A Vortex Electron Source for Nuclear Physics
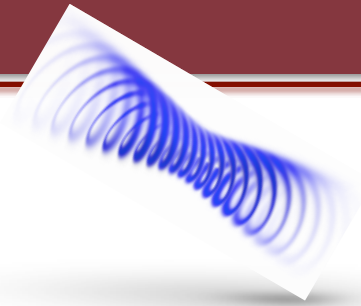
Dipangkar Dutta
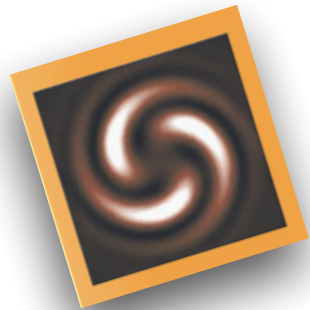### Mississippi State University

22nd International Spin Symposium

Sept 28, 2016
UIUC

Outline

- **What are vortex beams and how are they produced.**

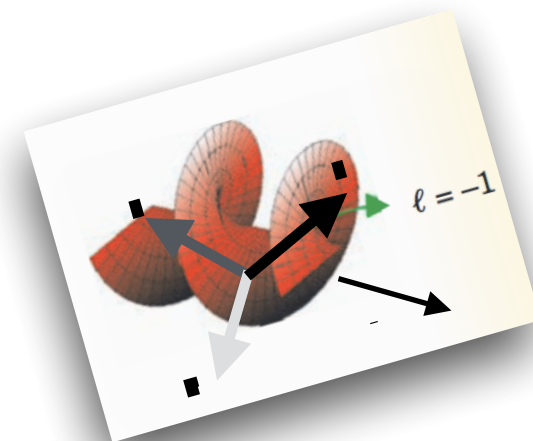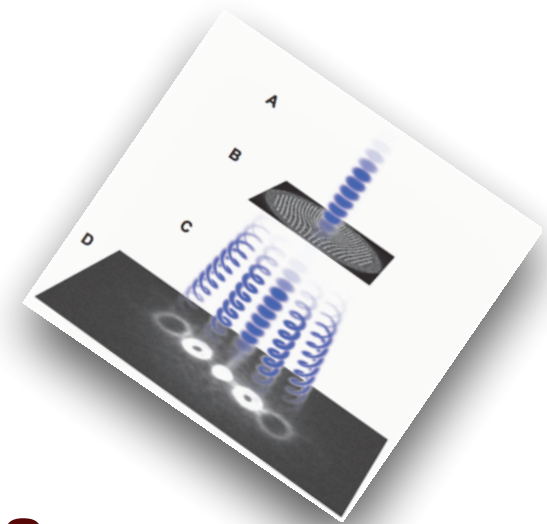 - **Photons**

  - **Electrons**

- **Applications of vortex beams.**

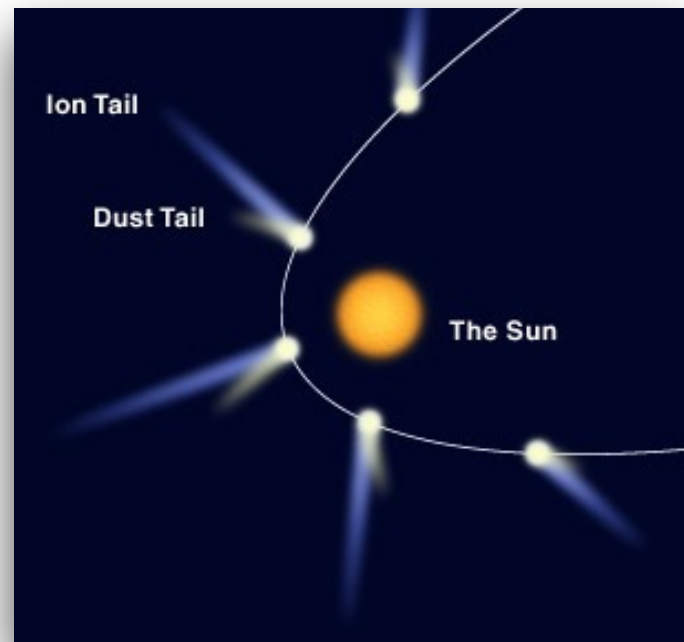 - **Nuclear physics with vortex beams**

- **R&D projects to develop accelerated vortex electron beams at JLab.**

  - **Source and detector**

- **Summary**

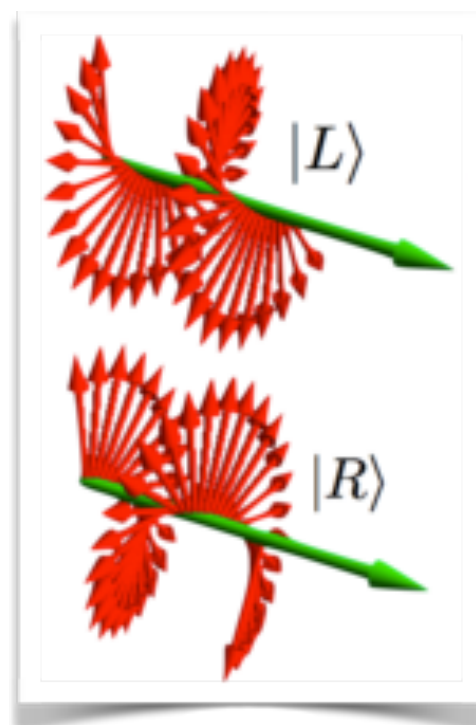# Photons carry linear momentum and angular momentum.

Kepler suggested that comet tails always point away from the Sun because light carries linear momentum

Einstein showed that linear momentum of a photon is $\hbar$k

In 1909 Poynting showed that light has angular momentum associated with circular polarization. For single photon **L=±$\hbar$**
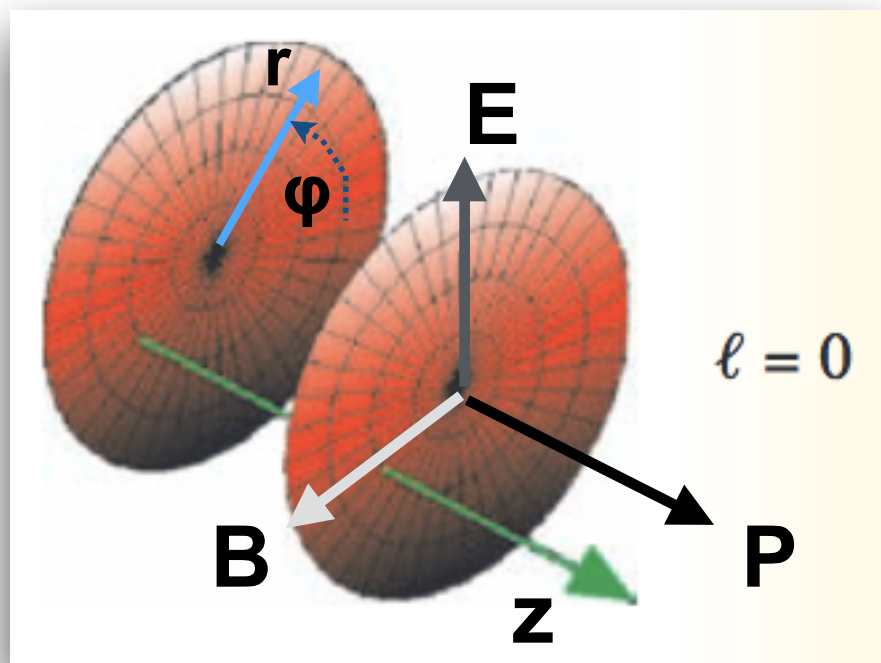
σ = -1

σ = +1

Spin angular momentum (SAM)
- circular polarization
- σ$\hbar$ per photon

Photons also carry angular momentum independent of polarization.

In 1992 L. Allen et al. showed that light beams with azimuthal phase dependence of **exp(-iℓφ)** carries angular momentum independent of polarization. For single photon **L=$\ell\hbar$**

L. Allen et al., Phys. Rev. A45, 8185 (1992)

plane wave

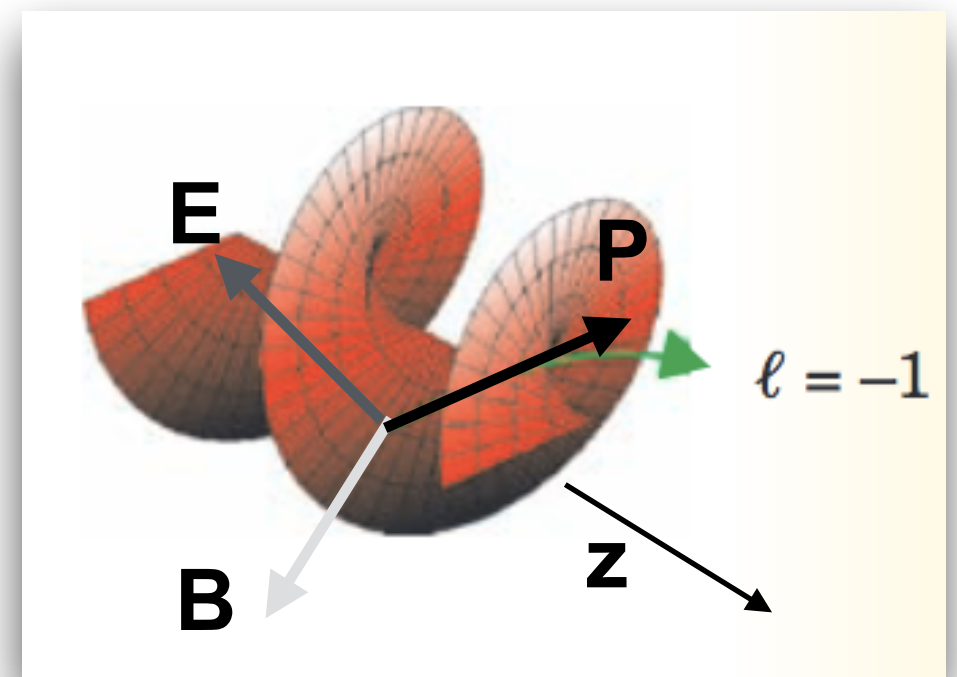**plane wave imprinted with azimuthal phase**

→

twisted wave

$\ell = 0$

$\ell = -1$

$$\psi(r,φ,z) \propto f(r)e^{ikz}e^{-i\ell φ}$$

$P_\theta = 0$

$P_\theta \neq 0$

(Poynting vector follows a spiral trajectory)

Images from M. Padgett et al., Physics Today, May 2004, p35

Orbital angular momentum (OAM) from helical phase fronts
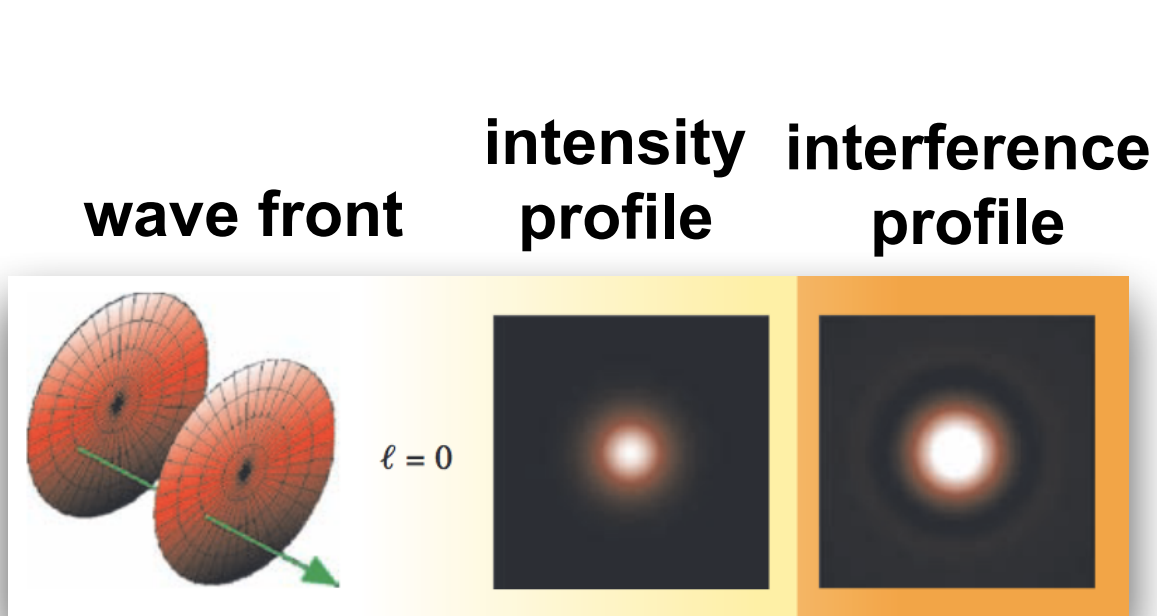
ℓ = **topological (vortex) charge**

ℓ = 0 (plane wave)

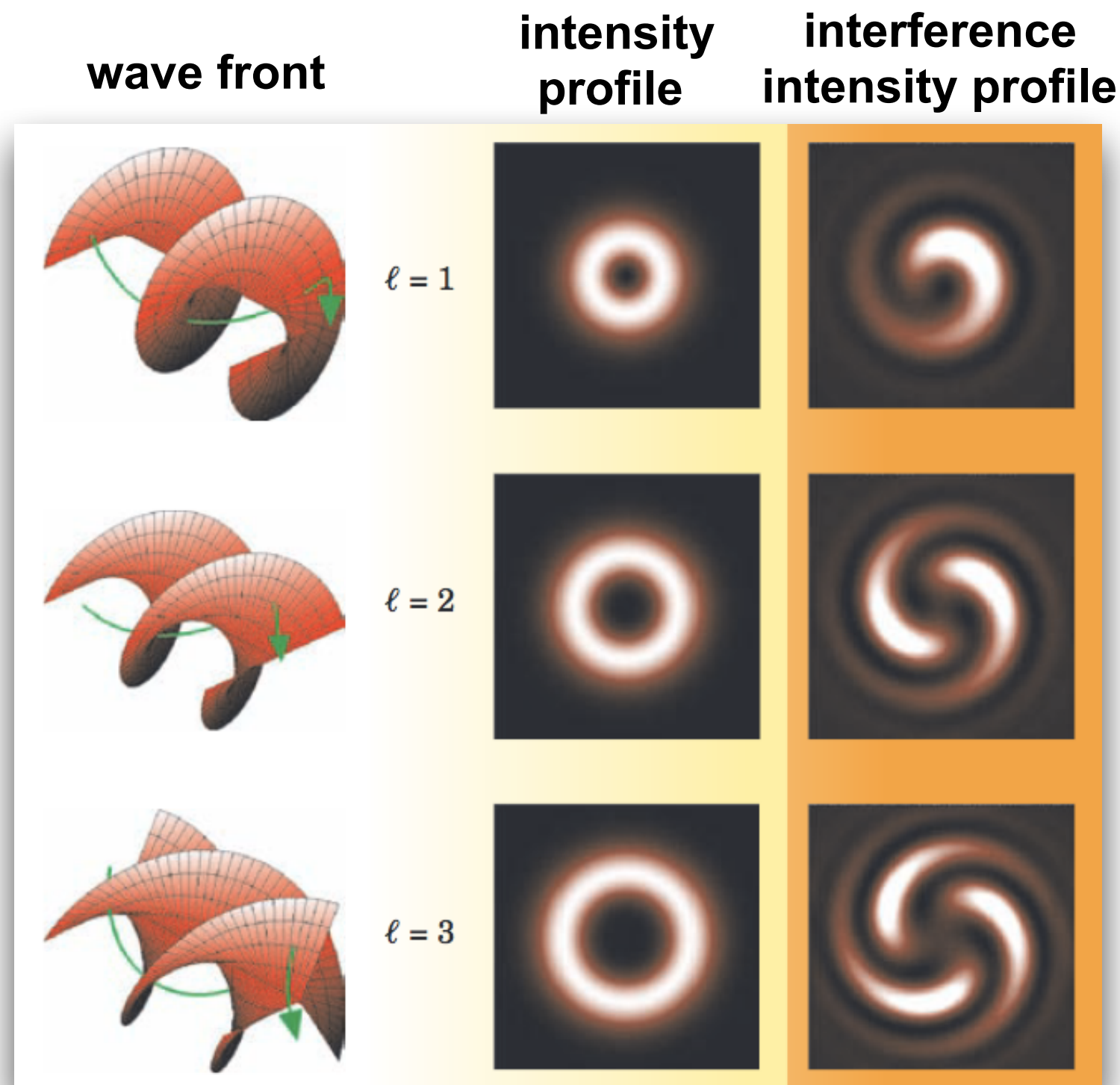ℓ = 1 (helical wave)

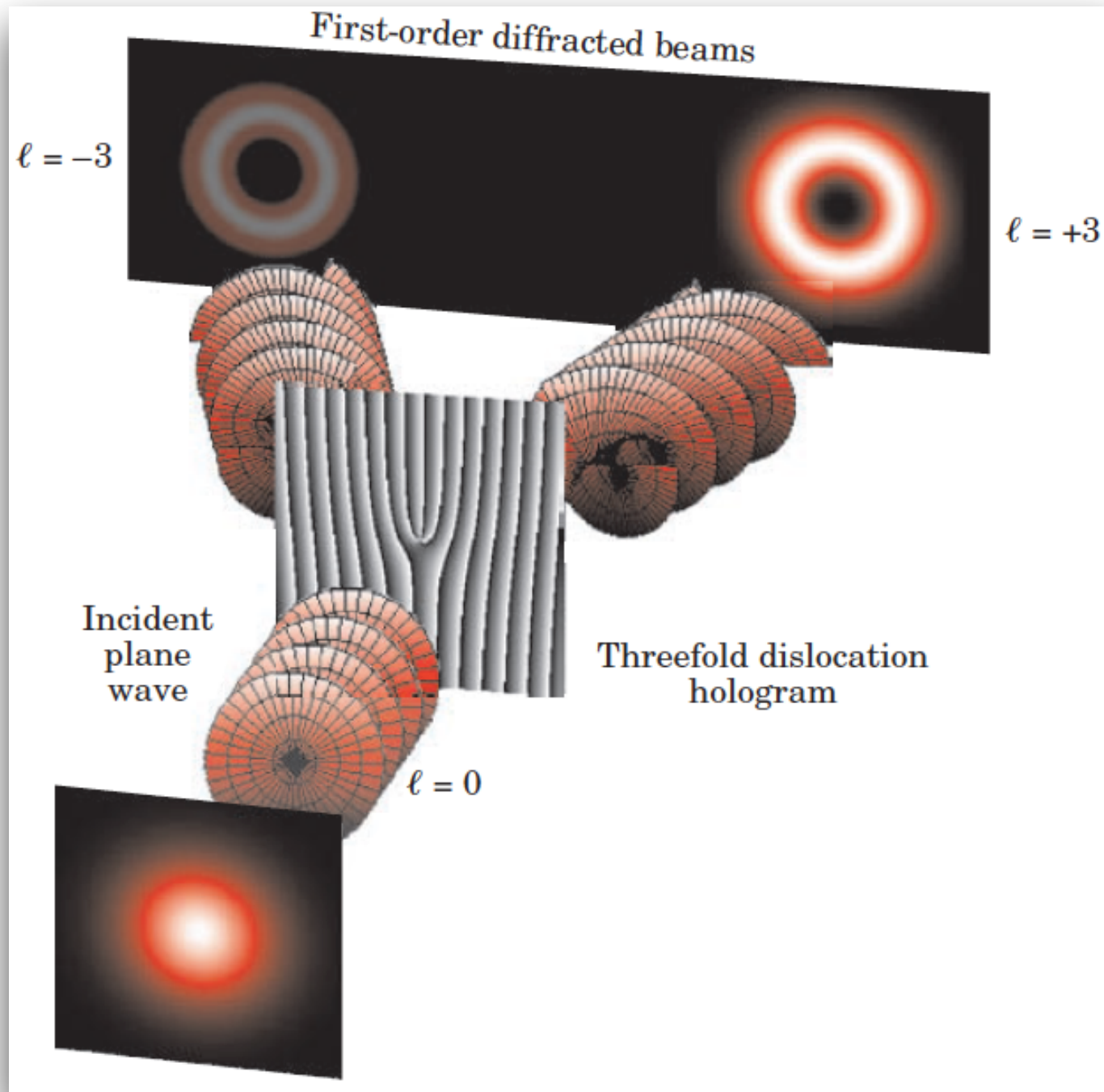ℓ = 2 (double helical wave)

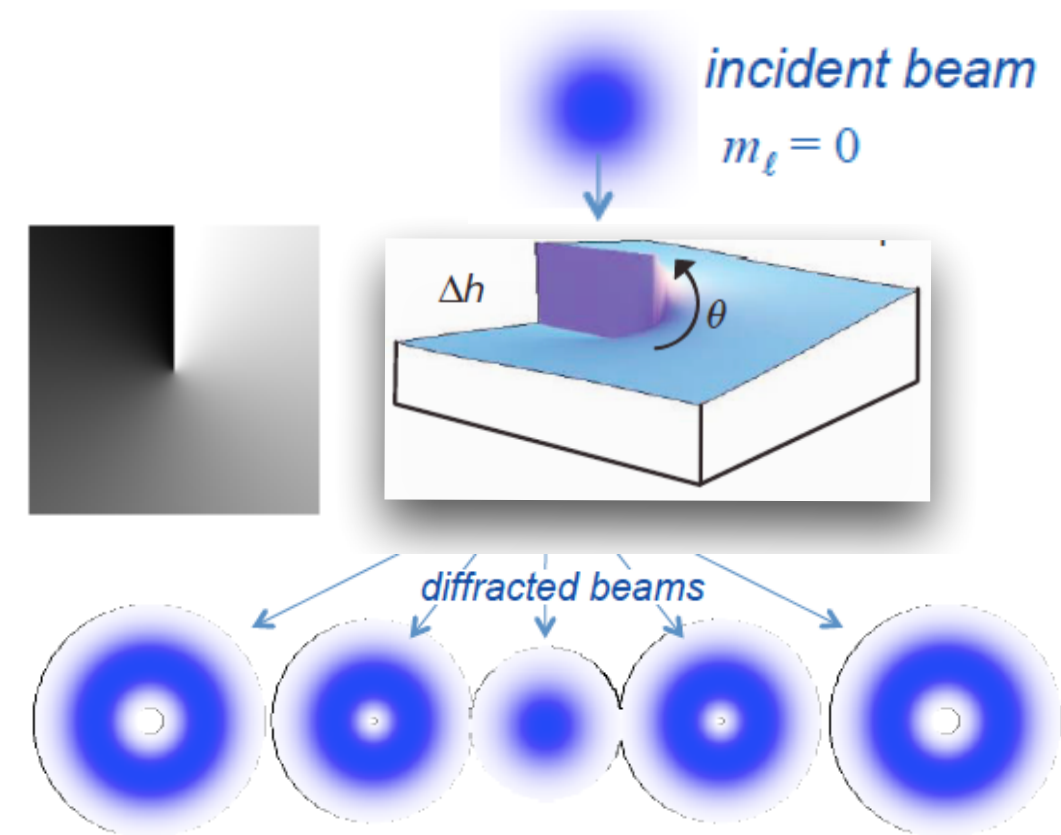ℓ =3 (pasta, fusilli wave)

Images from M. Padgett et al.,
Physics Today, May 2004, p35

Orbital angular momentum carried by photons has been experimentally demonstrated.

with holograms of dislocations & fork gratings

and with diffraction gratings with spiral phase
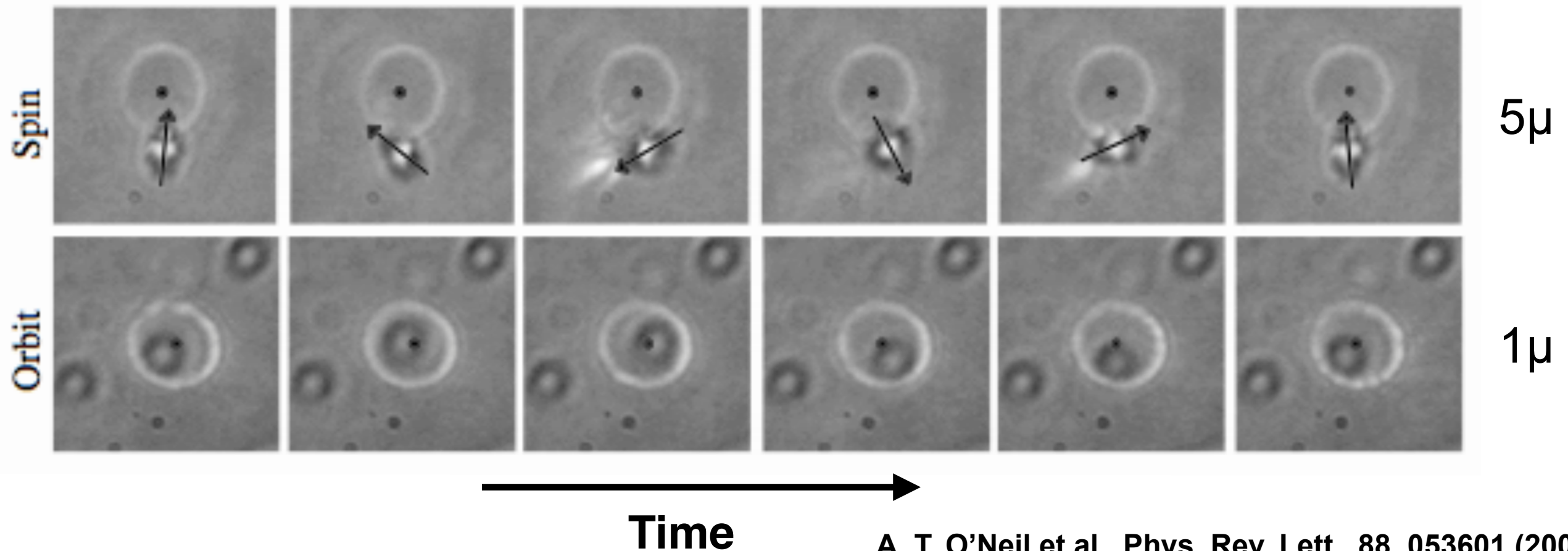(thickness varies with azimuthal angle)

Bazhenov, Soskin and Vasnetov, J. of Mod. Optics, 39, 985 (1992)

Difference between SAM and OAM in photons demonstrated with optical tweezers.

video frames of particles trapped at the focus of a vortex beam with:

$\ell = 8$ and $\sigma = 1$

Time

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

SAM is transferred where the photon is absorbed and the particle spins around their own axis
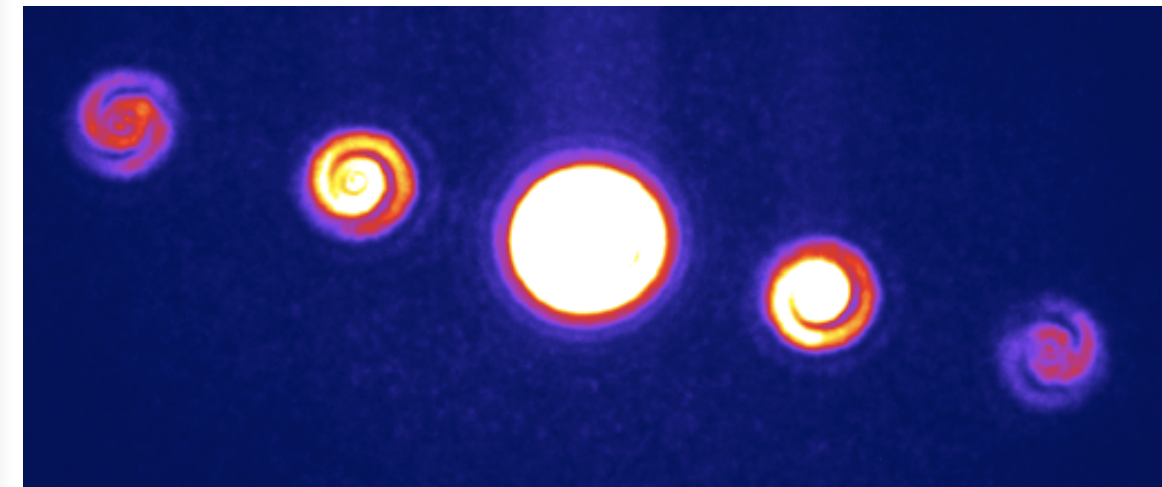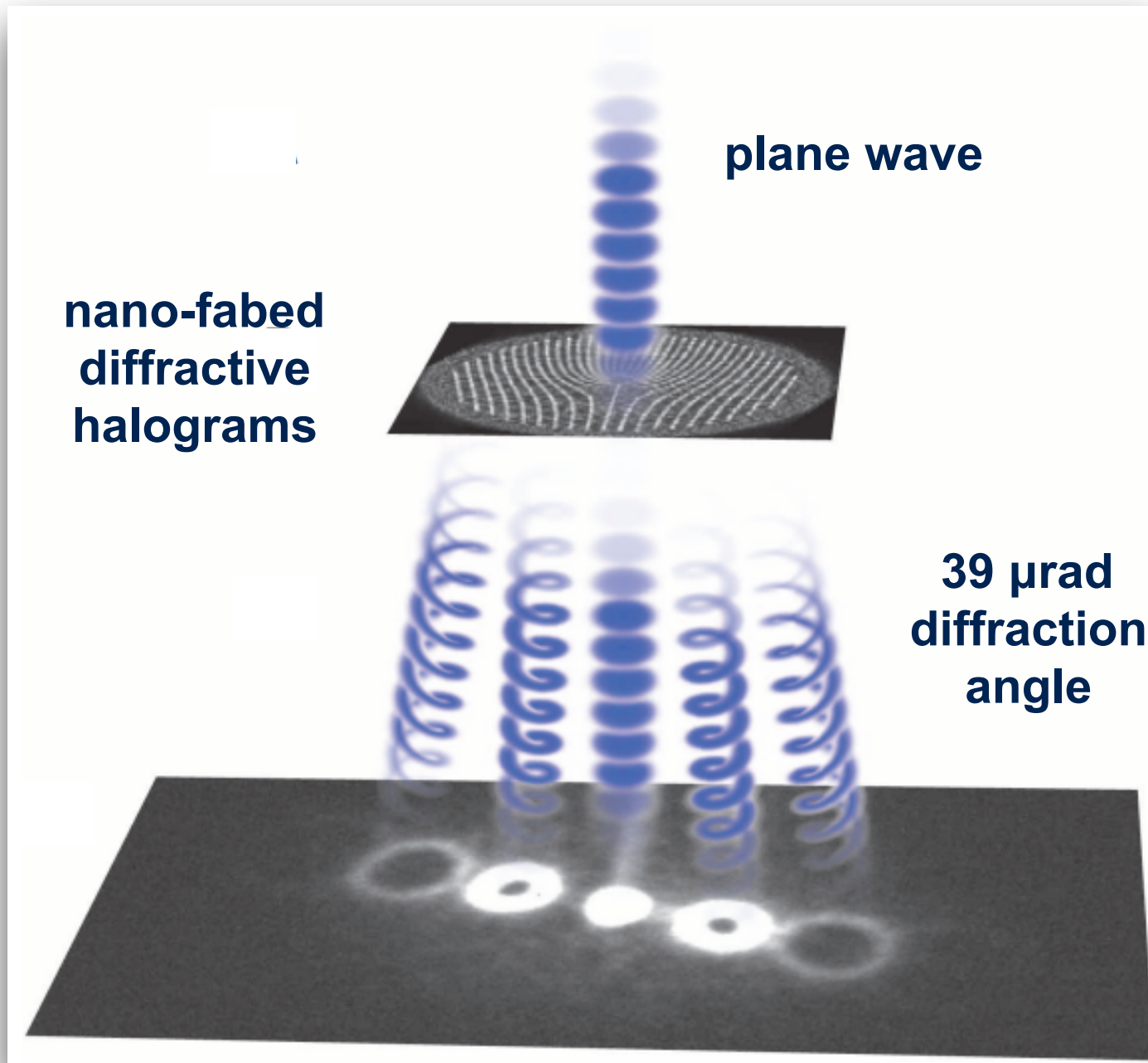(with rot. rate $\Omega_{spin} \sim 1/\rho$).

OAM transfer causes the particle to orbit around the beam axis
(with rot. rate $\Omega_{orbit} \sim 1/\rho^3$ as predicted by models of vortex beams).

300 keV electrons (λ = 2 pm)

plane wave

nano-fabed diffractive halograms

39 μrad diffraction angle

helical phase measured using electron interferometry

TEM image

B. J. McMorran et al., Science 331, 192 (2011)

Electron vortex beams imply orbital motion of unbound massive charged particle in free space.

Not a helical trajectory, but wave function with helical shape.
Orbital motion does not require closed trajectories (in electron's frame).

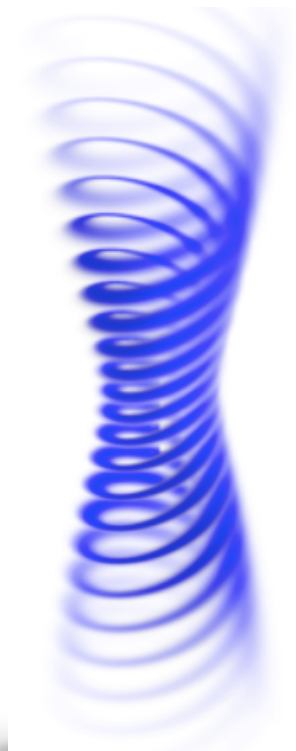A vortex beam is a superposition of straight line trajectories.

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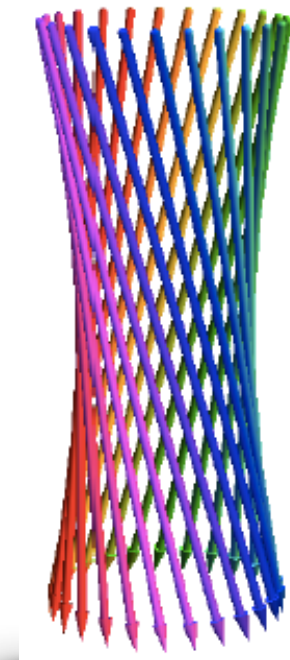

A vortex beam is a superposition of straight line trajectories.

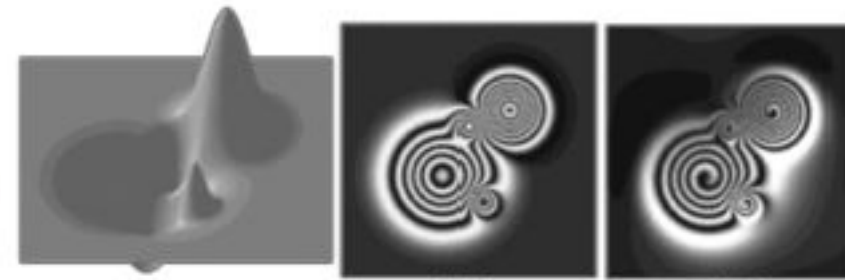**Free electrons with OAM can be modeled as**

helical
wave function

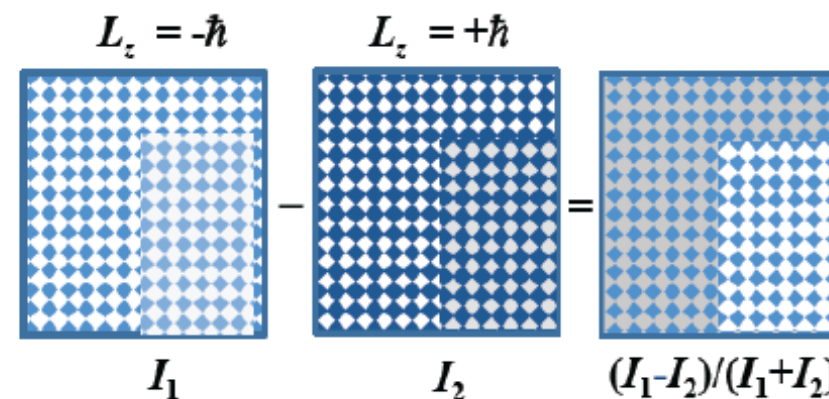

or

semi classical
trajectories

Courtesy of B. J. McMorran

Vortex beams - what are they good for?

Higher resolution imaging
(spiral interferometry)

Fürhapter et al. Opt. Lett. 2005

Novel microscopy
(STEM/EELS with vortex probe)

$L_z = -\hbar$ $L_z = +\hbar$

I_1 I_2 $(I_1-I_2)/(I_1+I_2)$

B. J. McMorran et al.

atomic resolution map
of magnetic moments

Terabit communication
(OAM multiplexing)
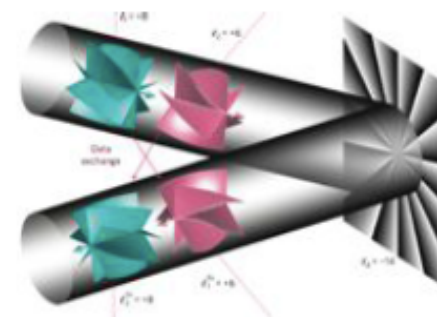
Nano fabrication
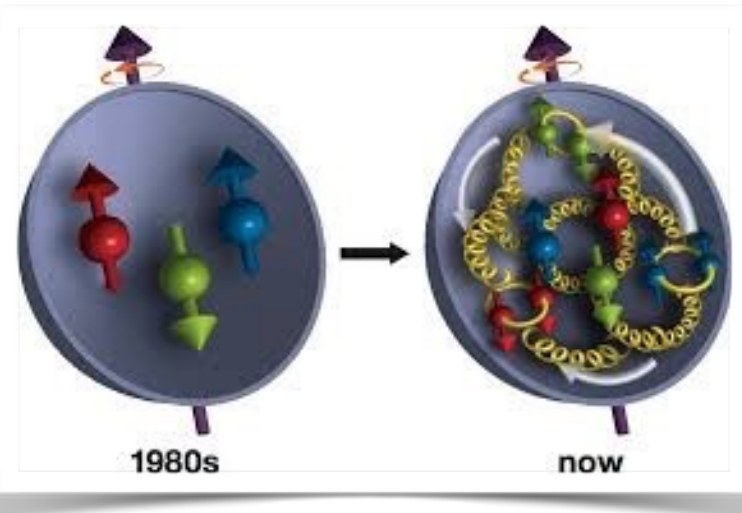
Wang et al. Nature Photon 2012

Quantum optics Mair et al. Nature 2001

Can we do nuclear physics with vortex beams?

Polarized deep inelastic scattering (DIS): ~30% of the protons's spin is due to quarks spins

Quest for the remaining ~70% is a major enterprise in NP

- **quark OAM**
- **gluon spin**
- **gluon OAM**

Significant effort underway: both theoretical **(GPDs, TMDs)**
& experimental **(JLab, RHIC, CERN, & proposed EIC)**

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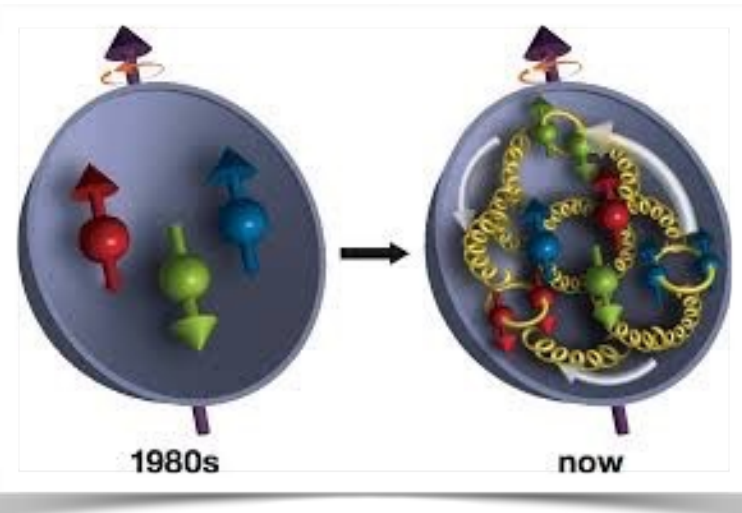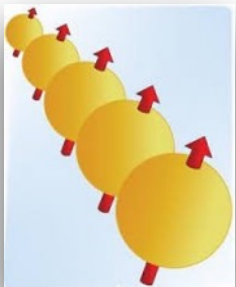**Polarized deep inelastic scattering (DIS): ~30% of the protons's spin is due to quarks spins**

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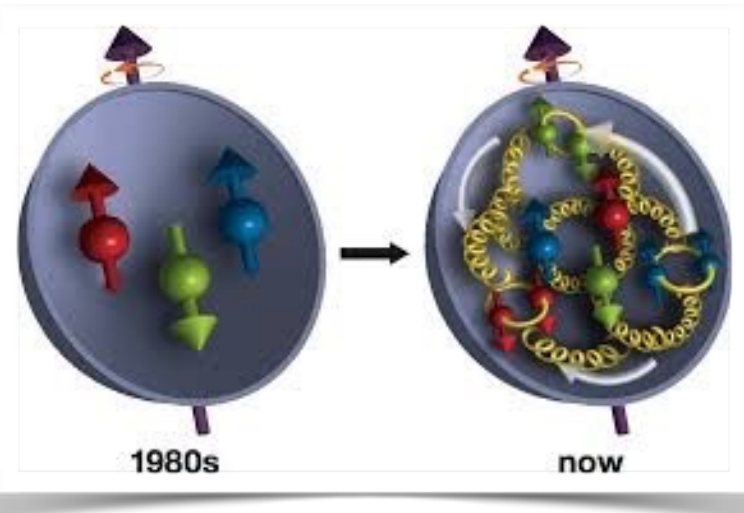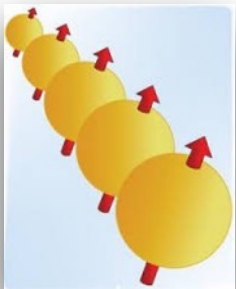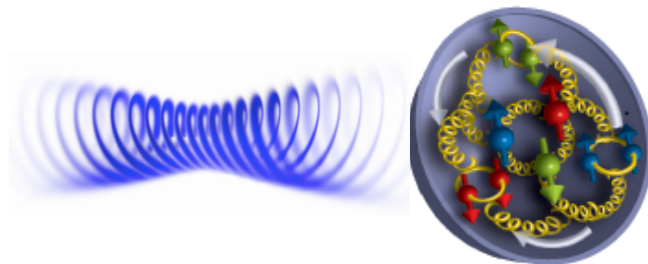- **gluon spin**
- **gluon OAM**

Significant effort underway: both theoretical **(GPDs, TMDs)**
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Spin polarized beams & targets have been the only tools in use

It is high time we explore new tools such as OAM/vortex beams (electrons)

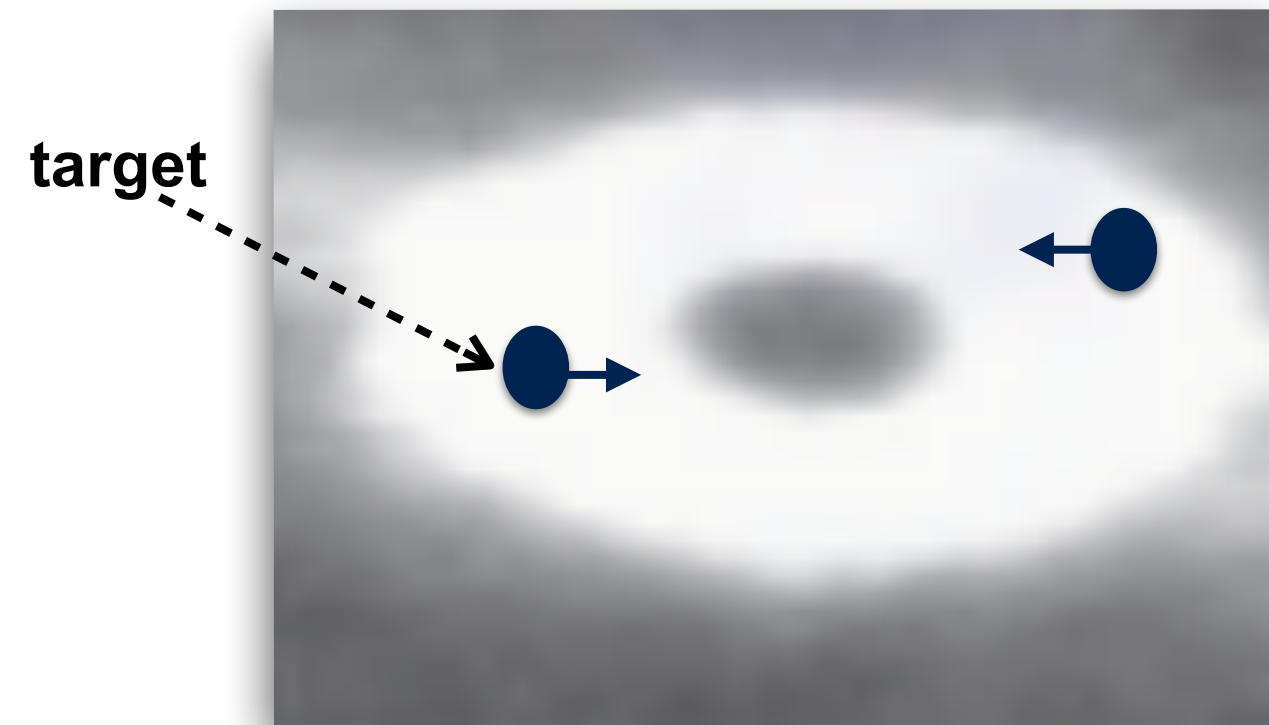**photon vortex beams in next talk (Y. Taira)**

Leader & Lorcé: the formalism of spin+OAM for photons, applies to quarks and gluons too.

E. Leader and C. Lorcé, Phys. Rept. 541, 163 (2014).

Can we do deep inelastic scattering with vortex beams?

The OAM in vortex electrons is carried by the entire wave.

ℓ = 1 vortex electron incident
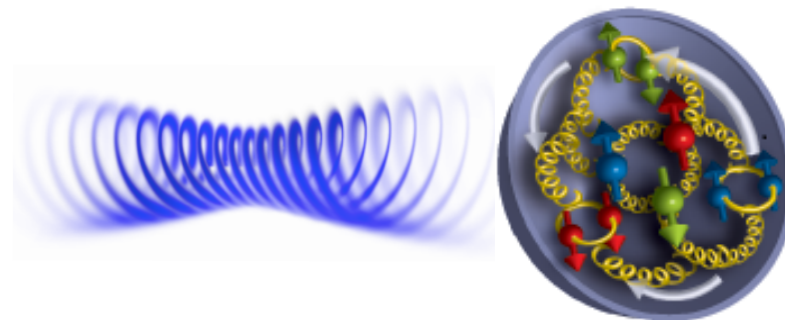on target (atom, nucleus, ….)

target

target "sees" a sightly tilted plane wave and receives a small kick in the direction of the tilt.
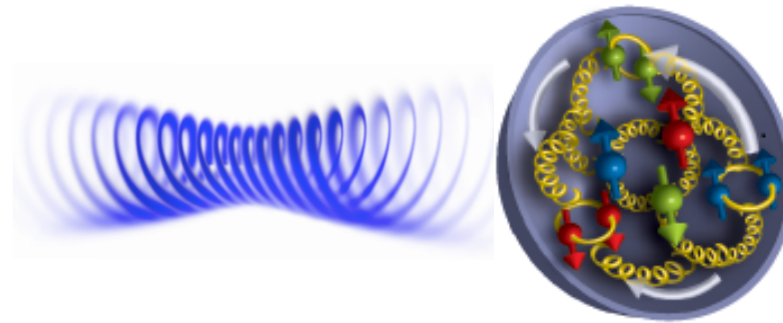
but

unlike photons, the electron OAM has a magnetic moment $\mu_z = g\mu_B\ell$ that can couple to external fields

G. M. Gallatin and B. McMorran, Phys. Rev. A 86, 012701 (2012)

Can focused electron vortex beams induce angular momentum dependent changes in scattering processes?

- Can we build accelerator ready vortex electron sources?
- Are there scattering observables that can be used to monitor OAM (twistedness)?
- What opening angles ($P_\perp/P_z$) are appropriate for scattering with vortex beams?
- Will the vortex beams retain their OAM after acceleration?
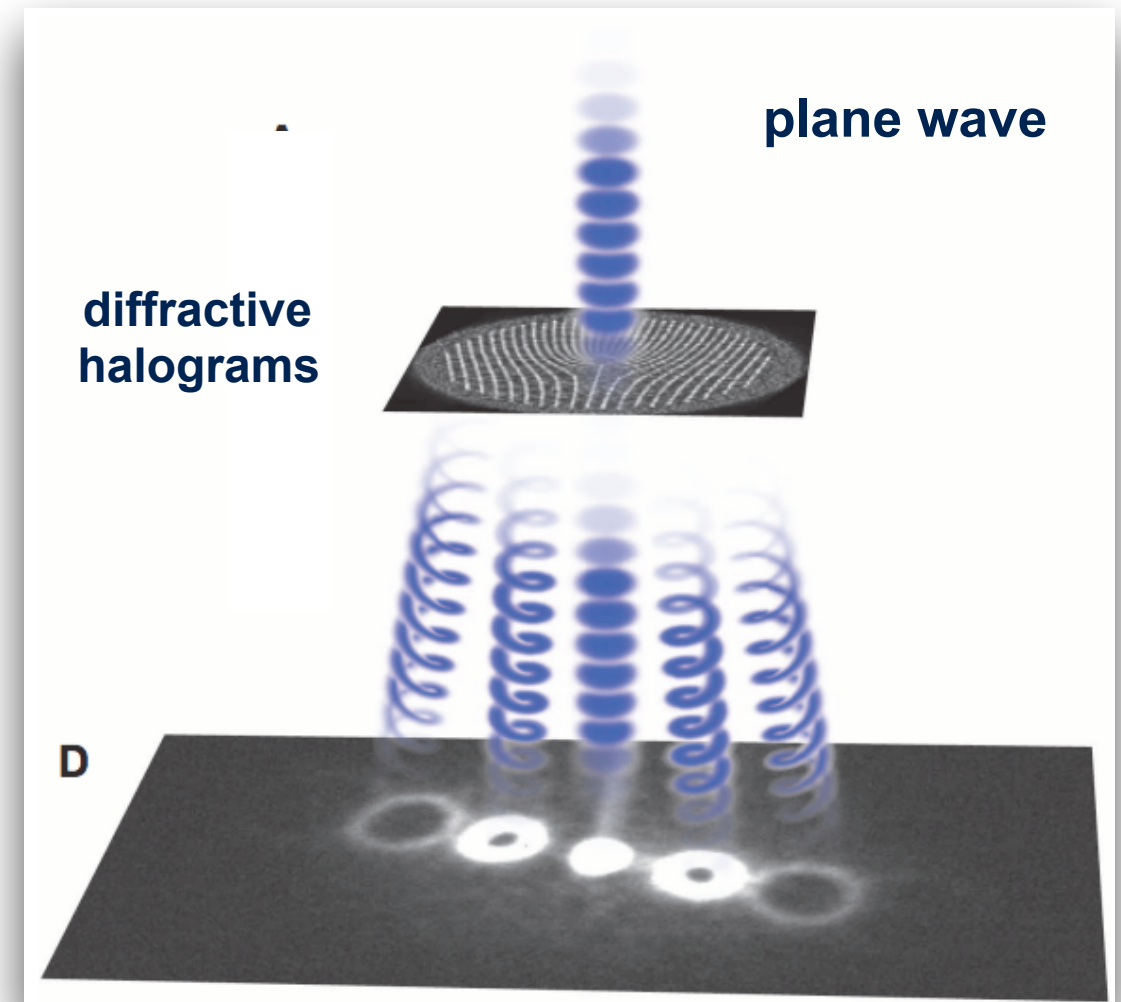- Are there spin-orbit correlations that can be useful observables?

R&D activities have been initiated at JLab to help address some of these questions.

First we need a source of vortex electrons.

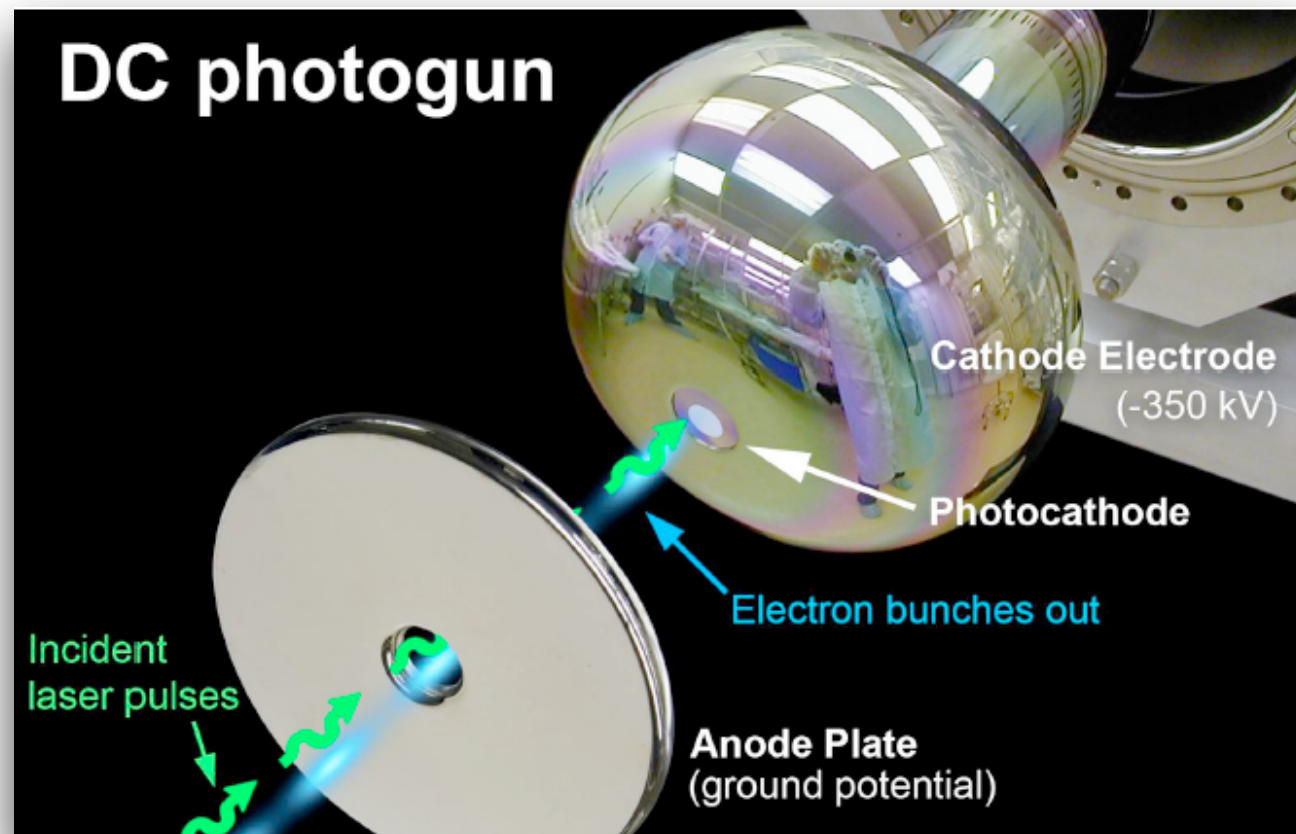**Existing vortex electron sources are high brightness field emission sources (electron microscope sources)**
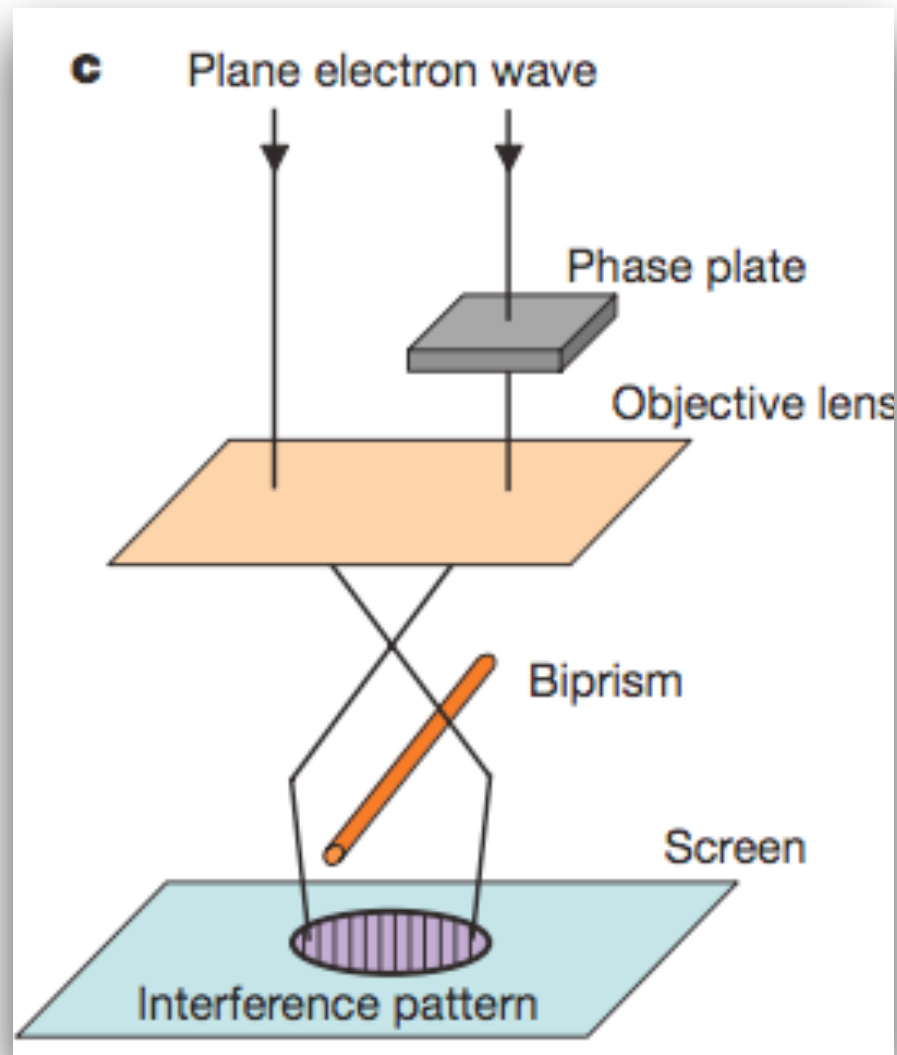
or

typical energy
100 - 300 keV

First we need a source of vortex electrons.

Accelerators sources are typically photoemission or thermionic emission

electrons generated when laser pulses are incident on a GaAs photocathode

from C. Hernandez-Garcia

photoemission sources have lower brightness (higher emittance) not ideal as vortex sources

Accelerators sources are typically photoemission or thermionic emission

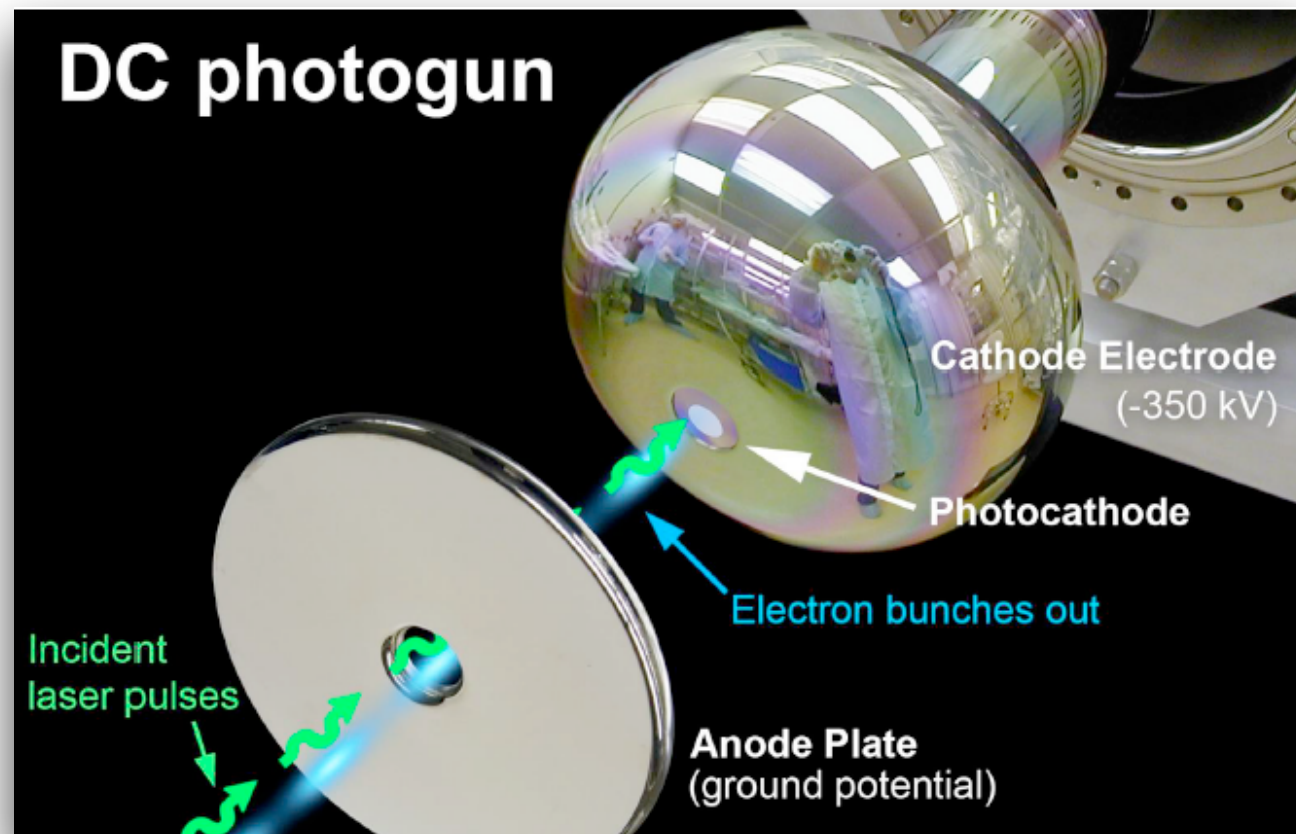electrons generated when laser pulses are incident on a GaAs photocathode

from C. Hernandez-Garcia

photoemission sources have lower brightness (higher emittance) not ideal as vortex sources

Explore field emission from GaAs tips for high brightness photoguns

M. Kuwahar et al. Jap. J. of Appl. Phys., 45, 6245 (2006)

&

**R&D on cryo-cooled photocathodes for low emittance dc high voltage photogun**

J. Grames, JLab

In existing vortex electron sources OAM is verified by interference or microscopy

For accelerator based sources we cannot use interference or microscopy

Mott scattering may help distinguish between plane wave and twisted wave.

V. Serbo, et al. Phys. Rev. A, vol. 92, Jul 2015, p. 012705.
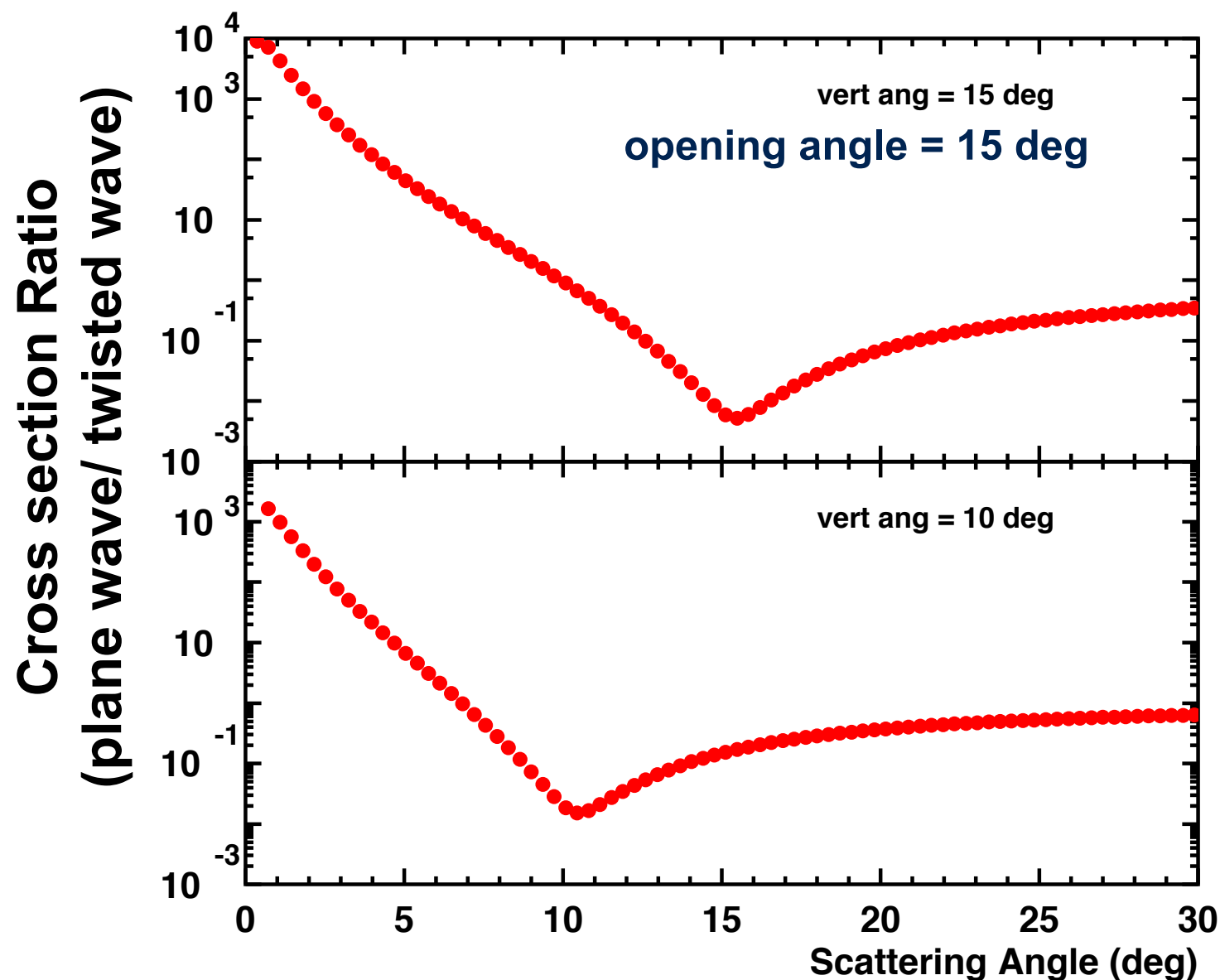
In 1929 Mott scattering was used to show that electrons could be spin-polarized. It introduced spin polarization as a new tool.
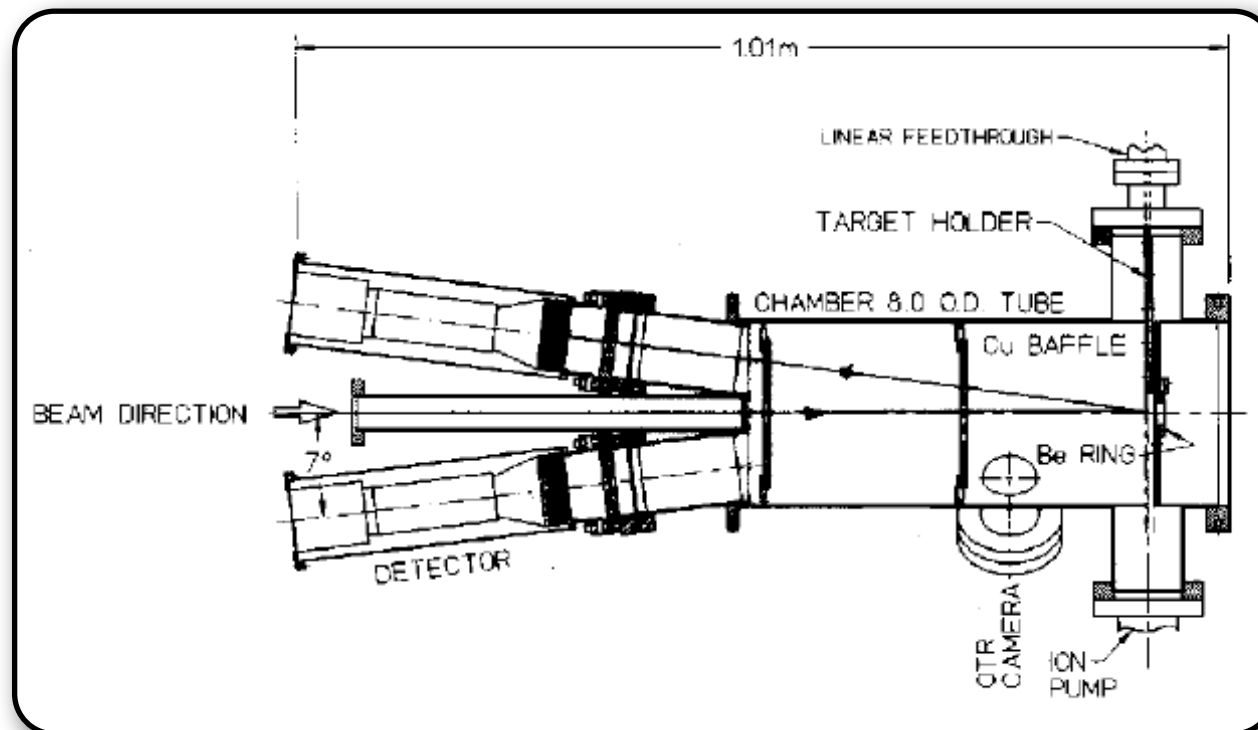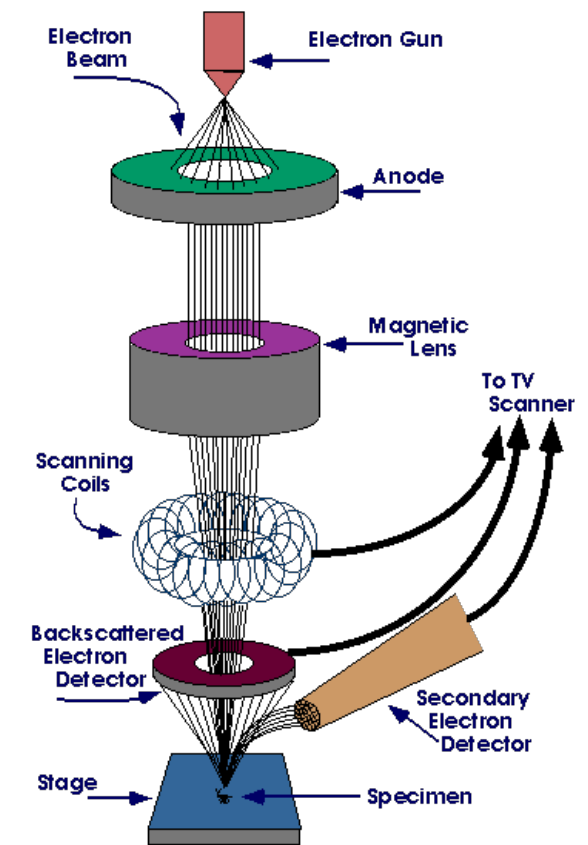
N. F. Mott, Proc. Roy. Soc.,124, no. 794, 425 (1929).

Modify/cannibalize existing SEM/TEM sources at the U. of Oregon to build a vortex electron source with fork gratings.
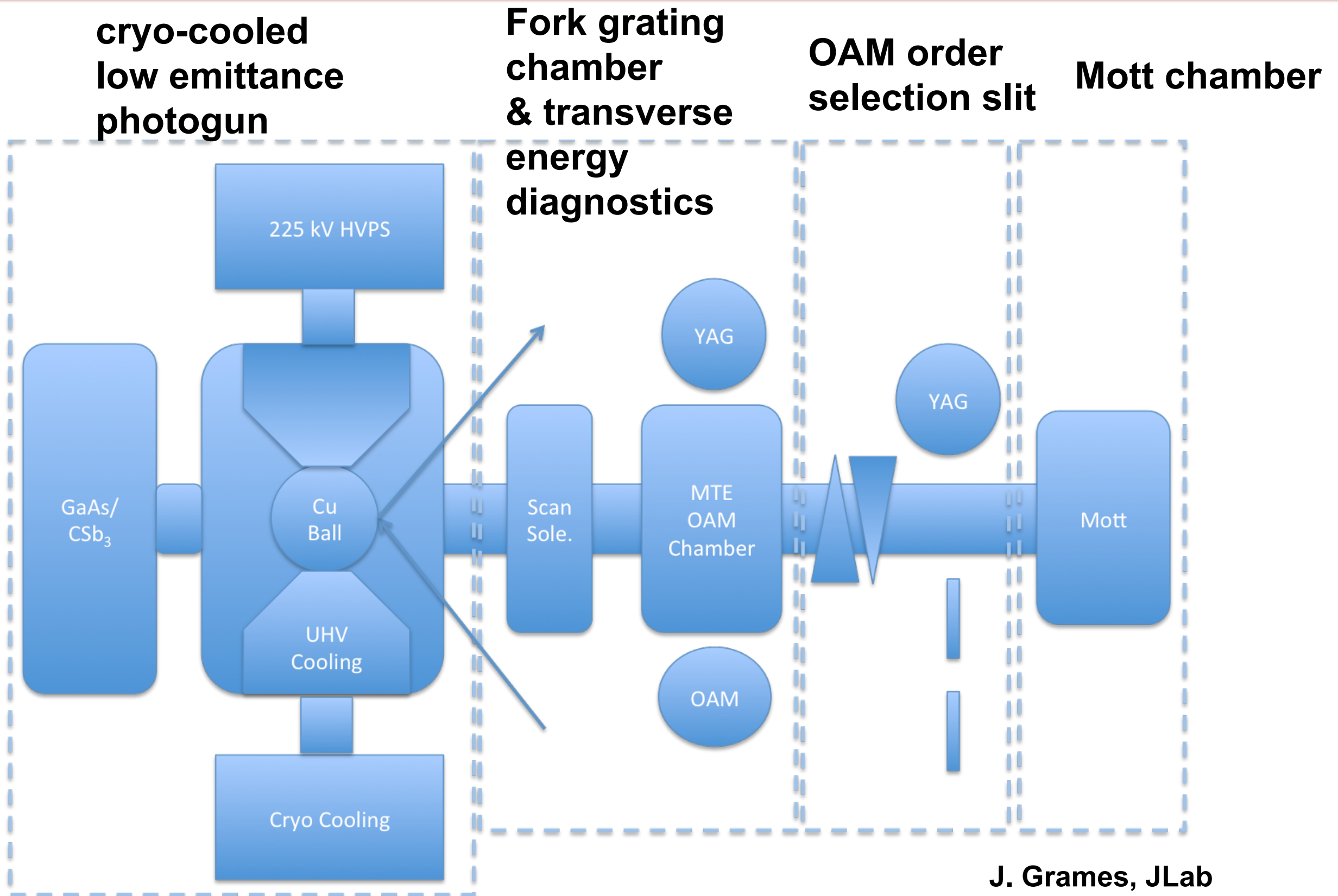
B. McMorran's group at UO

Couple source to spare Mott polarimeter chamber from JLab

Measurements to be performed at U. of Oregon

We also propose to study Mott scattering using a new cryo-cooled low emittance photogun at JLab.

J. Grames, JLab

A Mott scattering simulation for vortex electrons has also been built.

The formalism of V. Serbo et al. was used in the simulation.

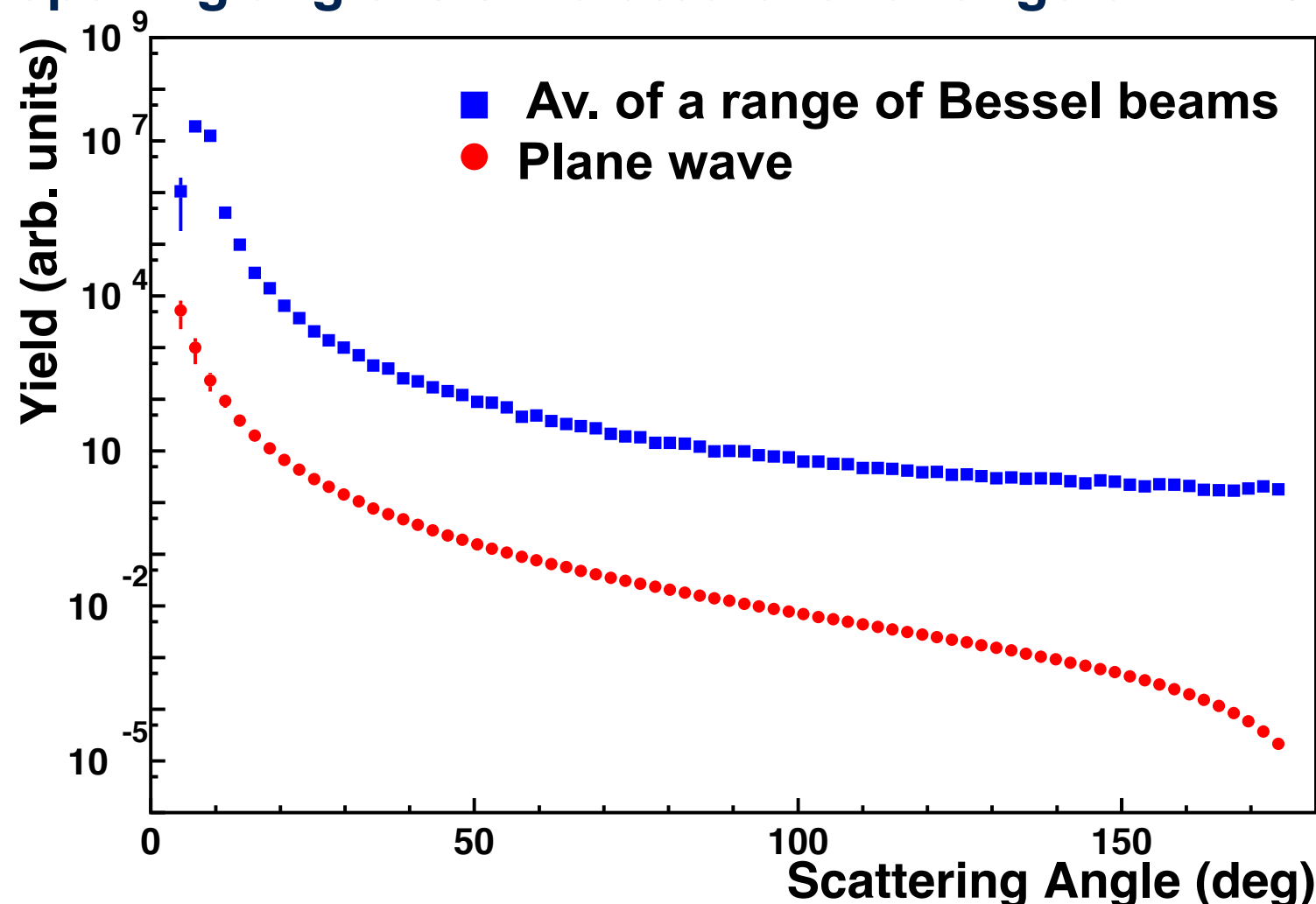V. Serbo, et al. Phys. Rev. A, vol. 92, Jul 2015, p. 012705.

The vortex electrons beam is approximated as a Bessel beam.

$$\psi(\rho, \phi, z) = \sqrt{\frac{\aleph}{2\pi}} e^{\iota p_z z} \sum_{\sigma} \iota^{-\sigma} e^{\iota(m-\sigma)\phi} d_{\sigma\lambda}^{1/2}(\theta_p) \times J_{m-\sigma}(\aleph\rho)U^{(\sigma)}(\epsilon, \lambda)$$

p_z - long. momentum, ε - energy, λ - helicity, σ - spin, θ_p - opening angle, m - total ang. momentum
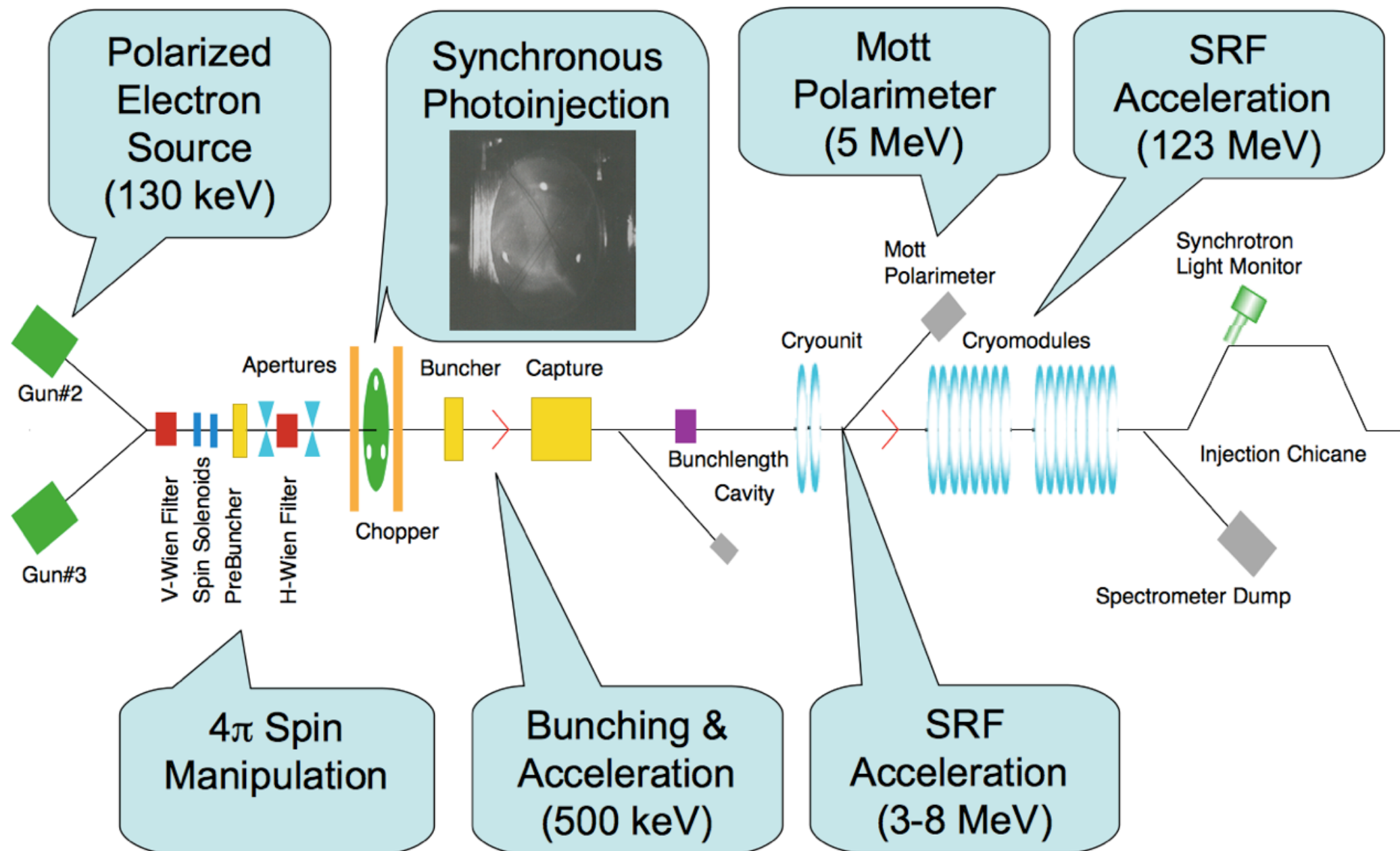
Based on the source at U. of Oregon:

- a realistic beam emittance/brightness is included
- opening angle is simulated over a range of 12 - 50 mrad

J. K. Madsen, Miss. State
undergrad thesis (2016)

If successful the high brightness source can be inserted in the CEBAF injector or at the Upgrade Injector Test Facility (UITF)

The OAM can be measured in the 5 MeV Mott after acceleration.

J. Grames, JLab

Summary

- Both photons and electrons can carry OAM.

- Focused beams of vortex electrons can be produced using fork gratings or phase plates.

- It is highly desirable to have new tools to probe the spin and OAM structure of nucleons.

- Vortex electrons maybe just the new tool we need.

- A new R&D program is being initiated at JLab to explore how to build vortex electron sources for accelerators and how to measure the OAM of such beams.