Fast Quantum Ghost imaging with SPADs: from basics to experimental validation with smart sensor architectures

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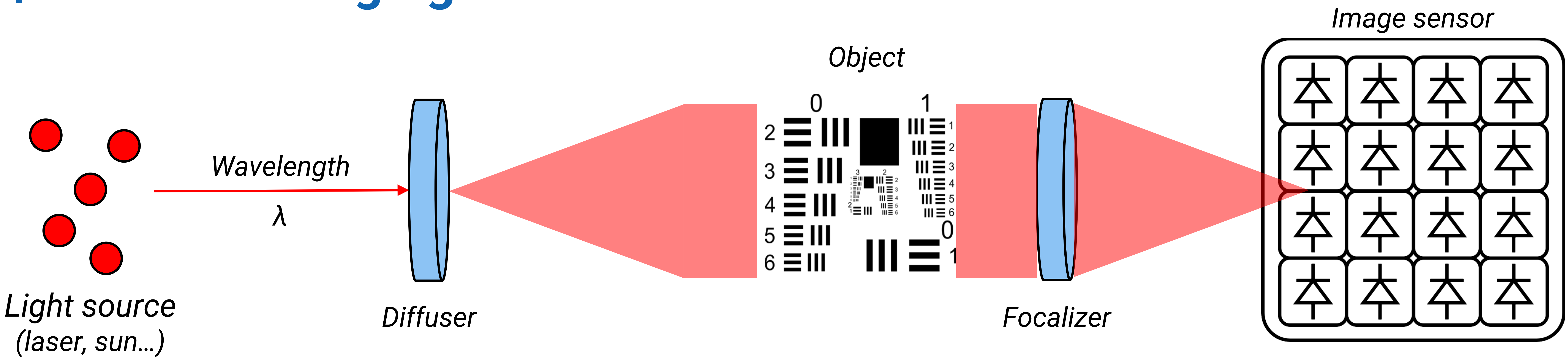
International SPAD Sensor Workshop 2022

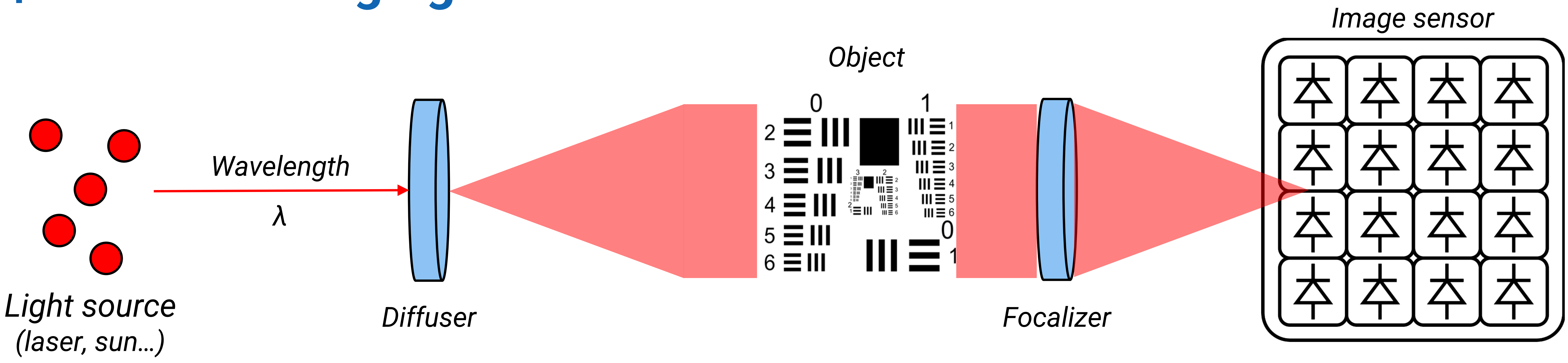
Fast Quantum Ghost imaging with SPADs
Outline

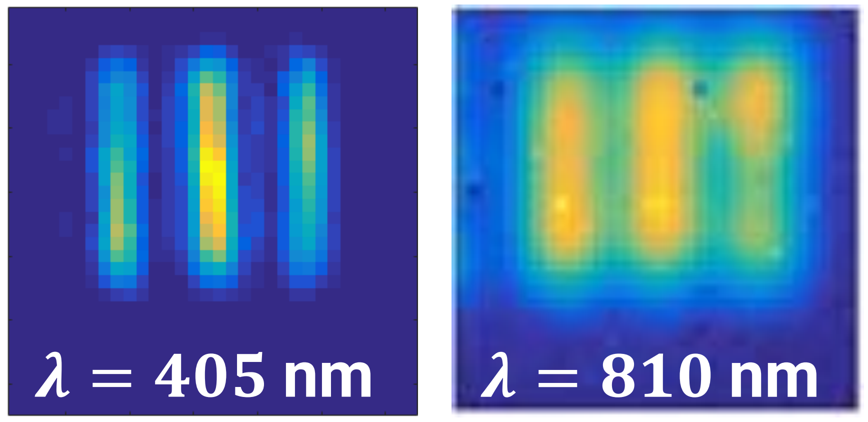
- Introduction
- Novel architectures for ghost imaging
- Experimental results
- Conclusions

Introduction to Ghost Imaging
Standard imaging



Introduction to Ghost Imaging
Standard imaging





Resolution limit: Depends to the wavelength λ (*Rayleigh limit*)

Sensitivity limit: $S \approx {}^{1}/_{\sqrt{n}}$ *Shot noise limit*

Detection: Photon detection efficiency of the image sensor depends to λ

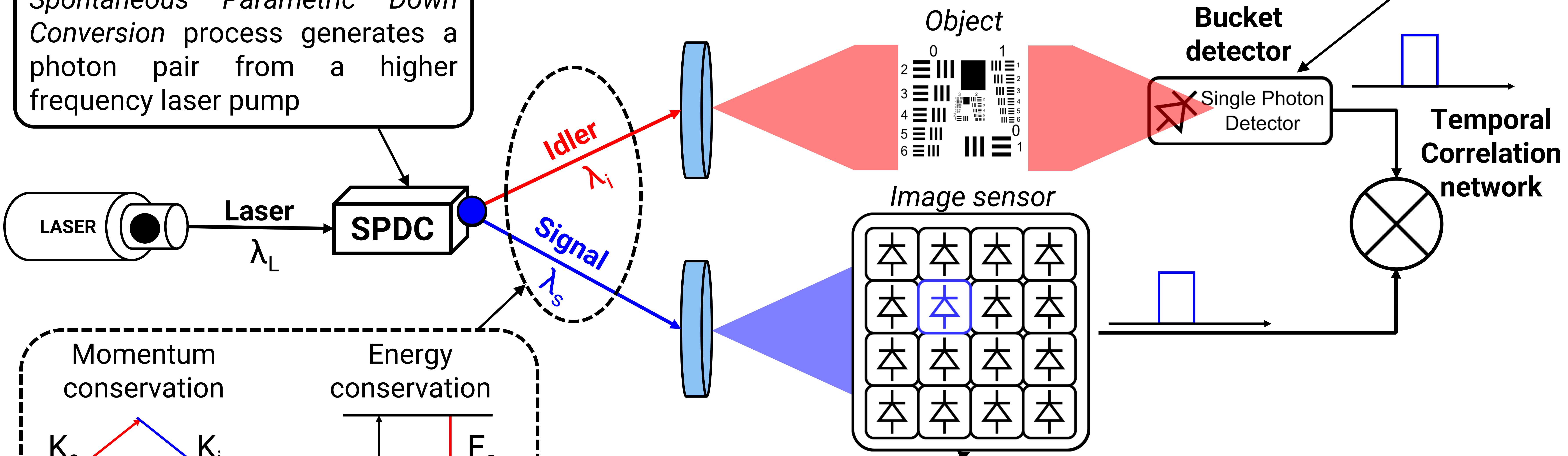
Introduction to Ghost Imaging
Ghost imaging

Nonlinear crystal

Spontaneous Parametric Down Conversion process generates a photon pair from a higher frequency laser pump

Bucket detector

Single-photon detector able to time resolving the Idler



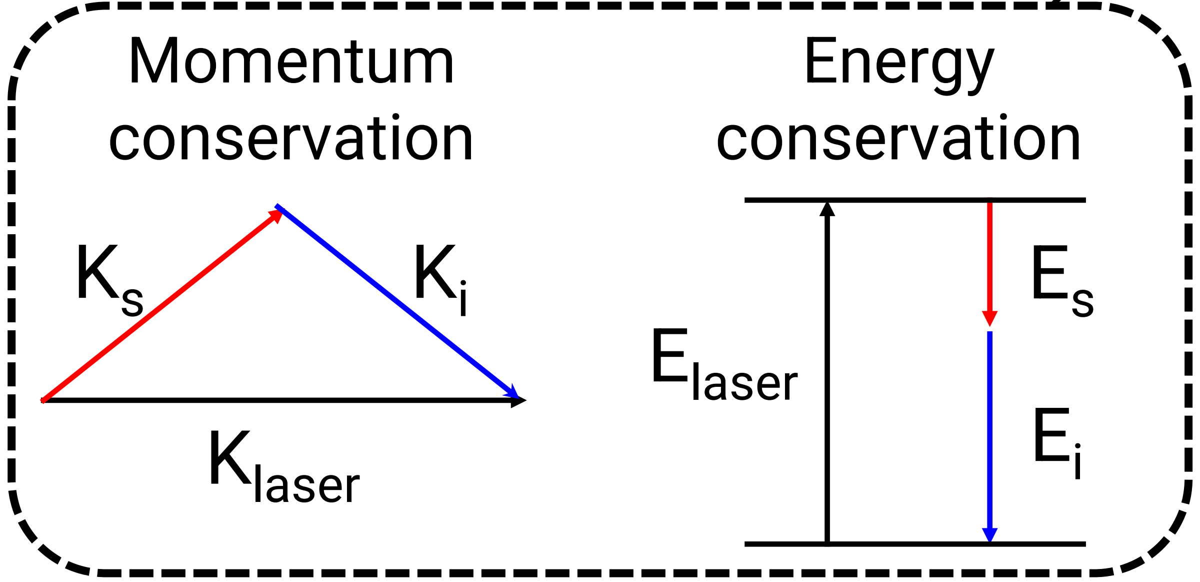
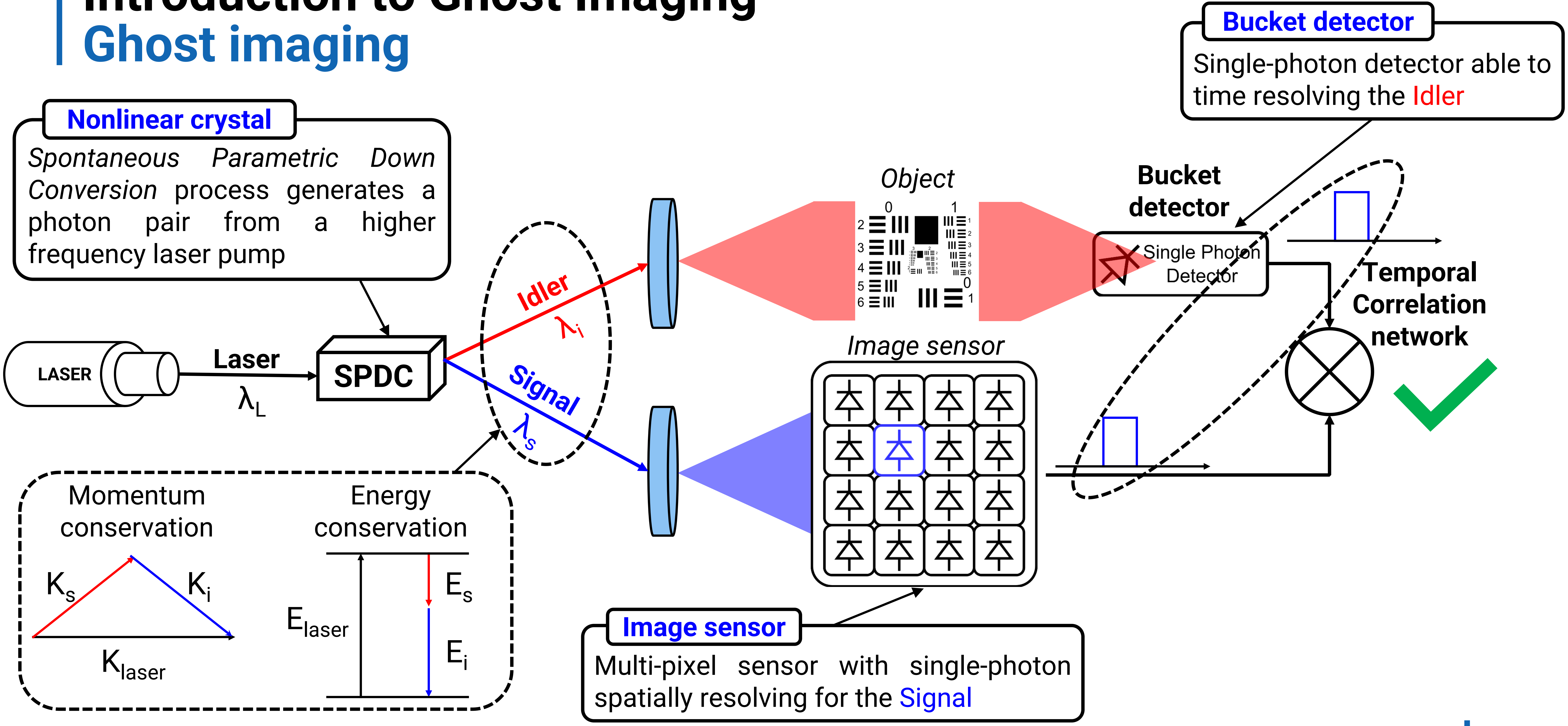


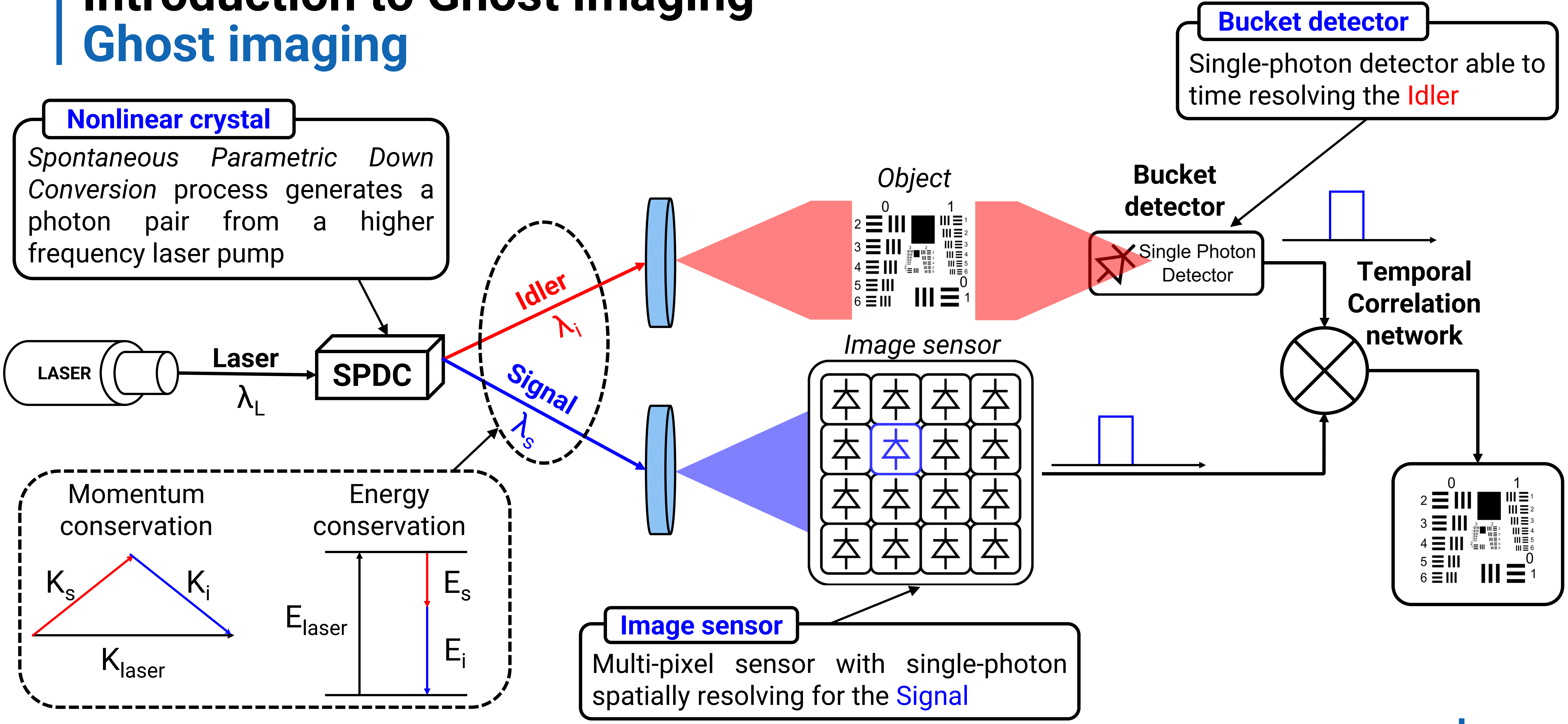
Image sensor

Multi-pixel sensor with single-photon spatially resolving for the Signal

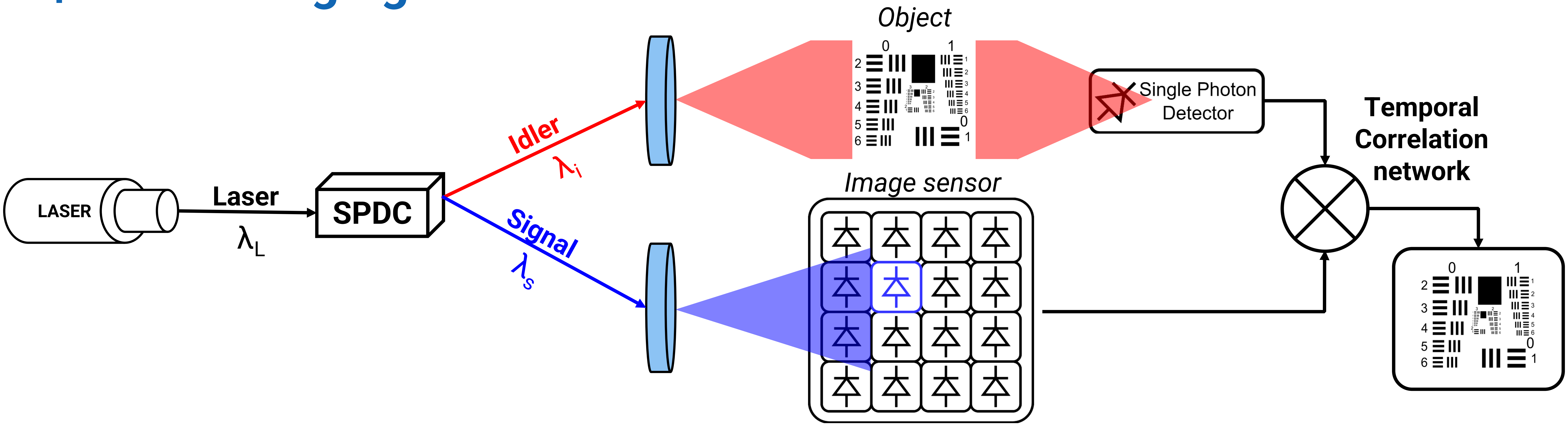
Introduction to Ghost Imaging
Ghost imaging



Introduction to Ghost Imaging
Ghost imaging



Introduction to Ghost Imaging
Ghost imaging



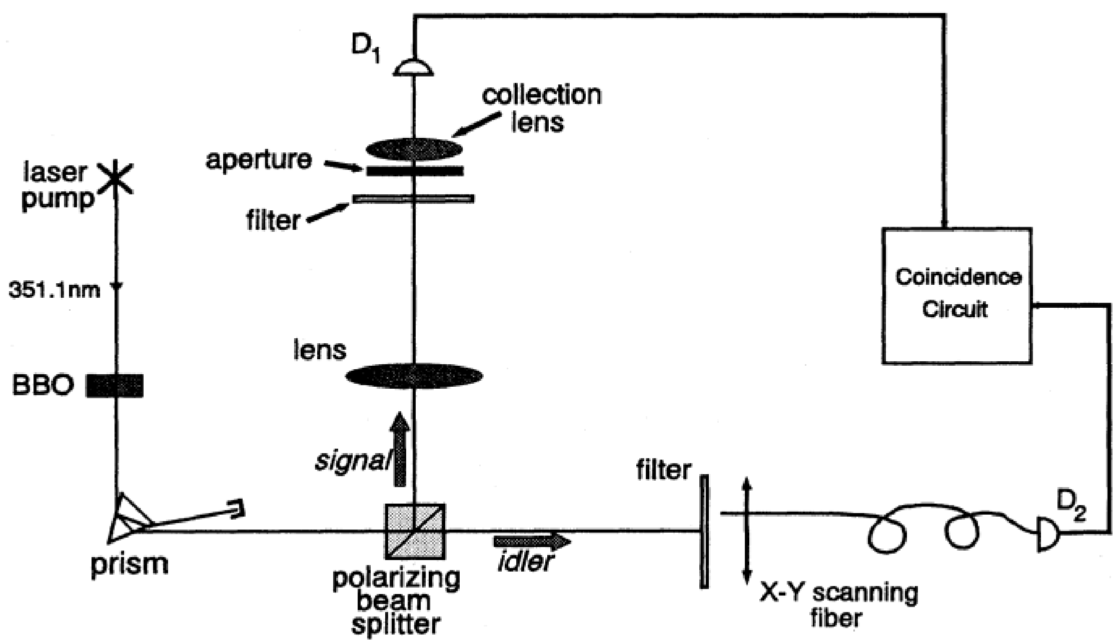
Resolution limit: Depends to the wavelength of the Idler path λ_s (*Rayleigh limit*)

Sensitivity limit: $S \approx {}^{1}/_{n}$

Detection: Imaging with sensor working in the visible (signal) but exploring the object with other wavelength photons (idler)

Introduction to Ghost Imaging
State of the art

Year	Reference	Pros	Cons
1995	Pittman et al., Phys. Rev. A 52, 5	First GI with SPDC	Point-to-point scan One color



T. B. Pittman et al., "*Optical imaging by means of two-photon quantum entanglement*", Physical Review A 52, 5, 1995

Introduction to Ghost Imaging
State of the art

Year	Reference	Pros	Cons
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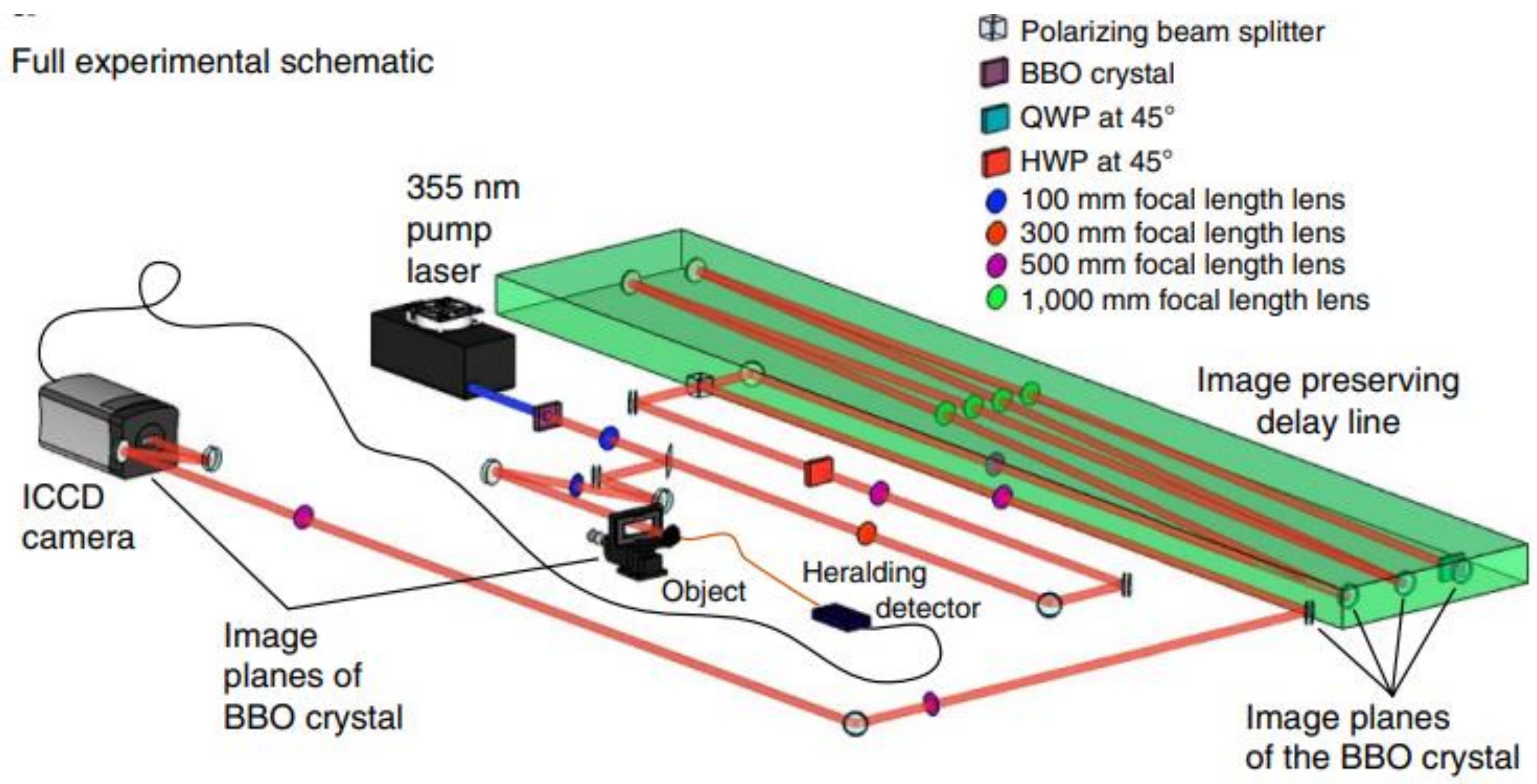
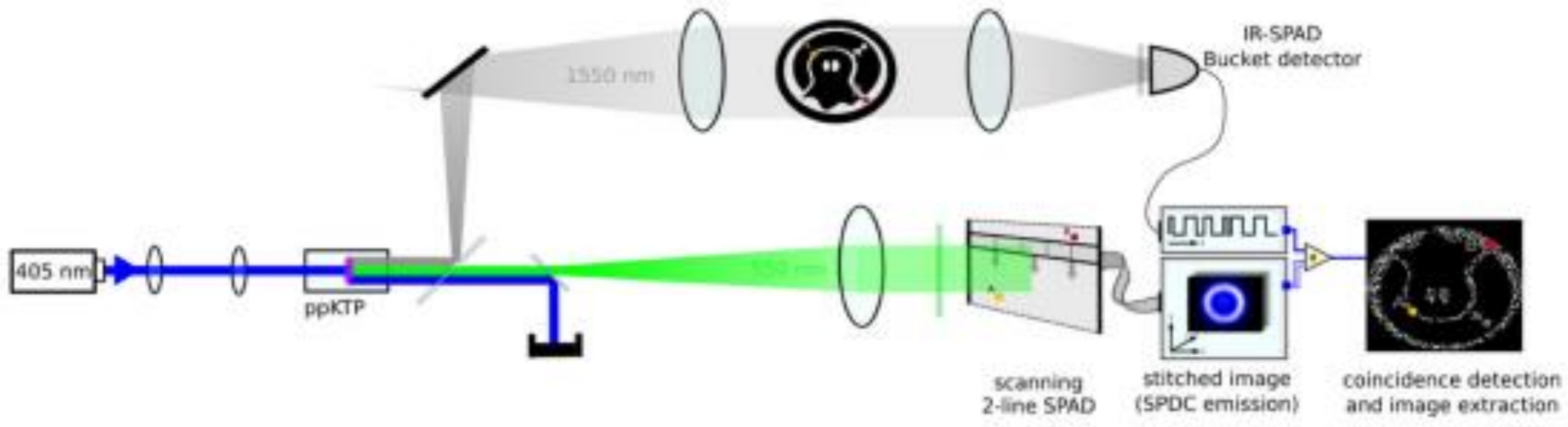
2015	Morris et al., Nat. Comm. 6	Two colors	Slow electronics



Peter A. Morris et al., "*Imaging with a small number of photons*", Nature communications, 2015

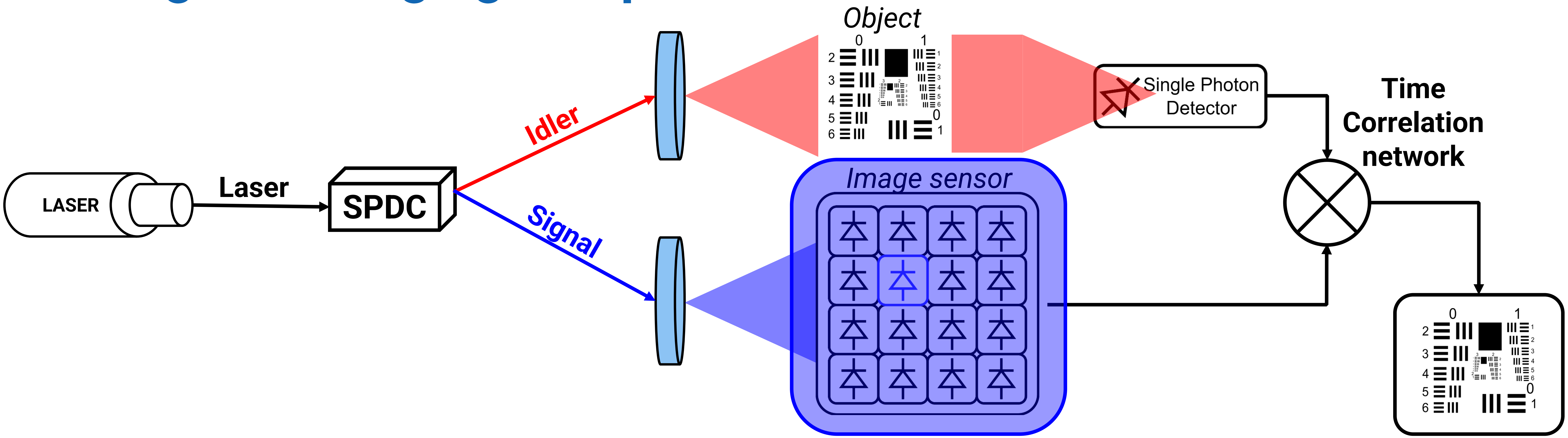
Introduction to Ghost Imaging
State of the art

Year	Reference	Pros	Cons
1995	Pittman et al., Phys. Rev. A 52, 5	First GI with SPDC	Point-to-point scan One color
2015	Morris et al., Nat. Comm. 6	Two colors	Slow electronics
2021	Pitsch et al., Appl. Opt. 60, 22	Two colors IR for idler path SPAD detector	Sequential scan Slow acquisition



Carsten Pitsch et al., "*Quantum ghost imaging using asynchronous detection*", Applied Optics, Vol. 60, No. 22, 2021

Introduction to Ghost Imaging
Ideal ghost imaging setup

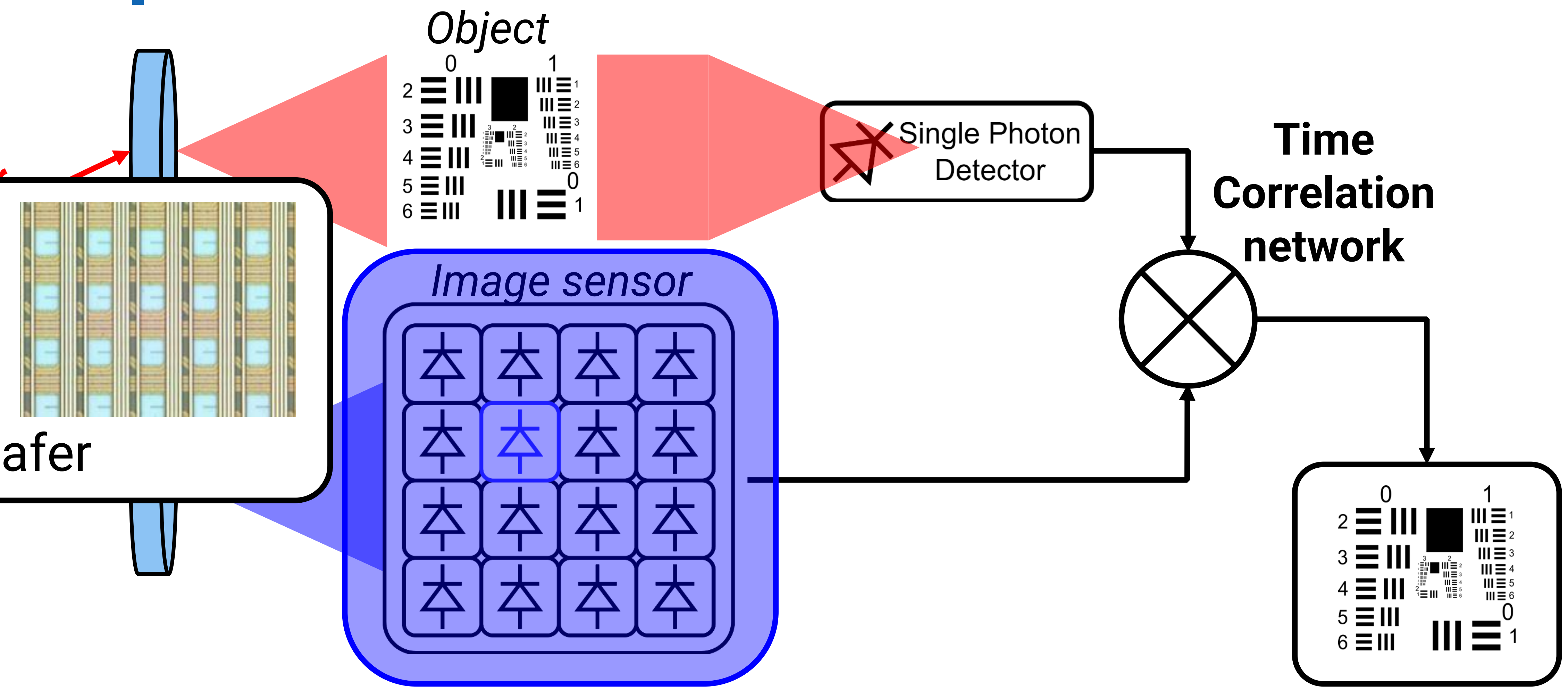


- High correlation rate
- High spatial resolution
- No false correlation
- Real time working operation

Introduction to Ghost Imaging
Single photon detector requirements

Silicon Photon Avalanche Diode

- Up to tens of kfps for Mpixel array
- PDE between 5 – 30%
- DCR down to tens of Hz
- Dedicated electronics in the same wafer



- High correlation rate → High Photon Detection Efficiency (PDE)
- High spatial resolution → Large array size and small pixel
- No false correlation → Low Dark Count Rate (DCR)
- Real time working operation → High frame rate and efficient readout

Fast Quantum Ghost imaging with SPADs
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Novel architectures for Ghost Imaging
FastGhost partner

fastGHOST

Develop a **real-time** and **high-resolution** quantum imaging microscope working in the **Middle-Infrared** wavelength up to 7 μm

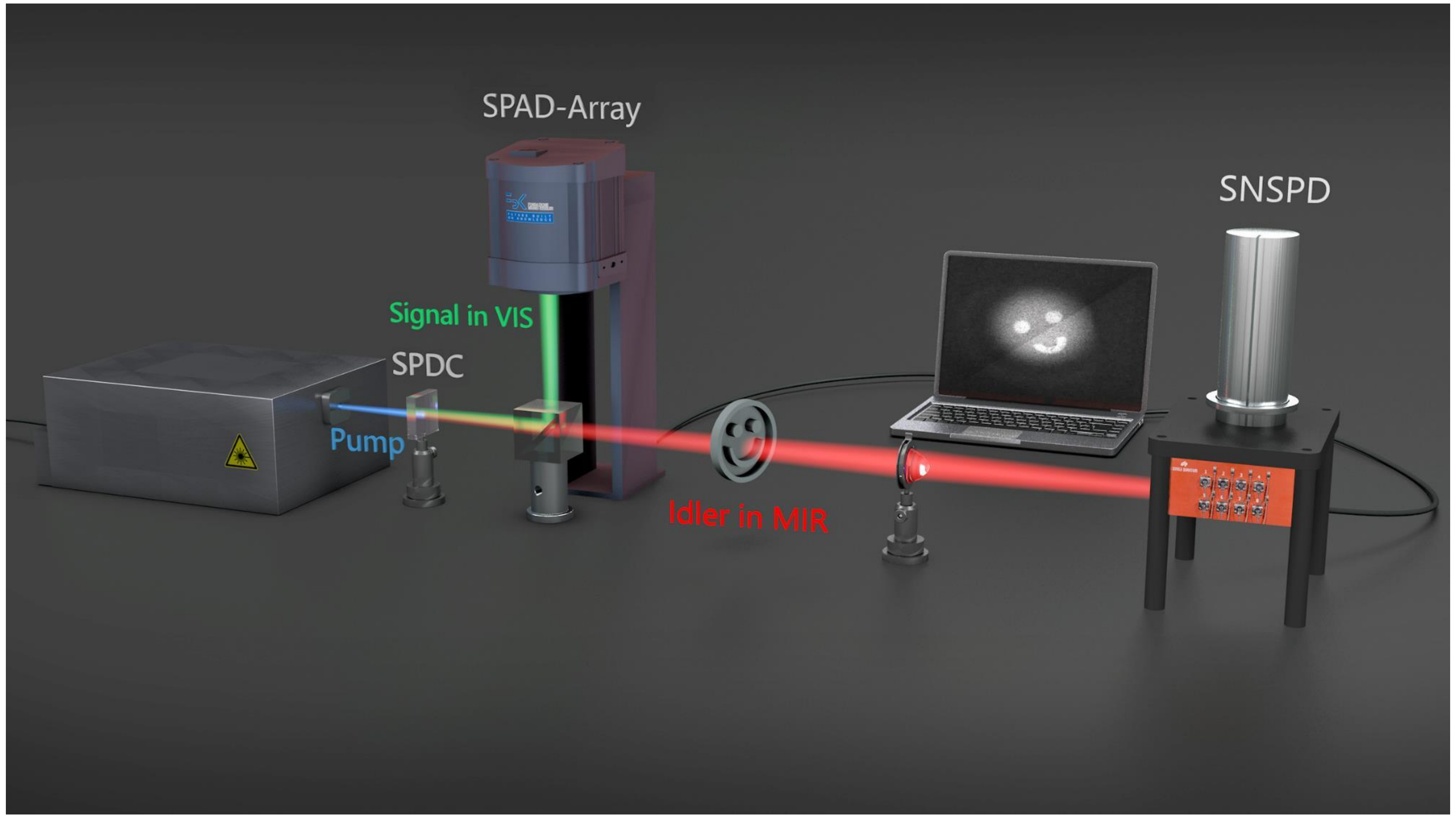
Fraunhofer IOF — Coordinator and MIR ghost microscopy

Friedrich-Schiller-Universität Jena — Real-time quantum imaging

Fondazione Bruno Kessler — High-resolution single-photon counting camera

Single Quantum (Excellence in photon detection) — Single-photon detectors for the midinfrared

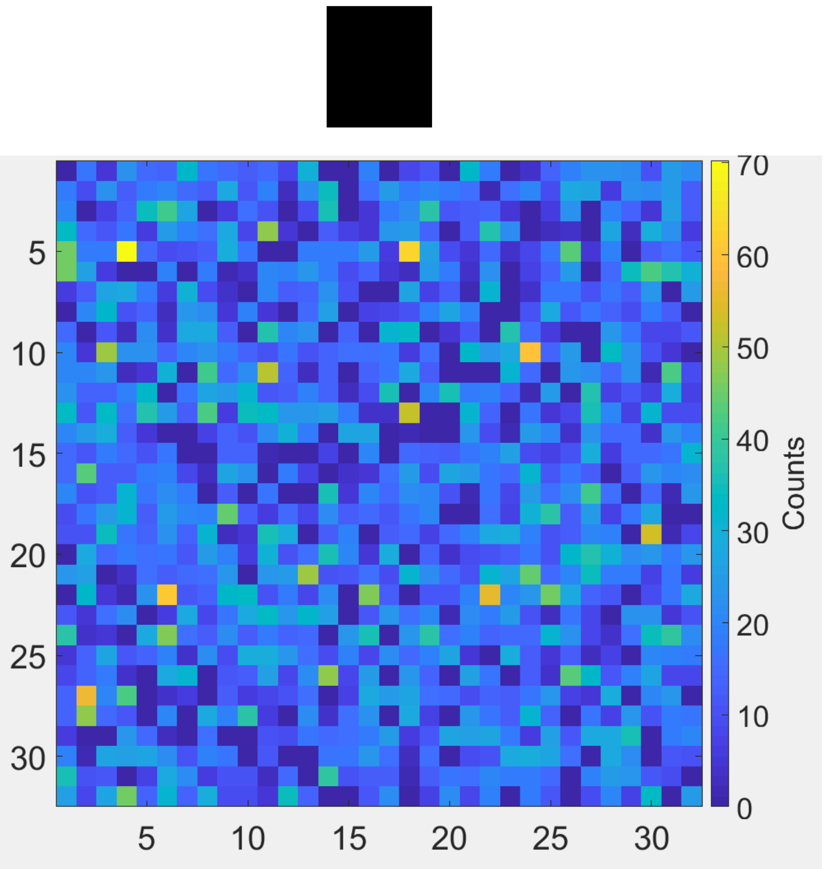
KTH Vetenskap och Konst — Optimized superconducting film for SNSPD detectors



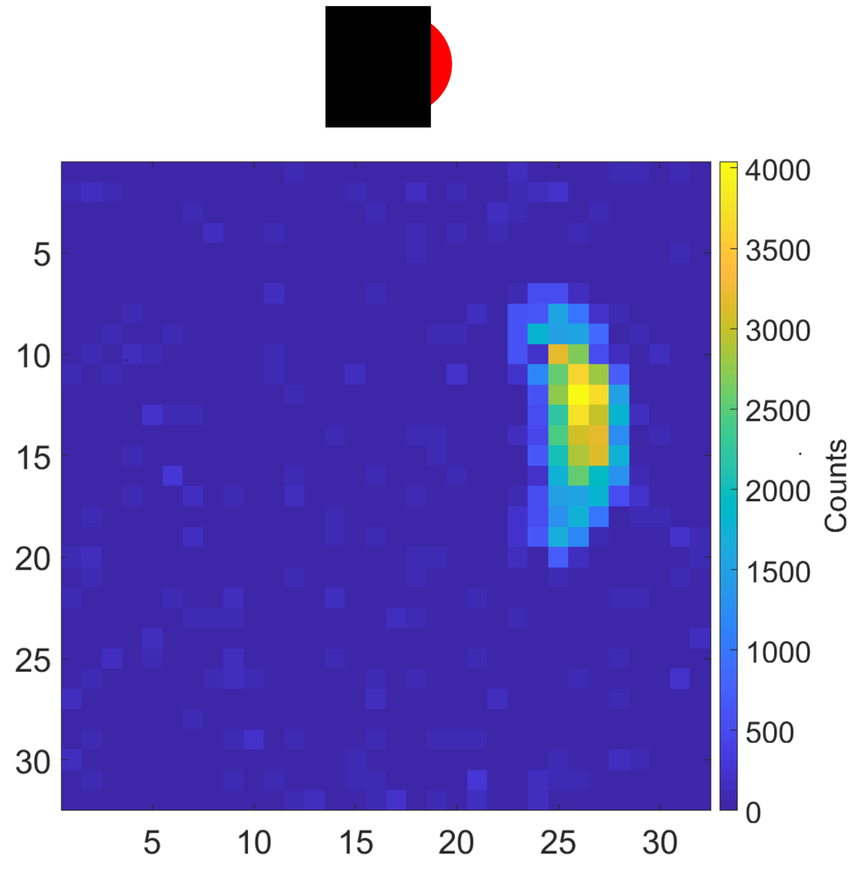
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 899580.

Novel architectures for Ghost Imaging
Black tape object characterization

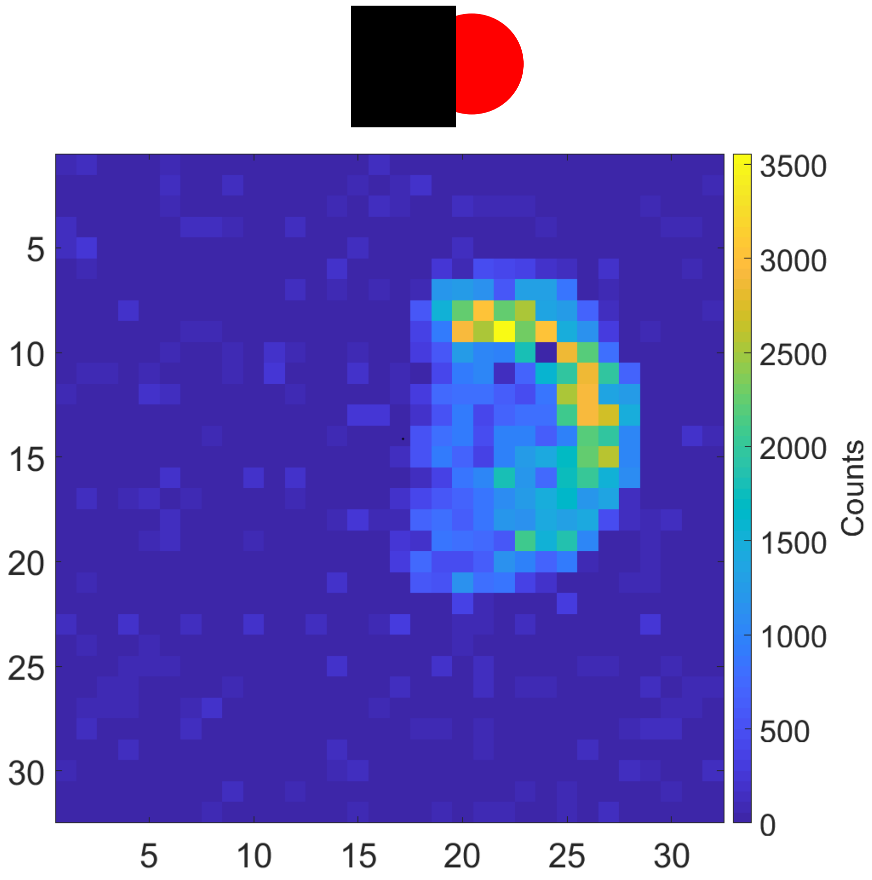
Position 1:
Tape completely blocking infrared photons



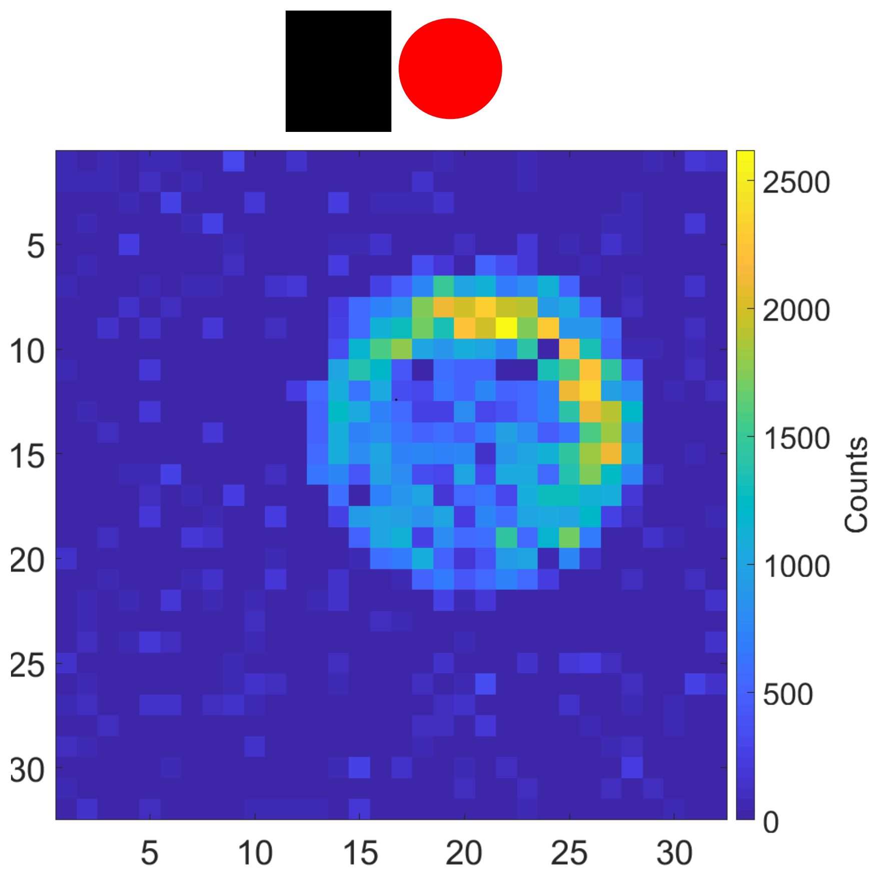
Position 2:
Almost completely blocking infrared photons



Position 3:
Partly blocking infrared photons



Position 4:
Tape not blocking infrared photons



1.4 µm (IR) wavelength photon-pair correlation spot acquired with **Ghost imaging** setup.
Visible photons are collected by a silicon detector

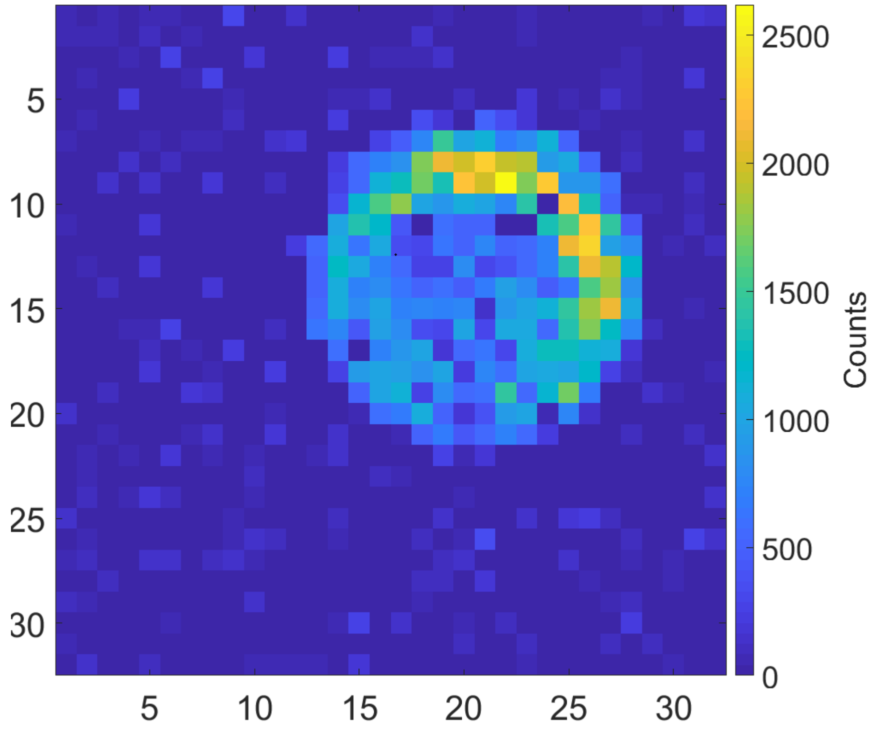
Laser = 420 nm
Visible wavelength = 600nm

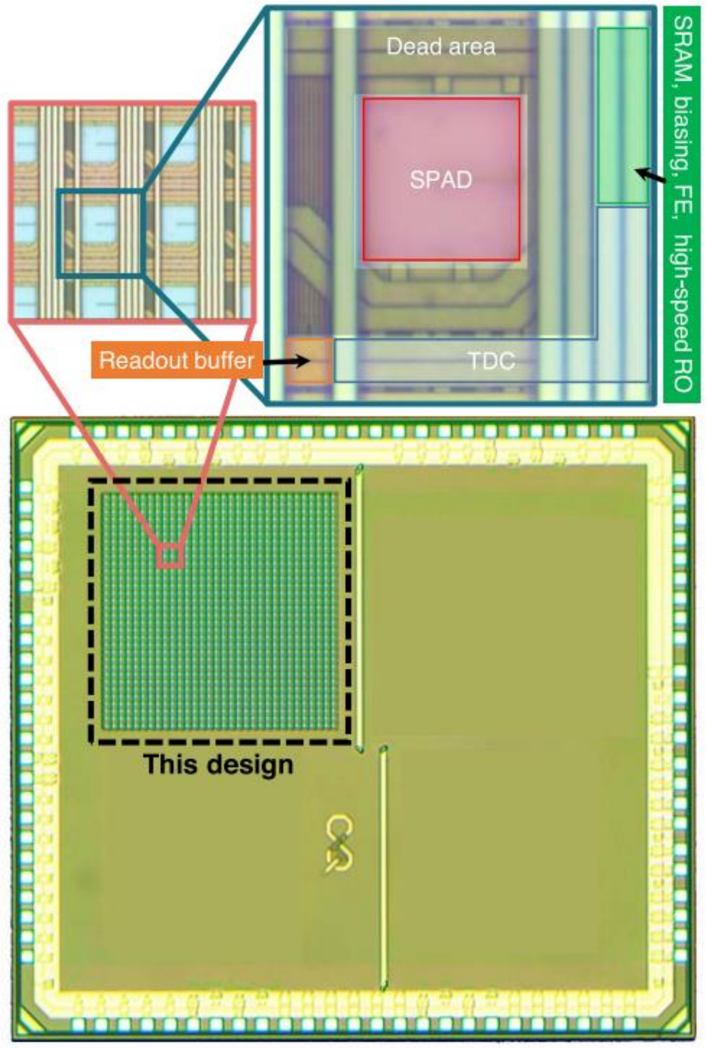
Credits to: FRIEDRICH-SCHILLER-UNIVERSITÄT JENA

Novel architectures for Ghost Imaging
FastGhost project overview

The SPAD image sensor is an array of 32 x 32 pixels working at 600 nm developed in *FBK* [1]

32 x 32 SPAD CMOS image sensor
- Synchronous working operation
- Pixel pitch 45 μm
- Array size 32 x 32
- Fill Factor 20 %
- 8-bits TDC for pixel
- Raster scan or row skipping readout method





[1] M. Zarghami *et al.*, ***"A 32 × 32-Pixel CMOS Imager for Quantum Optics With Per-SPAD TDC, 19.48% Fill-Factor in a 44.64-μm Pitch Reaching 1-MHz Observation Rate,"*** *IEEE Journal of Solid-State Circuits*, vol. 55, no. 10, pp. 2819-2830, Oct. 2020

Novel architectures for Ghost Imaging
FastGhost project overview

fastGHOST

Develop a **real-time** and **high-resolution** quantum imaging microscope working in the **Middle-Infrared** wavelength up to 7 μm

32 x 32 SPAD CMOS image sensor

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- Pixel pitch 45 μm
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Novel architectures for Ghost Imaging
FastGhost project overview

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Requirements for image sensor:

- Asynchronous working operation

Novel architectures for Ghost Imaging
FastGhost project overview

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- × Synchronous working operation
- × Pixel pitch 45 μm
- × Array size 32 x 32
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- 8-bits TDC for pixel
- Raster scan or row skipping readout method

Requirements for image sensor:

- Asynchronous working operation
- Pixel pitch 17 μm
- Array size target 512 x 512

Novel architectures for Ghost Imaging
FastGhost project overview

Develop a **real-time** and **high-resolution** quantum imaging microscope working in the **Middle-Infrared** wavelength up to 7 μm

32 x 32 SPAD CMOS image sensor
- ✗ Synchronous working operation
- ✗ Pixel pitch 45 μm
- ✗ Array size 32 x 32
- ✗ Fill Factor 20 %
- 8-bits TDC for pixel
- Raster scan or row skipping readout method

Requirements for image sensor:
- Asynchronous working operation
- Pixel pitch 17 μm
- Array size target 512 x 512
- Fill Factor > 20 %

Novel architectures for Ghost Imaging
FastGhost project overview

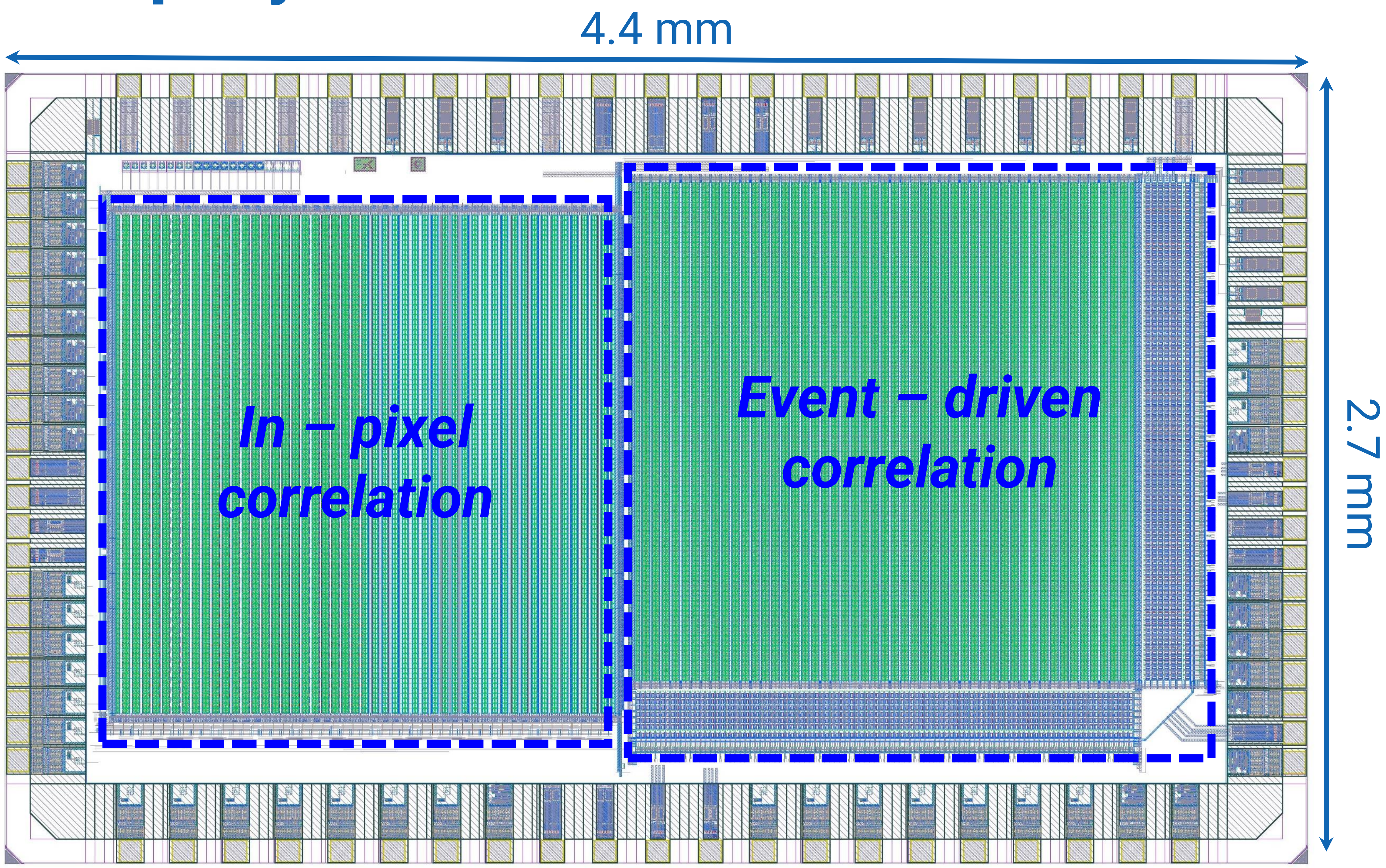
Develop a **real-time** and **high-resolution** quantum imaging microscope working in the **Middle-Infrared** wavelength up to 7 μm

32 x 32 SPAD CMOS image sensor
- × Synchronous working operation
- × Pixel pitch 45 μm
- × Array size 32 x 32
- × Fill Factor 20 %
- × 8-bits TDC for pixel
- ✓ Raster scan or row skipping readout method

Requirements for image sensor:
- Asynchronous working operation
- Pixel pitch 17 μm
- Array size target 512 x 512
- Fill Factor > 20 %
- Fast readout

The image sensor used so far is not suitable

Novel architectures for Ghost Imaging
Chip layout and the architectures

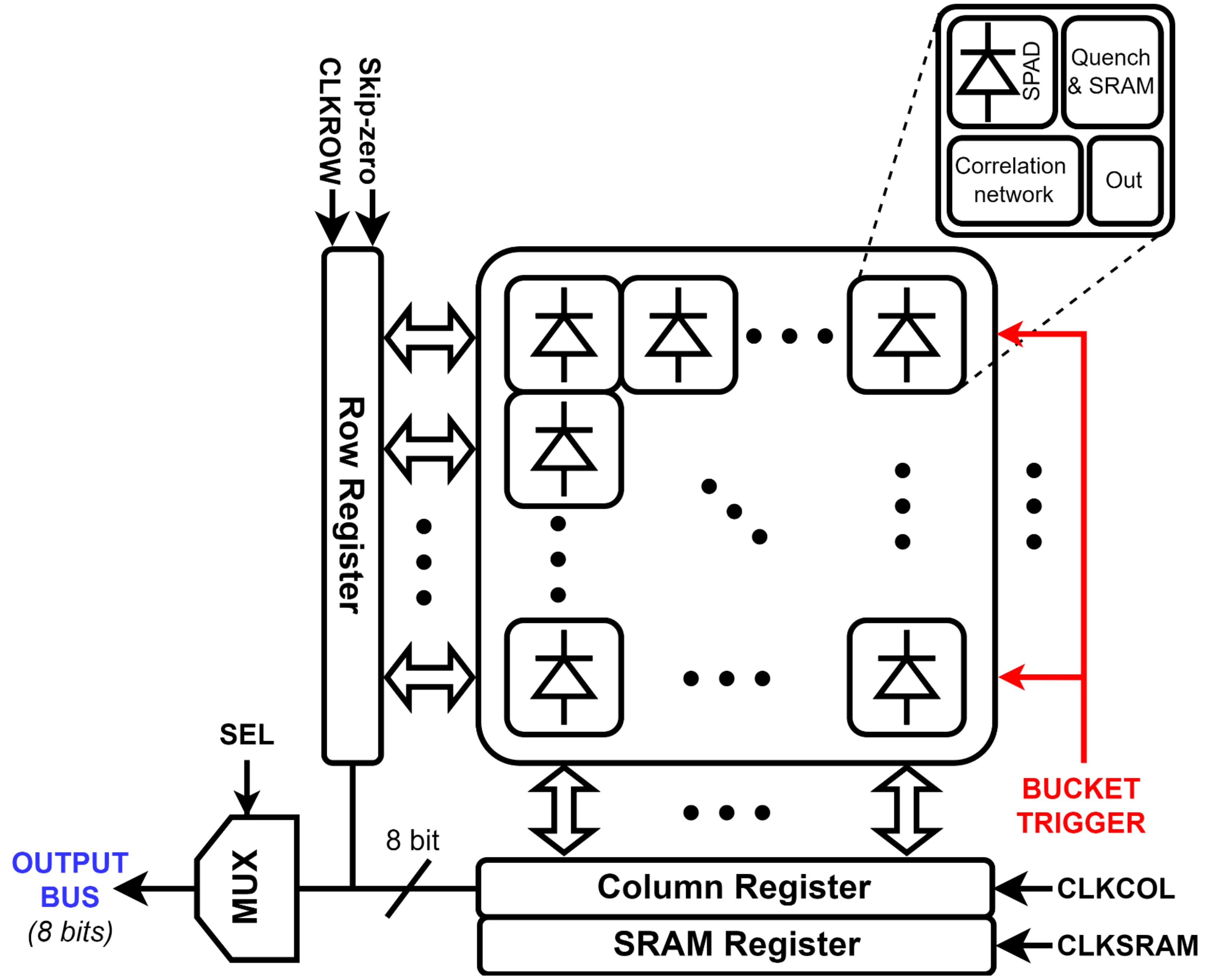


- LF 110 nm CMOS Technology
- 100 x 100 pixel each array
- Pixel size 17 µm x 17 µm
- 1.2V - 3.3V Power supply transistors
- 4 Metal layers available
- 12 mm^2

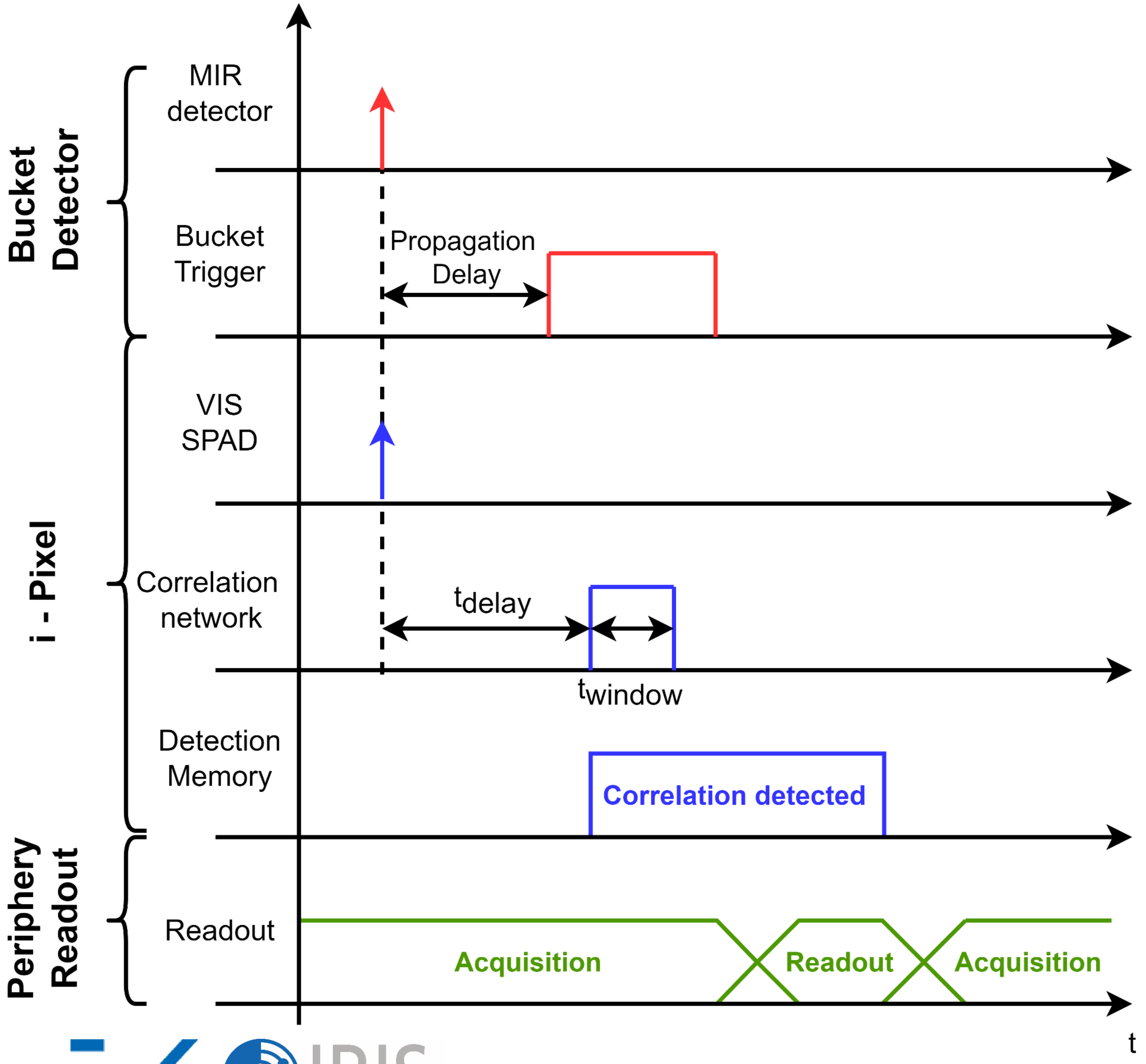
Novel architectures for Ghost Imaging
In-pixel architecture

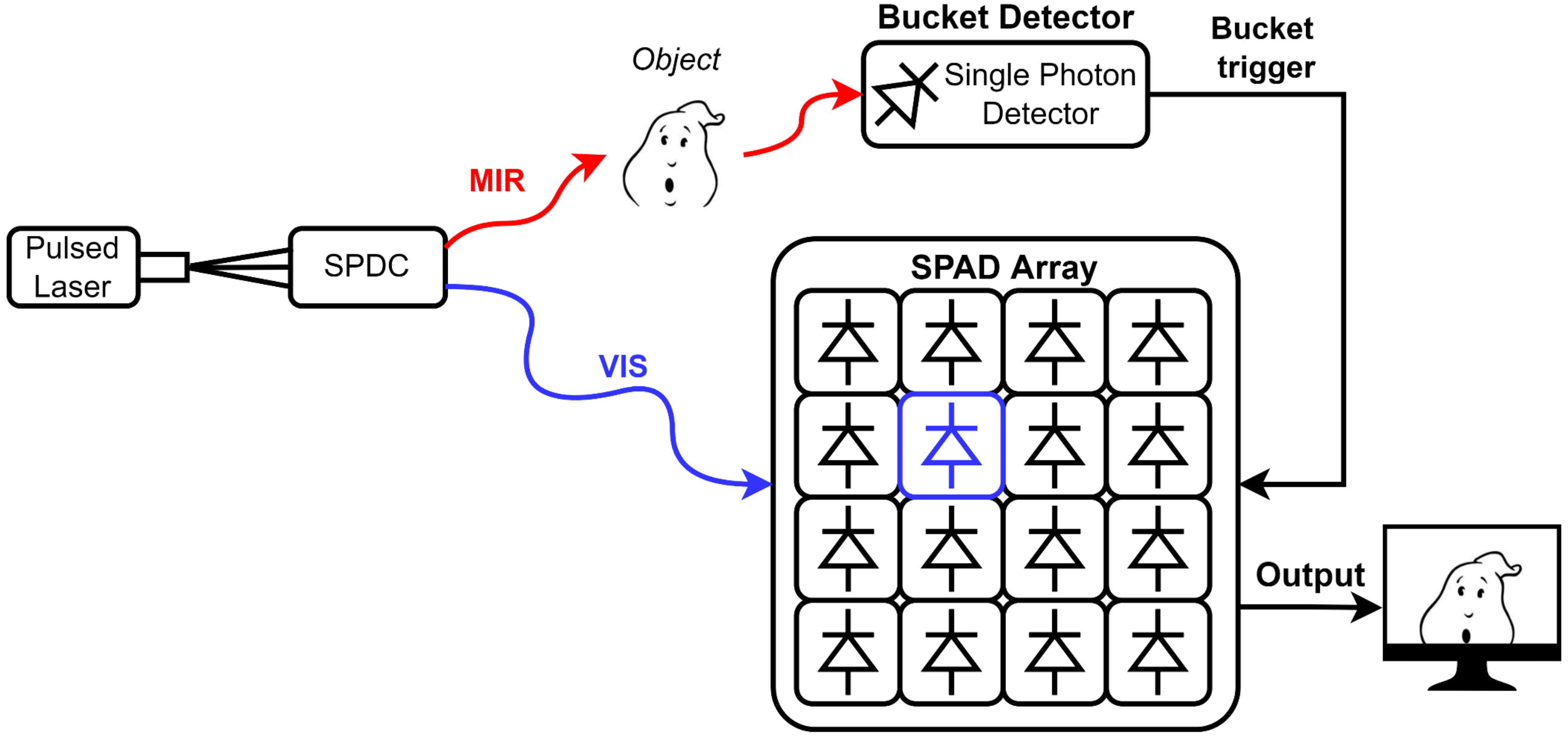
In-pixel correlation network

- Temporal correlation is performed in each pixel
- Bucket trigger propagated to the array
- Raster scan or Skip-zero readout method



Novel architectures for Ghost Imaging
Looking back principle



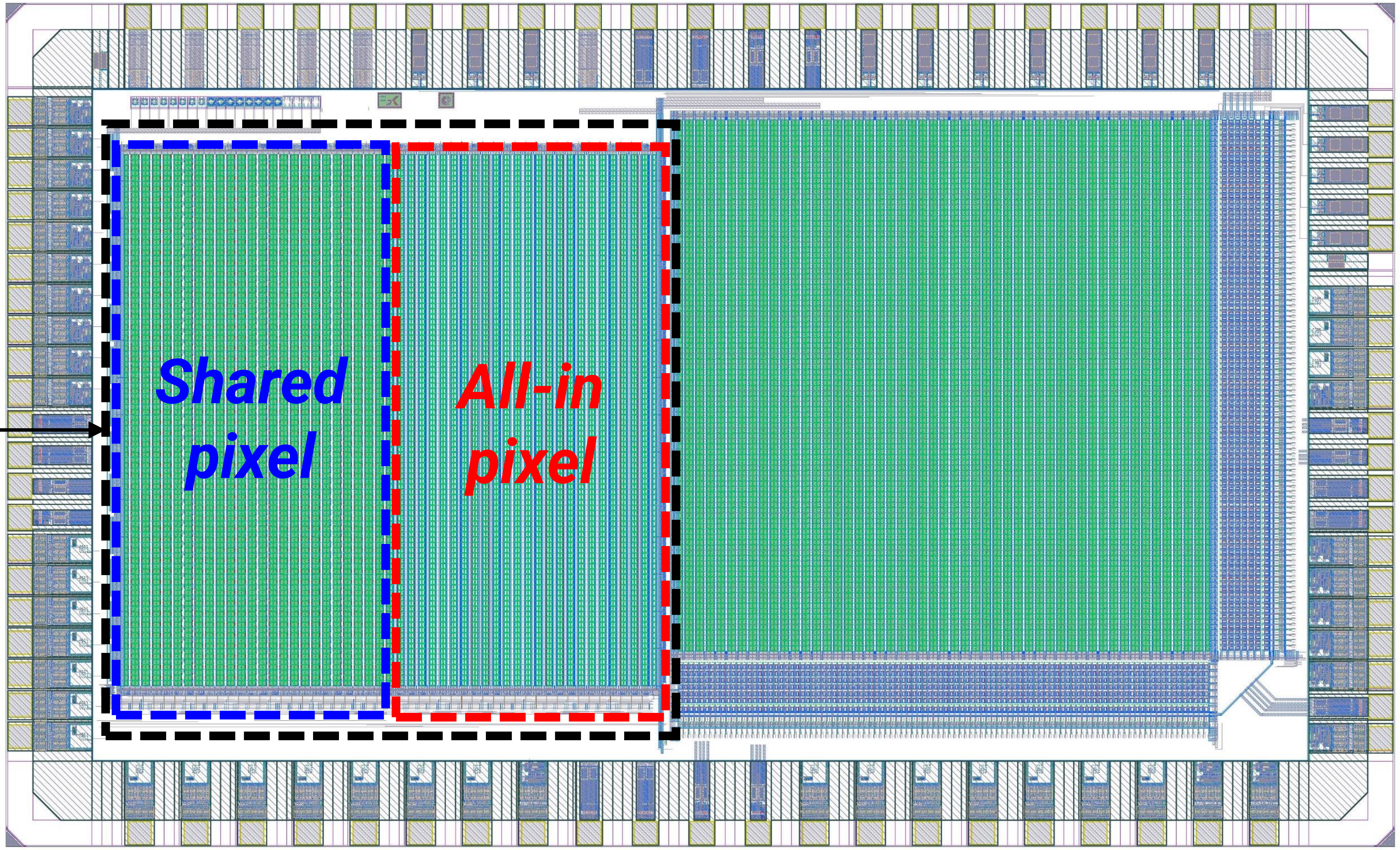


The position of the pixels with a correlation are readout

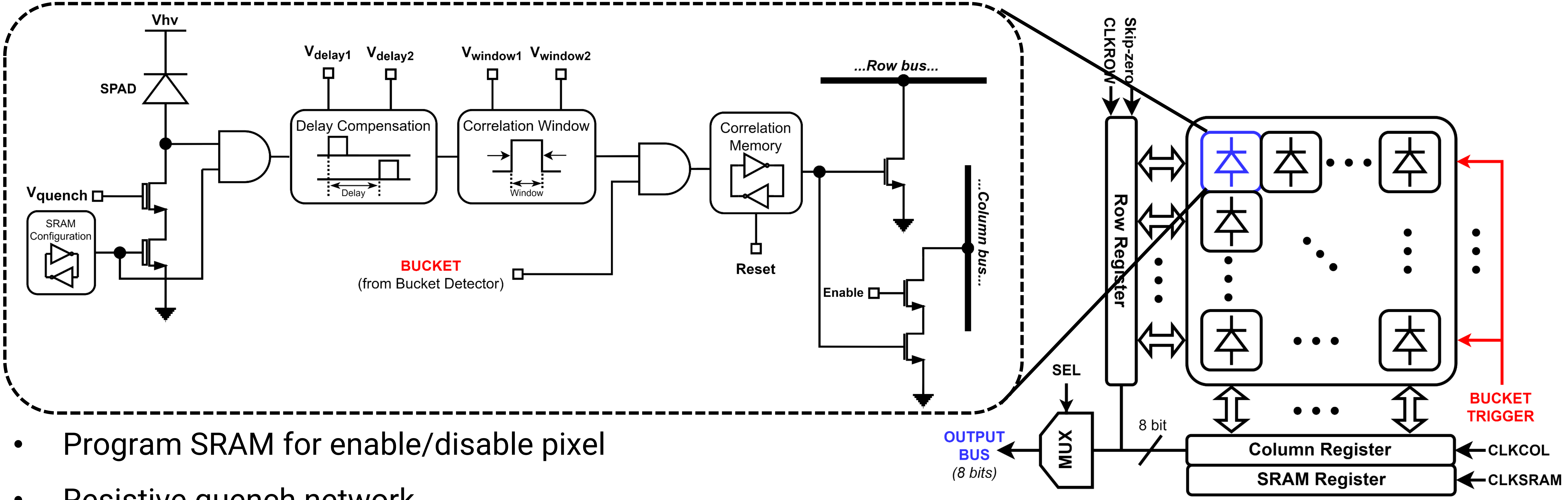
The Bucket delay has been evaluated around **20 ns**

Novel architectures for Ghost Imaging
In-pixel implementations

In-pixel architecture

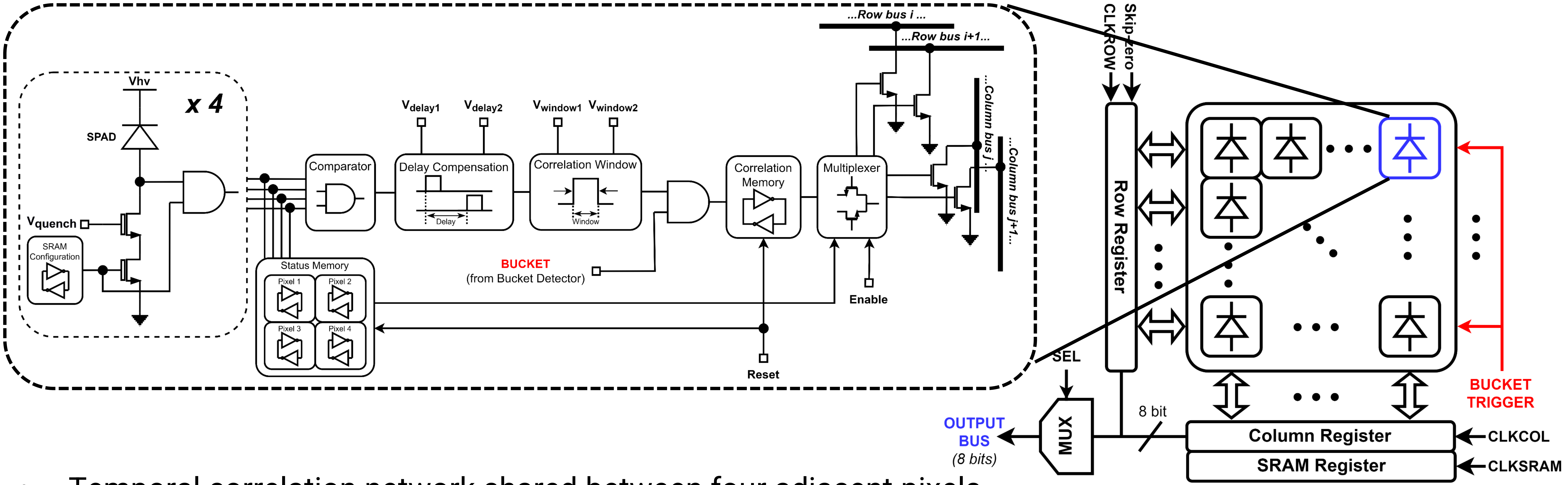


Novel architectures for Ghost Imaging
All-in pixel implementation



- Program SRAM for enable/disable pixel
- Resistive quench network
- Temporal Correlation network in pixel
- Correlation memory to store the correlation until the readout operation

Novel architectures for Ghost Imaging
Shared pixel implementation



- Temporal correlation network shared between four adjacent pixels
- Increasing active area of the SPAD and the fill-factor
- Spatial information is kept by the Status memory and the Multiplexer stages

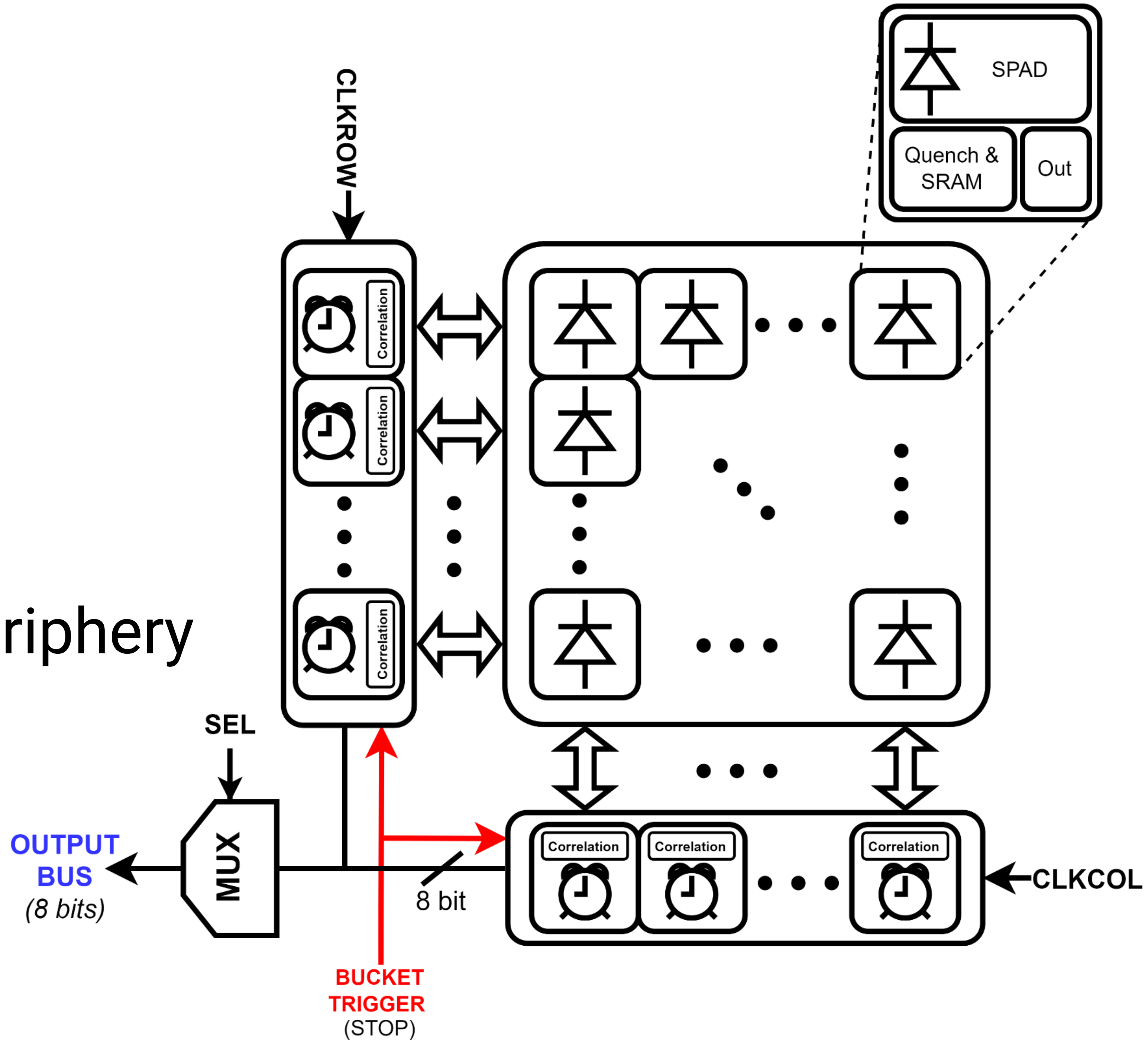
Novel architectures for Ghost Imaging
Event-driven Architecture

In-pixel correlation network

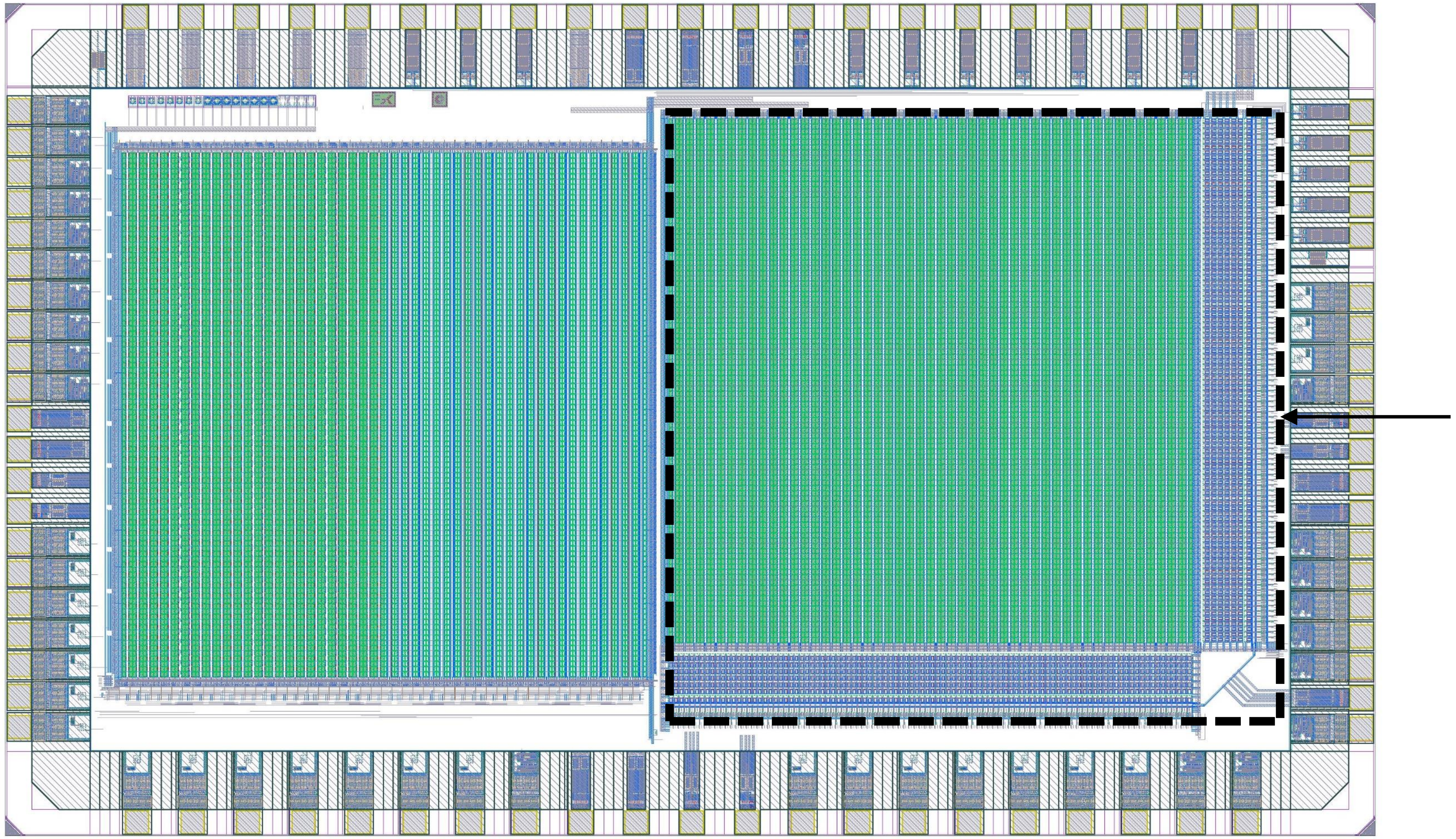
- Temporal correlation is performed in each pixel
- Bucket propagate in the array
- Raster scan or Skip-zero readout method

Event – driven correlation

- Temporal correlation performed in the row/column periphery
- Bucket propagate in the periphery
- Each event is time-stamped trough the TDCs with 100 ps of resolution
- Row and column TDCs are readout

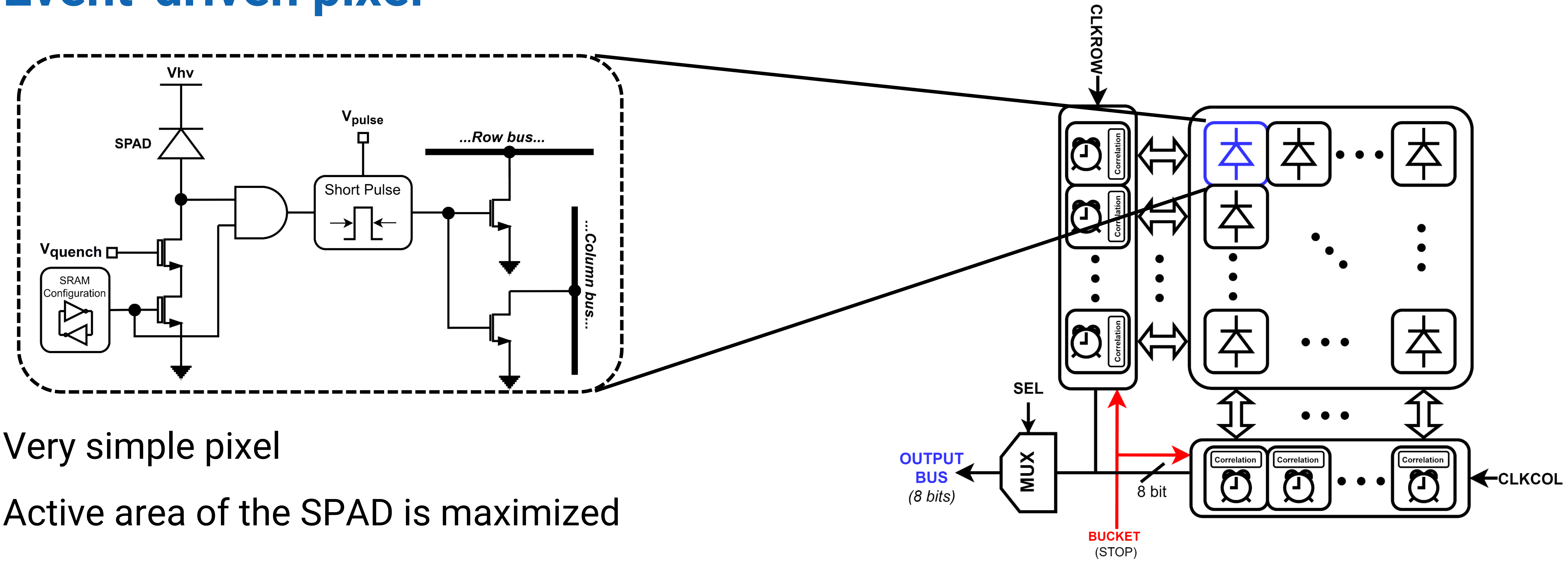


Novel architectures for Ghost Imaging
In-pixel implementations



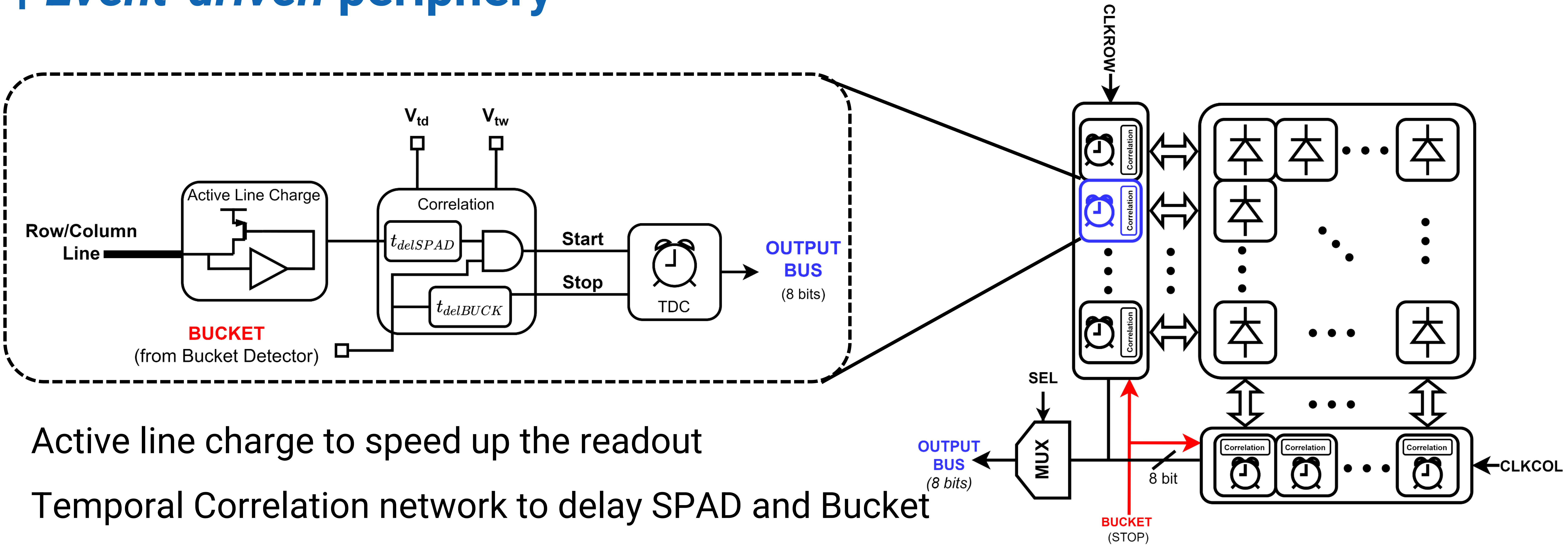
Event - Driven architecture

Novel architectures for Ghost Imaging
Event-driven pixel



- Very simple pixel
- Active area of the SPAD is maximized
- Program SRAM for enable/disable pixel
- The output of the front-end is narrowed to speed-up the readout

Novel architectures for Ghost Imaging
Event-driven periphery



- Active line charge to speed up the readout
- Temporal Correlation network to delay SPAD and Bucket
- Row and column 8-bits TDCs with 100 ps of resolutions
- TDC scale range from 0.1 ns up to 25.9 ns

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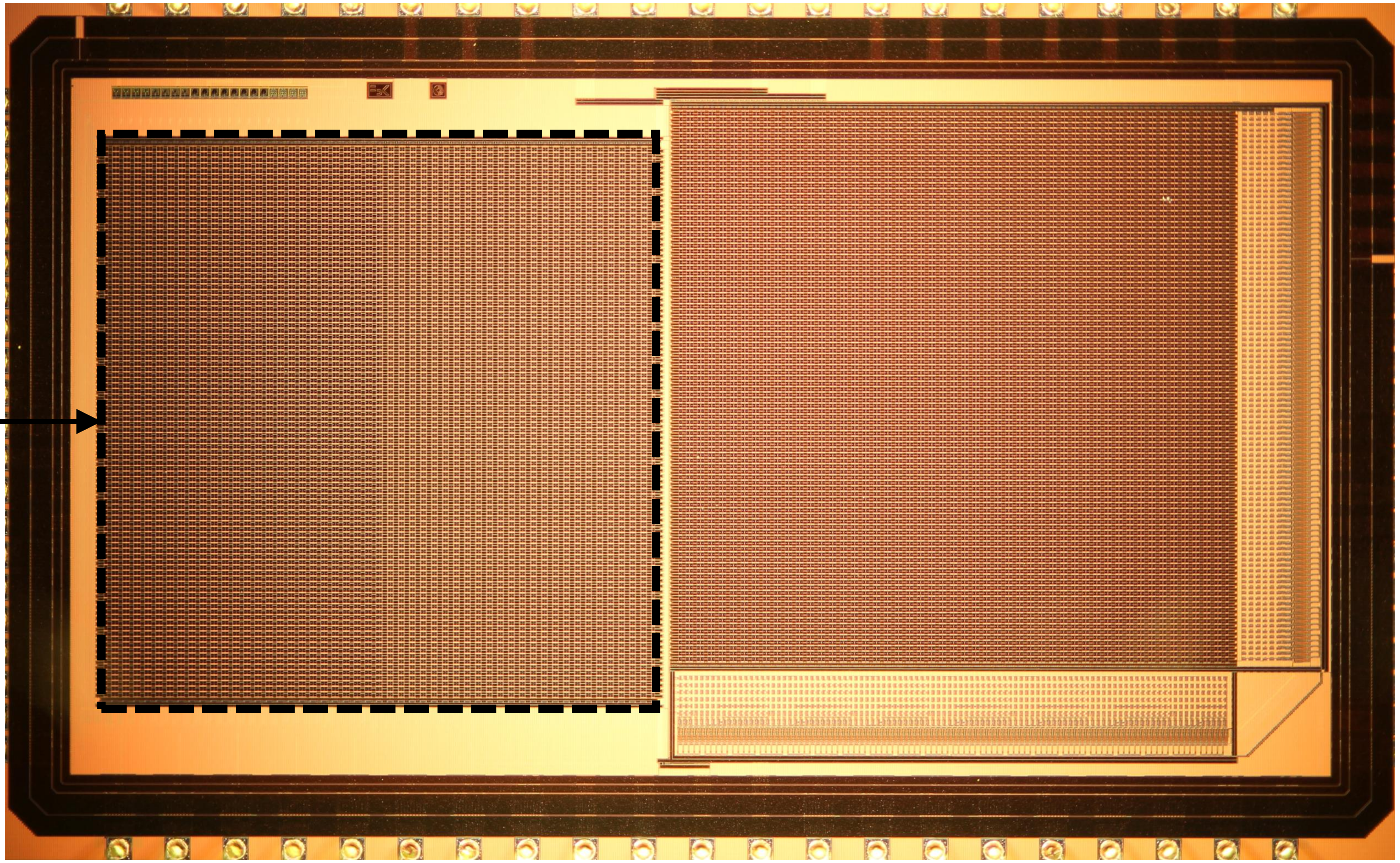
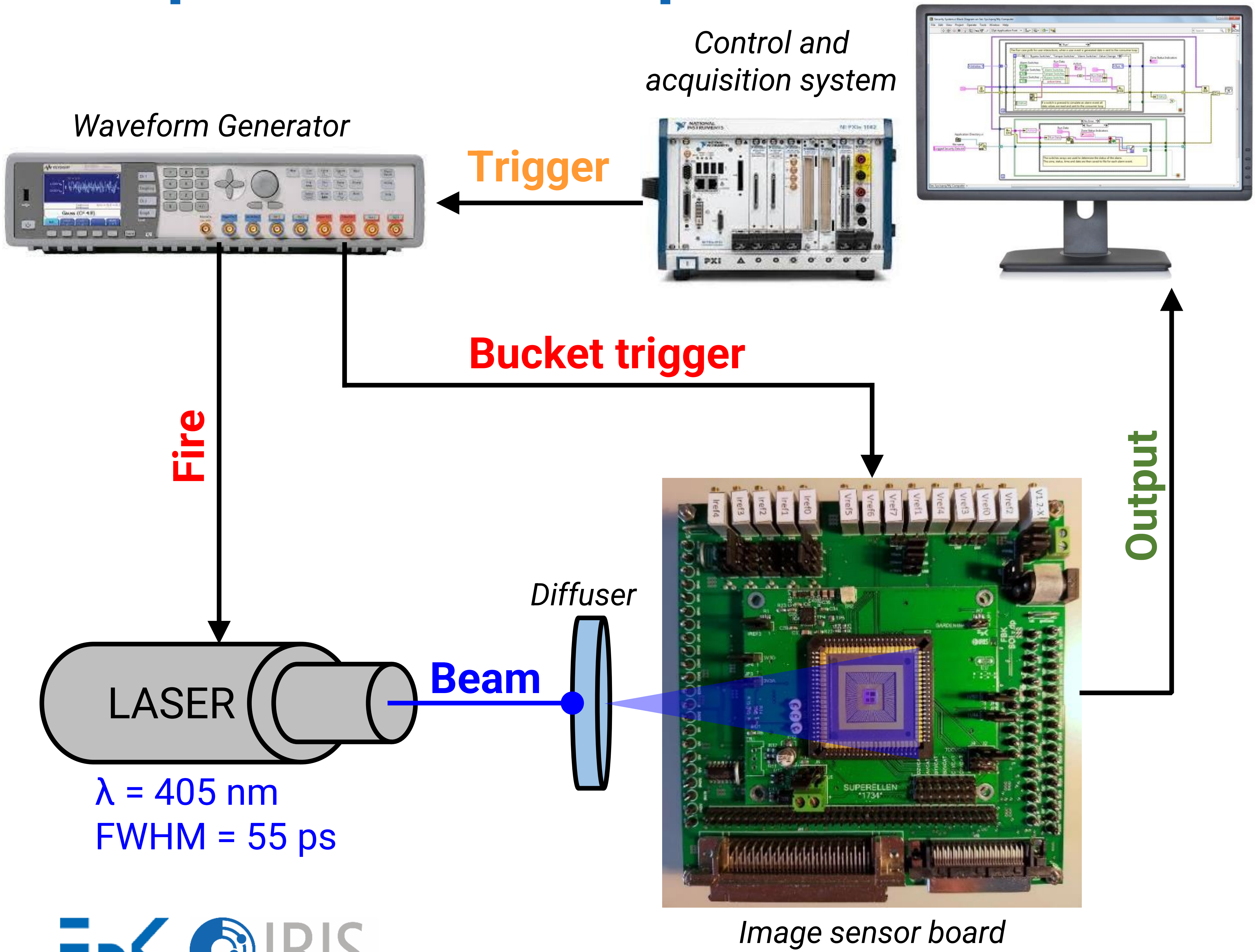
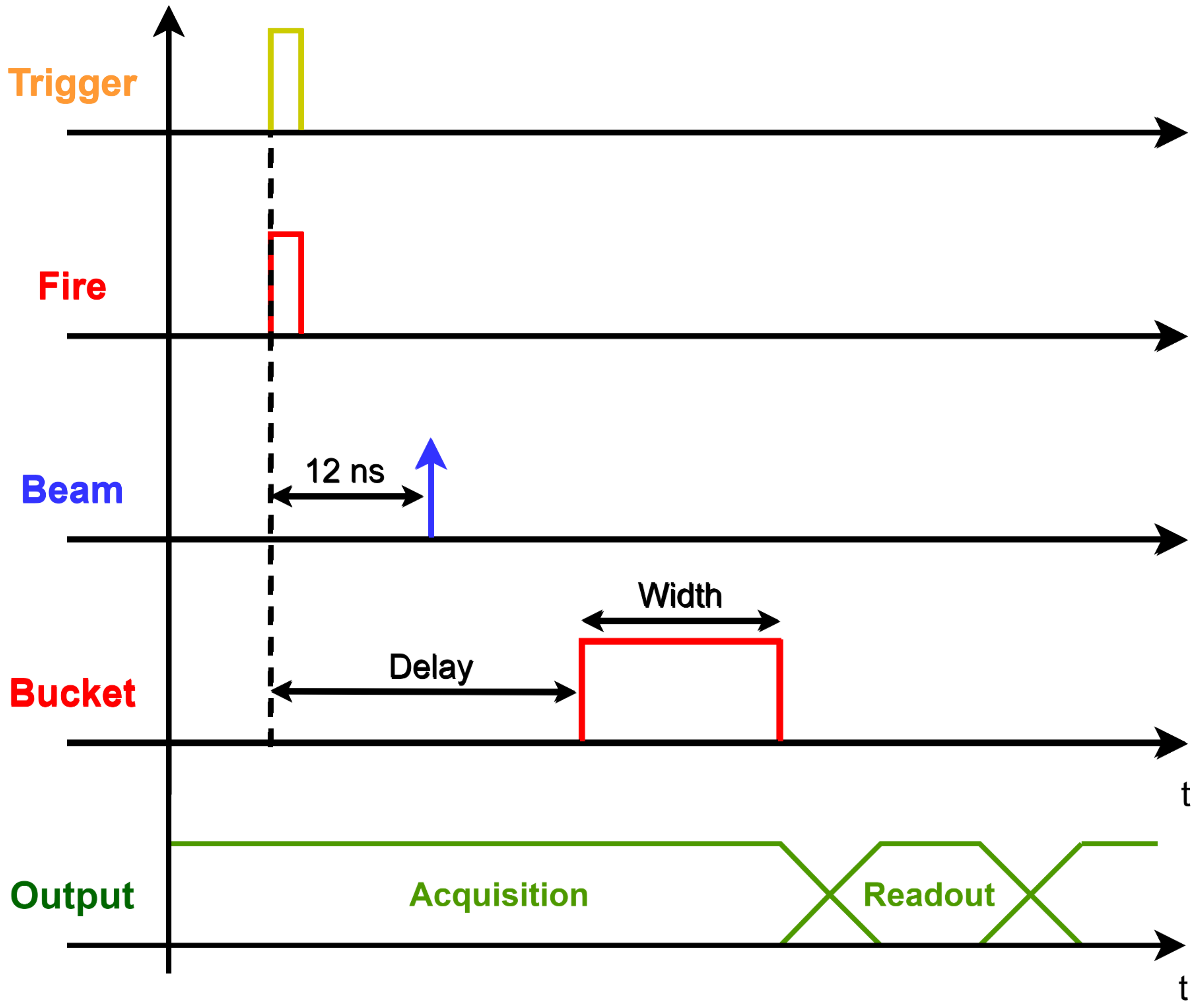
Experimental results

In-pixel architecture



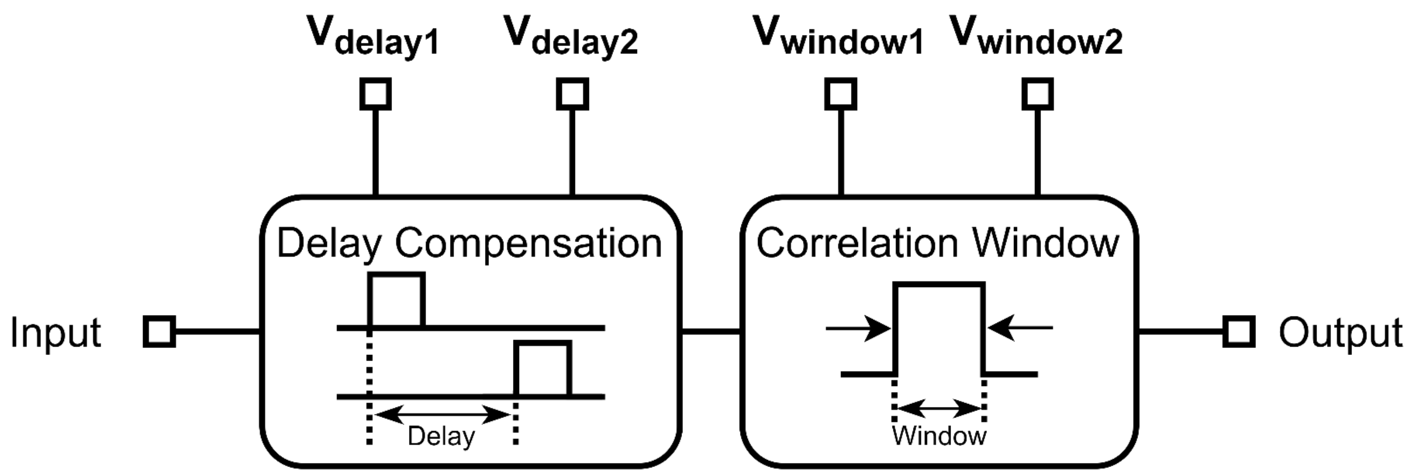
Experimental results
Experimental setup



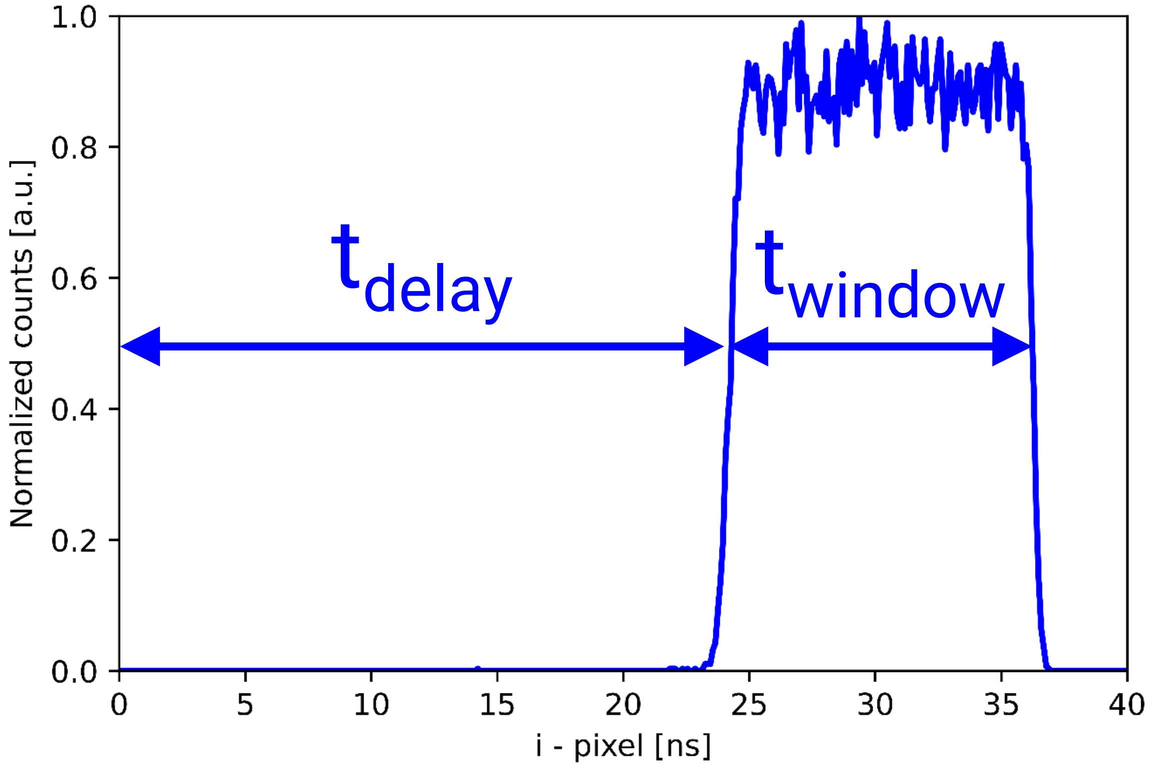


Experimental results
Delay compensation and Correlation window characterization

V_{delay1}, V_{delay2} and $V_{window1}$, $V_{window2}$ are respectively the coarse and fine control for the delay compensation and the correlation window width



Parameter	Architecture	Min [ns]	Max [ns]	Jitter [%]
Delay compensation t_{delay}	All – in	10.4	29.4	3
	Shared	12	32.1	2
Correlation window t_{window}	All – in	2.7	22.5	15
	Shared	3	24.3	12



Experimental results
Features

Parameters	All-in	Shared	Event-driven
Correlation performed	Pixel	Pixel	Periphery
Size	100 x 50	100 x 50	100 x 100
Active Area [μm^2] *1	55.85	90.41	**99.31**
Fill Factor [%]	19.3	31.3	**34.4**
PDE Estimated [%] *2	3.7	5.9	**6.5**
Max correlation rate [Hz]	**3M**	**3M**	500k
Max frame rate (fps)	50k - 3M	50k - 3M	500k
Delay compensation [ns]	**9 – 140**	**9 – 140**	10 – 50
Window correlation [ns]	3 – 30	3 – 30	**0.1 – 25.6**
Output	Binary map	Binary map	X-Y proj time-stamp
Readout method	Raster Skip-zero	Raster Skip-zero	Raster
SRAM	Yes	Yes	Yes
Post processing	**No**	**No**	Yes

*1 Pixel Area = 289 μm^2

*2 PDP = 19% estimated at 600 nm wavelength and 3V of excess bias

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Conclusions

- SPAD array specifically designed for the *FastGhost* european project aim to implement a microscope exploiting the ghost imaging advantages and working with wavelength up to 7 μm (MIR)
- Two reduce-scaled correlation architectures presented: **In-pixel** and **Event-driven** architectures
- Preliminary experimental characterizations of the *In-pixel* correlation array
- Acquired scene simulating a ghost imaging setup

Conclusions
Next steps

- Characterization of the *Event-driven* architecture
- Select the best architecture suitable for the extended version of 512 x 512 array size (submission expected at the end of 2022)
- Improving the readout in order to maximize the correlation rate even with a larger array
- Acquiring a “real” ghost imaging with *FastGhost* setup in Jena

thank you.

*fast*GHOST

Stay tuned: https://www.fastghost.eu/#/