National Institute of
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High energy X-ray vortex generation using inverse Compton scattering

Yoshitaka Taira

National Institute of Advanced Industrial Science and Technology (AIST), Japan

Visiting scientist: Mississippi State University and Jefferson Lab.

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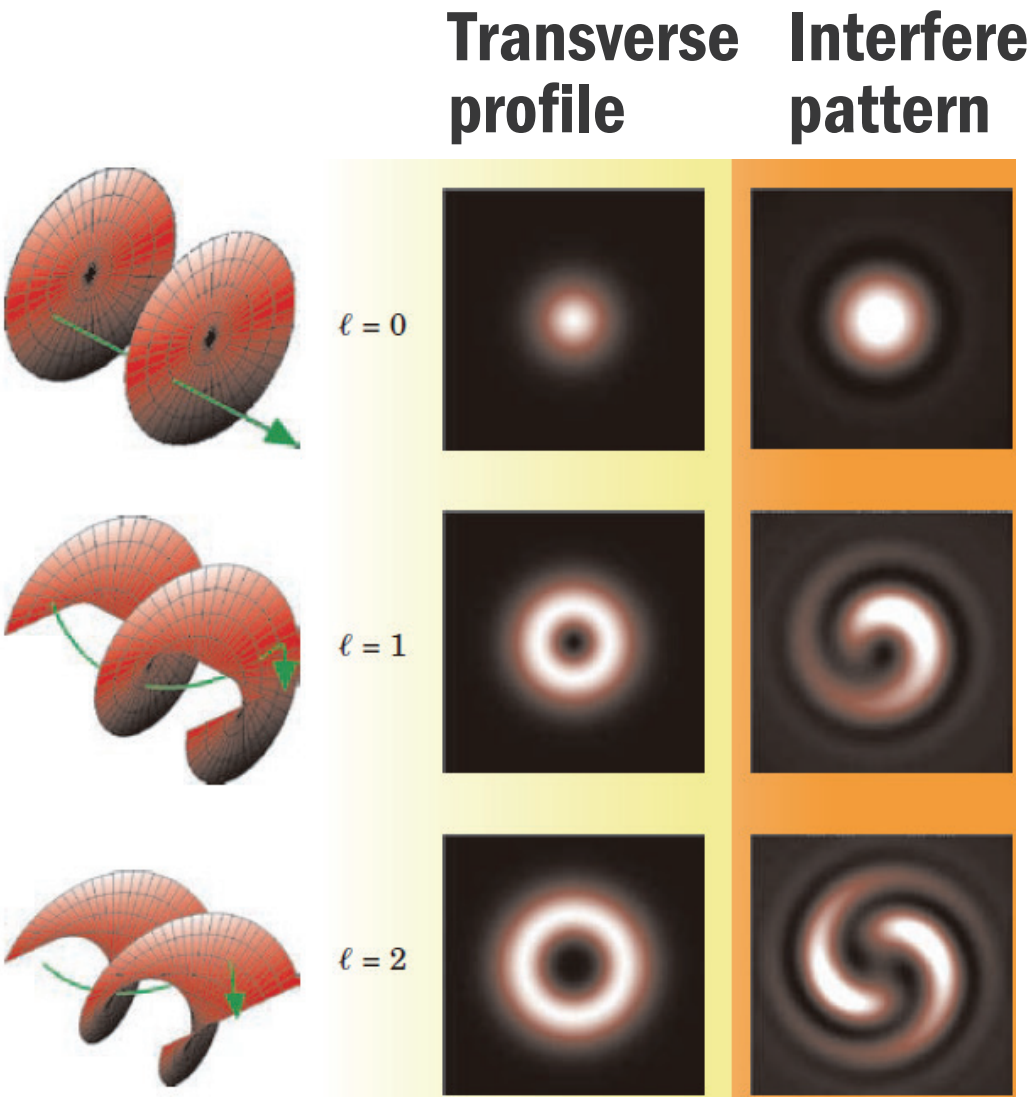
Outline

- Vortex beams carrying orbital angular momentum
- High energy X-ray (gamma-ray) vortex generation
- Summary

Optical vortex



- Forming a helical wave front.

$$E \propto \exp(i\ell\phi)$$

- Carrying orbital angular momentum (OAM)

$$\ell\hbar$$

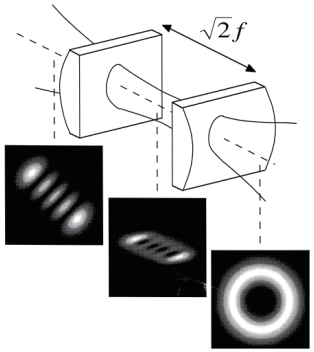
- Total AM
  = OAM + spin AM
  = $\ell\hbar + \hbar$

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

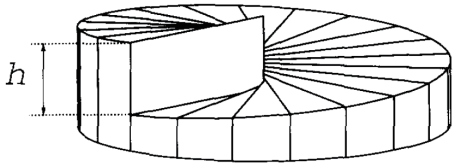
Generation

Special filters

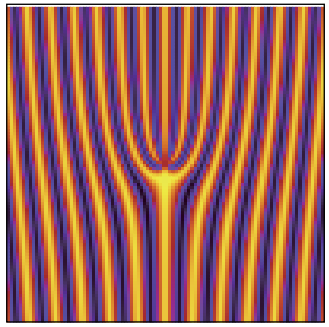
Cylindrical lens



Spiral phase plate

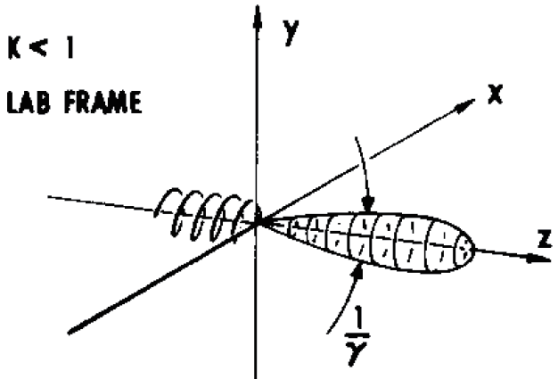


Hologram



J. Courtial et al., Opt. Comm. 159 (1999) 13.
M. W. Beijersbergen et al., Opt. Comm. 112 (1994) 321.

Without filters

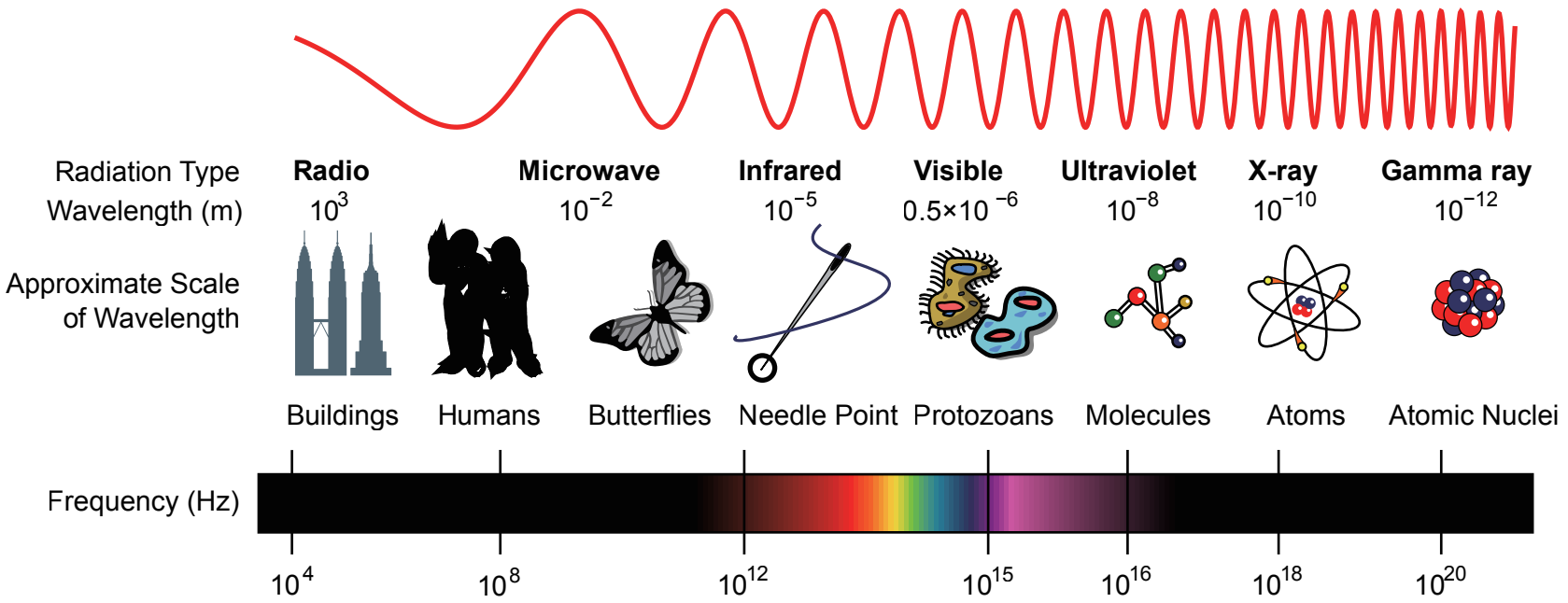


Electromagnetic radiation from an electron

Main topic of this talk

B. M. Kincaid et al., J Appl Phys 48 (1977) 2684.

Vortex beams



Micro/THz wave **Laser** **10 keV X-ray**

300 kV electron **Cold neutron**

Wikipedia.

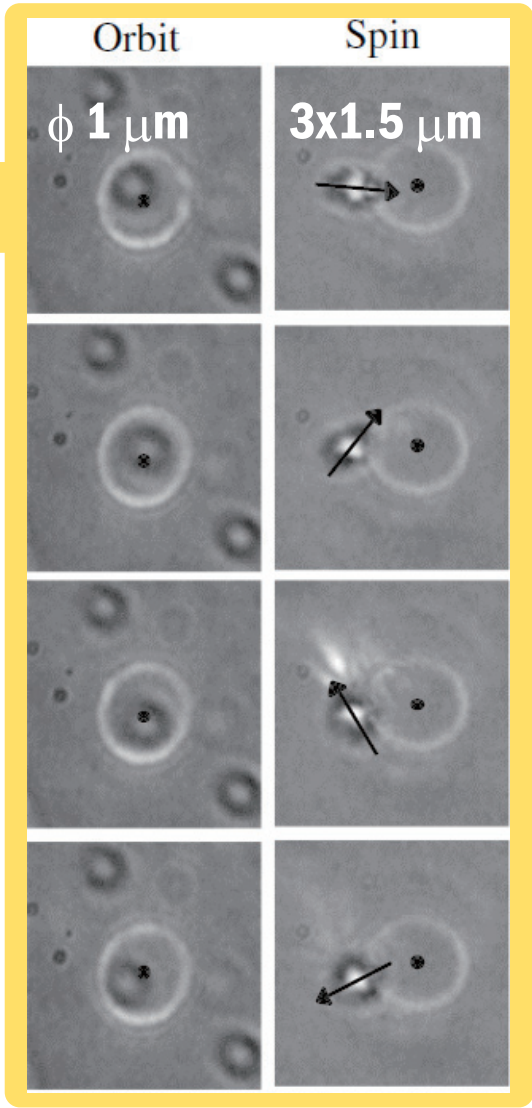
Application of vortex beams

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



A. T. ONeil et al., Phys. Rev. Lett. 88 (2002) 053601.

Outline

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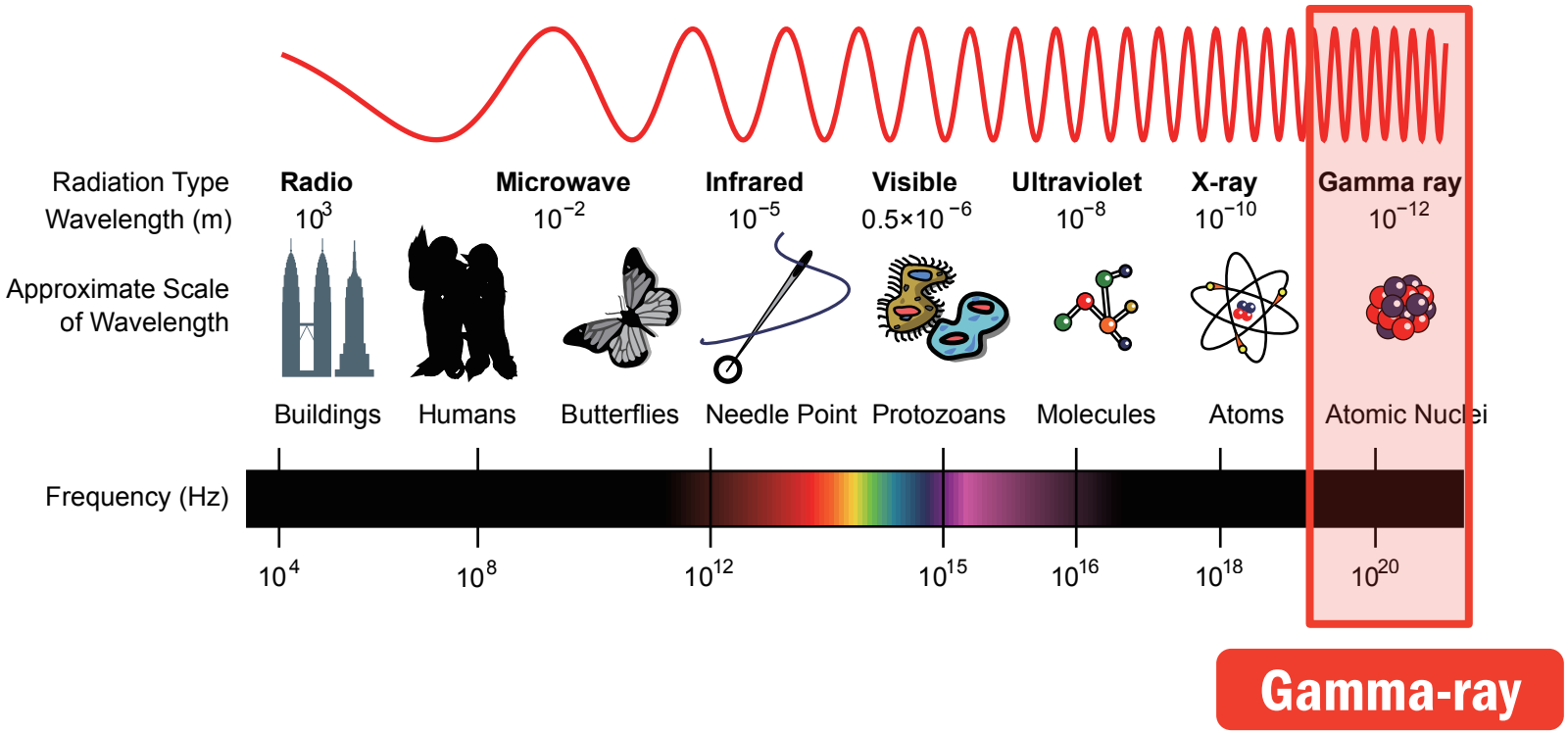
Purpose

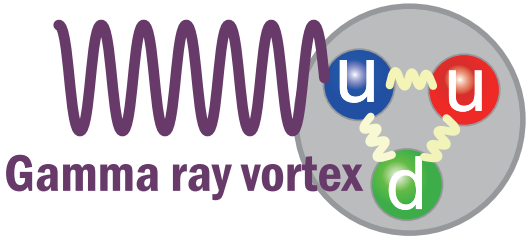
Generation of gamma ray vortex (> MeV) and development its application.



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.

How to generate gamma ray vortex ?

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

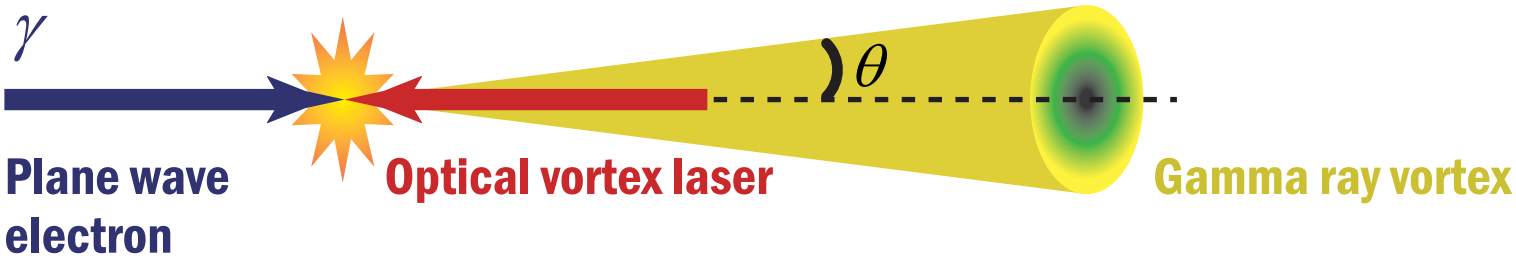
   U. D. Jentchura et al., PRL 106 (2011) 013001.

2. **Nonlinear inverse Compton scattering of intense circularly polarized laser (not vortex laser)**

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

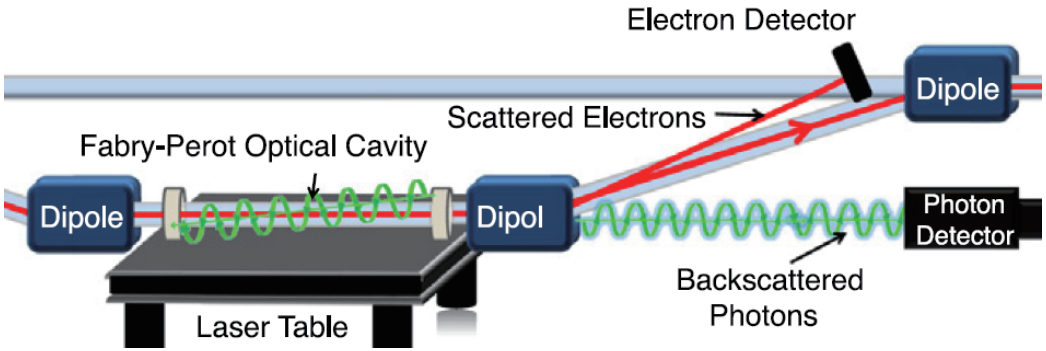
Compton backward scattering of circularly polarized gamma ray

1 ICS of optical vortex laser



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

JLab Compton polarimeter

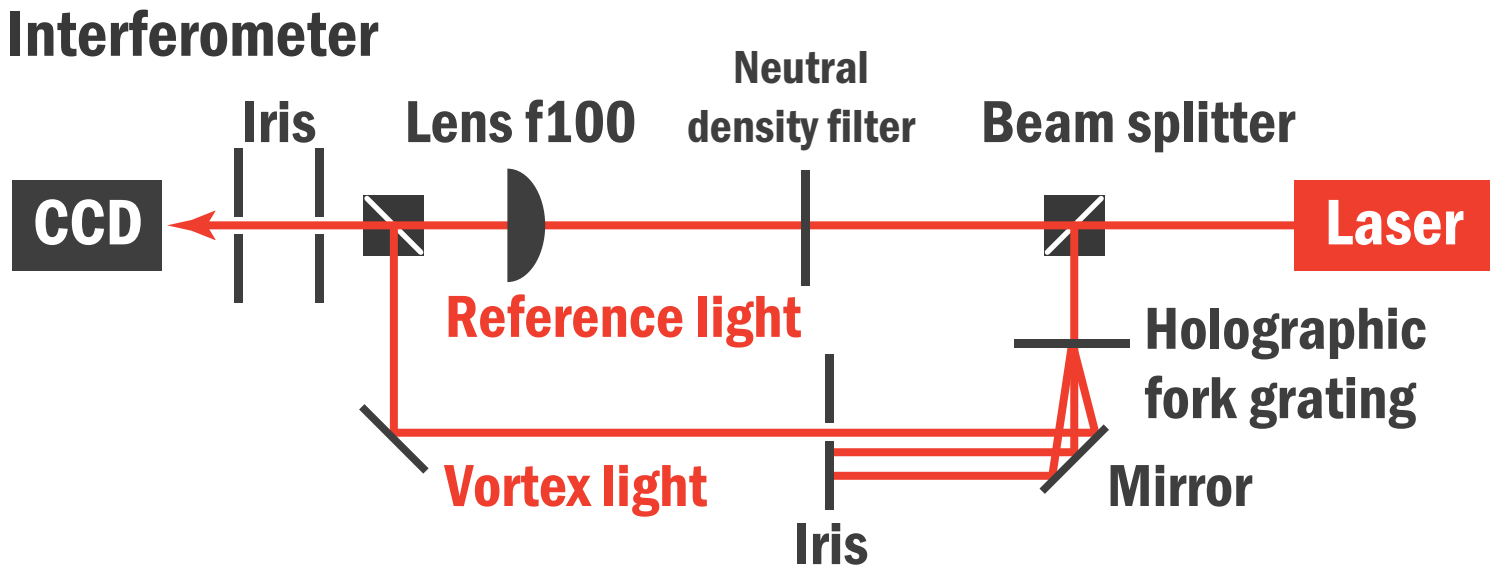


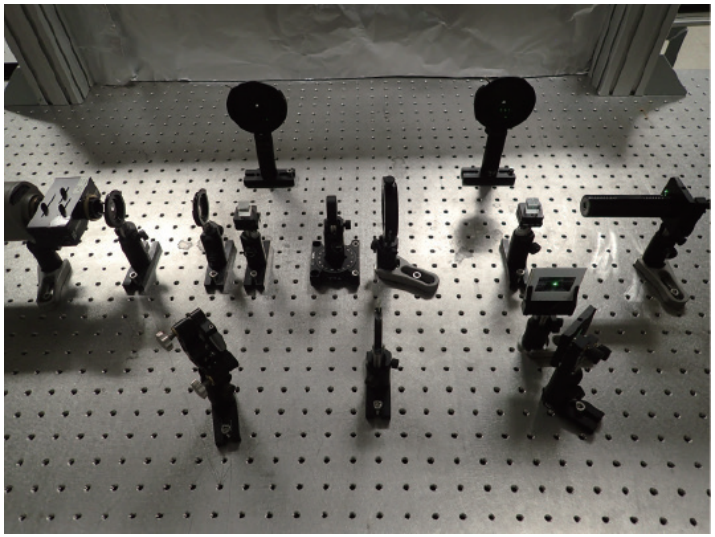
Fabry-Perot cavity
Stored power: 1000 W

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

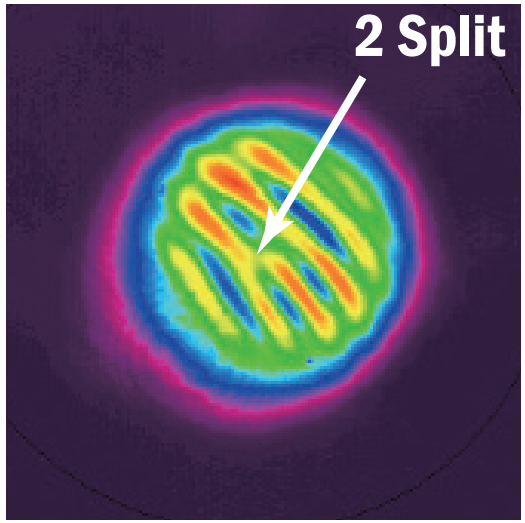
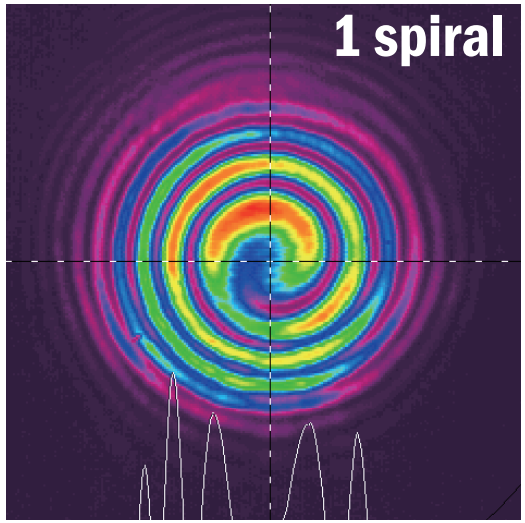
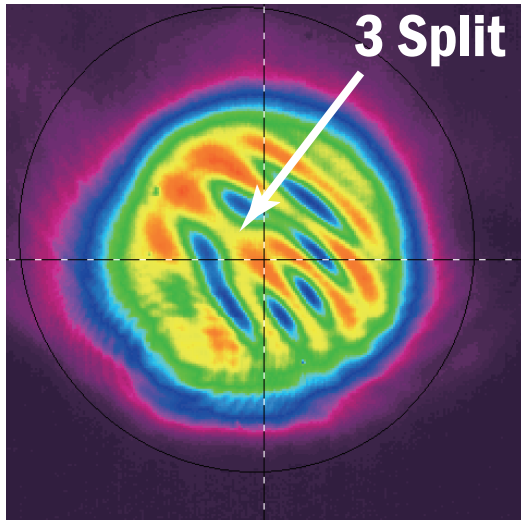
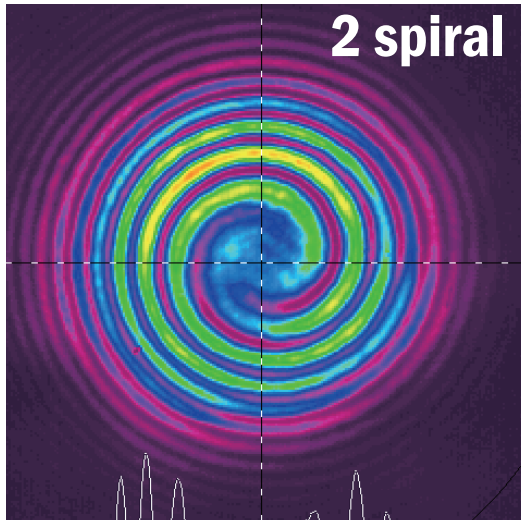
T. Allison et al., NIMA 781 (2015) 105.

Measurement technique of vortex laser

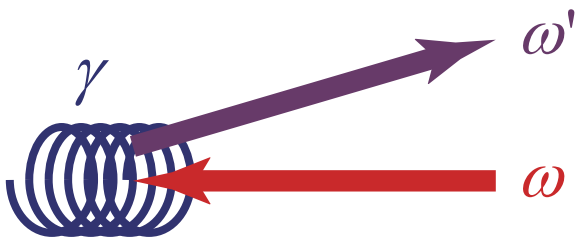




Interference pattern

OAM value	Plane wave + vortex	Spherical wave + vortex
1		
2		

2 Nonlinear ICS of circularly polarized laser

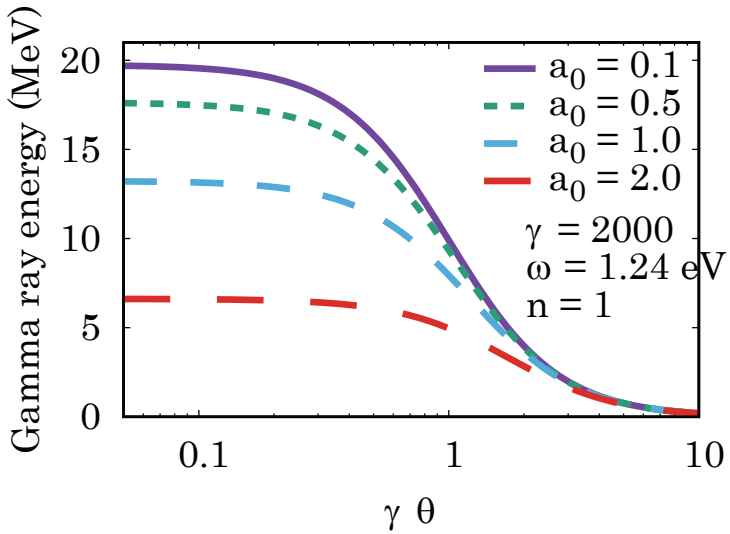


Intense laser with a laser strength parameter, a_0

Helical motion is induced by the circularly polarized laser ($a_0 \approx 1$) and this motion emits n-th higher harmonic and vortex radiation.

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

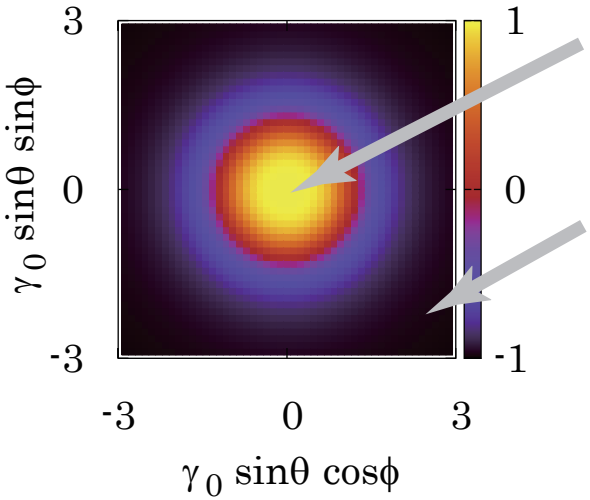
$$E = \frac{i}{\sqrt{2}}\left(C_\theta \cos\theta + C_\phi\right)\exp\left\{i\psi_0 + ikR + i(n-1)\phi\right\}e_+$$
$$+\frac{i}{\sqrt{2}}\left(C_\theta \cos\theta - C_\phi\right)\exp\left\{i\psi_0 + ikR + i(n+1)\phi\right\}e_-$$

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

Positive helicity carry (n-1)ħ OAM

Negative helicity carry (n+1)ħ OAM.

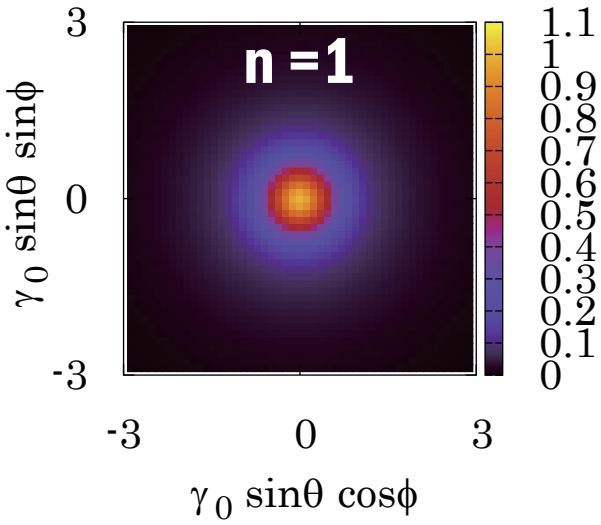
Degree of circular polarization

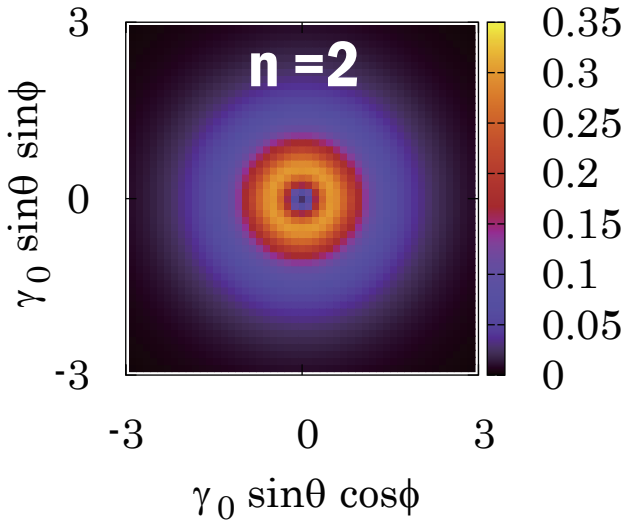


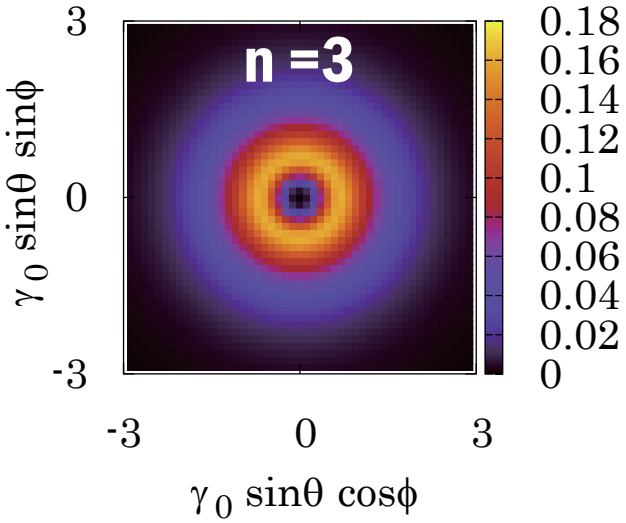
Positive helicity (n-1)ħ OAM

Negative helicity (n+1)ħ OAM

Spatial distribution







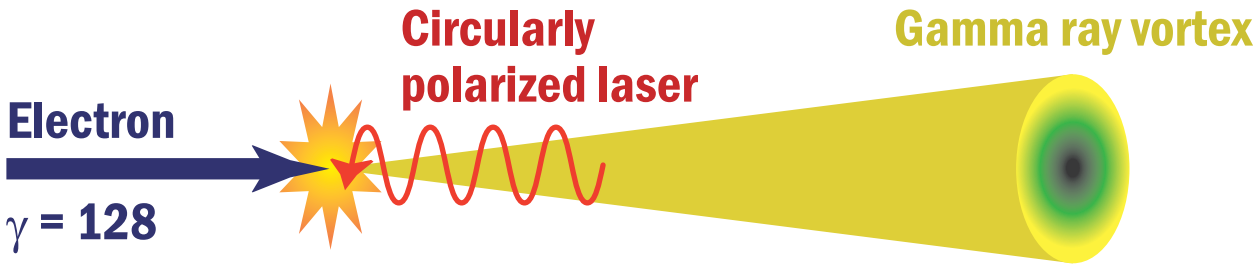
Annular shape of higher harmonic is due to the helical wavefront.

Characteristics of nonlinear ICS gamma-ray

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

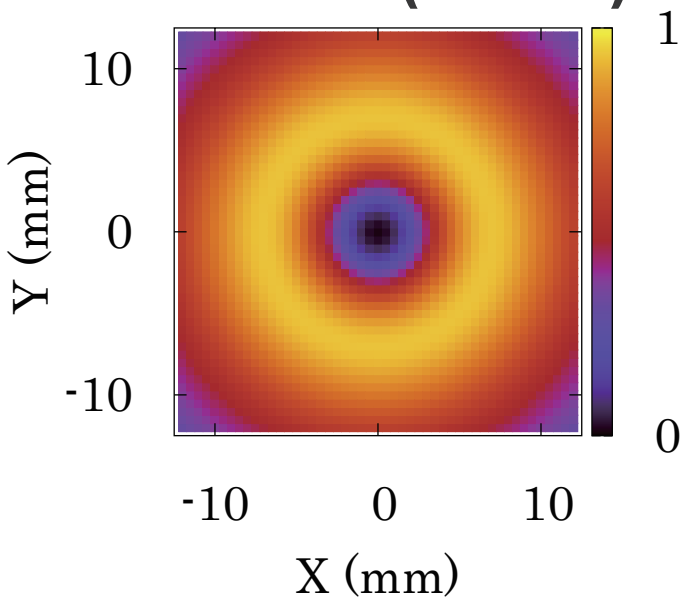
$a_0 = 1.0$, $\lambda_0 = 1.0\ \mu m$, $\gamma_0 = 2000$, $N_e = 10^9$ electrons/sec

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

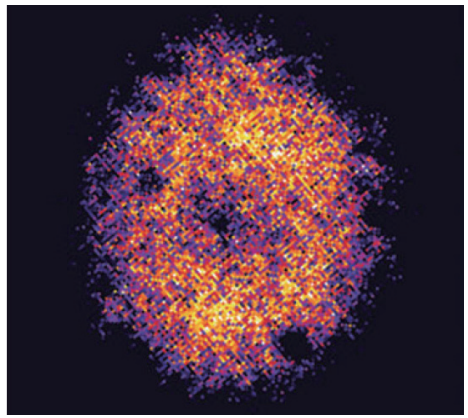


λ_0 = 10.6 μm, pulse energy = 2 J,
$2\omega_0$ = 100 μm, pulse width = 5 ps (FWHM)

Calculation (Y. Taira)



Measurement (BNL)



E = 13 keV (λ = 0.095 nm)

This will be the
X-ray vortex.

M. Babzien et al., PRL. 96 054802 (2006).
Y. Sakai et al., PRSTAB 18 060702 (2015).

Conclusion

- Gamma ray vortex providing an additional degree of freedom will open new research opportunities!

- Gamma-ray vortex can be generated by several methods using the Compton scattering.

- Measurement of gamma ray vortex is a big issue.

  Interferometry, Dichroism, and Pair production are candidates.

Thank you for your attention!