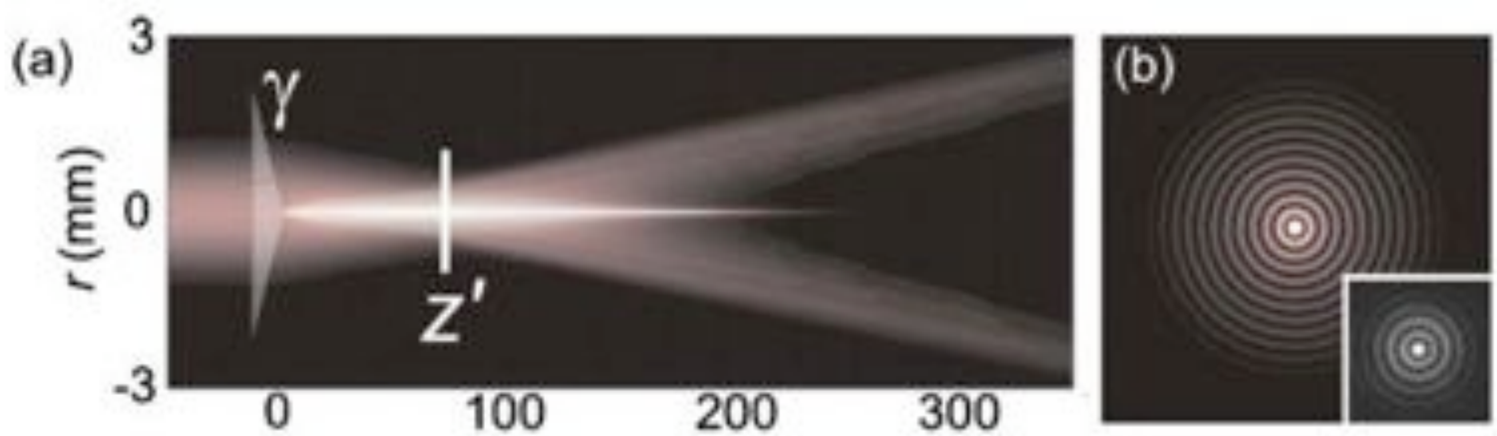
Creating Bessel Beams



Milne (2008)

Melia Bonomo, Dickinson College

Marissa Romano, Stony Brook University

Laser Teaching Center

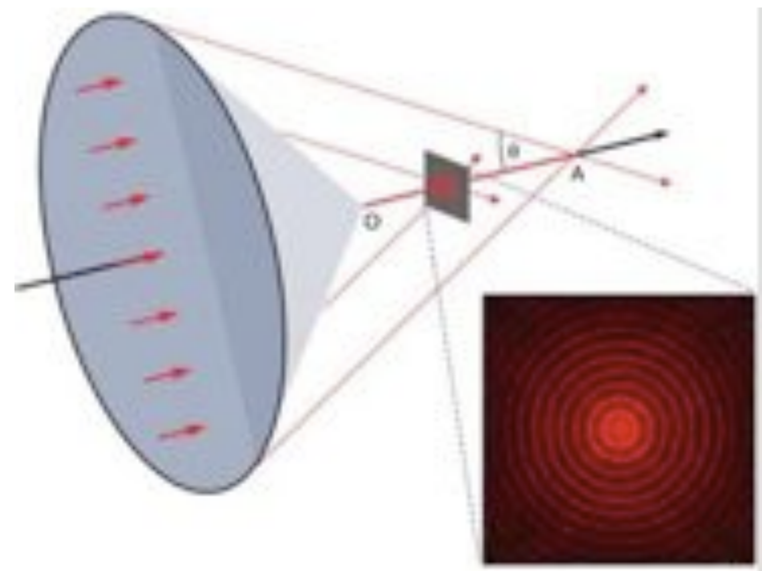
Summer 2012

Stony Brook University

Welcome to the Laser Center

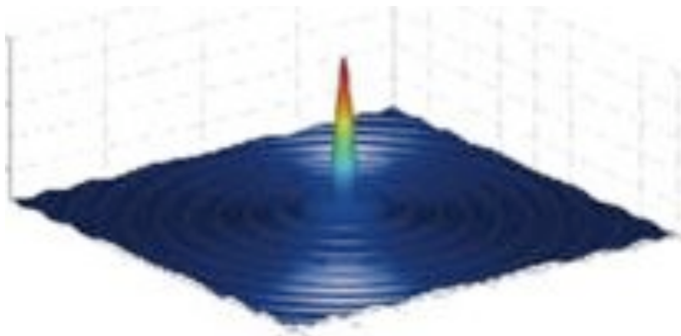
Overview

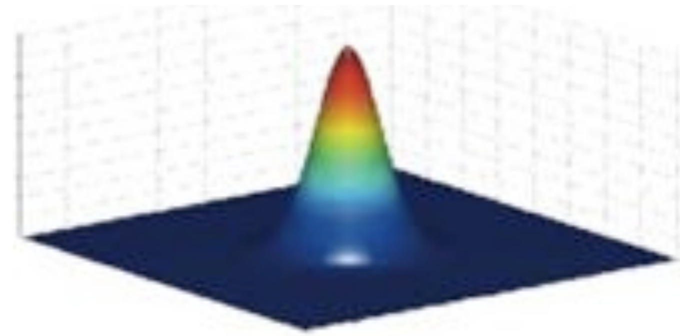
- Bessel beam properties
- Generating Bessel beams
  - Annular Aperture
  - 4-f Spatial Filtering
  - Axicon
  - TAG Lens



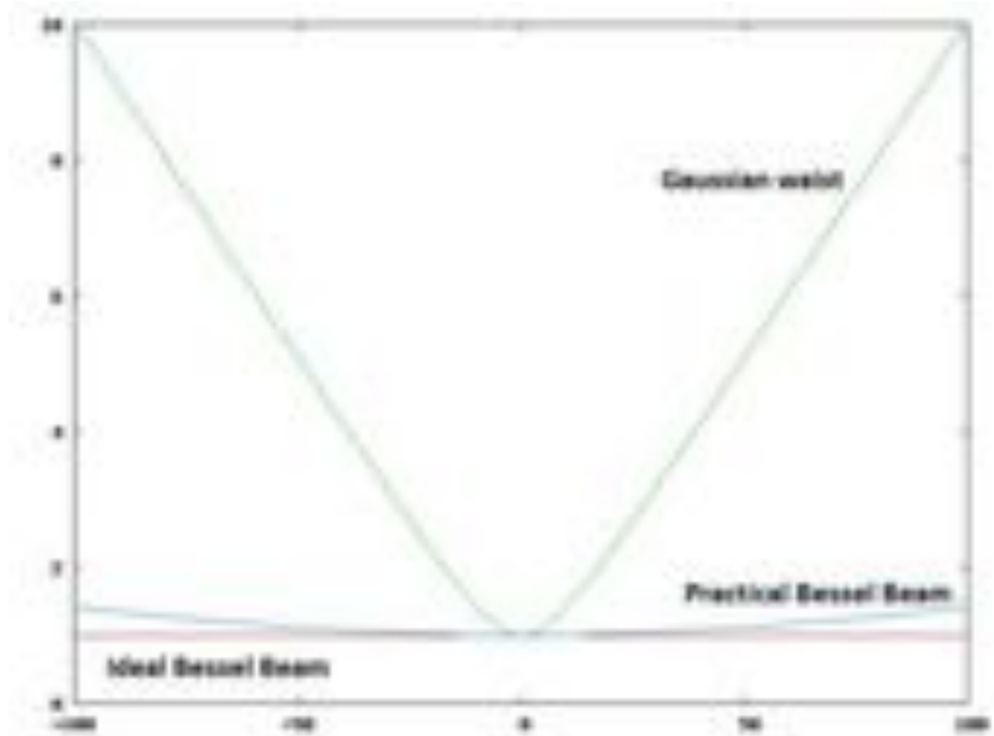
Jaroszewicz (2005)

Bessel vs. Gaussian Beams



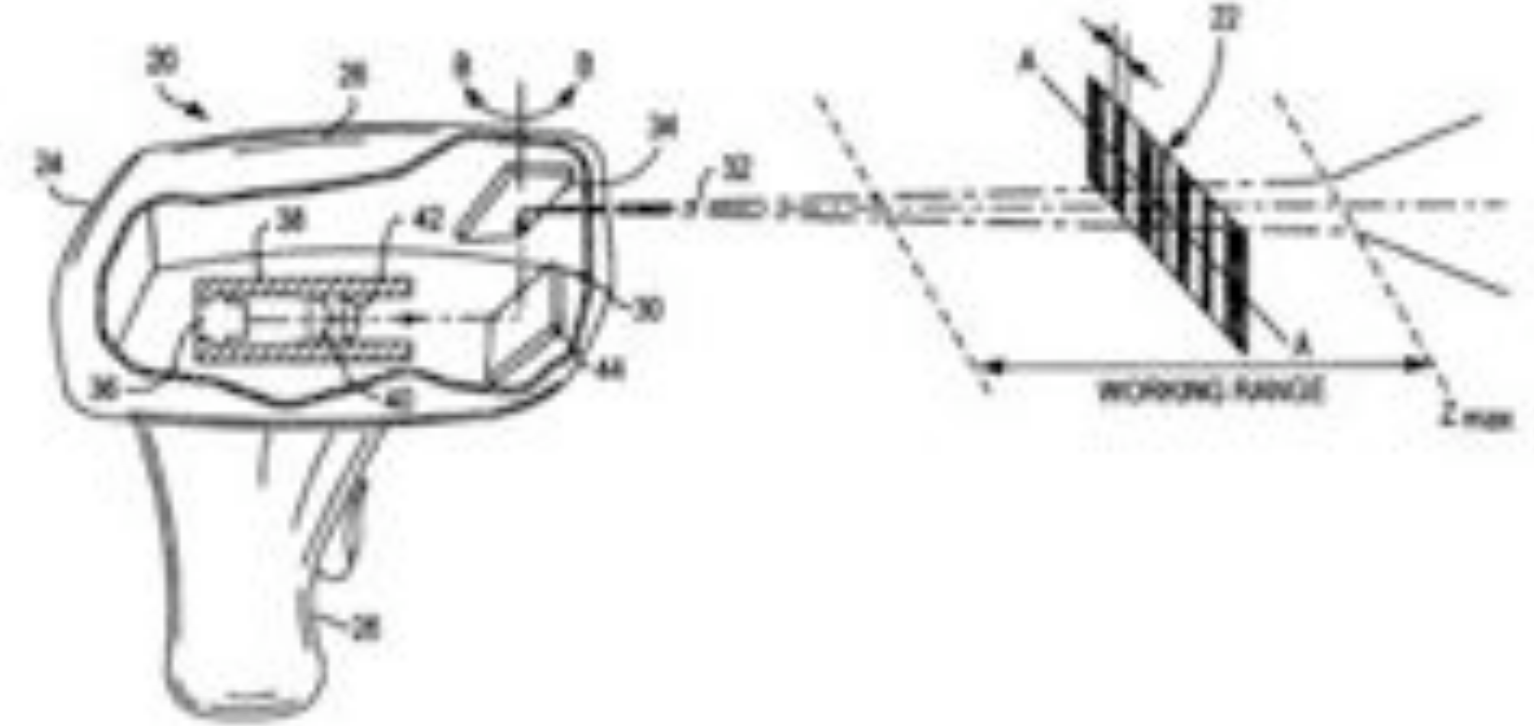


- Non-diffracting
- Thin, infinitely long core with concentric rings
- Ideal Bessel beams cannot be experimentally created
- Close approximations are possible



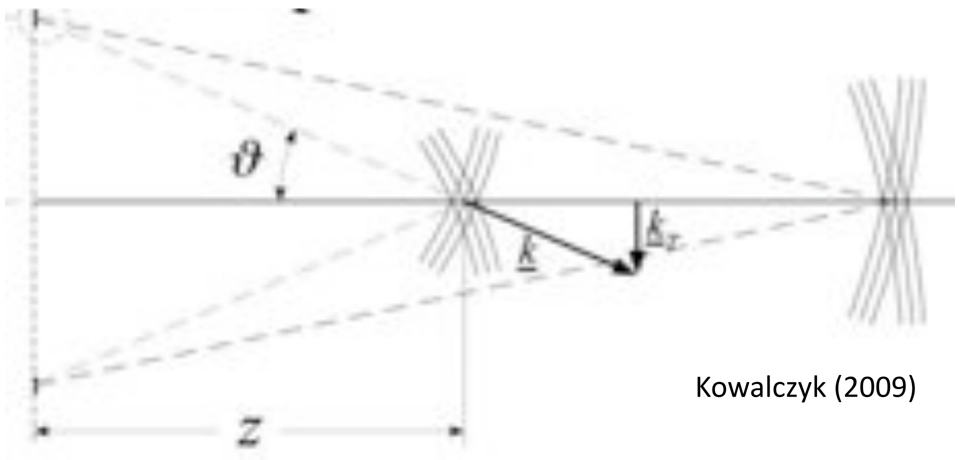
Most Widespread Application

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



Gurevich 2003

Geometry and Math

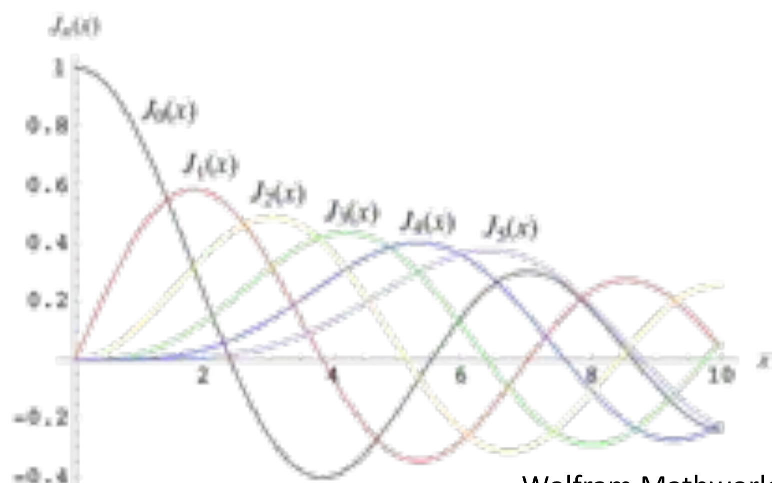


Kowalczyk (2009)

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

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

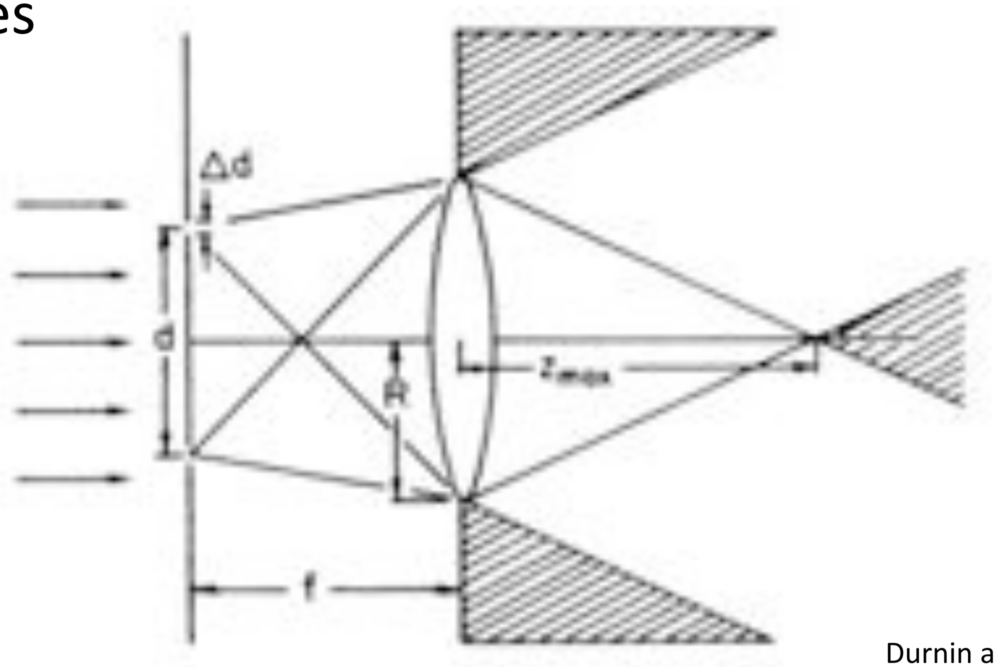
- Electric field amplitude proportional to Bessel function



Wolfram Mathworld, 2012

Creating Bessel beams with an Annular Aperture

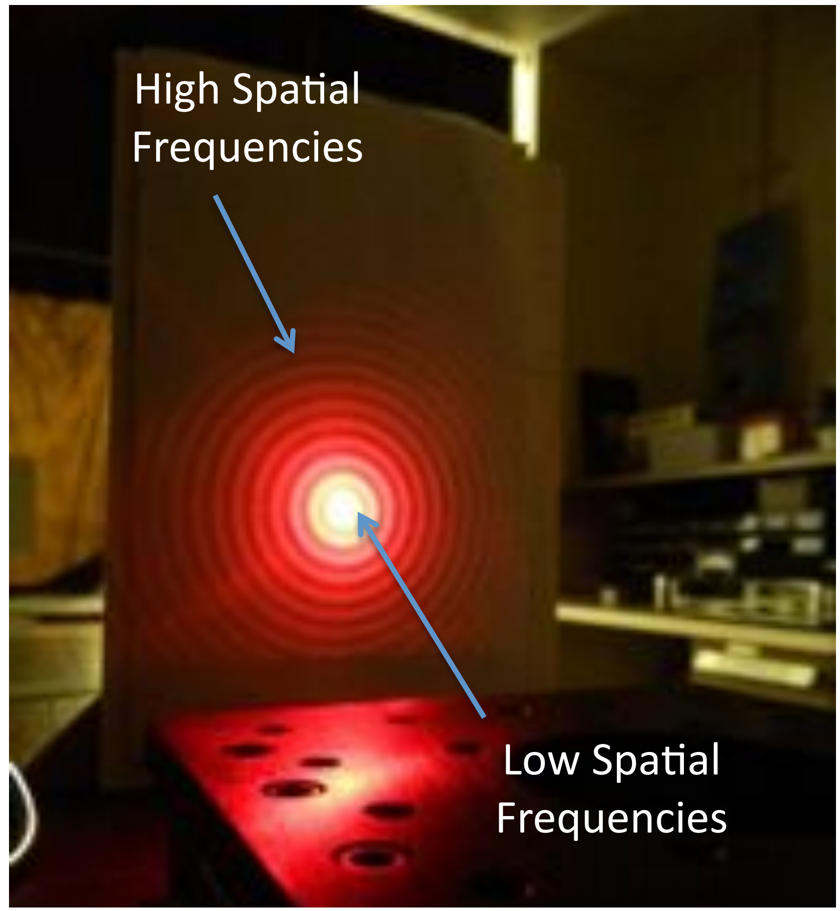
- Fresnel diffraction of thin ring light source
- Durnin and Eberly 1987
  - 2.5 mm diameter, 10 micron wide
- Lens collimates ring of light to create conical superposition of plane waves



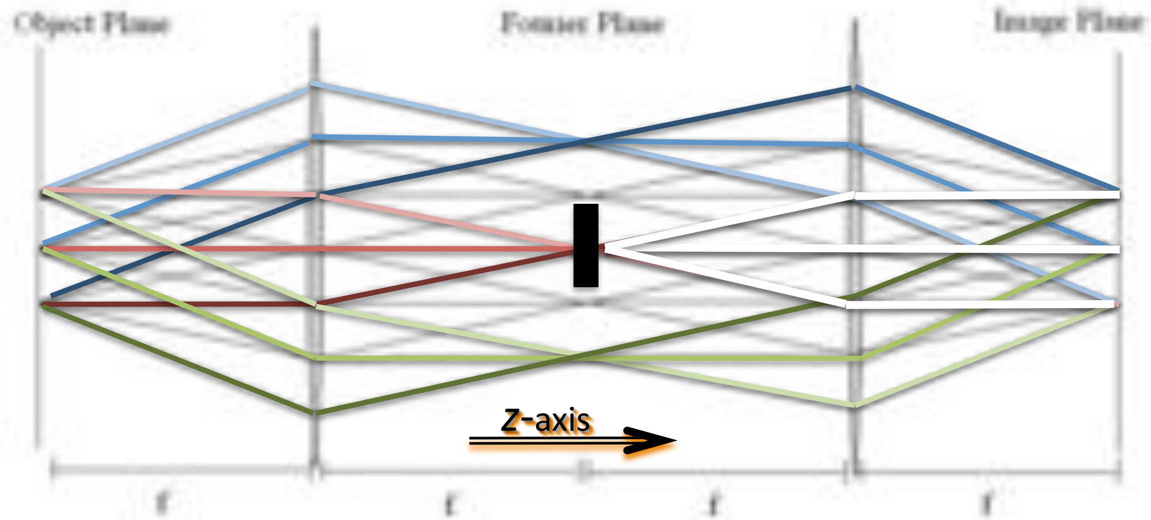
Durnin and Eberly (1987)

Creating a ring of light through spatial filtering a circular aperture

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



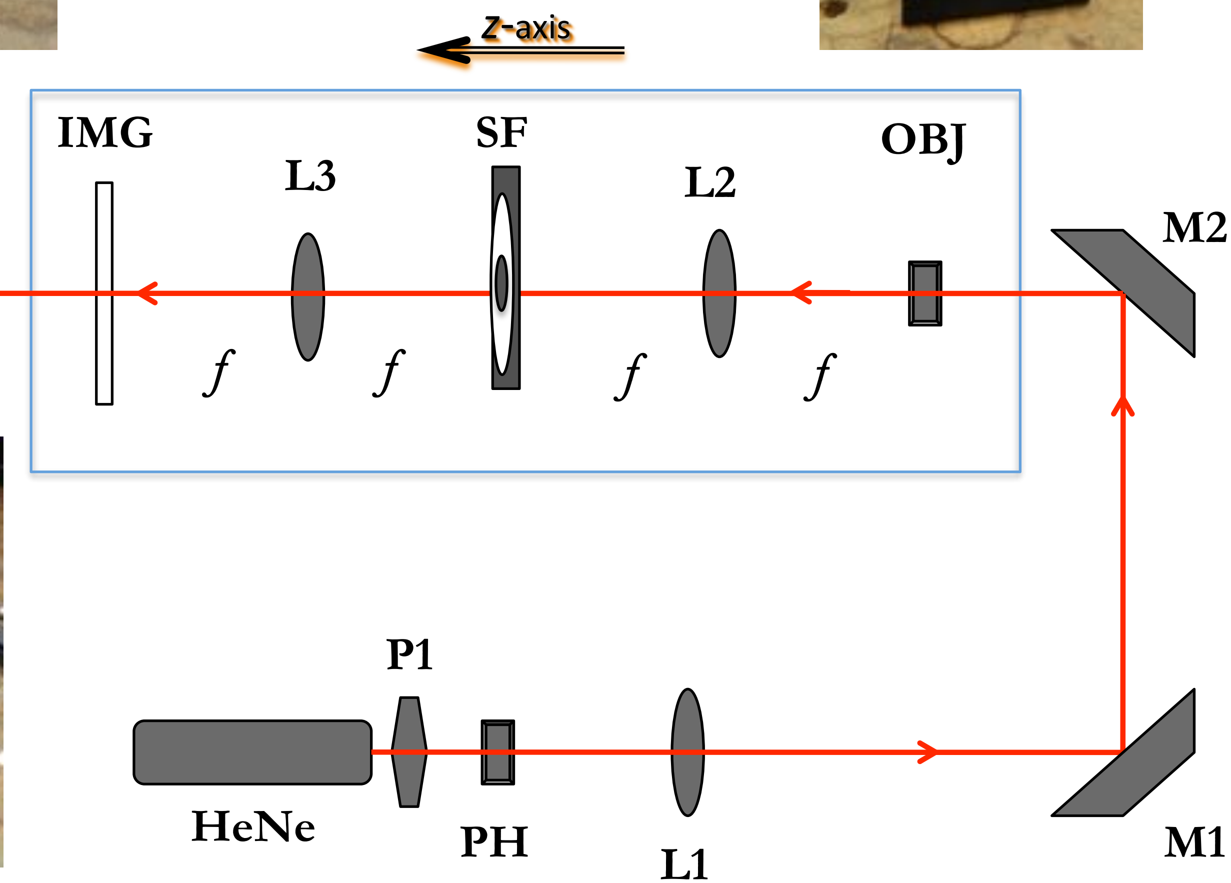
4-f Spatial Filtering Method



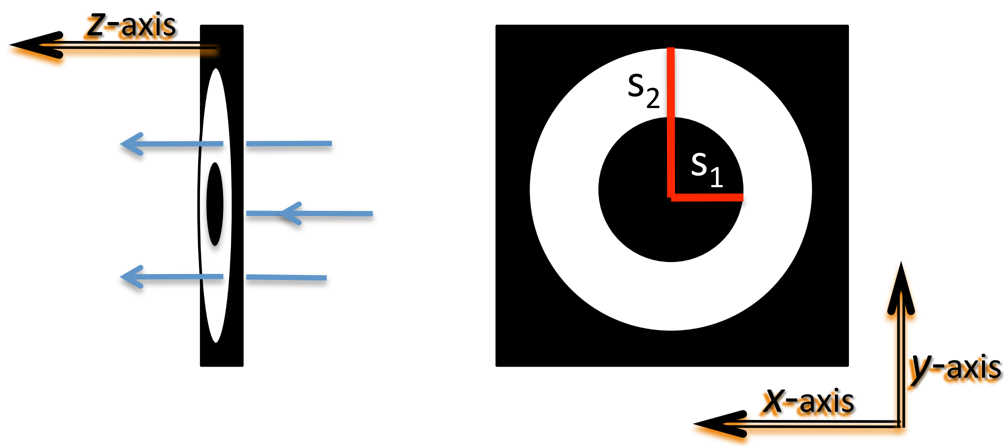
- Lens organizes spatial frequencies of object
  – Rays bent at same angle are part of the same diffraction order of the pattern in the Fourier plane
- The diffraction pattern is the Fourier transform of the object
- Inverse image created in image plane

http://laser.physics.sunysb.edu/~will/report/4f-system.png

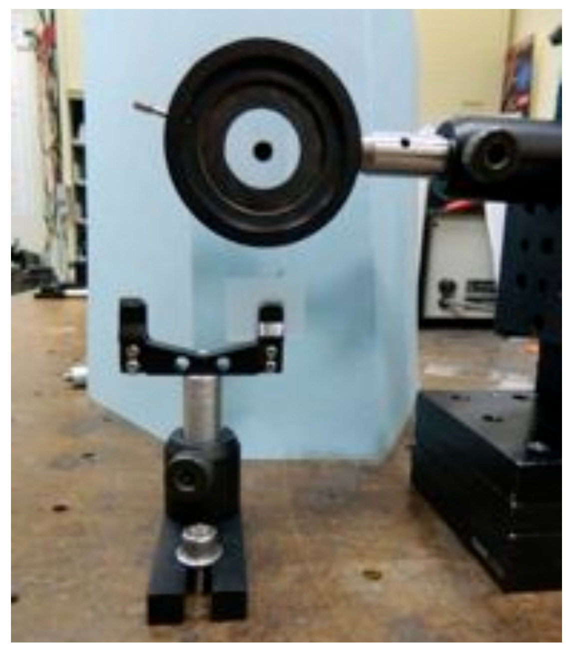
Setup Design



The filter dimensions



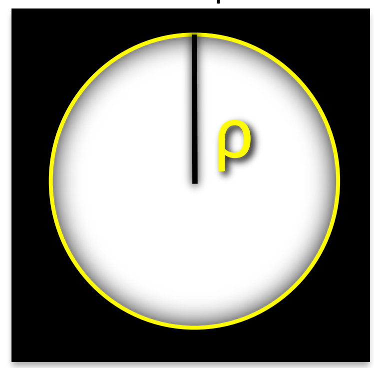
- Inner radius 3 mm
  - To block the low frequencies
- Outer iris diaphragm radius 10 mm
  - Limits the high frequencies coming through too
- Why is there a limit on the outer dimension?



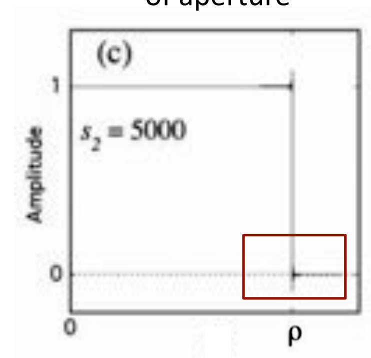
Gibb’s phenomenon

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

circular aperture

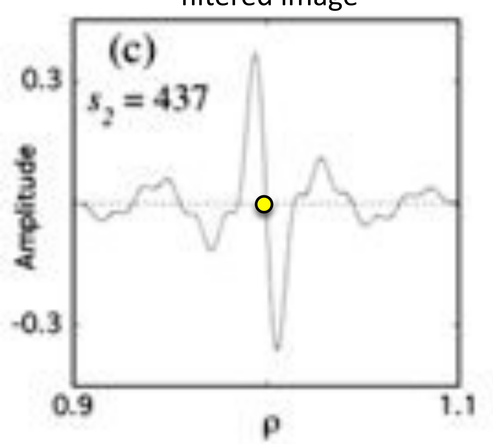


amplitude at edge of aperture

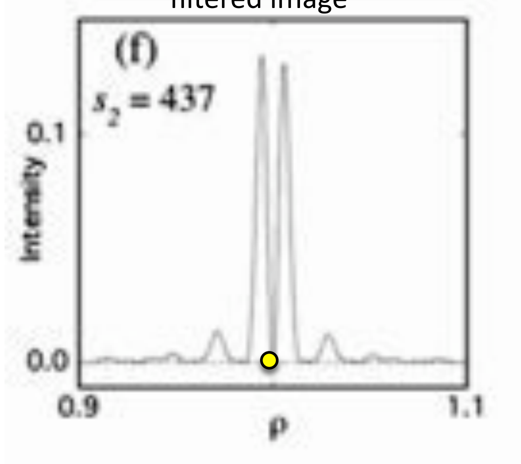


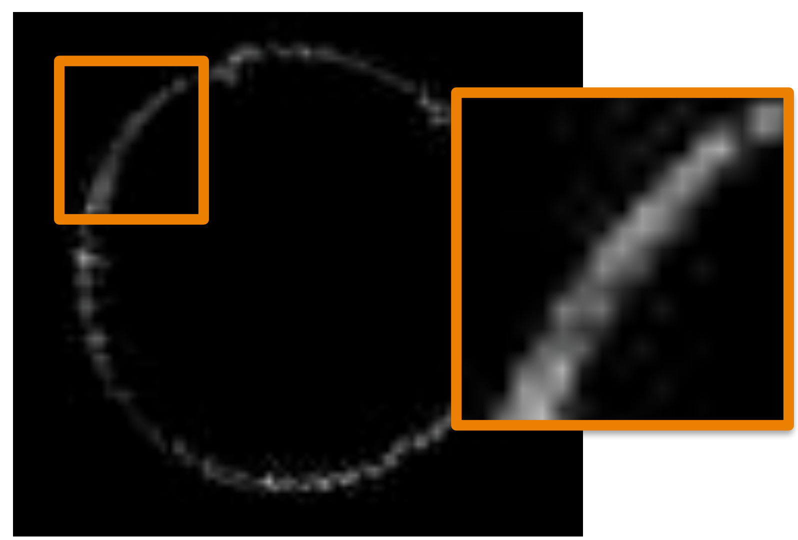
- This is the difference between our ring and that which would have come from a uniformly illuminated annular slit

amplitude at edge of filtered image



intensity at edge of filtered image

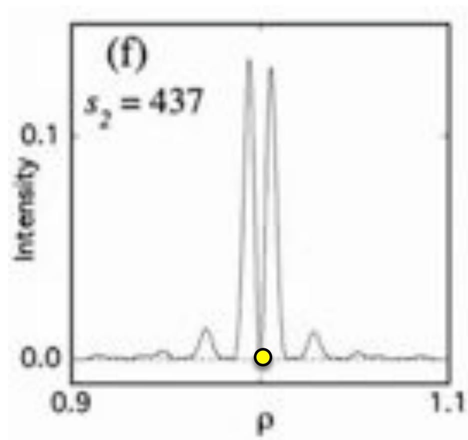




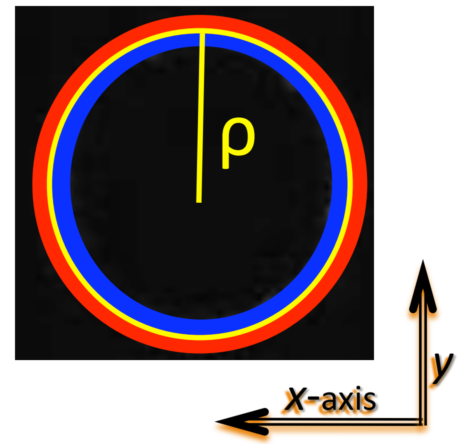
Kowalczyk (2009)

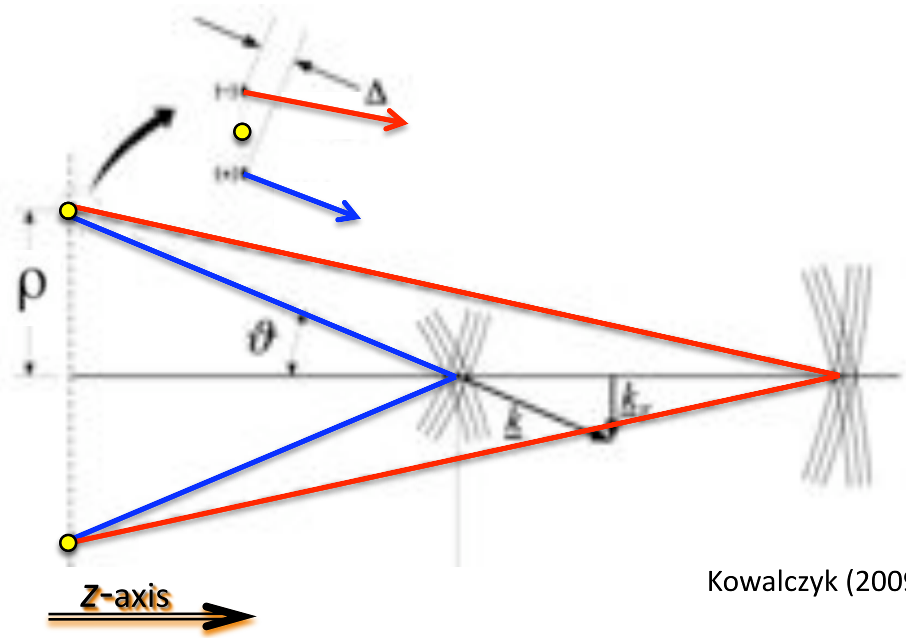
Forming the Bessel beam

- 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)

Technically speaking

- "Bessel beam" normally used to describe non-diverging beams
- Here, we're making use of a diverging pattern to create the Bessel-like beam
- Still has a Bessel function radial profile and exhibits the characteristic properties

Effect of outer frequency cutoff on separation between intensity lobes

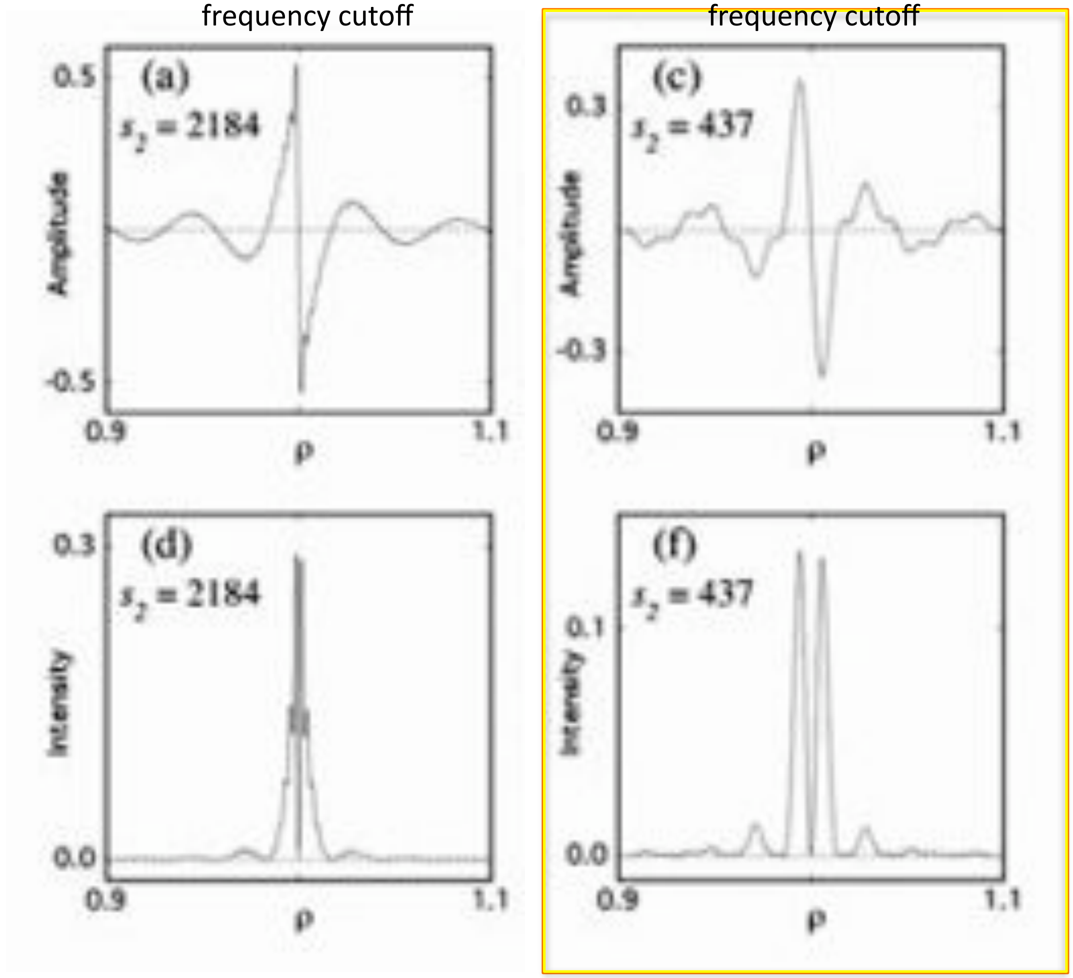
• Cutting off high frequencies:

→ 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

almost no high frequency cutoff

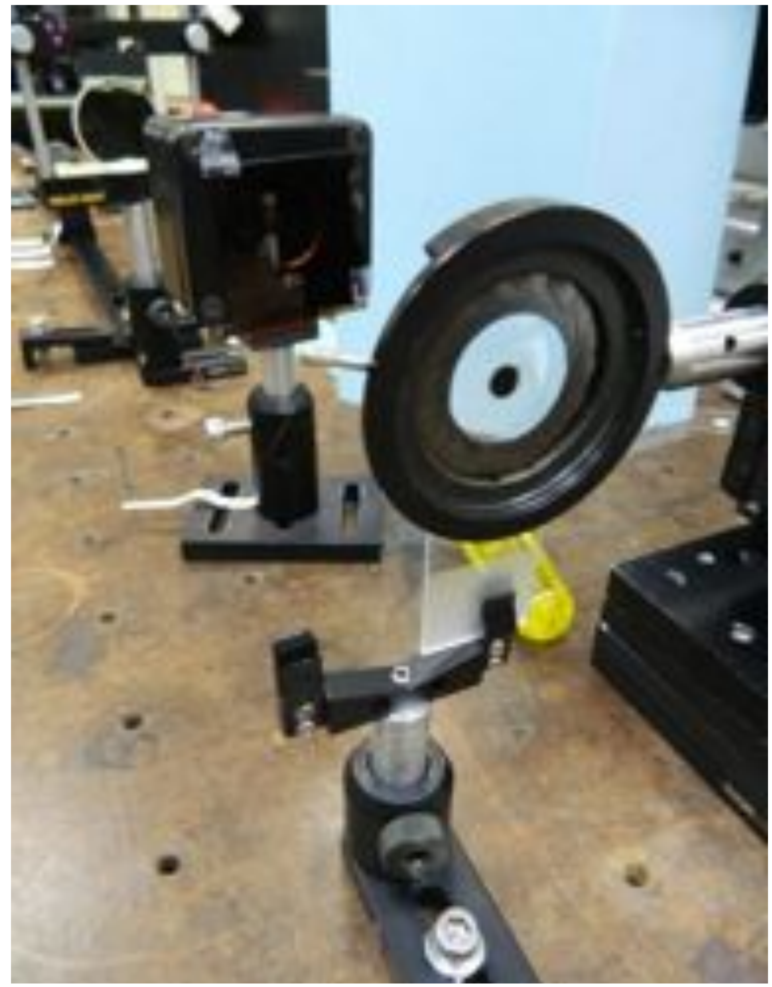
substantial high frequency cutoff



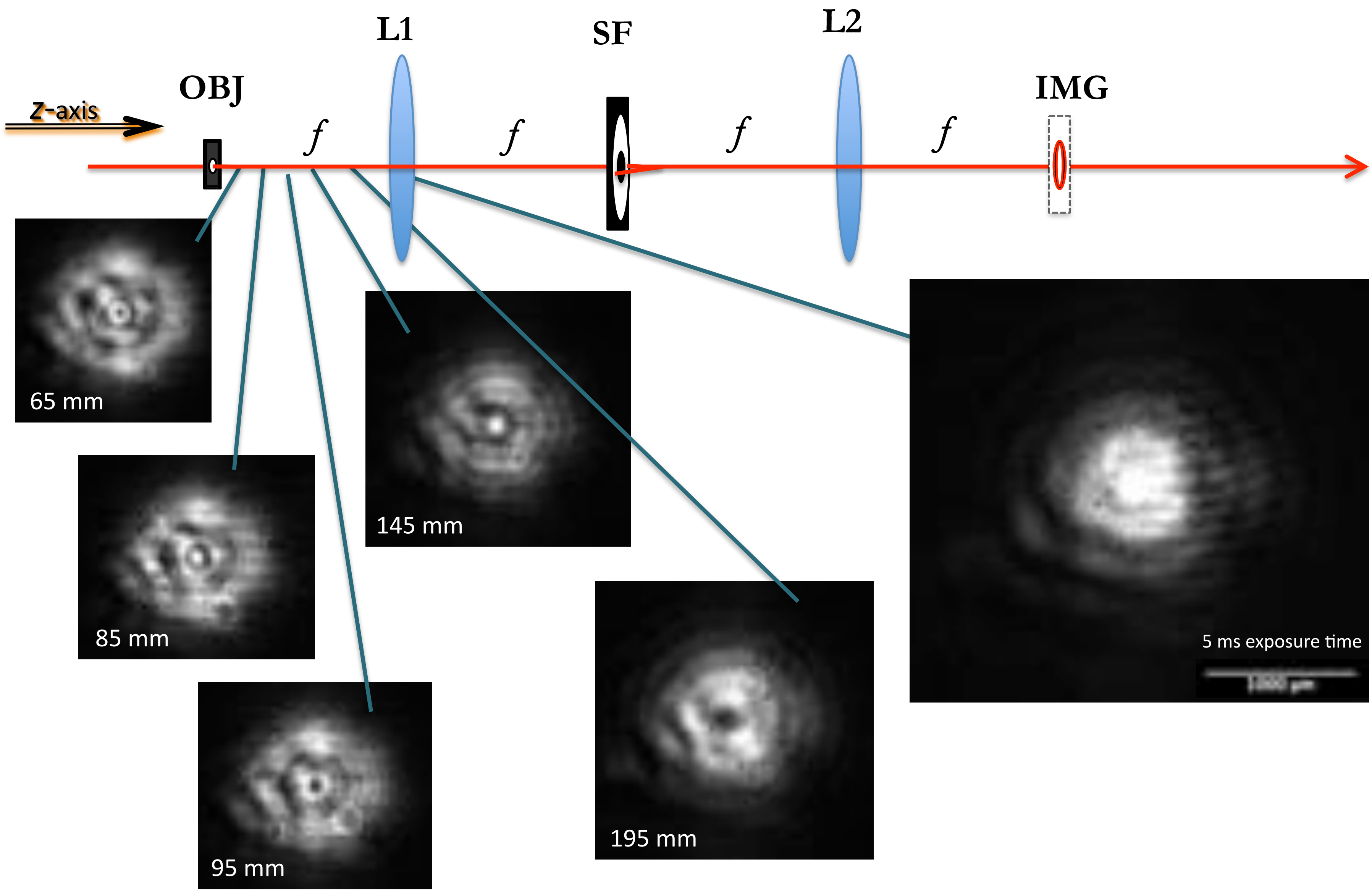
Kowalczyk (2009)

Electrim EDC 1000N images

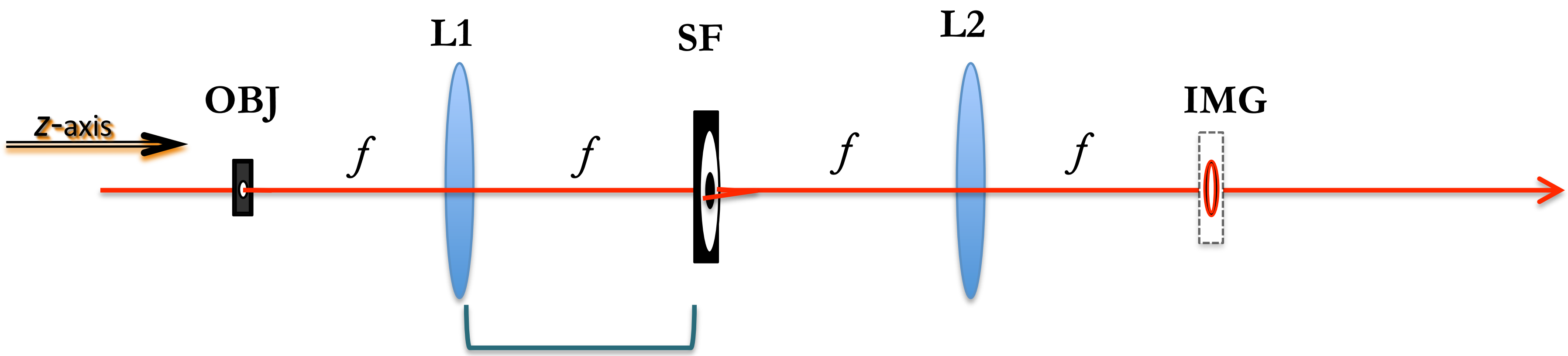
- 7.4 micron square pixels
- Polarizers to prevent saturation
- Recorded the evolution of the light field from the initial aperture to the final Bessel beam
- Images are transverse taken in transverse plane



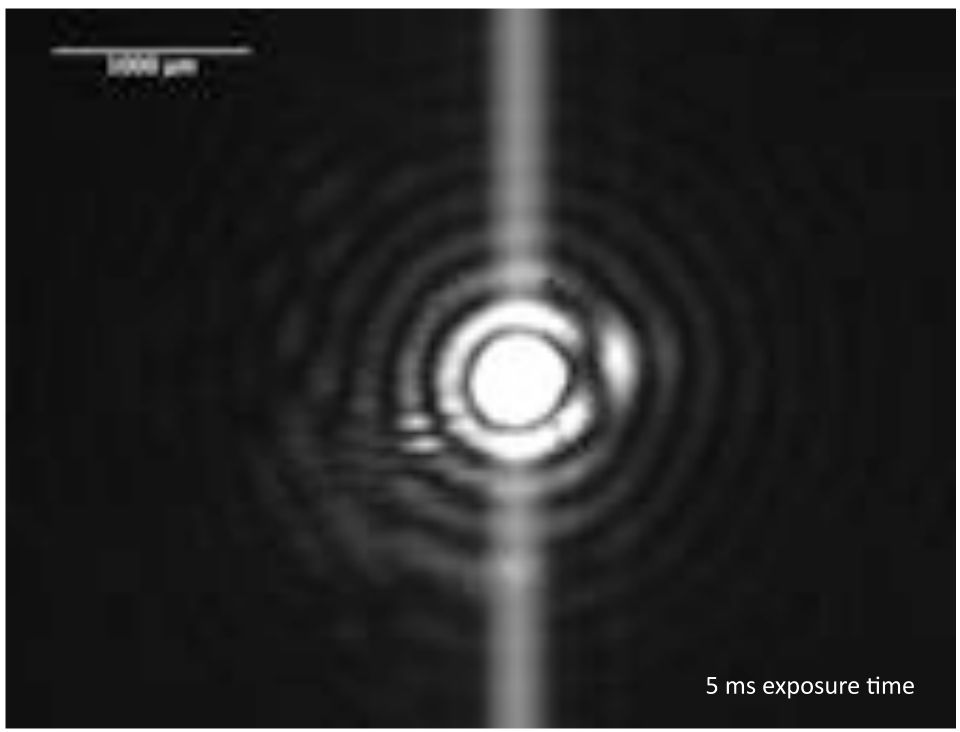
Object to Lens 1



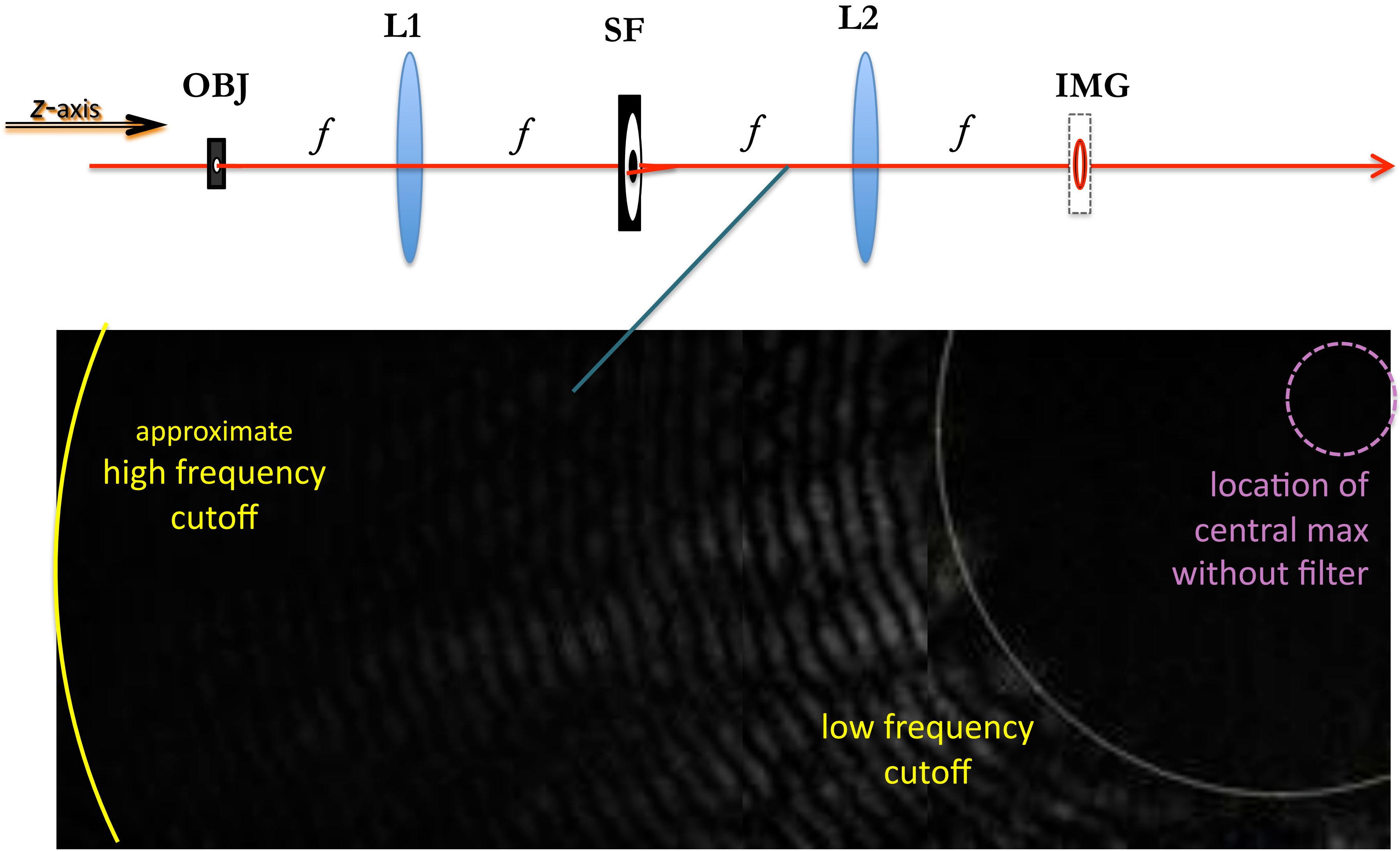
Lens 1 to Spatial Filter



classic Airy pattern

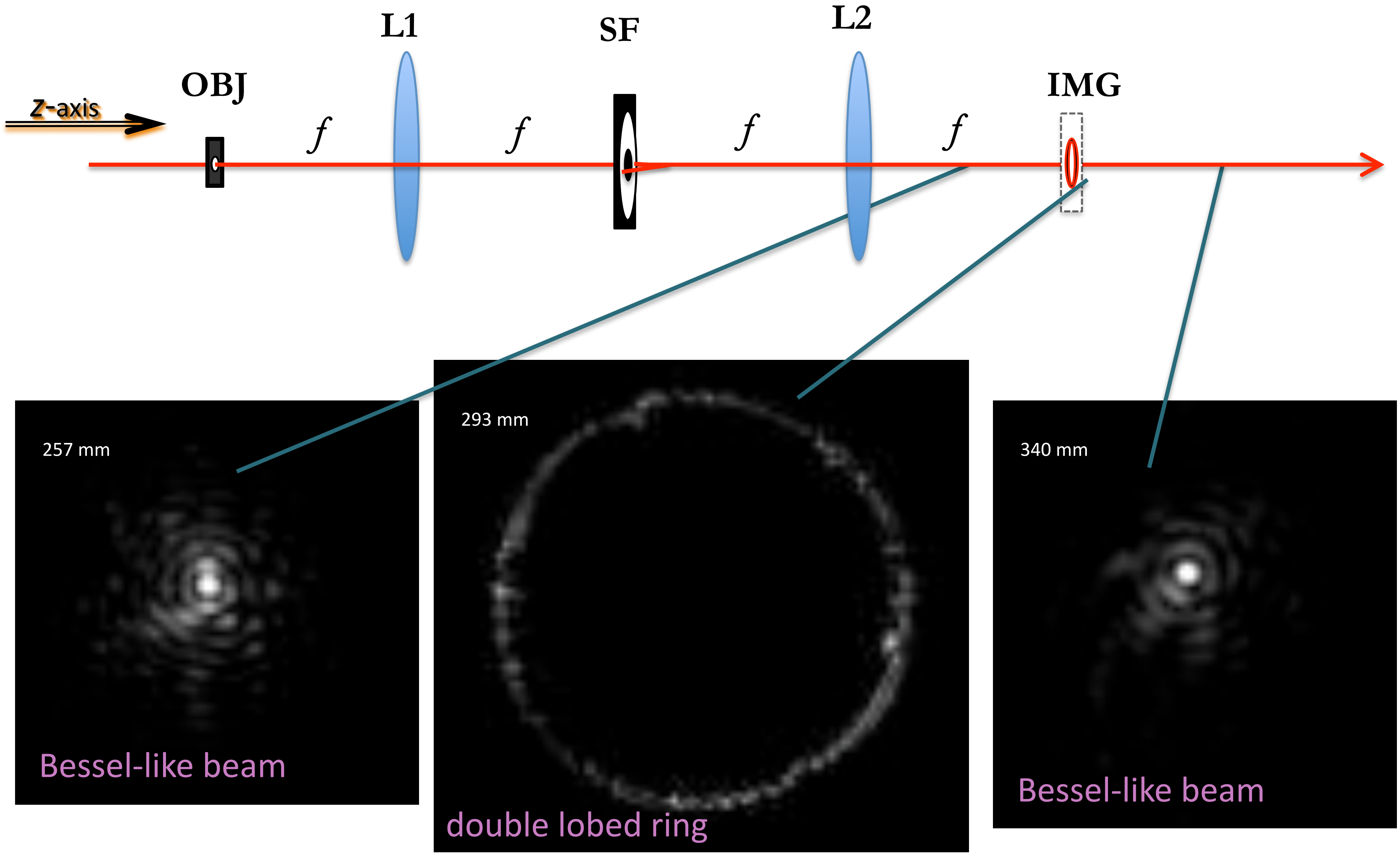


Spatial Filter to Lens 2

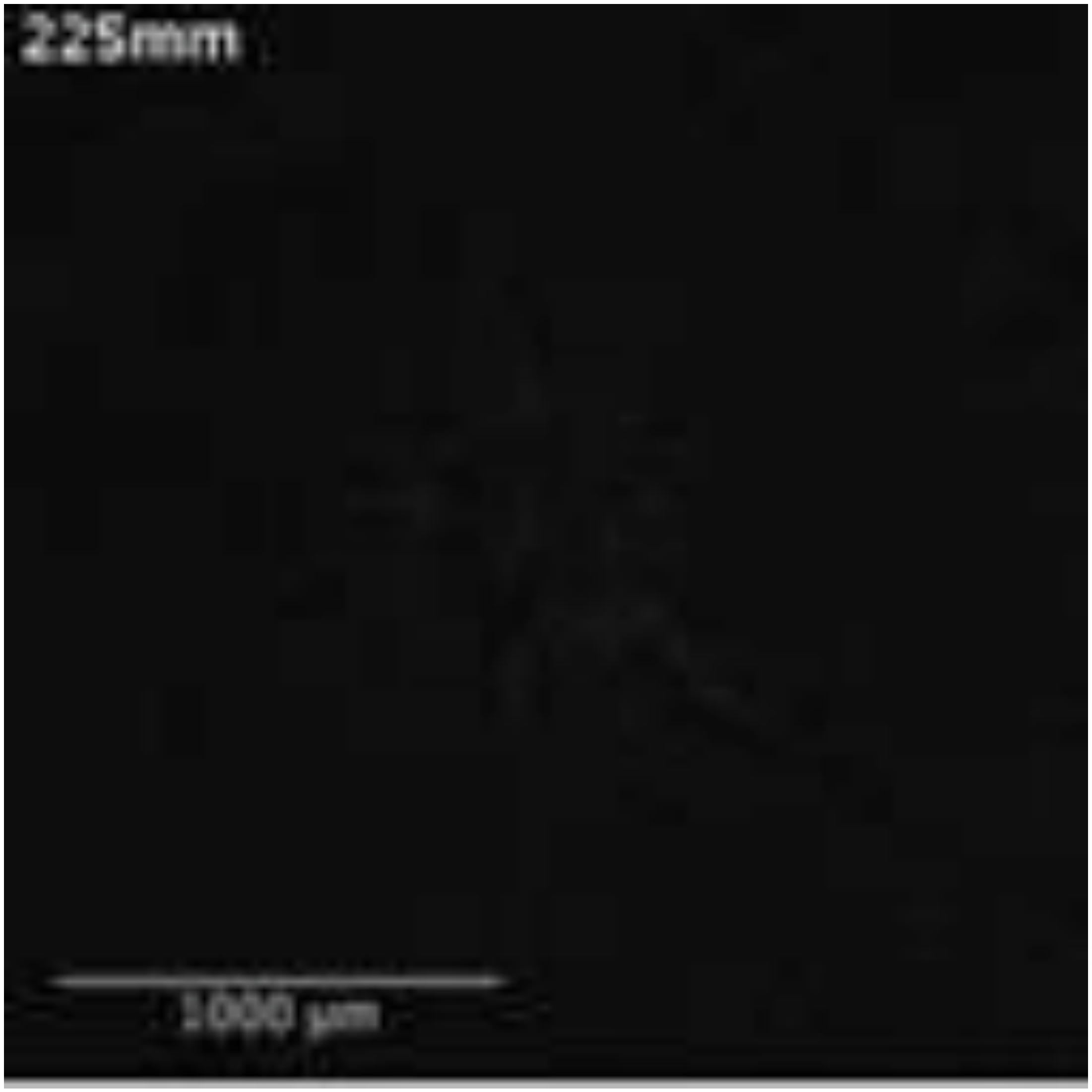


190 mm from Fourier plane

Lens 2 to Image Plane and Beyond



The formation of the Bessel beam



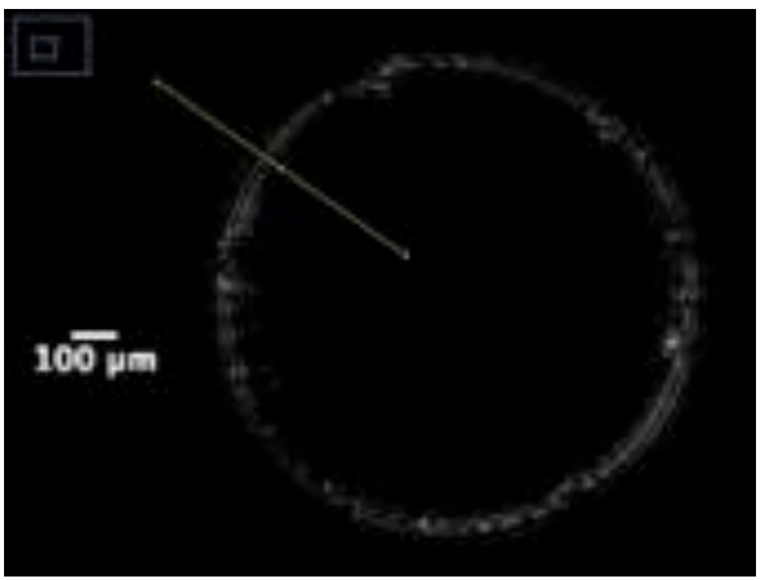
- First starts at about 220 mm from the final lens
- Propagates 47 mm
- Disappears 267 mm

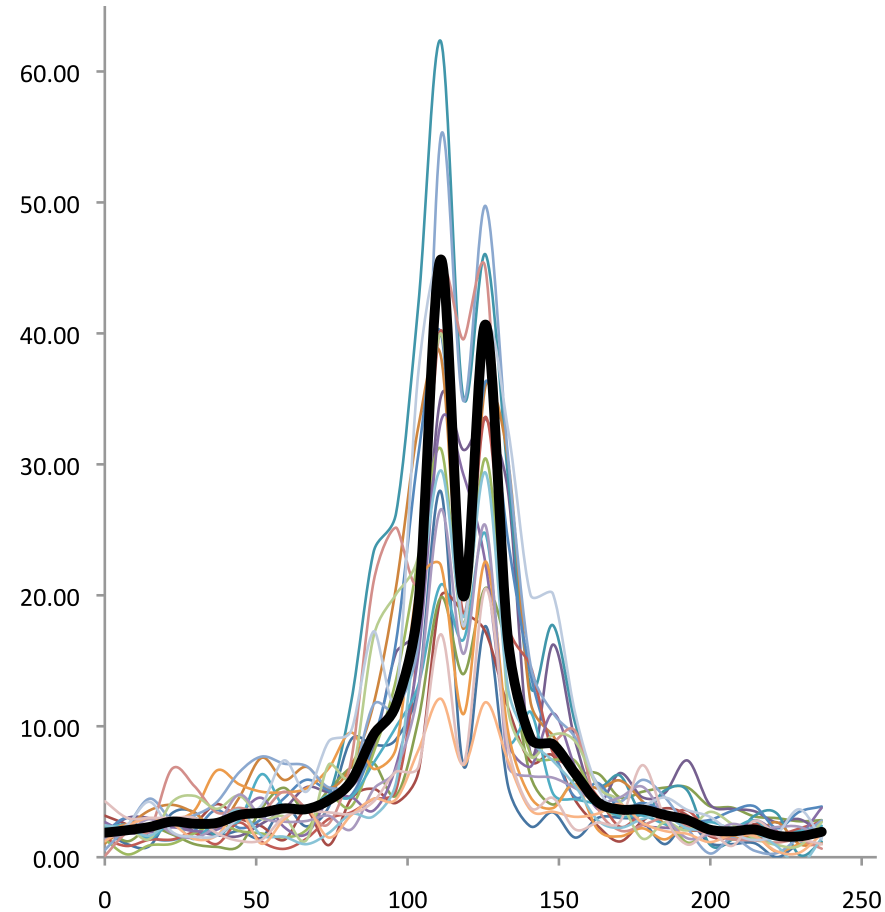
- Ring of light comes to focus at 293 mm

- Bessel beam appears again at 320 mm
- 47 mm propagation
- 376 mm it disappears

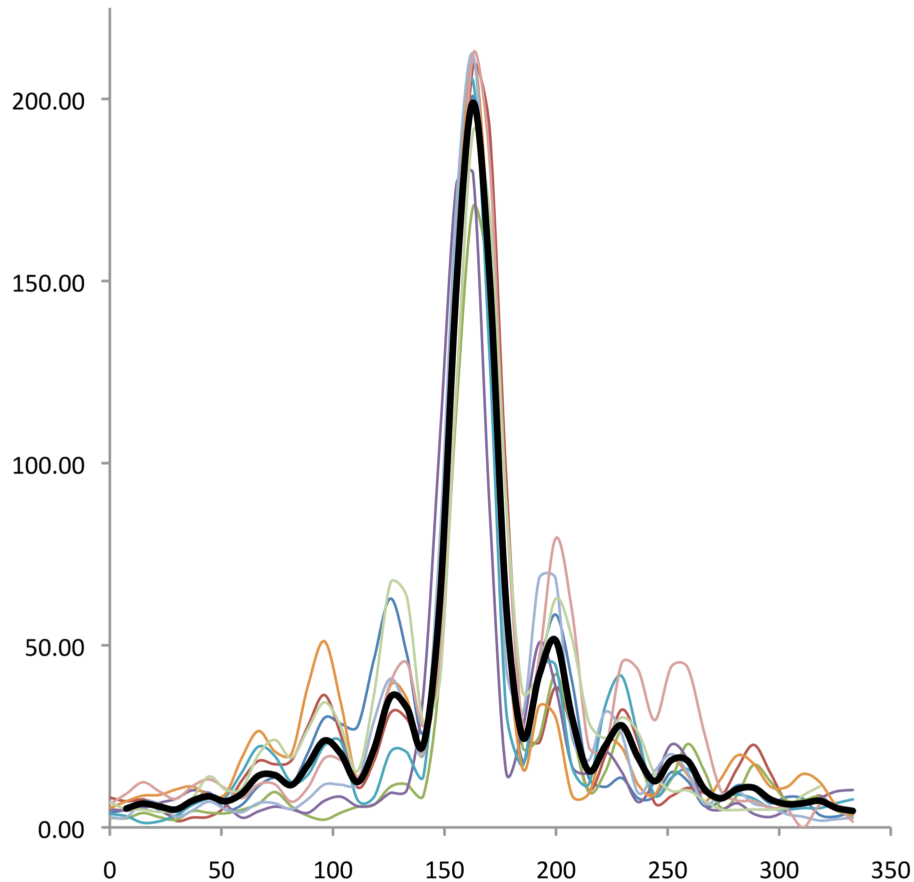
ImageJ Analysis: thin ring of light

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

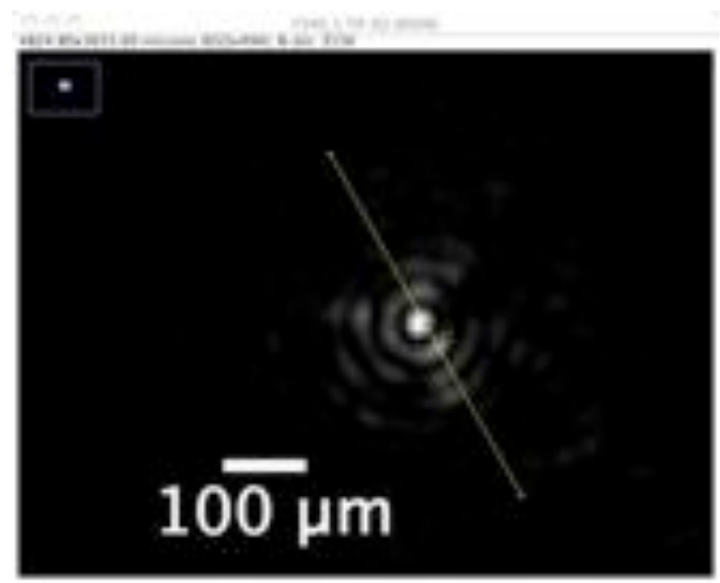




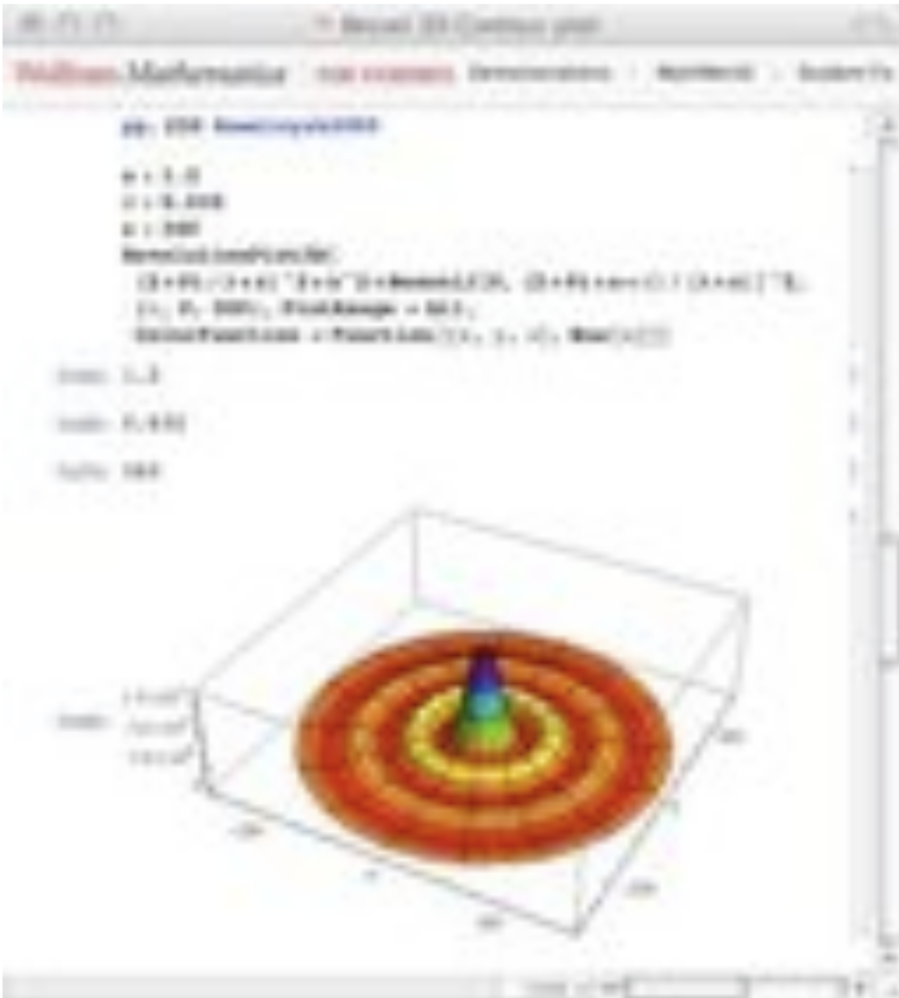
ImageJ Analysis: Bessel beam



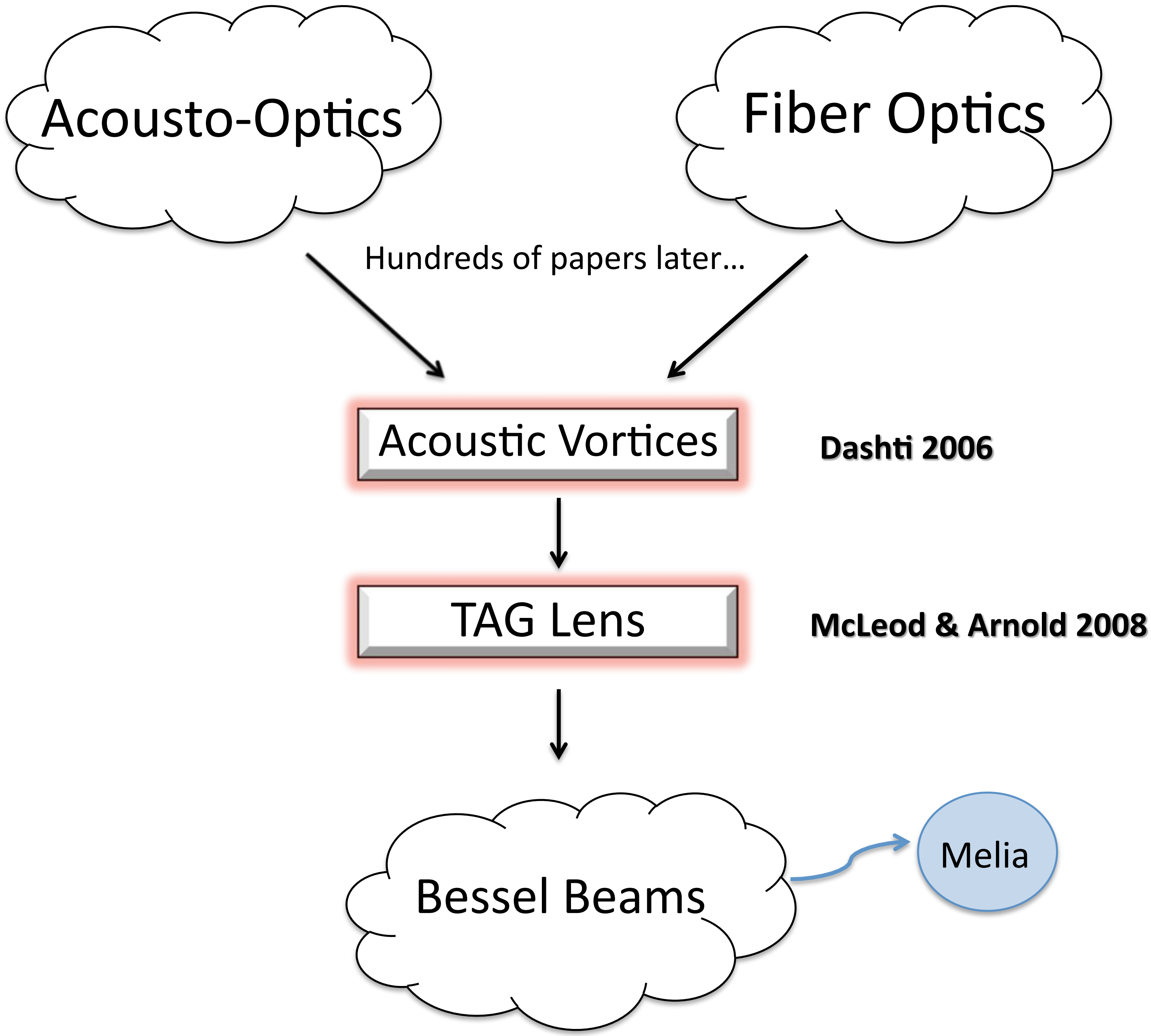
- Azimuthally averaged radial intensity profile of Bessel beam at a distance Z = 340 mm behind second Fourier lens
- Central spot size about 44.4 µm



Modeling in Mathematica

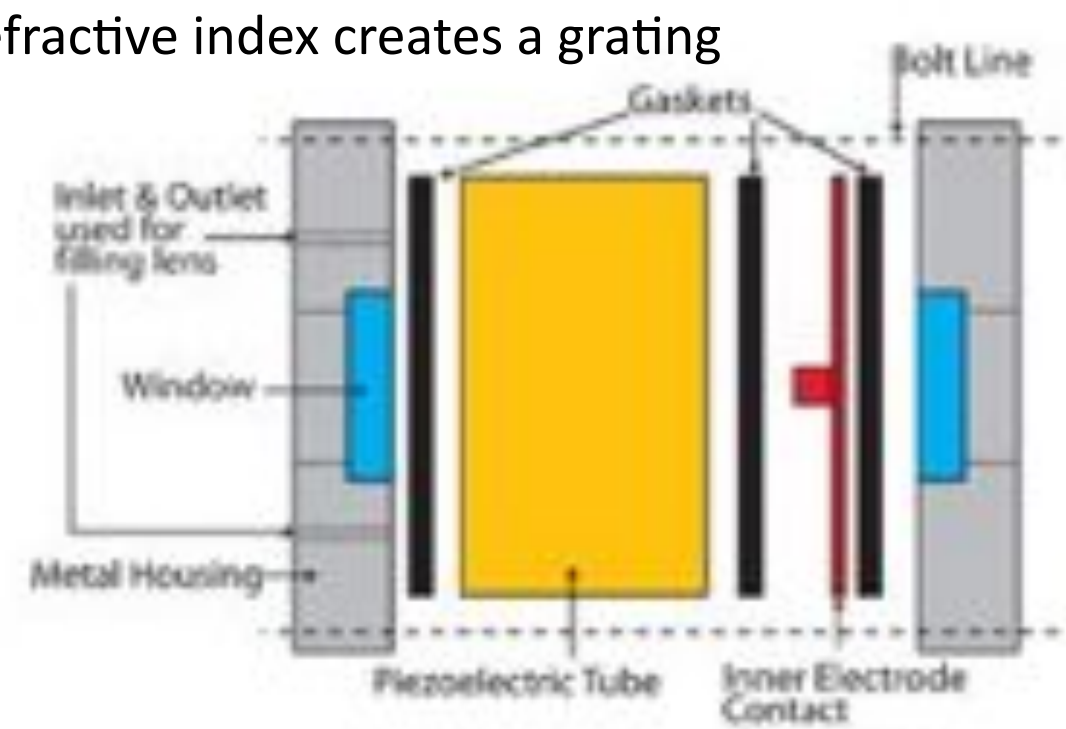


- Currently creating theoretical model of the beam's intensity profile
  - Fit this model to the average intensity of the beam at a certain *z* distance
- Also graphing the *z* dependence of the theoretical and experimentally determined central spot size


Acousto-Optics
Fiber Optics
Hundreds of papers later…
Acoustic Vortices
Dashti 2006
TAG Lens
McLeod & Arnold 2008
Bessel Beams
Melia

Tunable Acoustic Gradient Index of Refraction Lens (TAG lens)

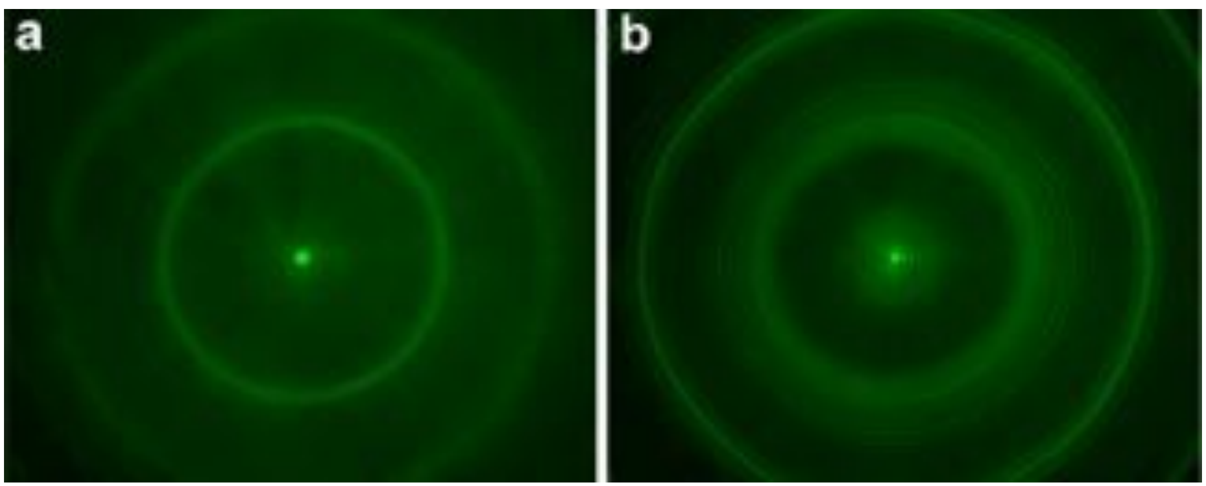
- A cylindrical cavity filled with a viscous fluid (silicone oil)
- A piezoelectric ring is driven to provide an radially symmetric acoustic wave
- Frequency range of 250-500 kHz at amplitudes from 0-100 V
- Change in refractive index creates a grating
- Tunability!



E. McLeod and C.B. Arnold (2008).

TAG Lens

- Invented by Craig Arnold, a professor at Princeton (2008 paper)
- Co-founded TAG Optics Inc. to commercialize
- Receive a device in several weeks
- Does not make higher-order Bessel beams

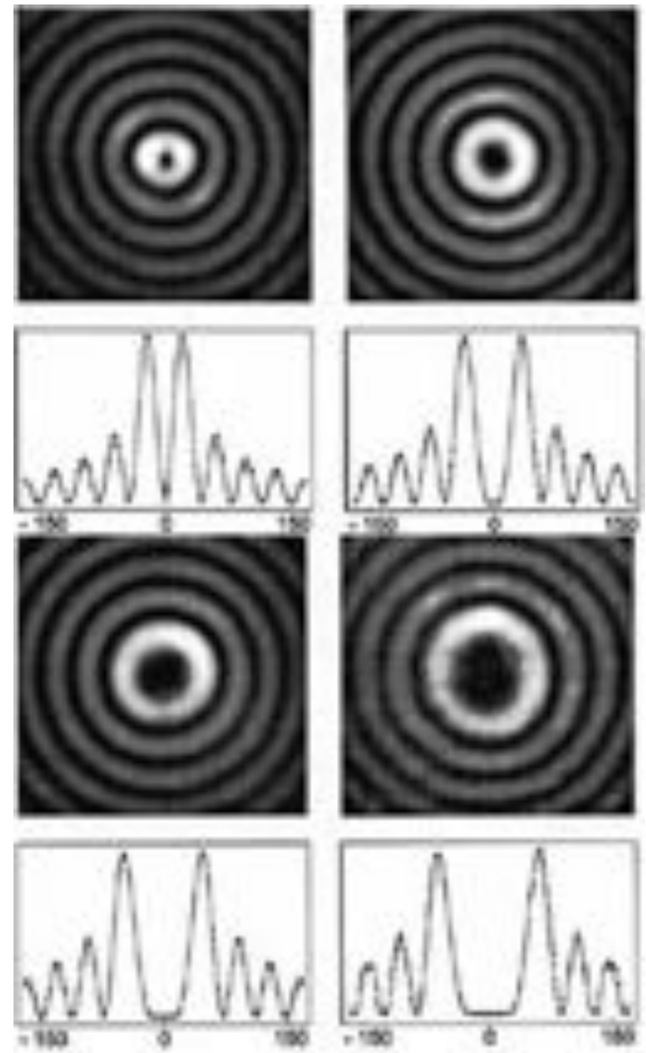


E. McLeod and C.B. Arnold (2008).

Azimuthal Phase Variation

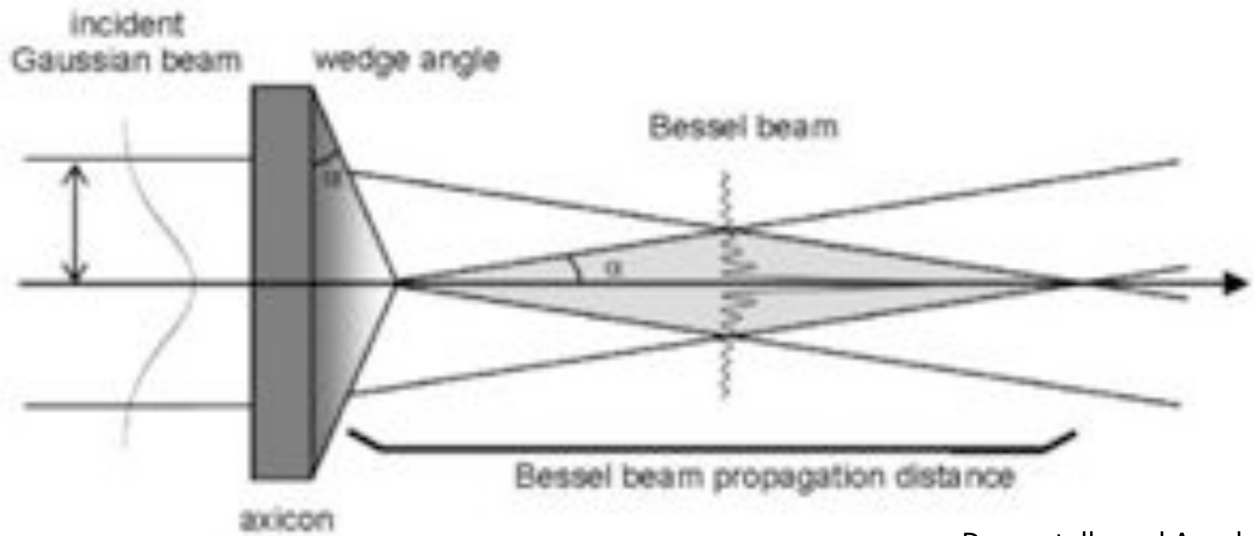
$$E_l(r,\phi,z) = Ae^{ik_z z} J_l(k_r r) e^{i\phi l}$$

- Zero order (l = 0)
  - No phase variation
  - Bright central maximum
- Higher-order (l > 0)
  - Azimuthal phase variation
  - Dark central
- Conservation of topological charge
  - Laguerre-Gaussian (LG) beam with initial orbital angular momentum



Arlt and Dholakia (2000)

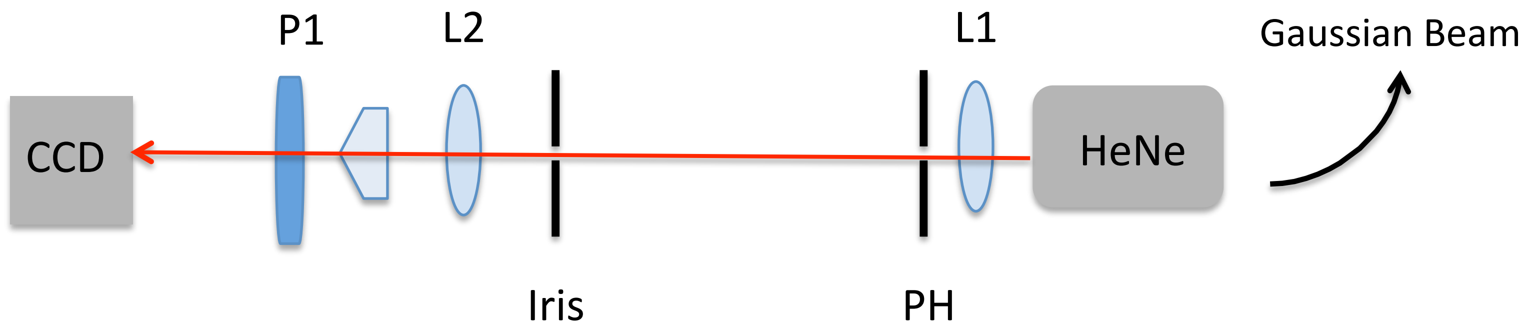
Axicon (Conical) Lens



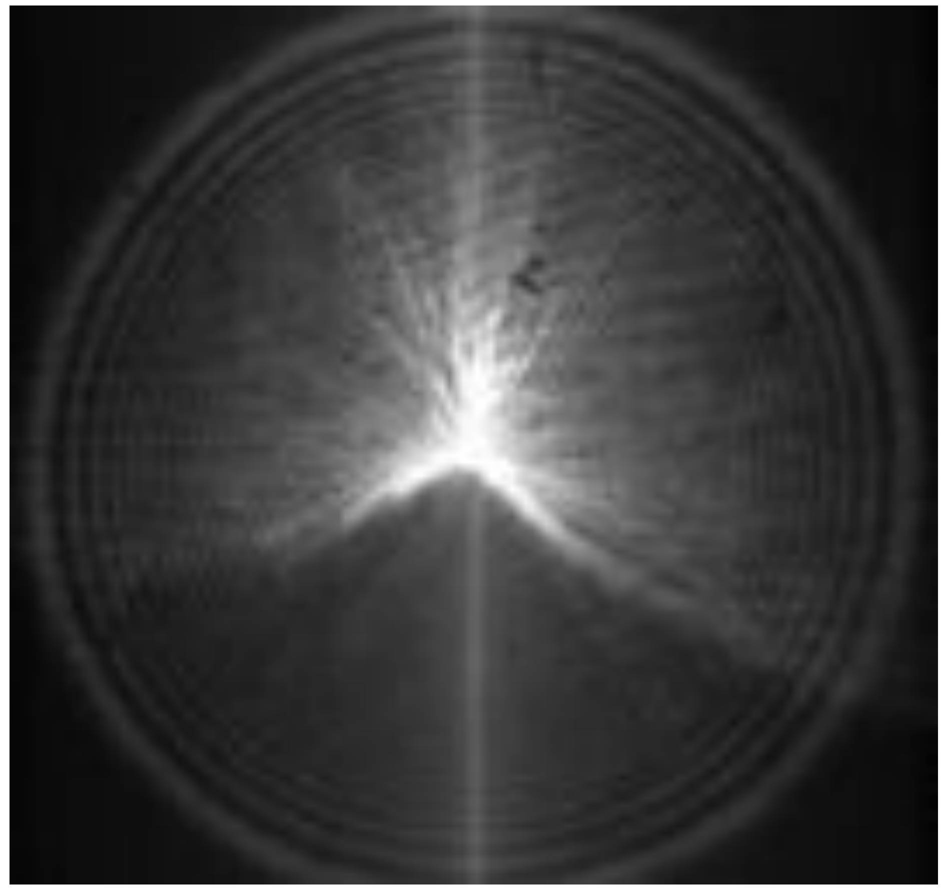
Duocastella and Arnold (2012)

- Conical lens with apex angle α and index of refraction ***n***
- Bessel beam length proportional to incident beam diameter
- Most efficient method of creating Bessel beams

Zero- Order Setup

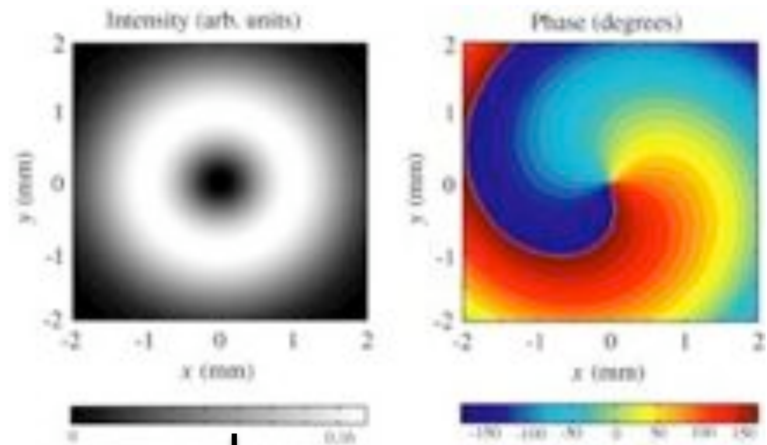


- Lens 1 and 75 micron pinhole
- Iris diaphragm and lens 2
  ➔ Cleans up Airy pattern and collimates
- Polarizer
- Axicon (borrowed from CCNY)
  ➔ 1° axicon angle & 25.44 mm diameter
  ➔ $n \approx 1.55$
- CCD for recording

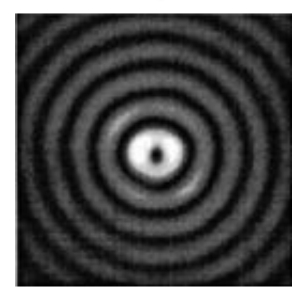


Higher-Order Setup

- Open Cavity HeNe Laser
- Astigmatic Mode Converter
  ➔ convert to LG beam
- Pair of Lenses (Telescope)
  ➔ f = 35 mm & 750 mm
- Axicon lens



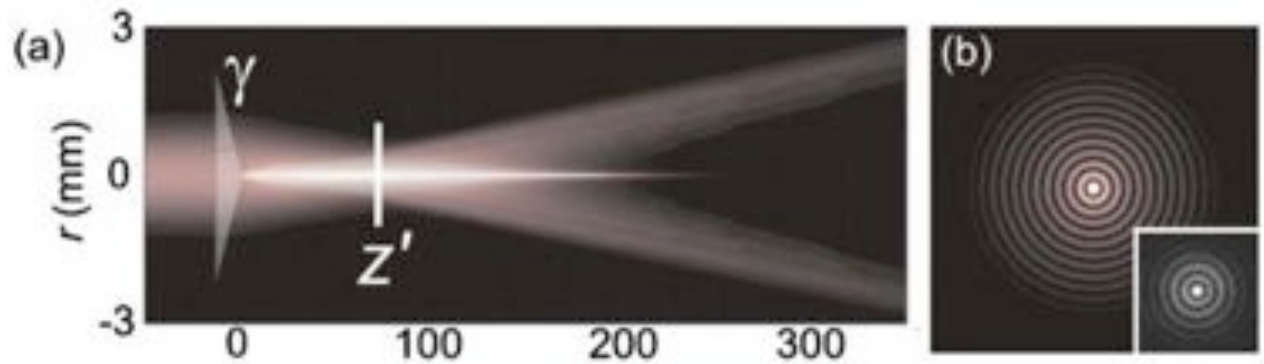
C.H Gan (2007).



Arlt and Dholakia (2000)

Conclusion

- Bessel beams have interesting properties and important applications
- There are a variety of ways to make them
- This was a good topic for a teaching laboratory!



Milne (2008)

Acknowledgements

Founder of the Laser Teaching Center

- Hal Metcalf

Mentors

- John Noé
- Marty Cohen

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McLeod, J. M. (1953). "The Axicon: A New Type of Optical Element." Optical Society of America 44(8): 592-597.