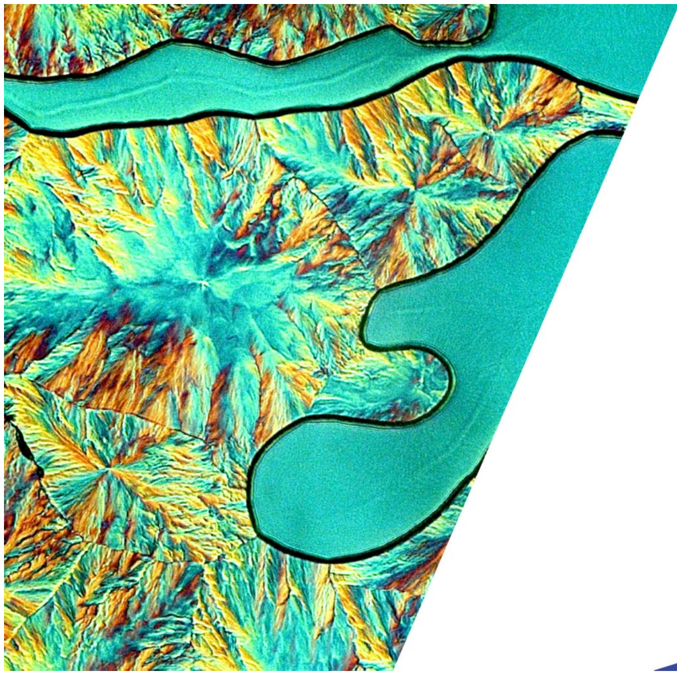
The OSA Quantum Computing and Communication Technical Group Welcomes You!



HIGH-DIMENSIONAL QUANTUM PHOTONICS USING STRUCTURED PHOTONS

22 October 2020 • 10:00 EDT

OSA Quantum Computing and Communication Technical Group

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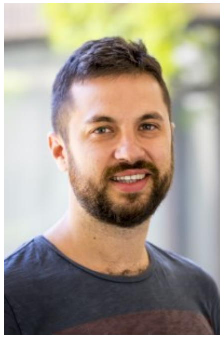
Technical Group Leadership 2020

Roberto de J. León-Montiel
Chair
UNAM, Mexico



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University of Naples “Federico II”

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CICESE, Mexico

Jorge L. Domínguez-Juárez
UNAM, Mexico

Technical Group at a Glance

- Focus
  - Theoretical and experimental aspects of quantum computing
  - Quantum communication systems - Cryptography
  - Generation, detection and applications of non-classical light
  - Quantum measurement and quantum control
- Mission
  - To maximize the exchange of information and the creation of networking opportunities for our community
  - Webinars, technical events (workshops, tutorials, poster sessions), outreach activities
  - Interested in presenting your research? Have ideas for TG events? Contact us at TGactivities@osa.org.
- Find us here
- Website: www.osa.org/OC
- Facebook: https://www.facebook.com/groups/OSAQuantumCC/

Today's Webinar

High-Dimensional Quantum Photonics Using Structured Photons

Dr. Robert Fickler

Group leader of research group "Experimental Quantum Optics" at the Tampere University, Finland.
robert.fickler@tuni.fi

Speaker's Short Bio:

Professor Robert Fickler obtained his Ph.D. at the University of Vienna and the Institute for Quantum Optics and Quantum Information (IQOQI). His Ph.D. thesis "Entanglement of Complex Structures of Photons" supervised by Anton Zeilinger received the Springer Thesis Award 2015. He has been acknowledged with several awards as the "Young Scientist Award 2015", "Banting Postdoctoral Fellowship 2016" and "Outstanding Postdoctoral Research Fellow 2016-17".

OSA Quantum Computing and Communication Technical Group

Tampere University

PREIN

High-dimensional quantum photonics using structured photons

OSA webinar, 22nd October 2020

Robert Fickler

Tampere University

Tampere, Sauna capital of Finland

overview

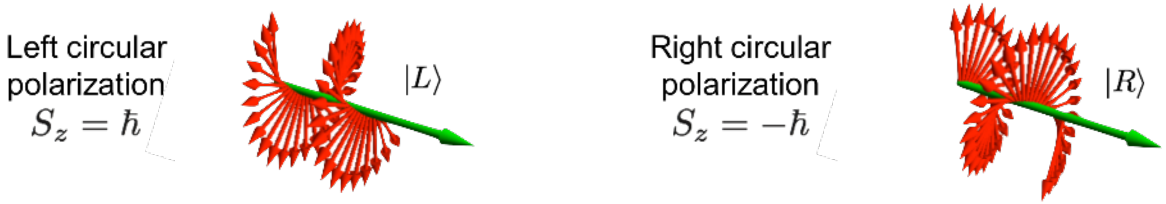
- angular momentum of light
- transverse modes of light -> structured light -> structured photons
- high-dimensional quantum information using structured photons
- advanced modulations of structured photons
  - high-dimensional quantum gates
  - two photon interferences in spatial structures
  - angular super-resolution
- outlook

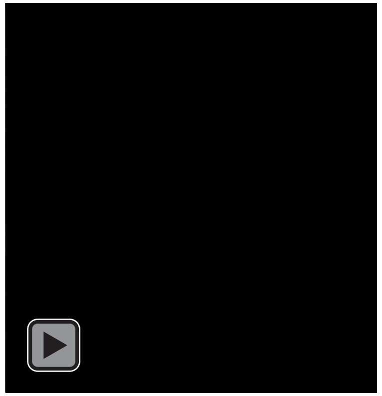
angular momentum of light

light fields can have angular momenta

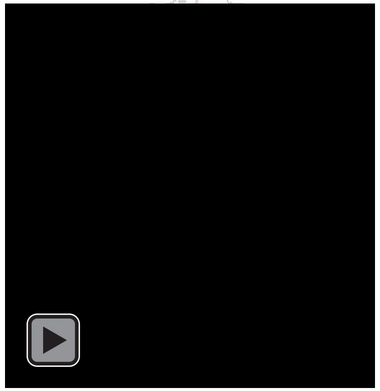
- **spin angular momentum (SAM)** determined by the polarisation

-> first noted by Poynting in 1909 / measured by Beth in 1936 [1,2]



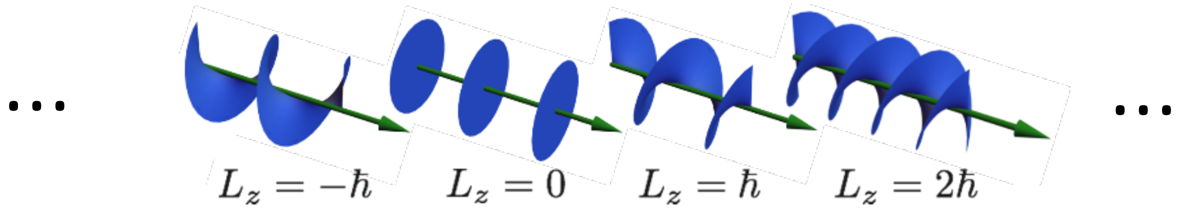


videos from Bo Thide



- **orbital angular momentum (OAM)** determined by the azimuthal phase

-> predicted by Allen, Woerdman and colleagues in 1992[3] / measured by Rubinsztein-Dunlop's group in 1995[4]

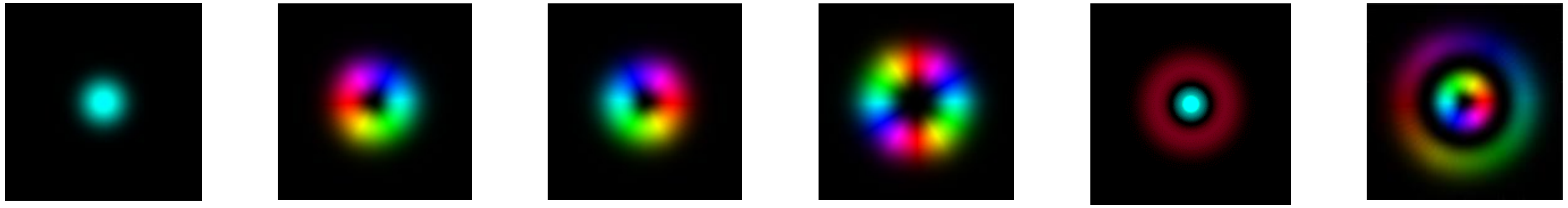


(1) Poynting, *Proc. Roy. Soc. A* 82 (1909) 560
(2) Beth, Phys. Rev. 50 (1936) 115
(3) Allen, Beijersbergen, Spreeuw, Woerdman, Phys. Rev. A 45 (1992) 8185
(4) He, Friese, Heckenberg, Rubinsztein-Dunlop, Phys. Rev. Lett. 75 (1995) 826

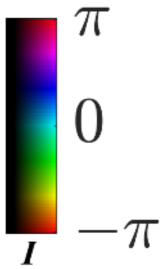
transverse mode of light

light fields can be decomposed into orthogonal sets of modes.

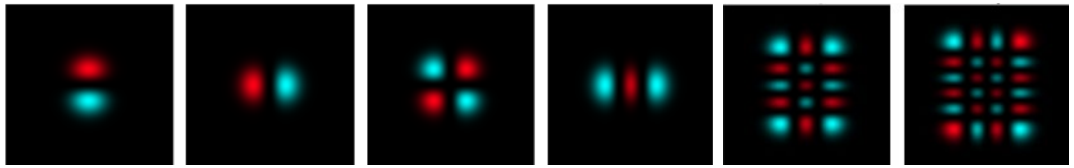
- Laguerre Gauss modes $LG_{p,l}$ are the solution in a cylindrical coordinate system



$LG_{0,0}$ $LG_{0,1}$ $LG_{0,-1}$ $LG_{0,2}$ $LG_{1,0}$ $LG_{1,1}$

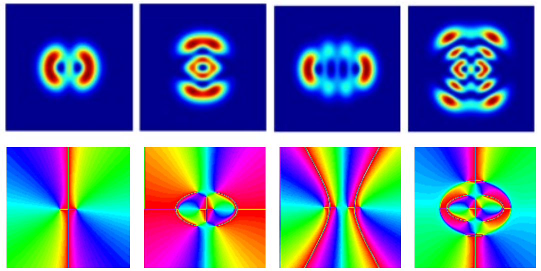


- Hermite Gauss modes $HG_{p,l}$ (Cartesian coordinates)



$HG_{0,1}$ $HG_{0,1}$ $HG_{1,1}$ $HG_{0,2}$ $HG_{4,2}$ $HG_{5,3}$

- Ince Gauss modes $IG_{p,m,\varepsilon}$ (elliptical coordinates)



transverse mode of light

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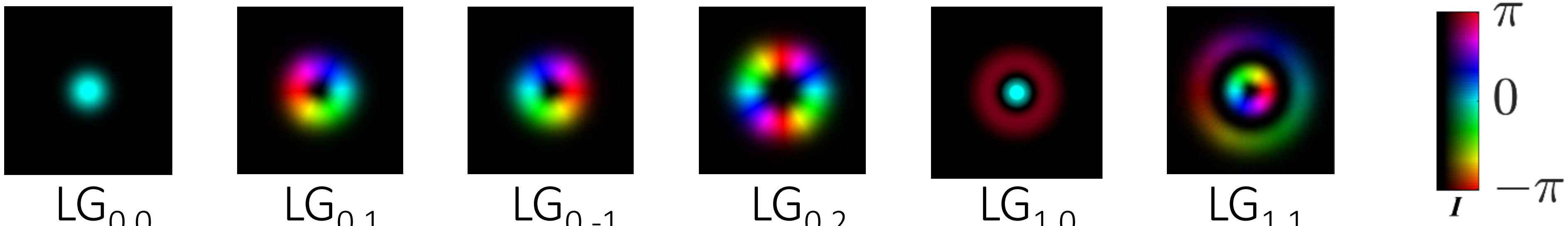
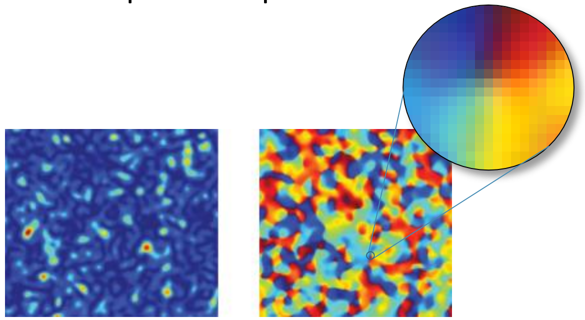
- Laguerre Gauss modes $LG_{p,l}$ are the solution in a cylindrical coordinate system



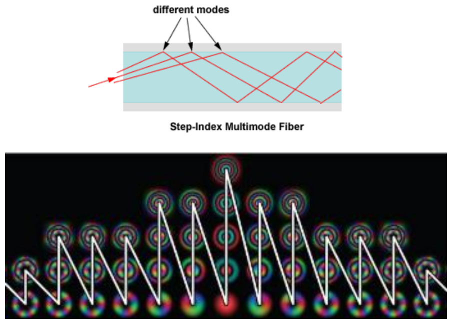
$LG_{0,0}$ $LG_{0,1}$ $LG_{0,-1}$ $LG_{0,2}$ $LG_{1,0}$ $LG_{1,1}$

phase singularities in speckle patterns



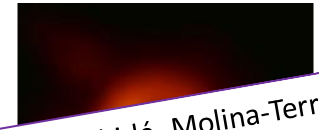
Nye, Berry, 336, 165 (1974).

eigenmodes of multi-mode fibers



Plöschner, Tyc, Čižmár, Nature Photonics 9, 529 (2015).

yet another donut mode…?!

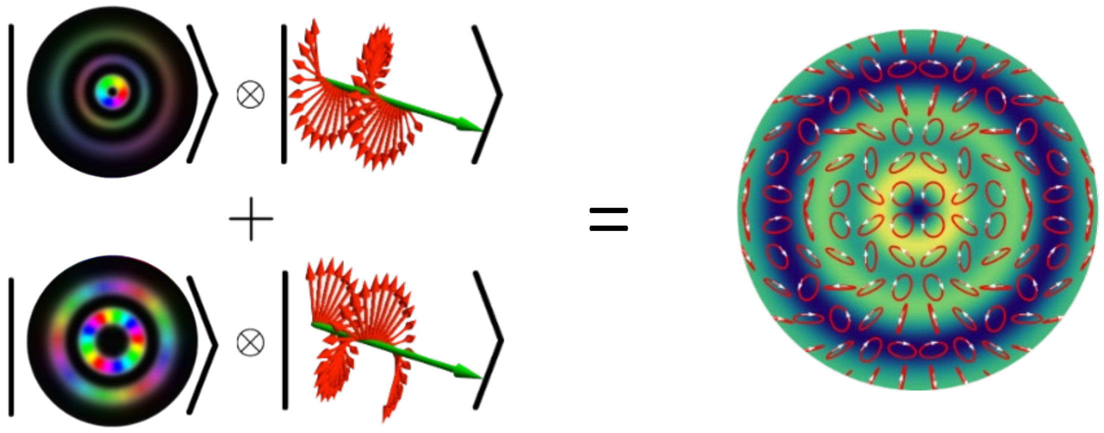


Tamburini, Thidé, Molina-Terriza, Anzolin,
Twisting of light around rotating black holes.
Nature Physics, 7, 195 (2011)

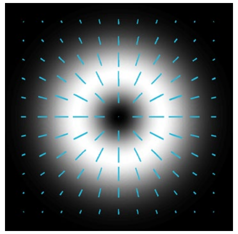
structured light

Including polarization leads to light with complex polarization patterns

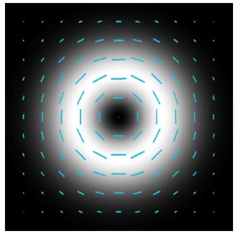
- superpositions of different modes with orthogonal polarization



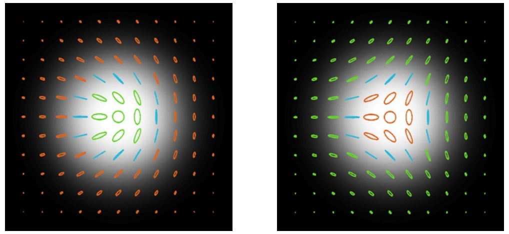
popular examples are....



radial polarization



azimuthal polarization

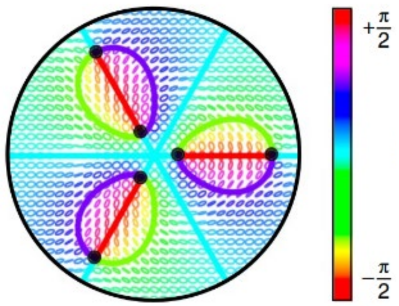


Poincaré beams

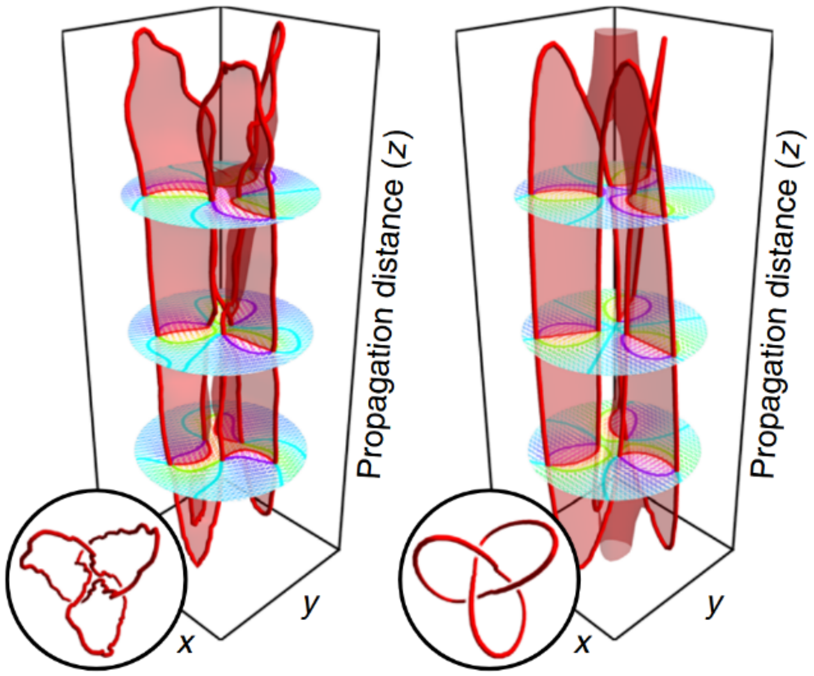
structured light

the polarization along the beam propagation can form knots and links

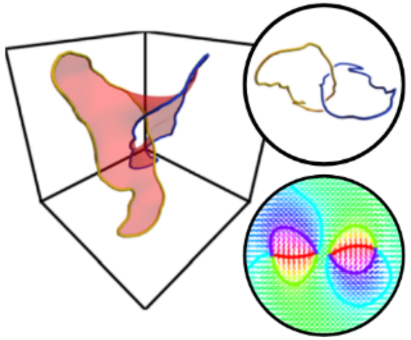
- superpositions of different modes with orthogonal polarization



trefoil knot



experiment theory



Hopf link

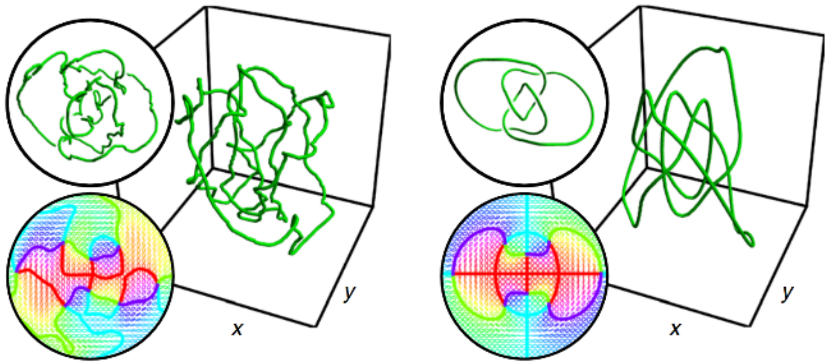


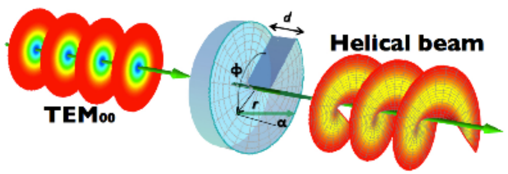
figure-eight knot

Larocque, Sugic, Mortimer, Taylor, Fickler, Boyd, Dennis, Karimi, Nature Physics 14 (11),1079 (2018).

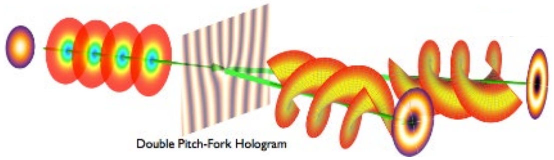
generation & detection of structured light

techniques to generate structured photons

- spiral phase plate[1]

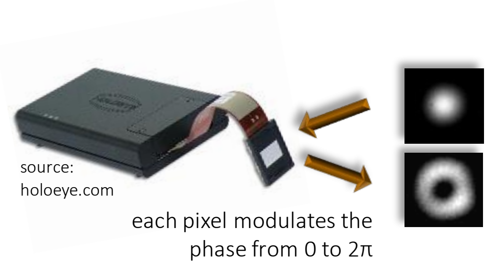


- holography[2]

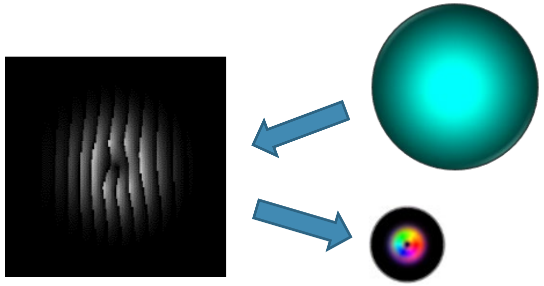


- spin-to-orbit coupling (q-plates[3], j-plates[4])

- spatial light modulator[5]



phase and amplitude modulation[6]

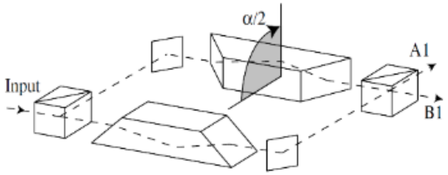


[1] Beijersbergen, Coerwinkel, Kristensen, Woerdman, Optics Communications 112, 5-6 (1994).
[2] Heckenberg, McDuff, Smith, White, Optics Letters 17, 221 (1992).
[3] Marrucci, Manzo, Paparo, Physical Review Letters 96, 163905 (2006).
[4] Devlin, Ambrosio, Rubin, Mueller, Capasso, Science, 358, 896 (2017)
[5] Bazhenov, Yu, Soskin, Vasnetsov, J.o.M.Optics 39, 985 (1992).
[6] Bolduc, Bent, Santamato, Karimi, Boyd, Optics Letters 38 (18), 3546 (2013)

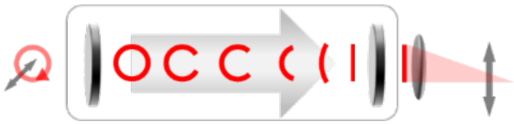
generation & detection of structured light

techniques to measure structured photons

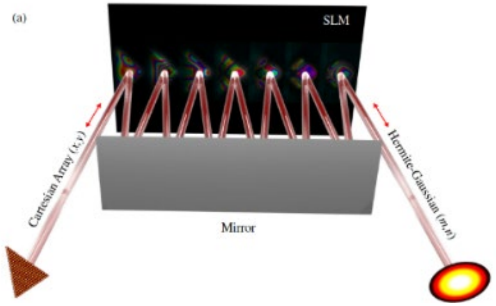
- Sorting using interferometric structures[1,2]



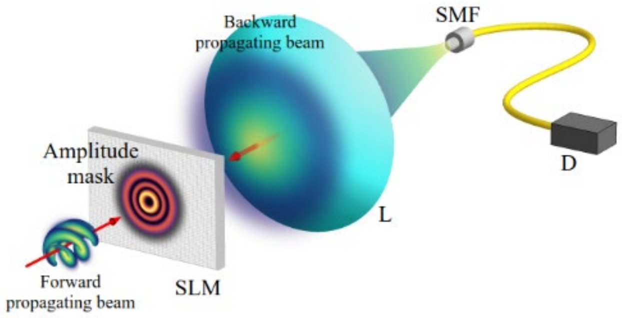
- Sorting via unwrapping[3]



- Sorting using multi-plane mode conversion[4]



- Filtering via mode conversion and fiber coupling[5,6]

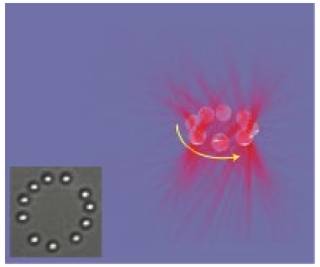


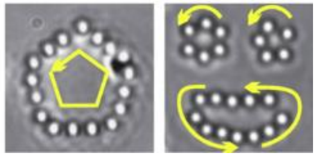
[1] Leach, Leach, Padgett, Barnett, Franke-Arnold, Courtial, PRL, 88, 257901 (2002).
[2] Zhou, Mirhosseini, Fu, Zhao, Rafsanjani, Willner, Boyd, PRL 119 263602 (2017).
[3] Berkhout, Lavery, Courtial, Beijersbergen, Padgett, PRL, 105, 153601 (2010).
[4] Fontaine, Ryf, Chen, Neilson, Kim, Carpenter, Nature Communications, 10, 1865 (2019).
[5] Mair, Vaziri, Weihs, Zeilinger, Nature 412, 313 (2001).
[6] Bouchard, Valencia, Brandt, Fickler, Huber, Malik, Optics Express 26, 31925 (2018).

applications of structured light

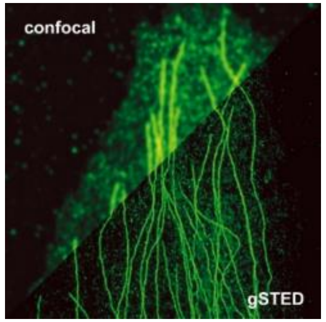
applications in classical optics

Optical tweezers [1]

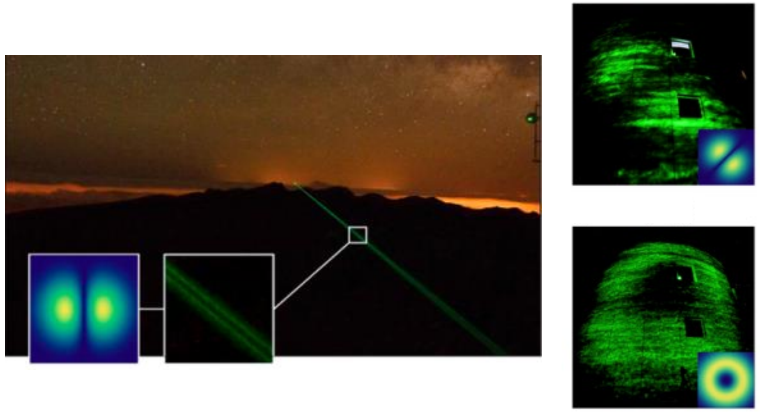




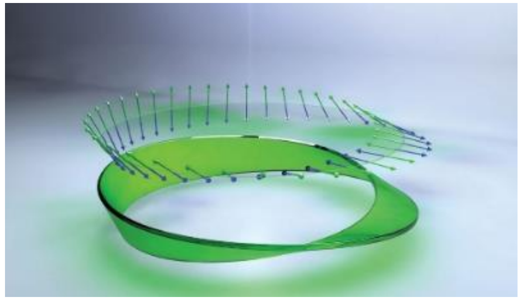
Superresolution microscopy (STED) [2]



Classical communication [3,4]



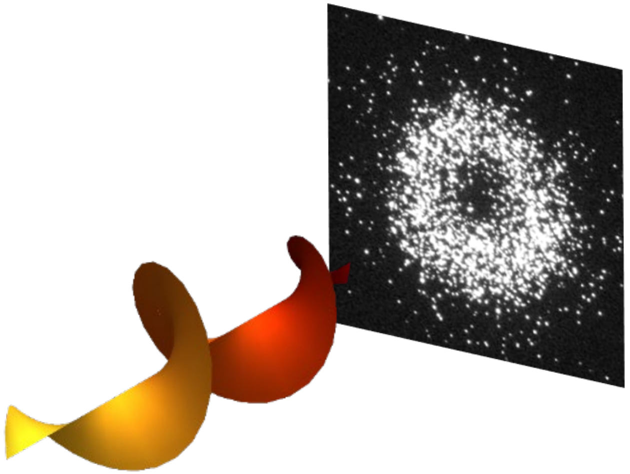
Optics Foundations[5]

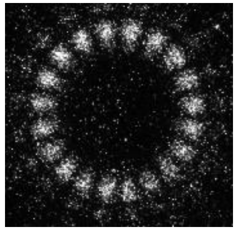


[1] Padgett, Bowman, Nature Photonics 5, 343–348 (2011).
[2] Hell, Wichmann, Optics Letters 19, 780 (1994).
[3] Willner, Huang, Yan, Ren, Ahmed, Xie, Bao, Li, Cao, Zhao, Wang, Lavery, Tur, Ramachandran, Molisch, Ashrafi, Ashrafi, Advances in Optics and Photonics 7, 66 (2015).
[4] Krenn, Handsteiner, Fink, Fickler, Ursin, Malik, Zeilinger, PNAS,113, 13648 (2016)
[5] T. Bauer, Banzer, Karimi, Orlov, Rubano, Marrucci, Santamato, Boyd, Leuchs, Science 347, 964 (2015).

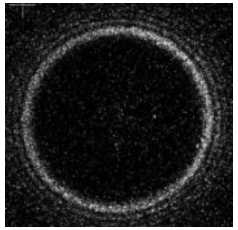
structured photons

single photons can also have a transverse spatial structure

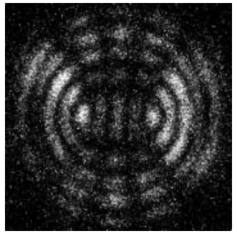




$LG_{\pm 10}$



LG_{50}



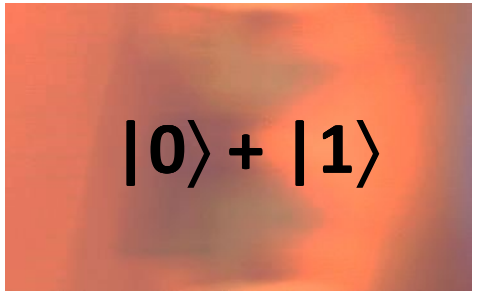
$IG_{10,4,3}$

$HG_{0,1}$ $LG_{0,1}$

summing up all frames to reveal the structure

quantum photonics with structured photons

2-dim quantum information is encoded in qubits

bit	qubit
	
either 0 or 1	either 0 **and** 1

-> the most common encoding in photonics uses polarization

$|0\rangle$ ➡  = $|L\rangle$

$|1\rangle$ ➡  = $|R\rangle$

$\frac{1}{\sqrt{2}}(|0\rangle \pm |1\rangle) \rightarrow \frac{1}{\sqrt{2}}(|L\rangle \pm |R\rangle) = |H\rangle, |V\rangle$

-> similar for $|D\rangle, |A\rangle$

mutually unbiased bases (MUB)

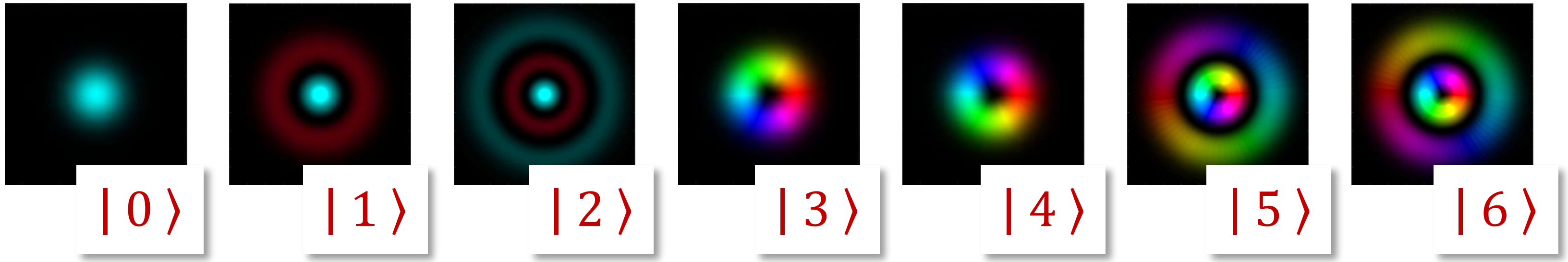
d-dimensional quantum information is encoded in qudits

 either 1,2,3,4,5 or 6

 either 1,2,3,4,5 **and** 6

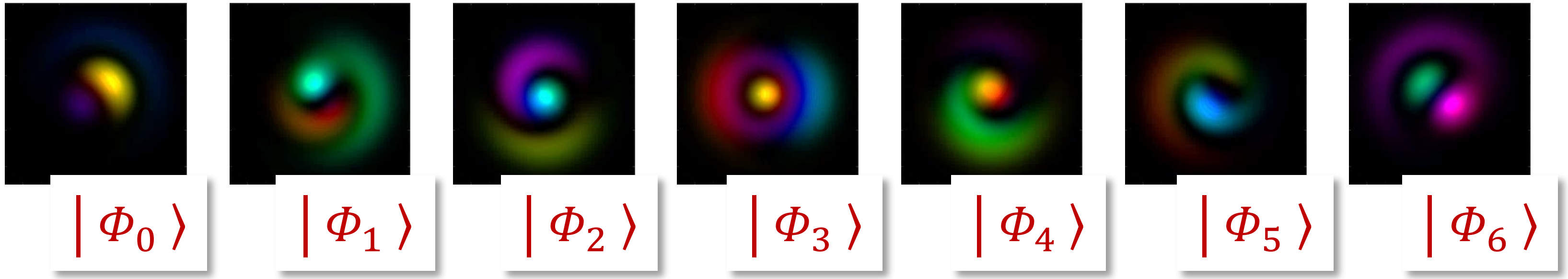
quantum photonics with structured photons

spatial modes can be used to encode high-dimensional quantum information



$\ldots|\Psi_d\rangle$

-> there are d+1 MUBs, if d is a power of prime...



$$\left|\phi_i^{(k)}\right\rangle = \frac{1}{\sqrt{d}} \sum_{m=0}^{d-1} \omega_d^{(im+(k-1)m^2)} |\psi_m\rangle$$

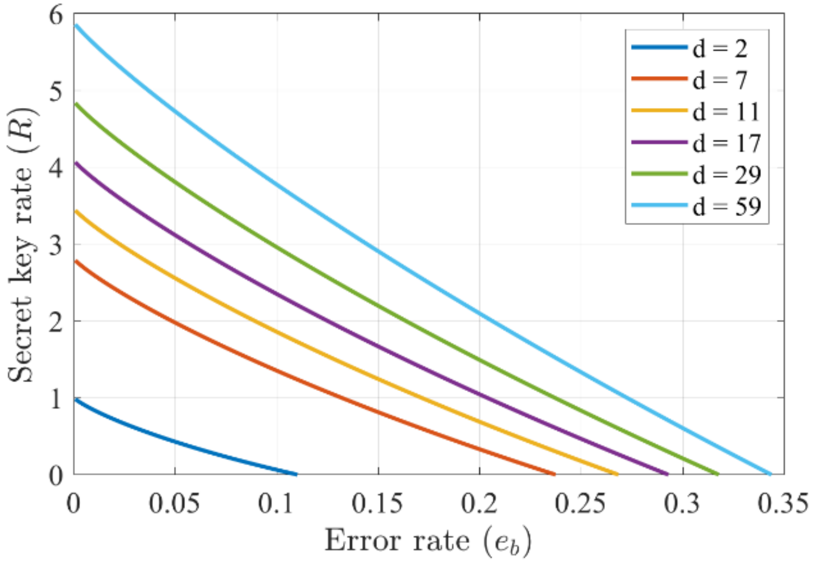
high-dimensional quantum information

advantages of qudits…

- more information capacity per single photon -> $\log_2(d)$ bits/photons
- simplification of quantum gates[1] -> Hilbert space dimension = d^n

  n = number of particles / d = dimensionality

- quantum cryptography[2]
  - increased noise tolerance
  - multiplexing
  - advanced QKD protocols



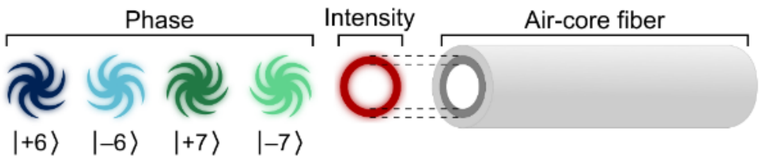
[1] Lanyon, Barbieri, Almeida, Jennewein, Ralph, Resch, Pryde, O'brien, Gilchrist, White, Nature Physics 5 (2), 134 (2009).
[2] Cerf, Bourennane, Karlsson, Gisin, Phys Rev Let 88 (12), 127902 (2002).

high-dimensional quantum information

advantages of qudits…

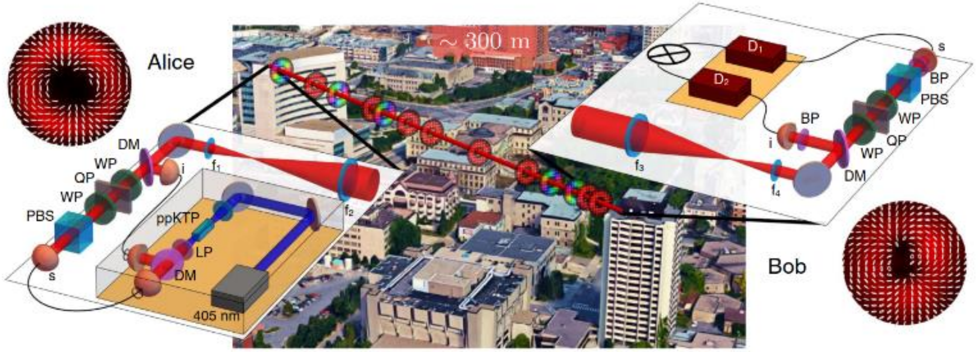
- long distance quantum cryptography with structured photons

1.2 km fiber[1]



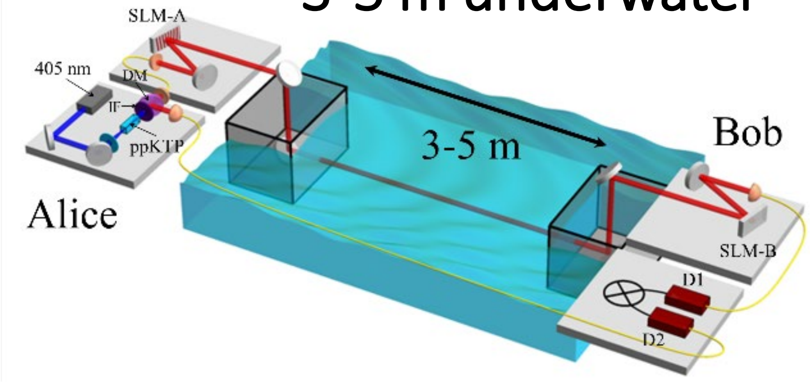
e_b^{4d} = 16 %
0.22 bit/photon

300 m free space[2]



e_b^{4d} = 11 %
0.65 bit/photon

3-5 m underwater[3]



e_b^{3d} = 12 %
0.31 bit/photon

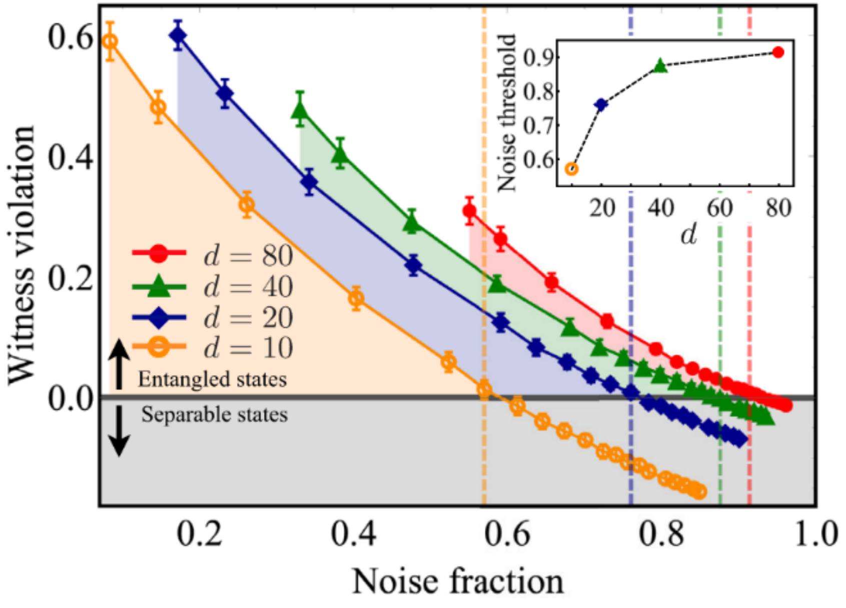
[1] Cozzolino, Bacco, Da Lio, Ingerslev, Ding, Dalgaard, Kristensen, Galili, Rottwitt, Ramachandran, Oxenløwe, Physical Review Applied 11.6, 064058 (2019).
[2] Sit, Bouchard, Fickler, Gagnon-Bischoff, Larocque, Heshami, Elser, Peuntinger, Günthner, Heim, Marquardt, Leuchs, Boyd, Karimi. Optica 4, 1006 (2017).
[3] Bouchard, Sit, Hufnagel, Abbas, Zhang, Heshami, Fickler, Marquardt, Leuchs, Boyd, Karimi, Optics Express 26, 22563 (2018).

high-dimensional quantum information

advantages of qudits…

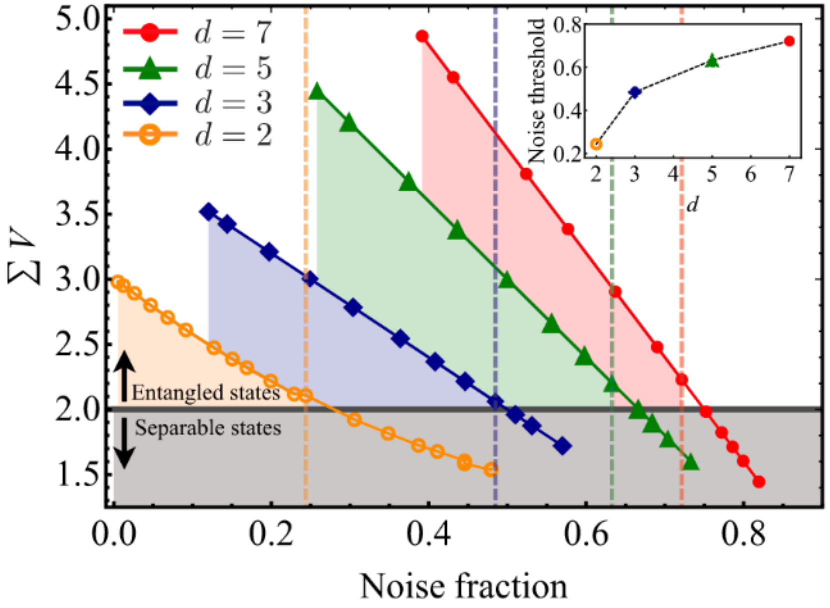
- entanglement verification in noisy conditions[1]

Pathway 1: fine graining to higher dim



time-bin encoding

Pathway 2: measuring in more MUBs



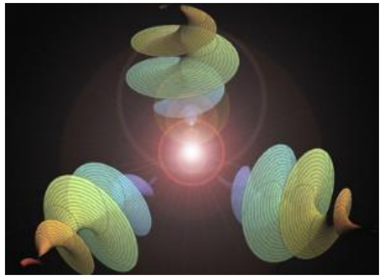
spatial mode encoding

Ecker, Bouchard, Bulla, Brandt, Kohout, Steinlechner, Fickler, Malik, Guryanova, Ursin, Huber, Phys. Rev. X 9, 041042 (2019)

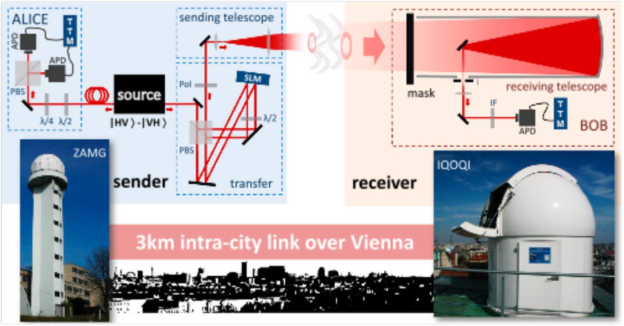
applications of structured photons

applications in quantum optics

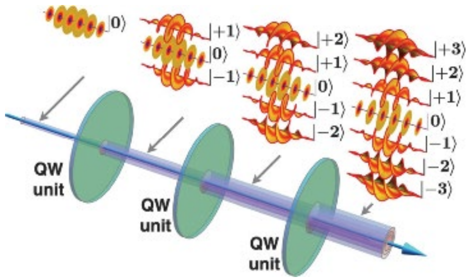
High-dimensional
quantum entanglement [1,2]



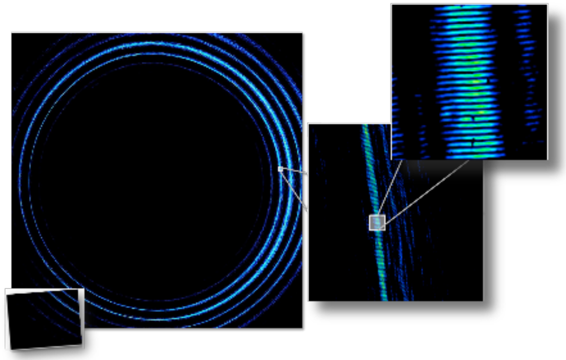
Quantum communication [3]



Quantum simulation
and computation[4]



Quantum optics
foundations[5]



Rubinsztein-Dunlop, Forbes, *et al.* "Roadmap on structured light." *Journal of Optics* 19 013001 (2016).

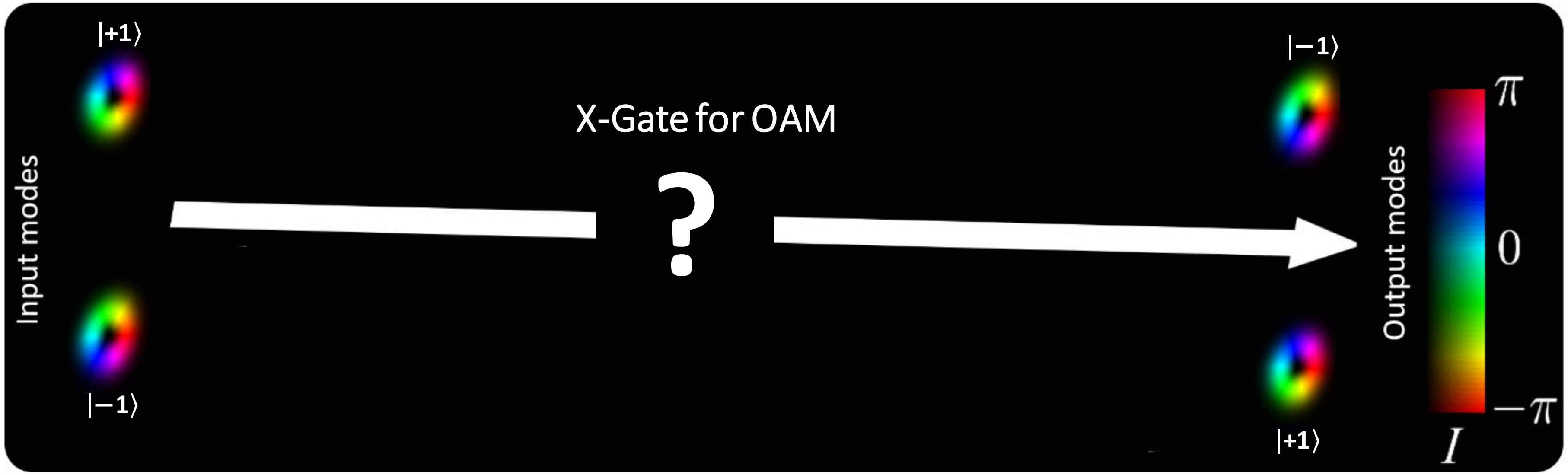
[1] Malik, Erhard, Huber, Krenn, Fickler, Zeilinger, Nature Photonics 10, 248–252 (2016).
[2] Erhard, Fickler, Krenn, Zeilinger, Light: Science & Applications 7 (3), 17146 (2018)
[3] Krenn, Handsteiner, Fink, Fickler, Zeilinger, PNAS 112, 14197-14201 (2015).
[4] Cardano, Massa, Qassim, Karimi, Slussarenko, Paparo, de Lisio, Sciarrino, Santamato, Boyd, Marrucci Science Advances 1, e1500087 (2015).
[5] Fickler, Campbell, Buchler, Lam, Zeilinger, PNAS 113, 13642-13647 (2016).

advanced manipulation of spatial modes

technique to perform complex transformations between spatial modes

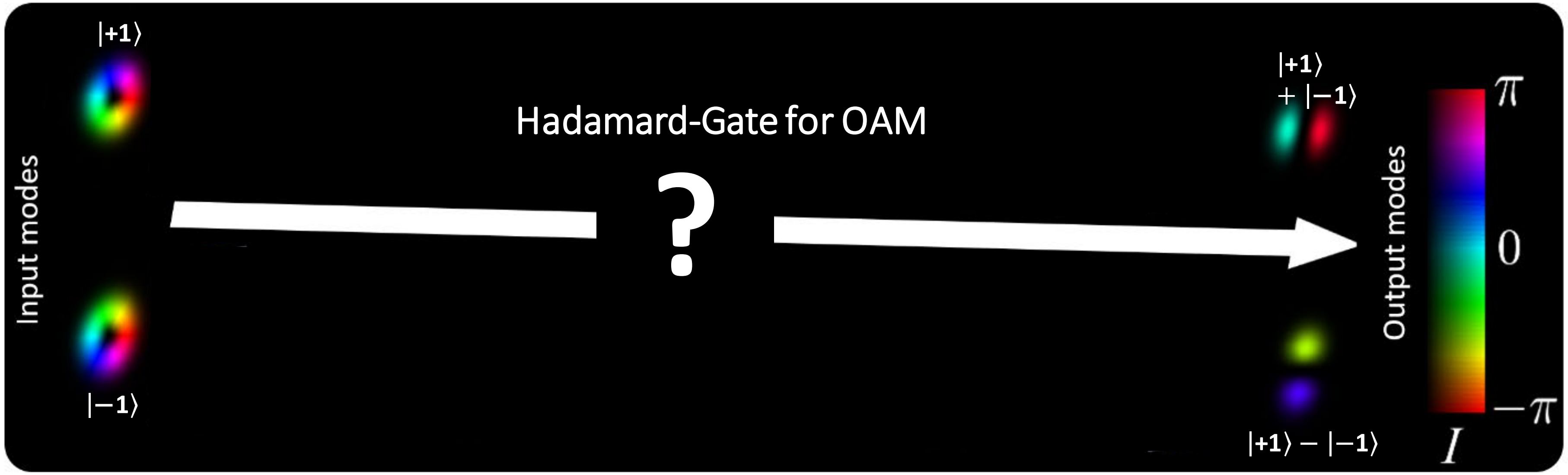
advanced manipulation of spatial modes

technique to perform complex transformations between spatial modes



advanced manipulation of spatial modes

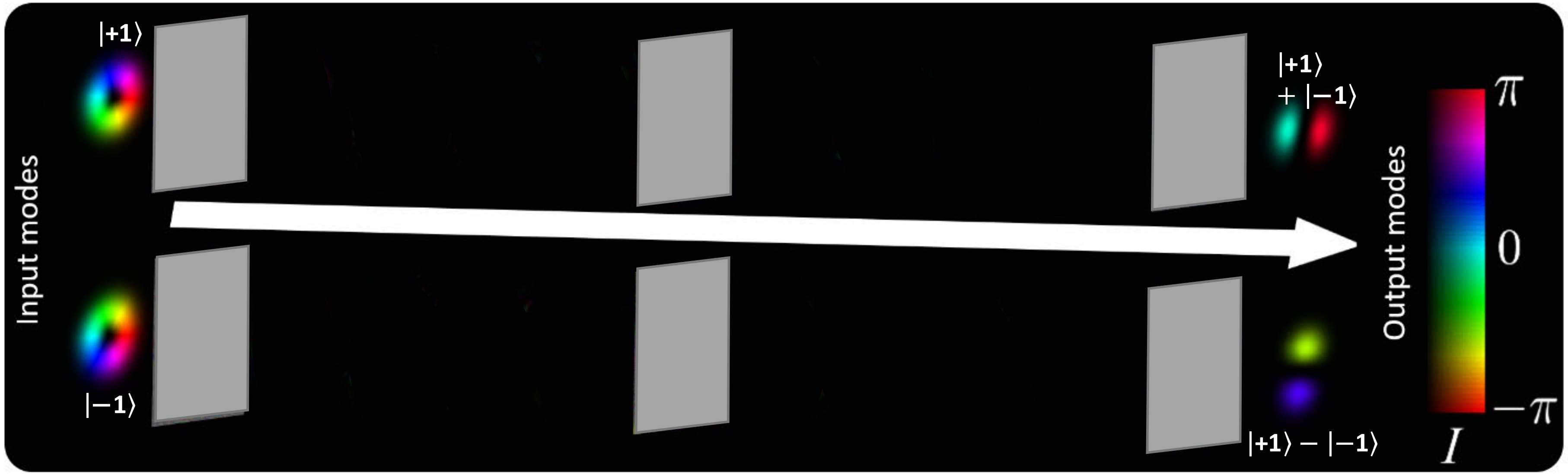
technique to perform complex transformations between spatial modes



advanced manipulation of spatial modes

technique to perform complex transformations between spatial modes

multi-plane light conversion[1] + wavefront matching[2,3] → spatial mode unitaries



calculate the required phase change: $\Delta\Phi_k(x,y) = -\arg(\sum_i o_{kii}(x,y)\exp(-\jmath\phi_i))$

with field overlap: $o_{kij}(x,y) = f_i(k,x,y)\overline{b_j(k,x,y)}\exp(\jmath\Phi_k(x,y))$

and ϕ_i is the average phase of o_{kii}

[1] Morizur, Nicholls, Jian, Armstrong, Treps, Hage, Hsu, Bowen, Janousek, Bachor, *JOSA A*, **27**, 2524 (2010).
[2] Hashimoto, Saida, Ogawa, Kohtoku, Shibata, Takahashi, *Optics Letters*, **30**, 2620 (2005).
[3] Fontaine, Ryf, Chen, Neilson, Kim, Carpenter, *Nature Communications*, **10**, 1865 (2019).

advanced manipulation of spatial modes

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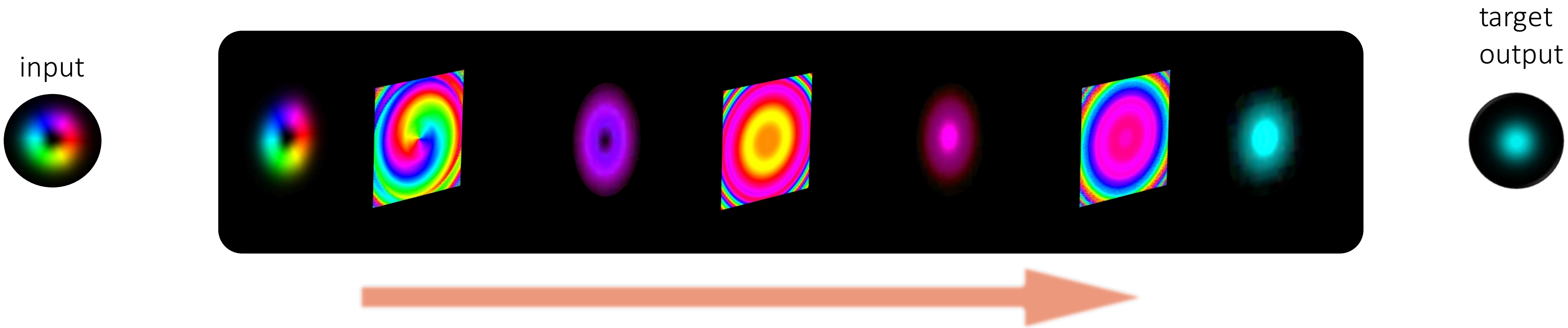
multi-plane light conversion[1] + wavefront matching[2,3] → spatial mode unitaries



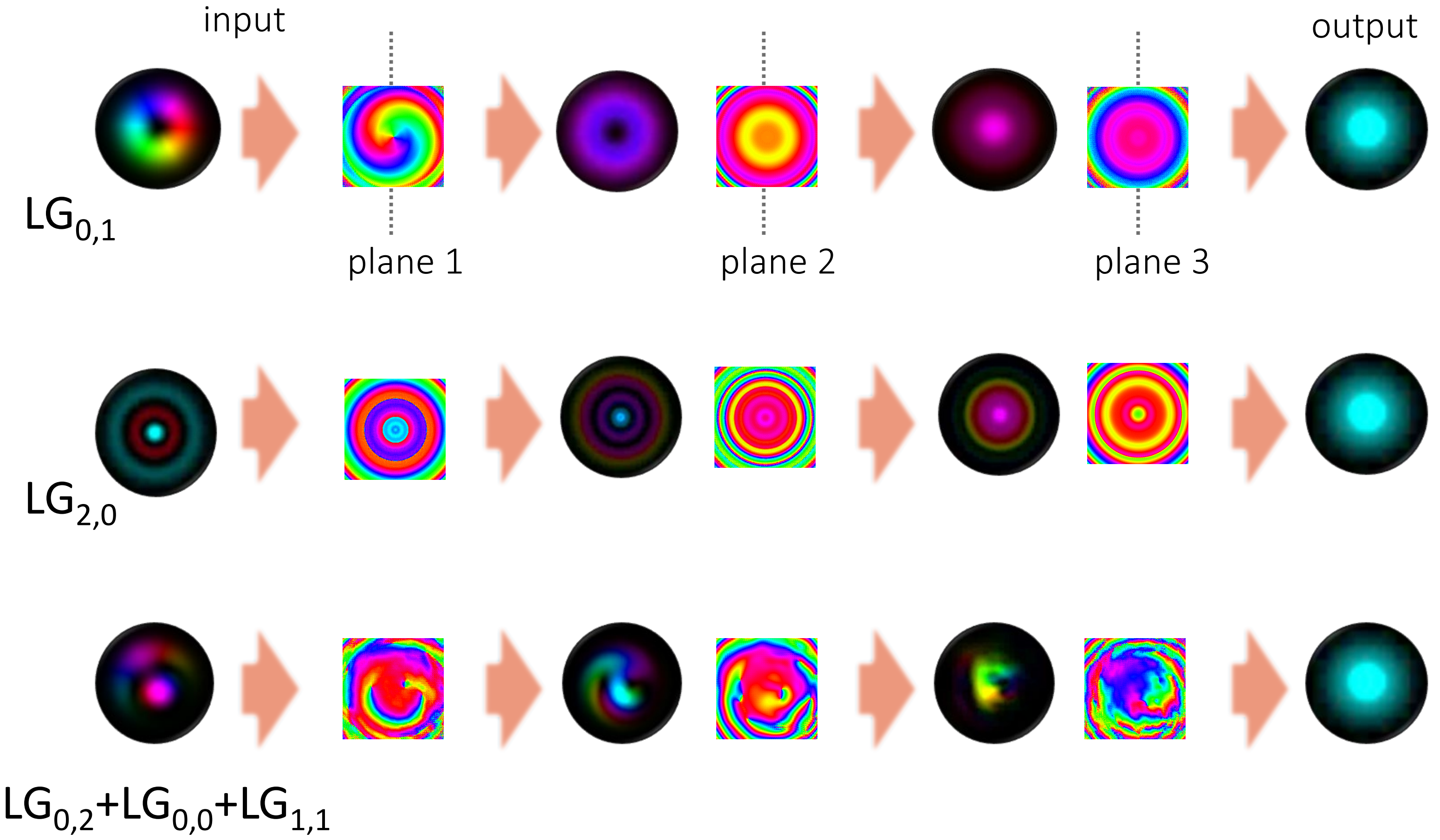
simpler task at first: unitary single mode conversion

[1] Morizur, Nicholls, Jian, Armstrong, Treps, Hage, Hsu, Bowen, Janousek, Bachor, *JOSA A*, **27**, 2524 (2010).
[2] Hashimoto, Saida, Ogawa, Kohtoku, Shibata, Takahashi, *Optics Letters*, **30**, 2620 (2005).
[3] Fontaine, Ryf, Chen, Neilson, Kim, Carpenter, *Nature Communications*, **10**, 1865 (2019).

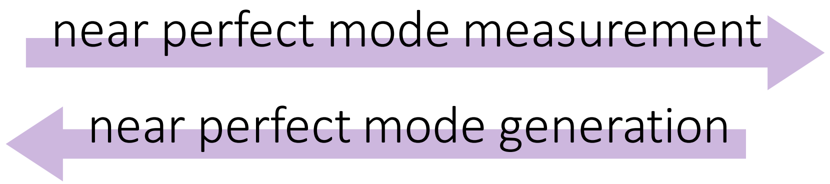
MPLC for perfect detection/generation

Near perfect mode projection (generation)

- Only three phase elements to convert any mode into a SMF mode (Gauss)



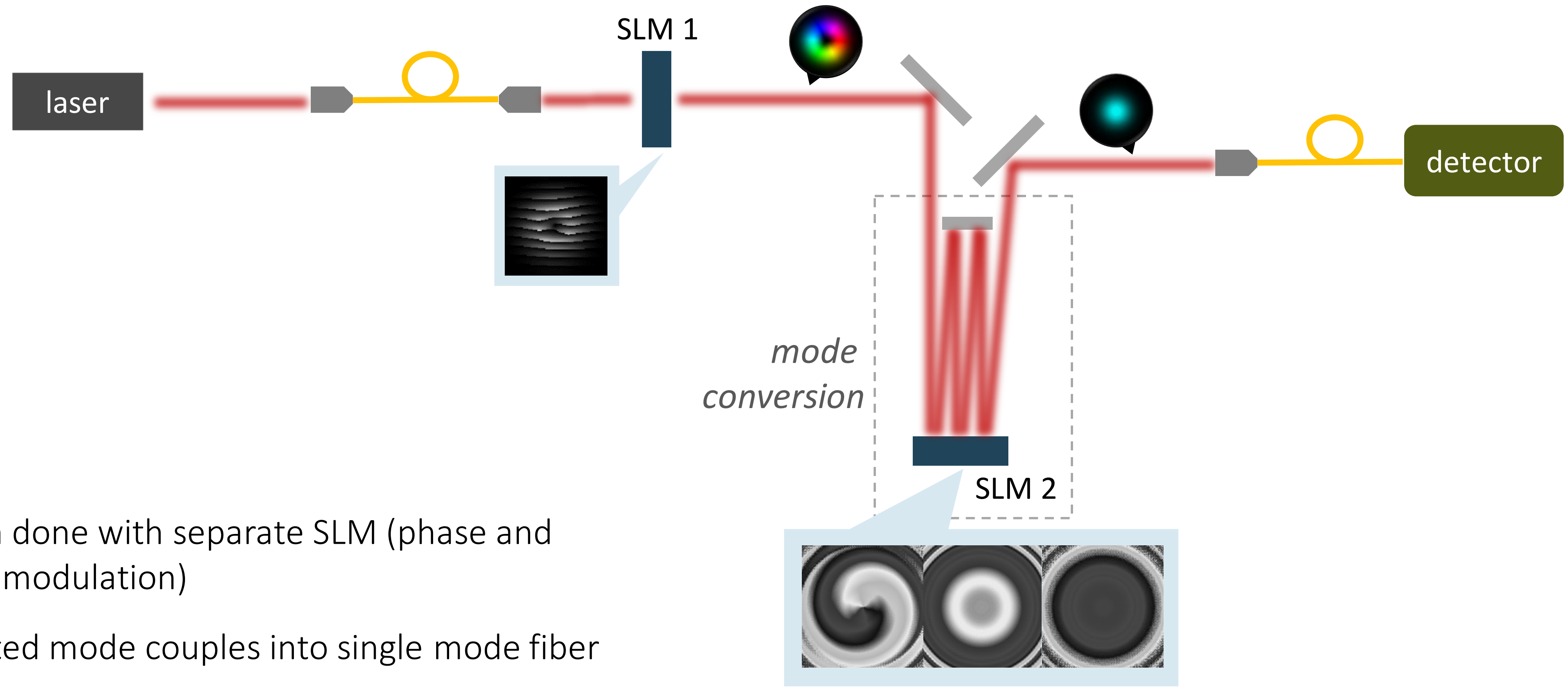
>99% overlap with Gauss



MPLC in the lab

sketch of the setup:

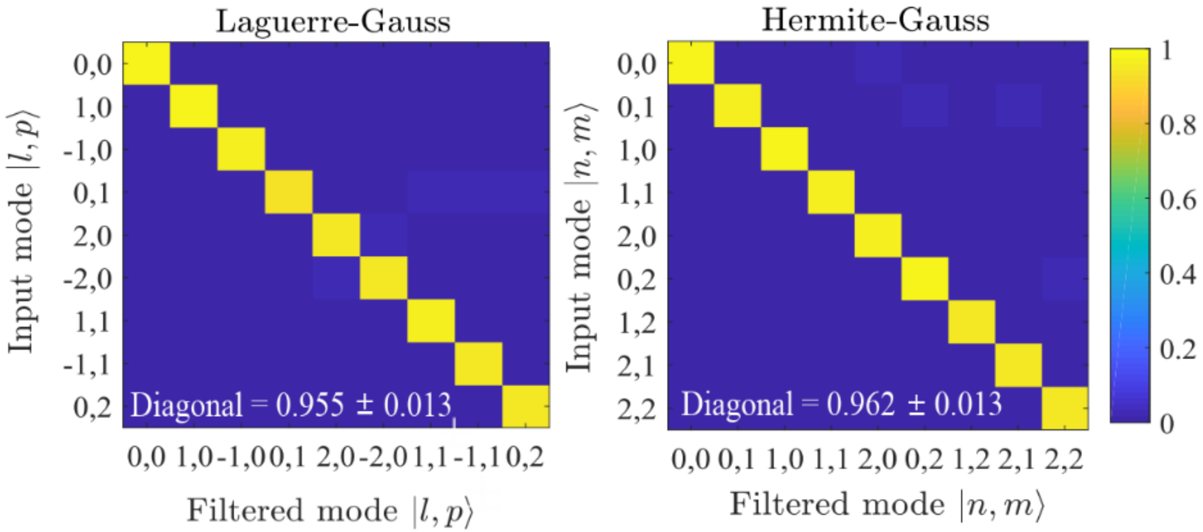
- 3 phase modulation displayed on 1 SLM

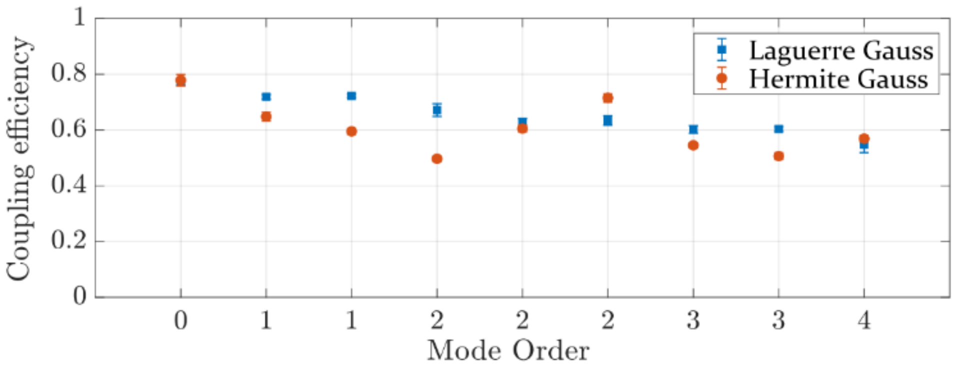


- generation done with separate SLM (phase and amplitude modulation)
- only targeted mode couples into single mode fiber

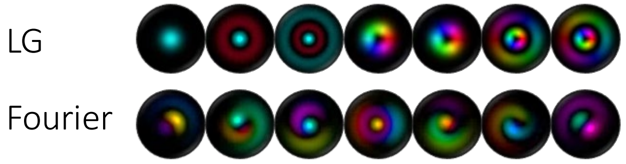
Near-perfect mode filterting

transform one specific LG mode or HG mode to a fundamental Gauss





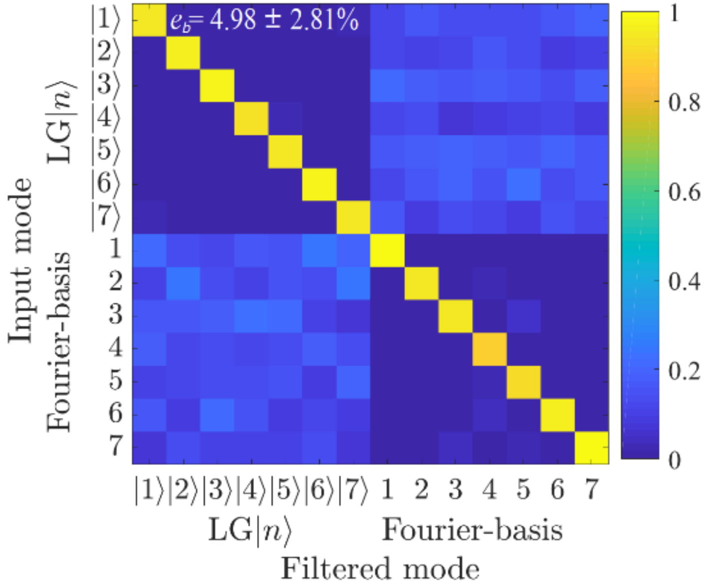
High-dimensional quantum cryptography



7-d QKD (BB84)

QBER < 23.8 %

2.8 bit/photon

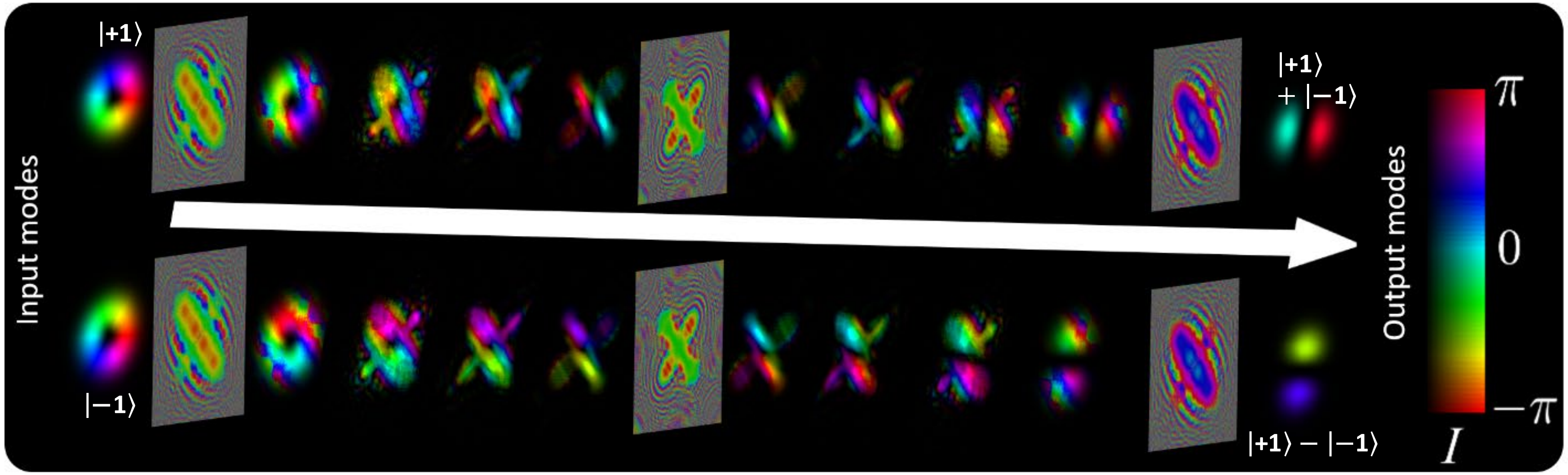


Hiekkamäki, Prabhakar, Fickler, Optics Express, 27, 31456 (2019)

advanced manipulation of spatial modes

technique to perform complex transformations between spatial modes

multi-plane light conversion[1] + wavefront matching[2,3] → spatial mode unitaries

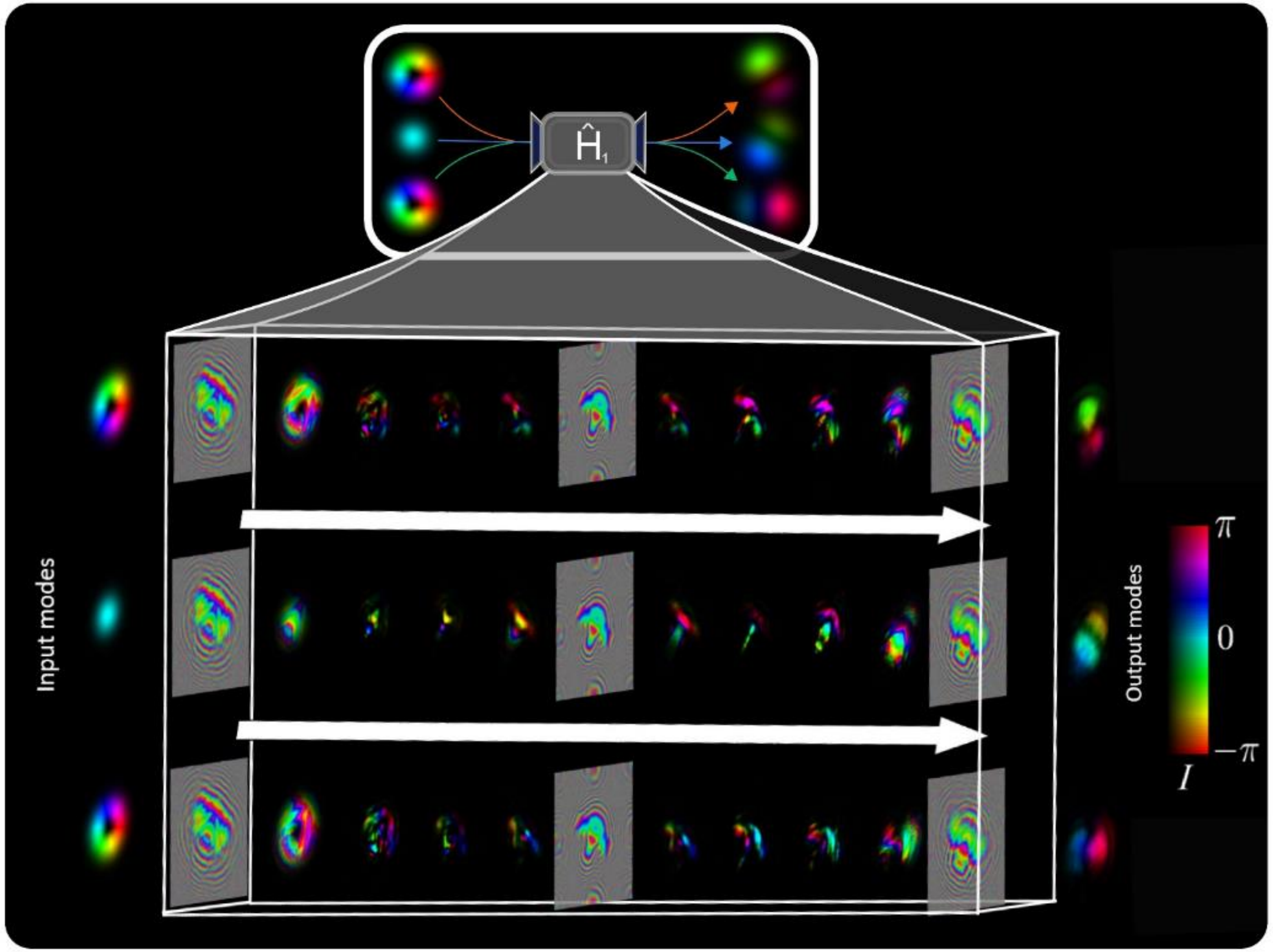


increase complexity of the modulations: unitary multiple mode conversion

[1] Morizur, Nicholls, Jian, Armstrong, Treps, Hage, Hsu, Bowen, Janousek, Bachor, *JOSA A*, **27**, 2524 (2010).
[2] Hashimoto, Saida, Ogawa, Kohtoku, Shibata, Takahashi, *Optics Letters*, **30**, 2620 (2005).
[3] Fontaine, Ryf, Chen, Neilson, Kim, Carpenter, *Nature Communications*, **10**, 1865 (2019).

advanced manipulation of spatial modes

technique to perform complex transformations between spatial modes



[1] Morizur, Nicholls, Jian, Armstrong, Treps, Hage, Hsu, Bowen, Janousek, Bachor, *JOSA A*, **27**, 2524 (2010).
[2] Hashimoto, Saida, Ogawa, Kohtoku, Shibata, Takahashi, *Optics Letters*, **30**, 2620 (2005).
[3] Fontaine, Ryf, Chen, Neilson, Kim, Carpenter, *Nature Communications*, **10**, 1865 (2019).

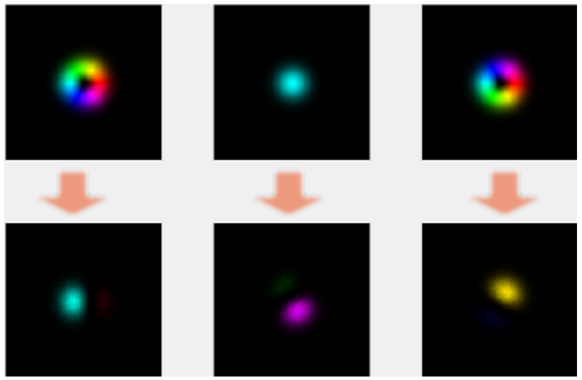
unitary operations using MPLC

simulation results:

- using 3 planes and qutrits (after around 50 iterations)

Hadamard gate for OAM

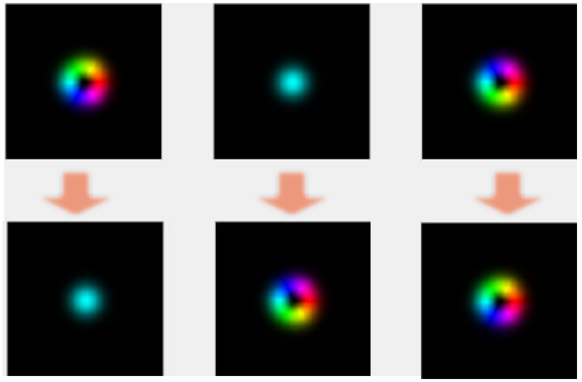
input



output

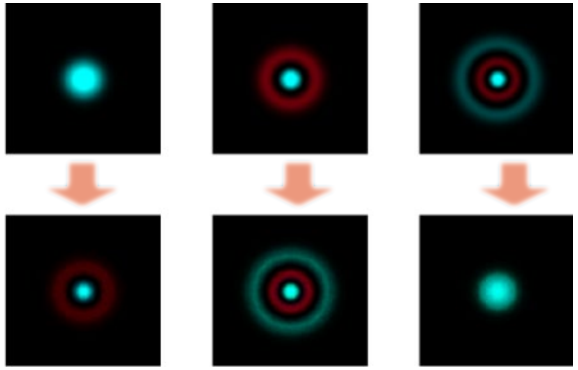
visibility = ~99%

X-Gate for OAM



visibility = ~99%

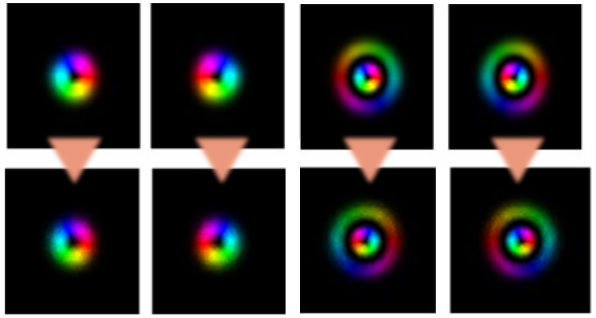
X-Gate for p modes



visibility = ~99%

p-mode controlled OAM-NOT gate

visibility = ~96%

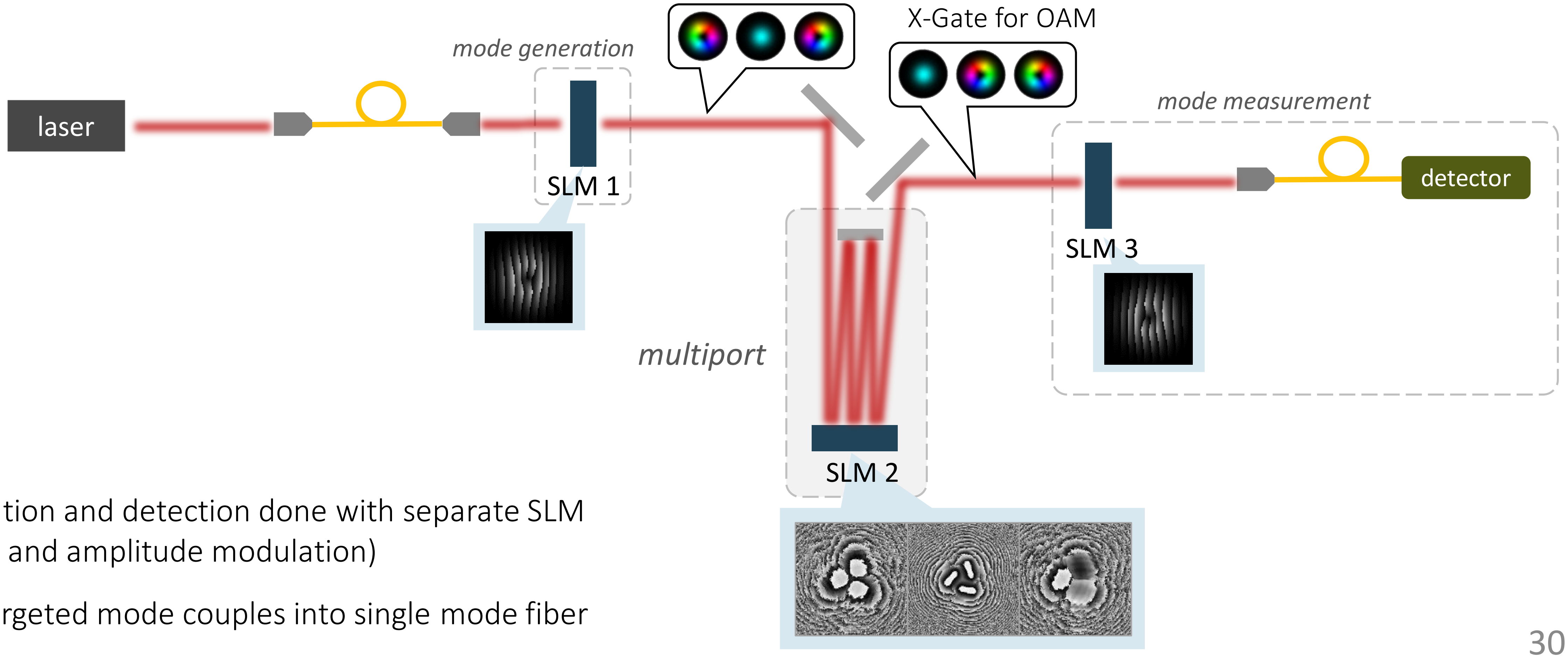


MPLC using wave front matching can be used as a multiport for spatial modes

MPLC in the lab

sketch of the setup:

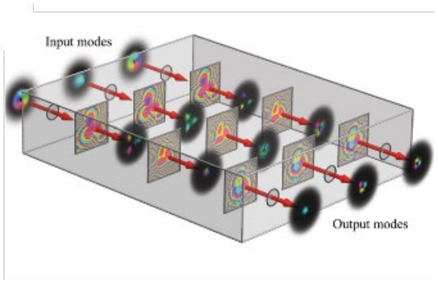
- 3 phase modulation displayed on spatial light modulator SLM 2

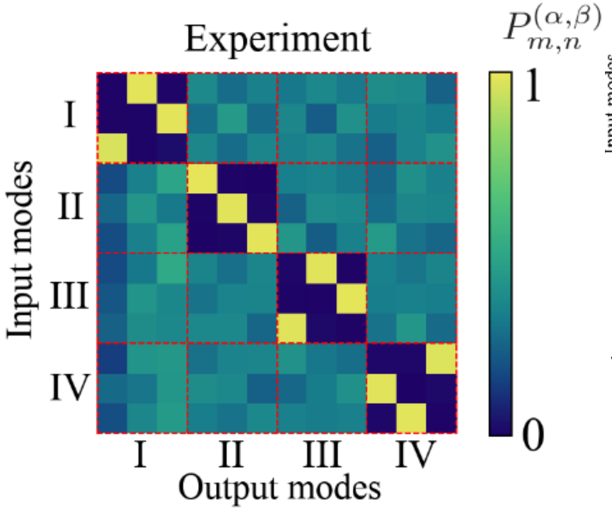


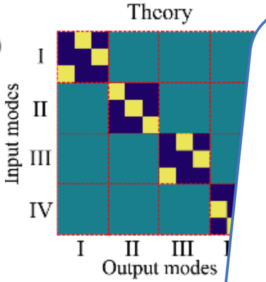
- generation and detection done with separate SLM (phase and amplitude modulation)
- only targeted mode couples into single mode fiber

high-dimensional quantum gates

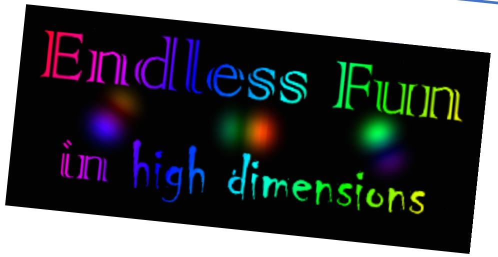
X-Gate for a OAM qutrit







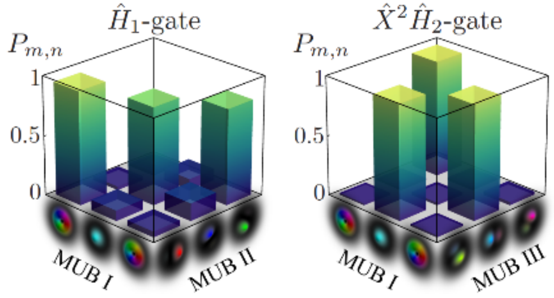
visibility:
98.4 %



Card Game: programming a high-dimensional quantum computer.

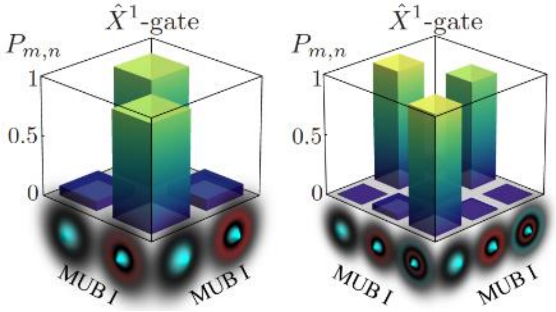
DOI: 10.5281/zenodo.4016359

OAM modes



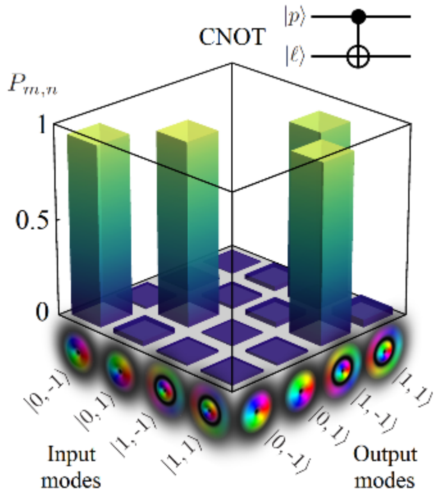
average visibility: 92.7 ± 3.8 %

radial modes



92.4 ± 3.4 %

OAM & radial modes



…done with single photons

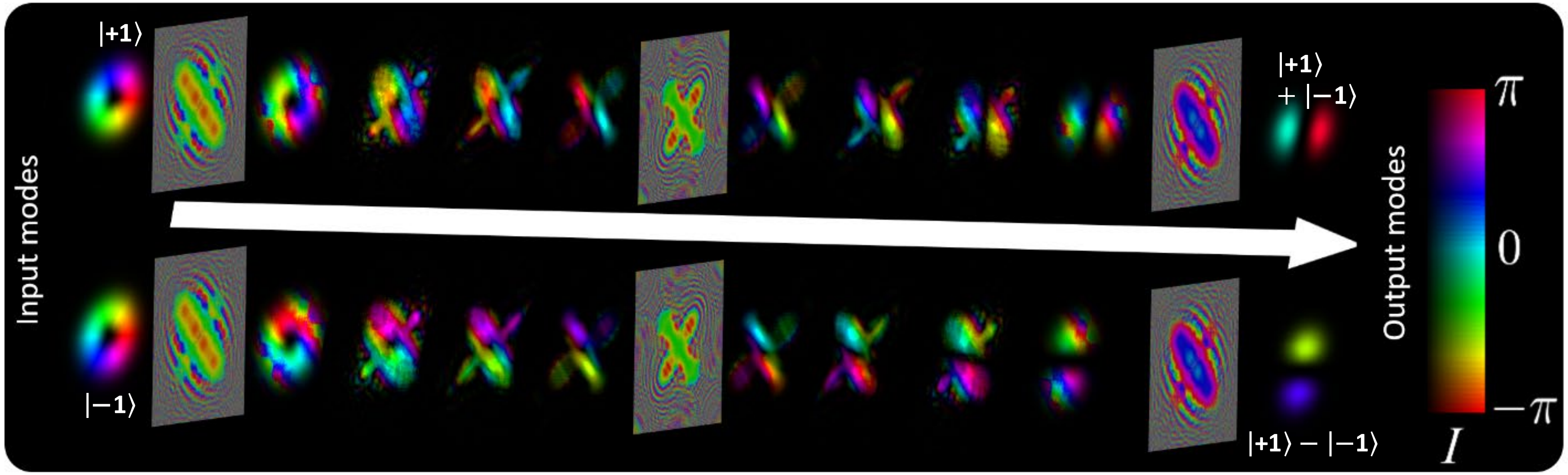
94.7 ± 1.4 %

Brandt, Hiekkamäki, Bouchard, Huber, Fickler, *Optica* **7**, 98 (2020)

advanced manipulation of spatial modes

technique to perform complex transformations between spatial modes

multi-plane light conversion[1] + wavefront matching[2,3] → spatial mode unitaries



increase complexity of experiment:

-> quantum interferences between to photons in unitary mode conversions

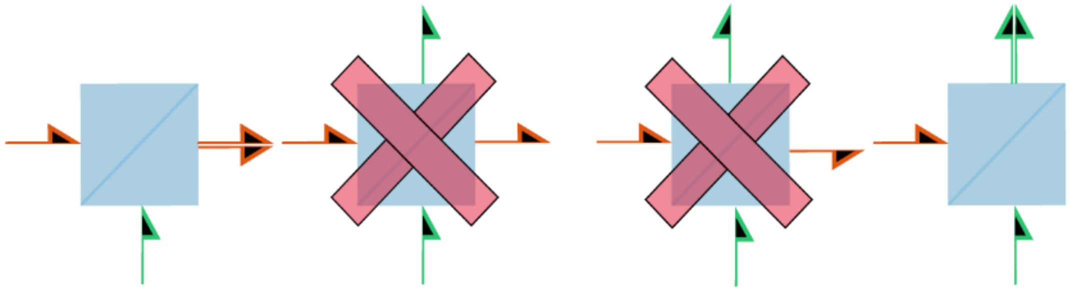
[1] Morizur, Nicholls, Jian, Armstrong, Treps, Hage, Hsu, Bowen, Janousek, Bachor, *JOSA A*, **27**, 2524 (2010).

[2] Hashimoto, Saida, Ogawa, Kohtoku, Shibata, Takahashi, *Optics Letters*, **30**, 2620 (2005).

[3] Fontaine, Ryf, Chen, Neilson, Kim, Carpenter, *Nature Communications*, **10**, 1865 (2019).

two-photon interference

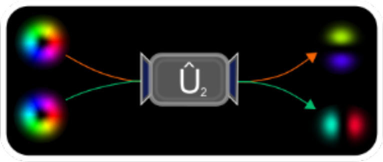
Hong-Ou-Mandel interference using a beamsplitter[1]

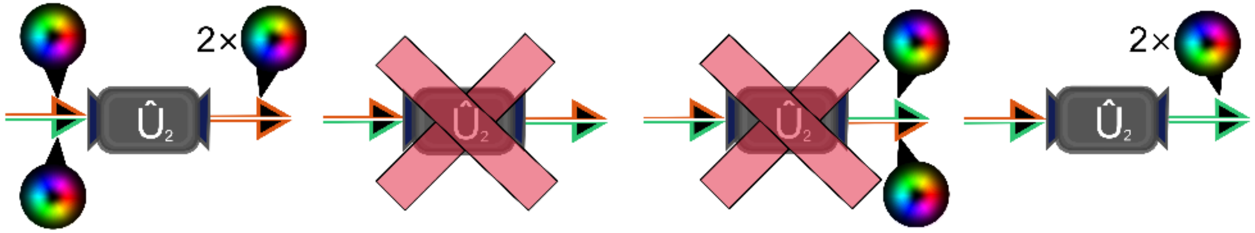


$$\hat{U}_2 = \frac{1}{\sqrt{2}}\begin{bmatrix}1 & -1\\ 1 & 1\end{bmatrix}$$

previous experiments using spatial modes[2,3,4,5]

Hong-Ou-Mandel interference using a 2d **mode-splitter**



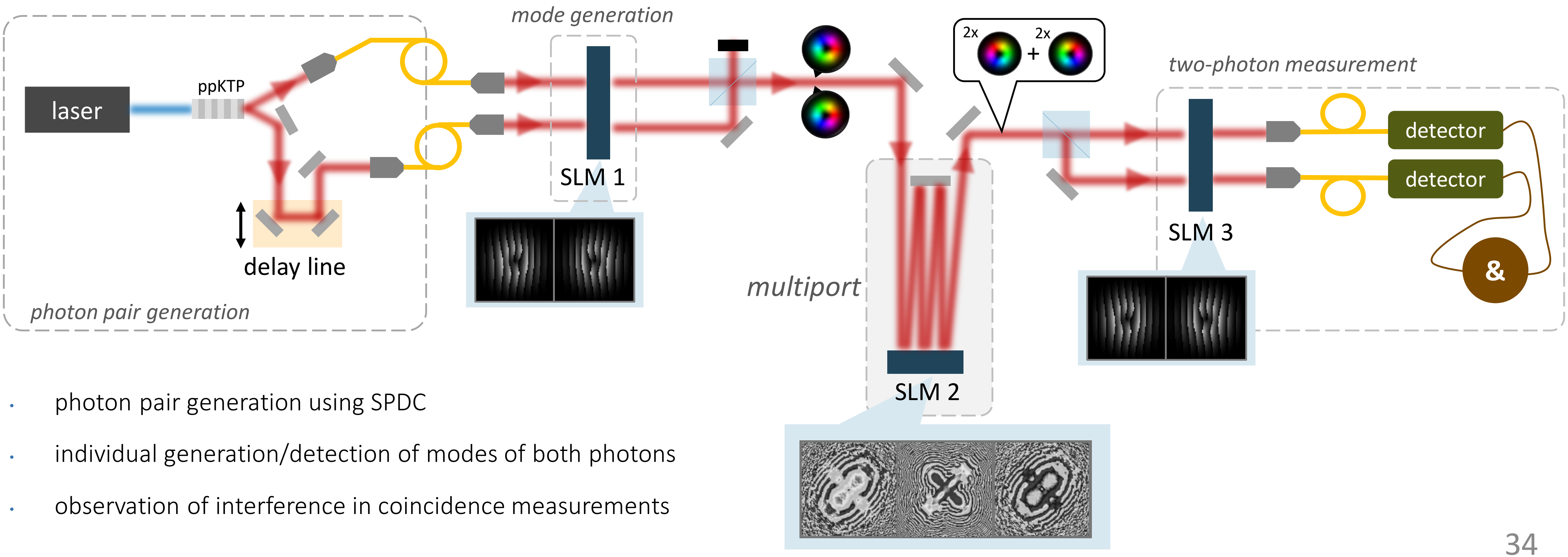


[1] Hong, Ou, Mandel, *PRL* **59**, 2044 (1987)
[2] Nagali, Sansoni, Sciarrino, De Martini, Marrucci, Piccirillo, Karimi, Santamato. *Nat. Phot*. **3**, 720 (2009).
[3] Karimi, Boyd, De La Hoz, De Guise, Řeháček, Hradil, Aiello, Leuchs, and Sánchez-Soto. *PRA* **89**, 1 (2014).
[4] Zhang, Prabhakar, Rosales-Guzmán, Roux, Karimi, and Forbes. *PRA* **94**, 1–5 (2016).
[5]] D'Ambrosio, Carvacho, Agresti, Marrucci, and Sciarrino. *PRL* **122**, 013601 (2019).

two-photon interference in the lab

sketch of the setup:

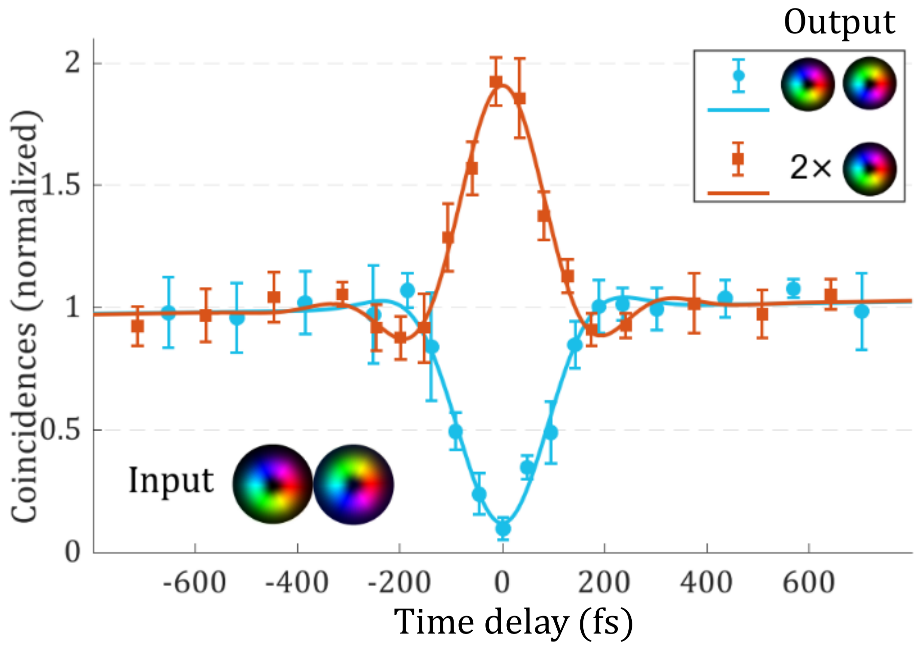
- 3 phase modulation displayed on spatial light modulator SLM 2

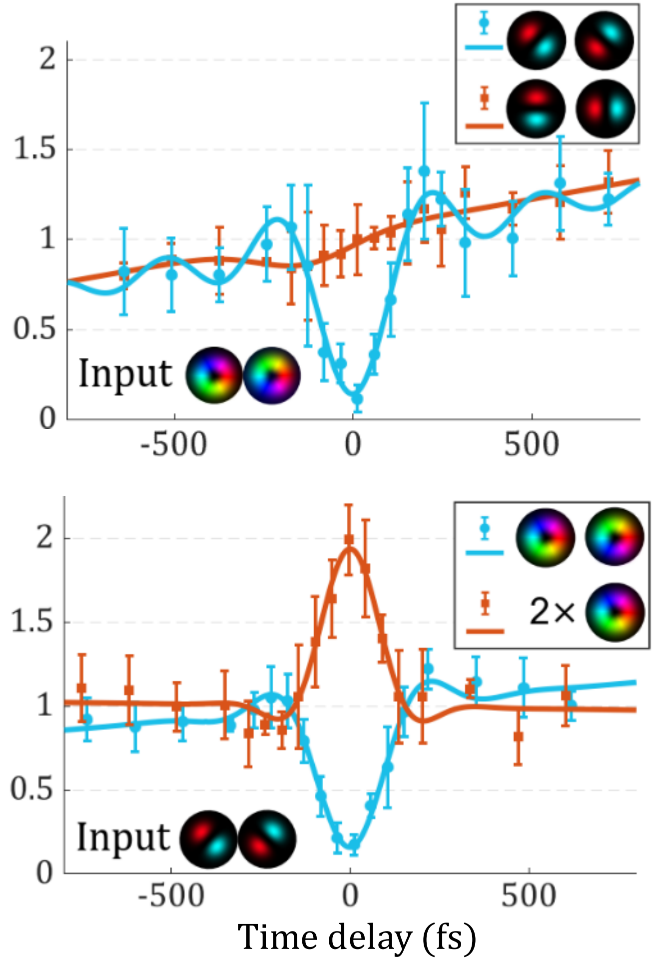


- photon pair generation using SPDC
- individual generation/detection of modes of both photons
- observation of interference in coincidence measurements

2d mode-splitter experimental results

single-path spatial mode HOM-experiment





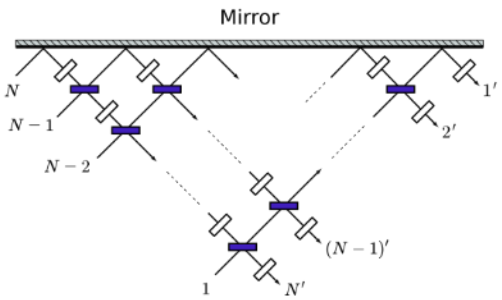
$$V = \frac{R_{cl} - R_{qu}}{R_{cl}} \in [0, 1]$$

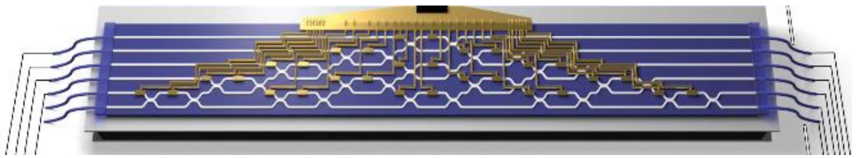
$$V_{dip} = 88\% \pm 3.8\%$$
$$V_{bump} = 90.9\% \pm 4.5\%$$

Hiekkamäki, Fickler. arXiv:2006.13288 (2020).

high-dimensional mode-splitter

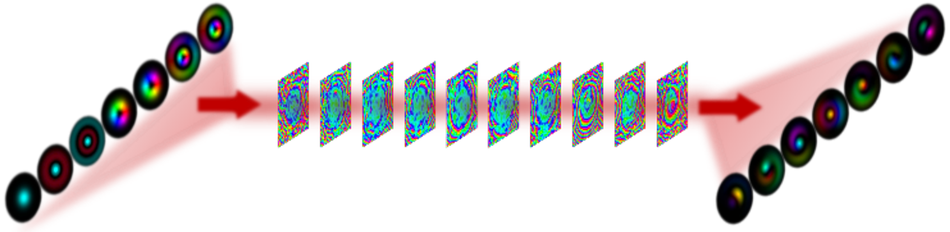
linear optical networks using different paths[1]



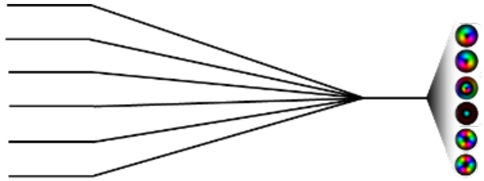


linear optical networks using a single paths

...but multiple spatial modes



combining both through multiplexers

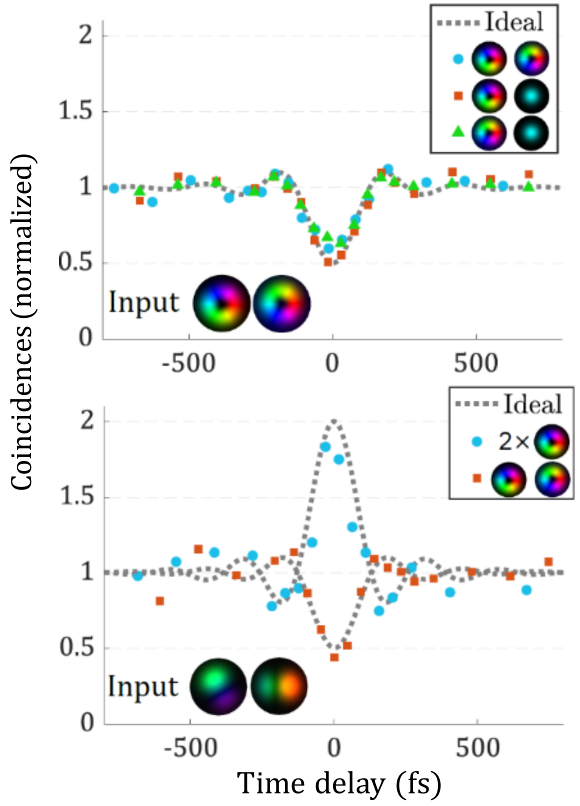


[1] Carolan, Harrold, Sparrow, Martín-López, Russell, Silverstone, Shadbolt, Matsuda, Oguma, Itoh, Marshall, Thompson, Matthews, Hashimoto, O'Brien, Laing, *Science* **349**, 711 (2015).

high-dimensional mode-splitter

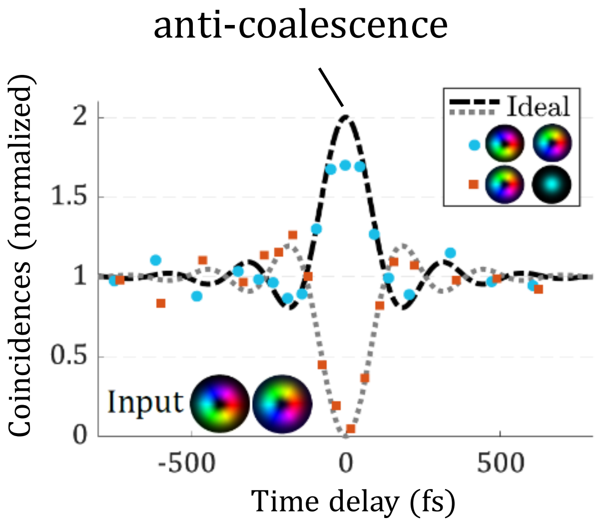
3d

$$\hat{U}_3 = \frac{1}{\sqrt{3}} \begin{bmatrix} 1 & e^{i\frac{4\pi}{3}} & e^{i\frac{2\pi}{3}} \\ 1 & e^{i\frac{2\pi}{3}} & e^{i\frac{4\pi}{3}} \\ 1 & 1 & 1 \end{bmatrix}$$



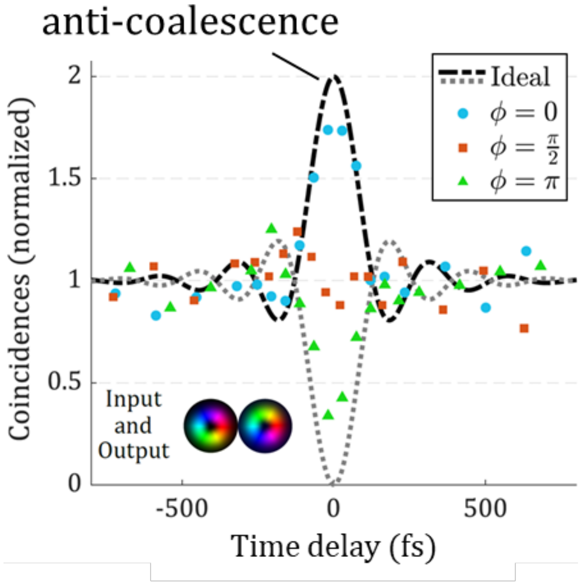
$$\hat{U}_{Rot+3} = \hat{U}_3 \hat{R}_3,$$

$$\hat{R}_3 = \frac{1}{2\sqrt{3}} \begin{bmatrix} \sqrt{2}+1 & \sqrt{2}-1 & -2\sqrt{\frac{3}{2}} \\ \sqrt{2}-2 & \sqrt{2}+2 & 0 \\ \sqrt{2}+1 & \sqrt{2}-1 & 2\sqrt{\frac{3}{2}} \end{bmatrix}$$



4d

$$\hat{U}_4 = \frac{1}{2} \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & e^{i\varphi} & -1 & -e^{i\varphi} \\ 1 & -1 & 1 & -1 \\ 1 & -e^{i\varphi} & -1 & e^{i\varphi} \end{bmatrix}$$



phase φ can be used to control coalescence

Hiekkamäki, Fickler. arXiv:2006.13288 (2020).

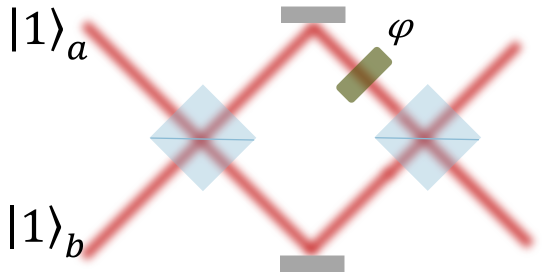
spatial-mode NOON states

phase super sensitivity with NOON-states: $\frac{1}{\sqrt{2}}(|N,0\rangle + |N,0\rangle)$

phase sensitivity scales with N[1,2]

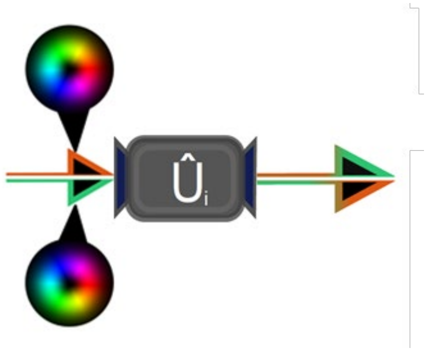
$$\Delta\varphi \sim \frac{1}{N}$$

(classically $\Delta\varphi = \frac{1}{\sqrt{N}}$)



$$\frac{1}{\sqrt{2}}(|2\rangle_a|0\rangle_b + |0\rangle_a|2\rangle_b)$$

2d mode-splitter generates spatial-mode NOON-states



$$\frac{1}{\sqrt{2}}(|2\rangle|0\rangle + |0\rangle|2\rangle)$$

entanglement verification using an entanglement witness

(<1 for separable states)

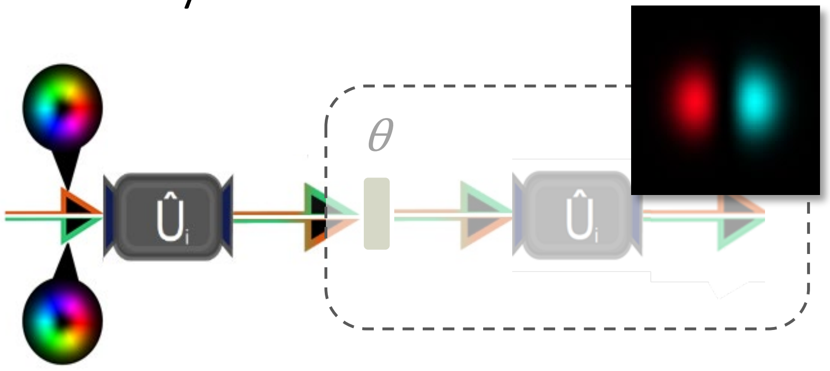
2.2 ± 0.1

Hiekkamäki, Fickler. arXiv:2006.13288 (2020).

[1] Caves, *Phys. Rev. D* **23**, 1693 (1981).
[2] Ou, *Phys. Rev. A* **55**,2598 (1997).

spatial-mode NOON states

angular super sensitivity with OAM NOON-states:



$$\frac{1}{\sqrt{2}}\left(|2\rangle|0\rangle + |0\rangle|2\rangle\right)$$

phase change φ corresponds to a rotation θ, which scales with the OAM quanta l [1,2]

$$\theta = \frac{\varphi}{l}$$

angular super sensitivity[3]

$$\Delta\theta \sim \frac{1}{l\,N}$$

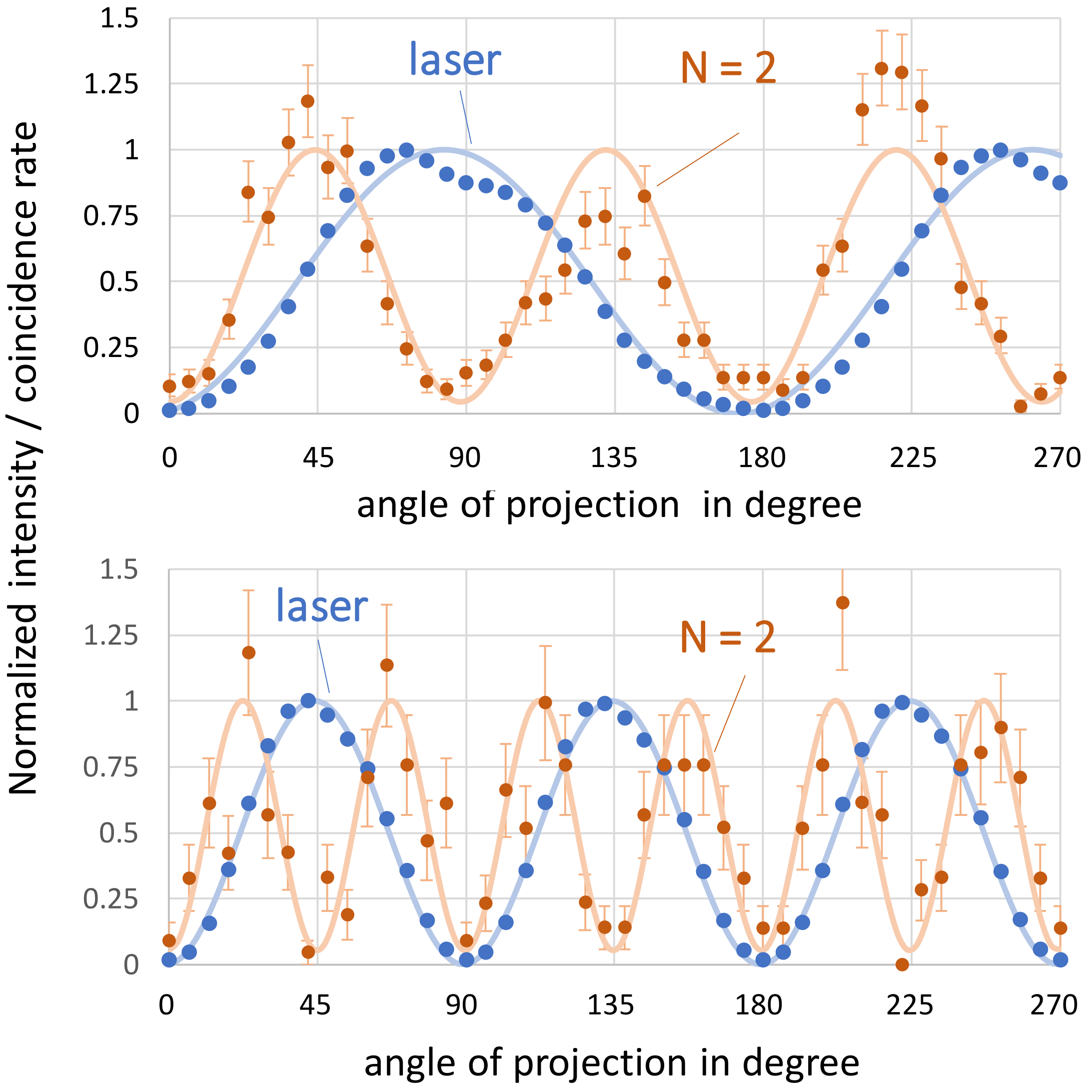
[1] Fickler, Lapkiewicz, Plick, Krenn, Schäff, Ramelow, Zeilinger, *Science,* **338,** 640 (2012).
[2] D'ambrosio, Spagnolo, Del Re, Slussarenko, Li, Kwek, Marrucci, Walborn, Aolita, Sciarrino, *Nature Communications* **4**.1, 1 (2013).
[3] Barnett, Zambrini, *Journal of Modern Optics*, **53**, 613-625 (2006).

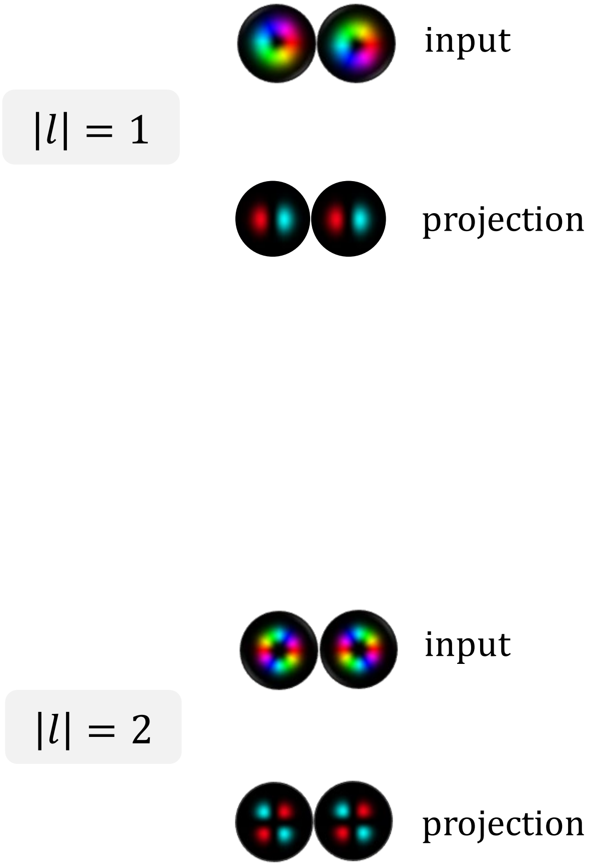
spatial-mode NOON states – very first results

angular super sensitivity with spatial mode NOON-states:

$$\Delta\theta = \frac{1}{l\,N}$$

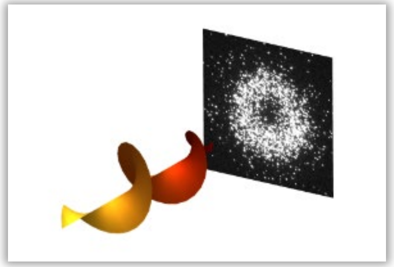
$$\frac{1}{\sqrt{2}}(|N,0\rangle + |N,0\rangle)$$





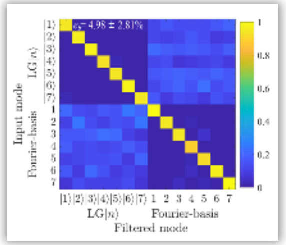
conclusion

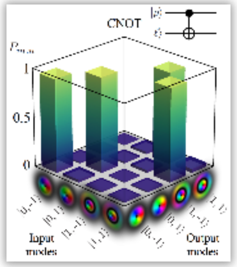
- structured photons are powerful realizations of high-dimensional quantum states

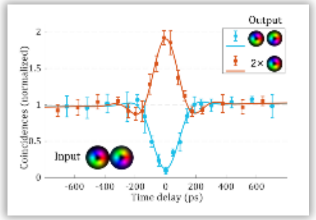


- high-dimensional quantum information offers many benefits for quantum photonics

- advanced modulations of structured photons using MPLC
  - -> near-perfect filtering
  - -> high-dimensional quantum gates
  - -> two-photon interferences along a single beam
  - -> angular super sensitivity







acknowledgement

Experimental Quantum Optics Team:

Robert Fickler, Lea Kopf, Markus Hiekkamäki, Shashi Prabhakar

Subhajit Bej

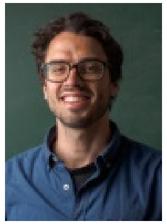
Stephen Plachta

Matias Eriksson

collaborators:

Marcus Huber

Florian Brandt



Frederic Bouchard

Tampere University

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Magnus Ehrnrooth Foundation

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Welcome to Tampere in 2021

Experimental Quantum Optics

https://research.tuni.fi/eqo/

Postdoc position available !

(submission deadline soon)

Hiekkamäki, Prabhakar, Fickler,
Optics Express, 27, 31456 (2019)

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arXiv:2006.13288 (2020).

ENDLESS FUN Card Game:
DOI: 10.5281/zenodo.4016359
...program a high-dimensional quantum computer !