



# **Gamma-ray vortex generation by inverse Compton scattering**

**Yoshitaka Taira**

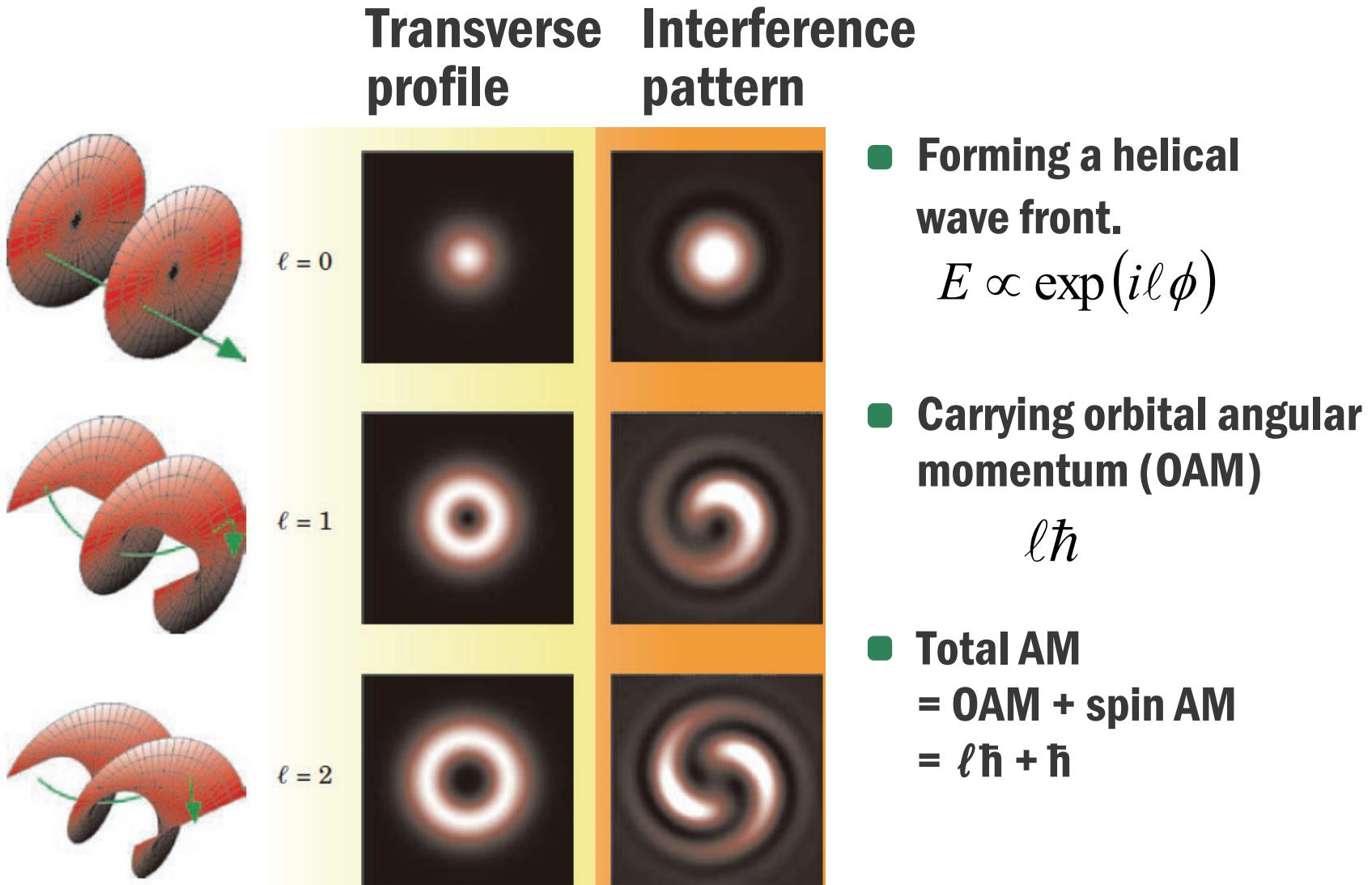
**National Institute of Advanced Industrial Science and Technology (AIST), Japan**  
**Visiting scientist: Mississippi State University and Jefferson Lab.**

# Outline

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- Vortex beams carrying orbital angular momentum
- Gamma-ray vortex generation
  - 1 Frequency upconversion of an optical vortex laser by inverse Compton scattering (ICS)
  - 2 Nonlinear ICS of intense circularly polarized laser (not vortex laser)
- Summary

# Optical vortex

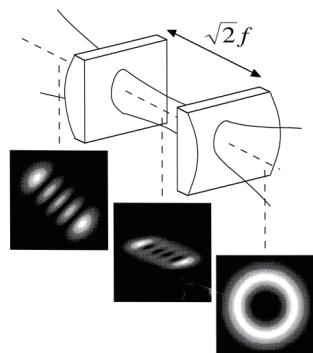


M. Padgett et al., Phys. Today 57 (2004) 35.

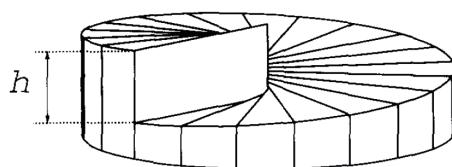
# Generation

## Special filters

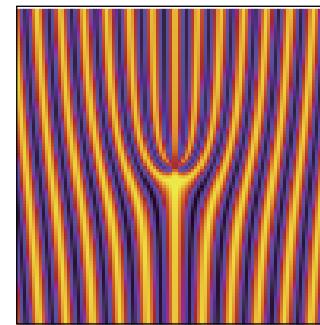
### Cylindrical lens



### Spiral phase plate



### Hologram

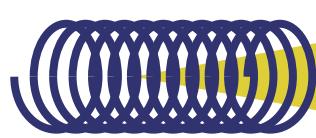


J. Courtial et al., Opt. Comm. 159 (1999) 13.

M. W. Beijersbergen et al., Opt. Comm. 112 (1994) 321.

## Without filters

### Electron



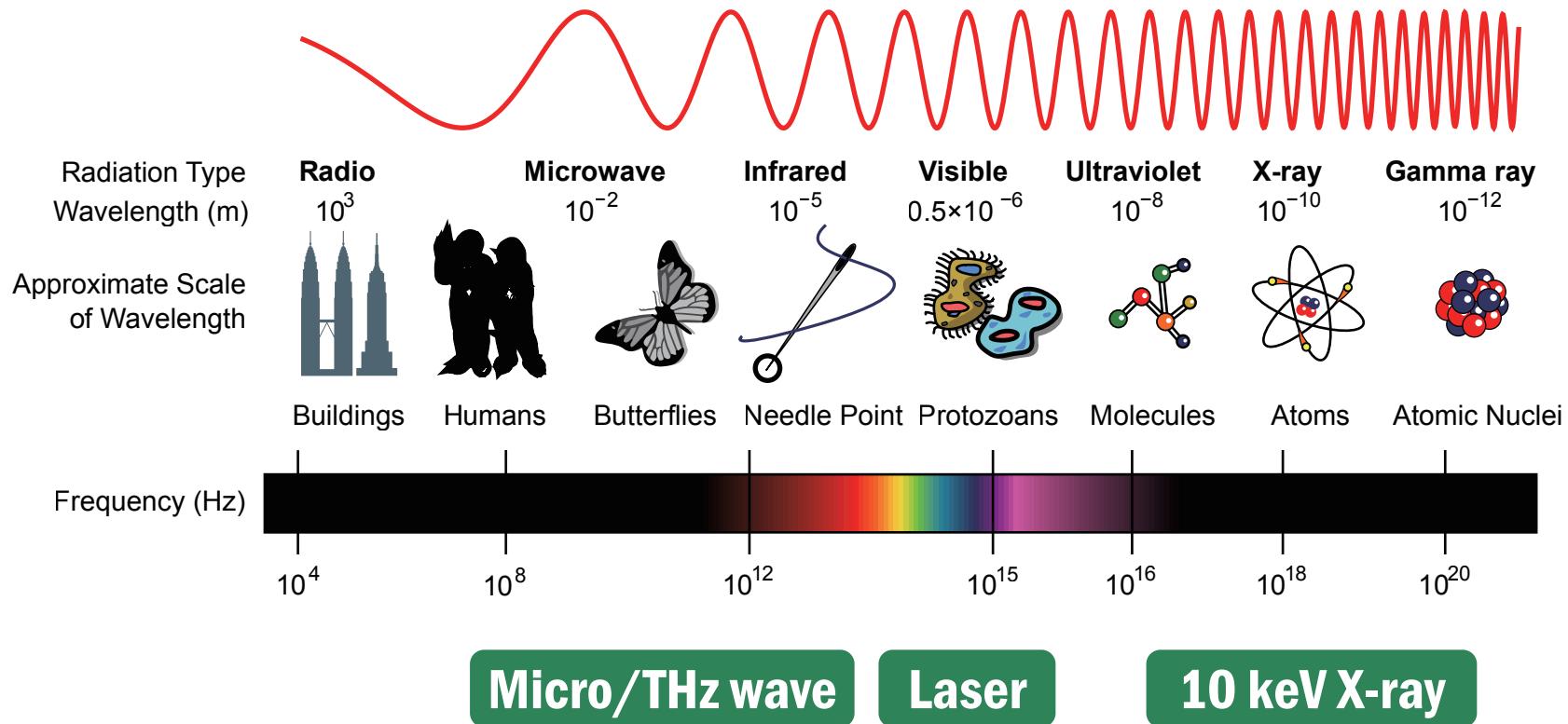
### Vortex beam



**Electromagnetic radiation  
from an electron**

**Main topic of this talk**

# Vortex beams



Except for the electromagnetic wave

300 kV electron

Cold neutron

Wikipedia.

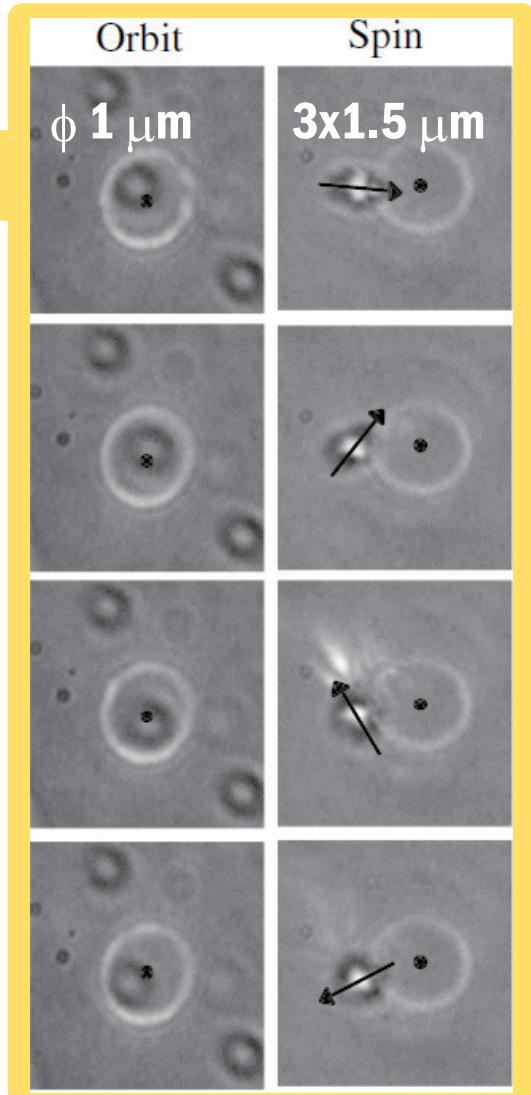
# Application of vortex beams

## Experimental demonstration

- OAM transfer to micro particle
- Quantum entanglement
- Creation of metal nano needle
- Terabit data transmission

## Theoretical proposal

- X-ray dichroism
- Magnetic mapping using electron vortex
- Direct observation of rotating black hole
- Excitation of atom



A. T. O'Neil et al., Phys. Rev. Lett. 88 (2002) 053601.

# **Review articles**

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## **Journal papers**

- M. Padgett, J. Courtial, and L. Allen, Phys. Today 57 (2004) 35.**
- G. M. Terriza, J. P. Torres, and L. Torner, Nat. Phys. 3 (2007) 305.**
- S. F. Arnold, L. Allen, and M. Padgett, Laser & Photon. Rev. 2 (2008) 299.**
- A. M. Yao and M. J. Padgett, Adv. Opt. Phot., 3 (2011) 161.**

## **Books**

- L. Allen et al., “Optical Angular Momentum” IoP publishing, 2003.**
- A. Bekshaev et al., “Paraxial Light Beams with Angular Momentum” Nova Science Publishers, 2008.**
- D.L. Andrews, “Structured Light and its Applications” Academic Press, 2008.**
- J. P. Torres and L. Torner, “Twisted Photons” Wiley-VCH, 2011.**
- D.L. Andrews and M. Babiker, “The Angular Momentum of Light” Cambridge University Press, 2013.**

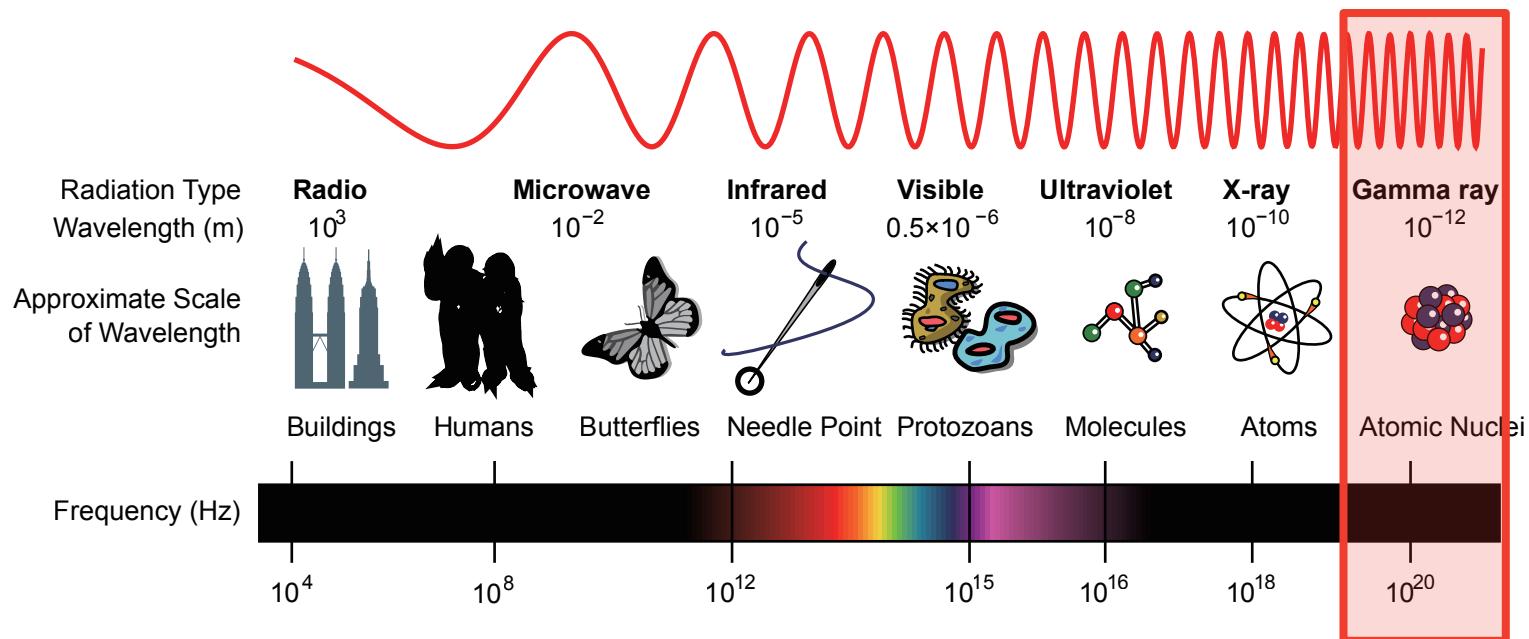
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# Purpose

**Generation of gamma ray vortex (> MeV)  
and development its application.**

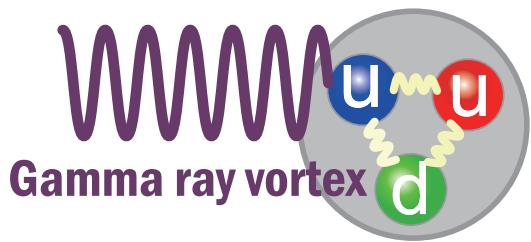


**Gamma-ray**

# Application possibility

Insight into the proton structure

I. P. Ivanov, Phys. Rev. D 83 (2011) 093001.



If the OAM of gamma ray is transferred to the quark/gluon, it becomes novel probe of the proton spin.

Nuclear physics

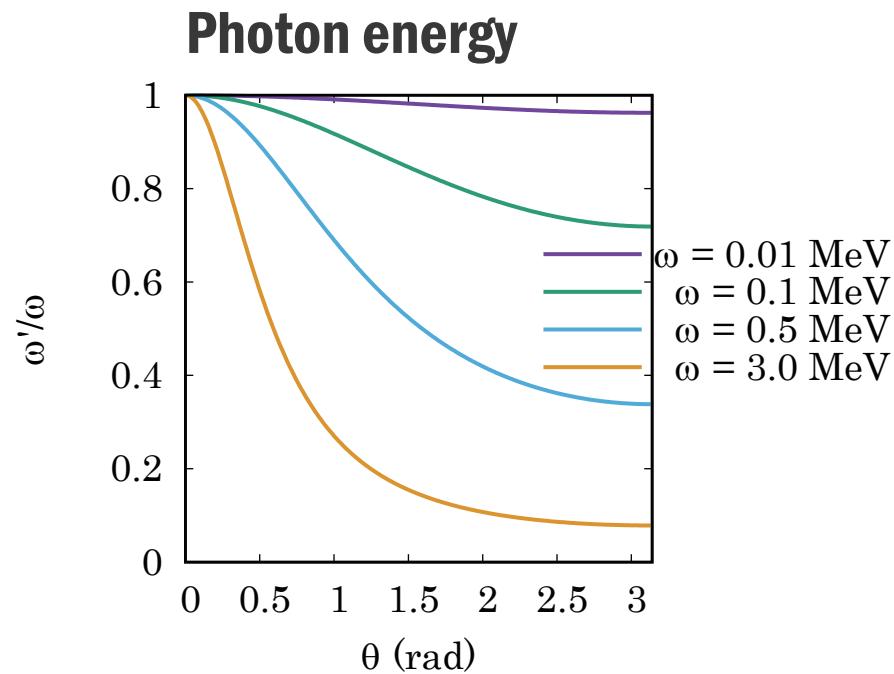
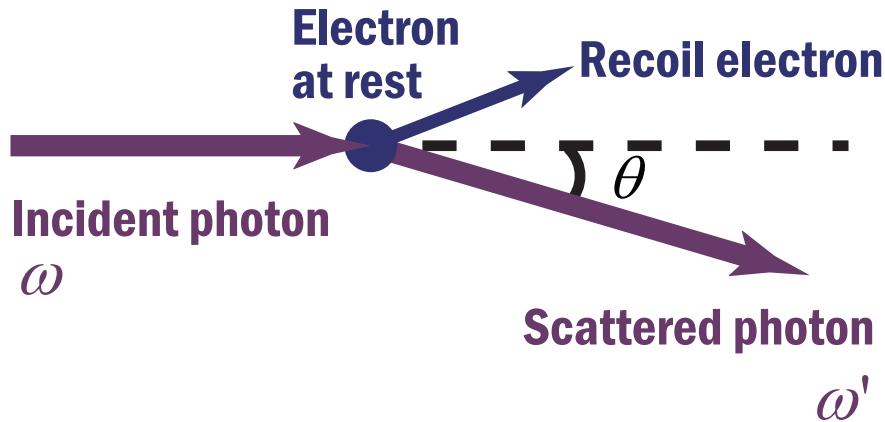
Y. Taira et al., arXiv 1608 (2016) 04894.

Excited states can be populated by high order transition.  
Photon-induced reaction cross section will be changed.

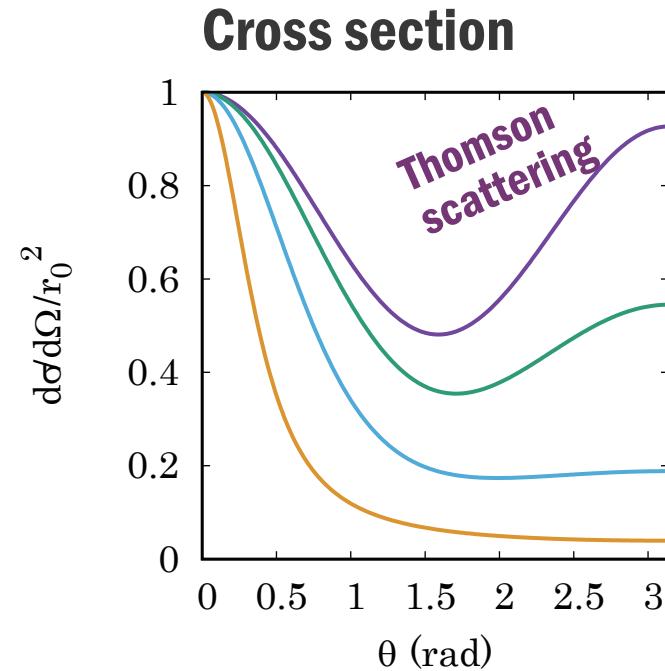
Generation of positron vortex via pair production

As a new particle source for high energy physics.

# Compton scattering

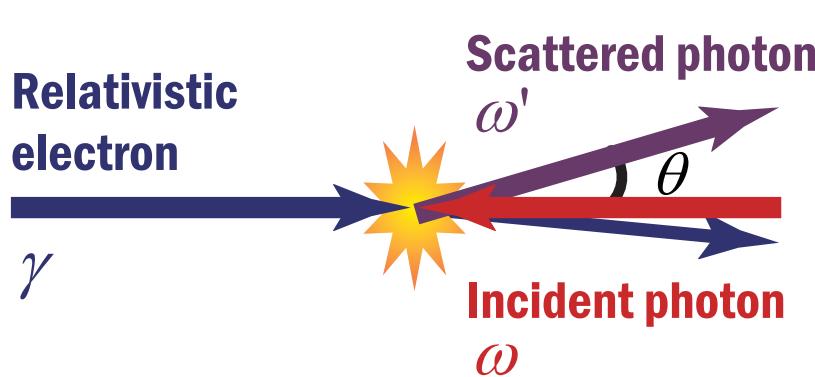


$$\omega' = \frac{\omega}{1 + \frac{\omega}{m_e c^2} (1 - \cos \theta)}$$
$$\frac{d\sigma}{d\Omega} = \frac{r_0^2}{2} \left( \frac{\omega'}{\omega} \right)^2 \left( \frac{\omega'}{\omega} + \frac{\omega}{\omega'} - \sin^2 \theta \right)$$

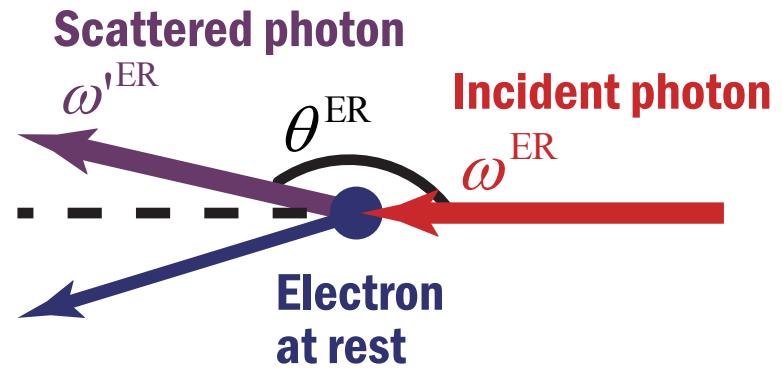


# Inverse Compton scattering (ICS)

## Laboratory frame



## Electron rest frame

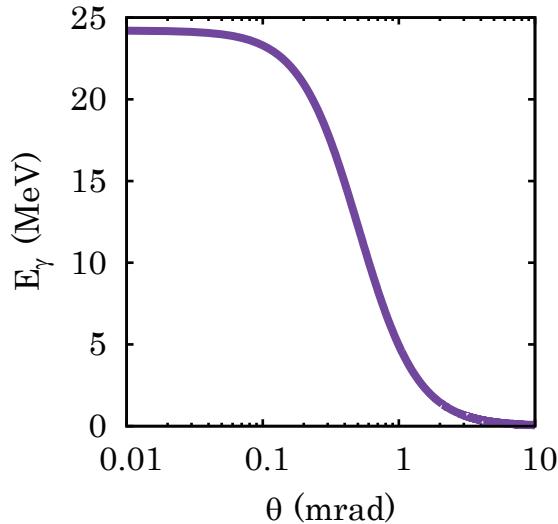


ICS can be derived by the Lorentz transformation  
of the Compton scattering.

$$\omega^{\text{ER}} = \gamma(1 + \beta)\omega = 6.2 \text{ keV} < m_e c^2 = 511 \text{ keV} \quad \text{Thomson scattering}$$

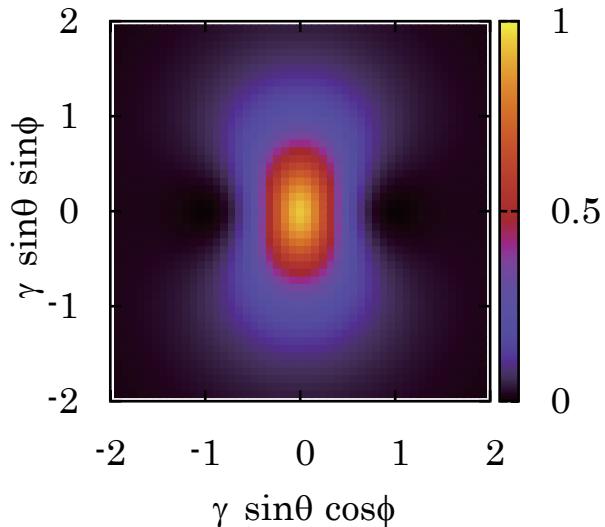
when  $\gamma = 2000$  and  $\omega = 1.5 \text{ eV}$

# Energy and Spatial distribution

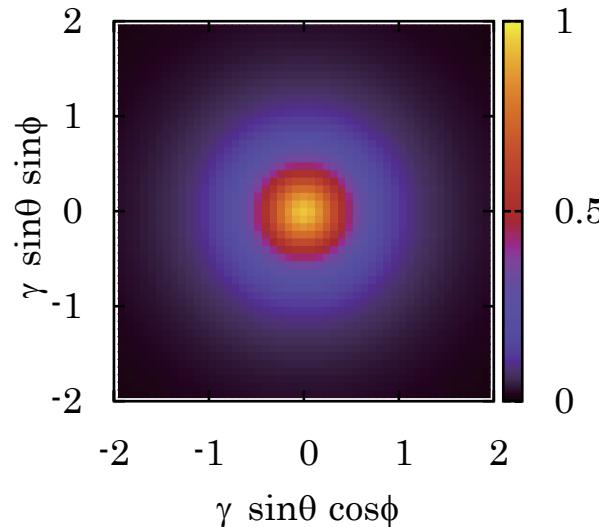


$\gamma = 2000$   
 $\omega = 1.55 \text{ eV} (\lambda = 800 \text{ nm})$

Linear polarization



Circular polarization



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- Vortex beams carrying orbital angular momentum
- Gamma-ray vortex generation

1

- Frequency upconversion of an optical vortex laser by inverse Compton scattering (ICS)**

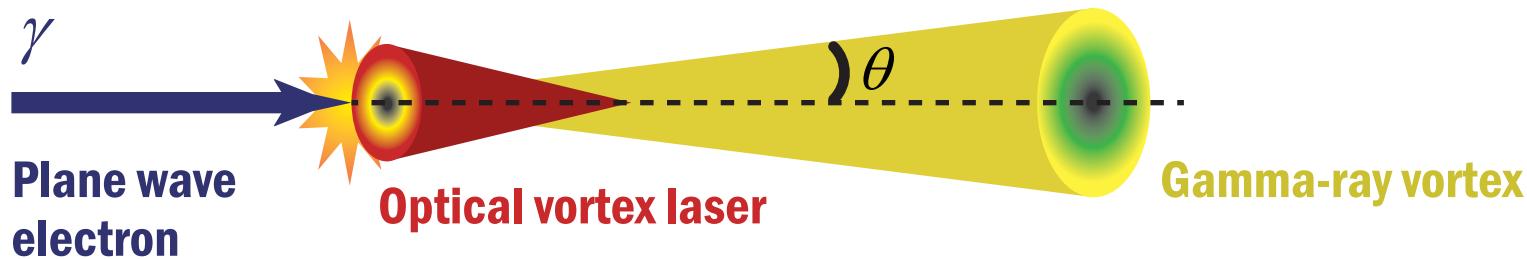
U. D. Jentchura et al., PRL 106 (2011) 013001.  
V. Petrillo et al., PRL 117 (2016) 123903.

2

- Nonlinear ICS of intense circularly polarized laser (not vortex laser)**

- Summary

# ICS of optical vortex laser



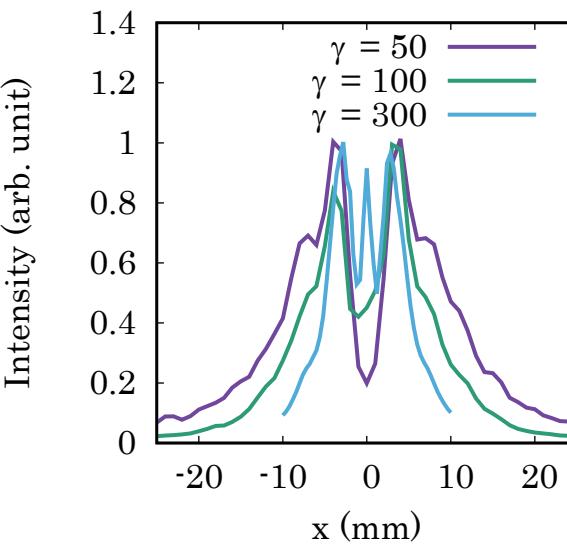
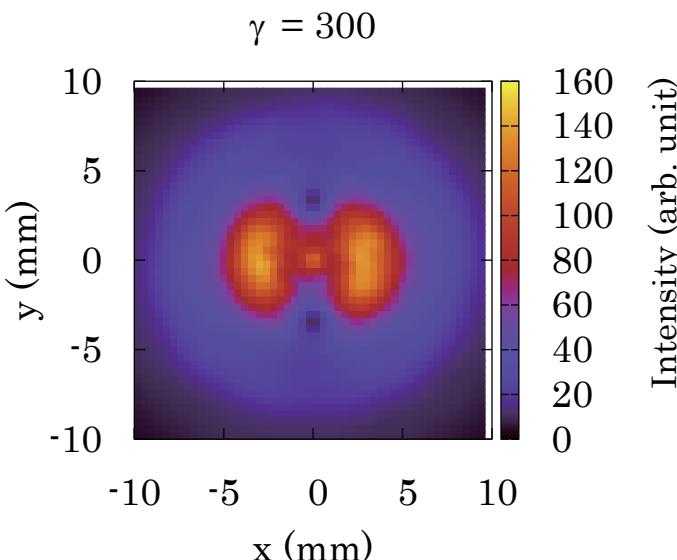
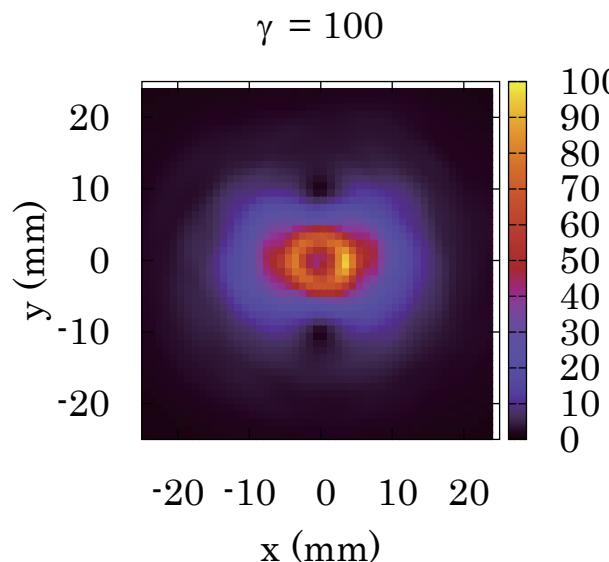
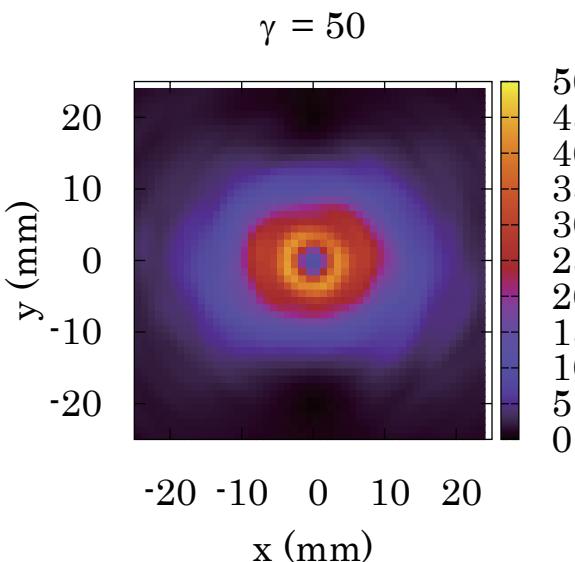
It was predicted that OAM of the gamma-ray preserved the OAM of the laser at the very small angle  $\theta < 1/\gamma^2$ .

U. D. Jentchura et al., PRL 106 (2011) 013001.

It was indicated that the spatial distribution of the X-ray vortex become annular profile in the case of  $\gamma = 50$ .

V. Petrillo et al., PRL 117 (2016) 123903.

# Spatial distribution of $|E|^2$ of X-ray vortex



Laser

Linearly polarized  
(y direction).  
 $OAM = 1\hbar$

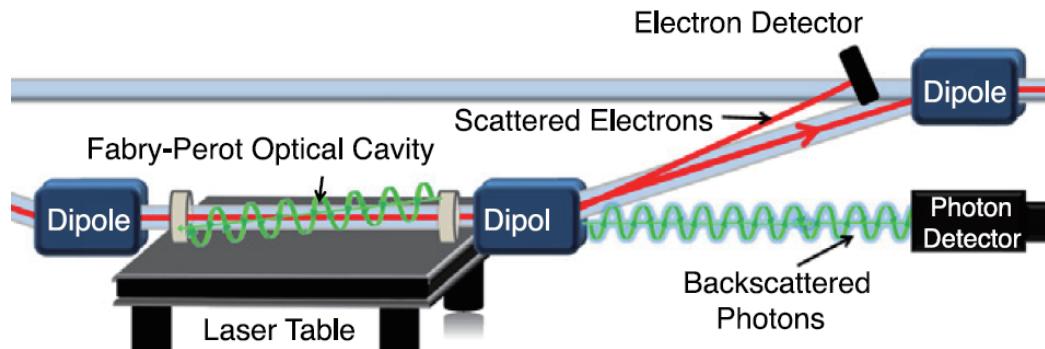
The diameter of  
the ring does not  
depend on the  
electron energy?

Further  
calculation is  
needed.

V. Petrillo' s calculation code was used.

# Experimantal demonstration

## JLab Compton polarimeter at Hall A and C



**Fabry-Perot cavity**

**Wavelength: 532 nm**

**Stored power: 1000 W**

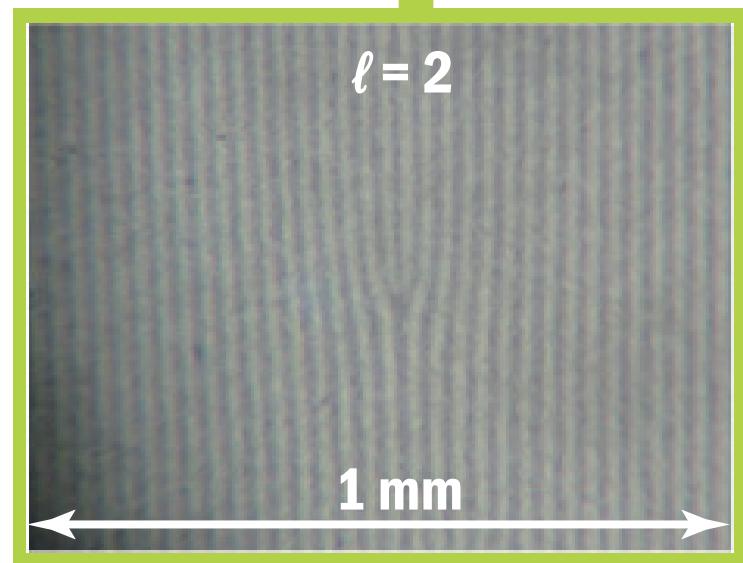
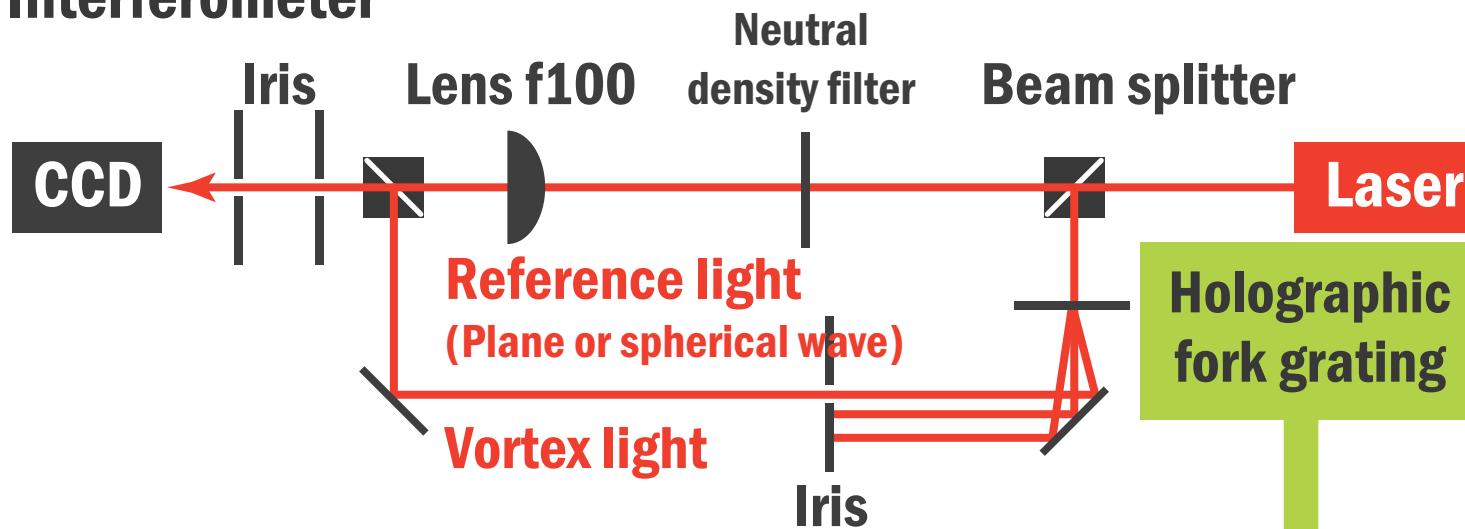
**To exceed background, more than 100 W vortex laser is required.**

**We can do the experiment by replacing the normal laser with vortex laser.**

T. Allison et al., NIMA 781 (2015) 105.

# Measurement technique of vortex laser

## Interferometer

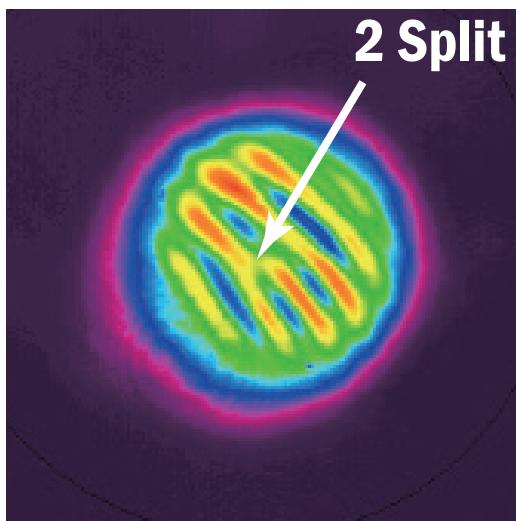


# Interference pattern

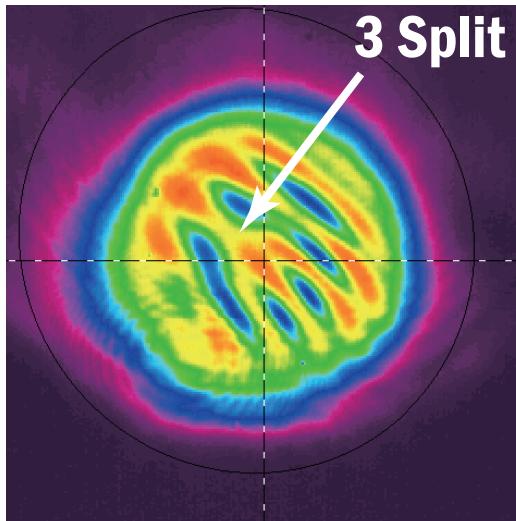
OAM value

Plane wave + vortex

1

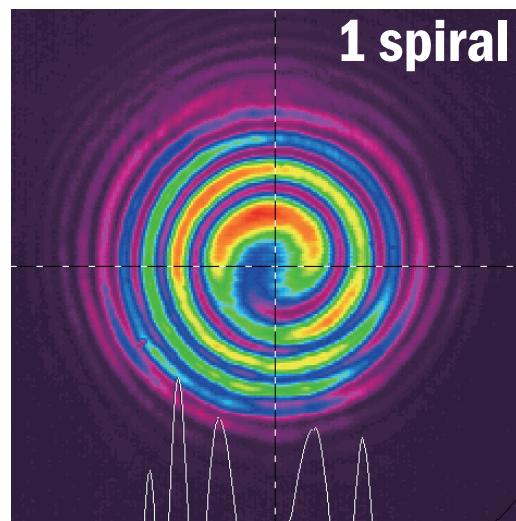


2

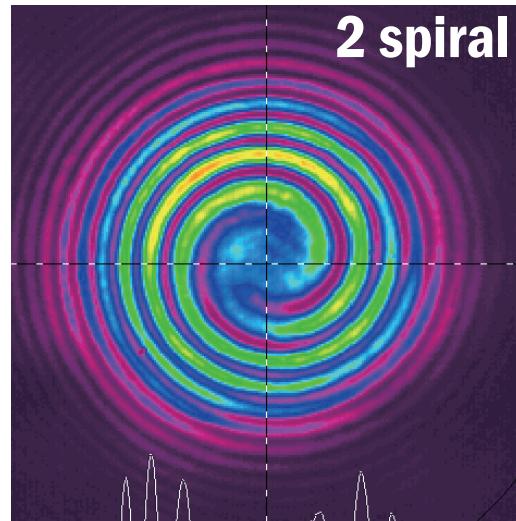


Spherical wave + vortex

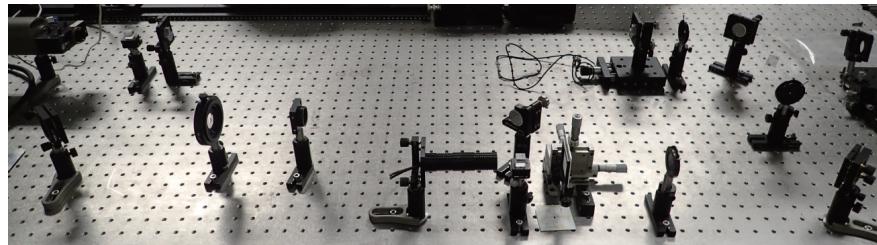
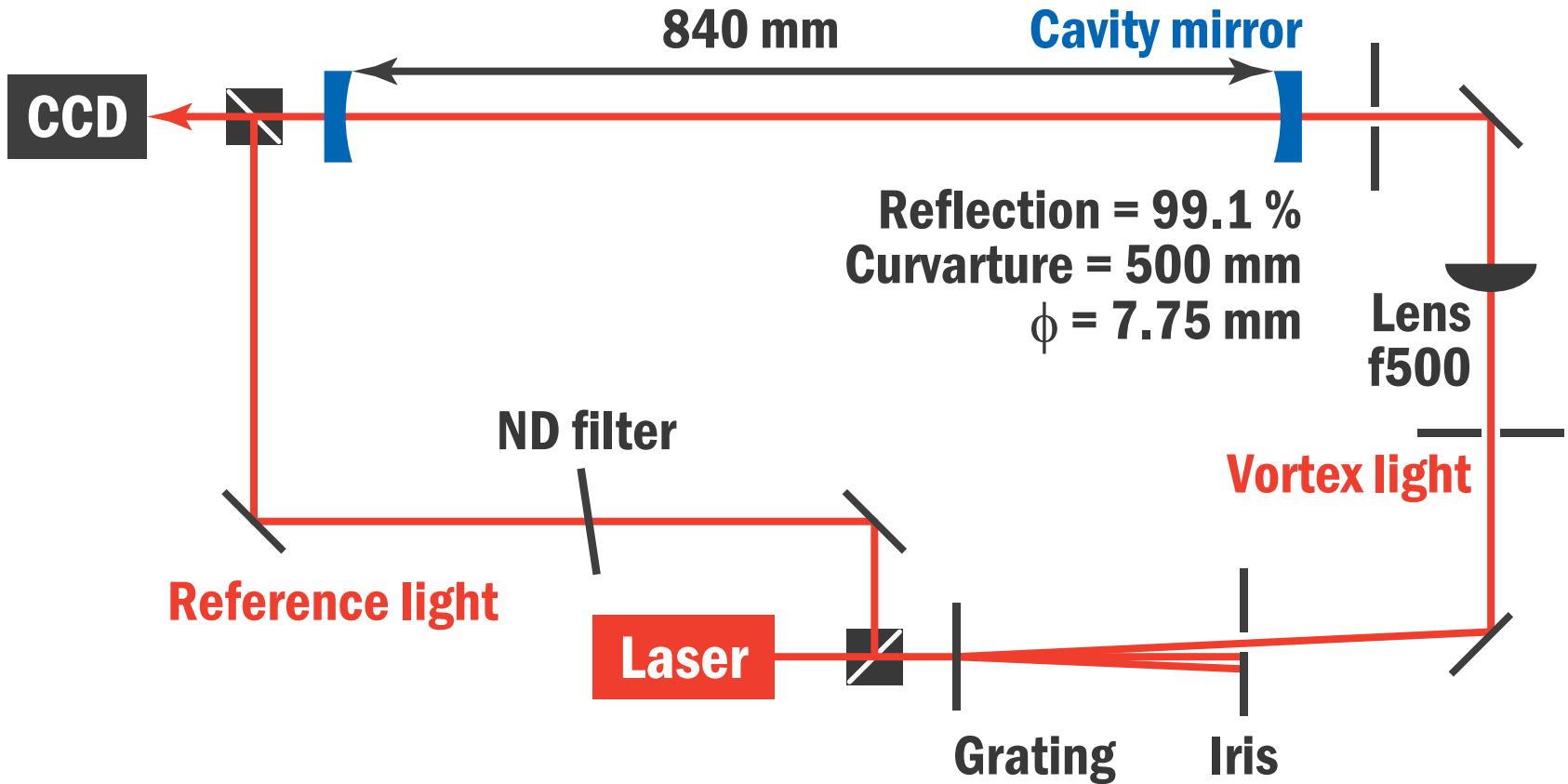
1 spiral



2 spiral



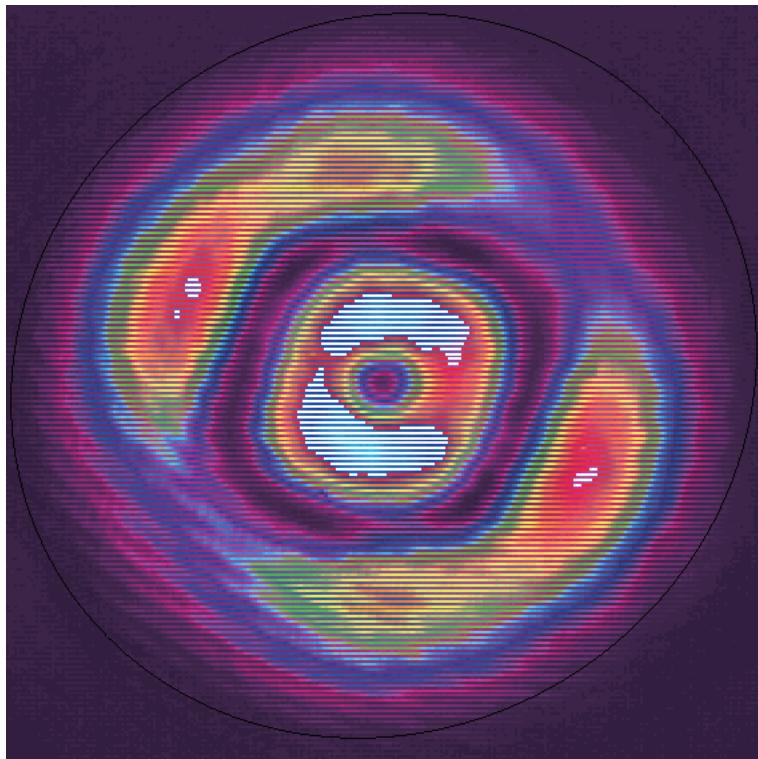
# Optical cavity test of vortex laser



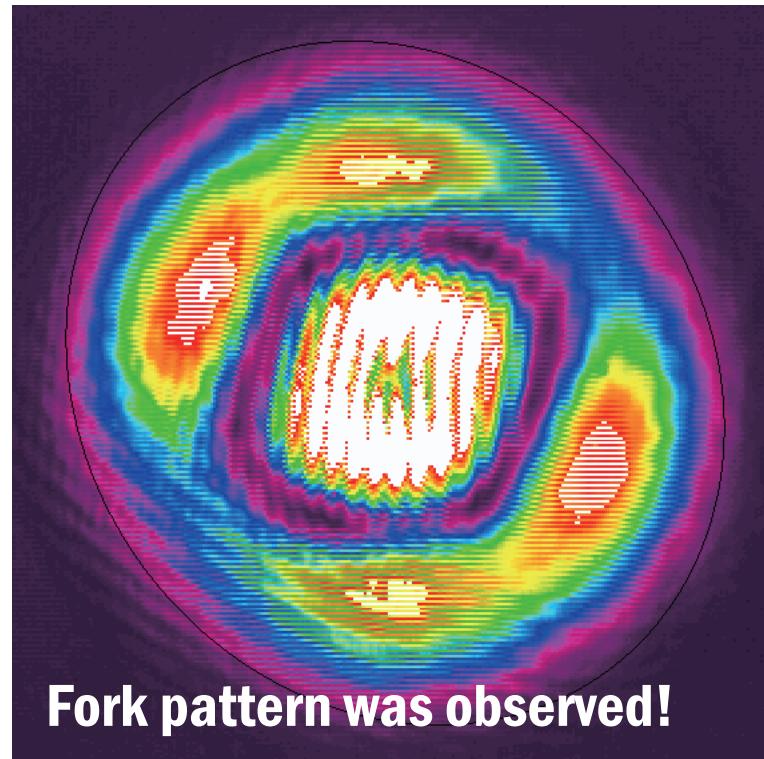
Note: two cavity mirrors are not controlled by any feedback system.

# Observation of good results

Spatial distribution after cavity



Interference pattern ( $\ell=1$ )



Fork pattern was observed!

Not the whole time, sometime  
no fork pattern.

Next step:  
Mode locking, estimation of storing power, etc..

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by inverse Compton scattering (ICS)**

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**Nonlinear ICS of intense circularly polarized laser  
(not vortex laser)**

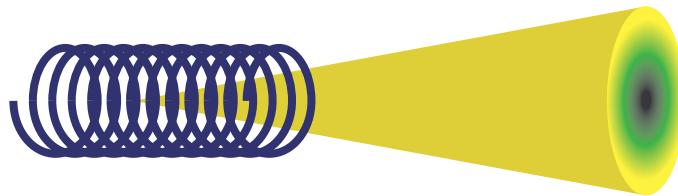
Y. Taira et al., arXiv 1608 (2016) 04894.

- Summary

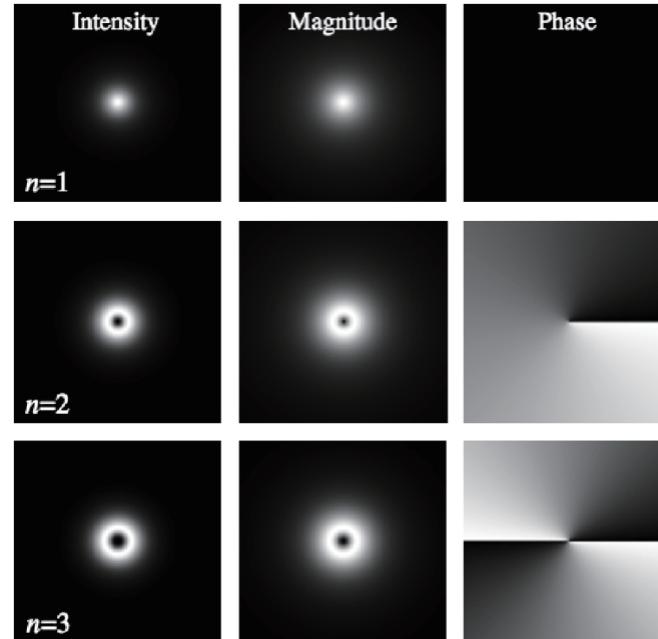
# Helical motioned electron emits vortex beam

X-ray vortex generation using helical undulator was proposed by S. Sasaki in 2008.

Electron in  
helical motion



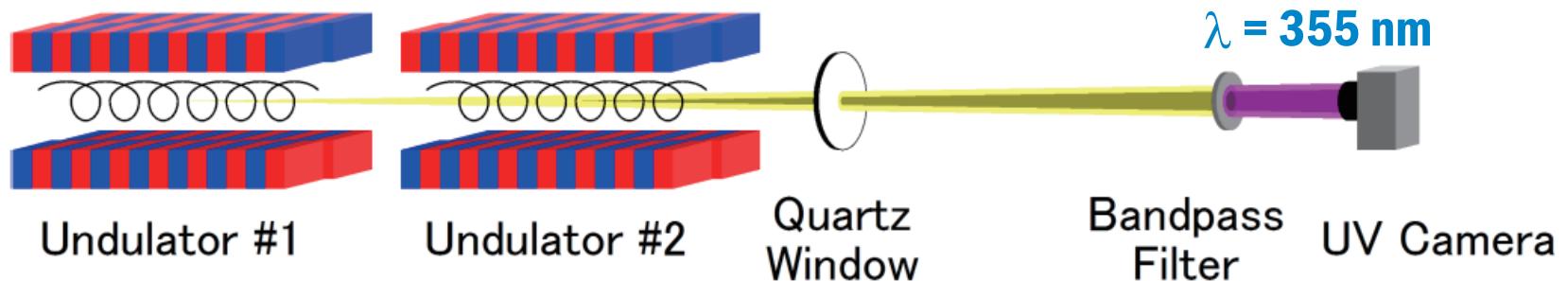
Transverse motion produces  
higher harmonics.



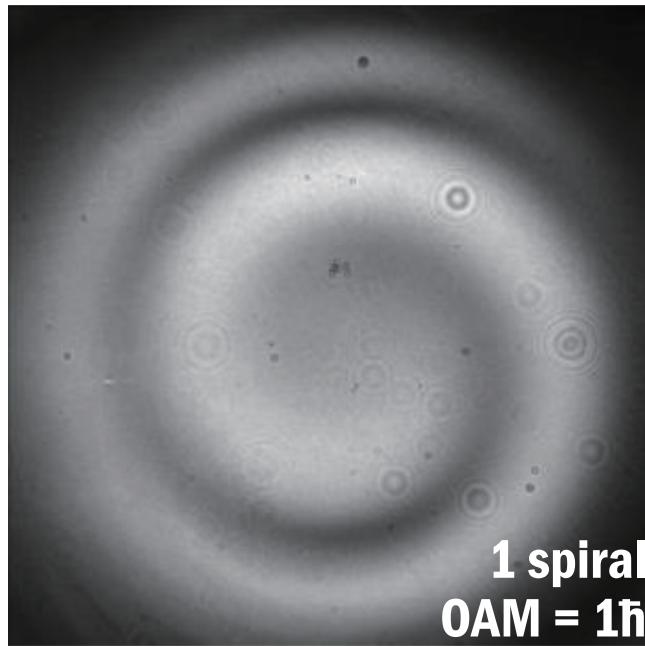
Higher harmonics  
carry OAM of  $(n-1)\hbar$ .

S. Sasaki et al., PRL. 100 124801 (2008).

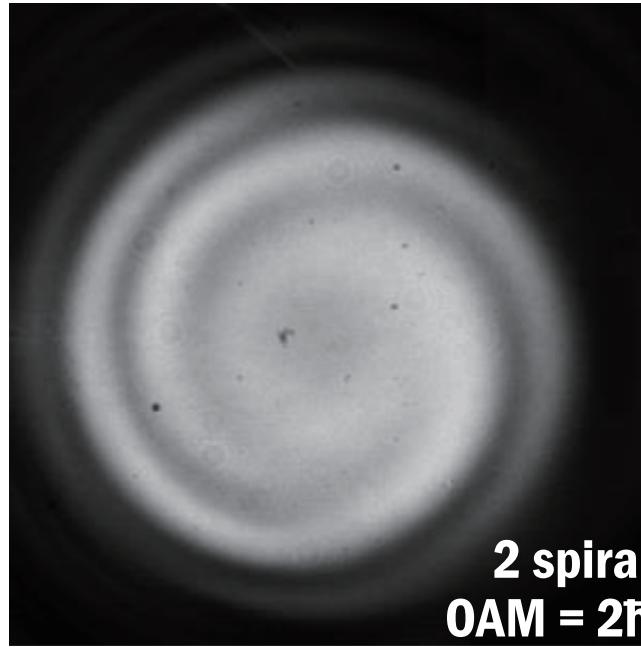
# UV measurement at UVSOR-III, Japan



2nd harmonics



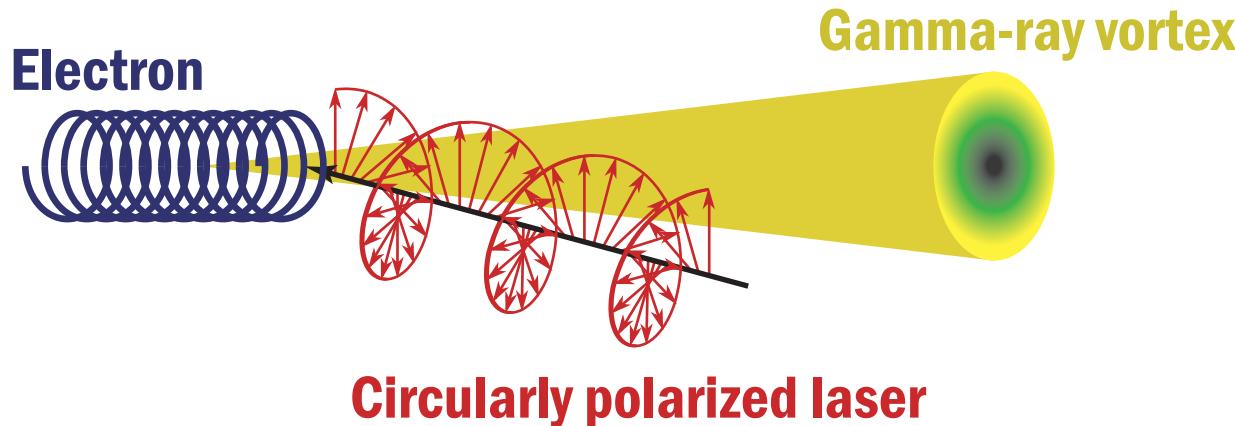
3rd harmonics



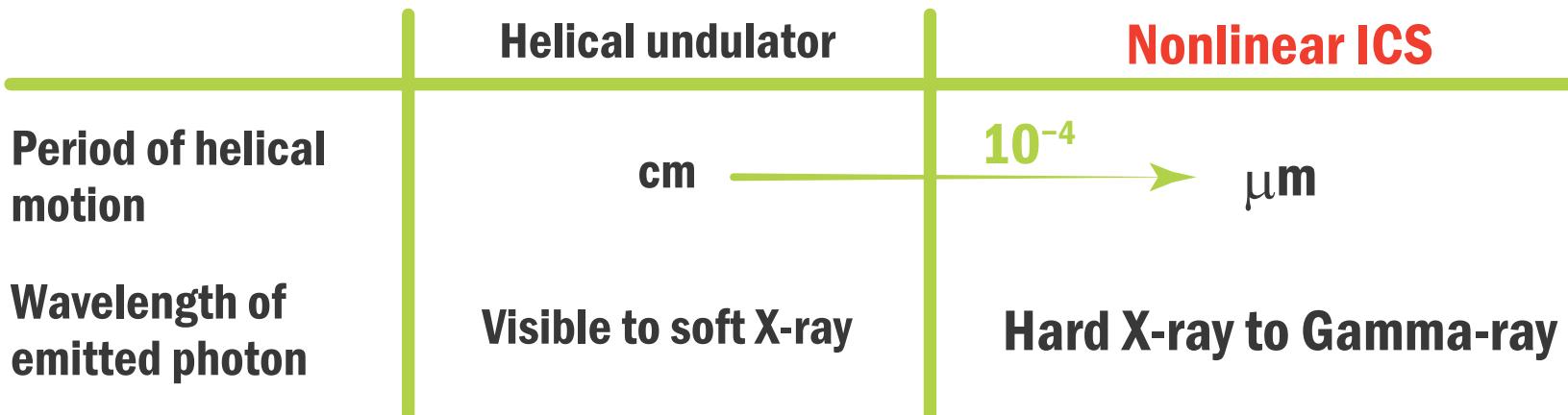
M. Katoh et al., arXiv 1609 03869 (2016).

## 2 Nonlinear ICS induces helical motion

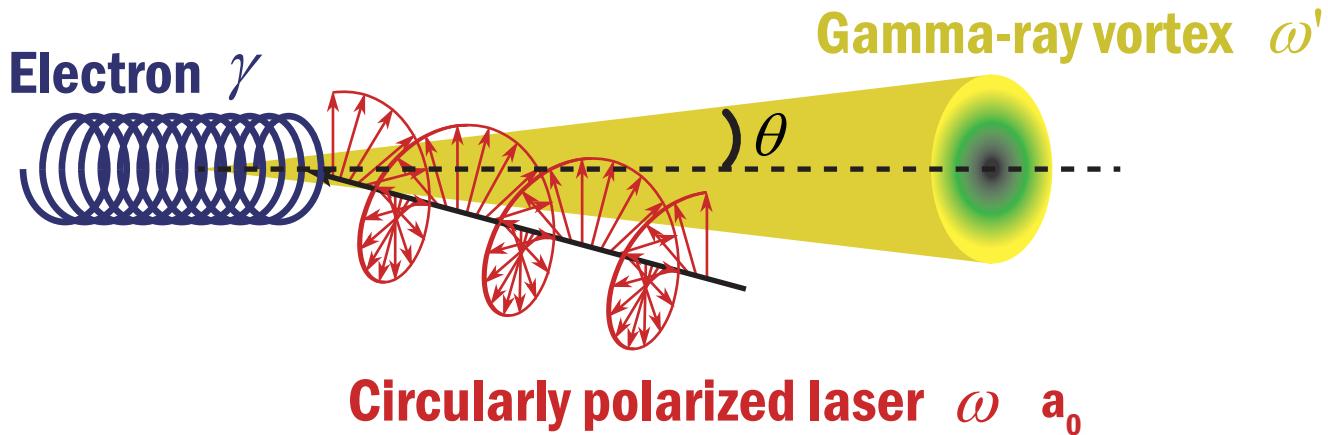
Nonlinear effect of the laser (a laser strength parameter,  $a_0 \approx 1$ ) induces helical motion of the electron.



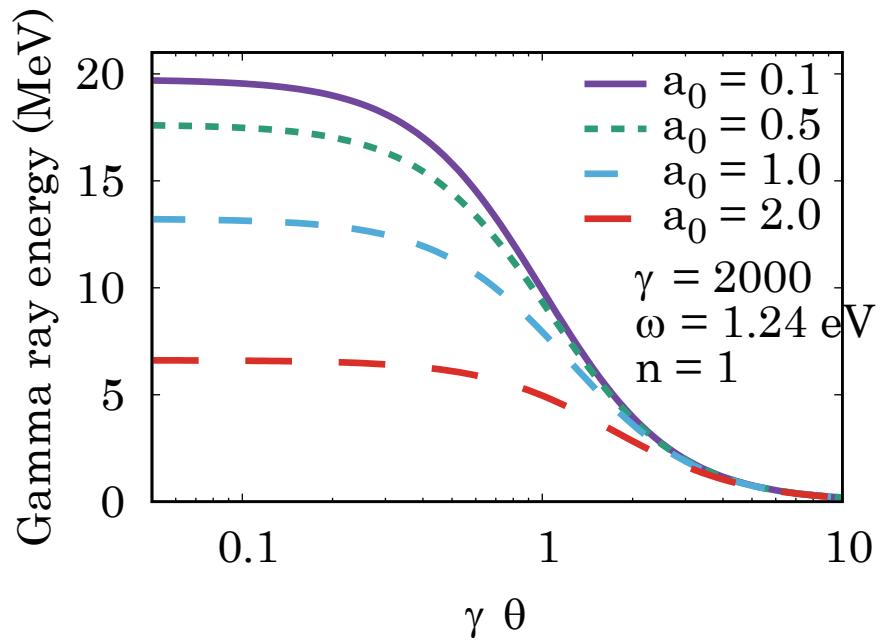
### Scaling of the emitted wavelength



# Gamma-ray energy



$$\omega' = \frac{8n\gamma^2\omega}{2\gamma^2\theta^2 + 2 + a_0^2}$$



# Electric field and Stokes parameter

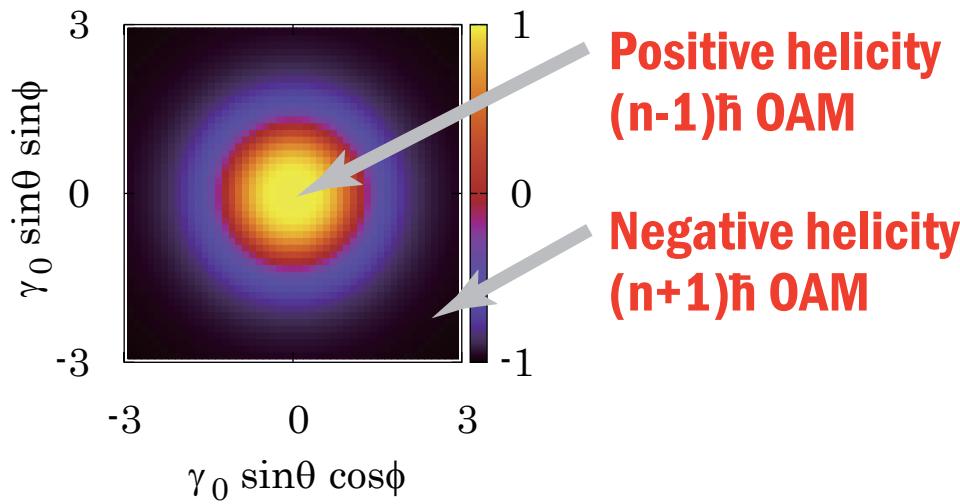
## Electric field in the x-y plane

$$E = \frac{i}{\sqrt{2}} (C_\theta \cos \theta + C_\phi) \exp \{i\psi_0 + ikR + i(n-1)\phi\} e_+$$
$$+ \frac{i}{\sqrt{2}} (C_\theta \cos \theta - C_\phi) \exp \{i\psi_0 + ikR + i(n+1)\phi\} e_-$$

$$e_\pm = \frac{e_x \pm ie_y}{\sqrt{2}}$$

Positive helicity carry  $(n-1)\hbar$  OAM  
Negative helicity carry  $(n+1)\hbar$  OAM.

## Degree of circular polarization



Y. Taira et al., arXiv 1608 04894 (2016).

# Why does gamma-ray carry $(n \pm 1)\hbar$ OAM?

## Quantum theory of nonlinear ICS



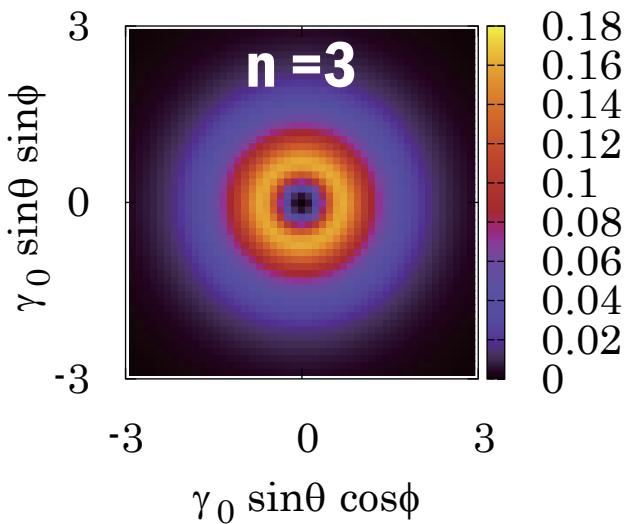
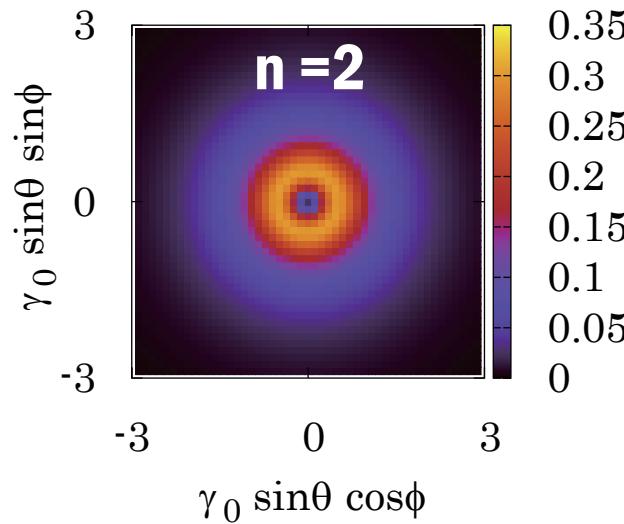
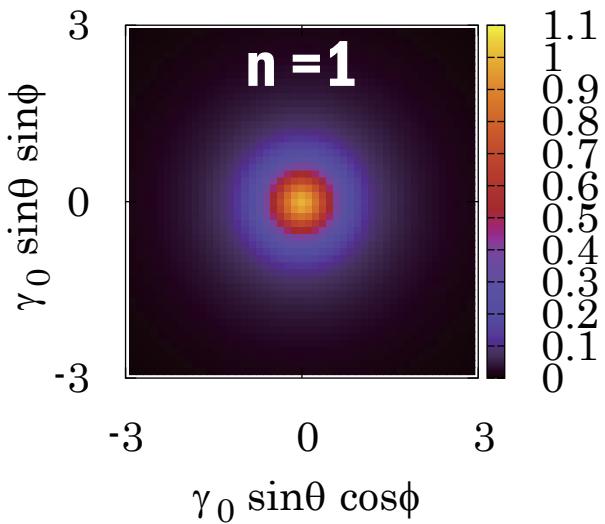
Electron absorbs circularly polarized “n” photons and emits circularly polarized one photons.  
n is the harmonic number.

## Conservation of total angular momentum of the photon

Helicity of emitted photon	Before interaction			After interaction		
	SAM	OAM	Total	SAM	OAM	Total
Positive	+n	0	+n	+1	n-1	+n
Negative	+n	0	+n	-1	n+1	+n

Under the assumption SAM and OAM can be separated each other.

# Spatial distribution



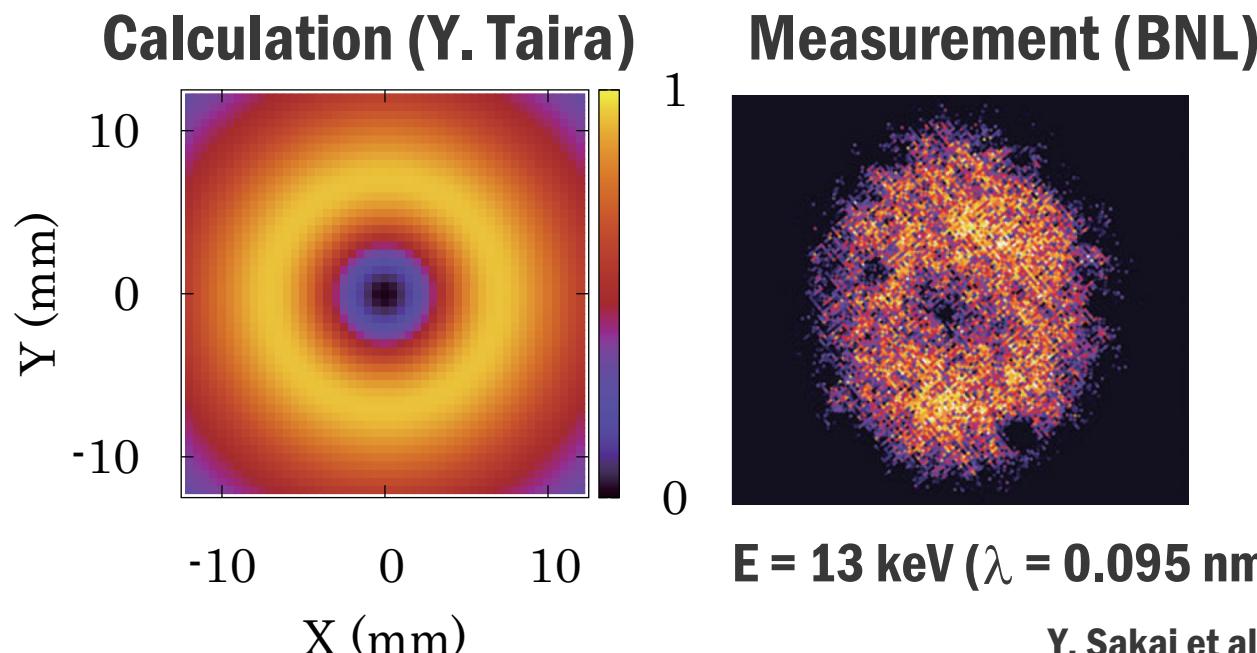
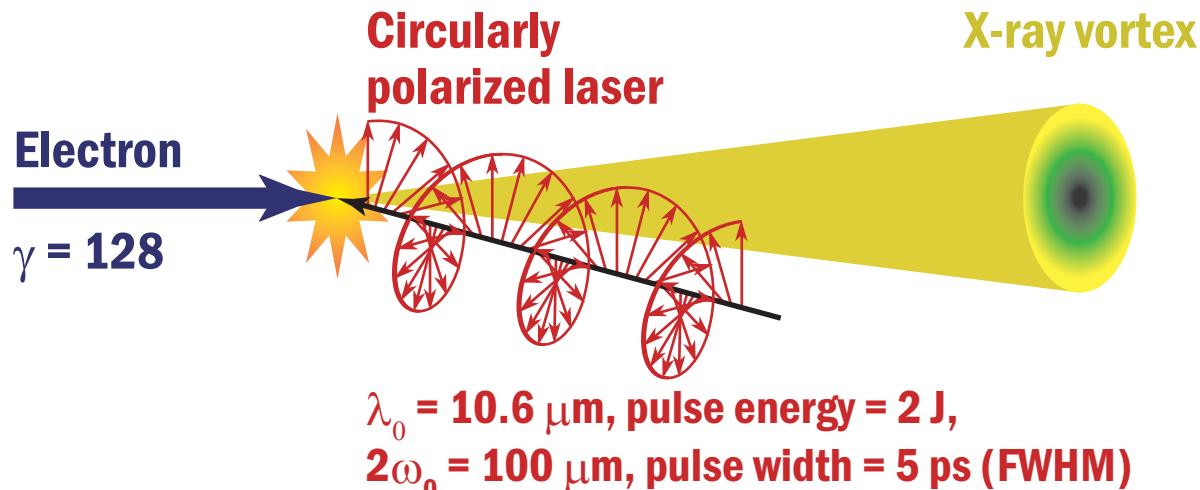
**Annular shape of higher harmonic  
is due to the helical wavefront.**

# Characteristics of nonlinear ICS gamma-ray

Helicity	Positive	Negative
Fundamental ( $n = 1$ )		
N	$60 \times 10^{10}$ photons/sec	$2 \times 10^{10}$ photons/sec
E	11-13 MeV	2.6-2.7 MeV
OAM	0	$2\hbar$
2nd harmonics		
N	$20 \times 10^{10}$ photons/sec	$2 \times 10^{10}$ photons/sec
E	21-26 MeV	5.2-5.5 MeV
OAM	$\hbar$	$3\hbar$

$$a_0 = 1.0, \lambda_0 = 1.0 \mu m, \gamma_0 = 2000, N_e = 10^9 \text{ electrons/sec}$$

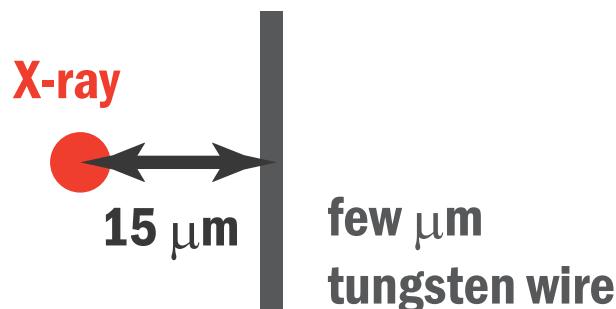
# Second harmonic X-rays at BNL ( $a_0=0.6$ )



This will be the  
X-ray vortex.

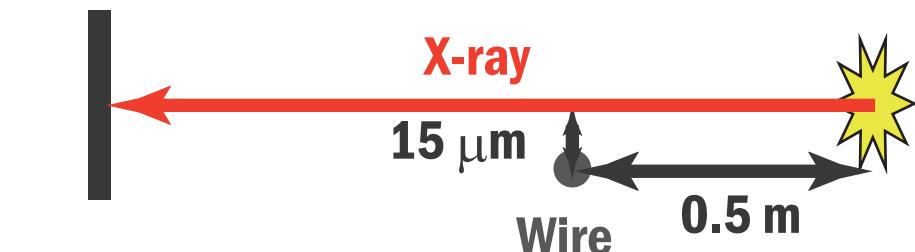
# Helical wavefront measurement

Oncoming X-ray

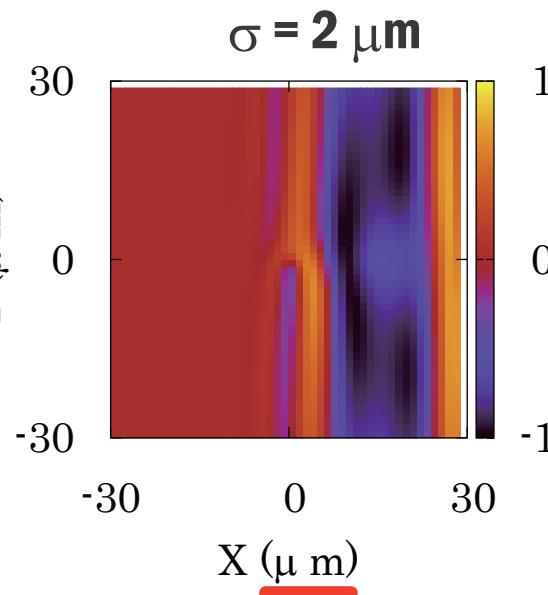
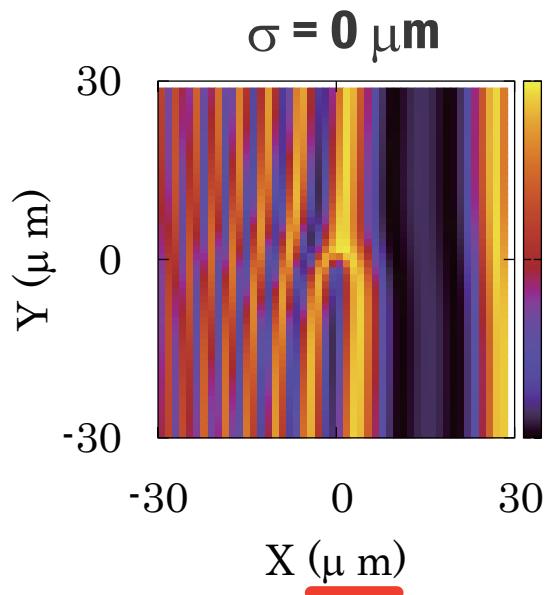


Top view

Detector (1.85 m from source)



Interference pattern between X-ray vortex and diffracted X-ray from the wire.



$\sigma$ : rms beam size  
of the electrons

# Conclusion

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- **Gamma ray vortex providing an additional degree of freedom will open new research opportunities!**
- **Gamma-ray vortex can be generated by the inverse Compton scattering.**
- **Measurement of gamma ray vortex is a big issue.**  
**Interferometry, Dichroism, and Pair production are candidates.**

# Acknowledgement

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**Thank you for your attention!**