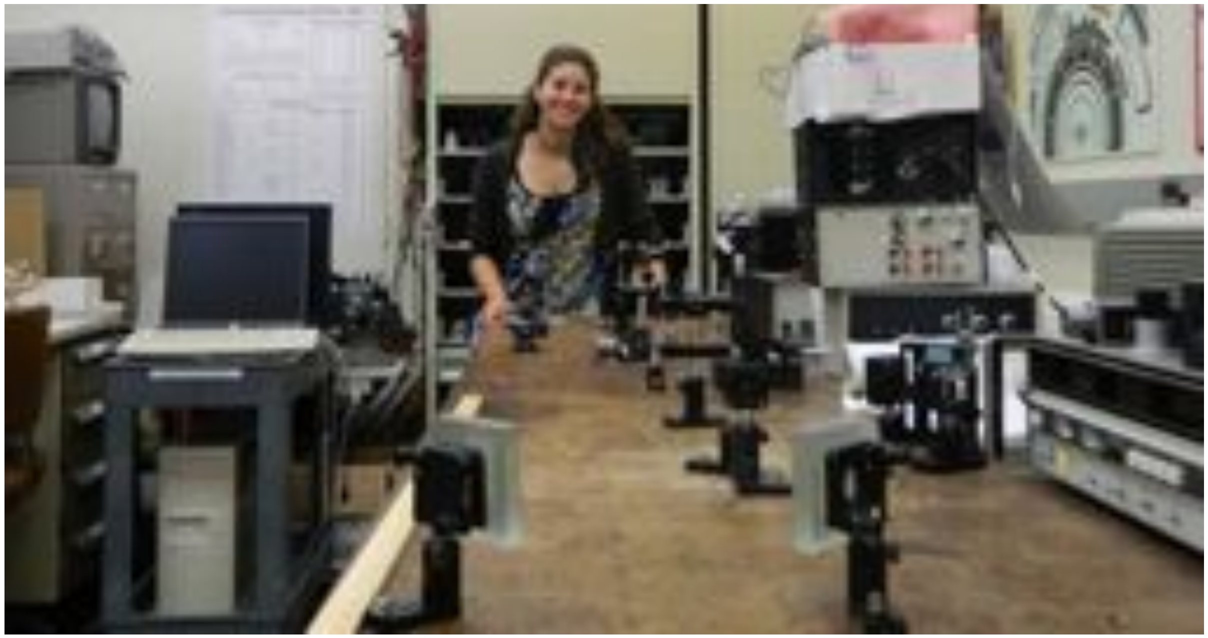
Creating Bessel Beams with a 4-f Spatial Filter



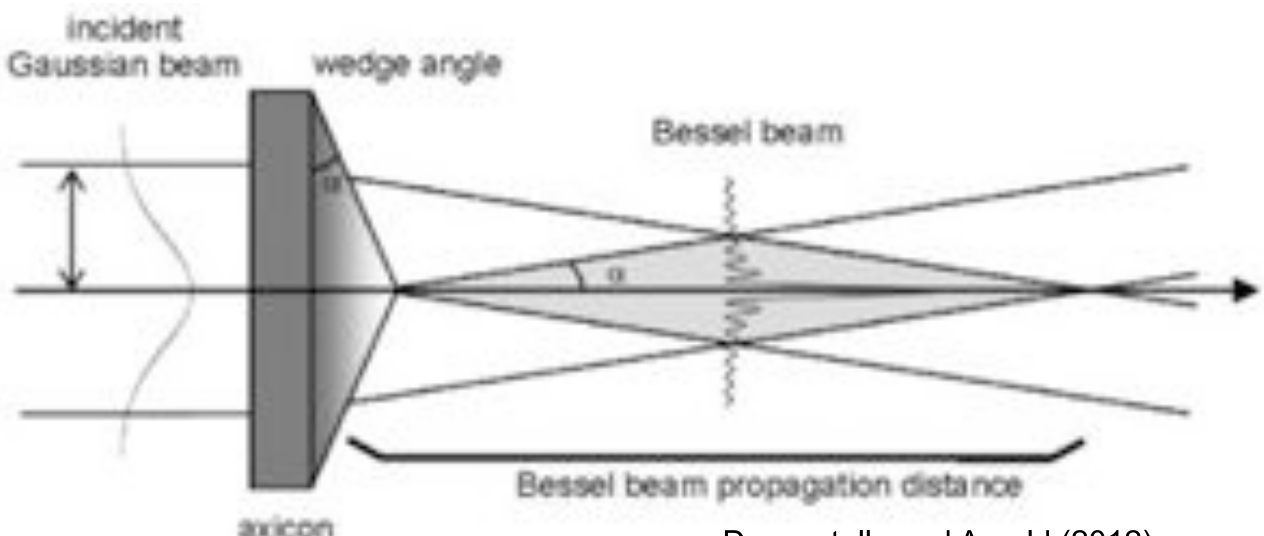
Melia Bonomo, Dickinson College ’13
John Noé and Marty Cohen
Stony Brook University
Laser Teaching Center
Summer 2012

Stony Brook University

Welcome to the Laser Center

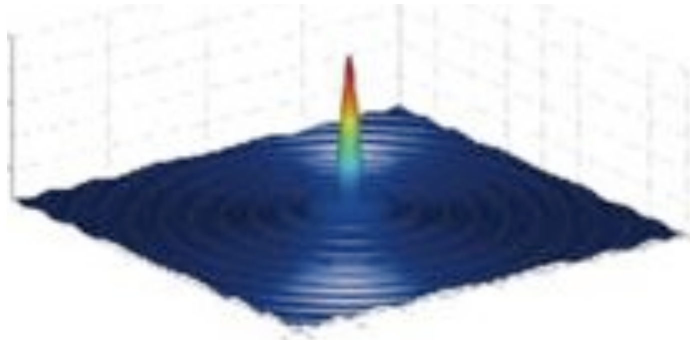
Overview

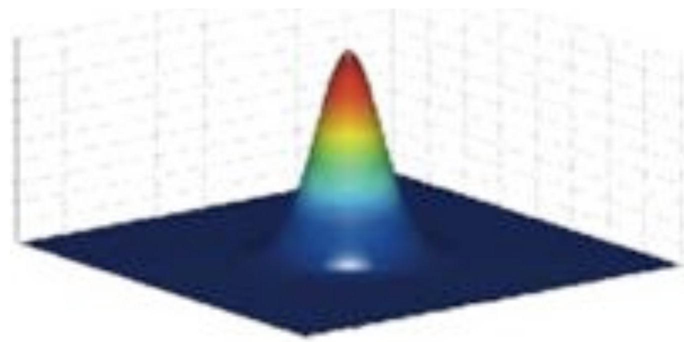
- Bessel beam properties
- Generating Bessel beams
  - (Axicon, 1953 McLeod)
  - Annular Aperture, 1987 Durnin, Eberly
  - 4-f Spatial Filter, 2009 Kowalczyk
- Imaging and analyzing the beam



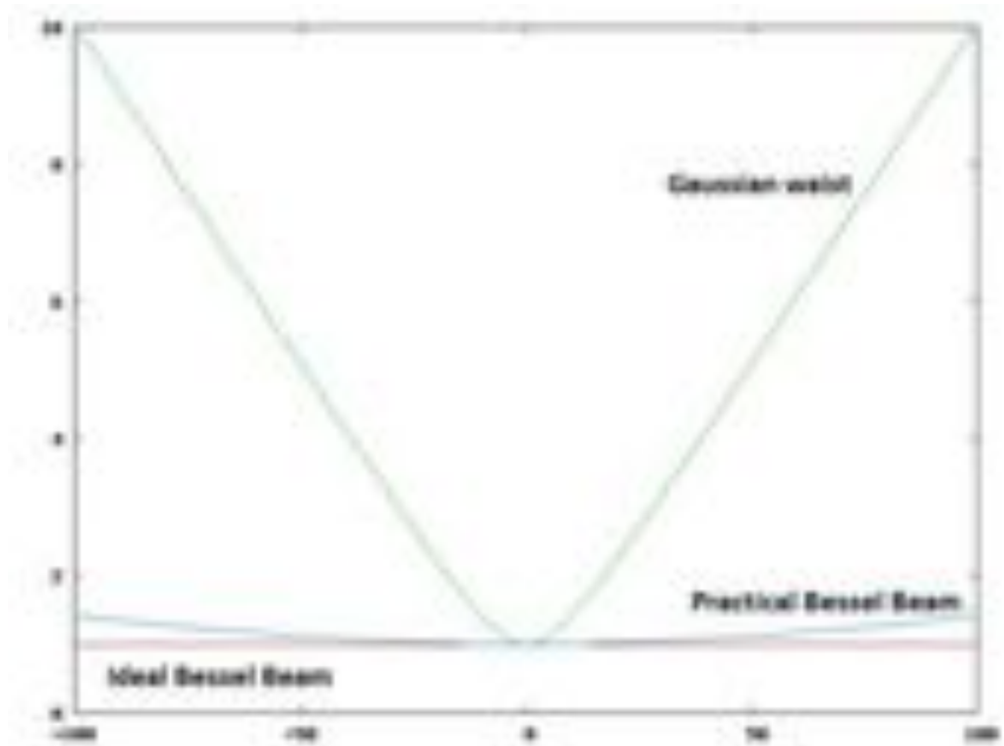
Duocastella and Arnold (2012)

Bessel vs. Gaussian Beams





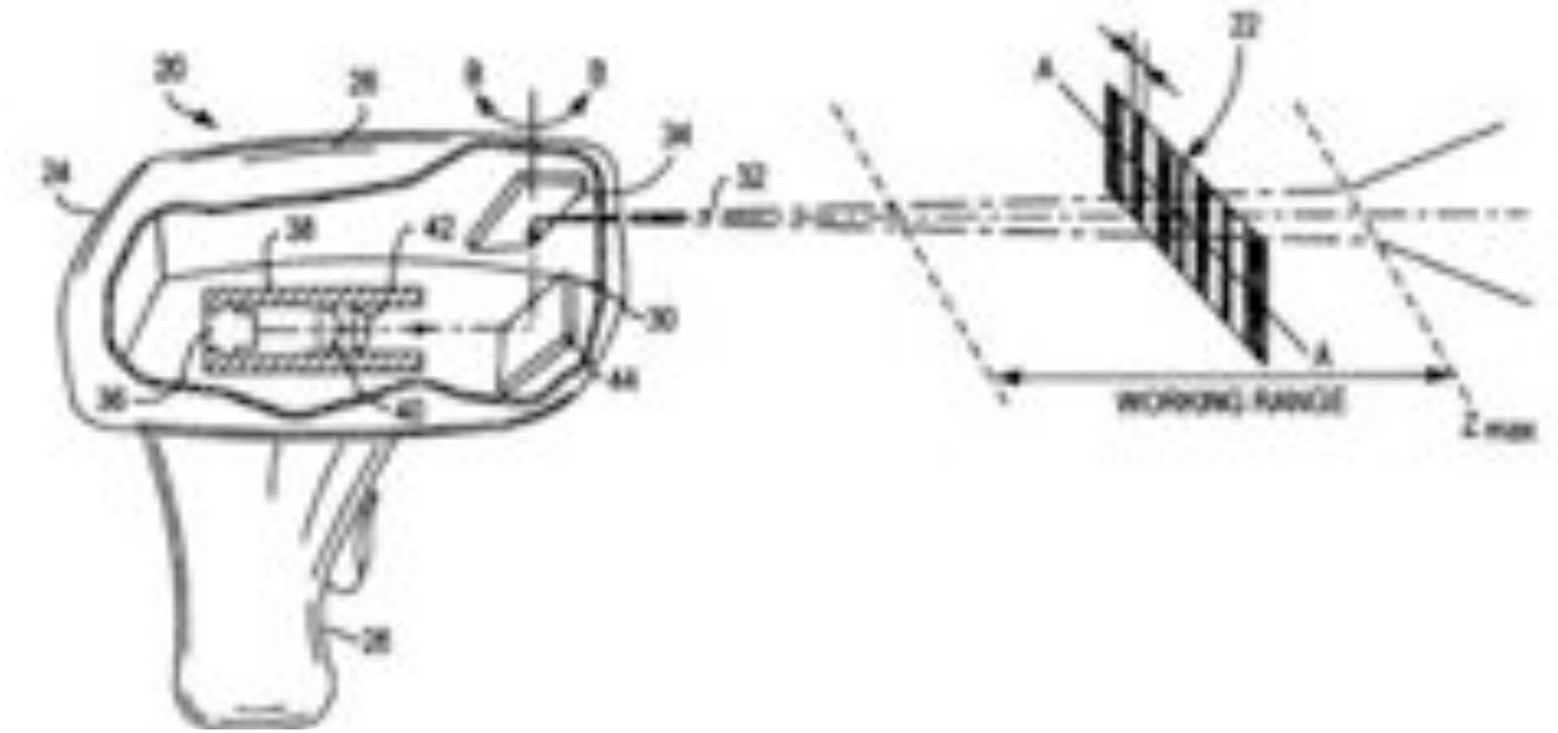
- Non-diffracting
- Thin, infinitely long core with concentric rings
- Ideal Bessel beams cannot be experimentally created
- Close approximations are possible



Marissa Romano, SBU '15

Most Widespread Application

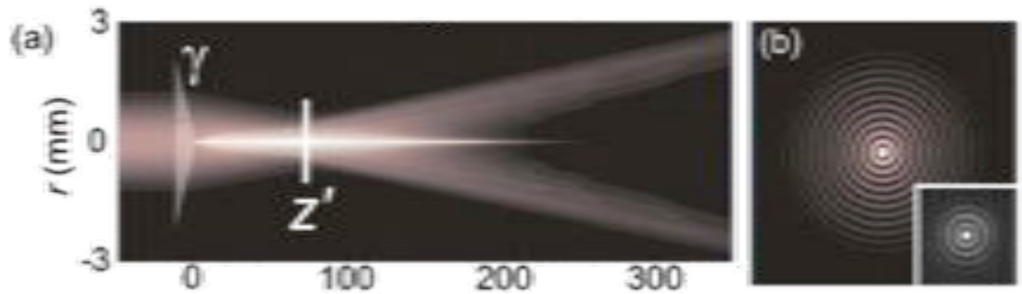
- Employing a Bessel beam greatly increases the working range of a barcode scanner



Gurevich 2003

Geometry and Math

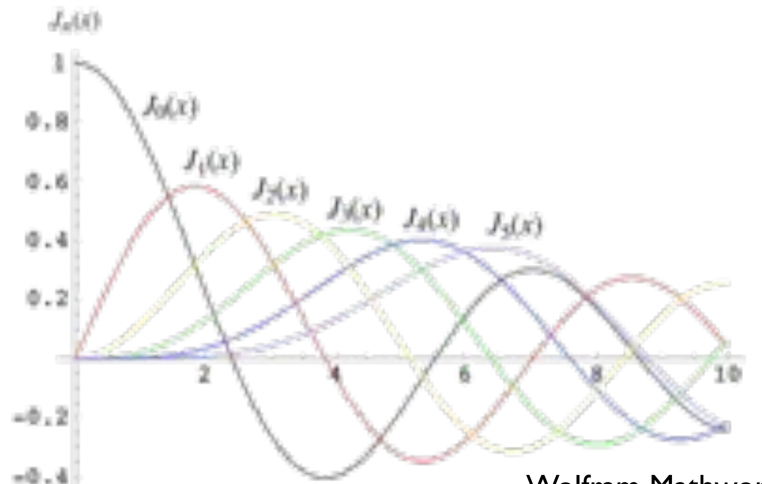
- Superposition of plane waves with k-vectors lying on surface of cone
  - Creates central max and plurality of side lobes



Milne (2008)

$$E_l(r, \phi, z) = Ae^{ik_z z} J_l(k_r r) e^{i\phi l}$$

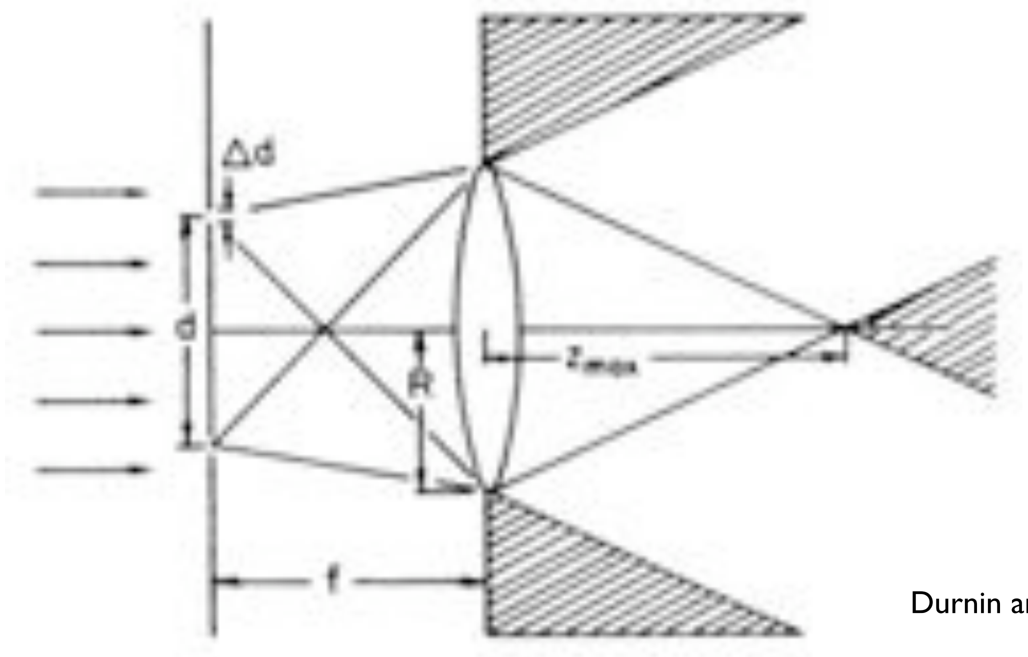
- Electric field amplitude proportional to Bessel function
- Zero-order or Higher-Order beams



Wolfram Mathworld, 2012

Creating Bessel beams with an Annular Aperture

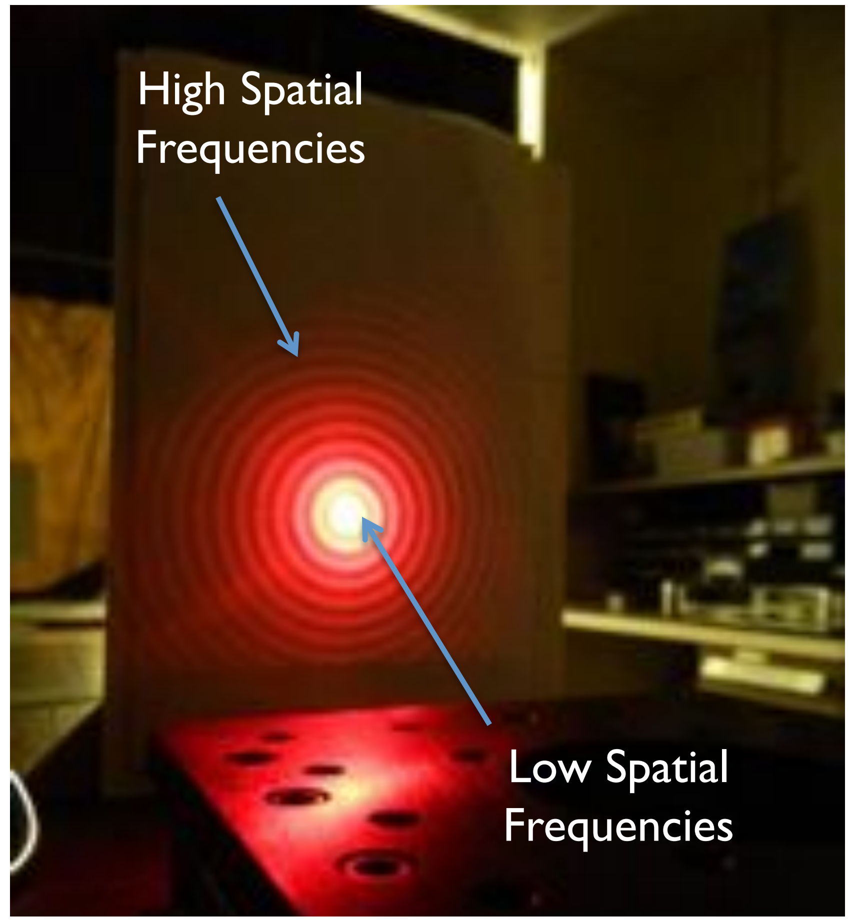
- Fresnel diffraction of thin ring light source
- Durnin and Eberly 1987
  - 2.5 mm diameter, 10 micron wide
- Lens refocuses the diffracted ring of light to create conical superposition of plane waves



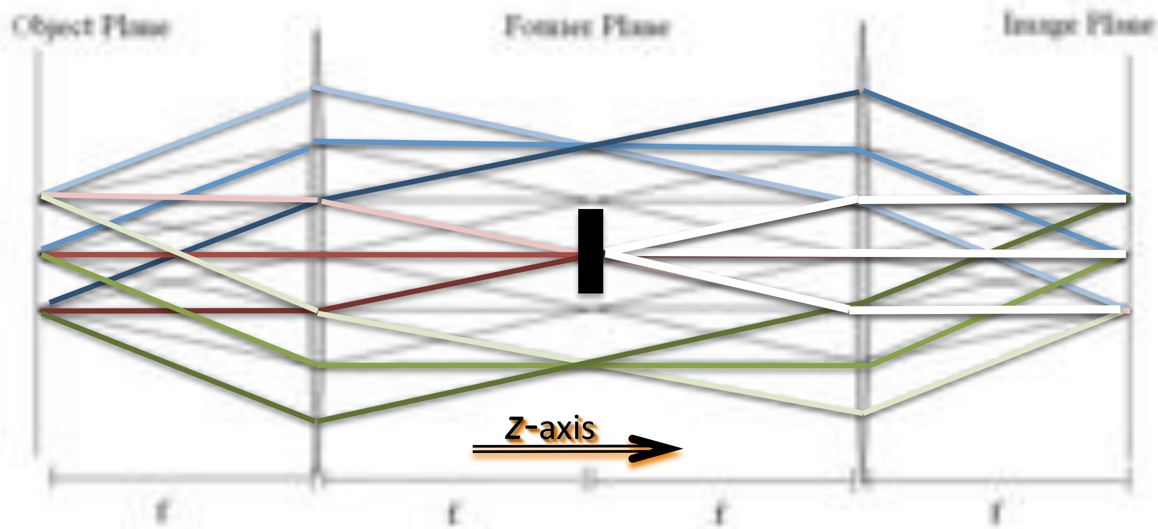
Durnin and Eberly (1987)

Creating a ring of light through spatially filtering a circular aperture

- Pinhole diffraction pattern in Fourier plane
- Fourier optics basics:
  - High spatial frequencies: object edges
  - Low spatial frequencies: overall quality
- Edge-enhanced image of the circular aperture

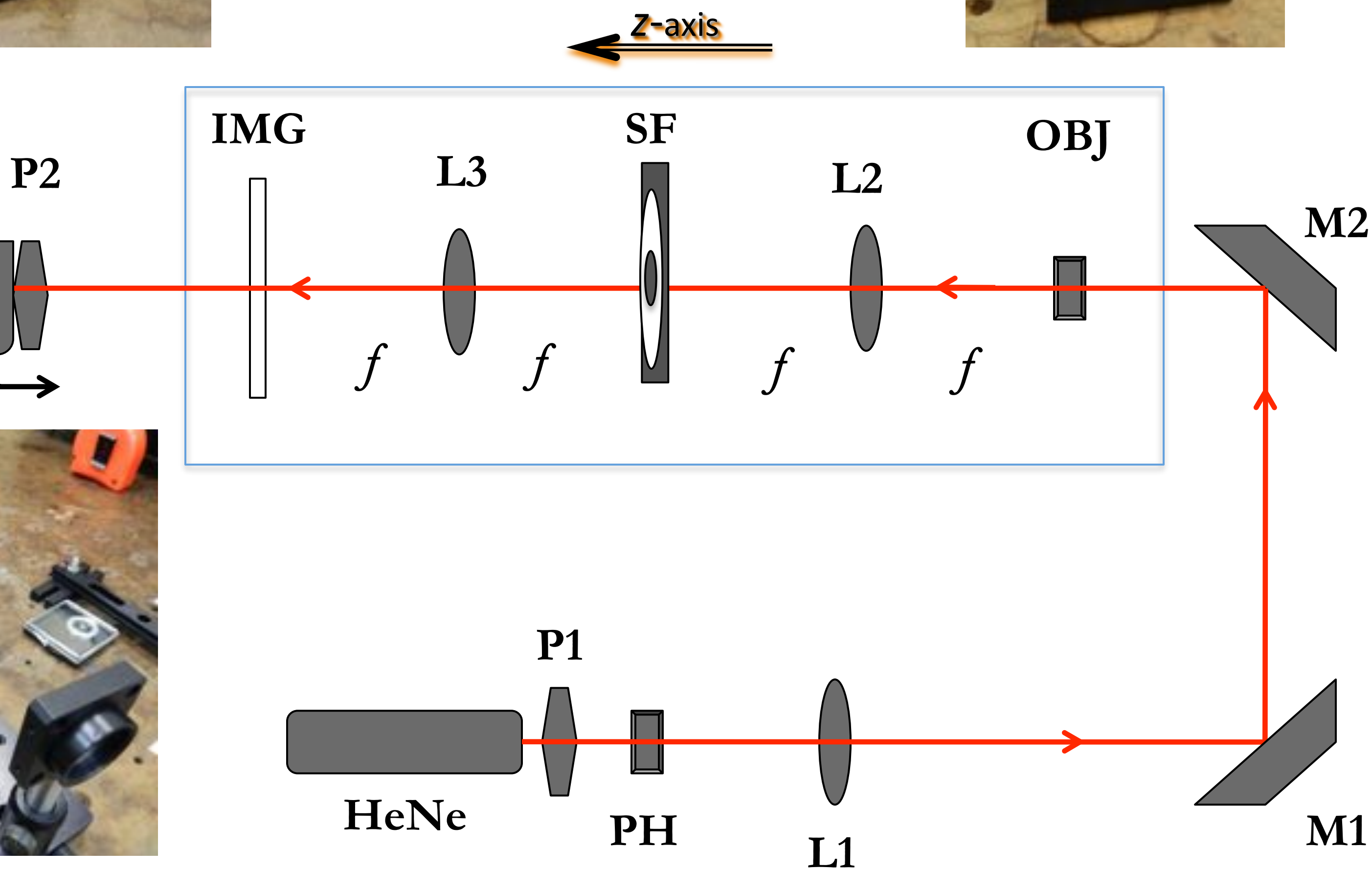


4-f Spatial Filtering Method

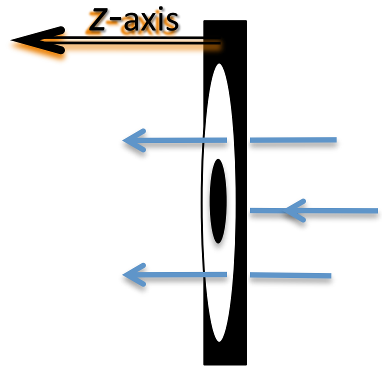


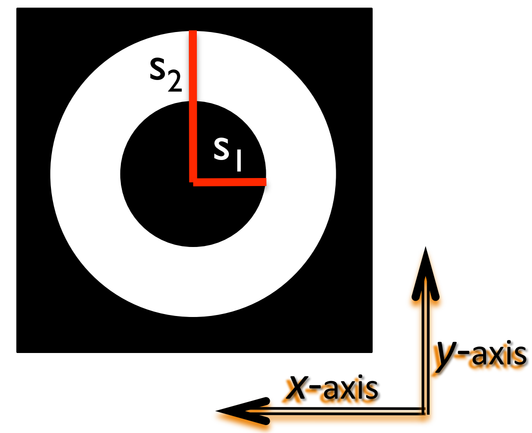
- Kowalczyk et al. (AJP, 2009)
- Lens organizes spatial frequencies of object
  - Rays bent at same angle are part of the same diffraction order of the pattern in the Fourier plane
- The diffraction pattern is the Fourier transform of the object
- Inverse image created in image plane

Setup Design

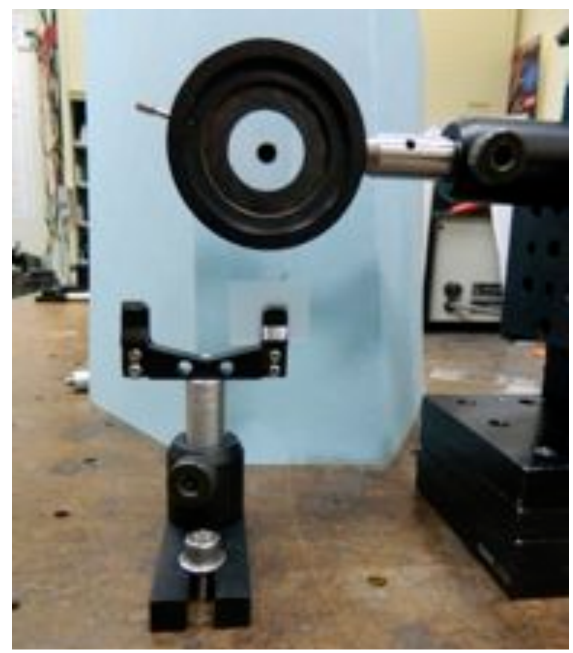


The filter dimensions





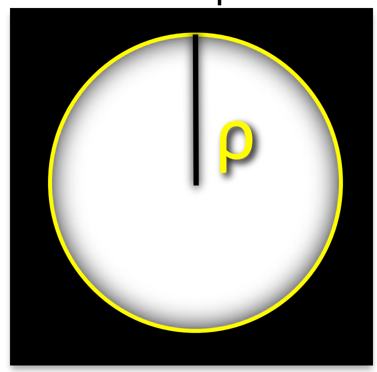
- Inner radius 3 mm
  - To block the low frequencies
- Outer iris diaphragm radius 10 mm
  - Limits the high frequencies coming through too
- Why is there a limit on the outer dimension?



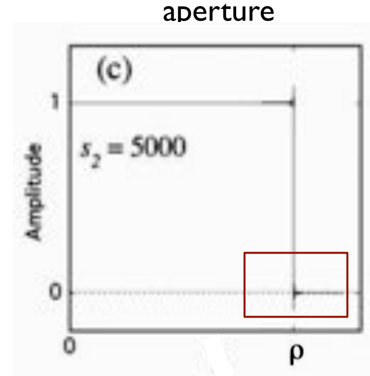
Gibb’s phenomenon

- Always a zero in the middle of the diffracted field at r = ρ
- Causes double-lobed amplitude at edge of aperture

circular aperture

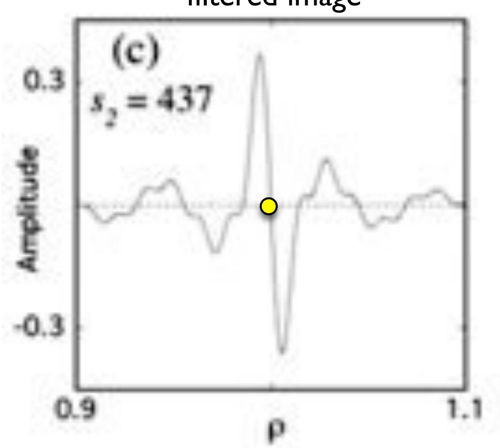


amplitude at edge of aperture

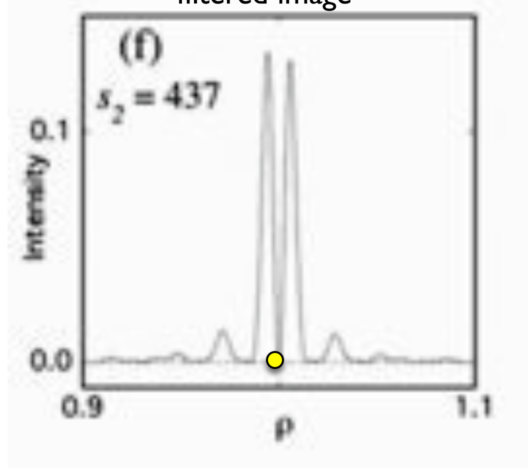


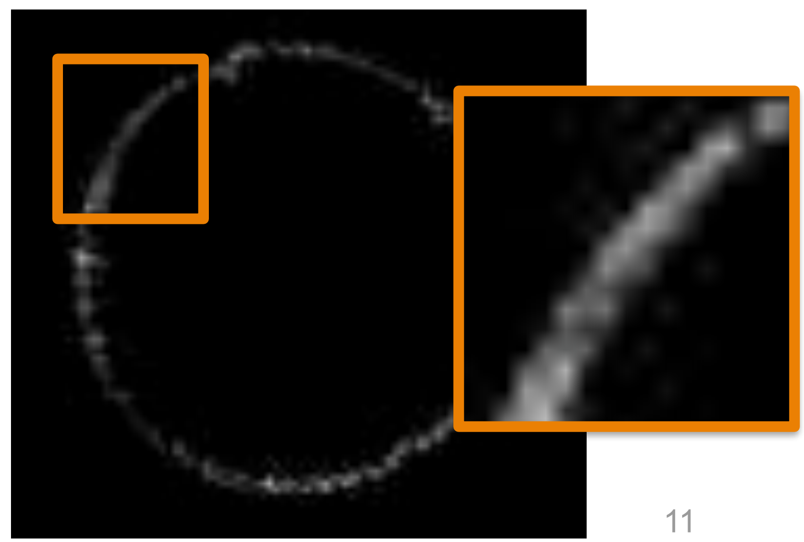
This is the difference between our ring and one that would come from a uniformly illuminated annular slit!

amplitude at edge of filtered image



intensity at edge of filtered image

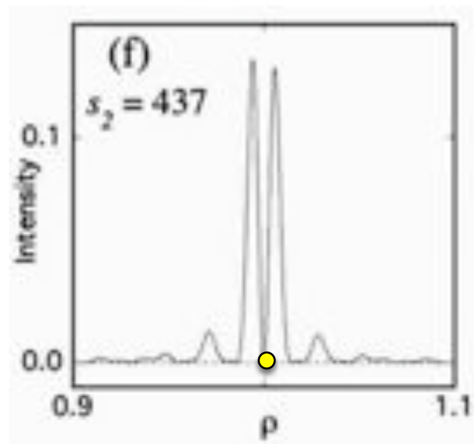




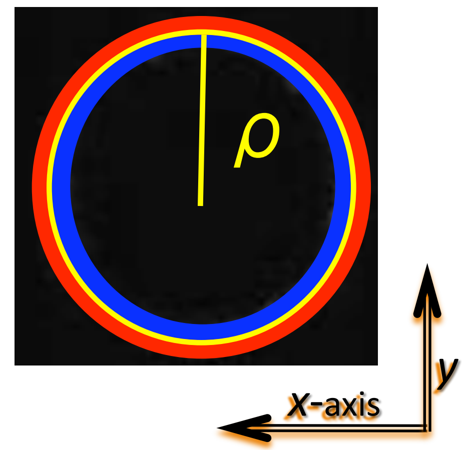
Kowalczyk (2009)

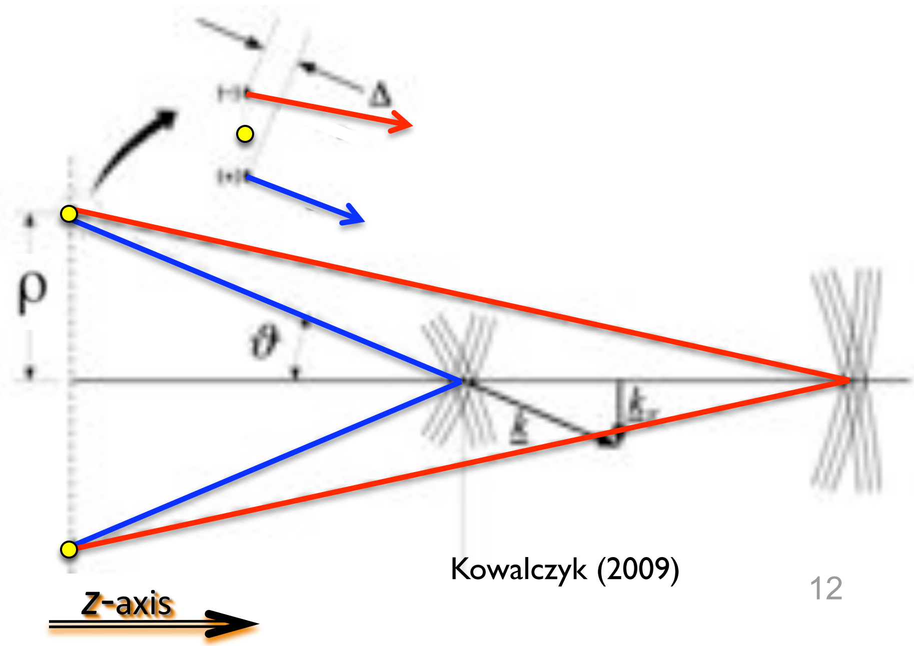
Forming the Bessel beam

- Propagation delay Δ between double-lobed intensity
- As you go farther on z-axis the lobes spread apart
  - constructive interference
  - start of Bessel beam
- Until a certain point where the lobes are too spread
  - destructive interference
  - end of the Bessel beam



edge-enhanced image





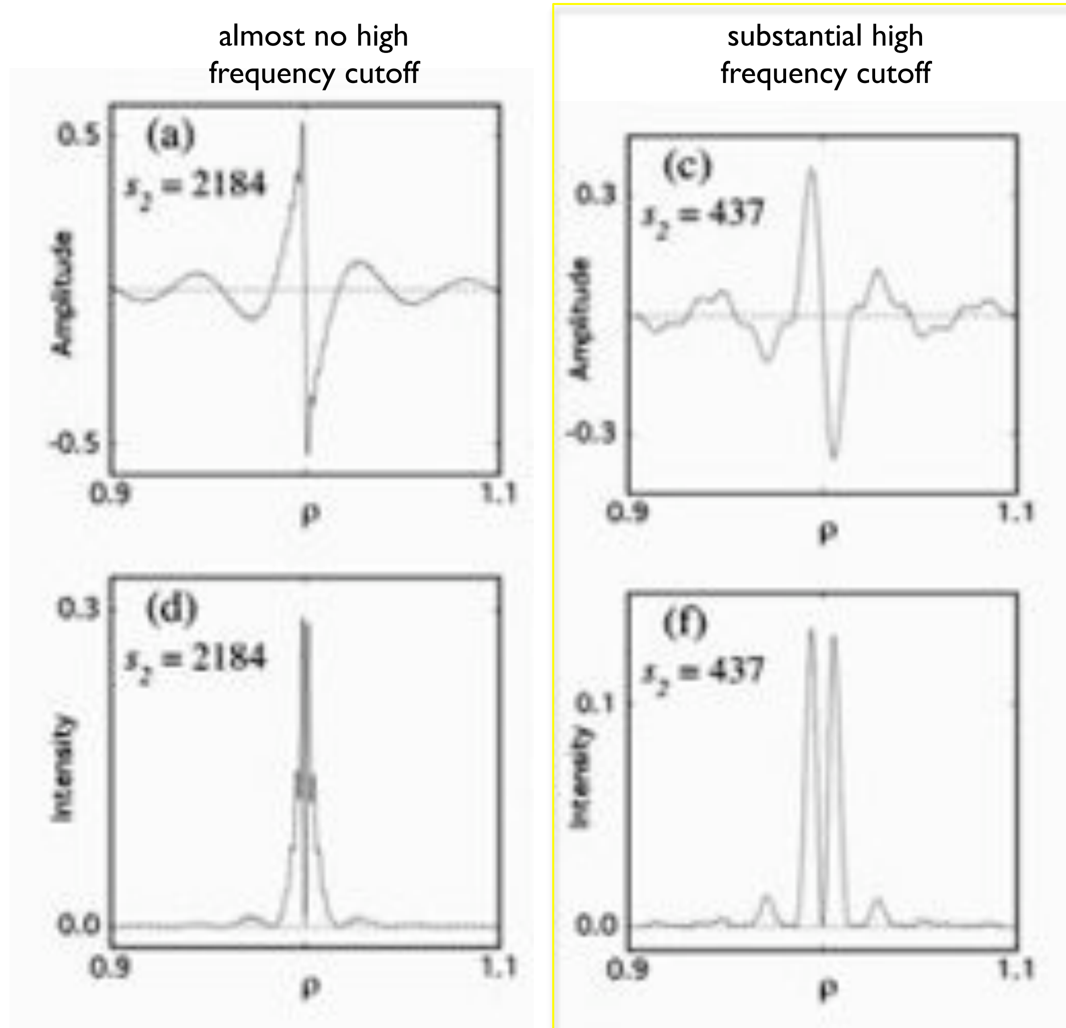
Kowalczyk (2009)

Effect of outer frequency cutoff on separation between intensity lobes

- Cutting off high frequencies:

→ less of an overshoot
→ lobes are more distinguishable from each other

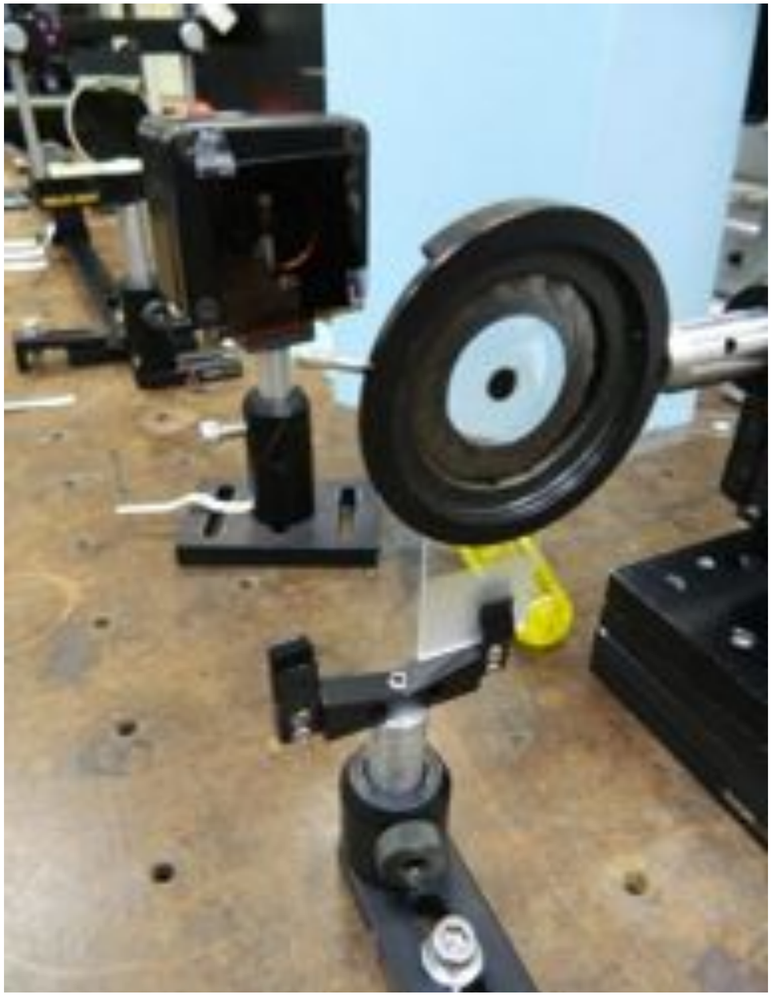
→ larger propagation delay between lobes
→ larger region of constructive interference on axis
→ longer Bessel beam



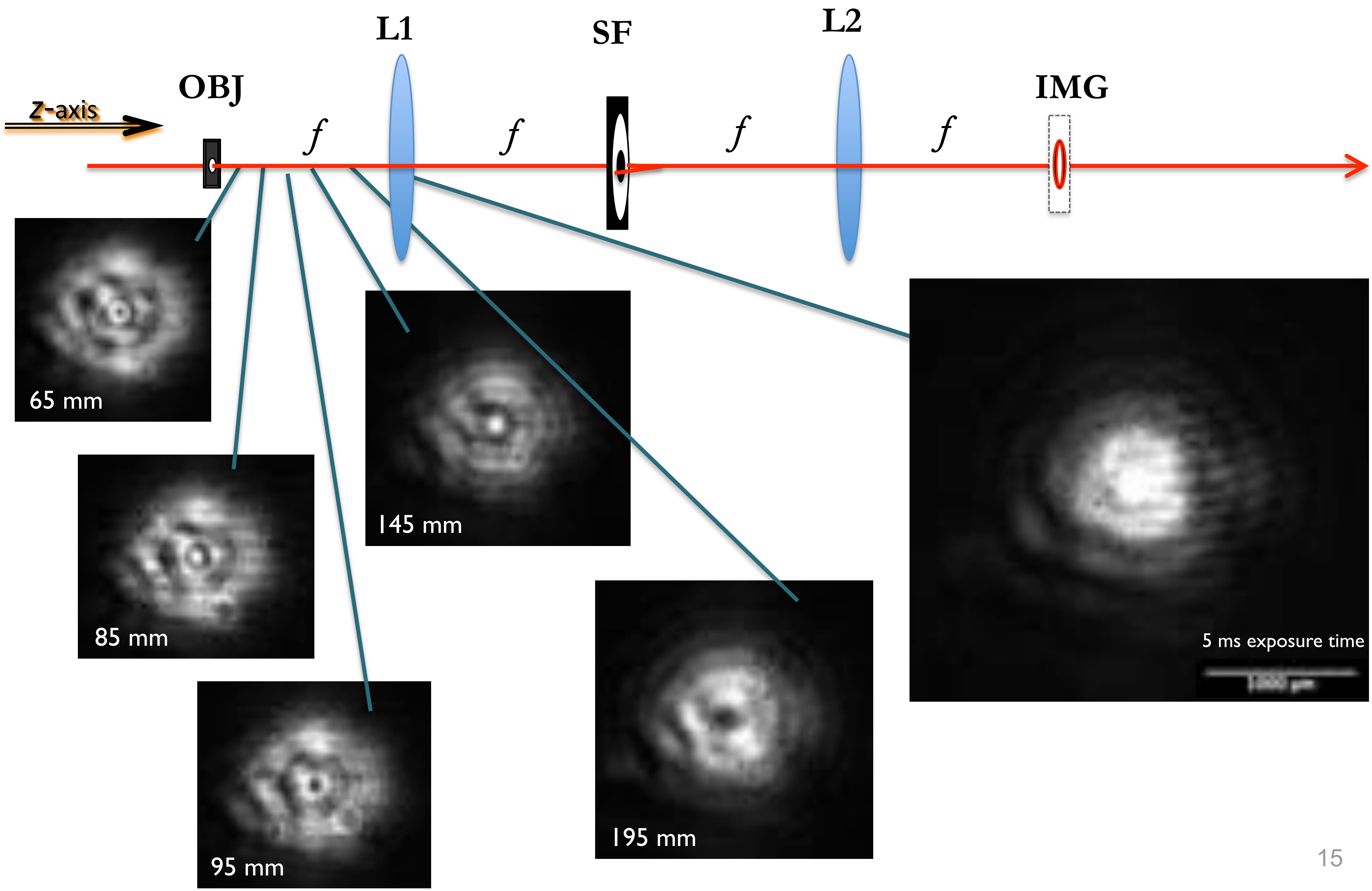
Kowalczyk (2009)

Electrim EDC 1000N images

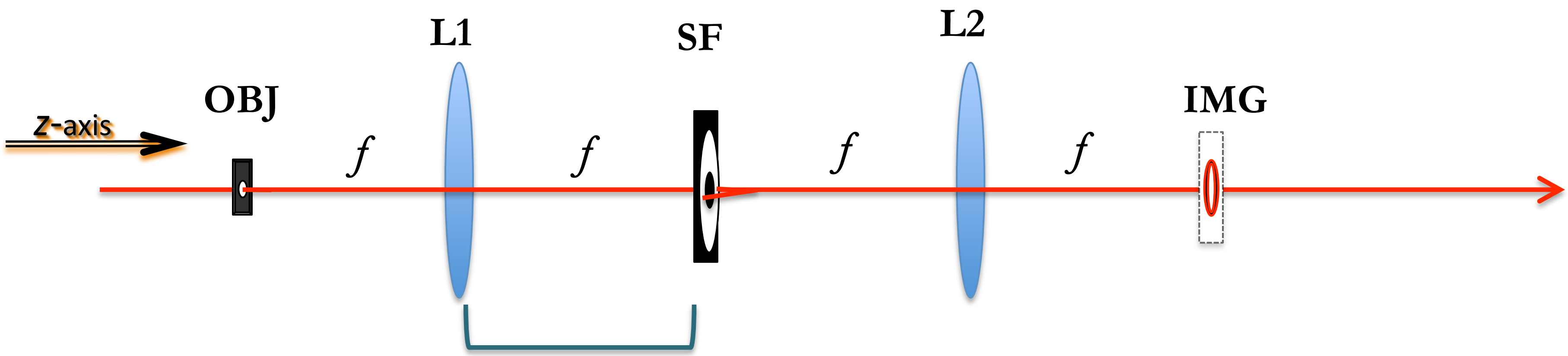
- 7.4 micron square pixels
- Polarizers to prevent saturation
- Recorded the evolution of the light field from the initial aperture to the final Bessel beam
- Images are transverse taken in transverse plane



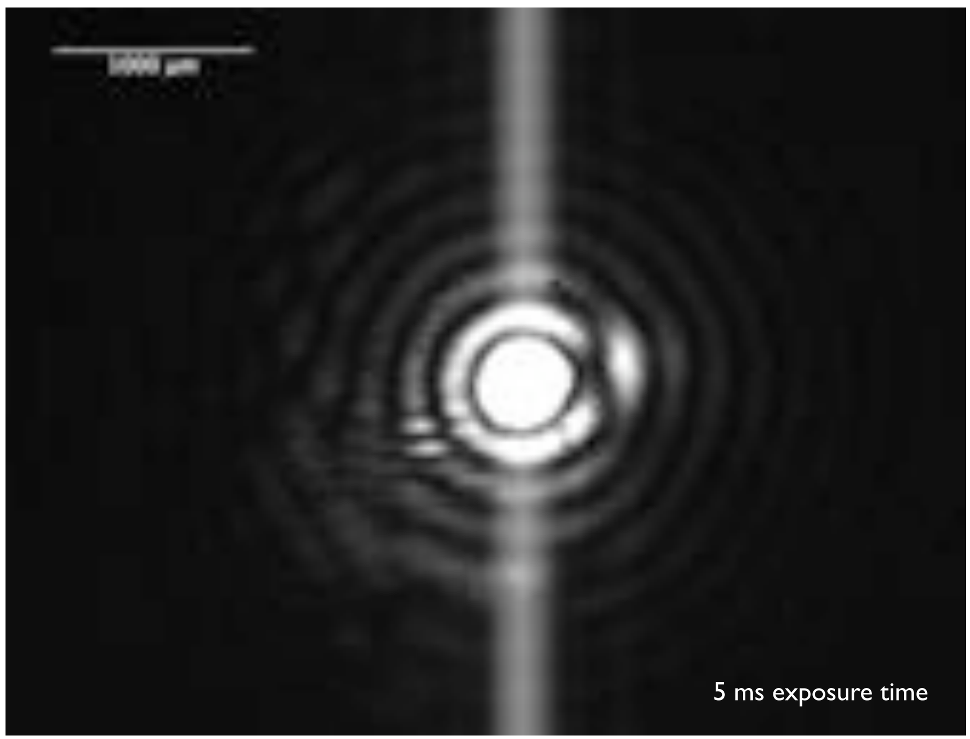
Object to Lens 1



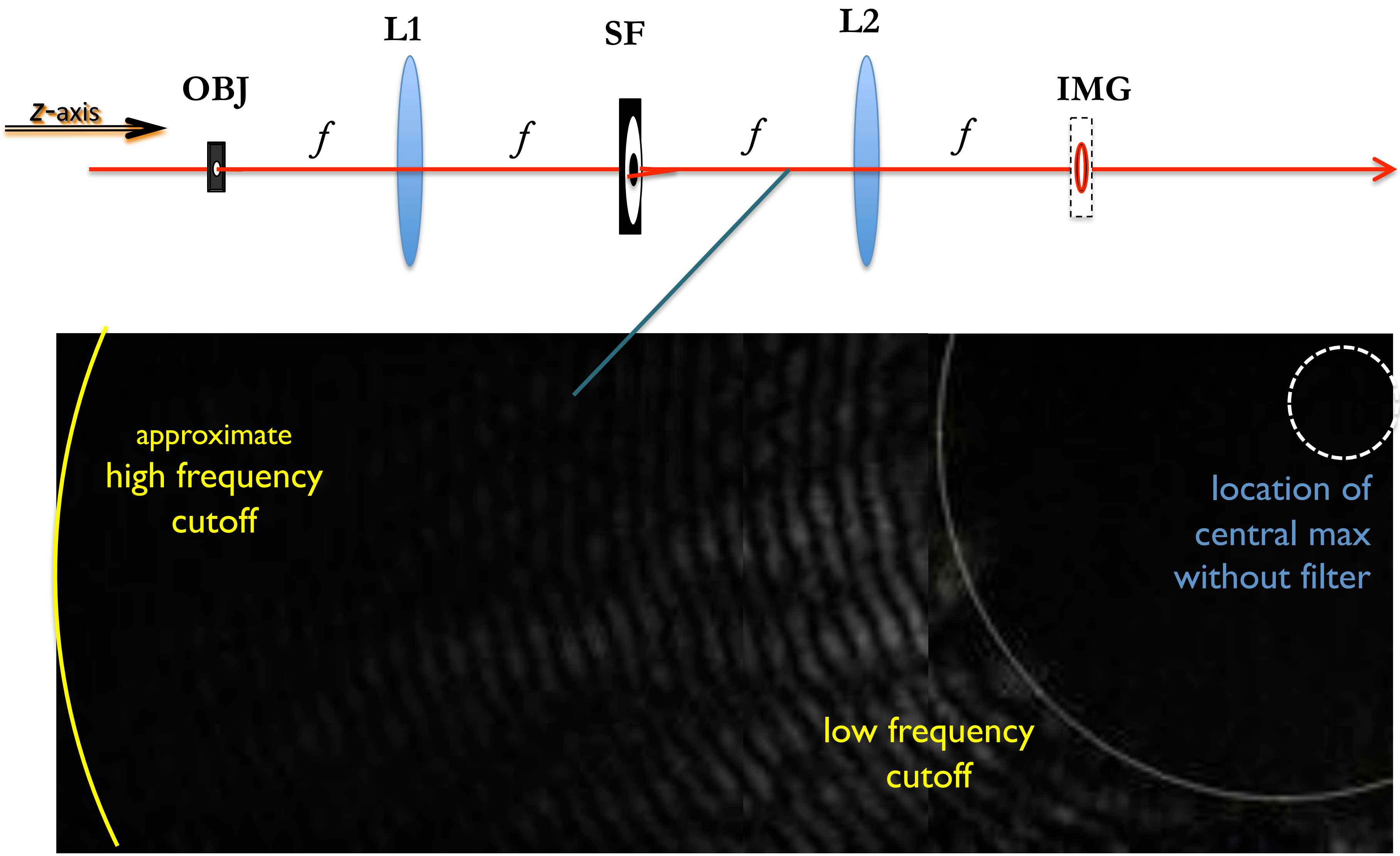
Lens 1 to Spatial Filter



classic Airy pattern

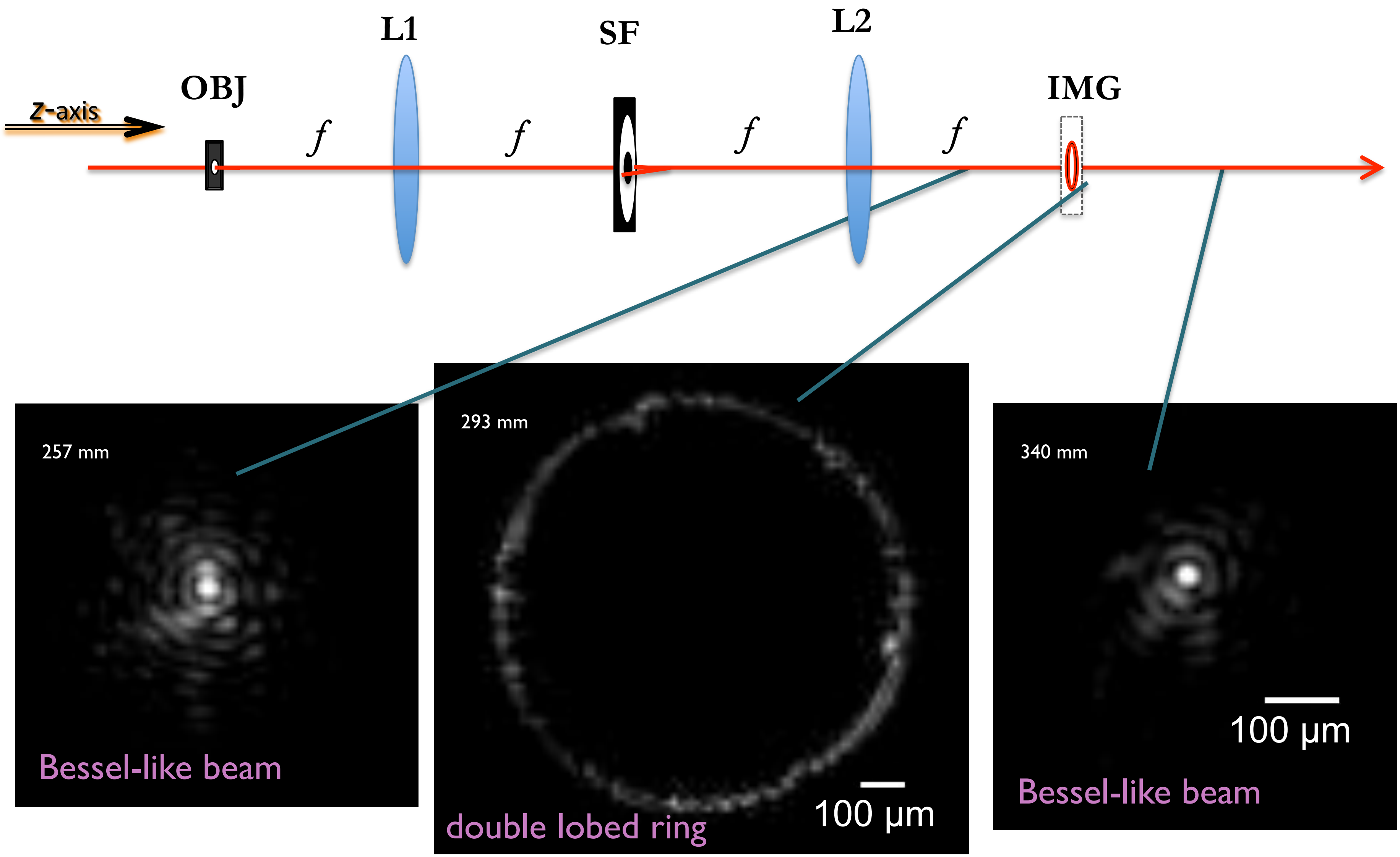


Spatial Filter to Lens 2

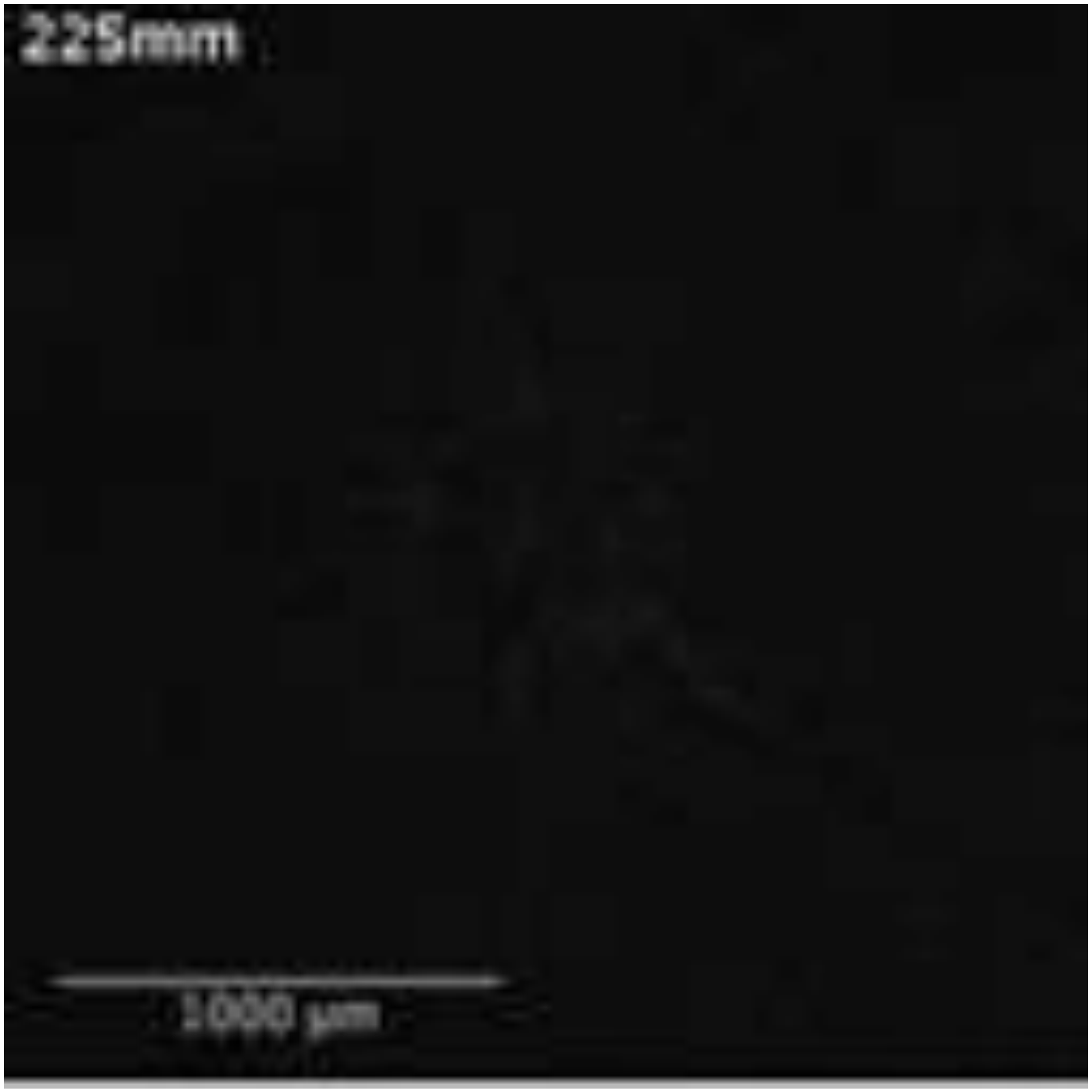


190 mm from Fourier plane

Lens 2 to Image Plane and Beyond



The formation of the Bessel beam

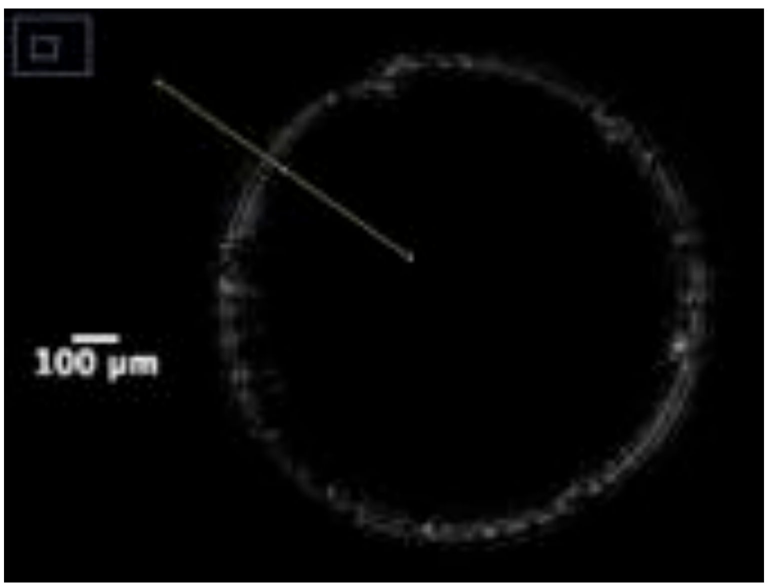


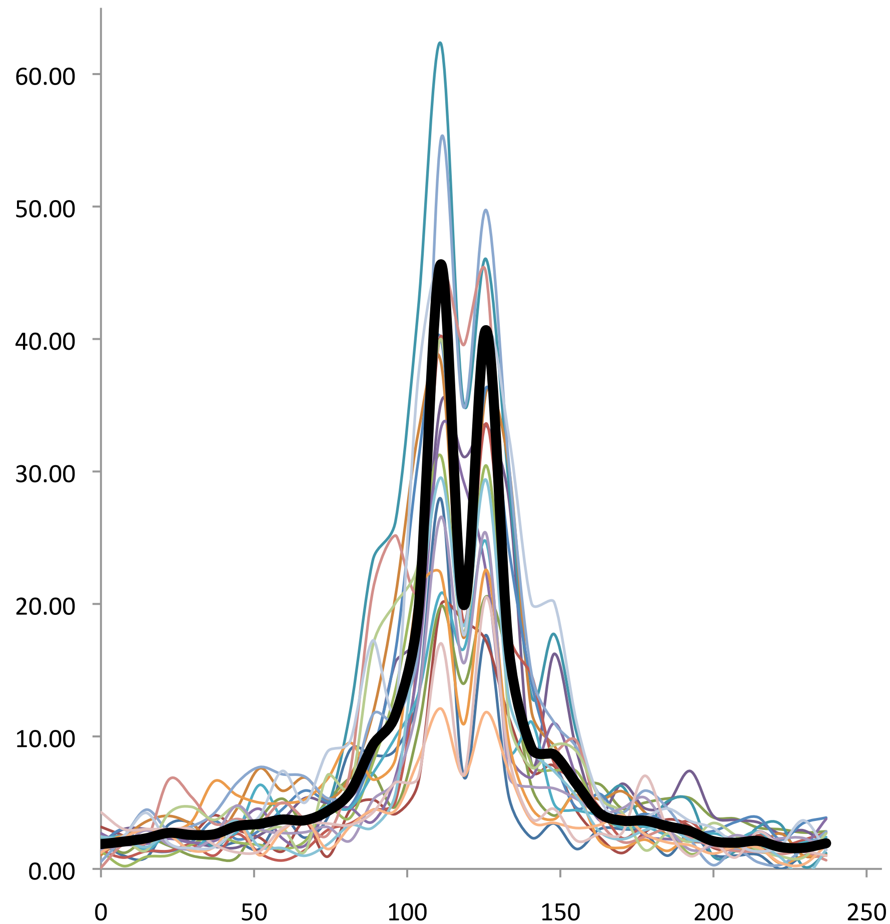
- Both Bessel beams (before and after the image plane) propagate for 47 mm with a core diameter under 45 microns

- Gaussian beam with an initial beam waist of 45 microns would double in area after 2.5 mm

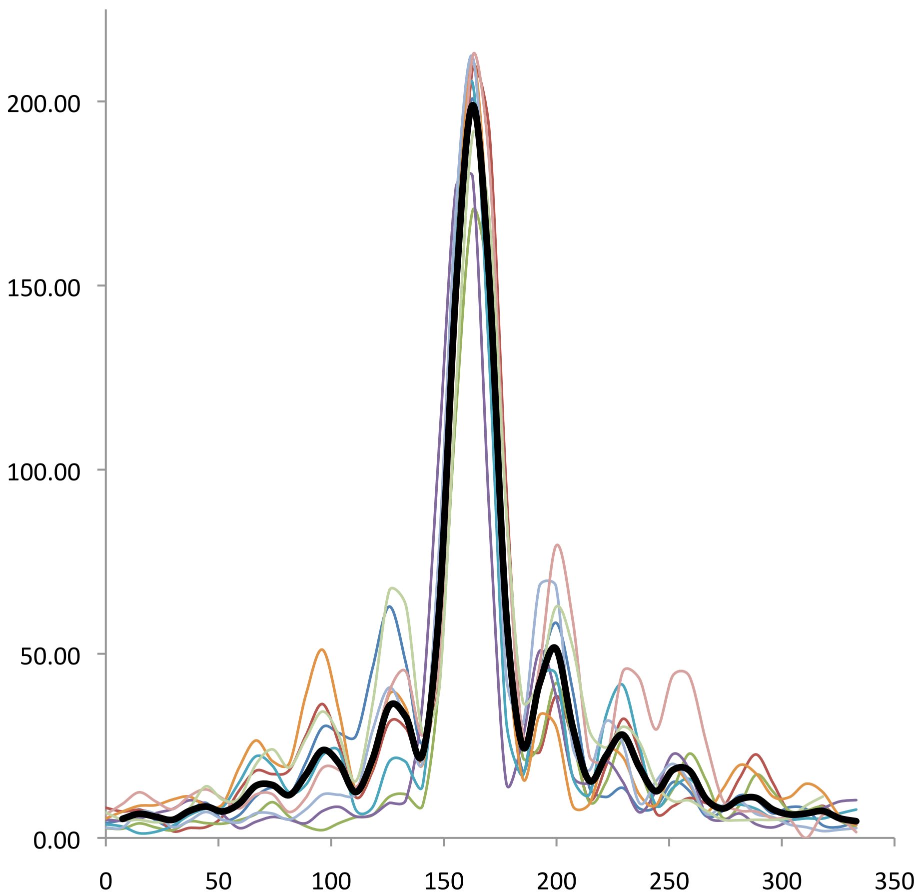
ImageJ Analysis: thin ring of light

- Average radial intensity profile of double-lobed ring source at focal point
- Spacing between lobes about 14.8 μm

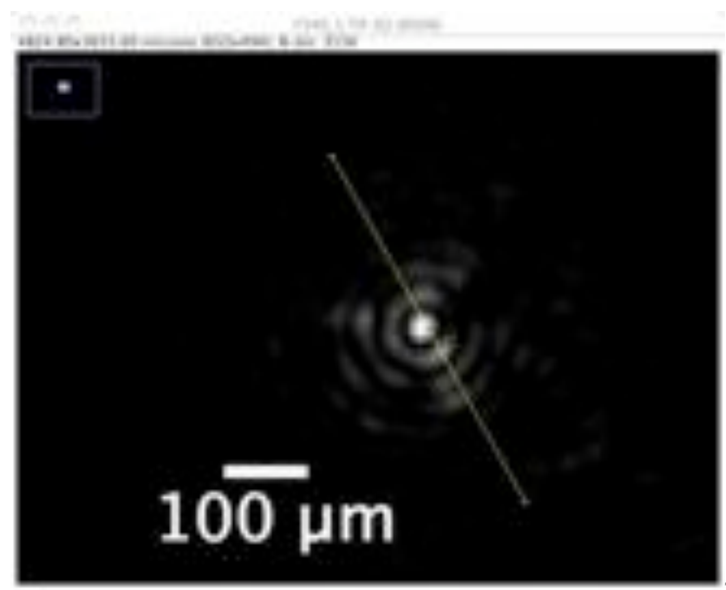




ImageJ Analysis: Bessel beam



- Azimuthally averaged radial intensity profile of Bessel beam at a distance Z = 340 mm behind second Fourier lens
- Central spot size about 44.4 μm



Conclusions

- We investigated an unusual way of creating Bessel beams.
- We studied the beam over a longer range than the original authors.
- This was a good topic for a teaching laboratory! It provided an introduction to Fourier optics and diffraction theory.

Key References

John M. McLeod, Optical Society of America **44** (8), 592 (1953).

J. Durnin, J. H. Eberly, and J. J. Miceli, Physical Review Letters **58** (15), 1499 (1987).

Jeremy M. D. Kowalczyk, Stefanie N. Smith, and Eric B. Szarmes, AJP 77 (3), 229 (2009).

Acknowledgements

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