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FUTURE BUILT ON KNOWLEDGE

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Virtual Edinburgh, 8-10 June 2020

Scalable, Multi-functional CMOS SPAD arrays for Scientific Imaging

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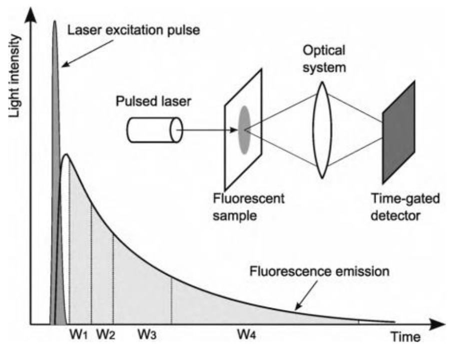
Scalable, Multi-functional CMOS SPAD arrays for Scientific Imaging

Outline

- Applications and requirements
- Technologies for Scientific Imaging
- CMOS SPAD imagers with fully parallel timestamping capabilities
- A 224×271 multi-functional CMOS SPAD imager

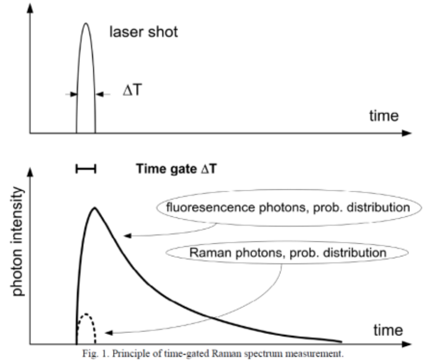
Scientific imaging
Applications

FLIM
Fluorescence decay times



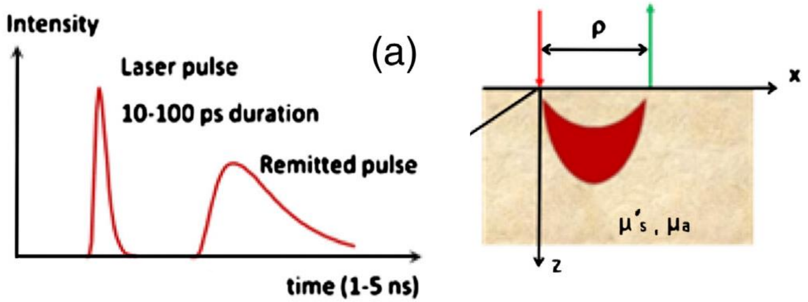
[Esposito, OpEx 2010]

Raman
Spectrum of a very short pulse



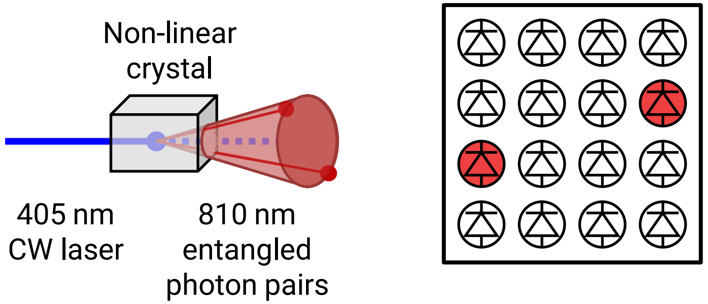
[Kostamovaara, OpEx 2011]

TD-NIRS
Scattering vs absorption



[Torricelli, JNI 2014]

QImg
Spatio-temporal correlations between photons



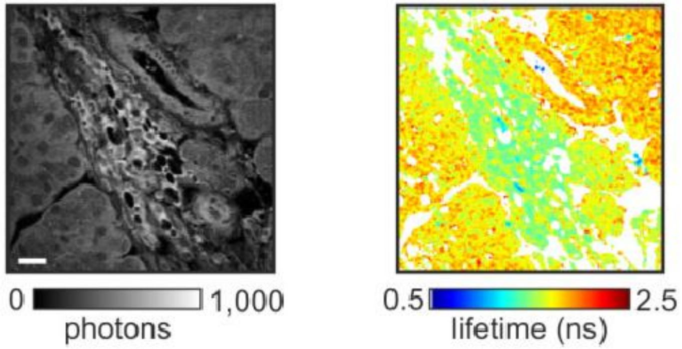
[Zarghami, JSSC 2020]

Scientific imaging

Applications

FLIM

Fluorescence decay times



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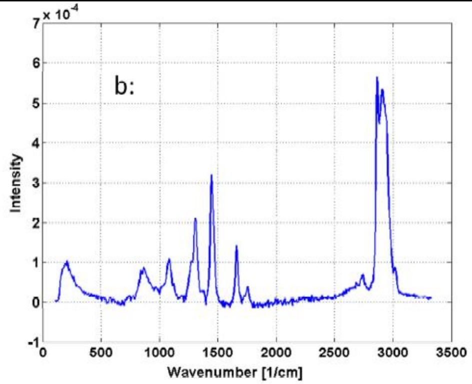
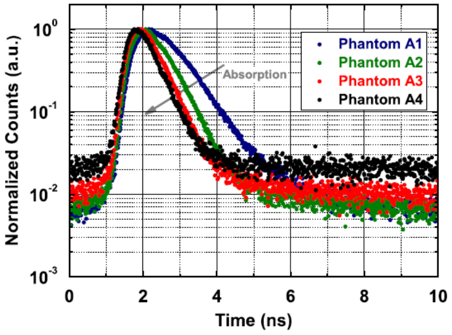


[Kostamovaara, OpEx 2011]

TD-NIRS

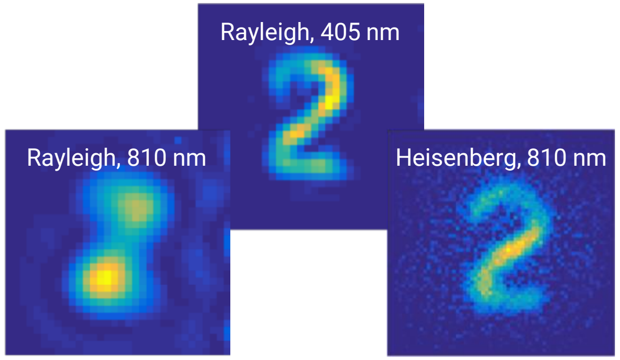
Scattering vs absorption



[Buttafava, IEEE PJ 2014]

QImg

Spatio-temporal correlations between photons



[Unternährer, Optica 2018]

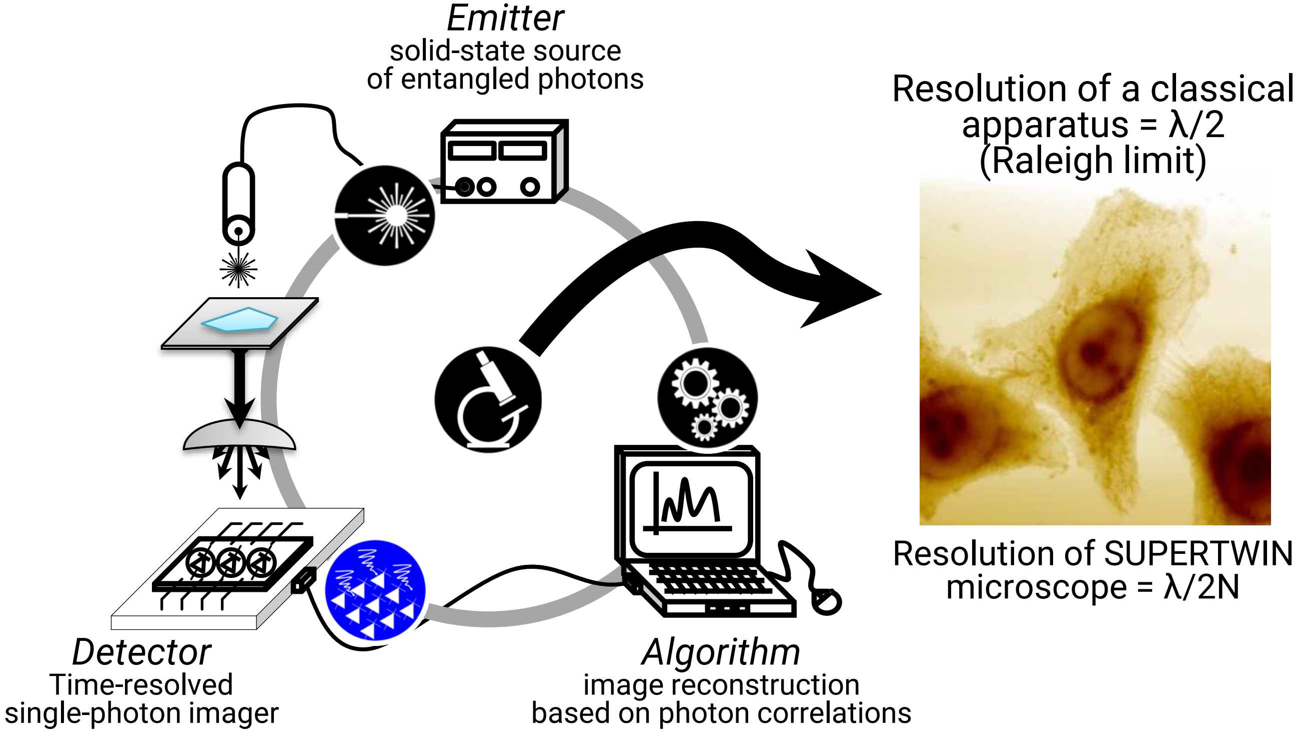
Scientific imaging

What a Physicist asks

1. 100% sensitivity
2. No noise (device noise, electronic noise)
3. Millions of channels in zero area
   - Fully parallel / Imaging
   - No correlated noise (crosstalk, afterpulsing)
4. 100% duty cycle / No dead times
5. Special features
   - Room temperature operation
   - Fast turn-on (~~electrical~~ device gating)
   - …

EU H2020 FET-OPEN Project *SUPERTWIN*

All Solid-State Super-Twinning Photon Microscope

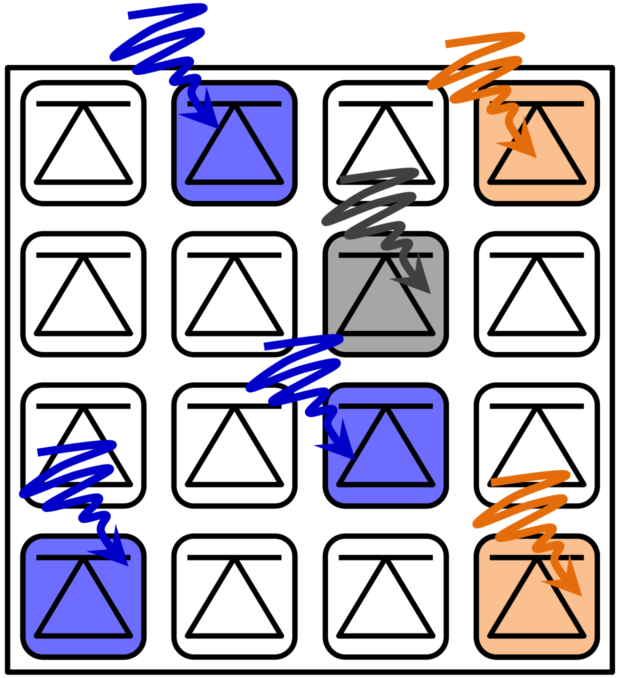


Goal: to develop the **solid-sate technology** foundation for the next generation of **super-resolution microscopes** based on **entangled photons**

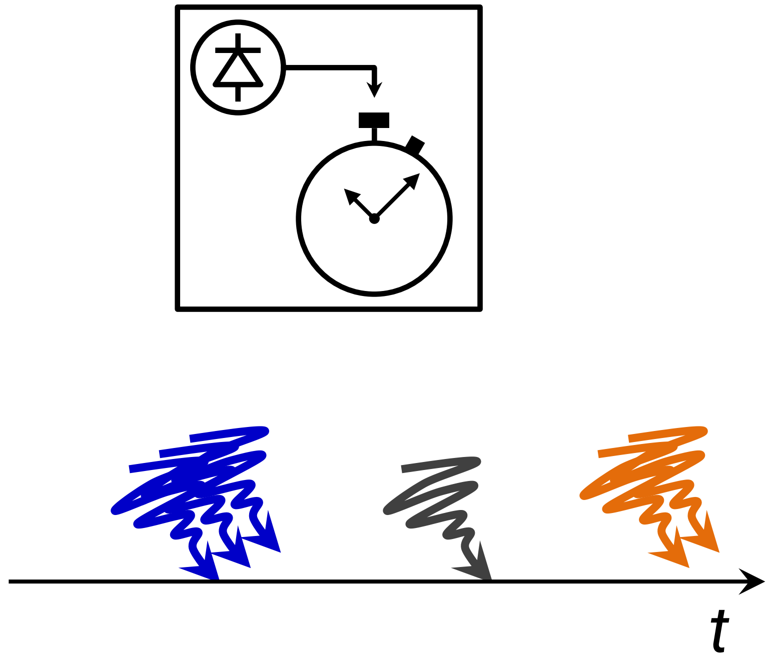
Detecting entangled photons

Measuring spatio-temporal correlations

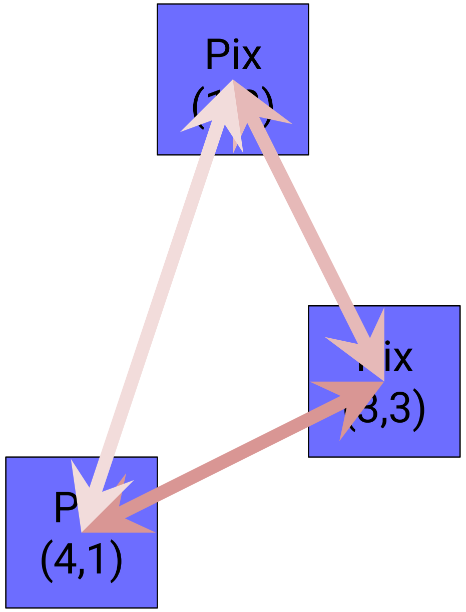
1. Detect single photons ⇨ 2. Identify coincidences in time (e.g. using timestamps) ⇨ 3. Extract their spatial correlations



(High sensitivity)^N



High-resolution/precision fully-parallel timestamping

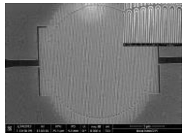
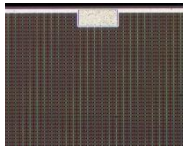


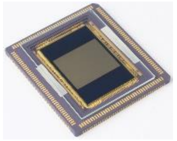
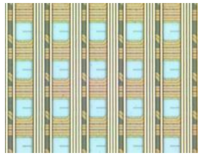
Many pixels (→ small pixels)

Single-photon technologies

That you can buy

New and future options:
Intensifier+TimePix3
QIS

	PMT	SNSPD	SiPM	EM-CCD	I-CCD	sCMOS	CMOS SPAD
Solid-state	✗	✓	✓	✓	✓	✓	✓
Imaging	✗	✗	✗	✓	✓	✓	✓
High-res. imaging	✗	✗	✗	✓	✓	✓✓	✗
High frame rate	-	-	-	✗	✗	✓	✓
Time-gating	✓✓	✓✓	✓✓	✗	✓	✓	✓✓
Photon timestamping	✓	✓✓	✓	✗	✗	✗	✓
Room temperature operation	✓	✗✗	✓	✗	✗	✓	✓
High PDE	✓	✓✓	✓	✓✓	✓(✓)	✓(✓)	✗
Low noise	✓	✓✓	✓	✓✓	✓	✓	✗

Single-photon technologies

That you can buy

New and future options:
Intensifier+TimePix3
QIS

	PMT	SNSPD	SiPM	EM-CCD	I-CCD	sCMOS	CMOS SPAD
Solid-state	✗	✓	✓	✓	✓	✓	✓
Imaging	✗	✗	✗	✓	✓	✓	✓
High-res. imaging	✗	✗	✗	✓	✓	✓✓	✗
High frame rate	-	-	[illegible]	✗	✗	✓	✓
Time-gating	✓✓	✓✓	[illegible]	[illegible]	[illegible]	[illegible]	✓✓
Photon timestamping	✓	✓✓	✓	✗	✗	✗	✓
Room temperature operation	✓	✗✗	✓	✗	✗	✓	✓
High PDE	✓	✓✓	✓	✓✓	✓(✓)	✓(✓)	✗
Low noise	✓	✓✓	✓	✓✓	✓	✓	✗

Technology development

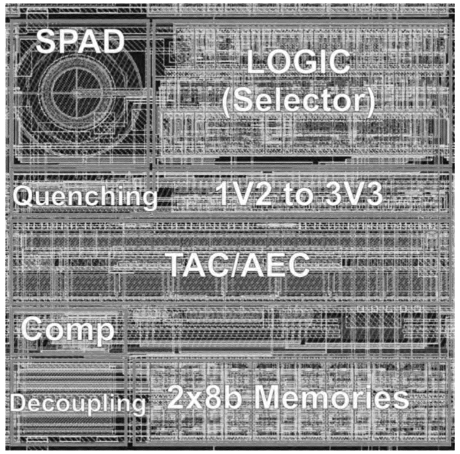
Single-photon technologies

SPAD imagers (fully parallel operation) in Research

Time-to-Digital Converter

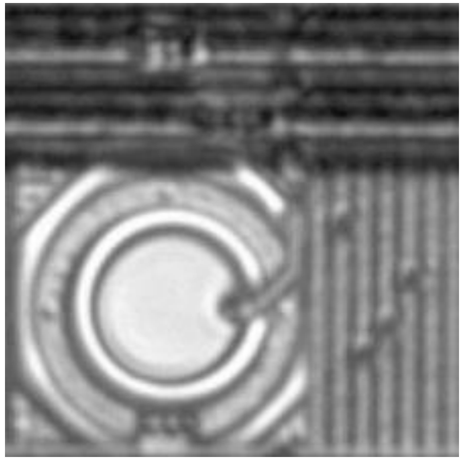
[Richardson, CICC 09]
[Veerappan, ISSCC 11]
[Villa, JSTQE 14]
[Field, JSSC 14]
[Vornicu, TCAS I 17]

Time-to-Analog Converter



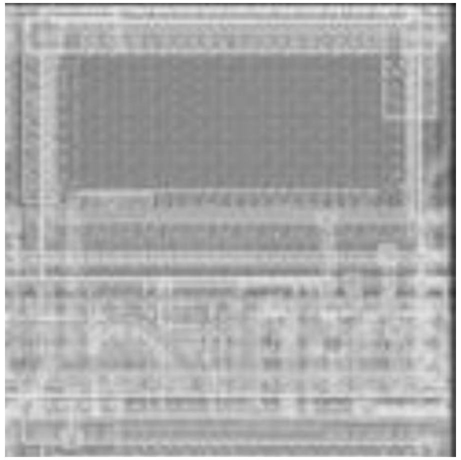
[Stoppa, ESSCIRC 09]
[Parmesan, IISW 15]

Time-gated Digital Counter



[Burri, OpEx 14]
[Al Abbas, IEDM 16]
[Ulku, JSTQE 19]
[Morimoto, Optica 20]

Time-gated Analog Counter

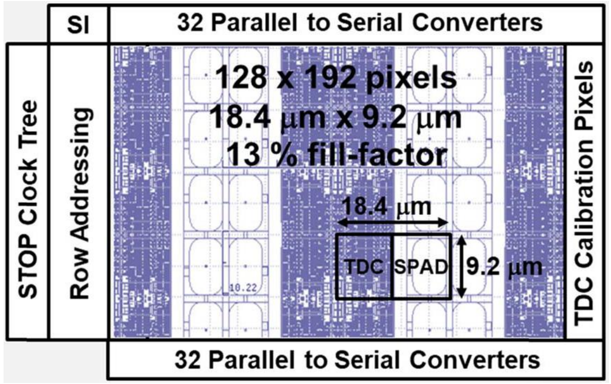


[Pancheri, TED 13]
[Perenzoni, ISSCC 15]

SPAD imagers (fully parallel operation) in Research

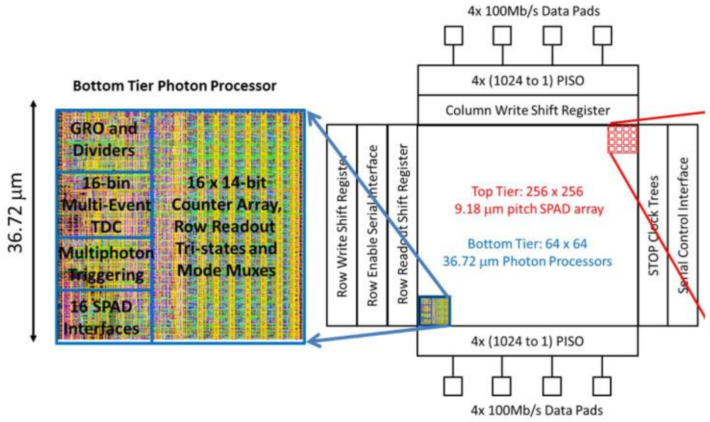
State-of-the-Art

[Henderson, JSSC 19]



- **40 nm**
- **192×128 pixels**
- **18.4×9.2 µm²**, 13% FF
- Well sharing, ~oval SPAD
- Photon timestamping
- **TDC: 33-120 ps**, 12 bit
- **18.6 kfps** → 0.9% duty cycle

[Hutchings, JSSC 19]



- **3D stacked 90/40 nm**
- 256×256 SPADs / 64×64 processing units
- 9.18 µm, **51% FF** / 36.72 µm
- Photon timestamping, photon counting
- **TDC:** 38-**560 ps, 14 bit**
- 760 fps → 0.7% duty cycle

1st SUPERTWIN SPAD array: *SuperEllen*

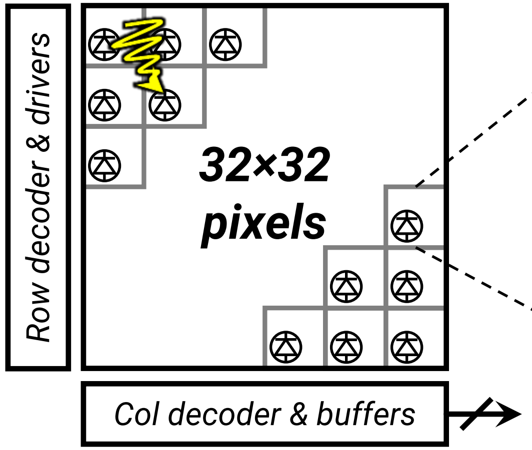
32×32 SPAD/TDCs in 150nm CMOS

[Gasparini, ISSCC 18]

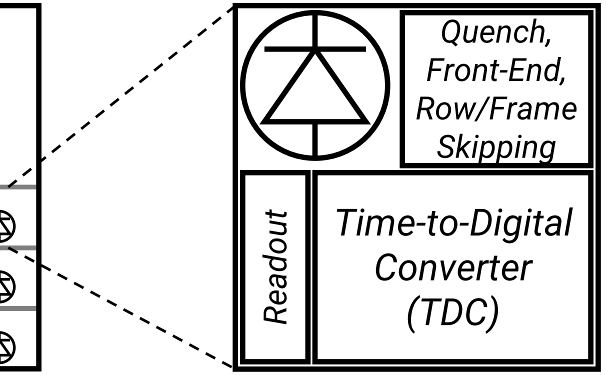
[Zarghami, JSSC accepted]

LFOUNDRY Solutions for great visions

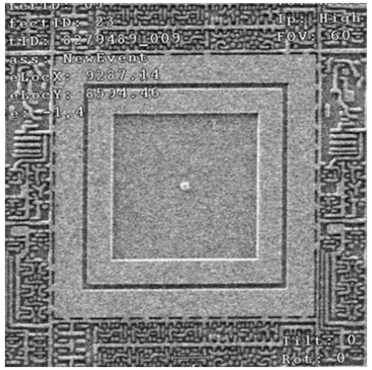
Sensor architecture



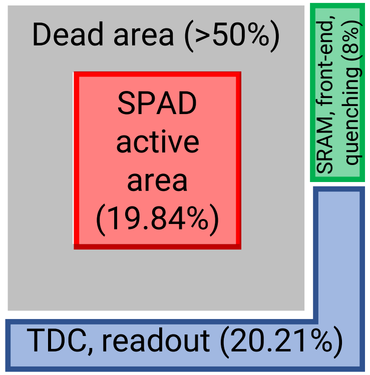
Pixel block diagram



After metal 1



Pixel area partitioning



Pixel

Pixel pitch	44.64 µm
SPAD size	19.8 µm
Pixel fill factor	**19.48 %**
Sharing of SPAD well (MTF distortion)	No
SPAD excess bias voltage	3.0 V
SPAD DCR, median	600 Hz
Crosstalk	0.1%

TDC

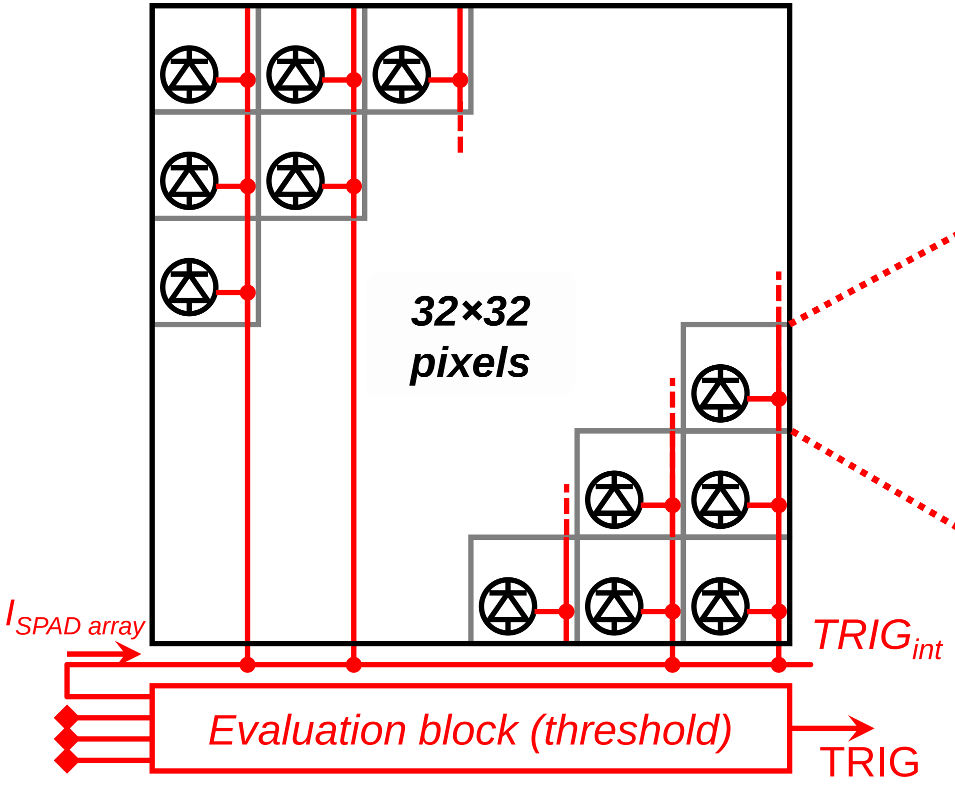
TDC area	**402.7 µm²**
Time resolution	204.5±2.7 ps
Depth / Range	8 bit / 52 ns
DNL	-149..+157 ps
INL	-190..+254 ps
Precision	240 ps (raw) 205 ps (calibrated)

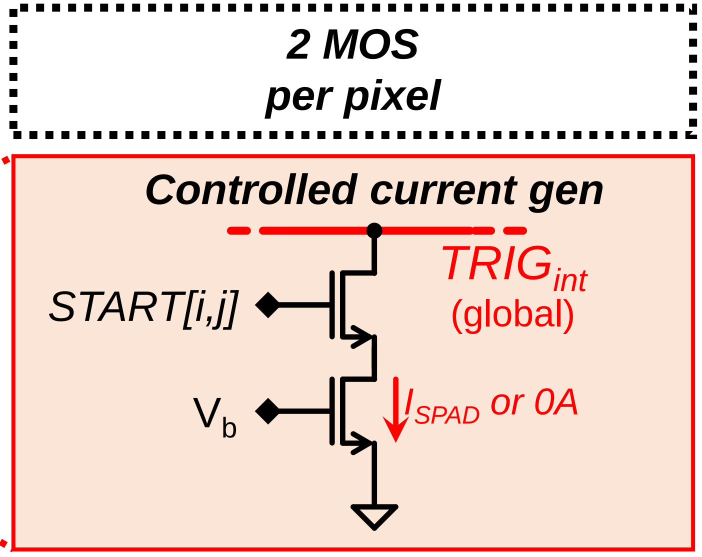
Chip

Array size	32×32 pixels
Chip size	1.69×1.88 mm²
Frame rate	80 kfps (full readout) 450 kfps (row skipping)
Obs. rate	**1 MHz (frame skipping)**
Duty cycle	**5%**
Power	11.1 mW (row skipping) 7.8 mW (frame skipping)

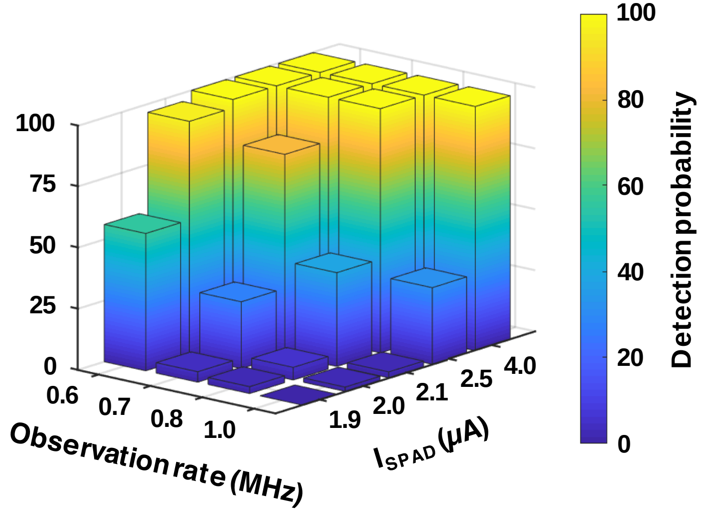
SuperEllen's Frame skip

High duty cycle (> 5× wrt SotA)





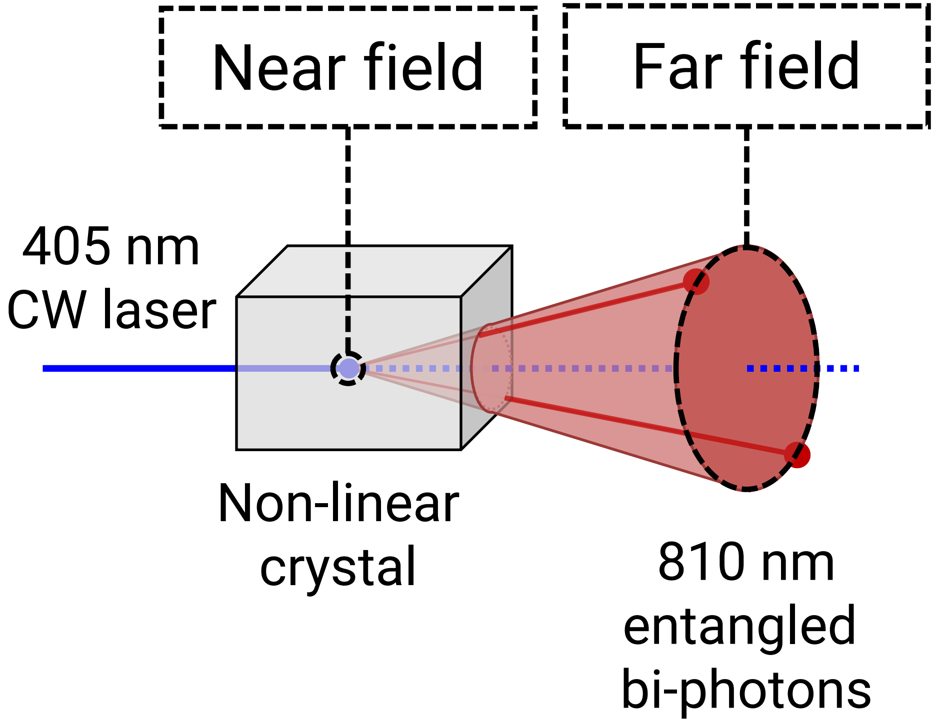
$I_{SPAD\ array} = N_{ph} \times I_{SPAD}$



Quantum optics experiments using SuperEllen

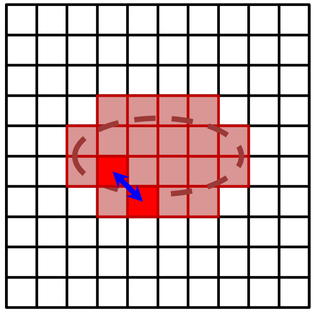
[Unternährer, Optica 18]

Demonstration of space-momentum entanglement of an SPDC source



Near field correlations

- Correlated in time
  - ~at the same time
- Correlated in space
  - ~in the same place



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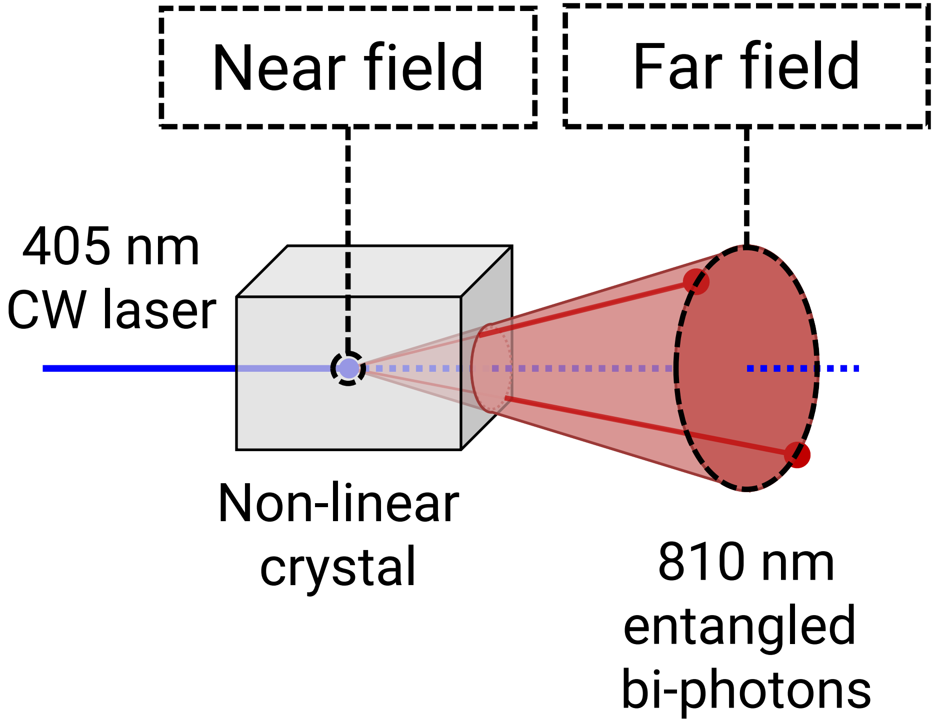

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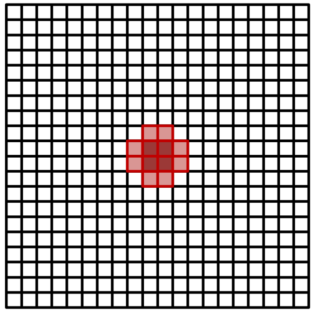

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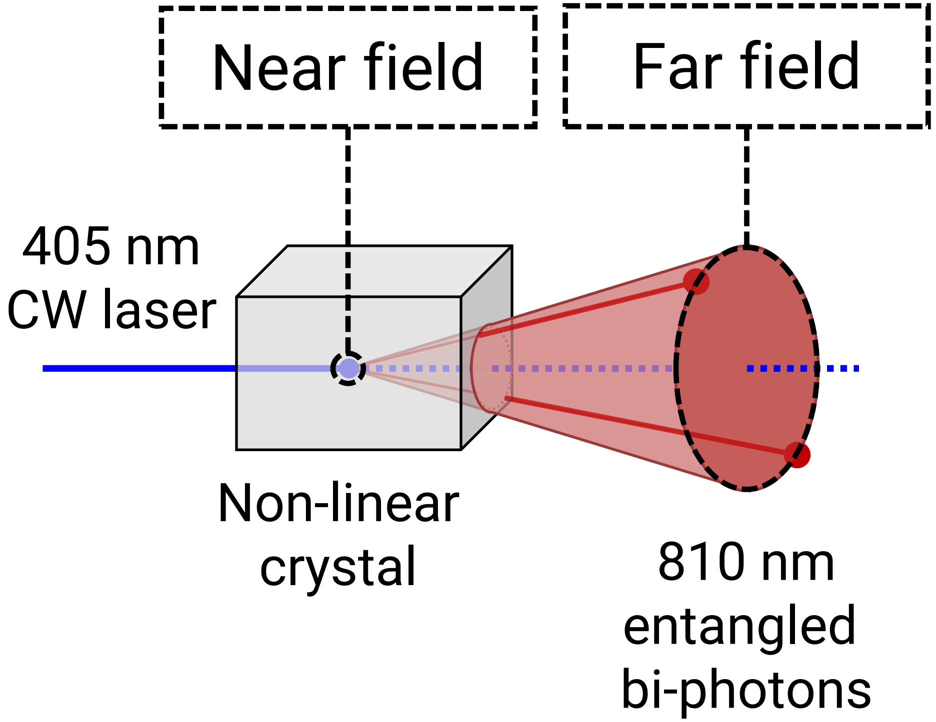

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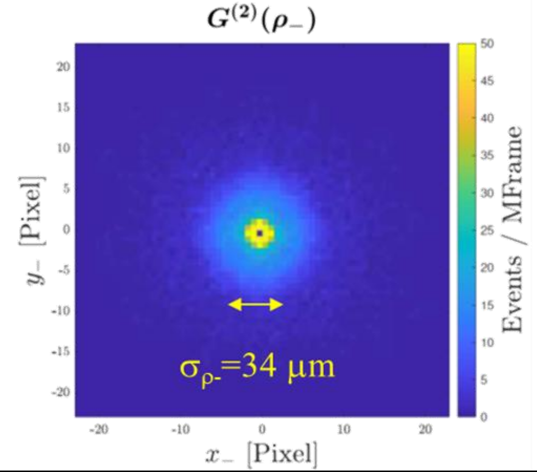

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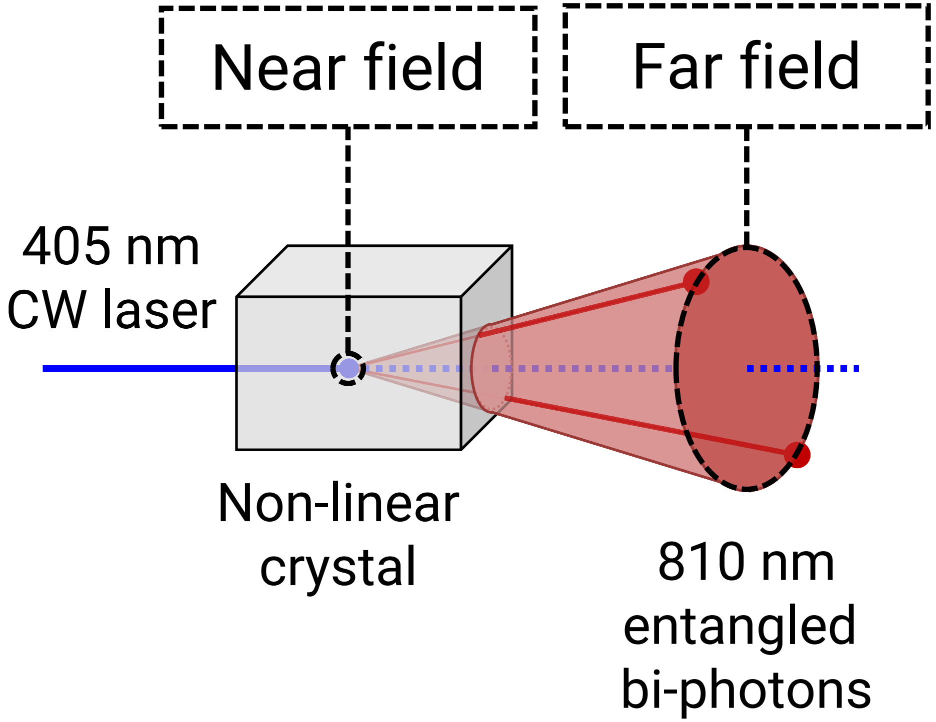

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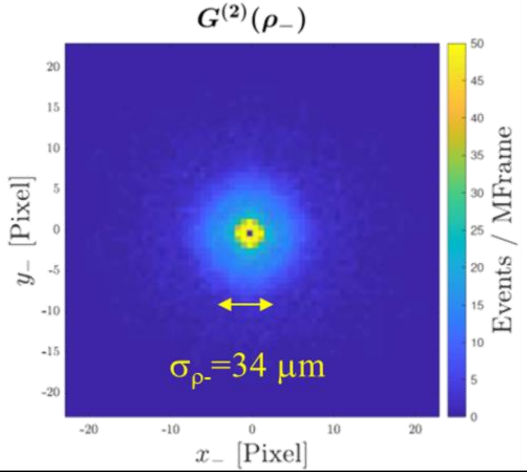
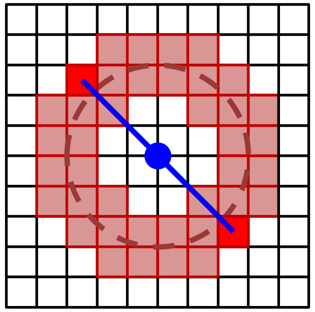


Far field correlations

- Correlated in time
  - ~at the same time
- Anti-correlated in momentum
  - in opposite direction



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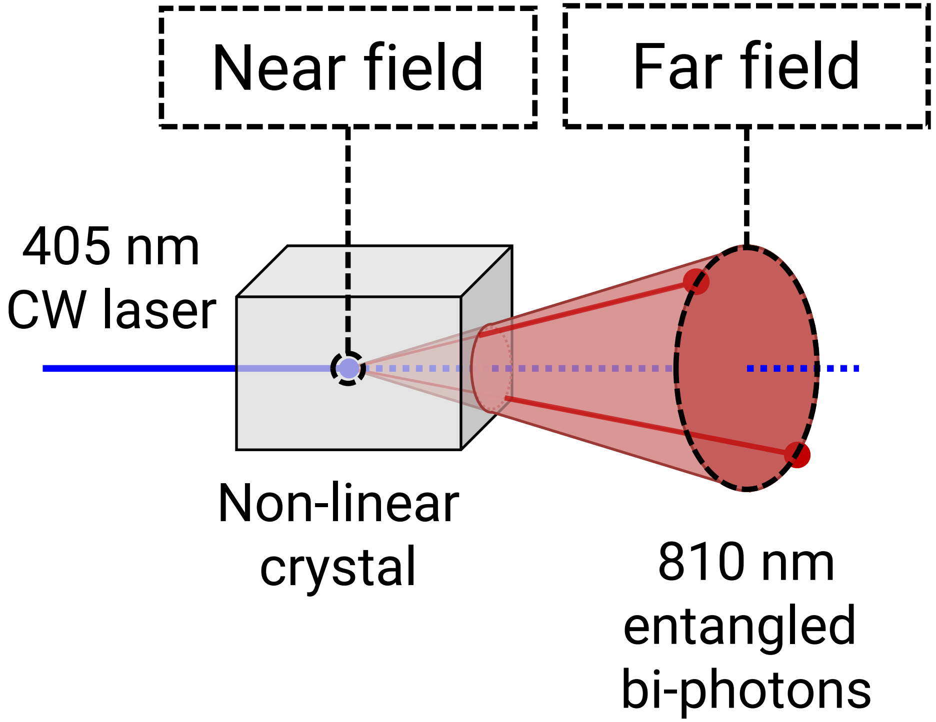

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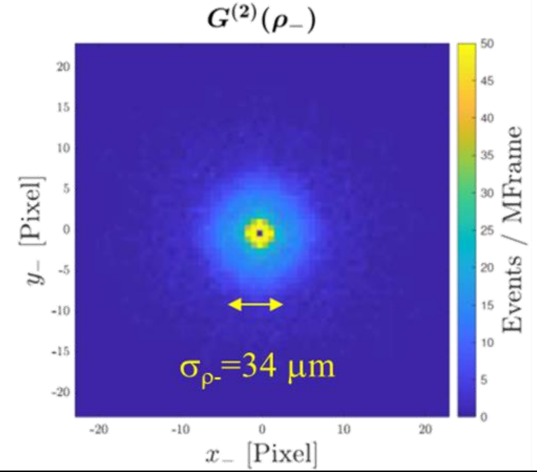

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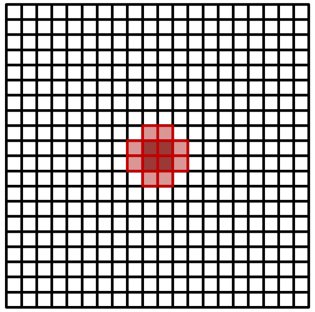

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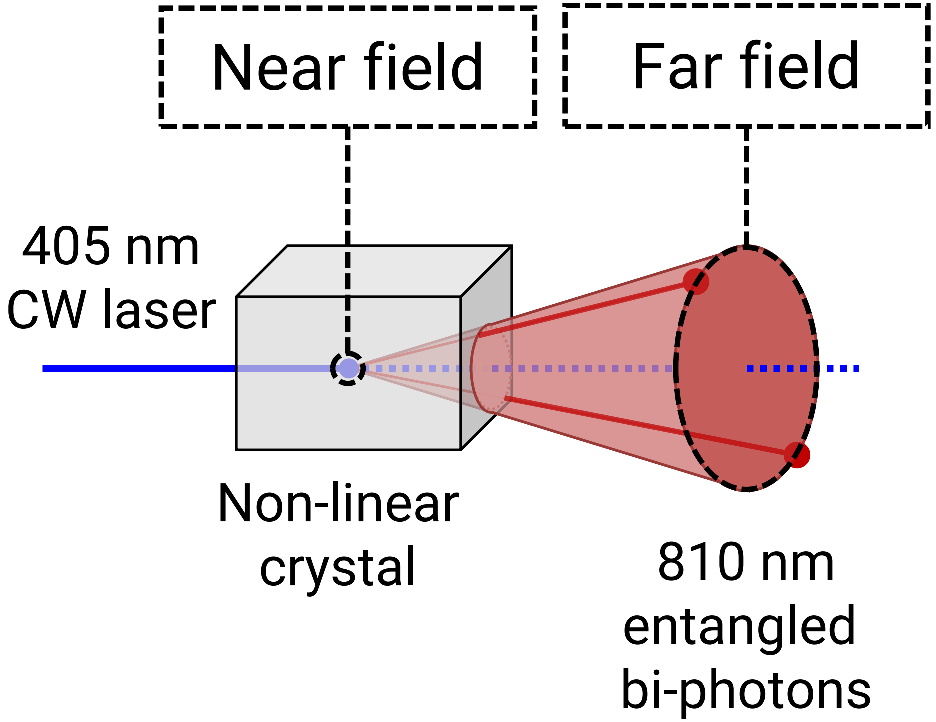

Einstein Podolski Rosen type violation

For Classical light	$\sigma_{q+}^2 \sigma_{\rho-}^2 > \frac{1}{4}$
We measure	$\sigma_{q+}^2 \sigma_{\rho-}^2 = 0.17$

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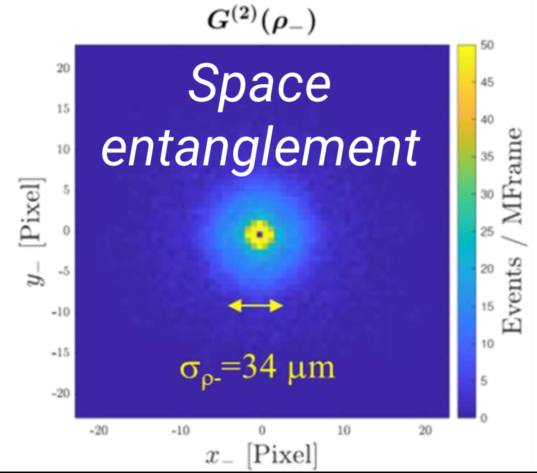

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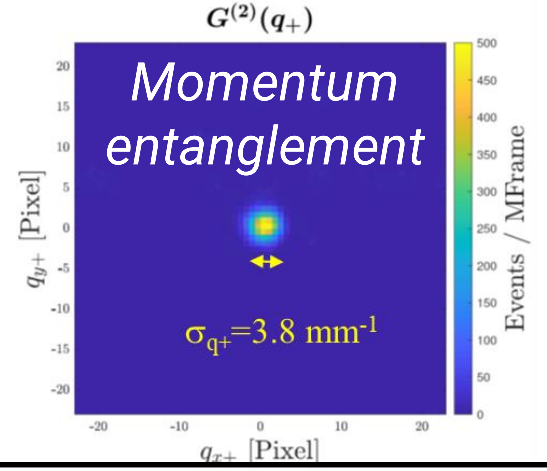
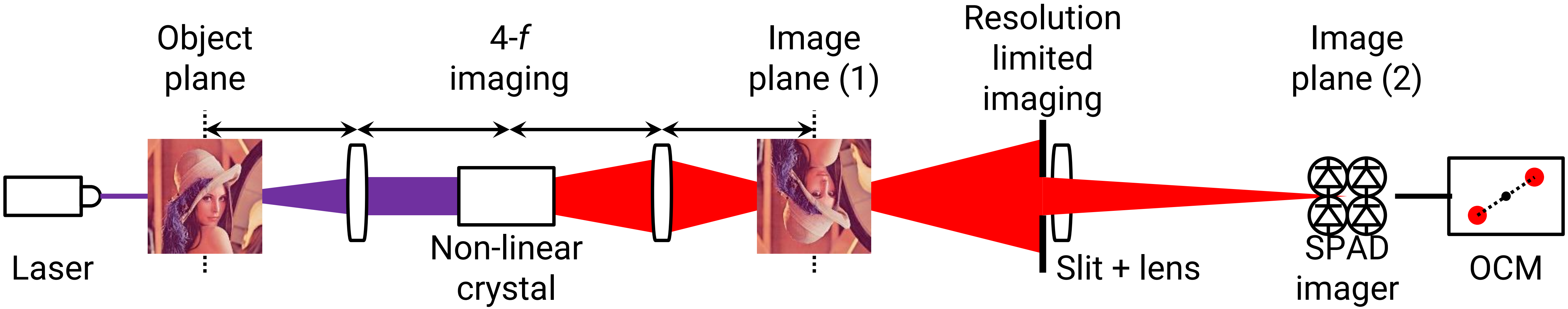
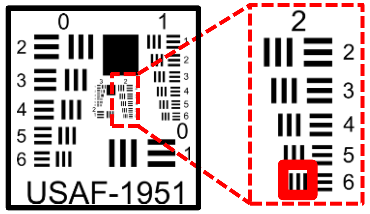


Quantum optics experiments using SuperEllen

Super-resolution quantum imaging at the Heisenberg limit

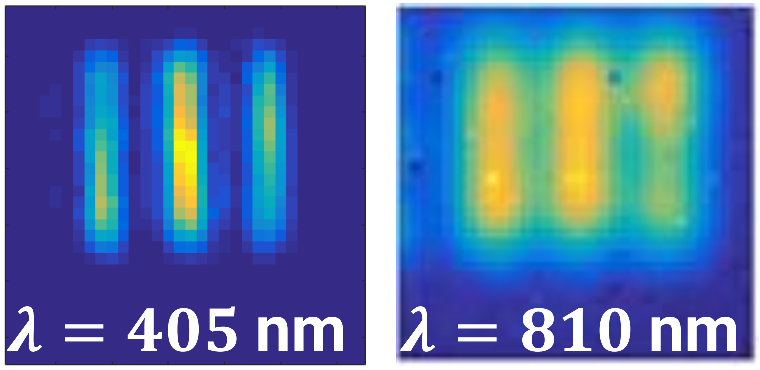




Selected object: **70.1 µm slits** in a resolution test chart

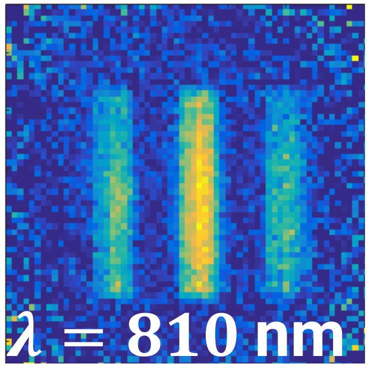
Rayleigh limit

$$R \propto \frac{\lambda}{\mathrm{NA}}$$



Heisenberg limit

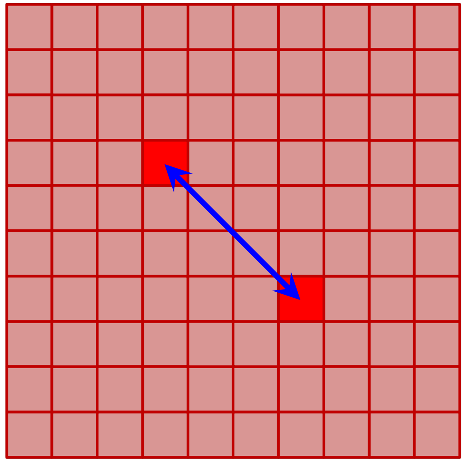
$$R \propto \frac{\lambda}{2\,\mathrm{NA}}$$



Side effects from working with quantum optics

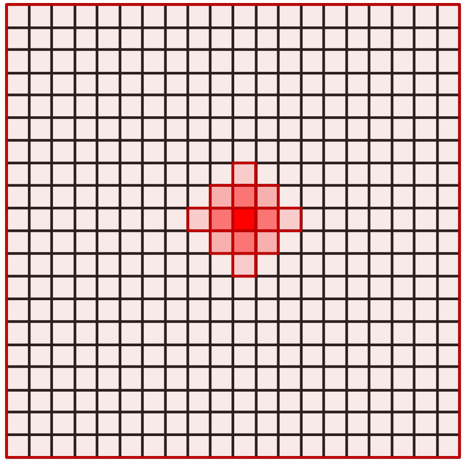
Crosstalk characterization from 2nd order correlations

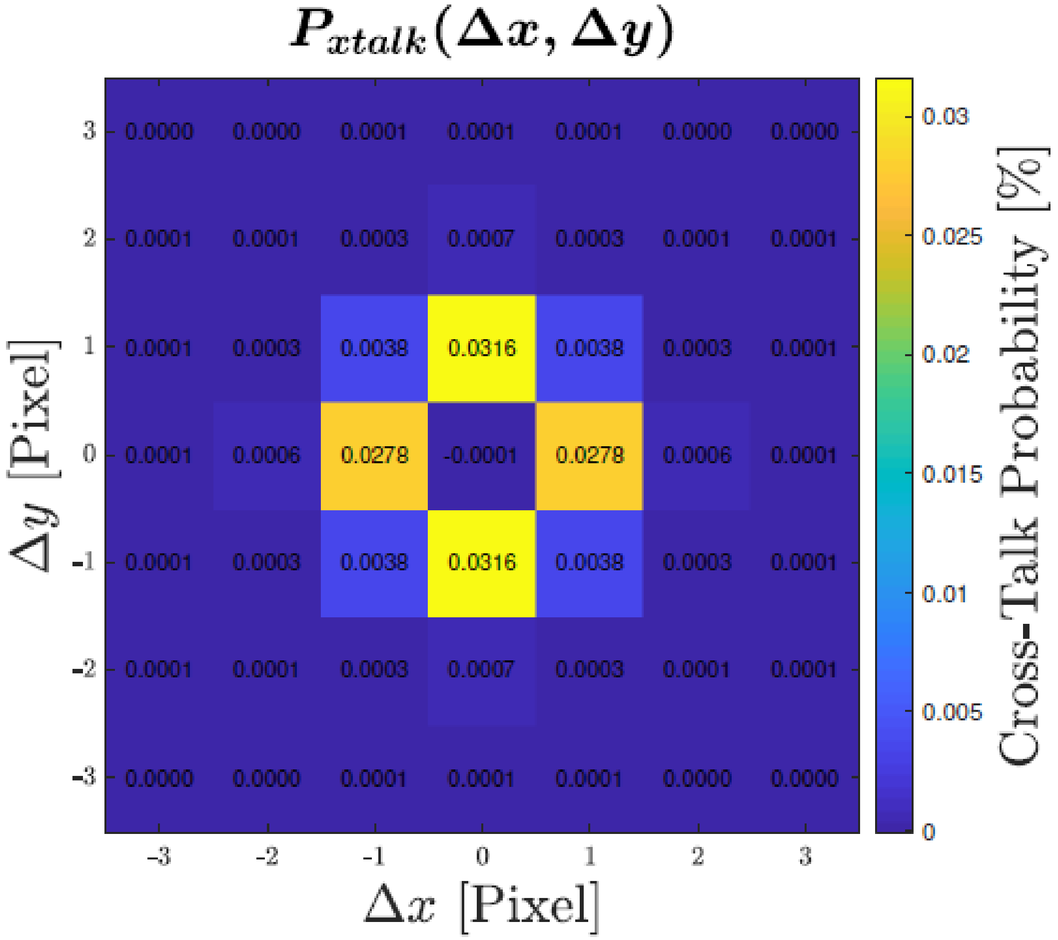
$G^{(1)}(x,y)$



Distance $\boldsymbol{\rho_-}$

$G^{(2)}(\rho_-)$



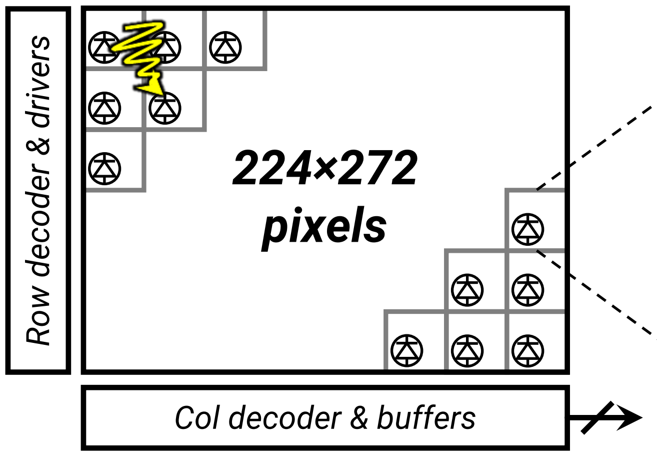


2^{nd} SUPERTWIN SPAD array: *SuperAlice*

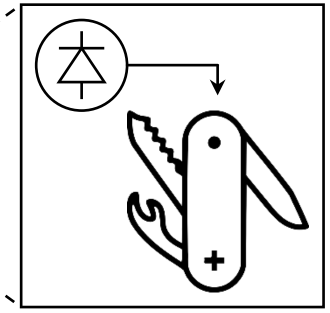
From requirements to architecture

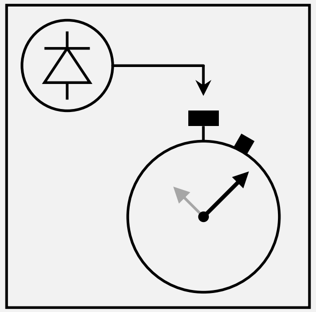
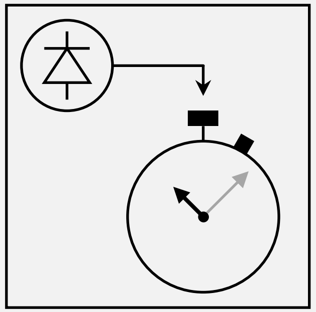
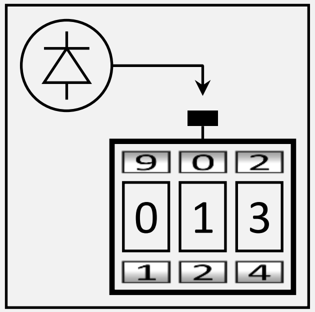
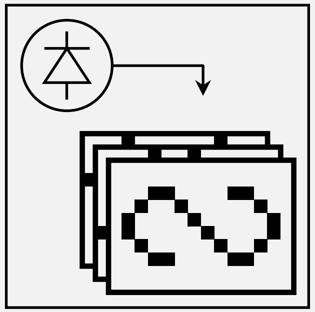
LFOUNDRY Solutions for great visions

Sensor architecture

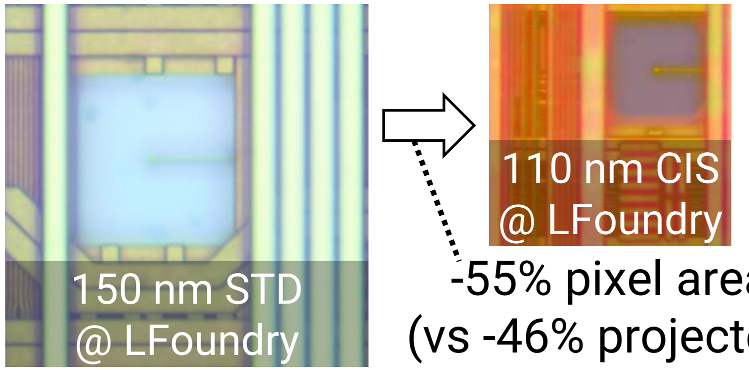


Multi-functional pixel



Fine timestamping	***Coarse timestamping***	***Photon counting***	***High-speed binary imaging***
			
$T_{ph} = n \times 180$ ps	$T_{ph} = n \times T_{clock}$ [$T_{clock} \geq 10$ ns]	$N_{ph} = 0 \ldots 127$	*Photon or not* [*7 images @* T_{clock}]

Pixel: SuperEllen vs SuperAlice

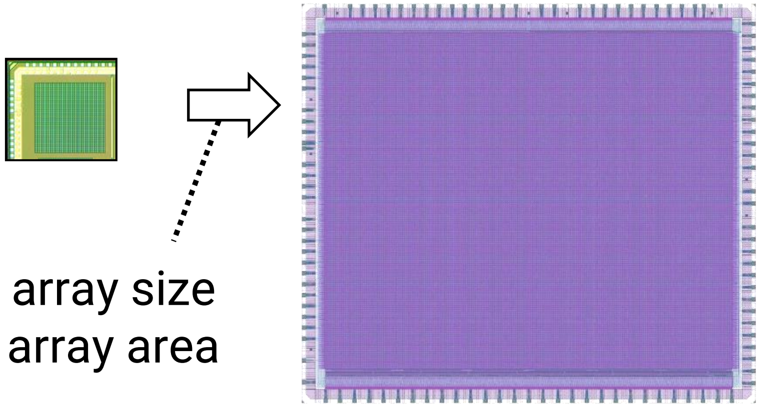


-55% pixel area
(vs -46% projected)

110 nm SPADs (vs 150 nm)
PDE@460 nm×2
DCR/7
Xtalk/3

[Moreno-García, ESSDERC 18]

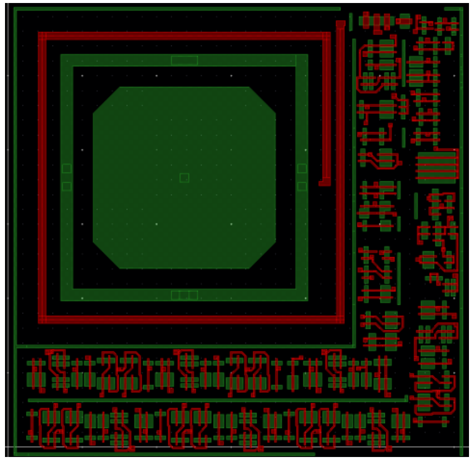
Chip: SuperEllen vs SuperAlice



×59 array size
×27 array area

224×272 Multi-functional pixel array

Working with a 1P4M 110 nm technology

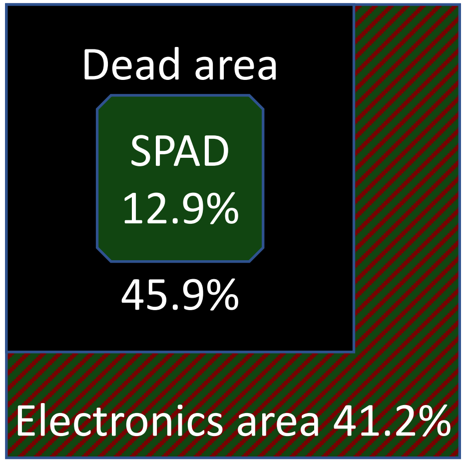


Constraints:
limited silicon area (370 µm², ≈ 14 flip-flops), routing (4 metals)

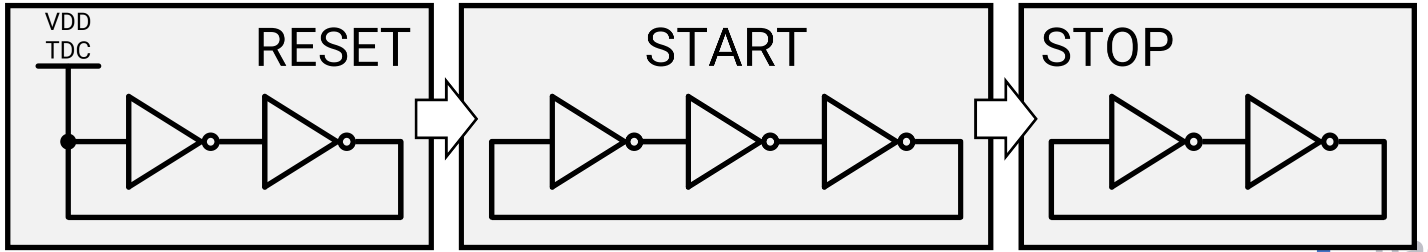
→New TDC architecture: new Gated Ring Osc (GRO)

register behaves as a counter/shift register

Reference	GRO type	#MOS/ GRO	# bits	Tech. [nm]	Area [µm²]	Proj. @ 110 nm [µm²]
[Henderson, JSSC 19]	Differential, 3-bit	n.a.	12	40	85	639
[Manuzzato, ESSCIRC 19]	Differential, 3-bit	108	10	150	1200	645
SuperEllen [Gasparini, ISSCC 18]	Single-end., sin interp. 3-bit	24	8	150	402	216
SuperAlice	Single-end., 1-bit	11	8	110	340	

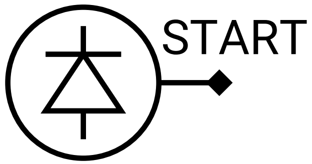


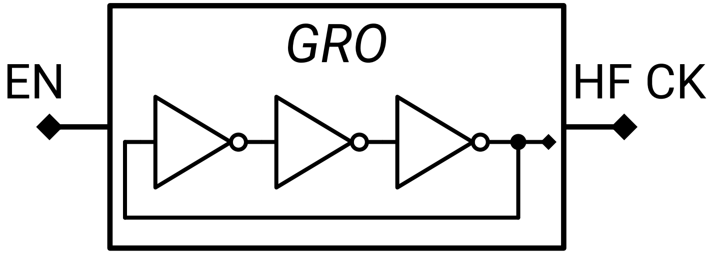
Compact, low power, 1-bit GRO

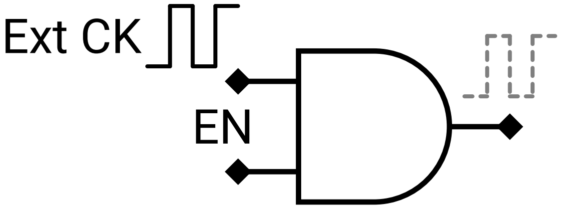


Multi-functional pixel

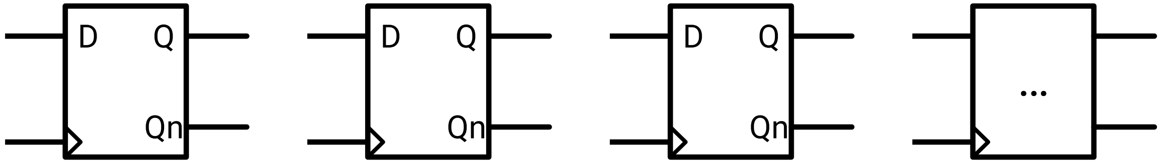
Main components





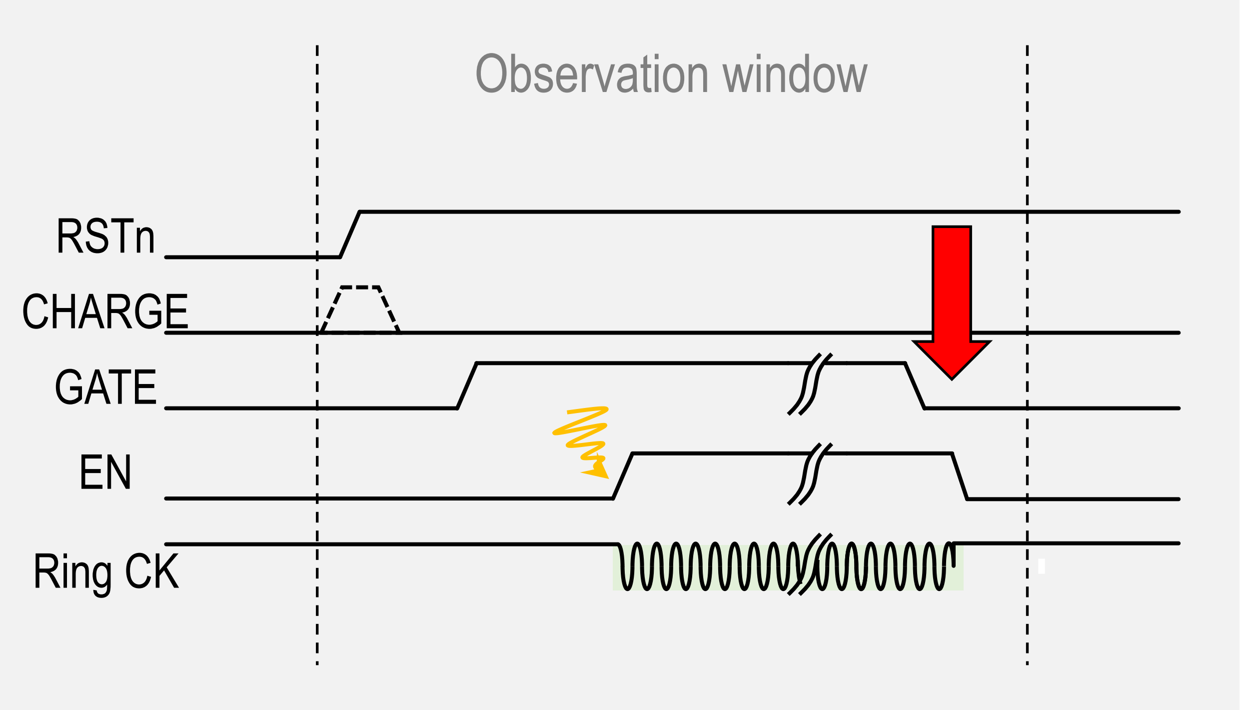


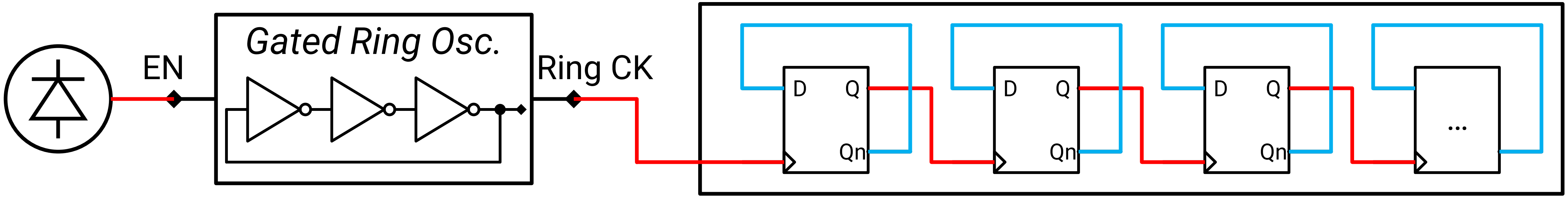
- SPAD + quench + gated FE+ 1b SRAM
- Digital stuff: 4 functionalities + readout
  - GRO
  - Gated external clock
  - 7-bit register: ripple counter / shift register
    - Routable inputs
    - Low area available→ get rid of RST



Multi-functional pixel
Fine timestamping mode

- SPAD enables the GRO
- GRO oscillates until a STOP is received (not shown)
- The timestamp has 8 bits
  - The LSB is fed into the register during readout



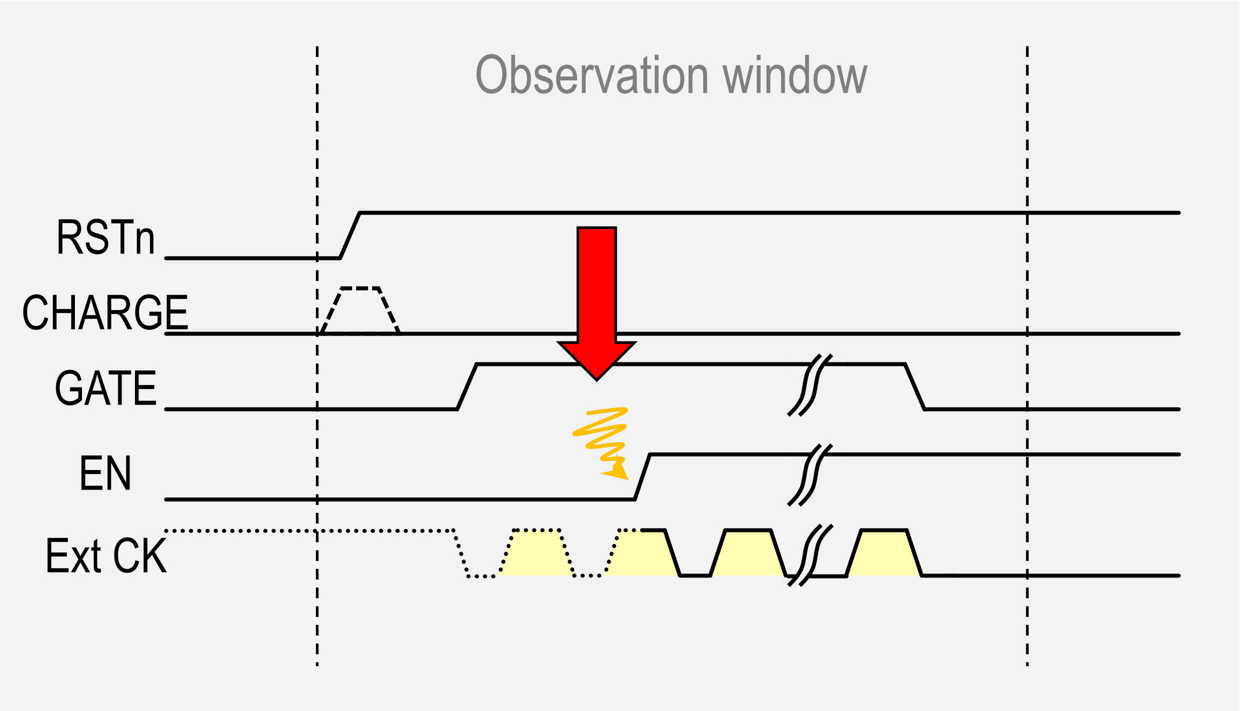


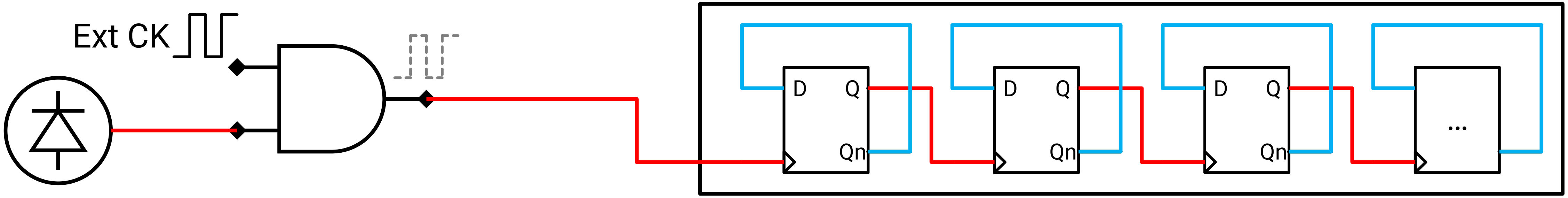
Multi-functional pixel

Coarse timestamping mode

- FPGA generates a low frequency clock
  - $T_{CK} \geq 10$ ns
  - T_{CK} can also change (e.g. 10/20/40/80 ns)

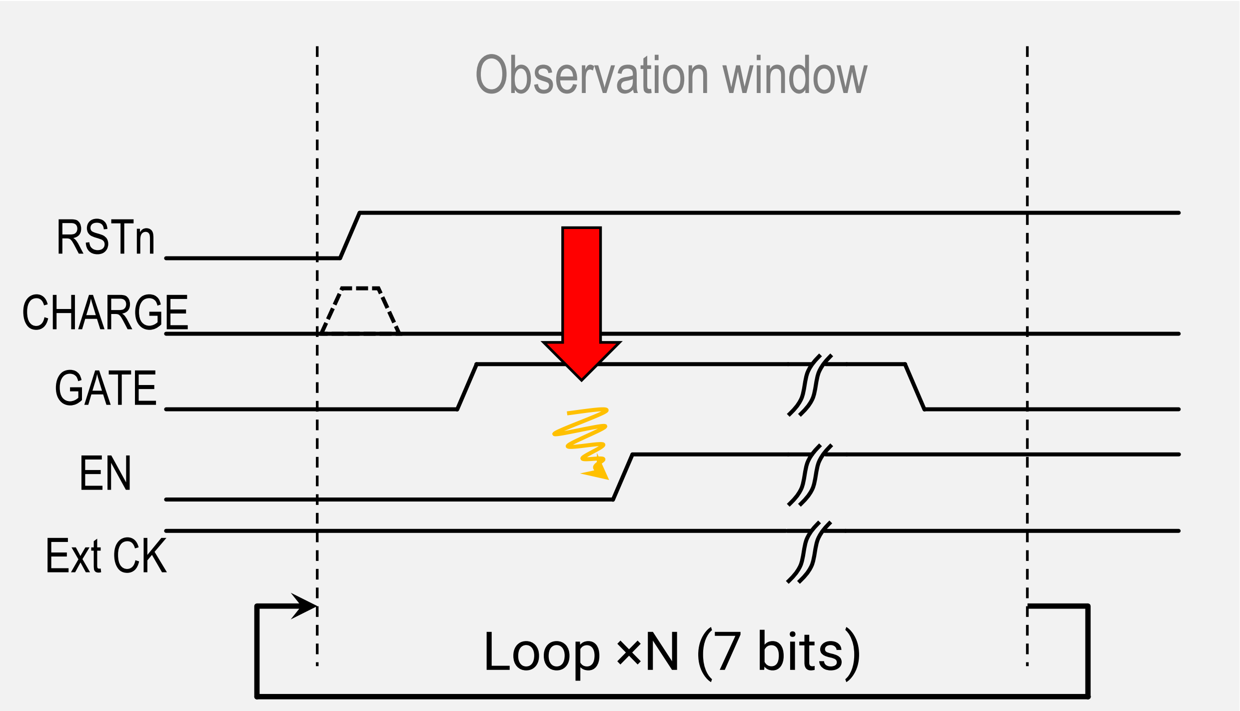
- SPAD triggers → clock unmasked

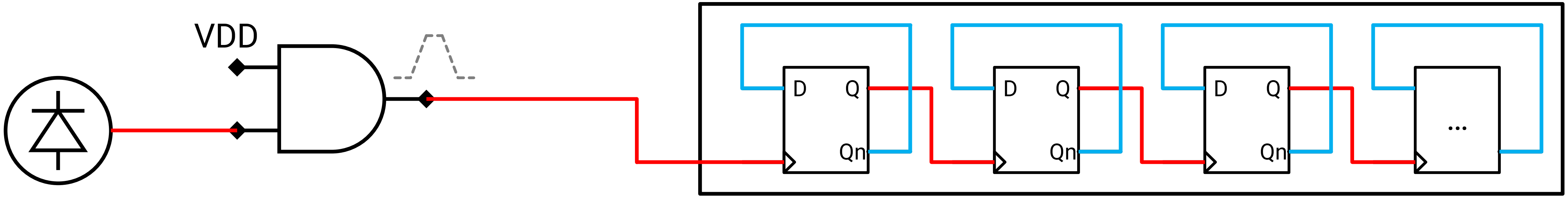




Multi-functional pixel
Photon counting mode

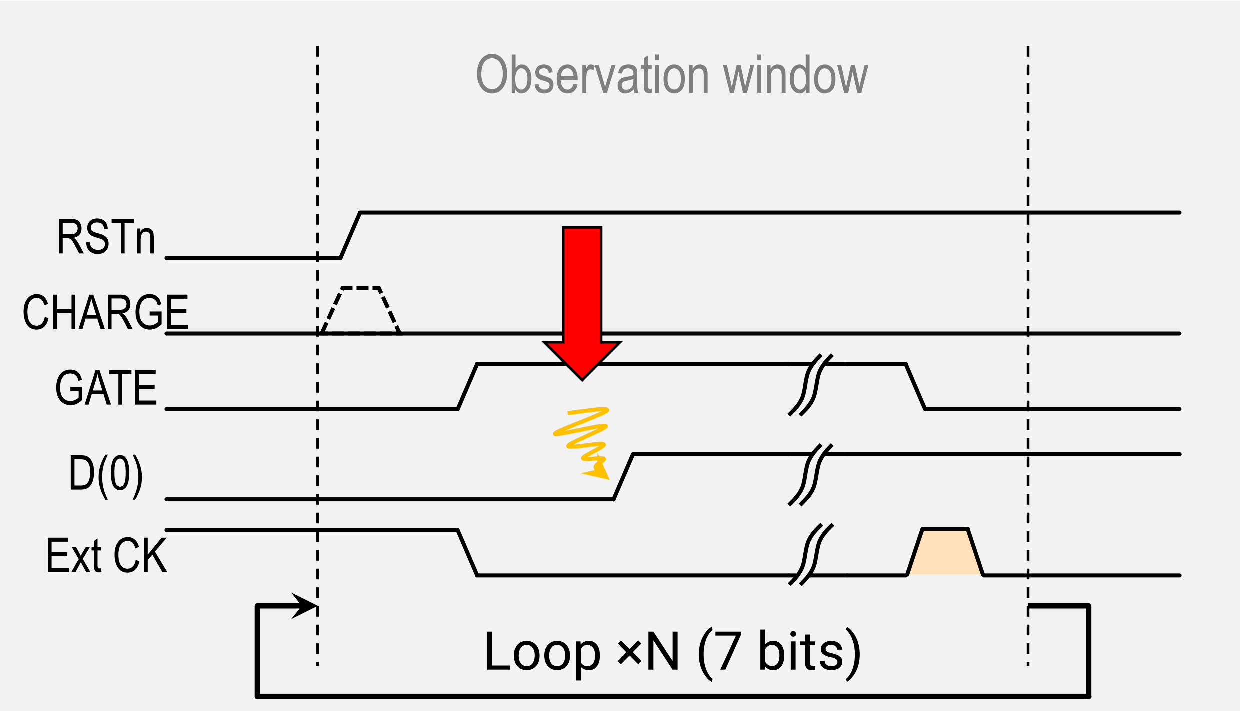
- Ext CK tied at VDD
- SPAD triggers → +1
- *N* observation windows are opened
  - $T_{Obs} \geq 10$ ns

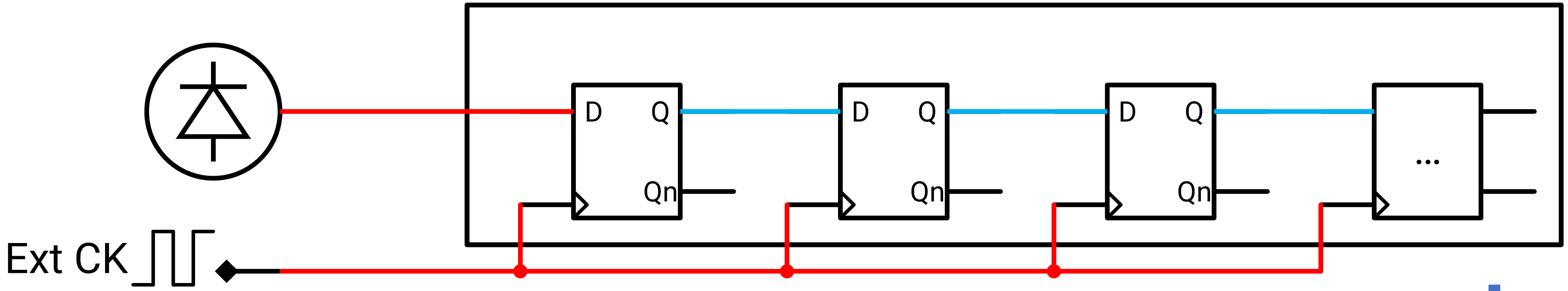




Multi-functional pixel
Binary imaging mode

- The SPAD may see a photon
- Ext CK pulsed **at the end** of the win
  → The SPAD state is shifted in the reg
- 7 observation windows are opened
  - $T_{Obs} \geq 10$ ns
  - T_{Obs} can change (e.g. 0.01/0.1/1/10 µs)



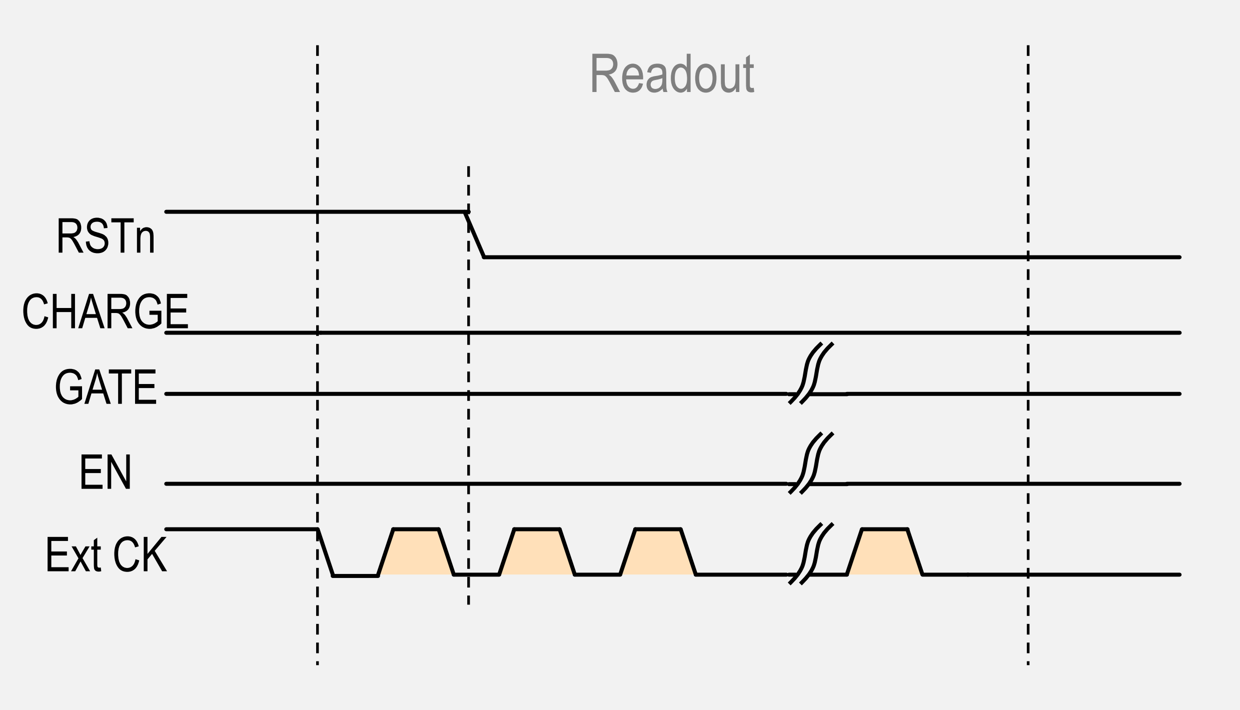


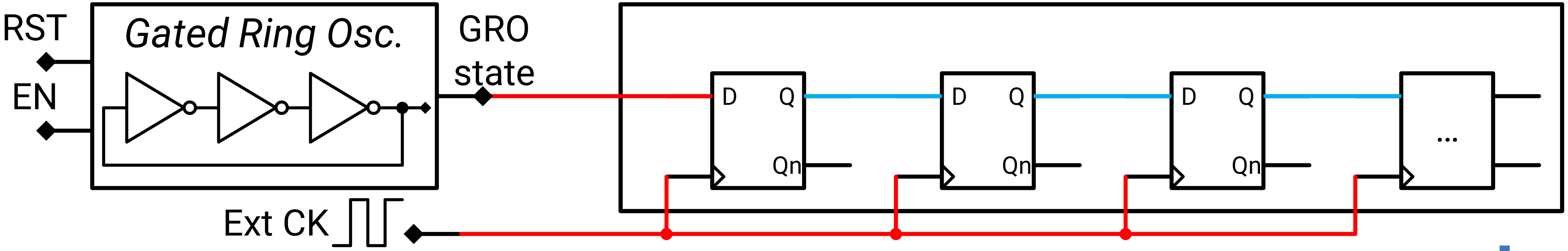
Multi-functional pixel

Readout

- Limited space for routing
  → serial readout

- HF CK provided as D input
  - 8^{th} bit of the fine timestamp
  - Or 0 (when GRO under reset)



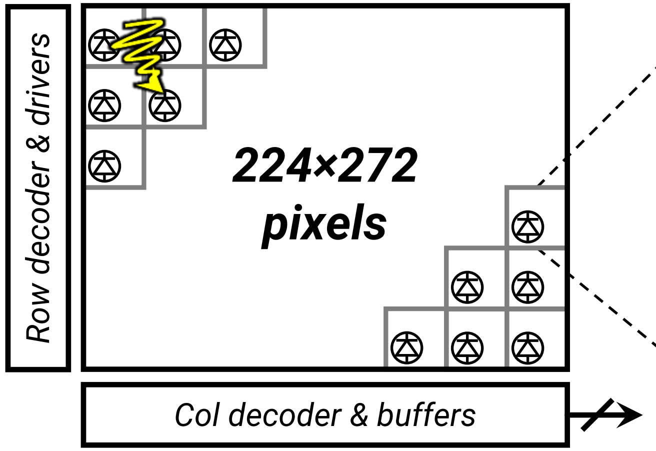


2nd SUPERTWIN SPAD array: *SuperAlice*

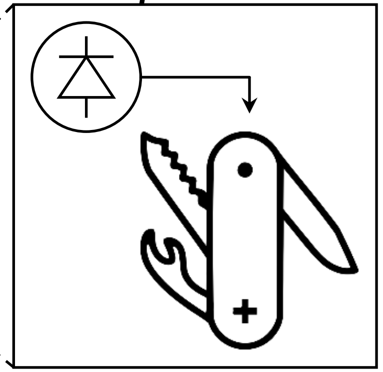
224×272 Multi-functional pixels in 110 nm CIS

LFOUNDRY Solutions for great visions

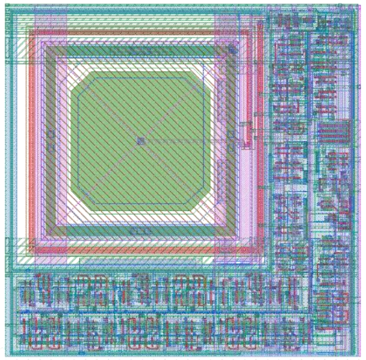
Sensor architecture



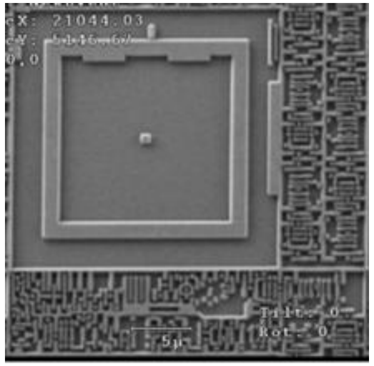
Multi-functional pixel



Pixel layout



After metal 1



Pixel

Pixel pitch	**30.0 µm**
SPAD size	11.0 µm
Pixel fill factor	12.9 %
Sharing of SPAD well (MTF distortion)	No
SPAD DCR, median, @ 3V	150 Hz
Crosstalk	0.03%

TDC

TDC area w/ reconf. FF	**340 µm²**
Time resolution	>180 ps
Depth / Range	8 bit / 46 ns
DNL (p-p)	0.3 LSB
INL (p-p)	1.0 :SB
Precision	360 ps (raw)

Chip

Array size	**224×272 pixels**
Chip size	**7.5×9.1 mm²**
Frame rate	2.5 kfps (row skipping)
Power	50.0 mW

2nd SUPERTWIN SPAD array: *SuperAlice*

Sample images

Photon counting

1k 1.27-µs-long observations

Image obtained from accumulated photon counts

Coarse timestamping

1k 635-ns-long observations

Image obtained from average photon arrival time

Fine timestamping

10k 45-ns-long observations

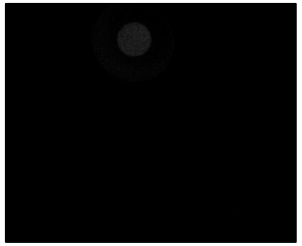
Image obtained from average photon arrival time

Binary imaging

256 combined observations

Image obtained from weighted combination of accumulated binary images

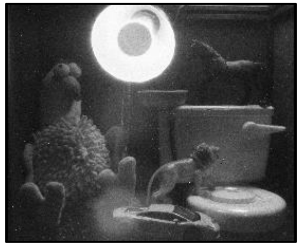
10 ns



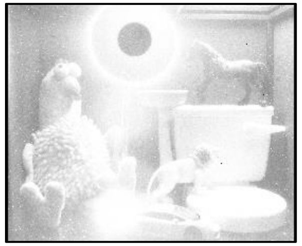
20 ns

40 ns

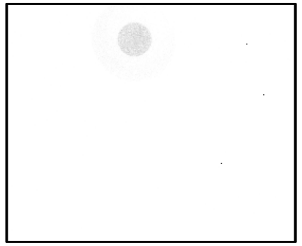
80 ns



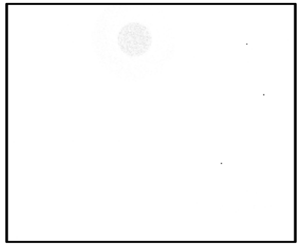
160 ns



320 ns



640 ns



2nd SUPERTWIN SPAD array: *SuperAlice*

Sample images (Matlab's Jet colormap)

Photon counting

1k 1.27-µs-long observations

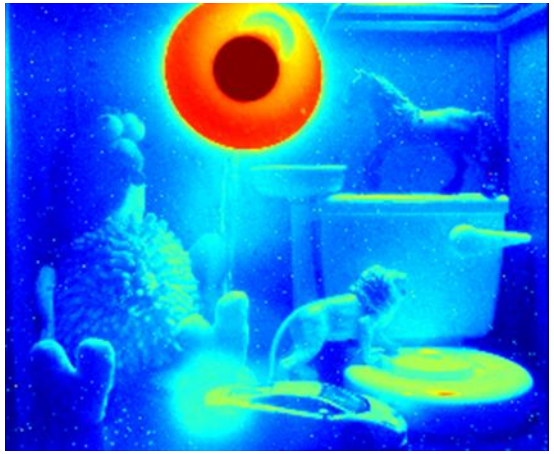


Image obtained from accumulated photon counts

Coarse timestamping

1k 635-ns-long observations

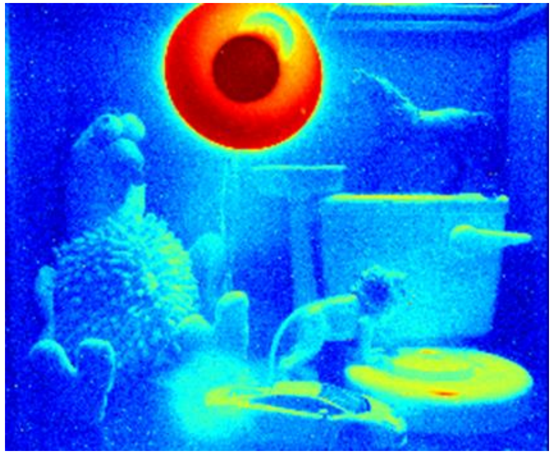


Image obtained from average photon arrival time

Fine timestamping

10k 45-ns-long observations

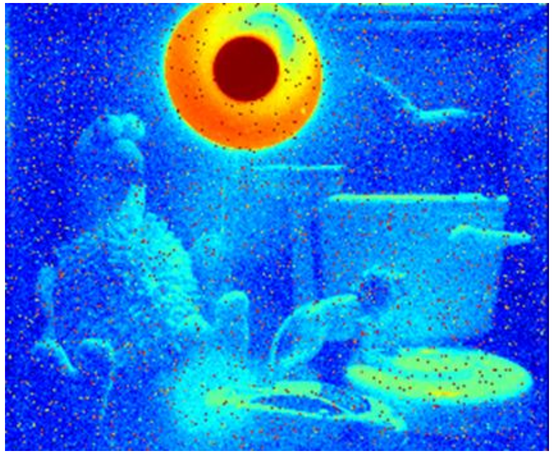


Image obtained from average photon arrival time

Binary imaging

256 combined observations

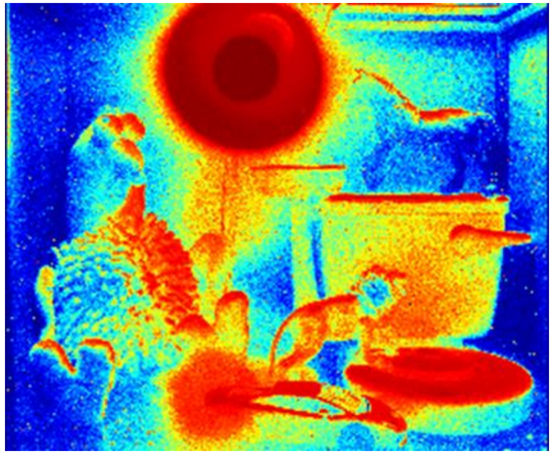
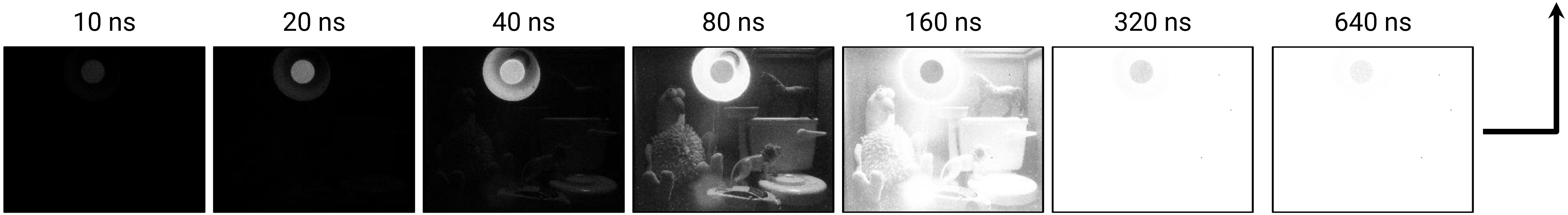


Image obtained from weighted combination of accumulated binary images

10 ns | 20 ns | 40 ns | 80 ns | 160 ns | 320 ns | 640 ns



SPAD imagers (fully parallel operation) in Research

SuperEllen and SuperAlice vs State-of-the-Art

[Henderson, JSSC 19]

- 40 nm
- 192×128 pixels
- 18.4×9.2 μm^2, 13% FF
- Well sharing, ~oval SPAD
- Photon timestamping
- **TDC: 33-120 ps**, 12 bit
- **18.6 kfps** → 0.9% duty cycle

[Hutchings, JSSC 19]

- 3D stacked 90/40 nm
- 256×256 SPADs / 64×64 processing units
- 9.18 μm, **51% FF** / 36.72 μm
- Photon timestamping, photon counting
- **TDC:** 38-**560 ps, 14 bit**
- 760 fps → 0.7% duty cycle

SuperEllen [Zarghami, JSSC accepted]

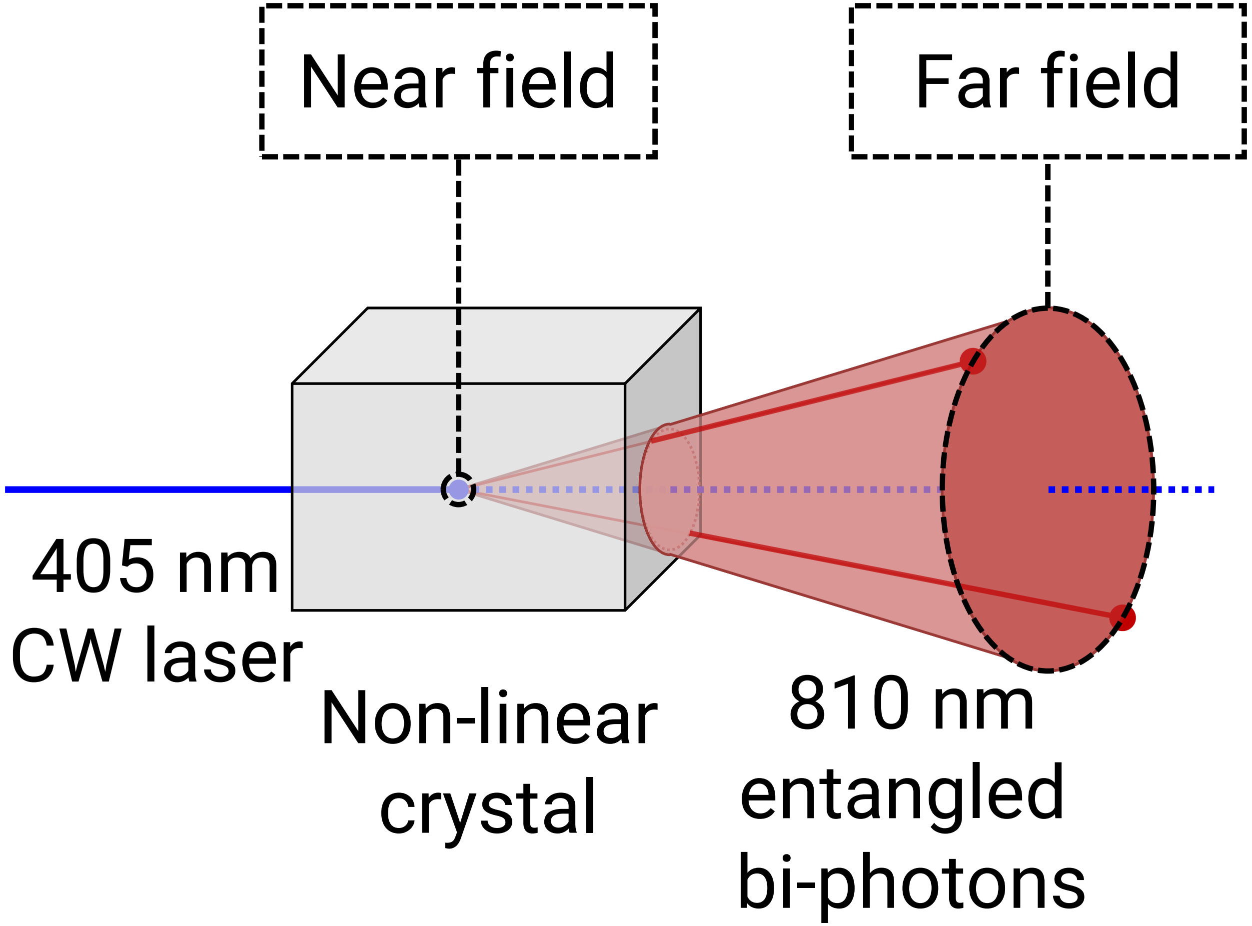
- 150 nm
- 32×32 pixels
- 44.64 μm, **19.8% FF**
- **No well sharing**, square SPAD
- Photon timestamping
- TDC: 205 ps, 8 bit
- **1 MHz obs. Rate → 5% duty cycle**

SuperAlice [to be published]

- 110 nm CIS
- **224×272**
- 30.0 μm, **12.9% FF**
- **No well sharing**, ~square SPAD
- **Multi-functional pixel**
- TDC: 180 ps, 8 bit
- < 1 Kfps (duty cycle depends on operating mode)

Use of SuperAlice in Quantum Optics

Acquisition of SPDC bi-photon



Near field correlations

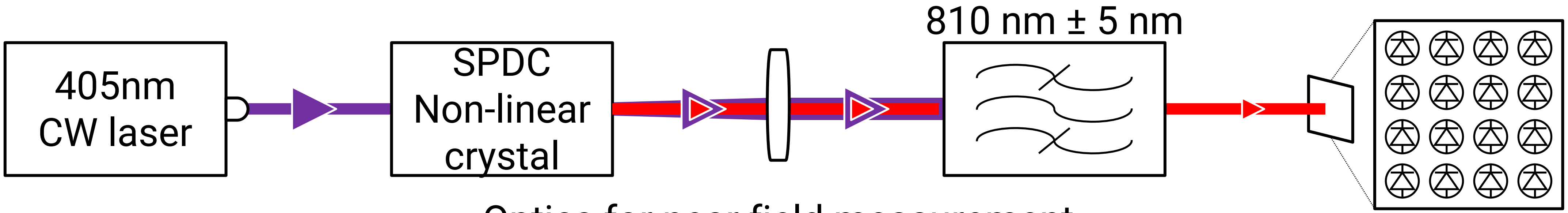
- Correlated in time
  - ~at the same time
- Correlated in space
  - ~in the same place

Far field correlations

- Correlated in time
  - ~at the same time
- Anti-correlated in momentum
  - in opposite direction

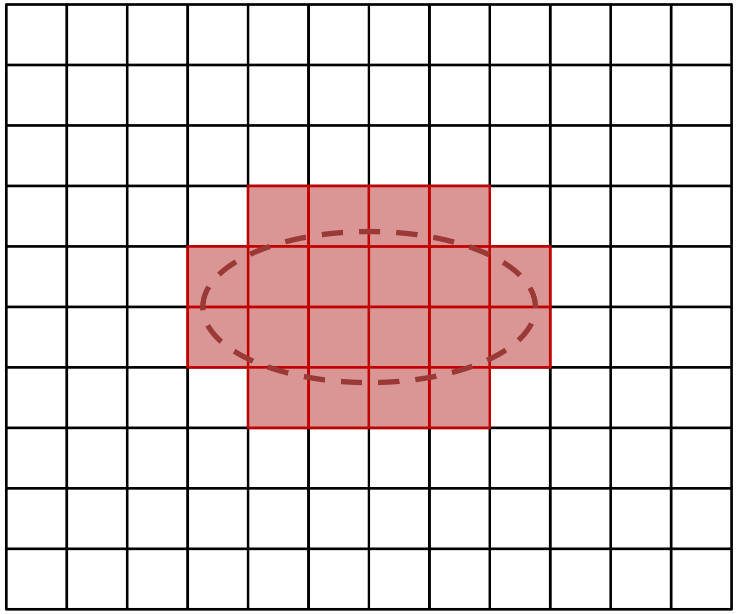
Use of SuperAlice in Quantum Optics

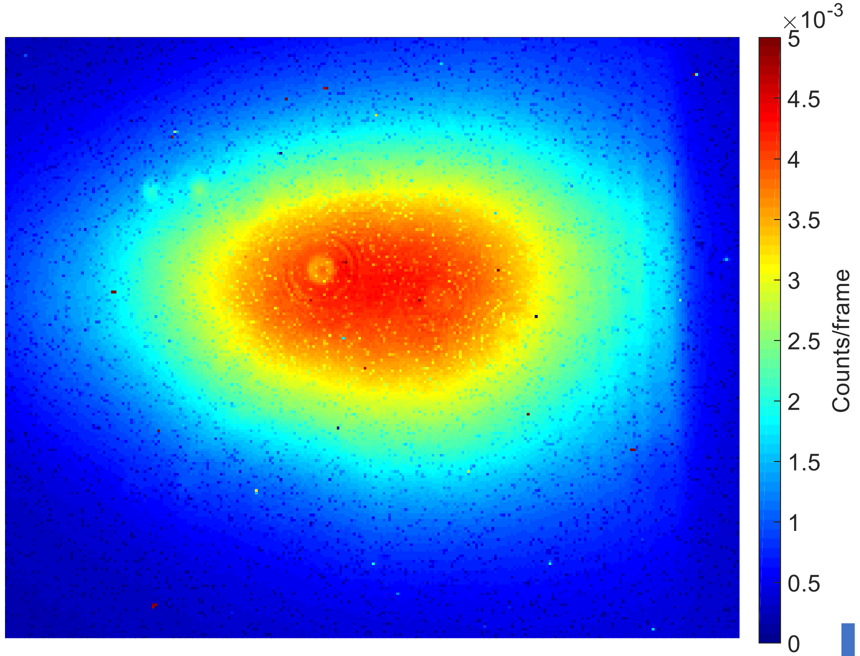
Acquisition of SPDC bi-photon in the near-field



Optics for near field measurement

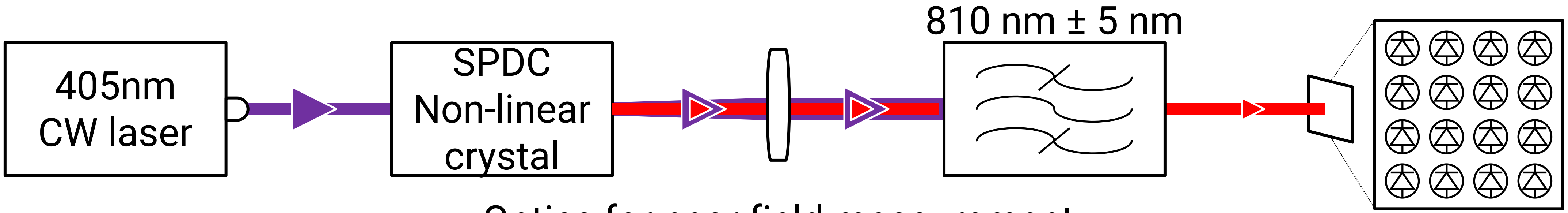
$$G^{(1)}(x,y)$$





Use of SuperAlice in Quantum Optics

Acquisition of SPDC bi-photon in the near-field



Optics for near field measurement

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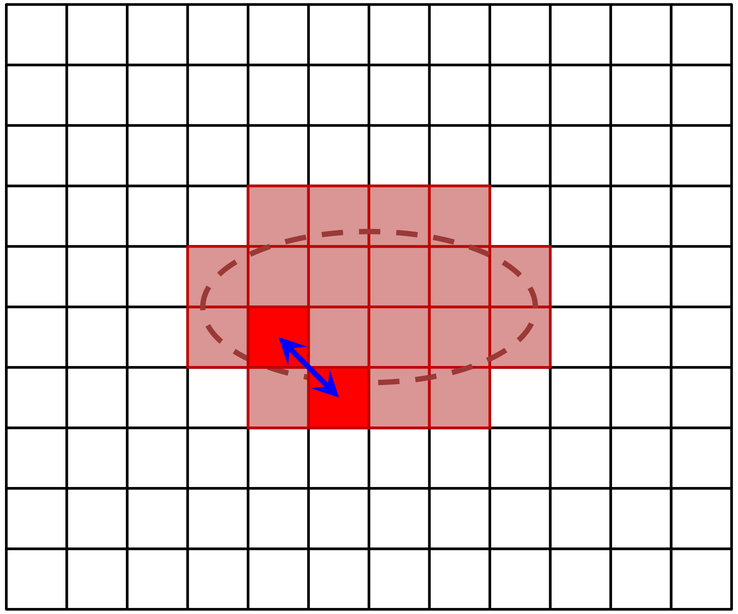
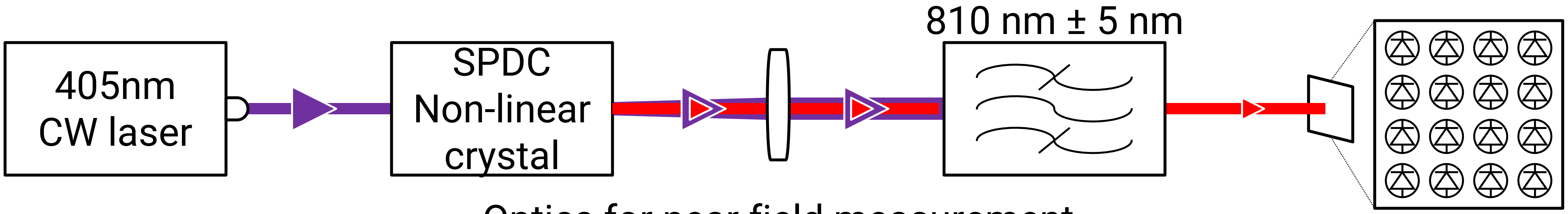


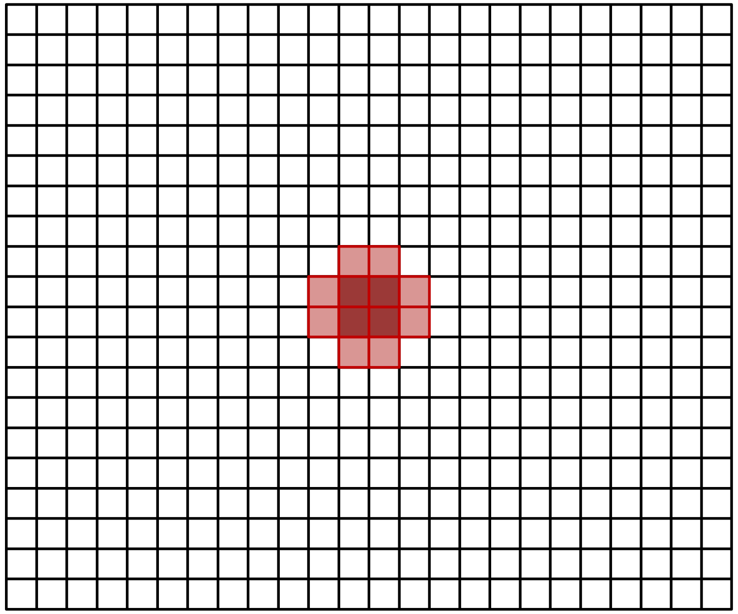
Use of SuperAlice in Quantum Optics

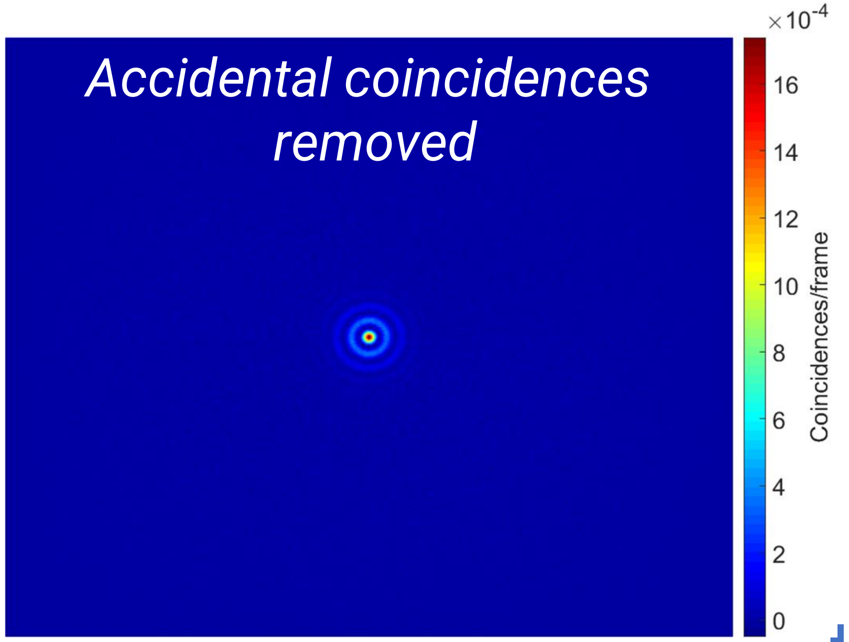
Acquisition of SPDC bi-photon in the near-field



Optics for near field measurement

$$G^{(2)}(p_-)$$





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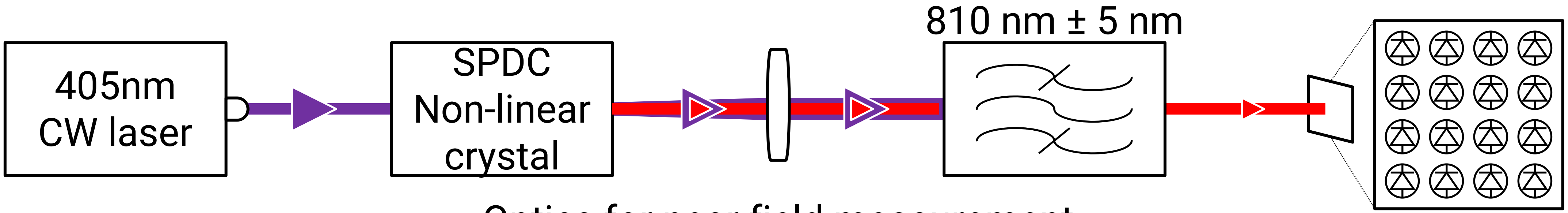
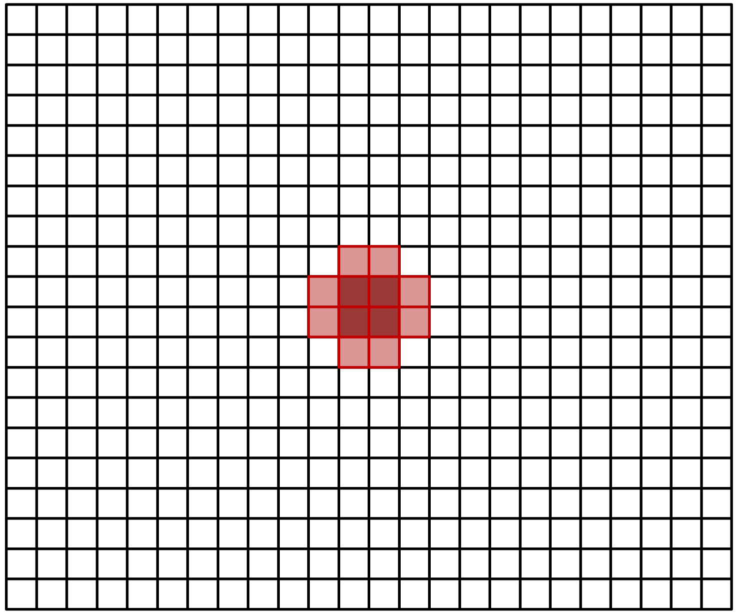
Use of SuperAlice in Quantum Optics

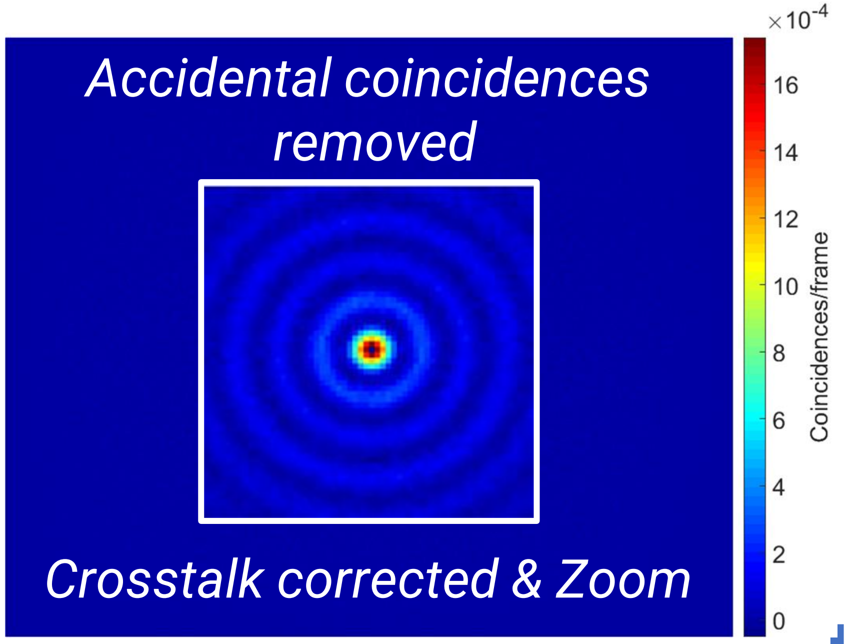
Acquisition of SPDC bi-photon in the near-field



Optics for near field measurement

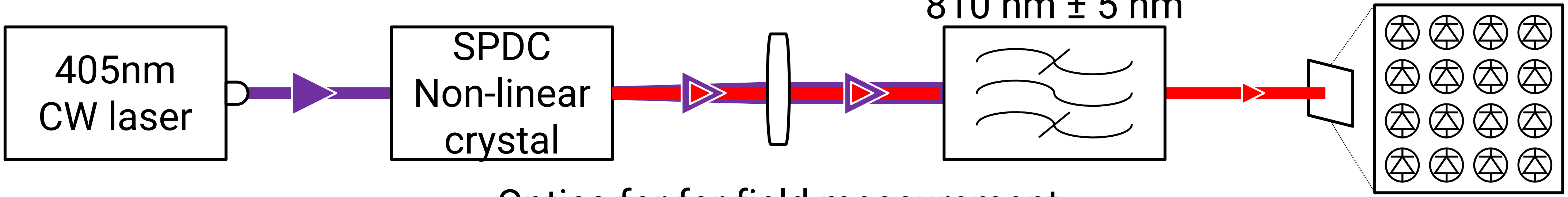
$$G^{(2)}(p_-)$$





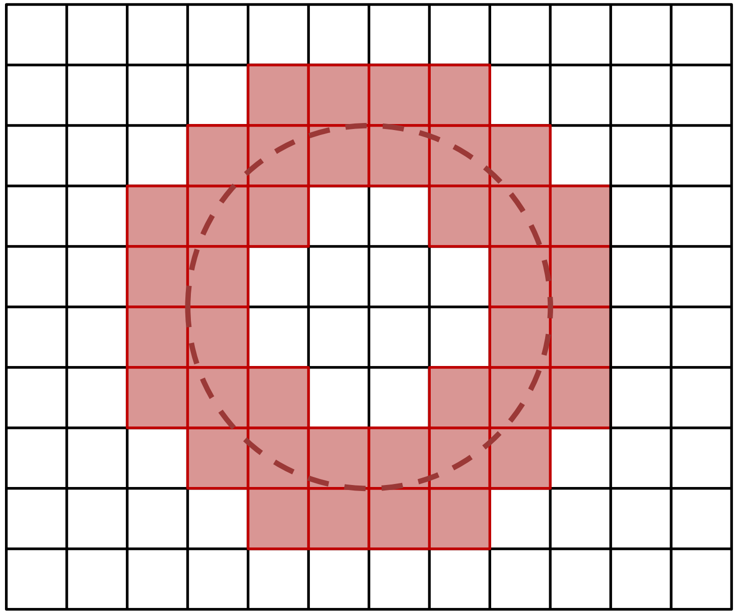
Use of SuperAlice in Quantum Optics

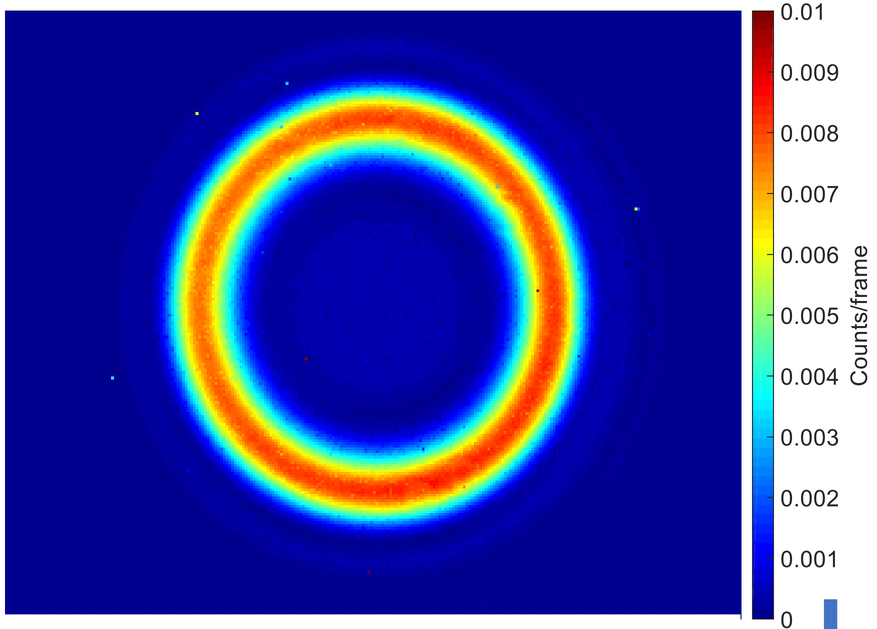
Acquisition of SPDC bi-photon in the far-field



Optics for far field measurement

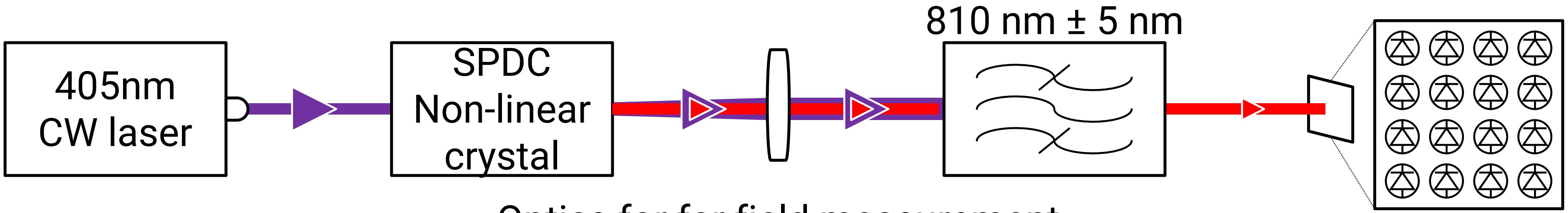
$$G^{(1)}(x, y)$$



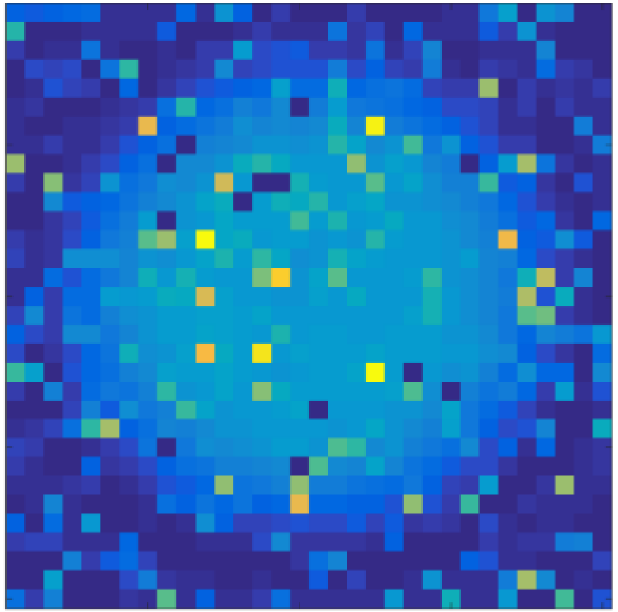


Use of SuperAlice in Quantum Optics

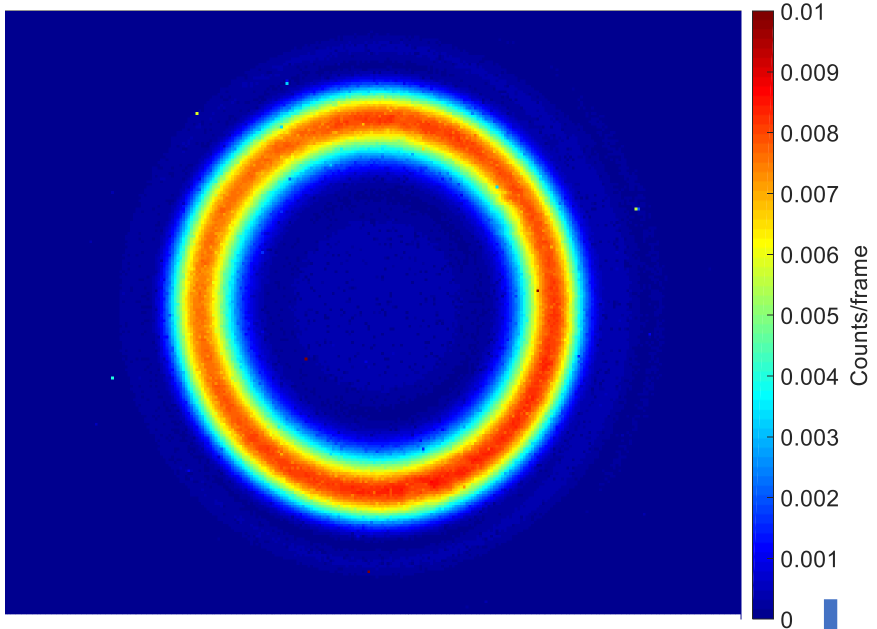
Acquisition of SPDC bi-photon in the far-field



$$G^{(1)}(x, y)$$

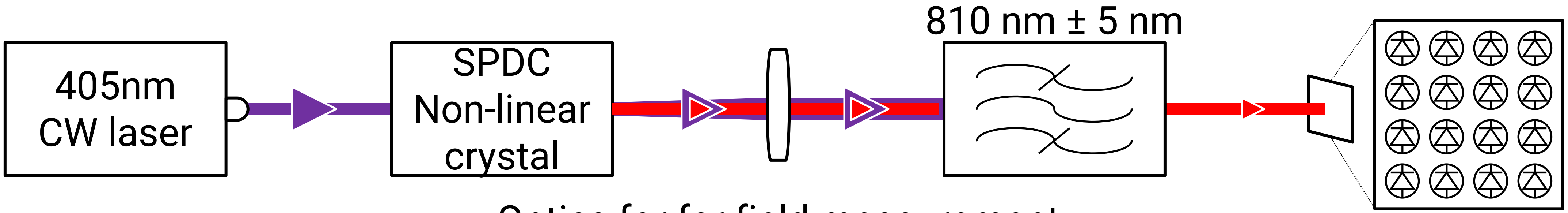


← SuperEllen vs SuperAlice →



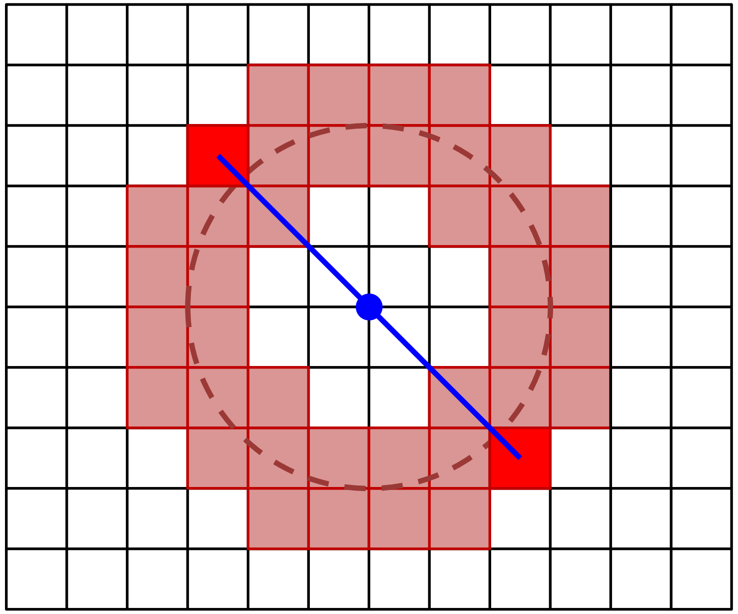
Use of SuperAlice in Quantum Optics

Acquisition of SPDC bi-photon in the far-field



Optics for far field measurement

$$G^{(1)}(x,y)$$



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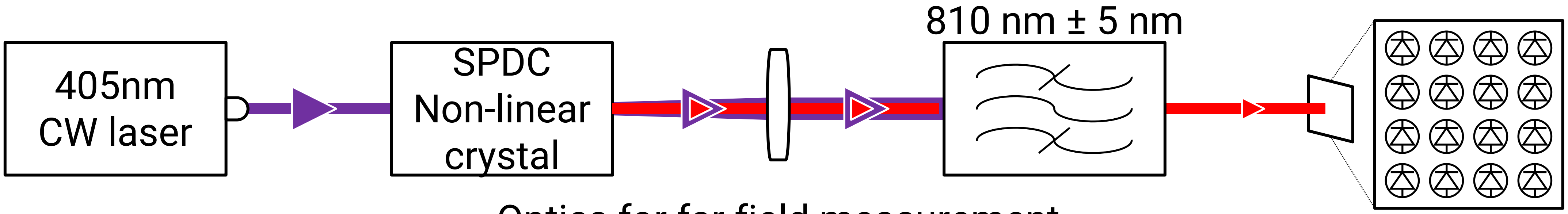
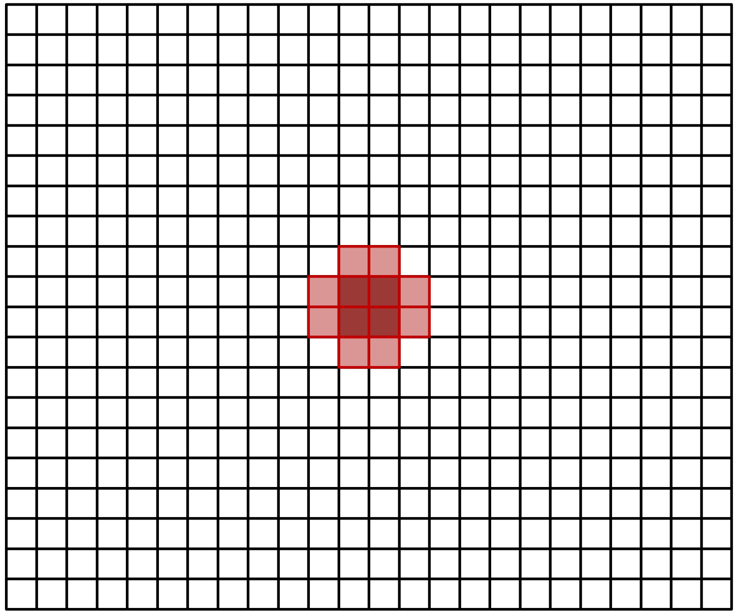
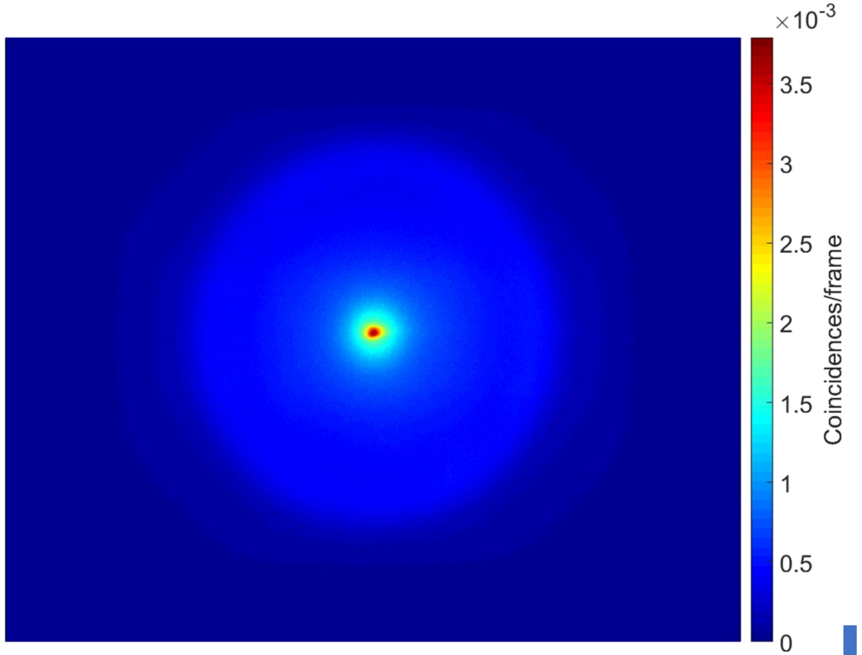


$$G^{(2)}(\rho_+)$$





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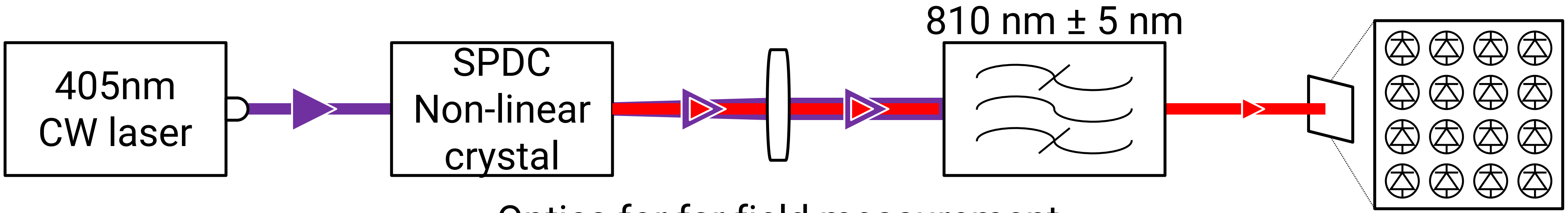

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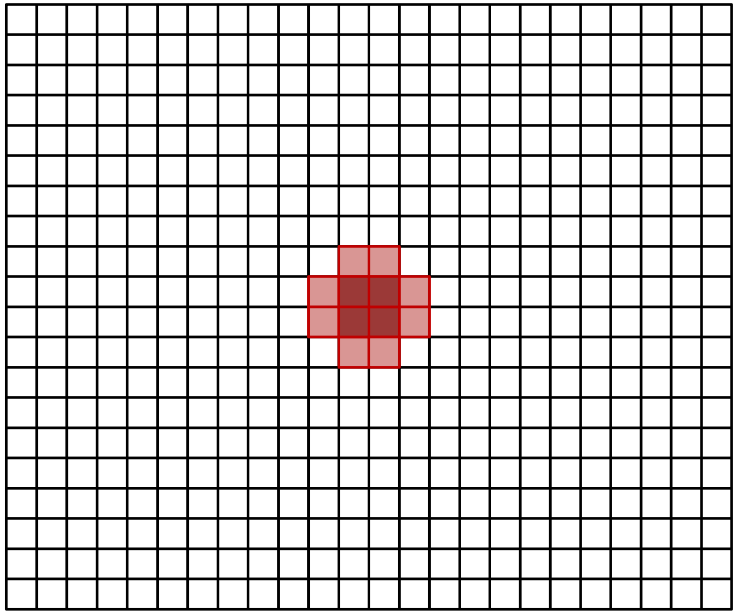

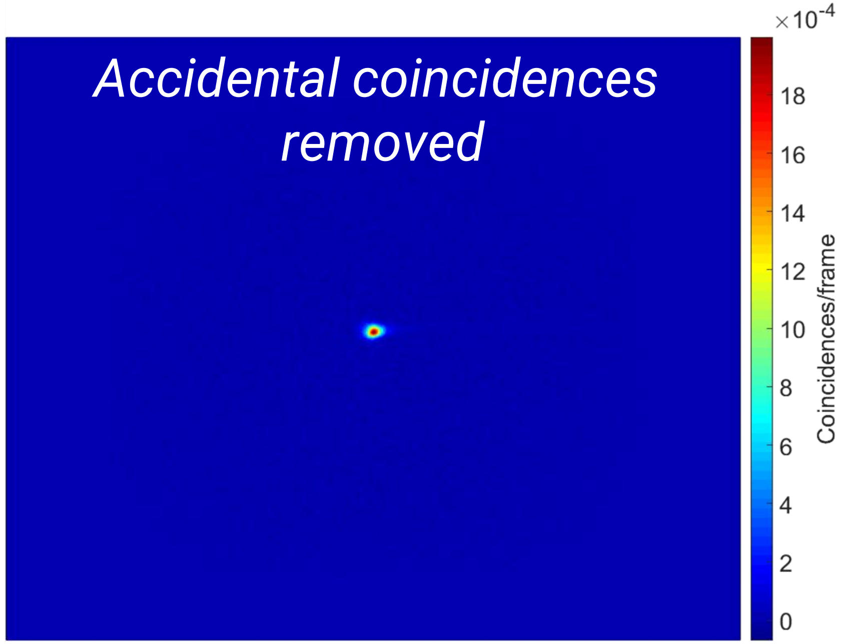

Use of SuperAlice in Quantum Optics

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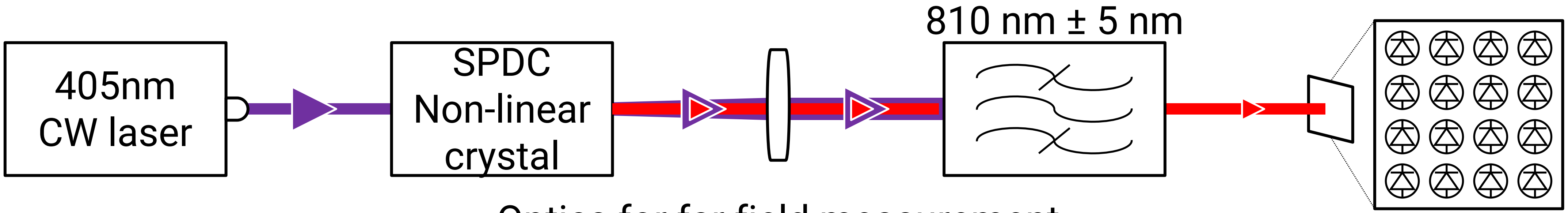

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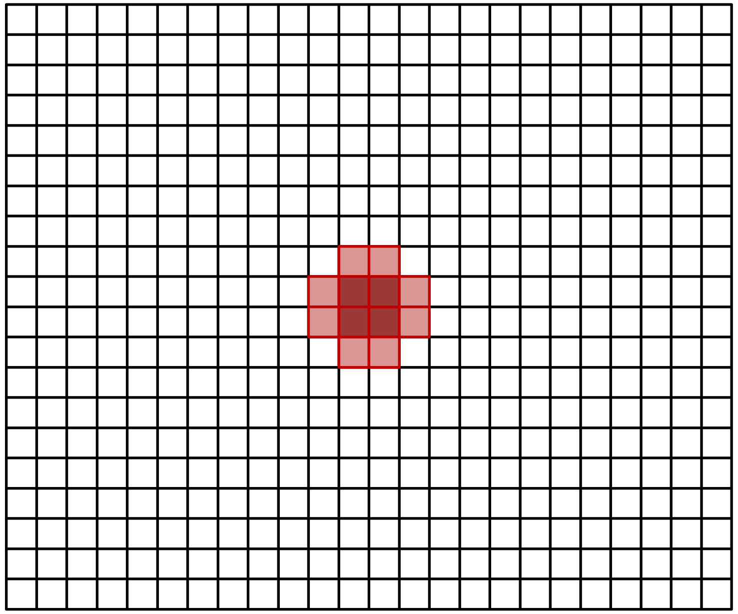
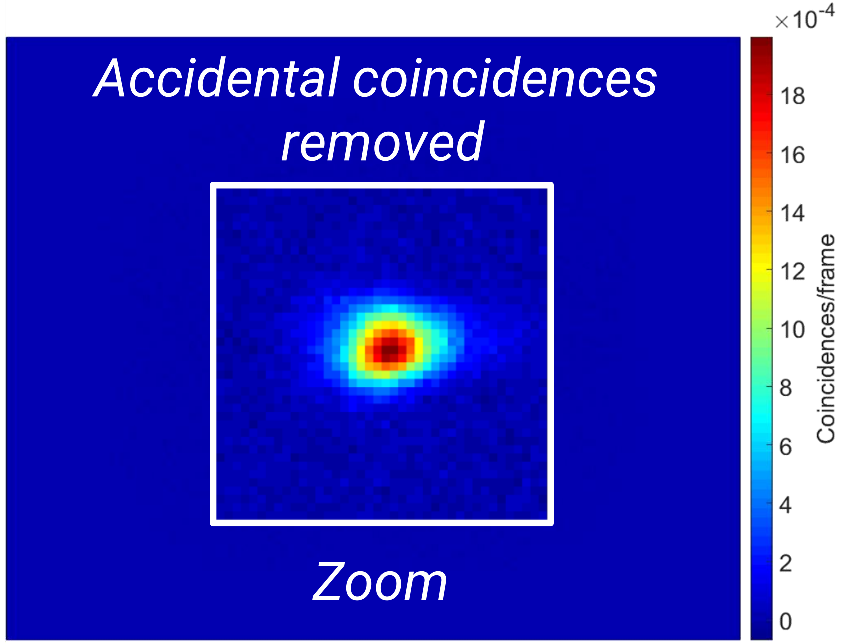


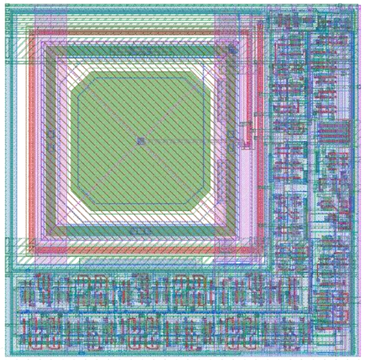


Conclusions

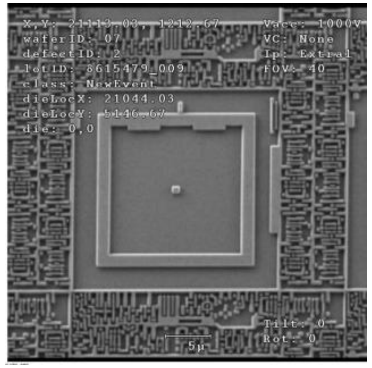
CMOS SPAD arrays for scientific imaging

- *SuperAlice*: **a 224×272-pixel multi-functional image sensor** for scientific imaging
  - Quantum optics experiments using SPDC photons @ Univ. Bern
- Multi-functional pixel provides **flexibility of application**
  - No sharing of the logic → Fully-parallel 2D acquisitions
- **FSI, 110 nm CIS technology** can compete with more advanced, stacked technology
  - High SNR (PDE vs DCR)
  - **Low cost**
- SUPERTWIN has shown the way towards Super-resolution Quantum Microscope
  - We achieved **630 nm resolution (vs 1 µm Rayleigh limit)** @ CSEM using SuperEllen
  - Further developments are needed, mostly on the entangled photon source side
- Ongoing and future activity:
  - More **quantum optics experiments** using SuperEllen / SuperAlice across Europe
  - Application of SuperEllen / SuperAlice to **FLIM and other applications**

Pixel layout



After metal 1



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- Antonio Venezia

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- Dr. Laurent Balet

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SUPERTWIN

All Solid-State Super-Twinning Photon Microscope

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