# Q-CMOS : Image sensors with single photon capabilities

**Ljiljana Durdevic, Sebastian Beer**

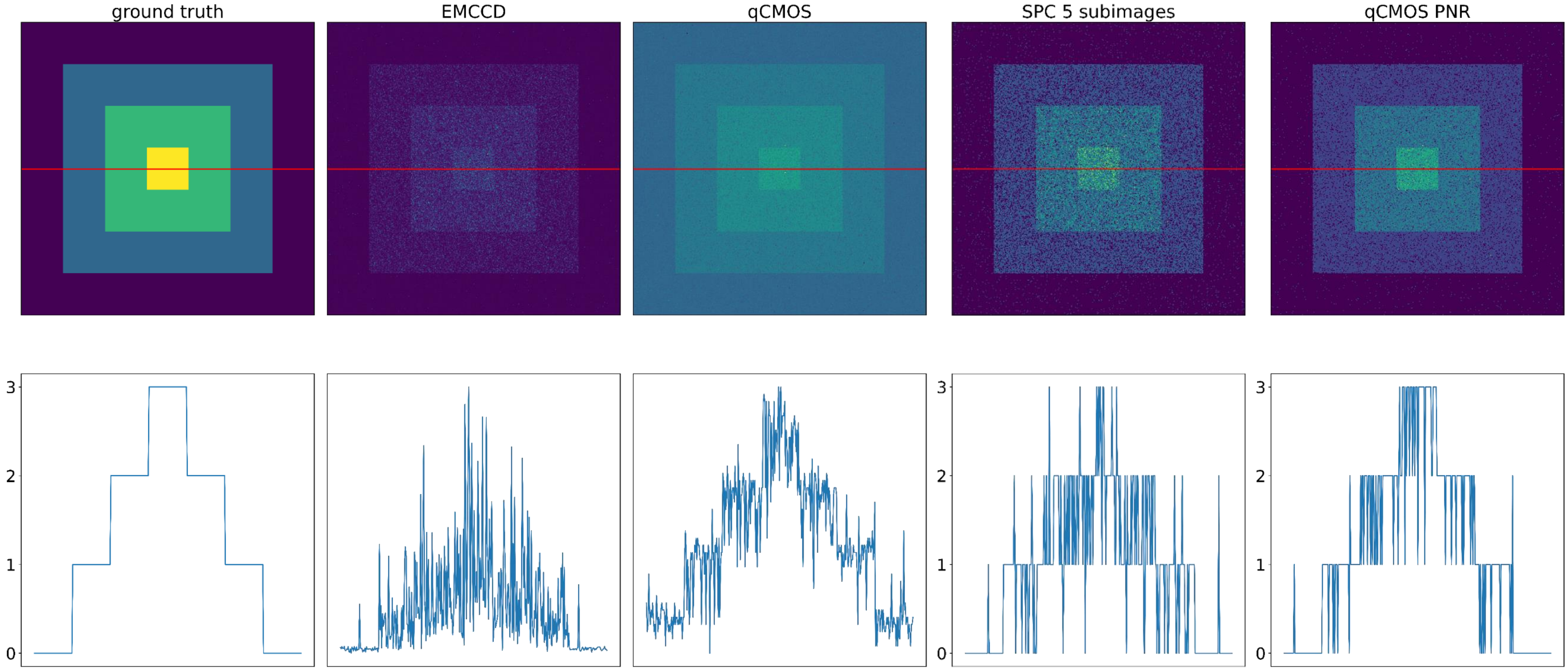
Hamamatsu Photonics

24/01/2025

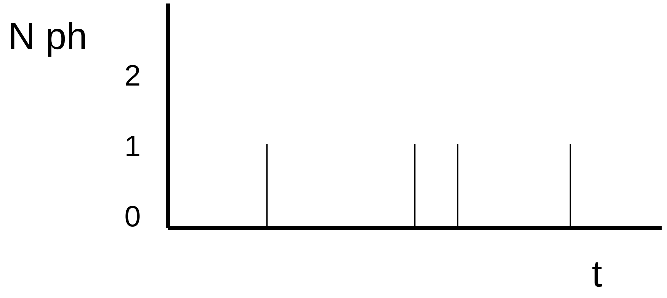
# Contents

# Motivation

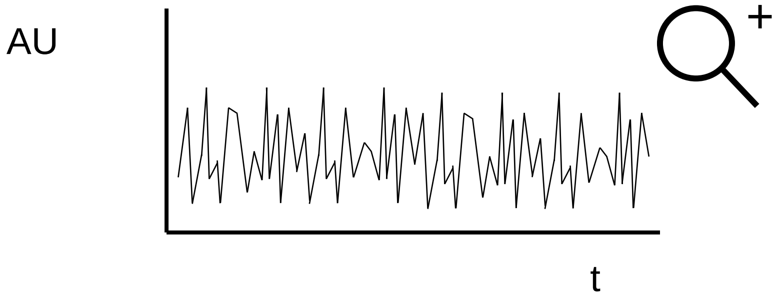


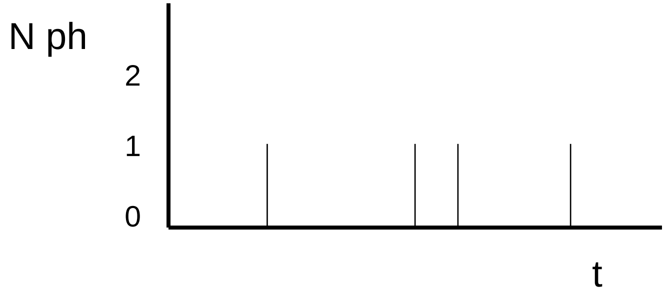
# Nomenclature

# What is a single-photon detector (SPD)?

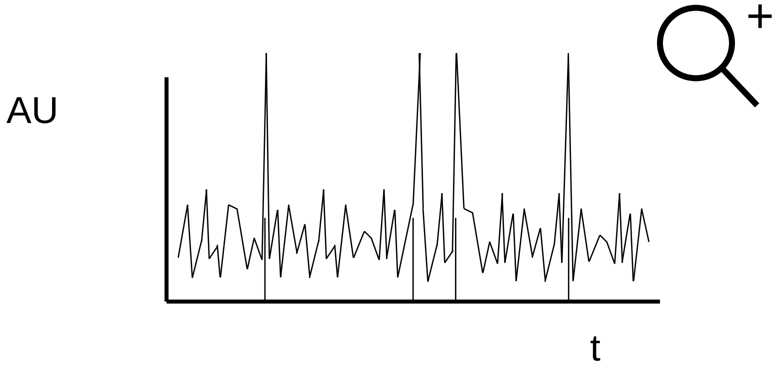



Photodetector unable to detect a single photon



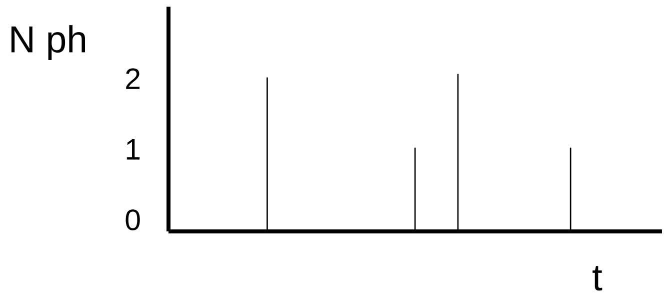




Photodetector able to detect a single photon

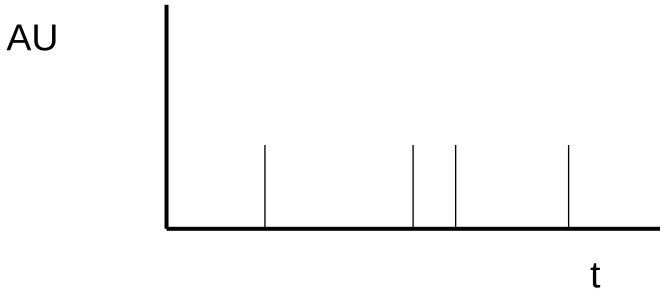


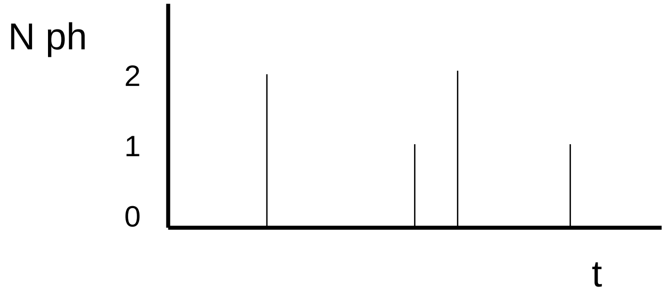

A single photon detector creates a signal from a single photon <u>above the noise level</u>

# What is a photon number resolving (PNR) detector?

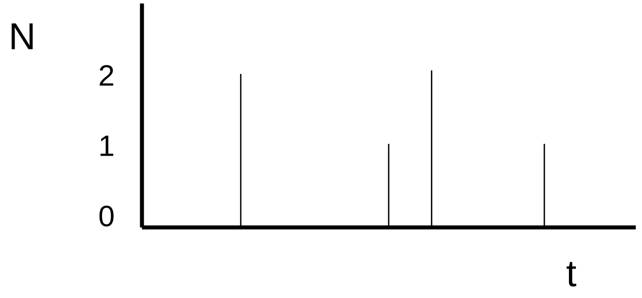



Photodetector able to detect a single photon
But unable to resolve photon numbers



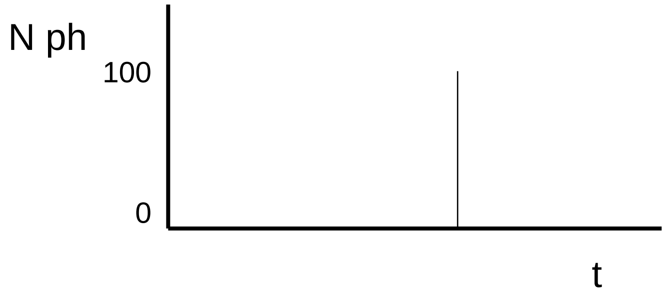

Photodetector able to resolve photon numbers



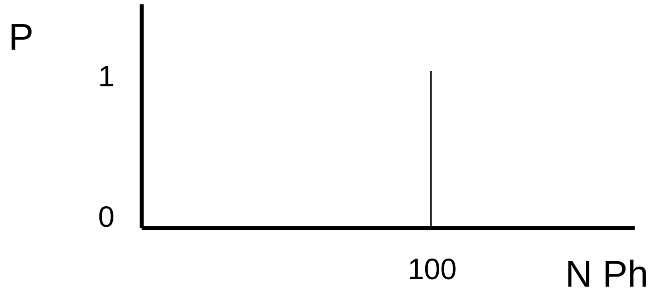
# Counting photons?

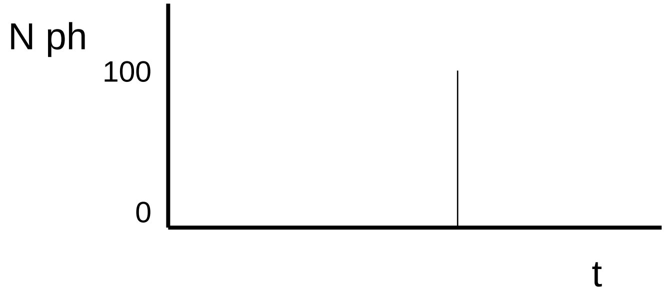
- The absorbtion efficiency, that triggers the response (called quantum efficiency, QE) is never perfect

# Counting photons?

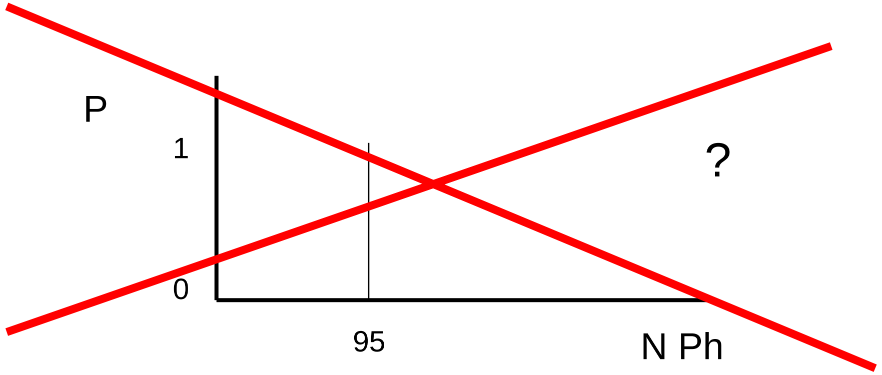


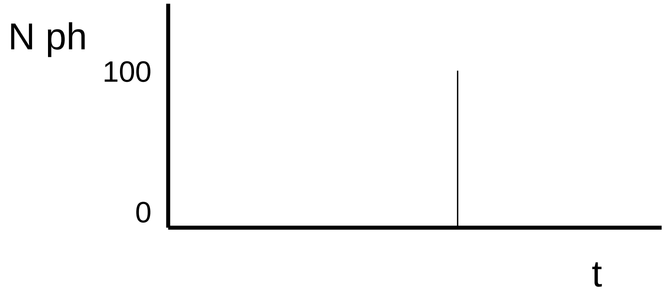

Perfect Photodetector able to resolve photon numbers



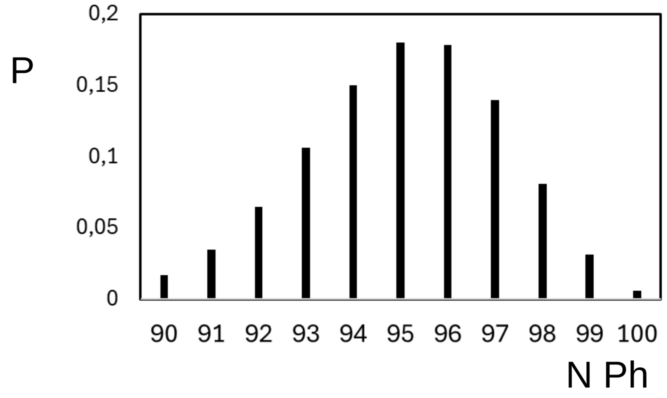




Photodetector able to resolve photon numbers, QE = 95%

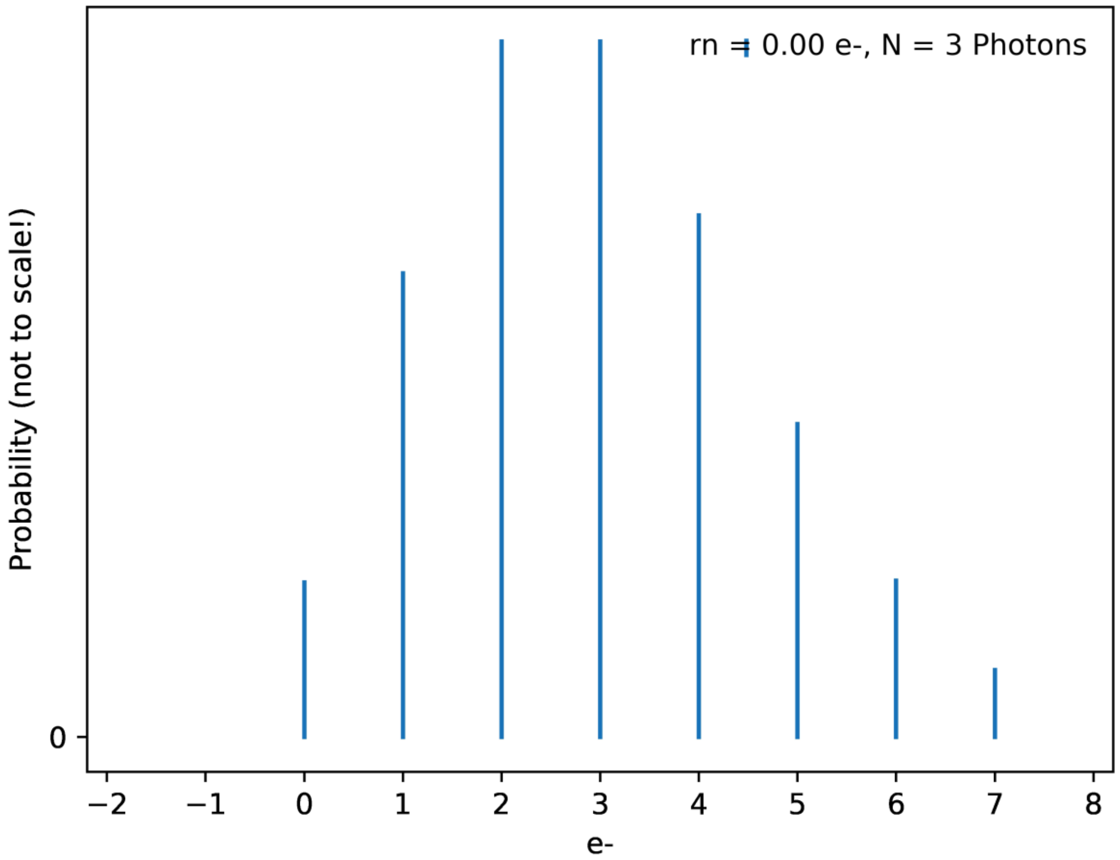


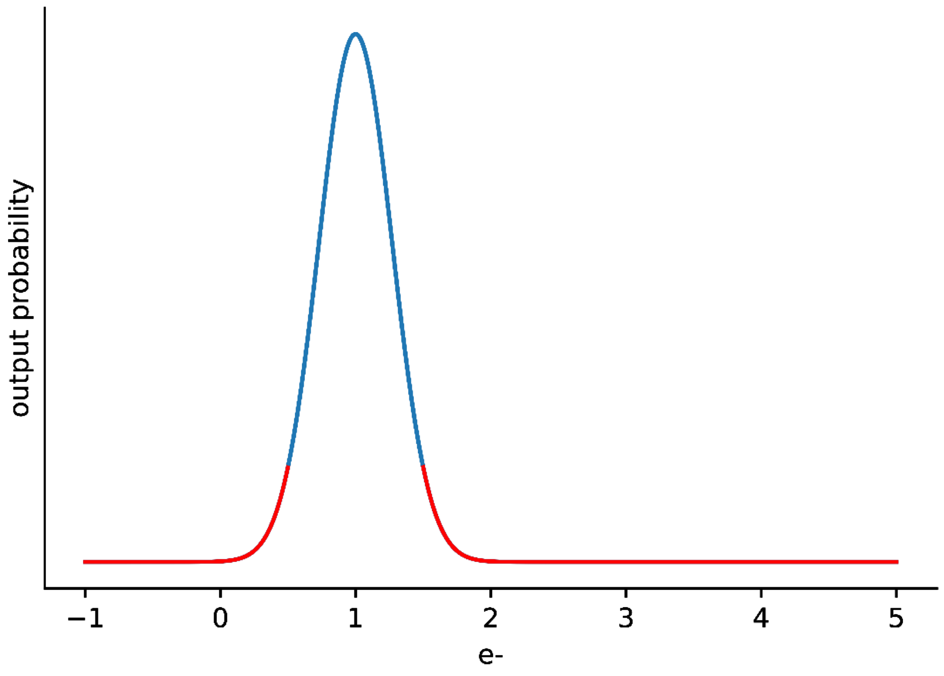

Photodetector able to resolve photon numbers, QE = 95%

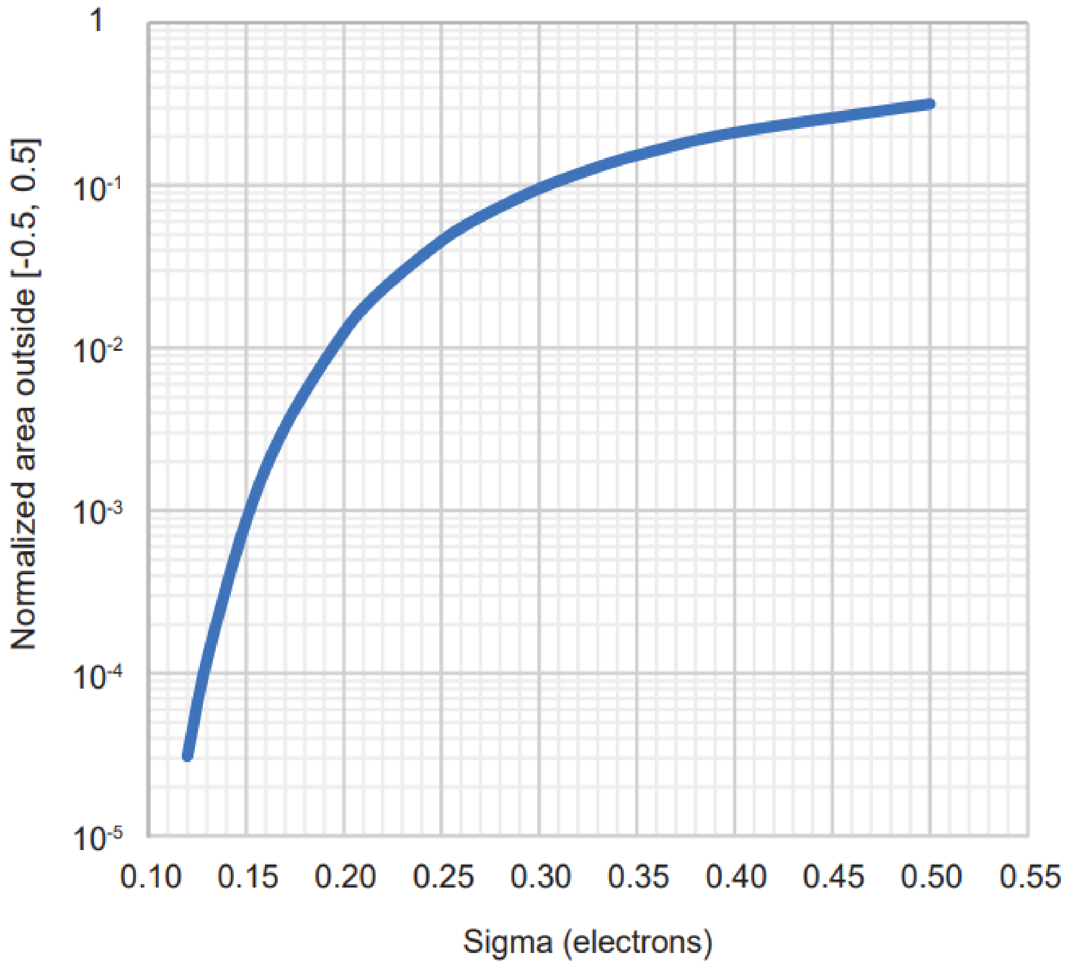


# Noise Performance



# Photon Number Resolving Performance



# Historical Perspective

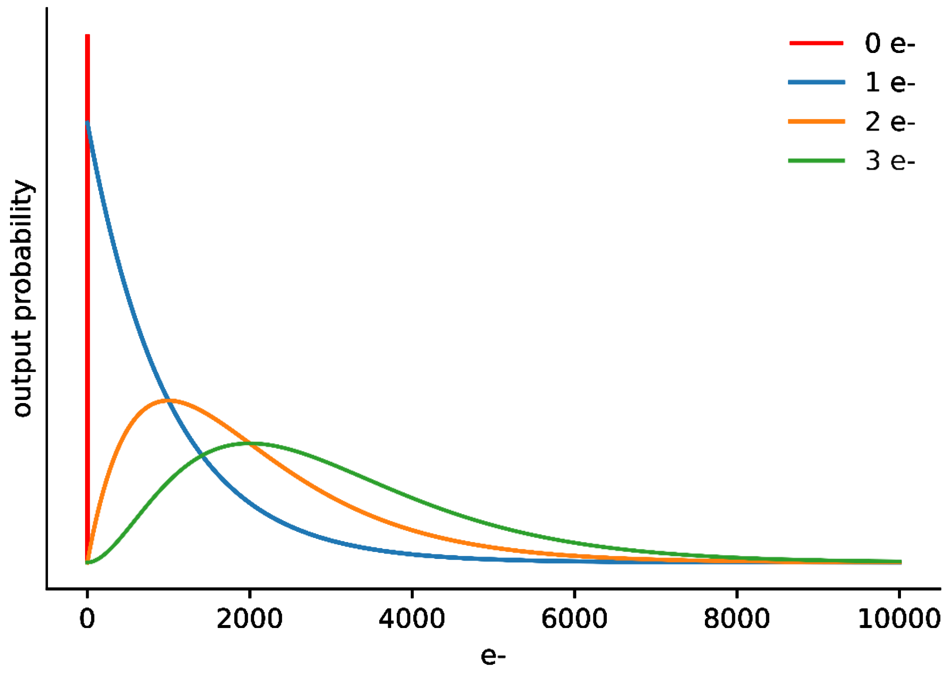
# Historical Perspective

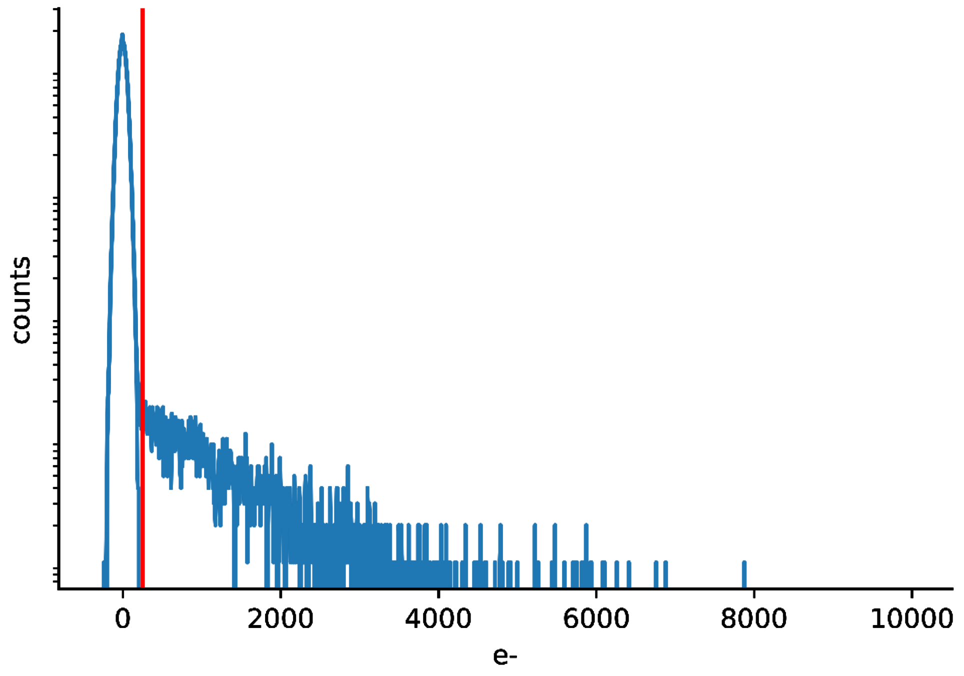
- Major focus: readout noise reduction
- Instead of reducing readout noise, amplify the signal before readout
- Image Intensifier

- Limit to photocathode materials (max QE ~45%)

# Historical Perspective

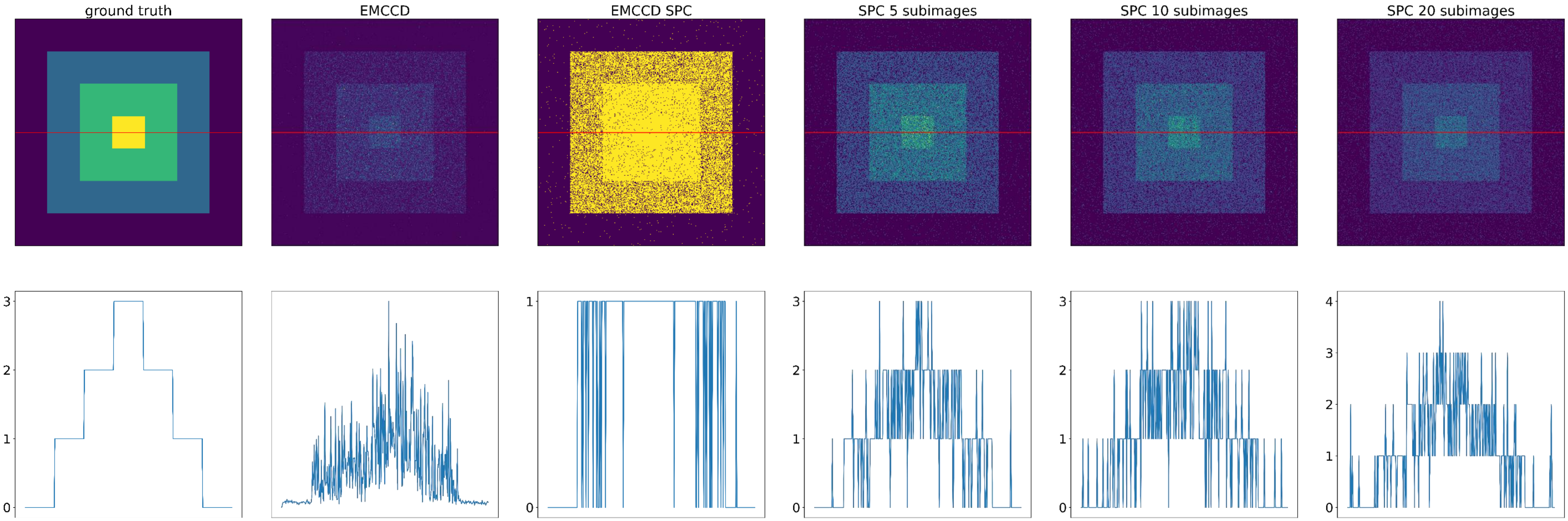
- Since 2001 EMCCDs (Peak QE 95%)
- Downside: gain fluctuations



# Historical Perspective

- Binary Image
- Solution: temporal subsampling



# Historical perspective – Status Quo

- Single photon counting image sensors available

- Photon number resolving detectors postulated:
  - Janesick et al 1990: Skipper CCD / Quantum CCD
  - Fossum 2005: Quanta Image Sensor

Janesick, James R., et al. "New advancements in charge-coupled device technology: subelectron noise and 4096 x 4096 pixel CCDs." *Charge-Coupled Devices and Solid State Optical Sensors*. Vol. 1242. SPIE, 1990.

Fossum, Eric R. "11 Some Thoughts on Future Digital Still Cameras." *IMAGE SENSORS and SIGNAL PROCESSING for DIGITAL* (2006): 305.

# Historical perspective – Status Quo

- Skipper CCD / Quantum CCD
  - Technical roadmap for noise reduction
  - General idea: reduce noise by averaging nondestructive readouts
- Quanta Image Sensor
  - Postulates the universal camera:
  - Pixel pitches well below diffraction limit
  - Readout noise below 0.15 e- (practically irrelevant)
  - High speed readout
  - Potentially single bit pixels
  - „lossless“ spatial and temporal binning

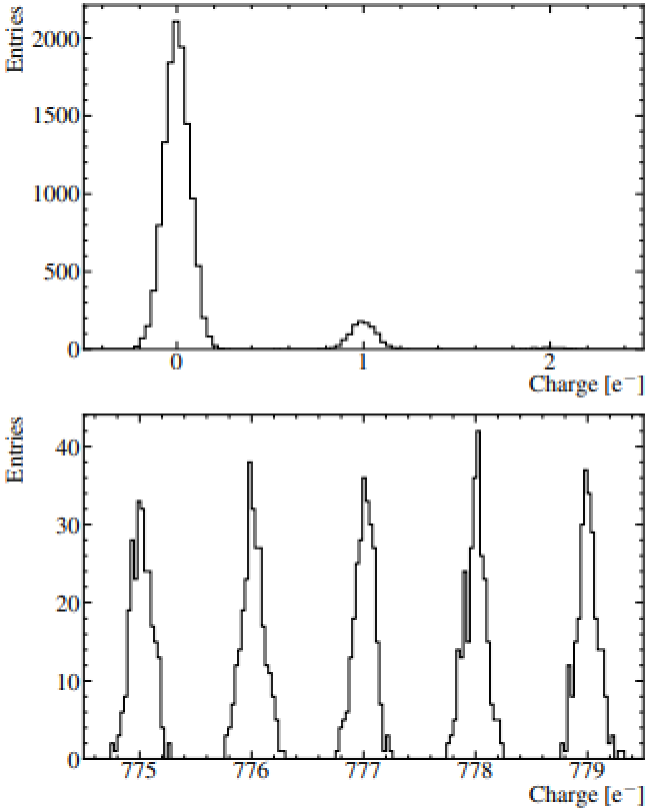
# Current Implementations

# Current Implementations – Skipper CCD / Quantum CCD

- Implemented in 2017
- Academic project
- Single frame readout:
  - 3h

TABLE I. Skipper CCD Detector Characteristics

| Characteristic | Value | Unit |
|---|---|---|
| Format | 4126 × 866 | pixels |
| Pixel Scale | 15 | $\mu$m |
| Thickness | 200 | $\mu$m |
| Operating Temperature | 140 | Kelvin |
| Number of Amplifiers | 4 | |
| Dark Current[a] | $< 10^{-3}$ | $e^-$/ pix/day |
| Readout Time (1 sample) | 10 | $\mu$s/pix/amp |
| Readout Noise (1 sample) | 3.55 | $e^-$ rms/ pix |
| Readout Noise (4000 samples) | 0.068 | $e^-$ rms/ pix |




Tiffenberg, Javier, et al. "Single-electron and single-photon sensitivity with a silicon Skipper CCD." *Physical review letters* 119.13 (2017): 131802.

# Current Implementations – Quanta Image Sensors

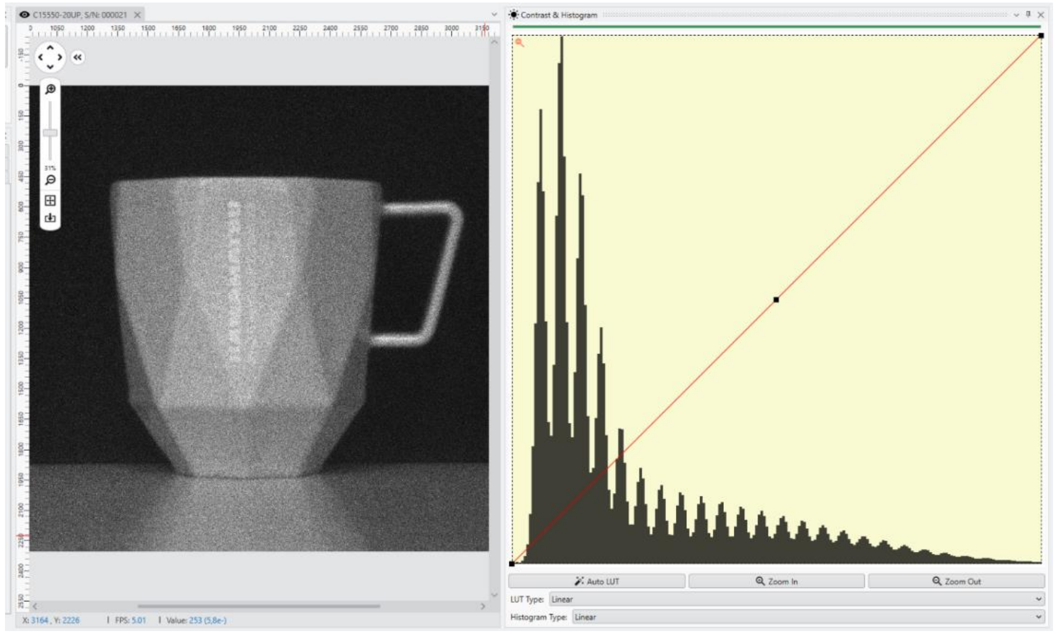
- Manufactured by Gigajot
- Spin Off of Dartmouth College (Eric Fossoms group)
- Disappeared from the market in 2022

| | | |
|---|---|---|
| Process Technology | | 45nm/65nm Stacked CIS BSI Process |
| Pixel Size | | 1.1 µm x 1.1 µm |
| Pixel Resolution | | 4096 x 4096 |
| Chroma | | RGB Bayer /Mono |
| Power Consumption | | 600 mW |
| ADC Bit Depth | | 1-14 bit programmable |
| Max Frame Rate | | 40 fps @ 4096 x 4096 |
| | | 60 fps @ 3840 x 2160 |
| Read Noise | 25 °C, CMS 8 | 0.19 e- rms @ Peak<br>0.22 e- rms @ Median |
| | -20 °C, CMS 8 | 0.17 e- rms @ Peak<br>0.20 e- rms @ Median |
| RTS (>10e- rms) | | <1 ppm |
| Linear Full-Well Capacity | | 1500 e- |
| Dynamic Range | | 77 dB |
| Non-Linearity | | <0.5% |
| PRNU | | <1.5% |
| Quantum Efficiency @ Peak | | 76% @ 520nm |
| Dark Current | 60C | 4.5 e-/pix/sec |
| | 20C | 0.086 e-/pix/sec |
| Lag | | <0.1 e- (less than the measurable level) |

Ma, Jiaju, et al. "A 0.19 e-rms read noise 16.7 Mpixel stacked quanta image sensor with 1.1 µm-pitch backside illuminated pixels." *IEEE electron device letters* 42.6 (2021): 891-894.

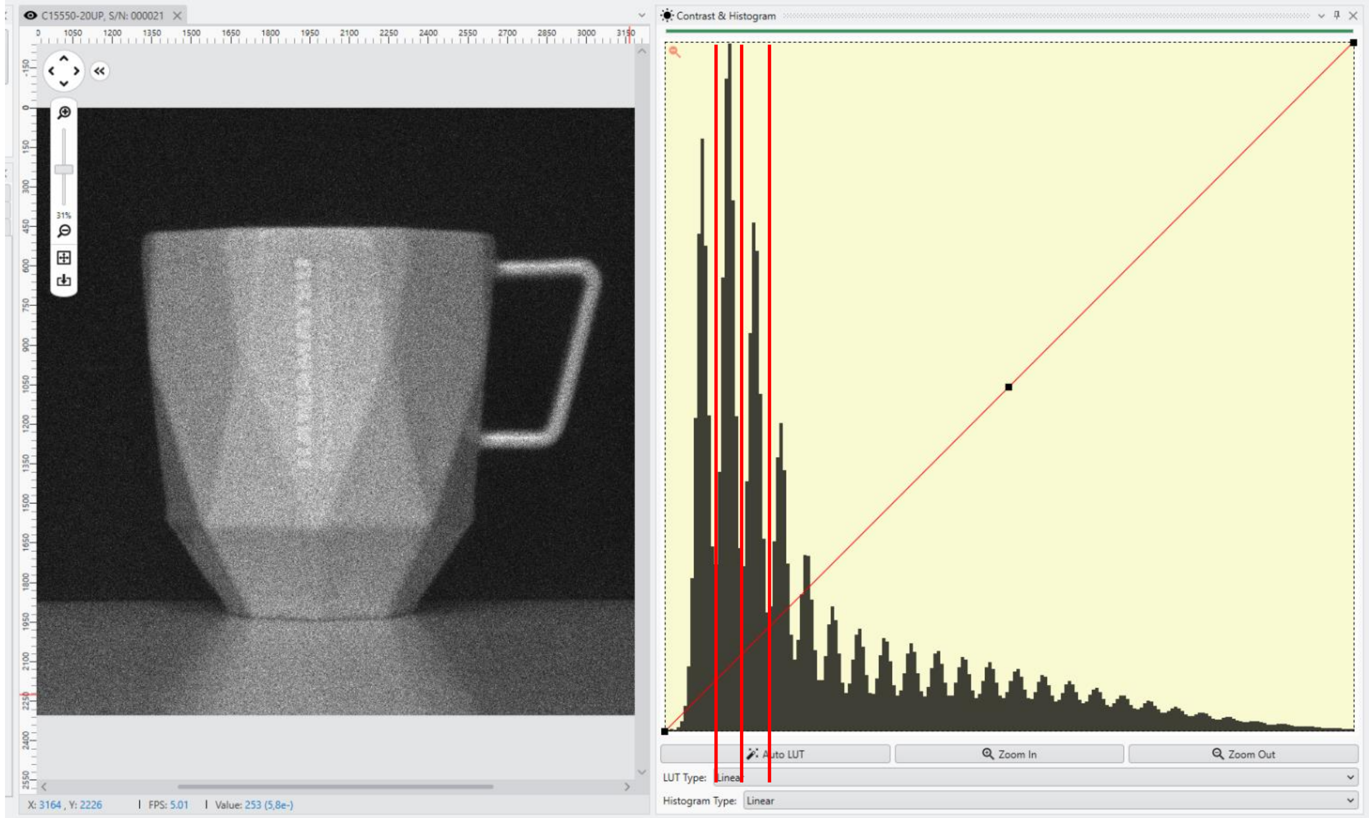
# Current Implementations – quantitative CMOS

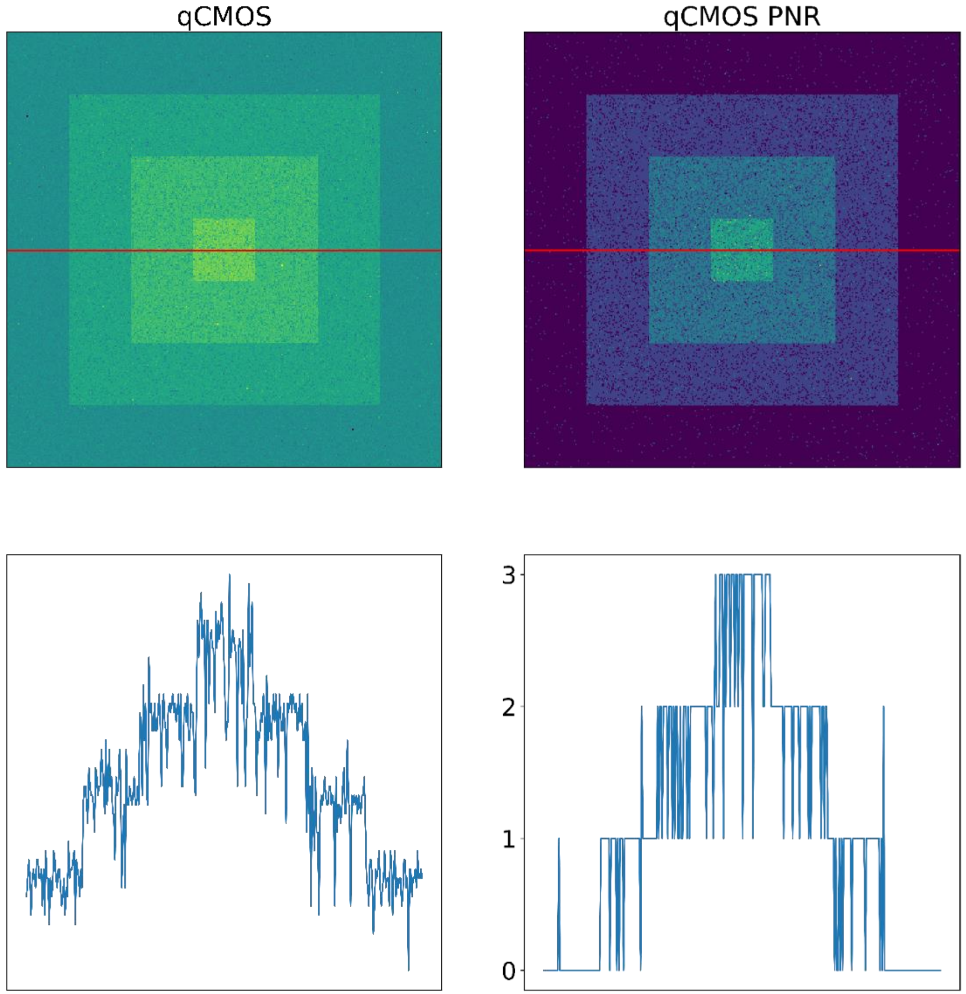
- Implemented by Hamamatsu
- Available since 2021




| | | |
|---|---|---|
| Imaging device | qCMOS image sensor | |
| Effective number of pixels | 4096 (H) × 2304 (V) | |
| Pixel size | 4.6 µm × 4.6 µm | |
| Effective area | 18.841 mm × 10.598 mm | |
| Conversion factor *1 | 0.107 electrons / count | |
| Readout noise (rms) *1 | Standard scan | 0.43 electrons |
| | Ultra quiet scan | 0.27 electrons |
| Quantum efficiency *1 | 300 nm | 34 % |
| | 460 nm | 85 % |
| | 900 nm | 30 % |
| Full well capacity *1 | 7000 electrons | |
| Dynamic range *1 | 26 000 : 1 *2 | |
| Dark current *1 | Cooling temperature: -20 °C | 0.016 electrons / pixel / s |
| | Cooling temperature: -35 °C | 0.006 electrons / pixel / s |
| Dark offset | Binning OFF | 200 counts |
| | Binning ON (2×2) | 800 counts |
| | Binning ON (4×4) | 3200 counts |
| Dark signal non-uniformity (DSNU) *1, 3 | 0.06 electrons r.m.s. | |
| Photo response non-uniformity (PRNU) (3500 electrons) *1, 3, 4 | Less than 0.1 % r.m.s. | |
| Linearity error *1 (EMVA 1288 standard) *1 | 0.5 % | |

# Current Implementations – Photon Number Resolving Operation



# Current status

- Skipper CCD
- 15μm pixel pitch
- 0.068 e- RON
- 0.3 fph ~ 7.2 fpd

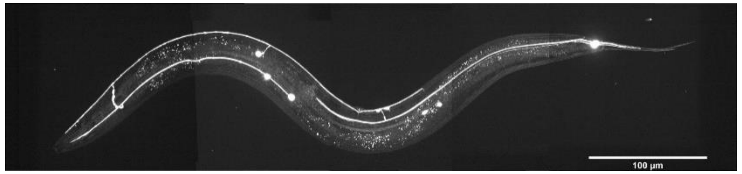
- qCMOS
- 4.6μm pixel pitch
- ~0.3 e- RON
- 5 – 25 fps

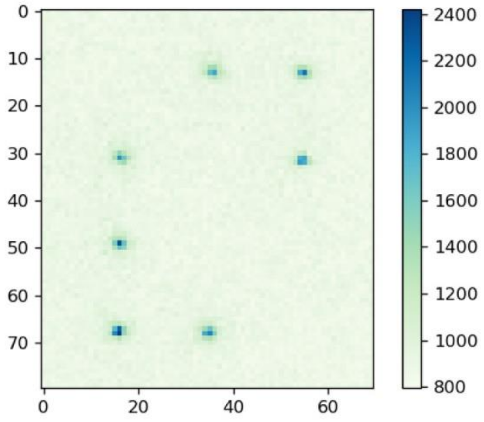
- Quanta Image Sensor
- 1.1μm pixel pitch
- 0.2 – 0.3 e- RON
- 5 – 40 fps

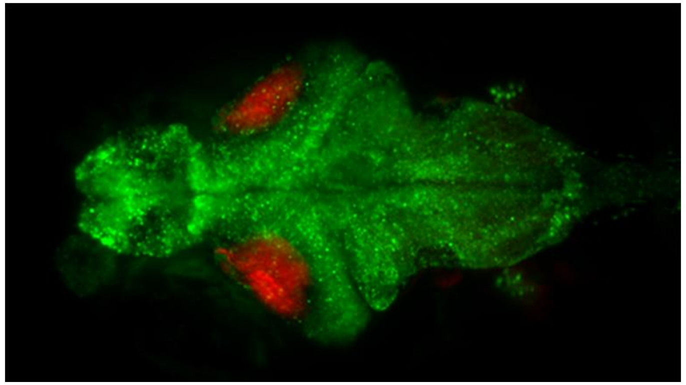
# Applications

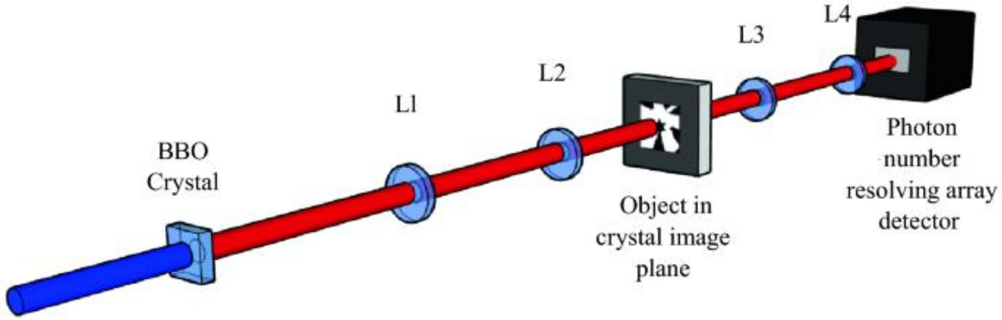
# Applications

- Low light imaging
- Quantum Imaging
- Quantum Computing



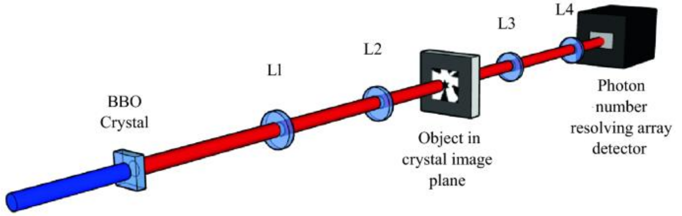





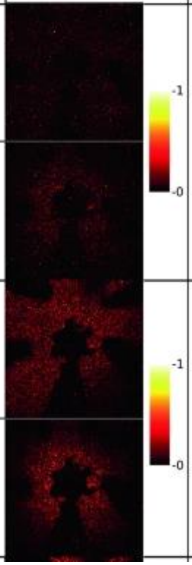
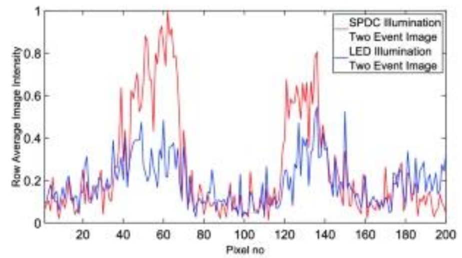
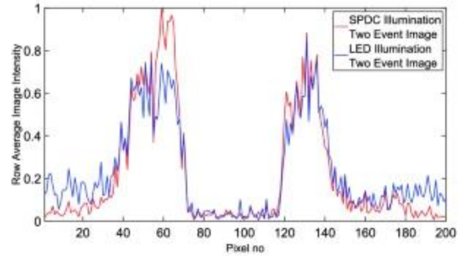
# Applications

- Quantum Imaging




qCMOS

- By detecting entangled photon pair(s):
  - Accurate measurements of quantum states

| | NEC | Events /Pixel | 2/1 Ratio | Two Photon Event Images | Image Intensity Cut Throughs |
|---|---|---|---|---|---|
| LED | 1.53 | 0.015 | 0.012 |  |  |
| SPDC | 1.73 | 0.017 | 0.020 | | |
| LED | 5.64 | 0.041 | 0.025 | |  |
| SPDC | 4.70 | 0.035 | 0.030 | | |



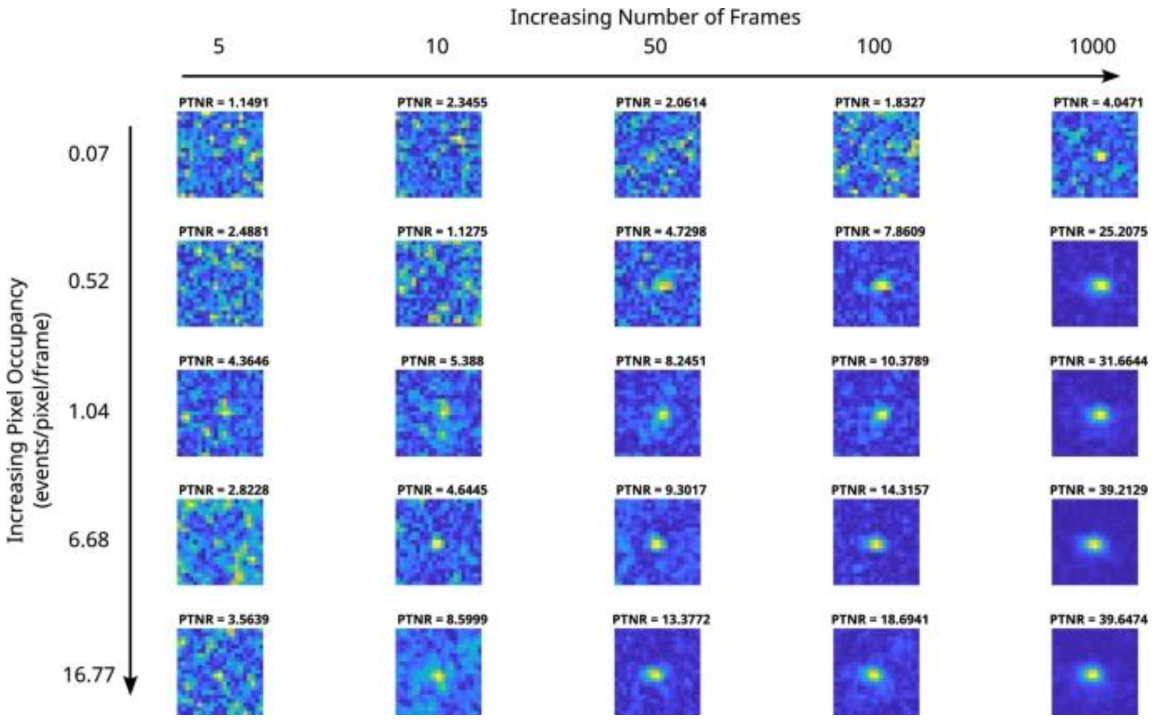
- Osian Wolley et al. "Quantum imaging with a photon counting camera." *Scientific Reports* (2022)

# Applications

- Quantum  Imaging

  - By detecting entangled photon pair(s):

    - Accurate measurements of quantum states
    - Characterization of entangled photons




Correlation Peak Array for the qCMOS camera

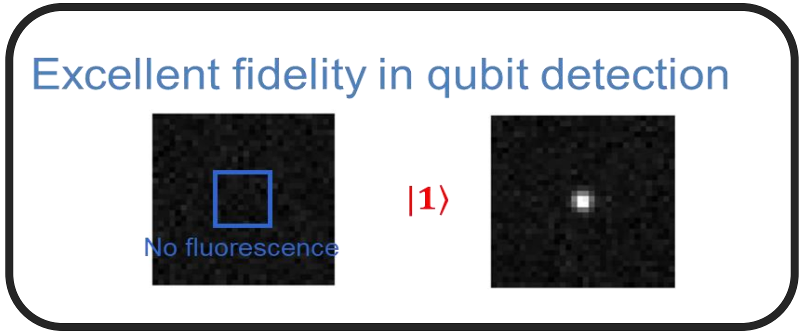
- K. Roberts et al.'' A comparison between the measurement of quantum spatial correlations using qCMOS photon-number resolving and electron multiplying CCD camera technologies'' Scientific Reports (2024)

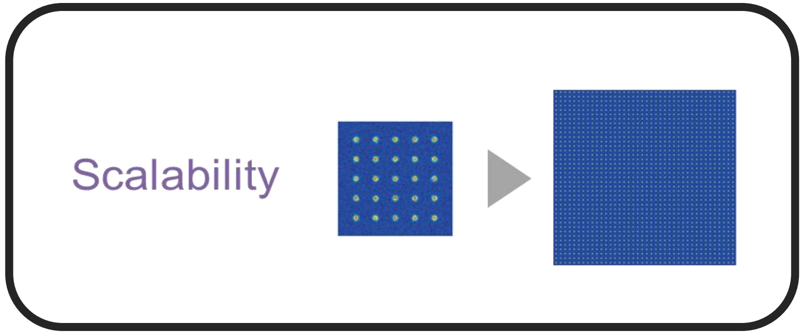
# Applications

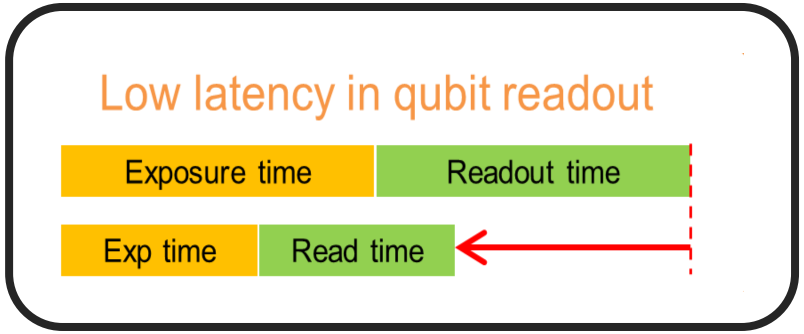
- Quantum Computing
  - Uses **quantum mechanics** principles to process information, based on fundamental units; qubits
  - Qubits leverage entanglement, superposition, interference

Applications

- Quantum Computing
  - Uses **quantum mechanics** principles to process information, based on fundamental units; qubits
  - Qubits leverage entanglement, superposition, interference
  - qCMOS helps with error rates, scalability and supports quantum gates

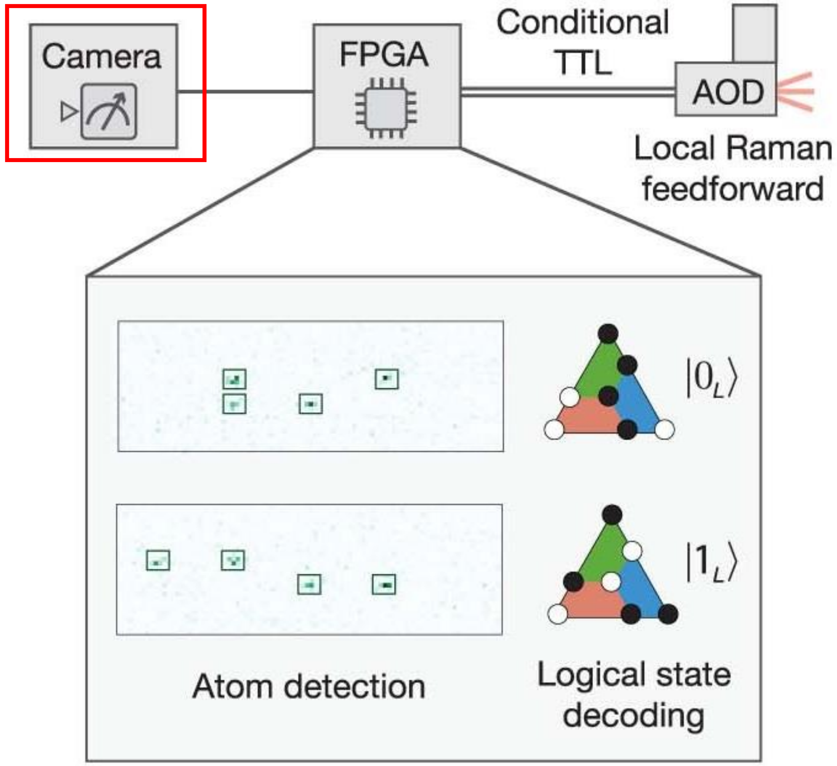


# Applications

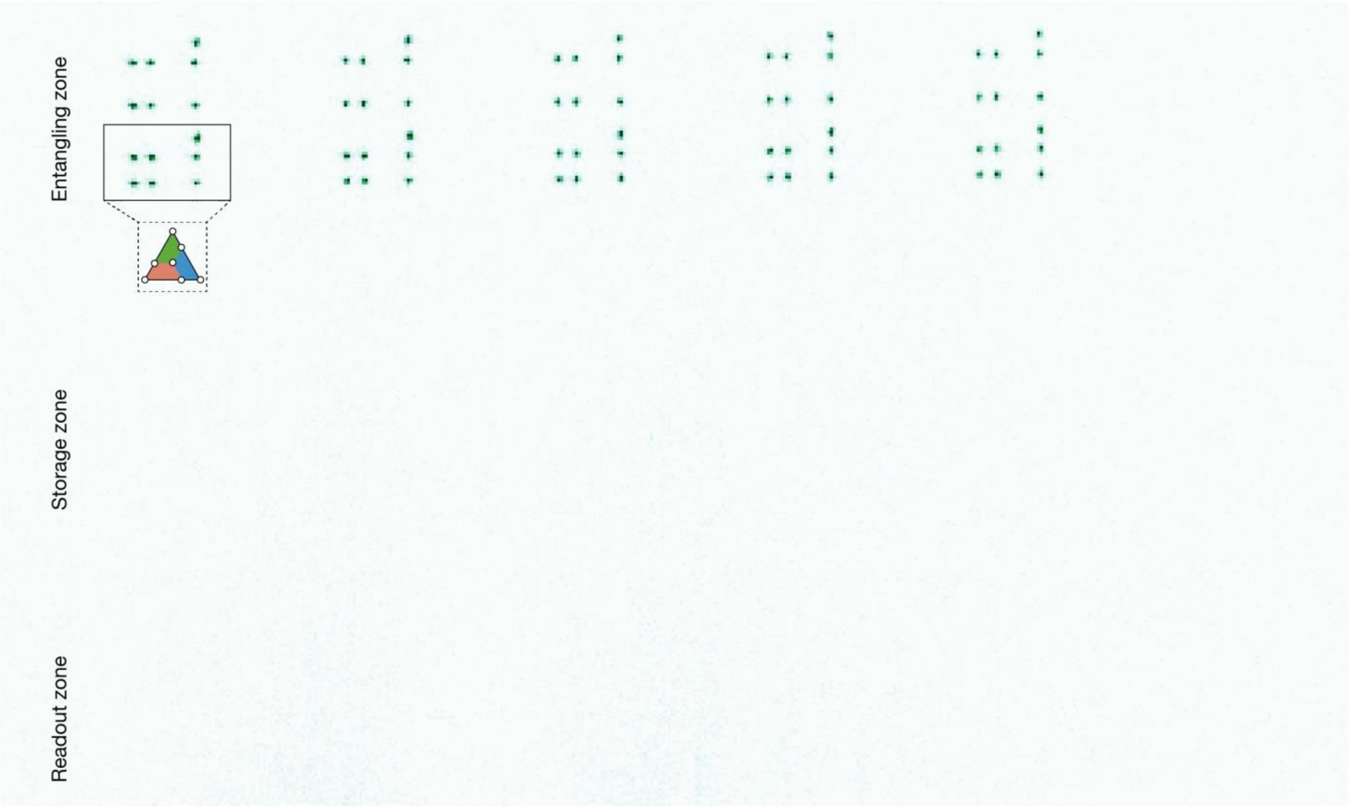
- Quantum Computing
  - Most commonly qCMOS are used for mid-circuit measurements in quantum controls




Bluvstein, D., Evered, S.J., Geim, A.A. et al. Logical quantum processor based on reconfigurable atom arrays. Nature 626, 58–65 (2024)

# Applications

- Quantum Computing
  - Most commonly qCMOS are used for mid-circuit measurements in quantum controls



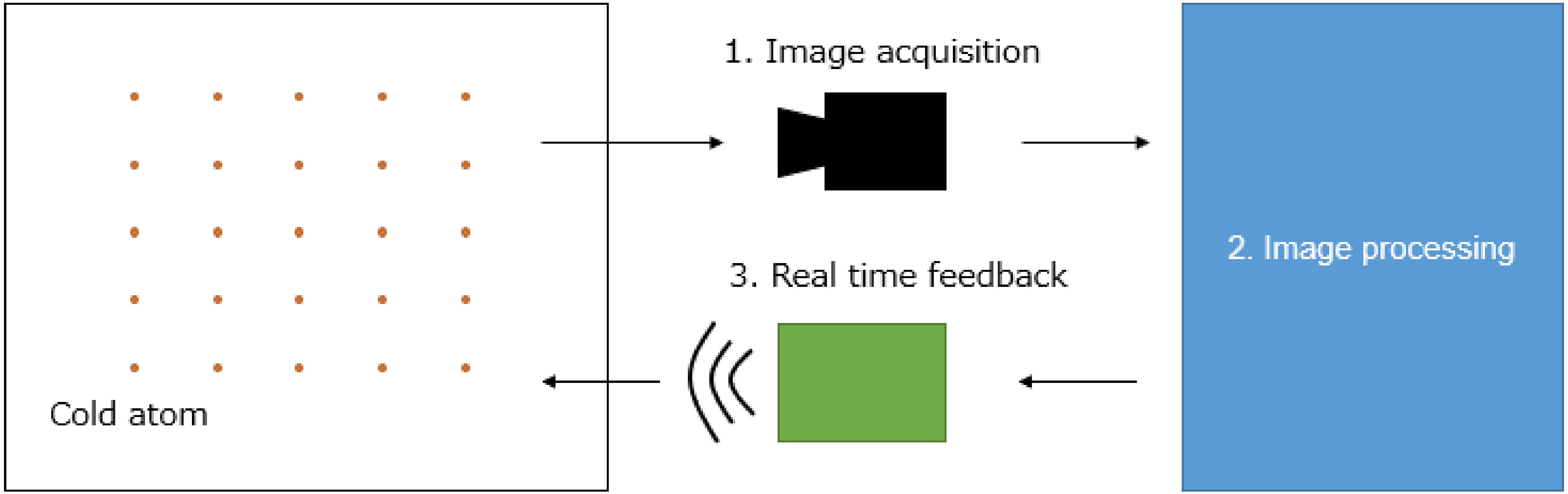

Bluvstein, D., Evered, S.J., Geim, A.A. et al. Logical quantum processor based on reconfigurable atom arrays. Nature 626, 58–65 (2024)

# Quantum Computing

- Most commonly qCMOS are used for mid-circuit measurements in quantum controls

QUANTUM MACHINES

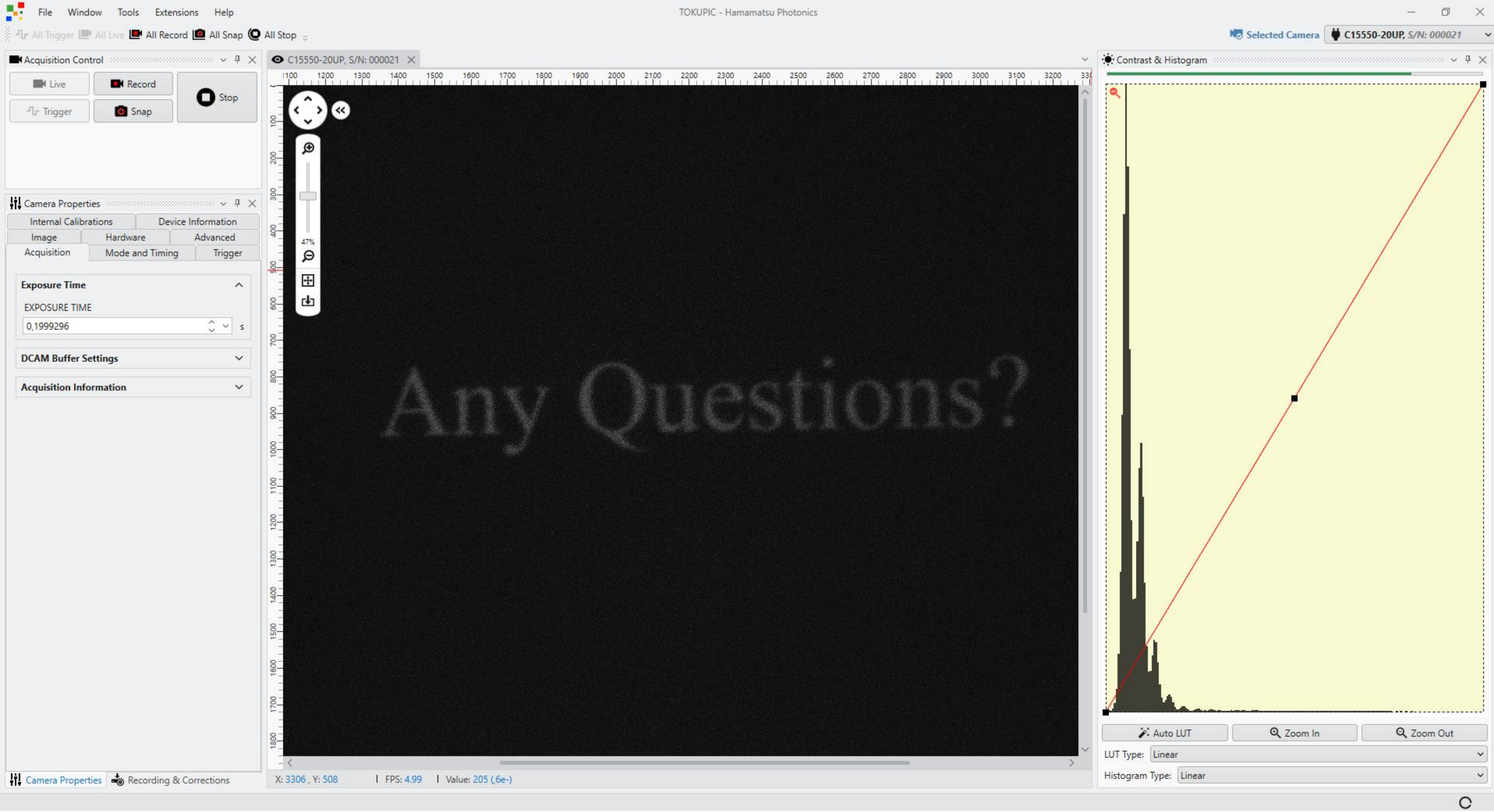
QPU



# Conclusion

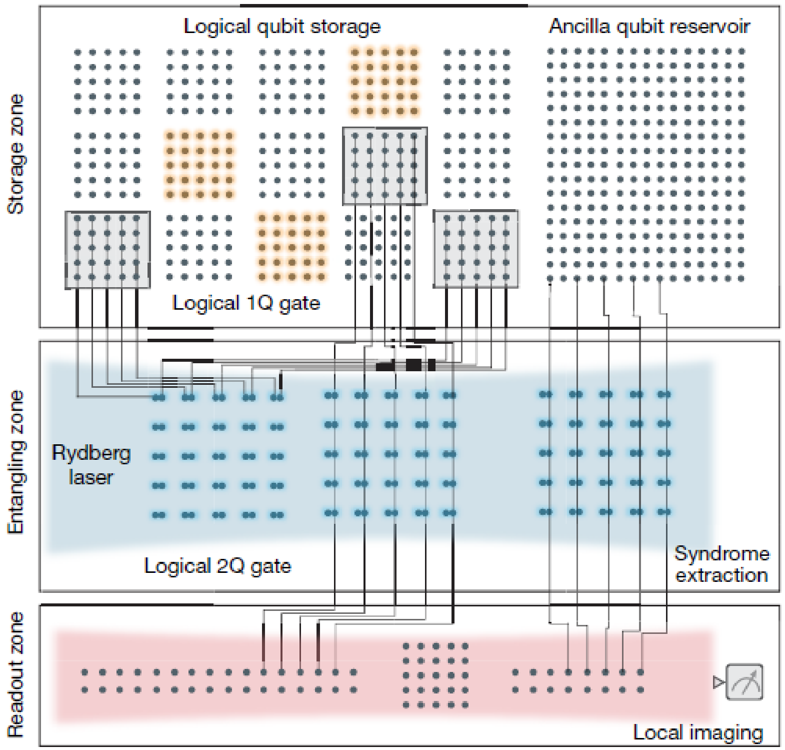
- PNR sensors available below 0.3 e- RON
- 3 major implementations exist, only one commercial
- Applications mostly in scientific low light applications and quantum systems

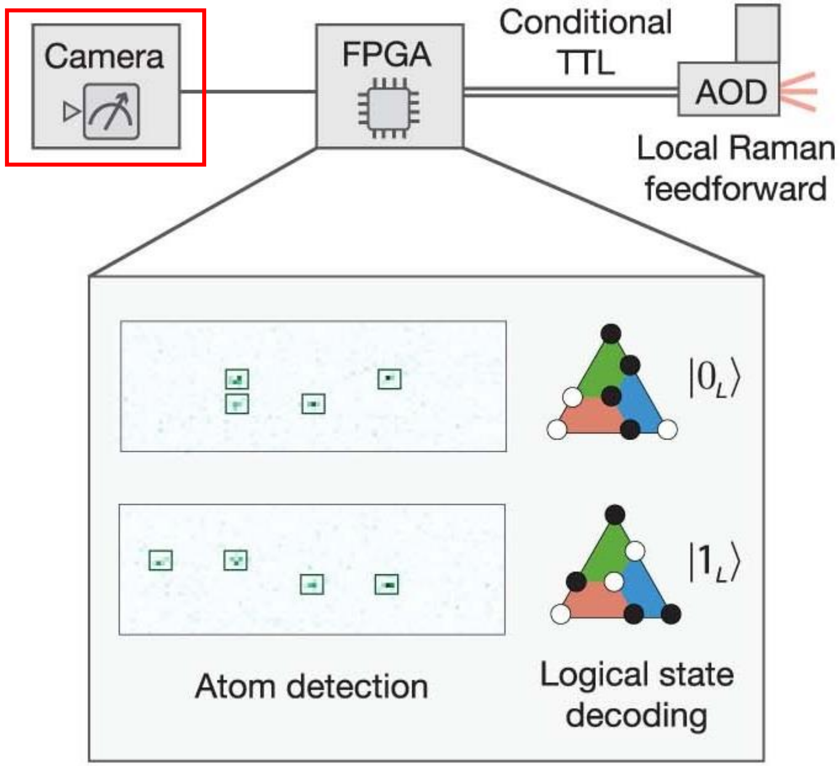
| | Skipper CCD | qCMOS | QIS |
|---|---|---|---|
| Max QE | ? | 85% | 76% |
| Speed | fpd | fps | fps |
| Dark current | Very low | low | low |
| Pixel count | + | ++ | +++ |
| Pixel pitch | 15 | 4.6 | 1.1 |


File
Window
Tools
Extensions
Help
TOKUPIC - Hamamatsu Photonics
All Trigger
All Live
All Record
All Snap
All Stop
Selected Camera
C15550-20UP, S/N: 000021
Acquisition Control
Live
Record
Stop
Trigger
Snap
Camera Properties
Internal Calibrations
Device Information
Image
Hardware
Advanced
Acquisition
Mode and Timing
Trigger
Exposure Time
EXPOSURE TIME
0,1999296
s
DCAM Buffer Settings
Acquisition Information
C15550-20UP, S/N: 000021
Any Questions?
47%
X: 3306 , Y: 508
FPS: 4.99
Value: 205 (,6e-)
Camera Properties
Recording & Corrections
Contrast & Histogram
Auto LUT
Zoom In
Zoom Out
LUT Type:
Linear
Histogram Type:
Linear

# Applications

- Quantum Computing
  - Most commonly qCMOS are used for mid-circuit measurements in quantum controls




Bluvstein, D., Evered, S.J., Geim, A.A. et al. Logical quantum processor based on reconfigurable atom arrays. Nature 626, 58–65 (2024)

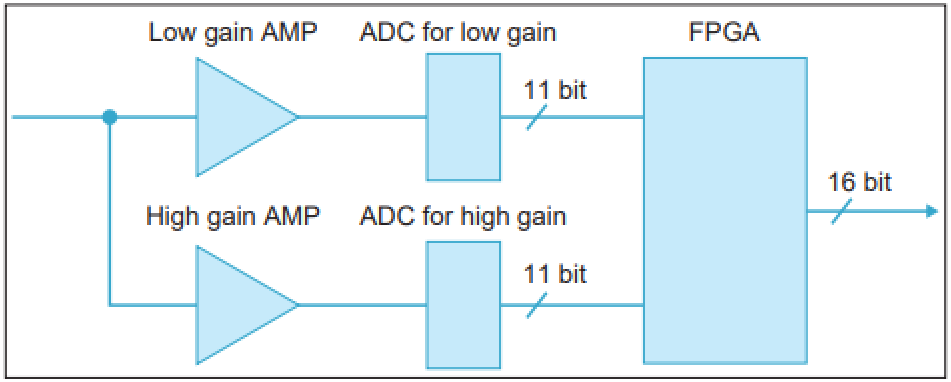


Fig. 2-8. Digitization structure

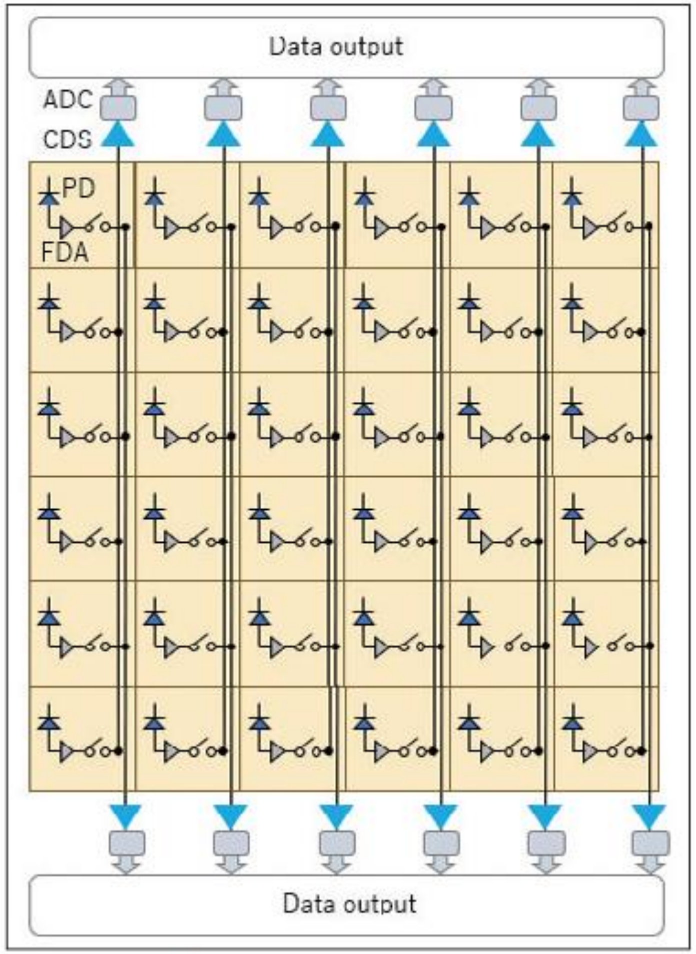
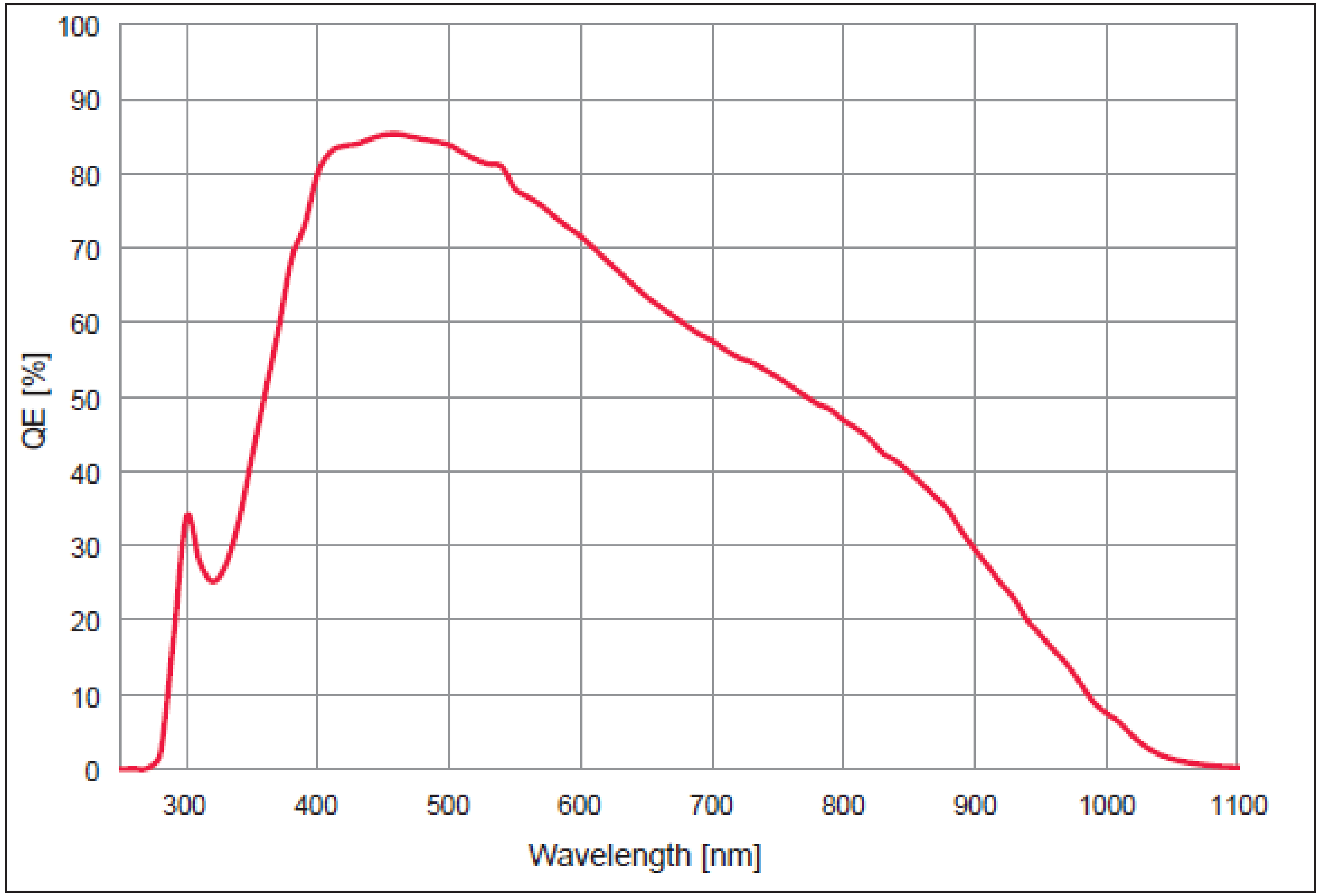


Fig. 2-1. Sensor structure

# QE


100
90
80
70
60
50
40
30
20
10
0
QE [%]
300
400
500
600
700
800
900
1000
1100
Wavelength [nm]

www.hamamatsu.com