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MPL uOttawa IASBS

Structured Quantum Waves

Présenté par : Ebrahim Karimi | Presented by: Ebrahim Karimi

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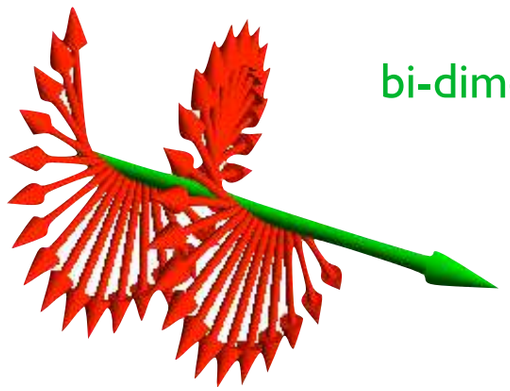
Structured Photons

Light: Degrees of Freedom



bi-dimensional variable

$|\pi\rangle$ Polarisation (Spin)

$|p\rangle$ Radial mode (p number)

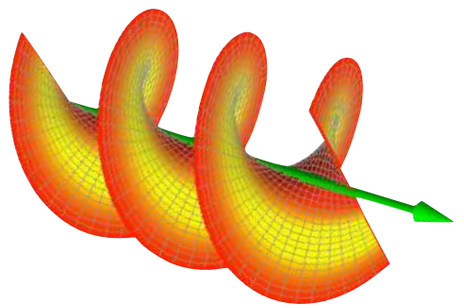
infinite dimension (discrete)

Linear momentum (k-vector)

continuous variable

$|\kappa\rangle$

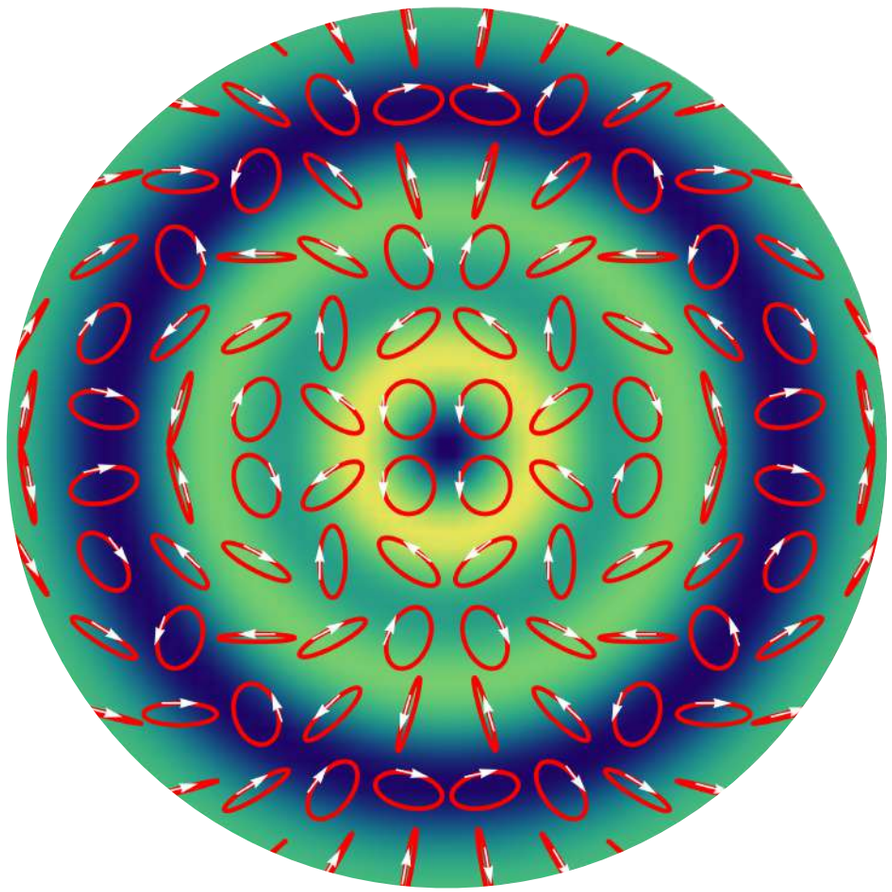
Orbital angular momentum (OAM)



$|o\rangle$

infinite dimension (discrete)

Structural Light (Photons)



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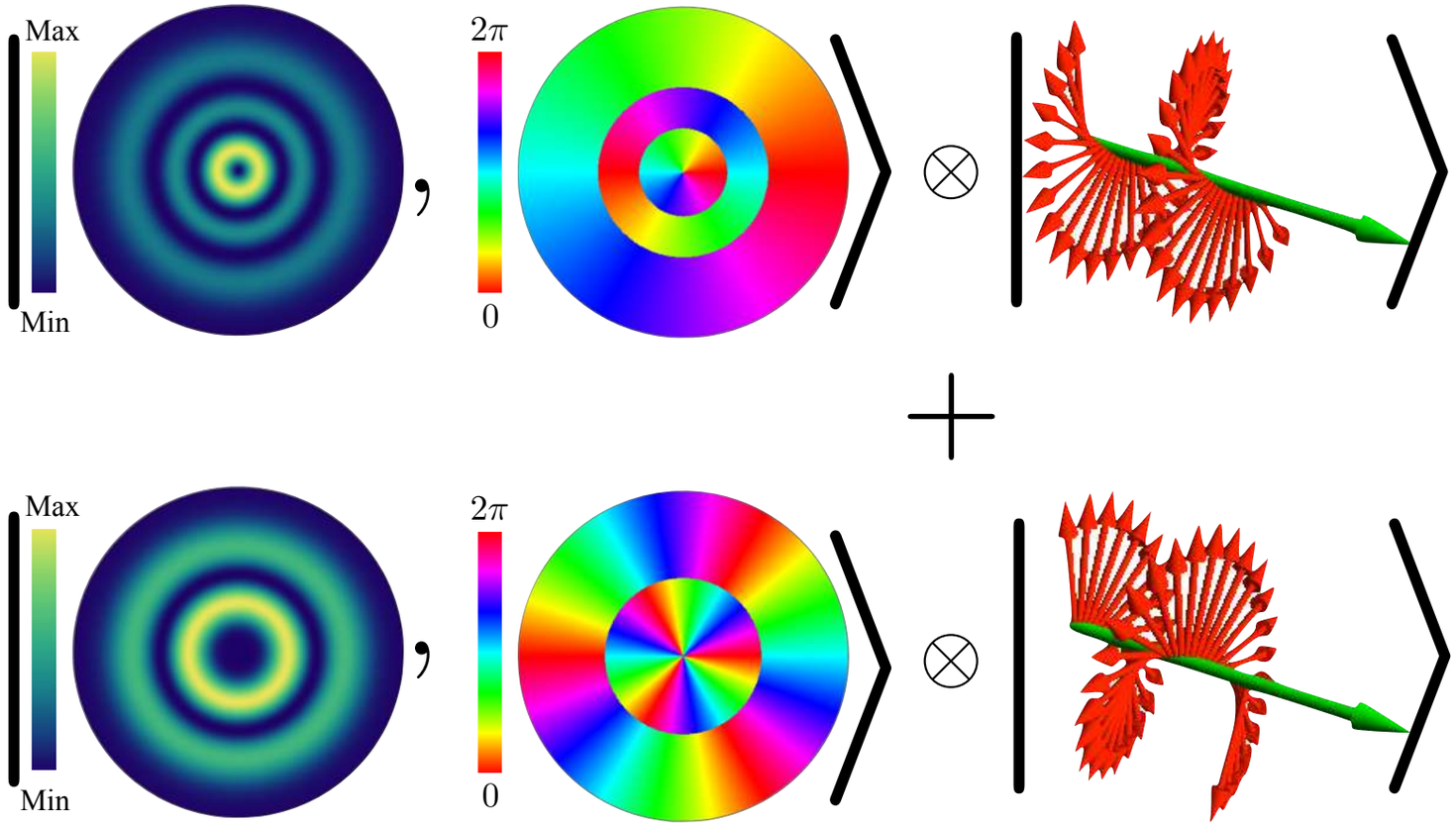
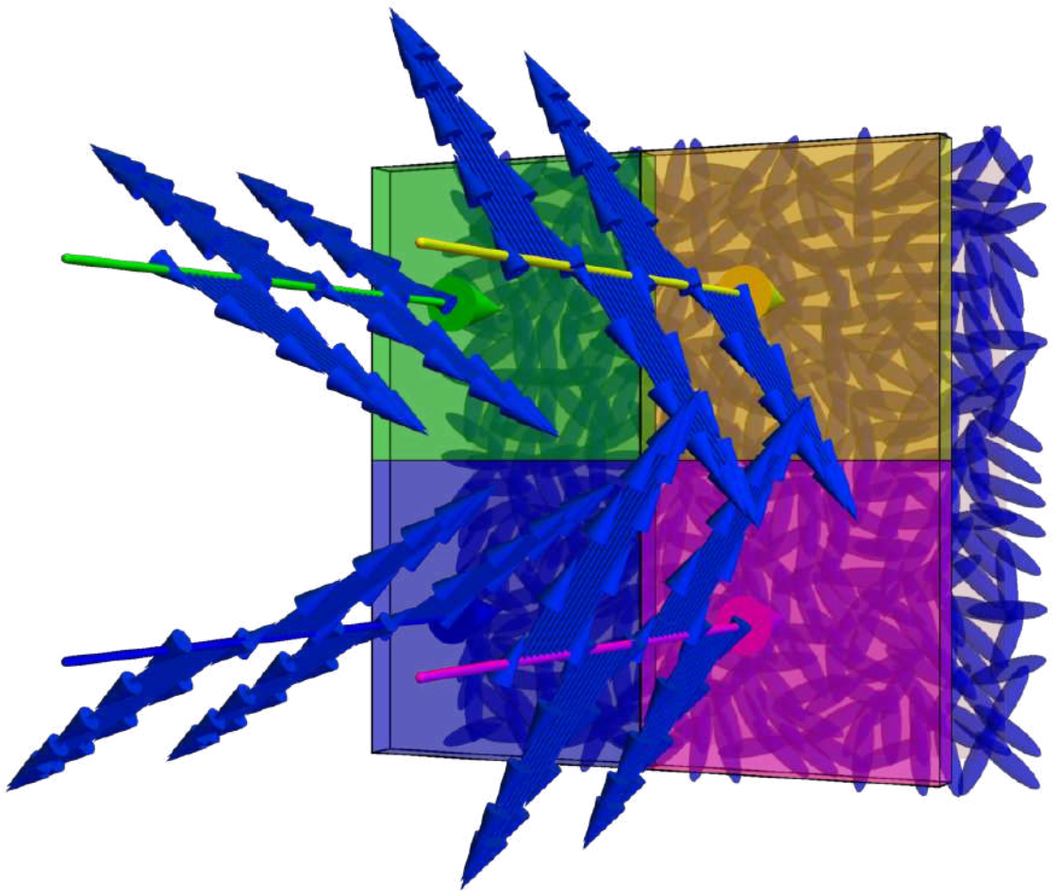
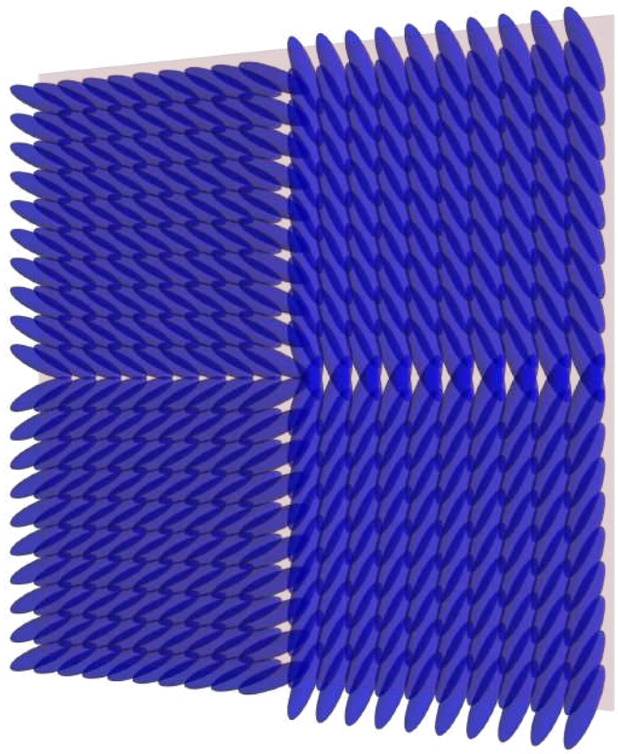


E.K. & R W Boyd, *Science* **350**, 1172 (2015).

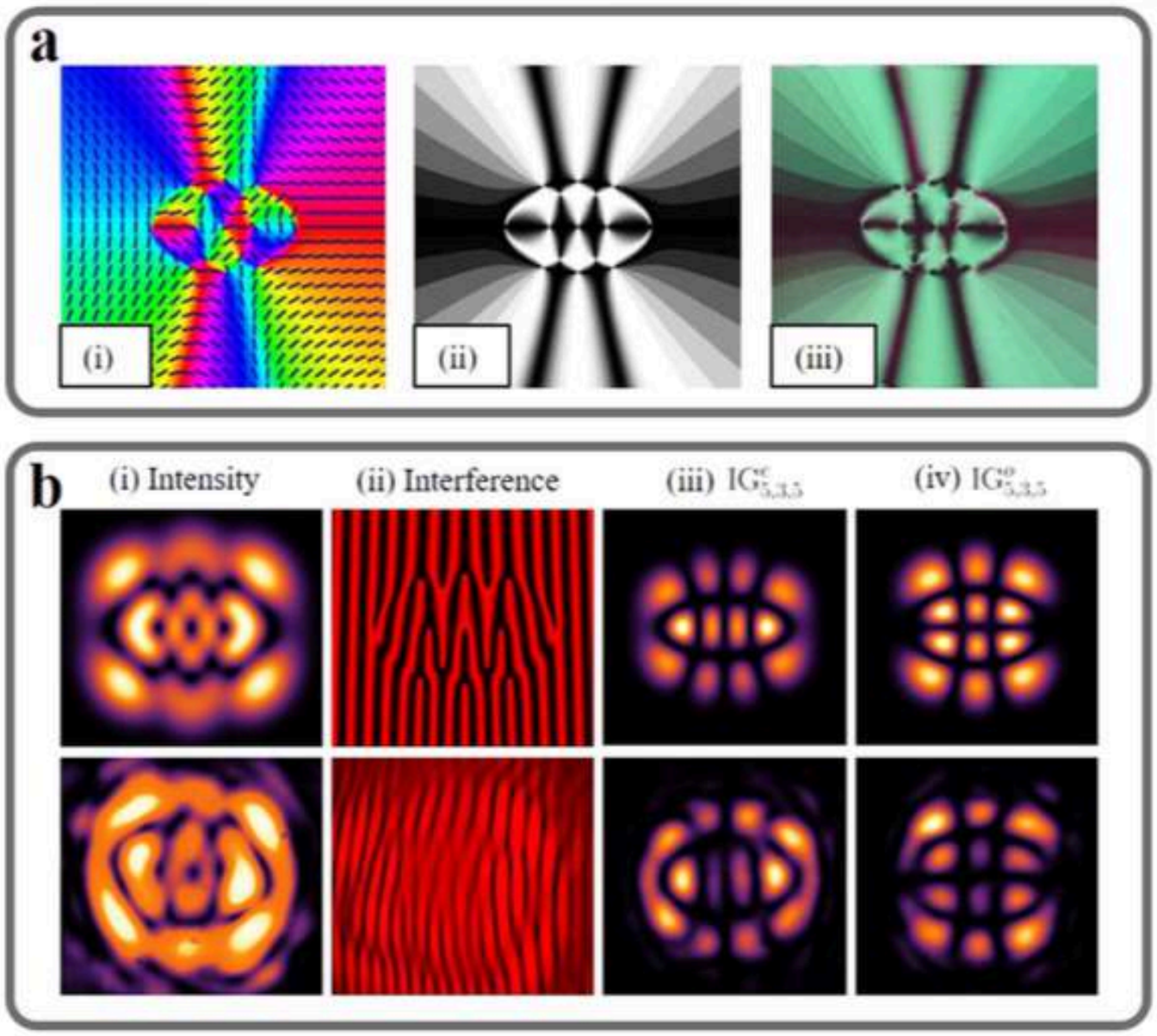
Generating different types of structured photons

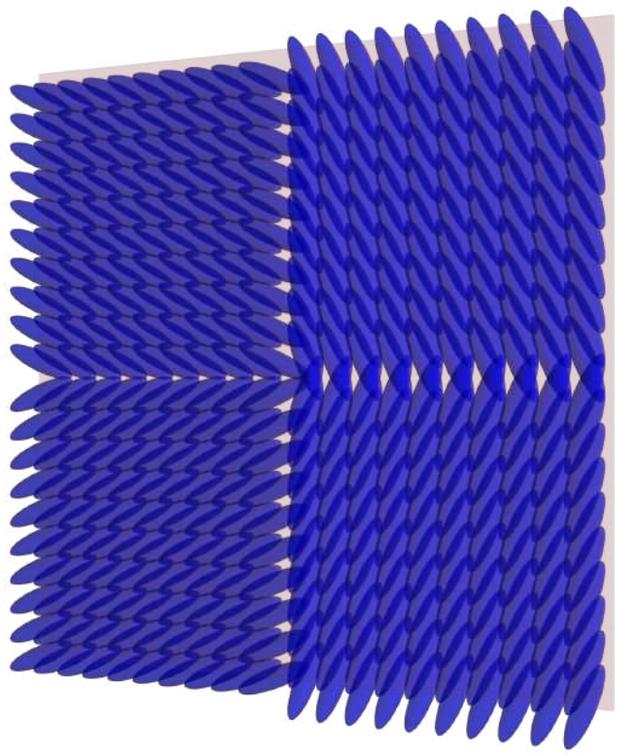




H Larocque, J Gagnon-Bischoff, F Bouchard, R Fickler, J Upham, R W Boyd & E K, *Journal of Optics* **18**, 124002 (2016)

Generating different types of structured photons





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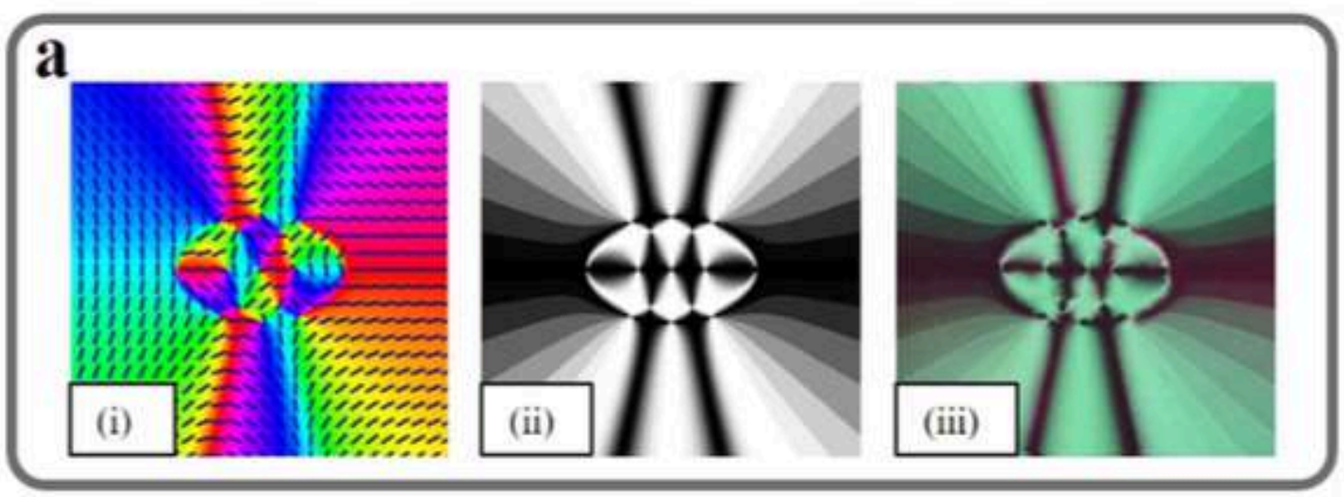
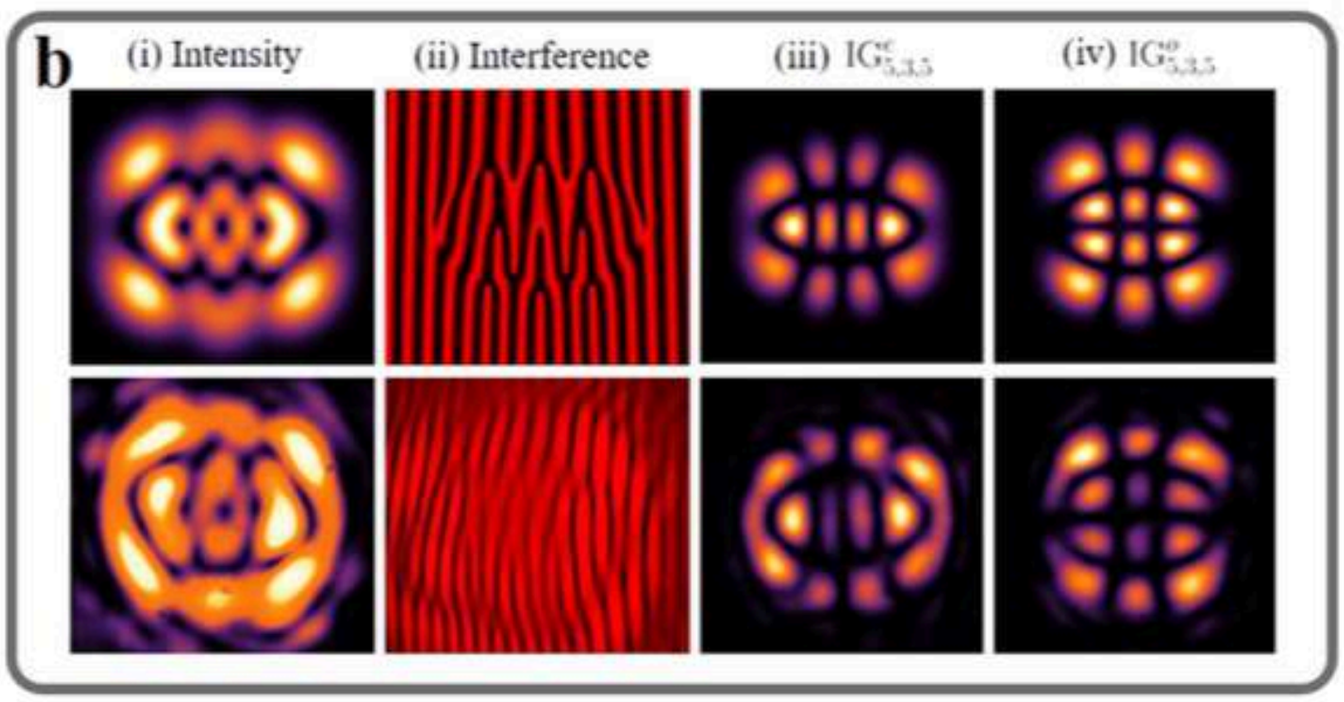
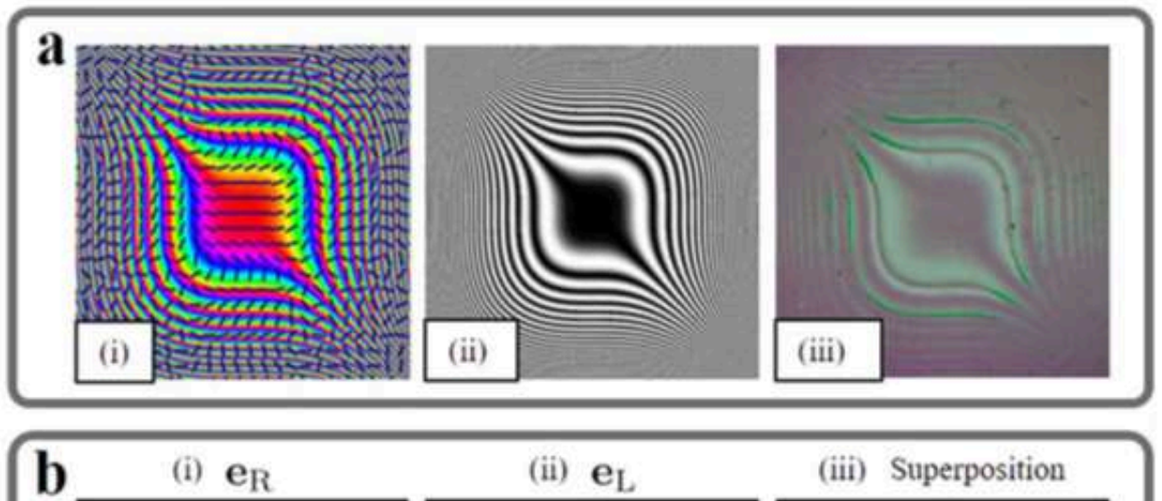
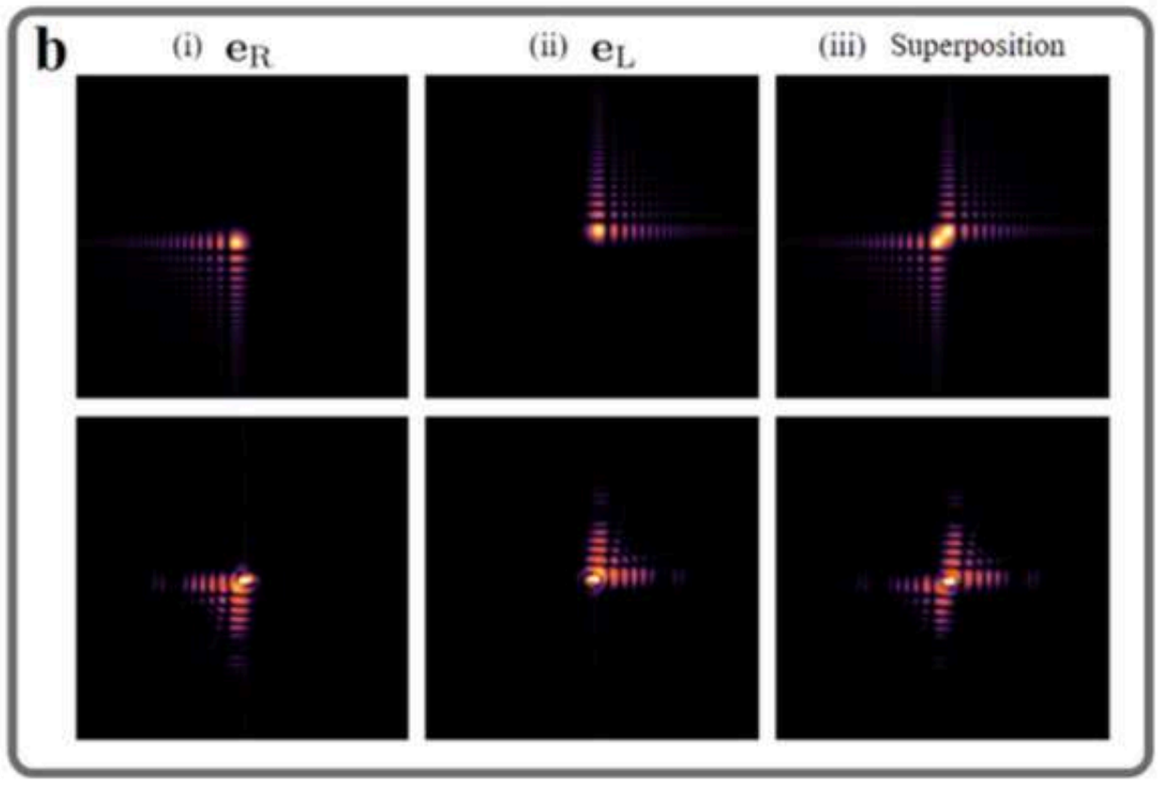
Generating different types of structured photons









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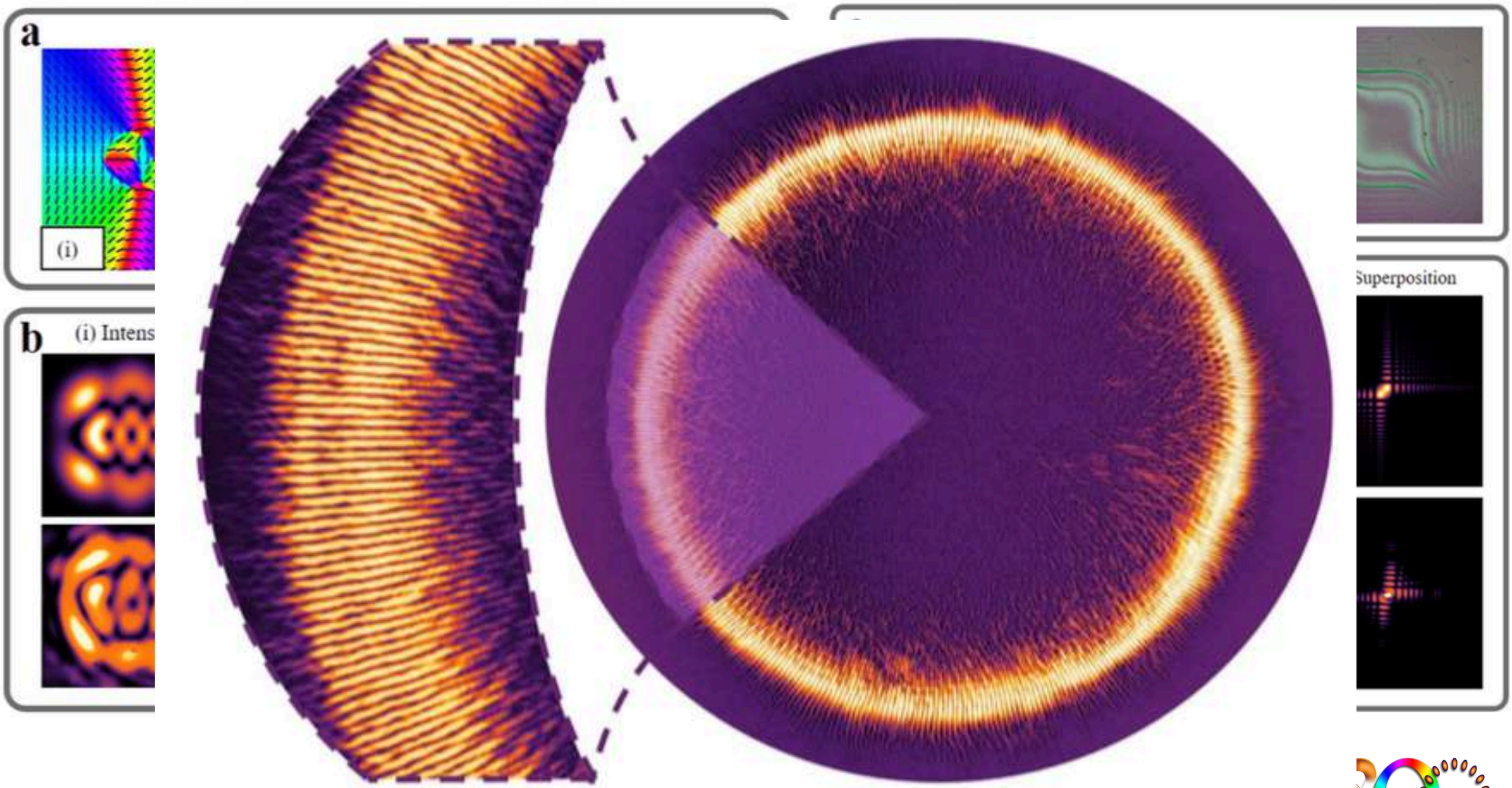
Generating different types of structured photons



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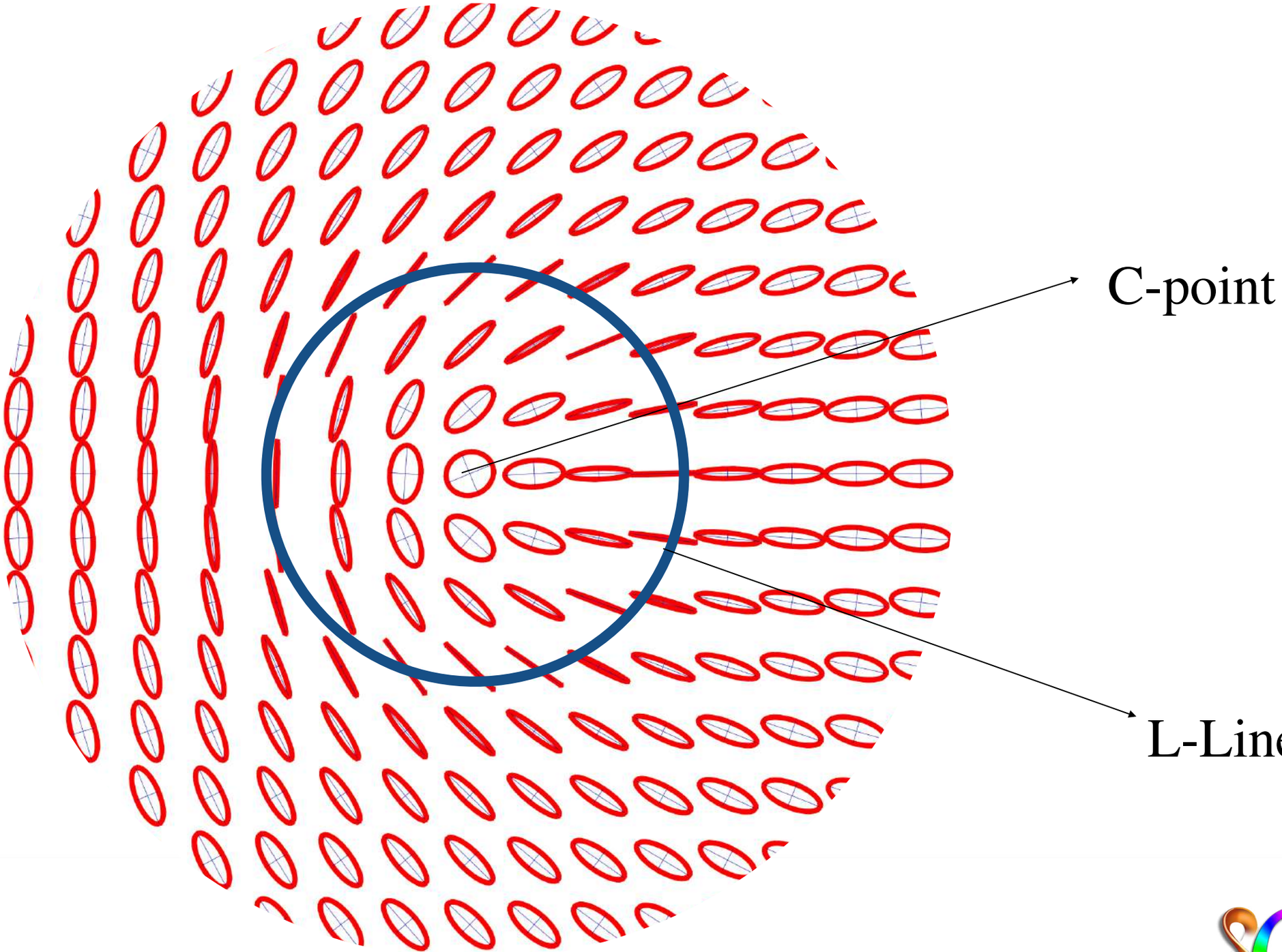
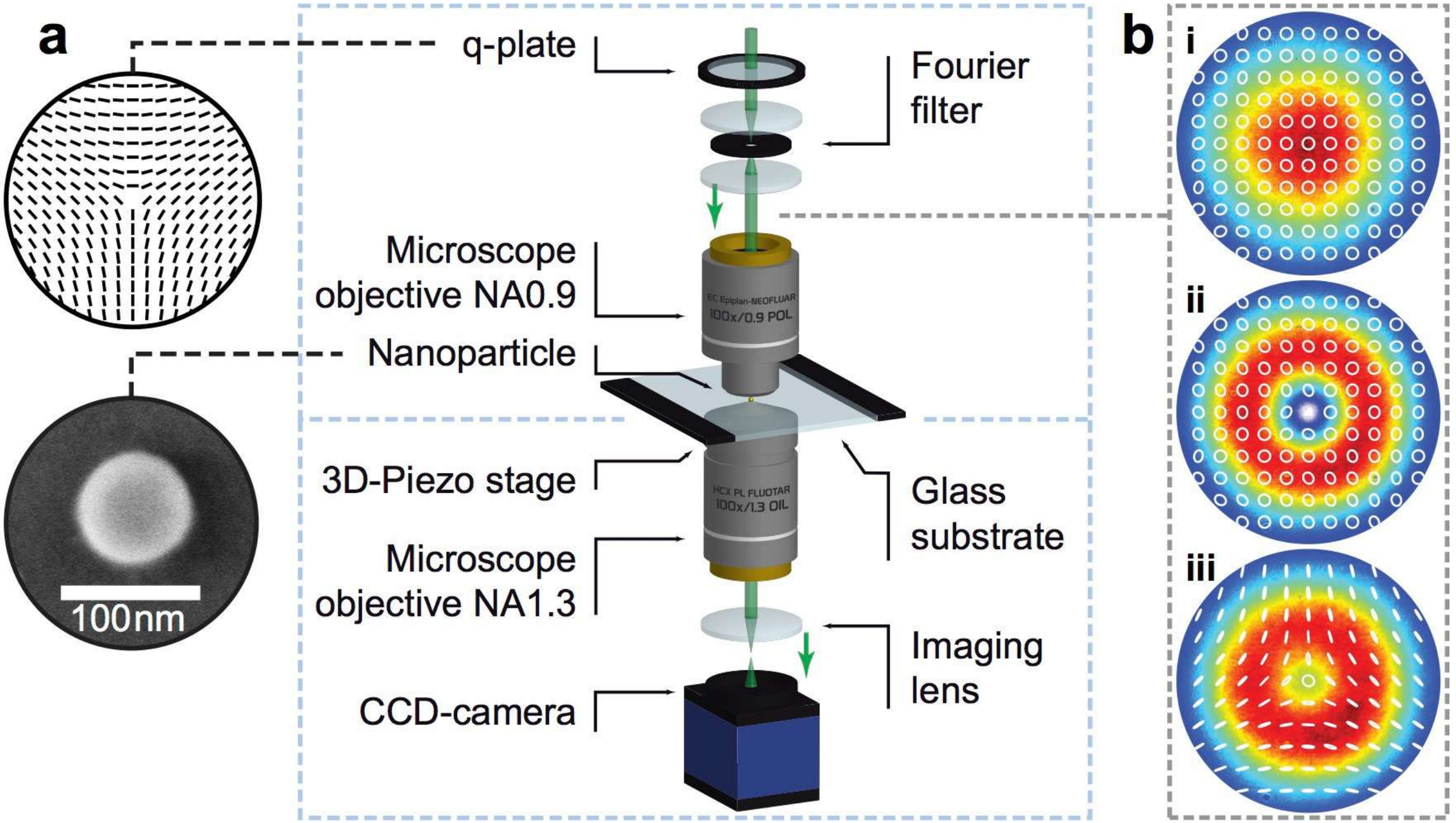
Polarisation Singularities

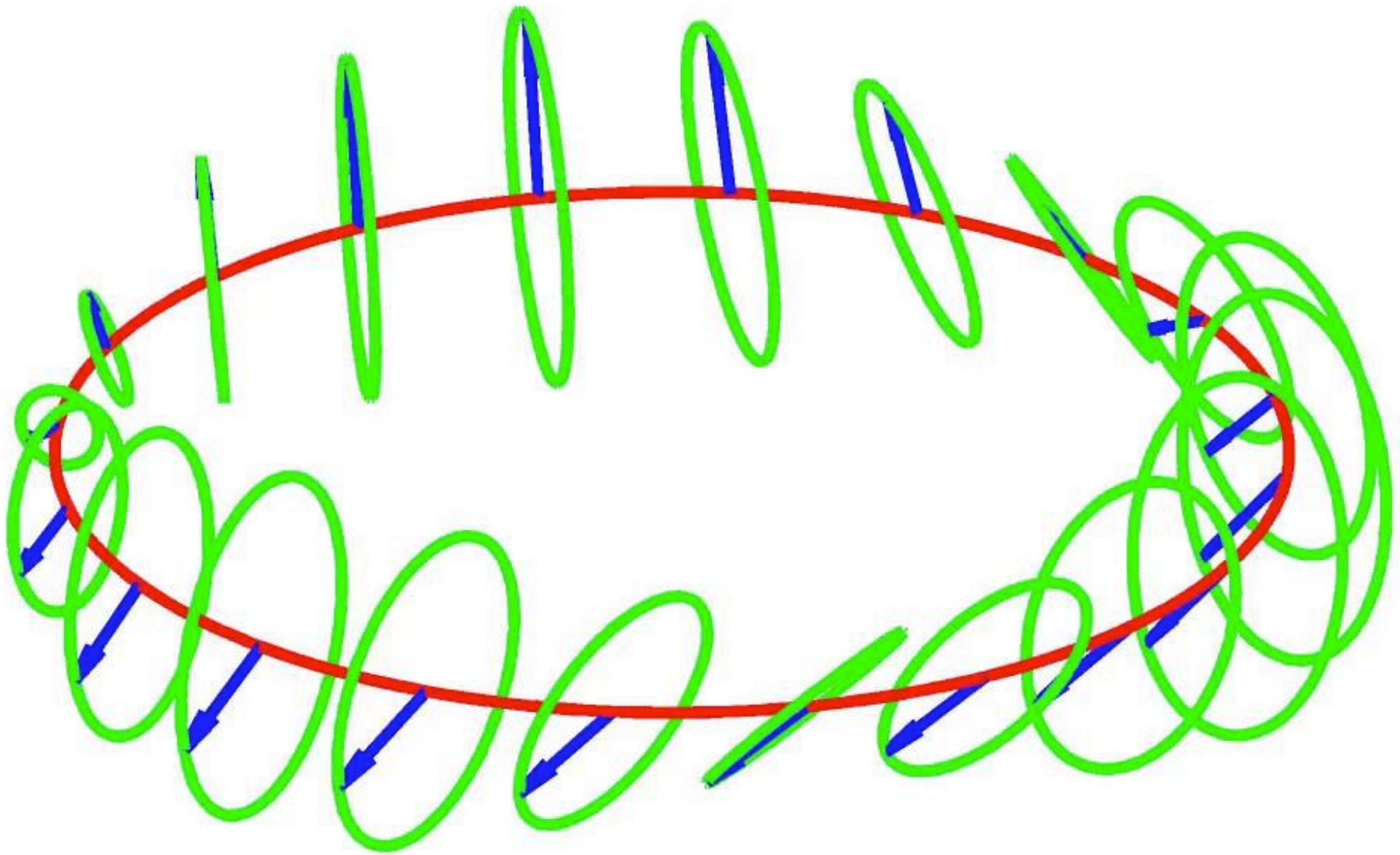


Poincaré beam under tight-focusing



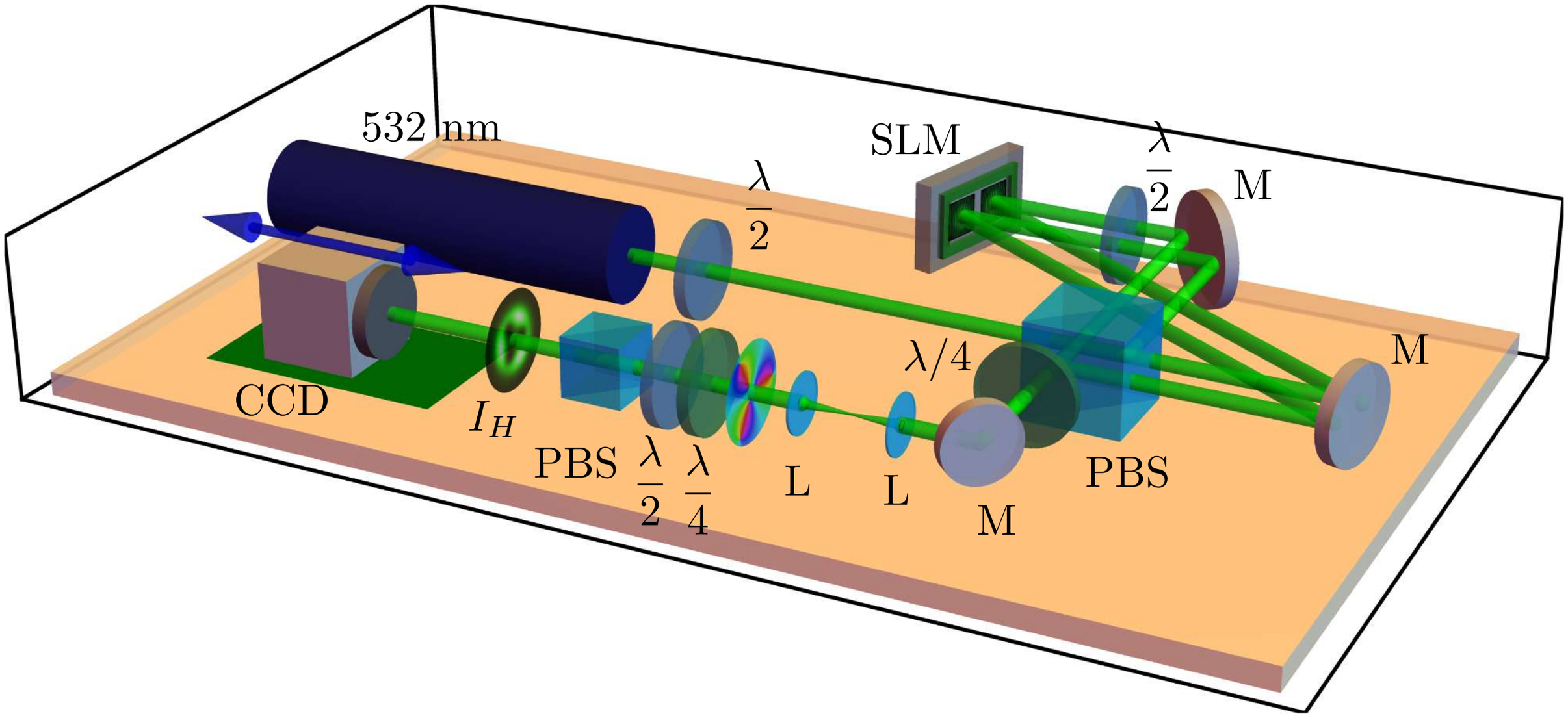
Science **29**, 1260635 (2015).

Poincaré beam under tight-focusing



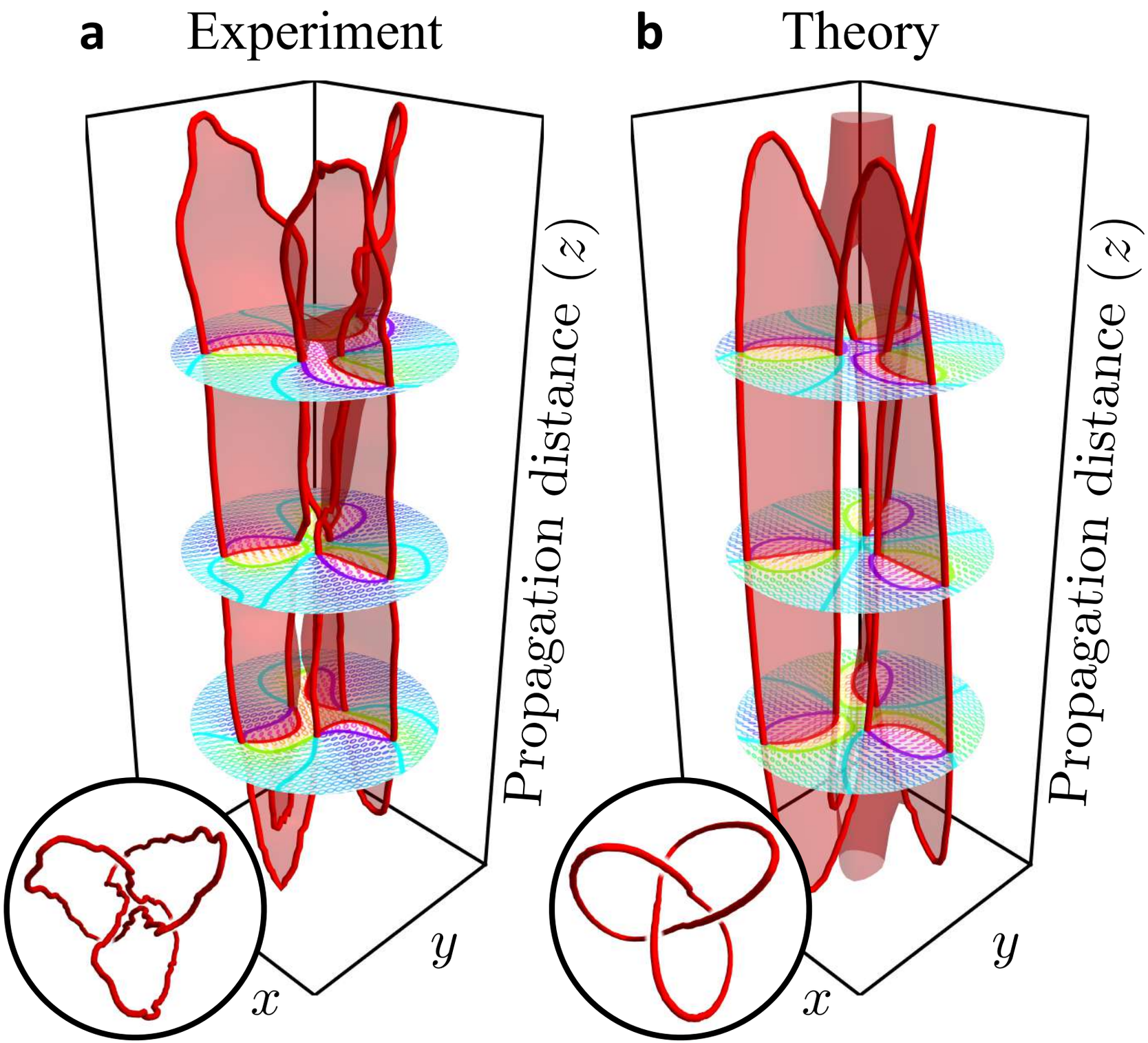
Science **29**, 1260635 (2015).

Generation of Space-Variant Polarized Beams



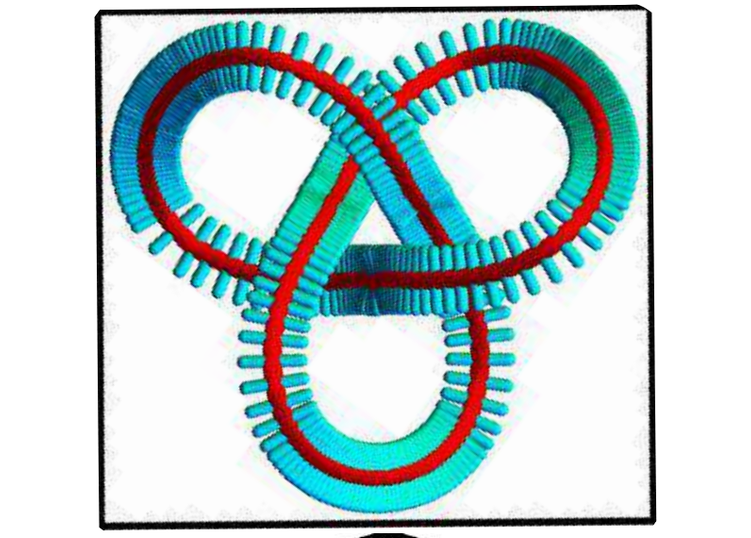
H. Larocque, D. Sugic, D. Mortimer, A. J. Taylor, R. Fickler, R. W. Boyd, M. R. Dennis & E. K. *Nature Physics* **14**, 1079 (2018)

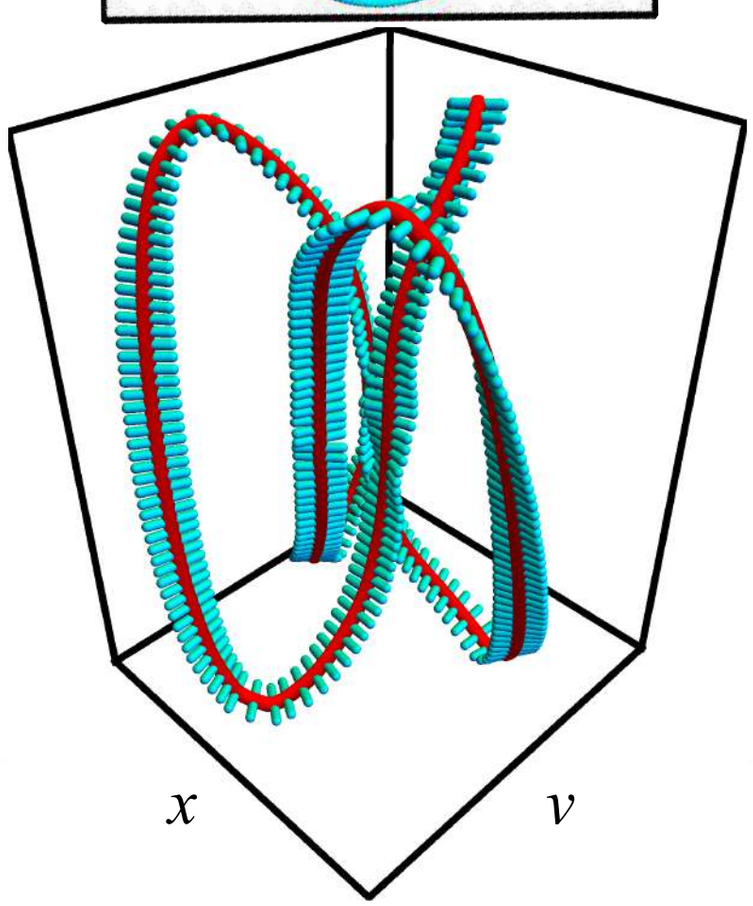
Forming knots upon free-space propagation

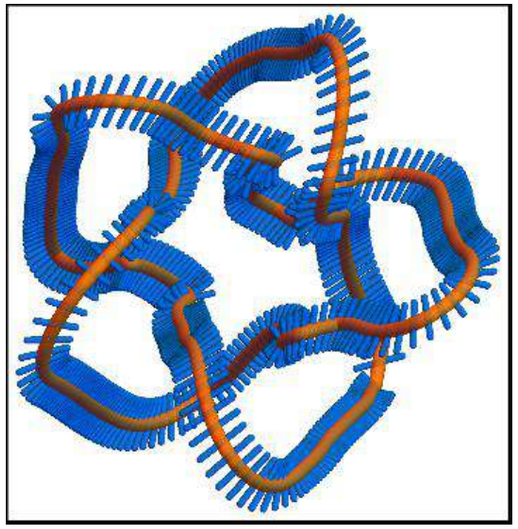


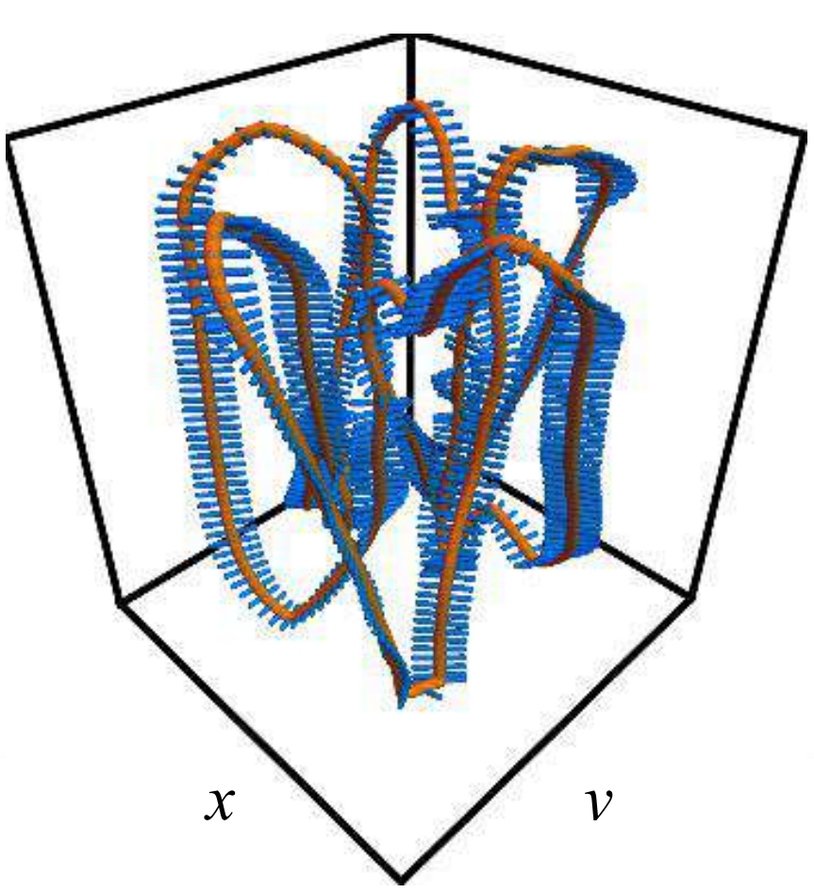
H. Larocque, D. Sugic, D. Mortimer, A. J. Taylor, R. Fickler, R. W. Boyd, M. R. Dennis & E. K. *Nature Physics* **14**, 1079 (2018)

Framed-knots







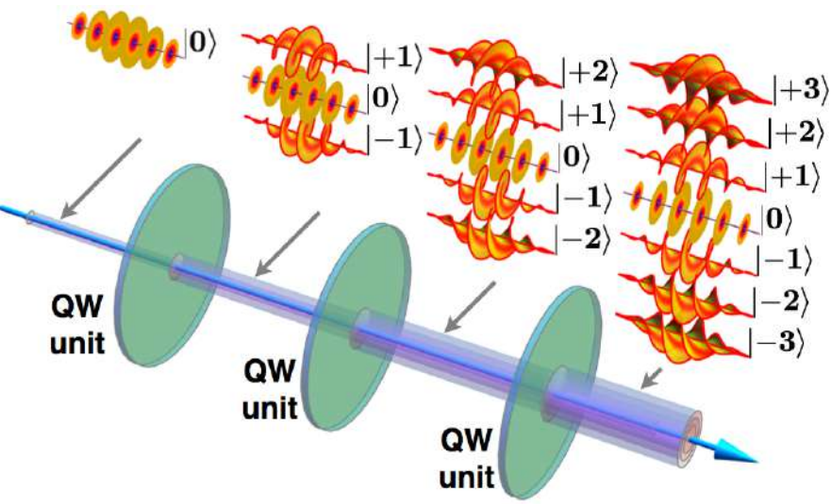


H. Larocque, A.Carmi, E. Chen & E. K. *in preparation* (2019).

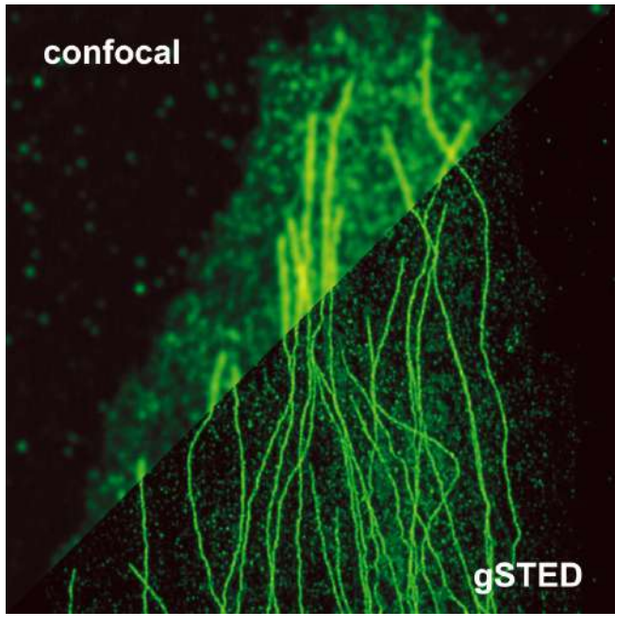
Application of Structured Photons

Application of Structural Photons

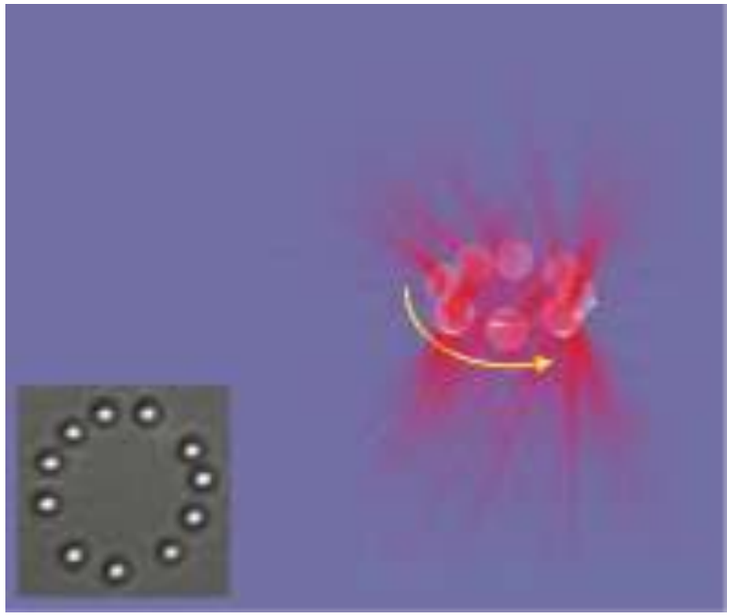
Quantum Computation



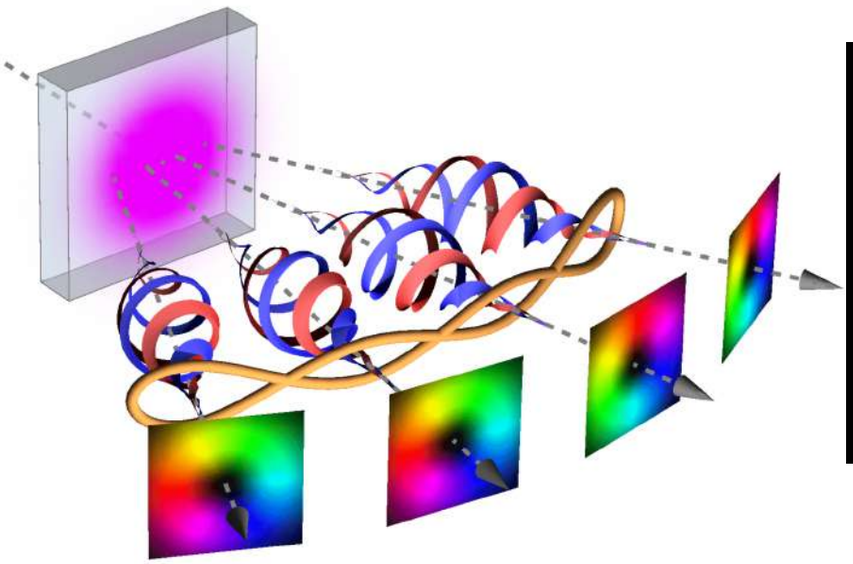
Optical Microscopy



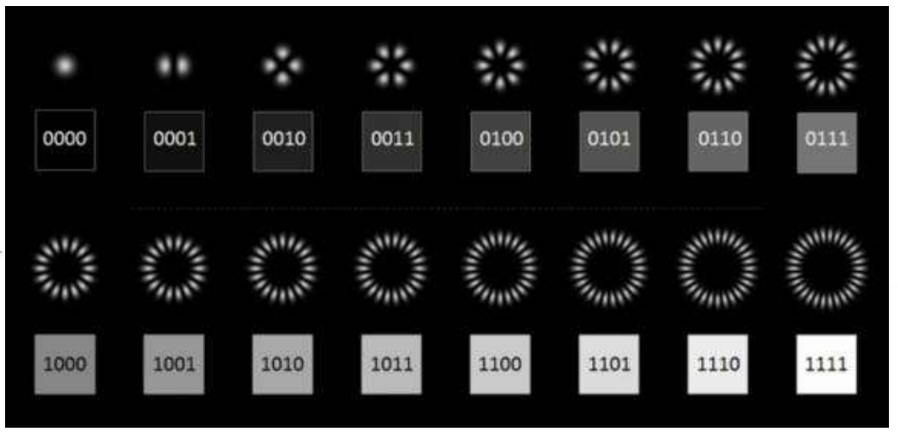
Optical Manipulation



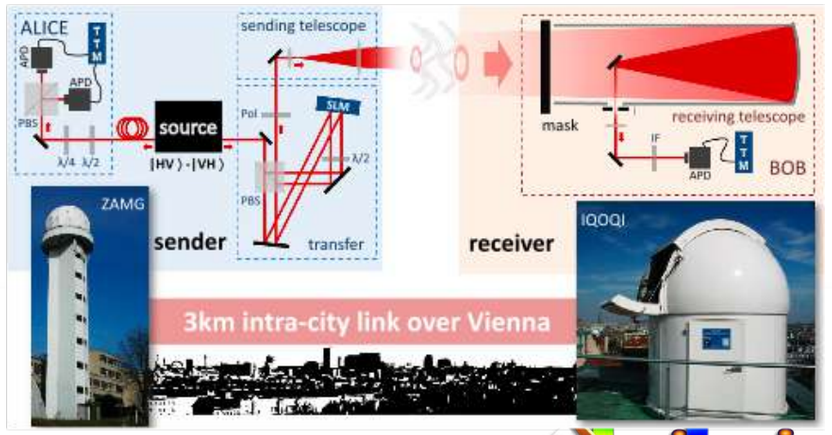
High-dimensional entanglement



Classical communication



Quantum Cryptography



H. Rubinsztein-Dunlop *et al*., Roadmap on structured light, *Journal of Optics* **19**, 013001 (2017).

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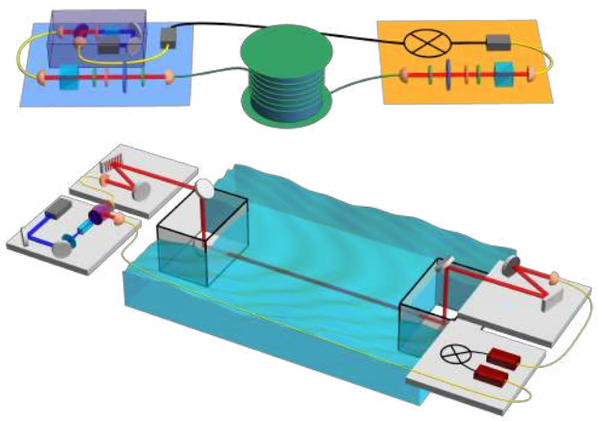


Quantum channel:
- Free-space
- Fibre
- Underwater

Classical channel:
- Error correction
- Privacy amplification

Bob

Detectors:
- Dark counts
- Jitter

Alice

$\{|0\rangle, |1\rangle\}$

$\{|0\rangle, |1\rangle, |2\rangle, |3\rangle, ...\}$

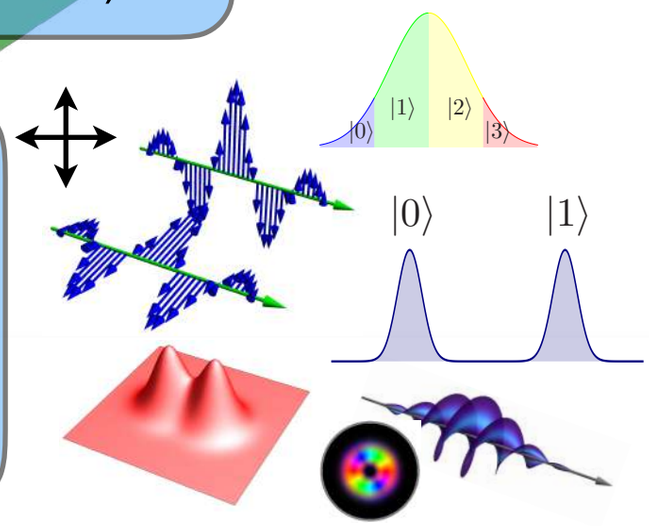
Generation:
- *q*-plates
- Spatial light modulator
- Metasurfaces

Detection:
- Sorter
- Phase-flattening
- Intensity-flattening

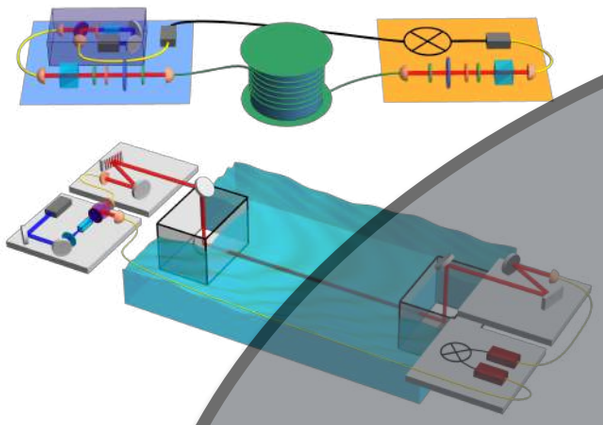
Quantum key distribution protocols
- BB84
- Six-states
- DPS (Round-robin, Chau15)

Single photon source:
- SPDC (Heralded)
- Weak coherent pulses
- Decoy states

Photonic degree of freedom:
- Polarization
- Time bins
- Frequency
- Continuous variables
- Spatial modes



Quantum Cryptography



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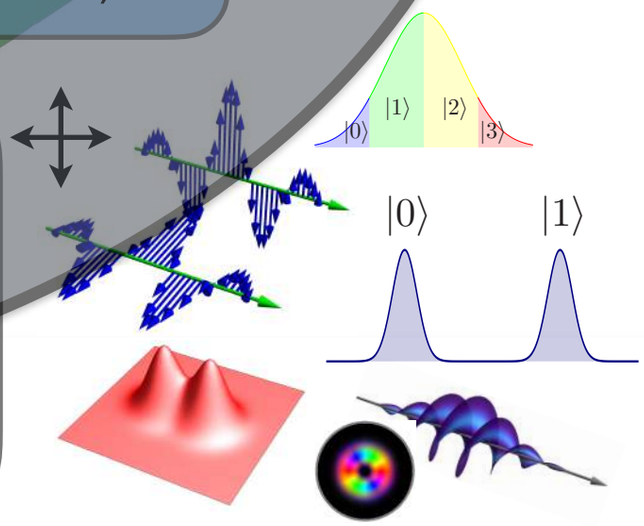
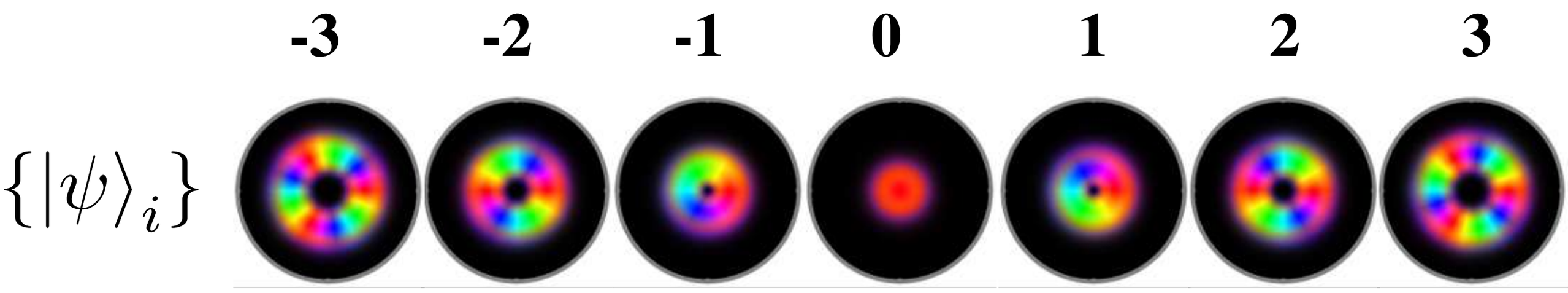


High-Dimensional QKD

-3 -2 -1 0 1 2 3

F. Bouchard, R. Fickler, R. W. Boyd & E. K., *Science Advances* **3**, e1601915 (2017)

High-Dimensional QKD



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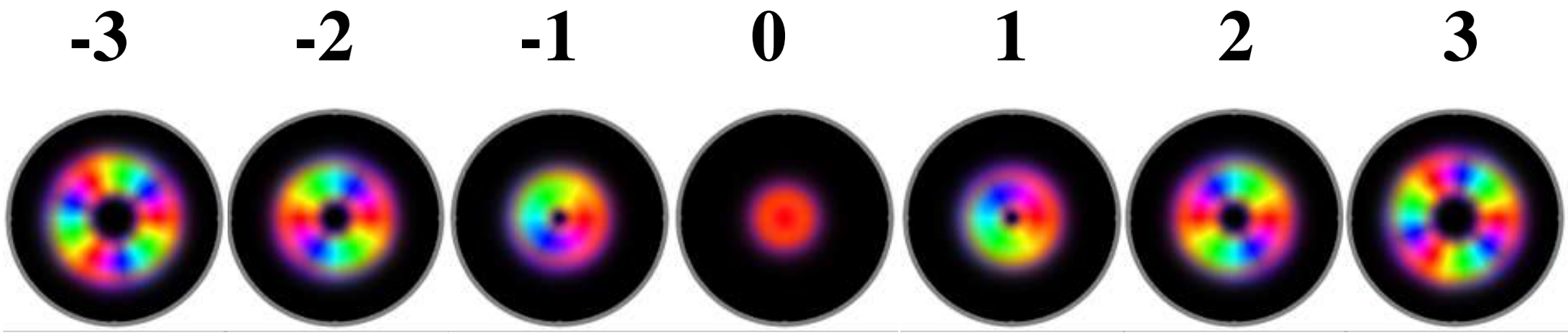
High-Dimensional QKD



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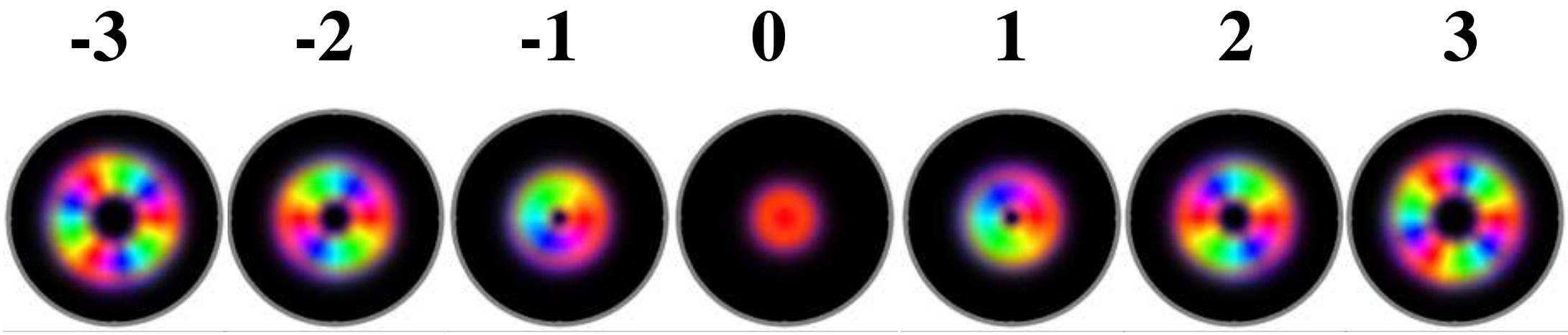
High-Dimensional QKD



$$|\langle\psi|\phi\rangle|^2 = \frac{1}{7}$$

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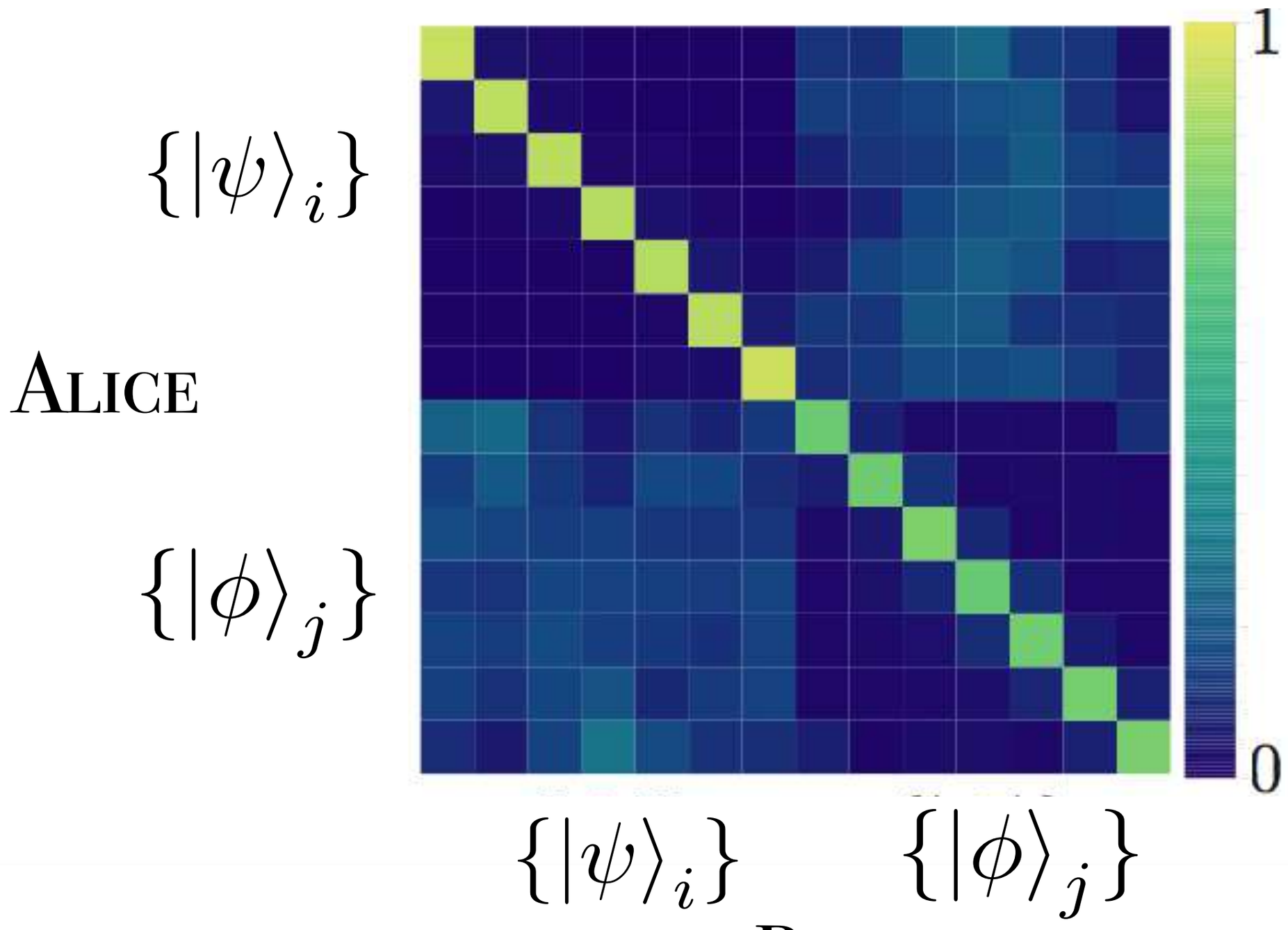
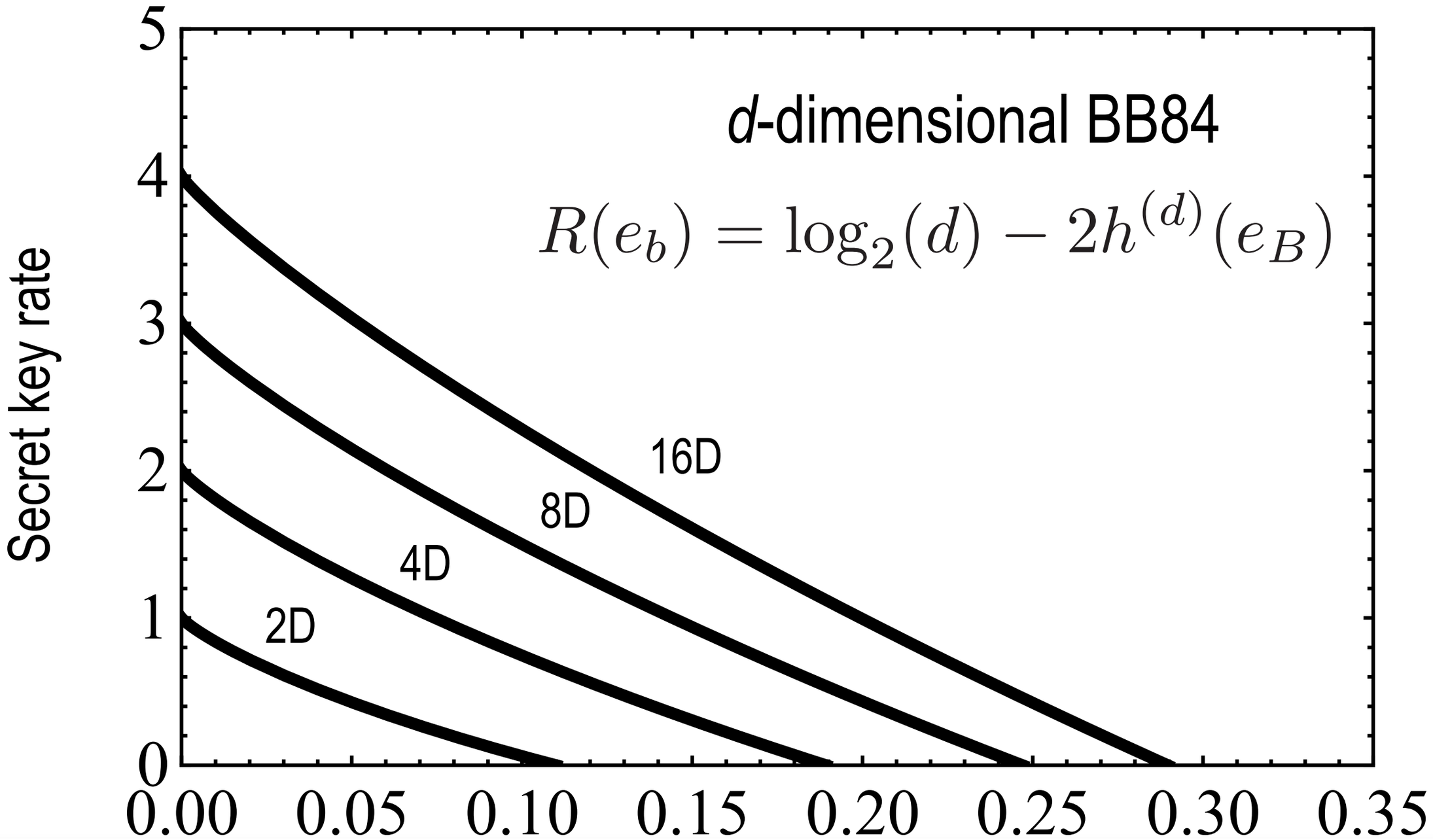
Experimental results

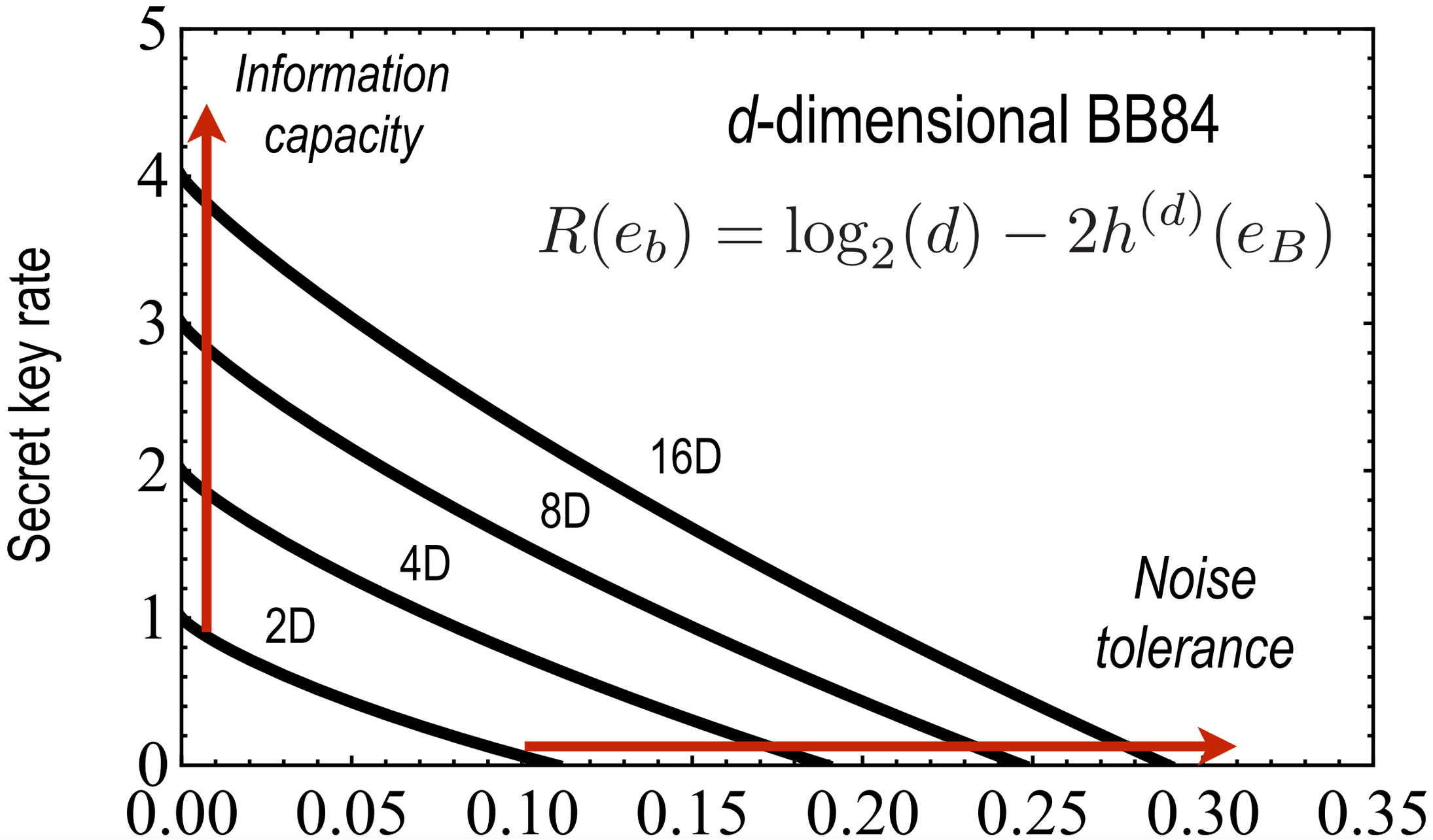


F. Bouchard, R. Fickler, R. W. Boyd & E. K., *Science Advances* **3**, e1601915 (2017)

Why High-Dimensional QKD?



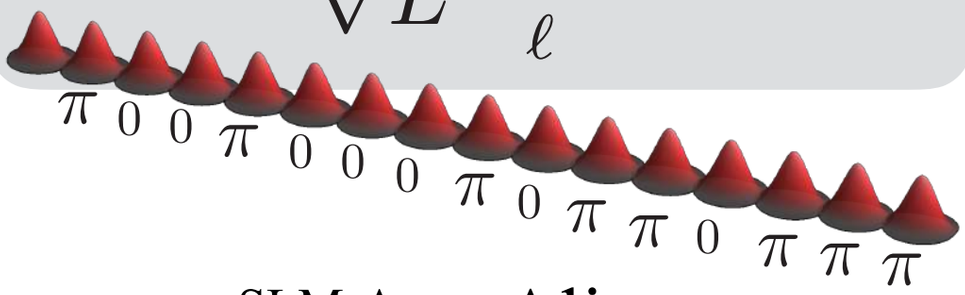
Why High-Dimensional QKD?



Protocols: Chau15

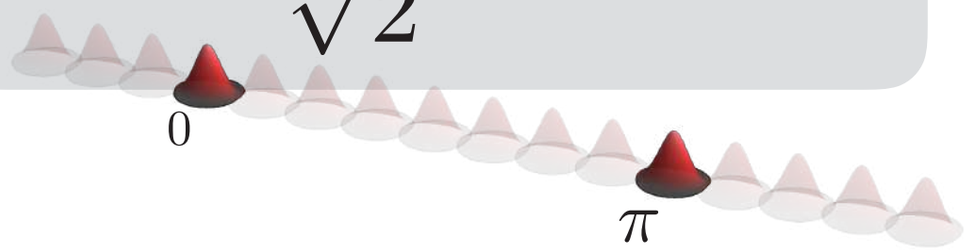
RRDPS

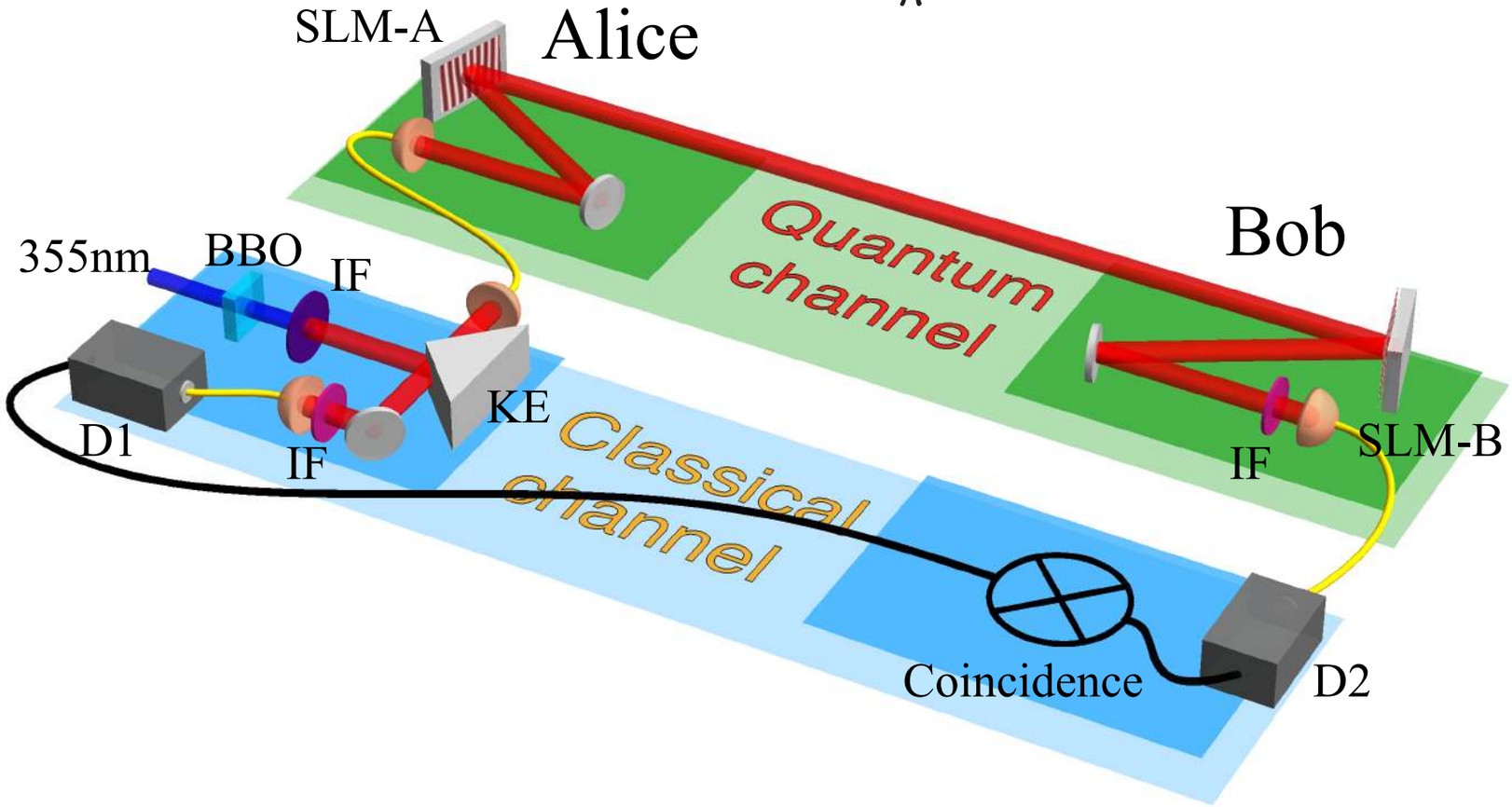
$$|\psi_L\rangle = \frac{1}{\sqrt{L}} \sum_{\ell} (-1)^{s_\ell} |\ell\rangle$$

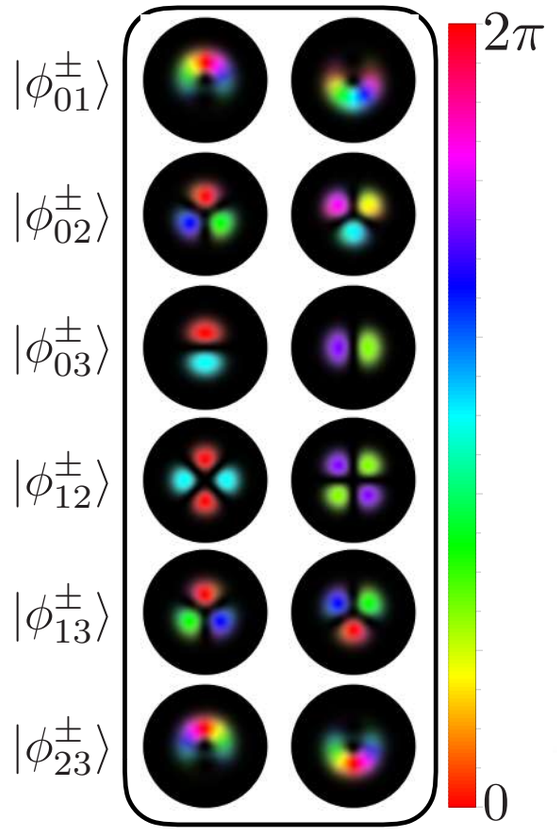


Chau15

$$|\psi\rangle = \frac{1}{\sqrt{2}} (|i\rangle \pm |j\rangle)$$





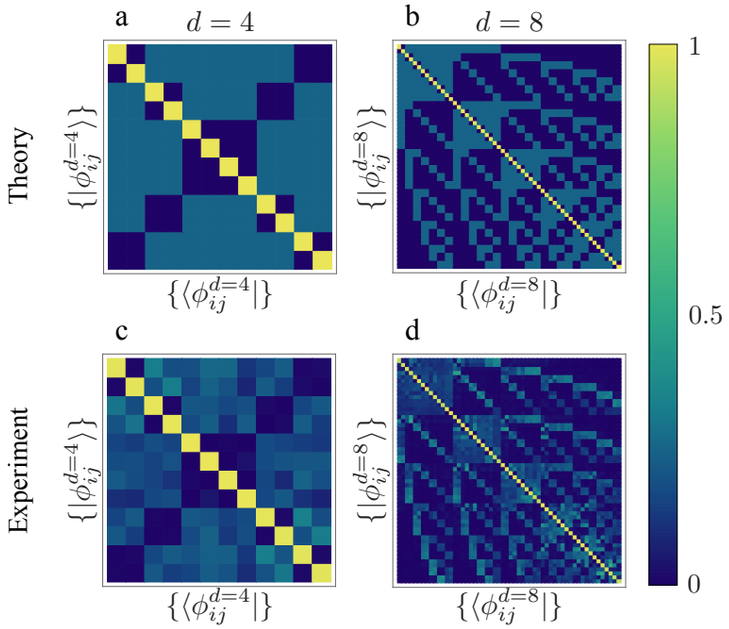


F Bouchard, K Heshami, D England, R Fickler, R W Boyd, B-G Englert, L L Sánchez-Soto & E.K., *Quantum* **2**, 111 (2018).

High-dimensional QKD: Different Protocols at a Glance

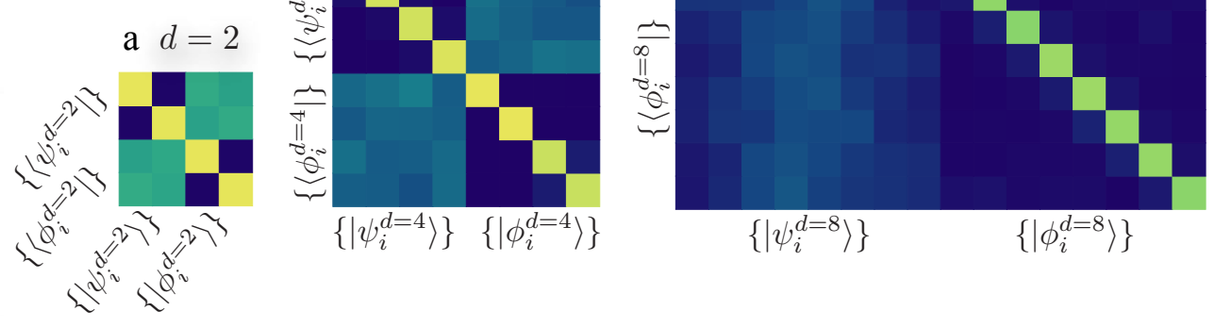
Protocol	d	$e_b^{\max}$	$e_b^{\exp}$	$R(0)$	$R^{\exp}$	Sifting	$R^{\exp}\times$ Sifting
Chau15	4	50 %	0.778 %	1	0.8170	1/6	0.1362
	8	50 %	3.11 %	1	0.8172	1/28	0.0292
BB84	2	11.00 %	0.628 %	1	0.8901	1/2 - 1*	0.4451 - 0.8901
	4	18.93 %	3.51 %	2	1.4500	1/2 - 1*	0.7250 - 1.4500
	8	24.70 %	10.9 %	3	1.3942	1/2 - 1*	0.6971 - 1.3942
MUB	2	12.62 %	0.923 %	1	0.8727	1/3 - 1*	0.2909 - 0.8727
	4	23.17 %	3.87 %	2	1.5316	1/5 - 1*	0.3063 - 1.5316
Singapore	2	38.93 %	1.23 %	0.4	0.374**	1	0.374**

Chau15

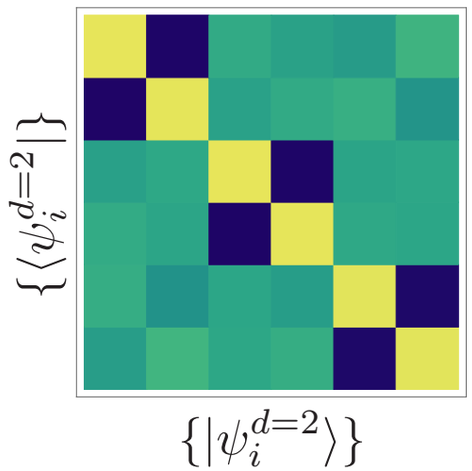


$\mathcal{P} = |\langle\varphi_i|\varphi'_{i'}\rangle|^2$

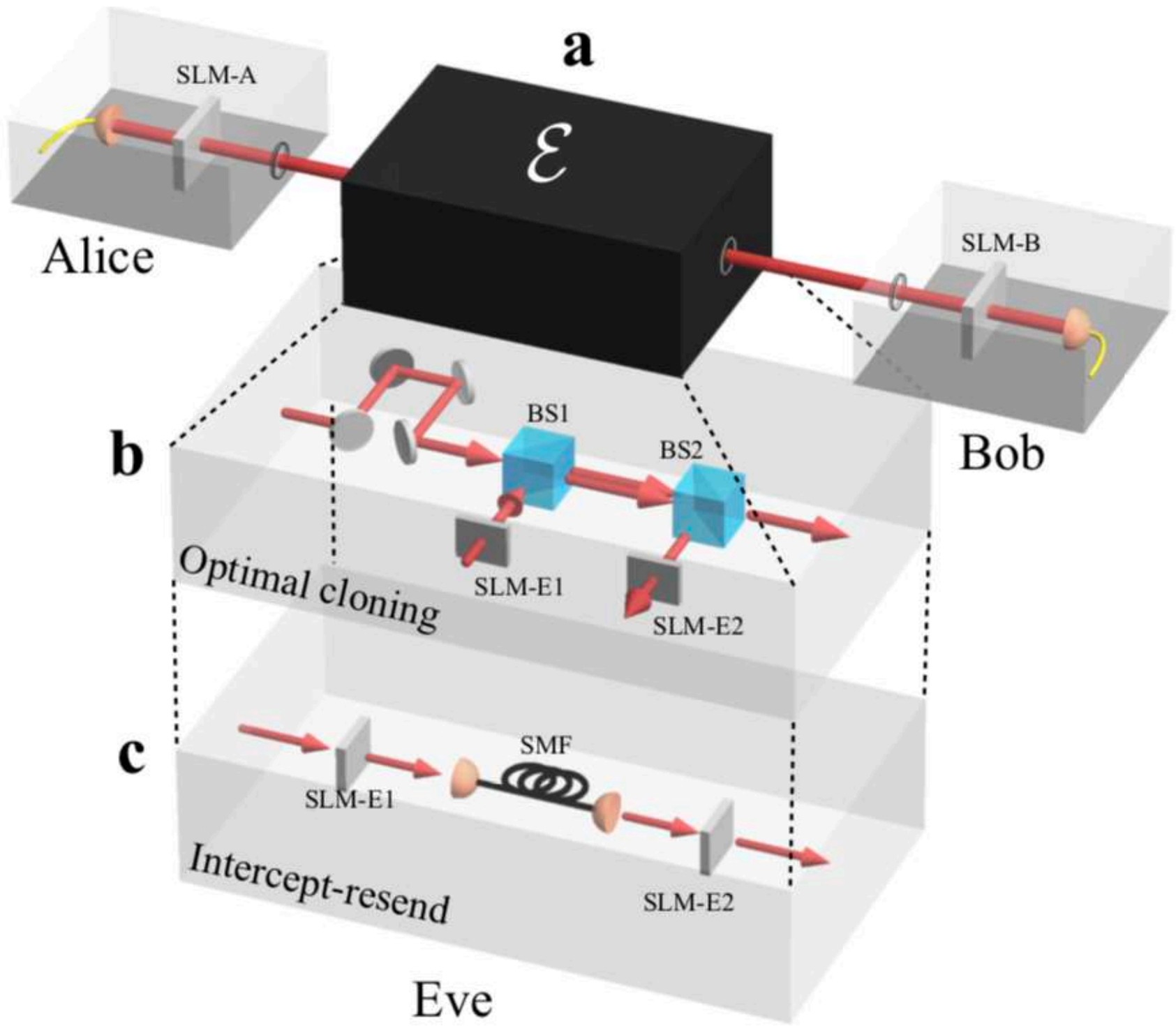
BB84



MUB



Characterizing a QKD channel



F Bouchard, F Hufnagel, D Koutnýˊ, A Abbas, A Sit, K Heshami, R Fickler & E.K., *Quantum in press* (2019).

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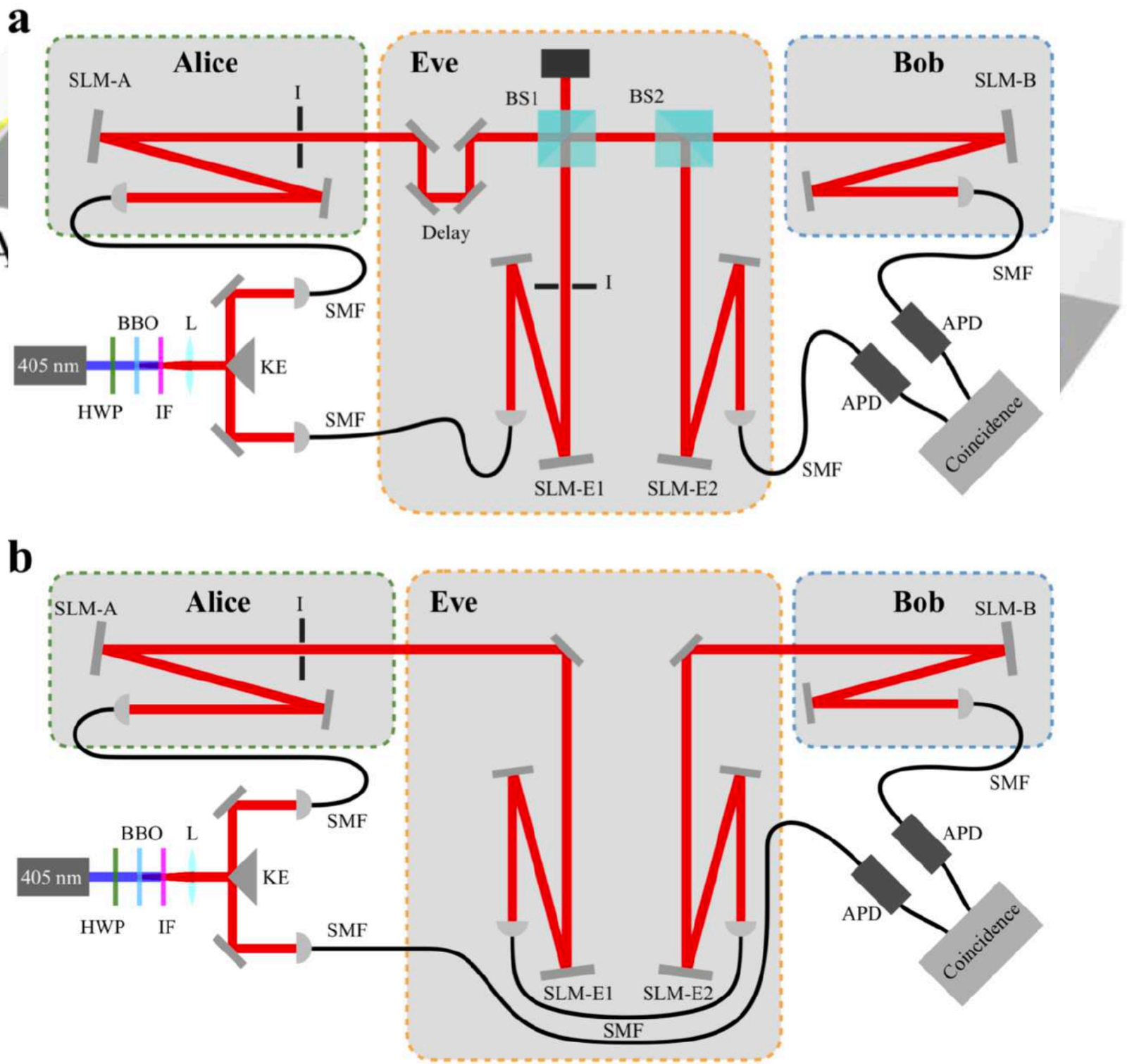
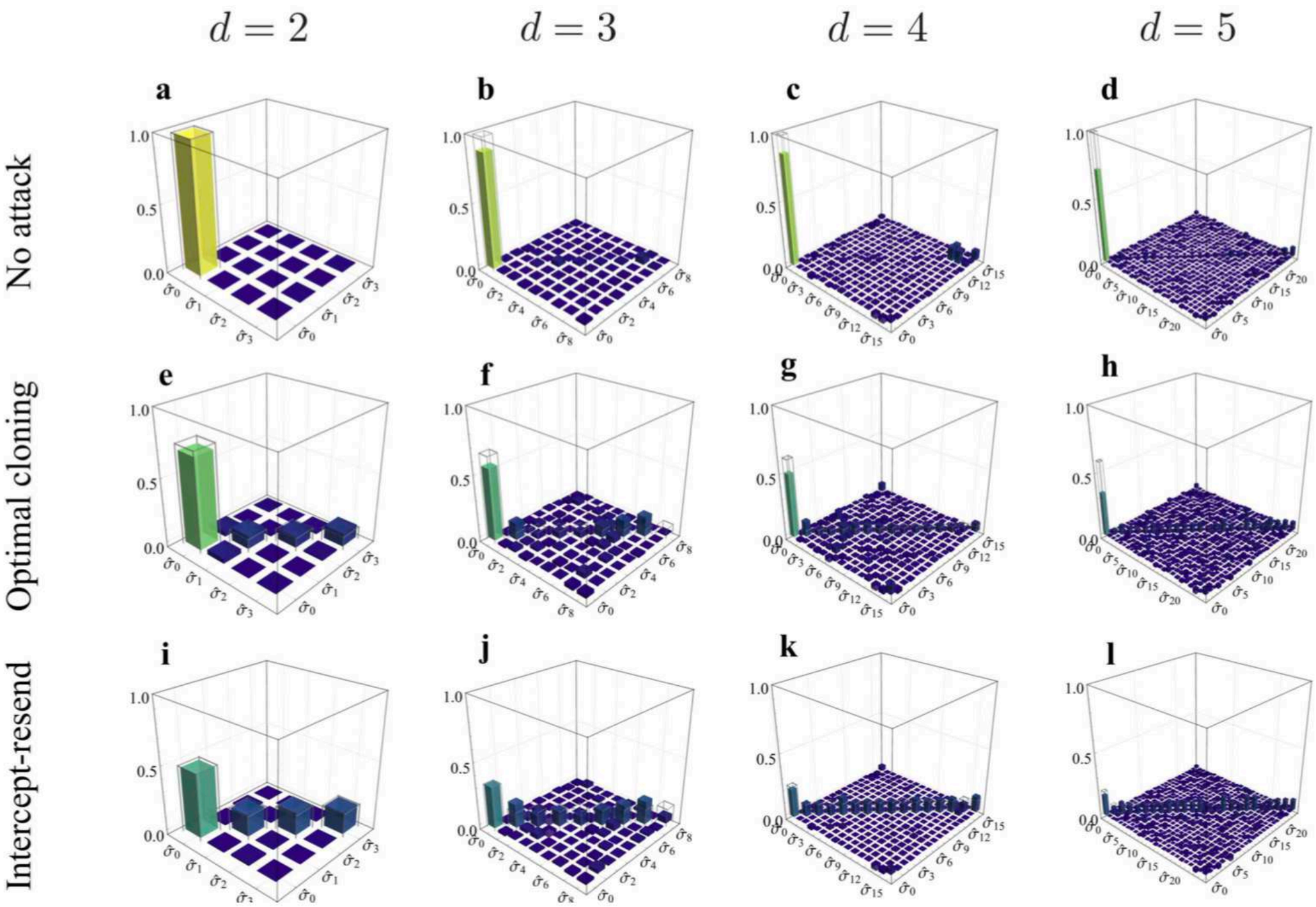


F Bouchard, F Hufnagel, D Koutnyˊ, A Abbas, A Sit, K Heshami, R Fickler & E.K., *Quantum in press* (2019).

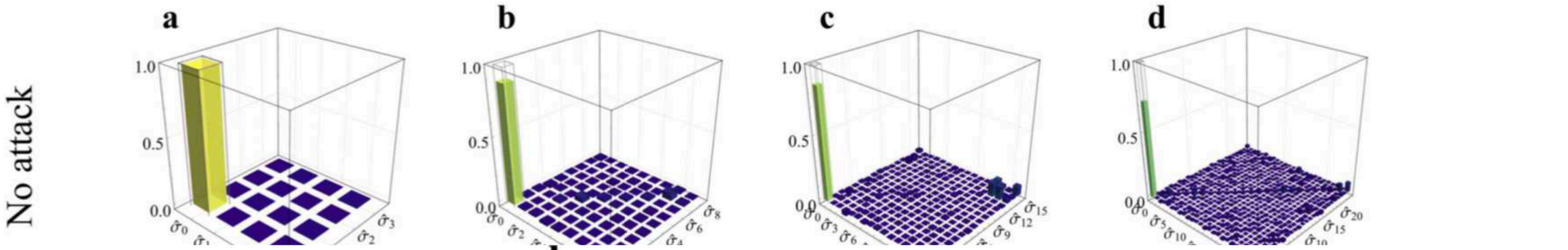
Characterizing a QKD channel

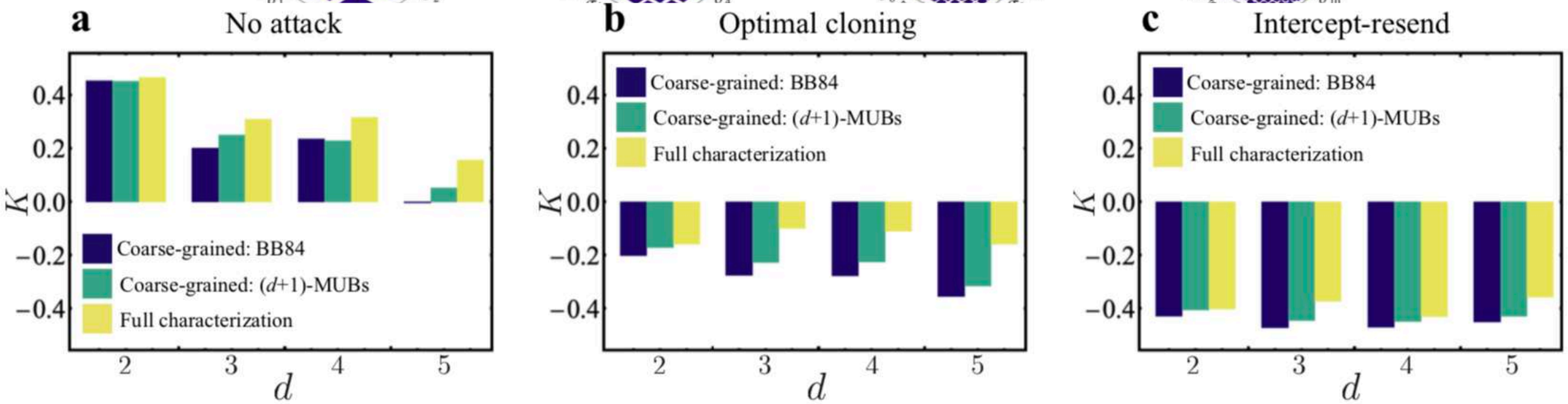


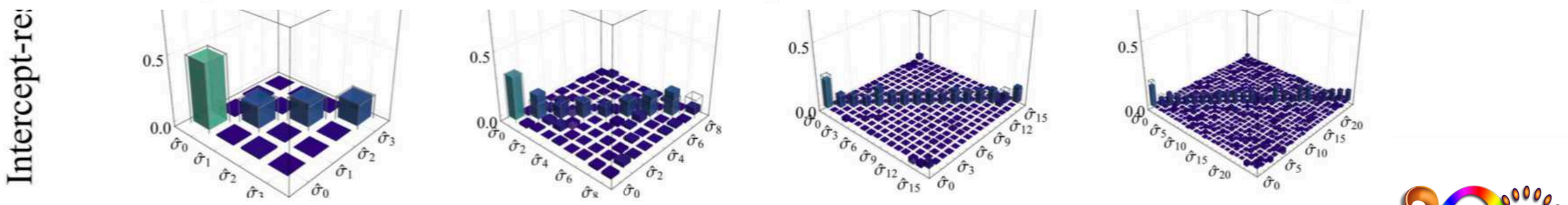
F Bouchard, F Hufnagel, D Koutny´, A Abbas, A Sit, K Heshami, R Fickler & E.K., *Quantum in press* (2019).

Characterizing a QKD channel

$d = 2$ $d = 3$ $d = 4$ $d = 5$

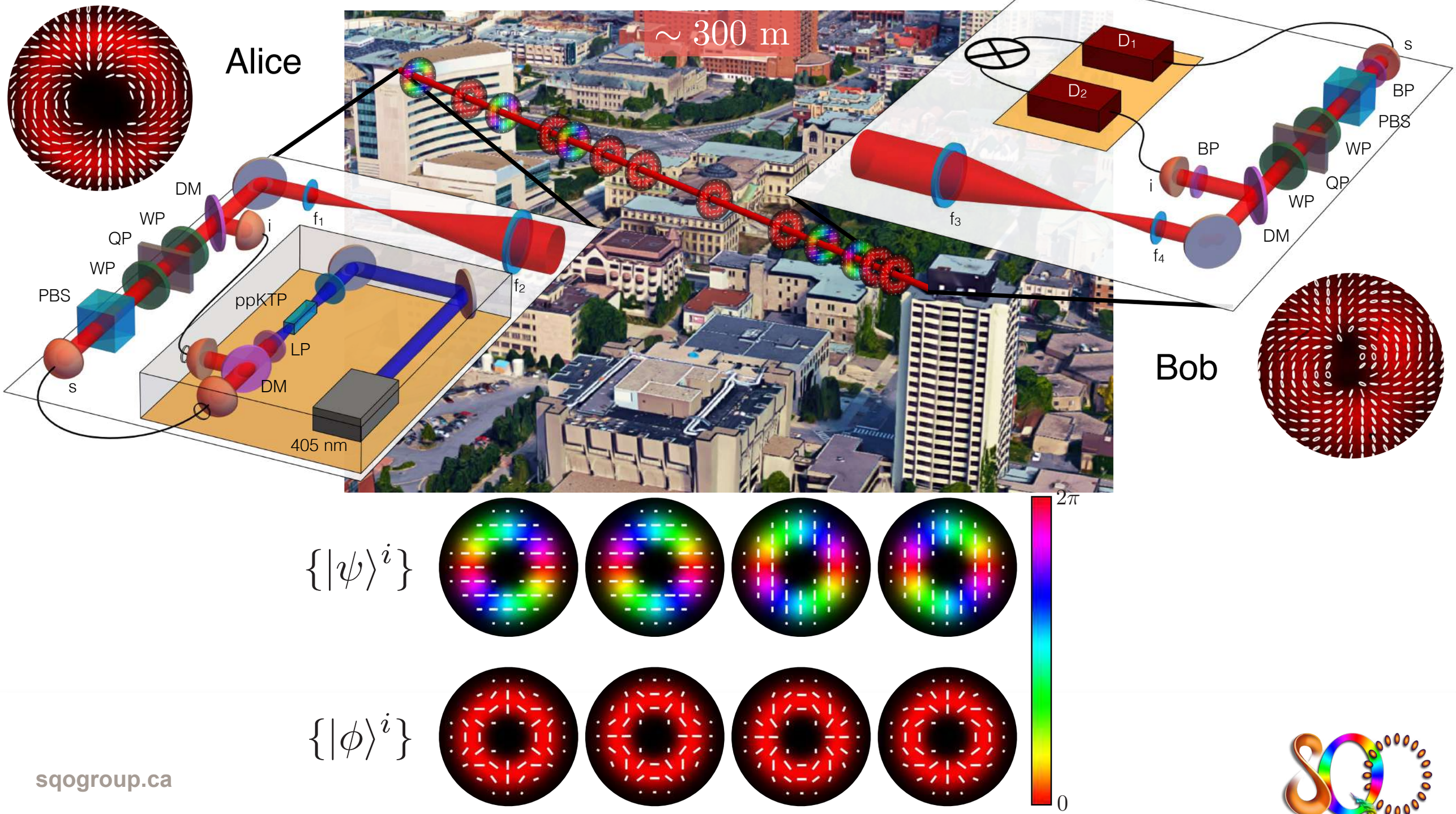






F Bouchard, F Hufnagel, D Koutnyˊ, A Abbas, A Sit, K Heshami, R Fickler & E.K., *Quantum in press* (2019).

Intra-city QKD experiment



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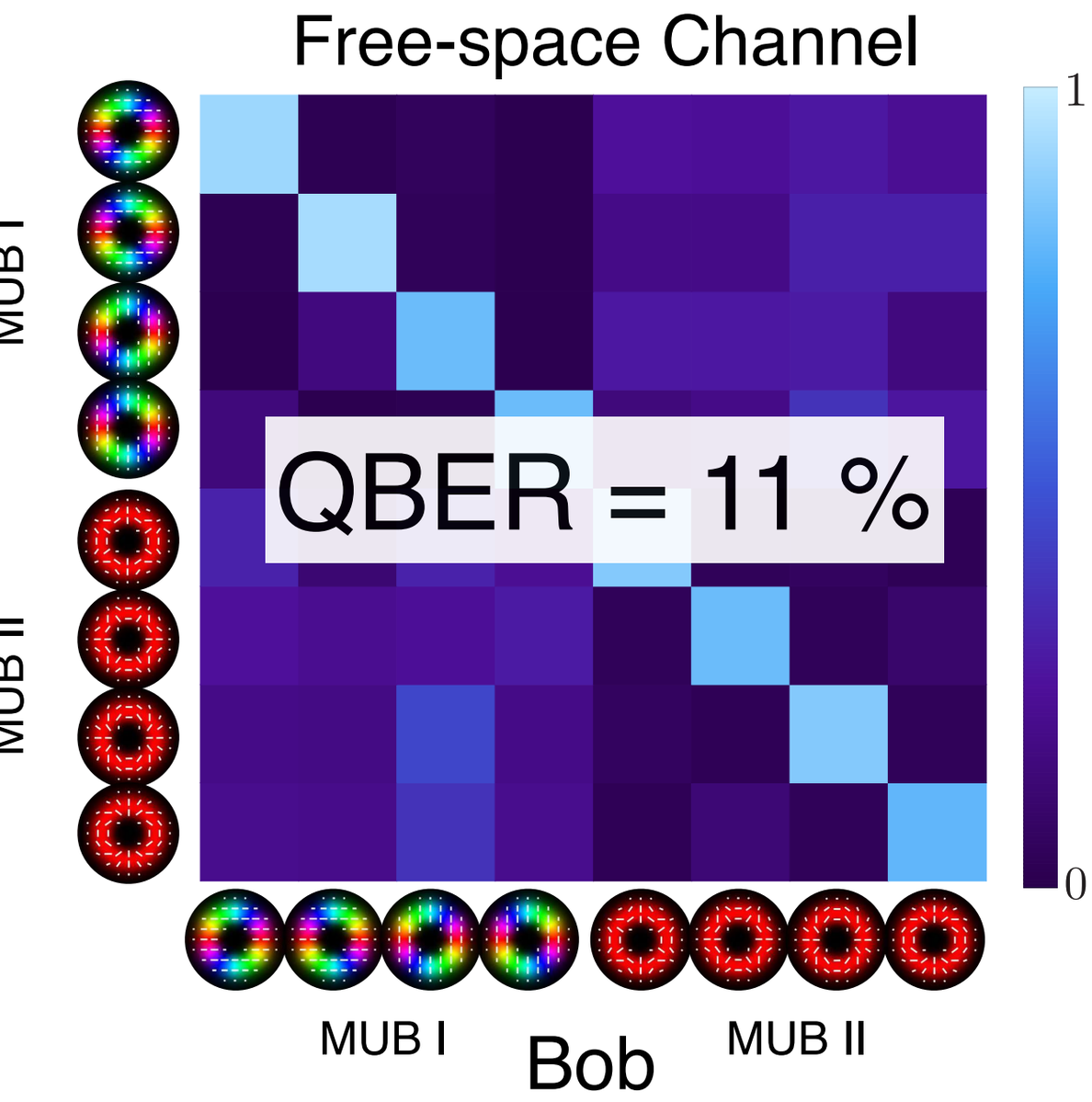
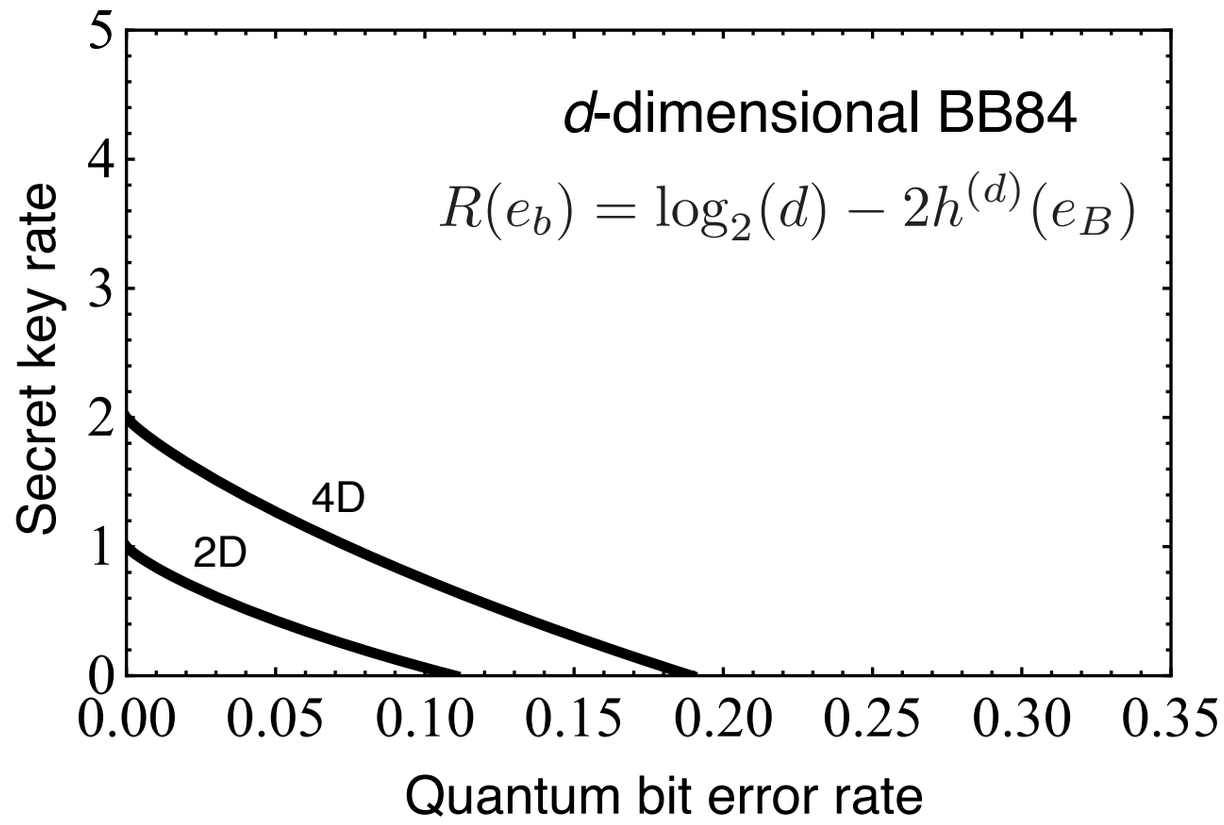
A. Sit, F. Bouchard, R. Fickler, J. Gagnon-Bischoff, H. Larocque, K. Heshami, D. Elser, C. Peuntinger, K. Günthner, B. Heim, C. Marquardt, G. Leuchs, R. W. Boyd & E. K., *Optica* **4**, 1006 (2017).

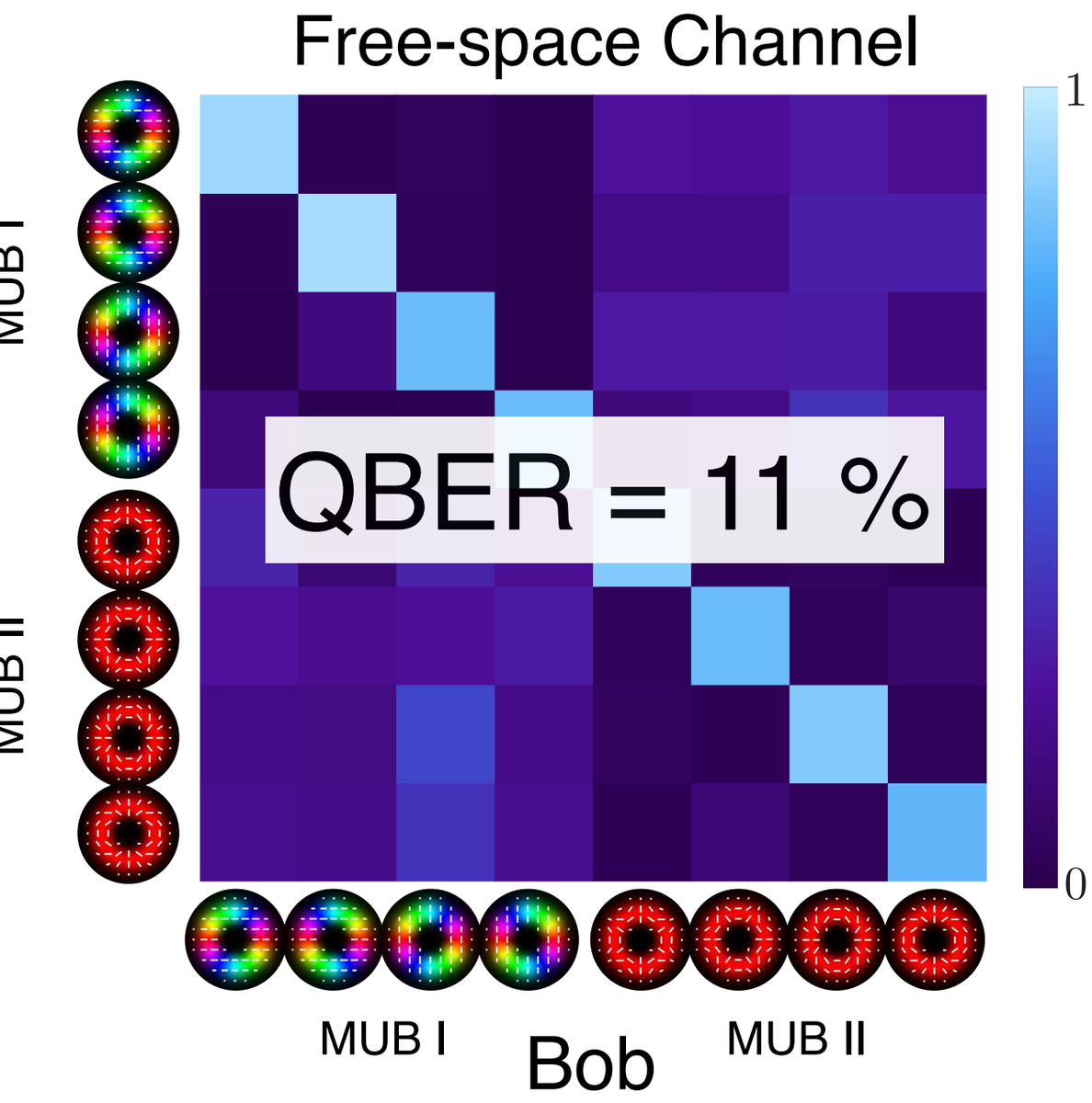
Experimental results of the intra-city QKD

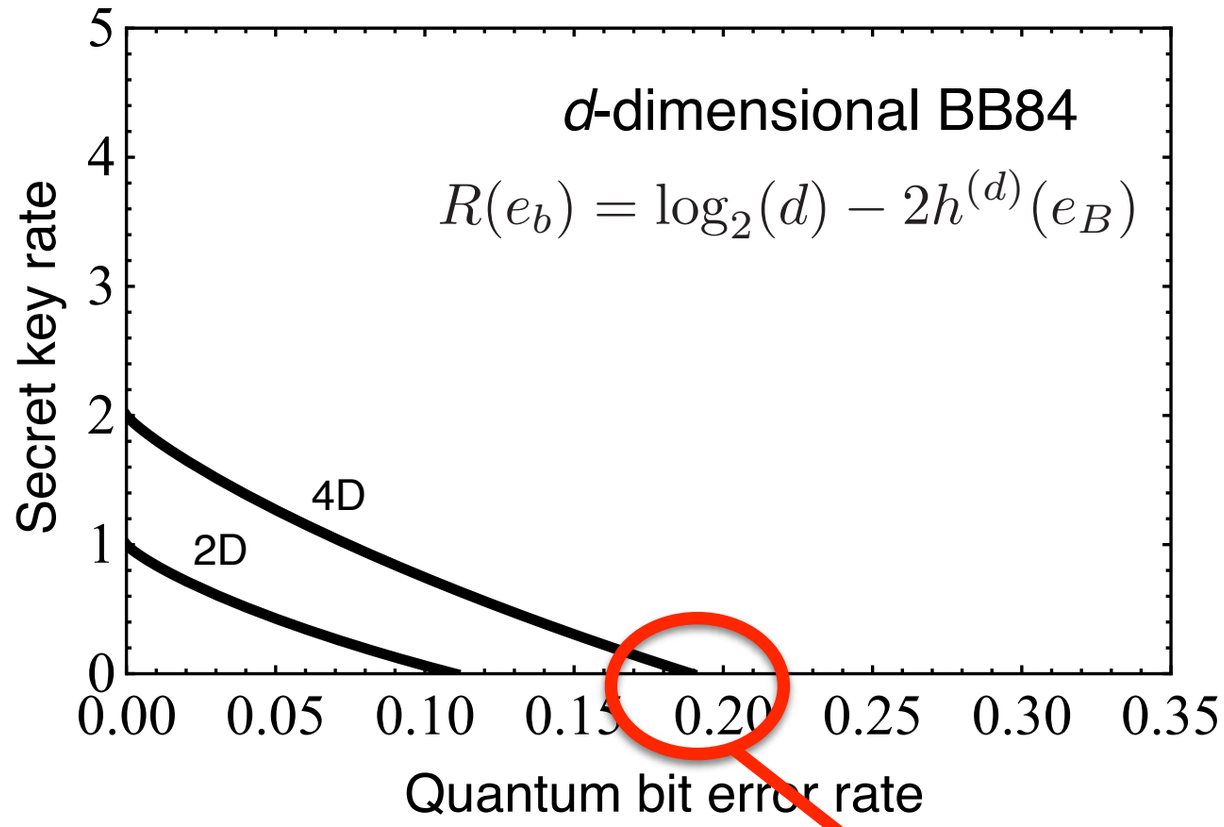




A. Sit, F. Bouchard, R. Fickler, J. Gagnon-Bischoff, H. Larocque, K. Heshami, D. Elser, C. Peuntinger, K. Günthner, B. Heim, C. Marquardt, G. Leuchs, R. W. Boyd & E.K., *Optica* **4**, 1006 (2017).

Experimental results of the intra-city QKD

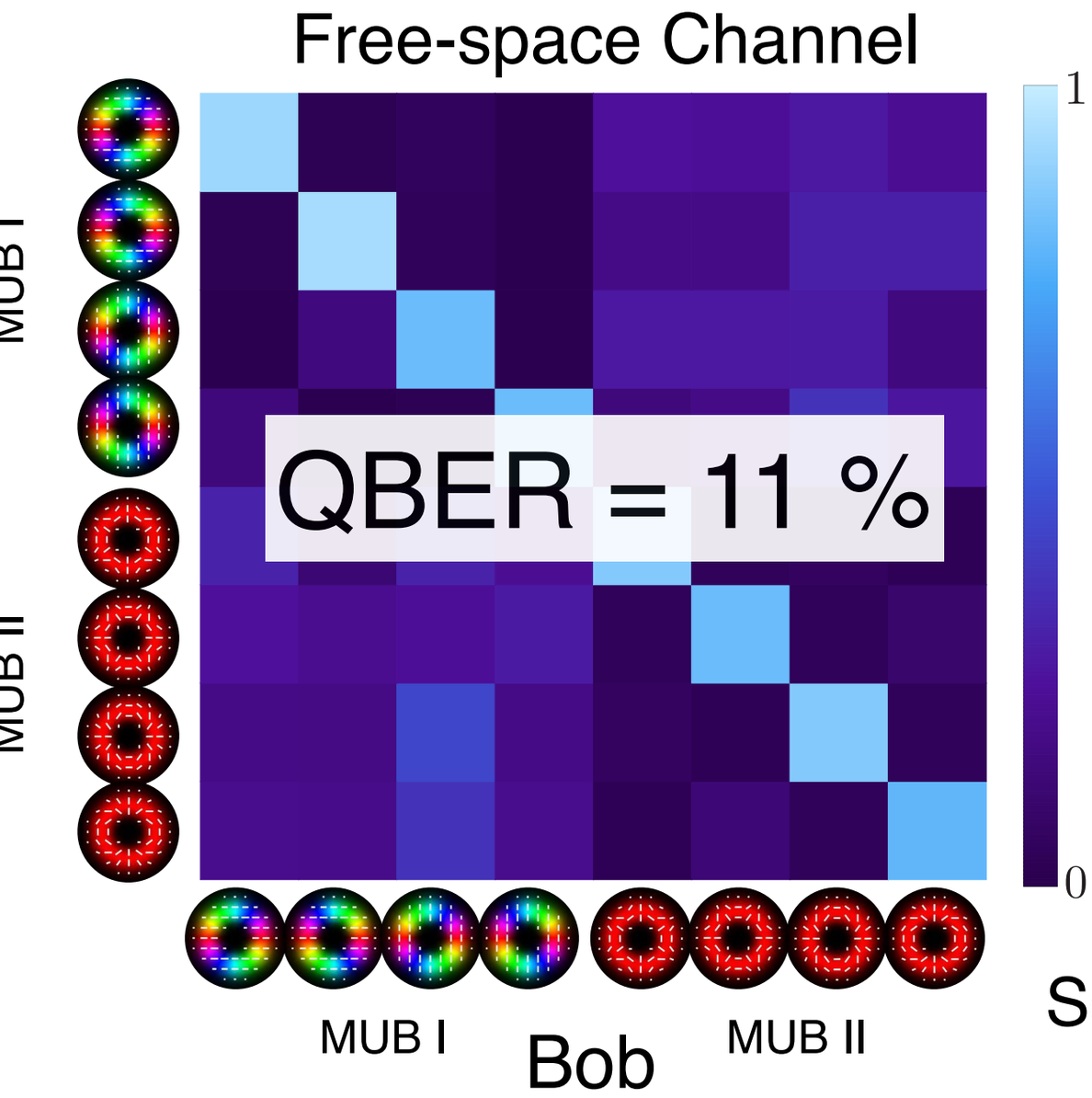


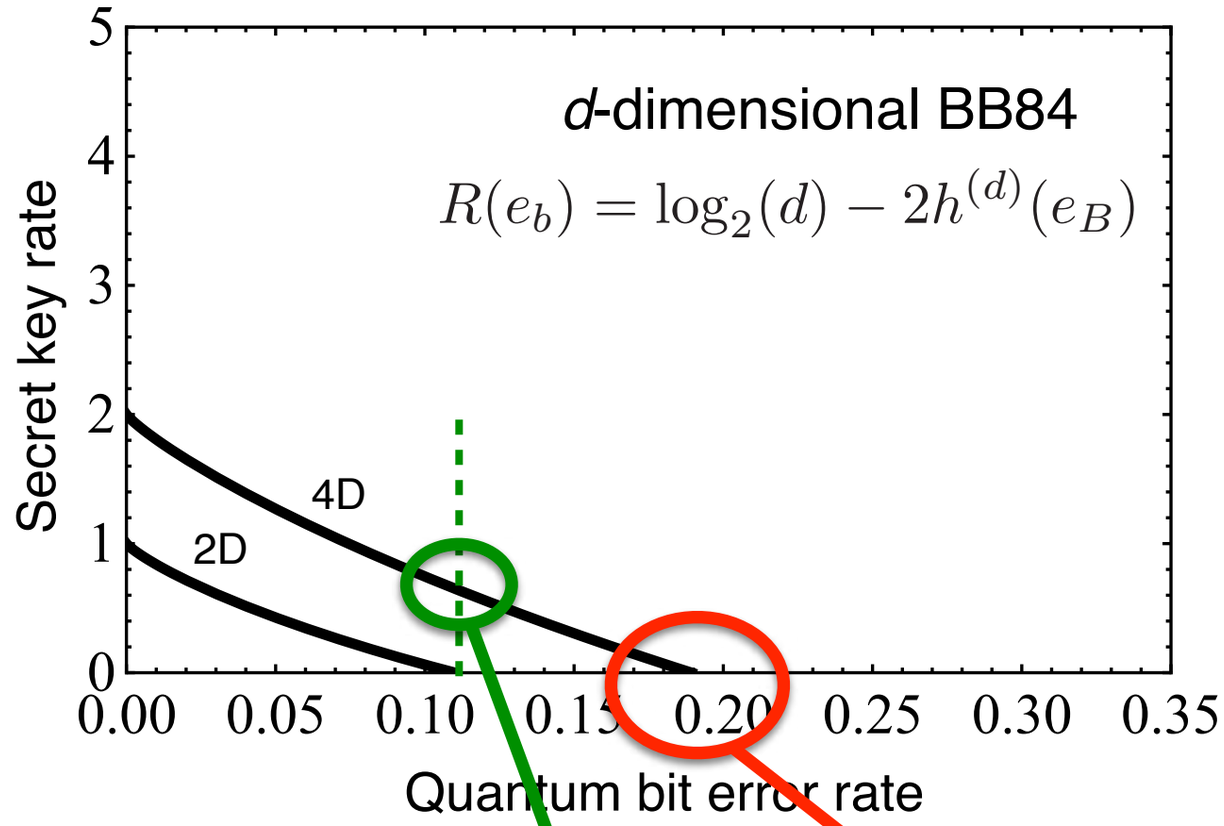


Threshold QBER = 18.9%

A. Sit, F. Bouchard, R. Fickler, J. Gagnon-Bischoff, H. Larocque, K. Heshami, D. Elser, C. Peuntinger, K. Günthner, B. Heim, C. Marquardt, G. Leuchs, R. W. Boyd & E.K., *Optica* **4**, 1006 (2017).

Experimental results of the intra-city QKD





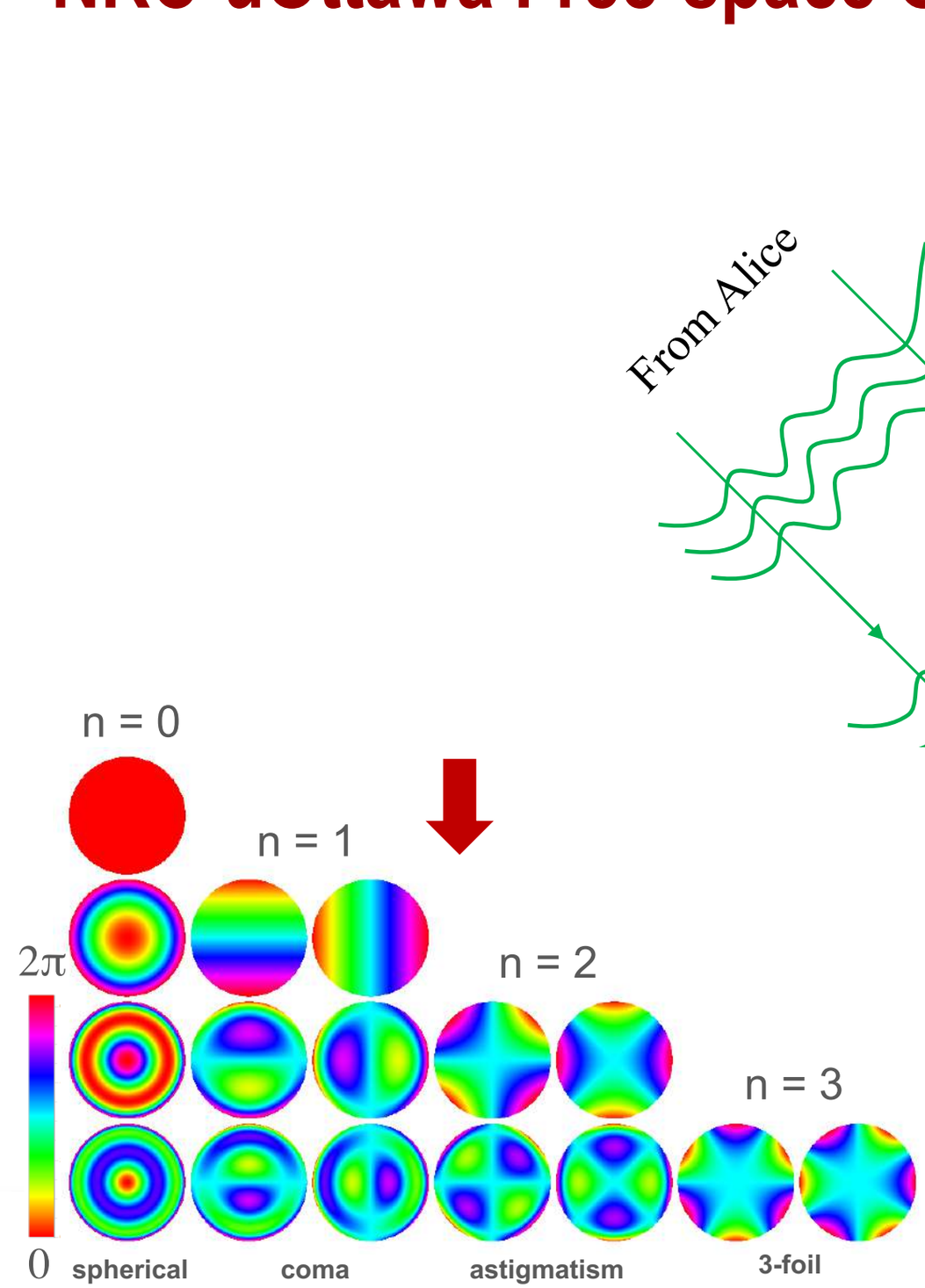
Secret key rate = 0.65 bit

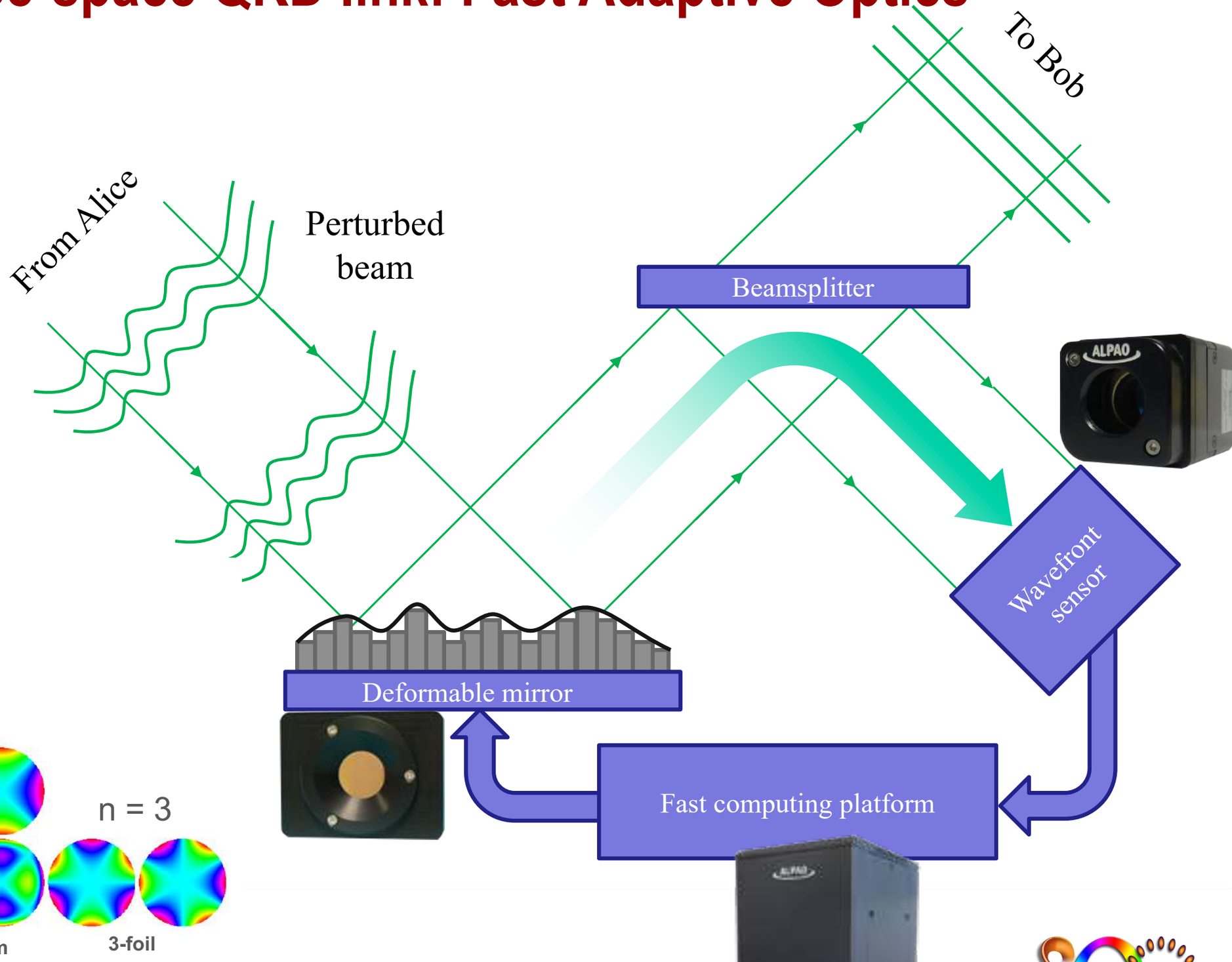
Threshold QBER = 18.9%

A. Sit, F. Bouchard, R. Fickler, J. Gagnon-Bischoff, H. Larocque, K. Heshami, D. Elser, C. Peuntinger, K. Günthner, B. Heim, C. Marquardt, G. Leuchs, R. W. Boyd & E.K., *Optica* **4**, 1006 (2017).

NRC-uOttawa Free-space QKD link

NRC-uOttawa Free-space QKD link: Fast Adaptive Optics





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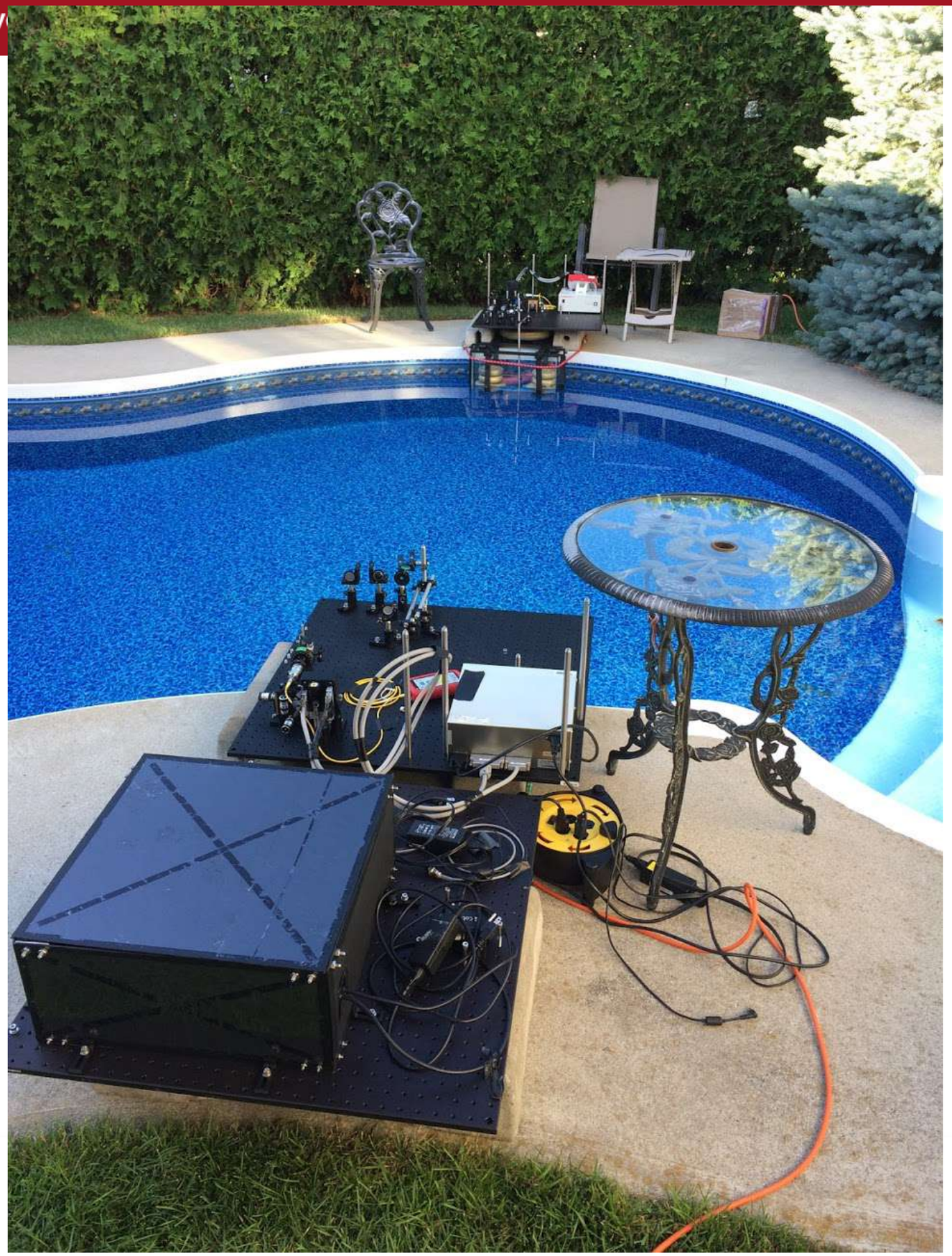
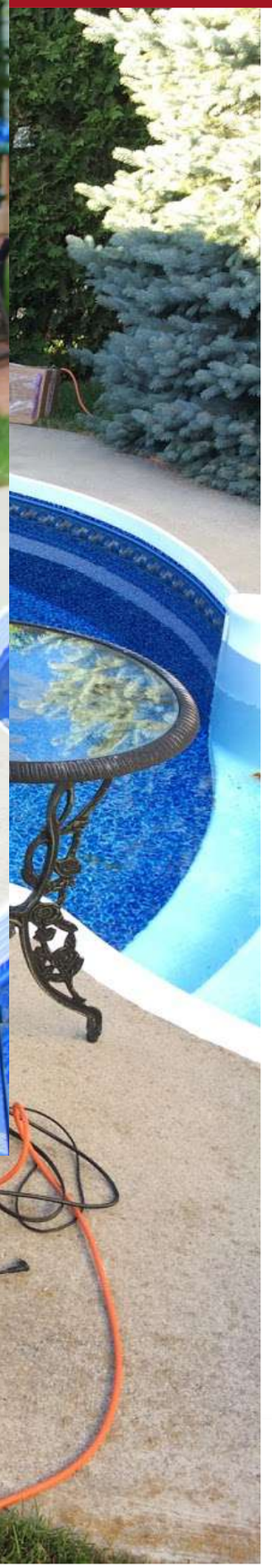
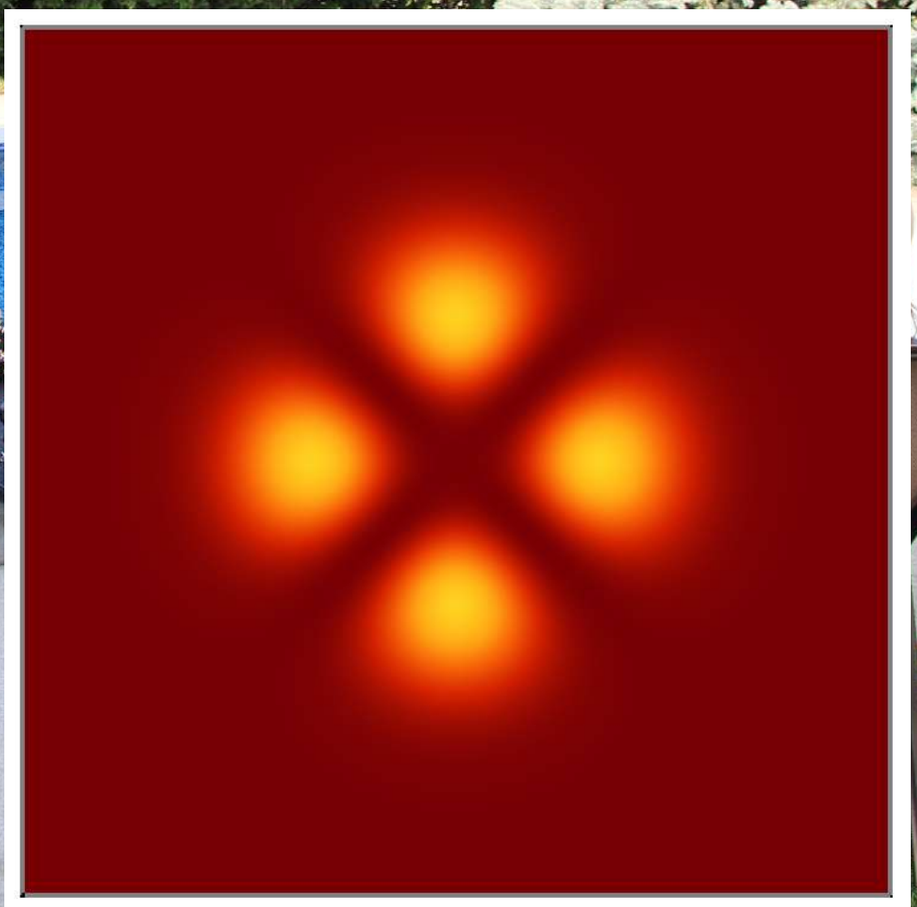
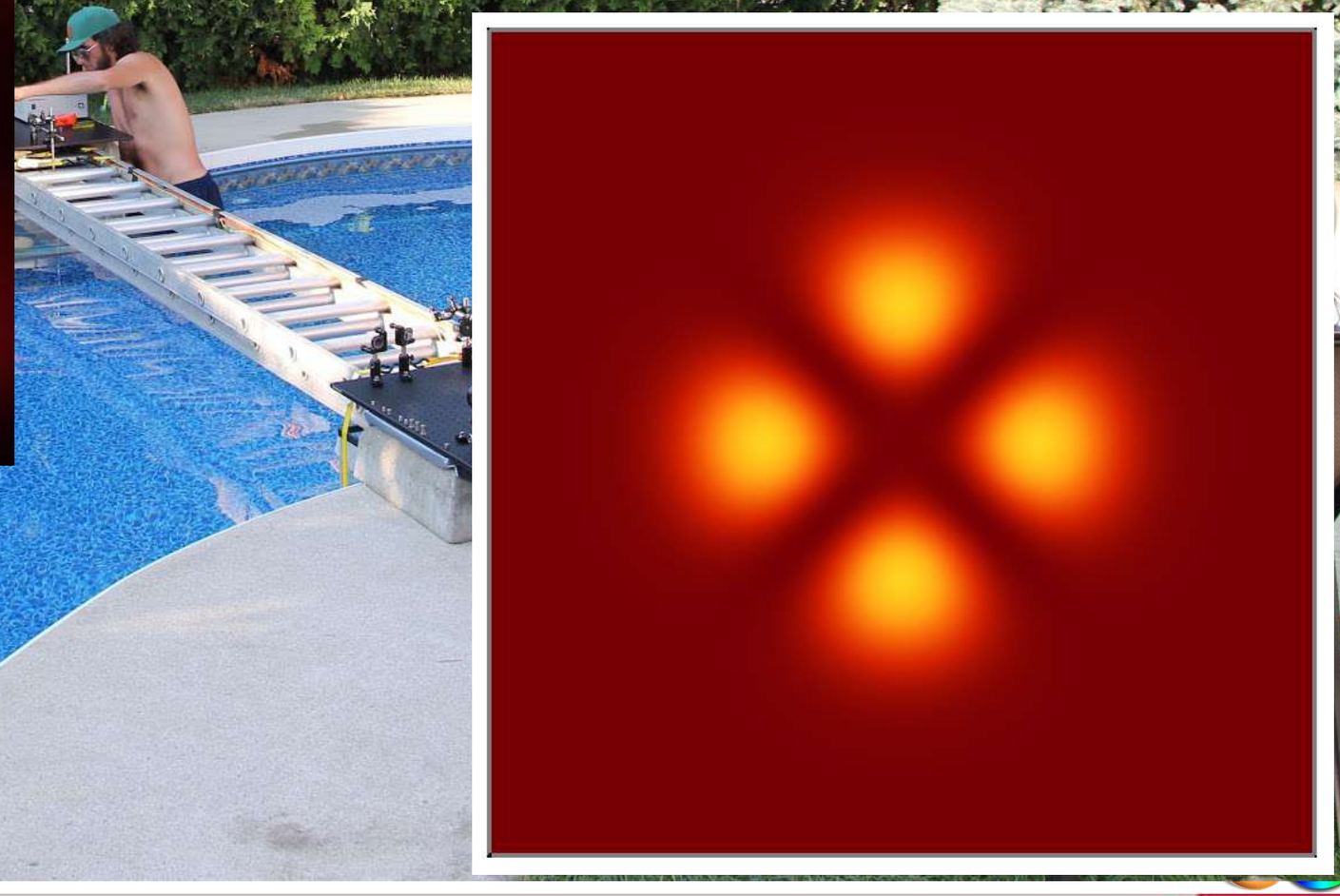
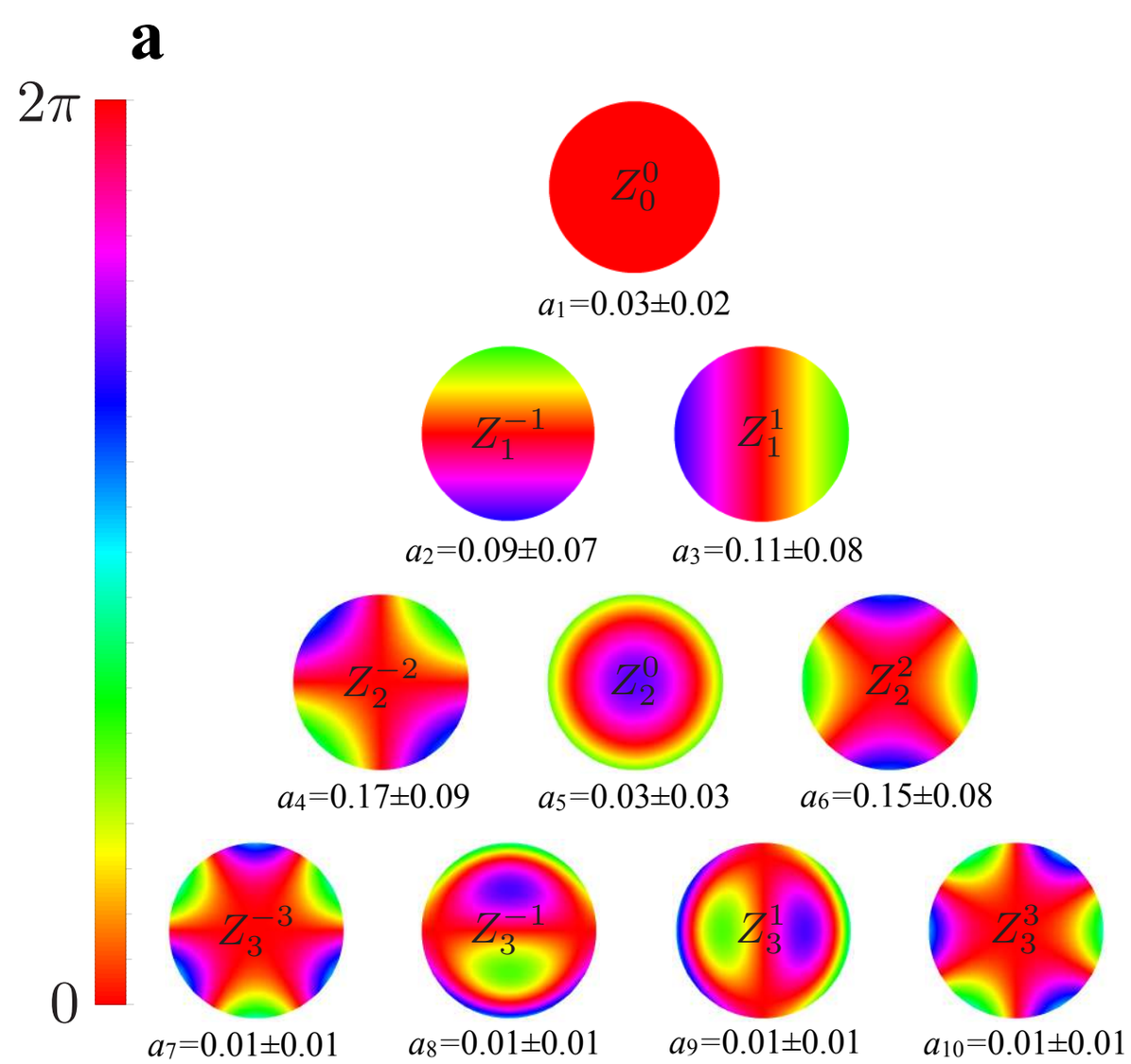


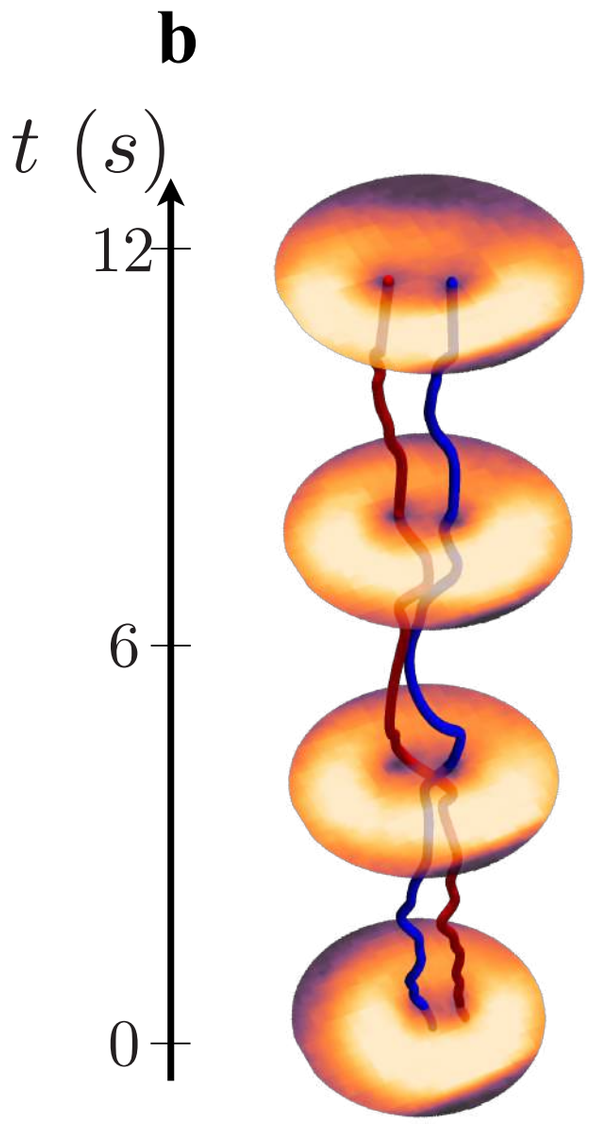


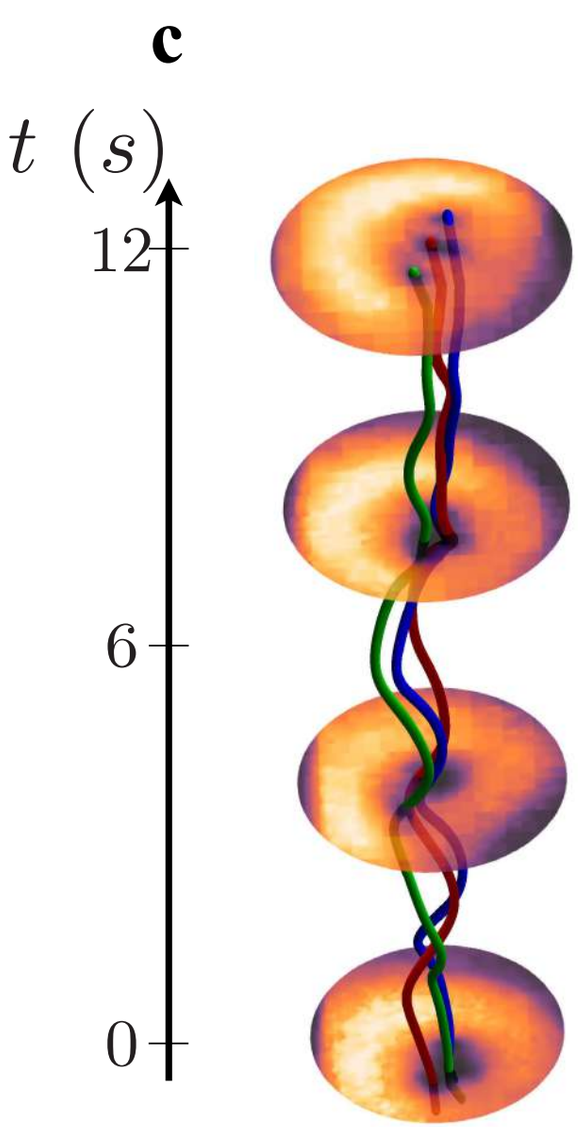




Experimental Setup







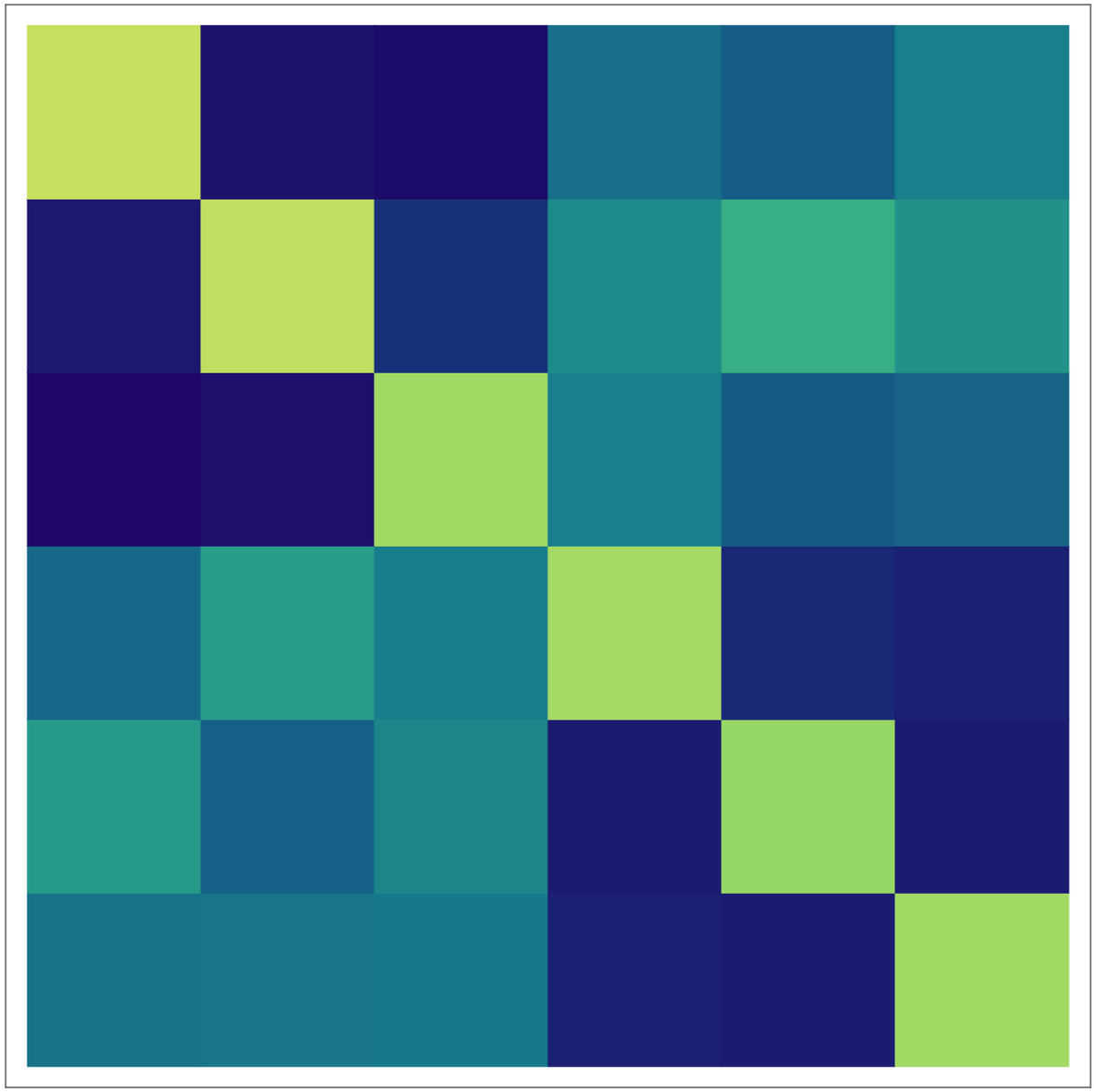
F. Bouchard, A. Sit, F. Hufnagel, A Abbas, Y. Zhang, K. Heshami, R. Fickler, C. Marquardt, G. Leuchs, R. W. Boyd & E.K., *Optics Express* **26**, 22563 (2018).

Experimental results: 3D QKD

$\{|\psi\rangle_i\}$

ALICE

$\{|\phi\rangle_j\}$



3D 0.302 BITS PER PHOTON
11.7% QUANTUM BIT ERROR RATE

$\{|\psi\rangle_i\}$ BOB $\{|\phi\rangle_j\}$

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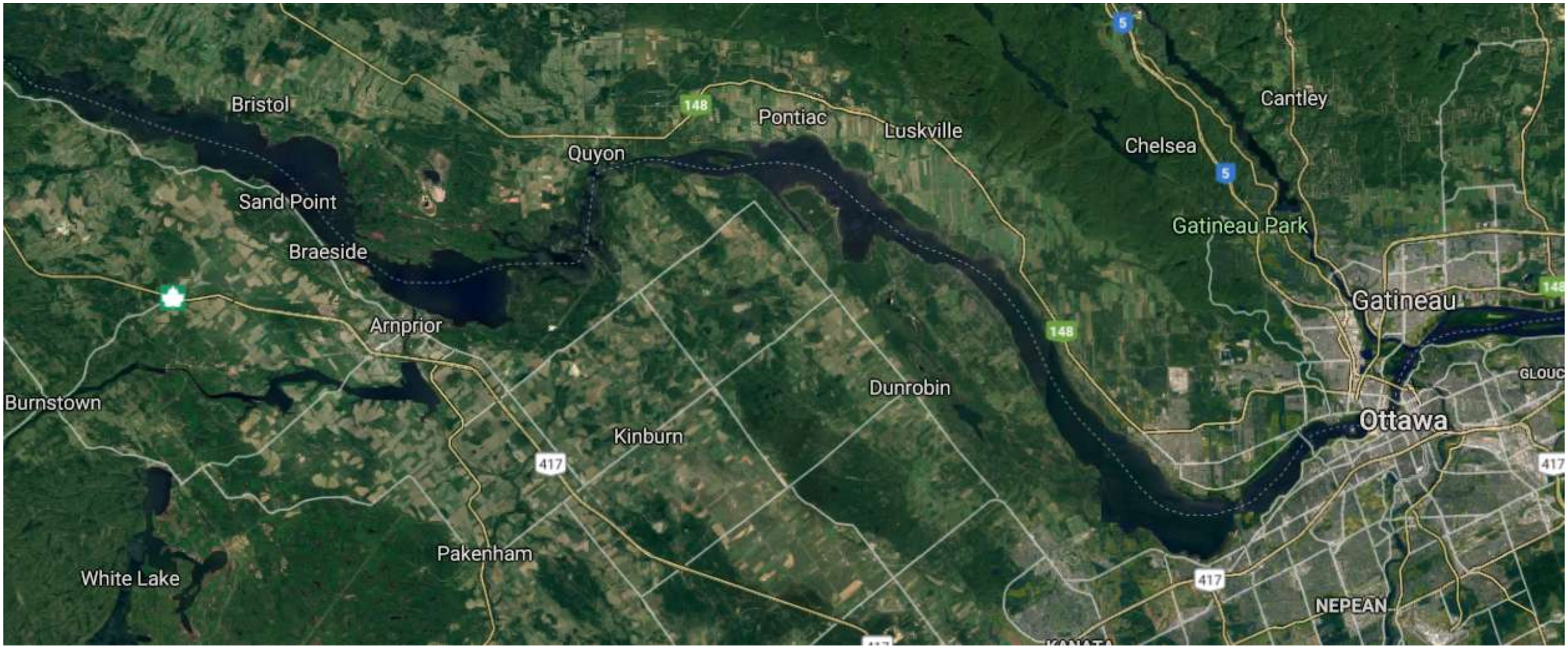
F. Bouchard, A. Sit, F. Hufnagel, A Abbas, Y. Zhang, K. Heshami, R. Fickler, C. Marquardt, G. Leuchs, R. W. Boyd & E.K., *Optics Express* **26**, 22563 (2018).

QKD in the Ottawa river

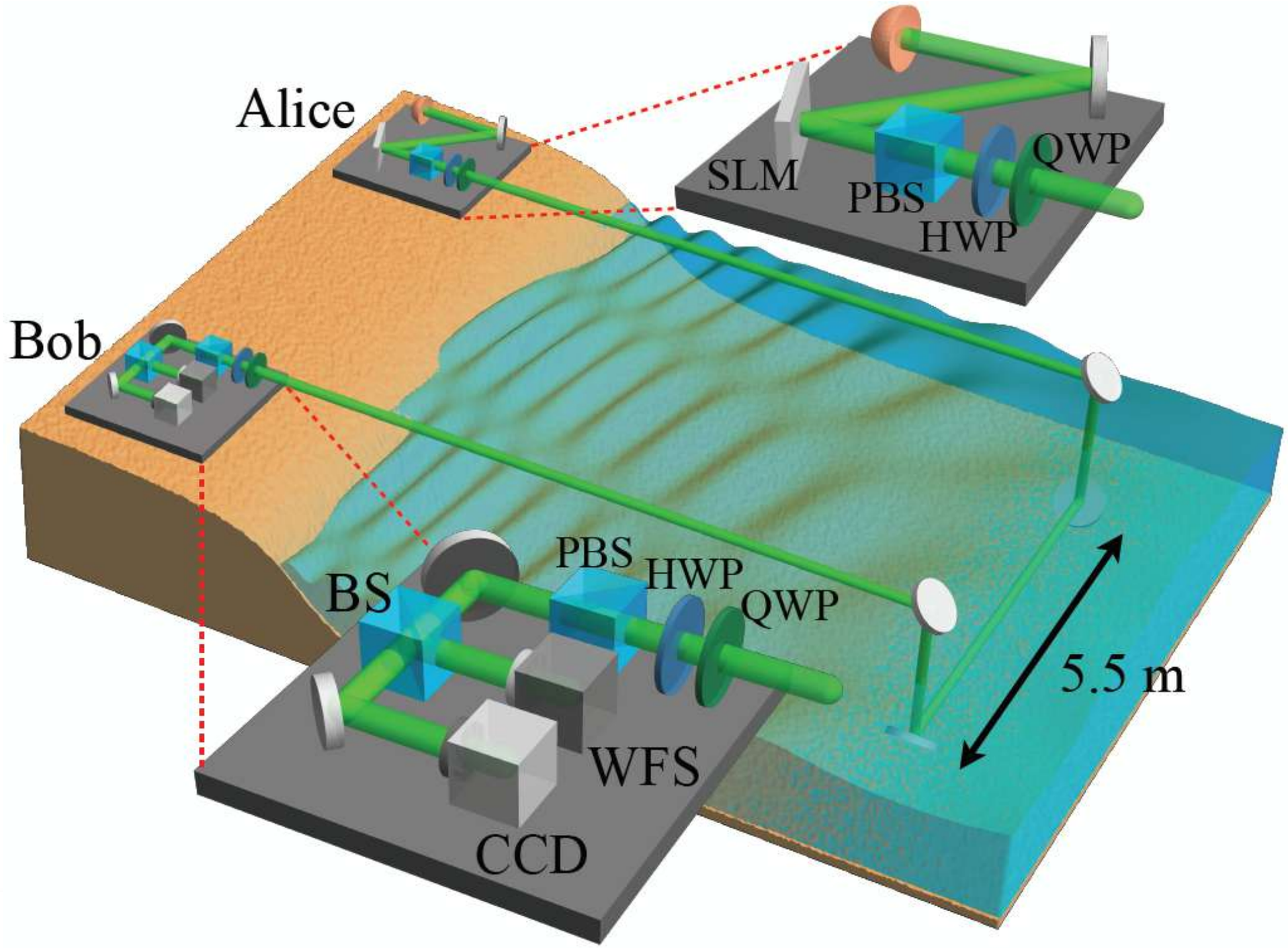


F Hufnagel, A Sit, F Grenapin, F Bouchard, K Heshami, D England, Y Zhang, K Heshami, G Leuchs, R W Boyd & E.K., in preparation

QKD in the Ottawa river

F Hufnagel, A Sit, F Grenapin, F Bouchard, K Heshami, D England, Y Zhang, K Heshami, G Leuchs, R W Boyd & E.K., in preparation

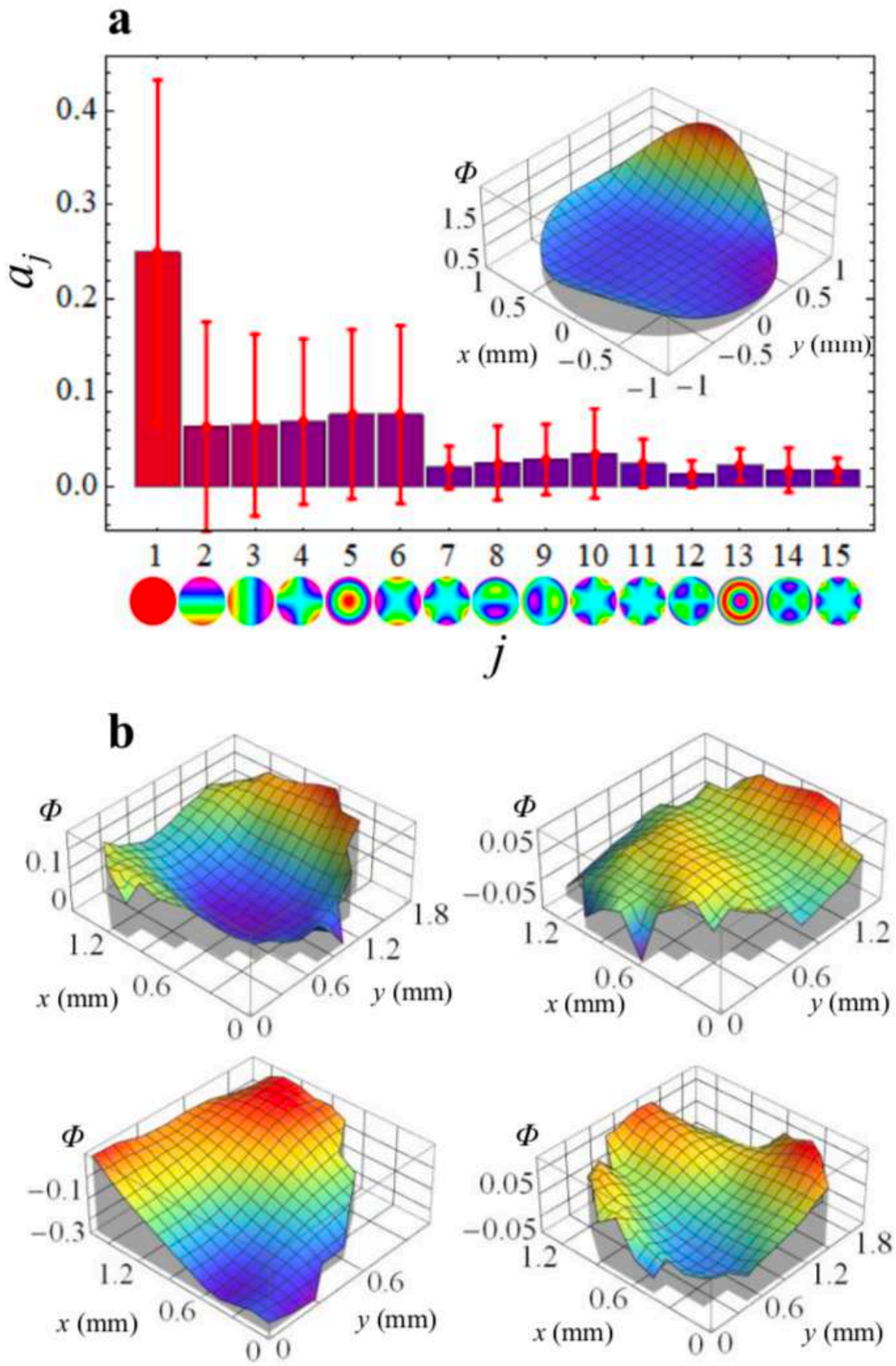
QKD in the Ottawa river



F Hufnagel, A Sit, F Grenapin, F Bouchard, K Heshami, D England, Y Zhang, K Heshami, G Leuchs, R W Boyd & E.K., in preparation

QKD in the Ottawa river

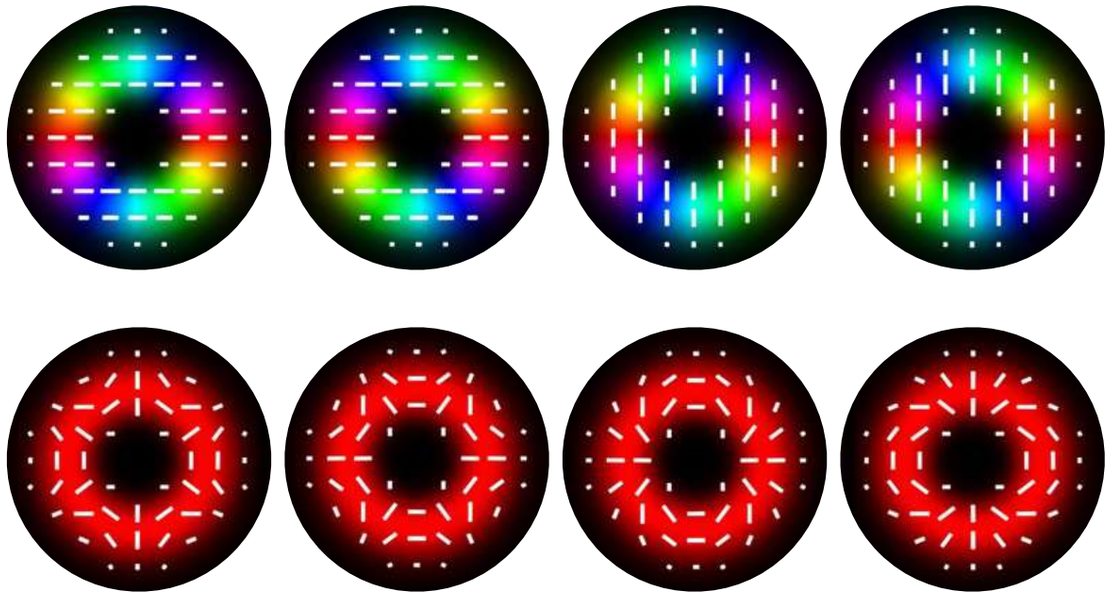
	$\|H\rangle$	$\|V\rangle$	$\|A\rangle$	$\|D\rangle$
$\|H\rangle$	0.93	0.06	0.40	0.59
$\|V\rangle$	0.02	0.97	0.45	0.54
$\|A\rangle$	0.49	0.50	0.97	0.03
$\|D\rangle$	0.53	0.47	0.04	0.96



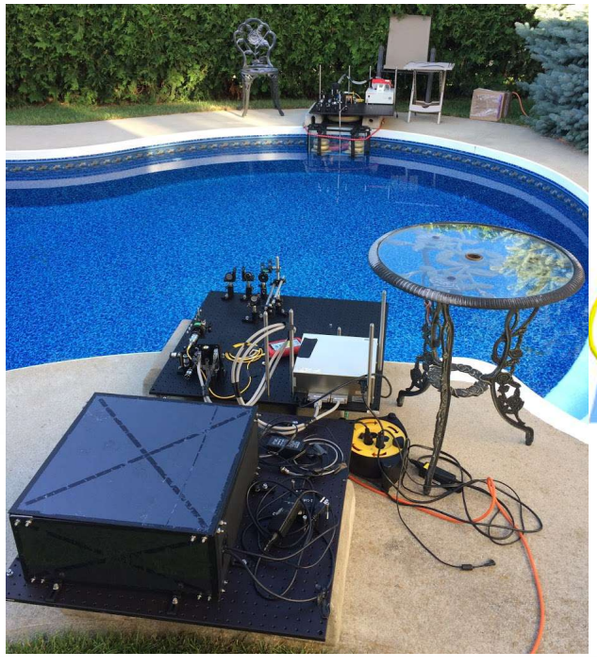
F Hufnagel, A Sit, F Grenapin, F Bouchard, K Heshami, D England, Y Zhang, K Heshami, G Leuchs, R W Boyd & E.K., in preparation

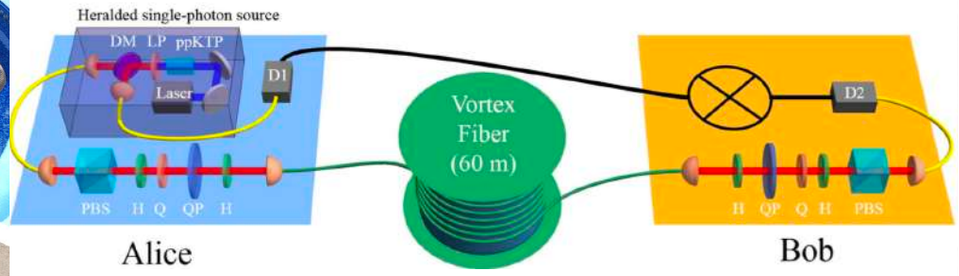
Summary

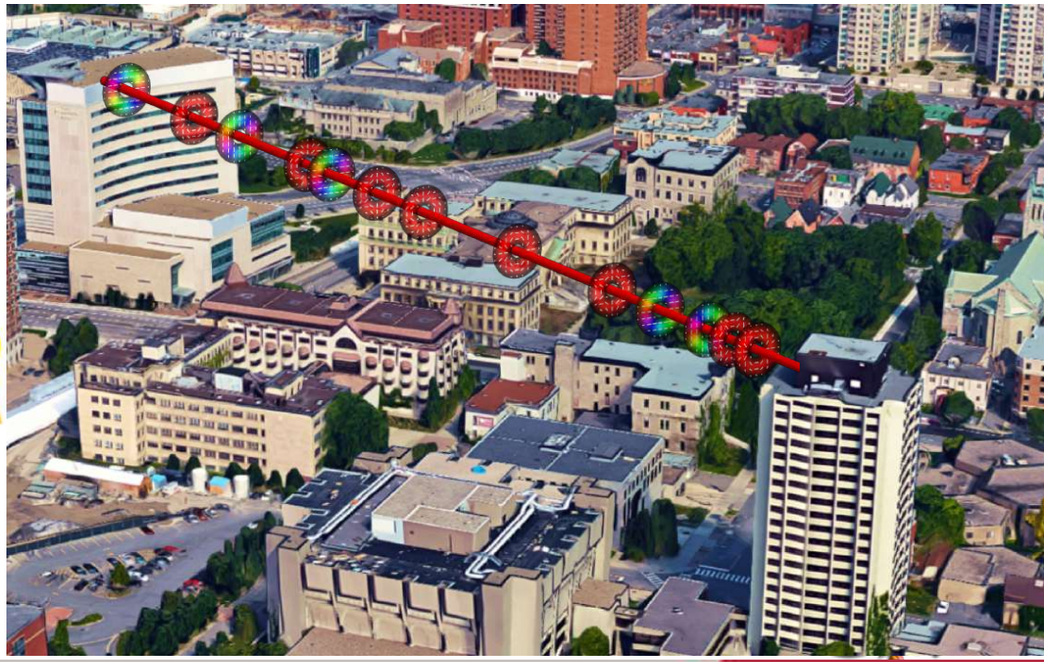
More information per carrier



They are robust in a noisier channel

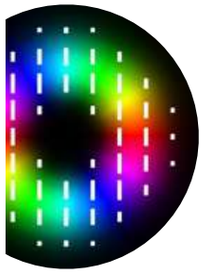


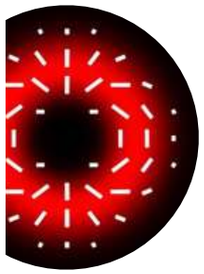




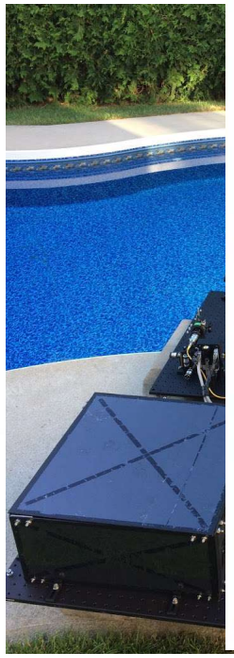
Summary

More inf

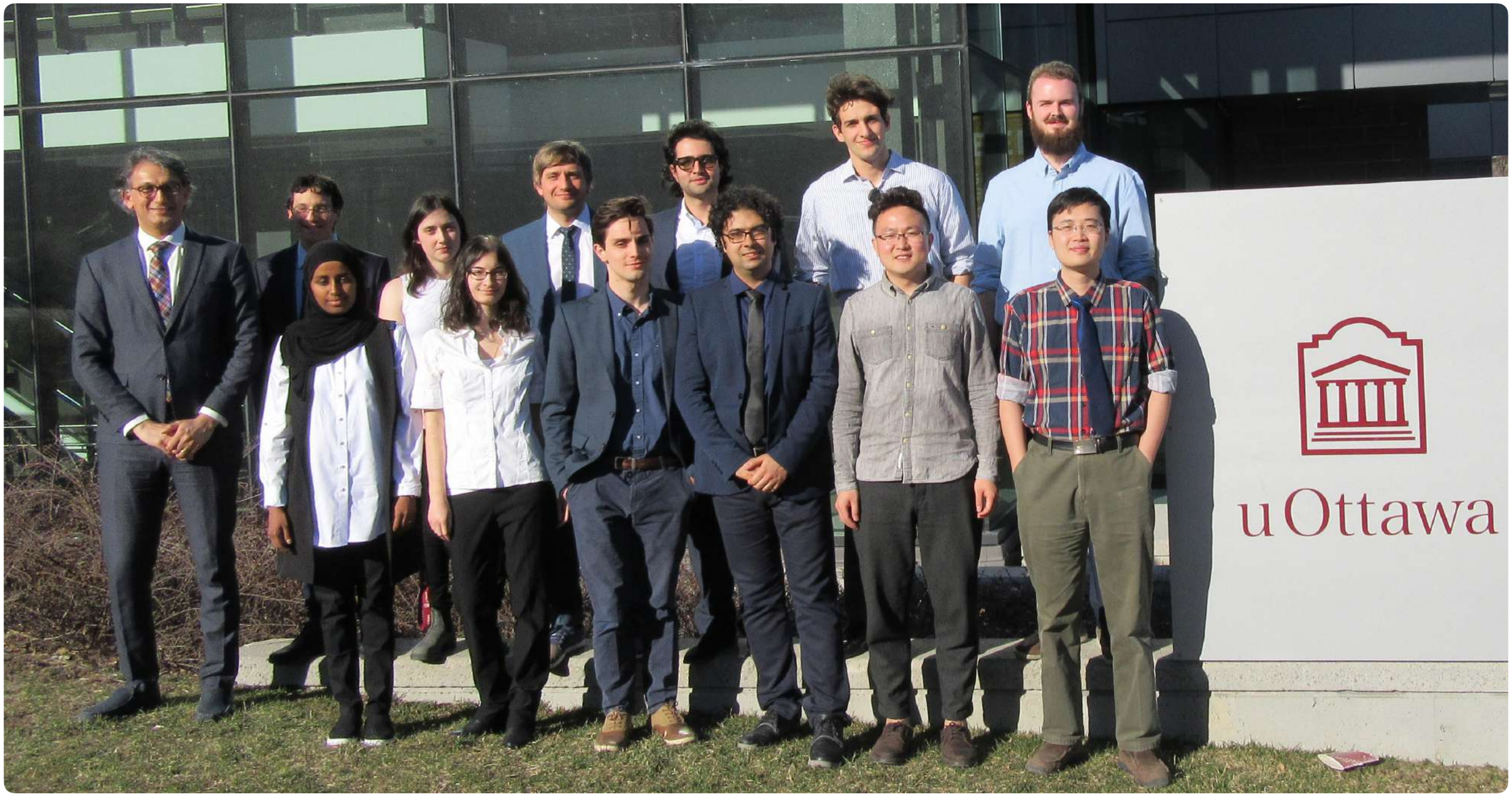




They ar



SQO team



Interested to join the group:

There are several postdoctoral and graduate students positions available.

Funding agencies

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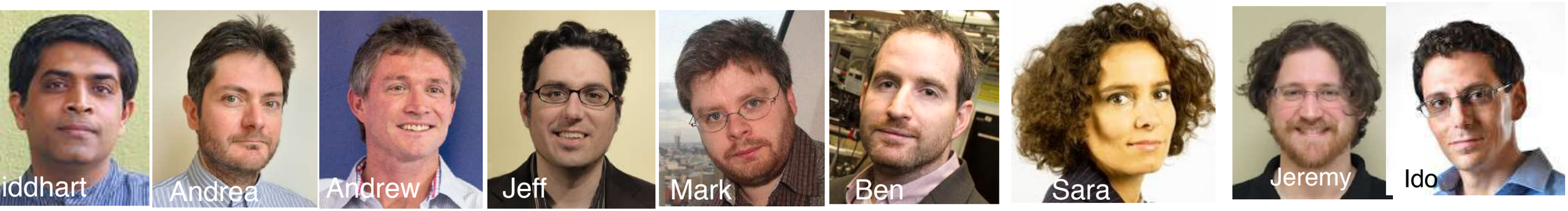
Collaborators



…, and many other members of these research teams