Imaging with entangled photons

L. Gasparini[1], M. Perenzoni[1], H. Xu[1], L. Parmesan[1], M. Moreno Garcia[1],
D. Stoppa[4], B. Bessire[2], M. Unternährer[2], A. Stefanov[2],
V.Mitev[3] and D.L. Boiko[3]

[1]Fondazione Bruno Kessler, Italy
[2]Institute of Applied Physics, University of Bern, Switzerland
[3]Centre Suisse d'Électronique et de Microtechnique CSEM, Switzerland
[4]now at AMS-Heptagon, Switzerland;

Outline

- Motivation
- Requirements for imaging with entangled photons
- SuperEllen imager design and characterization
- $G^{(2)}$ correlations in SPDC with bi-photons
- $G^{(2)}$-$G^{(4)}$ in thermal imaging
- Conclusions & future outlook

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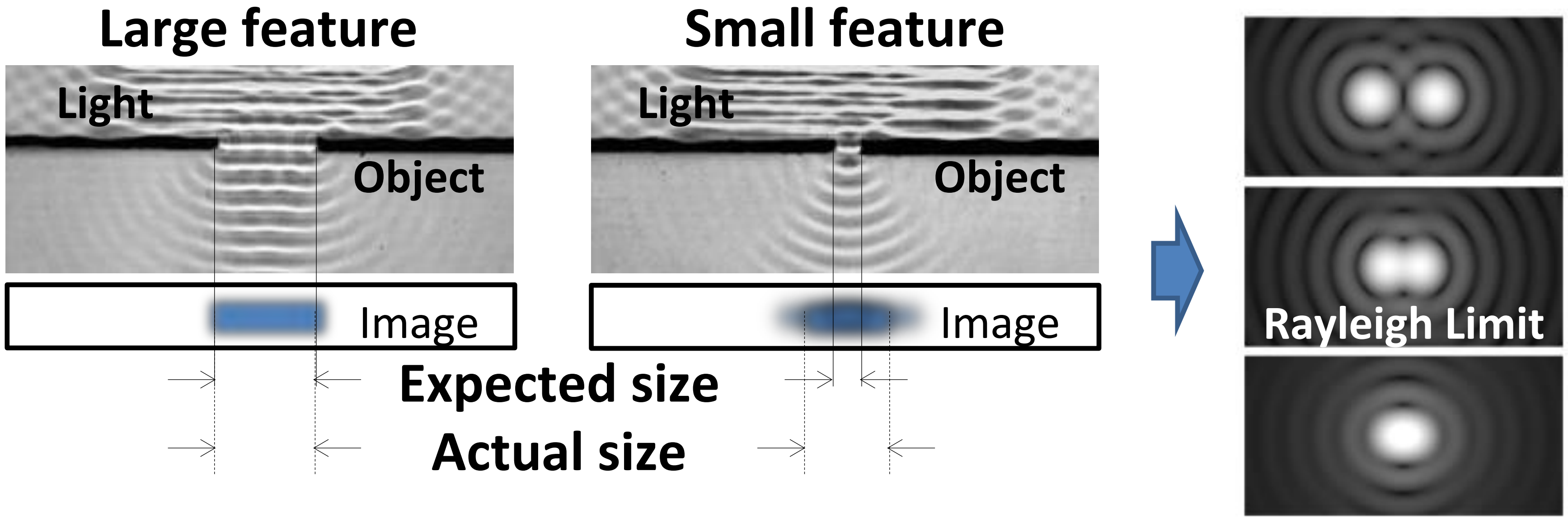
Conventional Optical Microscopy Limits

- Light as a wave: **diffraction** limits resolution



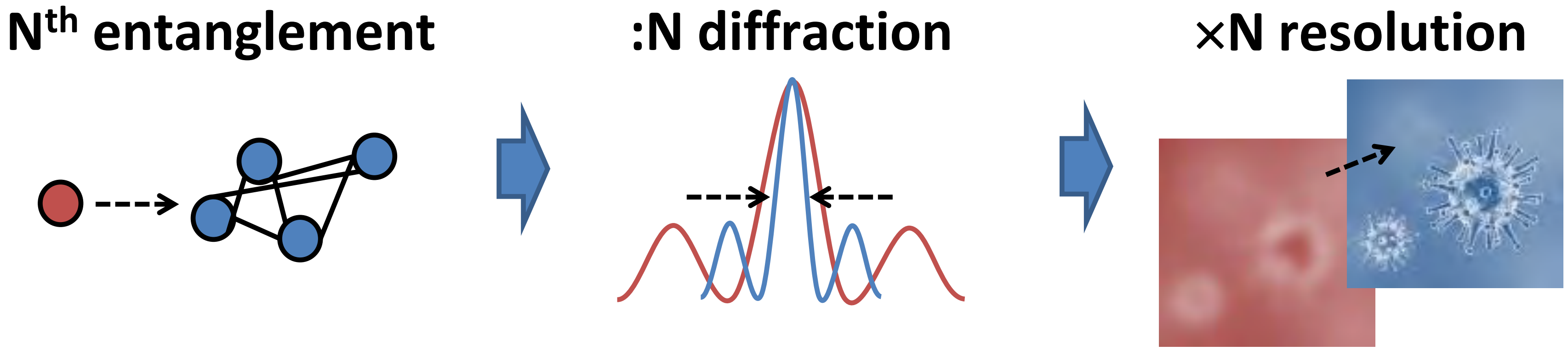
- Limit is the wavelength λ
  - With visible light: **λ/2**, about 250nm
  - Cells: ≈10um ☺ Viruses: ≈100nm ☹

Beyond Rayleigh: SUPERTWIN Concept

- Light as a particle
- N entangled photons → de Broglie wavelength λ/N

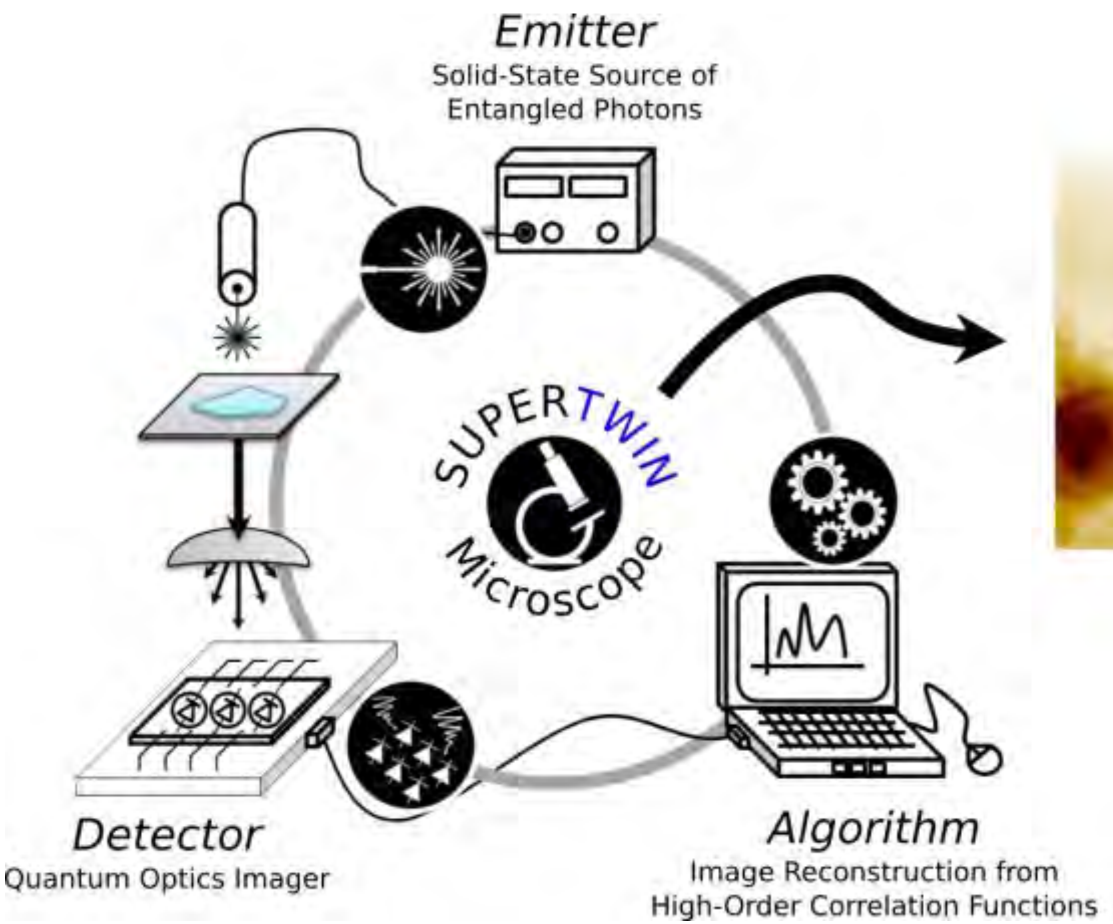
N measurements with N detectors give N times improvement

SUPERTWIN



N^{th} entanglement → **:N diffraction** → **×N resolution**

SUPERTWIN Concept & Goal



Advanced All-Solid State Optical Microscope Imaging
Beyond the Rayleigh Limit

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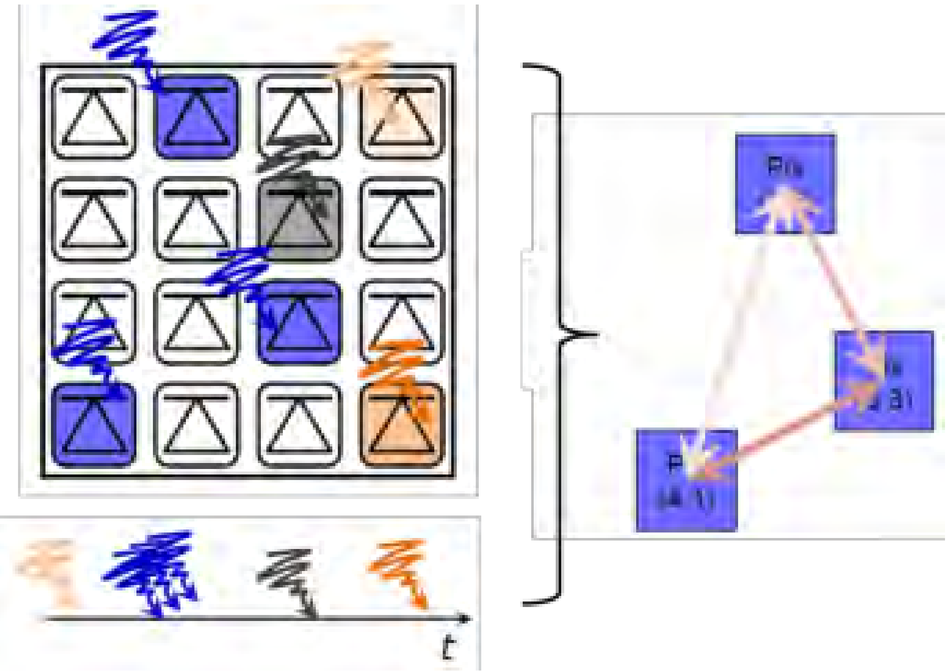
CMOS Single-Photon Imager

- Scattered entangled photons
  - Spread in space (non-local)
  - Simultaneous in time
- Single photon imager
  - **Position + Time**

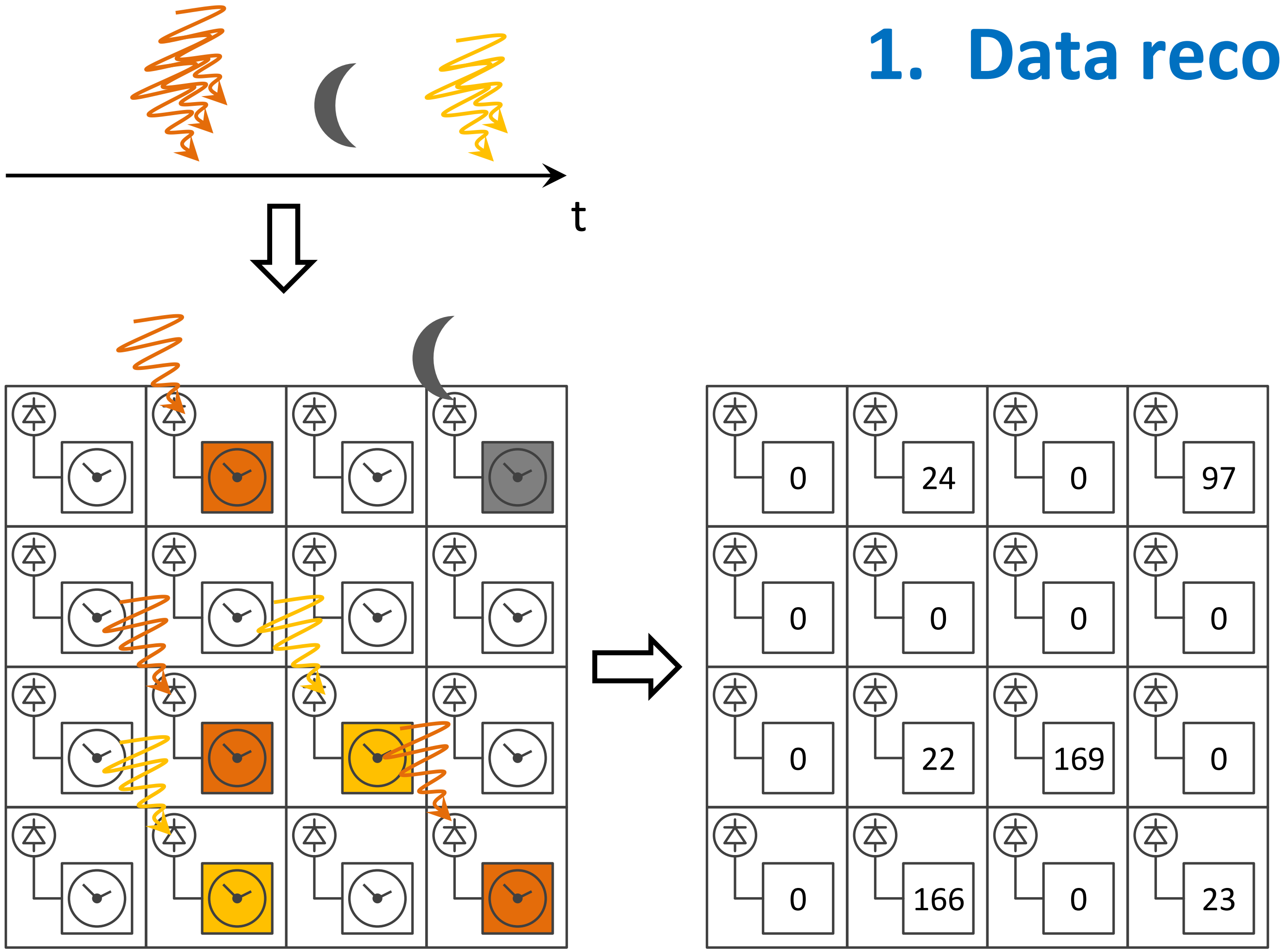
(x,y) + ⏲



Goal: extraction of N^{th} order correlation function $G^{(N)}$

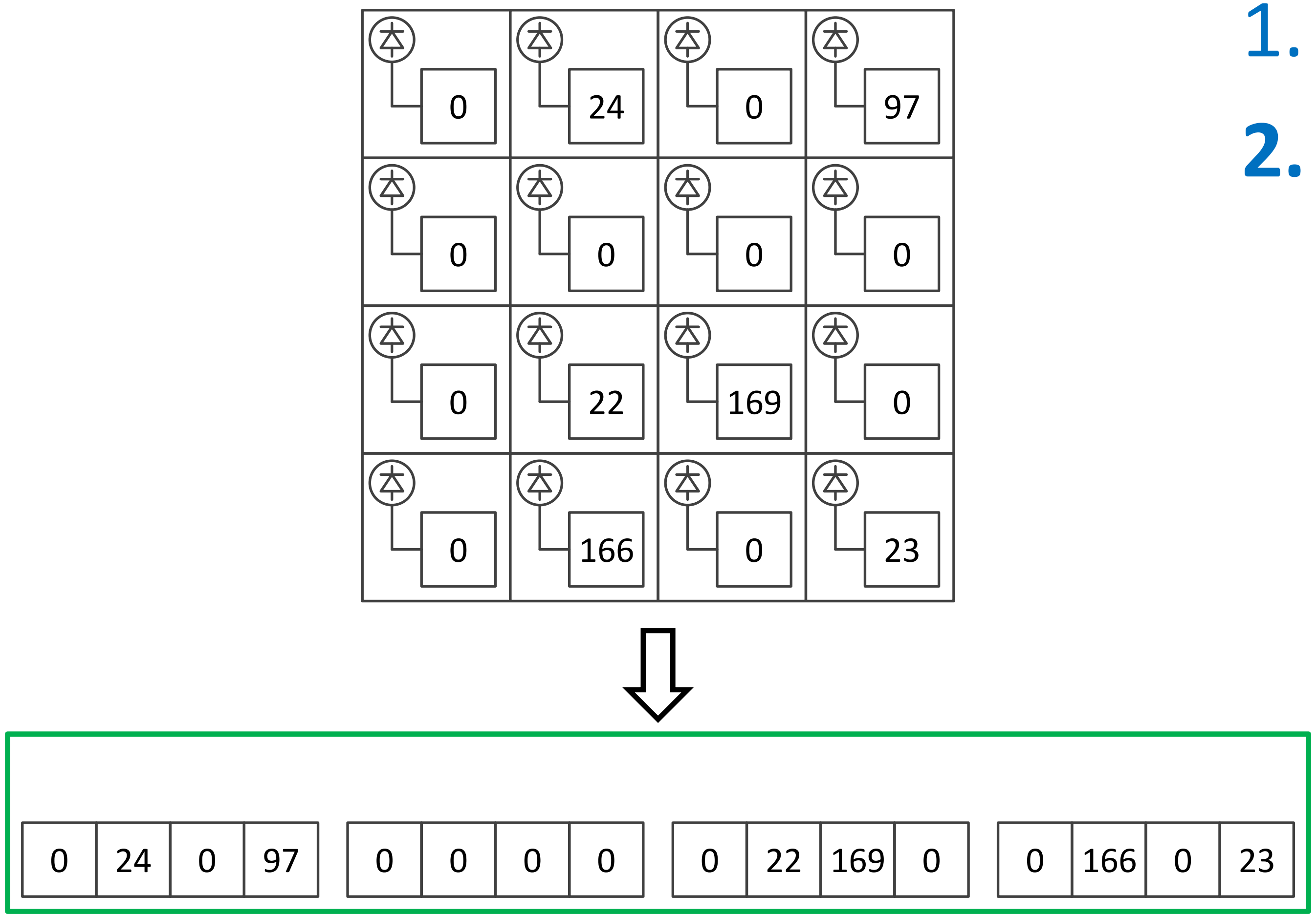
Data processing flow

1. Data recording



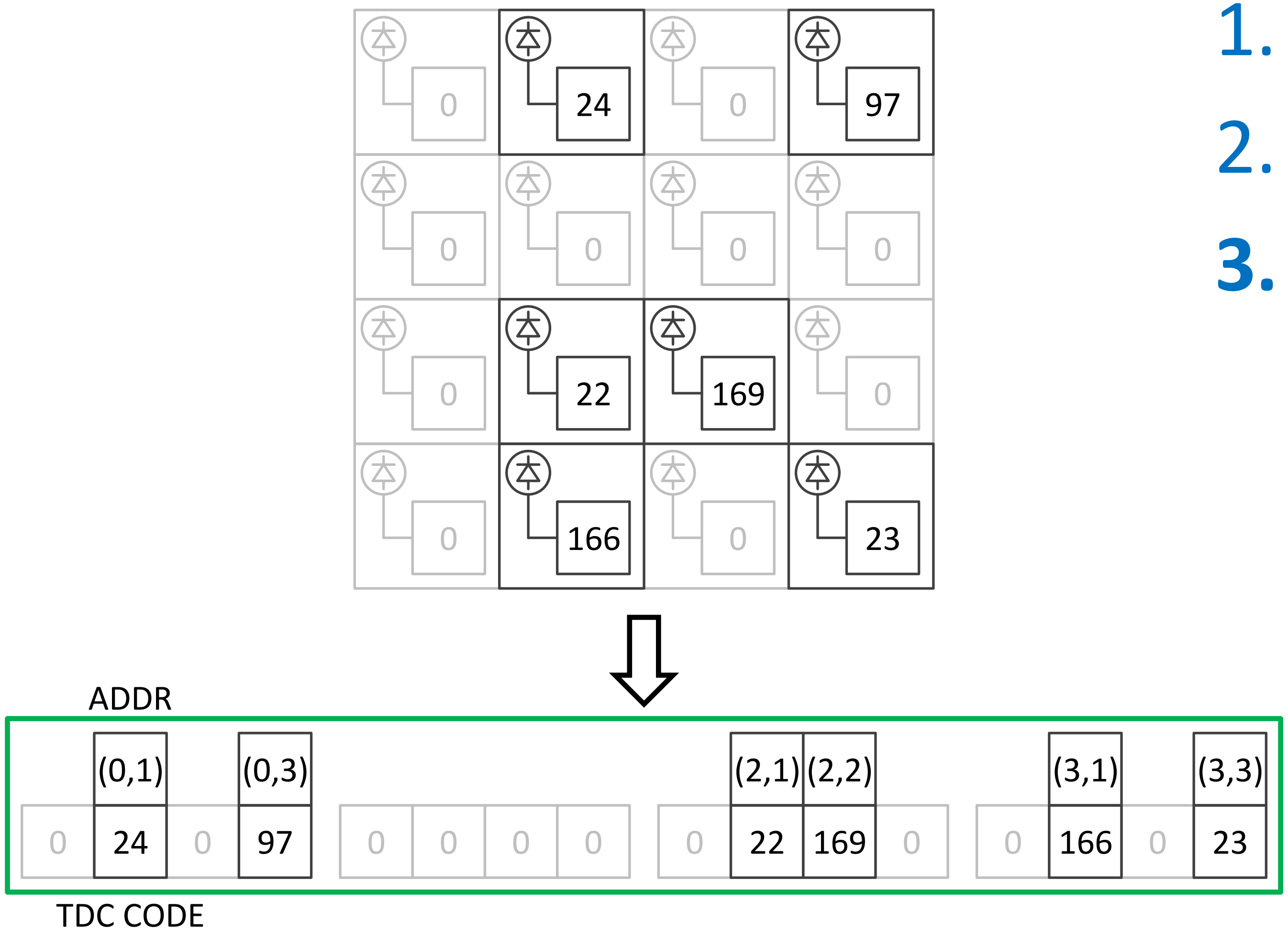
0	24	0	97
0	0	0	0
0	22	169	0
0	166	0	23

Data processing flow



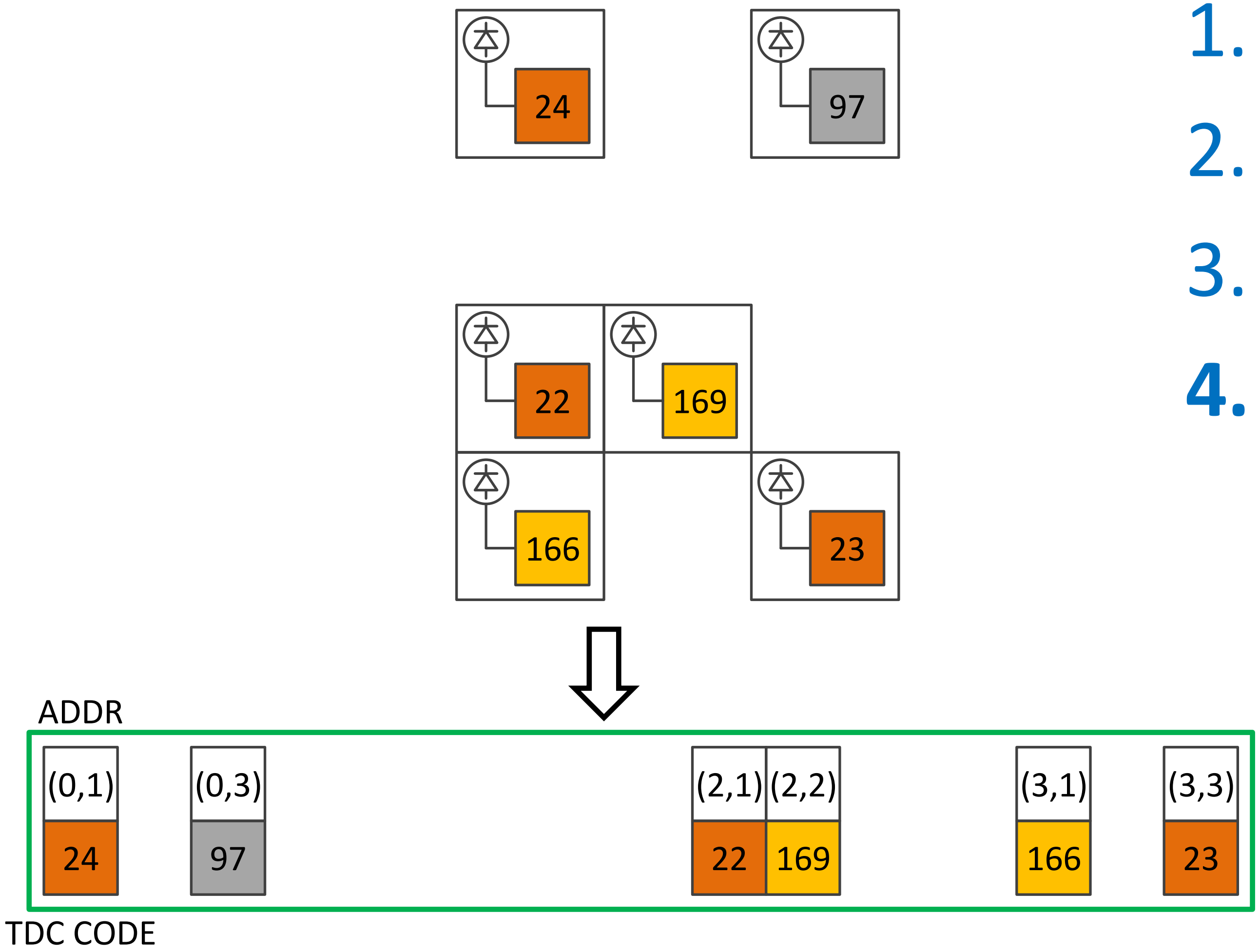
1. Data recording
2. **Readout**

Data processing flow



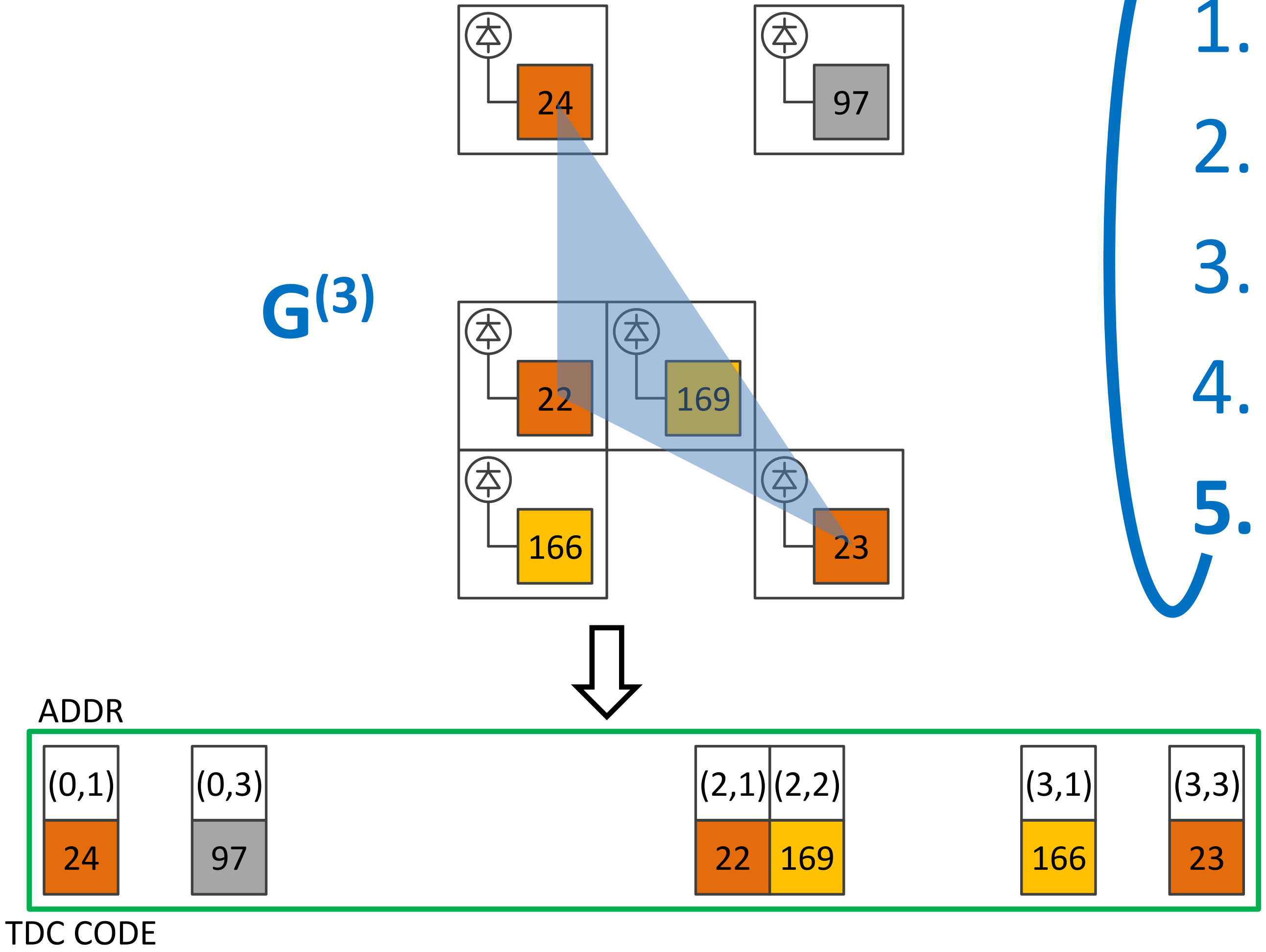
1. Data recording
2. Readout
3. **Compression**

Data processing flow



1. Data recording
2. Readout
3. Compression
4. **Coincidence detection**

Data processing flow



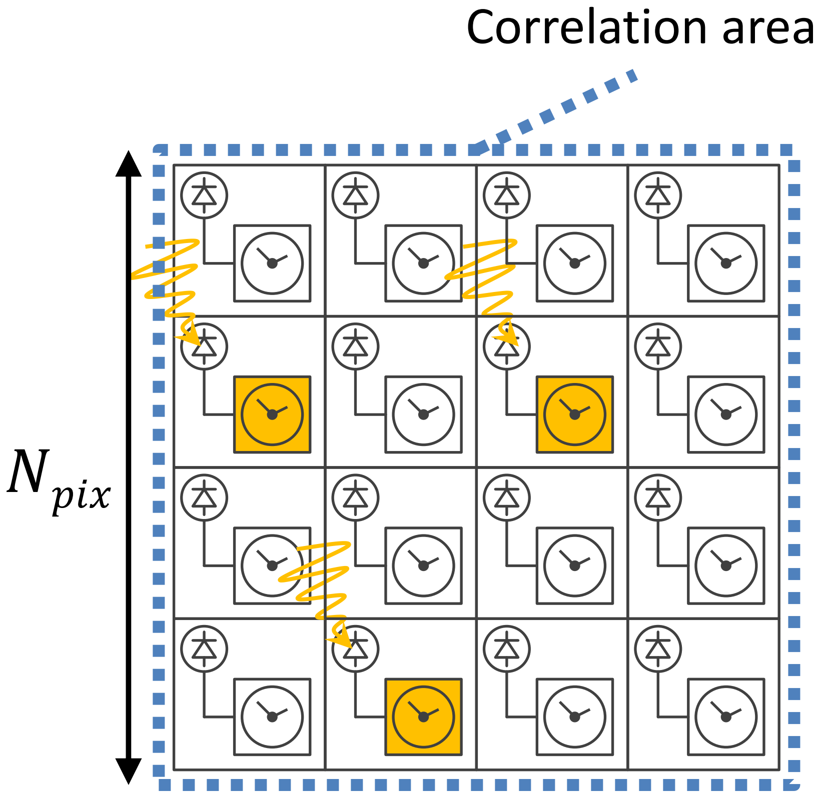
1. Data recording
2. Readout
3. Compression
4. Coincidence detection
5. **$G^{(N)}$ update**

Sensor

FPGA

PC

Memory requirements – Full area correlations

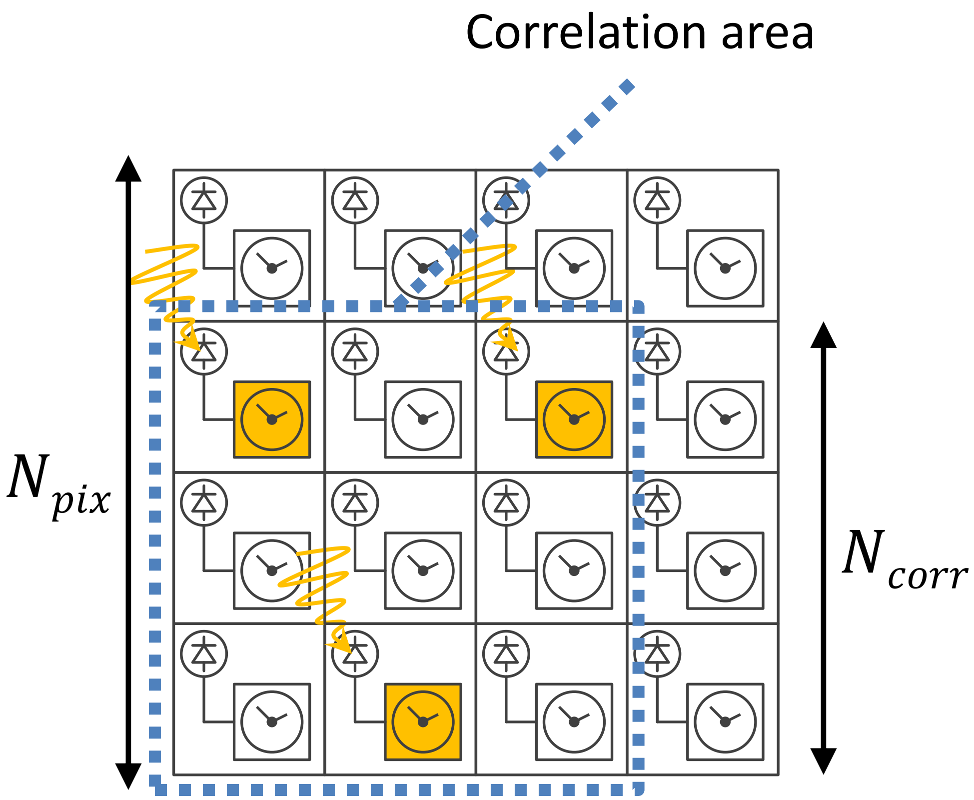


- $G^{(k)}$ → k-dimensional space
- Histogram size = $\frac{N_{pix}!}{k!(N_{pix}-k)!}$

Hypothesis: 2G memory

- Feasible up to:
  - 32×32 array ➡ $G^{(3)}$
  - 256×256 array ➡ $G^{(2)}$

Memory requirements – Reduced area correlations



- $G^{(k)}$ → k-dimensional space
- Histogram size = $\frac{N_{pix}!}{k!(N_{pix}-k)!}$
- Feasible up to:
  - $G^{(5)}$ with $N_{corr} = 16$
  - $G^{(4)}$ with $N_{corr} = 24$
  - $G^{(3)}$ with $N_{corr} = 48$
  - $G^{(2)}$ with $N_{corr} = 256$

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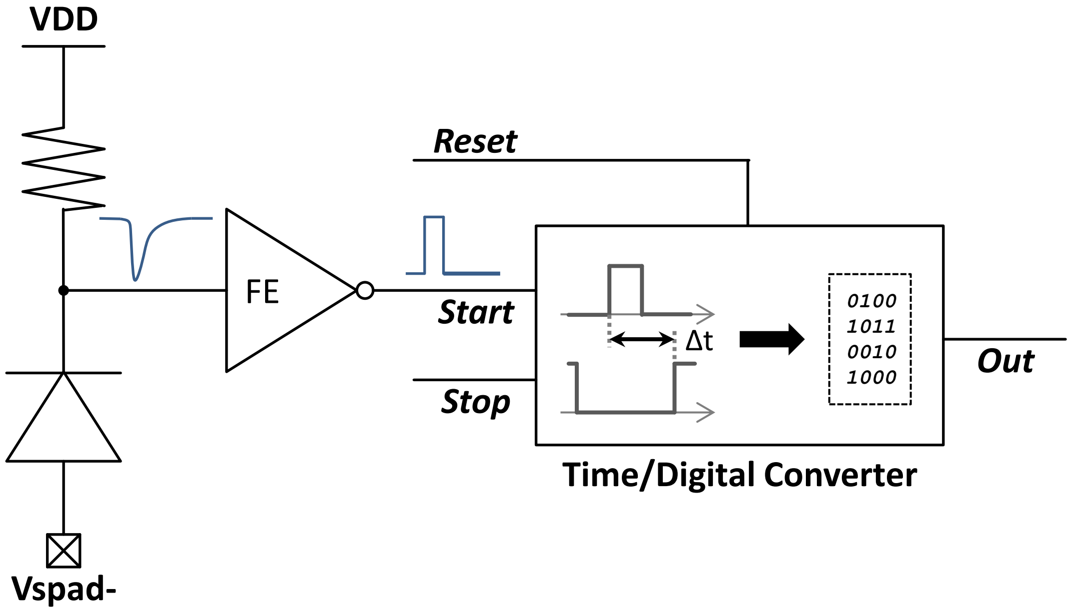
SuperEllen SPAD Imager

- Previous SPAD+TDC designs:
  - Large pixel >50µm
  - Small FF < 3%
  - Huge amount of data

- **Pixel array based on TDC, target:**
  - **Low pitch**
  - **High FF**
  - **Fast readout**



SuperEllen SPAD Imager

CMOS 150nm tech

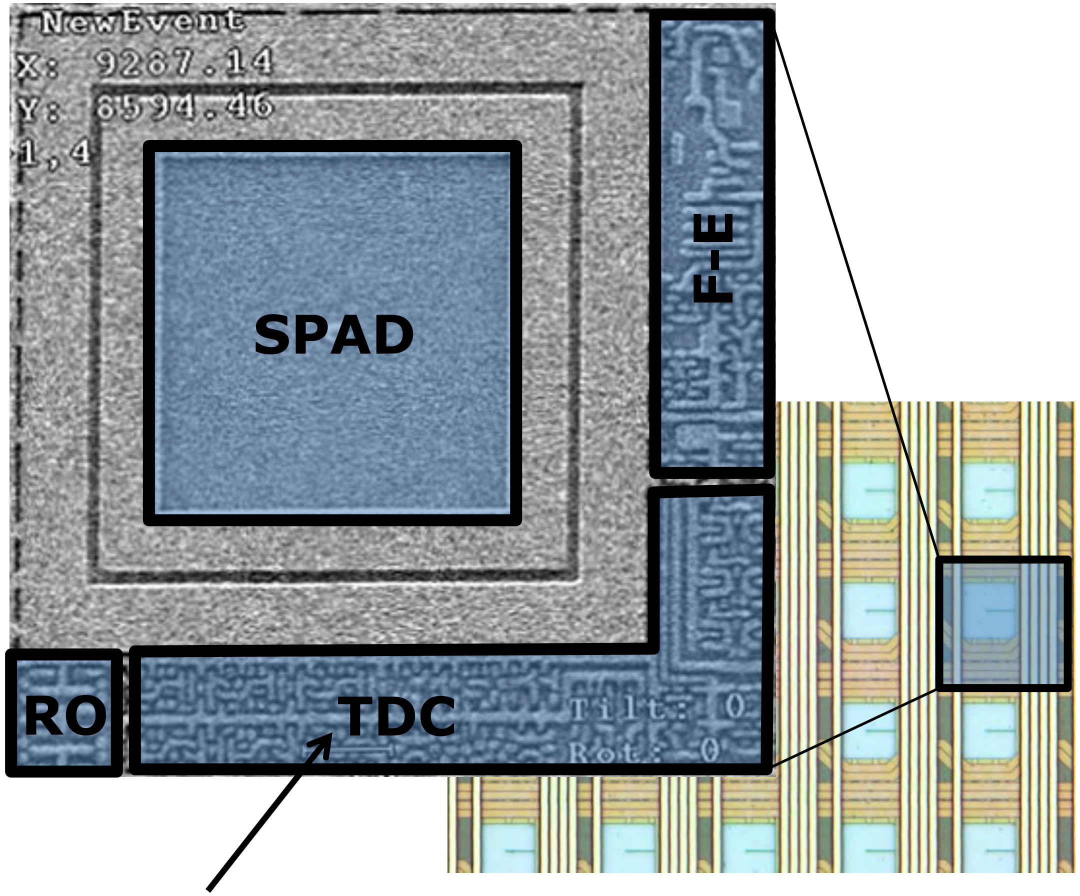
SPAD: p+/nwell

TDC: 8b, 205ps

R-O: row/frame skip

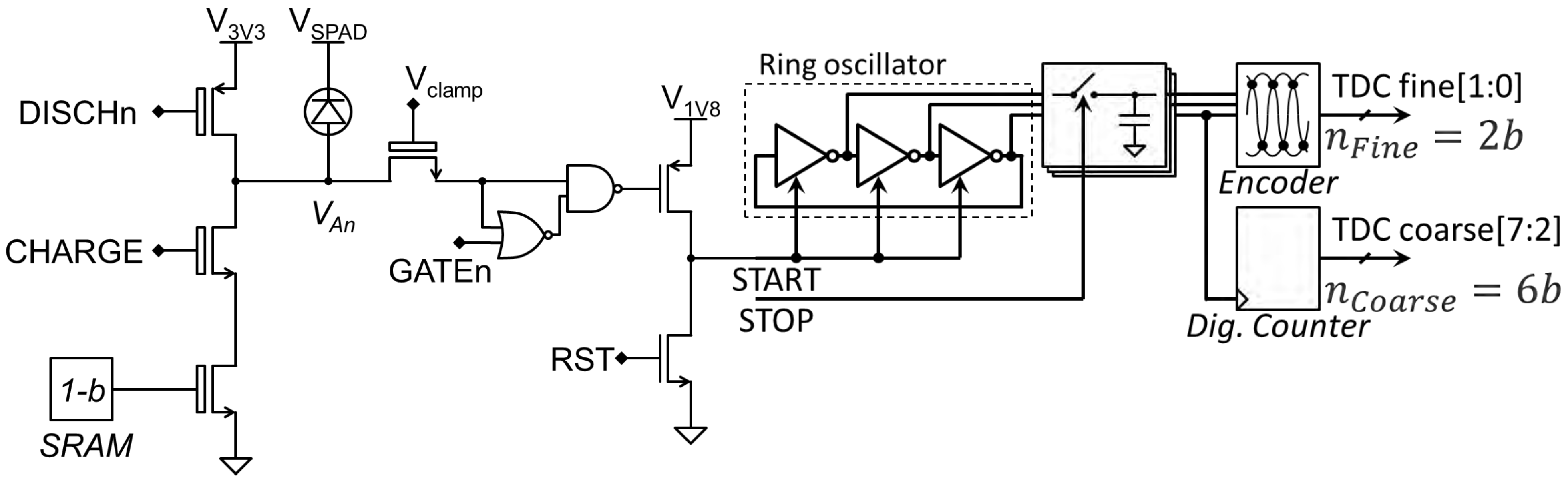
- **Pixel array based on TDC, result:**

– Low pitch	**44.6μm**
– High FF	**19.5%**
– Fast readout	**800kfps**



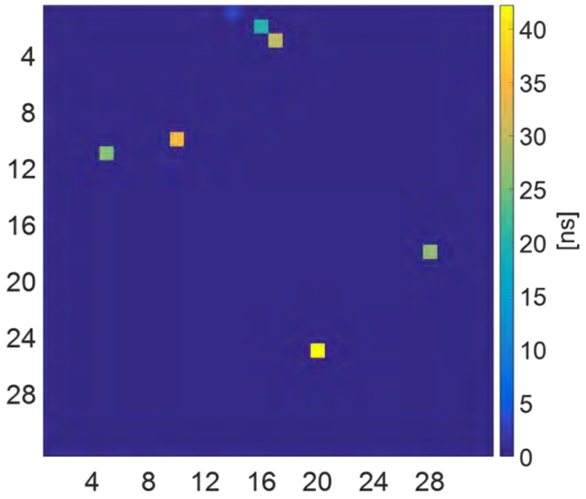
≈20T/bit
≈400μm²

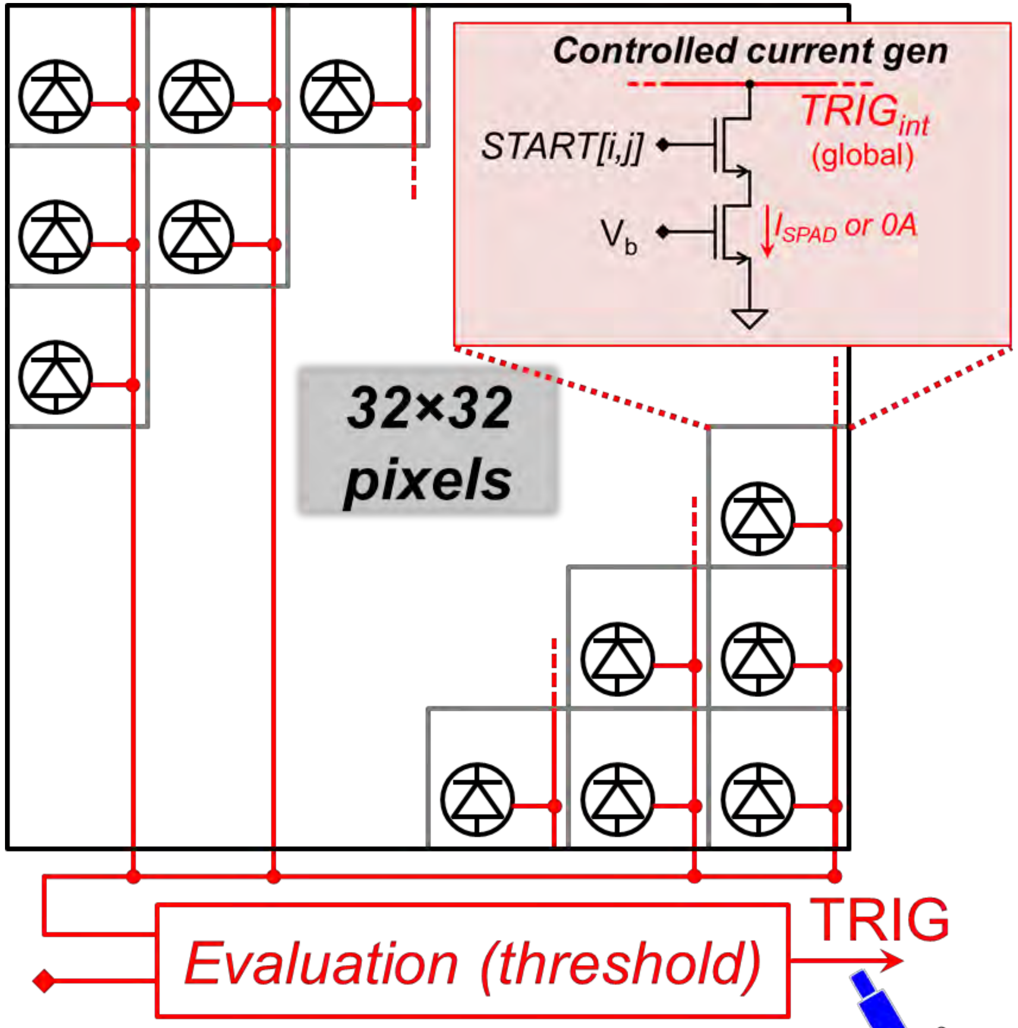
Pixel and TDC Concept



- Synchronous SPAD precharge with disable SRAM
- Edge-sensitive START and gated operation
- Ring-oscillator based TDC with 2b interpolation

Imager Readout Concept

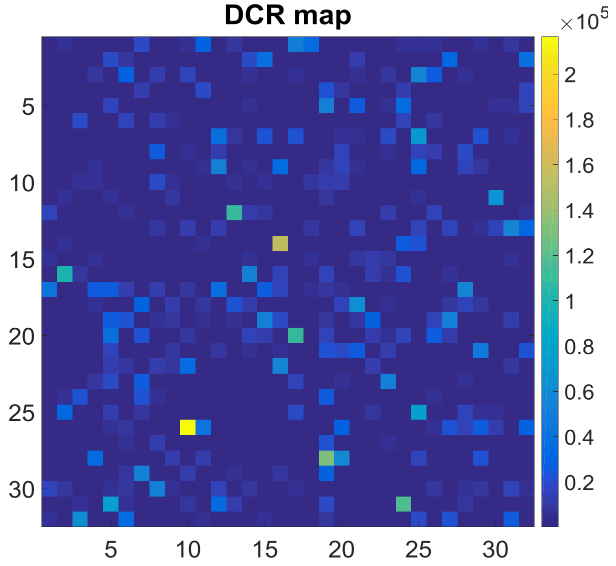


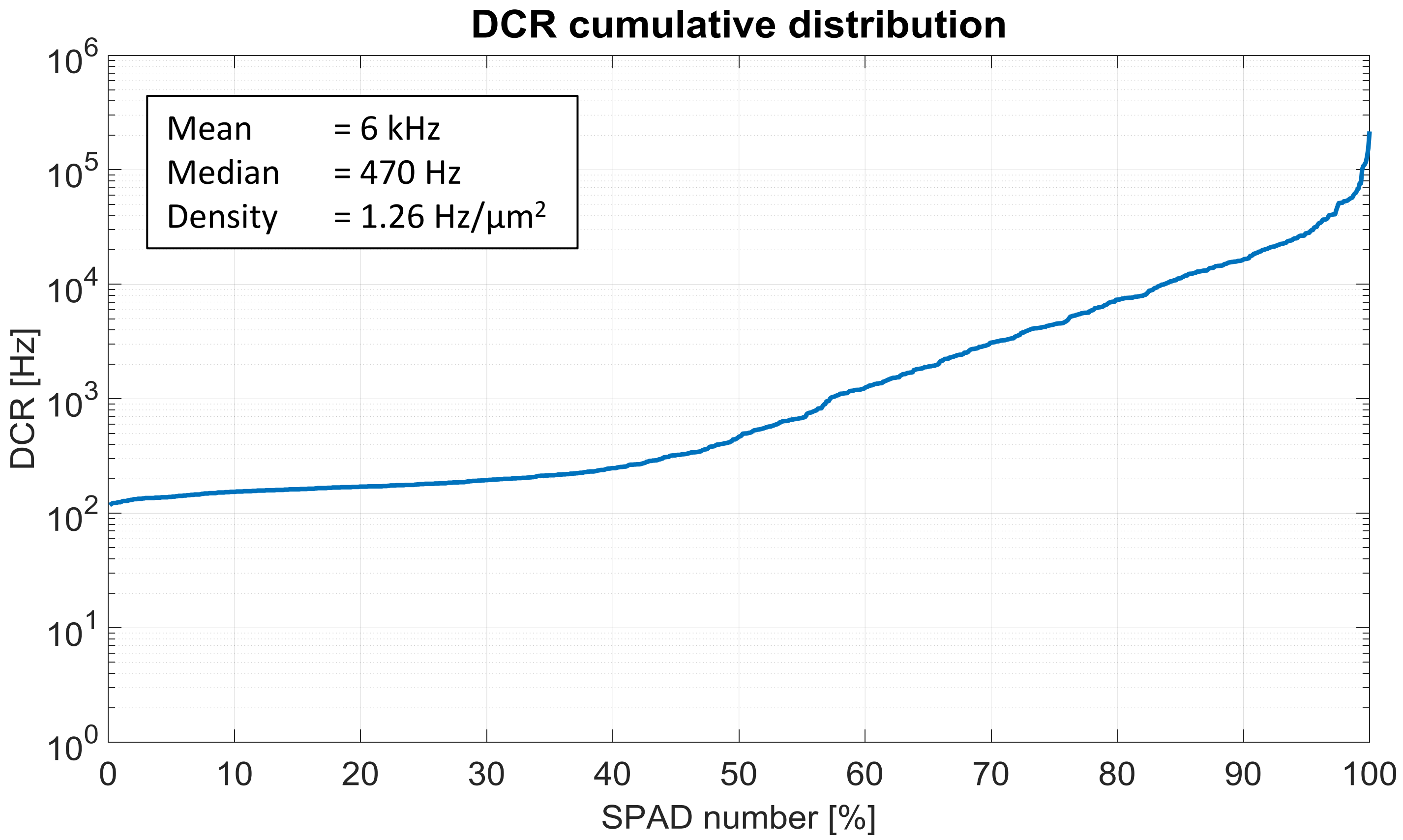


- Row-wise "empty row detection"
- Current-based global threshold

➡ **x10 gain in acq duty-cycle**

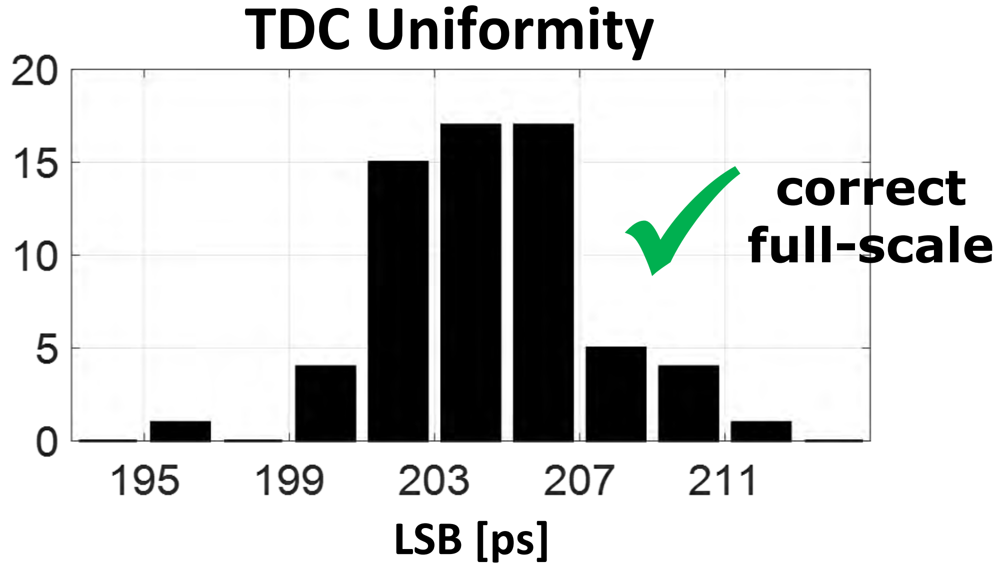
SPAD Dark Count Rate (DCR)



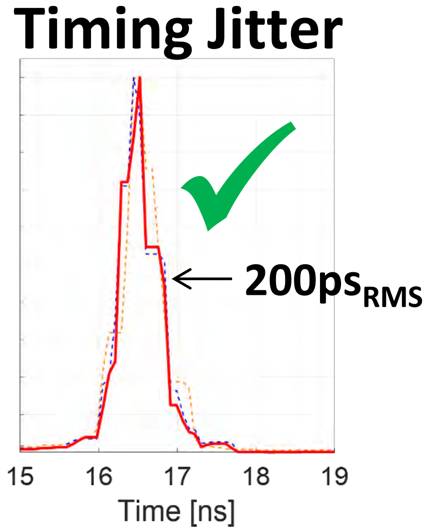


- SPAD
  - 20µm square w/rounded corners
  - p+/nwell (no sharing) ➡ **Minimize xtalk**

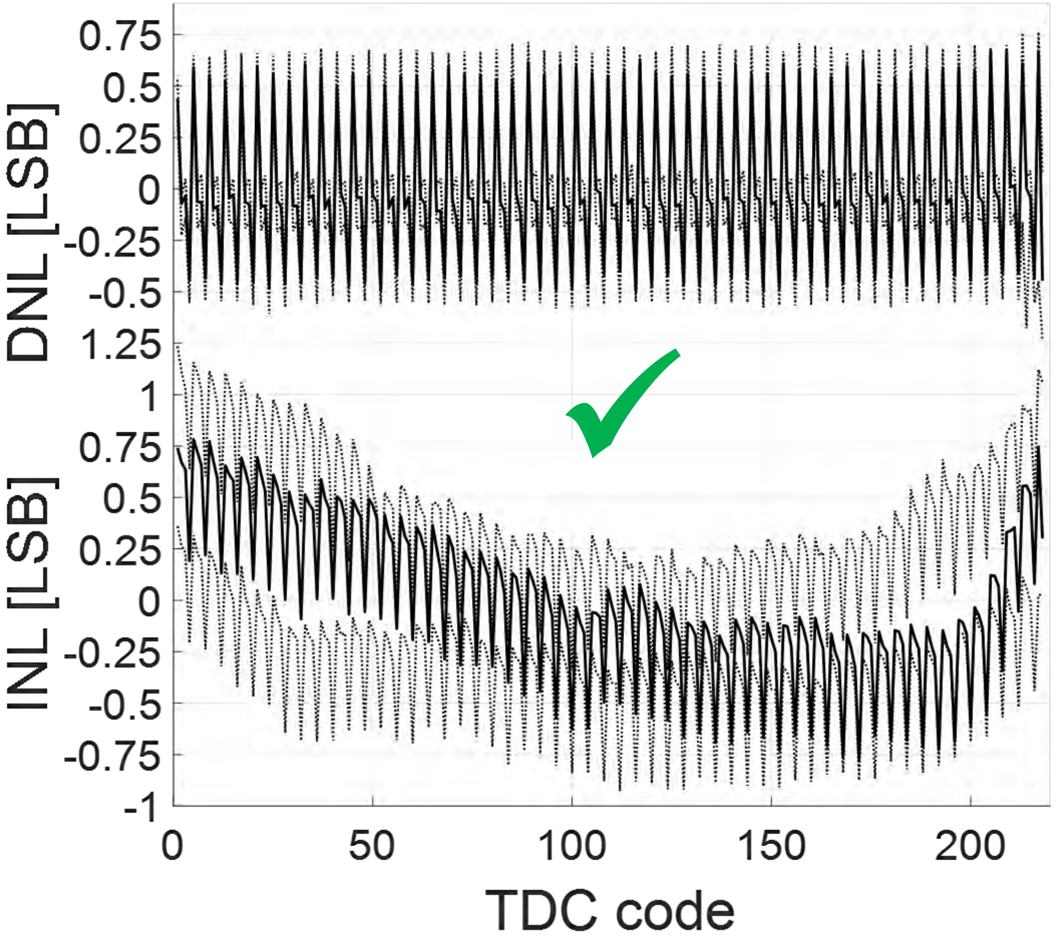
Pixel/Array Timing Performance



✓ correct full-scale



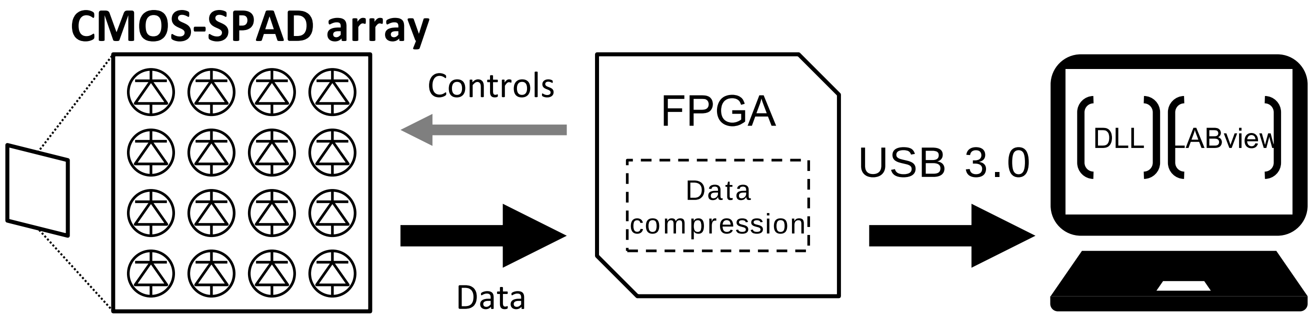
✓ 200ps$_{RMS}$

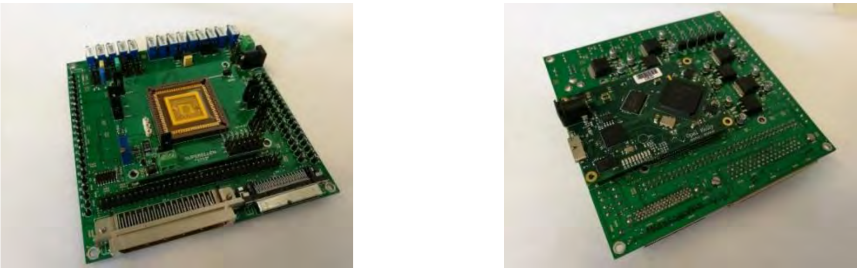


✓

➡ **Goal: detect non-local correlations**

Demonstrator of Quantum Imager





- Frame rate in the **80-500 kfps** range
- **Real-time data compression** exploiting sparsity of data
  - Raw frame = 1kB; compressed frame < 30B (typ) → **3% compression ratio**
  - Address assignment performed by the FPGA
- **Software-based** calculation of correlation functions $G^{(N)}$

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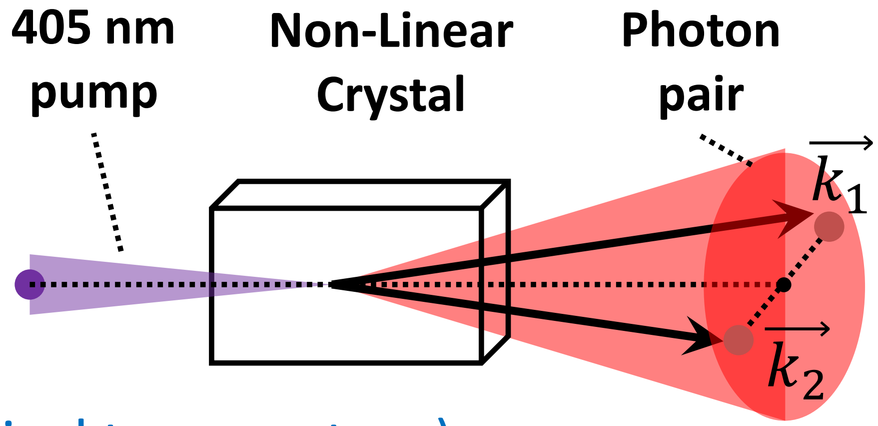
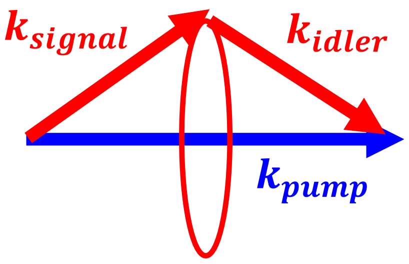
Generation of bi-photons

- PPKTP: phase matching in type-0 SPDC
  - Energy conservation:
    - 1 ph @405 nm → 2 ph @~810 nm
  - Momentum conservation
    - Different patterns wrt temperature (with T_C critical temperature)



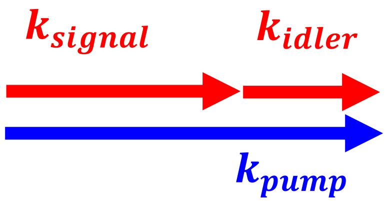
Non-collinear, degenerate:
Wavevectors of bi-photons on a cone, anticorrelated



$\omega_{signal} = \omega_{idler}$

$T<T_C$

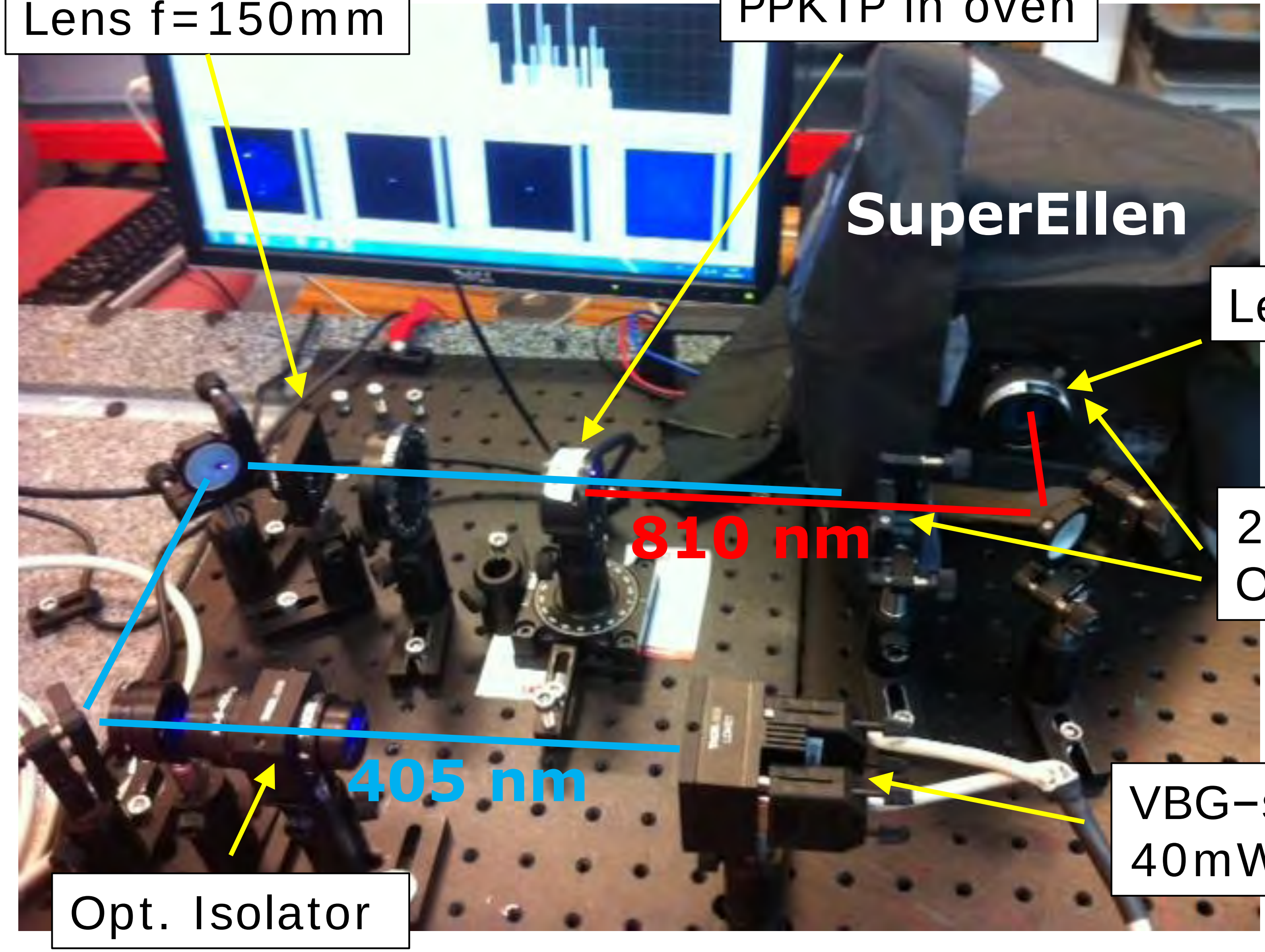
Collinear, non-degenerate:
Transversal wavevectors of bi-photons, correlated



$T>T_C$

$\omega_{signal} \neq \omega_{idler}$

SPDC Laboratory Setup



Lens f=150mm

PPKTP in oven

Lens f=45 mm

2x BP filters
OD12@405

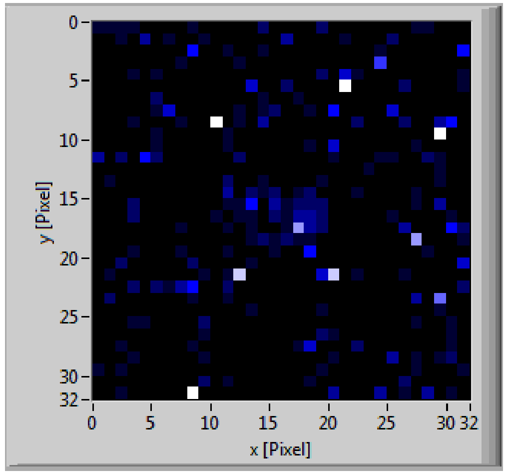
VBG-stabilized ECDL
40mW@405.7nm

Opt. Isolator

Effects of DCR and Crosstalk – Source OFF

- Intensity: just accumulation of hits
- $G^{(2)}$: linearized index on x and y axis of coincidences

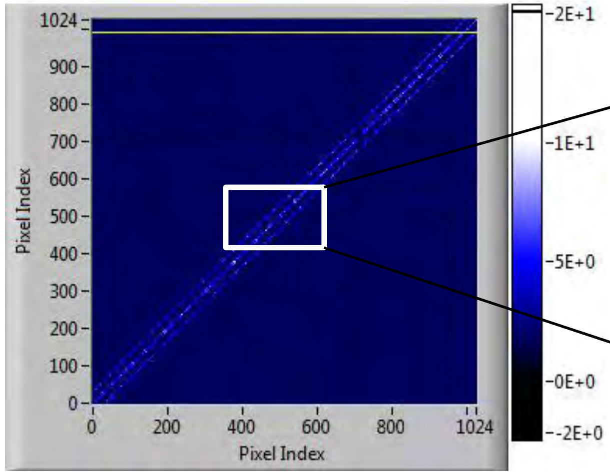
Integrated Intensity



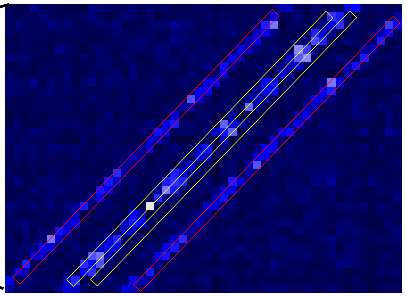
↓

DCR pattern

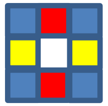
Glauber correlations
$G^{(2)}(Pixel_{x1y1},Pixel_{x2y2})$



Crosstalk effect

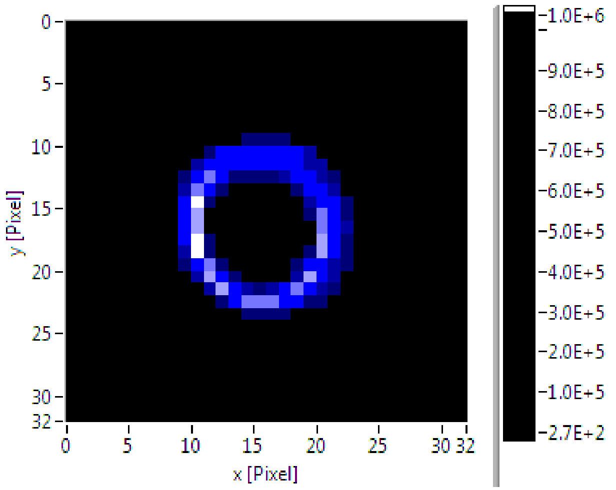


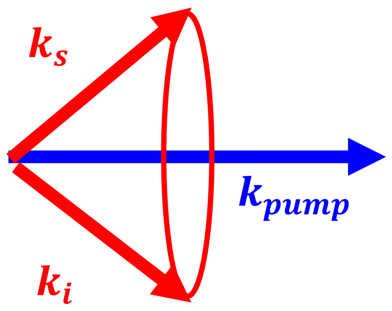
Nearby cols: +1,-1
Nearby rows: +32,-32



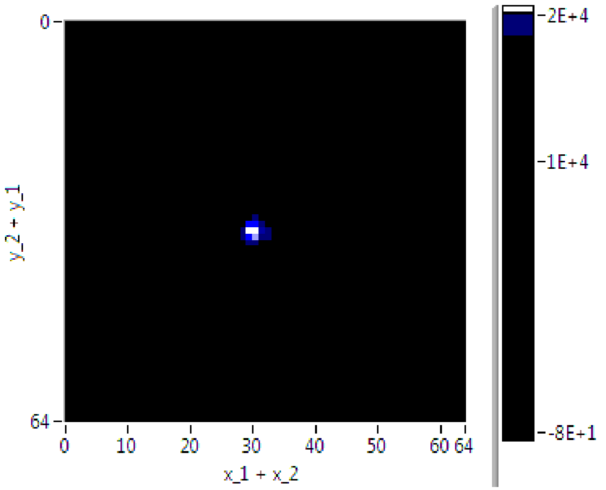
Anticorrelated Bi-photons ($T<T_C$)

Integrated Intensity



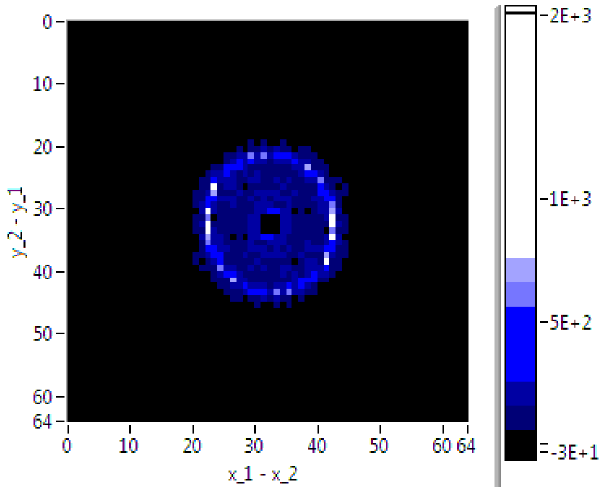


Integrated anticorrelations
$\int G^{(2)}(\Delta+k, \Delta+-k)dk$



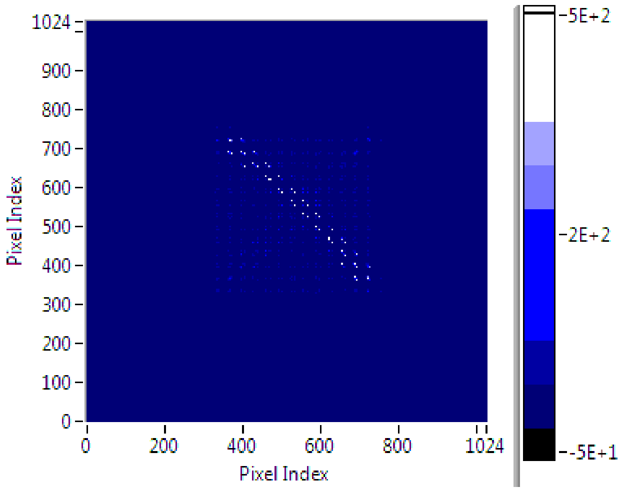
Narrow correlation range around central position of spot

Integrated correlations
$\int G^{(2)}(\Delta+k, \Delta+-k)d\Delta$



Reproduces ring of "constant distance", confirming correlations

Glauber correlations
$G^{(2)}(\text{Pixel}_{x1y1},\text{Pixel}_{x2y2})$



Anti-diagonal attests for anticorrelations

Matching Theory: SPDC Generation vs. Temperature

Integrated intensity

Integrated anticorrelations

Integrated correlations

$G^{(2)}(Pix_{x1y1},Pix_{x2y2})$

$52.5°C<T_C$

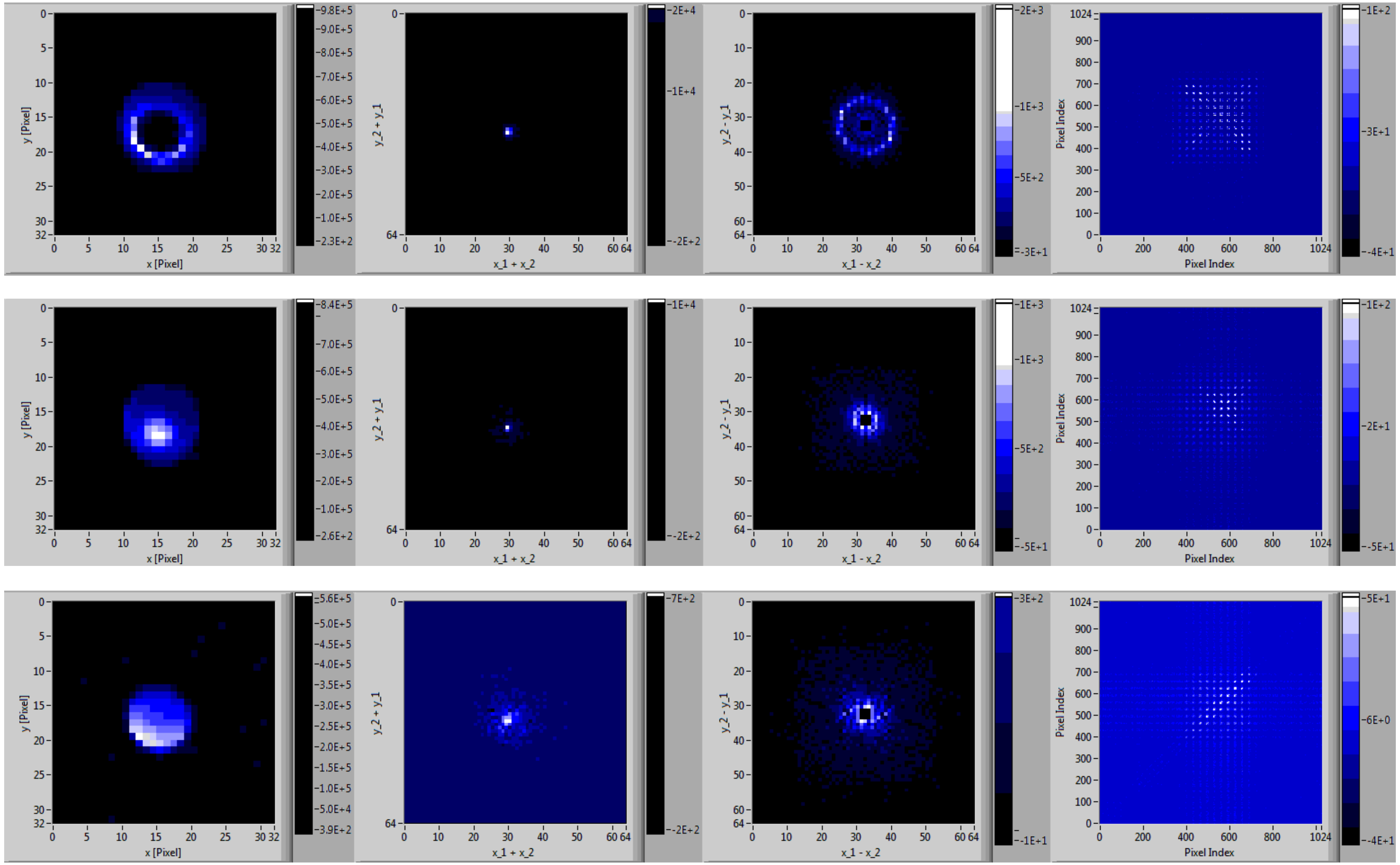
Anticorrelations

$55.0°C=T_C$

Degeneracy

$57.5°C>T_C$

Co-propagating bi-photons



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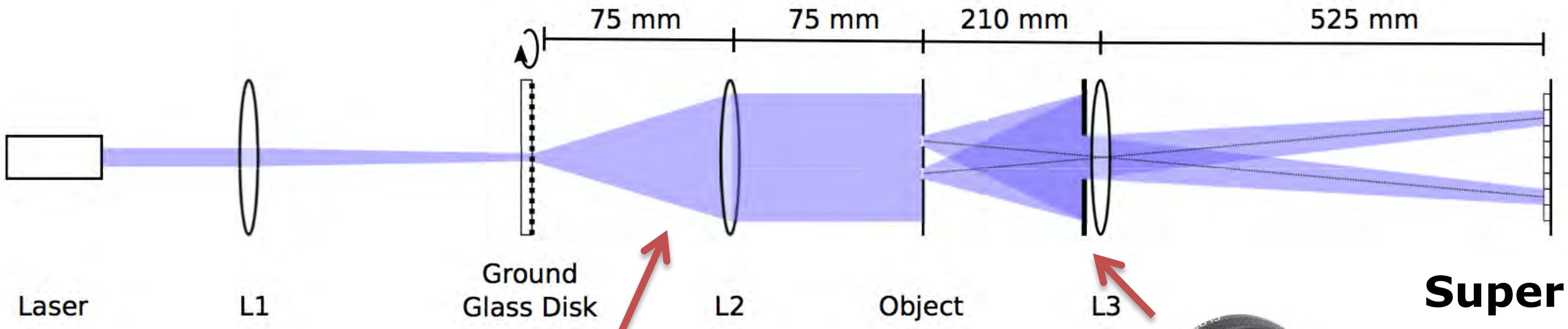
Higher Order $G^{(N)}$: Pseudo-Thermal Light Source

- Setup for thermal near-field imaging
- Rotating ground glass disk produces pseudothermal statistics

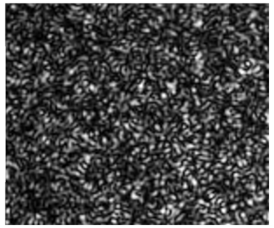


SuperEllen sensor

F

Reduced aperture

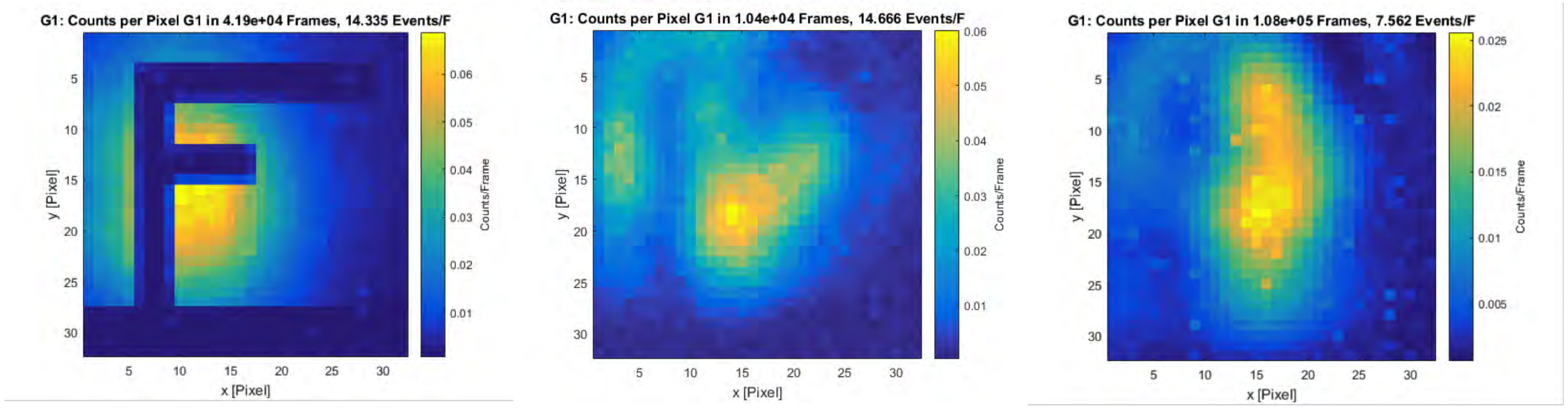
Pseudothermal statistics



$G^{(2)}$ Measurement with Pseudothermal Light

D = 12 mm **D = 0.8 mm** **D = 0.6 mm**

Coherent



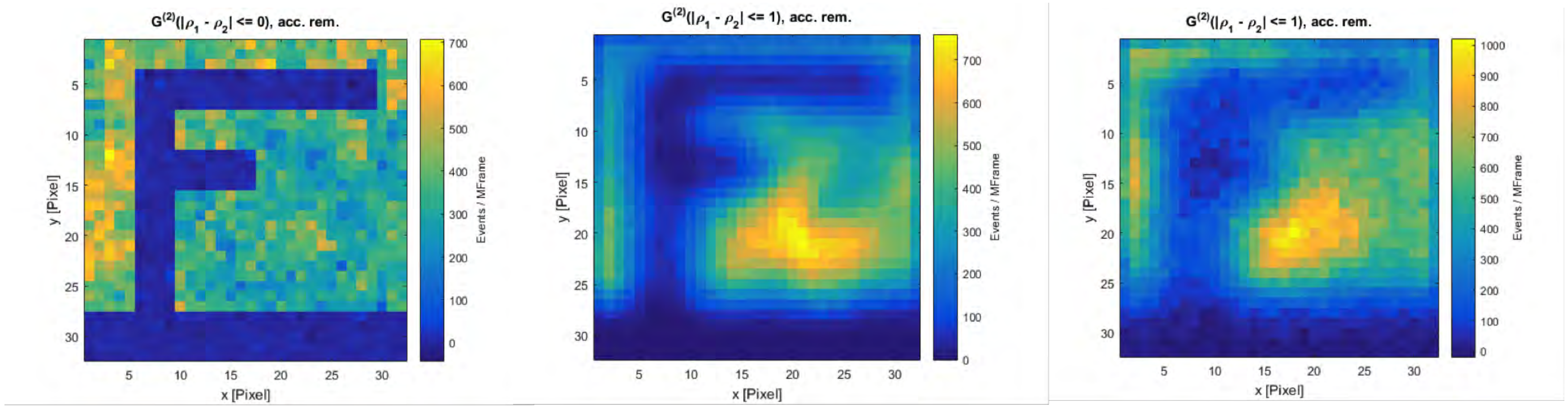
G1: Counts per Pixel G1 in 4.19e+04 Frames, 14.335 Events/F

G1: Counts per Pixel G1 in 1.04e+04 Frames, 14.666 Events/F

G1: Counts per Pixel G1 in 1.08e+05 Frames, 7.562 Events/F

↓ √2 improvement ↓

Thermal $G^{(2)}$



$G^{(2)}(|\rho_1 - \rho_2| <= 0)$, acc. rem.

$G^{(2)}(|\rho_1 - \rho_2| <= 1)$, acc. rem.

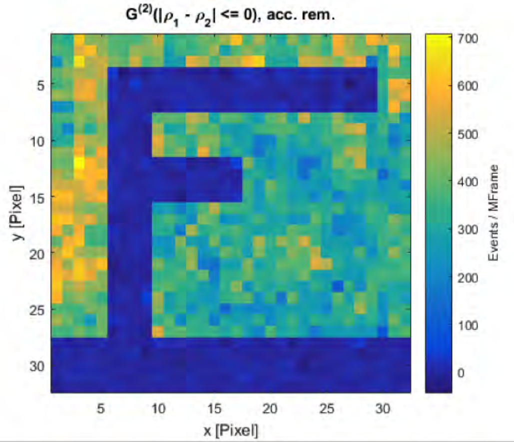
$G^{(2)}(|\rho_1 - \rho_2| <= 1)$, acc. rem.

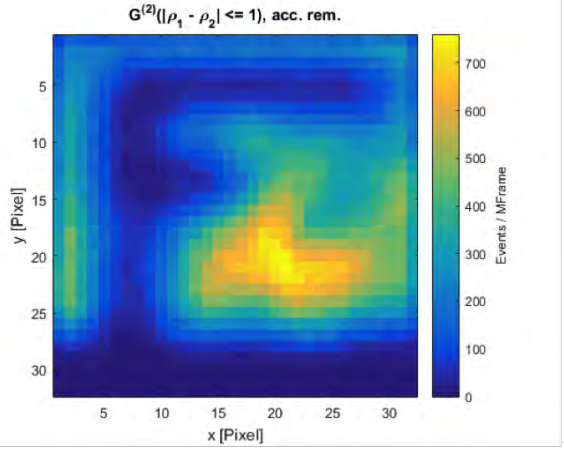
$$G^{(2)}(\boldsymbol{\rho}, \boldsymbol{\rho})$$

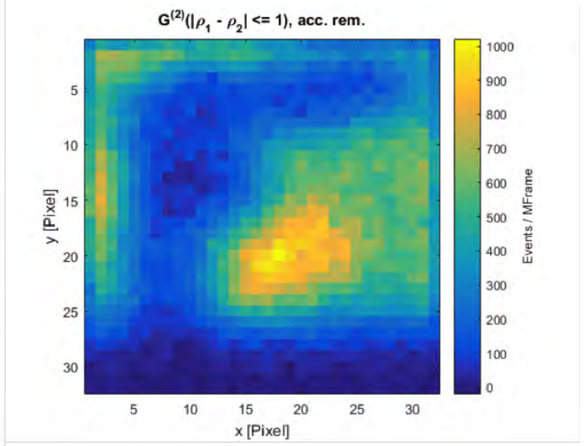
$G^{(3)}$ Measurement with Pseudothermal Light

D = 12 mm **D = 0.8 mm** **D = 0.6 mm**

Thermal G(2)



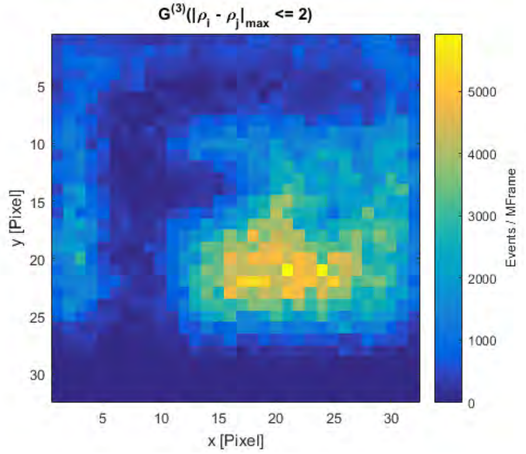


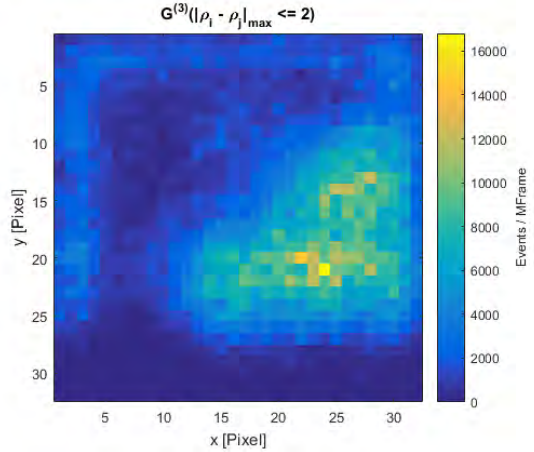


$$G^{(2)}(\boldsymbol{\rho},\boldsymbol{\rho})$$

↓ **no improvement!** ↓

Thermal G(3)

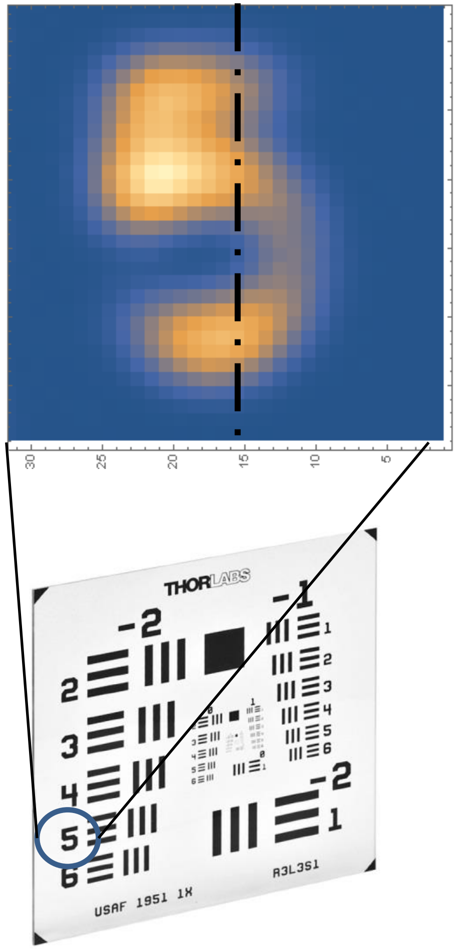




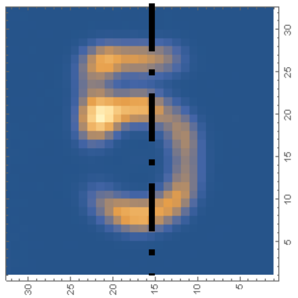
$$G^{(3)}(\boldsymbol{\rho},\boldsymbol{\rho},\boldsymbol{\rho})$$

Improvement Without Processing

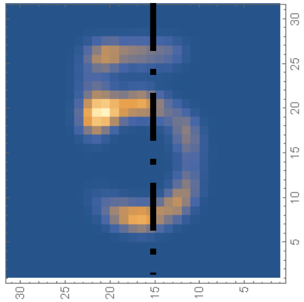
Intensity



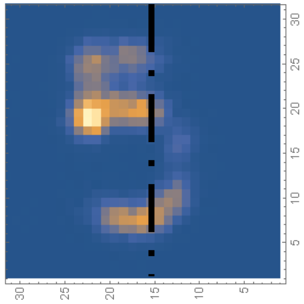
Thermal $G^{(2)}$

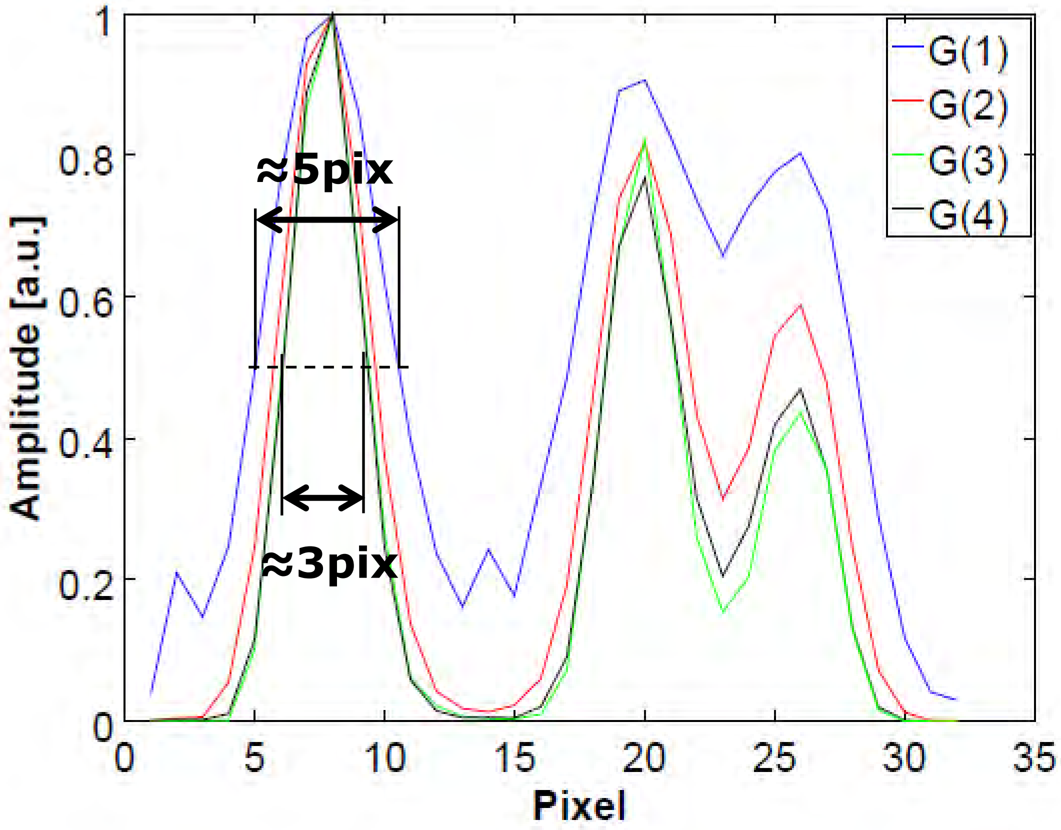


Thermal $G^{(3)}$



Thermal $G^{(4)}$





$G^{(N)}$ (ρ, … ρ)
diagonal terms

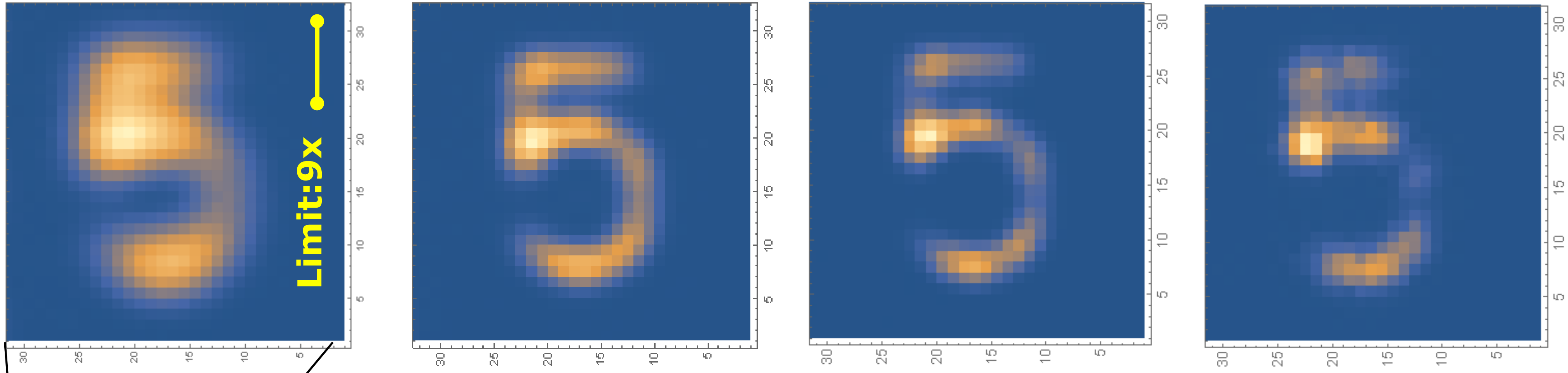
Applying Reconstruction Algorithm

Limit: 9x
D=0.3mm
Intensity

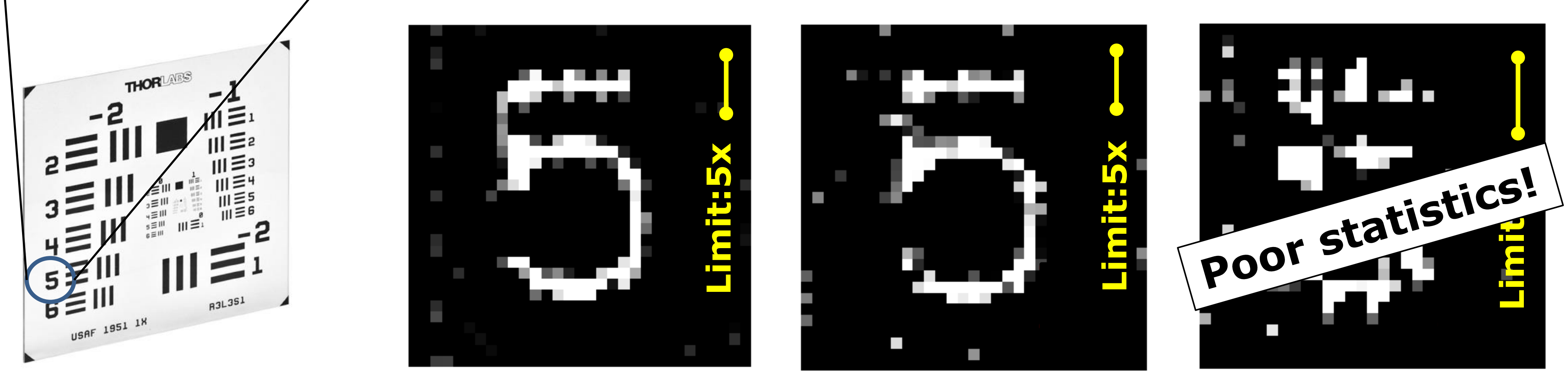
Limit: 5x
D=0.5mm
Thermal $G^{(2)}$

Limit: 5x
D=0.5mm
Thermal $G^{(3)}$

Limit: 7x
D=0.4mm
Thermal $G^{(4)}$



$G^{(N)}(\rho, \ldots \rho)$
diagonal
terms



Poor statistics!

$G^{(N)}(\rho_1, \ldots \rho_N)$
full
correlation

Outline

- Motivation
- Requirements for imaging with entangled photons
- SuperEllen fabrication and characterization
- $G^{(2)}$ correlations in SPDC with bi-photons
- $G^{(2)}$-$G^{(4)}$ in thermal imaging
- Conclusions & future outlook

Conclusions & Outlook

- Superresolution concept addressed by entangled photon detection
- Efficient detection of simultaneously impinging photons needs
  - TDC-based architecture
  - Thresholding mechanism
  - Efficient readout

→

32x32 SPAD array demonstrator with per-pixel TDC and row/frame skipping

- **200ps timing resolution**
- **20% fill-factor**
- **800 kfps max**

- Advantages are demonstrated in $G^{(2)}$ measurements of entangled photon pairs and $G^{(2)}$-$G^{(4)}$ measurements with quasi-thermal light.

- Future step: 256x256 detector for $G^{(5)}$ measurements

European Commission

HORIZON 2020

SUPERTWIN

All Solid-State Super-Twinning Photon Microscope

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FONDAZIONE BRUNO KESSLER

A.P.E.Research NANOTECHNOLOGY

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SINGLE QUANTUM
Excellence in photon detection

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