UNIVERSITAT POLITÈCNICA DE VALÈNCIA

*iCrea
INSTITUCIÓ CATALANA DE RECERCA I ESTUDIS AVANÇATS

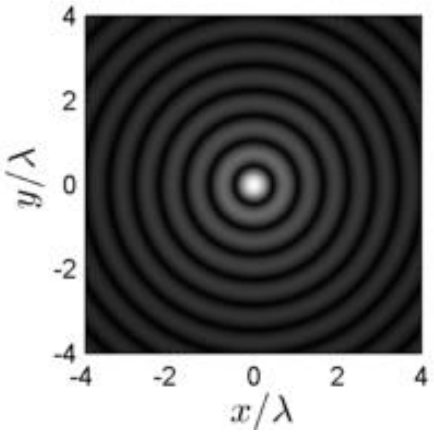
IUMPA

High-order acoustic Bessel beam generation by spiral gratings

Noé Jiménez, V.J. Sanchez-Morcillo, R. Pico, L.M. Garcia-Raffi, V. Romero-Garcia and K. Staliunas*

Why Bessel beams?

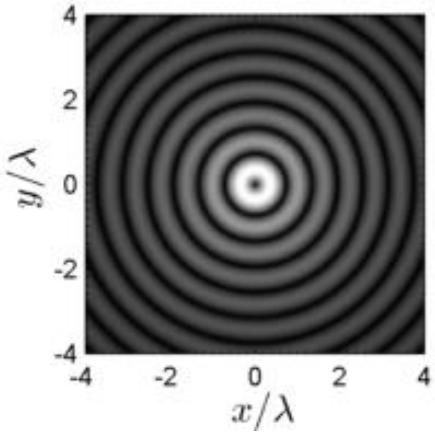
- Non diffracting beams
- Good FWHM
- Self-healing, …



Why High order Bessel beams?

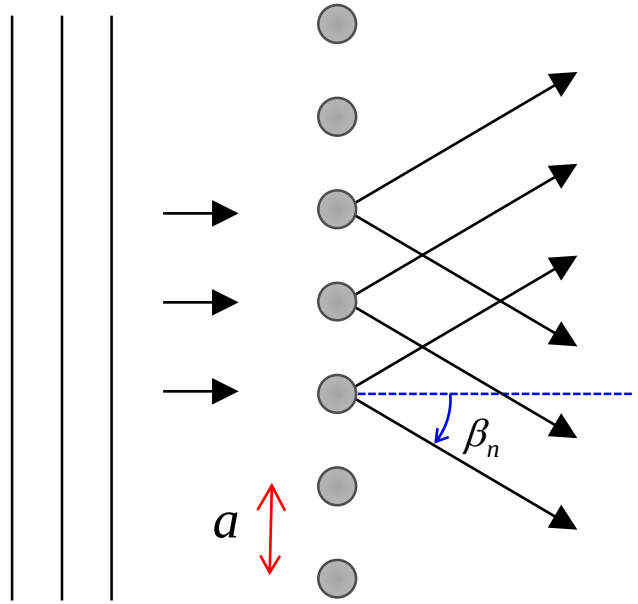
Same properties, but:

- Hollow beam
- Acoustic vortex
- Angular momentum transfer
- Special acoustic radiation force properties



From axisymmetric to chiral beams

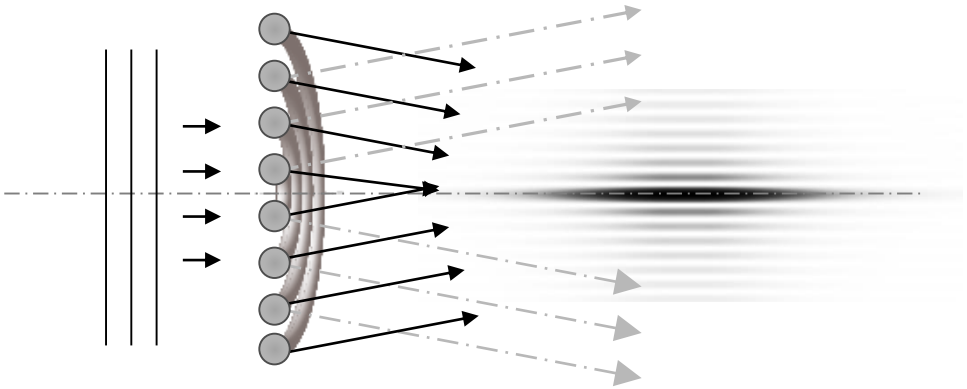
Diffraction grating



$$\sin \beta_n = \frac{n\lambda}{a}$$

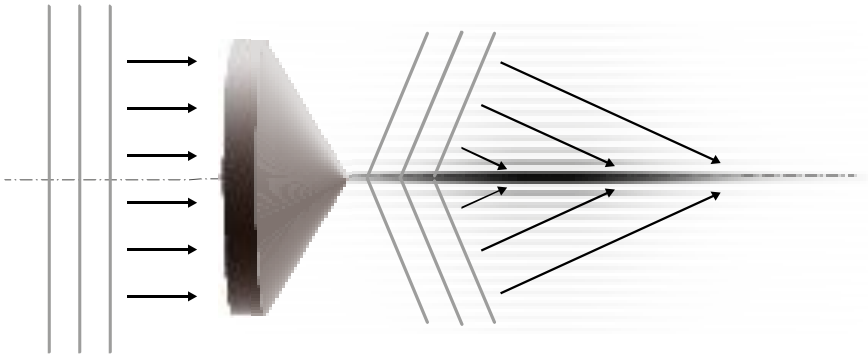
From axisymmetric to chiral beams

Axisymmetric diffraction grating: **zero-th order Bessel beam**



$$\sin \beta_n = \frac{n\lambda}{a}$$

Axicon



N. Jimenez, et al. *Europhysics Letters*, **106**, pp 24005, (2014)

From axisymmetric to chiral beams

Axisymmetric diffraction grating

A

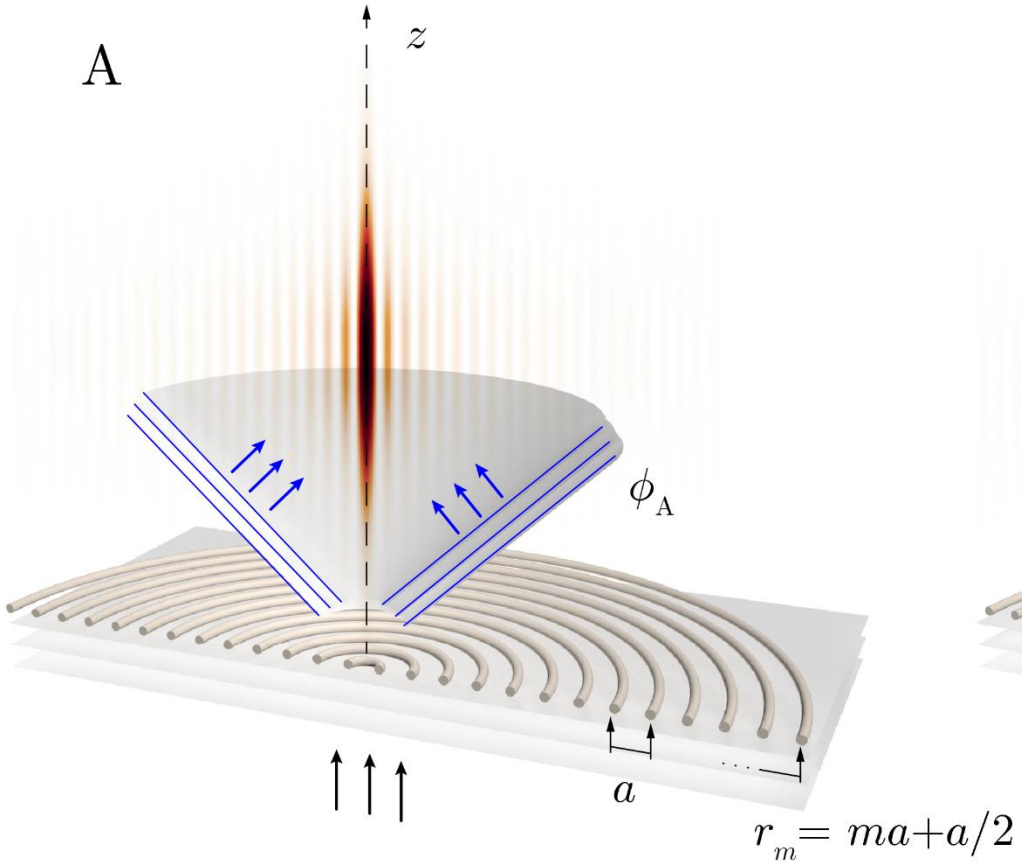


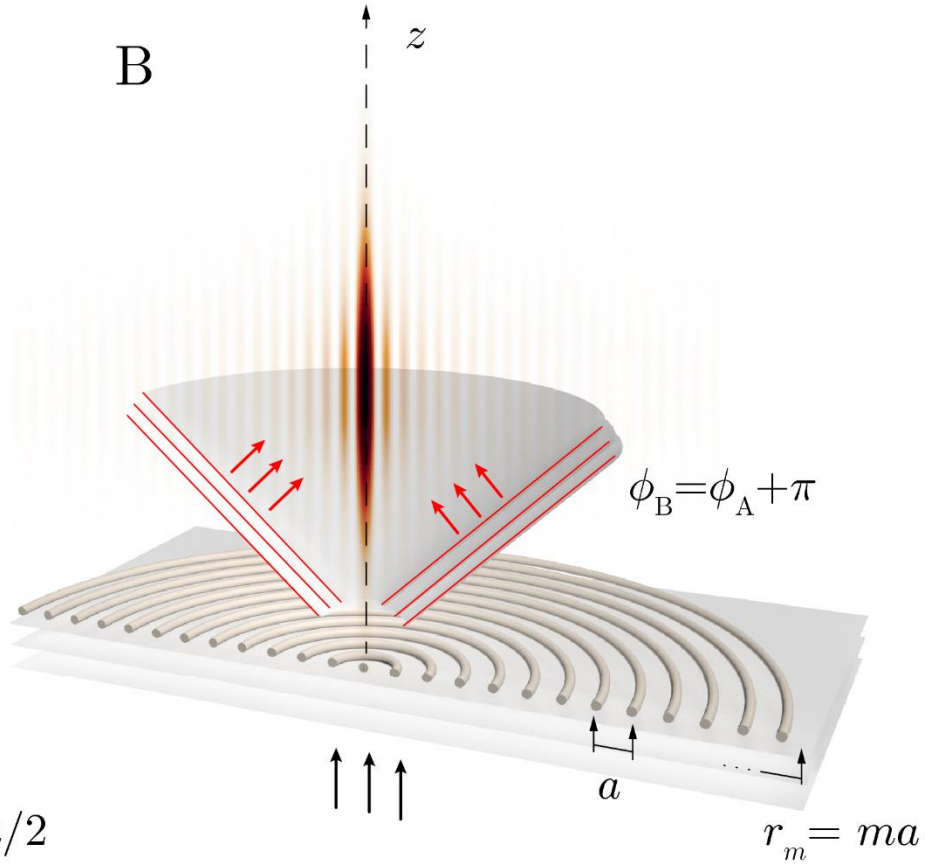
B



From axisymmetric to chiral beams

Axisymmetric diffraction grating





From axisymmetric to chiral beams

- Axisymmetric diffraction grating

$$\Delta\phi = \frac{2\pi\Delta r}{a}$$

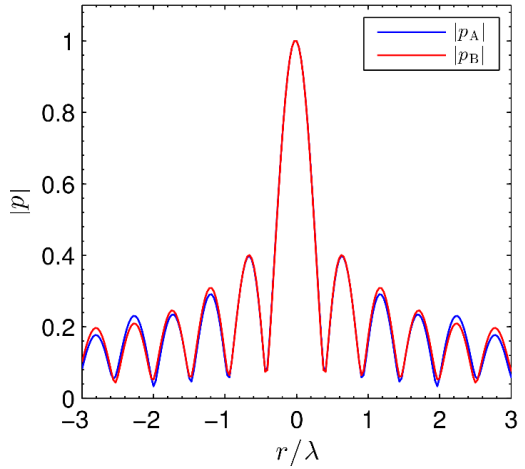
- Design conditions for hollow beam:

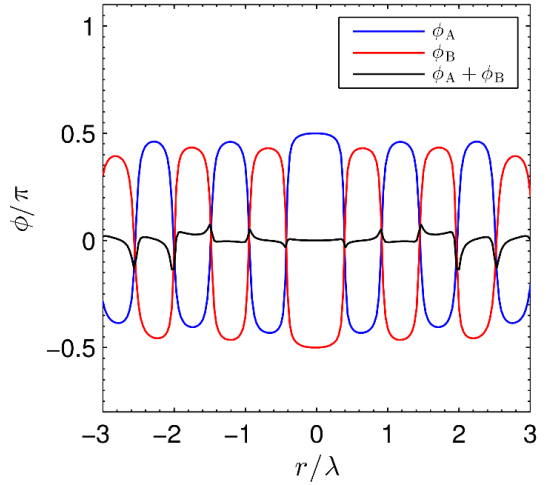
$$\phi(\theta) = \phi(\theta+\pi) \pm \pi$$

$$\phi = \alpha\theta \qquad \alpha = 1$$

- Archimedean spiral equation:

$$\frac{\Delta r}{\Delta\theta} = \pm\frac{a}{2\pi} \qquad r(\theta) = \pm\frac{a}{2\pi}\theta$$





Chiral beams generated by spirals

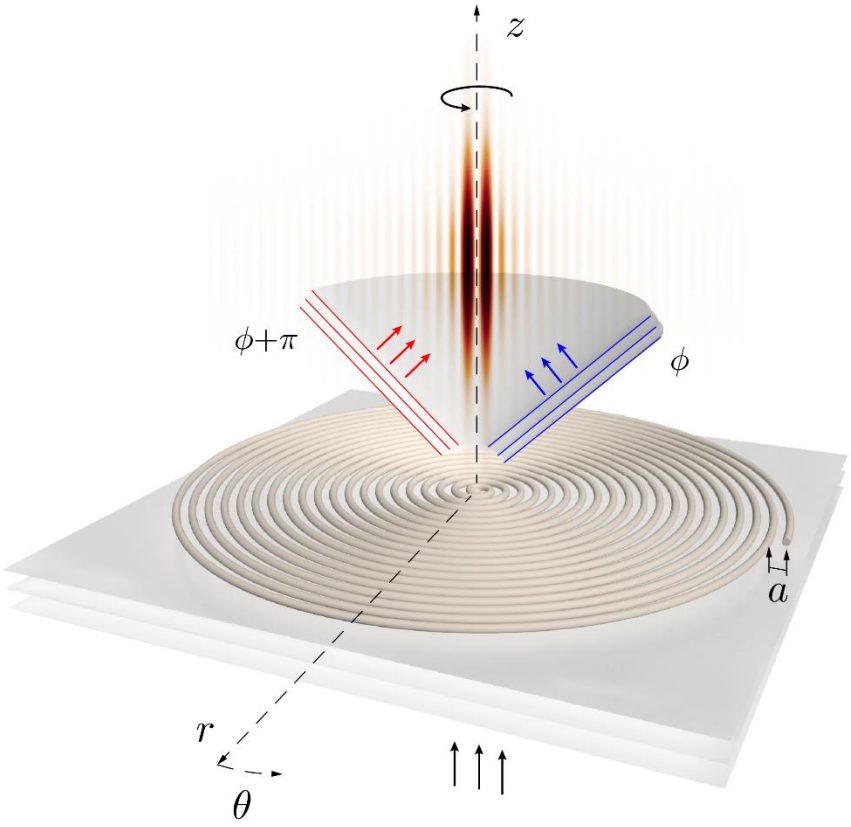
- Grating angles $\sin\beta = \dfrac{n\lambda}{a}$

- Ideal *m*-th order Bessel beam

$$\psi(r,\theta,z) = \psi_0 J_m(k_r r)\exp(ik_z z \pm im\theta)$$

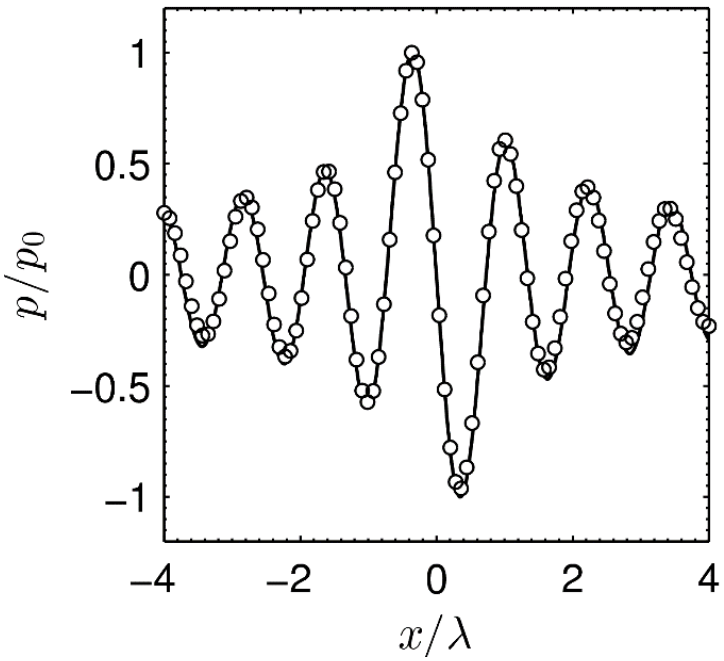
$$\sin\beta = k_r / k \qquad \cos\beta = k_z / k$$

$$\psi(r,\theta,z) = \psi_0 J_m\left(\frac{2\pi}{a}r\right)\exp\left(i\frac{2\pi n}{a\tan\beta}z \pm im\theta\right)$$

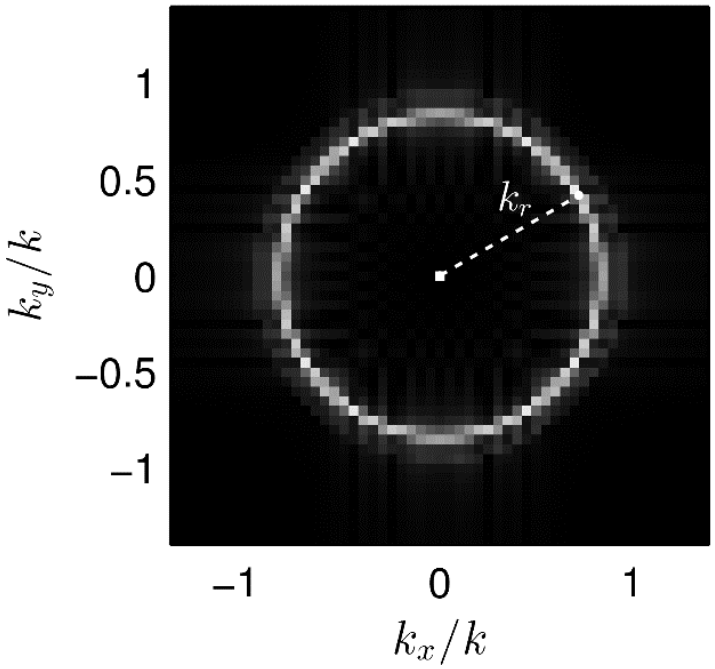


1st order Bessel beams

Truncated + Ideal Bessel

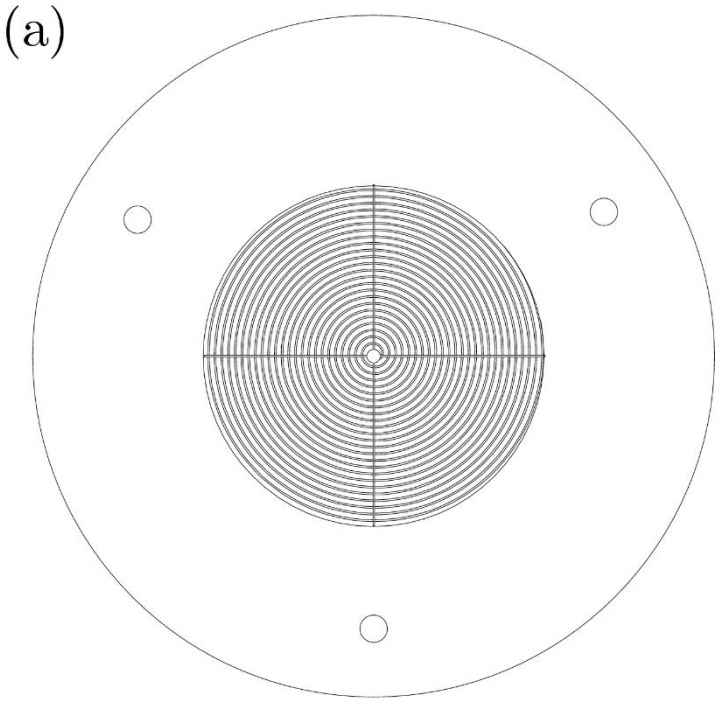


Far field



Experimental test

Stainless-steel grating, a = 1mm, f_0 = 2,2 MHz, A = 50 mm

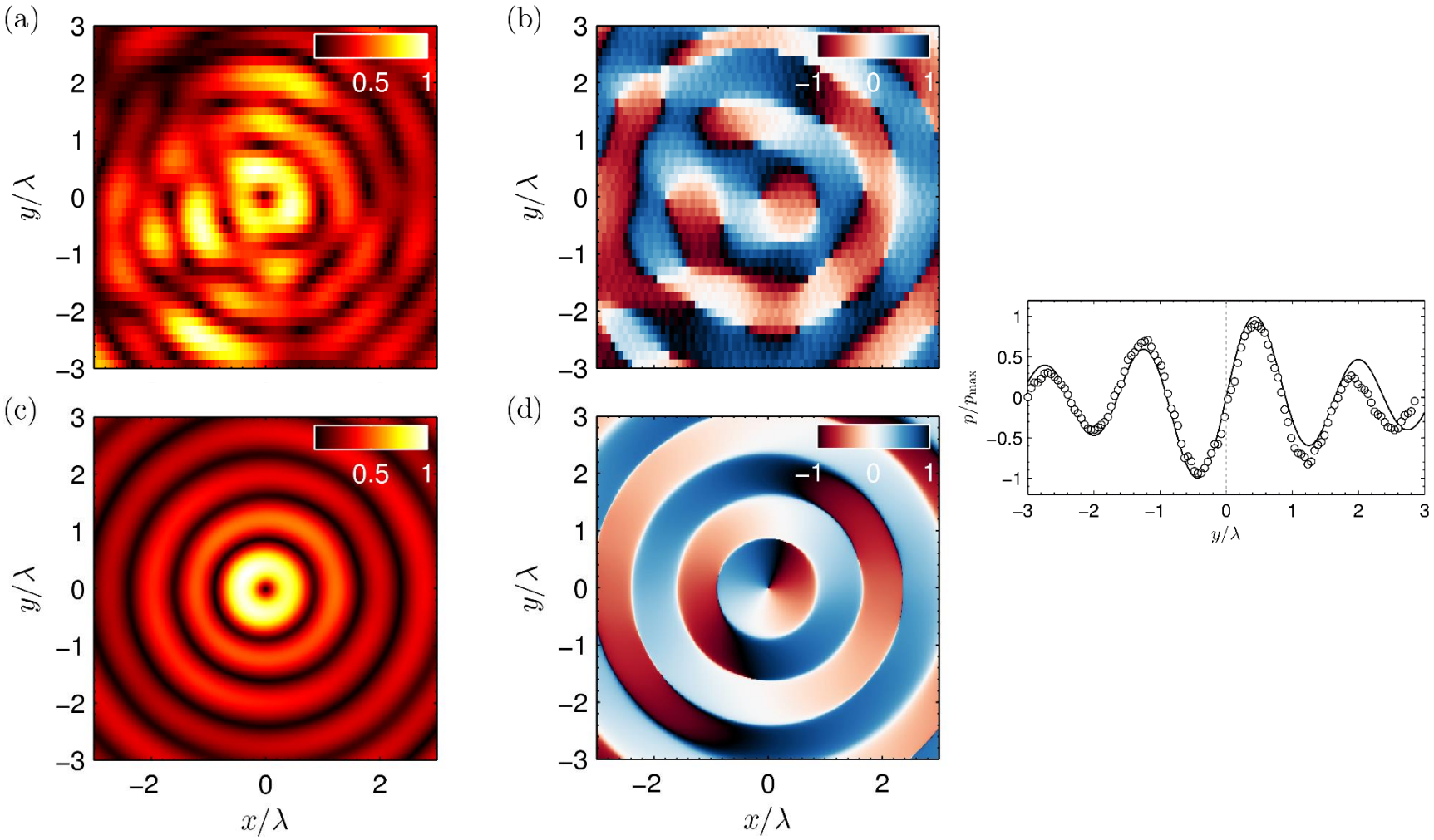




Experimental test

Experimental

Analytic

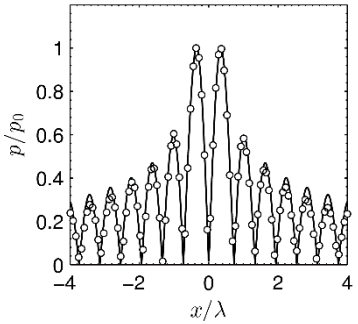


High-order Bessel Beams

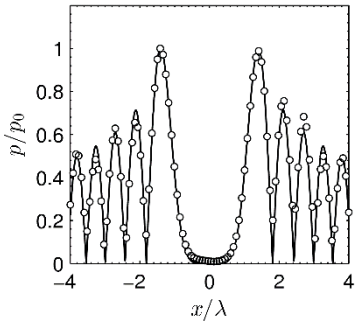
Design equations → high diffraction grating orders

$$\phi(\theta) = \phi(\theta + \pi) \pm m\pi \qquad r(\theta) = \pm m \frac{a}{2\pi}\theta$$

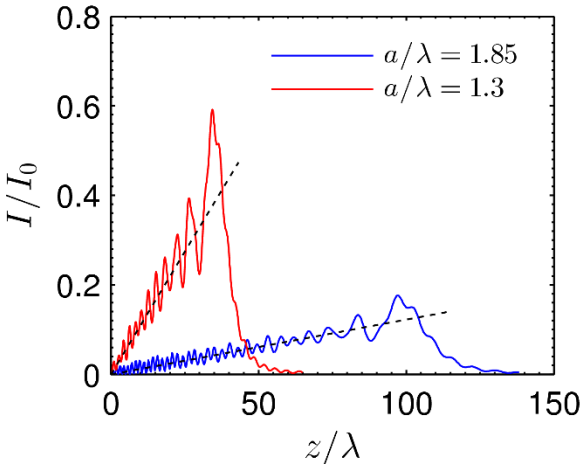
m = 1



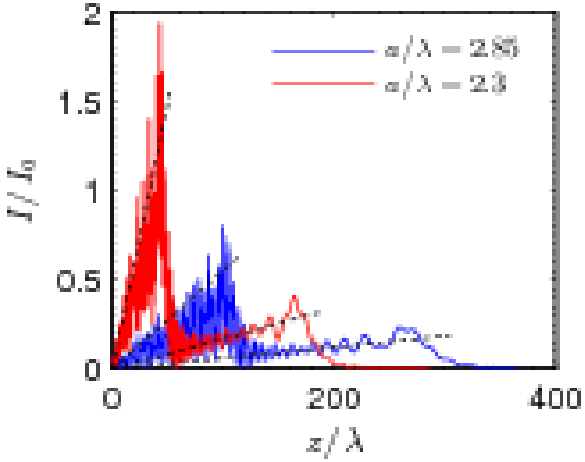
m = 7



1st order diffraction

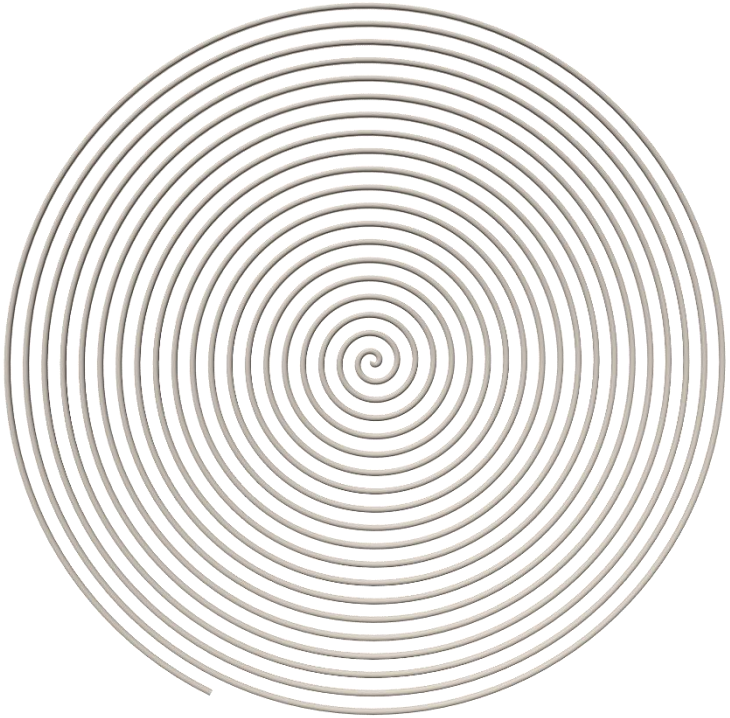


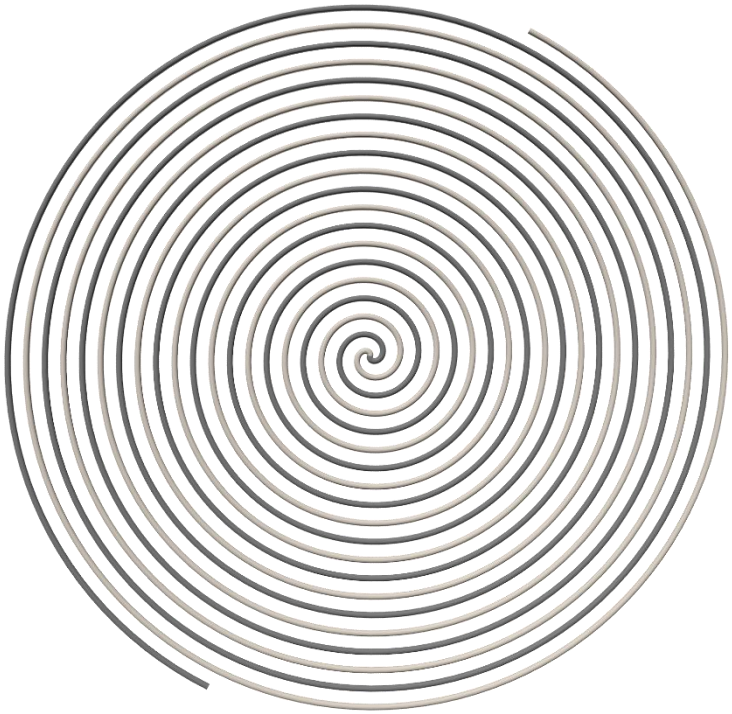
2nd order diffraction



High-order Bessel Beams

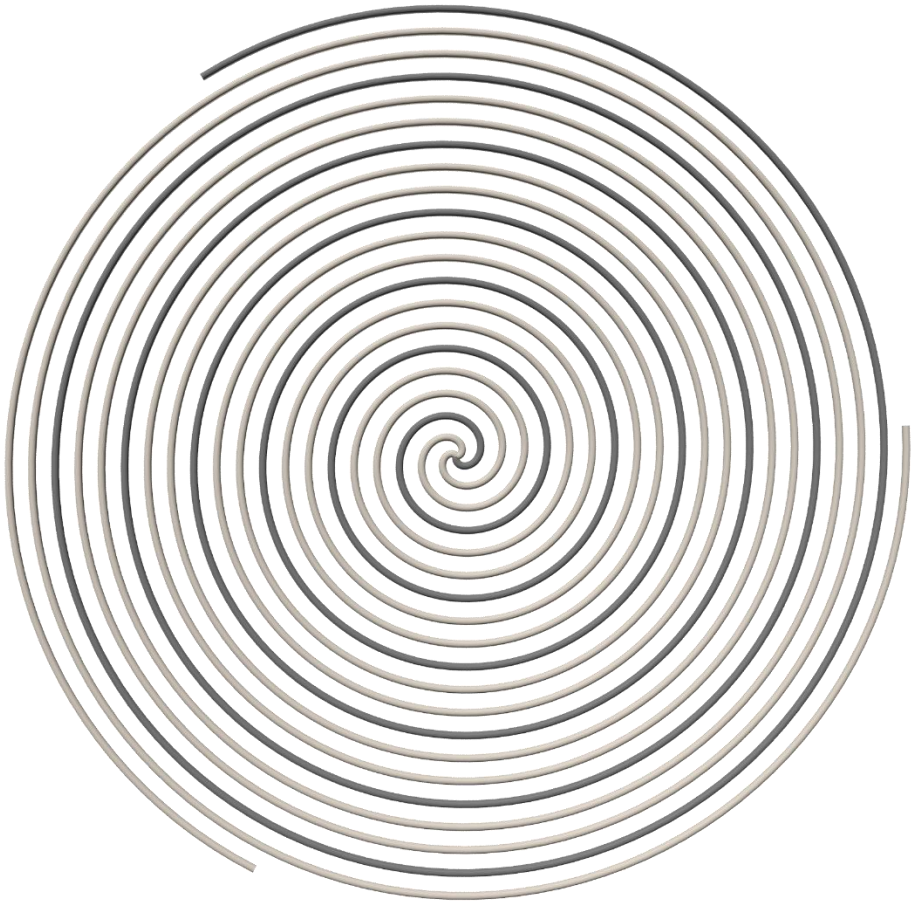
Use m-arms spiral → m-th order Bessel beams



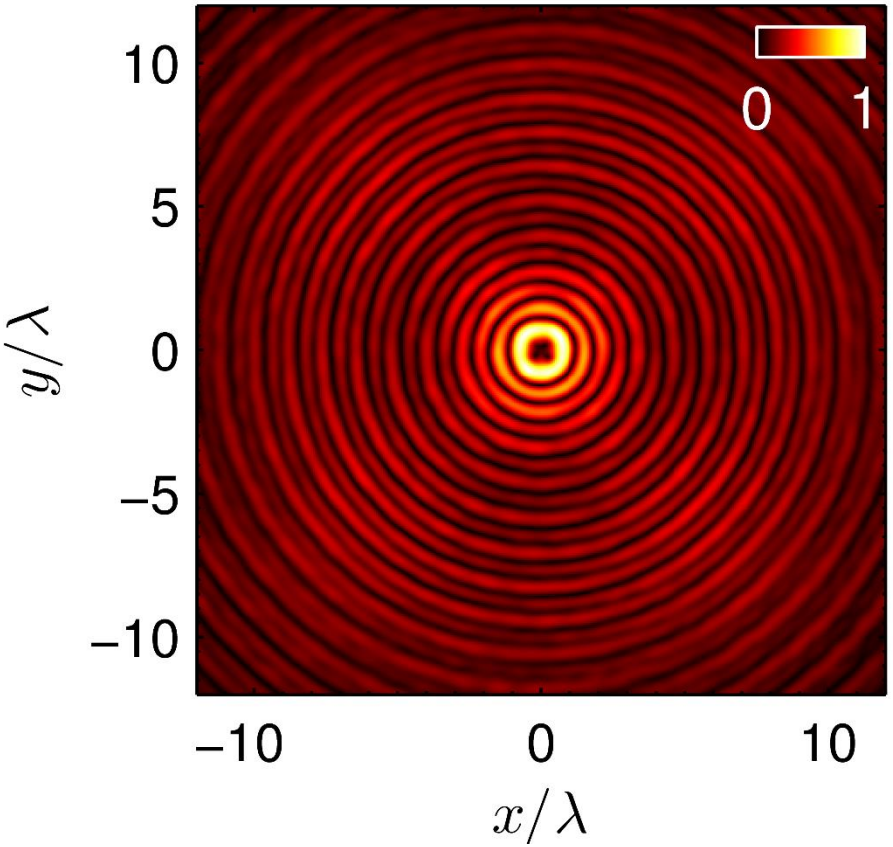


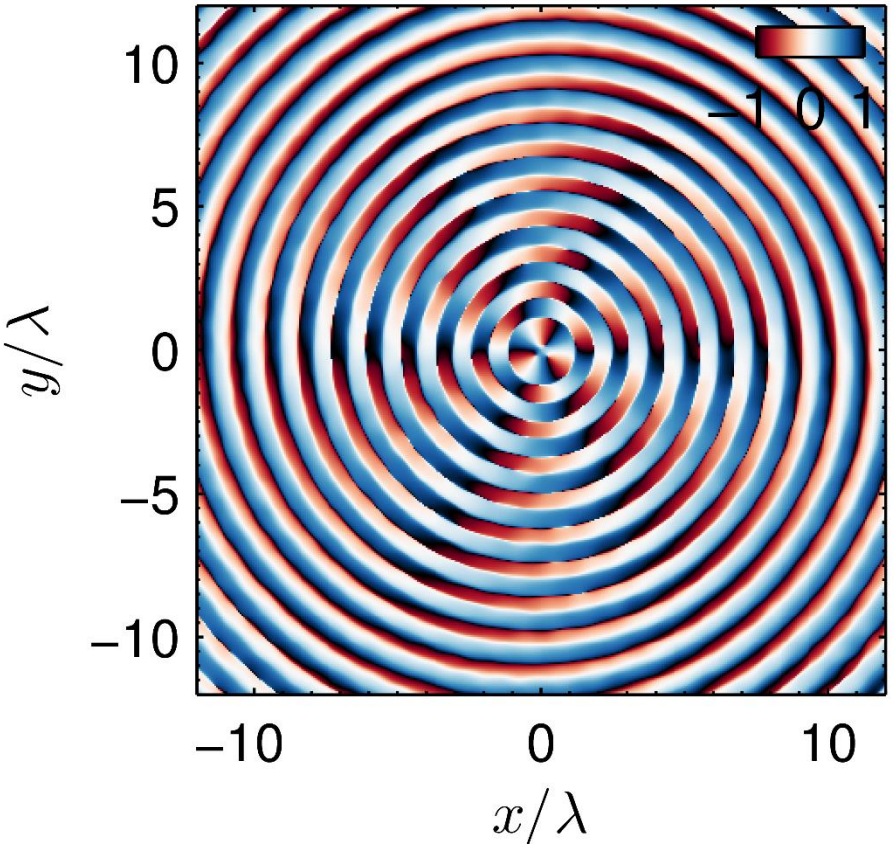
High-order Bessel Beams

3rd order ($m = 3$)



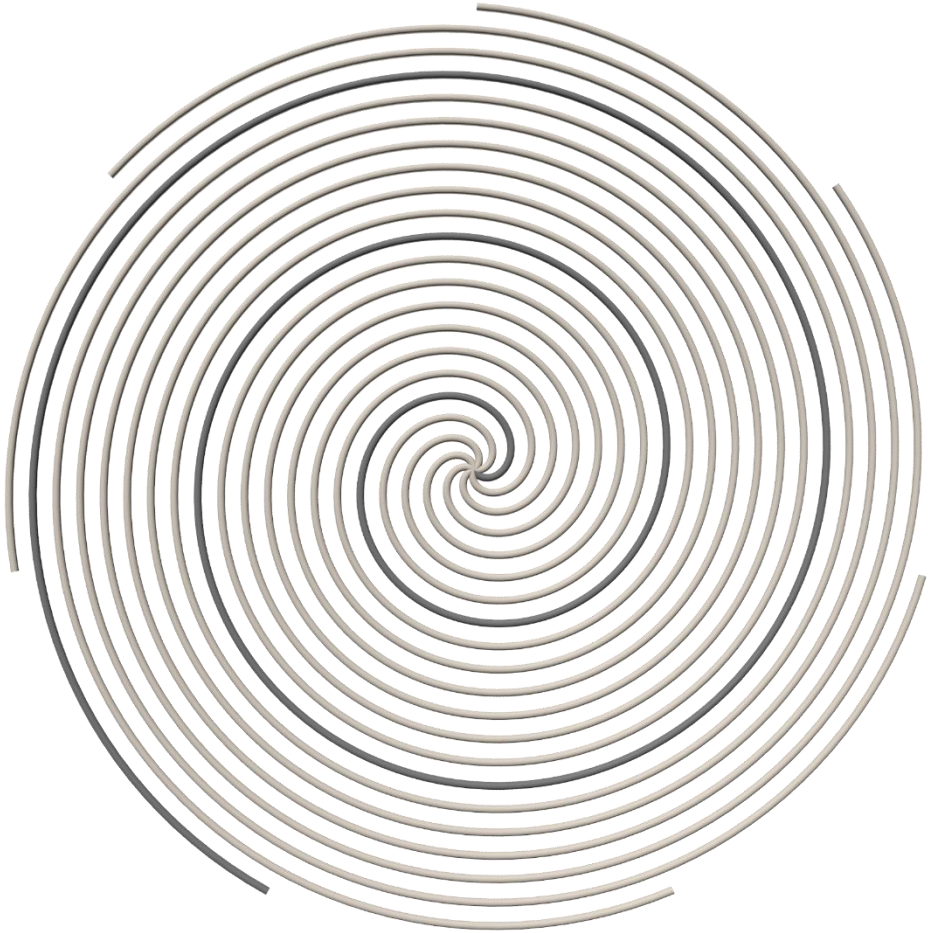
3rd order Bessel beam ($m = 3$)



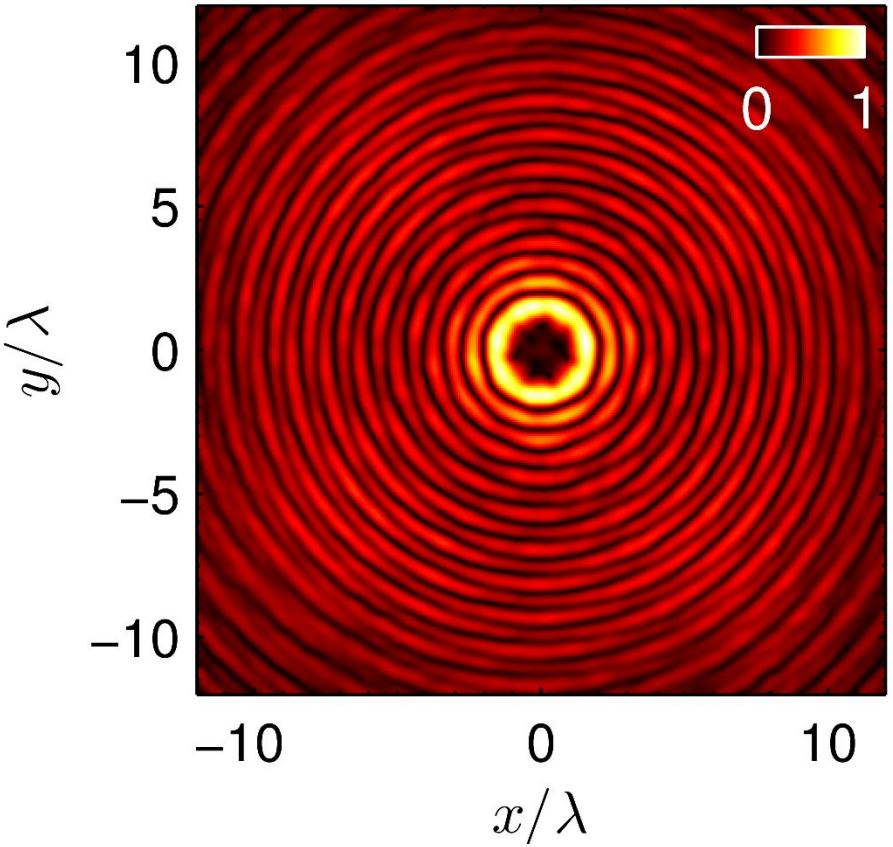


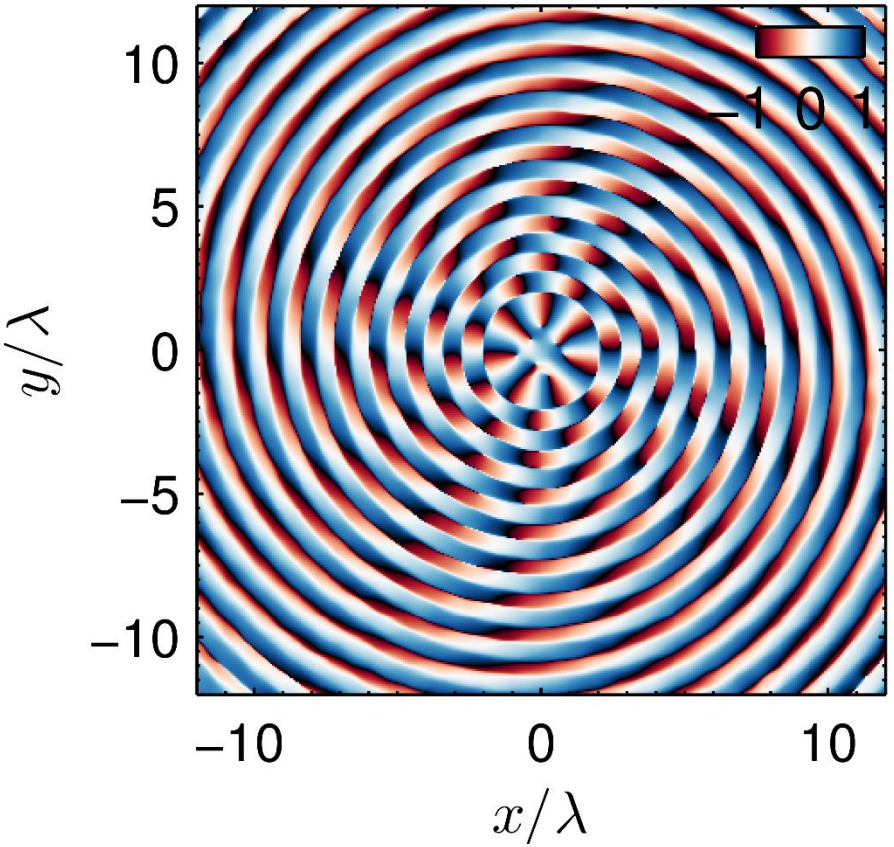
High-order Bessel Beams

7^{th} order ($m = 7$)



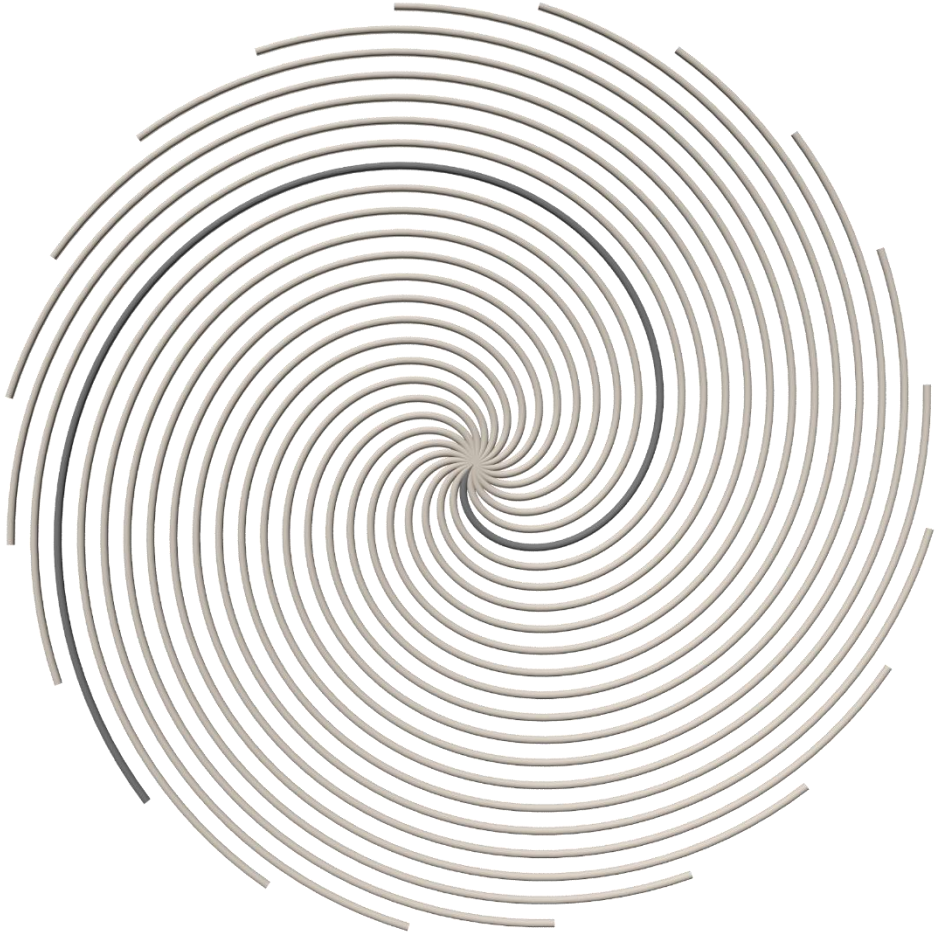
7th order Bessel beam (m = 7)



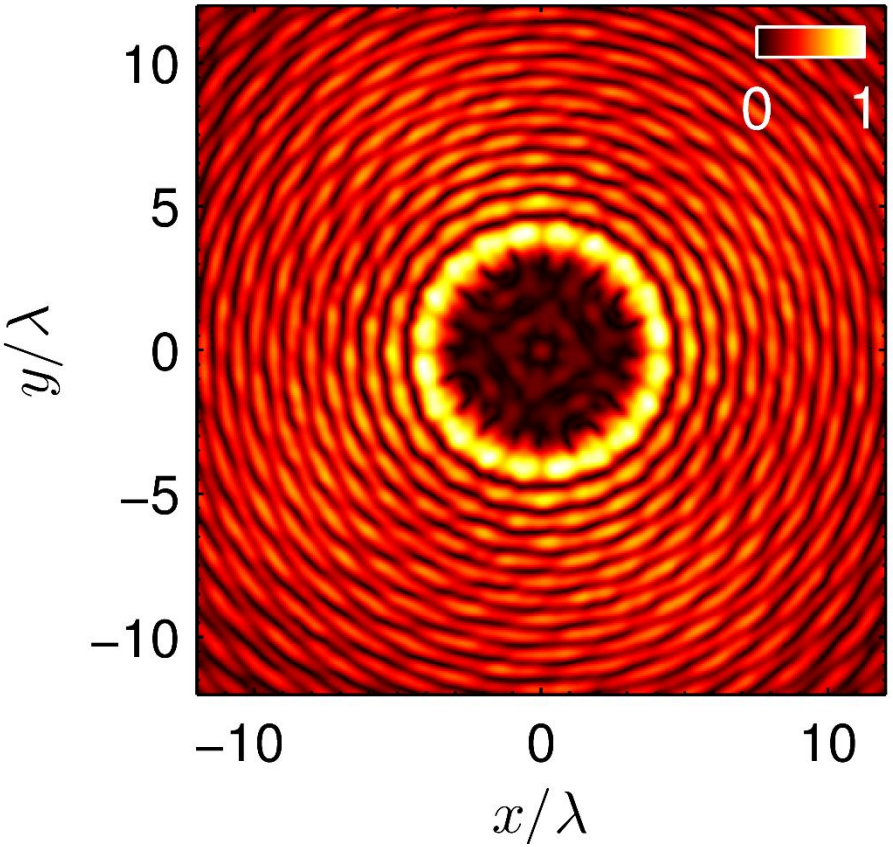


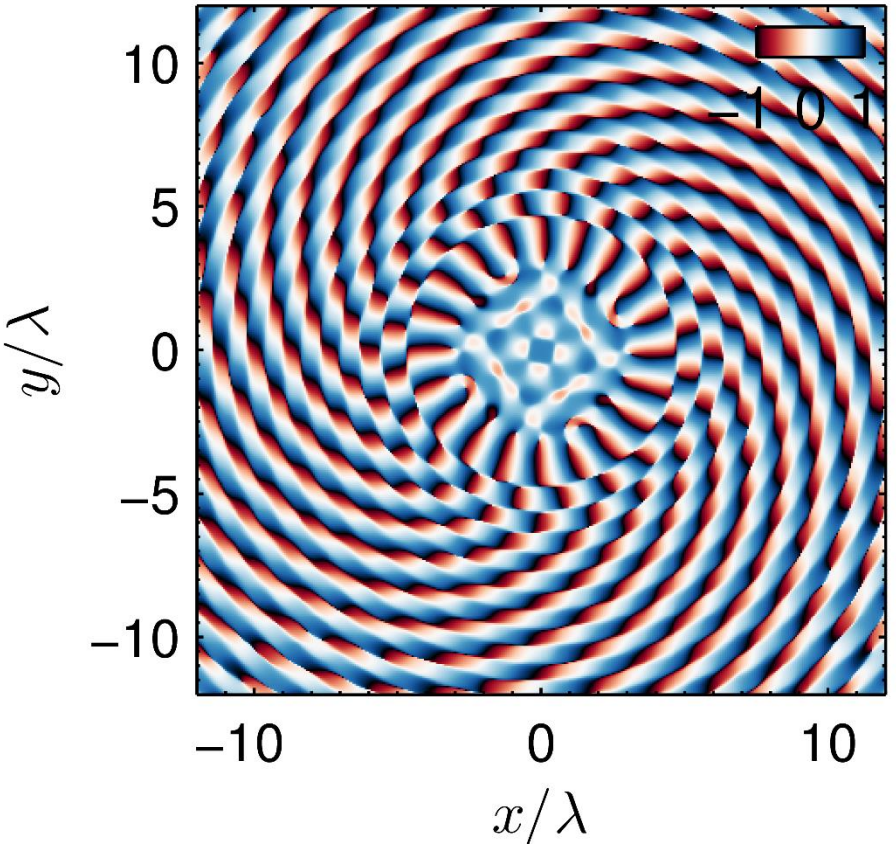
High-order Bessel Beams

20th order (m = 20)



20th order Bessel beam ($m = 20$)



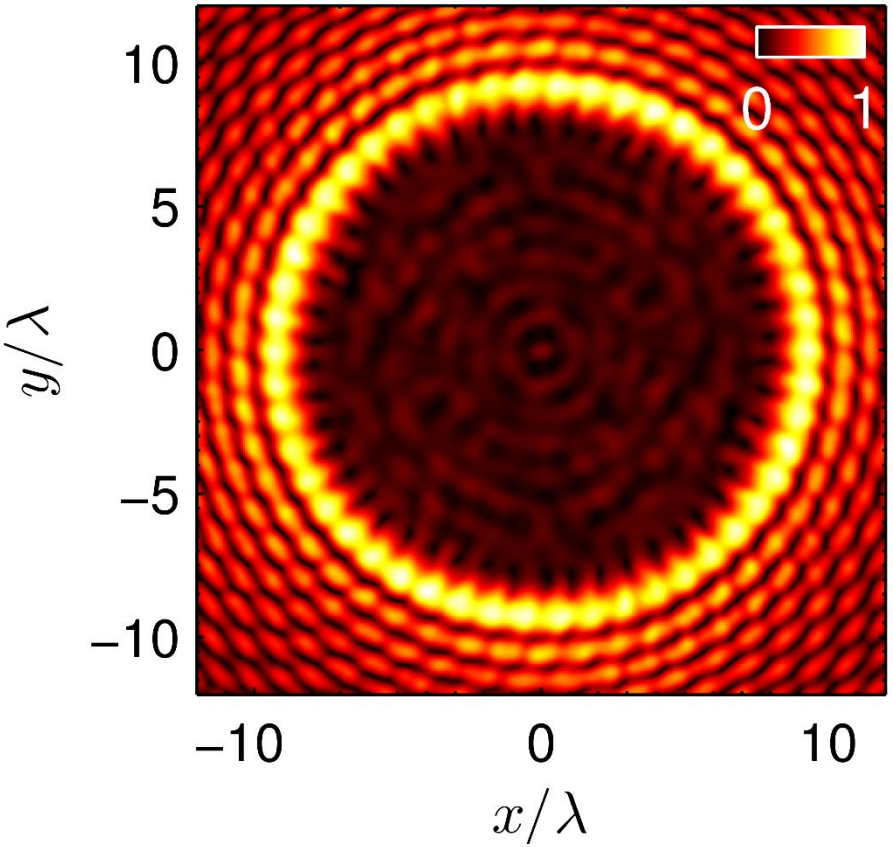


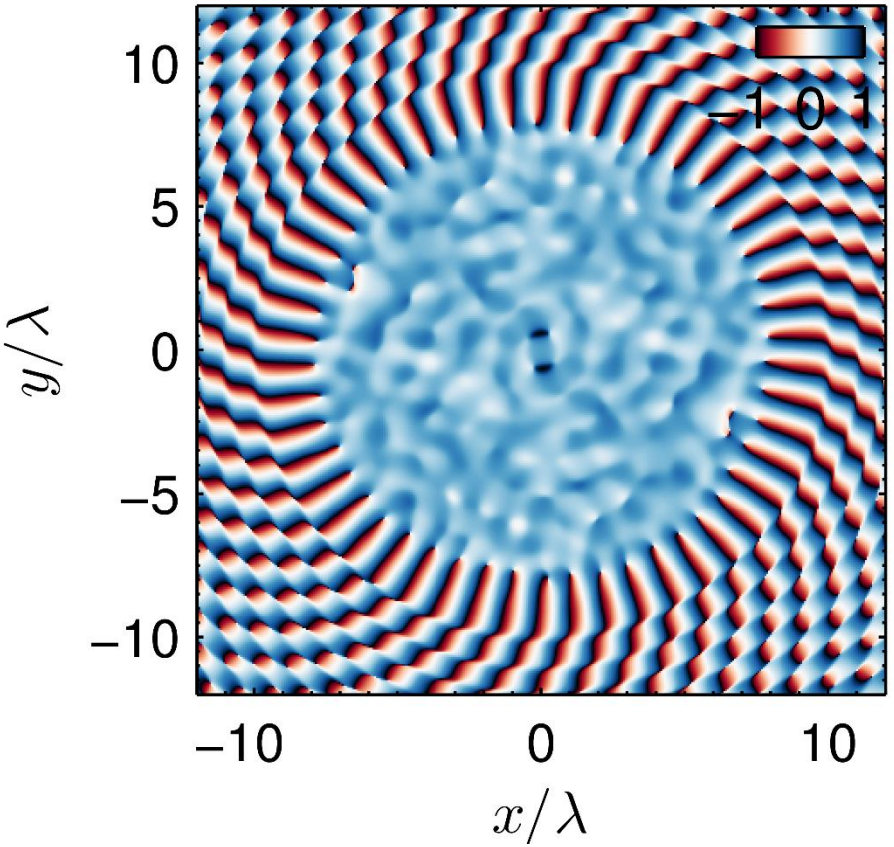
High-order Bessel Beams

50th order (m = 50)



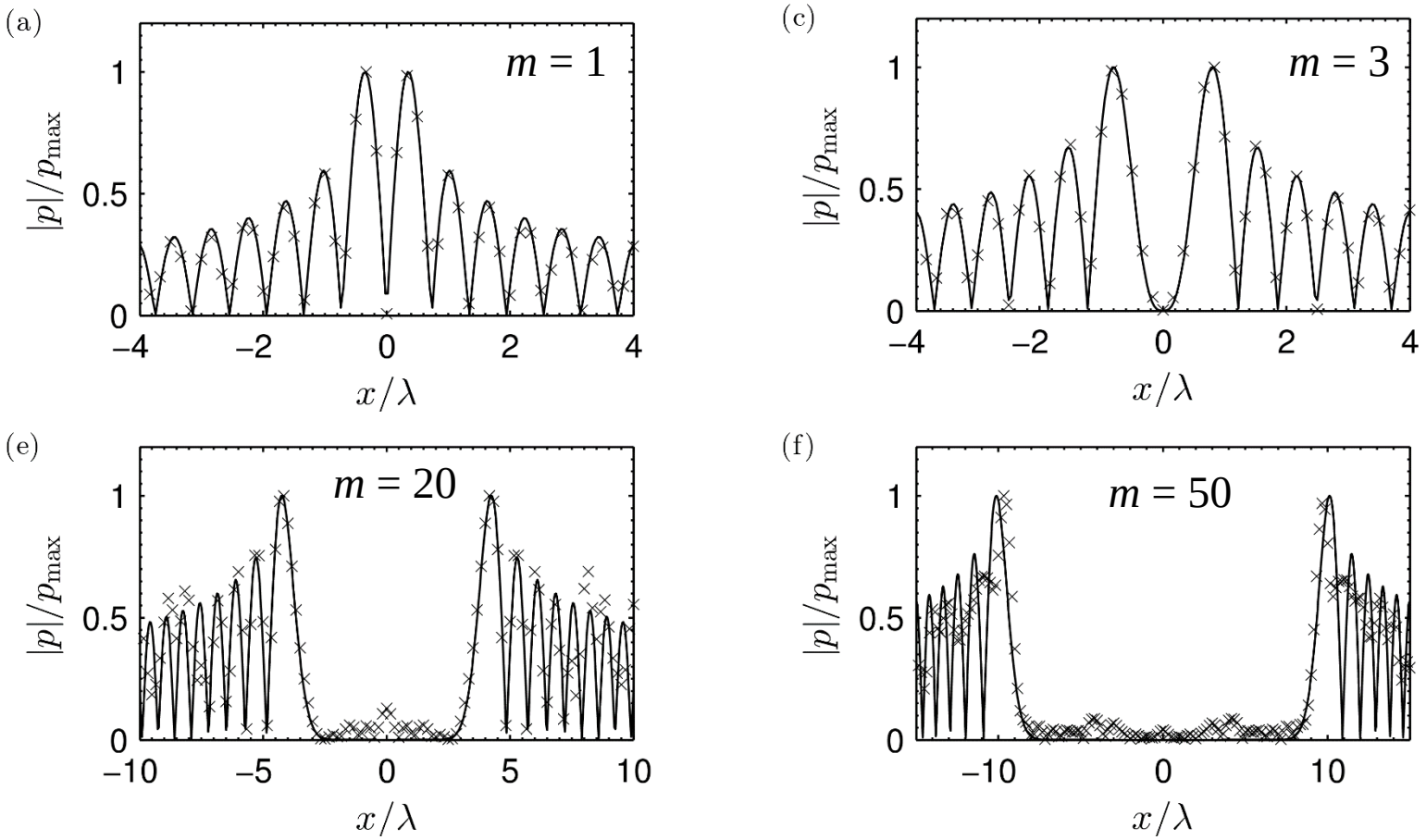
50th order Bessel beam ($m = 50$)





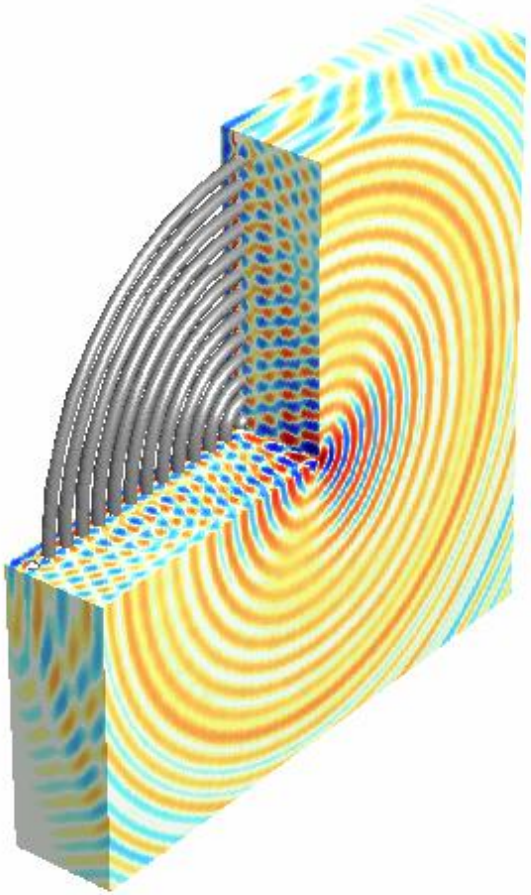
High-order Bessel Beams

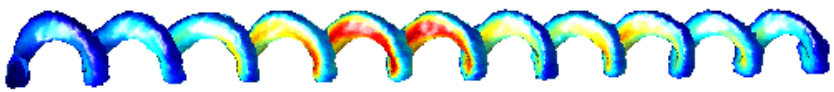
Hollow beam: 3D *k*-space simulations

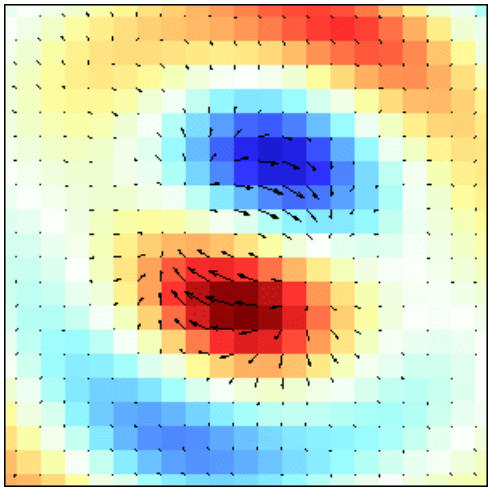


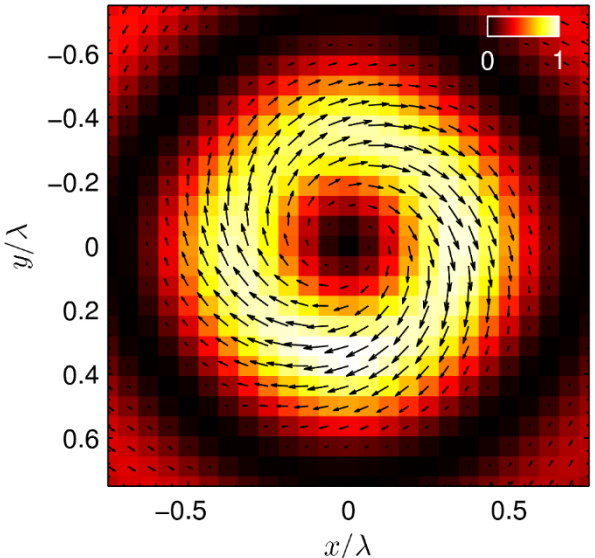
Acoustic vortex

Vortex Intensity → angular momentum







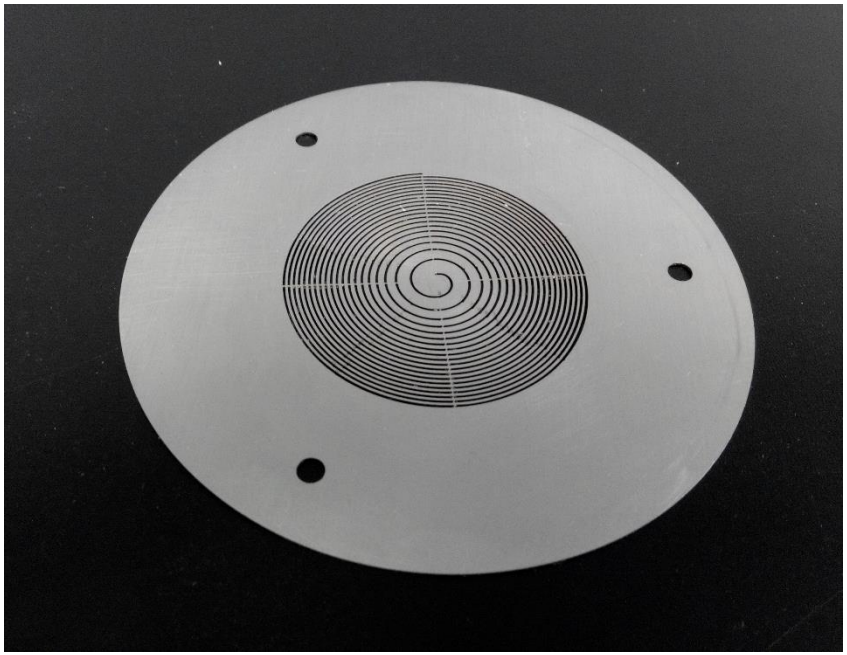


Angular momentum enhancement:

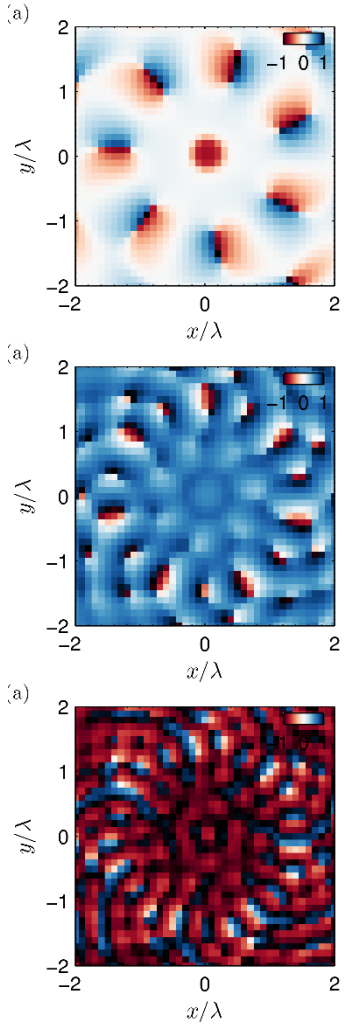
Increase topological charge ($t = m\ n\ i$)

- m → Arms
- n → High order diffraction
- i → Nonlinear harmonic generation → shock waves

Focusing: Fresnel spiral lens



nonlinearity



Conclusions

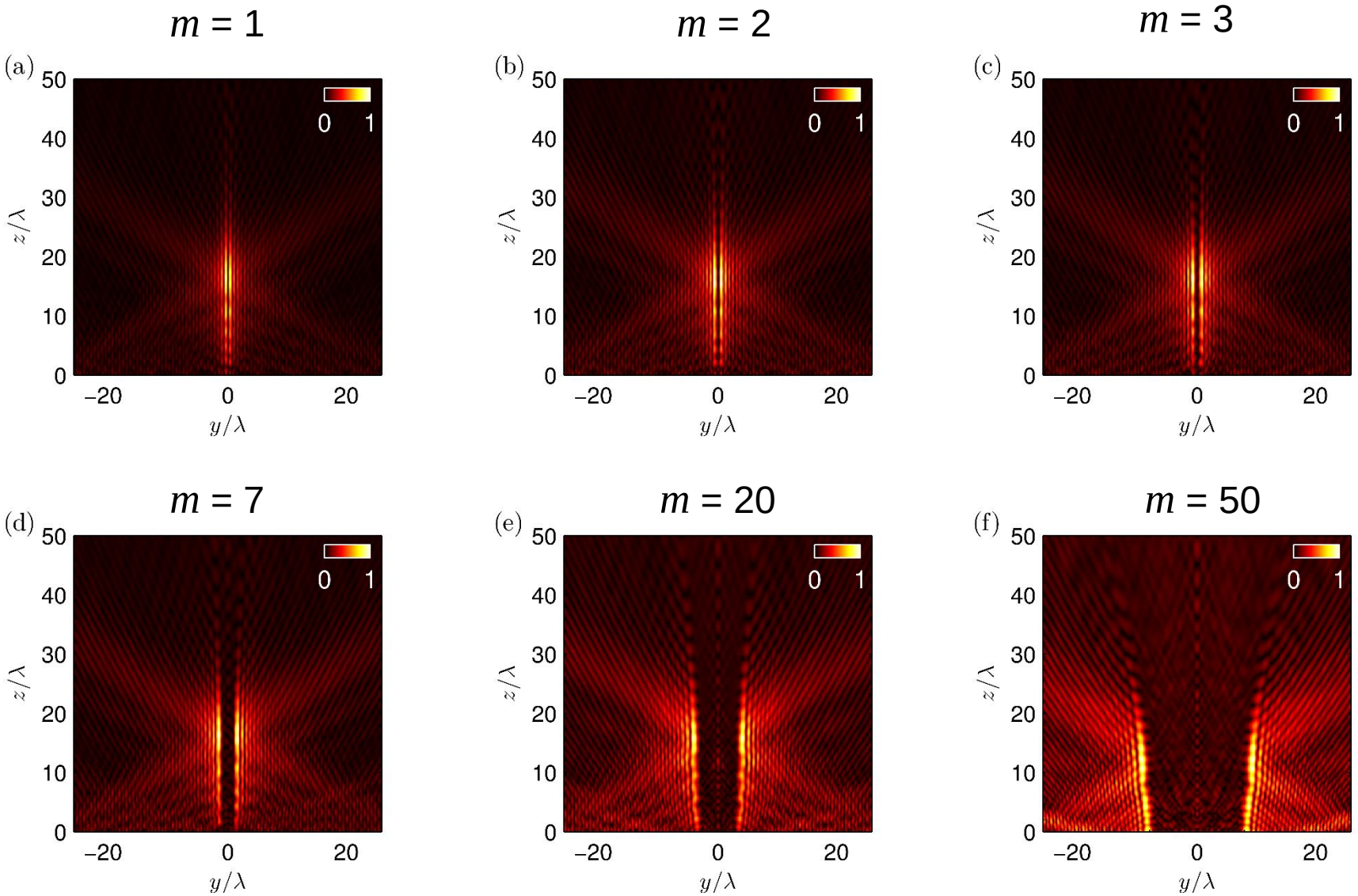
High order Bessel beams

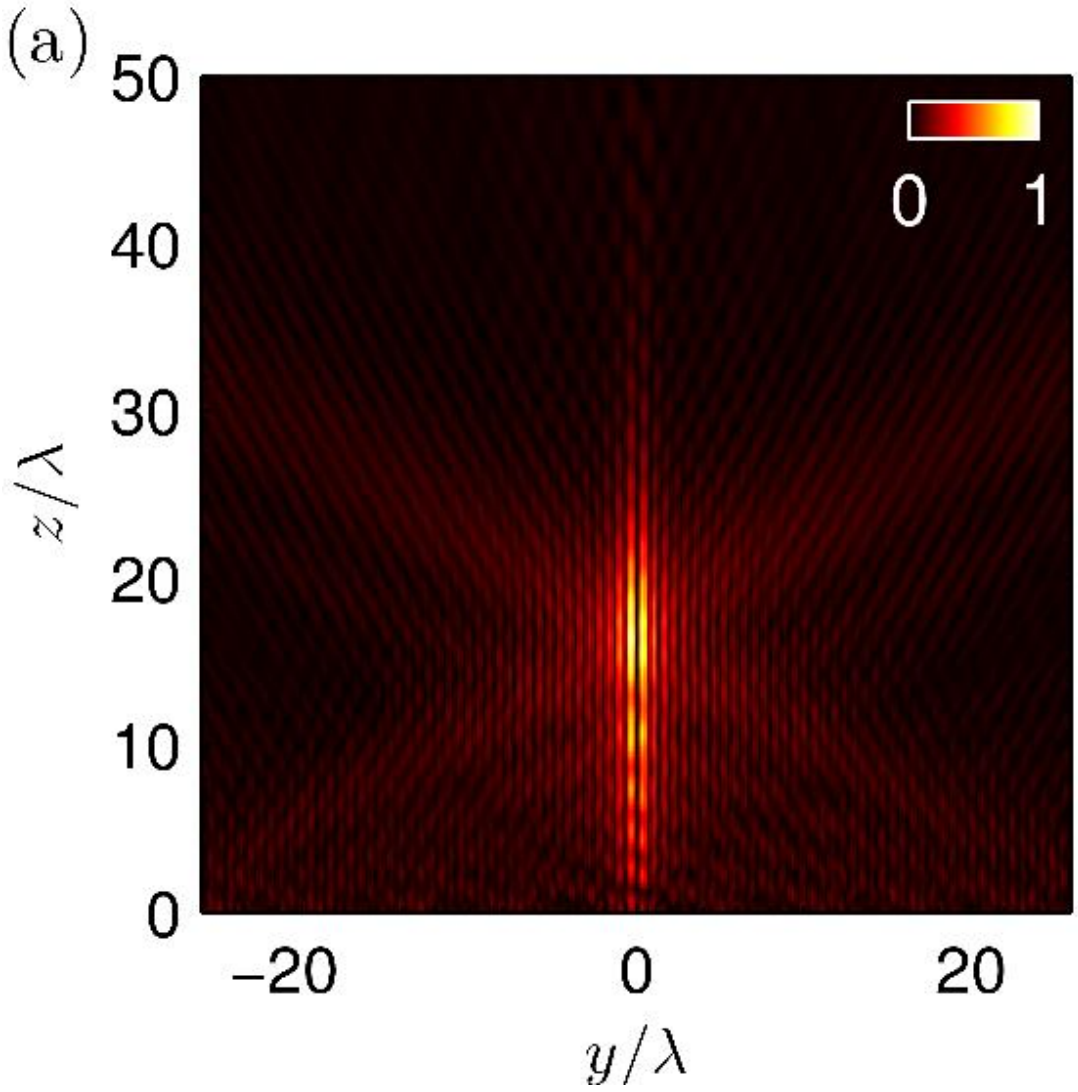
- High order Bessel beams can easily generated by gratings
- Higher order by spiral gratings
- Cheap, robust lens construction
- High frequency bandwidth

Acoustical vortex

- Potential for ARF applications: particle manipulation, elasticity imaging, …
- Increase topological charge with:
  - Number of arms
  - Diffraction order
  - Harmonics
  - Shock waves

Axial profiles




(a)
50
40
30
20
10
0
z/λ
0
1
−20
0
20
y/λ