Resolution limits of quantum ghost imaging and quantum Fourier ptychography

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Ghost imaging with (quantum) correlated light

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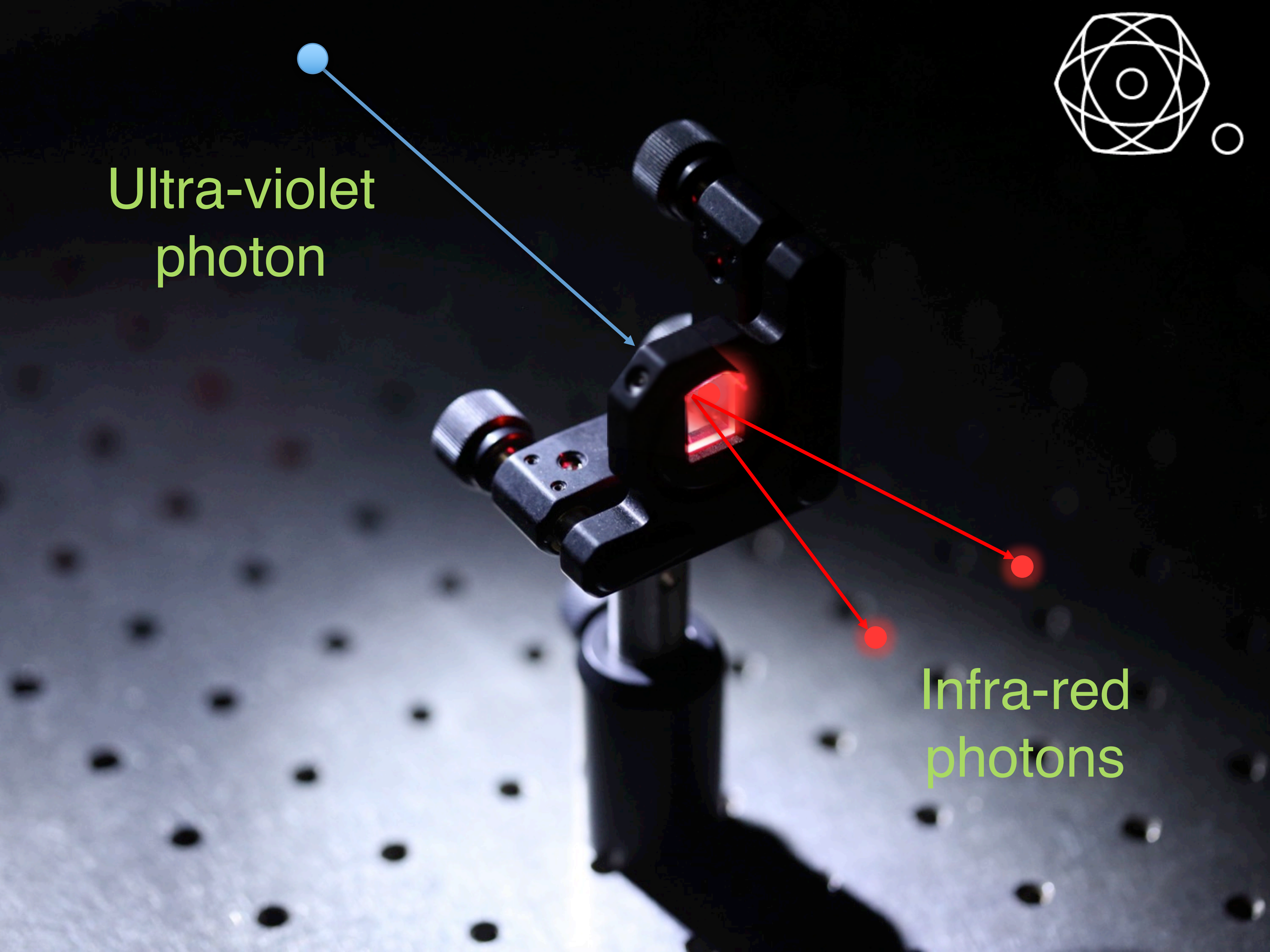
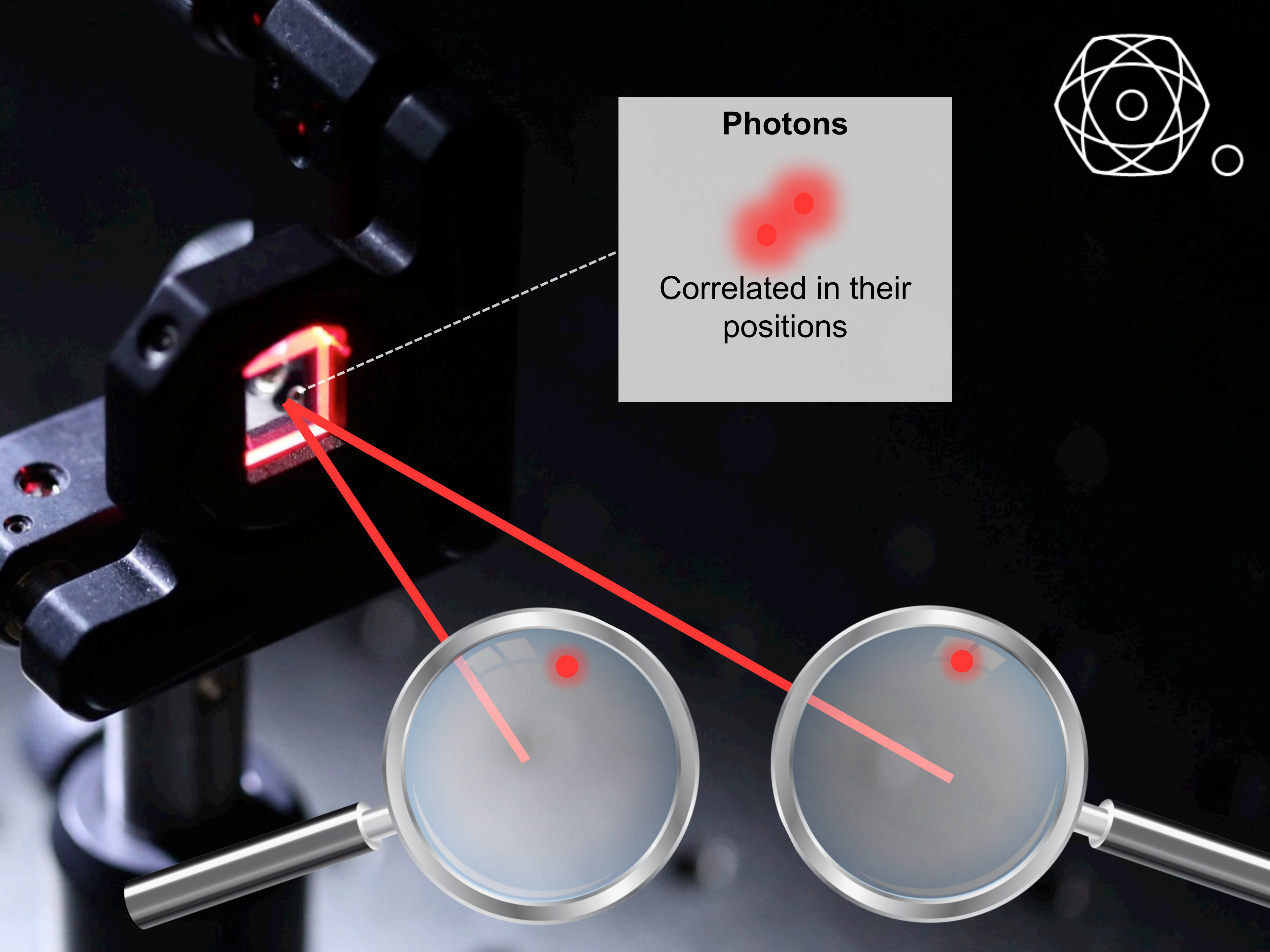
Reuben Aspden

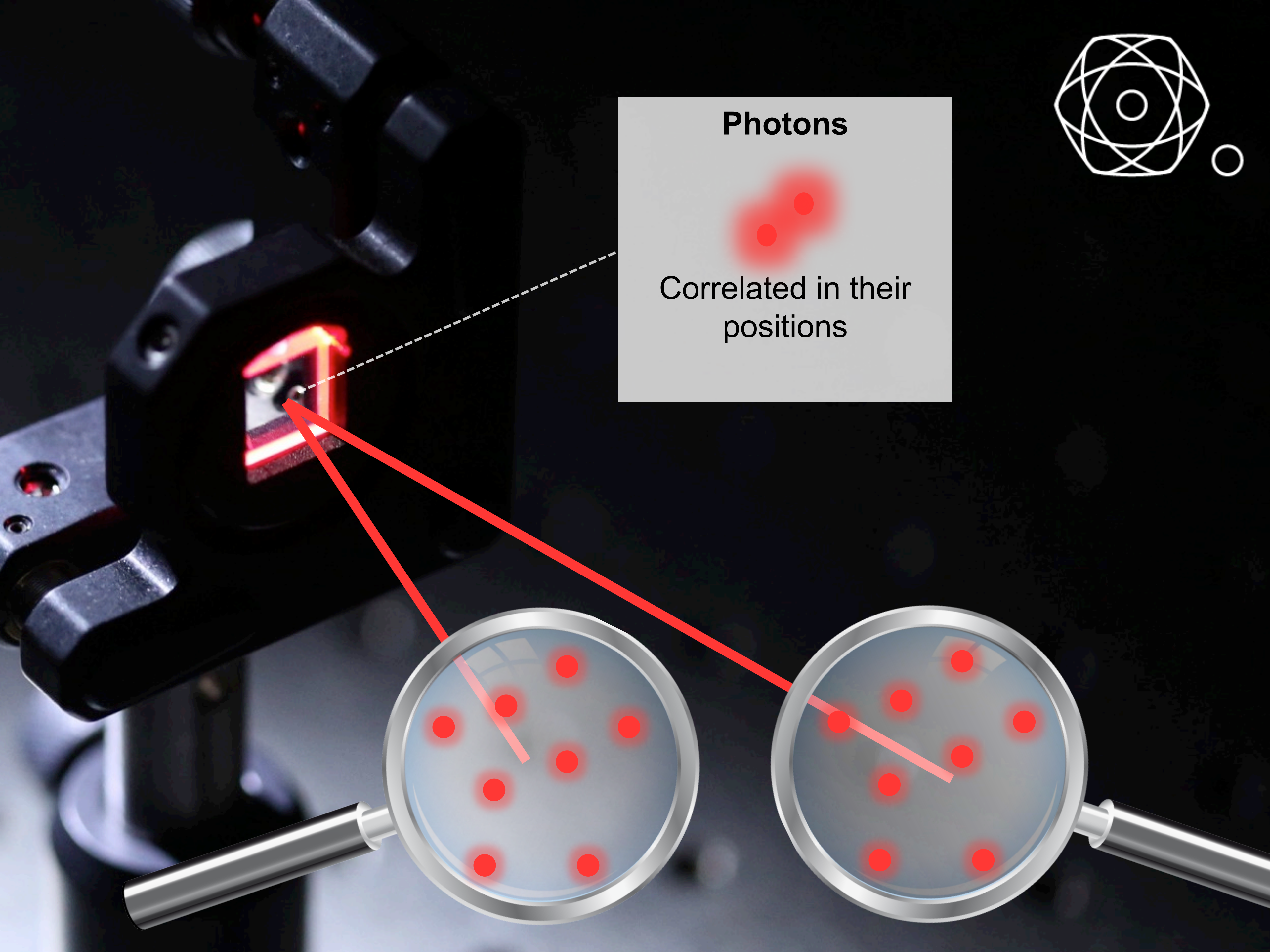
Peter Morris

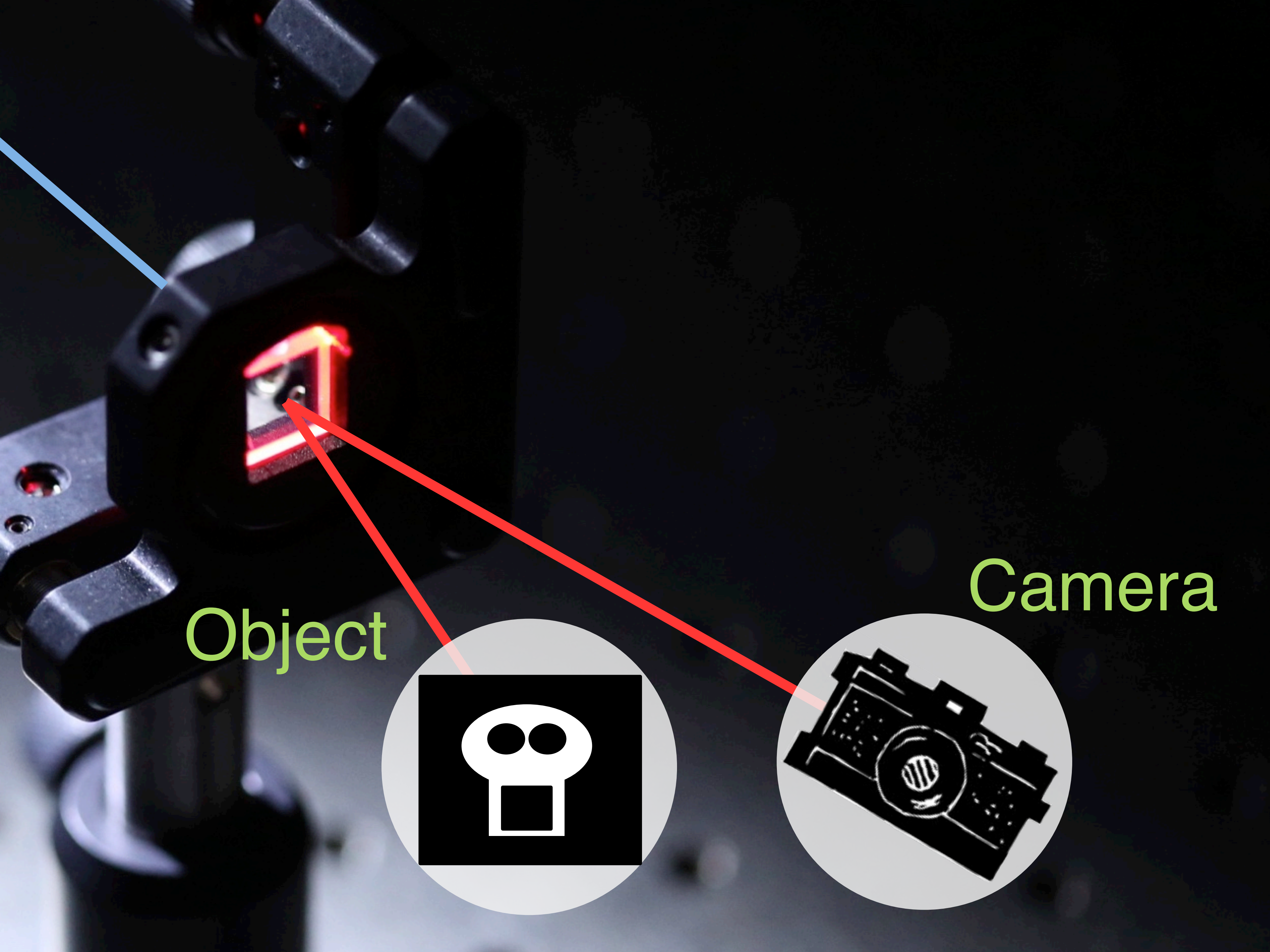
Ermes Toninelli

I- Ghost imaging with quantum correlated light: an efficient system

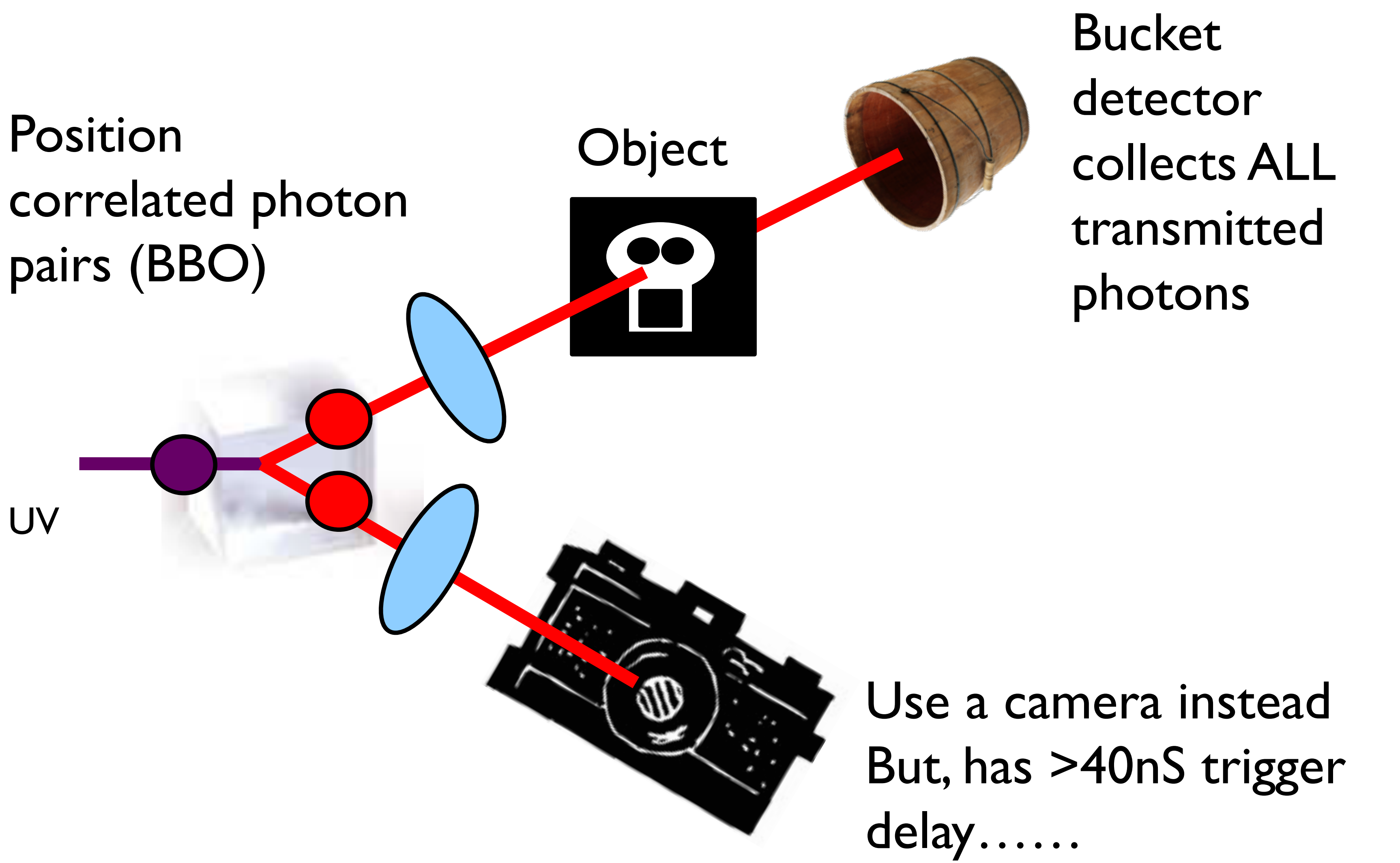

Ultra-violet
photon
Infra-red
photons


Photons
Correlated in their positions

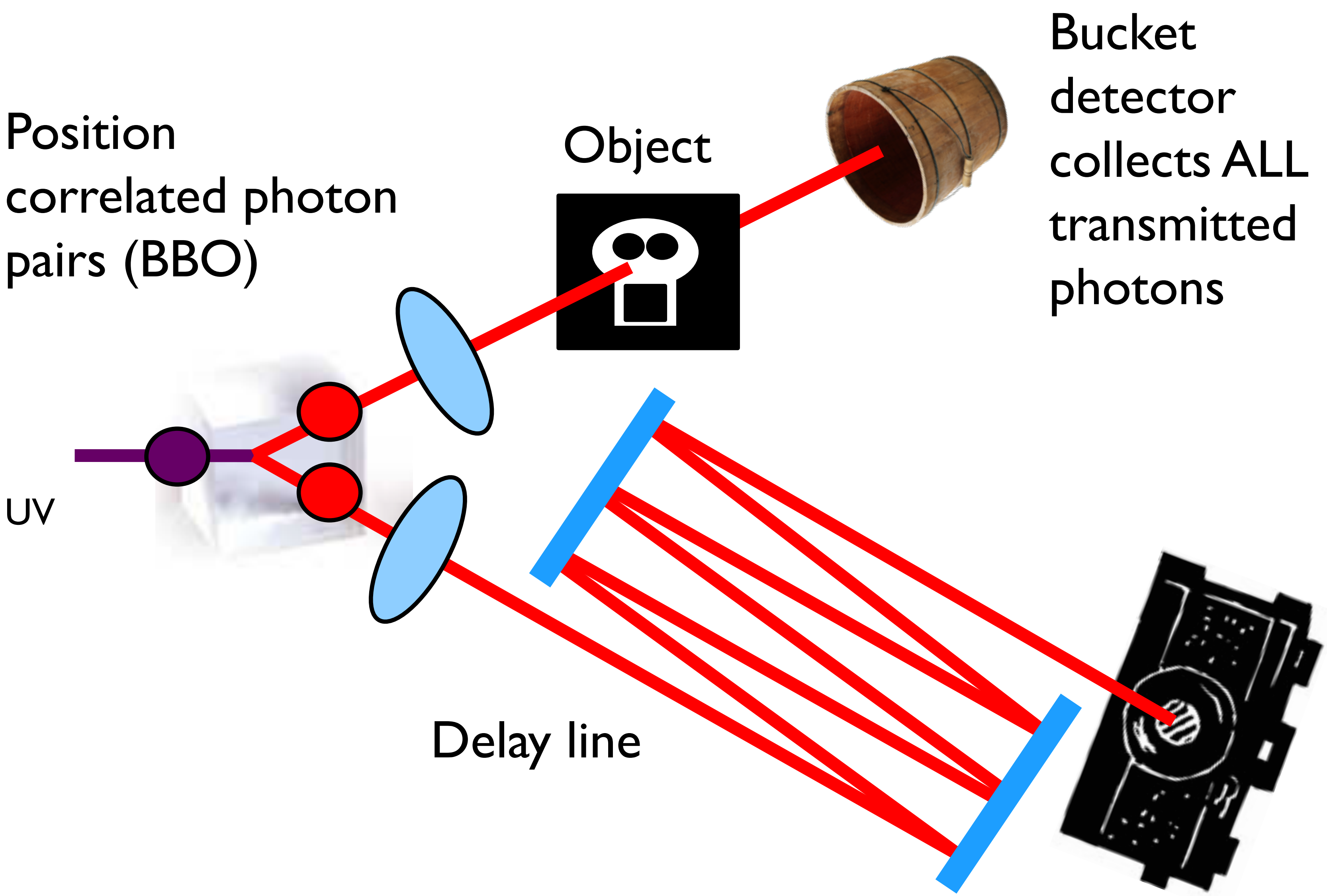

Photons
Correlated in their positions

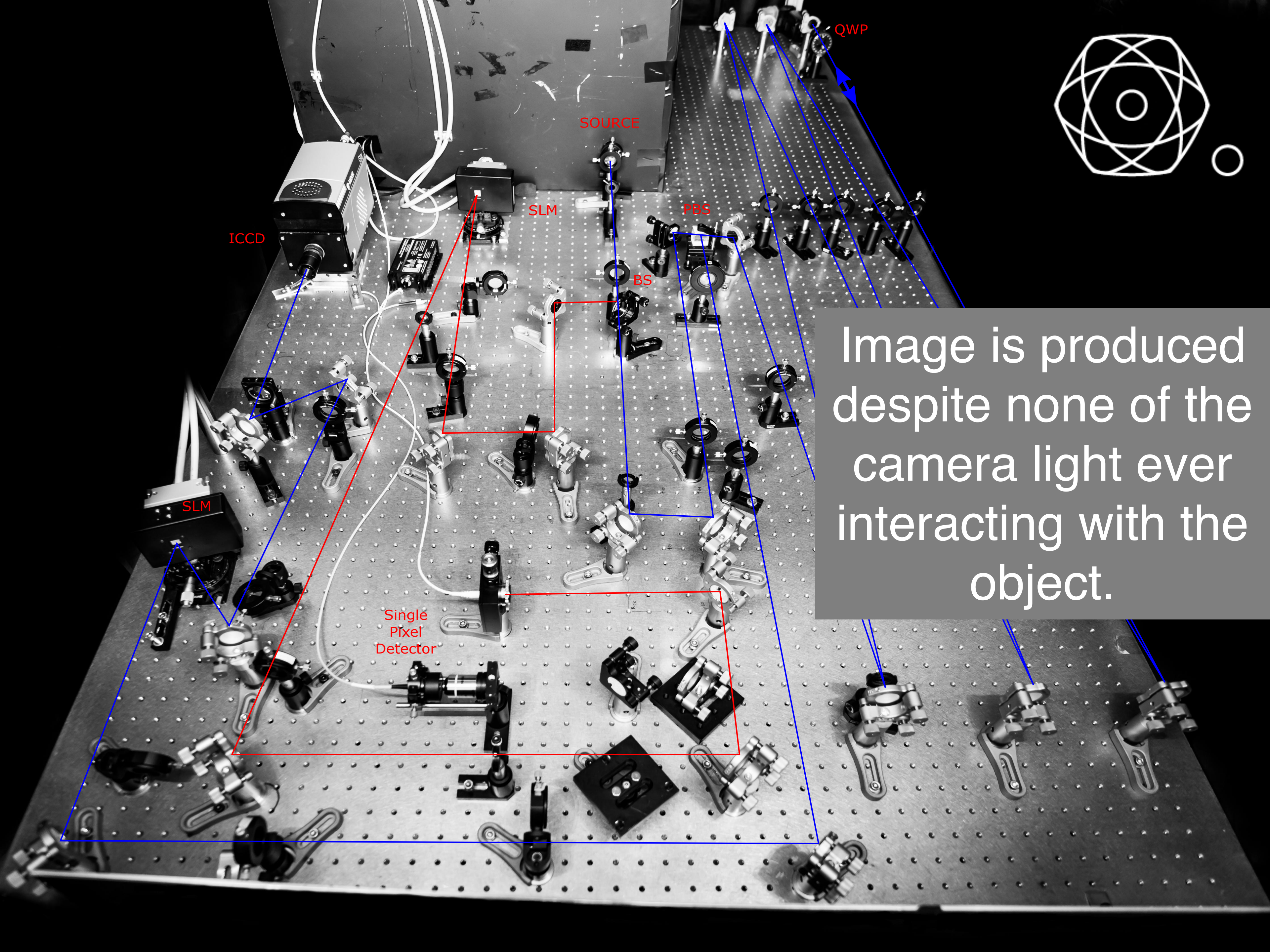

Object
Camera

Ghost imaging with (quantum) correlated light

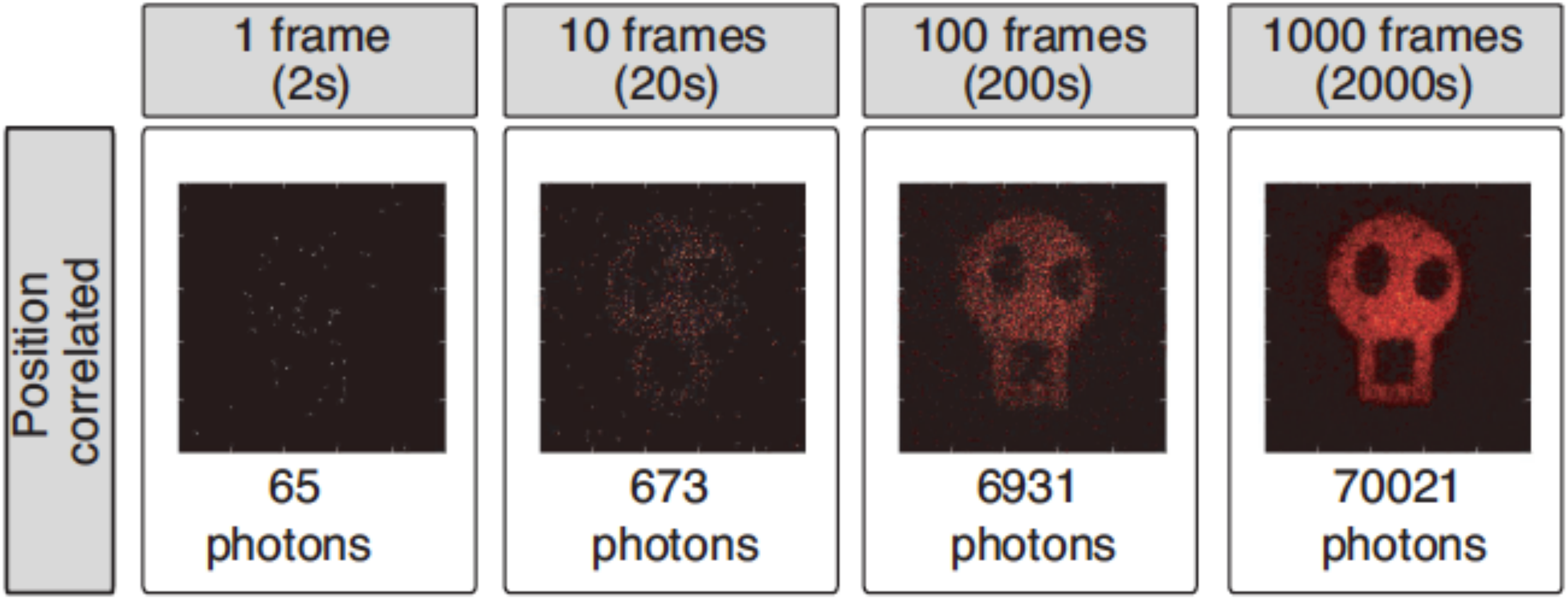


Compensating for the delay



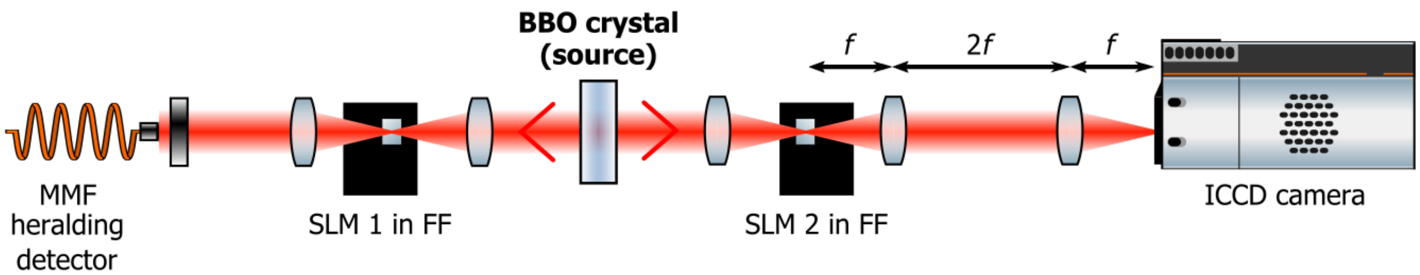

QWP
SOURCE
SLM
PBS
ICCD
BS
SLM
Single
Pixel
Detector
Image is produced despite none of the camera light ever interacting with the object.

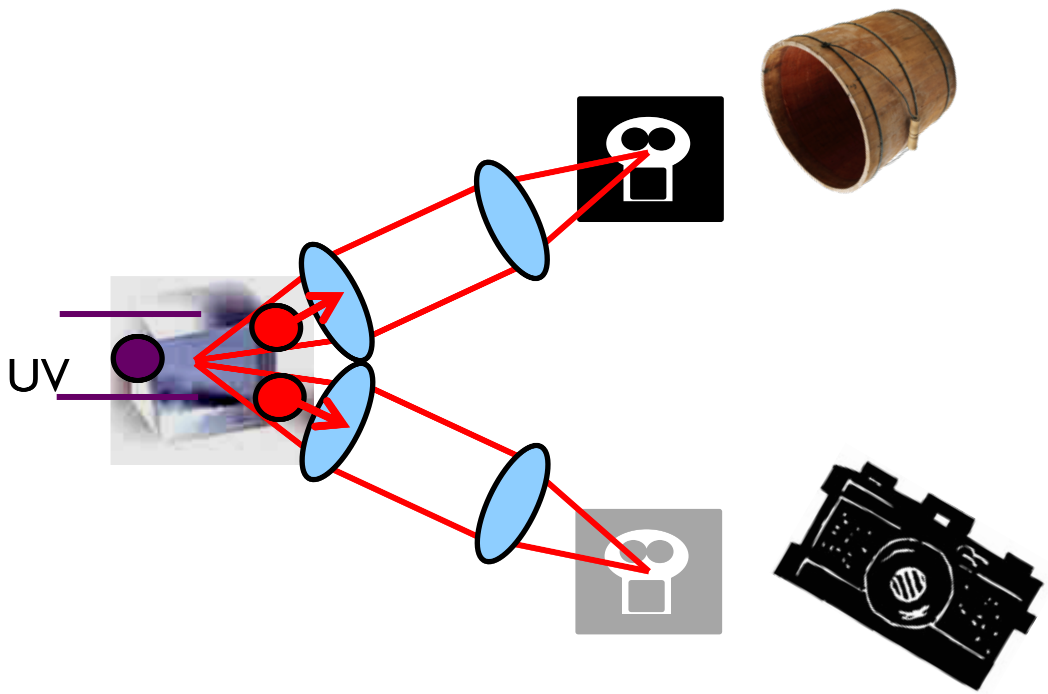
Ghost imaging with (many) single photons



Improved efficiency since then : can obtain simple objects ghost image in a few seconds

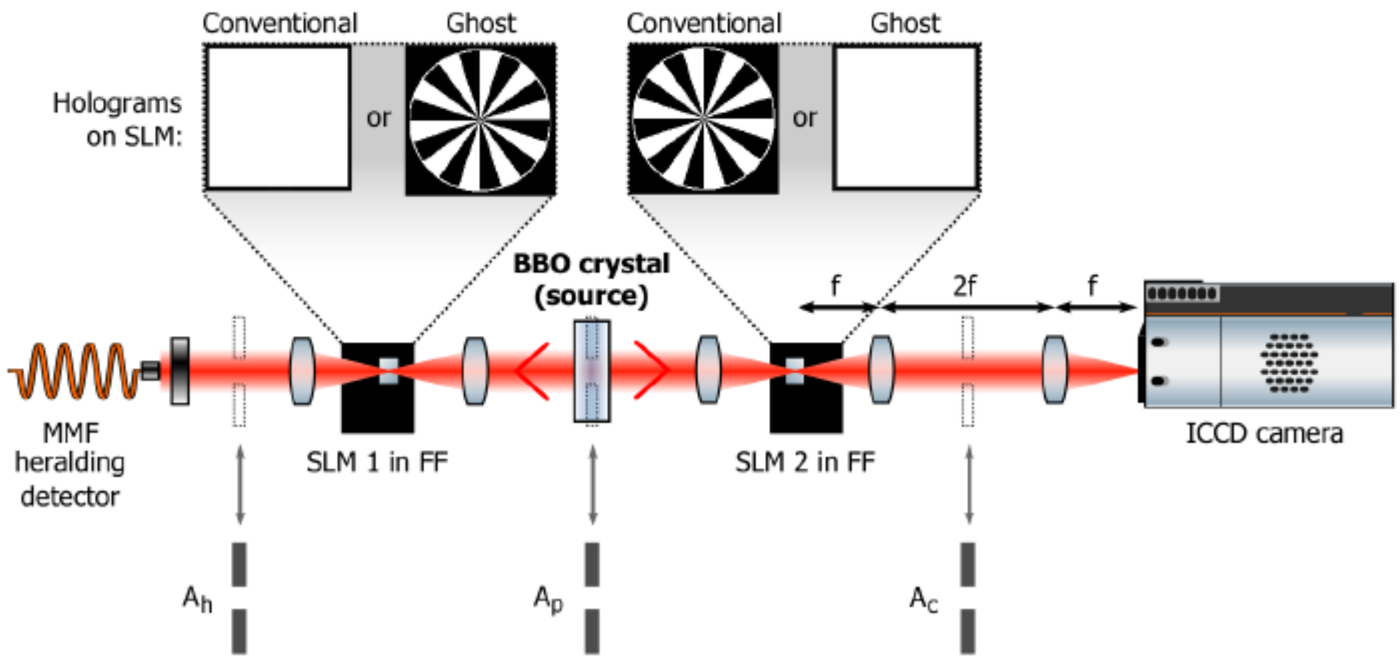
Simplified Experimental setup: Omitting the delay line



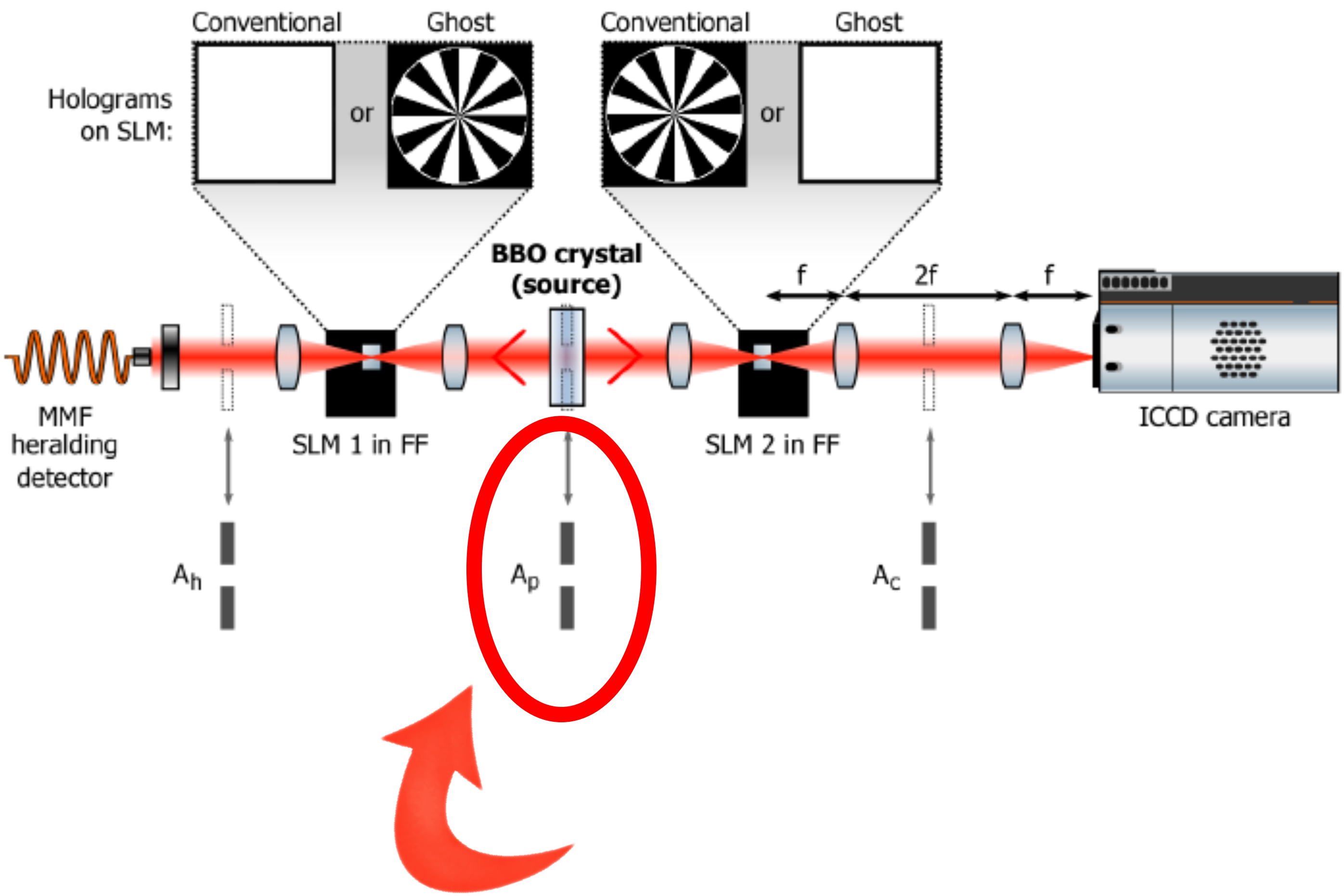


What sets the resolution ?

Studying the resolution. Ghost imaging vs Conventional imaging.



Ghost imaging ≠ to heralded imaging



University of Glasgow

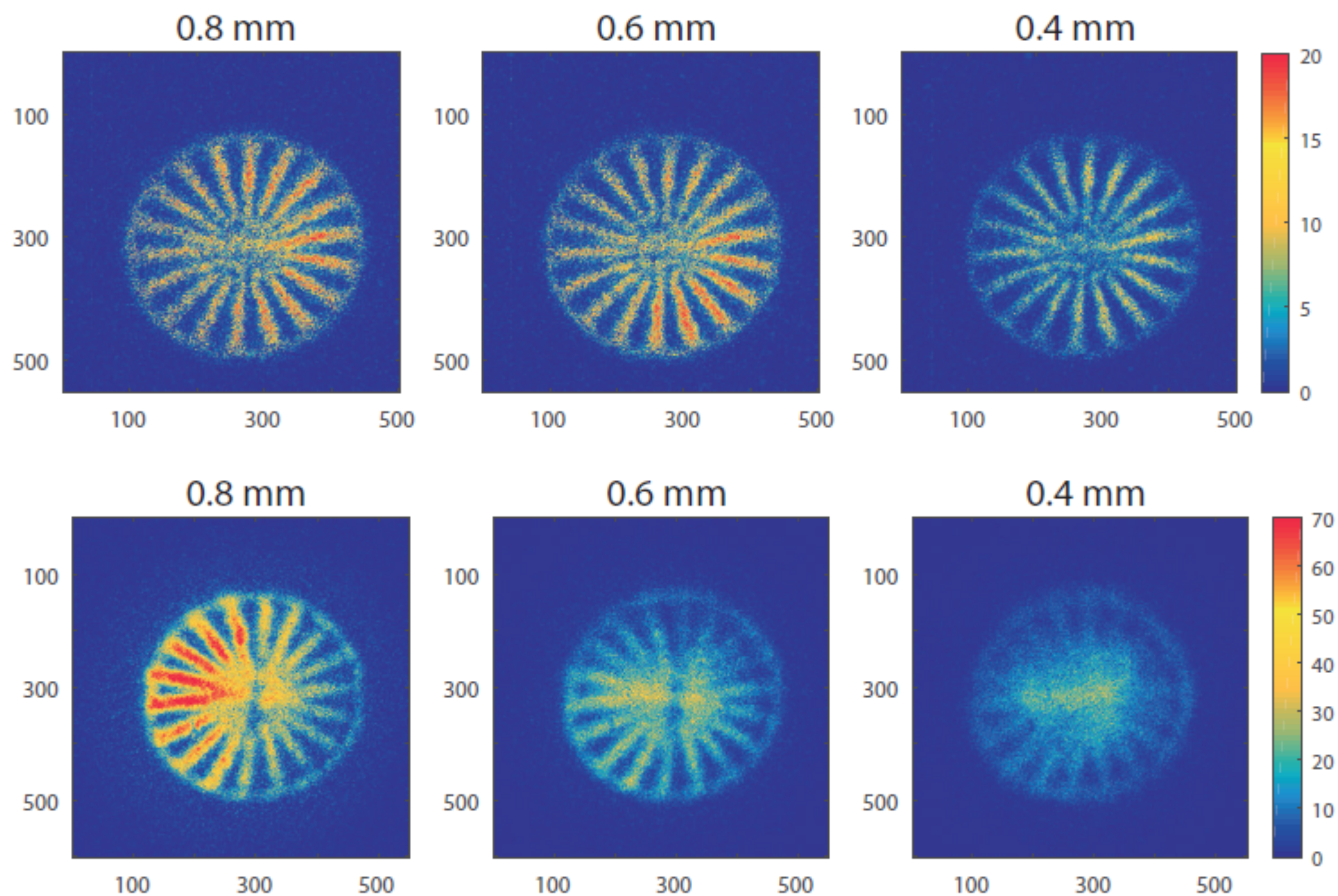
Ghost imaging ≠ to heralded imaging

Large pump beam

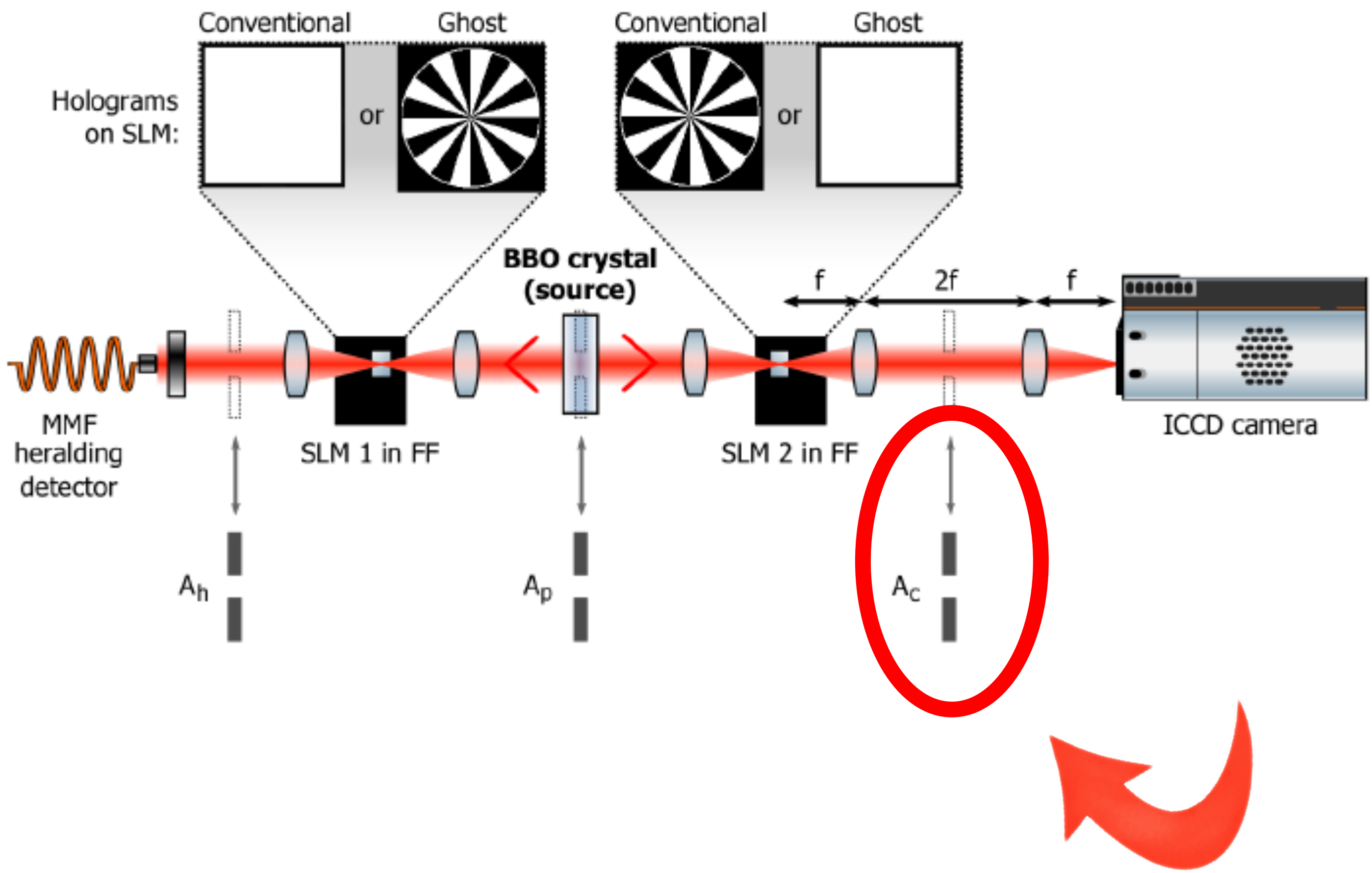
Small pump beam

Heralded imaging

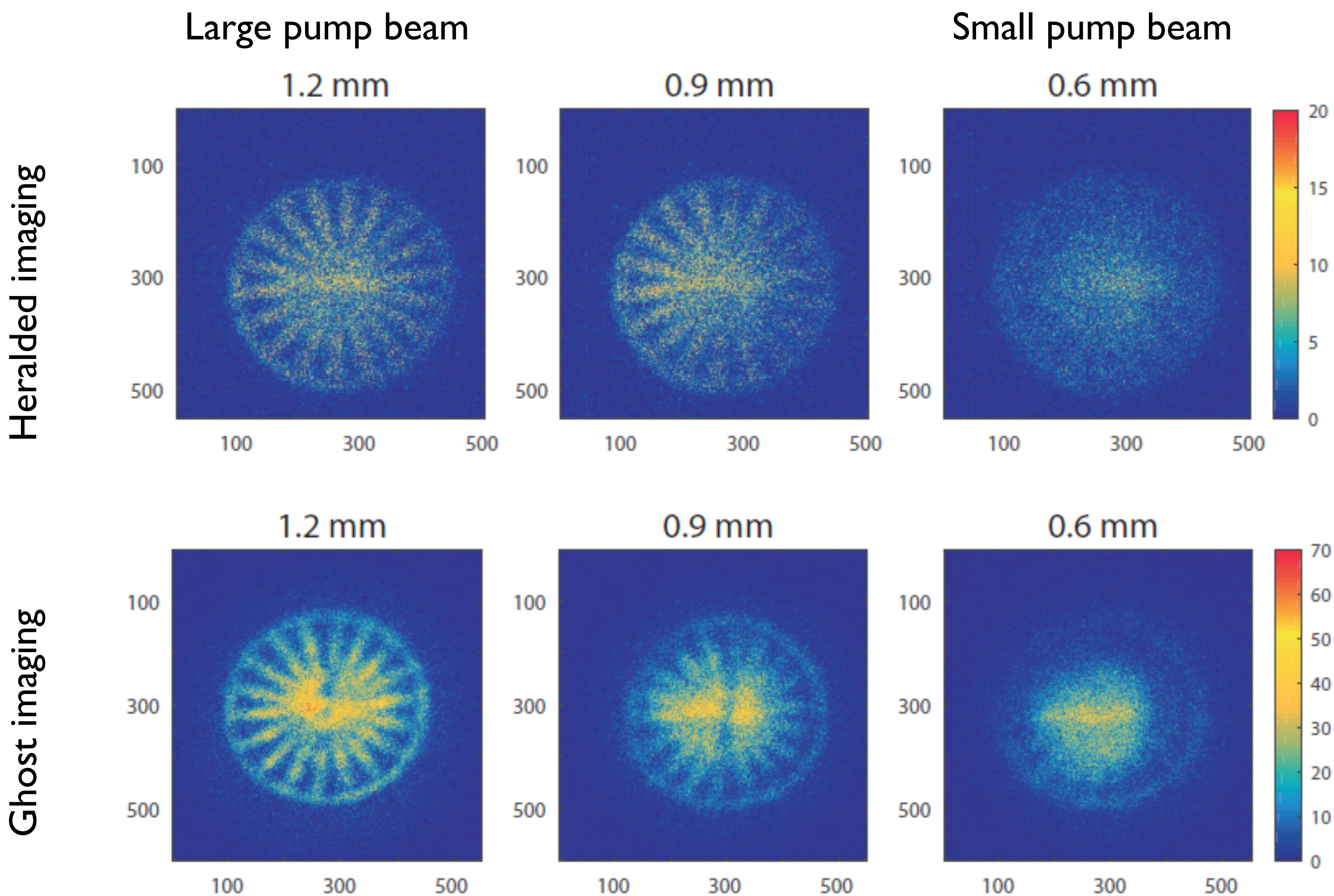
Ghost imaging



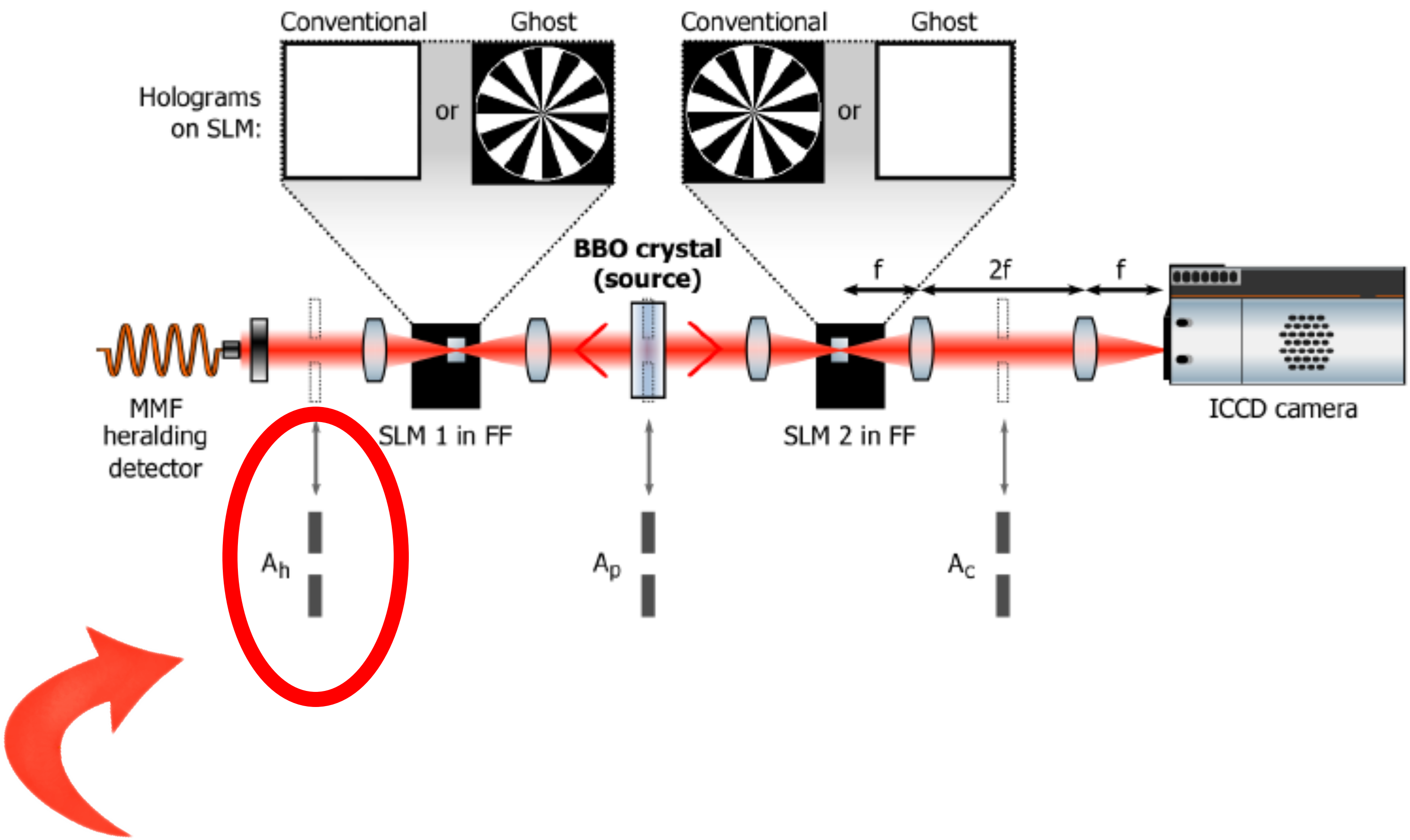
Ghost imaging ≠ to heralded imaging



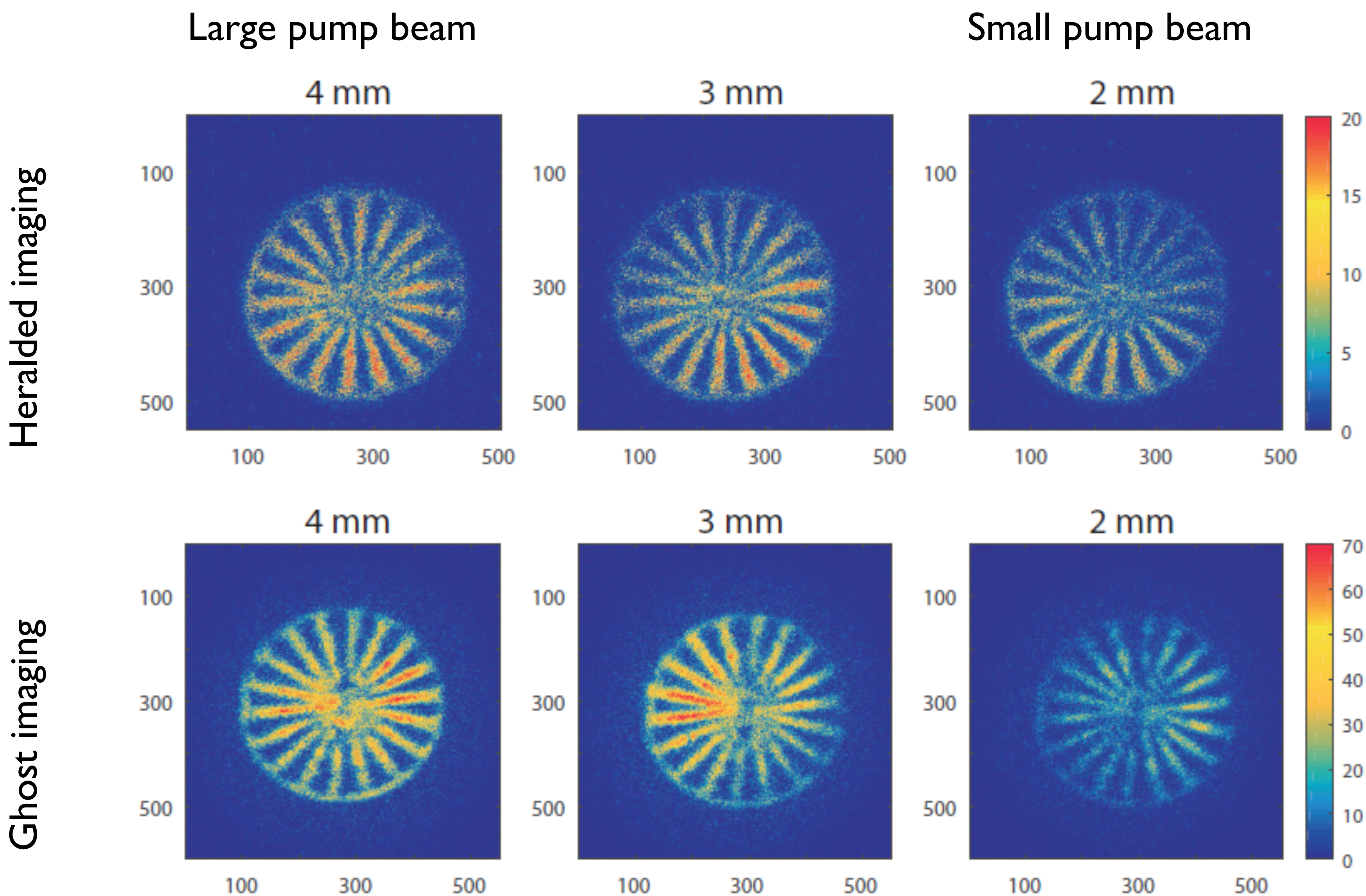
Ghost imaging ≠ to heralded imaging



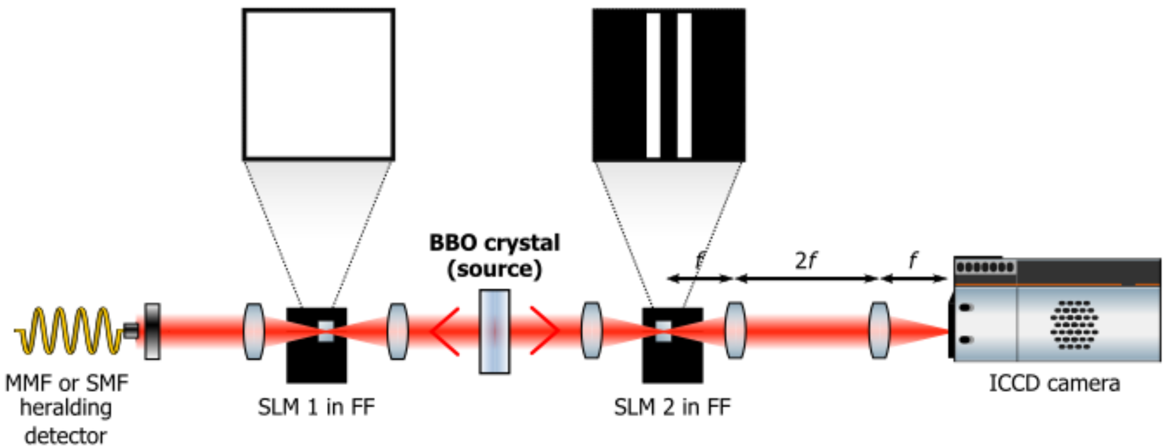
Ghost imaging ≠ to heralded imaging



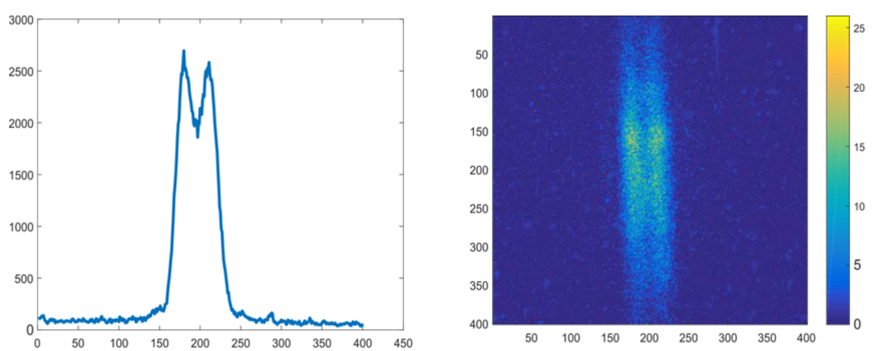
Ghost imaging ≠ to heralded imaging



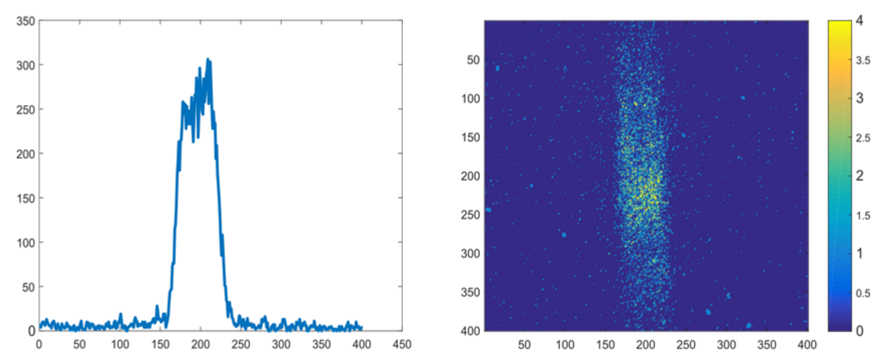
Degraded resolution when aperturing the Heralding arm ?



Heralded imaging with a multi-mode fiber (MMF) :

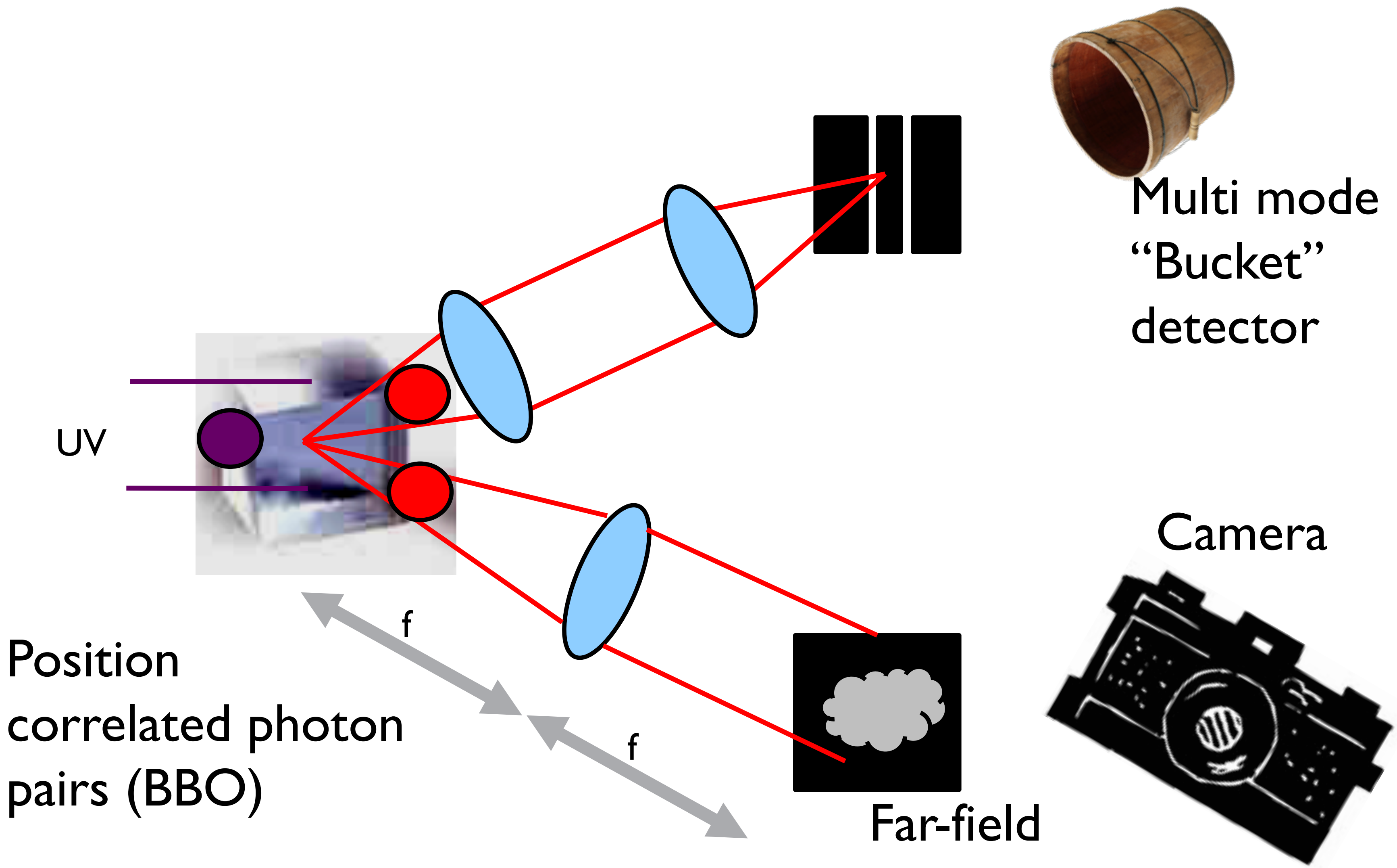


Heralded imaging with a single mode fiber (SMF):

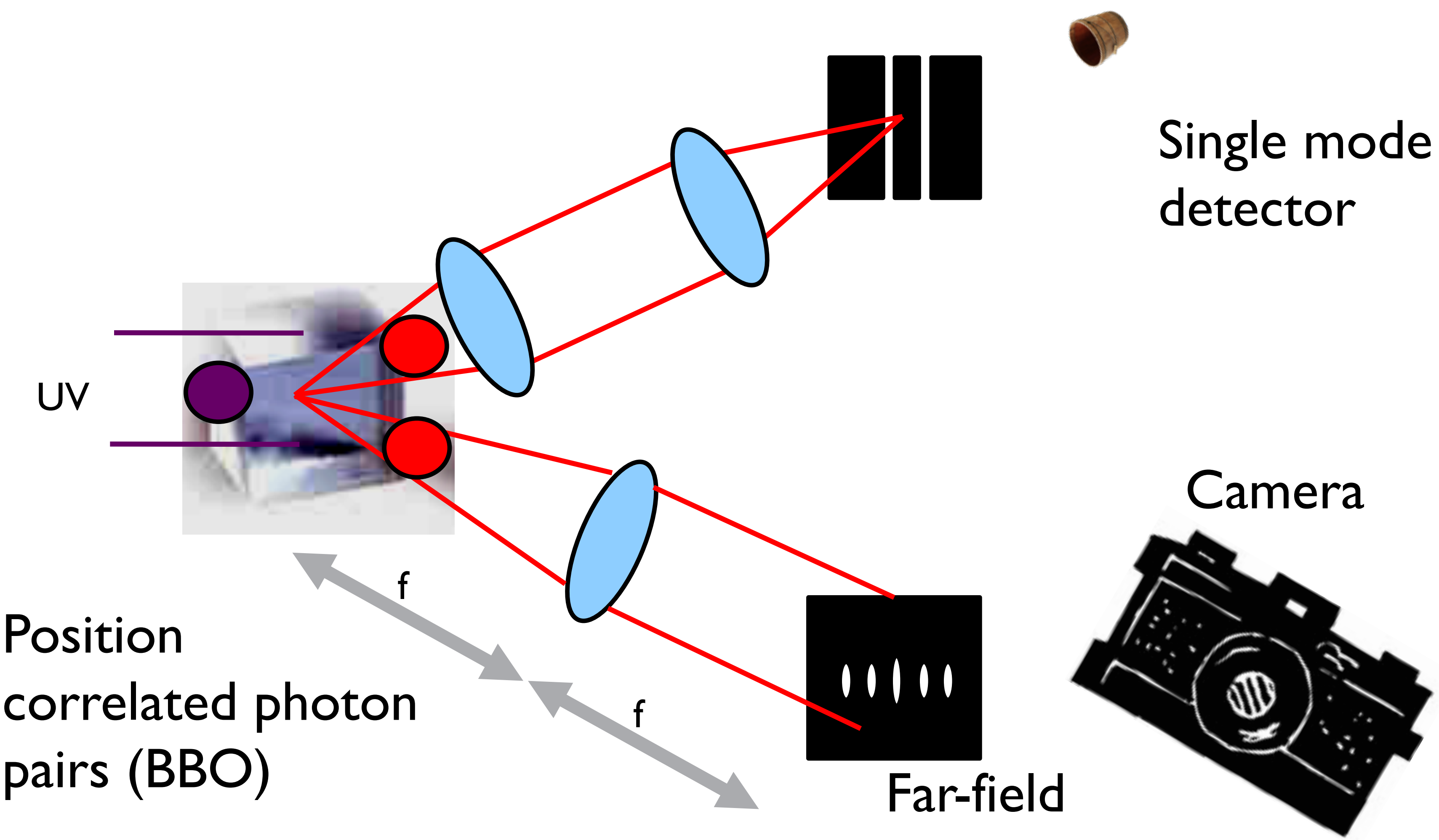


How about diffraction?

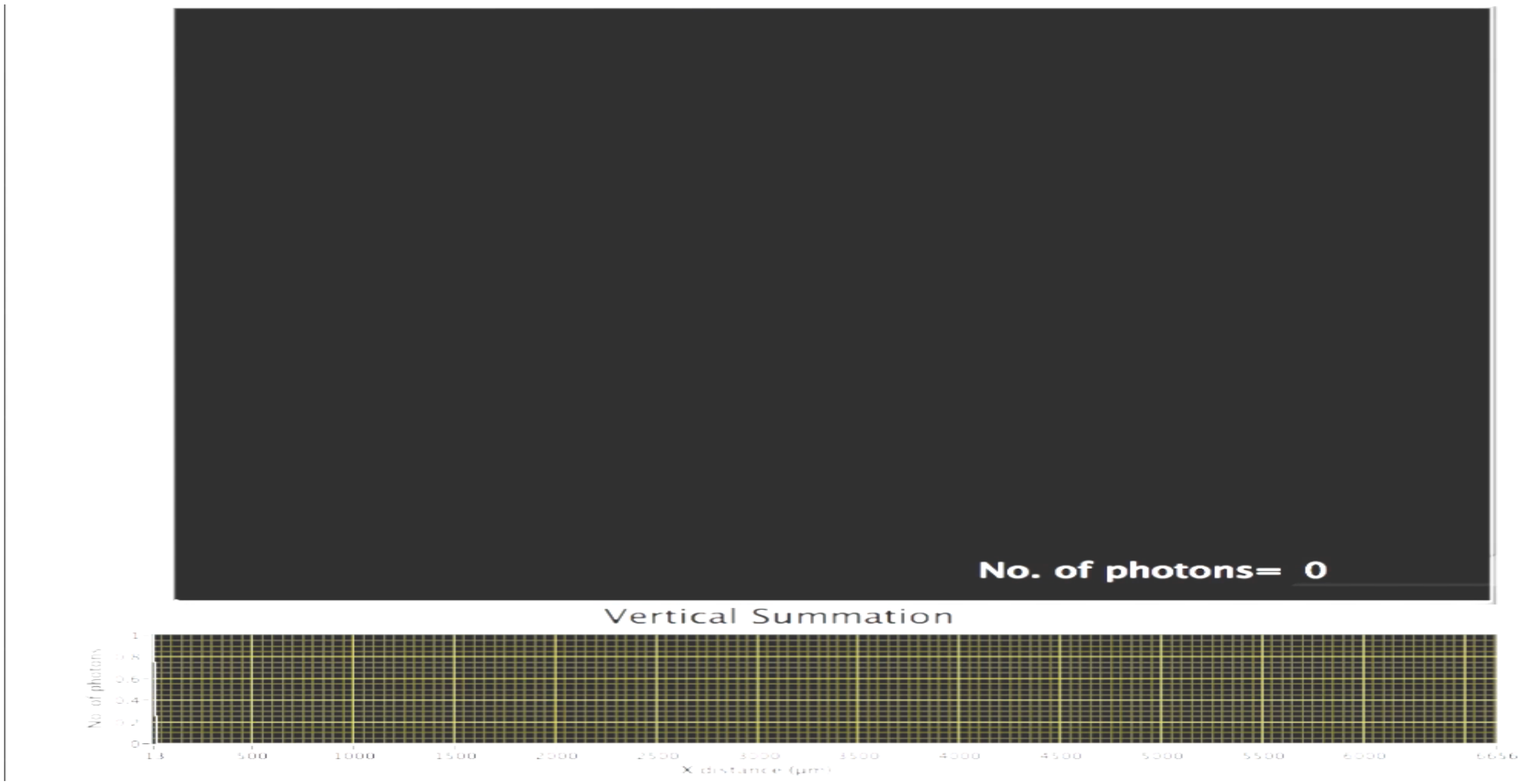
Ghost diffraction with position correlated light



The size of the “bucket” detector matters!



Single-photon diffraction

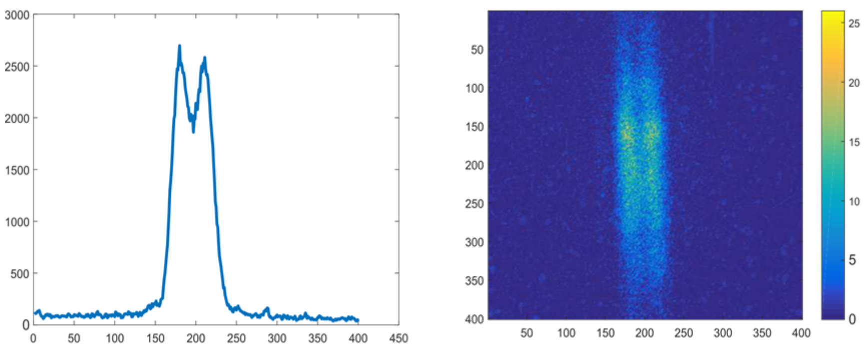


Pattern obtained in around 10 minutes of acquisitions.

Not as efficient as the Ghost image acquisition, because of the mono-mode spatial filtering of the detector to ensure coherence.

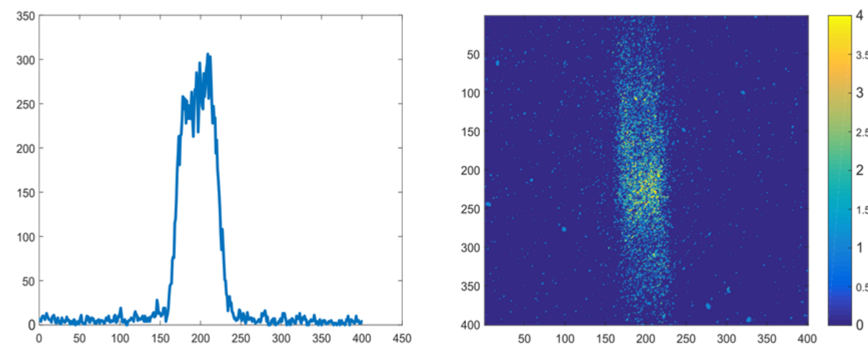
Degraded resolution when aperturing the Heralding arm ?

Heralded imaging with a multi-mode fiber (MMF) :



Incoherent Imaging

Heralded imaging with a single mode fiber (SMF):



Coherent Imaging

One can actually exploit the propriety of the system of being exhibiting both:

- a spatially extended illumination, and
- some underlying coherence

II- Fourier Ptychography with quantum correlations

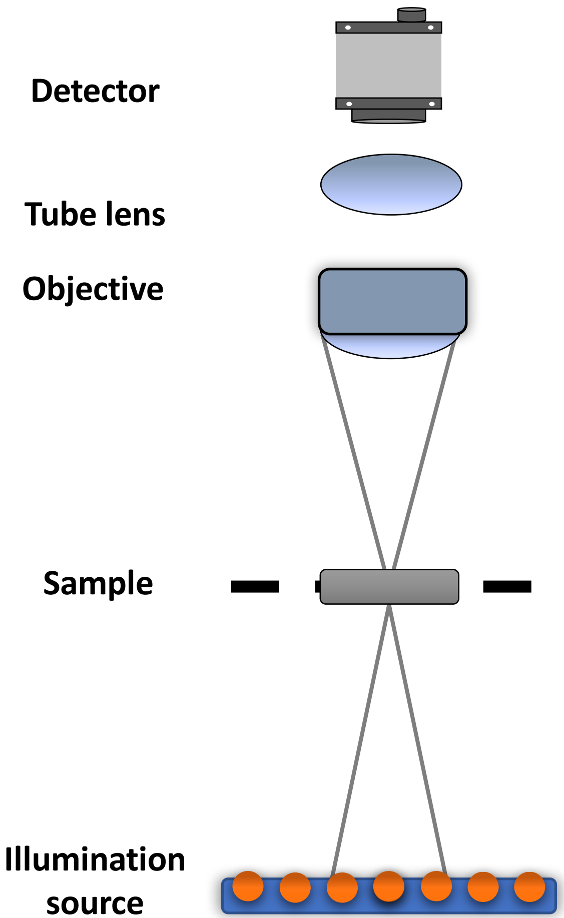
With the additional collaboration of :

Tomas Aidukas

Pavan Kondas

Prof. Andy Harvey

Fourier ptychography



Fourier ptychography

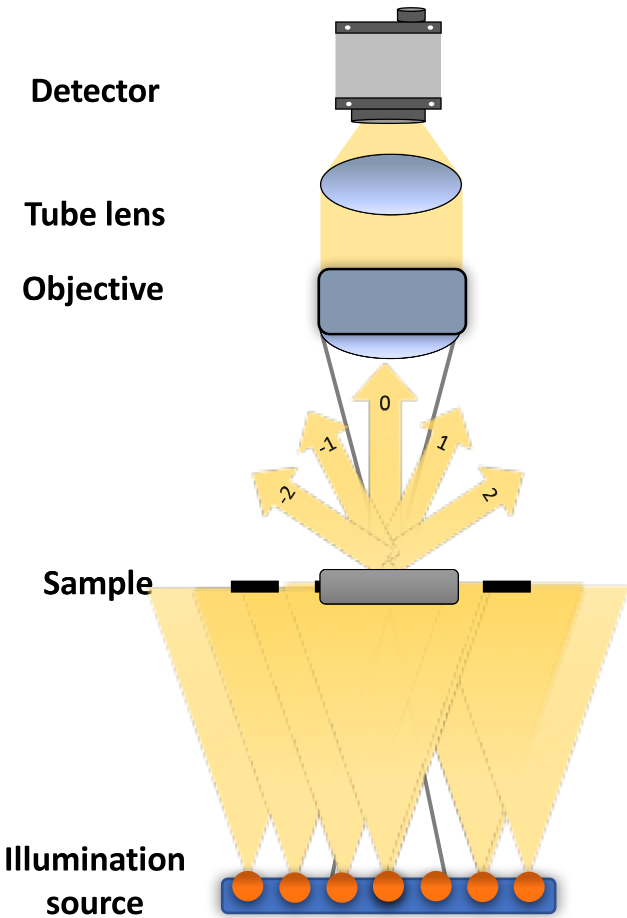
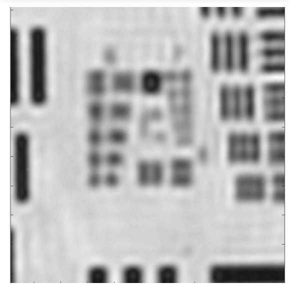
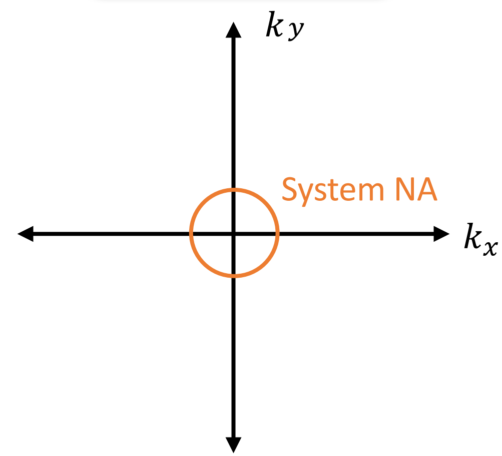


Image space

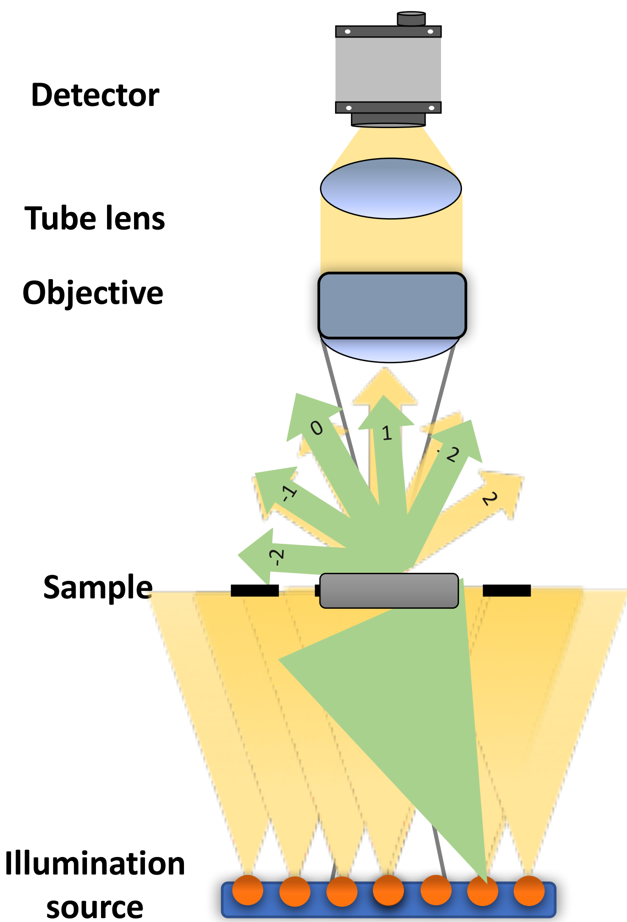


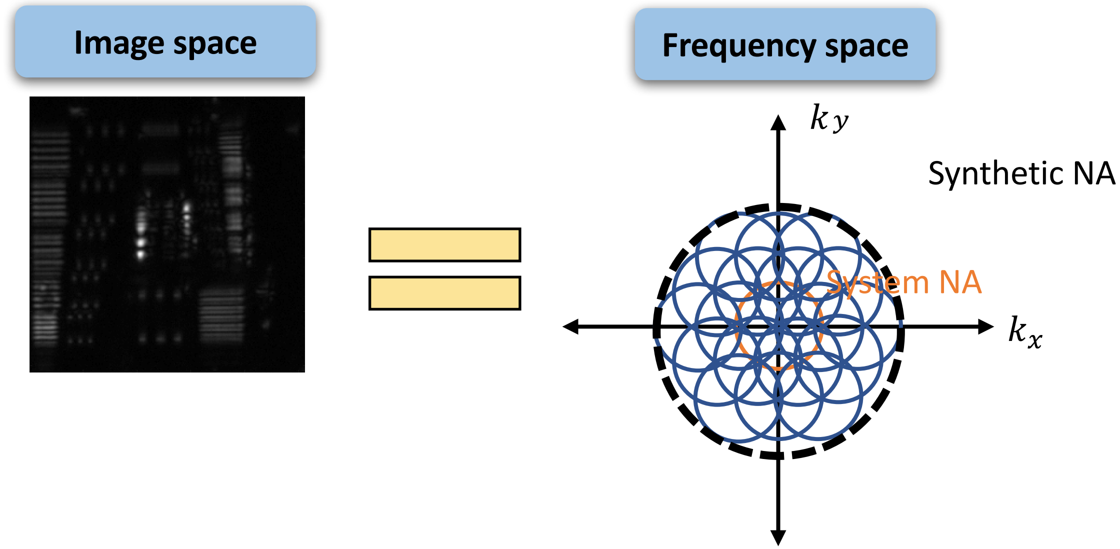
Frequency space



- More frequencies = higher resolution

Fourier ptychography





- More frequencies = higher resolution
- Off-axis illumination is equivalent to frequency space scanning
- Time-sequential image acquisition to get all frequencies

Fourier ptychography

Detector

Tube lens

Objective

Sample

Illumination source

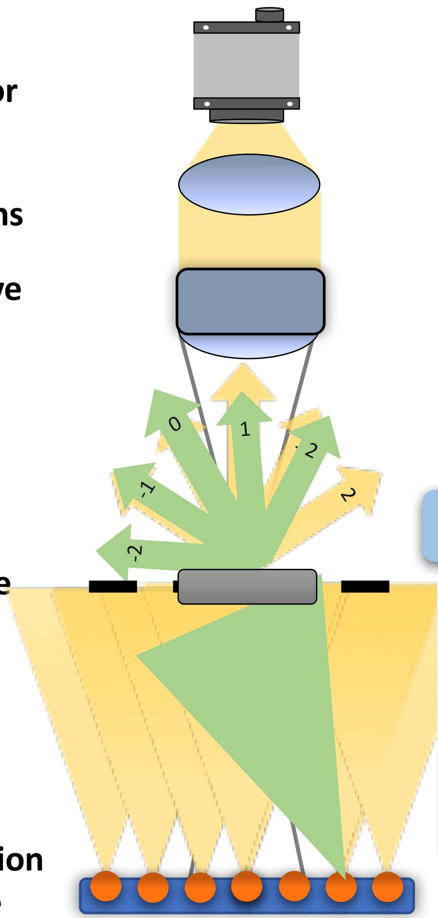
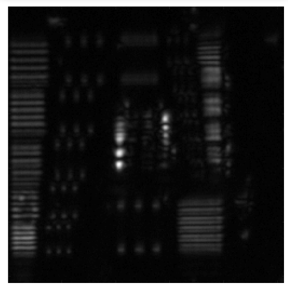
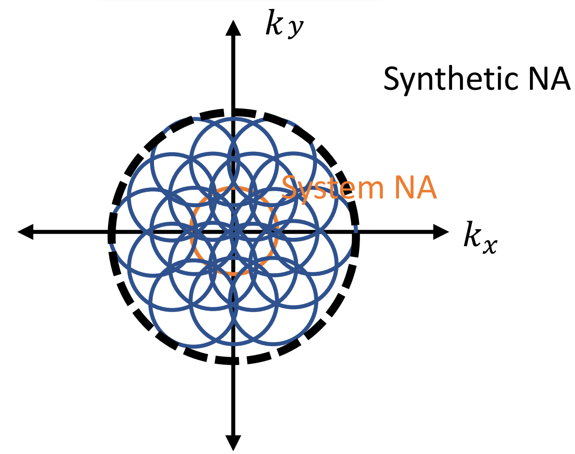


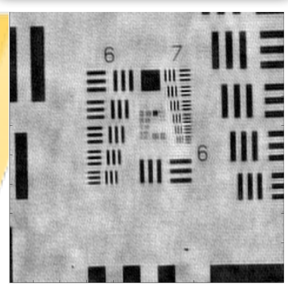
Image space



Frequency space



Reconstruction



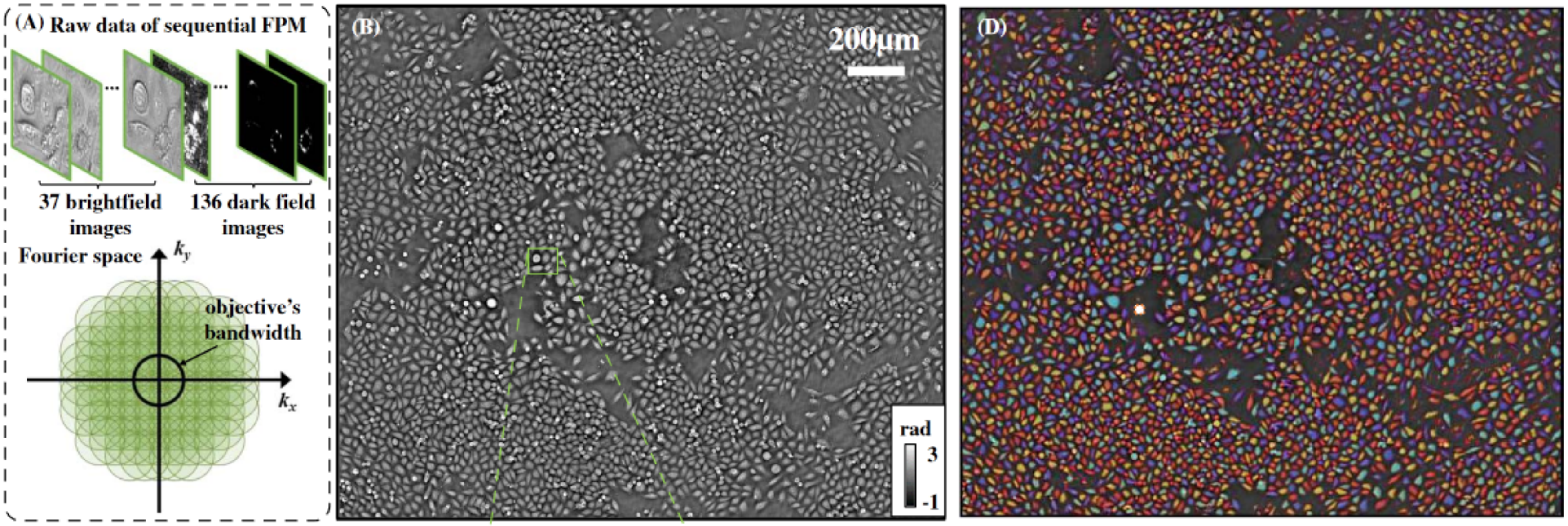
Central LED image

More frequencies = higher resolution
Off-axis illumination is equivalent to frequency space scanning
Time-sequential image acquisition to get all frequencies

- Gerchberg-Saxton based algorithms for reconstruction

Fourier Ptychography

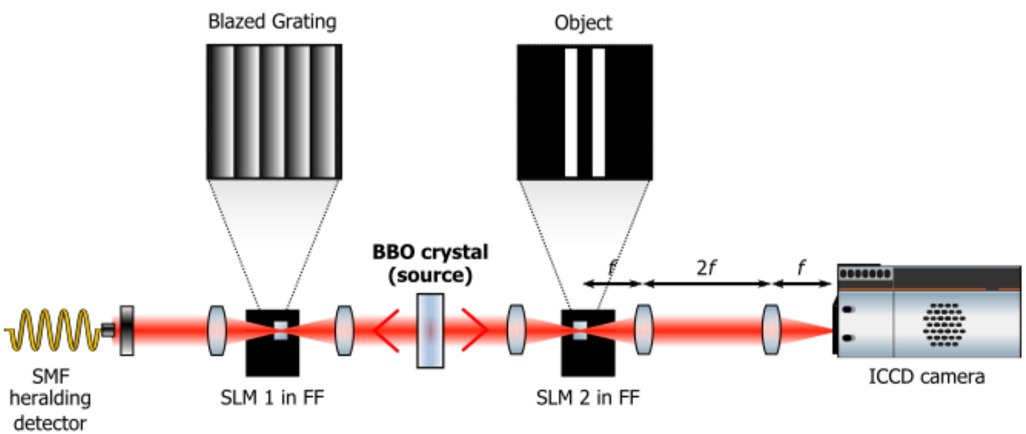
Allows intensity and phase retrival :



Lei Tian, Ziji Liu, Li-Hao Yeh, Michael Chen, Jingshan Zhong, and Laura Waller, Optica **2**, 904-911 (2015)

Fourier Ptychography with quantum correlations

Going back to our setup, using quantum correlations using an SMF and heralded imaging:



The idealized state produced by the BBO crystal is an EPR state.
Measurement of heralding photon at the position of the fiber x_f therefore reduce the :

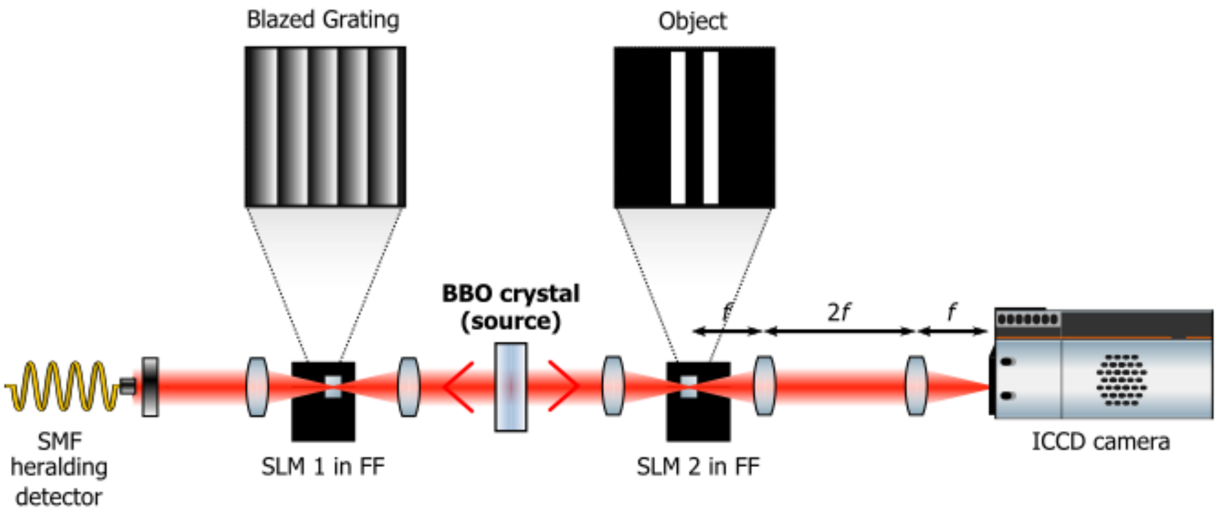
$$\left\{ |EPR\rangle = \int_{-\infty}^{\infty} |x, x\rangle \, dx = \int_{-\infty}^{\infty} |k, -k\rangle \, dk \quad , \quad \widehat{\mathcal{P}} = |x_f\rangle \langle x_f| \otimes \mathbb{I}_2 \right\}$$

$$\Rightarrow \qquad |\Psi_2\rangle = |x_f\rangle = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} e^{ix_f k} \, |k\rangle \, dx$$

Depending on the position of the fiber we obtain a single photon plane wave function with a particular inclination on the object.

Fourier Ptychography with quantum correlations

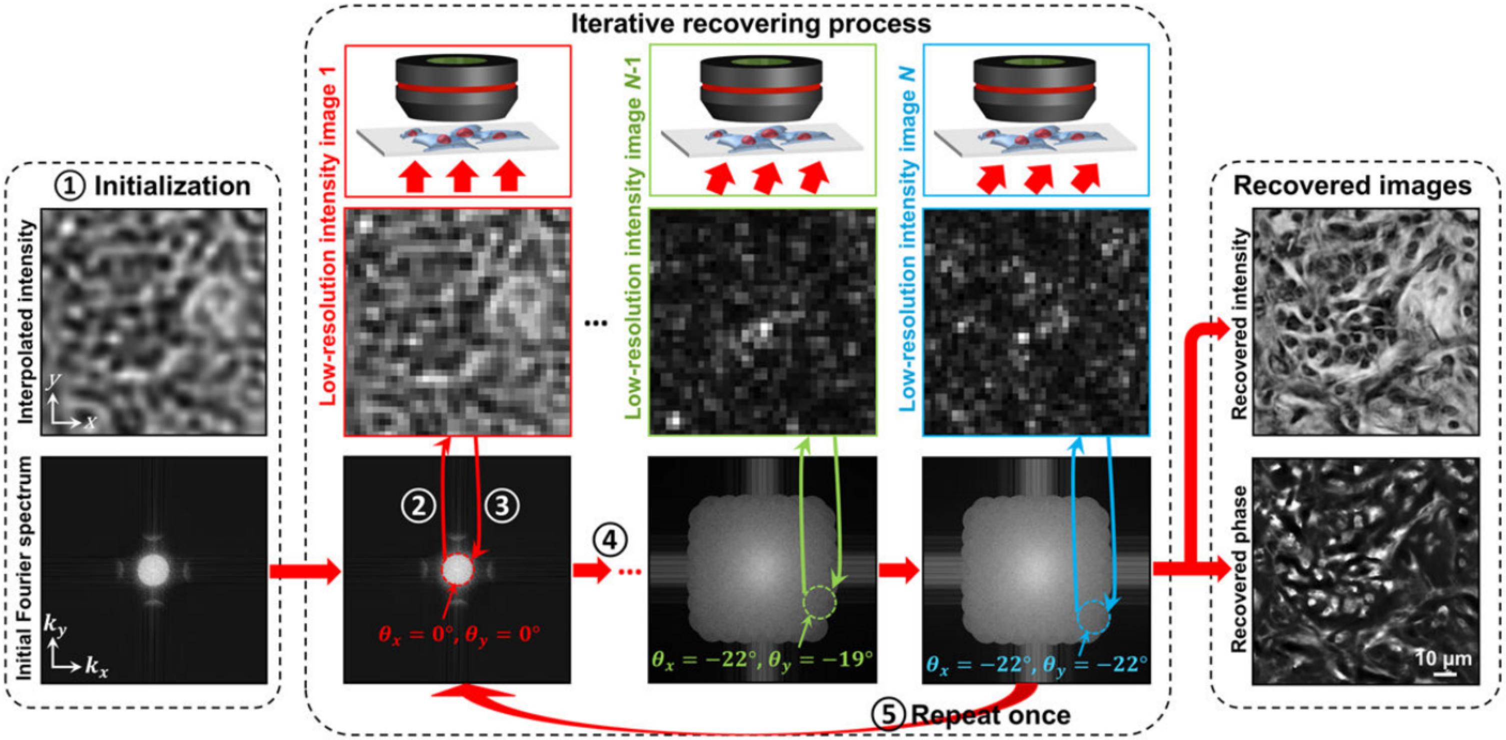
By changing the blazed grating, one can acquire the object image at the single photon level with different illumination angles (ie as with the usual ptychography)



Possible Fourier Ptychographic reconstruction with the same algorithms than classically.

Phase and amplitude acquisition.

Reconstruction algorithm.

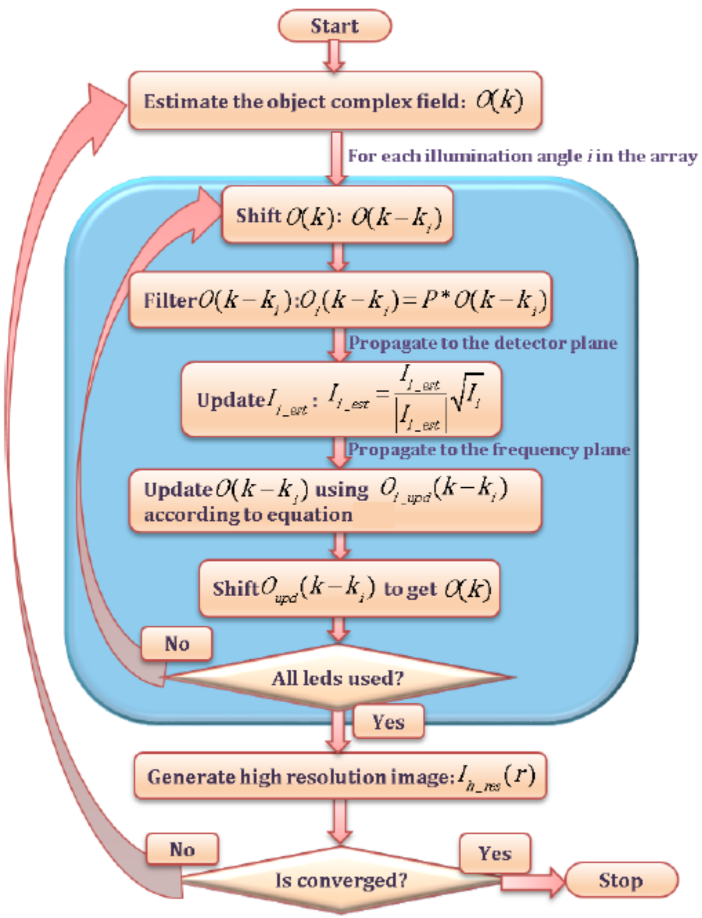


Zheng, G., Horstmeyer, R., & Yang, C., *Nature photonics*, **7**(9), 739-745 (2013).

Too sensible to noise: not usually converging in our case due to shot noise.

Reconstruction algorithm.

The reconstruction is an optimization problem.
Cost function : Distance between the amplitude found by the algorithm the recorded amplitude



$$min\left|\sqrt{I_i}-|\mathfrak{F}\left[P\cdot O\left(k-k_i\right)\right]|\right|$$

Using the following update equation correspond to a Gerchberg-Saxton method:

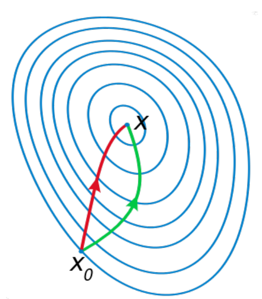
$$O_{upd}(k-k_i)=O(k-k_i)+\frac{\tilde{P}}{|P|_{\max}^2}(O_{i\_upd}(k-k_i)-O_i(k-k_i))$$

It is also a gradient descent.

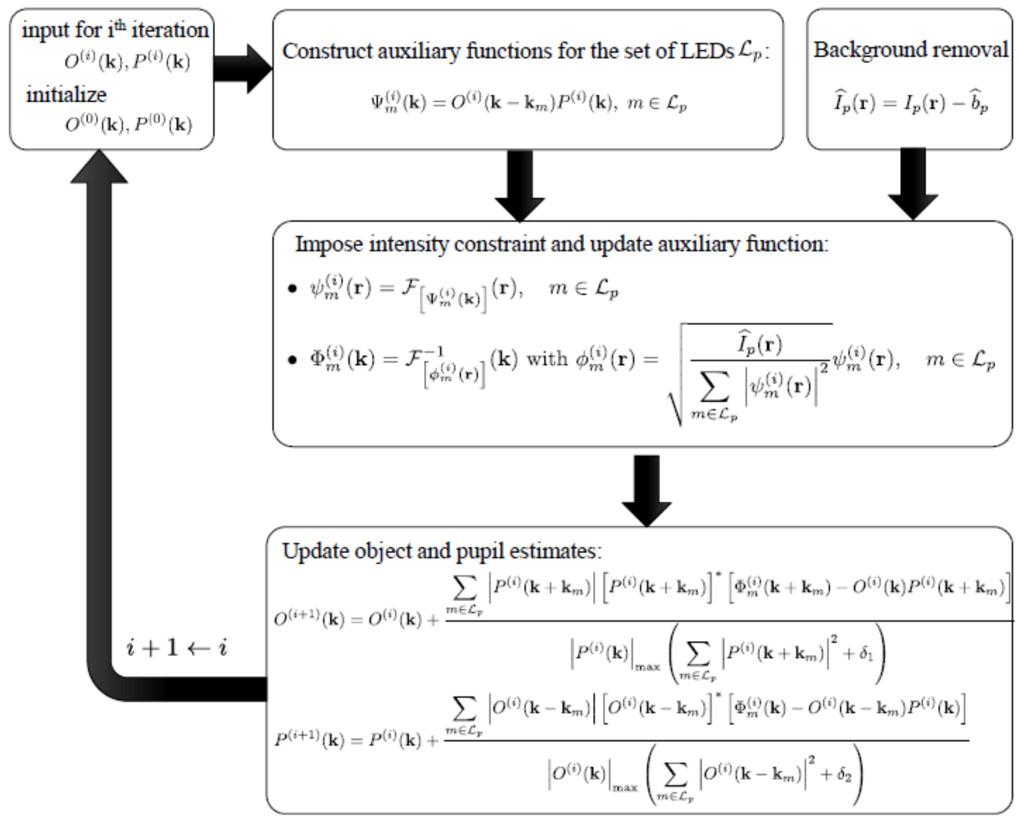
Reconstruction algorithm.

Using Newton method in optimization one can reduce the noise

Uses curvature (second derivative) to determine the route of optimisation

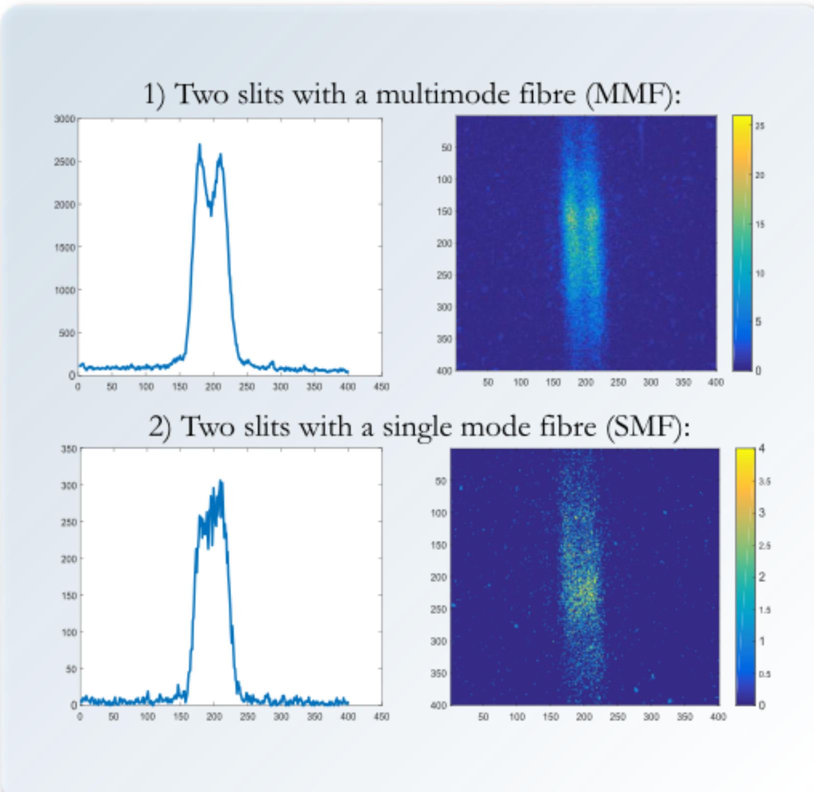


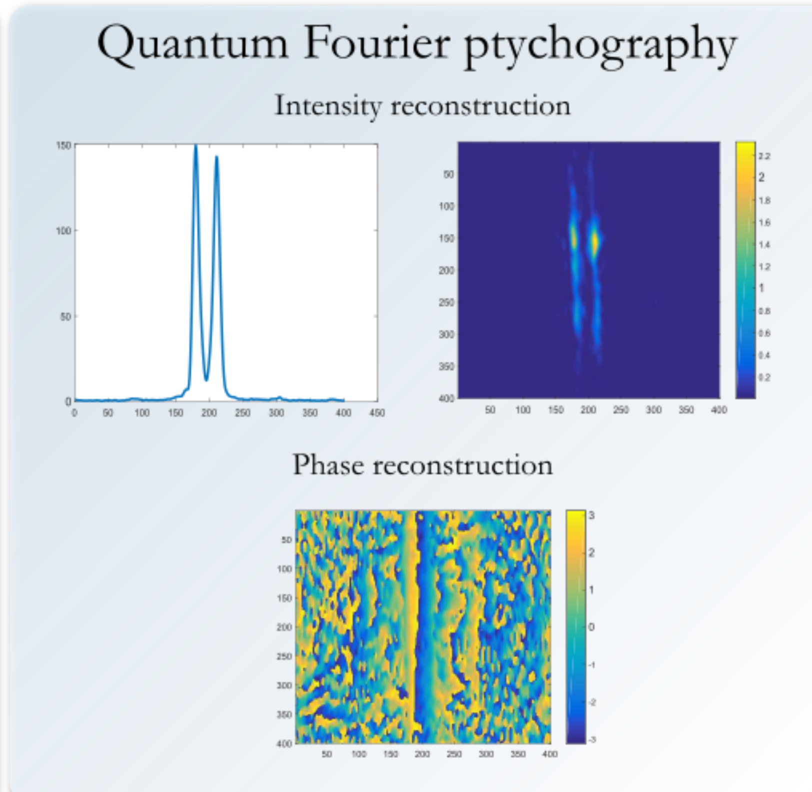
Allows additionally to update the pupil.
$\Rightarrow$ Aberration corrections



Tian, L., Li, X., Ramchandran, K., & Waller, L., *Biomedical optics express*, ***5***(7), 2376-2389 (2014). .

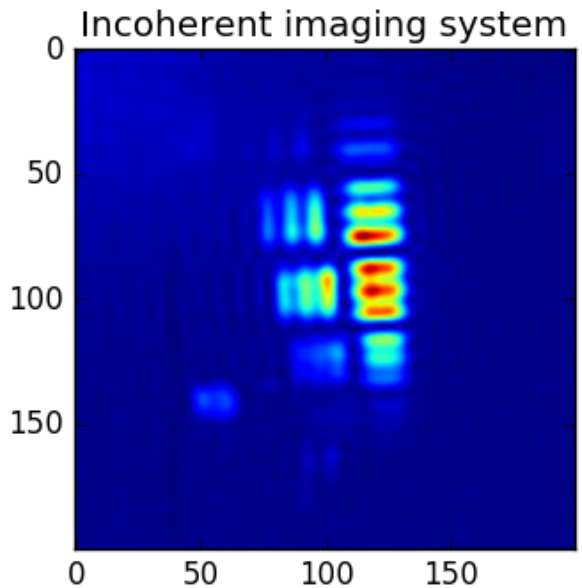
Results, 1 dimensional.

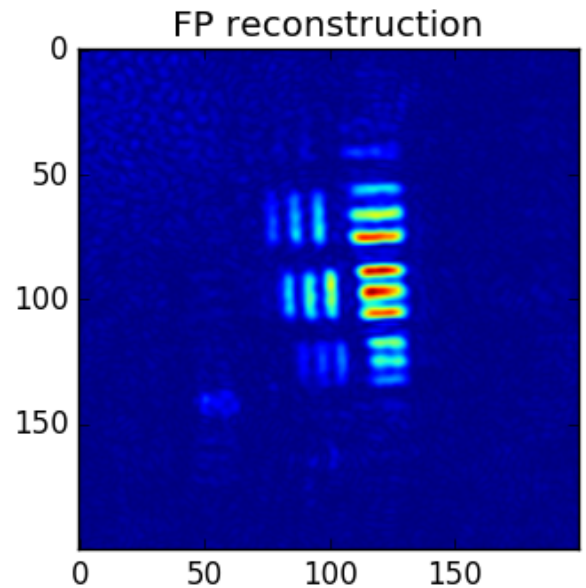




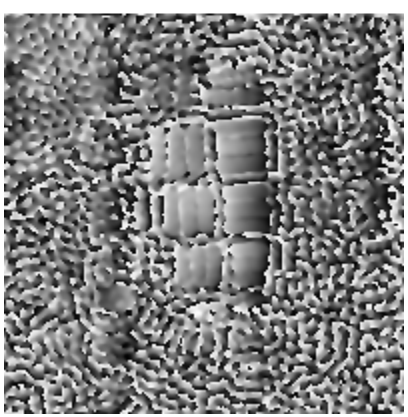
⇒ Increased NA
⇒ Phase imaging.

Results, 2 dimensional : Test Target.

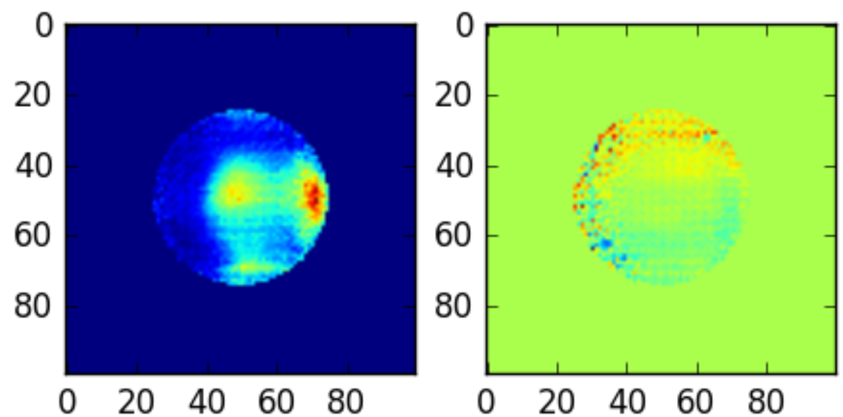




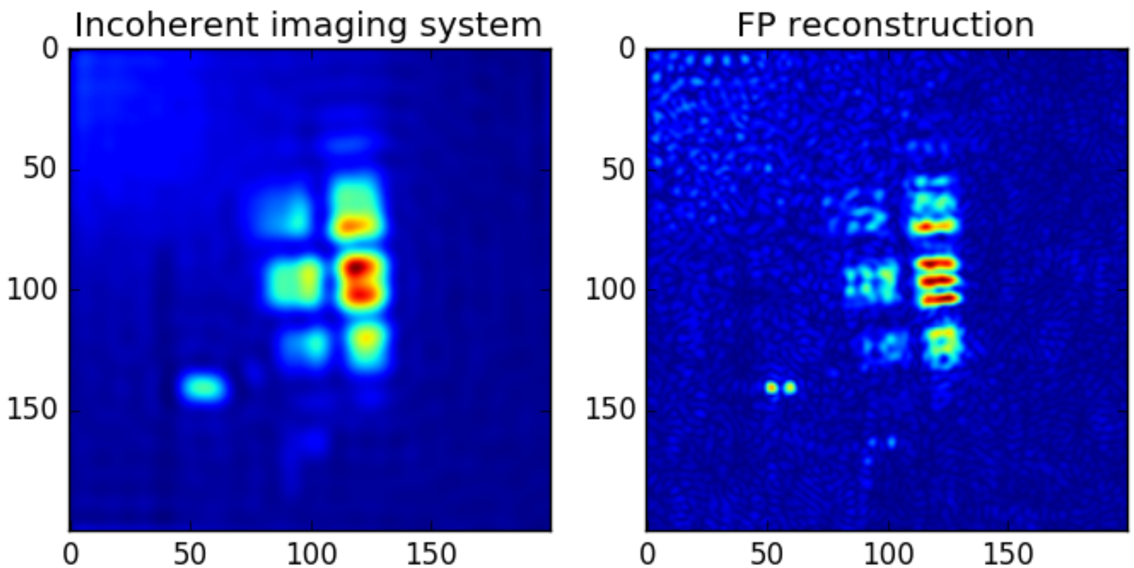
Phase



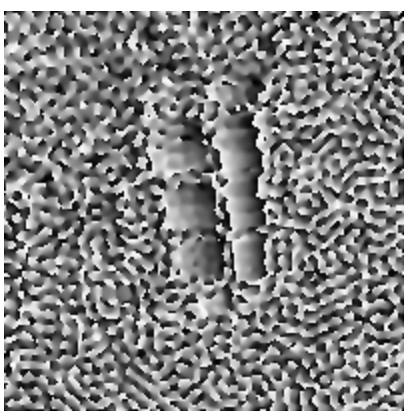
Pupil amplitude and phase



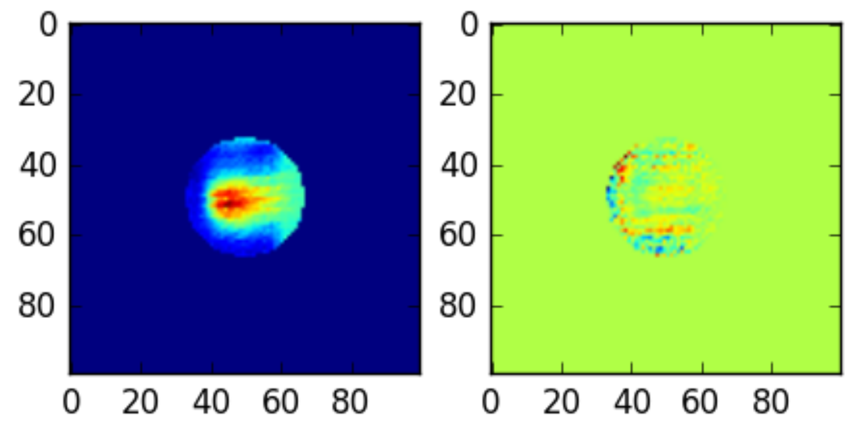
Results, 2 dimensional :
Test Target with pupil reducing NA.



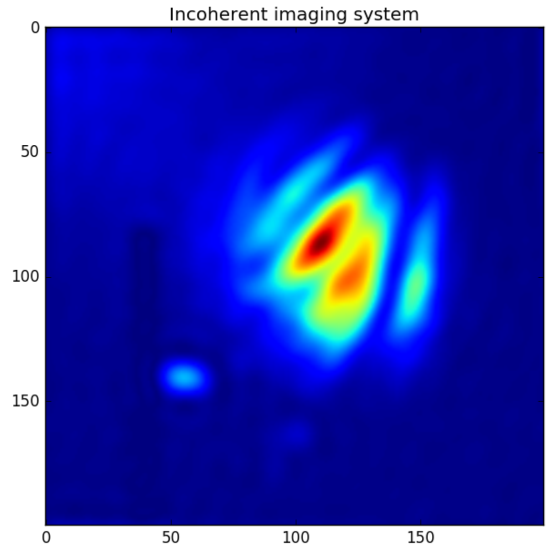
Phase

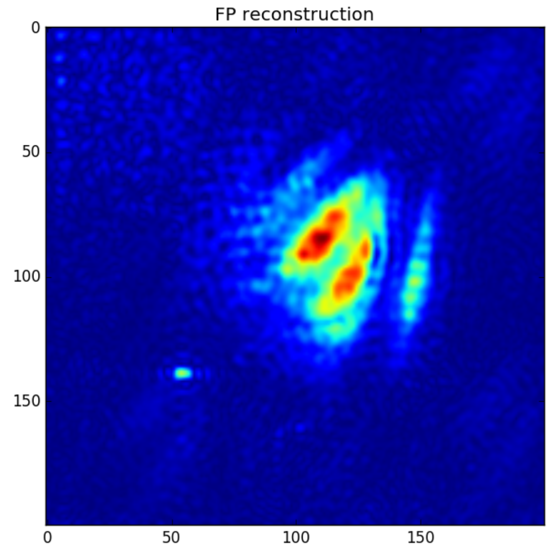


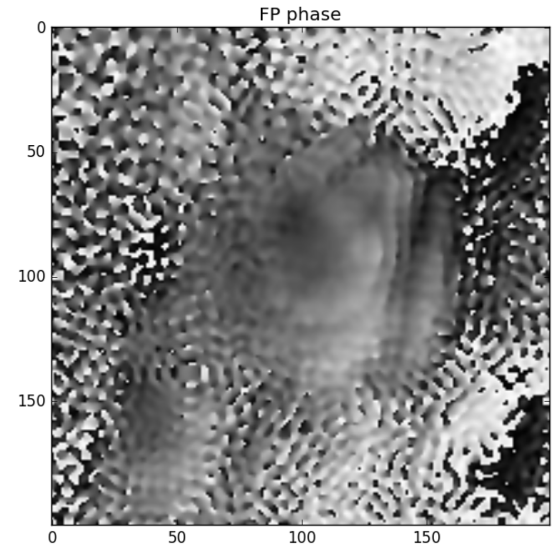
Pupil amplitude and phase



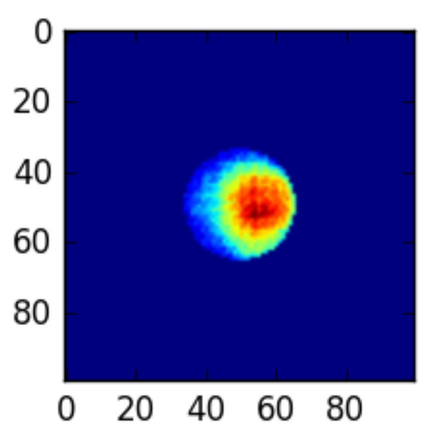
Results, 2 dimensional : part a wasp wing.

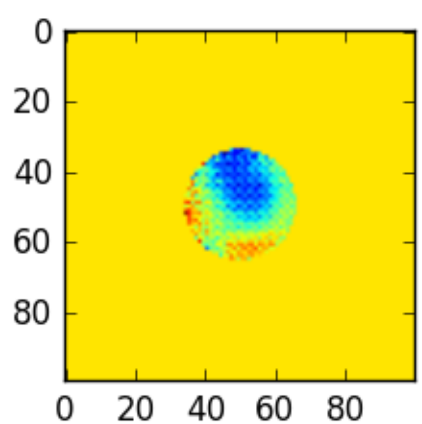






Pupil amplitude and phase





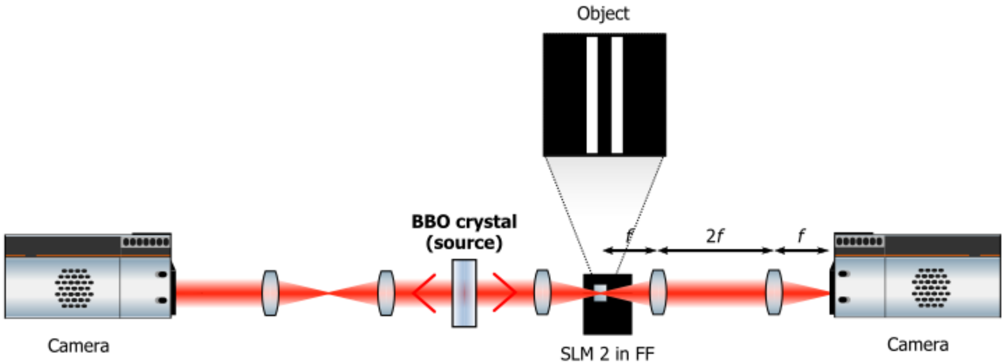
Conclusion and outlook

We have shown it is possible to harness EPR like quantum correlations to acquire phase-amplitude images without interferometry measurement.

It was done by analogy to the classical Fourier-Ptychography technique.

Outlooks :

Two cameras scheme would actually allow the parallel acquisition of the different images used for the reconstruction: No scanning is actually necessary by using such correlations.



Sub-shot noise features could potentially be used in the ptychographic reconstruction : enhanced phase reconstruction ?

Thank you for your attention.