Effective Image Recognition using High-Order Symmetry of Correlated Orbital Angular Momentum (OAM) States

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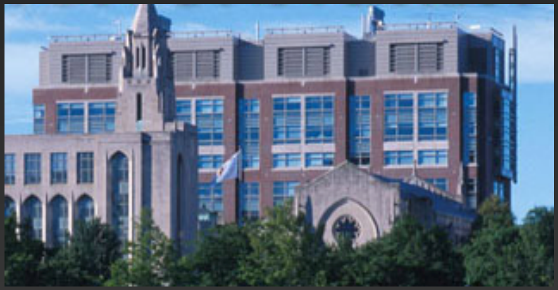

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The Boston University photonics center

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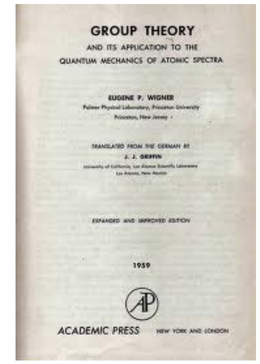
INTRODUCTION

- **Wigner pioneered the use of symmetry to construct angular momentum eigenstates.**

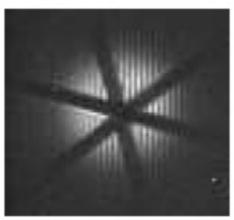
- **Wigner, E. P. "Einige Folgerungen aus der Schrödingerschen Theorie für die Termstrukturen." *Z. Physik* 43, 624-652, 1927.**
- **Wigner, E. P. *Group Theory and Its Application to the Quantum Mechanics of Atomic Spectra, expanded ed.* Academic Press, 1959.**


GROUP THEORY
AND ITS APPLICATION TO THE
QUANTUM MECHANICS OF ATOMIC SPECTRA
EUGENE P. WIGNER
EXPANDED AND IMPROVED EDITION
1959
ACADEMIC PRESS NEW YORK AND LONDON

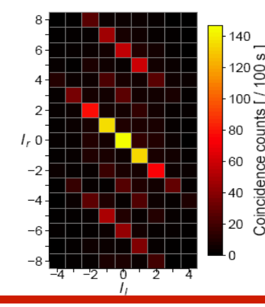
Our goal here is roughly the converse:

- **To use quantized optical angular momentum (OAM) eigenstates to evaluate symmetries of objects.**

Object



The rotational symmetry of an object is reflected in its effect on two-photon joint orbital angular momentum spectrum



Correlation Spectrum

- **This approach holds promise for a number of novel applications such as rapid object identification and detection of geometric symmetries with few photons.**

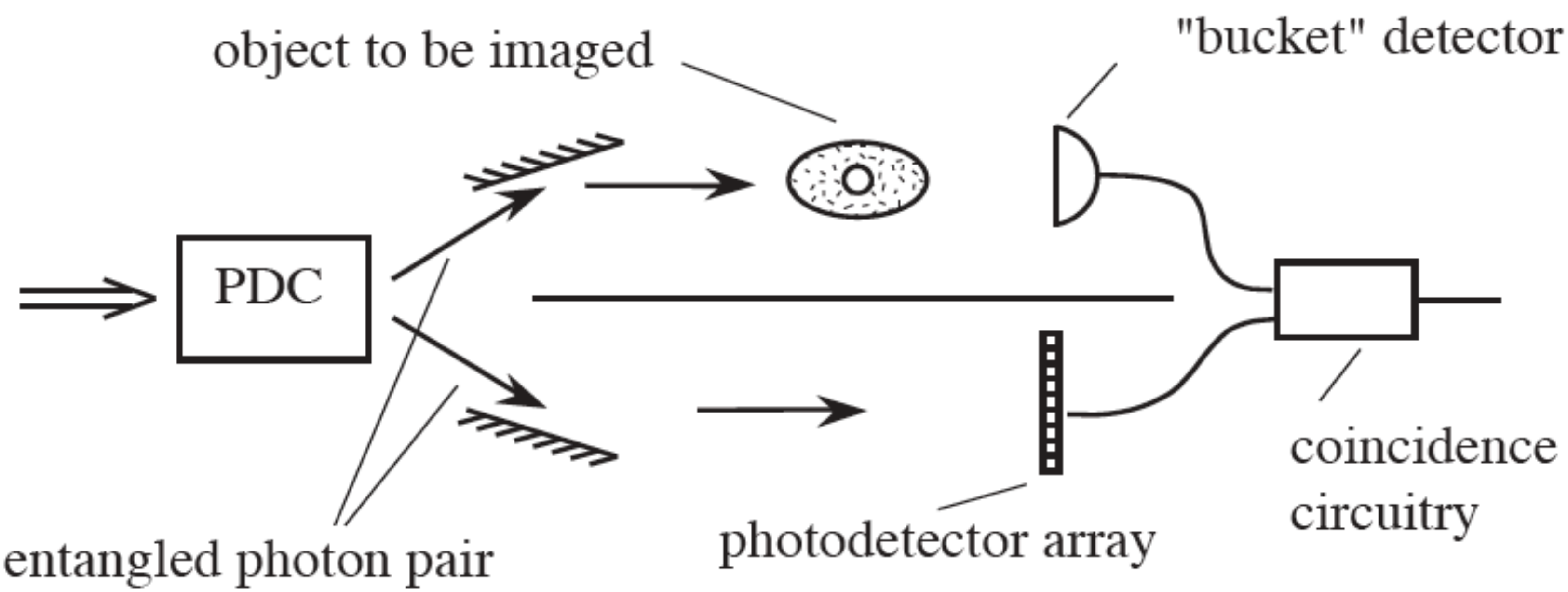
Motivation

How to achieve more efficient recognition of complex unstable (rotating) objects in comparison with existing pixel-by-pixel imaging techniques?

1) Correlated photon illumination and correlated detection provides additional information in imaging .

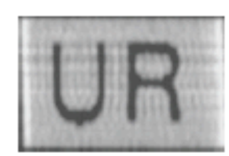
2) High-order OAM states occupying multi-dimensional Hilbert space provide efficiency in recognition of symmetry features.

Ghost (Coincidence) Imaging



- Obvious applicability to remote sensing!
  (imaging under adverse situations, bio, two-color, etc.)

- Is this a purely quantum mechanical process? (No)
- Can Brown-Twiss intensity correlations lead to ghost imaging? (Yes)

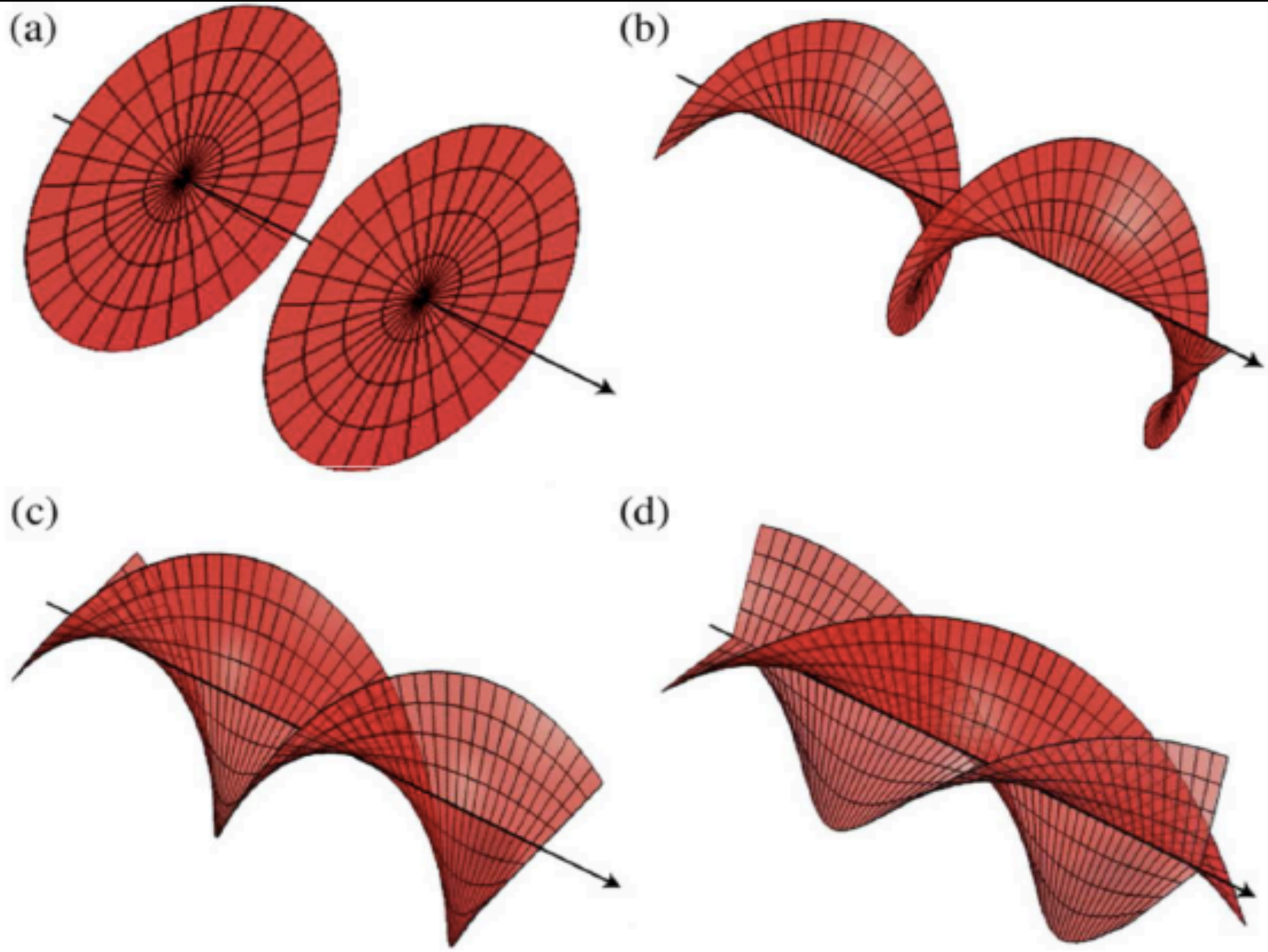


D. N. Klyshko, Sov. Phys. JETP 67, 1131 (1988).

Strekalov et al., Phys. Rev. Lett. 74, 3600 (1995).
Pittman et al., Phys. Rev. A 52 R3429 (1995).
Abouraddy et al., Phys. Rev. Lett. 87, 123602 (2001).
Bennink, Bentley, and Boyd, Phys. Rev. Lett. 89 113601 (2002).

Bennink, Bentley, Boyd, and Howell, PRL 92 033601 (2004)
Gatti, Brambilla, and Lugiato, PRL 90 133603 (2003)
Gatti, Brambilla, Bache, and Lugiato, PRL 93 093602 (2003)

Rotating wavefronts

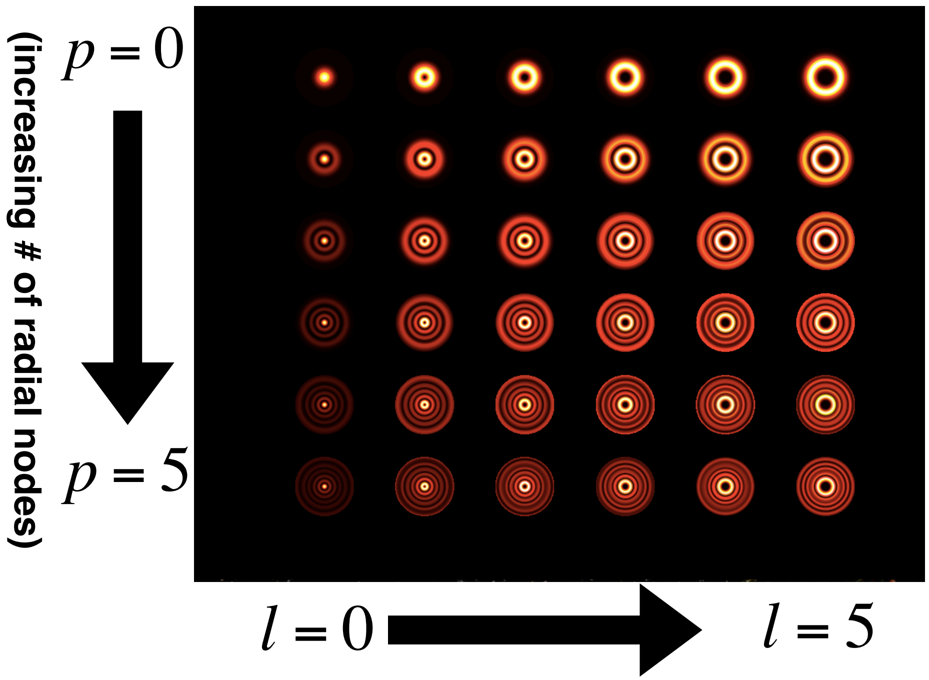


Helical phase fronts for (a) $\ell = 0$, (b) $\ell = 1$, (c) $\ell = 2$, and (d) $\ell = 3$.

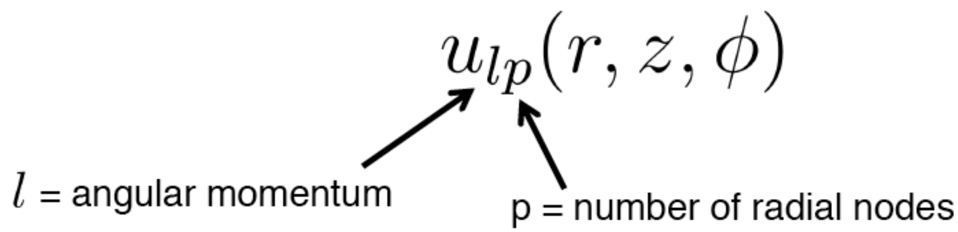
OAM States

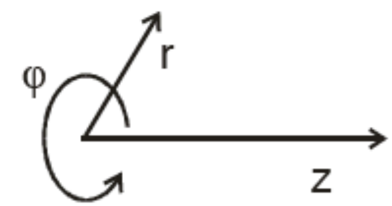
- Each Laguerre-Gauss mode, $u_{lp}(r,\phi,z)$, **carries OAM** $l\hbar$ and has p radial nodes : $p \in [0,1,2,...]$ $l \in [-\infty,...-1,0,1,...,\infty]$

Intensity Plots (l,p)

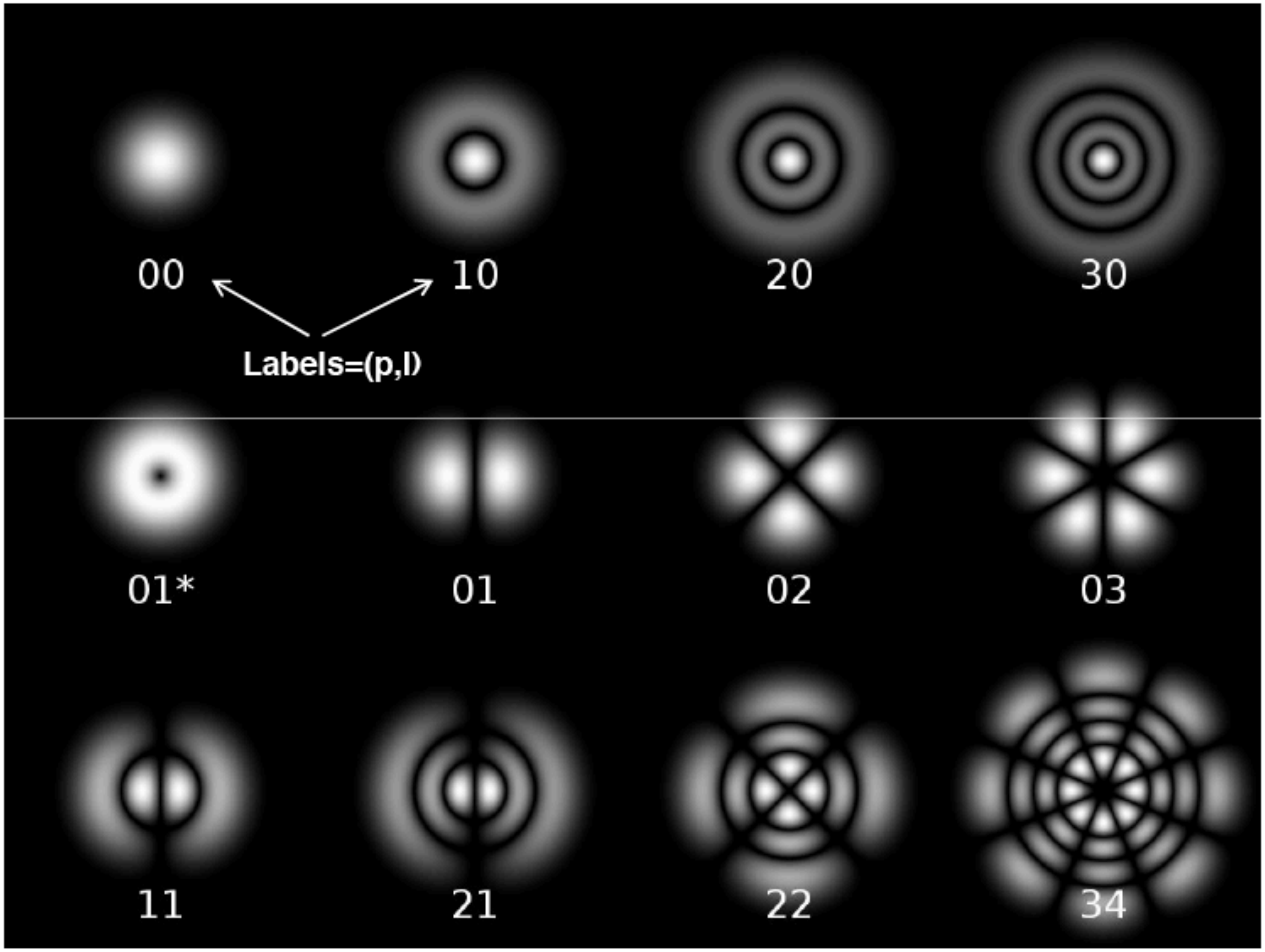


(increasing value of OAM)



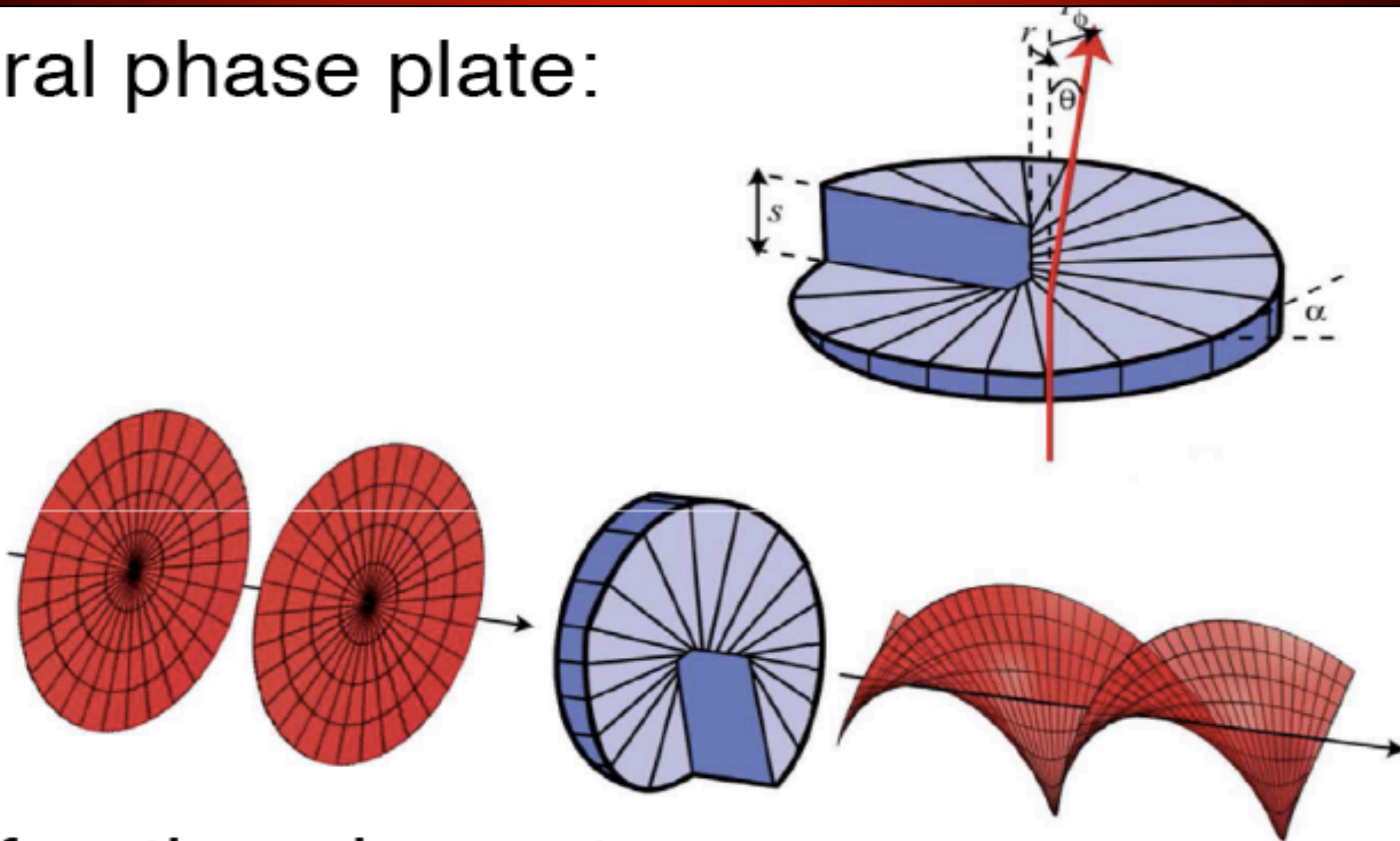


Laguerre-Gauss Interfered with Plane Wave



How to produce OAM states?

- Spiral phase plate:



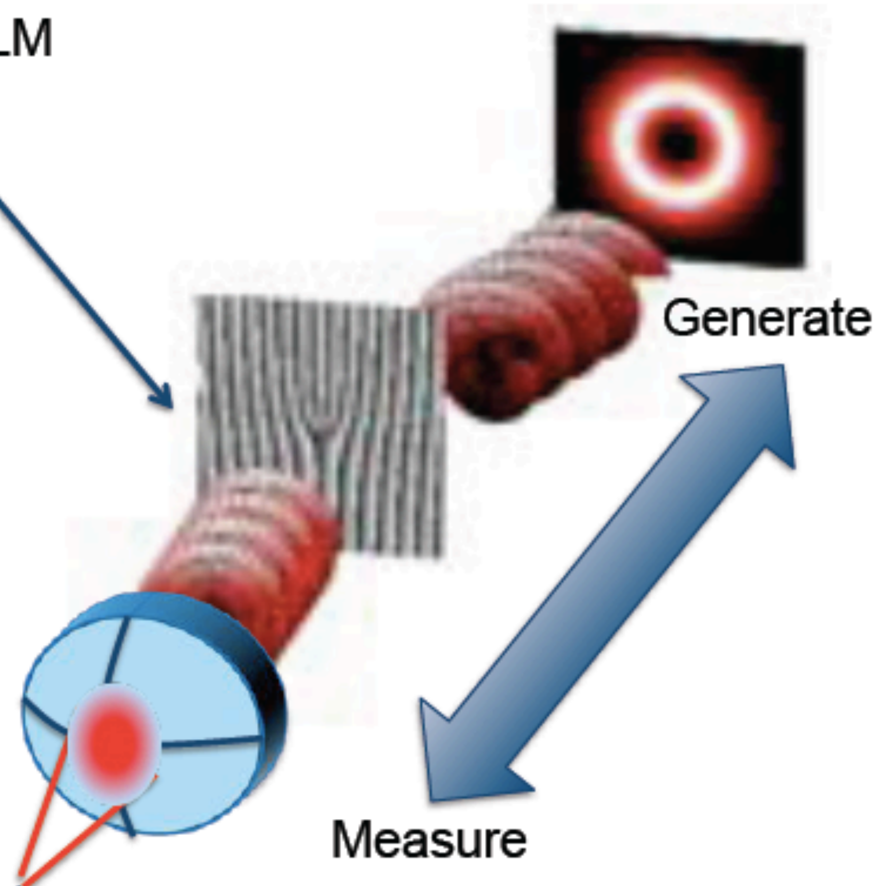
- Refractive element.
- Optical thickness: $t = \lambda l \phi / 2\pi$

Illustration from A.M. Yau & M.J. Padgett, Advances in Optics and Photonics 3, 161–204 (2011)

How to produce OAM states?

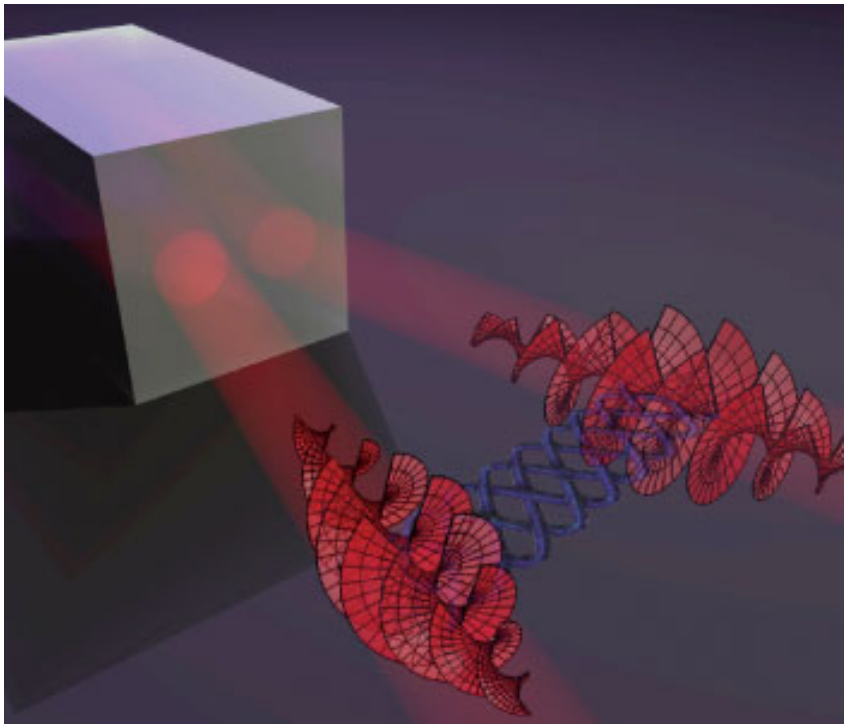
Make interactive by using SLM

Switching time
≈5-20mSec
Efficiency ≈50%



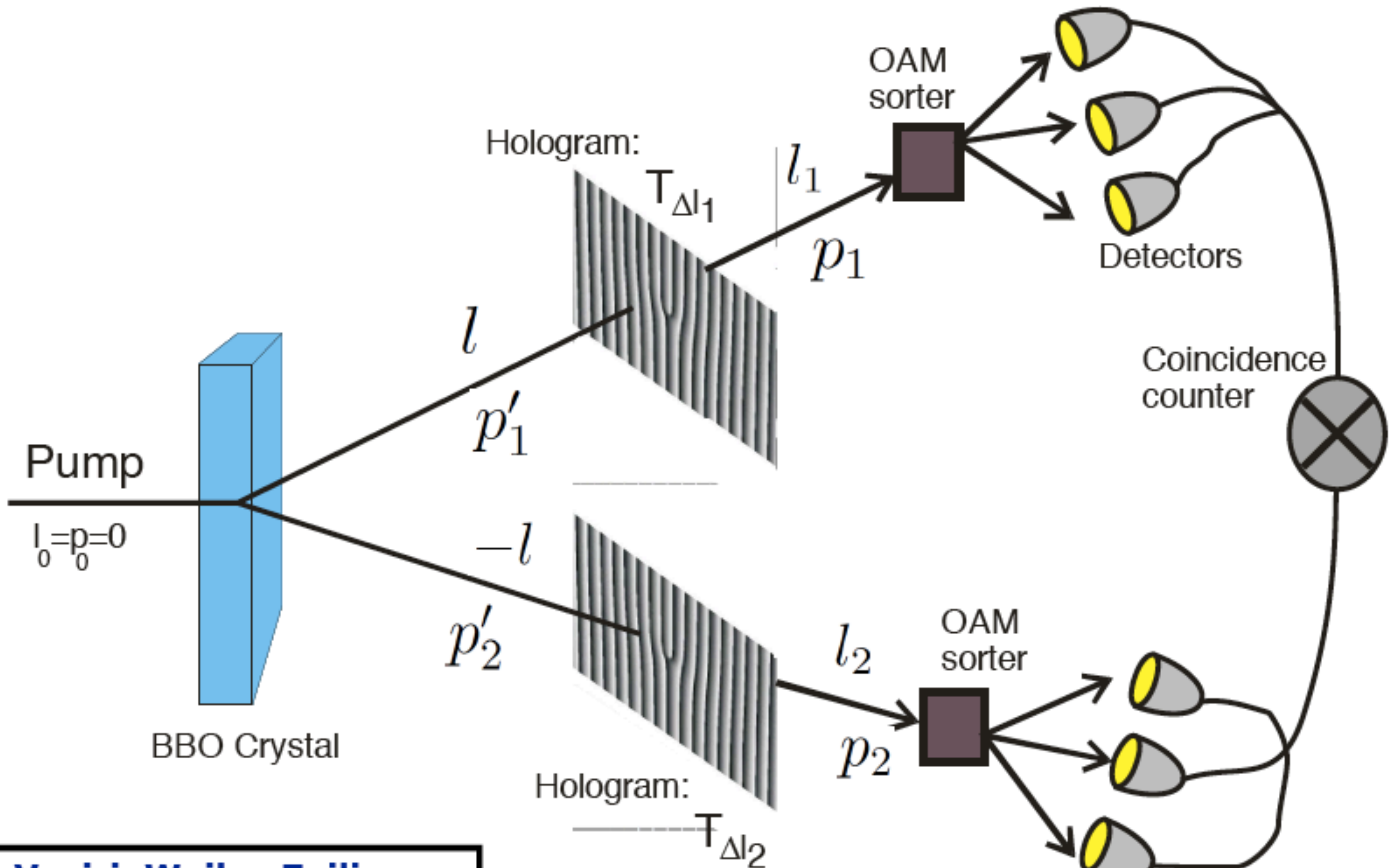
Light source
OR detector

Conservation of OAM in parametric down conversion (in paraxial case):



$$l_{signal} + l_{idler} = l_{pump}$$

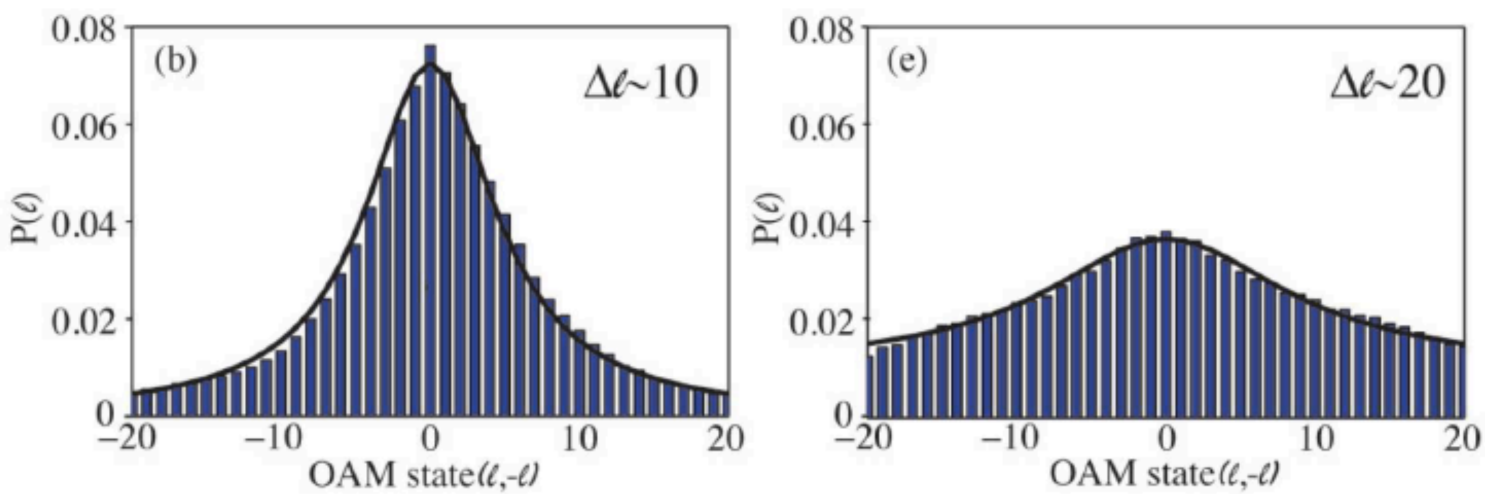
Entangled OAM



Mair, Vaziri, Weihs, Zeilinger, Nature 412, 313 (2001)

Entangled OAM

- The width of the span of OAM values (*the spiral spectrum*) depends on properties of pump and crystal.
- Entangled spiral spectra several dozen values wide have been achieved:

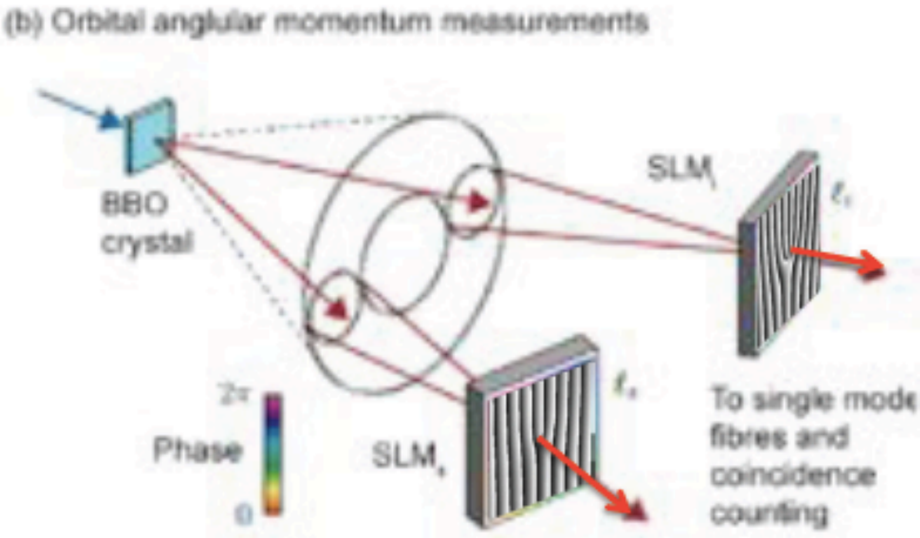


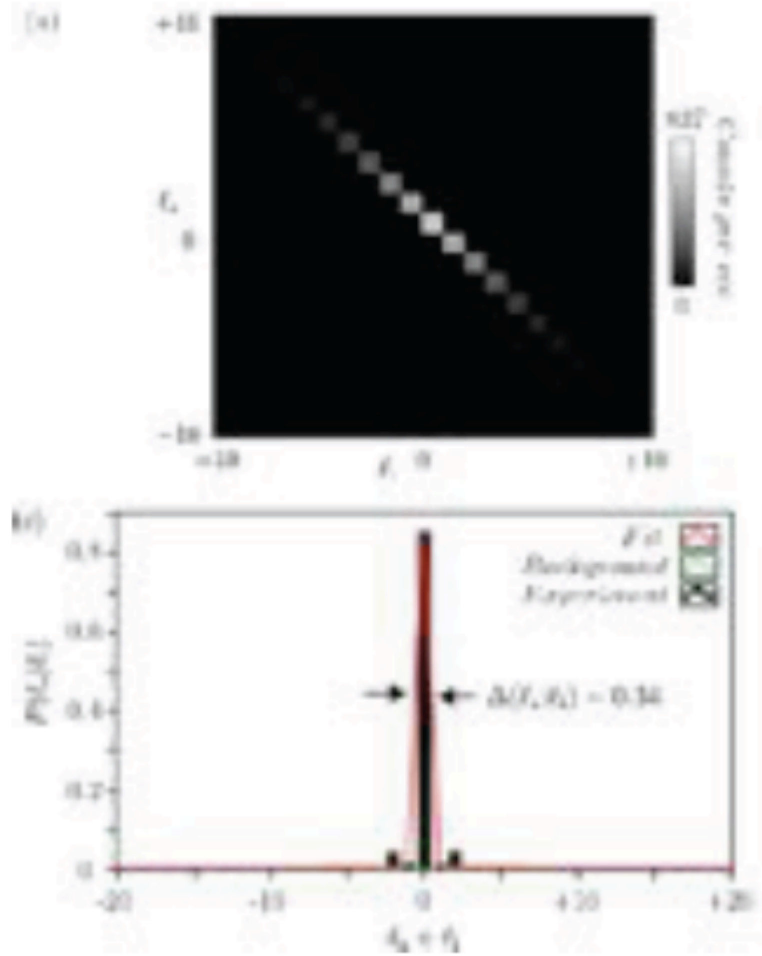
J. Romero, D. Giovannini, S. Franke-Arnold, S. M. Barnett, M. J. Padgett, arXiv:1205.1968.v1[quant-ph] (2012).

University of Glasgow

SPDC and correlated OAM

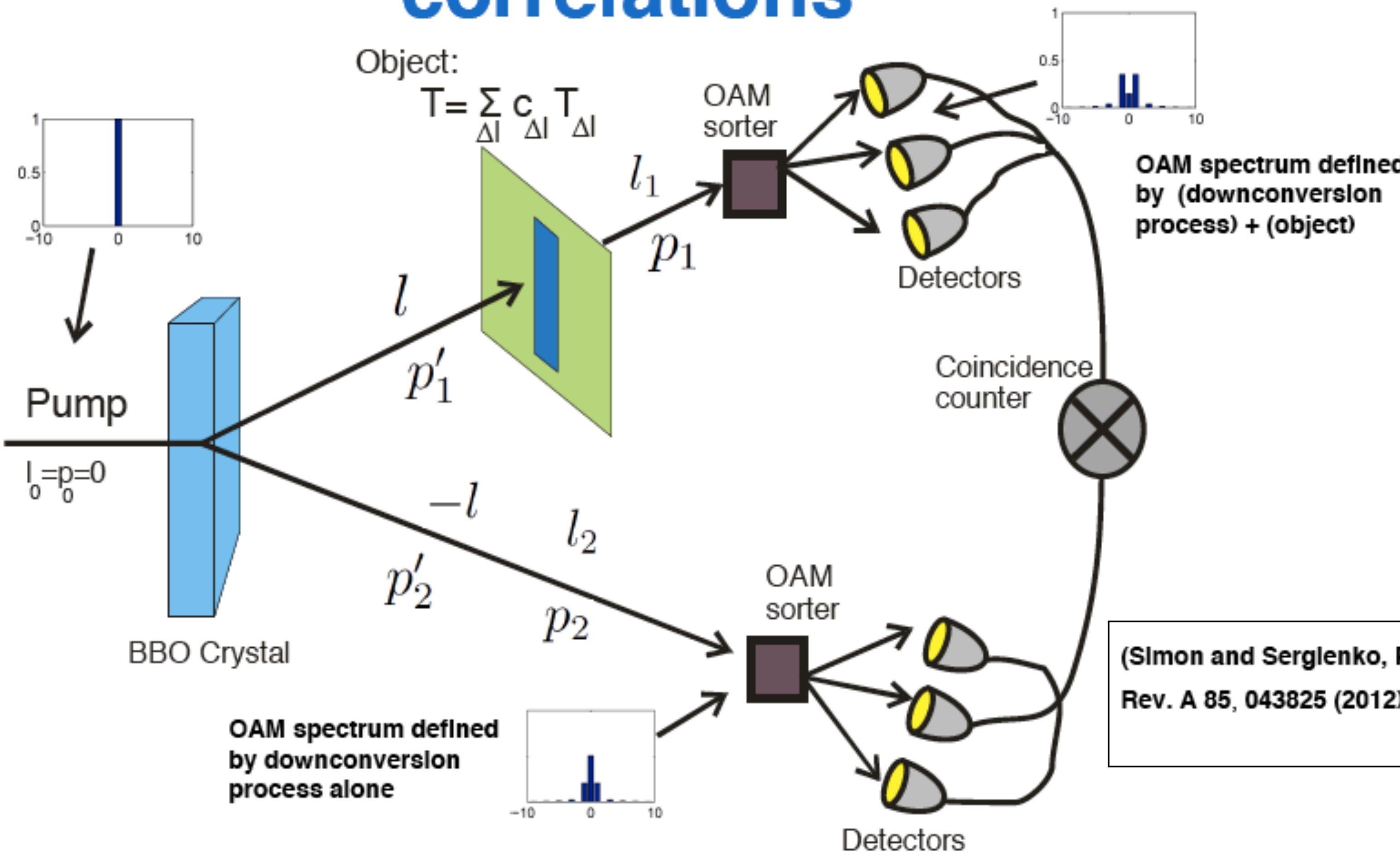
Correlations angular momentum





Near perfect (anti)
Correlations in Angular
momentum

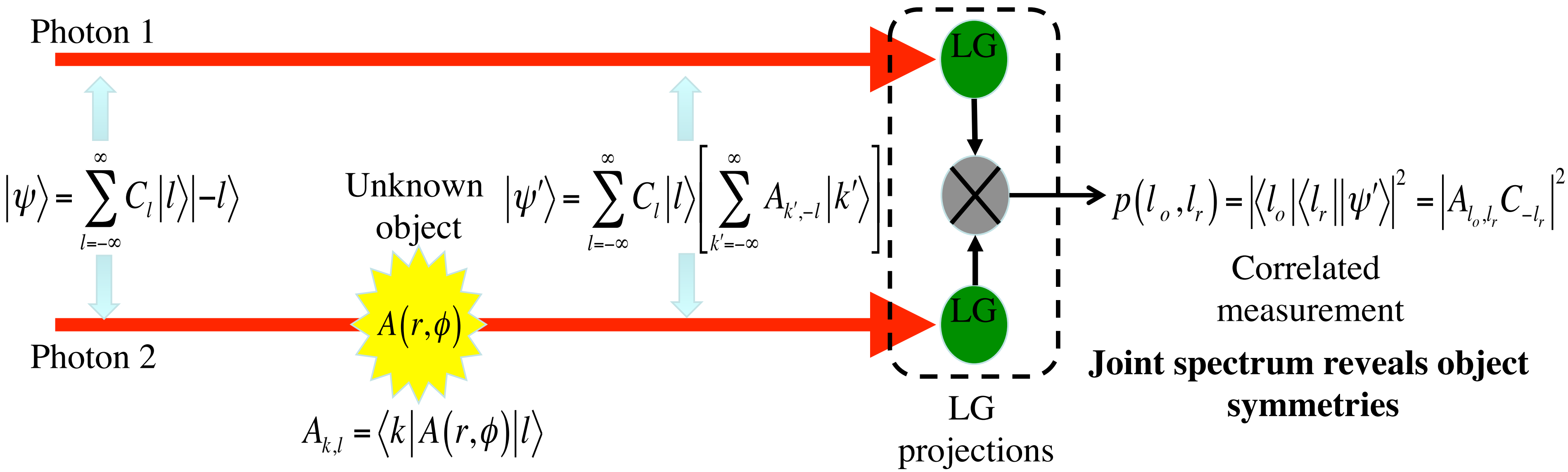
Studying effect of object on OAM correlations



(Simon and Sergienko, Phys. Rev. A 85, 043825 (2012))

- Correlations should be capable of reconstruction object.

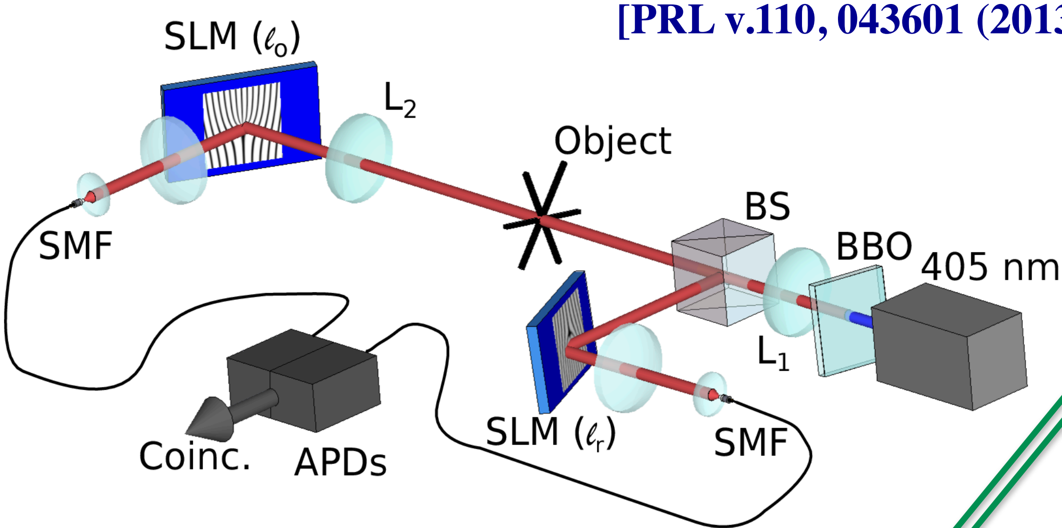
Correlated OAM Imaging



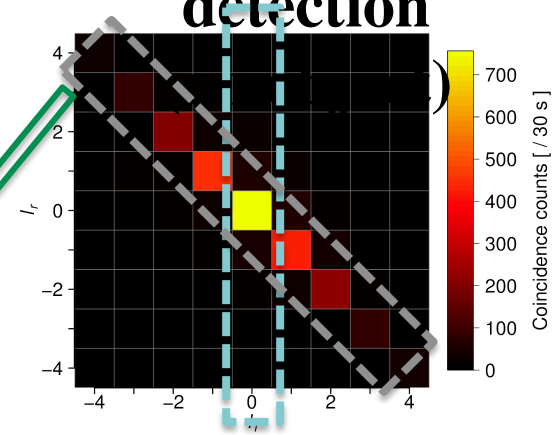
Hi-efficiency object identification using correlated orbital angular momentum states

OAM base is more sensitive to symmetry features of objects

[PRL v.110, 043601 (2013)]

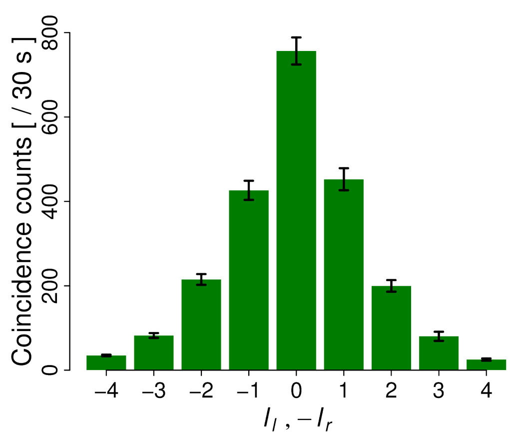


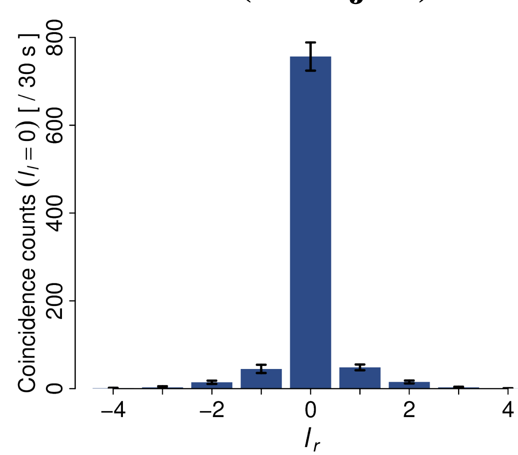
Correlated OAM detection



Diagonal elements ($l_0 = -l_r$) conventional OAM imaging (no object)

Off-diagonal elements - OAM signatures of scattering objects (no object)





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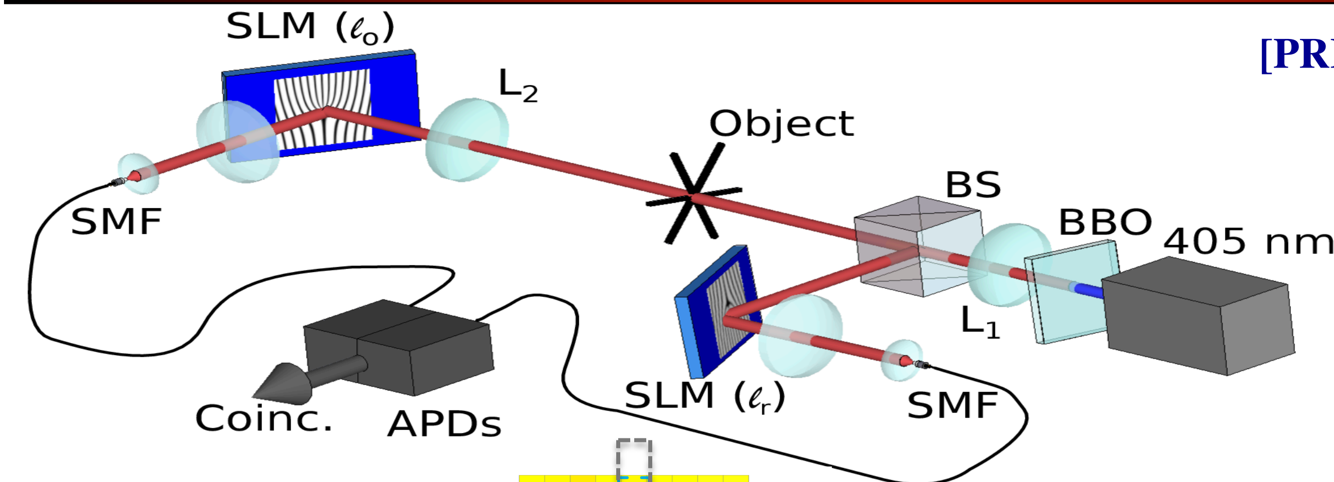
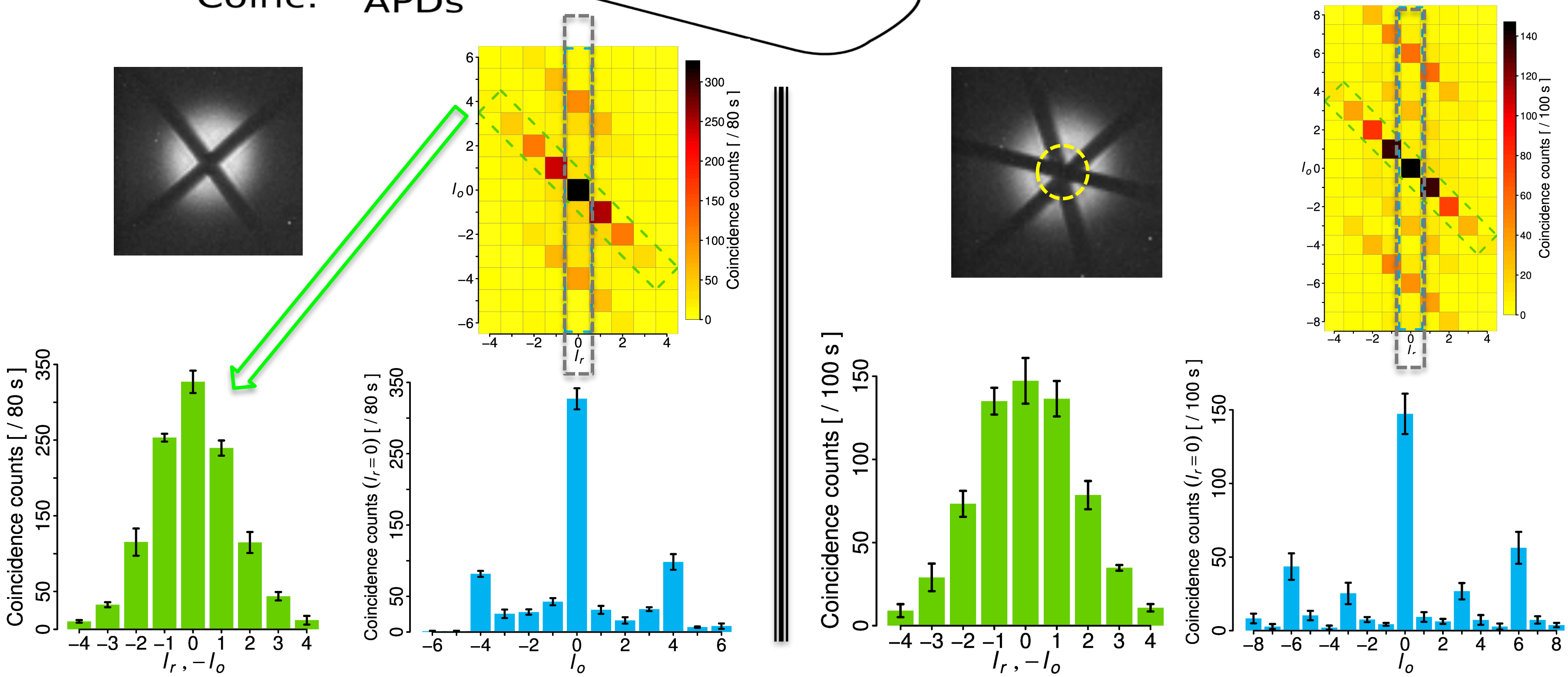
Hi-efficiency object identification using correlated orbital angular momentum states

Novelty: Off-diagonal correlation elements reveal OAM signatures of the object

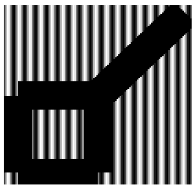
[PRL v.110, 043601 (2013)]



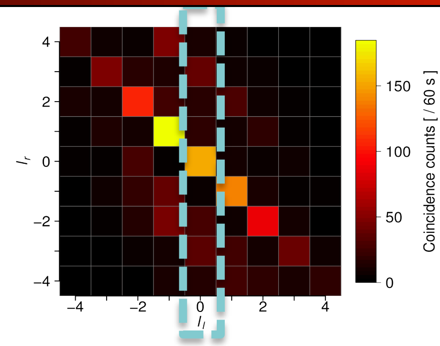


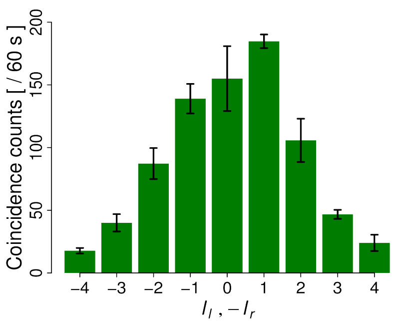
Hi-efficiency object identification using correlated orbital angular momentum states

Correlated OAM provides more information about the object per detected photon

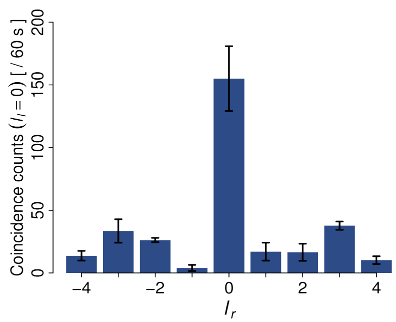


"Tank"





Traditional OAM imaging (diagonal)



New correlated OAM imaging (vertical)

Shannon information:

$$I = \sum_{l_0,l_r} p(l_0,l_r)\log_2 p(l_0,l_r)$$

$p(l_0,l_r)$ = probability distribution for coincidences

No object: terms restricted to diagonal, contain information about SPDC and pump.

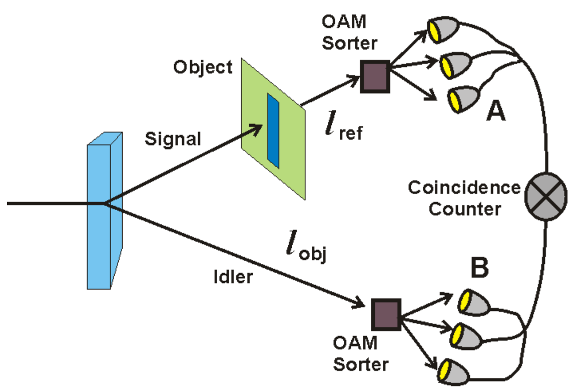
With object: Off-diagonal terms contain information *only* about object.

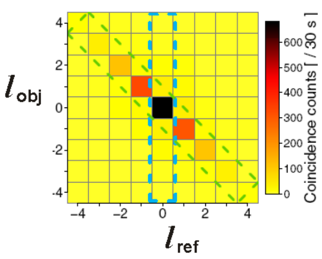
For objects considered, information per photon pair carried by off-diagonal elements: ***I* ≈ 5.7 bits**

[PRL v.110, 043601 (2013)]

Object Recognition with Correlated OAM

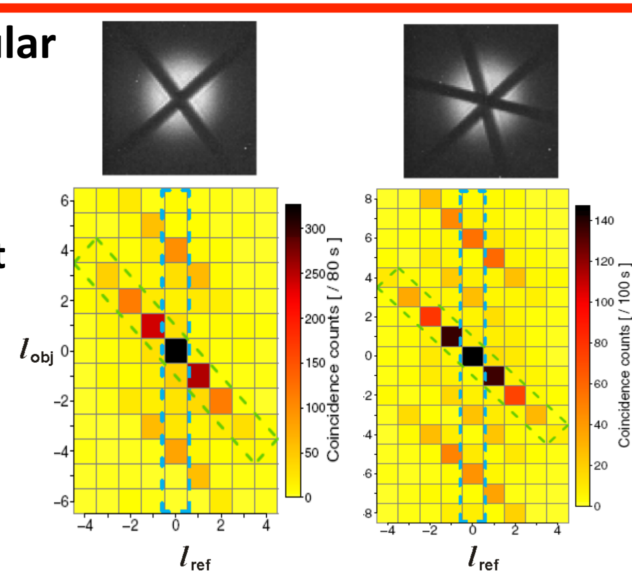
Sensing symmetry: coincidence counts versus orbital angular momenta (OAM) of two entangled photons:





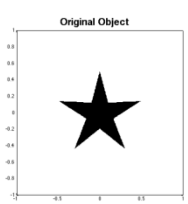
No Object

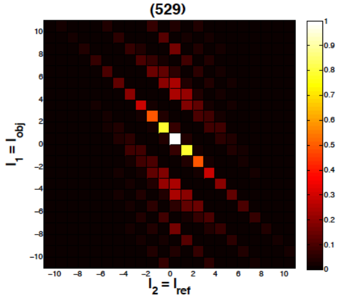
Insert Object

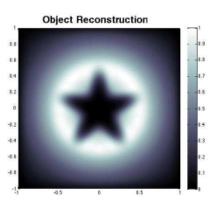


Uribe-Patarroyo, Fraine, Simon, Minaeva, Sergienko, Phys. Rev. Lett. 110, 043601 (2013)

Correlated OAM Imaging : reconstruction of objects based on OAM coincidence spectrum detection:

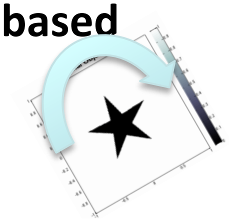


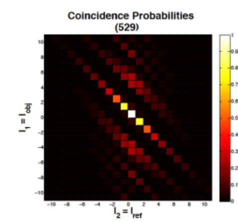




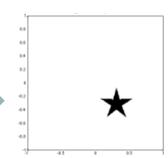
Object Fixed & Centered

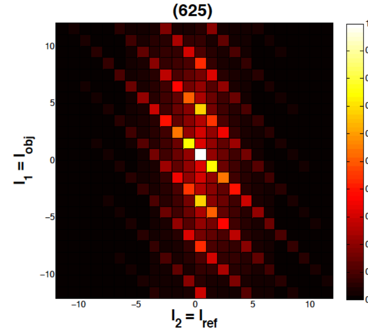
Rotation

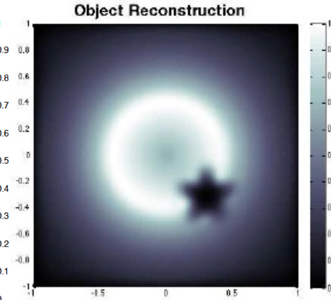




Shrink & Translate







Fitzpatrick, Simon, Sergienko, (arXiv 1310.2453(2013))

Object Recognition with Correlated OAM

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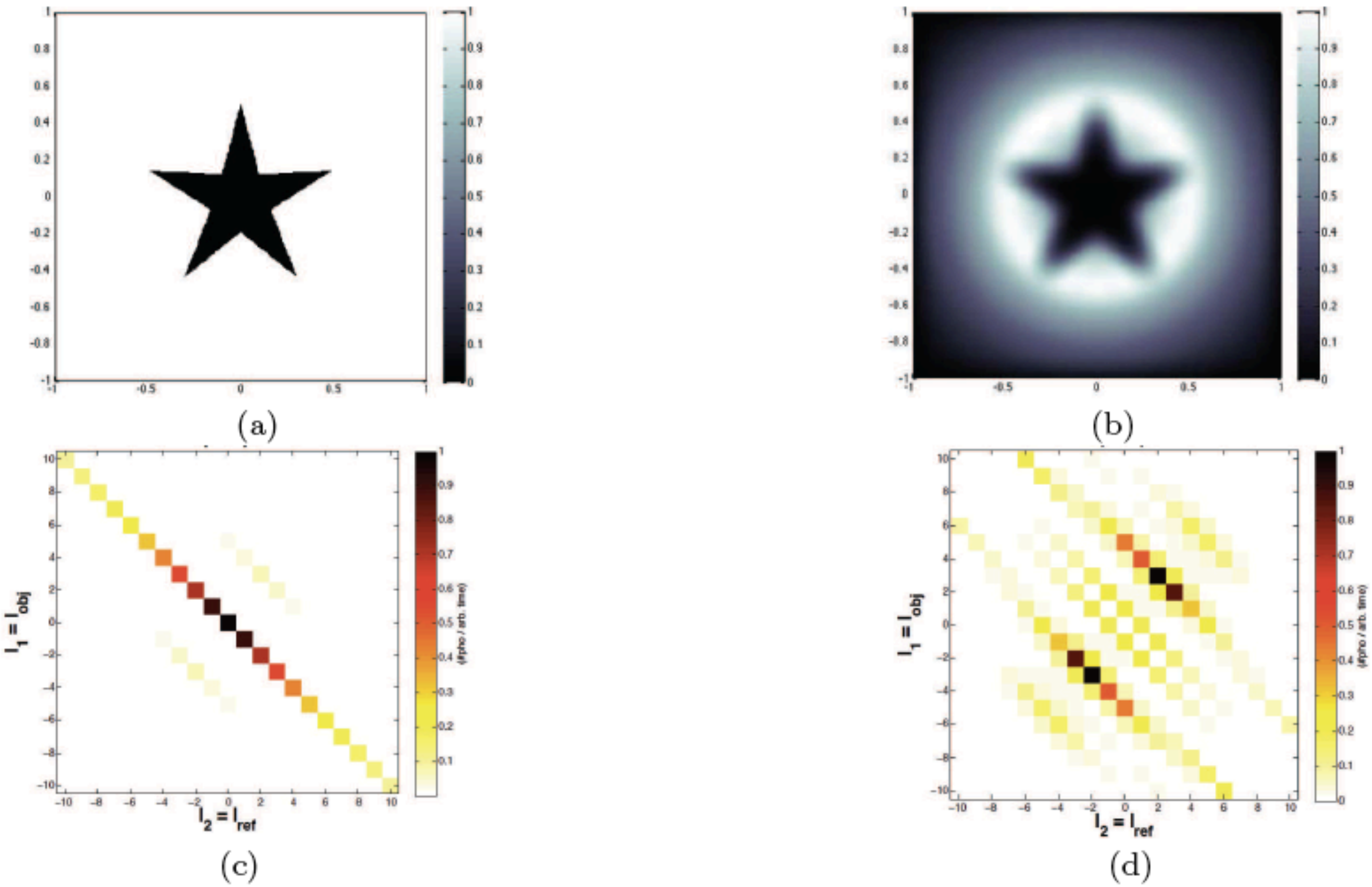

FIG. 15: (a) Opaque star object of max width $0.9w_0$ and, (b) the ESI reconstruction using $l_{max} = 10$, $p_{max} = 7$; (c) The joint OAM spectrum of the star, having summed over all p, and (d) the same spectrum with the conservation diagonal removed.

(arXiv 1310.2453(2013))

Object Recognition with Correlated OAM

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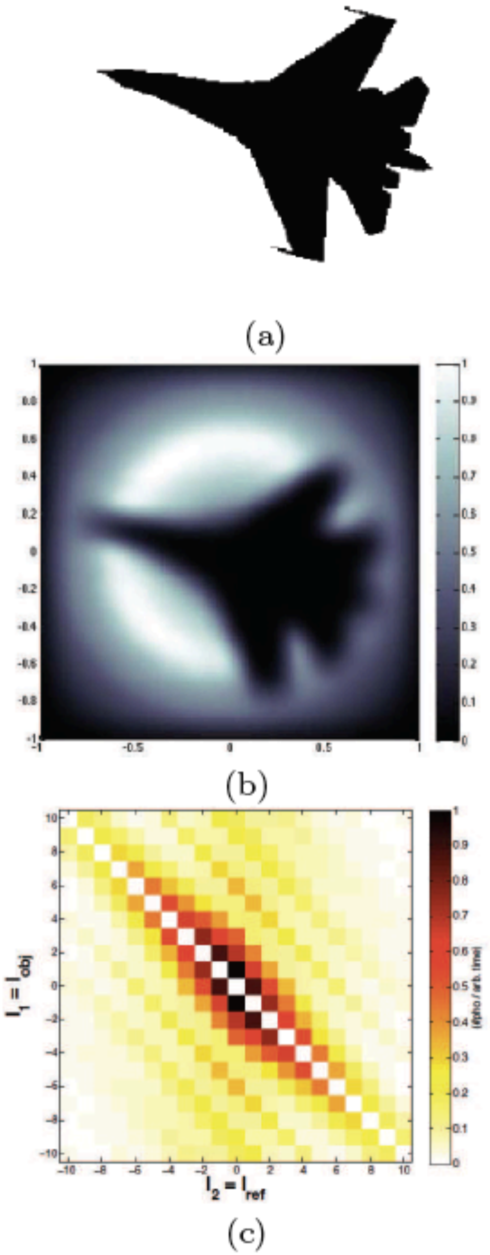
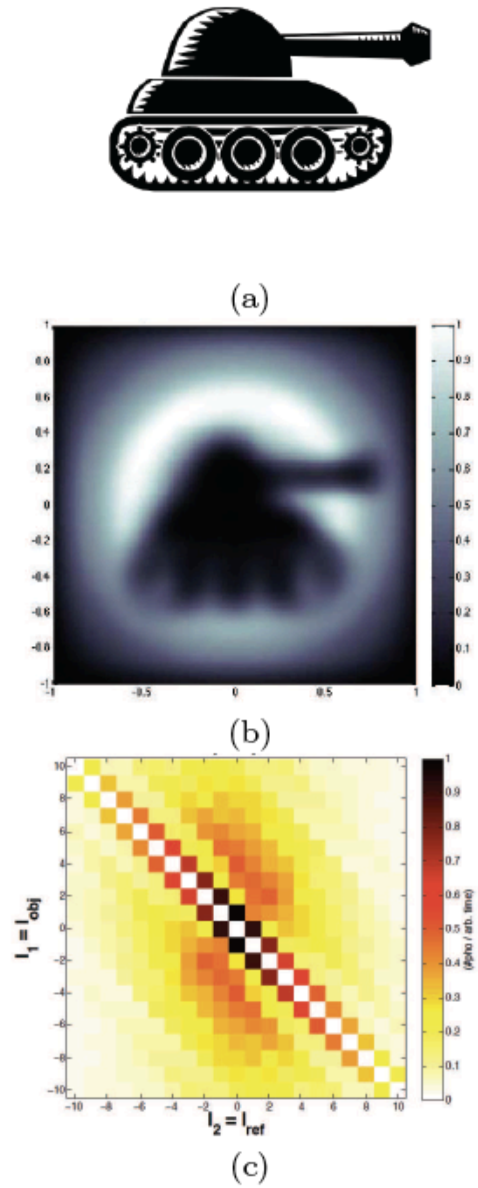
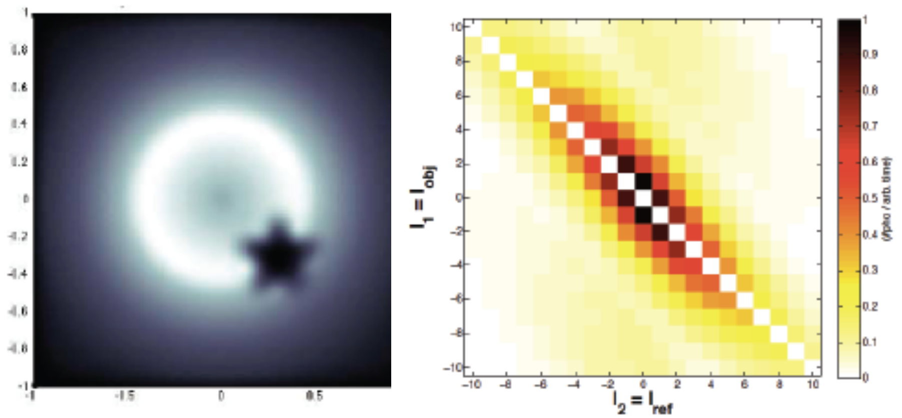


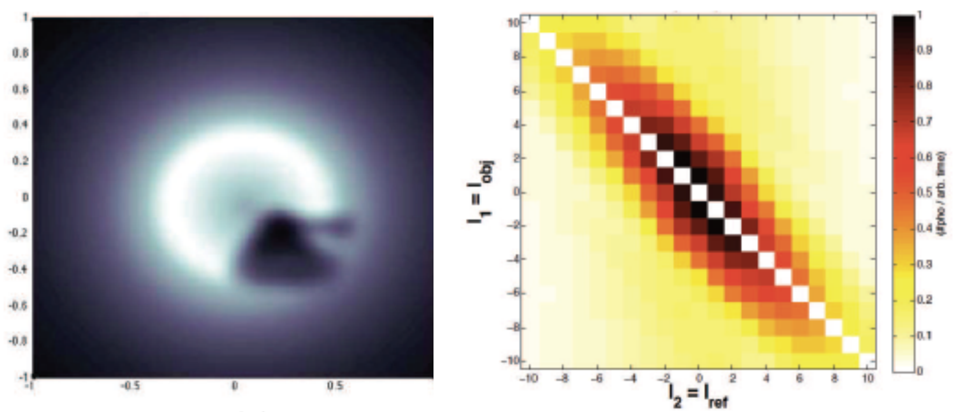


(arXiv 1310.2453(2013))

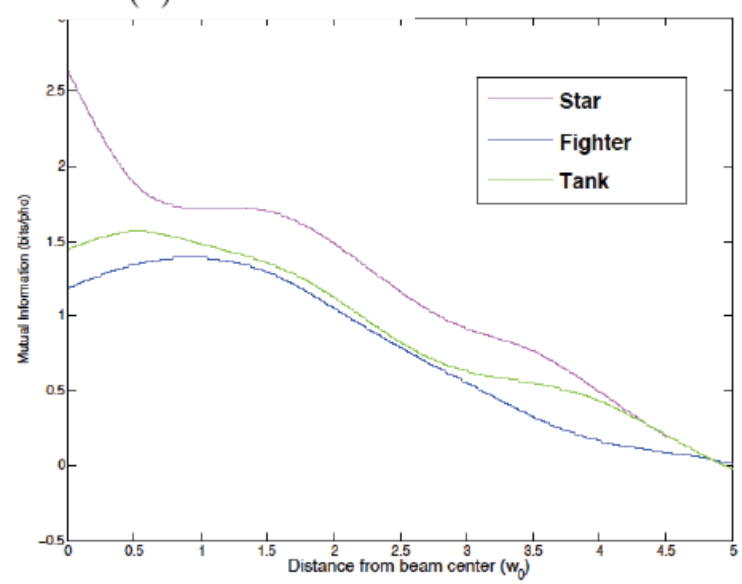
Object Recognition and Imaging with Correlated OAM
(off-axis)



(a) (b)



(a) (b)



(arXiv 1310.2453(2013))

FIG. 21: *Mutual information carried by off-diagonal components of joint OAM spectrum, for various objects, as a function of distance from beam center with* $l_{max} = 10, p_{max} = 5$; *increasing* p_{max} *will increase the mutual information substantially. Note that each object's off-diagonal information content exceeds one bit per photon at the beam center.*

Conclusions and Future

Conclusions:

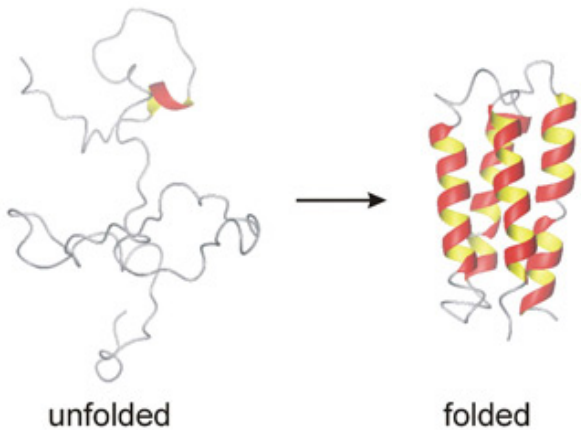
- Experimental demonstration of efficient object identification with correlated OAM spectrum detection
- Hi-information capacity object recognition due to enhanced sensitivity of OAM to symmetry components of the object

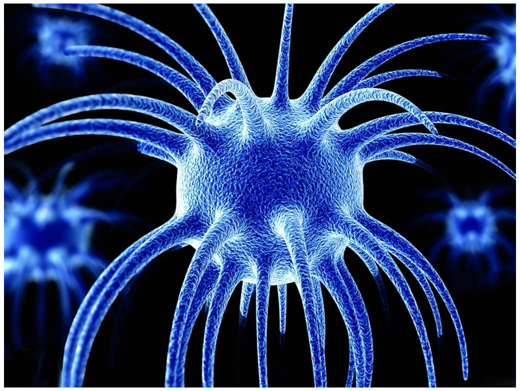
[PRL v.110, 043601 (2013)]

Conclusions and Future

Future:

Possible applications in biology include efficient non-invasive recognition of biological samples with particular symmetries in known states. For example, protein folding and virus detection. In addition, efficient recognition of fabrication abnormalities in industrial quality control could benefit from efficient symmetry detection.





Different biological objects have distinct azimuthal symmetries

Future:

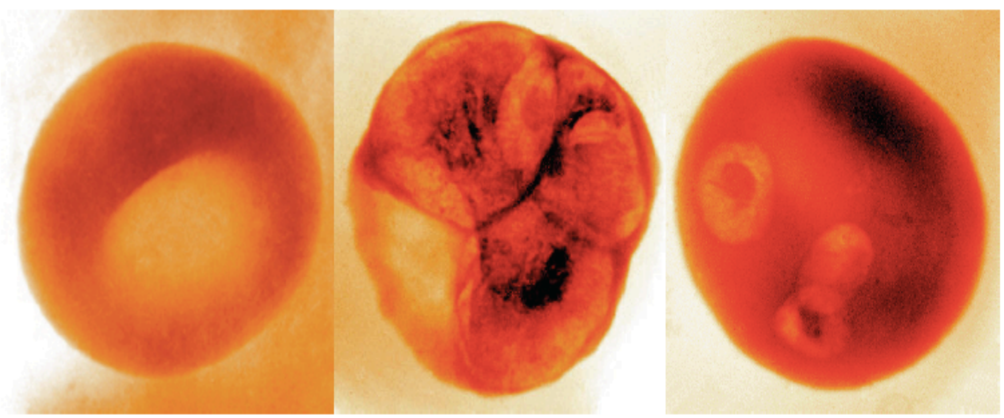
Efficient Object Imaging using Correlated (Compressive) imaging with OAM X-rays

Applications in biology and security

Single-photon X-ray correlation and phase gratings for OAM creation and detection is technologically feasible

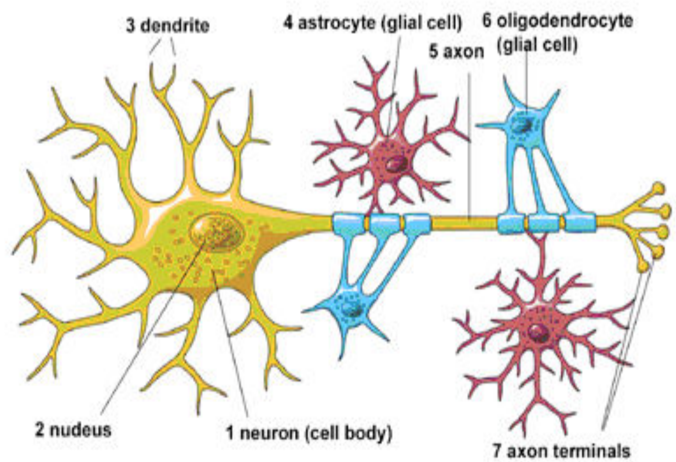
Phase sensitive detection will be replaced by X-ray tomography

Conventional X-ray imaging of symmetry-dependent changes in blood cells that could be replaced by more efficient correlated OAM detection



X-ray images of malaria infected blood cells obtained at 2.4nm wavelength. Left: uninfected cell, Center: newly infected cell, Right: cell 36h after infection.

C. Magowan, W. Meyer-Ilse and J.Brown, LBNL



The architecture of the neuron.

Acknowledgements

- *DARPA "Information on a Photon" program*
- *DARPA "QUINESS" program*
- *NSF*
- *Boston University Photonics Center*

Thank You For Your Attention!!