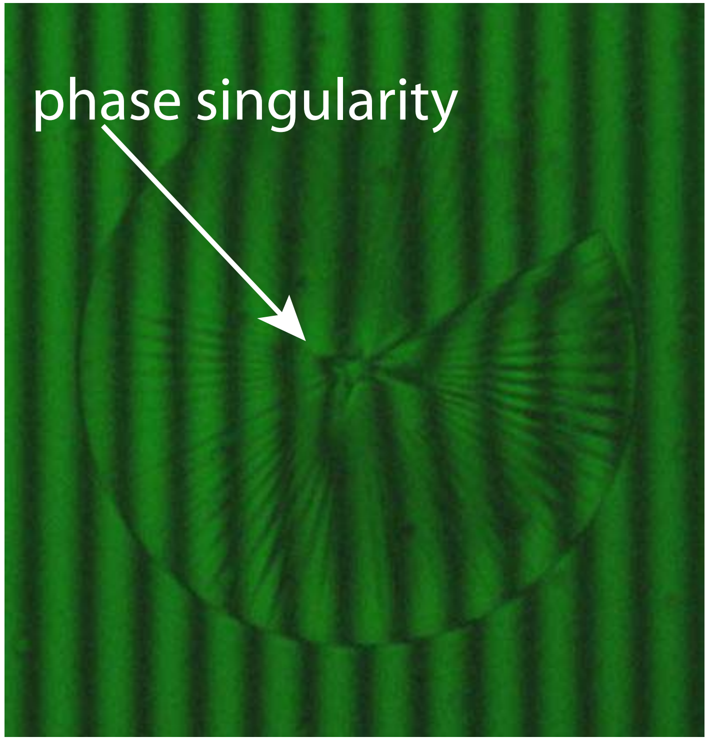
↓

Low Contrast Development
with 1:1 MIBK/IPA →

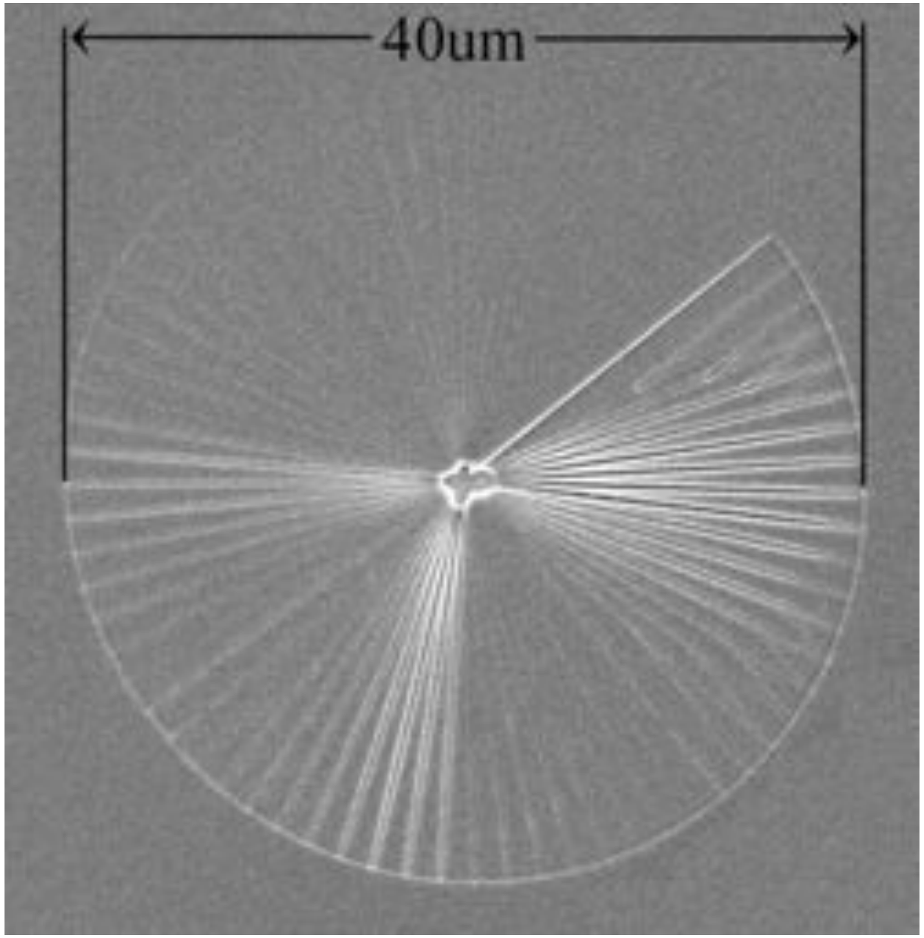
- Spiral Phase Plate (SPP) with grayscale scanning e-beam lithography (SEBL)



Spiral-Phase Plates (SPPs) are hard to fabricate



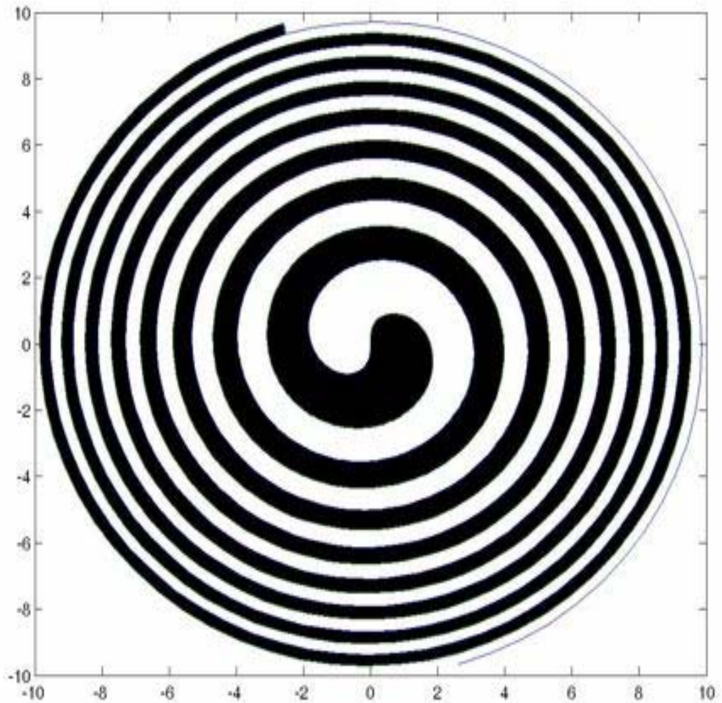
- LINNIK interferogram of fabricated SPP



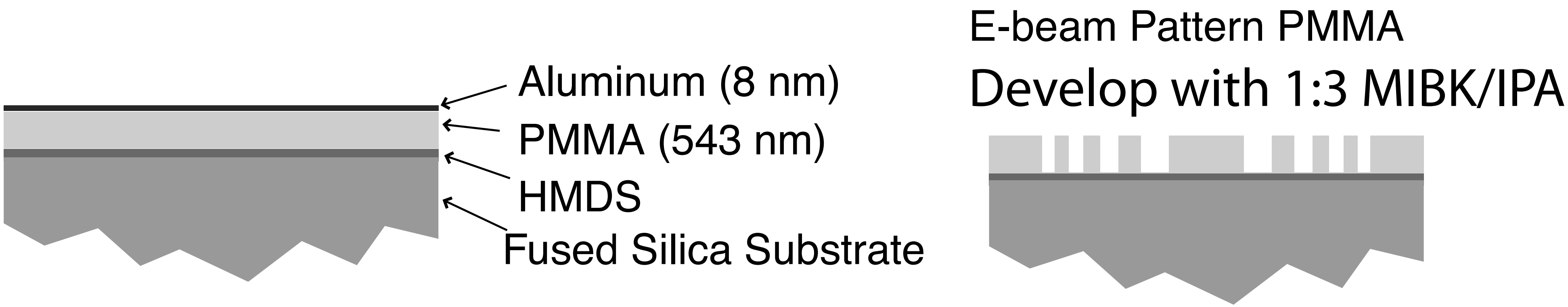
- SEM of a fabricated SPP

Proximity Effects due to backscattered electrons wreak havoc!

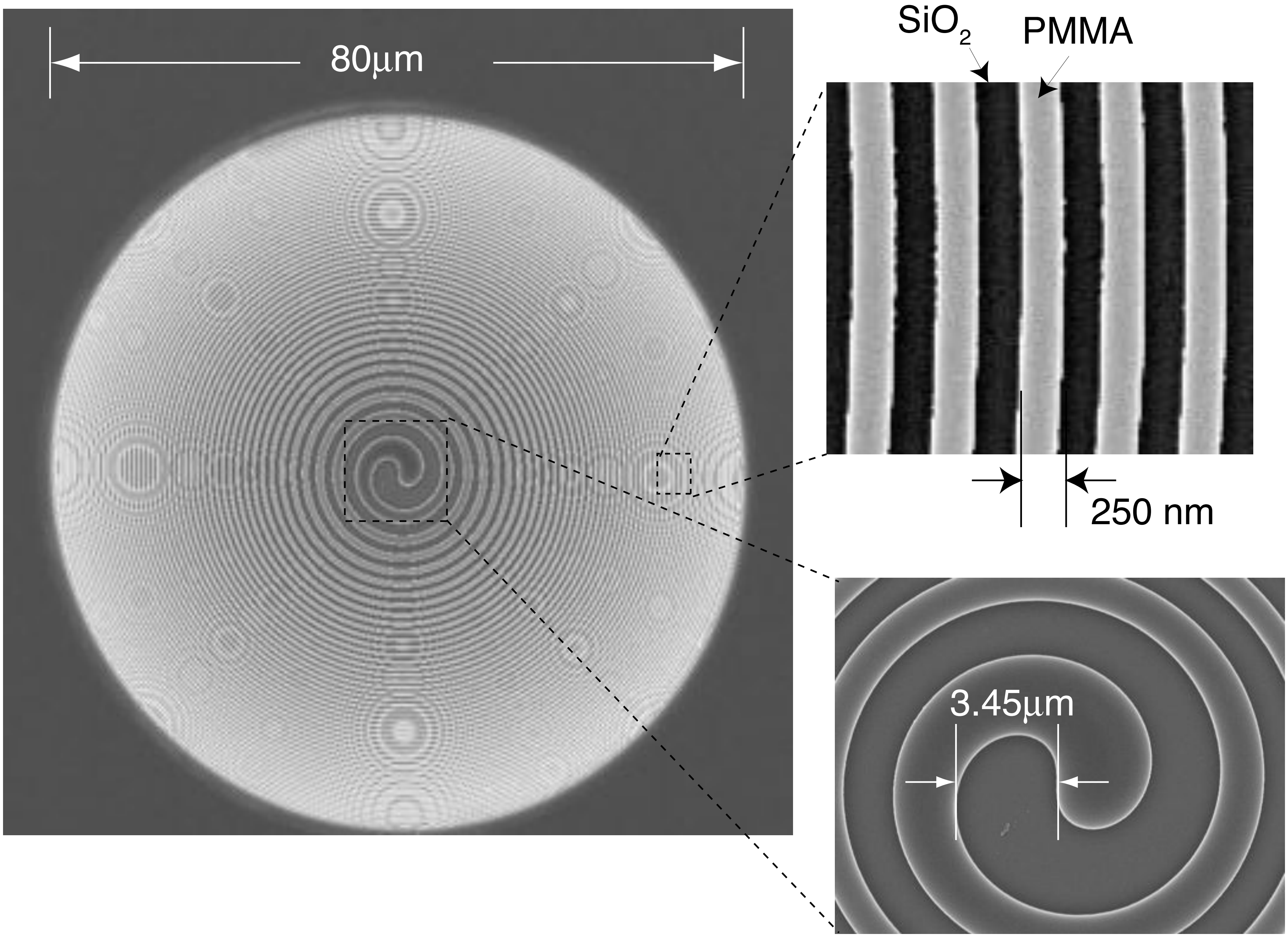
Spiral-Zone-Plate (SZP) is easier to fabricate



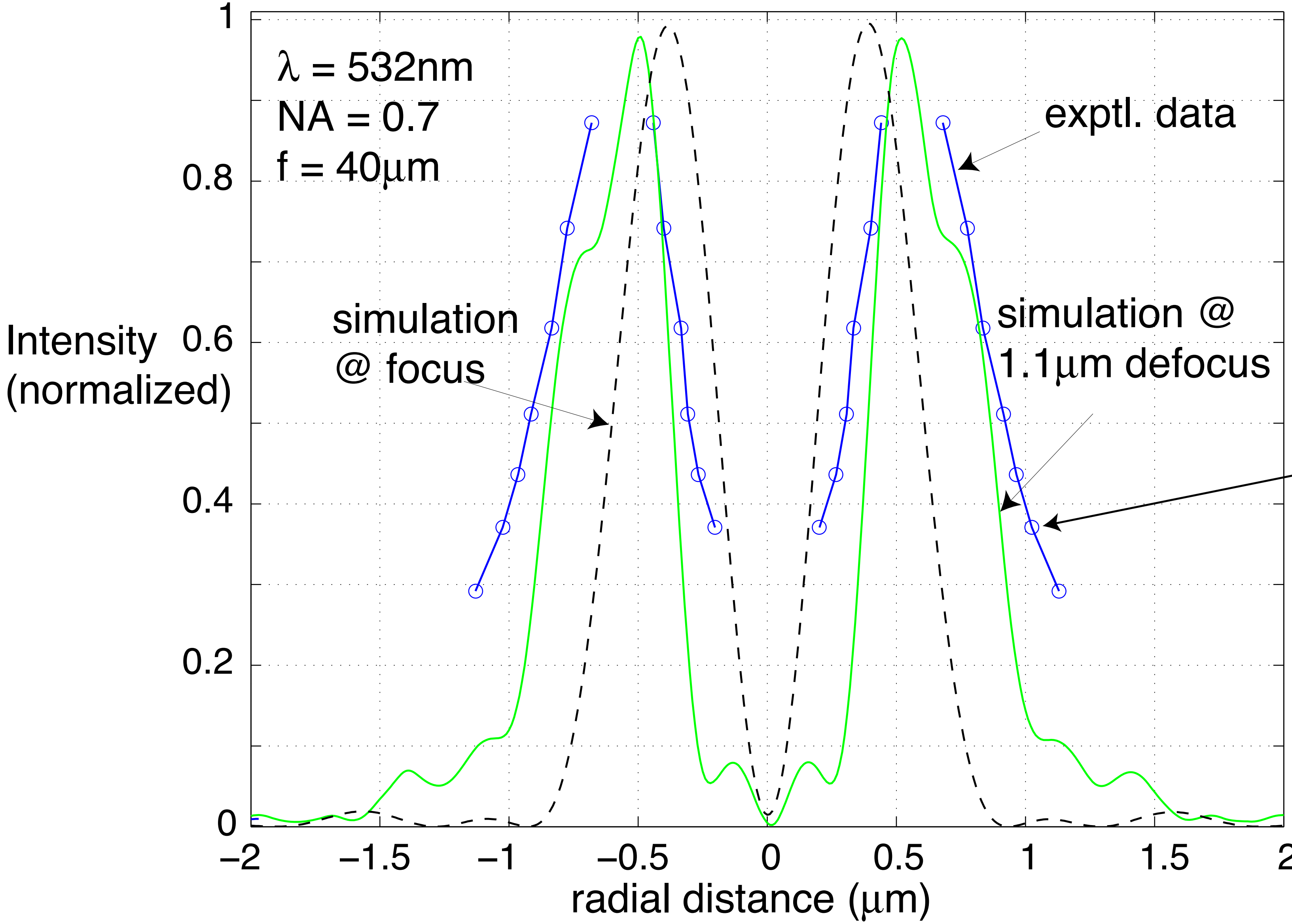
Binary phase spiral-zone plate (SZP) generates a ring-focus.

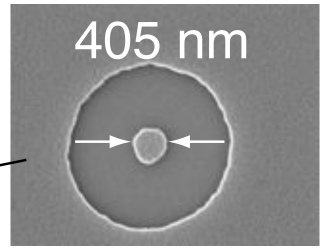


A fabricated Spiral-Zone-Plate (SZP) of NA = 0.7



Characterizing the Spiral-Zone-Plate of NA = 0.7



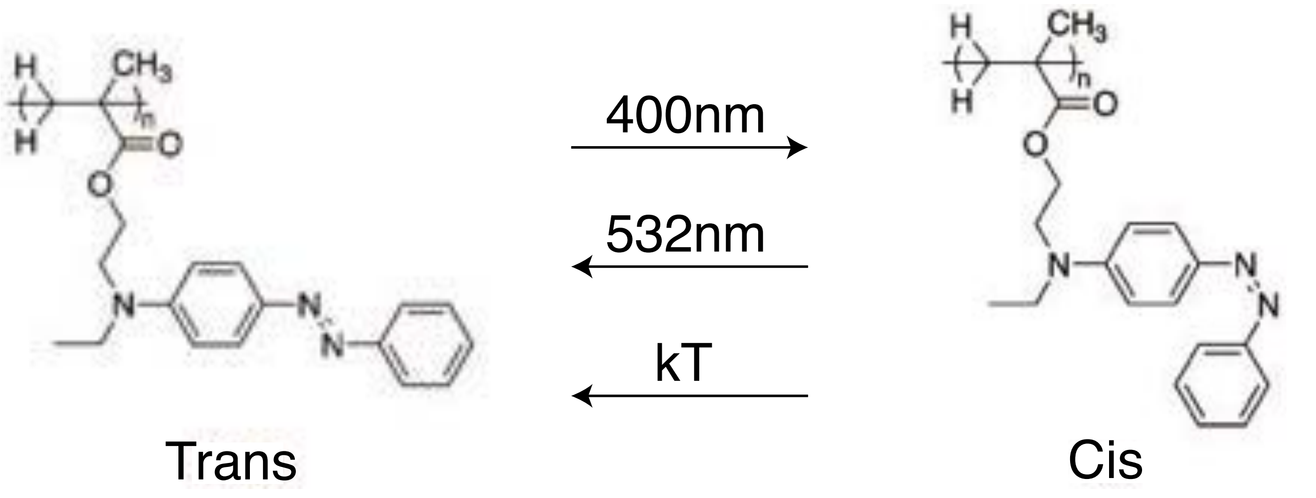


- Focus errors during exposure
- Fabrication errors in phase shift & zone duty cycle

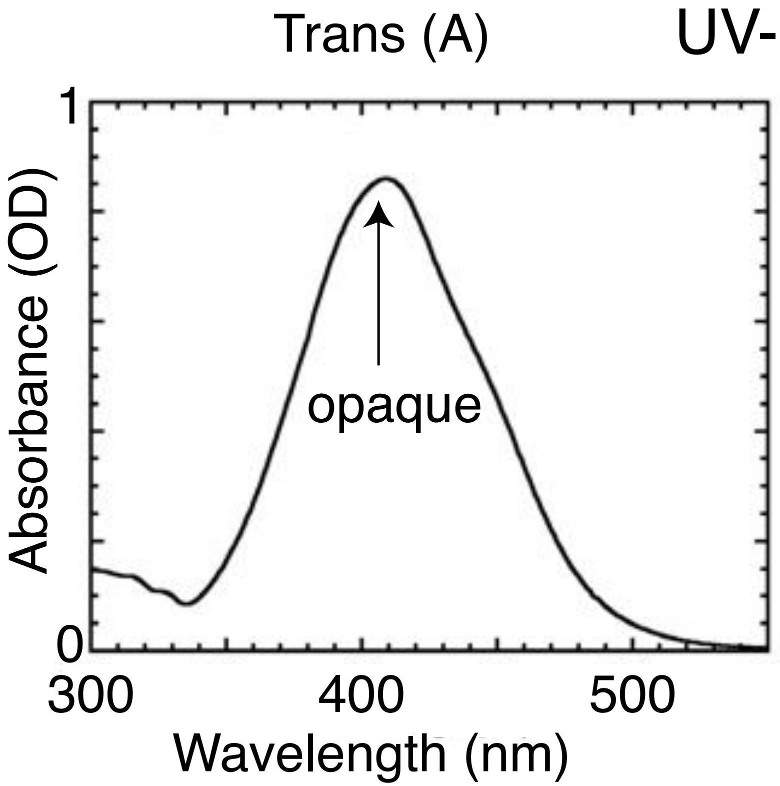
→ larger ring-diameter & higher noise in null

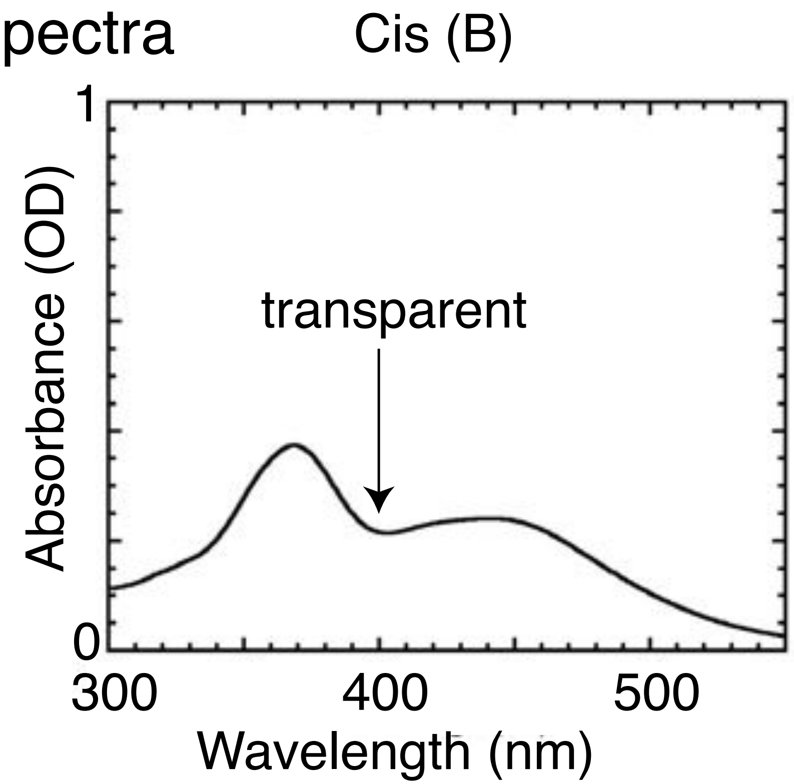
H-Y. Tsai, *et. al. J. Vac. Sci. Technol. B*, 25(6), 2068 (2007)

Photochromic molecule: Azobenzene polymer

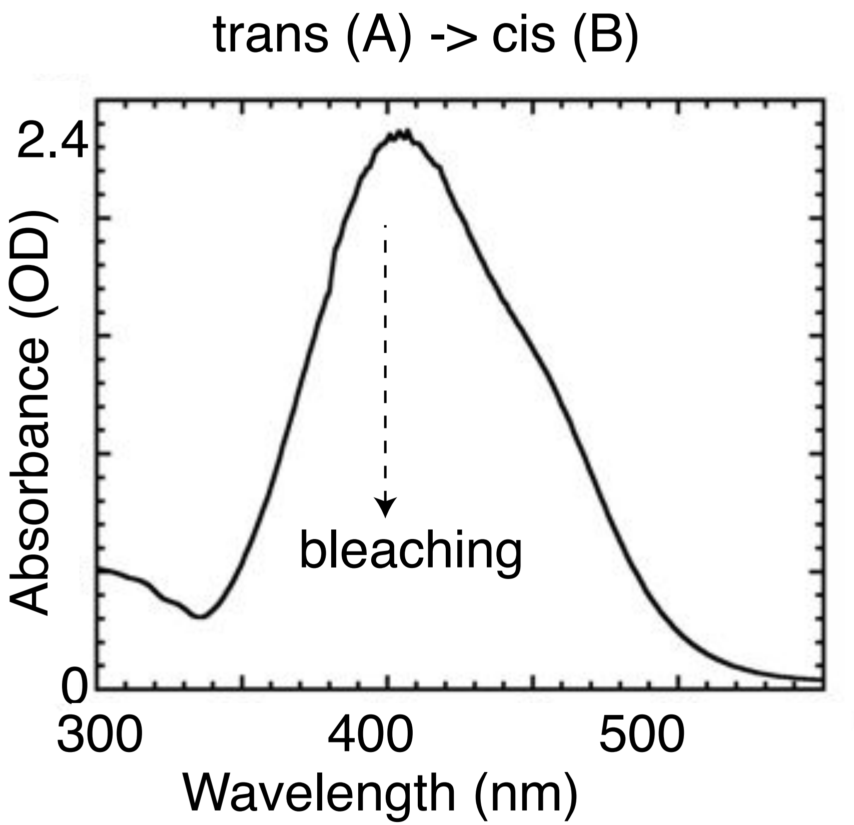


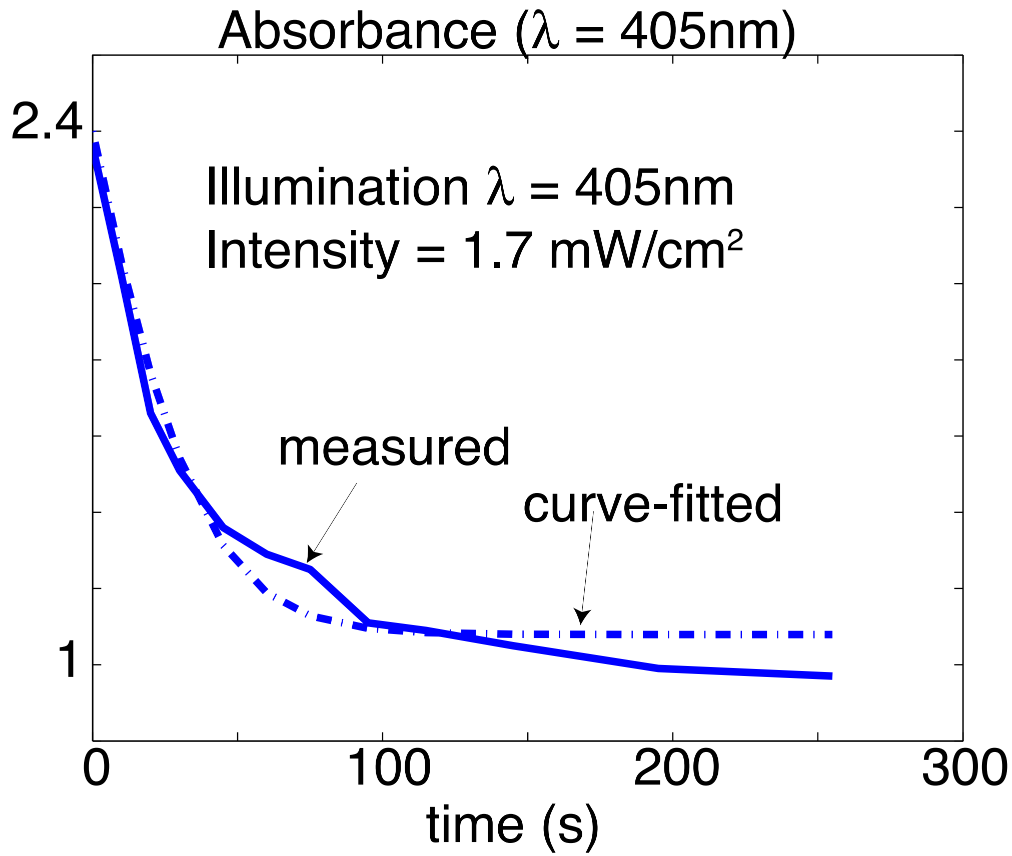
UV-Vis Spectra





Extraction of parameters from UV-Vis spectra





- 200nm dye spun on glass substrate
- spectrum measured in transmission

Molar Absorptivities

$$\varepsilon_{1A} = 3\times10^{4}\, m^{2}/mol$$

$$\varepsilon_{1B} = 1.25\times10^{4}\, m^{2}/mol$$

Thermal Rate Constant

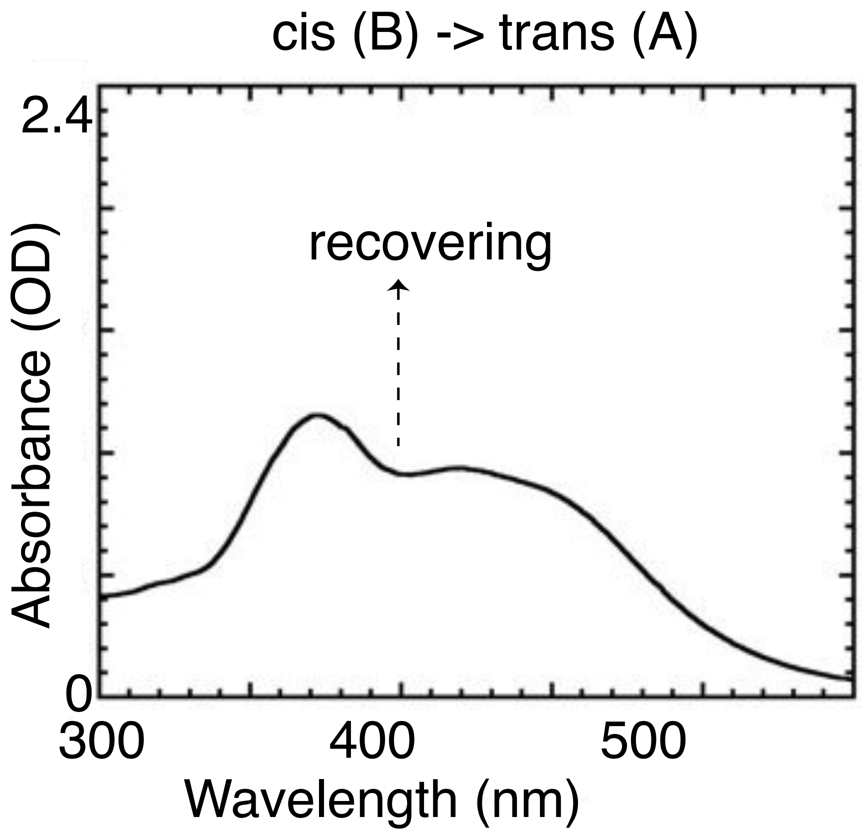
$$k_{BA} = 2\times10^{-3}\, s^{-1}$$

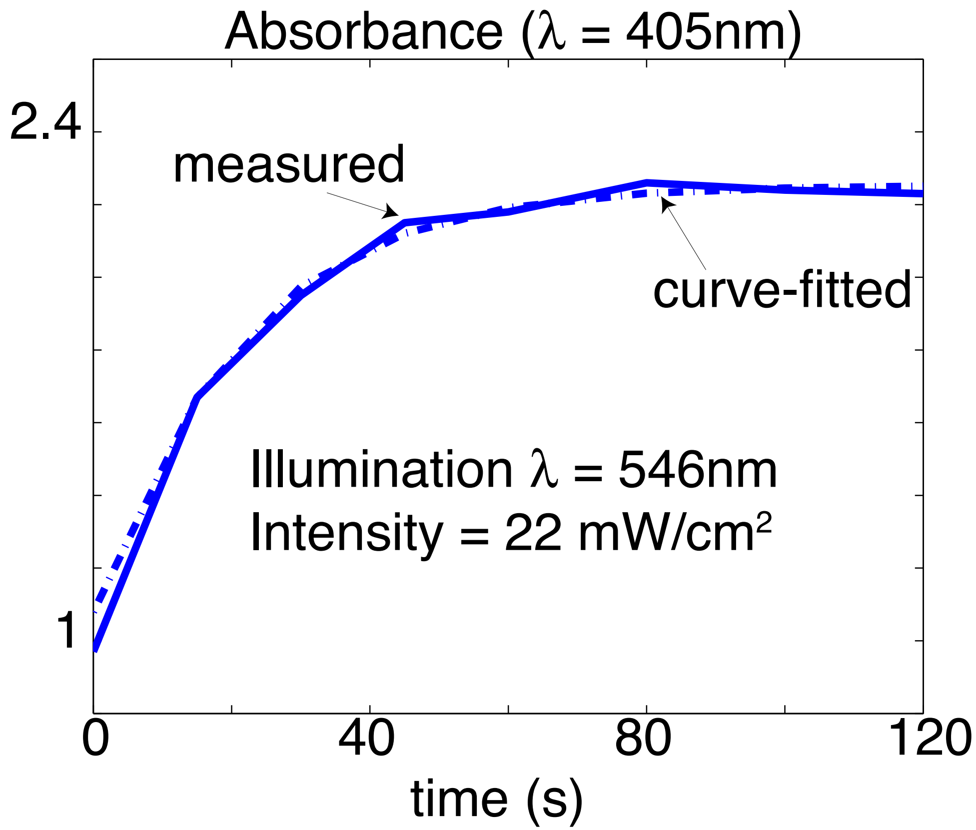
Quantum Efficiencies

$$\phi_{1AB} = 3.7\times10^{-3}$$

$$\phi_{1BA} = 2.1\times10^{-3}$$

Extraction of parameters from UV-Vis spectra





- 200nm dye spun on glass substrate
- spectrum measured in transmission

Molar Absorptivities

$$\varepsilon_{2A} = 1.25 \times 10^3 m^2 / mol$$

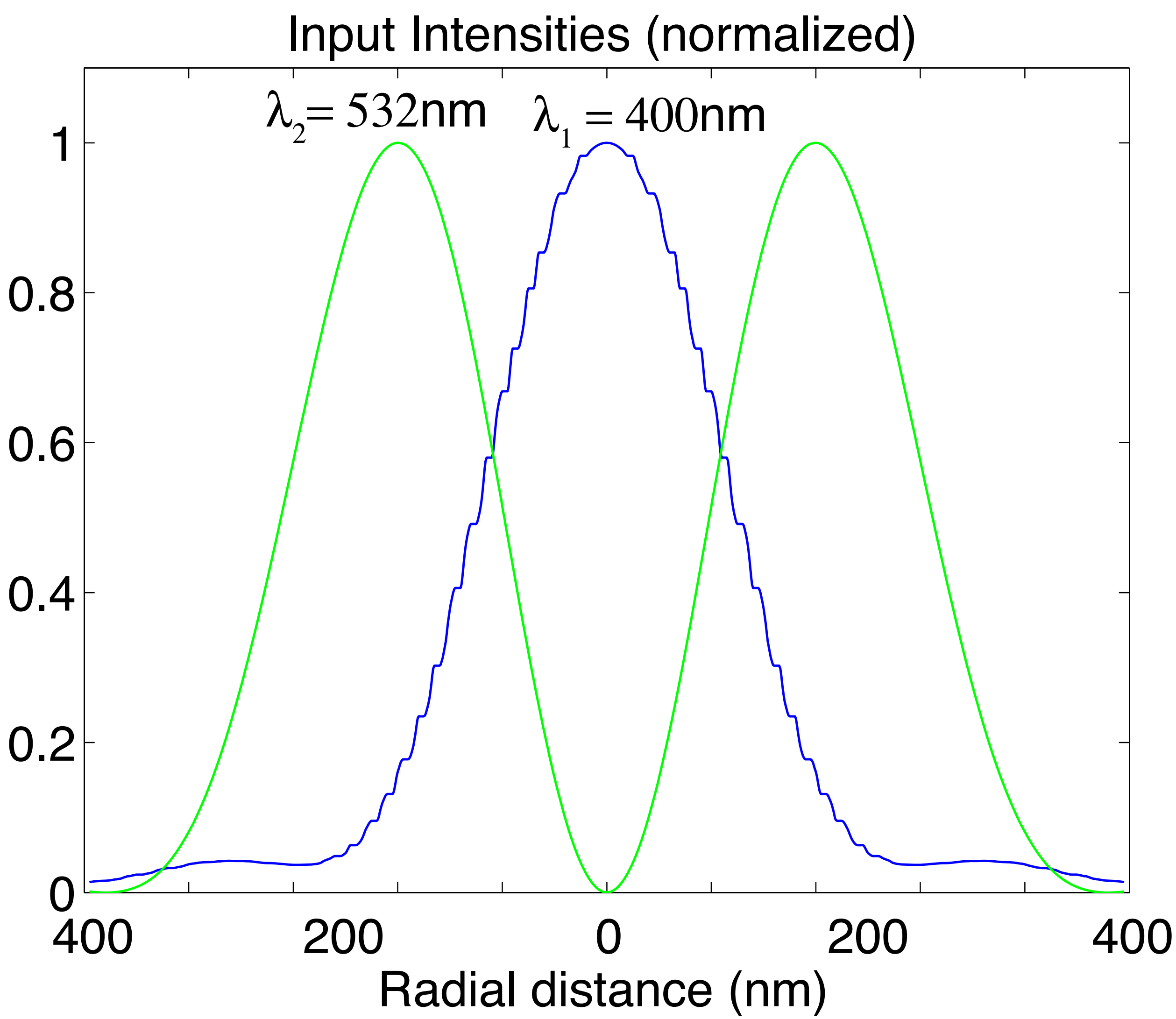
$$\varepsilon_{2B} = 3 \times 10^3 m^2 / mol$$

Quantum Efficiencies

$$\phi_{2BA} = 7.2 \times 10^{-3}$$

$$\phi_{2AB} = 2.1 \times 10^{-3}$$

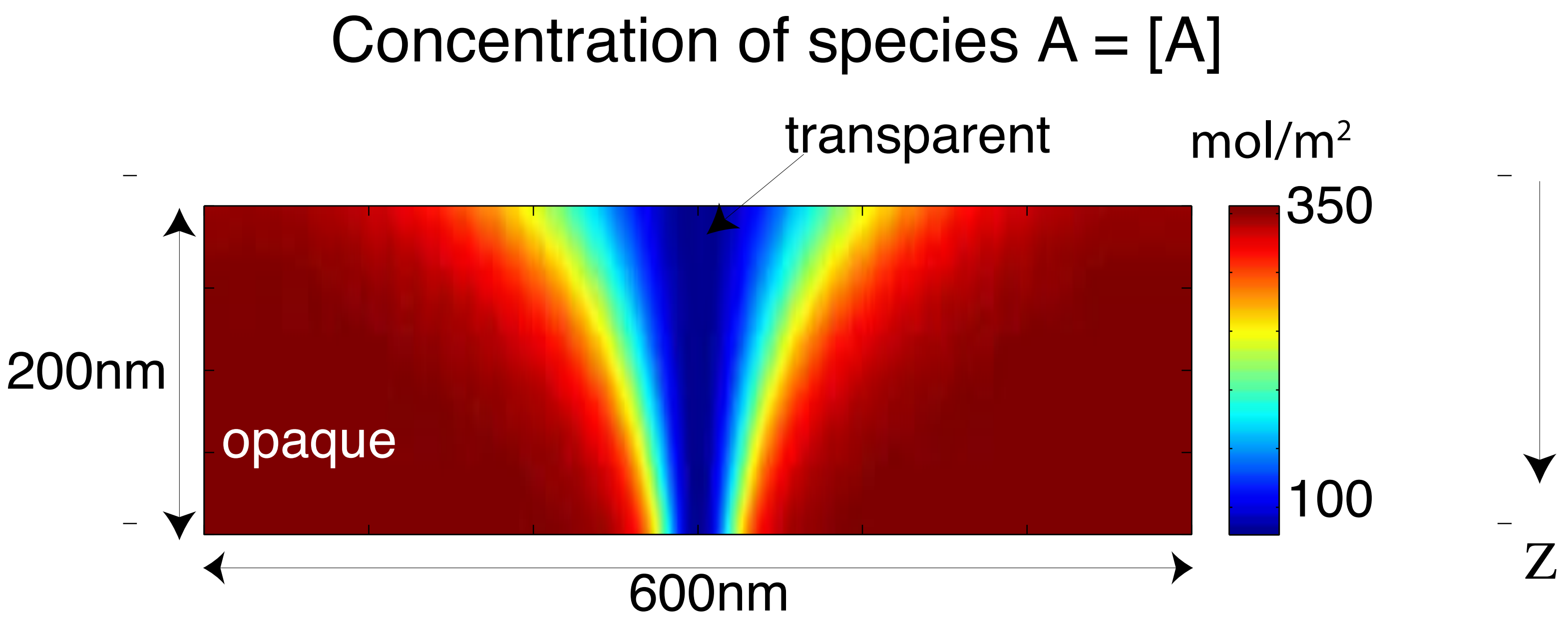
Absorbance Modulation Simulation

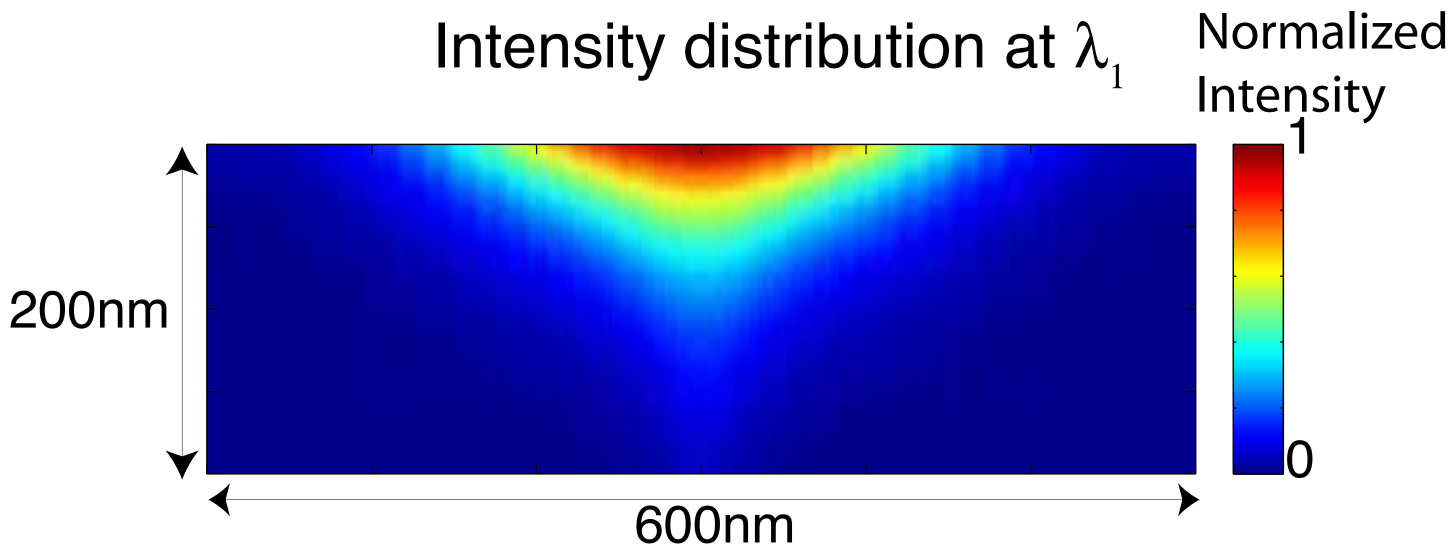


- λ_1 Binary Phase zone plate of numerical aperture (NA) 0.85
- λ_2 Spiral Phase plate of NA 0.72

Absorbance Modulation Simulation

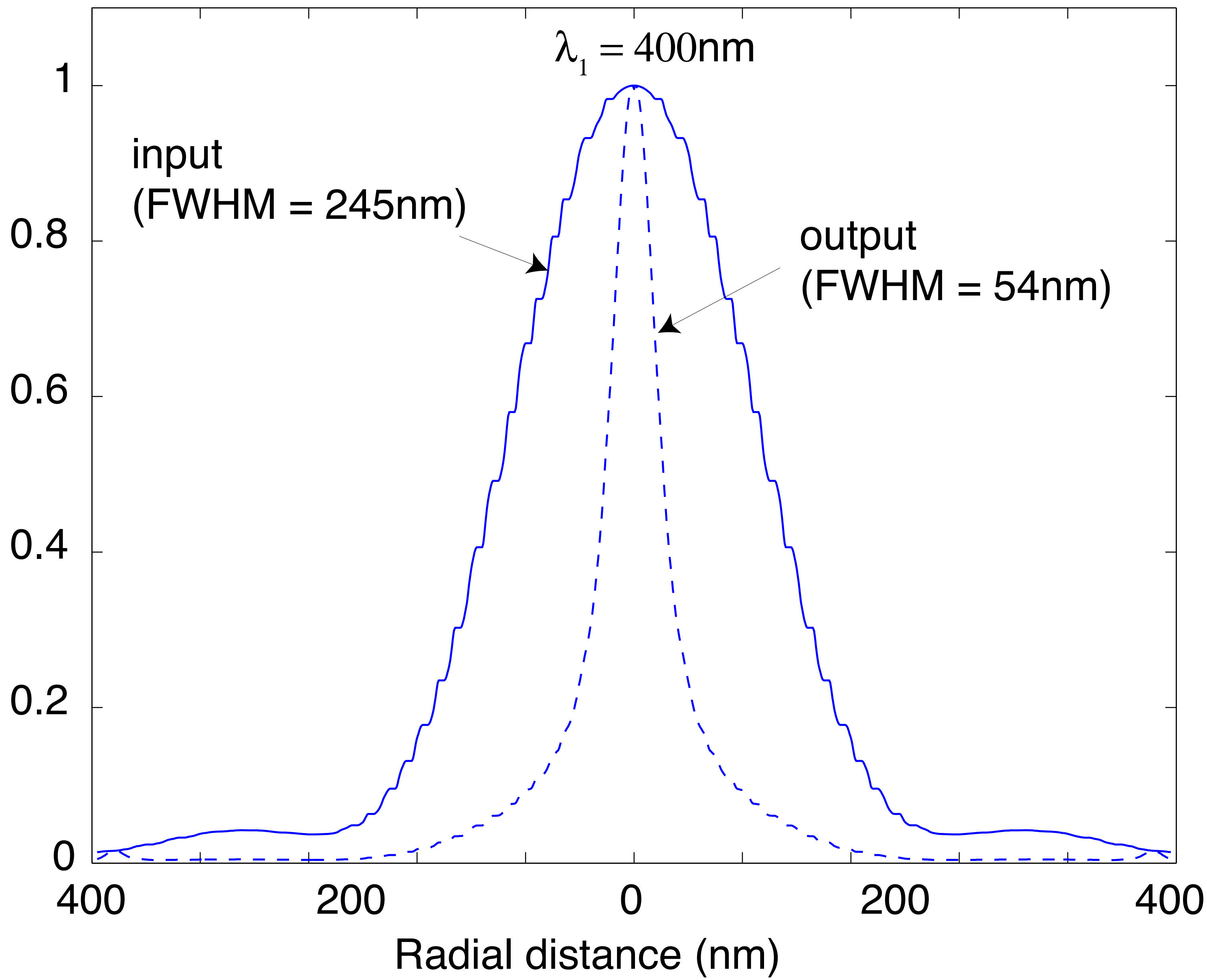
Beam propagation (λ_1) through 200nm of azobenzene polymer (AML)



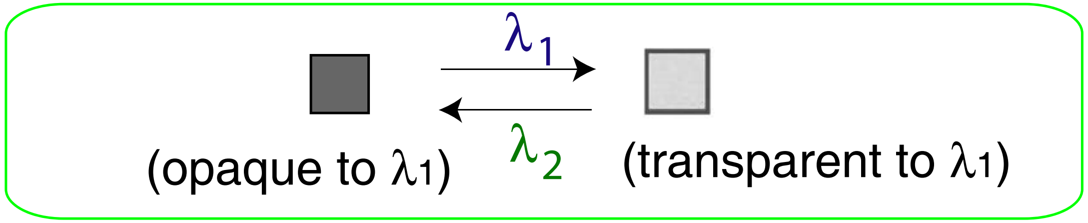


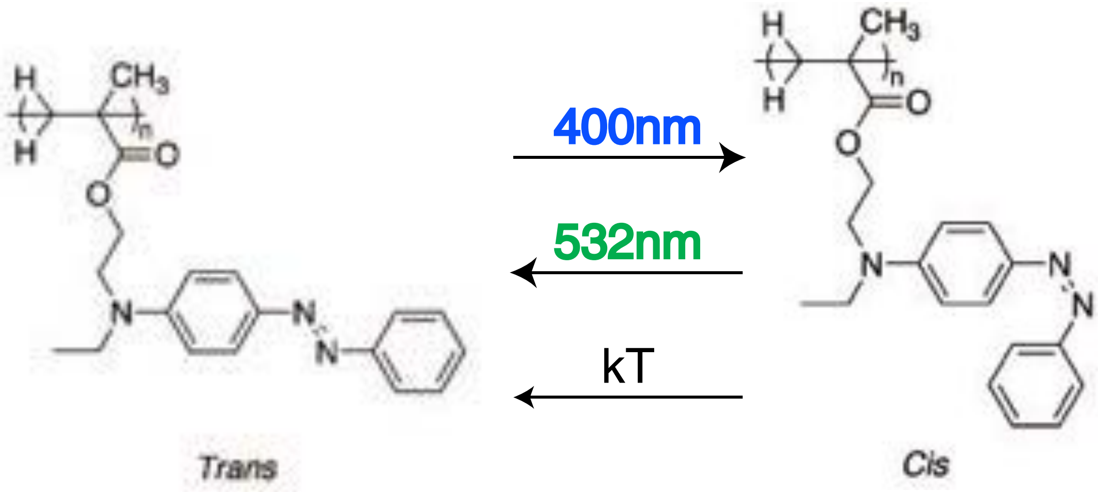
Absorbance Modulation Simulation

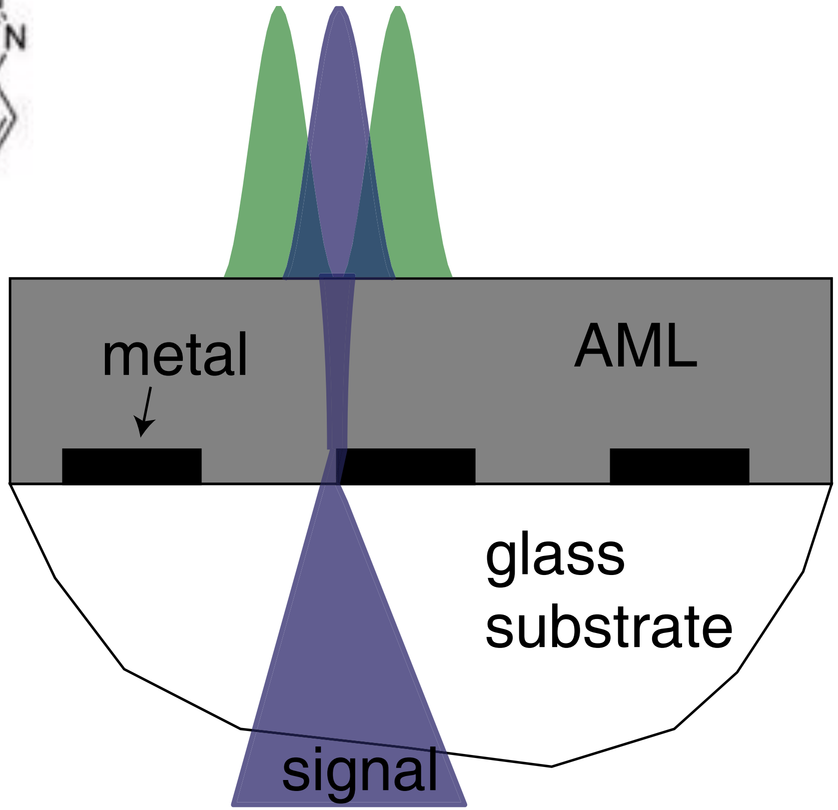
Output Intensity is “squeezed”



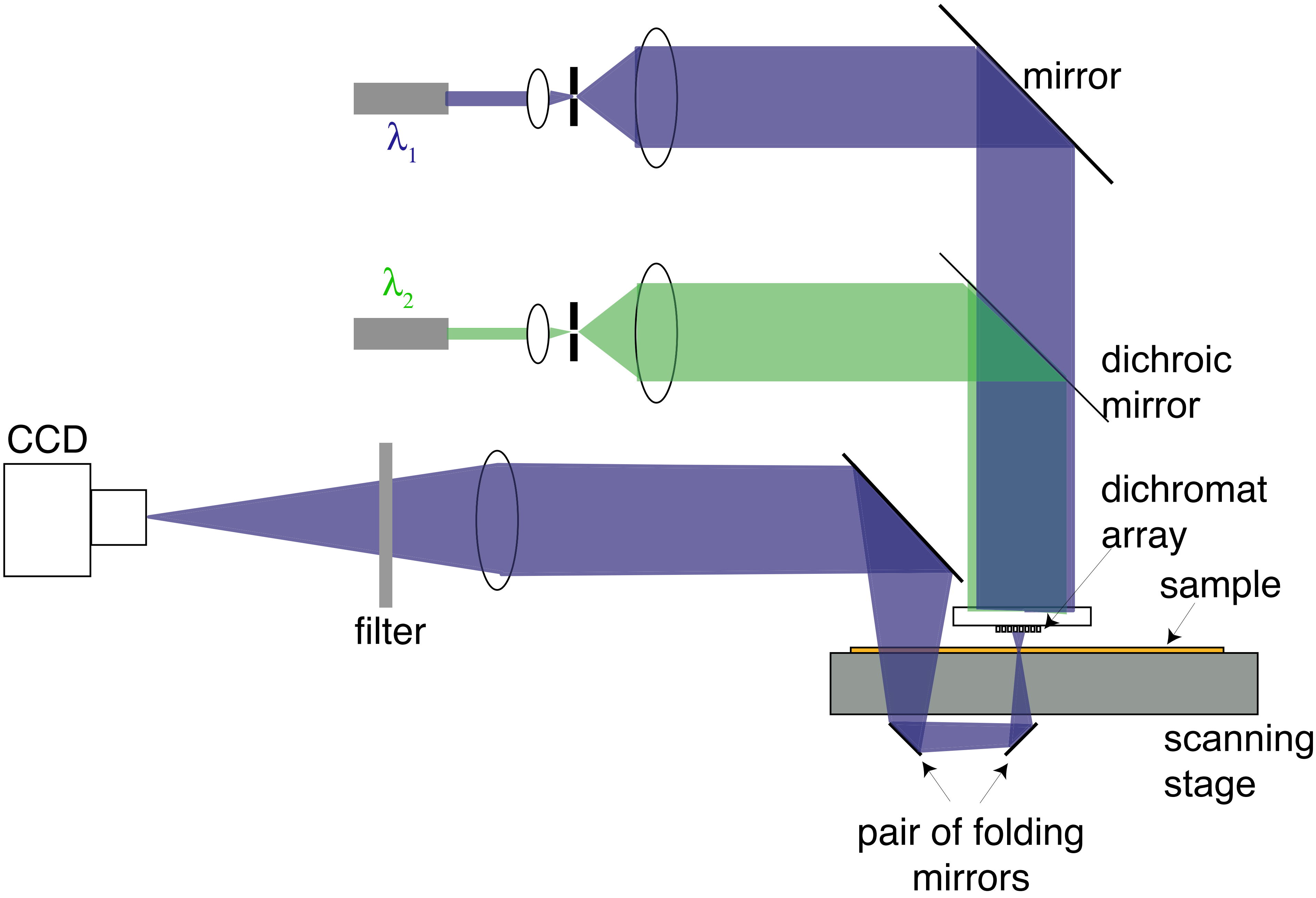
Absorbance Modulation for Imaging



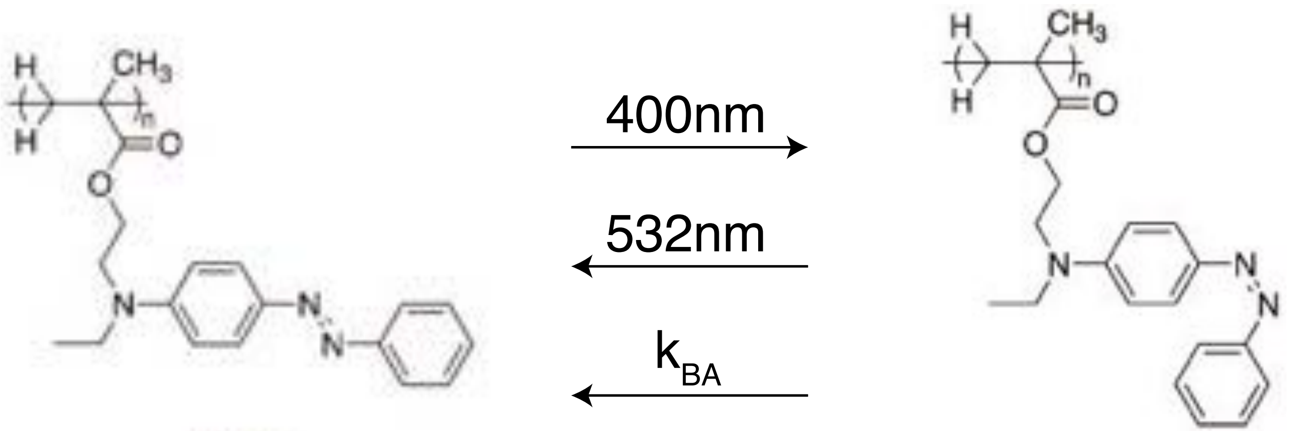




Schematic of current Microscope

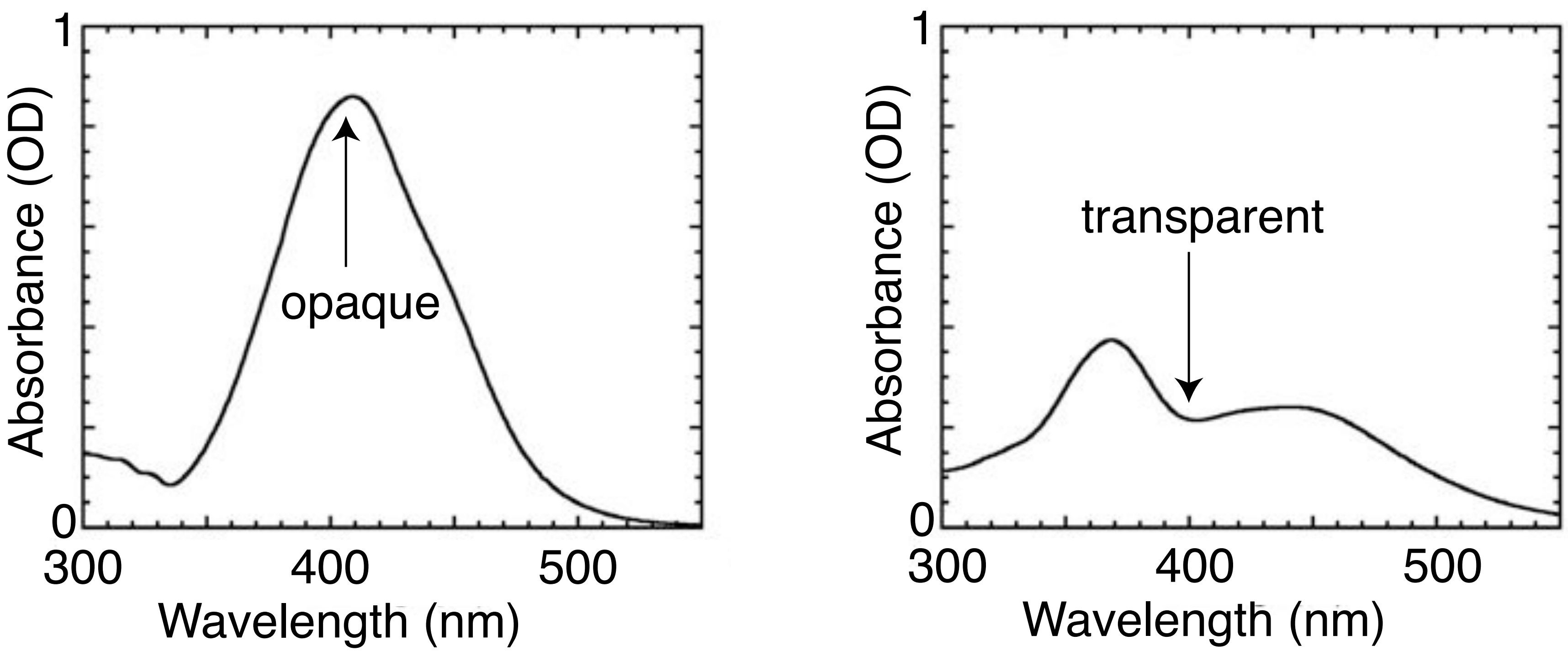


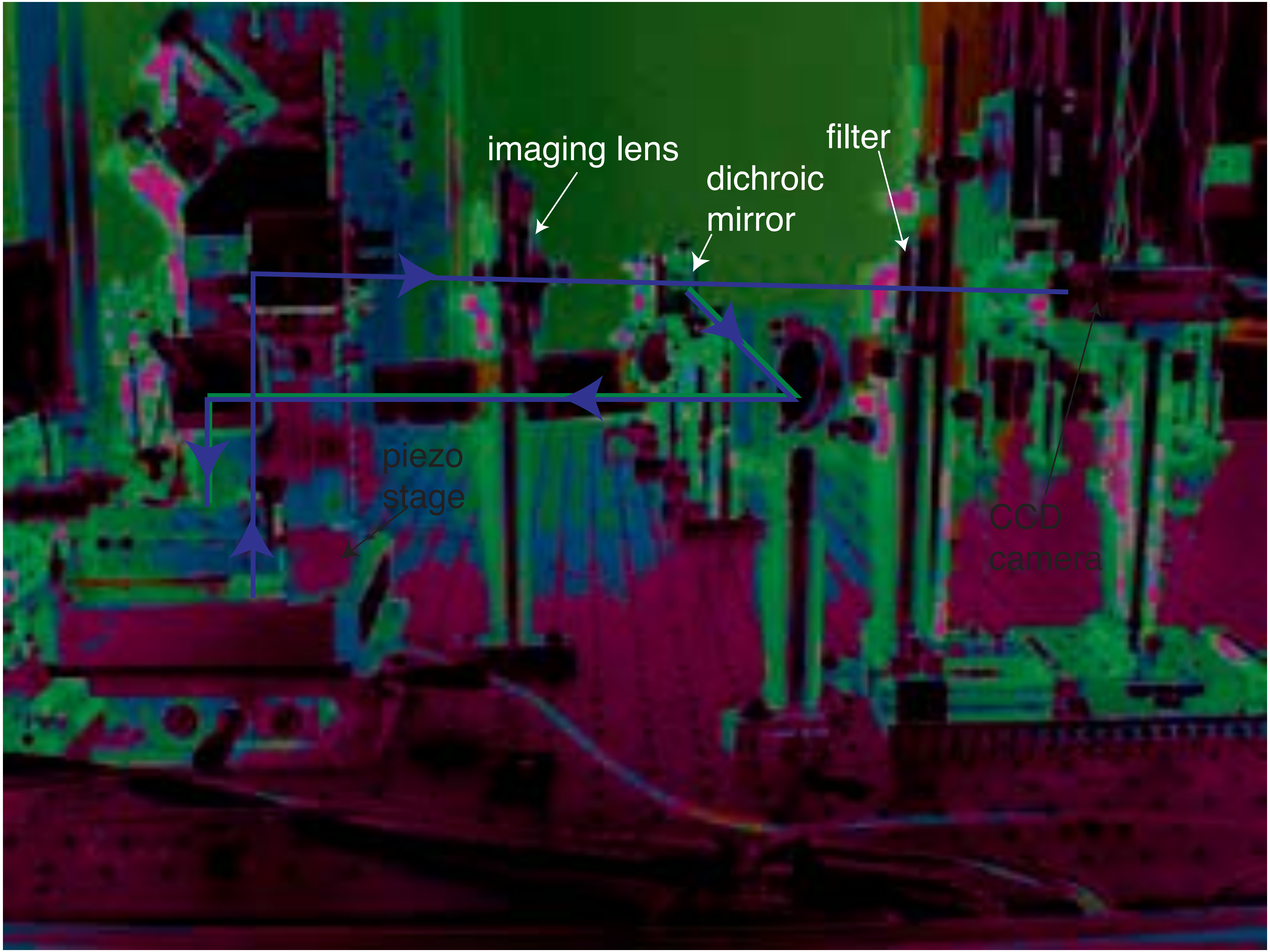
Photochromic molecule: Azobenzene polymer

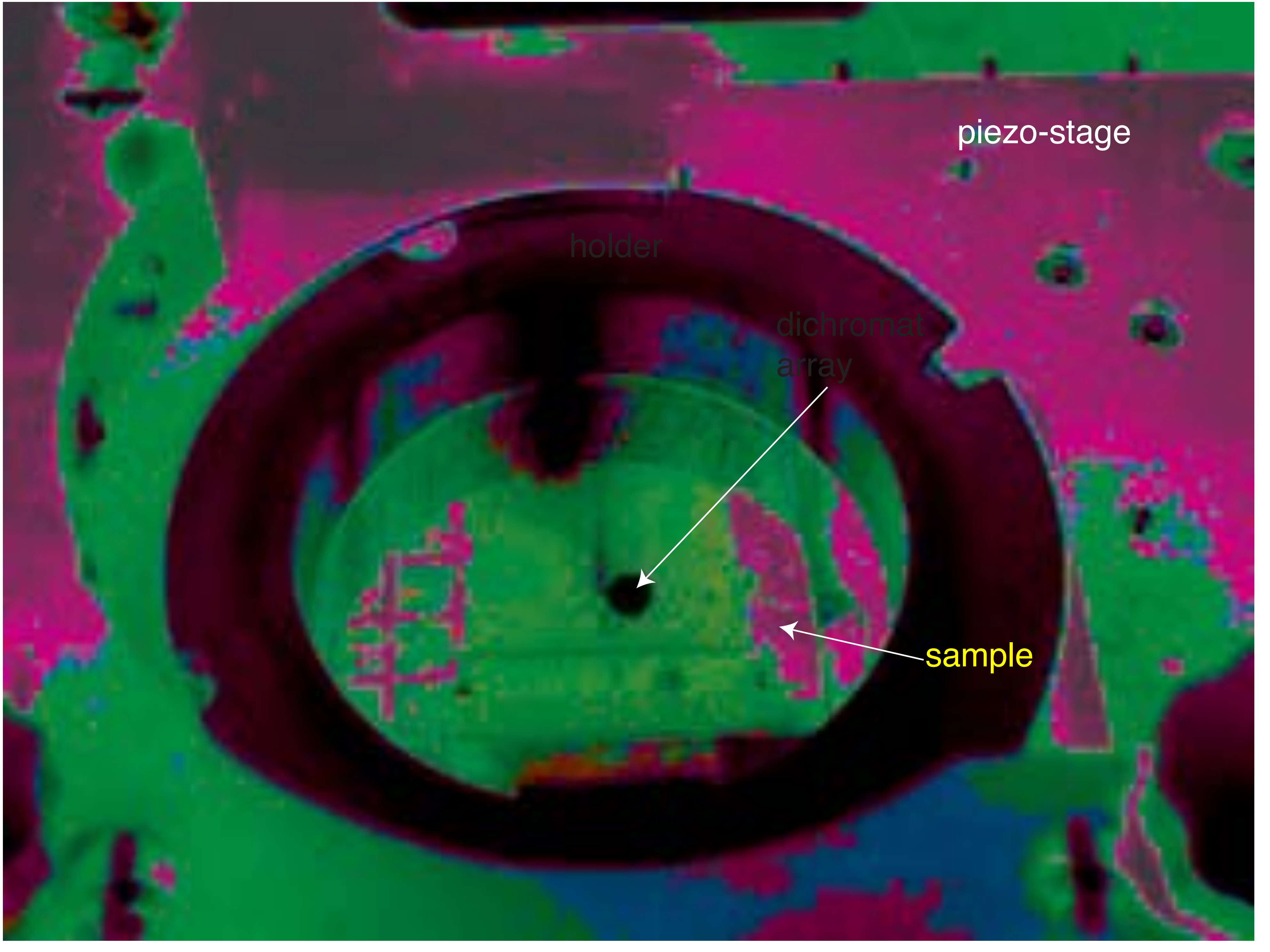


Trans Cis

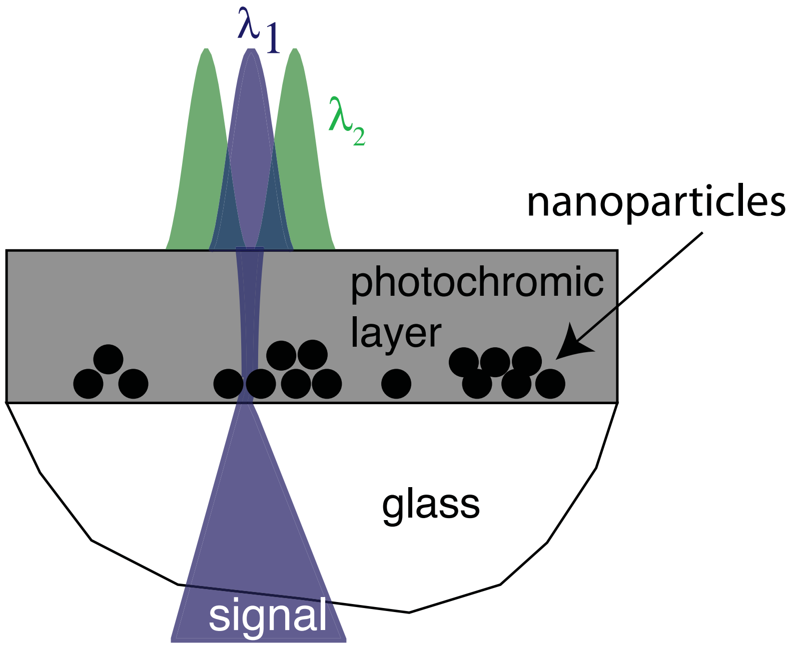
Trans (A) UV-Vis Spectra Cis (B)

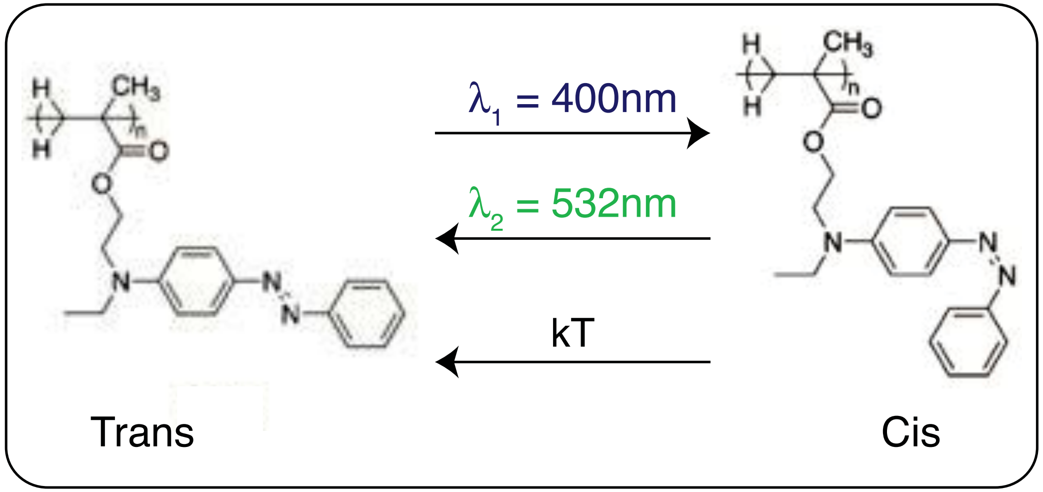


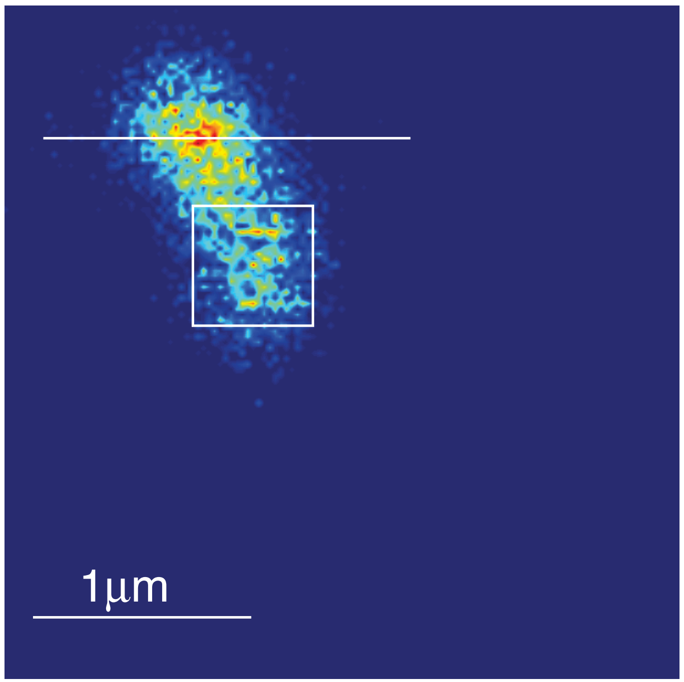

imaging lens
filter
dichroic
mirror
piezo
stage
CCD
camera

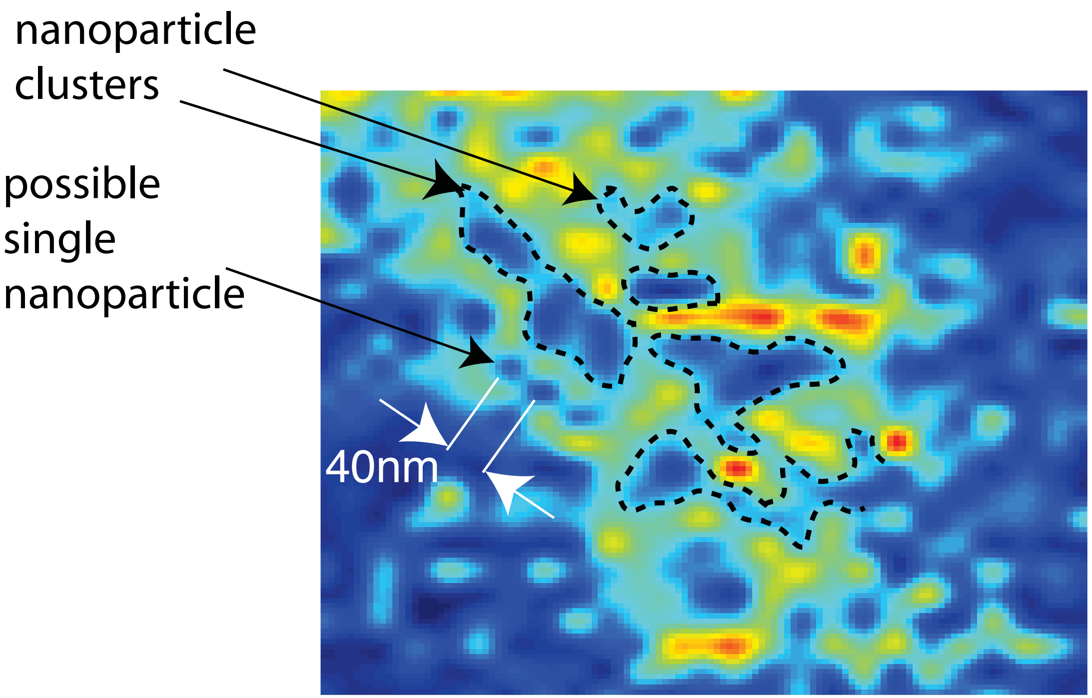

piezo-stage
holder
dichromat
array
sample

Absorbance-Modulation Nanoscopy





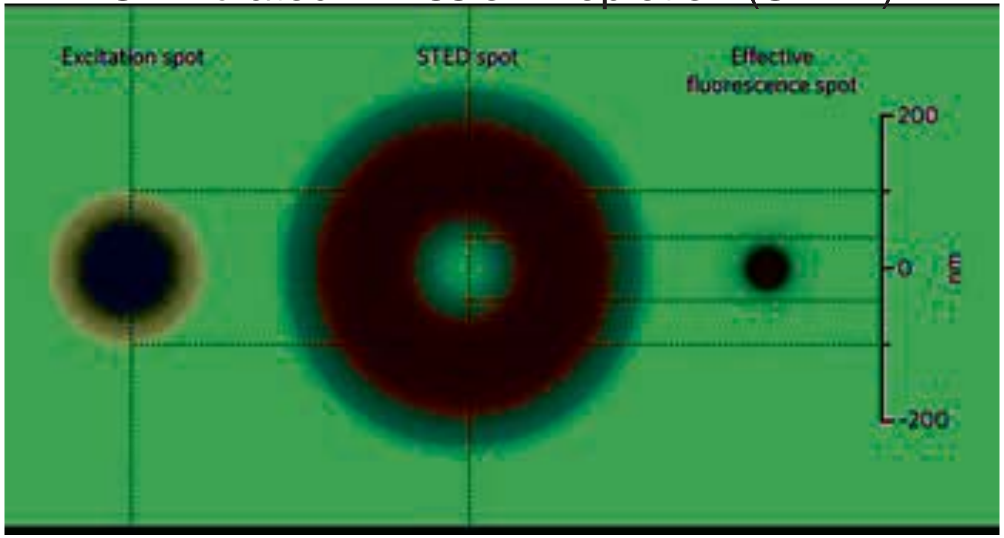




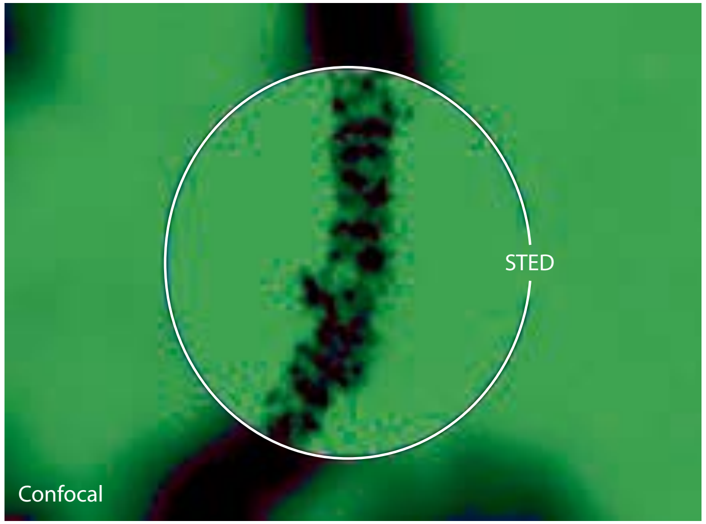
H-Y. Tsai, S.W. Thomas & R. Menon, *Opt. Exp.* 18(15), 16015 (2010)

Superresolution using Fluorescence

STimulated Emission Depletion (STED)

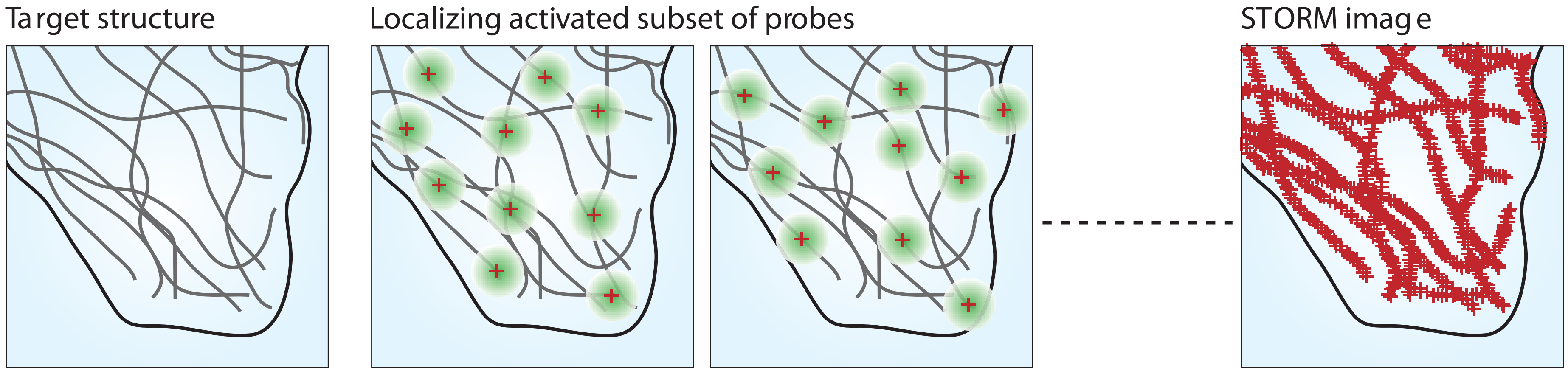


Folds of the mitochondrial inner membrane



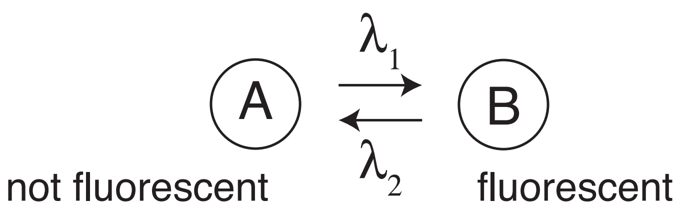
T. A. Klar, *et. al, PNAS* 97, 8206 (2000).

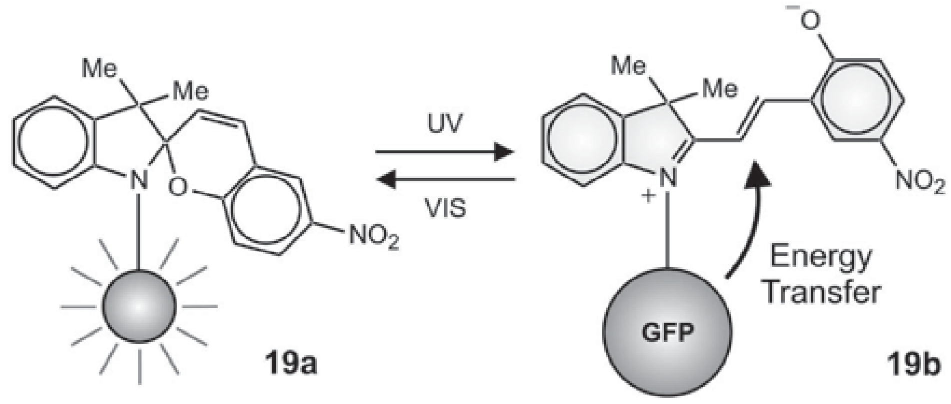
STochastic Optical Reconstruction Microscopy (STORM)

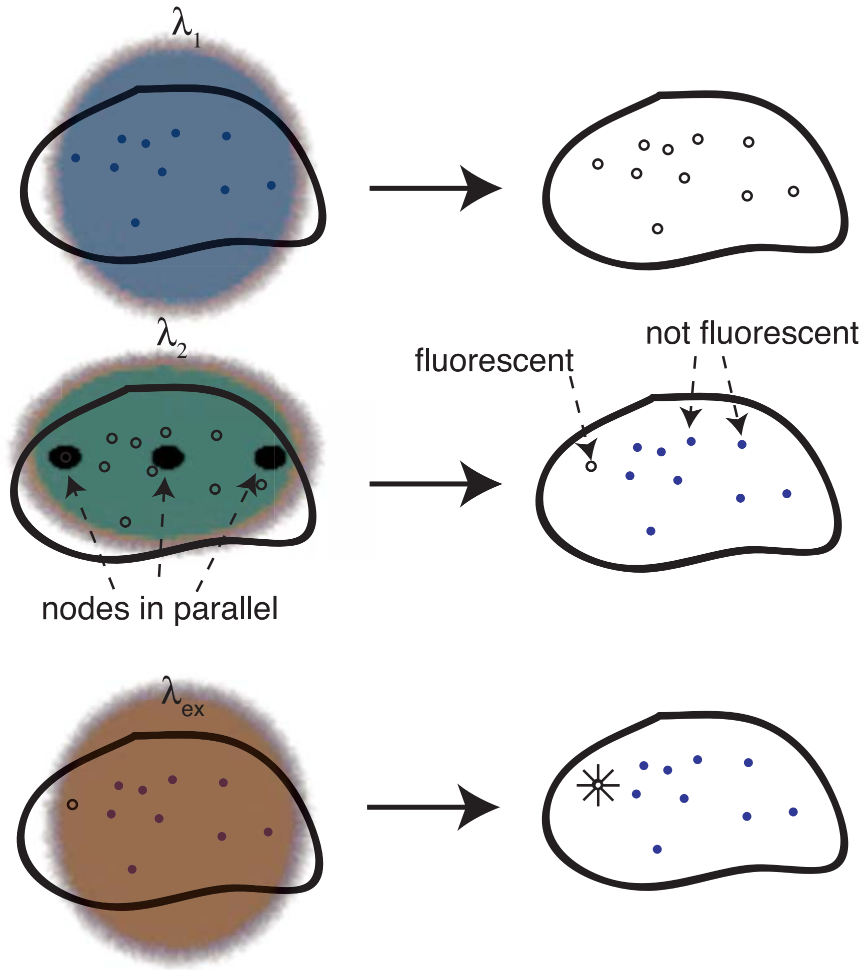


X. Zhuang, *Nat. Photonics*, 3, 365 (2009).

Fast 3-D Optical nanoscopy with optically switchable fluorofores



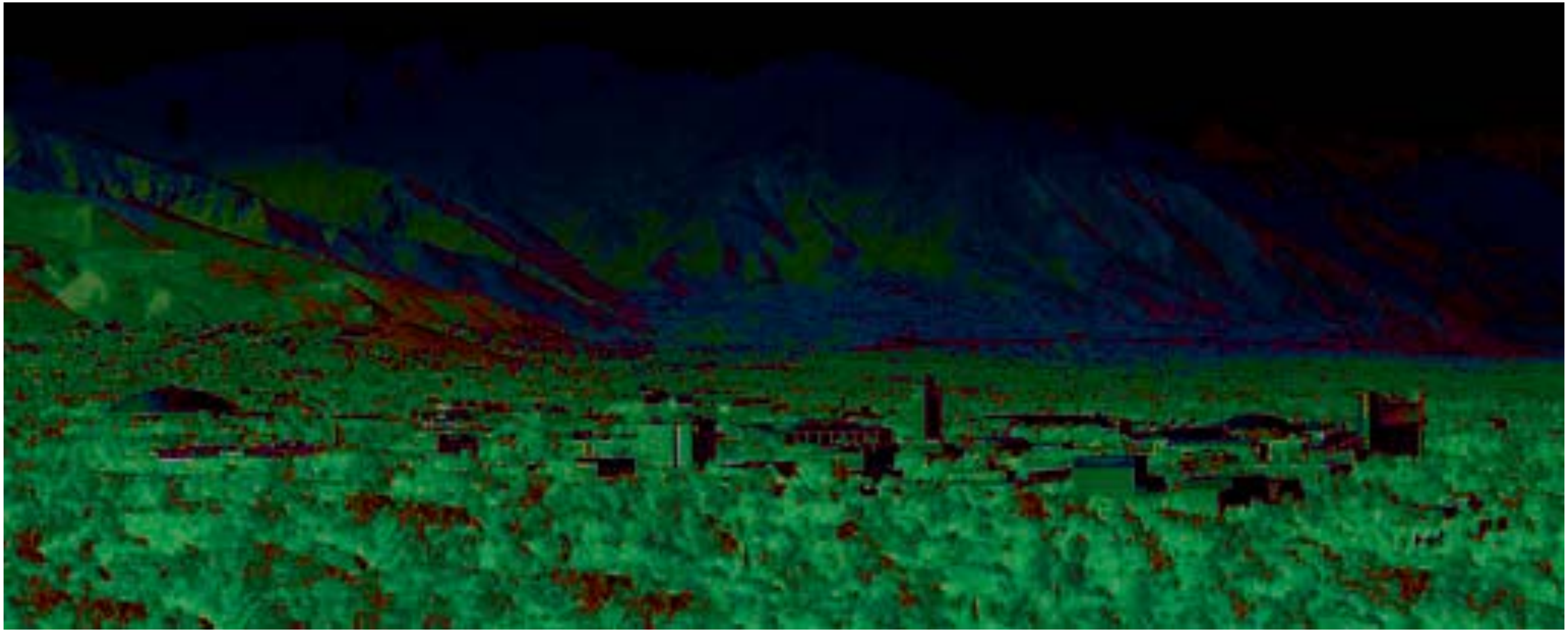




- Single molecule resolution in 3-D
- 3-D node at λ_2 created by fast spatial-light modulator (SLM). Node may be scanned by SLM.
- Massively parallel - 1000s of nodes at 100Hz-25kHz frame rates -> live-cell imaging
- Low power levels (CW laser or lamp sources) compared to STED (& related approaches)
- Deterministic raster scan (smaller data sets, much lower post-processing) compared to STORM/PALM. Real-time imaging feasible.


Jason Kleinschmidt
Precious Cantu
Raja Manthena
Ganghun Kim
Sidney Tsai
Trisha Andrews
Niki Brimhall
Mohit Diwekar
Farhad Mahdavi

The University of Utah



- 1st year fellowship open to the best PhD students (including international students)
- Infra-structures & facilities
- Highly inter-disciplinary research
- Entrepreneurship opportunities

http://lons.utah/edu/
rmenon@eng.utah.edu