# Hanbury Brown and Twiss Interferometry with Twisted Light

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The Institute of Optics and
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RESEARCH ARTICLE

OPTICS

# Hanbury Brown and Twiss interferometry with twisted light

Omar S. Magaña-Loaiza,[1]* Mohammad Mirhosseini,[1] Robert M. Cross,[1] Seyed Mohammad Hashemi Rafsanjani,[1] Robert W. Boyd[1,2]

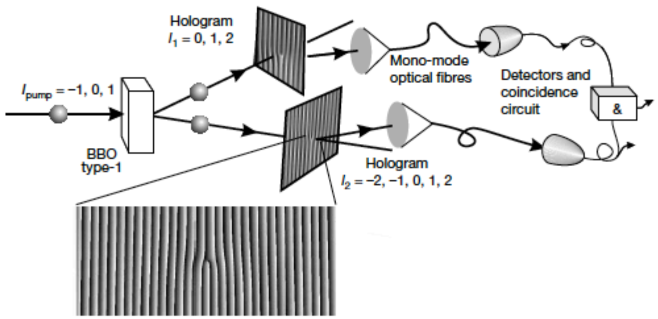
# Background

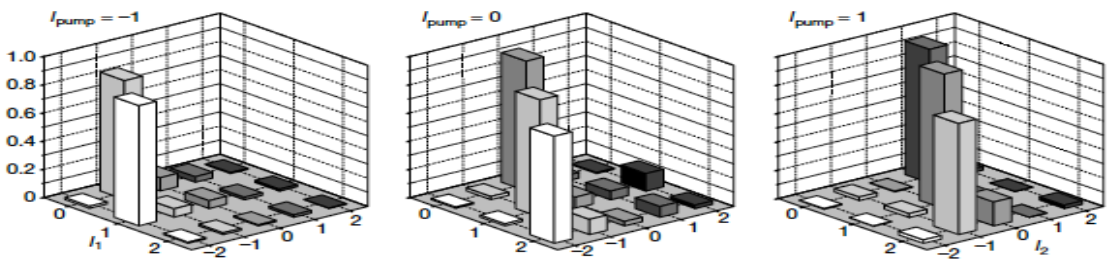
## Entanglement of the orbital angular momentum states of photons

**Alois Mair*, Alipasha Vaziri, Gregor Weihs & Anton Zeilinger**

*Institut für Experimentalphysik, Universität Wien, Boltzmanngasse 5, 1090 Wien, Austria*

NATURE | VOL 412 | 19 JULY 2001 | www.nature.com

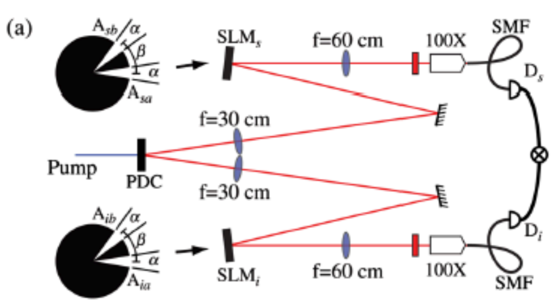


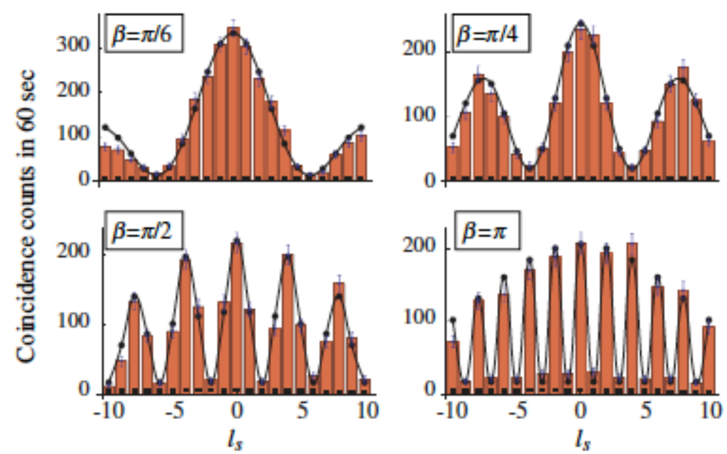




PRL 104, 010501 (2010) PHYSICAL REVIEW LETTERS week ending 8 JANUARY 2010

## Angular Two-Photon Interference and Angular Two-Qubit States

Anand Kumar Jha,[1] Jonathan Leach,[2] Barry Jack,[2] Sonja Franke-Arnold,[2] Stephen M. Barnett,[3] Robert W. Boyd,[1] and Miles J. Padgett[2]



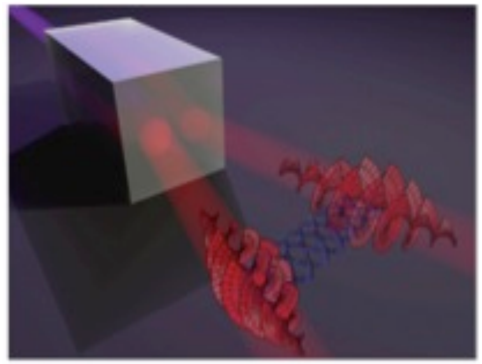



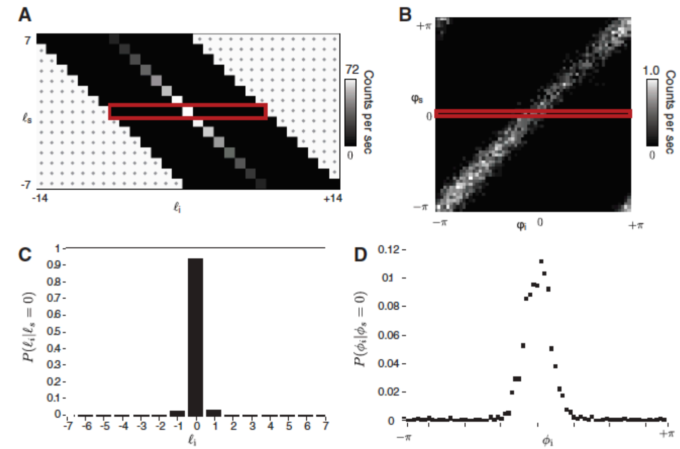
# Background

## Quantum Correlations in Optical Angle–Orbital Angular Momentum Variables

Jonathan Leach,[1] Barry Jack,[1] Jacqui Romero,[1] Anand K. Jha,[2] Alison M. Yao,[3] Sonja Franke-Arnold,[1] David G. Ireland,[1] Robert W. Boyd,[2] Stephen M. Barnett,[3] Miles J. Padgett[1*]

6 AUGUST 2010 VOL 329 SCIENCE www.sciencemag.org

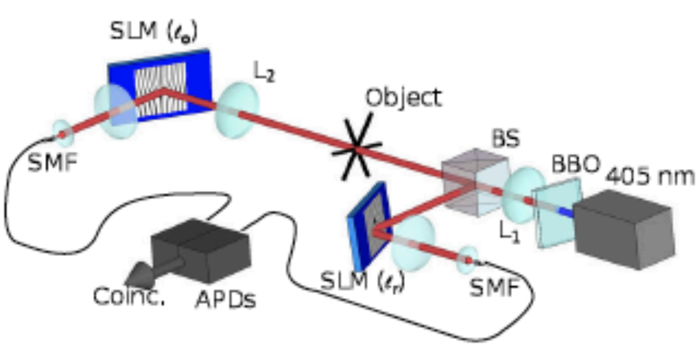


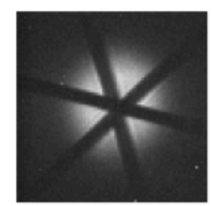



PRL 110, 043601 (2013) PHYSICAL REVIEW LETTERS week ending 25 JANUARY 2013

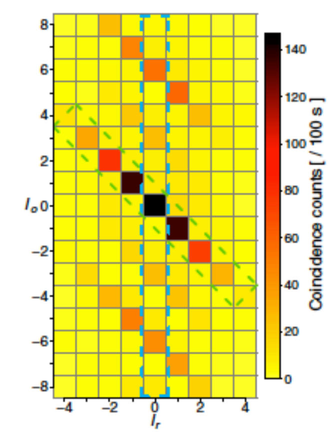
## Object Identification Using Correlated Orbital Angular Momentum States

Néstor Uribe-Patarroyo,[1,*] Andrew Fraine,[1] David S. Simon,[1,2] Olga Minaeva,[3] and Alexander V. Sergienko[1,4]



(a)

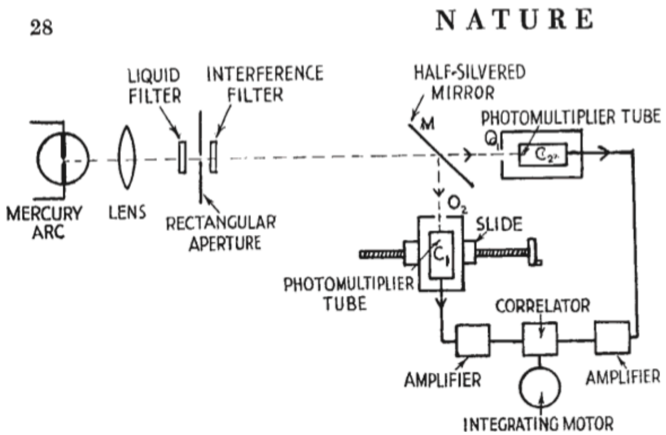



(b)

# Chaotic fields of light

## Random wave fields

### HBT Effect




REVIEW ARTICLES | FOCUS
nature photonics
PUBLISHED ONLINE: 27 FEBRUARY 2013 | DOI: 10.1038/NPHOTON.2013.29

**Disordered photonics**

Diederik S. Wiersma

VOLUME 93, NUMBER 9 PHYSICAL REVIEW LETTERS week ending 27 AUGUST 2004

**Ghost Imaging with Thermal Light: Comparing Entanglement and Classical Correlation**

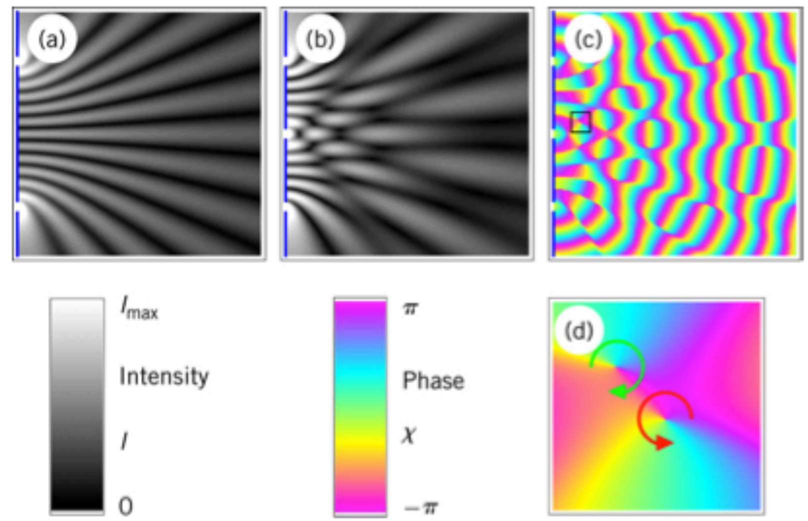
A. Gatti, E. Brambilla, M. Bache, and L. A. Lugiato

nature photonics
FOCUS | REVIEW ARTICLES
PUBLISHED ONLINE: 27 FEBRUARY 2013 | DOI: 10.1038/NPHOTON.2013.30

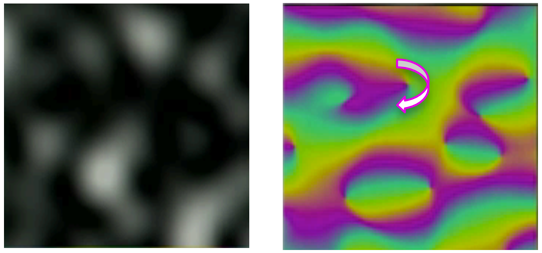
**Anderson localization of light**

Mordechai Segev[1,2]*, Yaron Silberberg[3] and Demetrios N. Christodoulides[4]

### Vortices in wave superposition




### Vortices in chaotic light



Berry, M. V. J. Phys. A: Math. Gen. 11 , 27-37 (1978).
Dennis, M. R. Optical Vortices and Polarization Singularities , vol. 53 (Elsevier B.V., 2009).

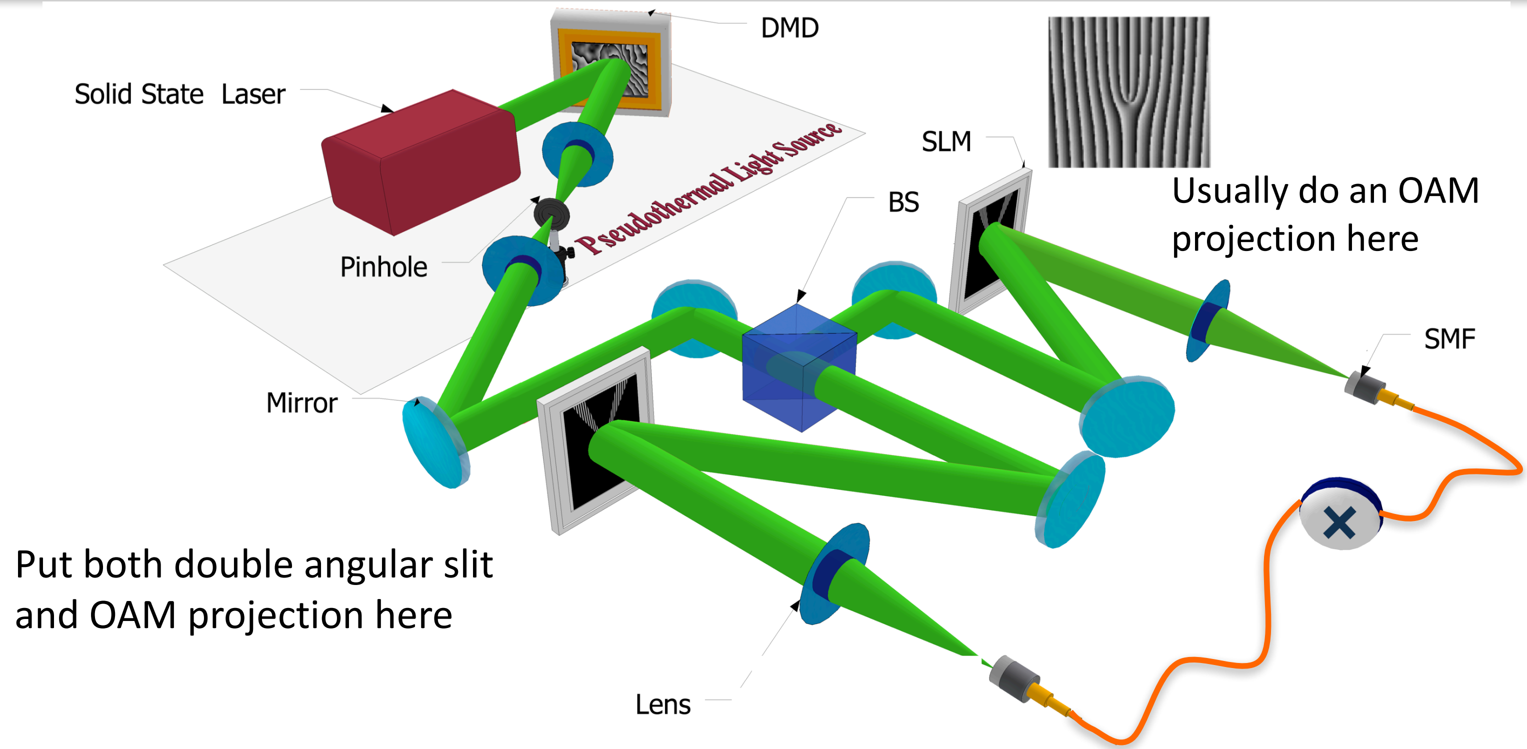
# Motivation for this study

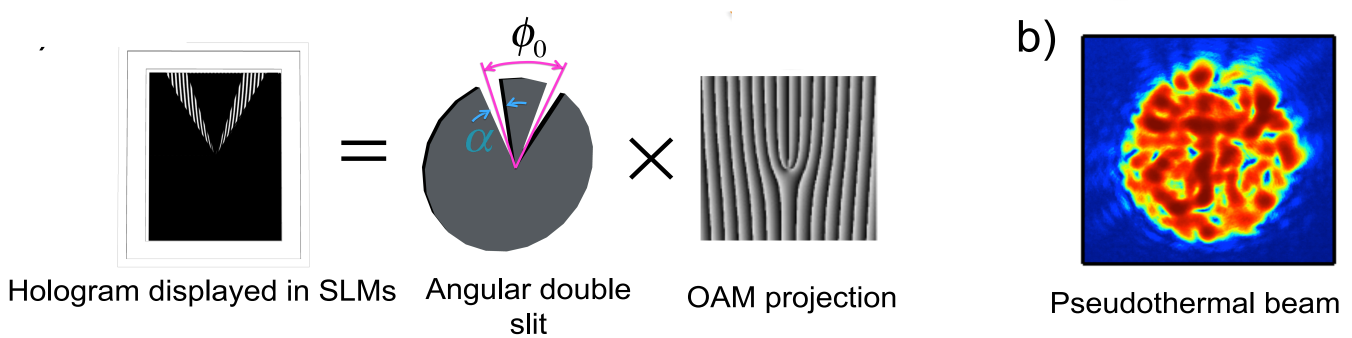
We know what Young's interference and HBT correlations look like in real space.

- What do they look like in OAM space?
- And could this be useful?

# Azimuthal Hanbury Brown and Twiss Interference

## Experimental Setup

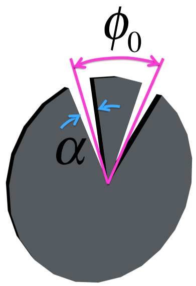


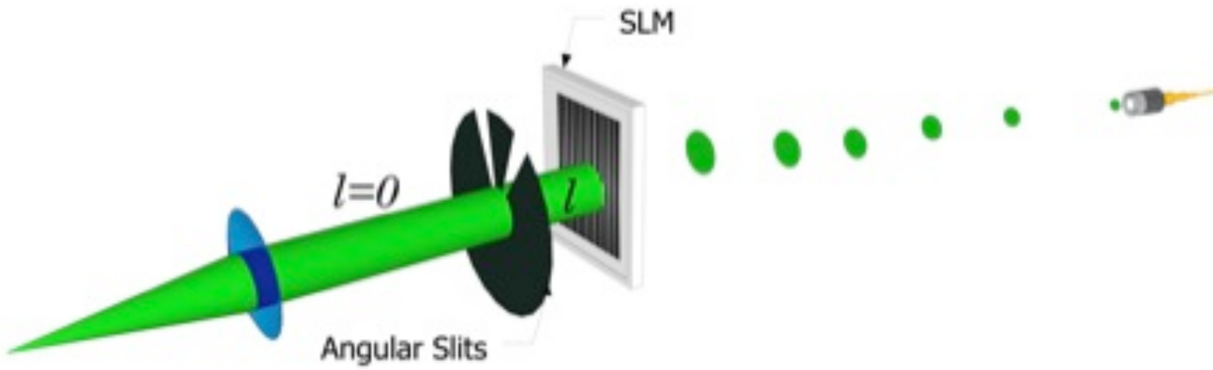




O. S. Magana-Loaiza et al., Science Advances 2, e1501143 (2016).

# Azimuthal Hanbury Brown and Twiss Interference

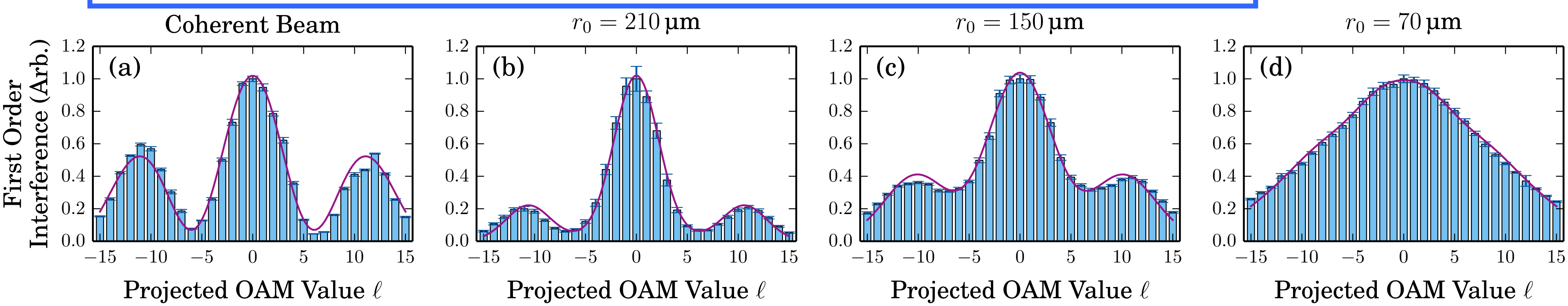
## First order Interference

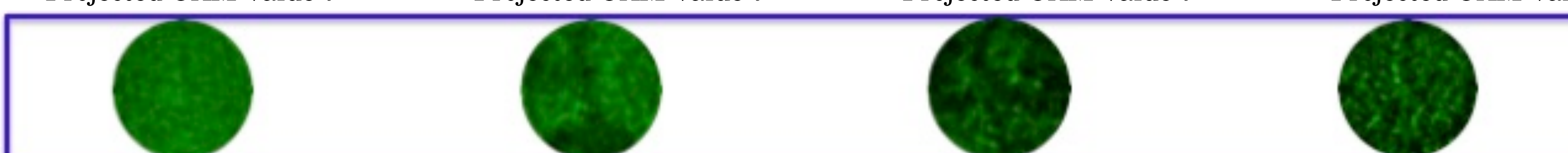



We control the spatial coherence of the illumination through use of the DMD.

$$\langle I_l \rangle \propto \frac{\alpha^2}{2\pi^2} Sinc^2\left(\frac{l\alpha}{2}\right) \int r\,dr E^2(r) \left\{ 2 + e^{-il\phi_0} \left\langle \Phi^*(r,0)\Phi(r,\phi_0) \right\rangle + e^{il\phi_0} \left\langle \Phi^*(r,\phi_0)\Phi(r,0) \right\rangle \right\}$$

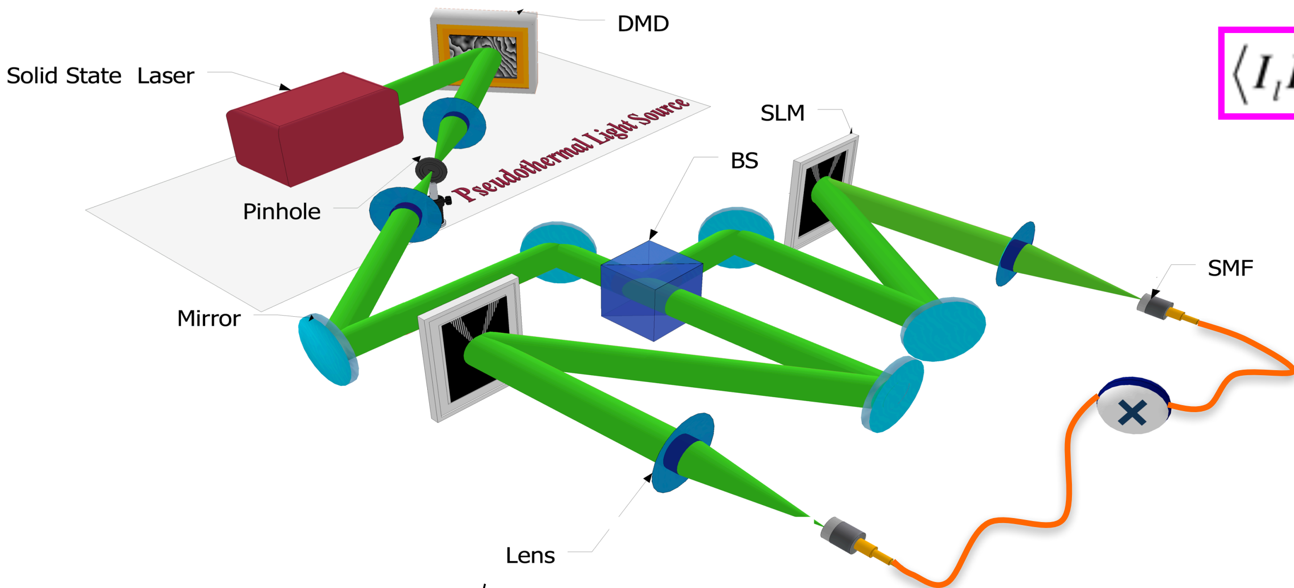


O. S. Magana-Loaiza et al., Science Advances 2, e1501143 (2016).

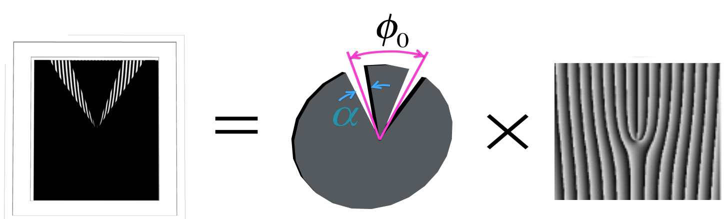
# Azimuthal Hanbury Brown and Twiss Interference

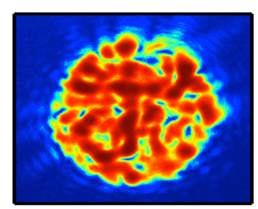
## Measurement of the azimuthal HBT effect




$$\langle I_l I_{-l}\rangle = \langle G_0\rangle + \langle G_l\rangle + \langle G_{2l}\rangle$$

Constant term



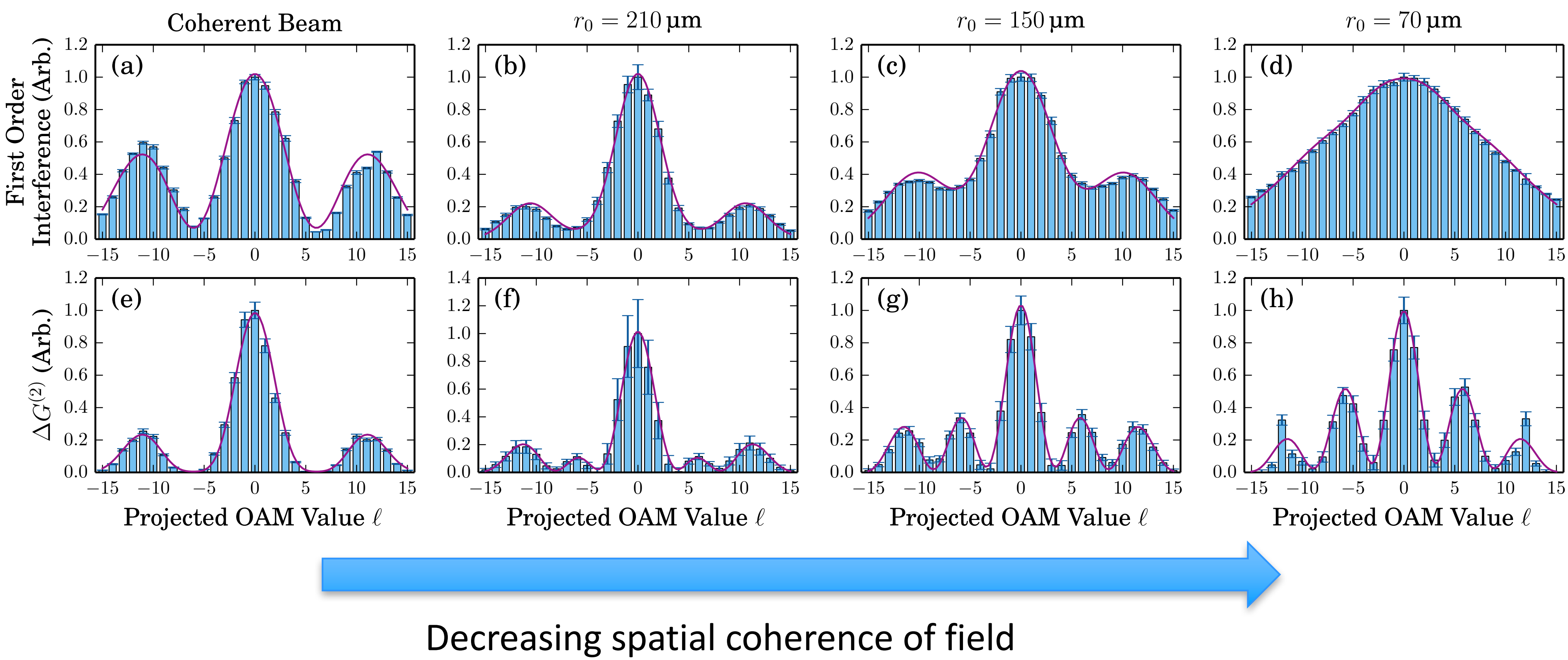
Pseudothermal beam

$$\langle G_l\rangle \propto \int r_1\, dr_1 r_2\, dr_2 \left(e^{-il\phi_0}\left\{\left\langle \Phi^*(r_1,0)\Phi(r_1,\phi_0)\right\rangle + \left\langle \Phi^*(r_2,0)\Phi(r_2,\phi_0)\right\rangle\right\} + c.c.\right)$$

$$\langle G_{2l}\rangle \propto \int r_1 dr_1 r_2 dr_2 \left(e^{-2il\phi_0}\left\{\left\langle \Phi^*(r_1,0)\Phi(r_1,\phi_0)\Phi^*(r_2,\phi_0)\Phi(r_2,0)\right\rangle\right\} + c.c.\right)$$

# Azimuthal Hanbury Brown and Twiss Interference

## OAM correlations: Experimental results

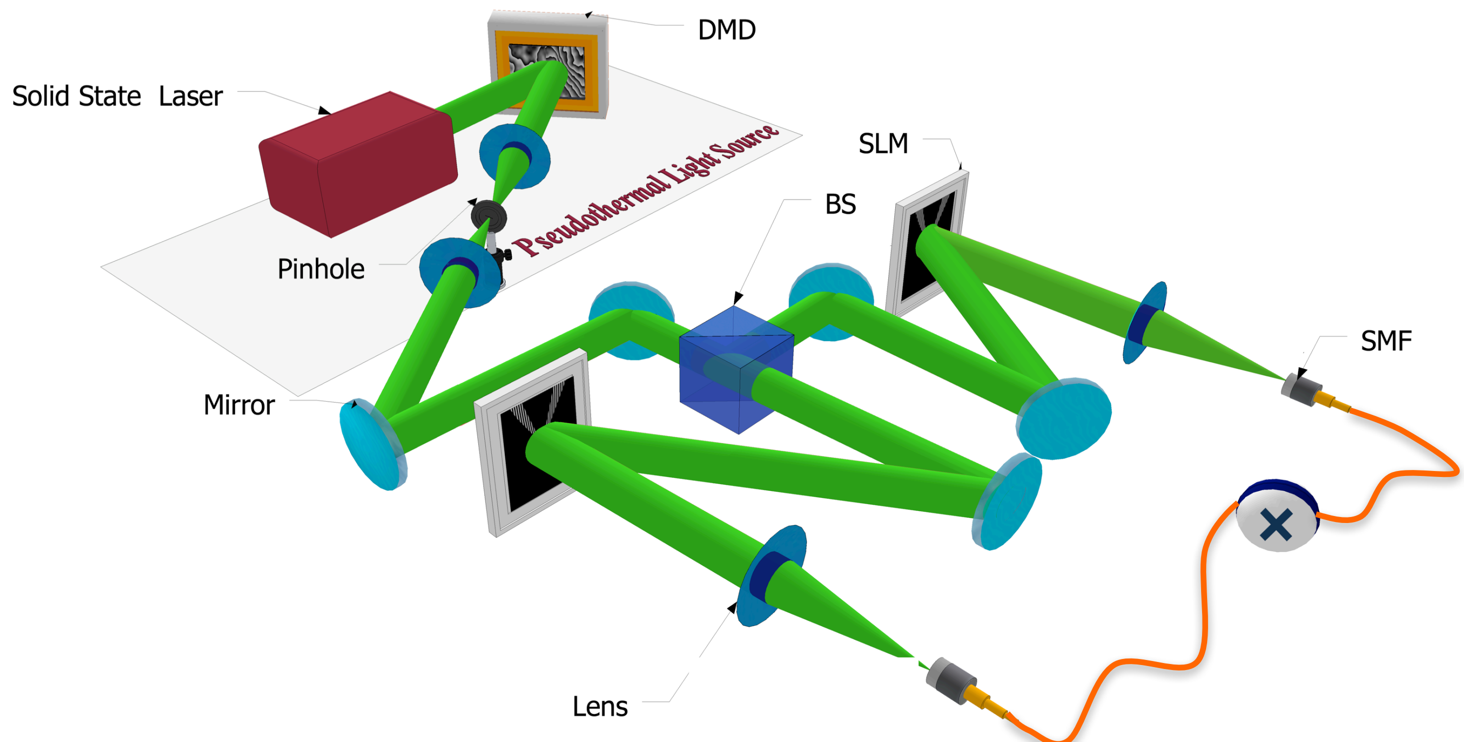


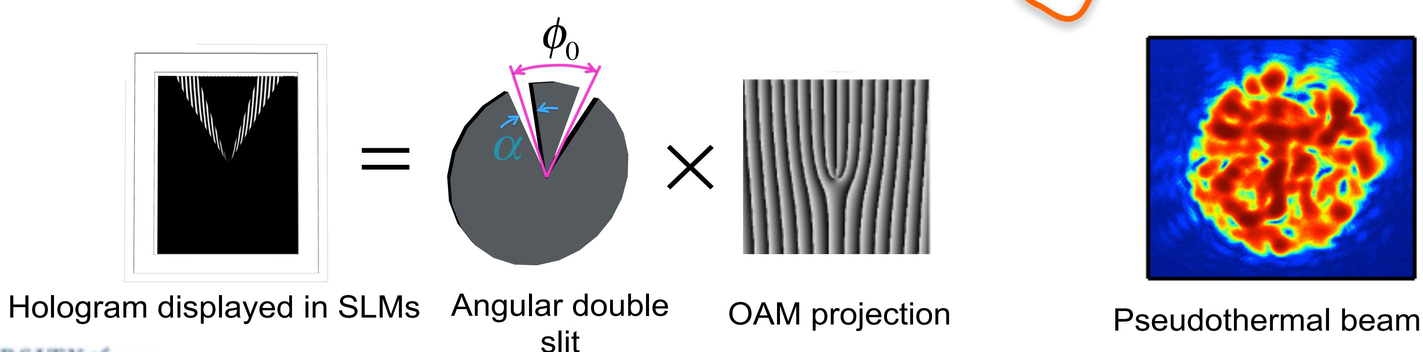

Formation of Second-Order Correlations in OAM!

A. K. Jha, et al., Phys. Rev. Lett. **104**, 010501 (2010)

# Azimuthal Hanbury Brown and Twiss Interference

## Experimental Setup

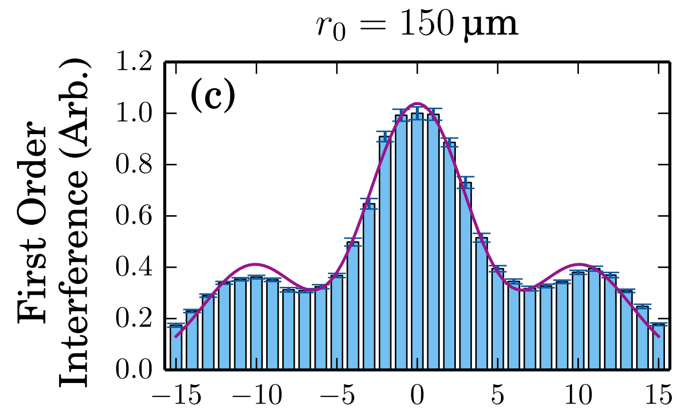



O. S. Magana-Loaiza et al., Science Advances 2, e1501143 (2016).

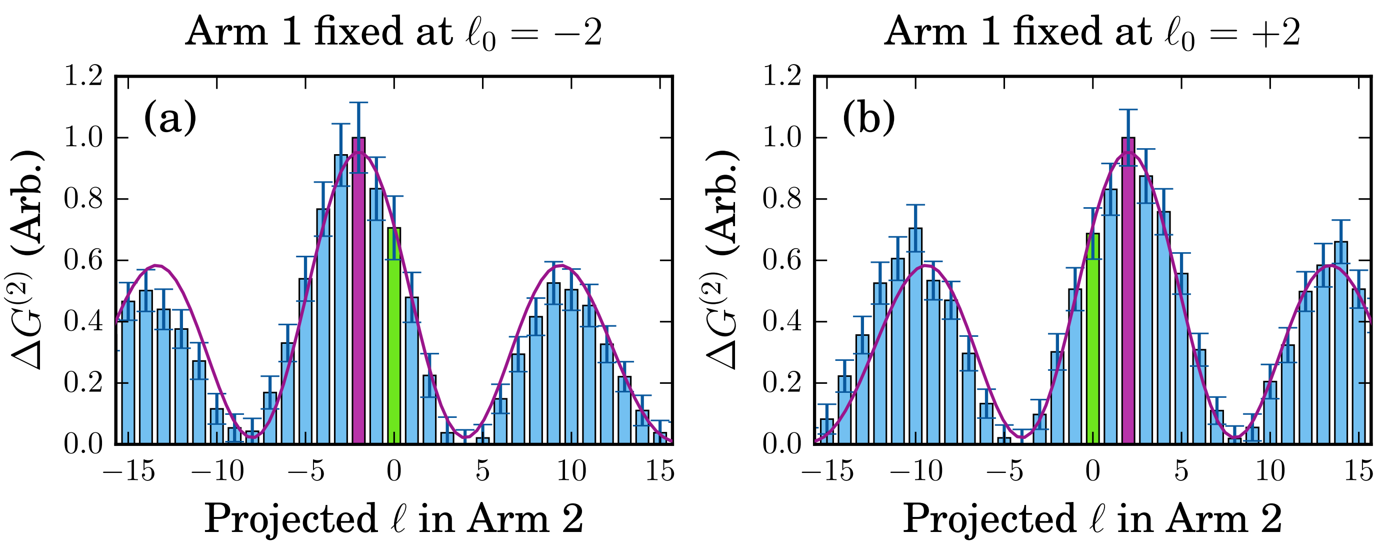
# Hanbury Brown and Twiss effect with Twisted Light

**Arm 1: Constant Intensity** **Arm 2:**




$$\left\langle G_{l,l_0}\right\rangle \propto \frac{\alpha^4 Sinc^4\left(\left[l-l_0\right]\alpha/2\right)}{4\pi^4}\int r_1 dr_1 r_2 dr_2 \left(e^{-i(l-l_0)\phi_0}\left\{\Phi^*(r_1,0)\Phi(r_1,\phi_0)\Phi^*(r_2,\phi_0)\Phi(r_2,0)\right\}+c.c.\right)$$

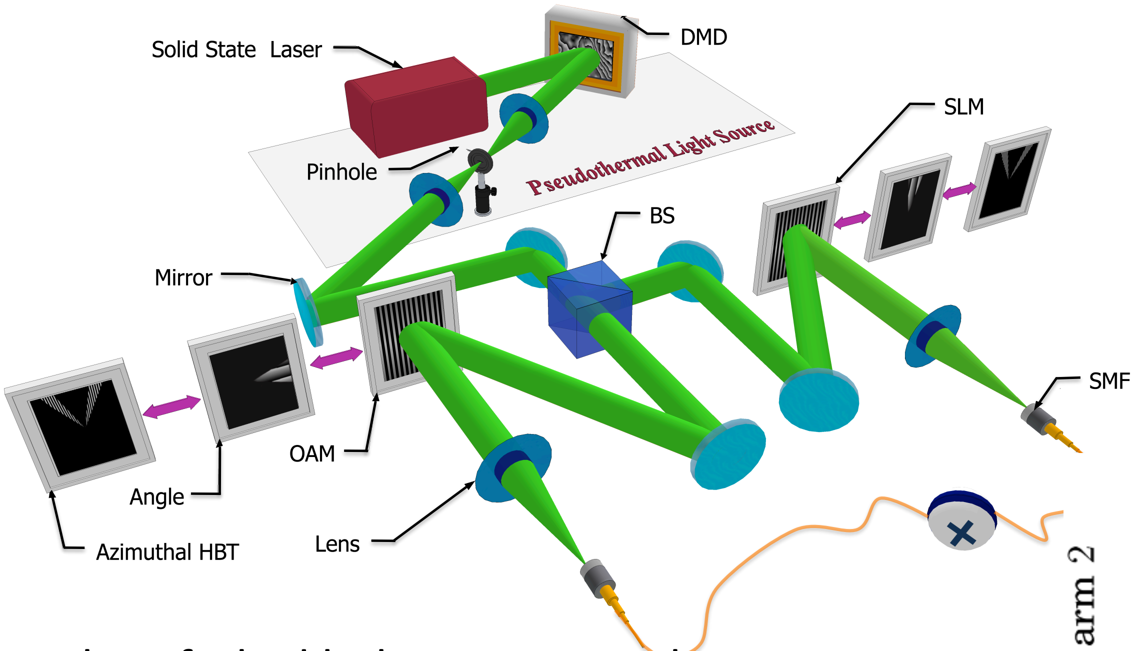
**Correlations:**




O. S. Magana-Loaiza et al., Science Advances 2, e1501143 (2016).

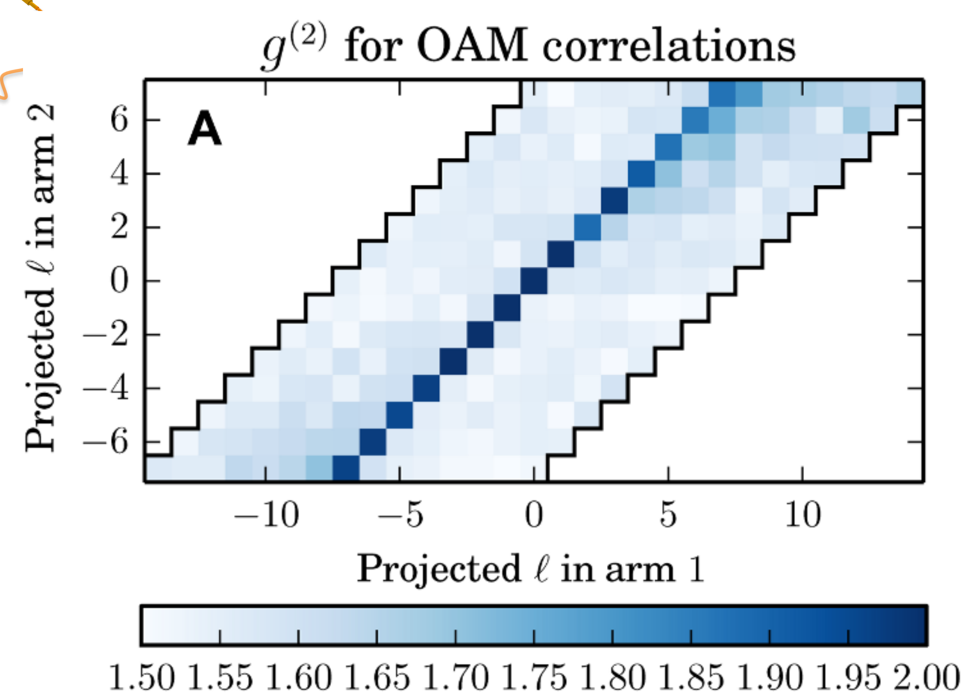
# Second-Order Correlations of Pseudothermal light

## Correlations in Angular Position and OAM

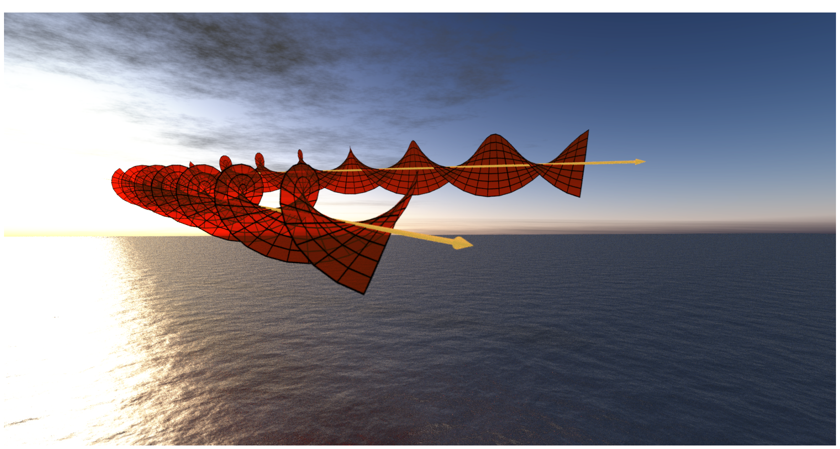



$$\langle I_{l_1} I_{l_2} \rangle = \langle I_{l_1} \rangle \langle I_{l_2} \rangle \left(1 + \delta_{l_1, l_2}\right)$$

- Note that (unlike SPDC) OAM correlations sit on top of a background.
- Note also that this expression is non-separable.

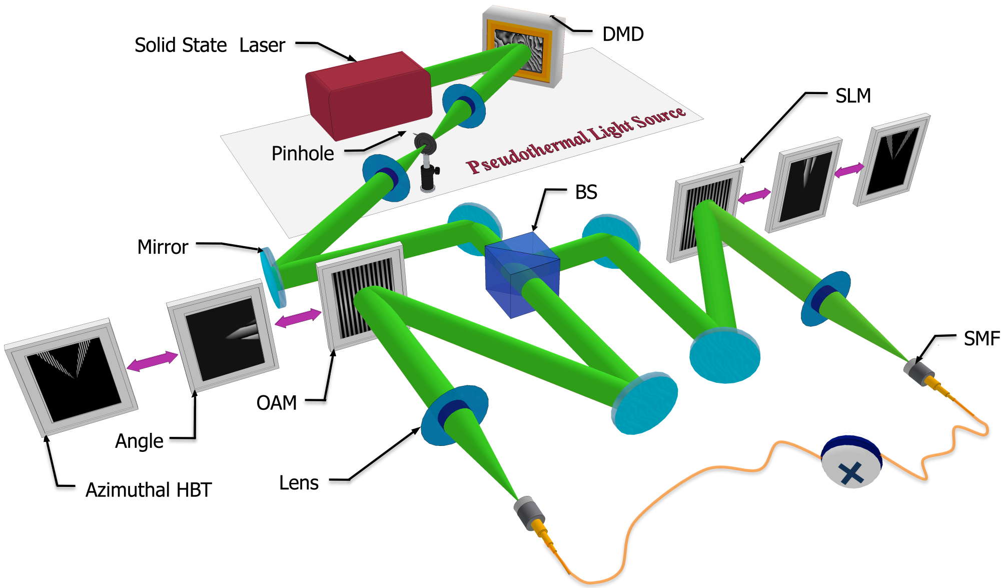



Place forked hologram on each SLM



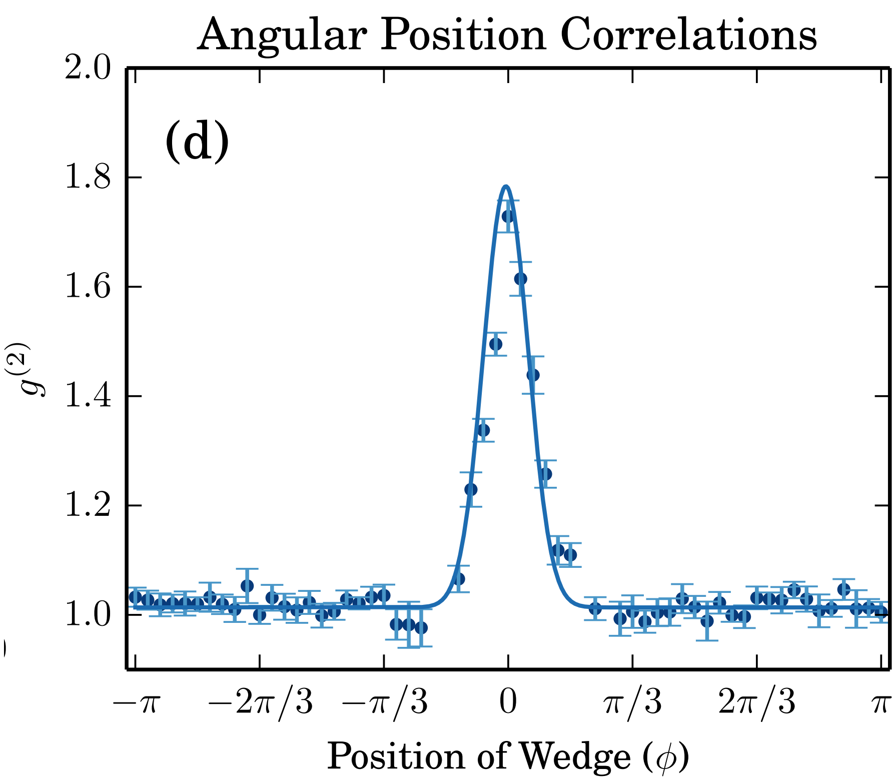
# Second-Order Correlations of Pseudothermal light

## Correlations in Angular Position and OAM




Slit in arm 1 is fixed at $0^0$ Slit in arm 2 is rotated

$$\langle I_\phi I_{\phi_0} \rangle = \langle I_\phi \rangle \langle I_{\phi_0} \rangle (1 + f(\phi - \phi_0))$$



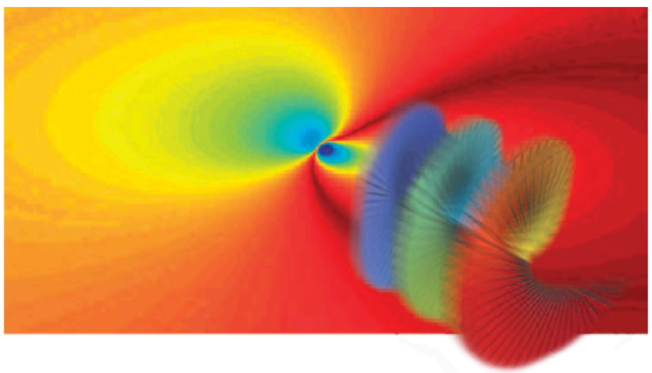

Similar to correlations of entangled photons, except that in our case the correlations sit on top of a constant background

# POSSIBLE APPLICATIONS

nature physics — LETTERS
PUBLISHED ONLINE: 13 FEBRUARY 2011 | DOI:10.1038/NPHYS1907

## Twisting of light around rotating black holes

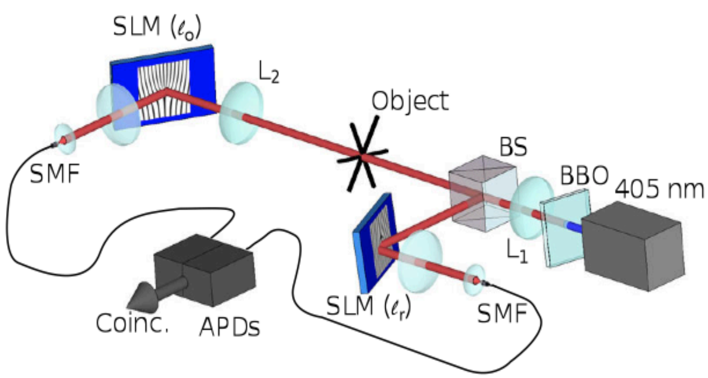
Fabrizio Tamburini[1], Bo Thidé[2]★, Gabriel Molina-Terriza[3] and Gabriele Anzolin[4]



PRL 110, 043601 (2013) PHYSICAL REVIEW LETTERS week ending 25 JANUARY 2013

## Object Identification Using Correlated Orbital Angular Momentum States

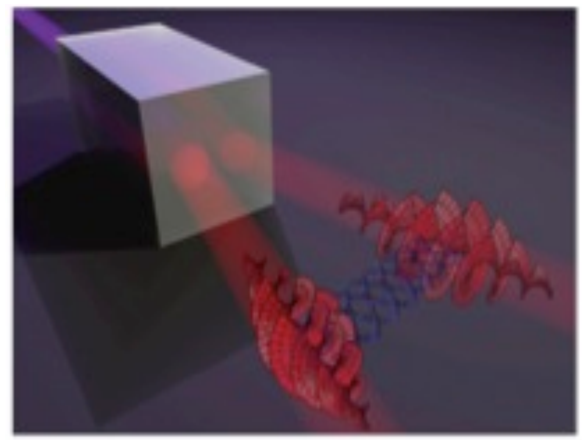
Néstor Uribe-Patarroyo,[1,*] Andrew Fraine,[1] David S. Simon,[1,2] Olga Minaeva,[3] and Alexander V. Sergienko[1,4]
[1]*Department of Electrical and Computer Engineering, Boston University, 8 Saint Marys Street, Boston, Massachusetts 02215, USA*
[2]*Department of Physics and Astronomy, Stonehill College, 320 Washington Street, Easton, Massachusetts 02357, USA*




## Quantum Correlations in Optical Angle–Orbital Angular Momentum Variables

Jonathan Leach,[1] Barry Jack,[1] Jacqui Romero,[1] Anand K. Jha,[2] Alison M. Yao,[3] Sonja Franke-Arnold,[1] David G. Ireland,[1] Robert W. Boyd,[2] Stephen M. Barnett,[3] Miles J. Padgett[1]*

6 AUGUST 2010 VOL 329 SCIENCE www.sciencemag.org



PRL 106, 100407 (2011) PHYSICAL REVIEW LETTERS week ending 11 MARCH 2011

## Entangled Optical Vortex Links

J. Romero,[1,2] J. Leach,[1] B. Jack,[1] M. R. Dennis,[3] S. Franke-Arnold,[1] S. M. Barnett,[2] and M. J. Padgett[1]

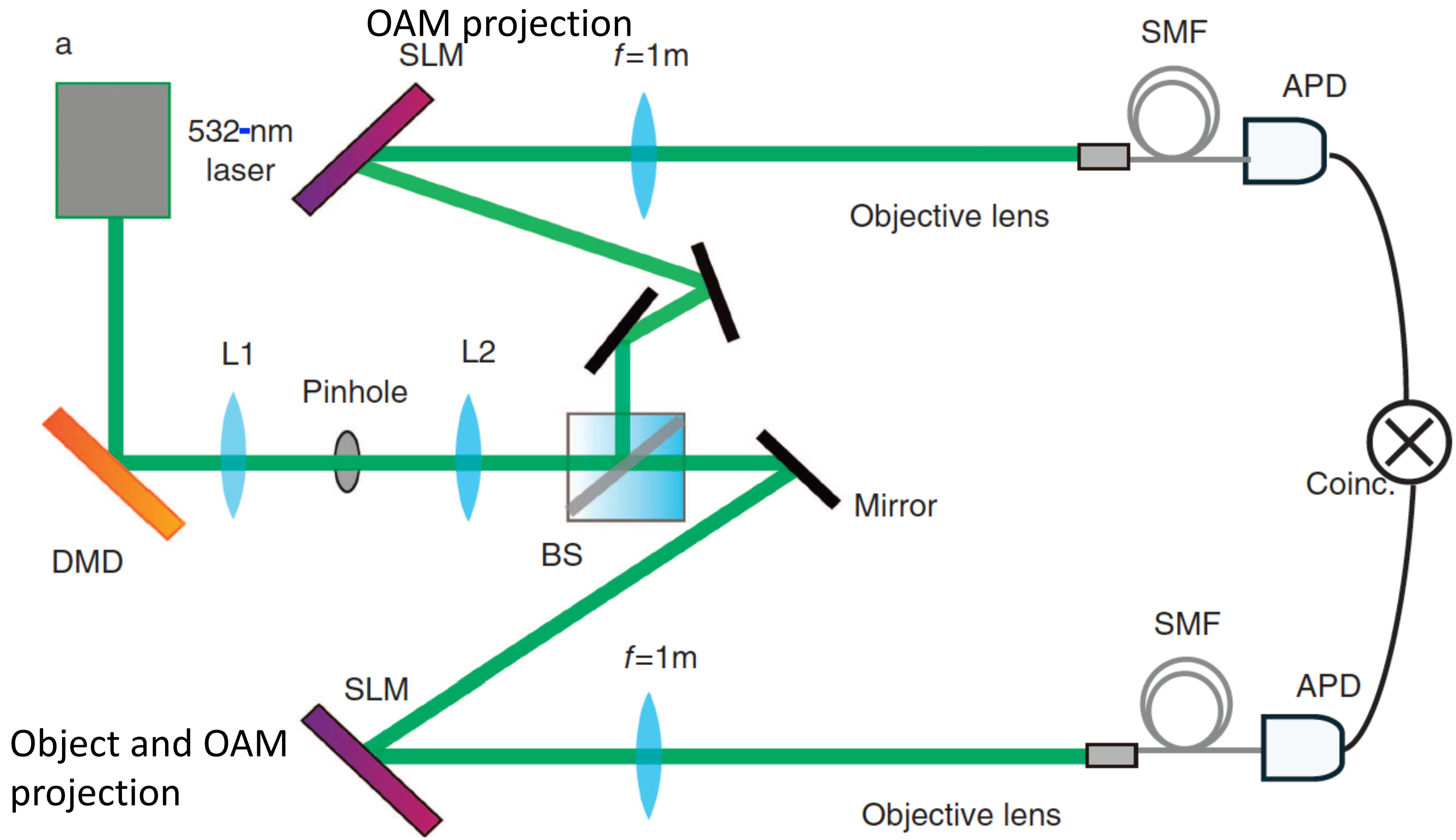
# Digital spiral object identification using random light

Zhe Yang[1,2], Omar S Magaña-Loaiza[2], Mohammad Mirhosseini[2], Yiyu Zhou[2], Boshen Gao[2], Lu Gao[2,3], Seyed Mohammad Hashemi Rafsanjani[2], Guilu Long[1,4] and Robert W Boyd[2,5]

[1] State Key Laboratory of Low-dimensional Quantum Physics and Department of Physics, Tsinghua University, Beijing 100084, China;
[2] The Institute of Optics, University of Q3 Rochester, Rochester, New York 14627, USA;
[3] School of Science, China University of Geosciences, Beijing 100083, China;
[4] Tsinghua National Laboratory for Information Science and Technology, Beijing 100084, China
[5] Department of Physics, University of Ottawa, Ottawa, Ontario, Canada

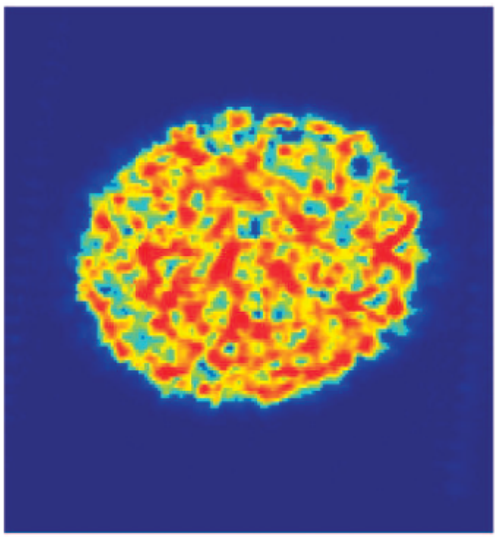
# Digital spiral object identification using random light

## Experimental Setup

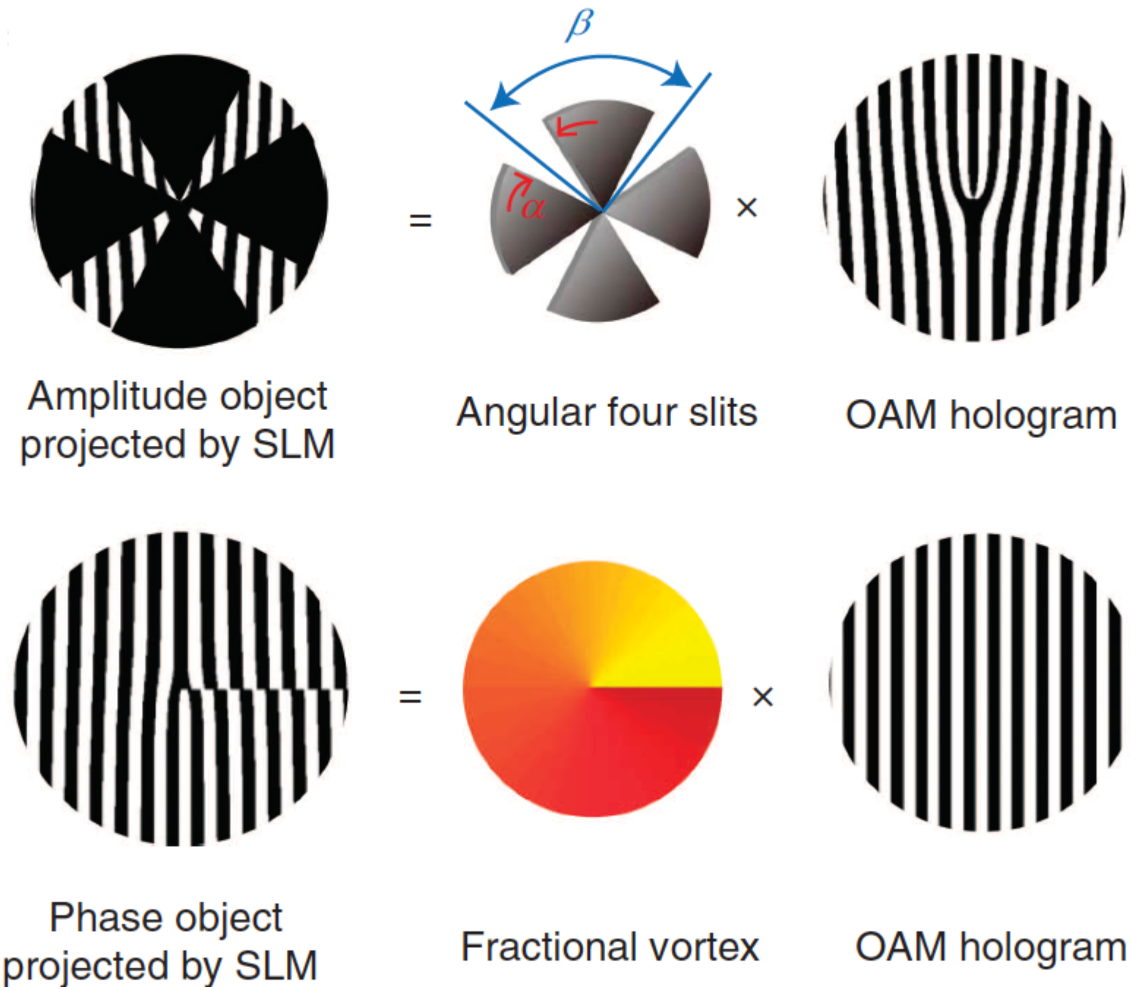


# Digital spiral object identification using random light

## Some examples

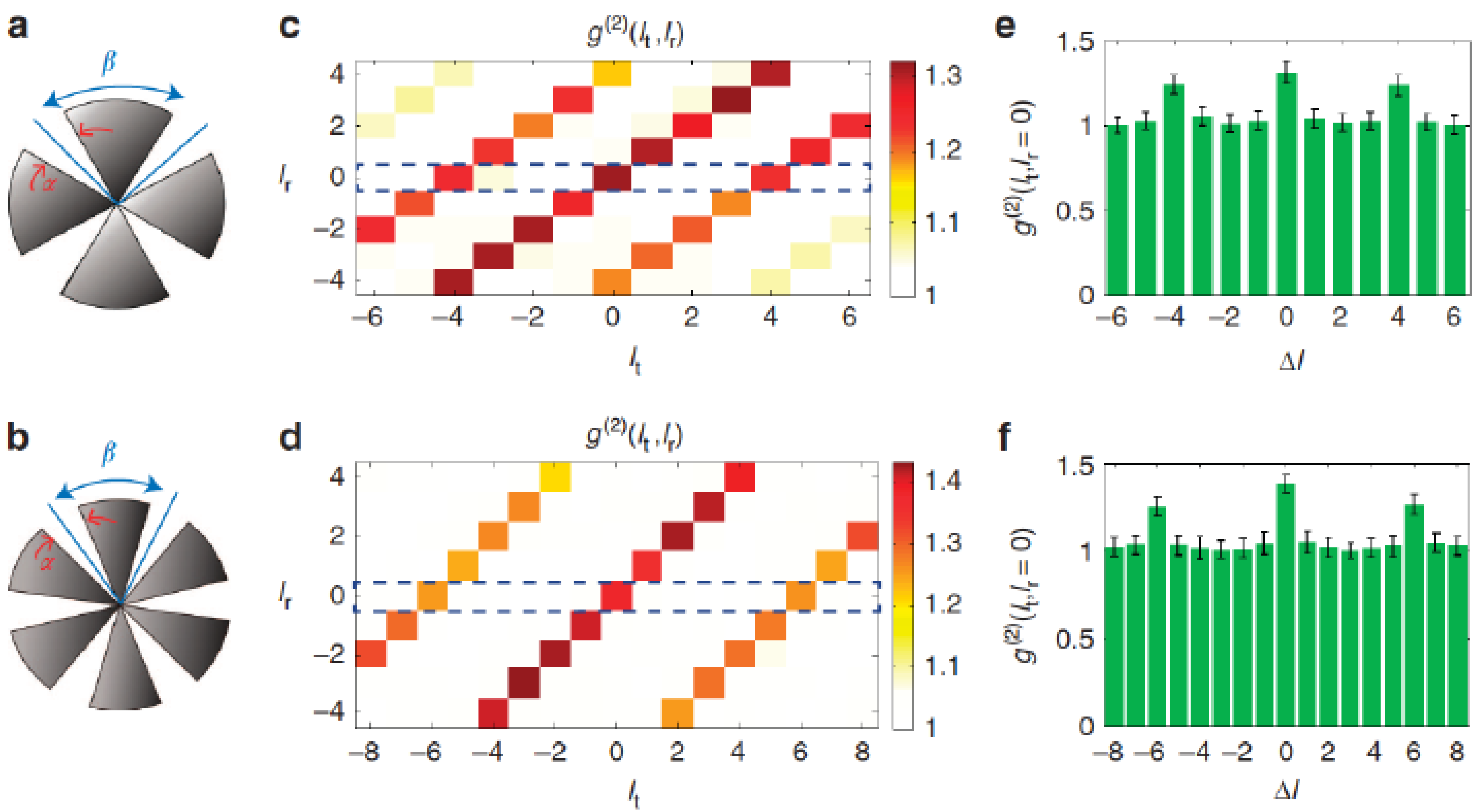


Pseudothermal light



# Digital spiral object identification using random light

## Symmetry of object shows up in OAM correlations




- Could this method be applied to more complicated objects?

# An Application


The end