Quantum imaging with SPAD array cameras

6 June 2024

ISSW2024 - The International SPAD Sensor Workshop 2024

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ICFO - The Institute of Photonic Sciences

Barcelona

Castelldefels

Optoelectronics Group

ICFO

Prof. Valerio Pruneri

Applied science:

- Surfaces/material science
- Quantum technology:
  - Quantum imaging
  - Quantum communication
- Imaging using consumer electronics
- Spin-offs:

LUXQUANTA

Quside

?

sixsenso
• SENSE DIFFERENT •

Outline

1. Quantum imaging

2. Results
   1. Quantum imaging for phase microscopy
   2. Quantum imaging for endoscopy

3. Conclusions & Outlook

Outline

1. **Quantum imaging**

2. Results
   1. Quantum imaging for phase microscopy
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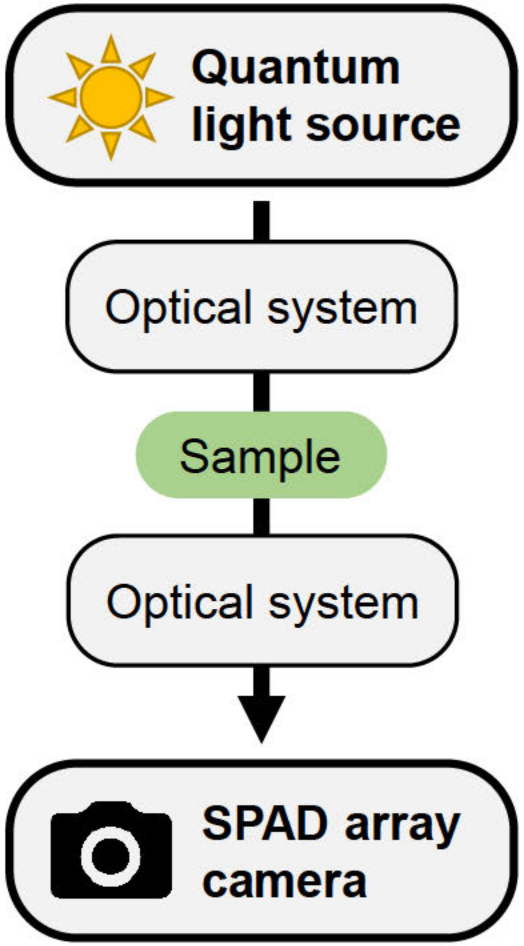
3. Conclusions & Outlook

Quantum imaging

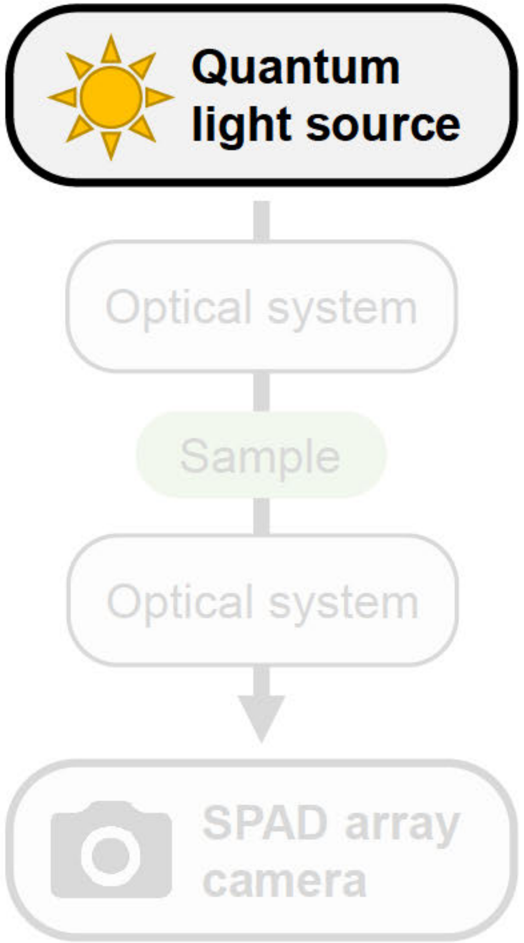
Imaging with quantum states of light.
➢ Advantages over classical light.

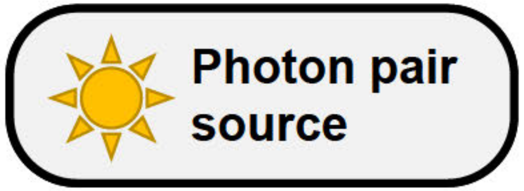
Examples:
- Noise resistance
- Super-sensitivity
- Super-resolution
- Imaging at exotic wavelengths

Setup

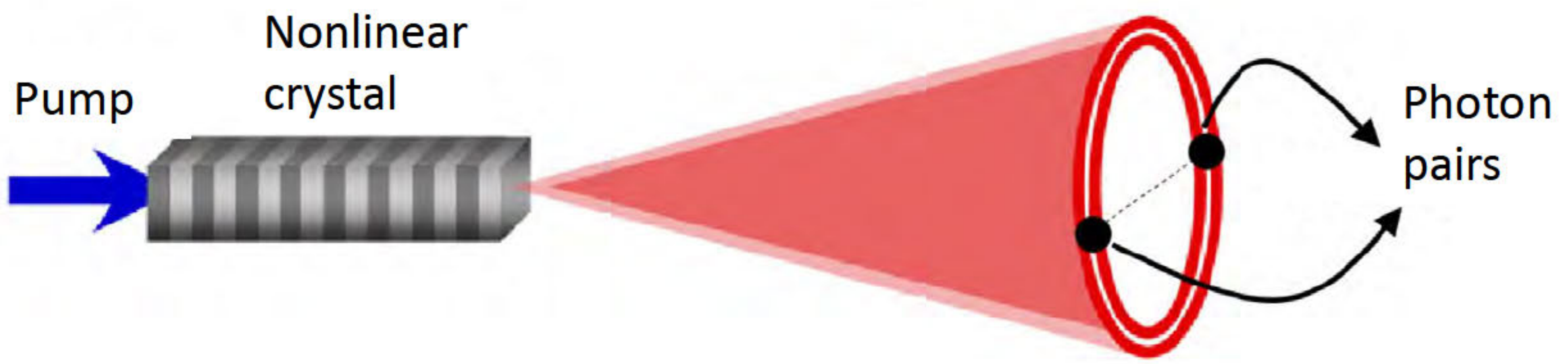

Quantum
light source
Optical system
Sample
Optical system
SPAD array
camera

Quantum light source





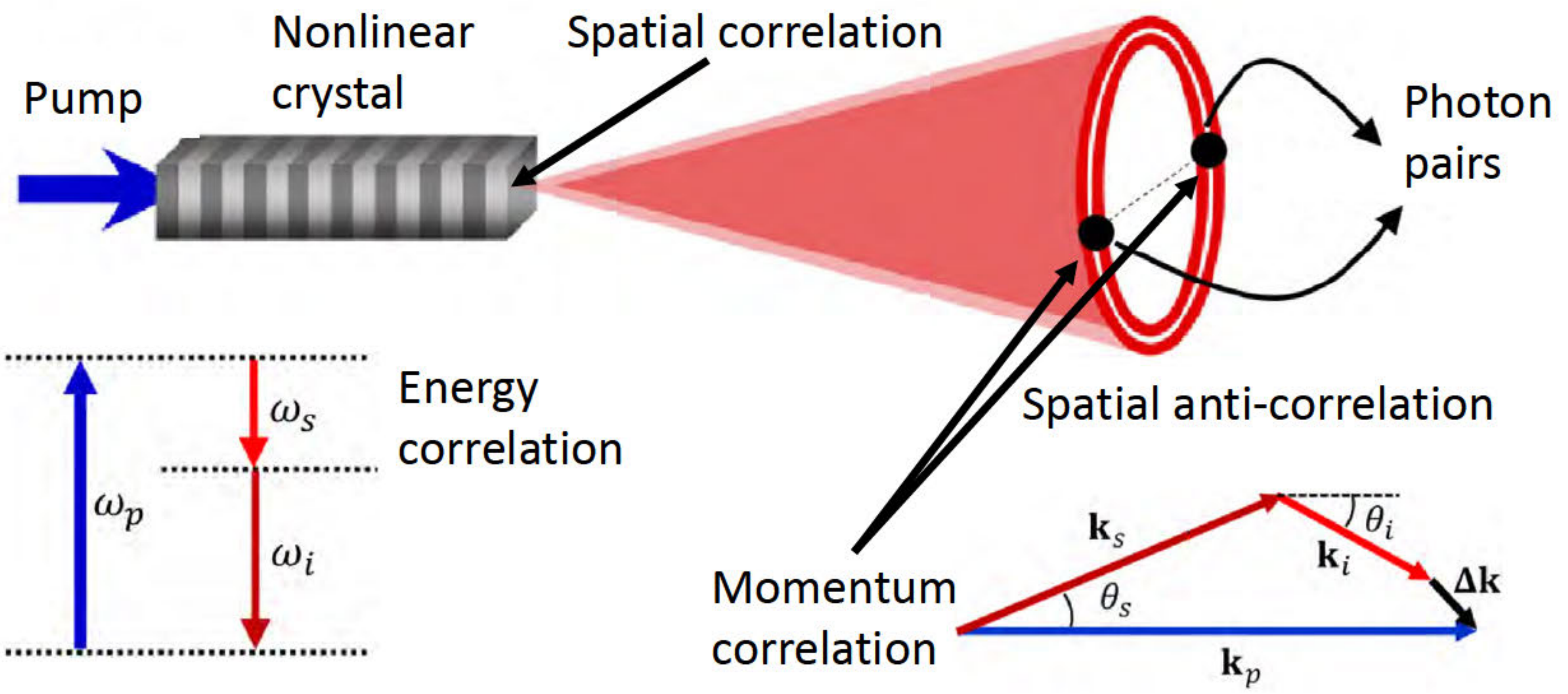
Spontaneous parametric down conversion (SPDC)



Figures adapted from 10.1063/5.0023103

Photon pair source

Spontaneous parametric down conversion (SPDC)



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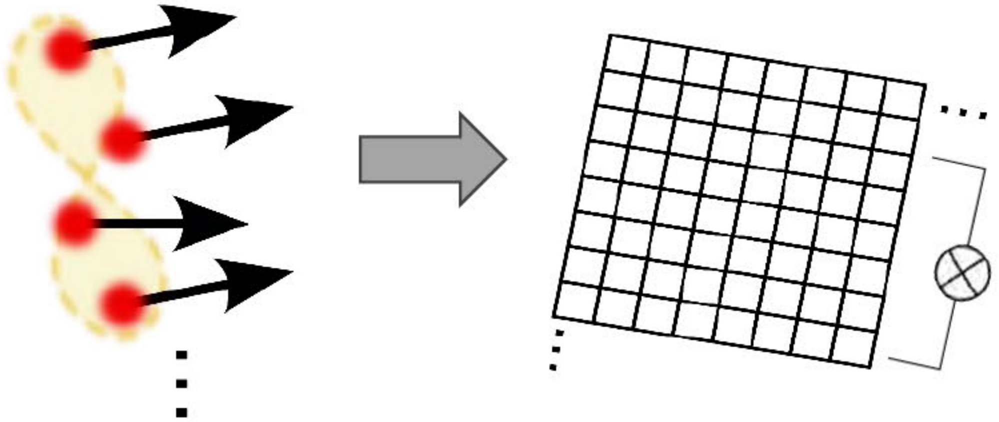
Quantum imaging – coincidence imaging



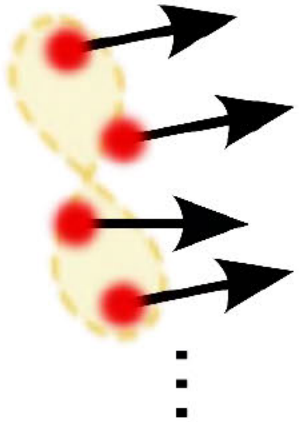
2-photon state

- Quantum correlations
- Entanglement

Image sensor

- Sensitive
- Many pixel-modes
- Time resolution to identify photon pairs
- => coincidences

Quantum imaging – coincidence imaging



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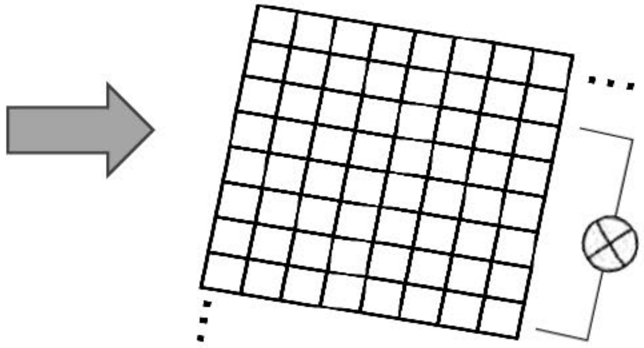

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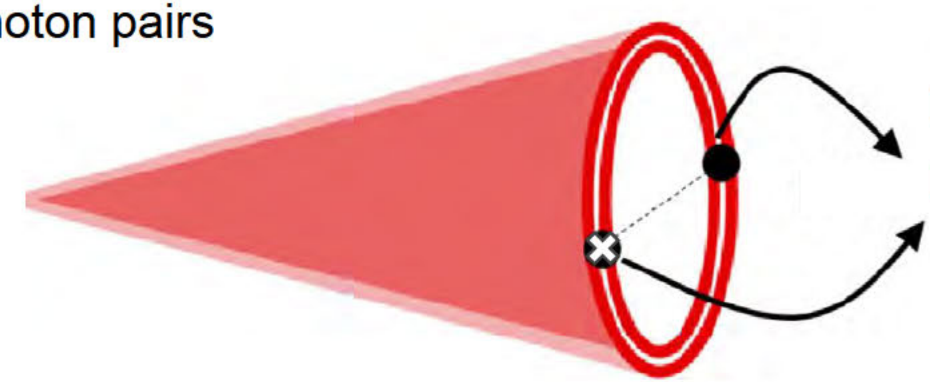
Spontaneous parametric down conversion (SPDC) photon pairs



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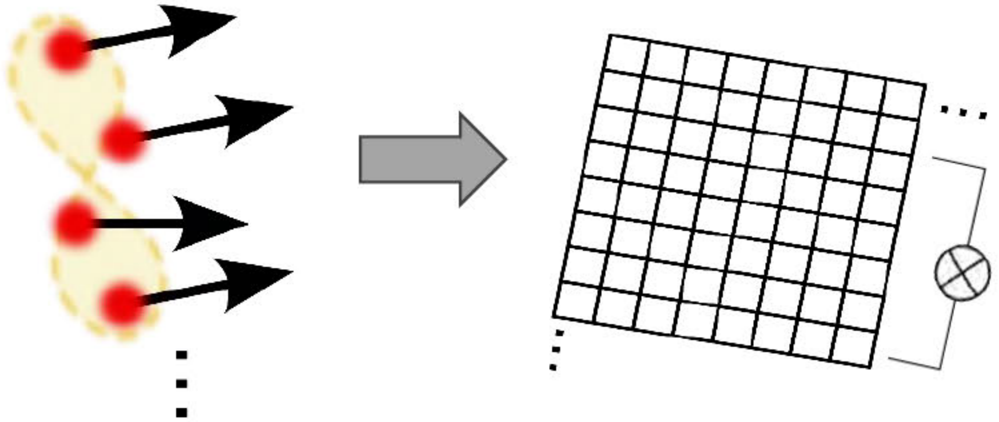

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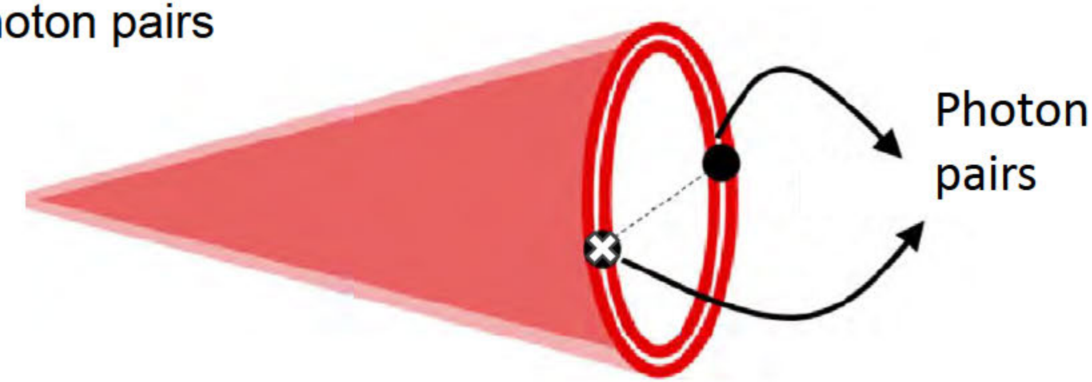
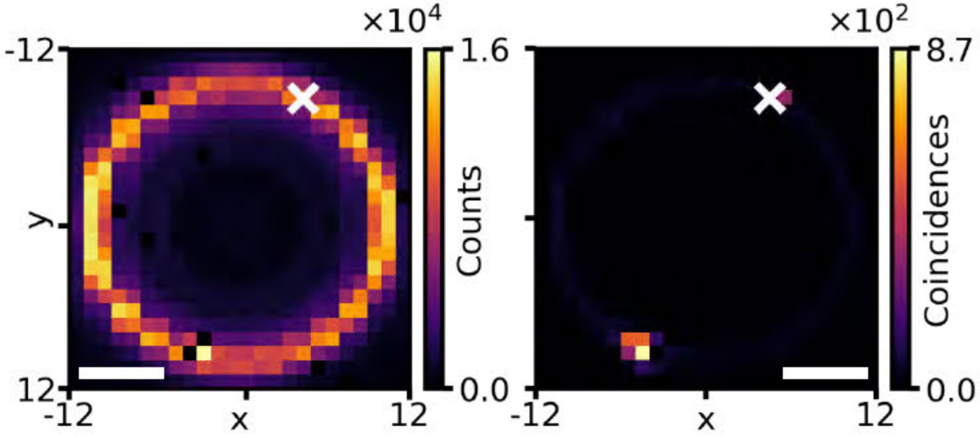
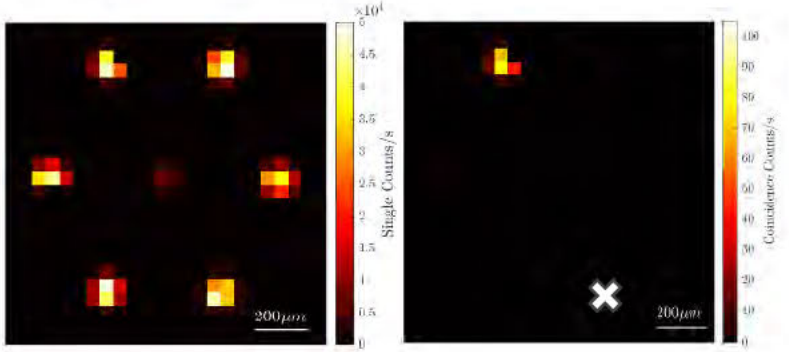




Alexander Demuth, et al. **Quantum light transport in phase-separated Anderson localization fiber**. *Communications Physics* **5**(261), 2022.

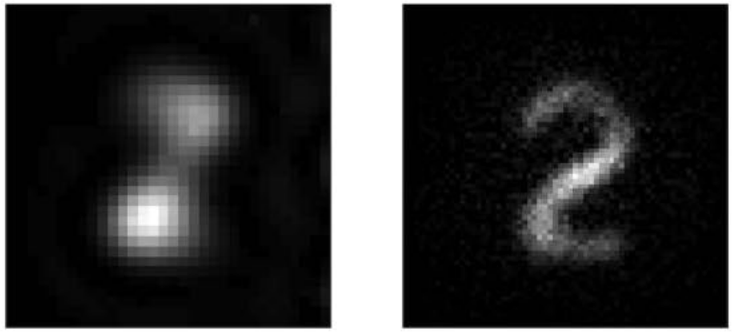
Applications of coincidence imaging

- Quantum communication
  - free-space
  - fibre-based



Adrián Sanchez Blanca et al., in preparation

- Super-resolution imaging



10.1364/OPTICA.5.001150

- Imaging through noise
- Super-sensitivity imaging
- …

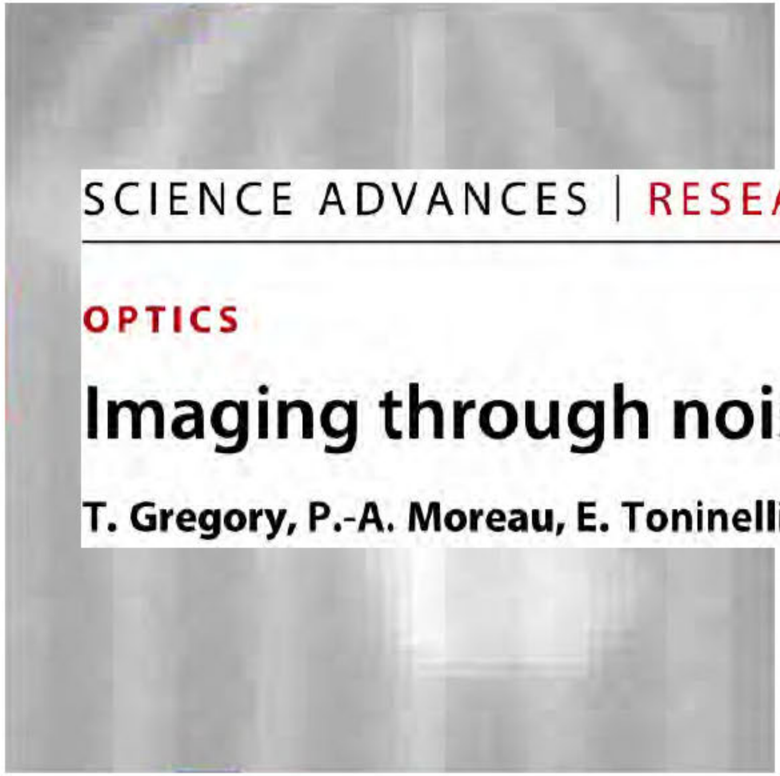
Imaging through noise with quantum illumination

SCIENCE ADVANCES | RESEARCH ARTICLE

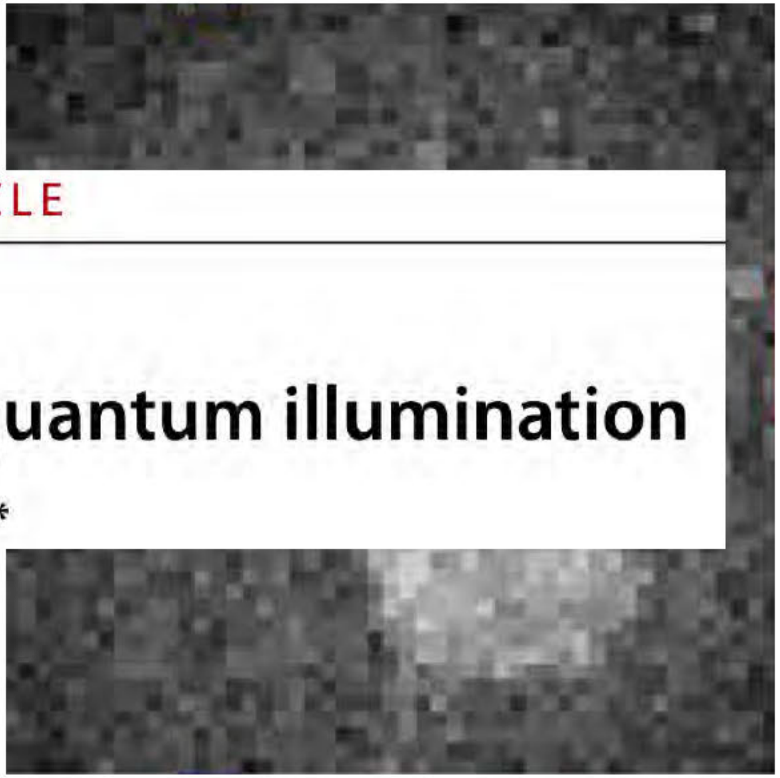
OPTICS

Imaging through noise with quantum illumination

T. Gregory, P.-A. Moreau, E. Toninelli, M. J. Padgett*



Classically acquired image
(quantum + classical light)



Coincidence (quantum) image

10.1126/sciadv.aay2652

Imaging through noise with quantum illumination

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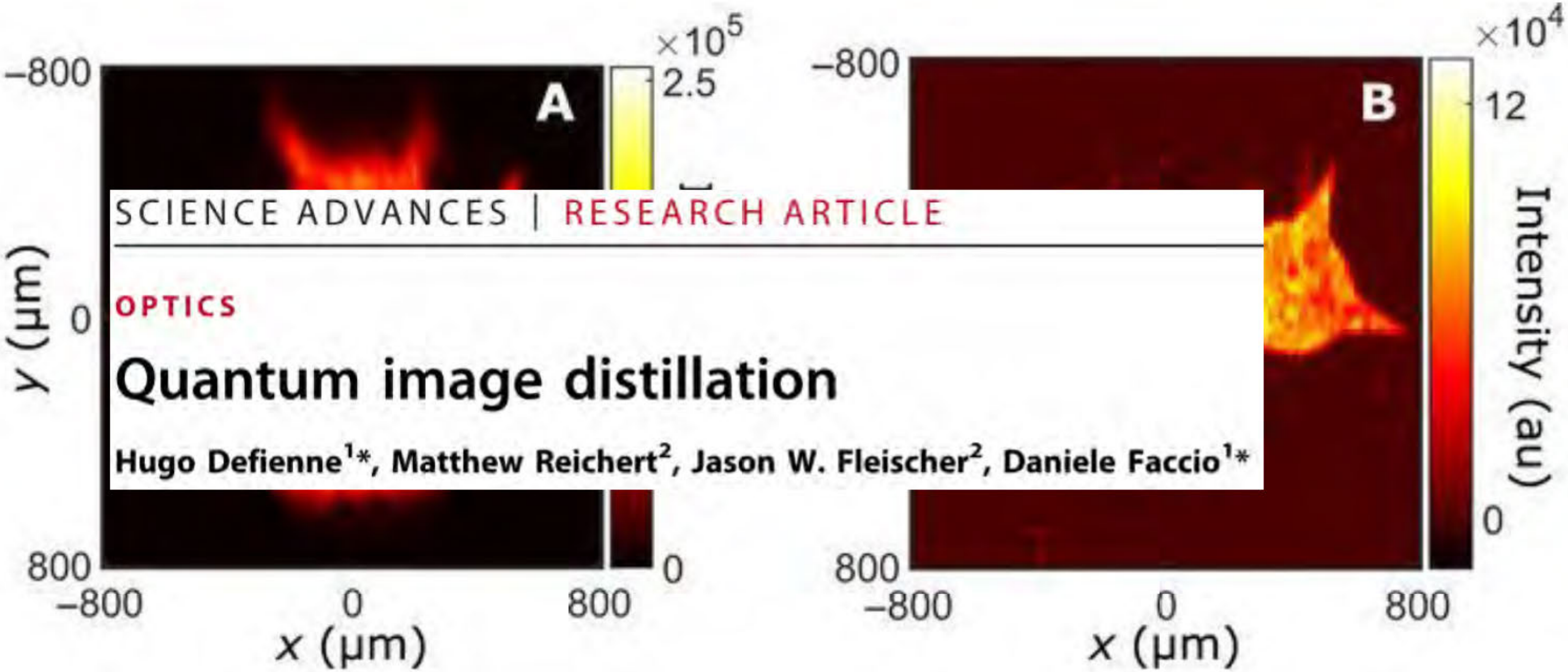
10.1126/sciadv.aay2652

Quantum image distillation



SCIENCE ADVANCES | RESEARCH ARTICLE

OPTICS

Quantum image distillation

Hugo Defienne[1]*, Matthew Reichert[2], Jason W. Fleischer[2], Daniele Faccio[1]*

Classically acquired image
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Coincidence (quantum) image

10.1126/sciadv.aax0307

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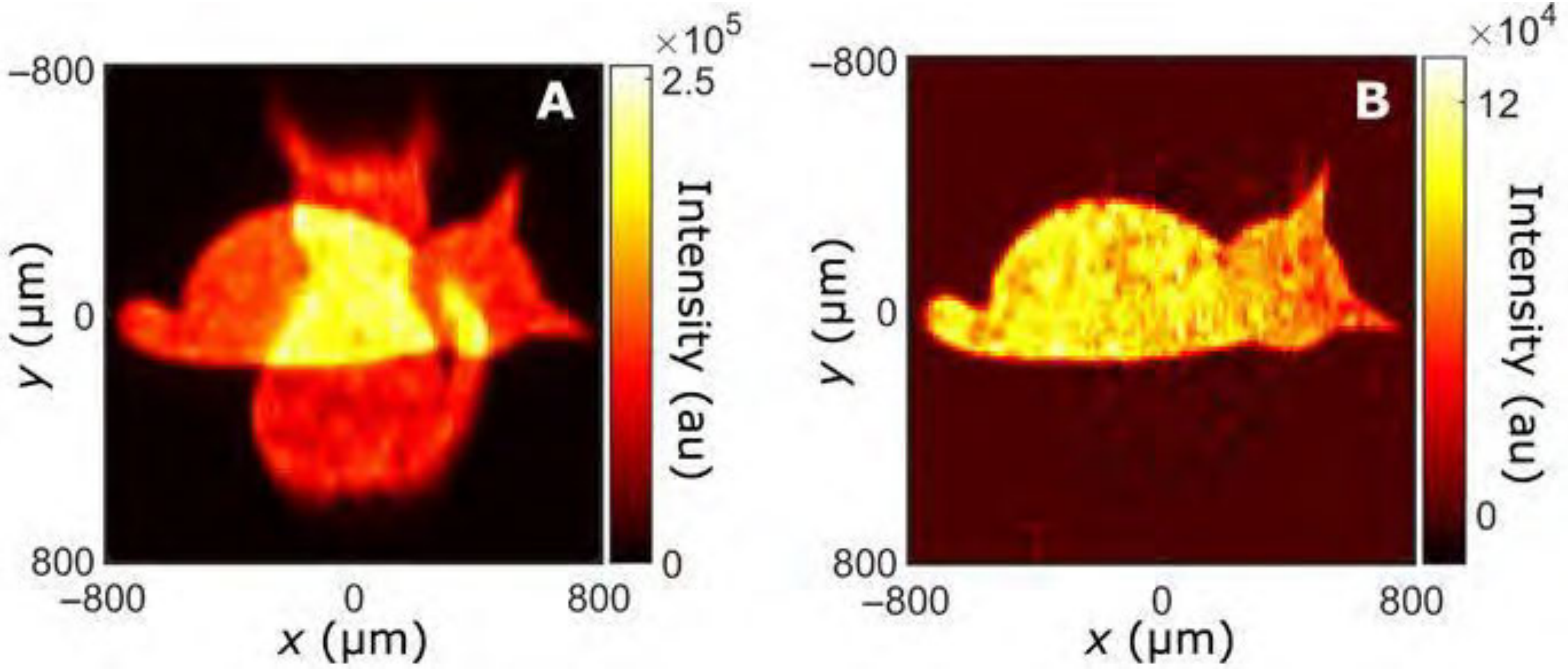


Classically acquired image (quantum + classical light)

Coincidence (quantum) image

10.1126/sciadv.aax0307

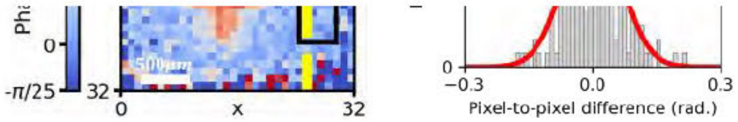
A quantum-enhanced wide-field phase imager

SCIENCE ADVANCES | RESEARCH ARTICLE

OPTICS

A quantum-enhanced wide-field phase imager

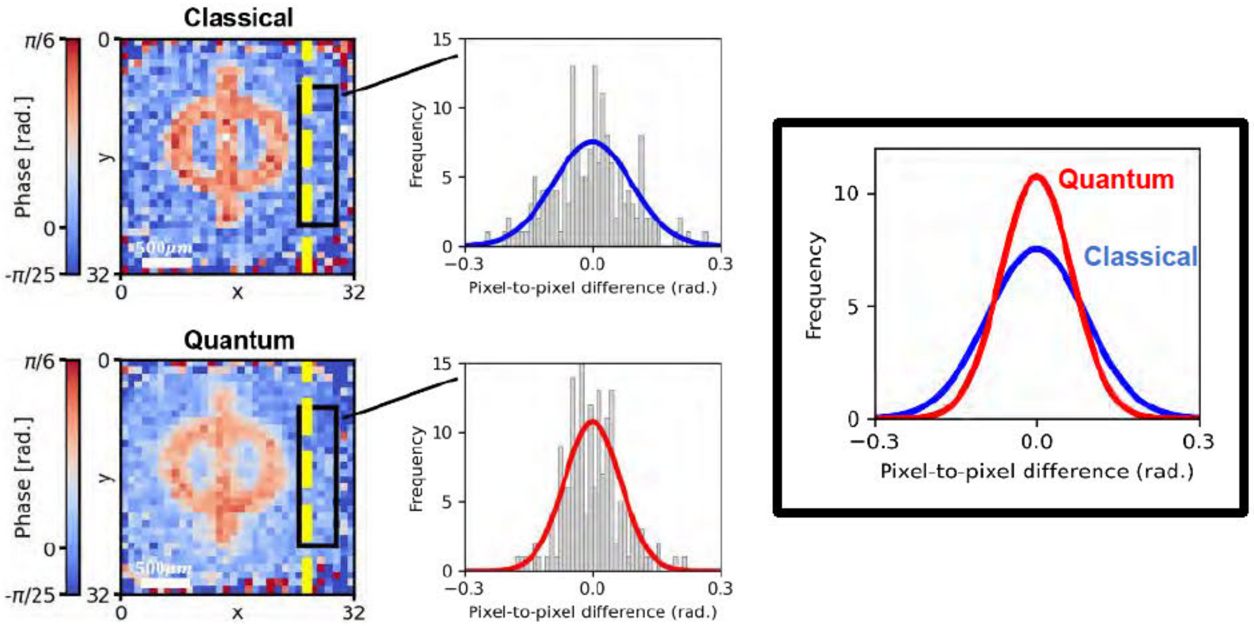
Robin Camphausen[1]*, Álvaro Cuevas[1]*, Luc Duempelmann[1], Roland A. Terborg[1], Ewelina Wajs[1], Simone Tisa[2], Alessandro Ruggeri[2], Iris Cusini[3], Fabian Steinlechner[4,5], Valerio Pruneri[1,6]*



Phase imaging with N00N-state entanglement
→ super-sensitivity

10.1126/sciadv.abj2155

A quantum-enhanced wide-field phase imager



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Slow acquisition times:

OPTICS

Imaging through noise with quantum illumination

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Acquisition time **~1 week**

OPTICS

Quantum image distillation

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Acquisition time **~days**

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Acquisition time **~2 days**

(Classical light: <1 second)

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2. **Results**
    1. **Quantum imaging for phase microscopy**
    2. Quantum imaging for endoscopy

3. Conclusions & Outlook

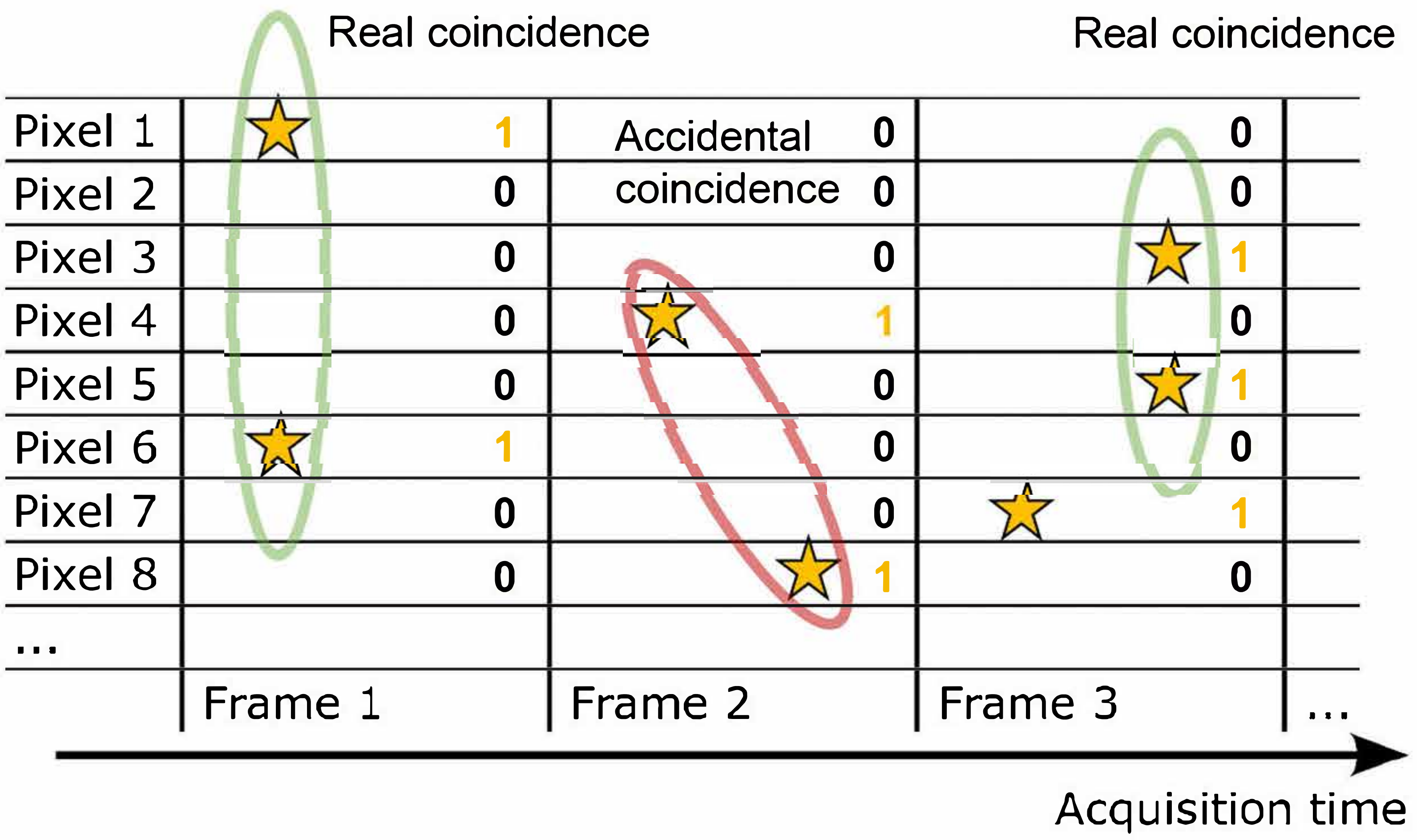
Aim of QMIC

Towards *practical* quantum imaging platform

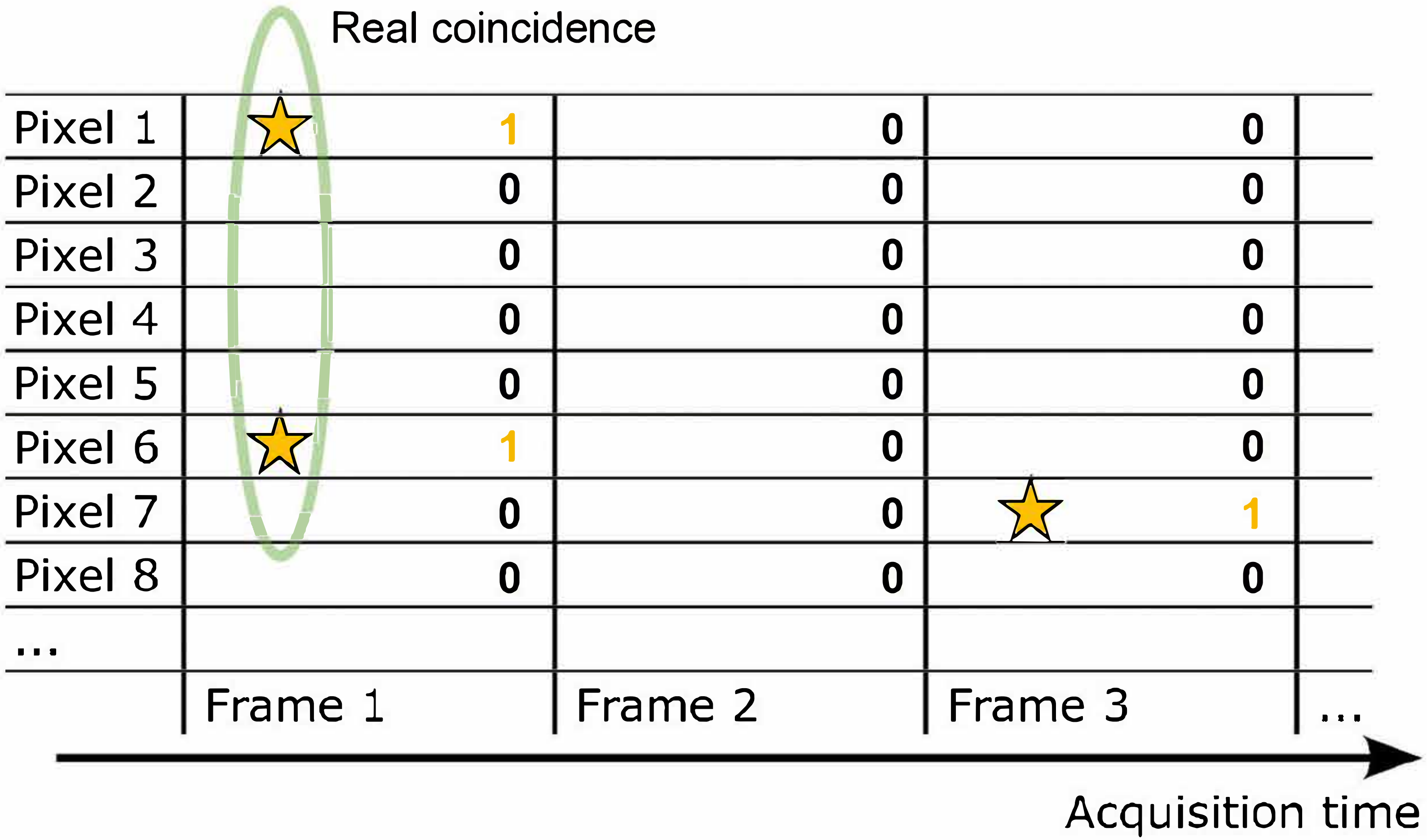
"Real-time" (~Hz rate) coincidence imaging with entangled photon pairs

Identify room for improvement:
- "Photon-counting" cameras → slow coincidence imaging
- ...

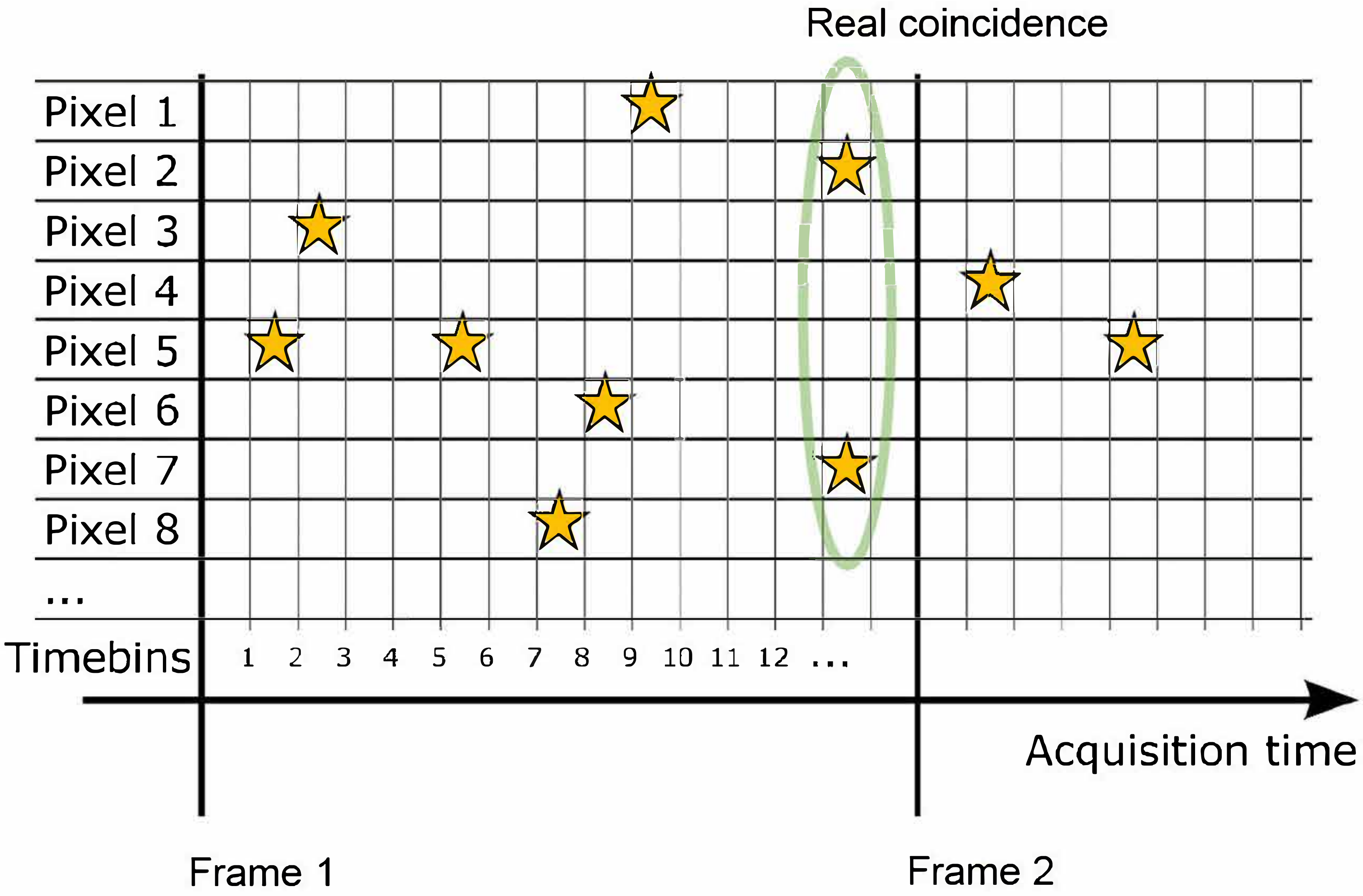
"Photon- counting" cameras (i.e. no timing information)



Have to keep counts low → slow coincidence imaging



Better: "time-tagging" cameras

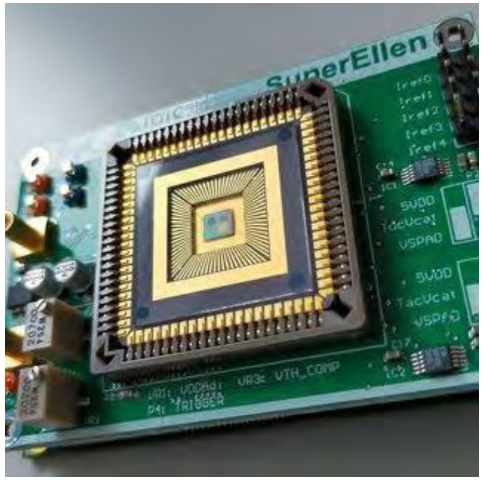


Time-tagging cameras

SPAD array

photon-force.com

piimaging.com



FBK - 10.1364/AO.492208

MPD/Polimi - 10.1117/12.2592088

Time-tagging with image intensifier

TPX3CAM/Phoebe

amscins.com

QMIC 24x24 camera

ICFO

SPAD array camera

Features:

- 24x24 pixels – modular design extendable to 96x96 pixels
- Time-tagging with 2 ns timebins
- Optimized readout (row-skipping, variable frame rate) $\rightarrow \sim 100\%$ duty cycle
- Microlens array

New SPAD array camera

MPD/Polimi - 10.1117/12.2592088

Francesca Madonini

Alessandro Ruggeri

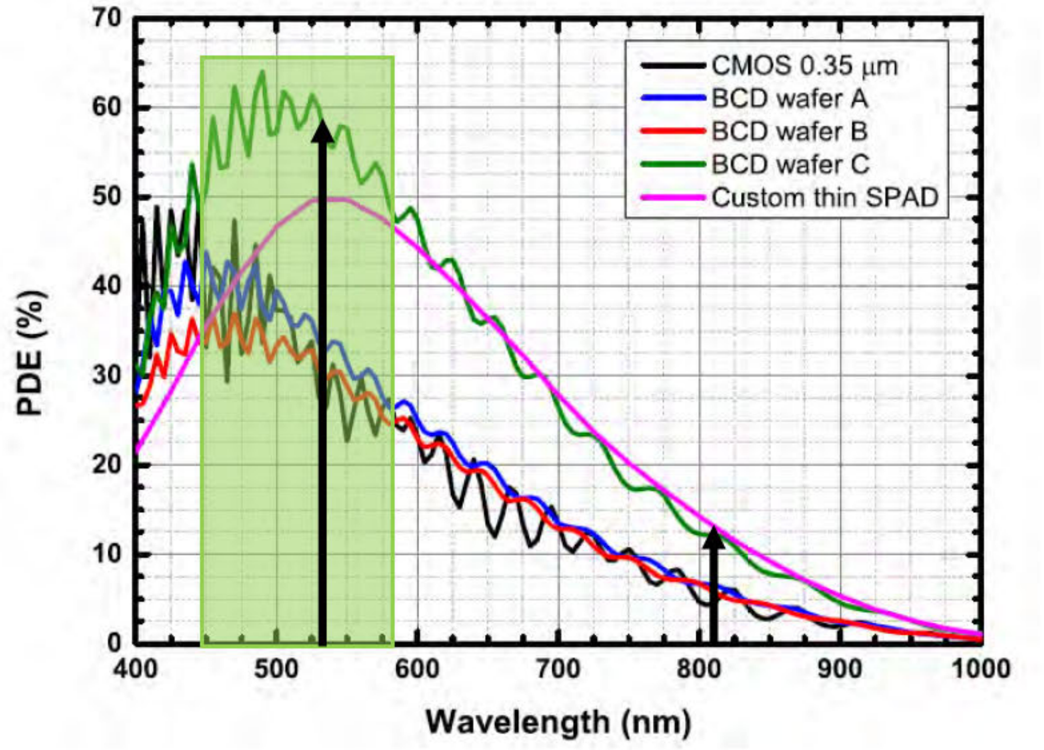
POLITECNICO MILANO 1863

MPD MICRO PHOTON DEVICES

Photon pair source

Visible wavelength SPDC

SPAD array camera
photon detection probability (PDP)



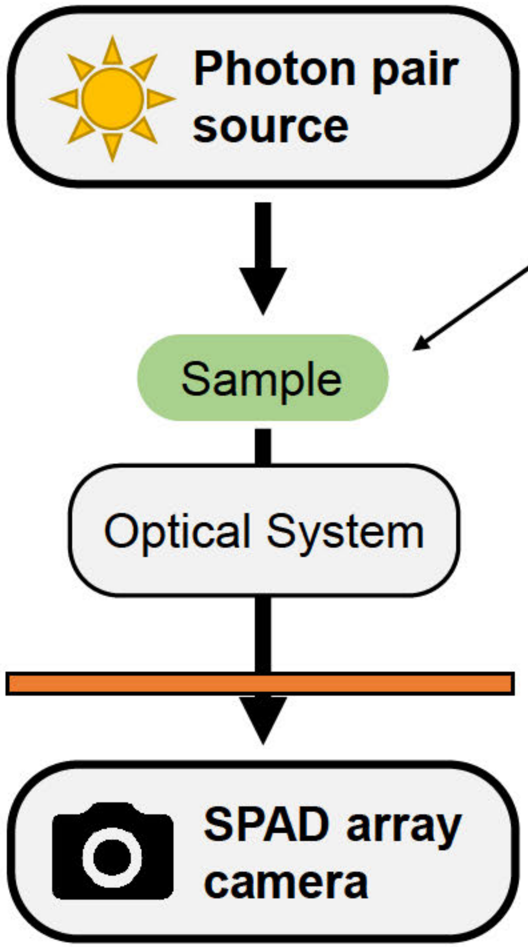
Sanzaro, M., et al. *IEEE J. Sel. Top. Quantum Electron.* **24**(2), 2017.

Adrià Sansa Perna

Fraunhofer IOF

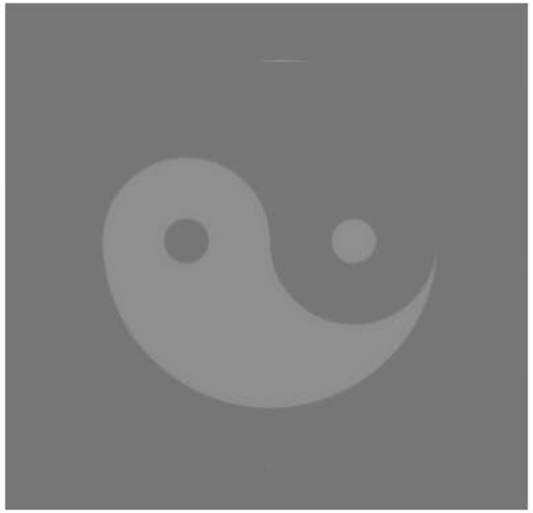
10.1063/5.0069992

Phase imaging with entangled photon pairs

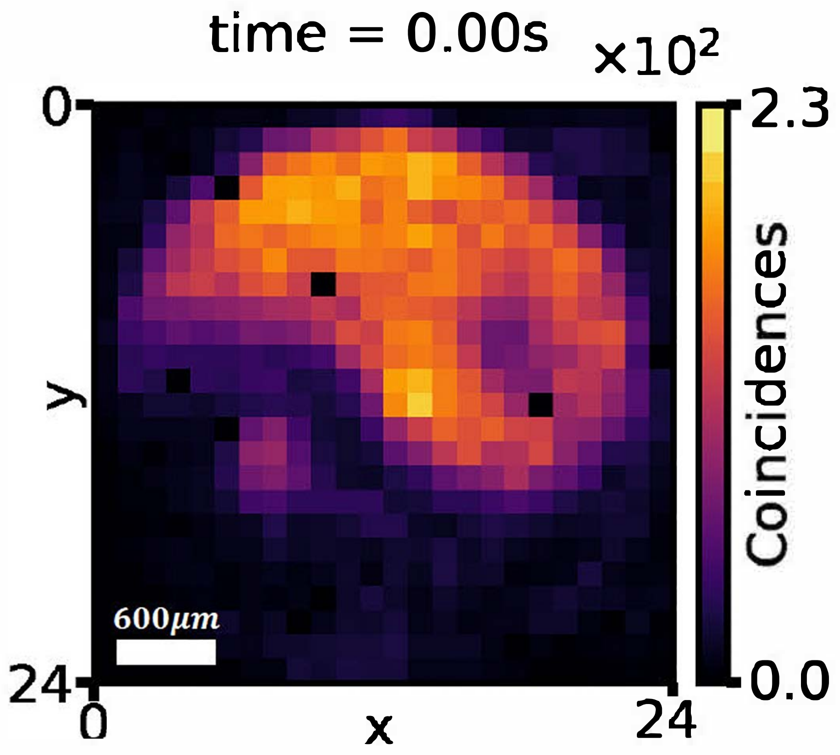


i.e. get images of $\phi(x, y)$

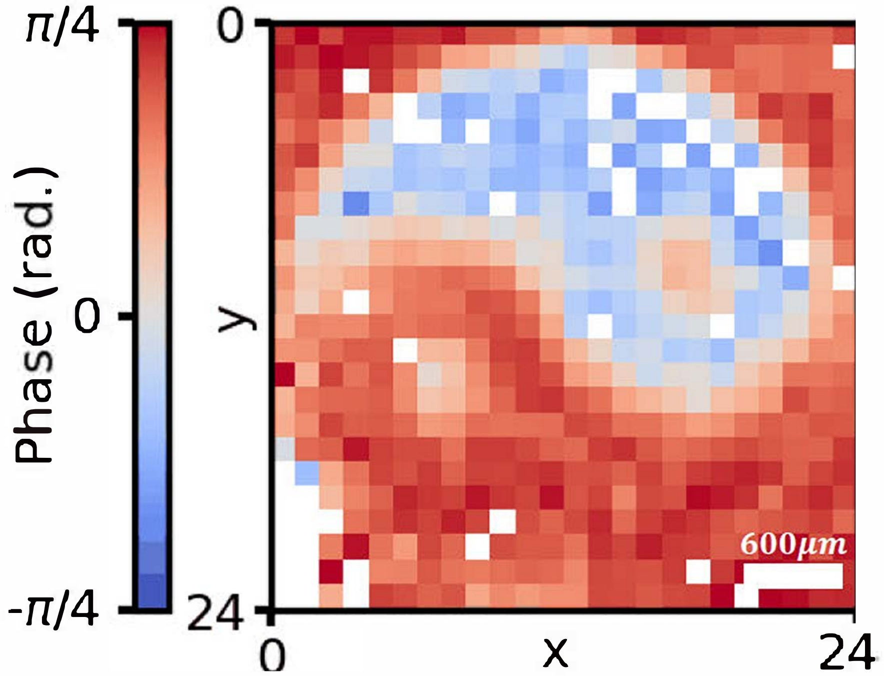
Test sample:
Video on phase-only SLM



Entangled photon pair "video"



Coincidence imaging video rate ~1.5Hz



N00N-state phase "video"

Recall:

OPTICS

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had acquisition time **~2 days**

1. Quantum imaging

2. Results
    1. Quantum imaging for phase microscopy
    2. **Quantum imaging for endoscopy**

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Endoscopy

Minimally invasive imaging.
Endoscope: flexible optical fibre.

Where no direct image can be obtained, for example inside tissue

Improve endoscopy with quantum

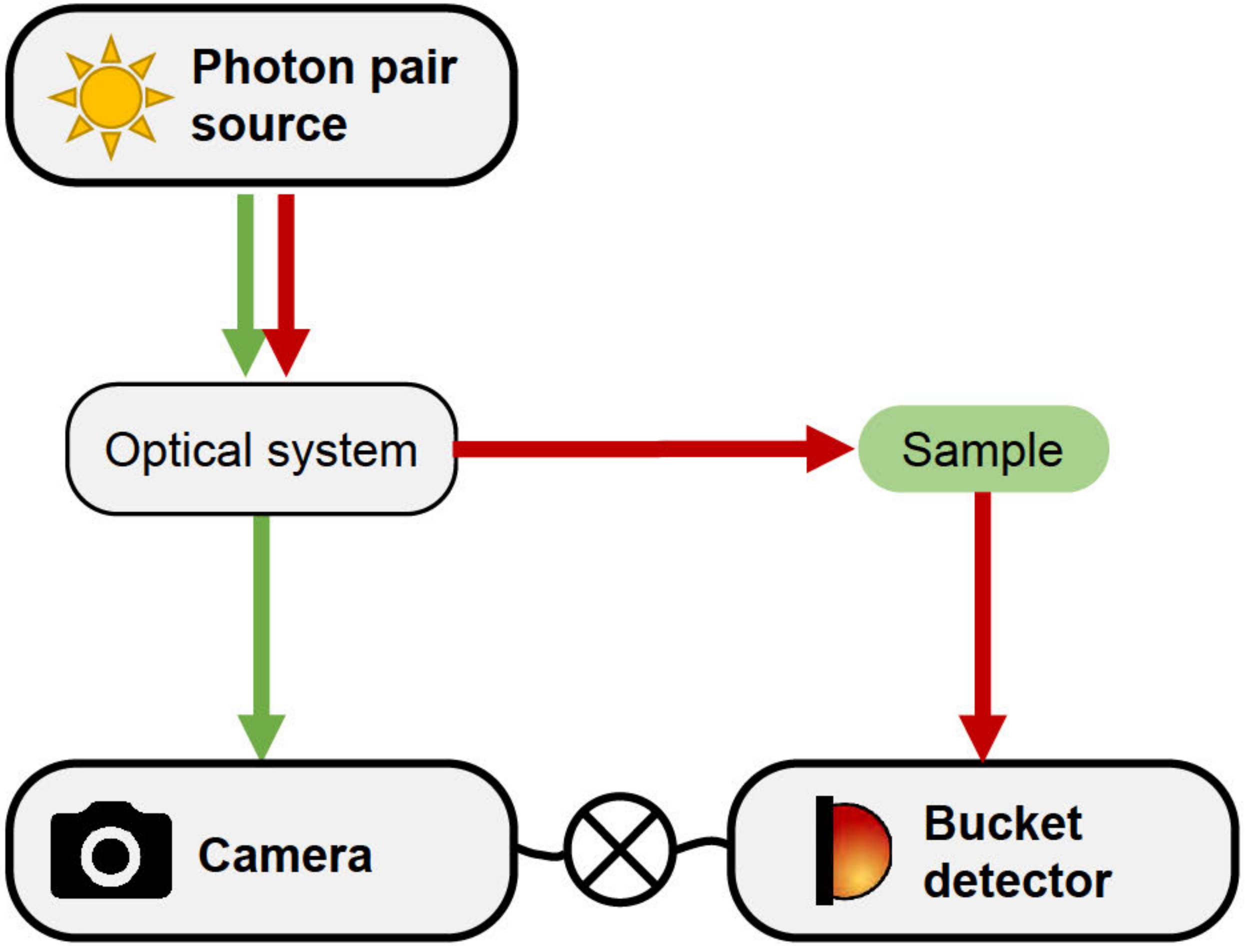
Quantum ghost imaging

- Imaging at “exotic” wavelengths, where cameras are not readily available.
- Signal-to-noise ratio
  - photosensitive samples
  - covert imaging

Combine this with an endoscope:

➢ Minimally invasive imaging at “exotic” wavelengths, with low-intensity light.

Quantum ghost imaging



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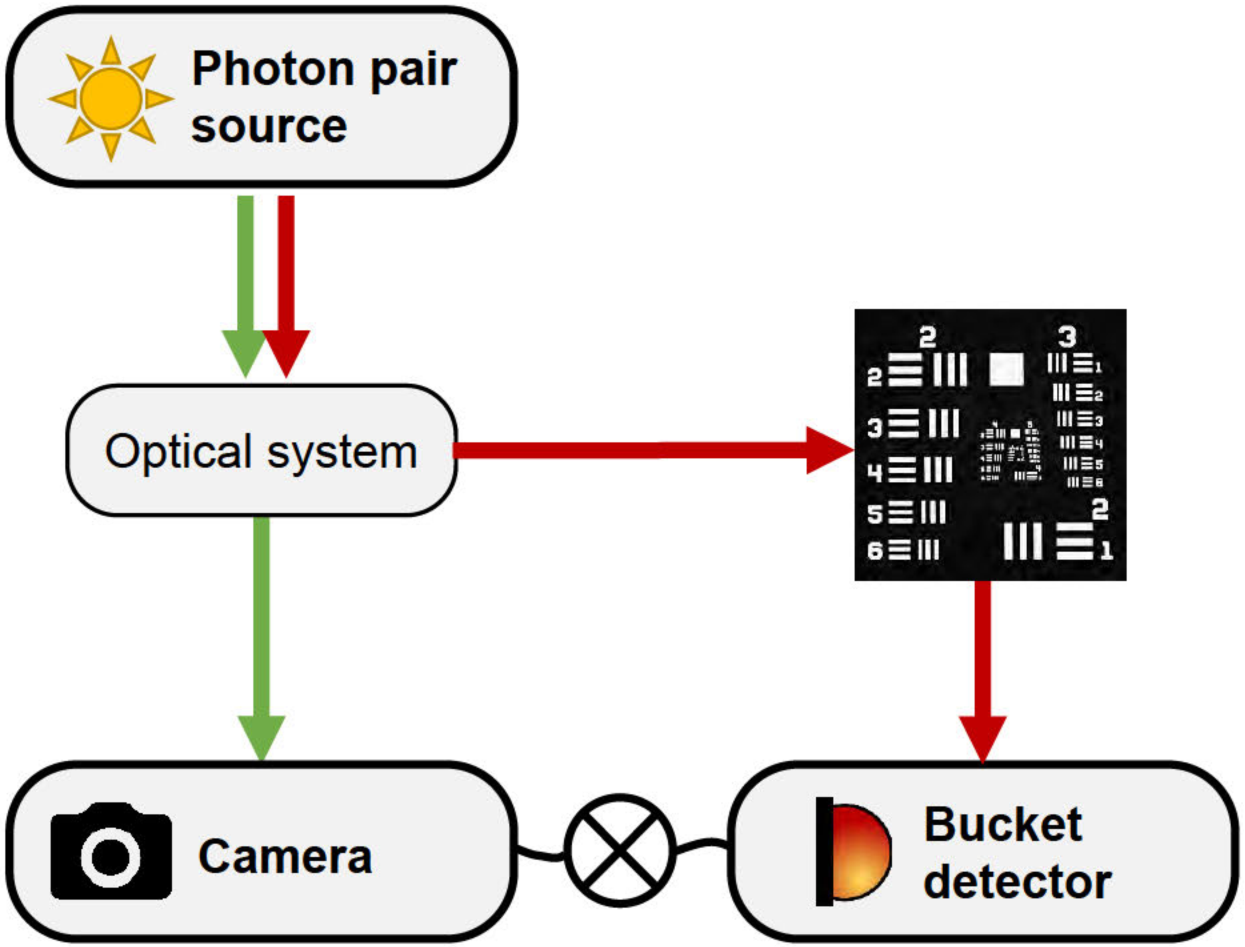

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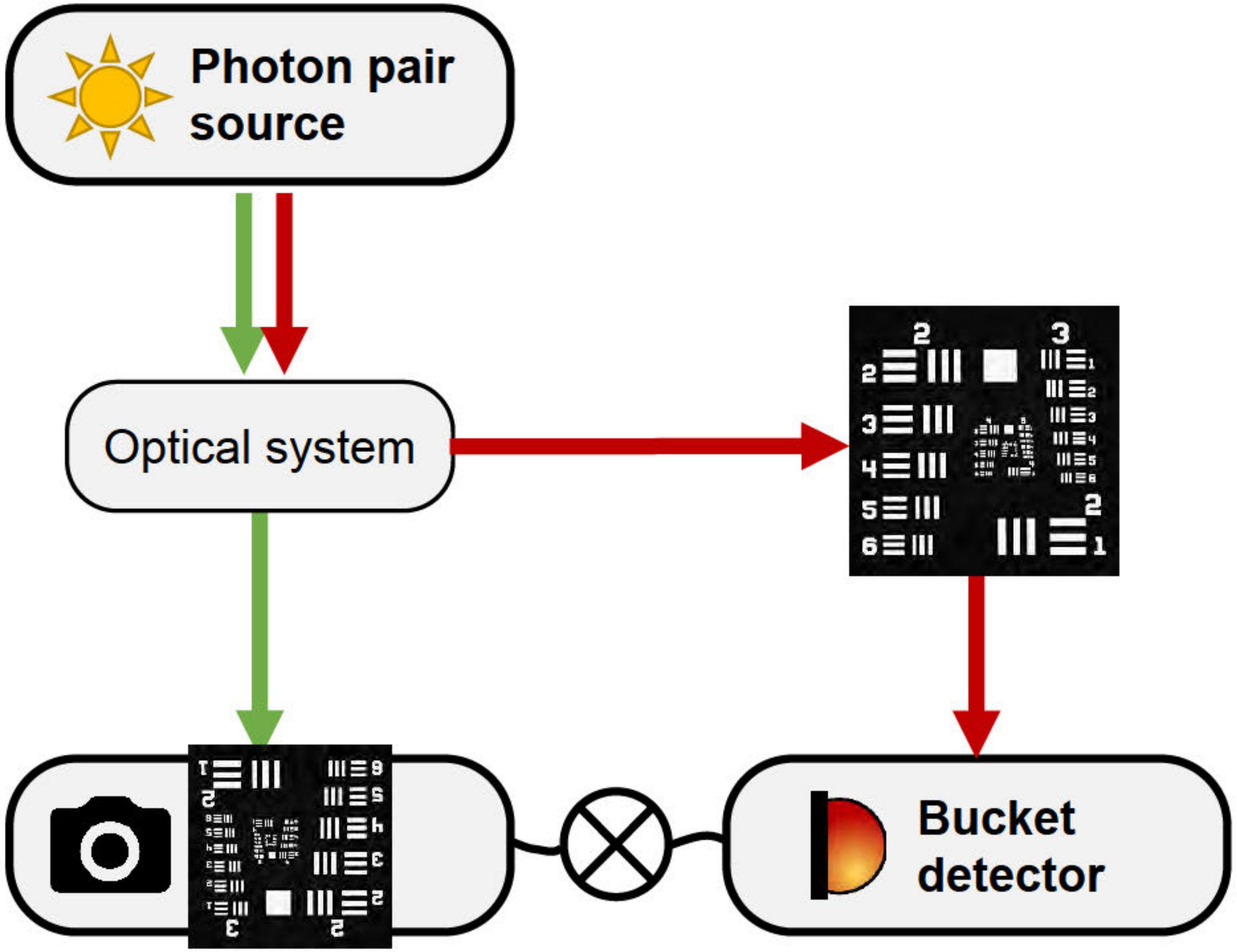

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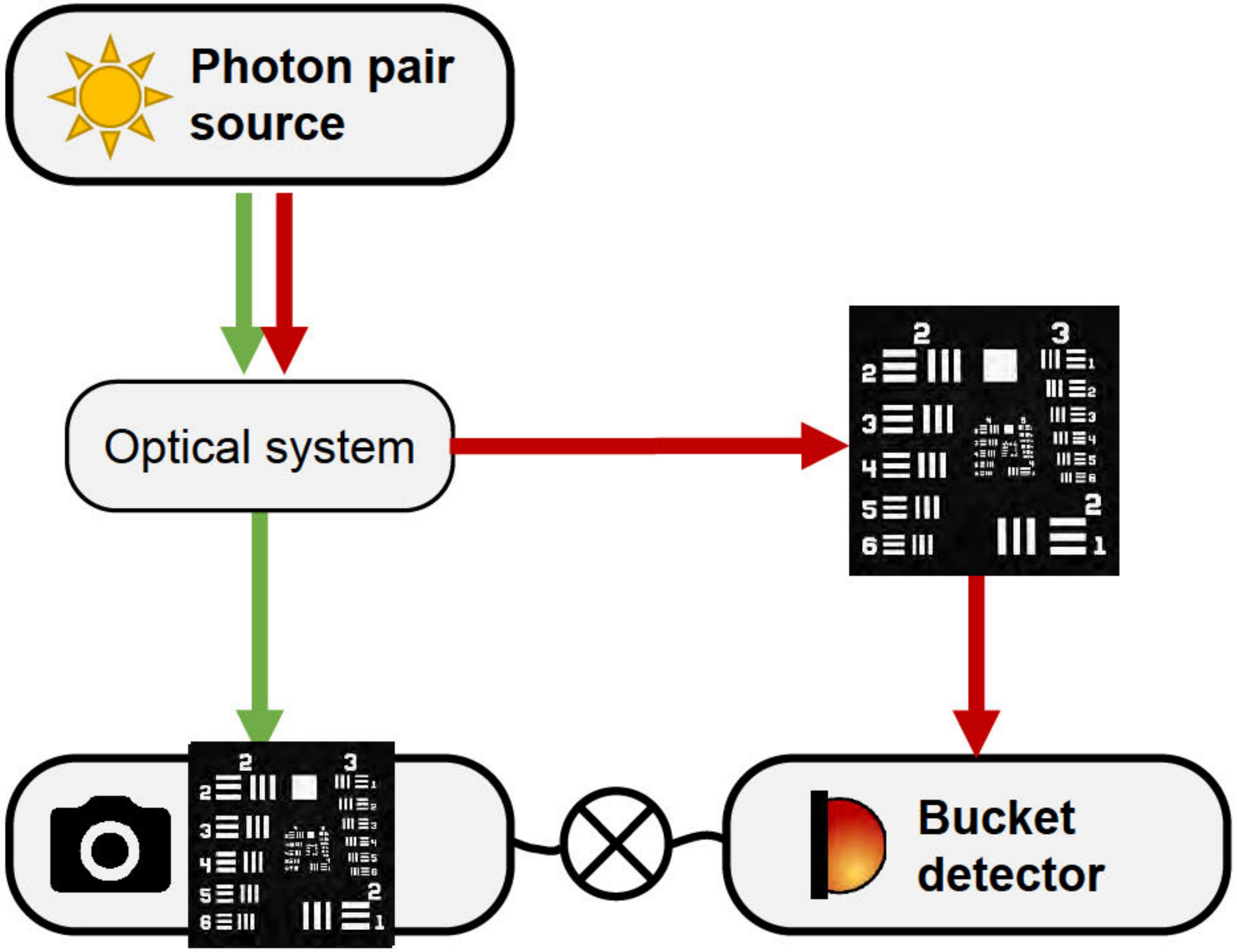
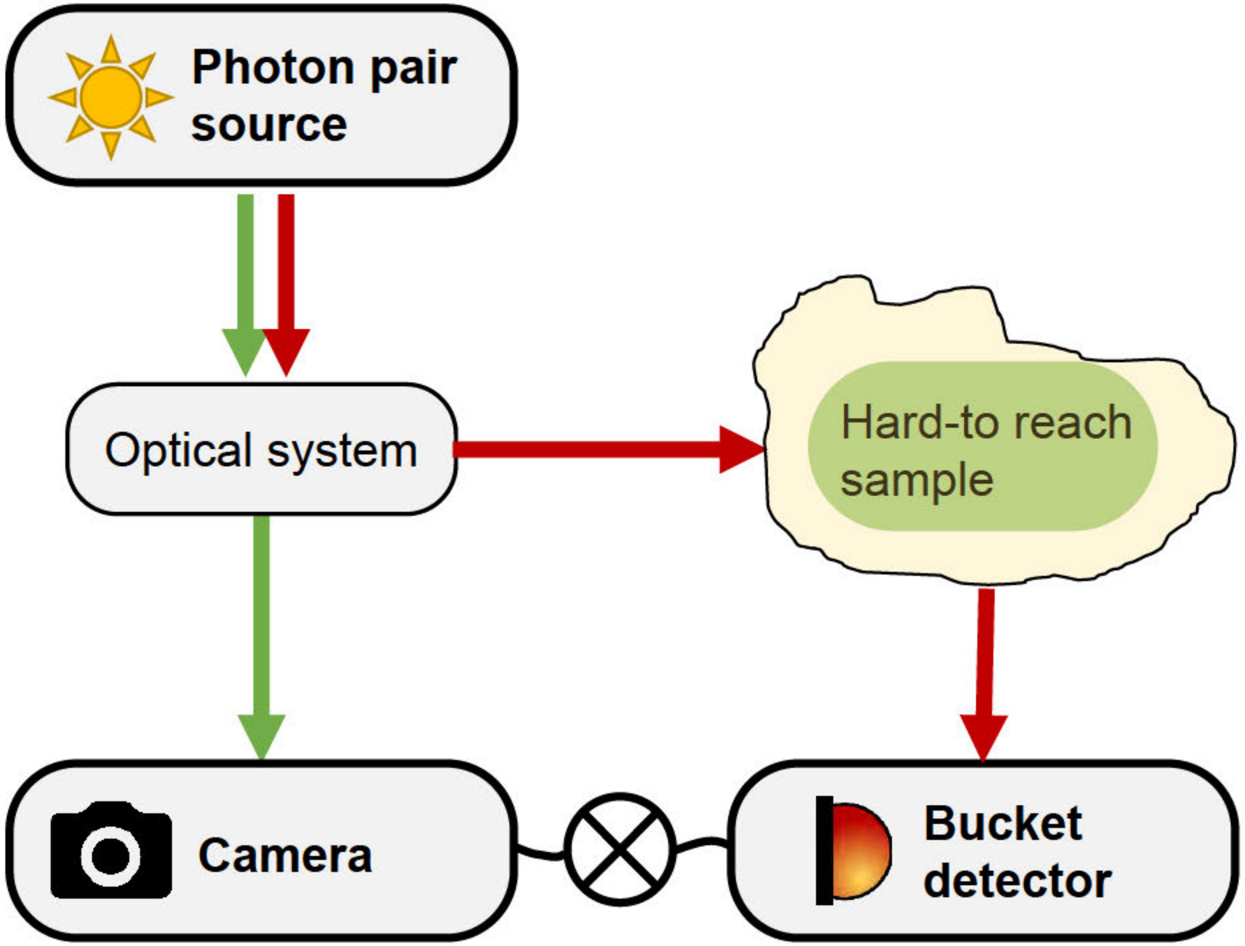


Endoscopy-type quantum ghost imaging



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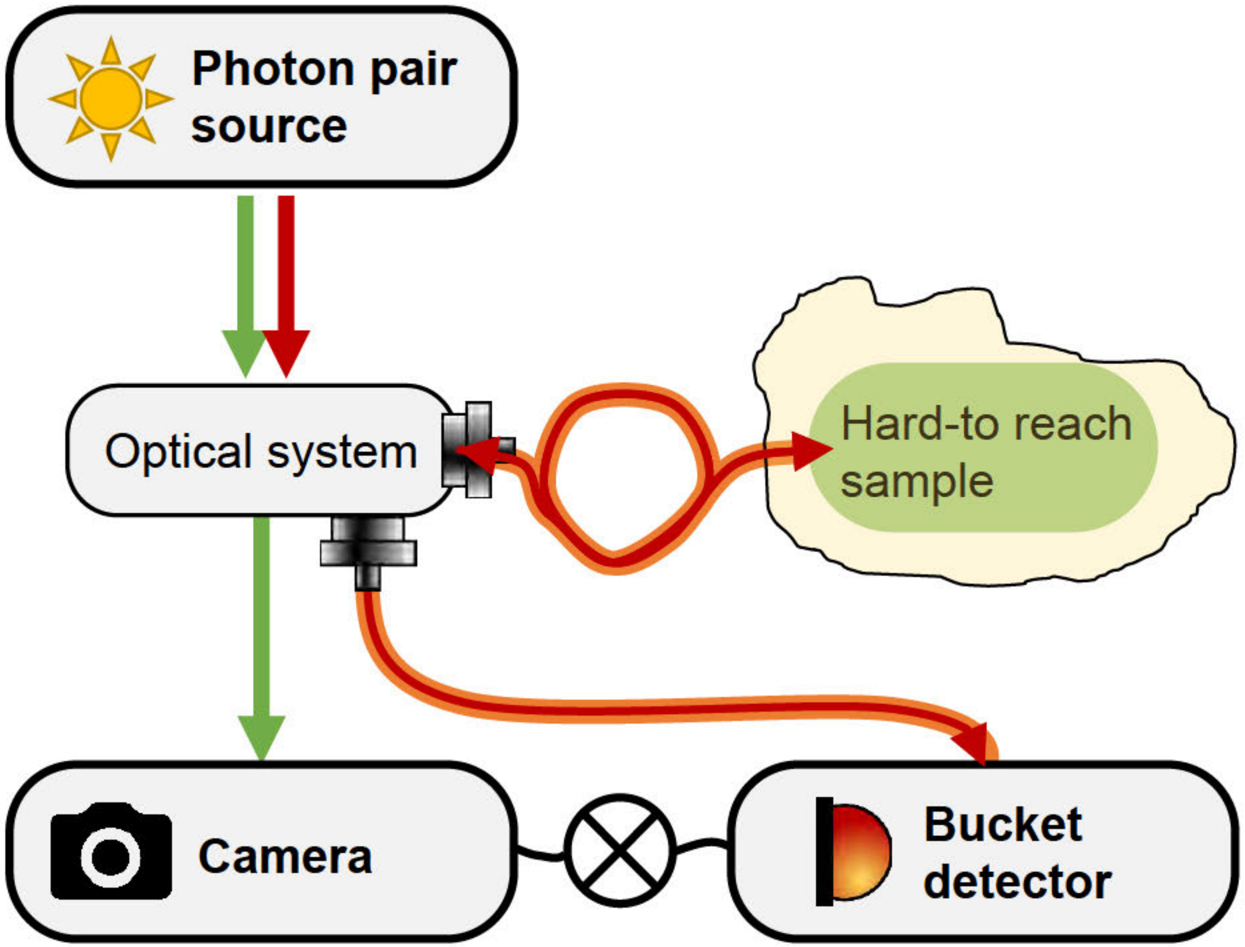


Image fibre

Requirement:

- conserve quantum correlations

➢ Quantify experimentally

State-of-the-art

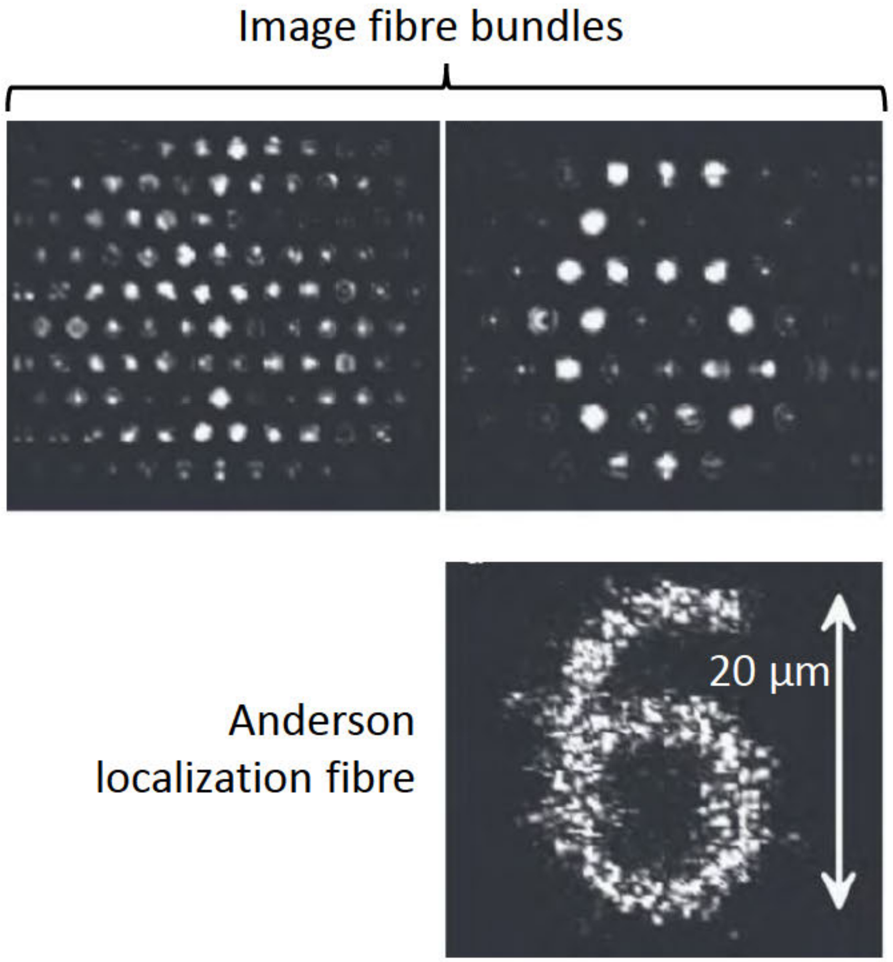
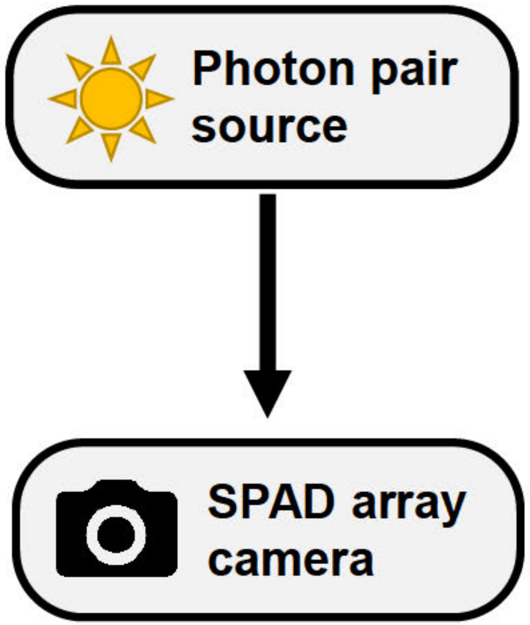
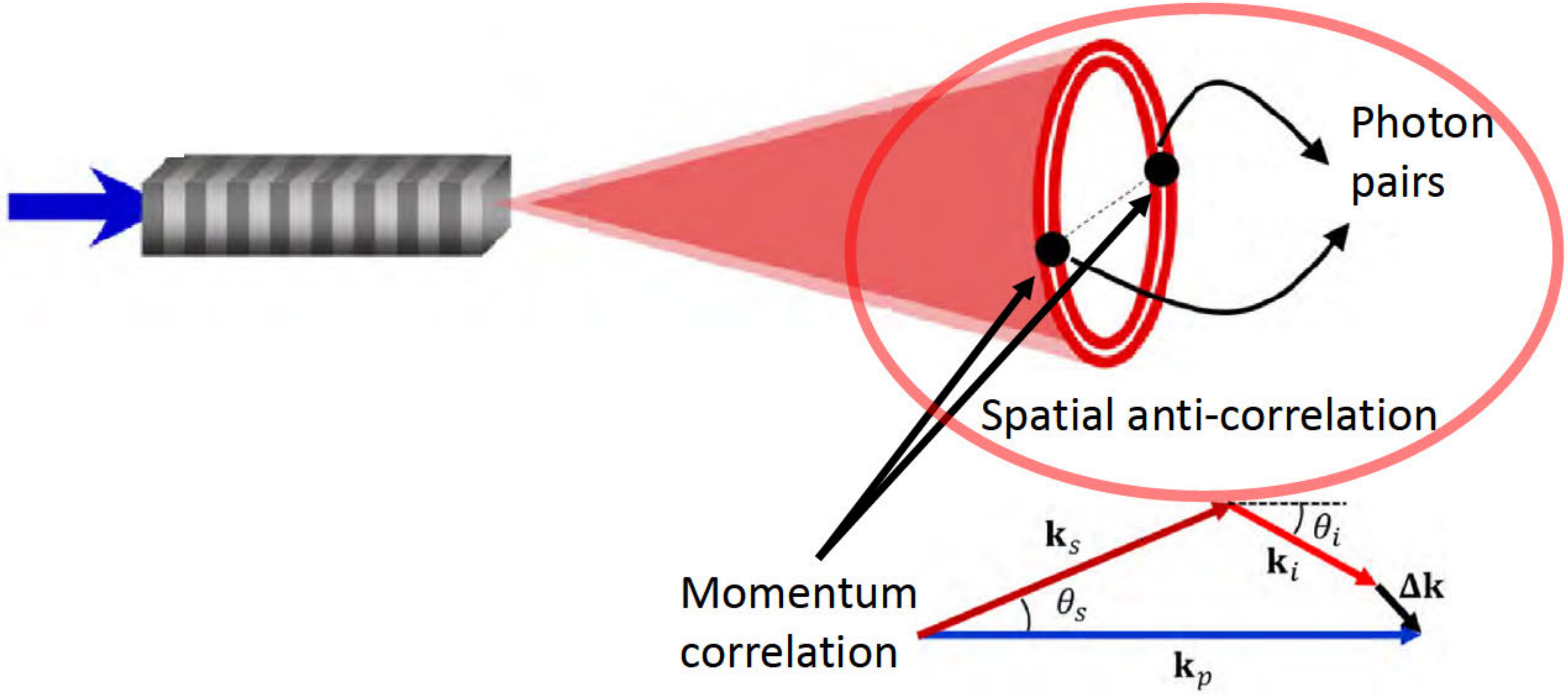


Figure from 10.1109/JLT.2019.2916020

Figure adapted from 10.1038/ncomms4362

Reminder: spatial anti-correlation





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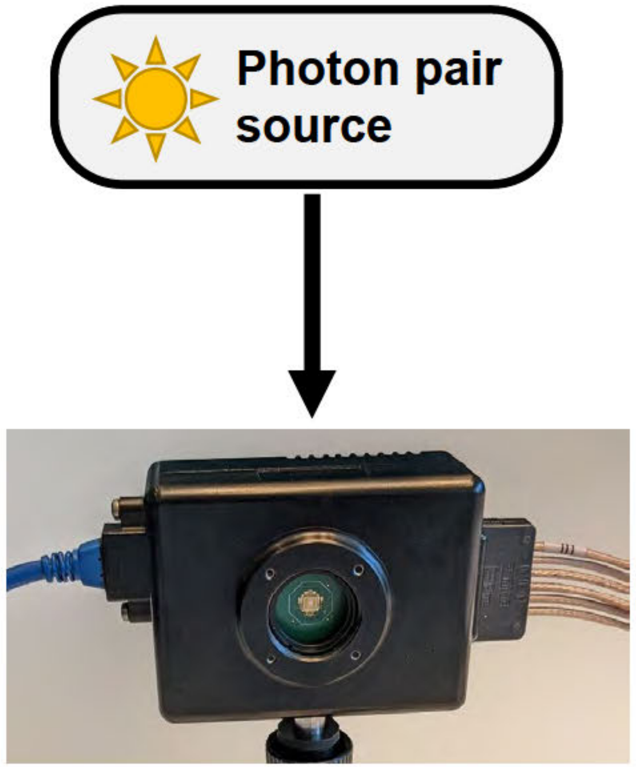

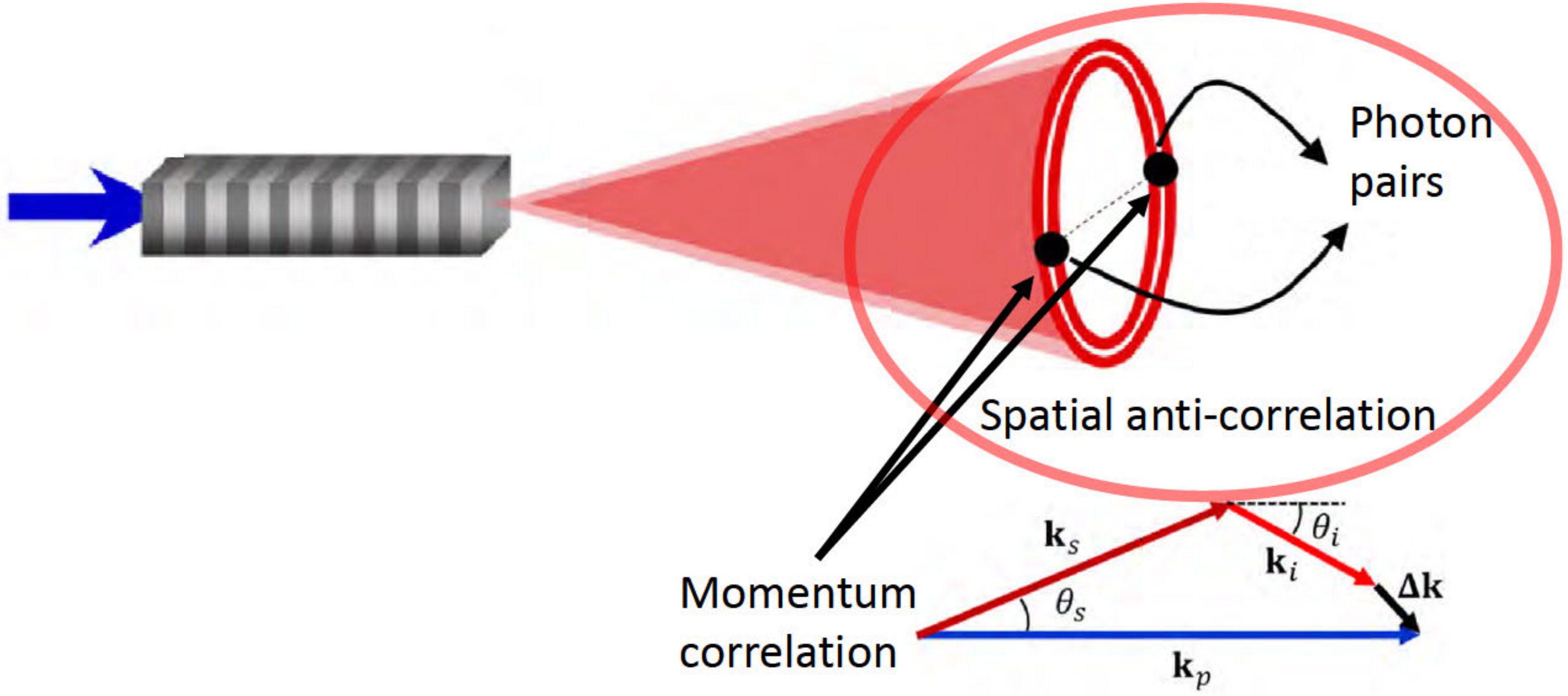

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Quantifying correlations via coincidence measurement

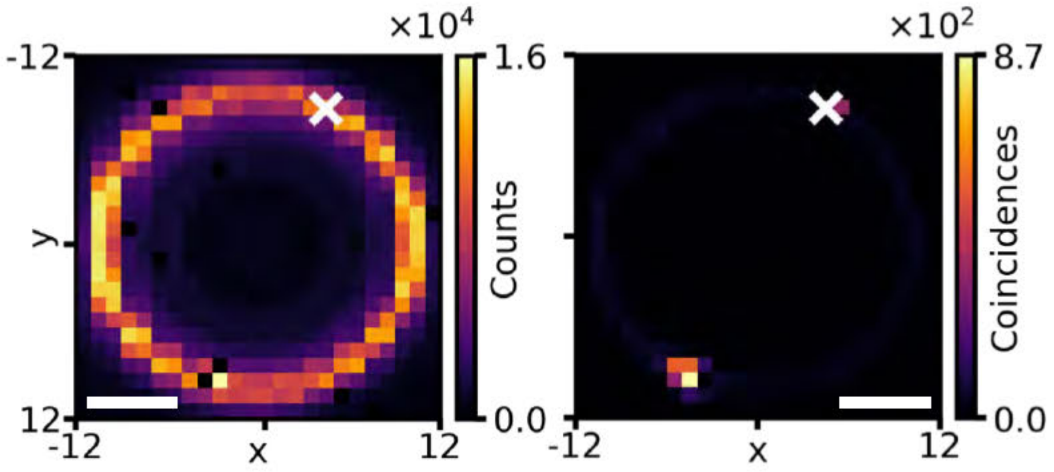
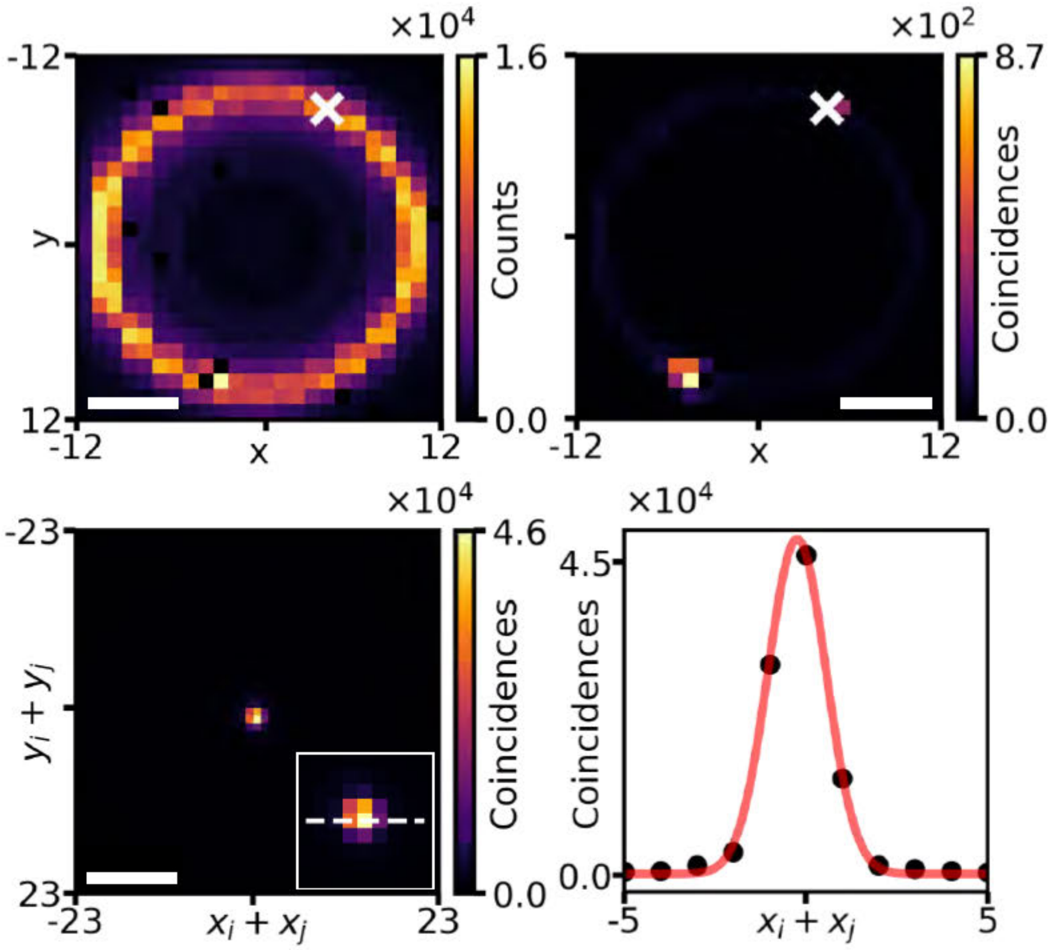


Figure from: Alexander Demuth, et al. **Quantum light transport in phase-separated Anderson localization fiber**. *Communications Physics* **5**(261), 2022.

Quantifying correlations via coincidence measurement



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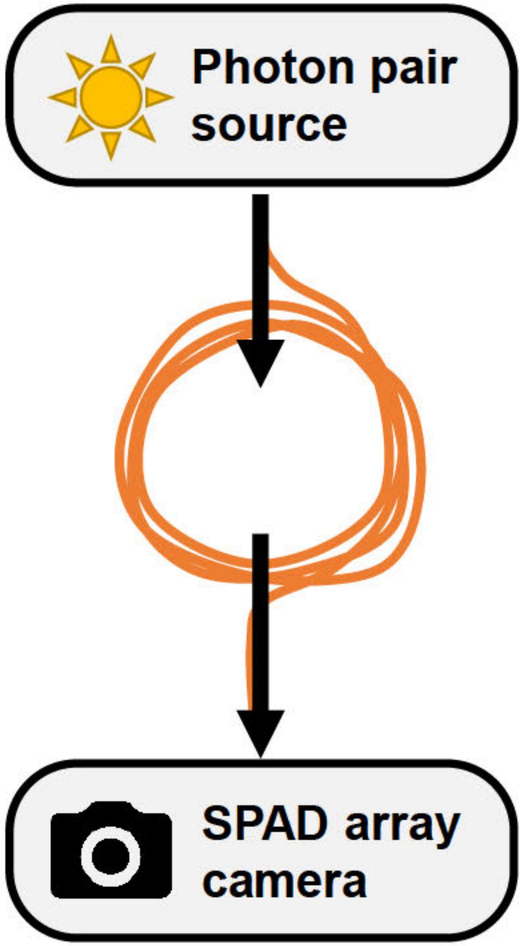
Setup



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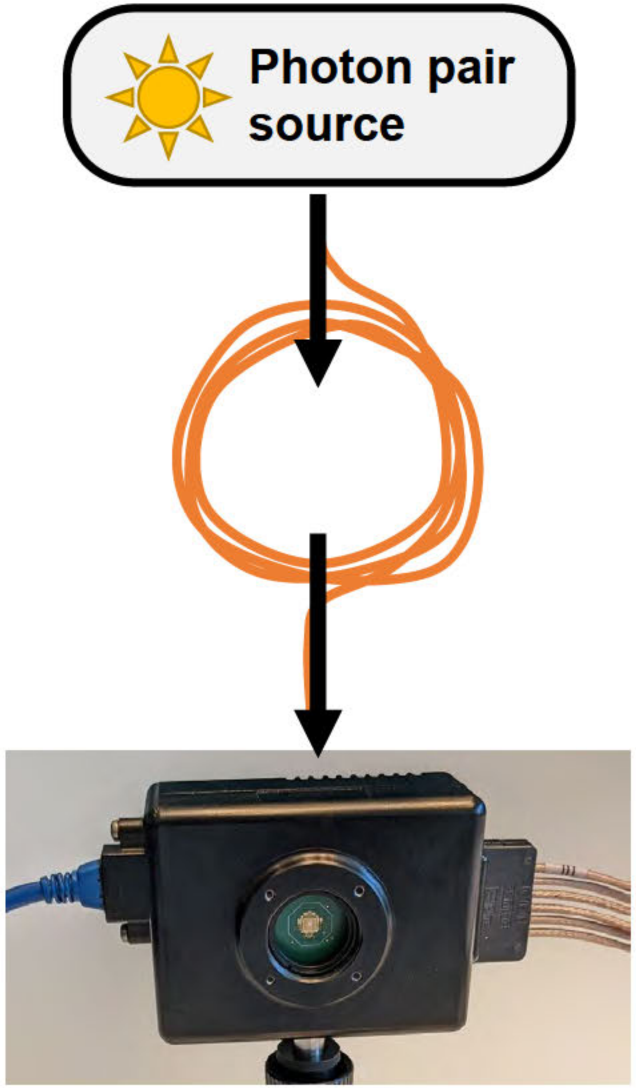

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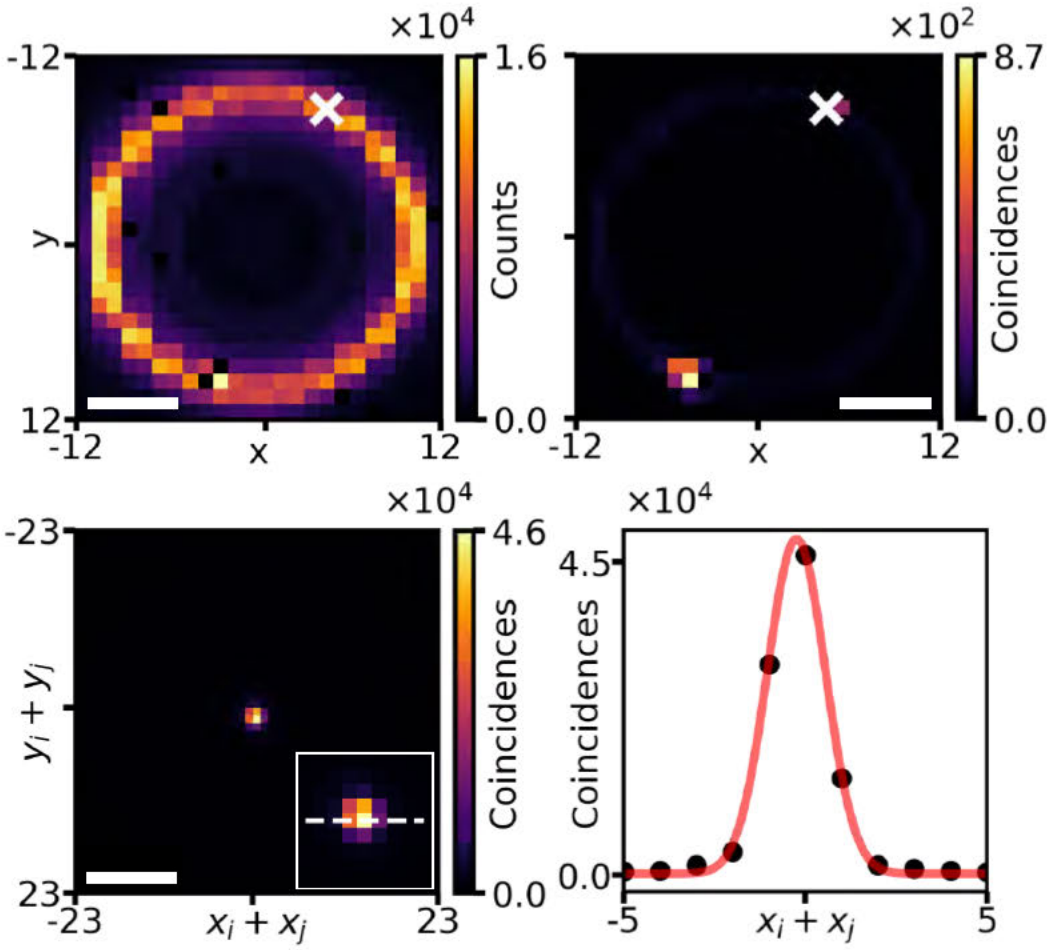

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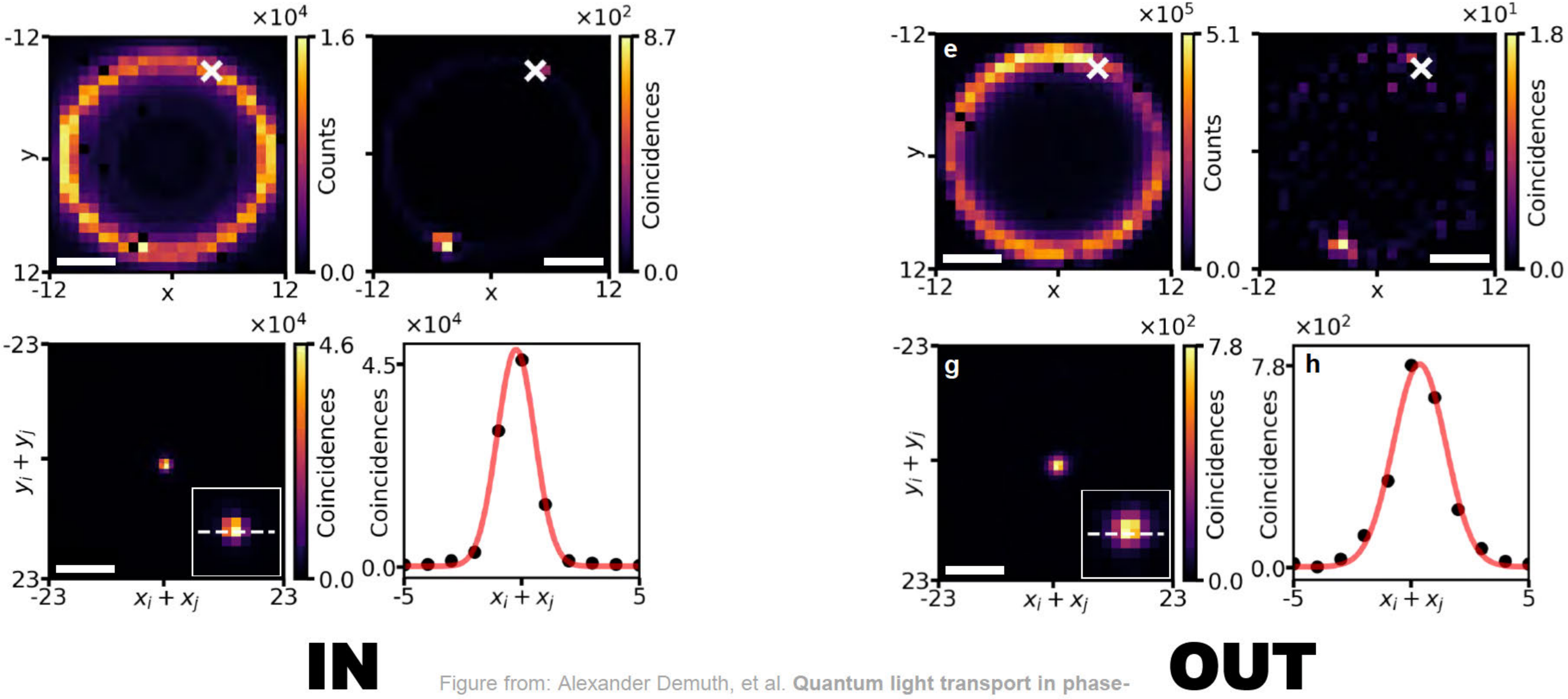

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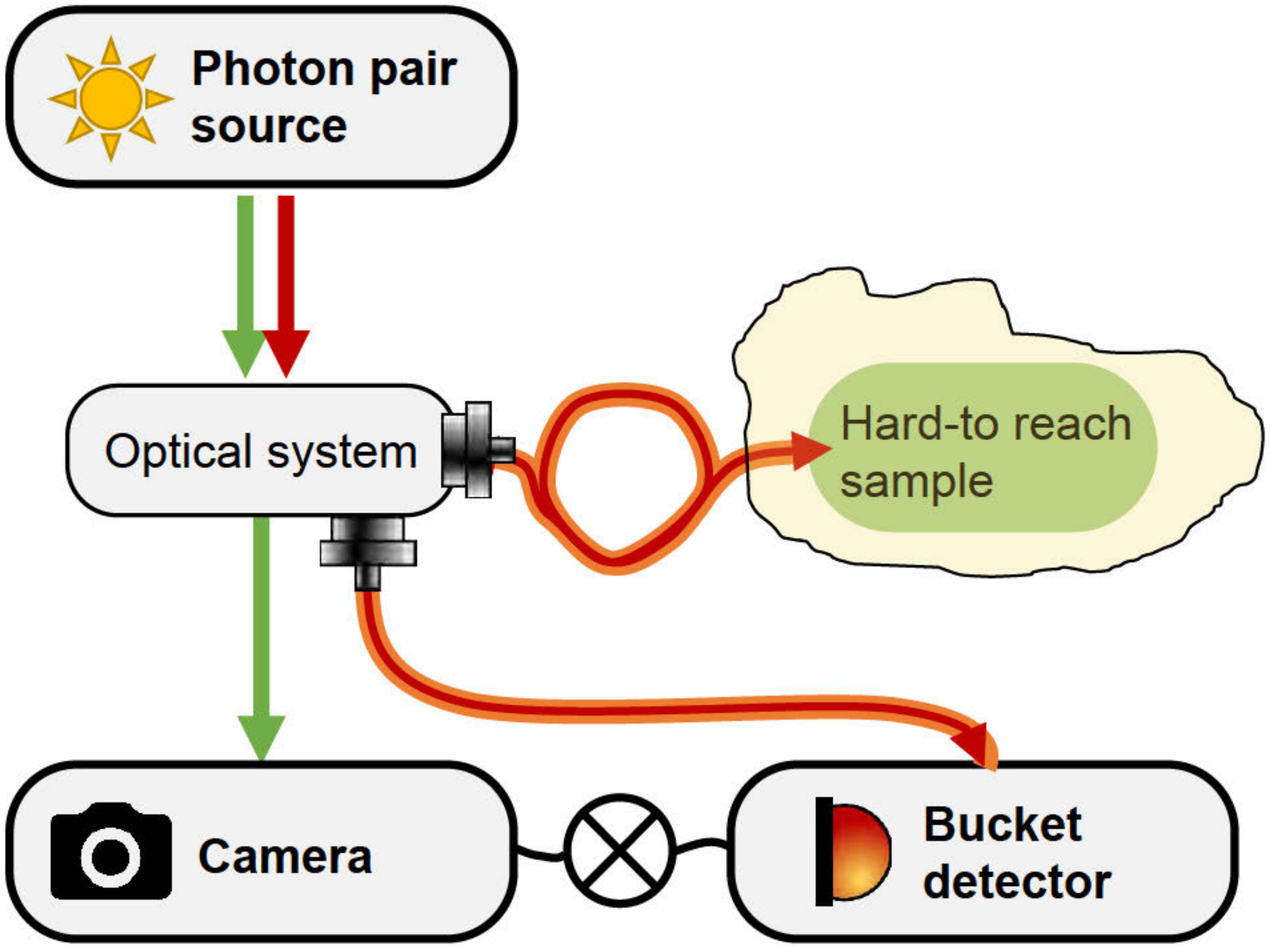
Endoscopy-type quantum ghost imaging



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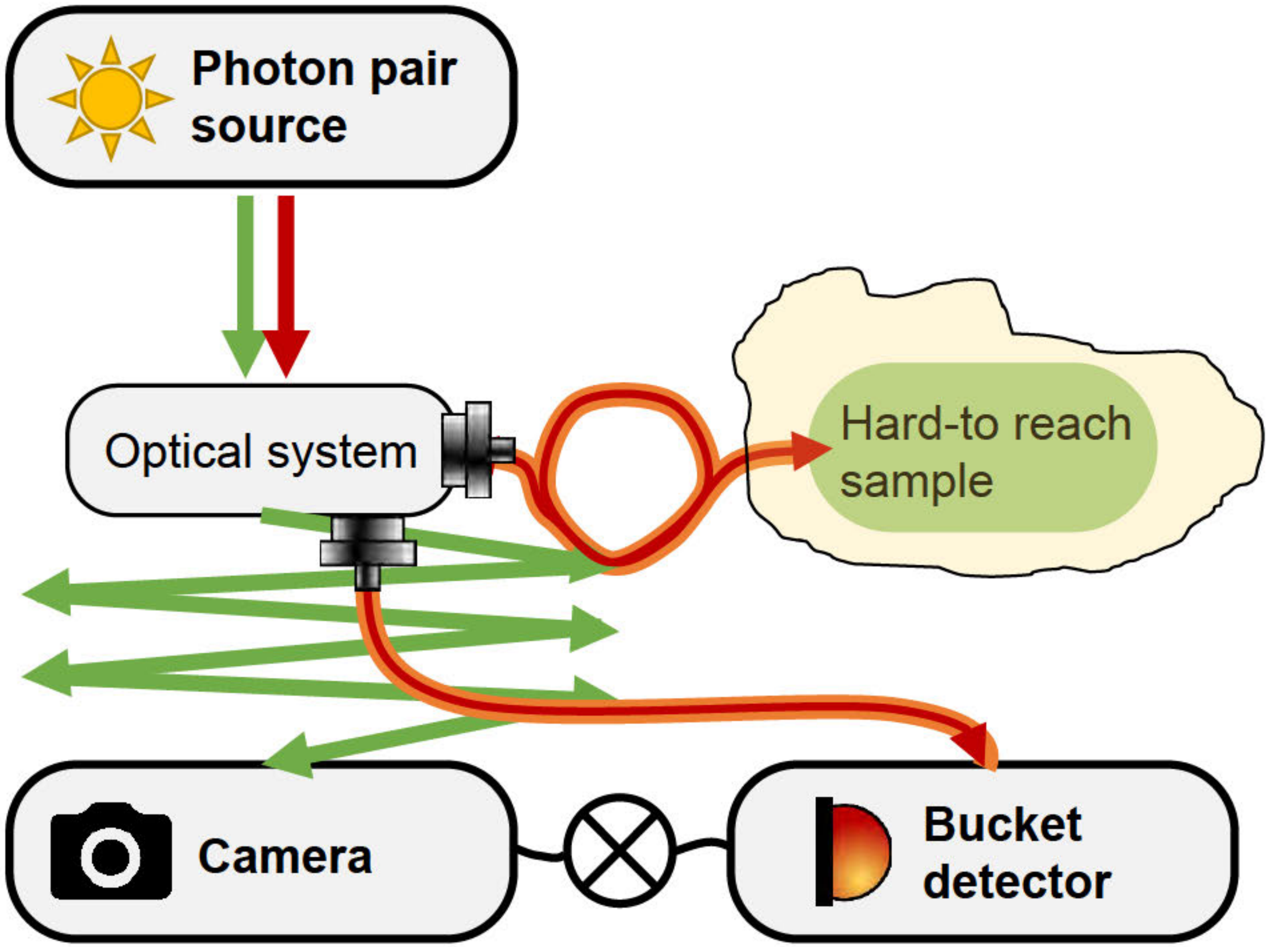
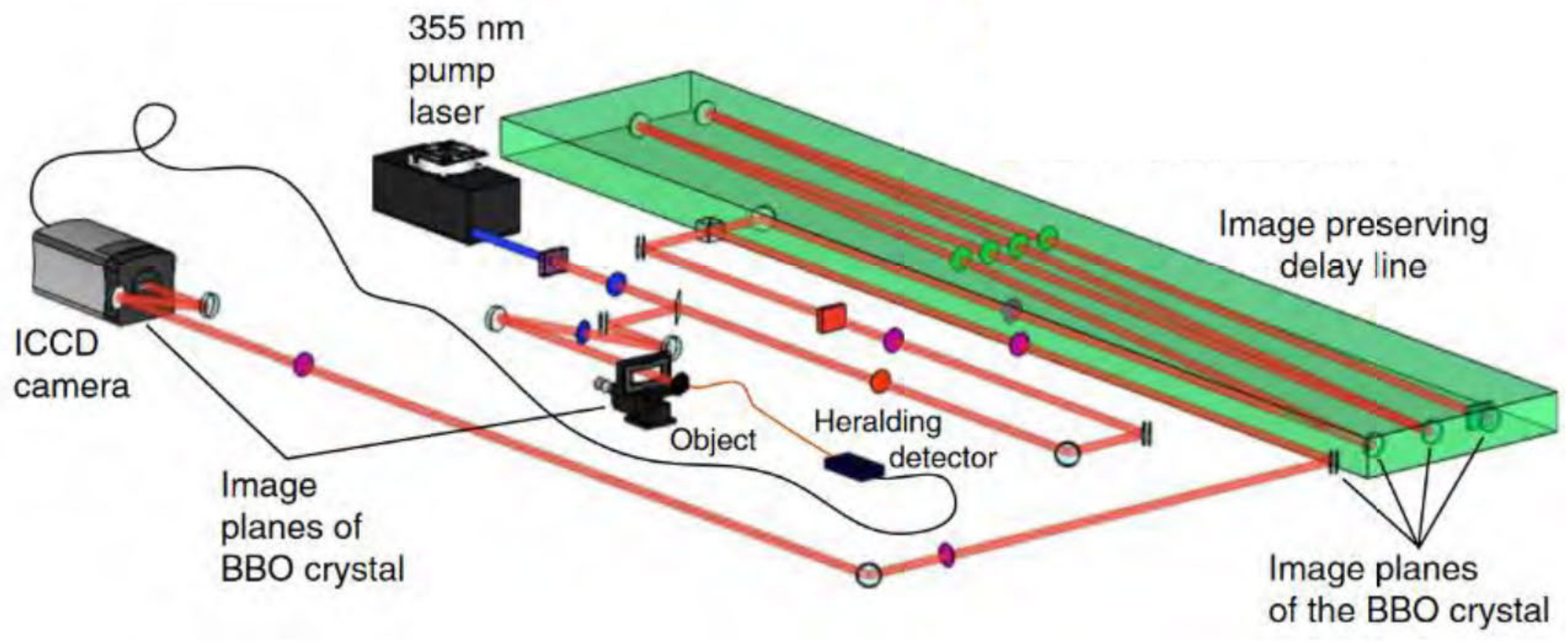


Experiments so far

- ICCD camera is not time-tagging, needs low light exposure.
- Image preserving delay lines of ~20 m.

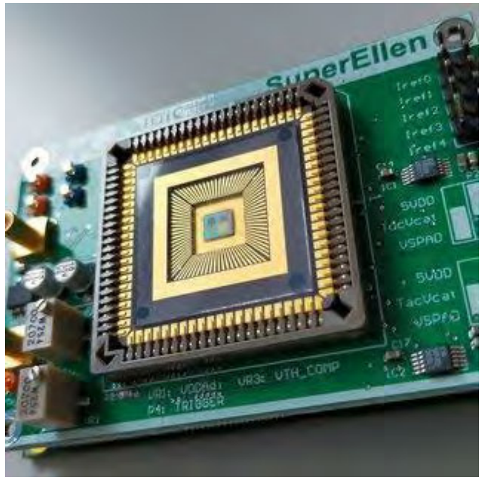


10.1038/ncomms6913

Looking-back-in-time SPAD arrays…

… as an alternative to image-preserving delay lines.

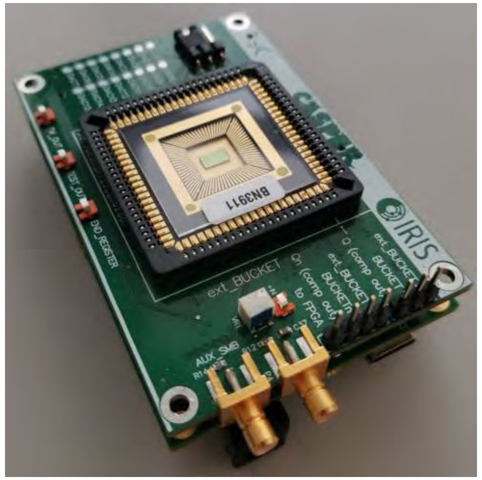
FBK SuperEllen



10.1364/AO.487084

- Time-tagging

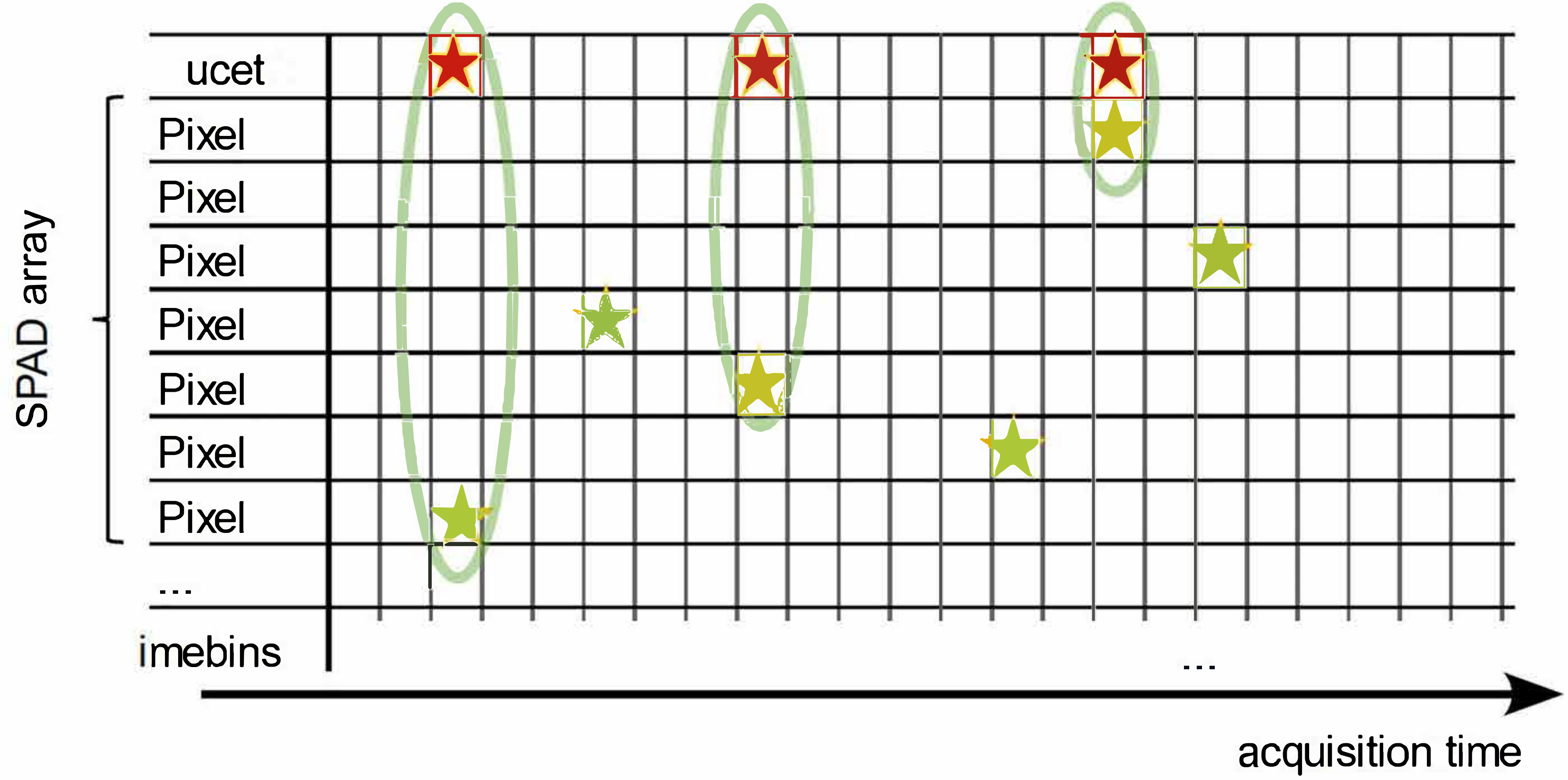
FBK Casper



10.1109/ESSCIRC59616.2023.10268722

- Not time-tagging

FBK SuperEllen – time-tagging



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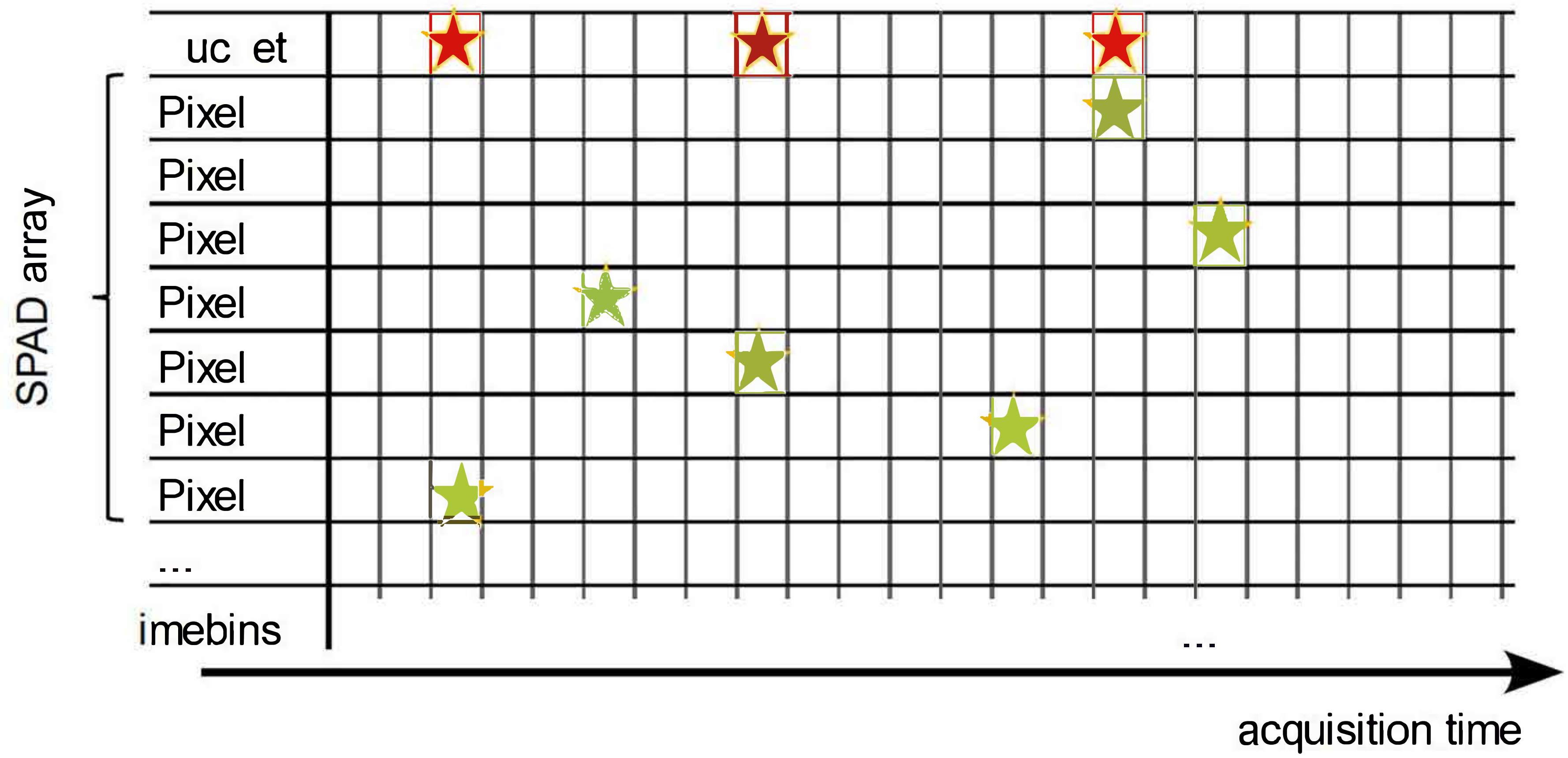

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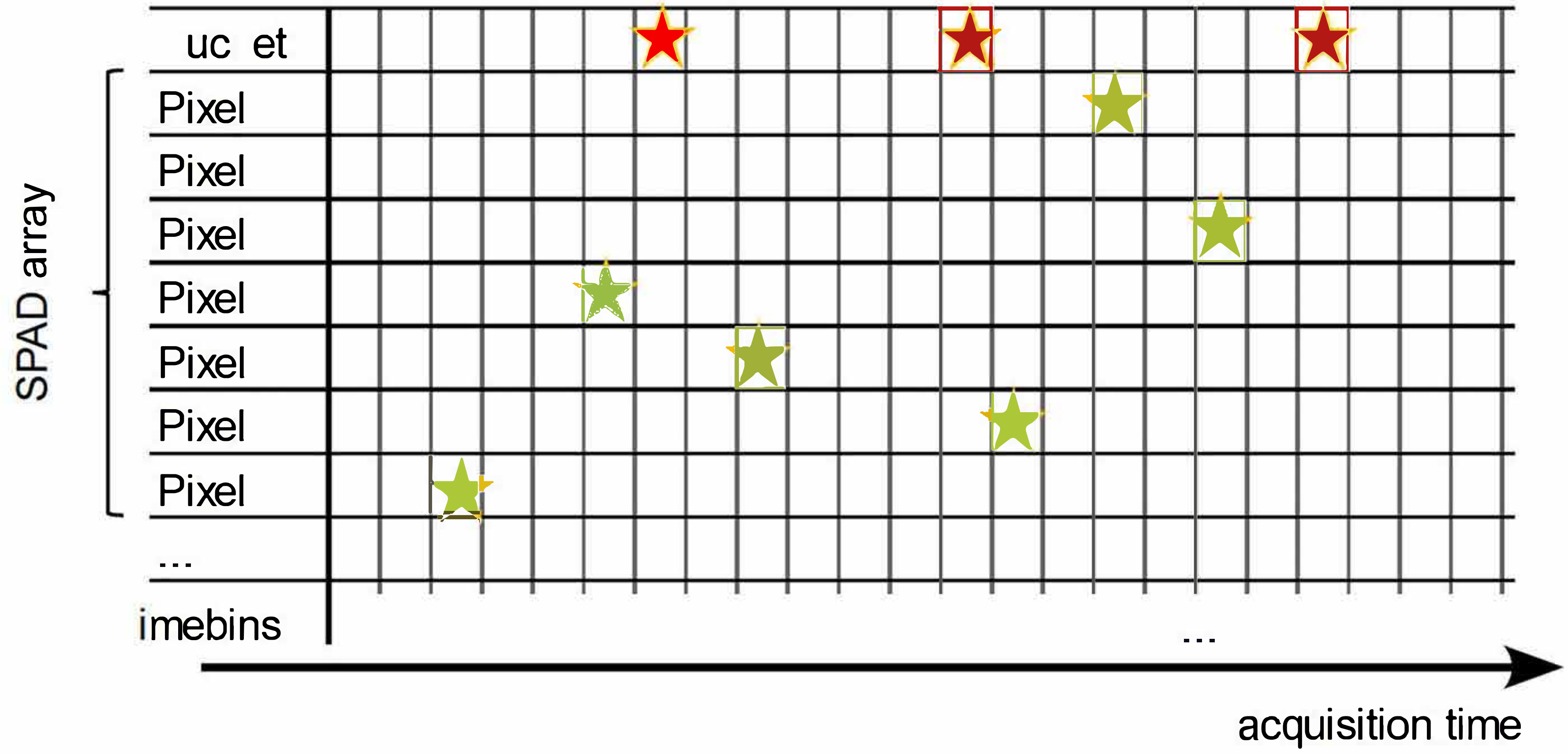

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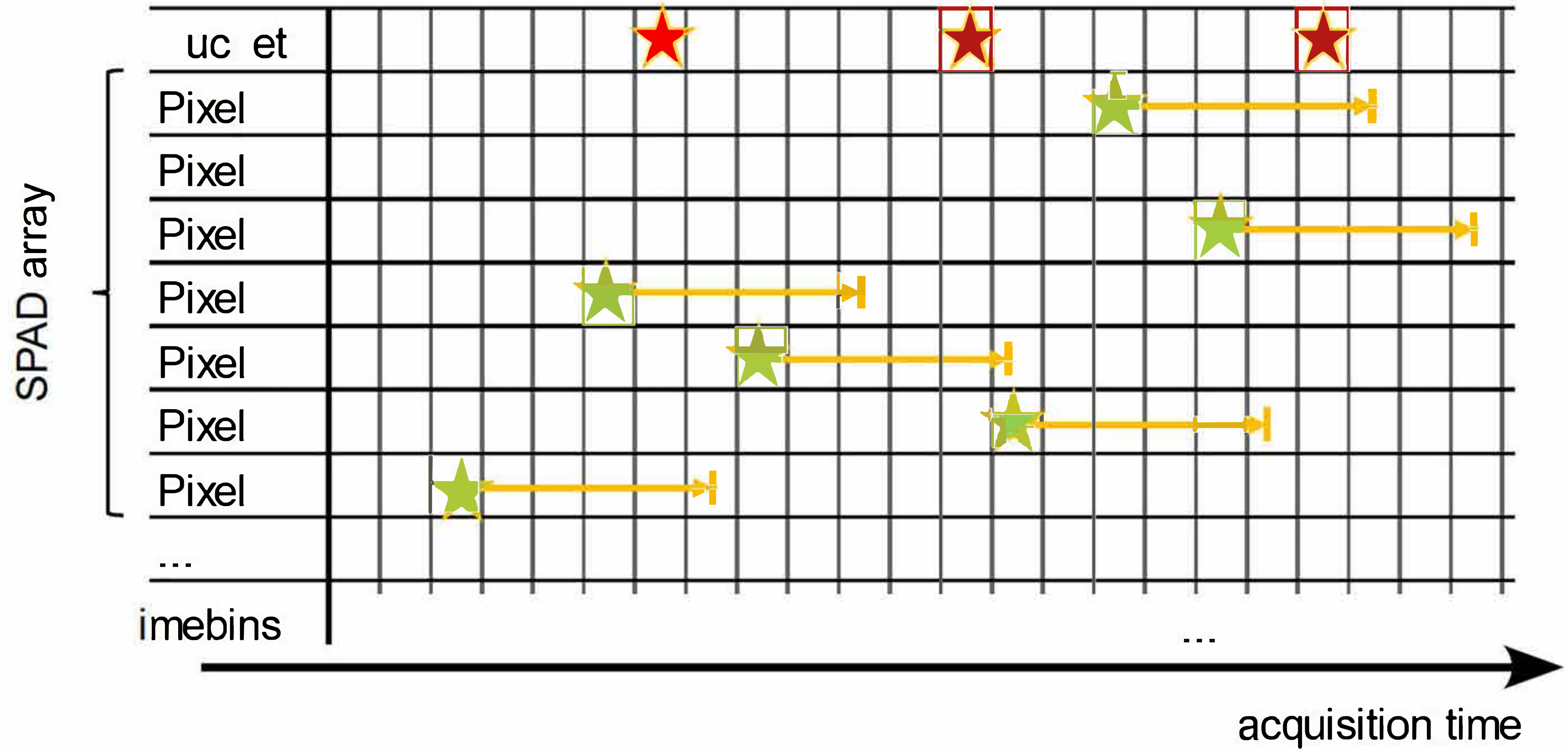

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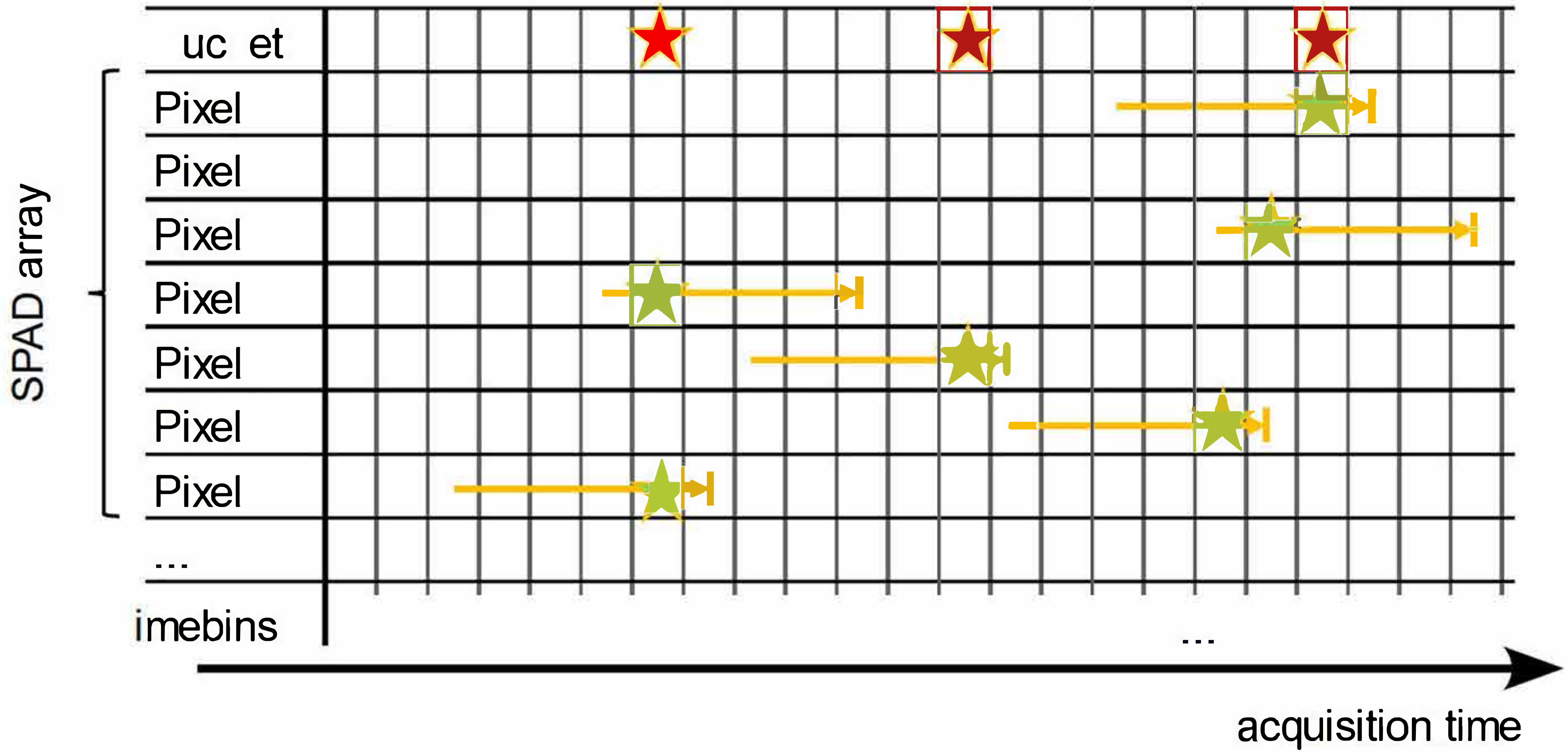

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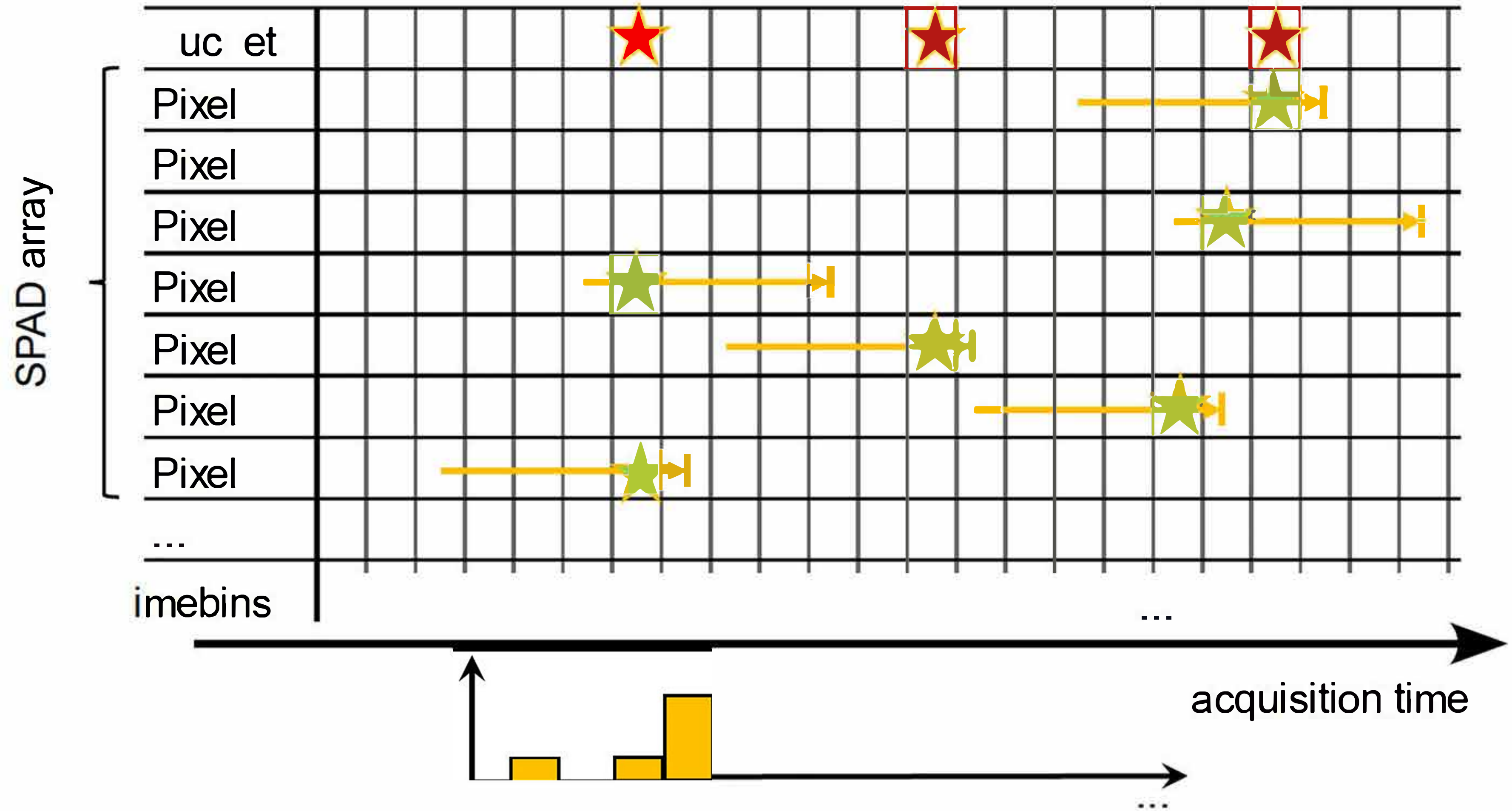

Accumulate histogram of timestamps (delays)

10.1364/AO.487084

FBK Casper – delaying

FBK Casper – delaying

FBK Casper – delaying

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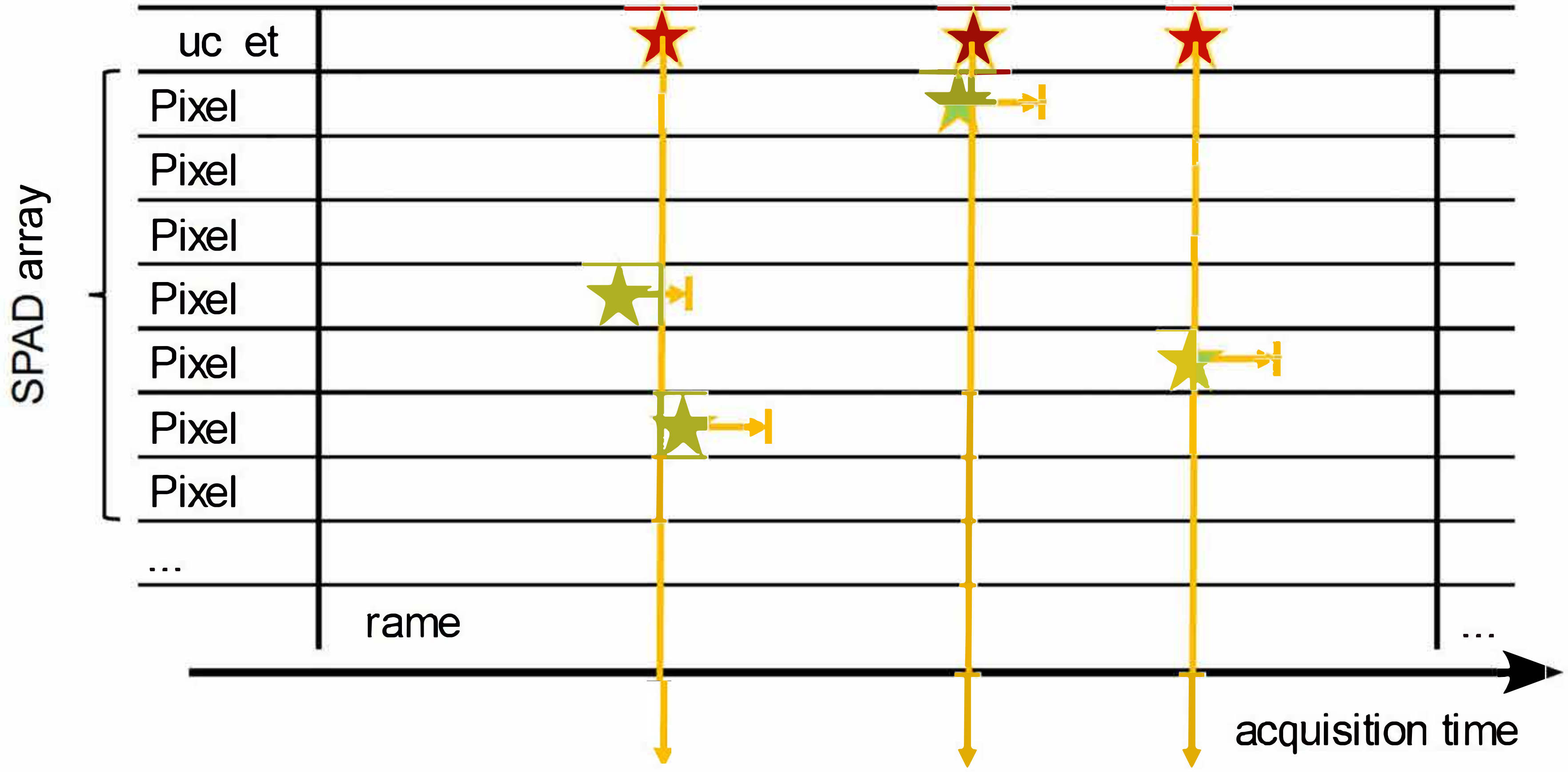
FBK Casper – delaying



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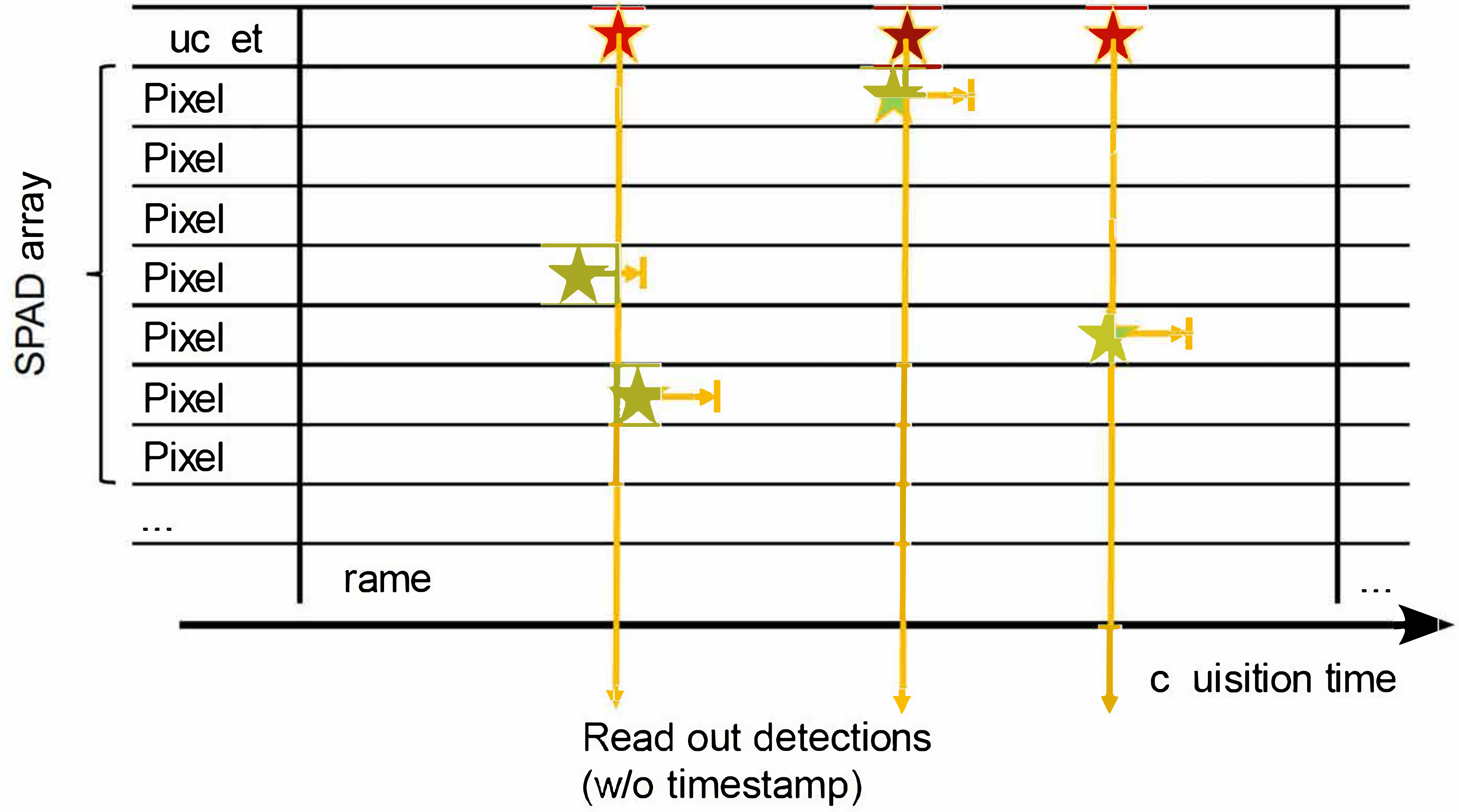
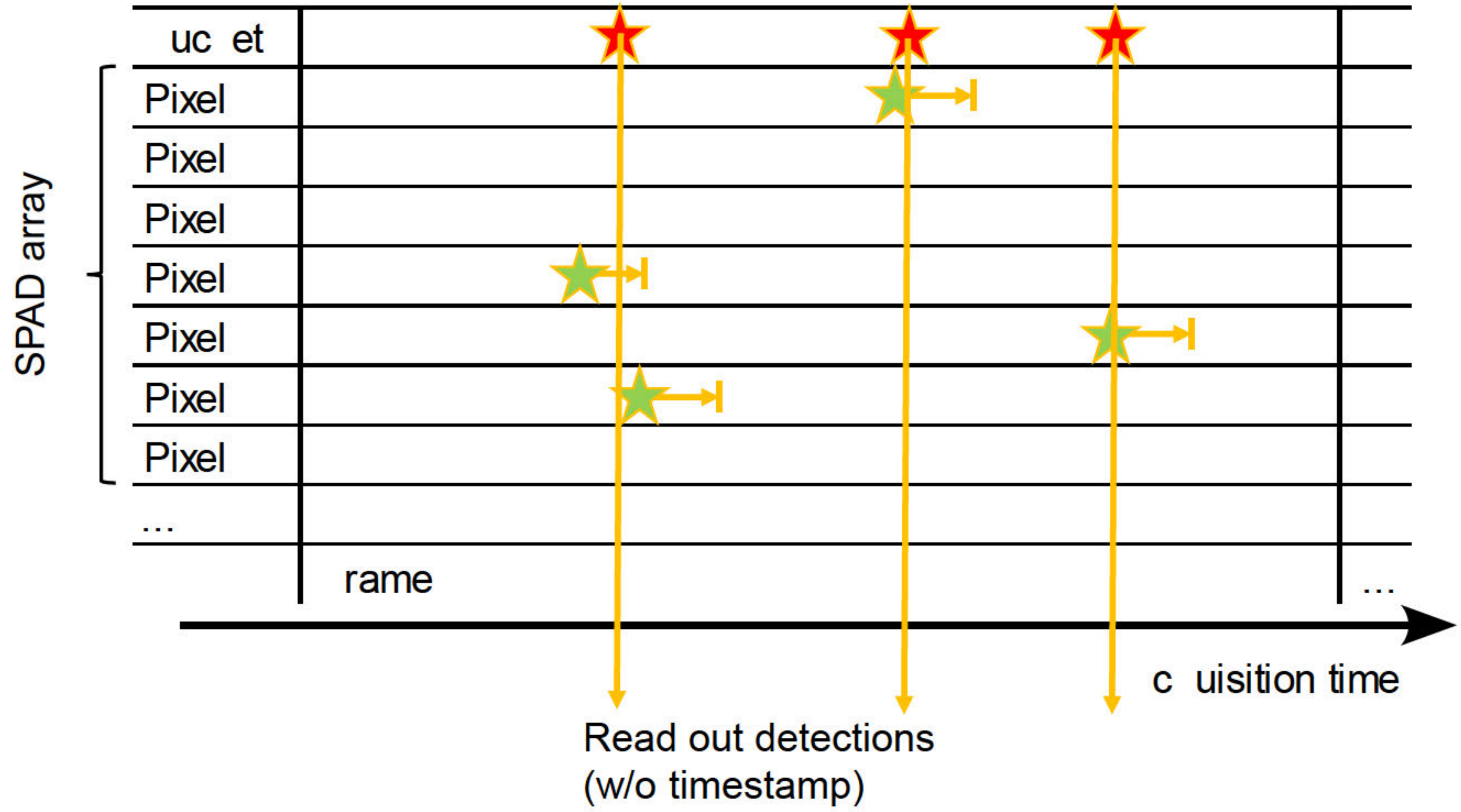


FBK Casper – delaying



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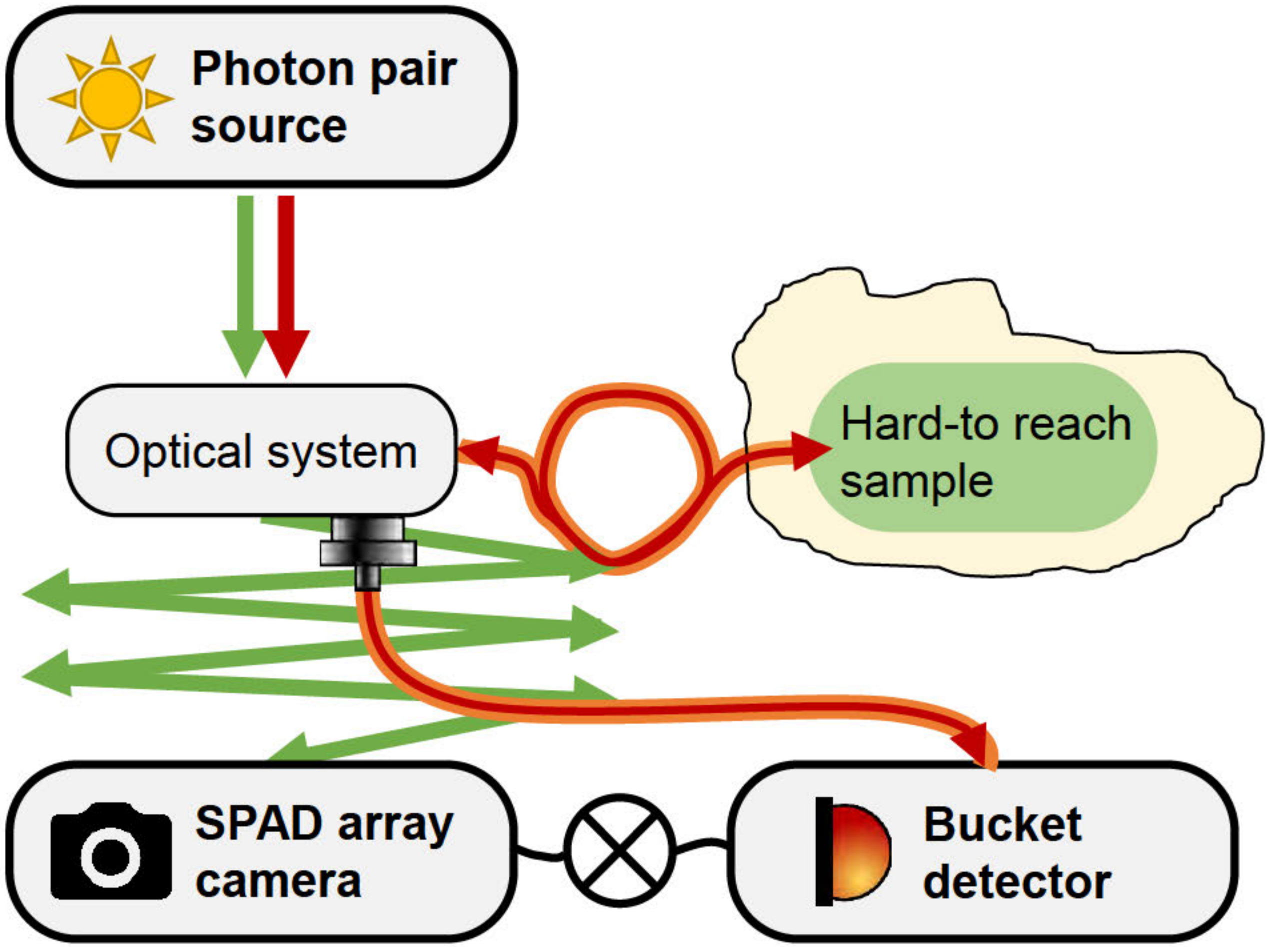
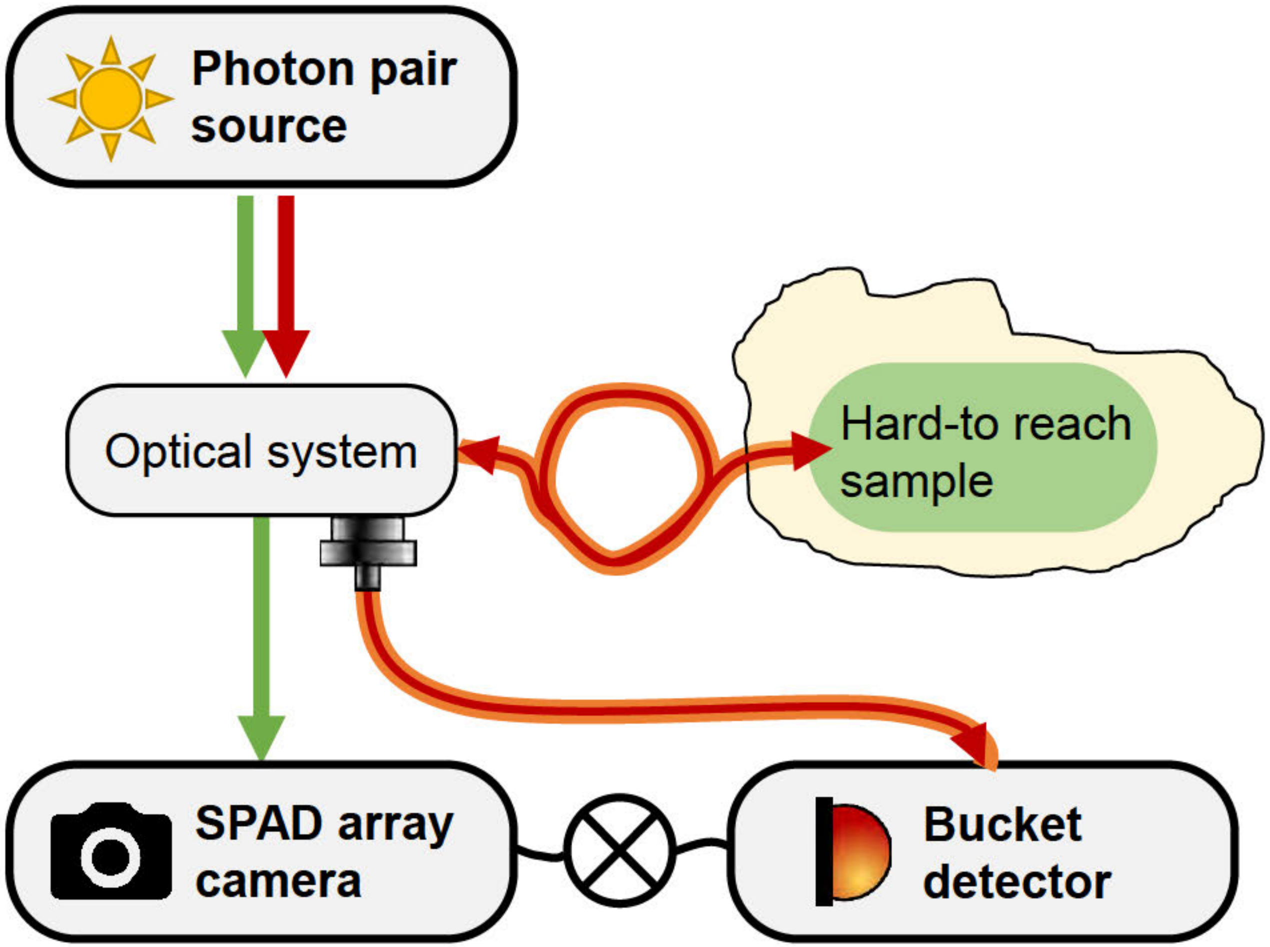
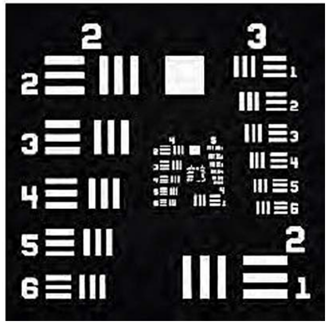
Quantum ghost imaging



Quantum ghost imaging



Preliminary experimental data



Bars from USAF resolution test.

1. Quantum imaging

2. Results
    1. Quantum imaging for phase microscopy
    2. Quantum imaging for endoscopy

3. **Conclusions & Outlook**

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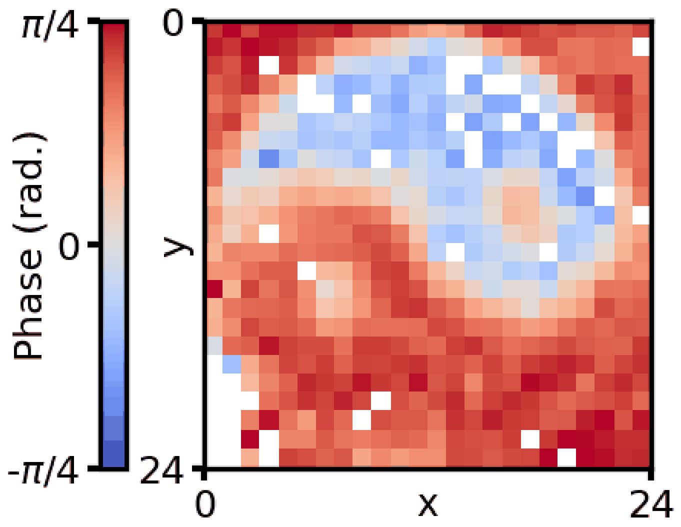
Conclusions & Outlook

Our systems enabled:

- ~Hz rate coincidence imaging with entangled photon pairs
- Transport of quantum correlations through optical fibre
- Endoscopy-type quantum ghost imaging



Future:

- Endoscopy-type quantum ghost imaging of photosensitive samples
- SPAD array technology rapidly advancing – faster, more efficient detection, more pixels…

Thank you