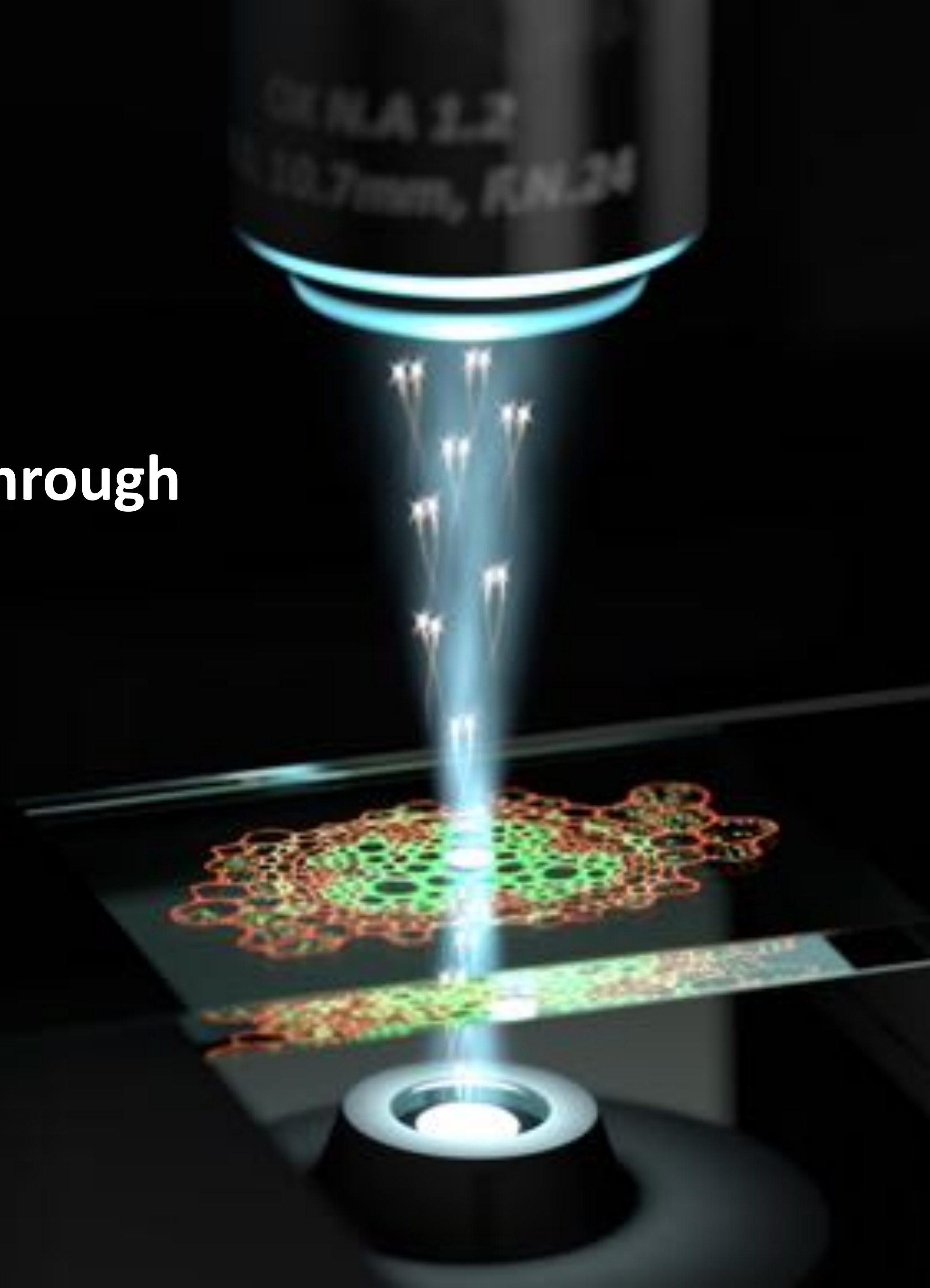
Focusing entanglement through scattering media

Hugo Defienne

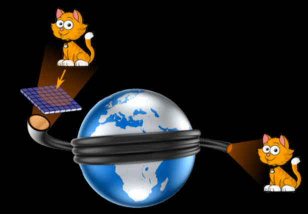


Motivations

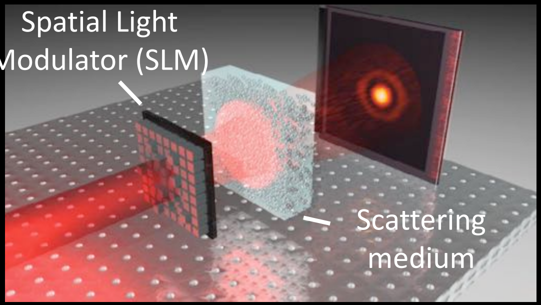
Microscopy

Optical computing

Optical communications

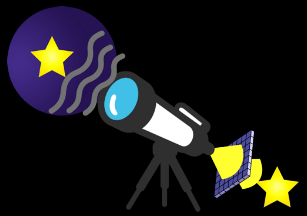


Wavefront shaping



Cao, Most & Rotter. Nat.Phys. 18, 994–1007 (2022)

Astronomy



Fondamental questions

Quantum optical technologies

e.g. quantum communication, computing, imaging, sensing, …

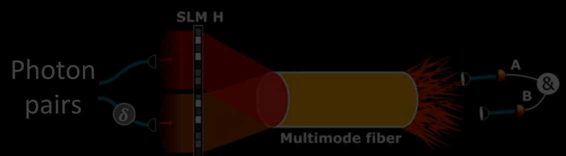
Non-classical properties

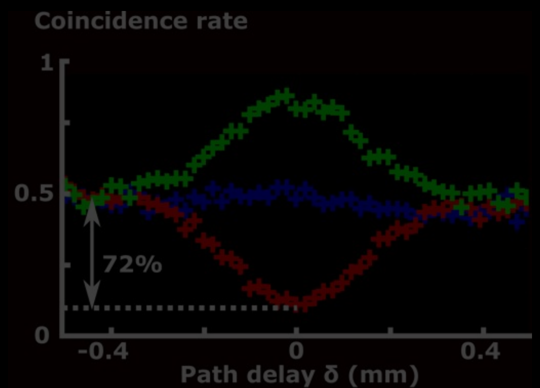
Weak intensity

Fragiles

Some examples

Manipulation of quantum interferences

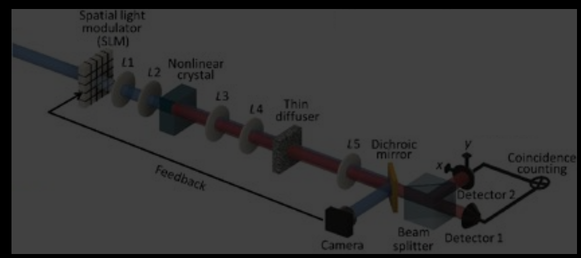


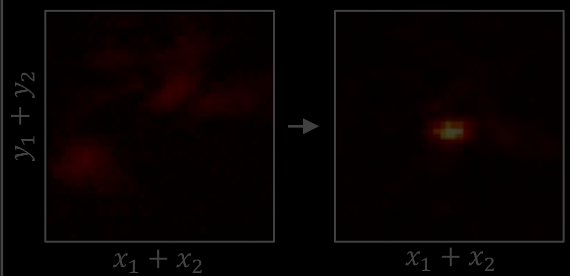


Defienne, Barbieri, Walmsley, Smith & Gigan. Sci. Adv., 2(1), e1501054 (2016).

Wolterink, Uppu, Ctistis, Vos, Boller & Pinkse. PRA 93, 053817 (2016).

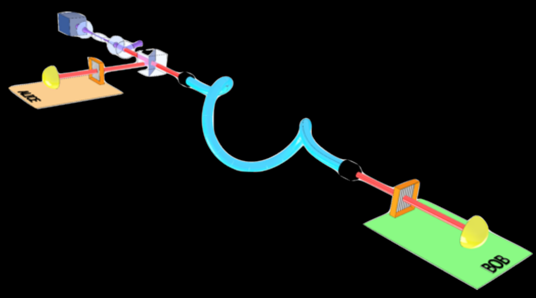
Real-time photon correlations shaping

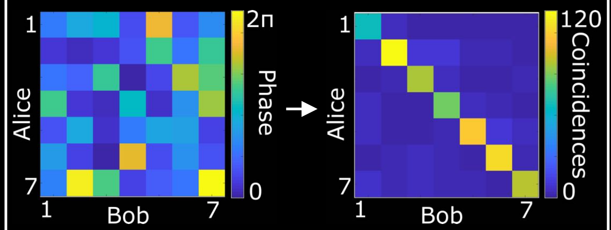




Lib, Hasson, Bromberg. Sci. Adv. 6.37: eabb6298 (2020)

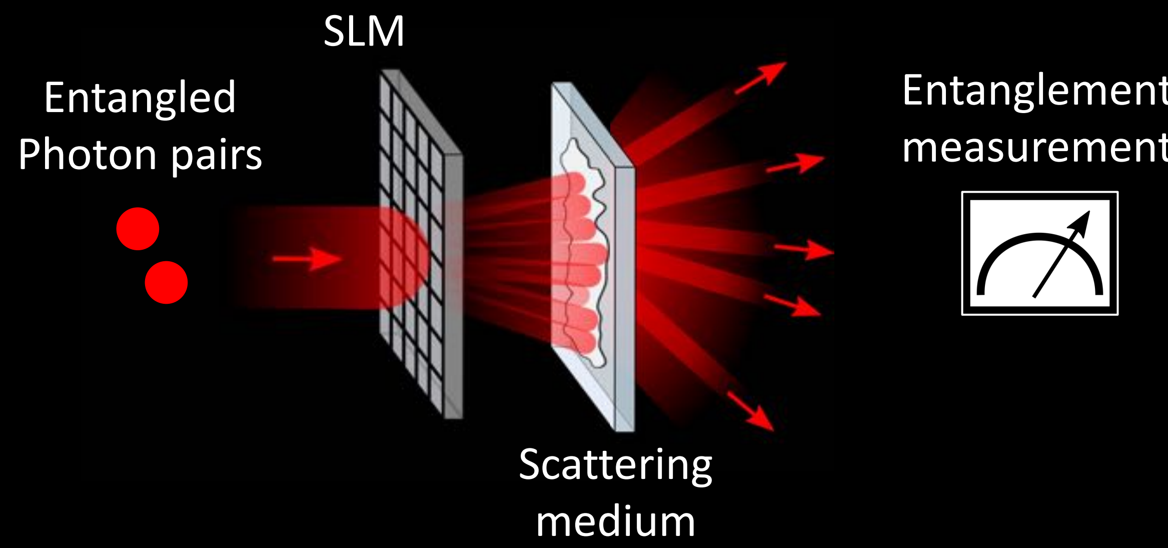
Unscrambling entanglement



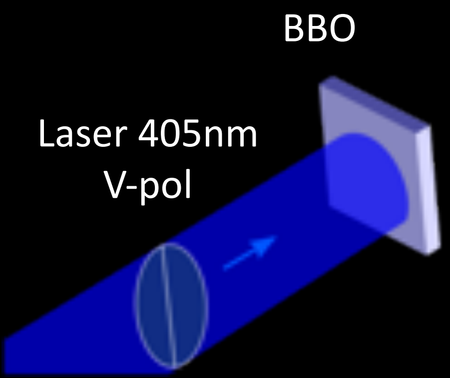


Valencia, Goel, McCutcheon, Defienne & Malik. Nat. Phys., 16(11), 1112-1116 (2020) entanglement

Goal: Manipulating entanglement through scattering media by wavefront shaping



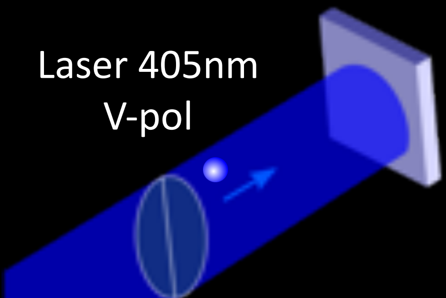
Spatial entanglement



Spatial entanglement

$$|\Psi\rangle = \sum_{\boldsymbol{k}} |H\rangle_{\boldsymbol{k}} |H\rangle_{-\boldsymbol{k}}$$

Spatially-entangled photon pairs
810nm | H-pol

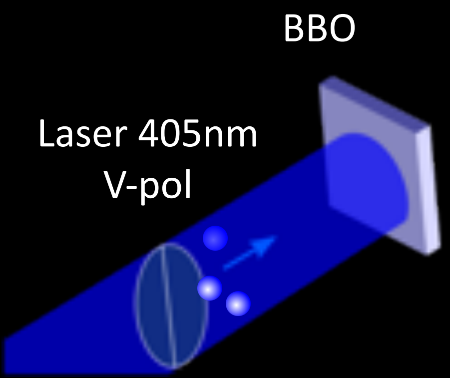


Spontaneous parametric down conversion (Type I)

Spatial entanglement

$$|\Psi\rangle = \sum_{\boldsymbol{k}} |H\rangle_{\boldsymbol{k}} |H\rangle_{-\boldsymbol{k}}$$

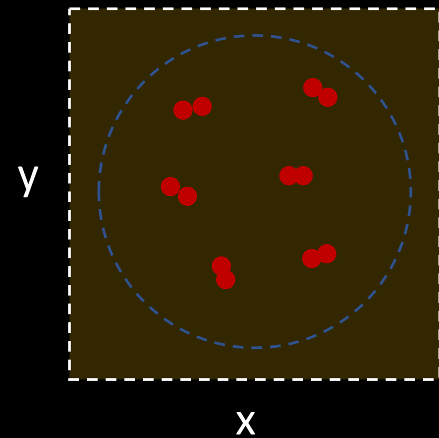
Spatially-entangled photon pairs
810nm | H-pol



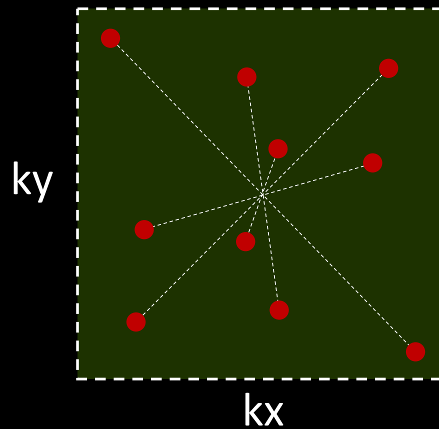
Spontaneous parametric down conversion (Type I)

Spatial entanglement

Position basis



Momentum basis



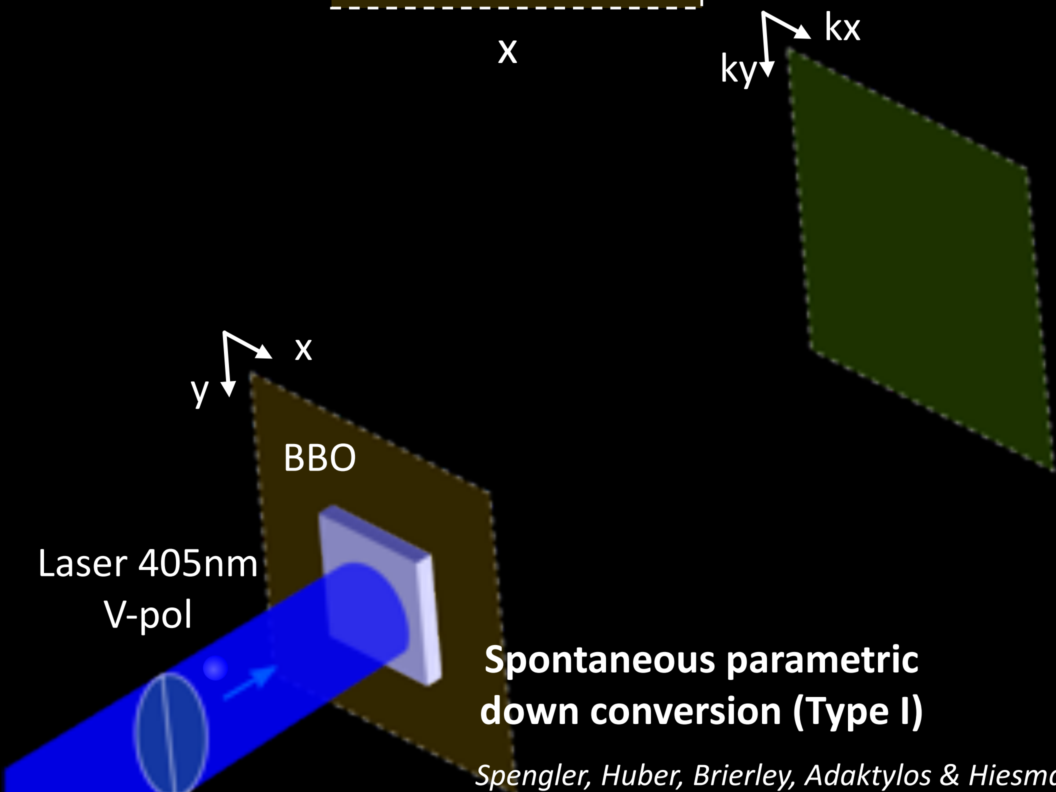
Mutually Unbiased Bases 'MUB'

$$|\Psi\rangle = \sum_{\boldsymbol{k}} |H\rangle_{\boldsymbol{k}} |H\rangle_{-\boldsymbol{k}}$$

Strong position correlations
AND
Strong momentum correlations

Spatially-entangled photon pairs
810nm | H-pol

Spatial entanglement

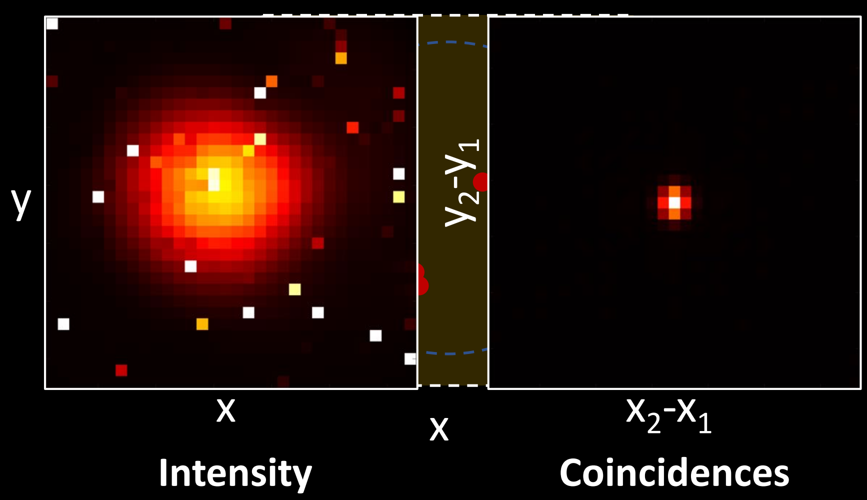


Spontaneous parametric down conversion (Type I)

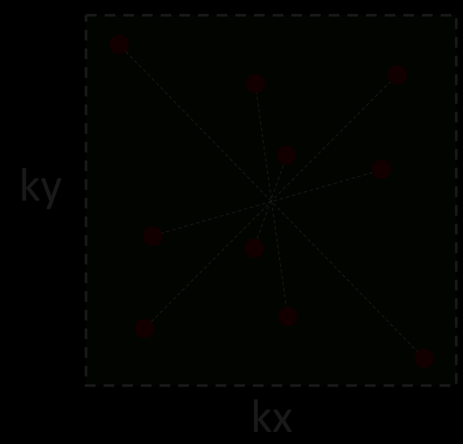
Spengler, Huber, Brierley, Adaktylos & Hiesmayr. PRA, 86(2), 022311 (2012)

Spatial entanglement

Position basis

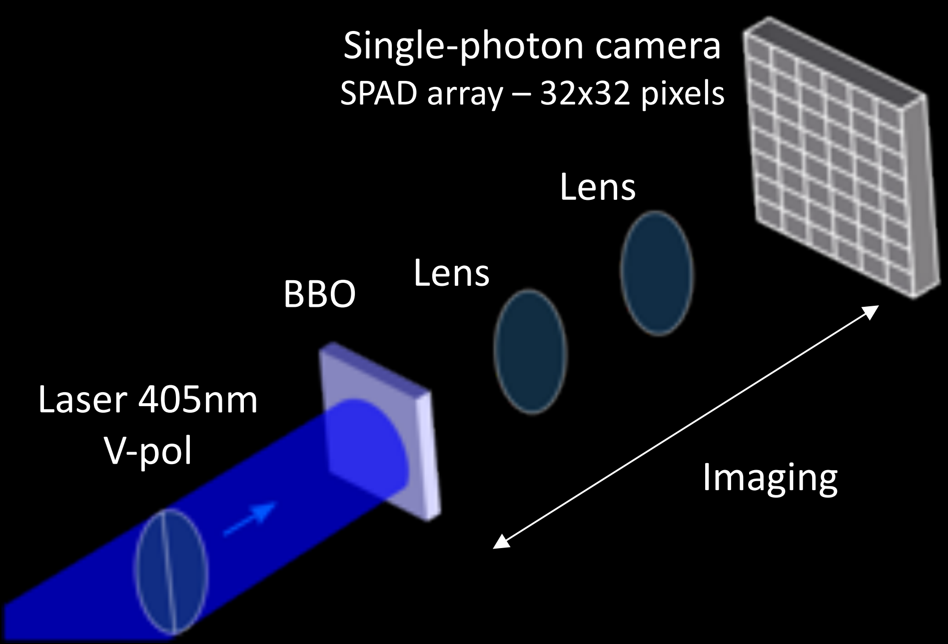


Momentum basis



Strong position correaltions
AND
Strong momentum correlations

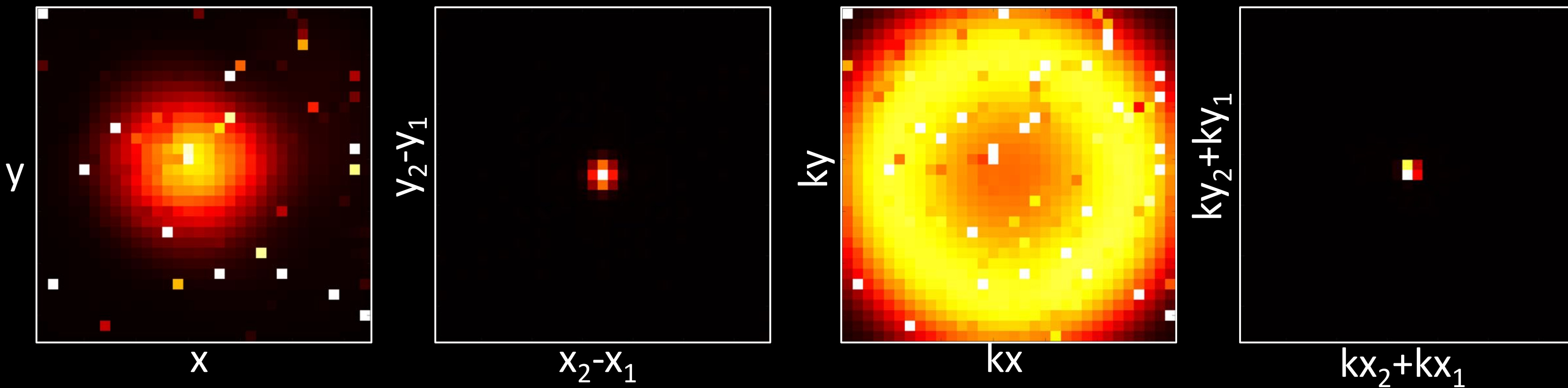
Spatial entanglement



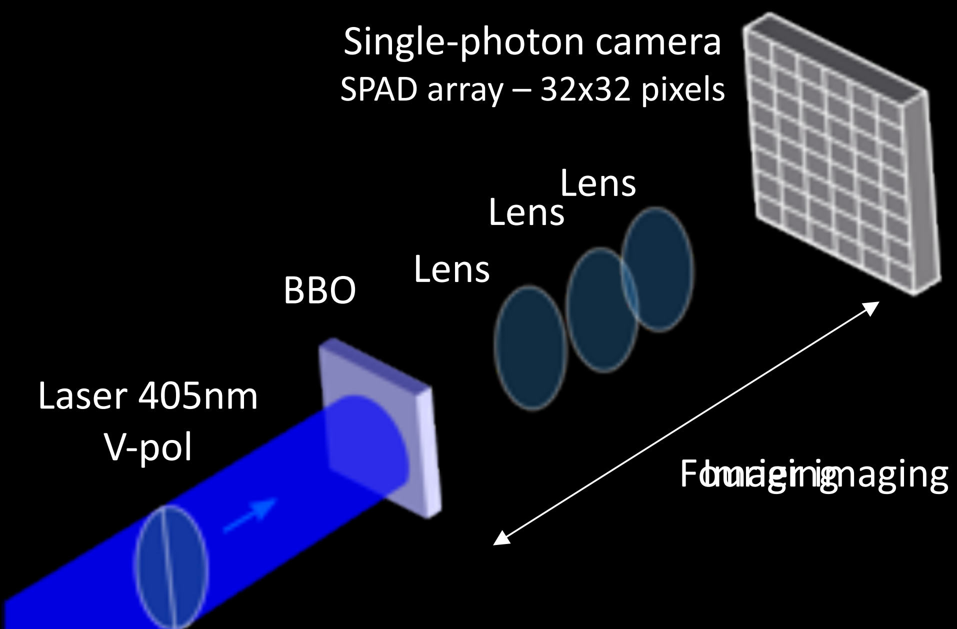
Spatial entanglement

Position basis

Momentum basis



Intensity **Coincidences** **Intensity** **Coincidences**



Strong position correaltions
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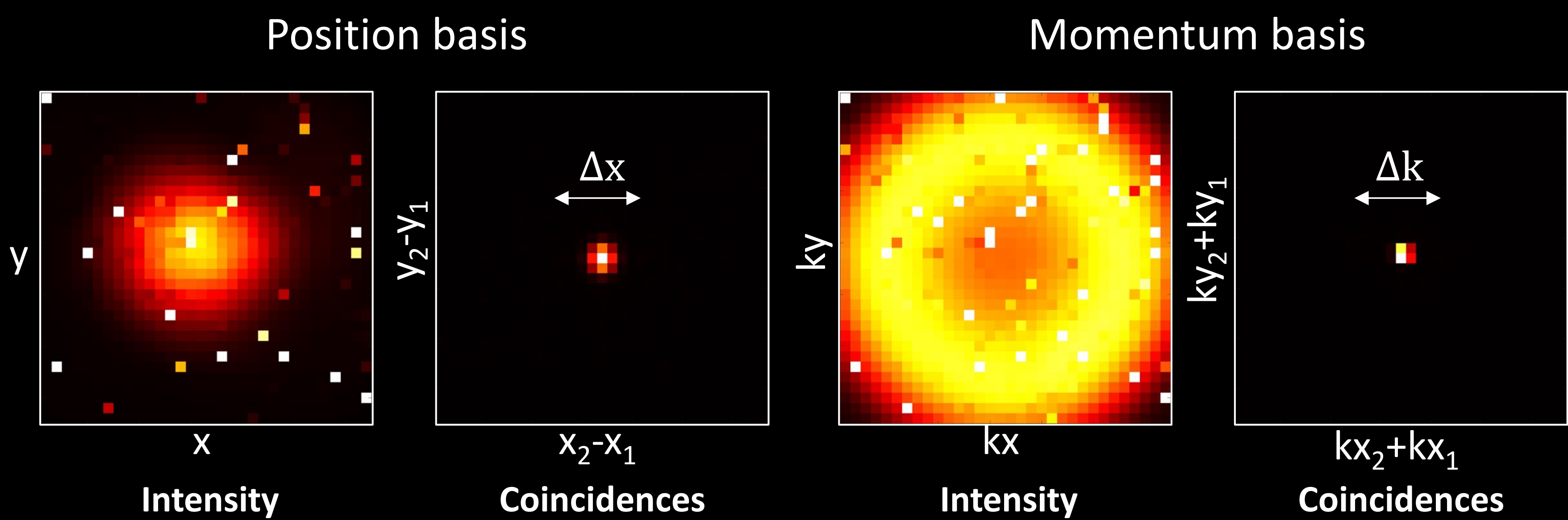
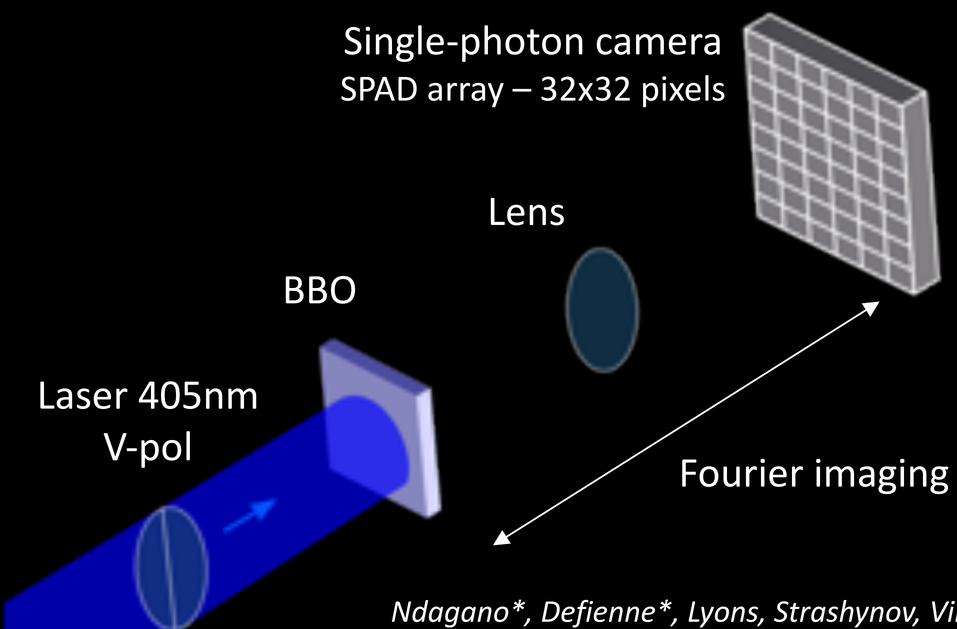
Spatial entanglement

Spatial entanglement





$\Delta x \, \Delta k = 0{,}1013(1) < 1$

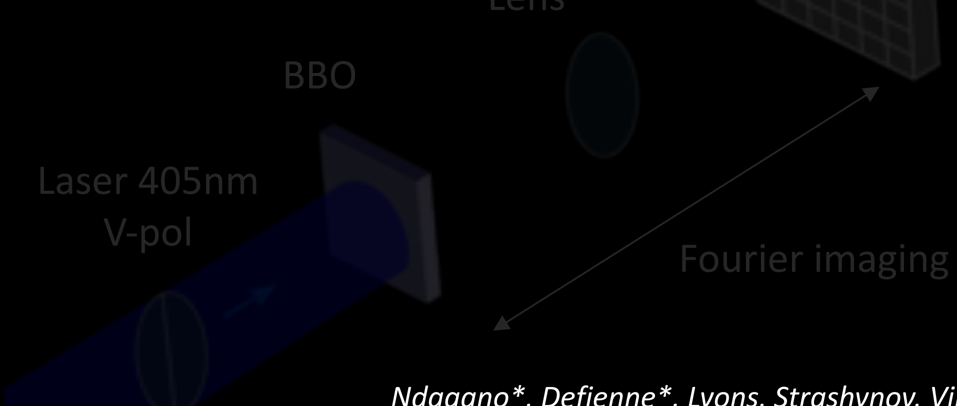
⬇

Spatial entanglement

Ndagano, Defienne*, Lyons, Strashynov, Villa, Tisa, Faccio. npj Quant. Info. 6, 94 (2020)*

Spatial entanglement

Position basis | Momentum basis



$$\Delta x\, \Delta k = 0{,}1013(1) < 1$$

⇓

Spatial entanglement

Ndagano, Defienne*, Lyons, Strashynov, Villa, Tisa, Faccio. npj Quant. Info. 6, 94 (2020)*

Spatial entanglement

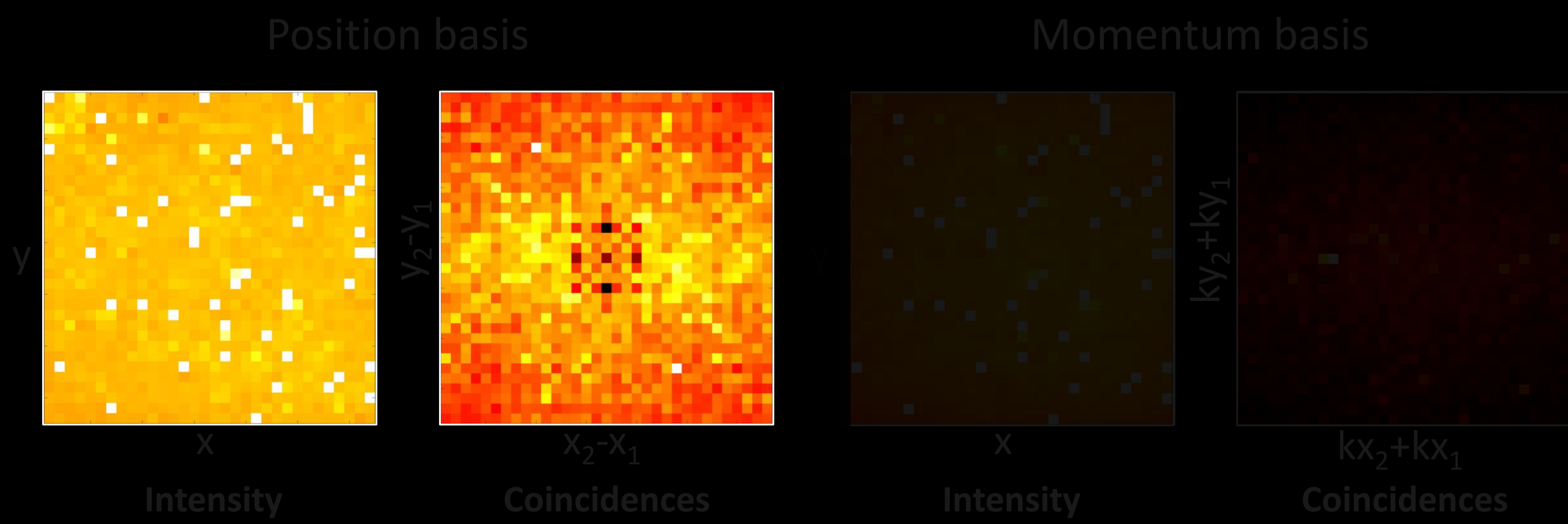
Entanglement is a form of correlations robust to change of basis

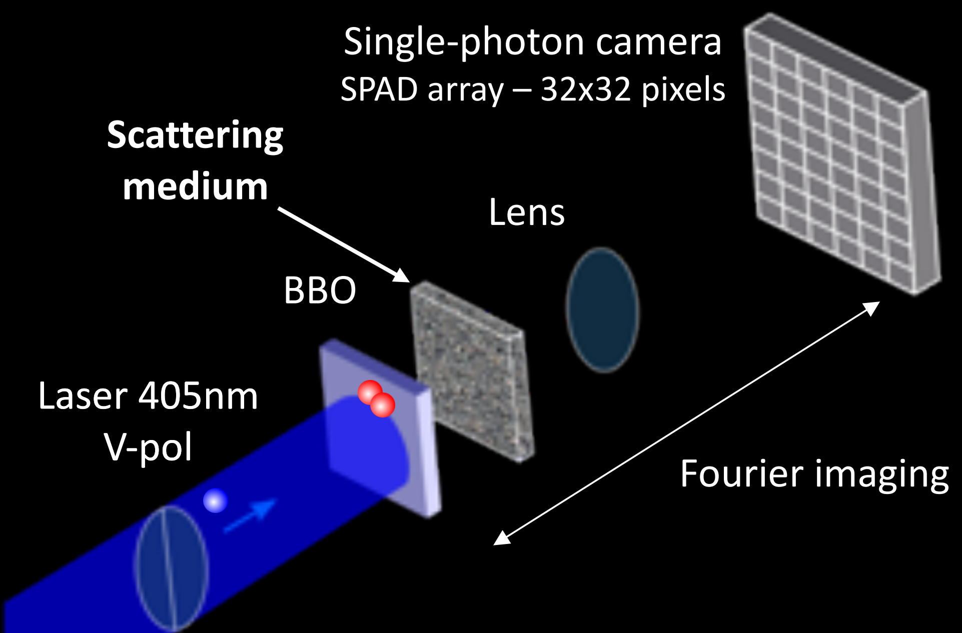
→ Preserved in MUBs

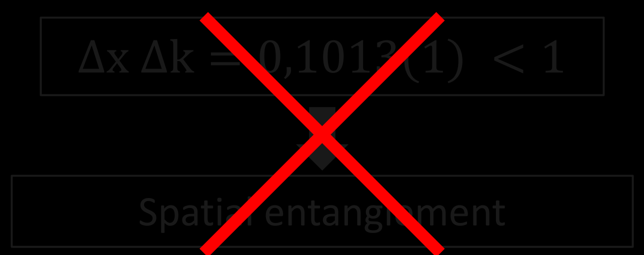
In practice, we use them to certify its presence

Ndagano, Defienne*, Lyons, Strashynov, Villa, Tisa, Faccio. npj Quant. Info. 6, 94 (2020)*

Spatial entanglement through scattering



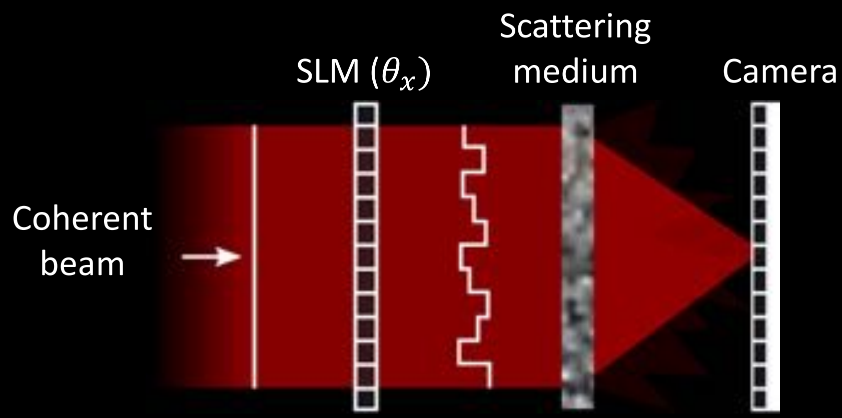




How can we retrieve it ?

Wavefront shaping and coherence

Classical light



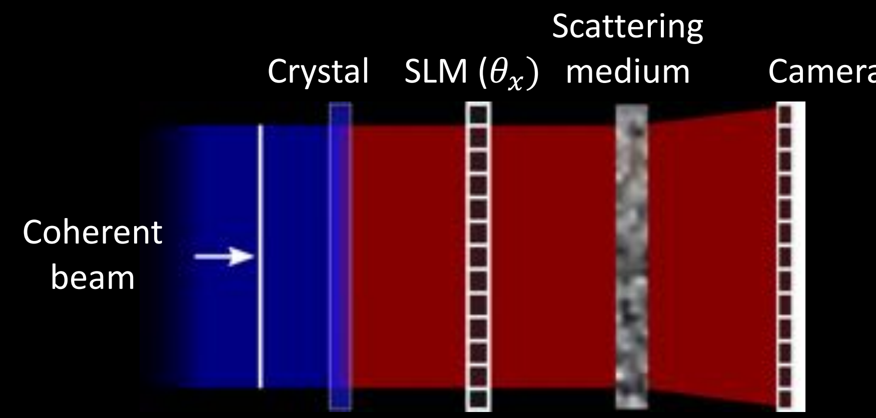
1st order spatial coherence

$$E^{in} = \sum_{x} e^{i\theta_x}$$

Propagation

$$E^{out} = TE^{in}$$

Entangled photons



2nd order spatial coherence

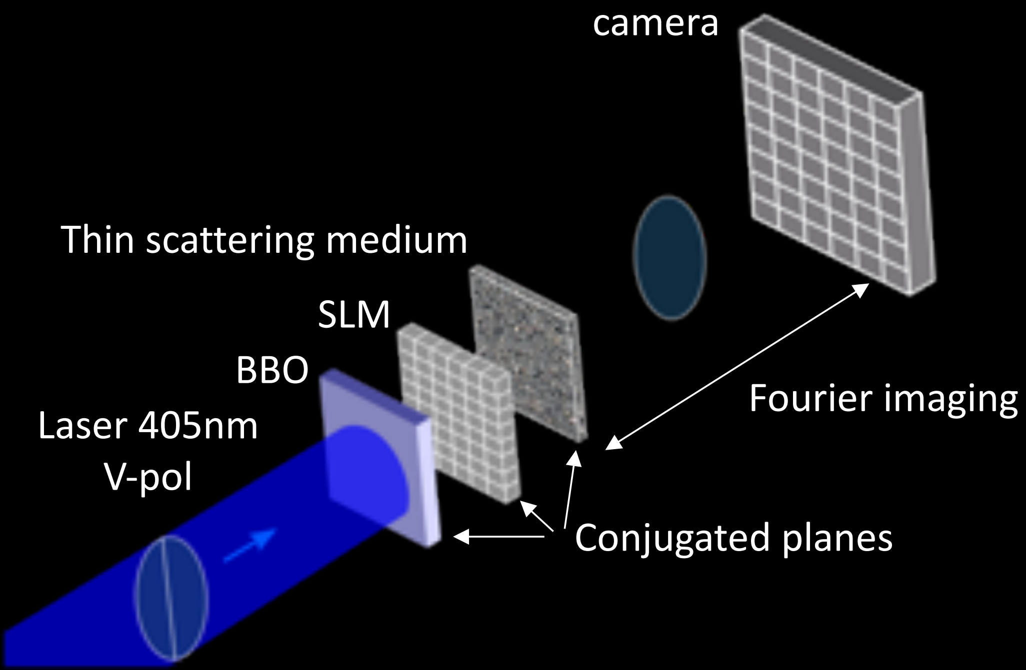
$$\phi^{in} = \sum_{x_1,x_2} \delta_{x_2-x_1} e^{\,i(\theta_{x_1}+\theta_{x_2})}$$

Propagation

$$\phi^{out} = T\phi^{in}\, T^t$$

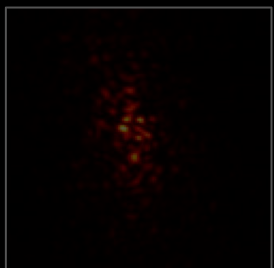
Popoff, Lerosey, Carminati, Fink, Boccara & Gigan, Physical review letters, 104(10), 100601 (2010)

Experimental results



Experimental results

1. Transmission matrix measurement



Intensity image

$\rightarrow T$

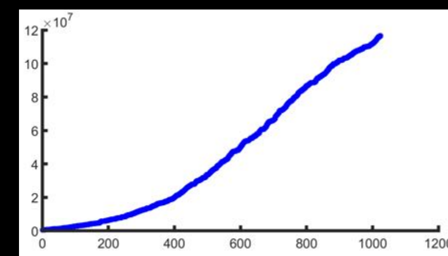
Popoff et al. PRL104, 100601 (2010)

2. Propagation on computer

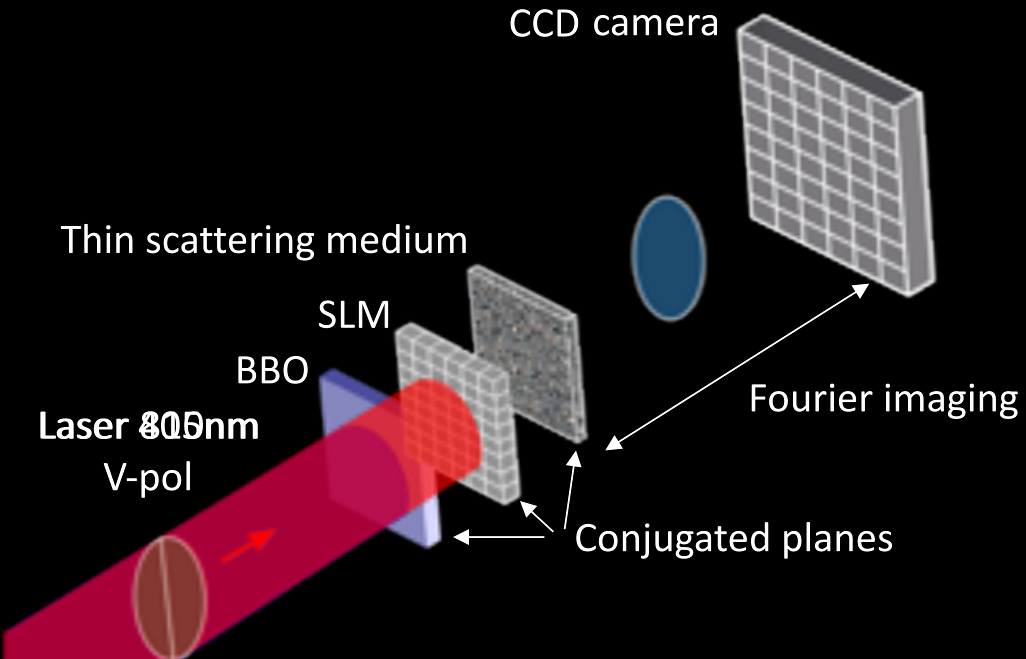
$$\phi^{out} = T\phi^{in}\, T^{t}$$

3. Find SLM pattern optimizing entanglement criteria

$\Delta x\, \Delta k$ ↘

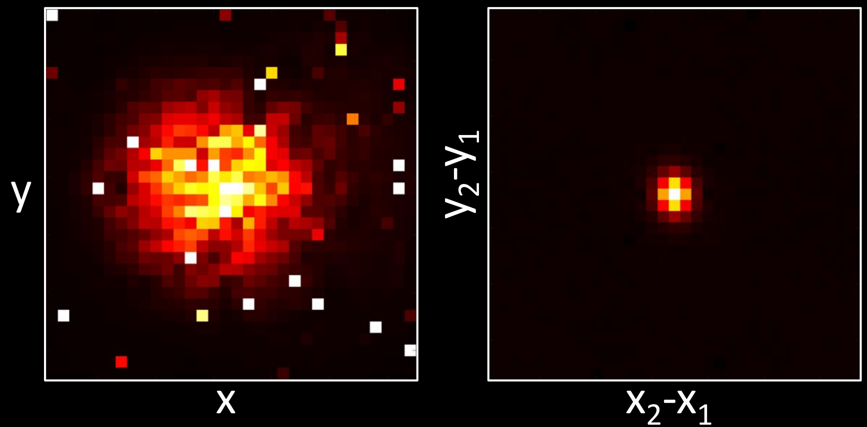


Optimal phase
32×32

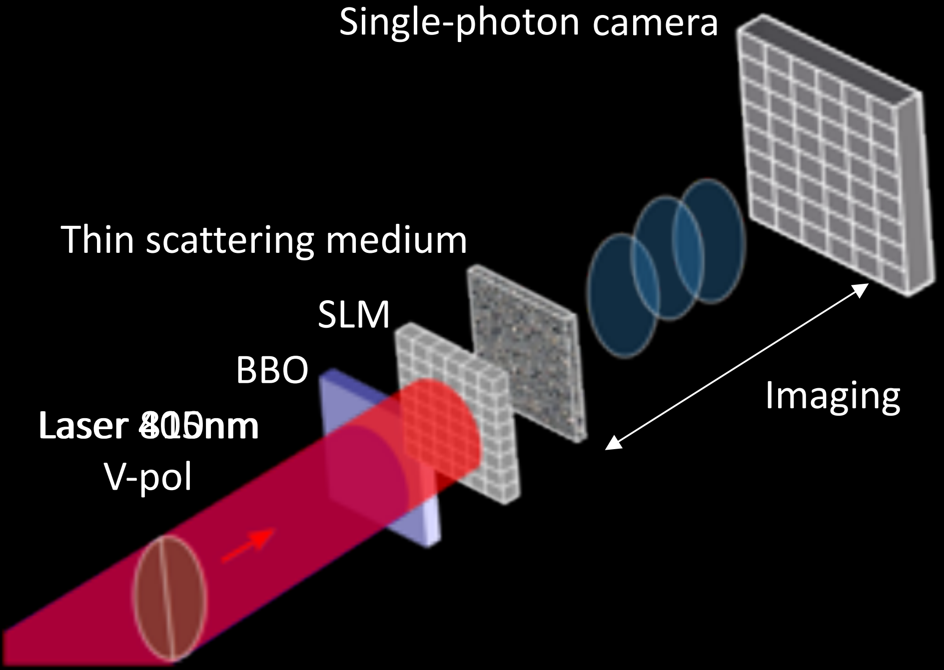


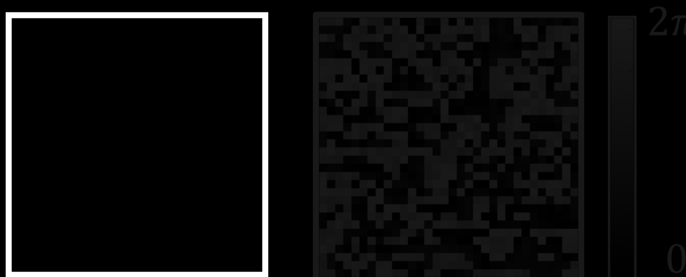
Experimental results

Position basis



Intensity **Coincidences**

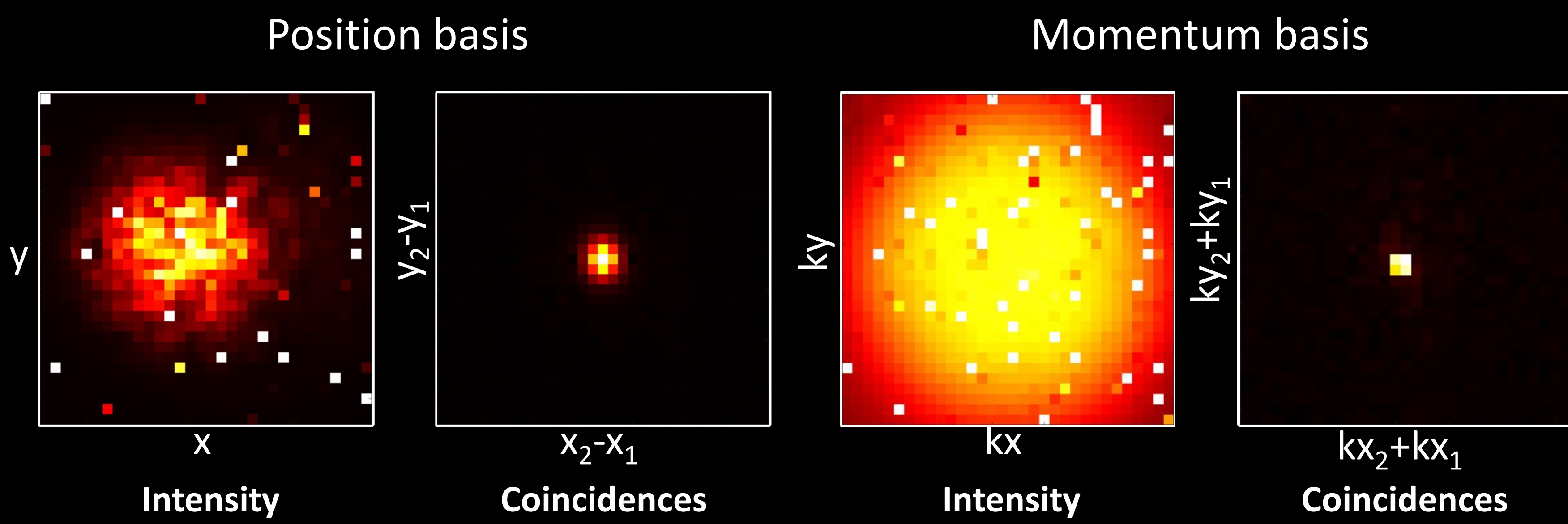


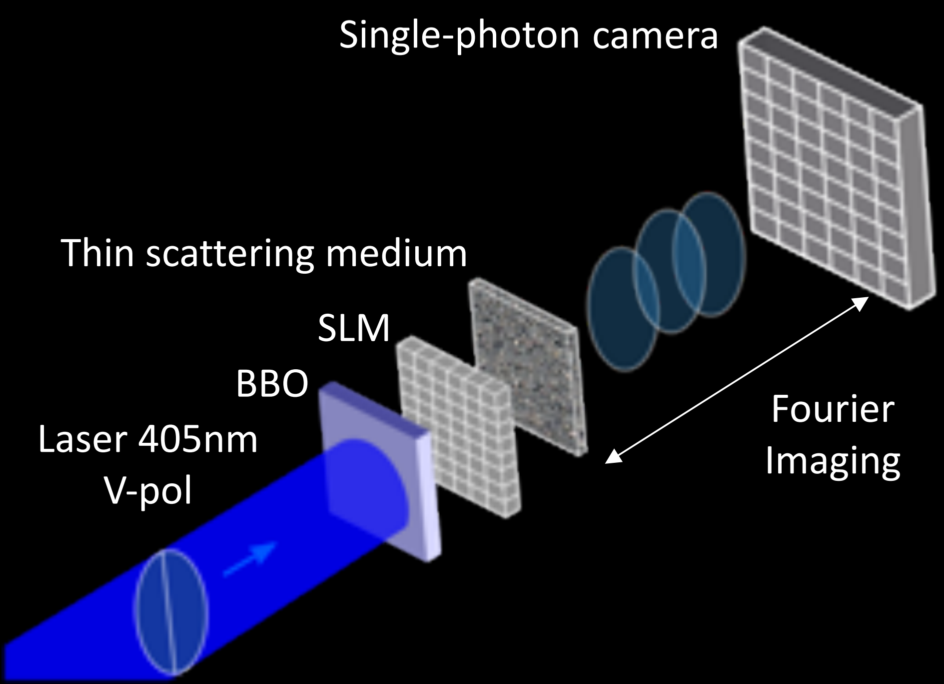


Flat phase

Optimal phase
32×32

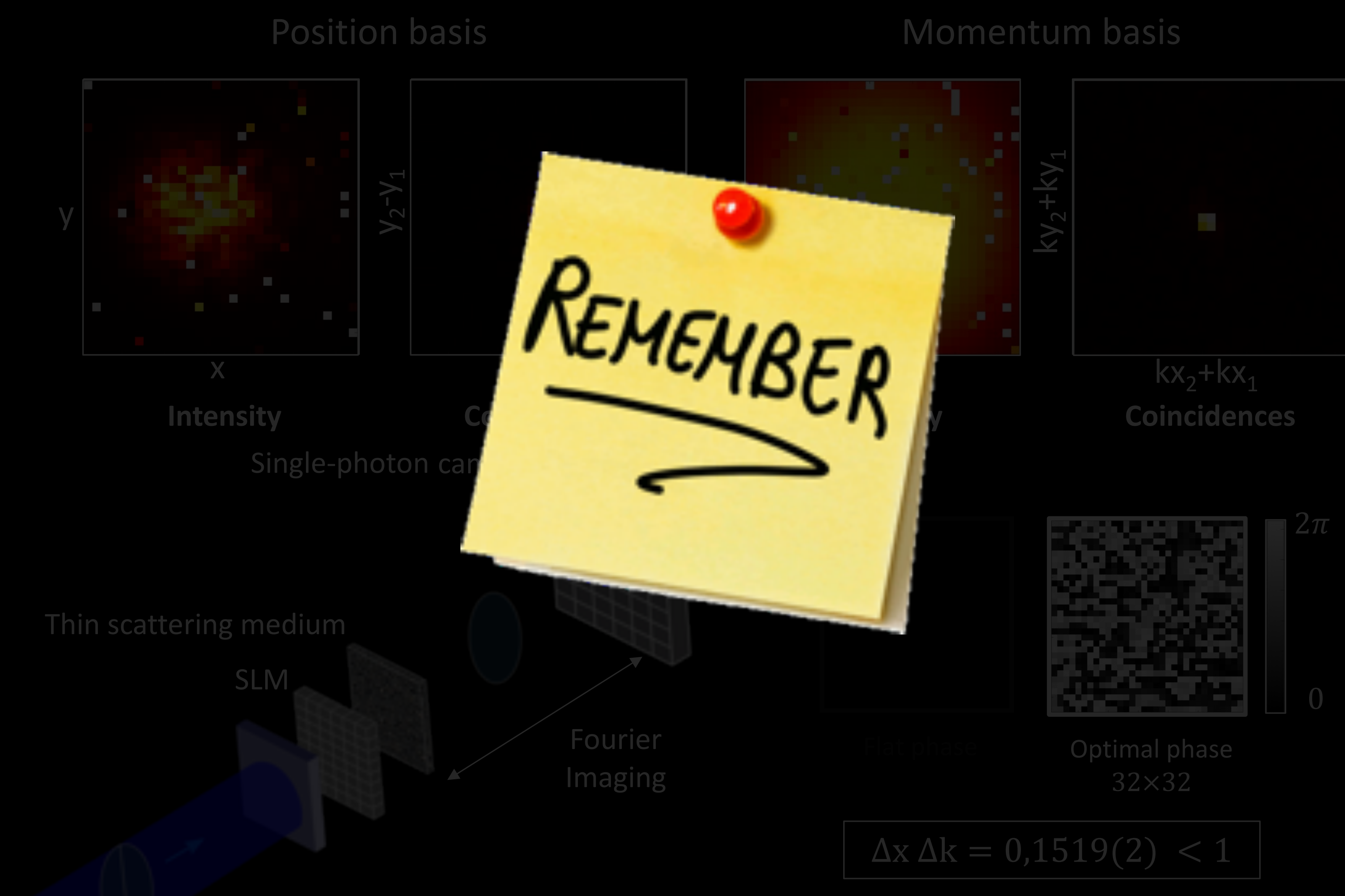
Experimental results





$$\Delta x \, \Delta k = 0{,}1519(2) \; < 1$$

Experimental results



Courme, Cameron, Faccio, Gigan and Defienne. PRX Quantum (in press: ArXiv 2207.02333)

Experimental results

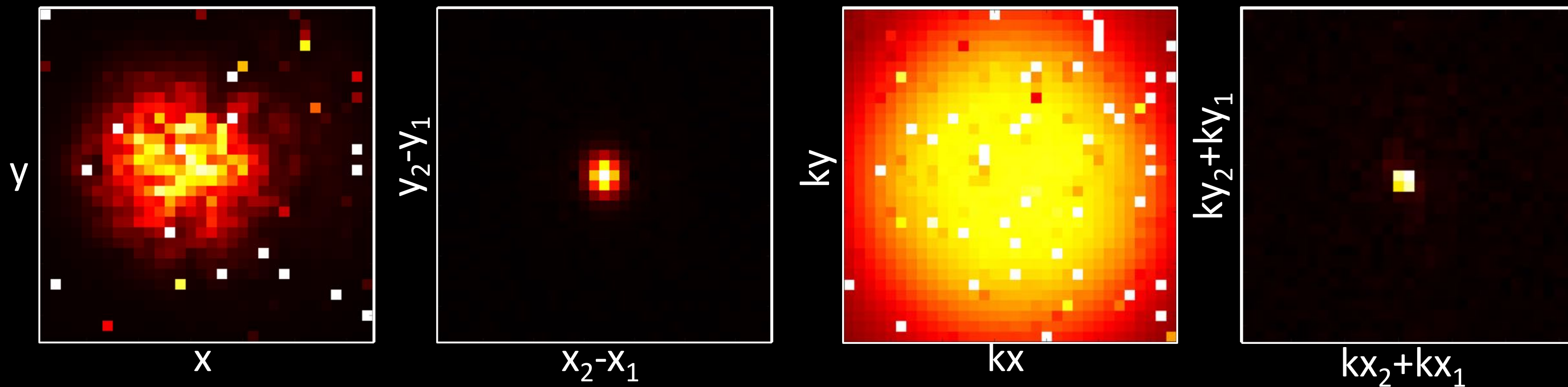
Manipulate second-order spatial coherence

Certify the presence of entanglement after the medium

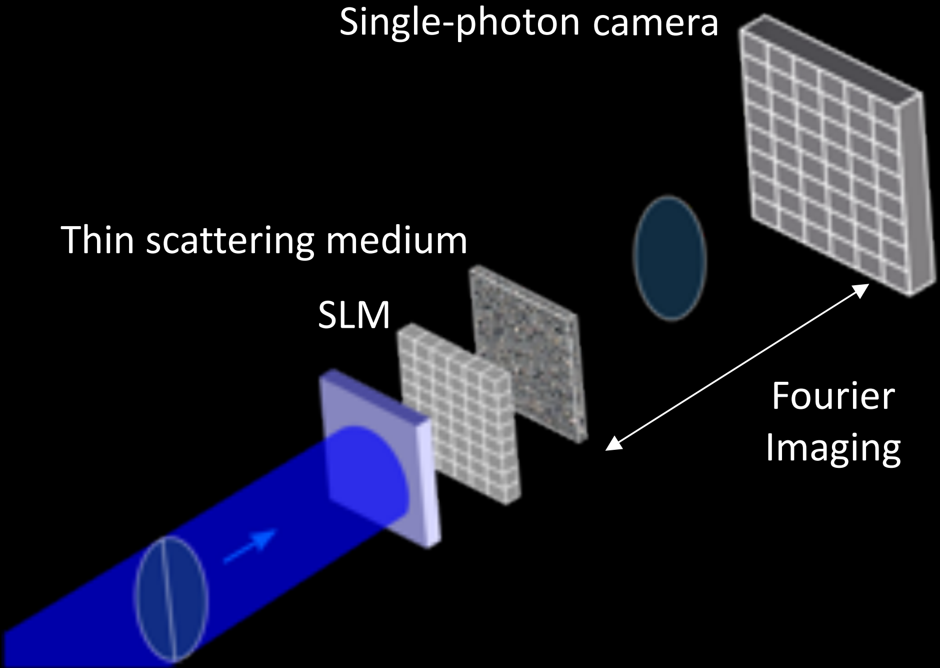
Courme, Cameron, Faccio, Gigan and Defienne. PRX Quantum (in press: ArXiv 2207.02333)

Experimental results

Position basis | Momentum basis



Intensity **Coincidences** **Intensity** **Coincidences**

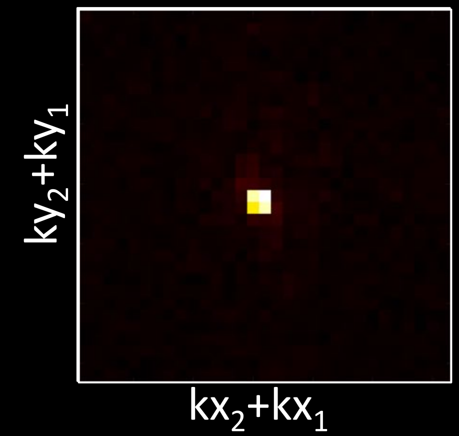


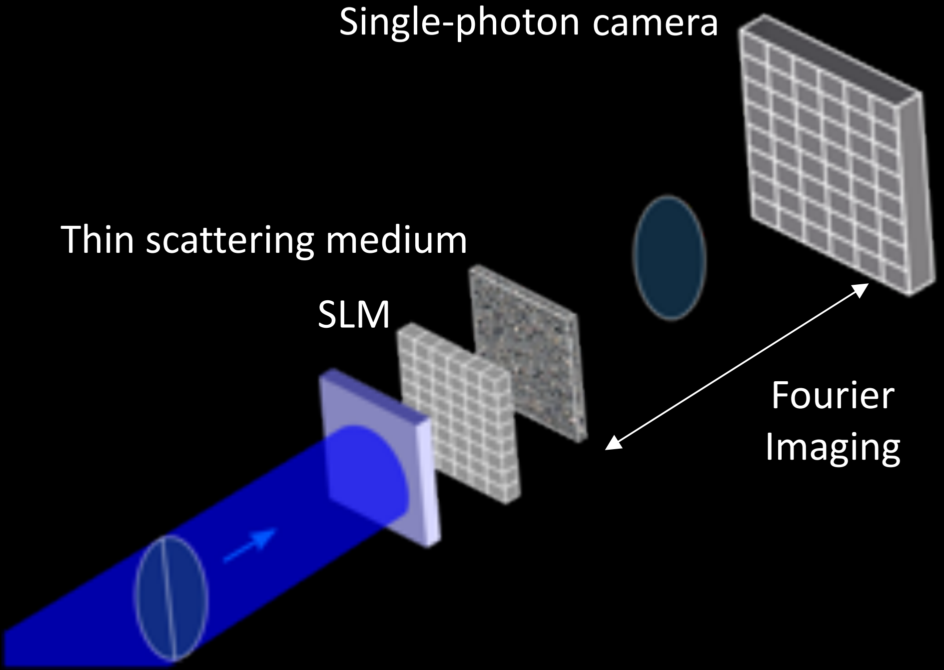
Flat phase

Optimal phase 32×32

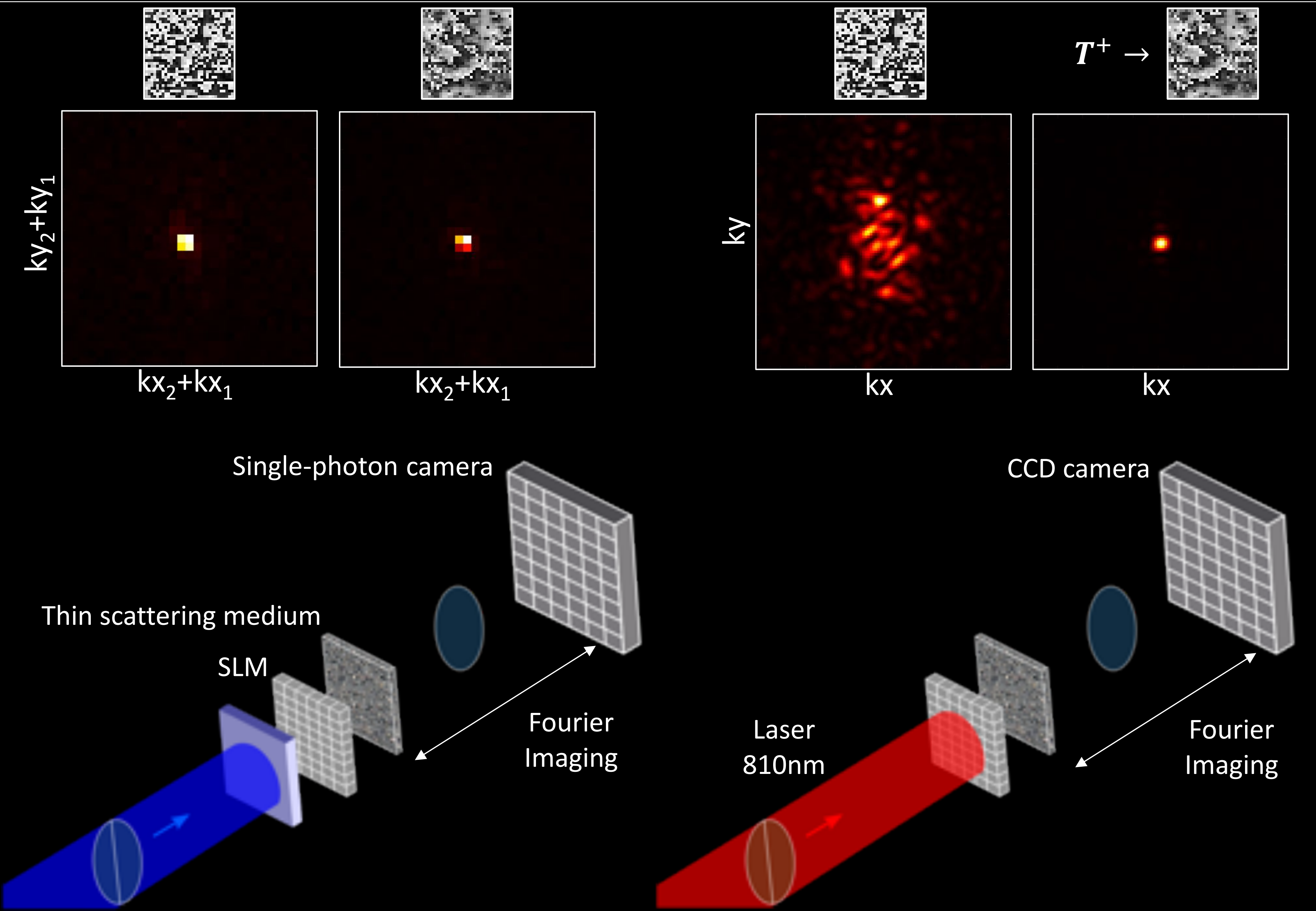
$$\Delta x\, \Delta k = 0{,}1519(2) < 1$$

Experimental results

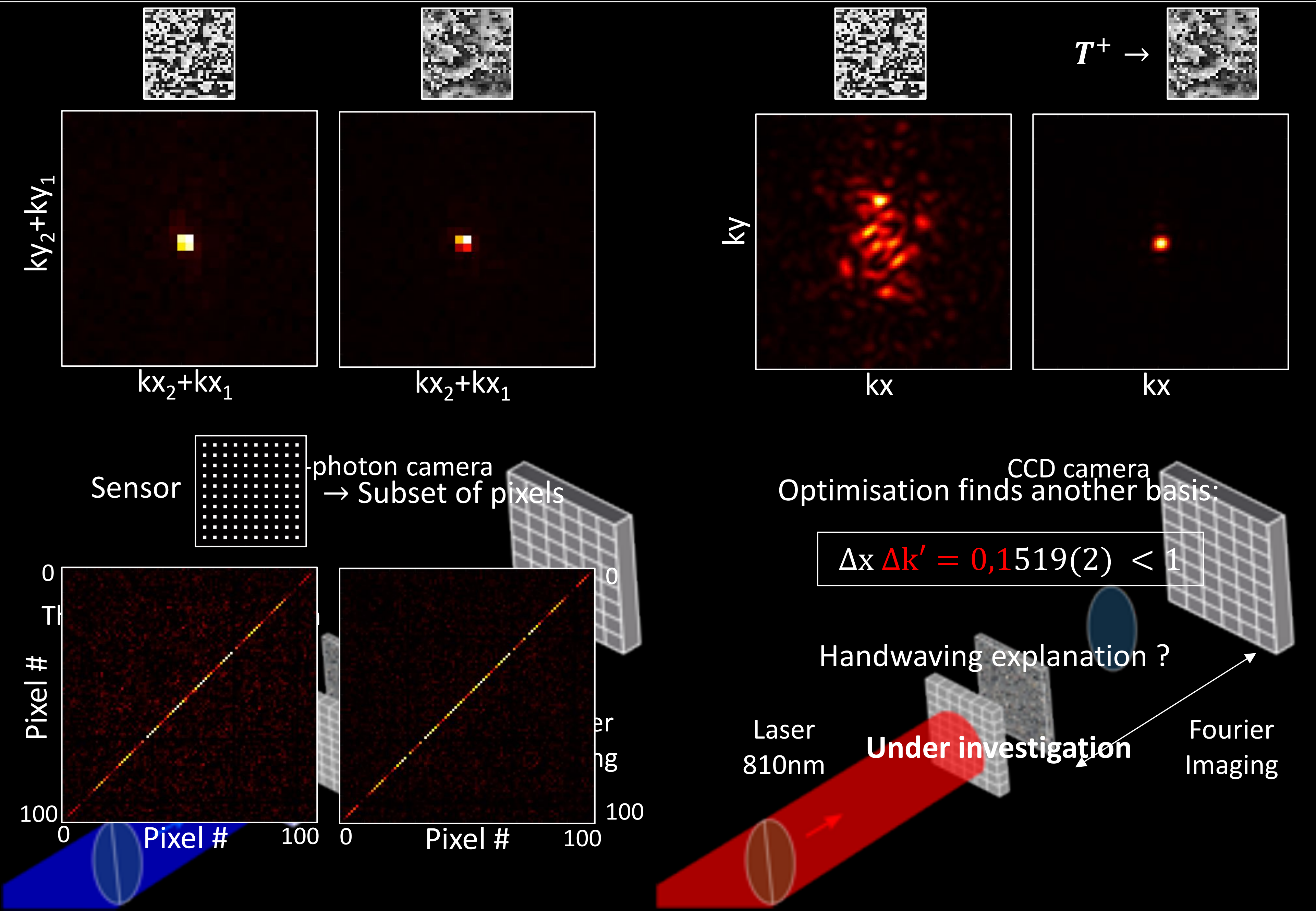




Experimental results

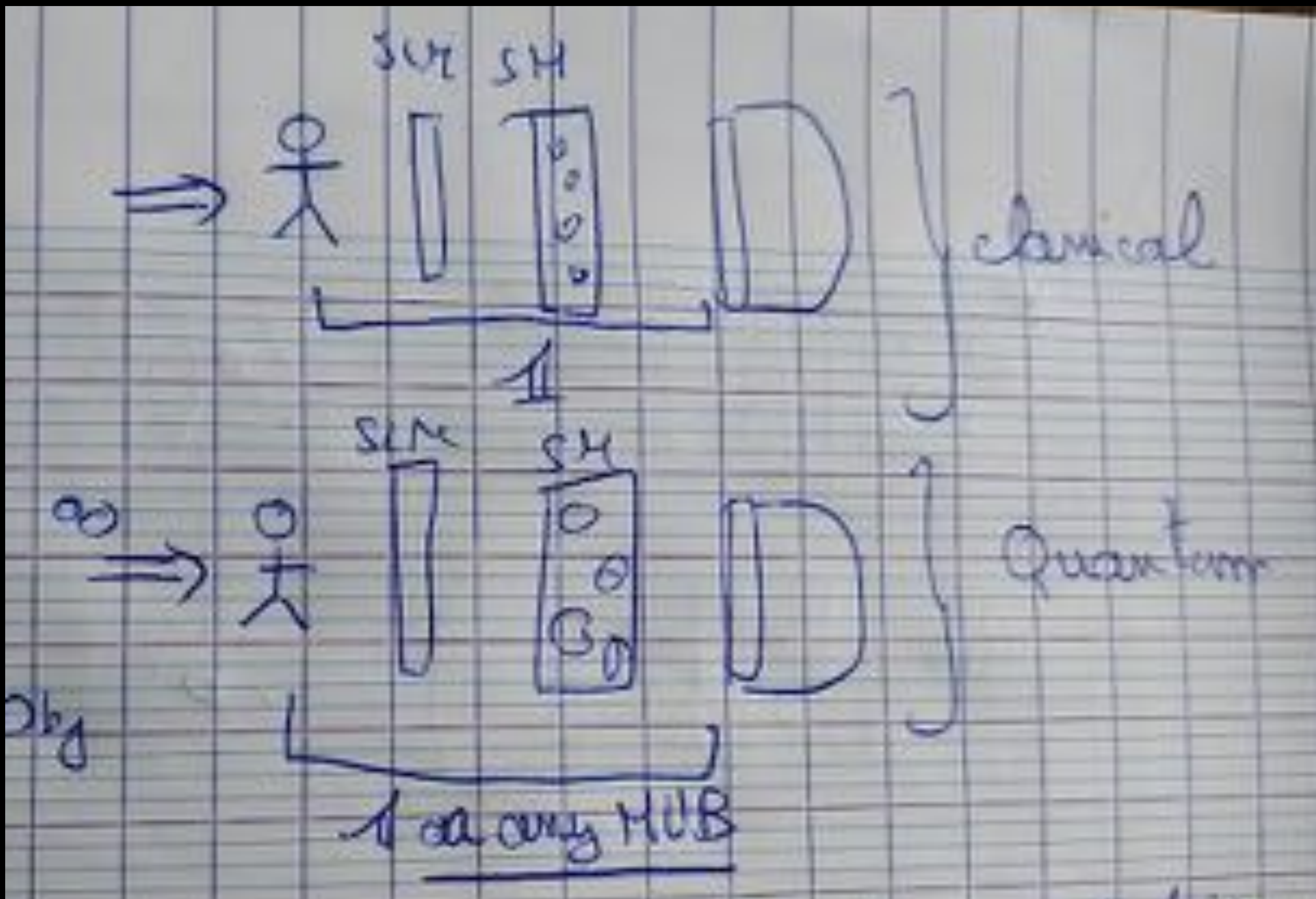


Experimental results



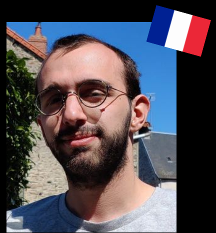
Towards imaging ?

Entanglement is a form of correlations <u>robust</u> to change of basis



Thank you

PhD students



Baptiste Courme
→ **Poster !**

Patrick Cameron

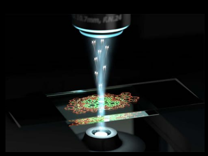
Chloé Vernière

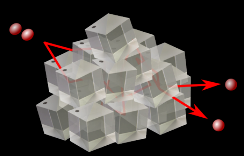
Collaborators

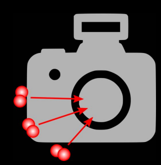
Prof. D. Faccio
Prof. S. Gigan

New team: Quantum Imaging Paris

Quantum imaging | Quantum optics in scattering media | Quantum entanglement



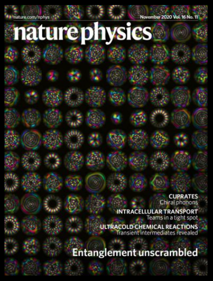




www. quantumimagingparis.com - hugo.defienne@insp.upmc.fr

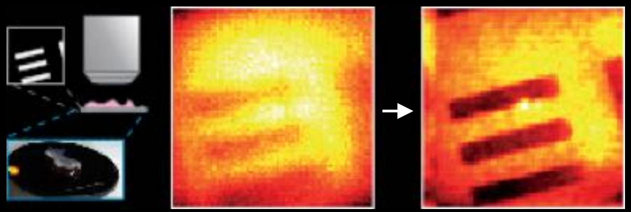
Mentioned papers of quantum optics + wavefront shaping:

- Courme, Cameron, Faccio, Gigan and Defienne. PRX Quantum (in press: ArXiv 2207.02333) (2022)
- Devaux Mosset, Popoff & Lantz. arXiv preprint arXiv:2206.00299 (2022).
- Ndagano, Defienne, Lyons, Strashynov, Villa, Tisa, Faccio. npj Quant. Info. 6, 94. (2020)
- Valencia, Goel, McCutcheon, Defienne, Malik. Nature Physics 16 (11), 1112-1116 (2020)
- Lib, Hasson, Bromberg. Science Advances 6(37), eabb6298 (2020)
- Wolterink, Uppu, Ctistis, Vos, Boller & Pinkse. PRA 93, 053817 (2016).
- Defienne, Barbieri, Walmsley, Smith & Gigan. Science Advances, 2(1), e1501054 (2016)
- Spengler, Huber, Brierley, Adaktylos & Hiesmayr. PRA, 86(2), 022311 (2012)



Motivations

Microscopy

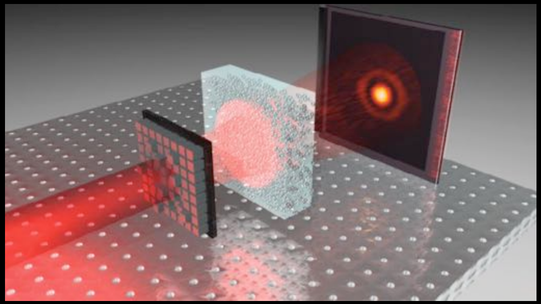


Badon et al. Sci. adv. 6(30), eaay7170.

Optical computing

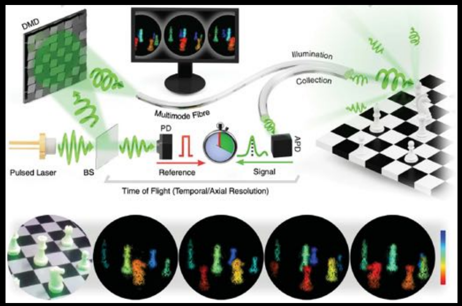
Optical communications

Wavefront shaping



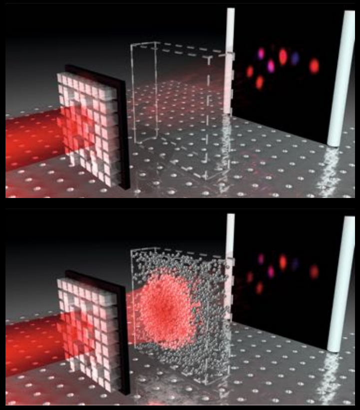
Cao, Most & Rotter. Nat.Phys. 18, 994–1007 (2022)

LiDAR



Stalinga et al. Science 374,1395-1399. (2021)

Fondamental questions



Pai et al. Nat. Phot. 15(6), 431-434. (2021)

Quantum optical technologies ?