CENTER FOR
SENSORS & DEVICES

FONDAZIONE
BRUNO KESSLER

EPIC
European Photonics
Industry Consortium

EPIC Meeting on Photonics at the Final Frontier at European Space Agency (ESA)
Noordwijk, The Netherlands

CMOS SPAD Technology for Space LiDAR Systems

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CMOS SPAD Technology for Space LiDAR Systems

Outline

- Introduction to Fondazione Bruno Kessler (FBK)
- CMOS SPAD Arrays for Flash LiDAR in Space
- Current prototype: 64×64-pixel Flash LiDAR sensor
- Future perspectives and challenges

Fondazione Bruno Kessler (FBK)
About us

PROFILE

FBK is a research not-for-profit public interest entity result of a history that is more than half a century old.

MISSION

FBK aims to excellence in science and technology with particular emphasis on interdisciplinary approaches and to the applicative dimension.

- **11 research centers**
- **410 researchers**
- **2 specialized libraries**
- **7 laboratories**

Fondazione Bruno Kessler (FBK)
Center for Sensors & Devices

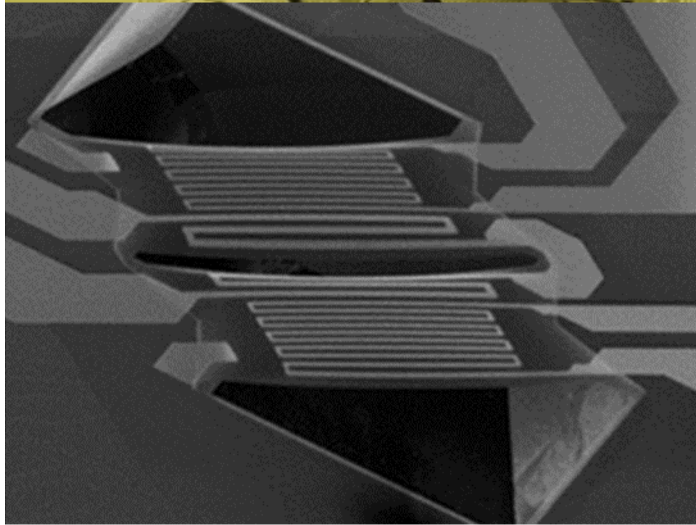
PROFILE

The Center focuses on the development of **highly integrated sensors and devices** based on **MEMS, CMOS, photonics and surface functionalization techniques and interfaces.**

VALUE PROPOSITION

We cover the entire development cycle, from feasibility studies & architecture definition, design, testing & characterization, prototyping and setup of a supply chain with wafer-level tests.

Fondazione Bruno Kessler (FBK)
Sensors & Devices for Space



FBK technology

Radiation Detectors (SDD, microstrip & pixel, SiPM, LGAD, …)
MEMS – RF (flow sensors, hydrogen peroxide microthrusters, …)
Silicon Photonics (Integrated optical circuit for microwave filter)

CMOS technology

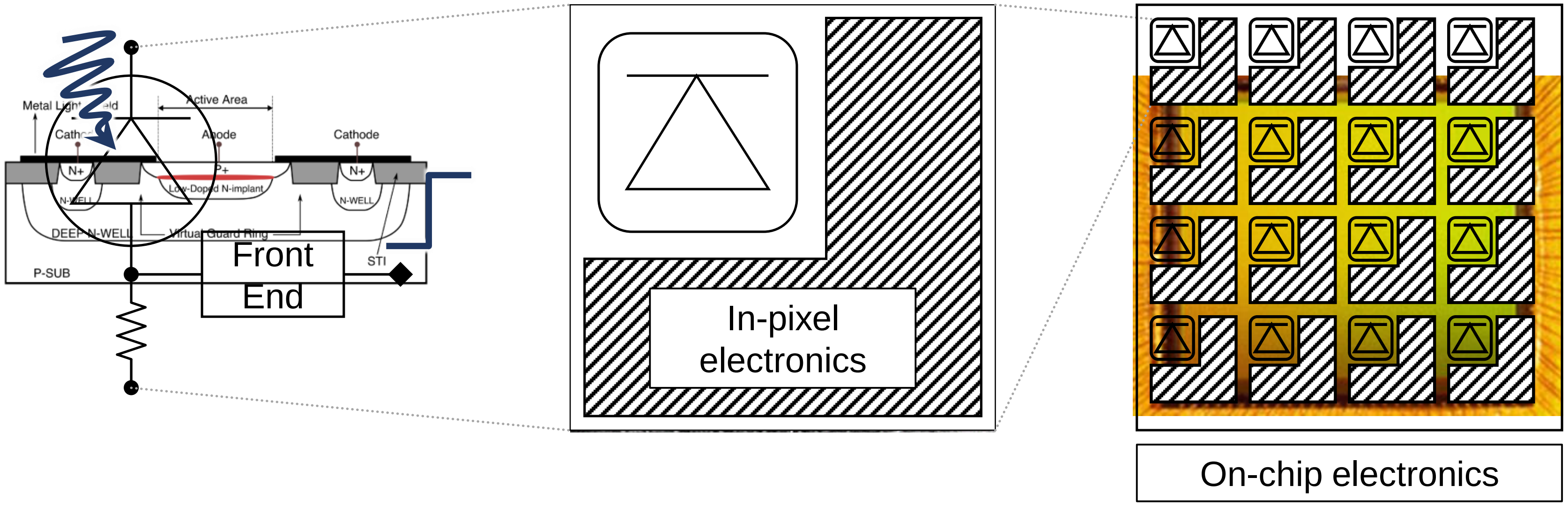
Vision sensors
Monolithic active pixel sensors
Quantum random number generators
Single-photon imagers (incl. LiDAR sensors)

CMOS SPAD Arrays for Flash LiDAR in Space

Single Photon Avalanche Diodes in CMOS

- Diode biased beyond breakdown → photon triggers an avalanche
- Direct photon to digital-edge conversion
- In-pixel / on-chip processing of the signal
  - e.g., counting, timestamping, event detection, correlation
- Imaging configuration

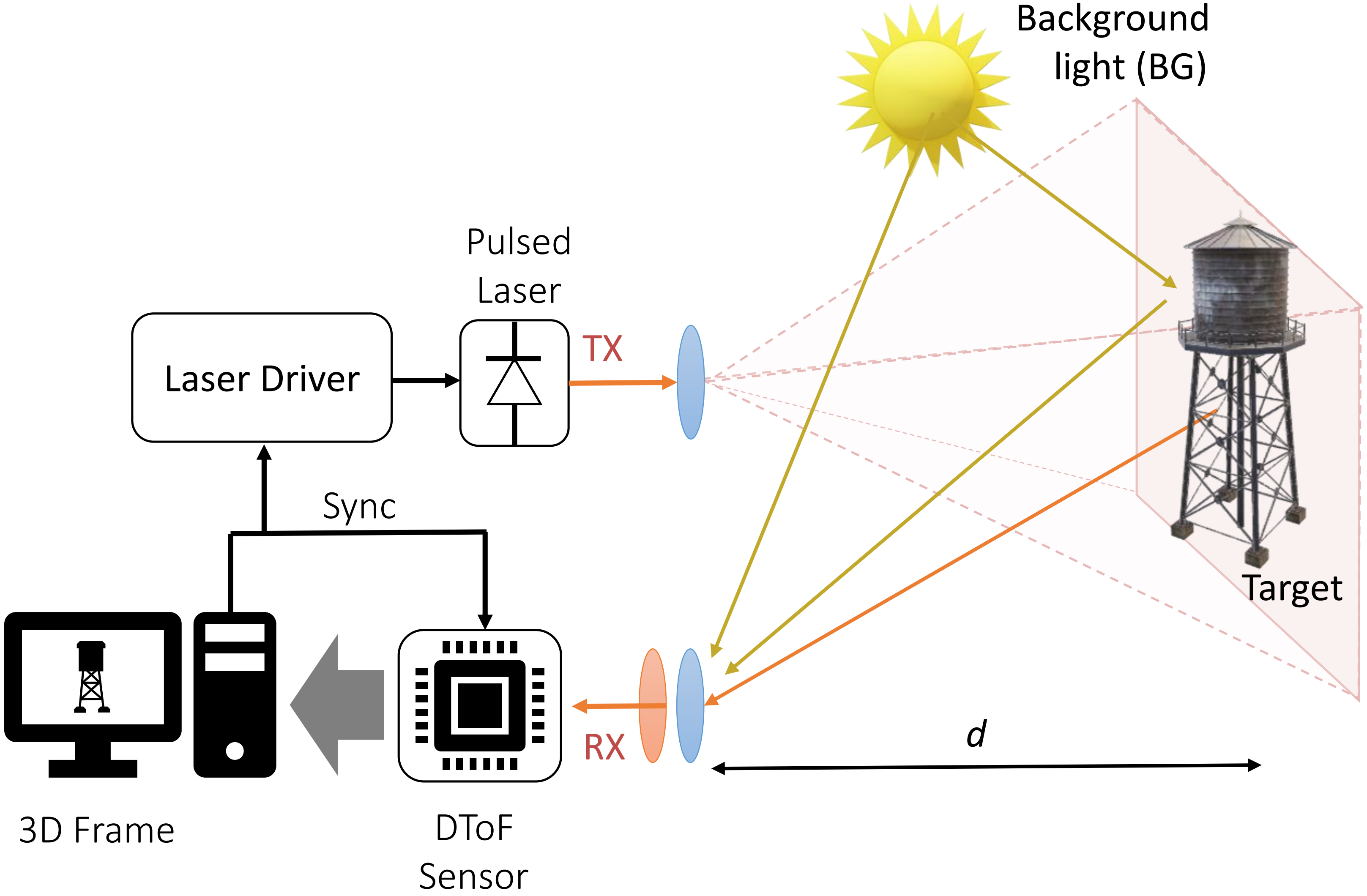
SPAD | Pixel | Imager



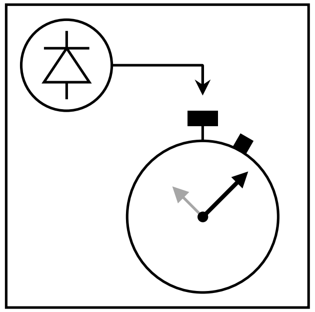
5-30µm | 7-100µm | 1k – 1M+ pix

CMOS SPAD Arrays for Flash LiDAR in Space

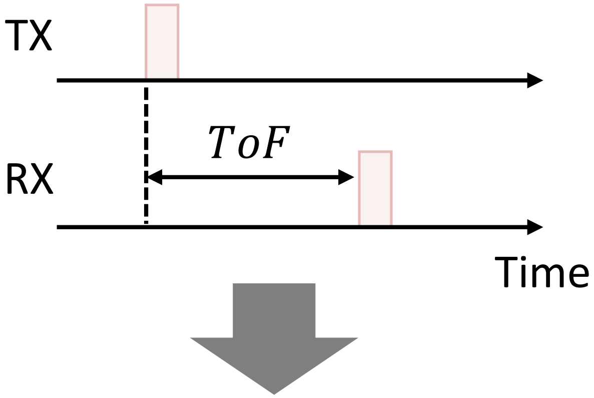
Application to LiDAR – Direct Time-of-Flight (DToF)



Photon timestamping
(integrated on-chip or in-pixel)



$T_{ph} = n \times \sim 100\ ps$



$$d = c \cdot \frac{ToF}{2}$$

CMOS SPAD Arrays for Flash LiDAR in Space

Challenges in image sensor technology

- Imaging technology → **Pixel size and power matters**
  - The smaller, the better → High resolution images
  - Typical values:
    - Pixel pitch: 60 µm → 7 µm
    - Pixel power: 50 µW → 3 µW

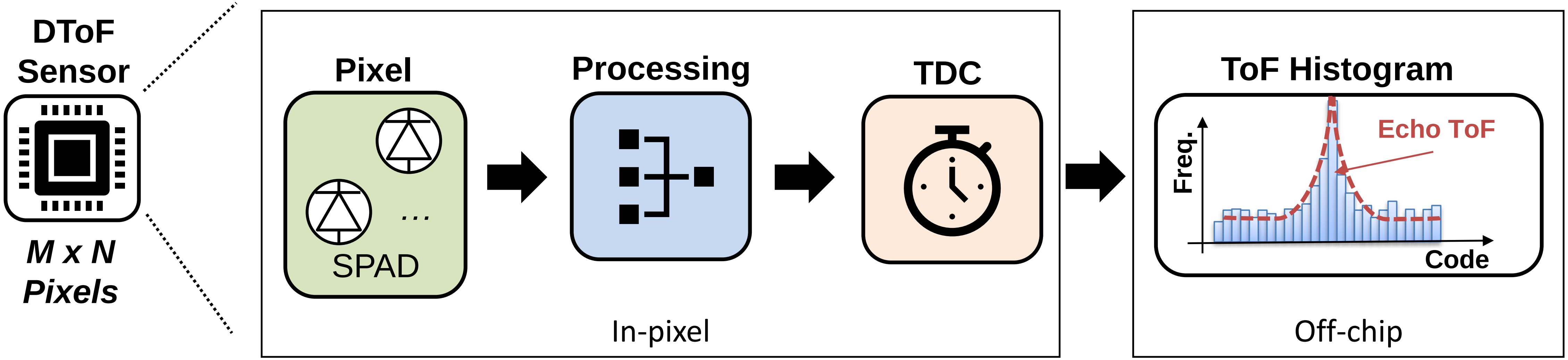
⇨ Depending on the level of in-pixel integration and technology node (typ. 40 nm – 180 nm)

- **Flash** → Flood illumination
  - No scanning → no moving parts, simple control
  - Parallel acquisition → no distortions, high data rate, high memory requirements

- **Background light rejection**
  - False events → depth estimation from multiple acquisitions (histograms)
  - Detector saturation (at SPAD, pixel, or chip level!) ← **TO BE AVOIDED**!

CMOS SPAD Arrays Flash LiDAR in Space

DToF acquisition process



- **Key blocks:**
  - Single Photon Avalanche Diode (SPAD)
  - Processing Unit → **Dark count & Background** noise suppression
  - Timestamping through Time to Digital Converters (TDC)

CMOS SPAD Arrays Flash LiDAR in Space

FBK technology over the years – Funding

csem

FONDAZIONE BRUNO KESSLER SENSORS AND DEVICES

MILS

Miniaturized Flash Imaging Lidar for Space Robotic

Evaluation of CMOS SPAD technology for space LiDAR

MILA

Miniaturized Imaging Laser Altimeter

1st generation of Flash LiDAR imager based on CMOS SPAD technology

WALLIE

Wide range high-resolution LiDAR Imager

2nd generation of Flash LiDAR imager based on CMOS SPAD technology

CMOS SPAD Arrays Flash LiDAR in Space

FBK technology over the years – Results

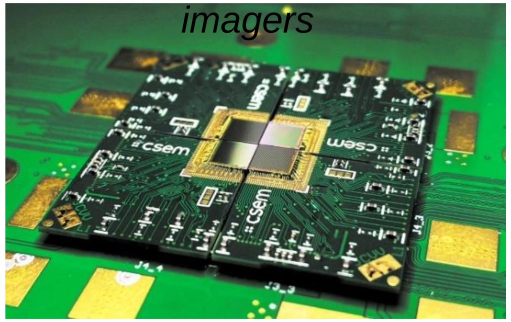
MILA

Miniaturized Imaging Laser Altimeter

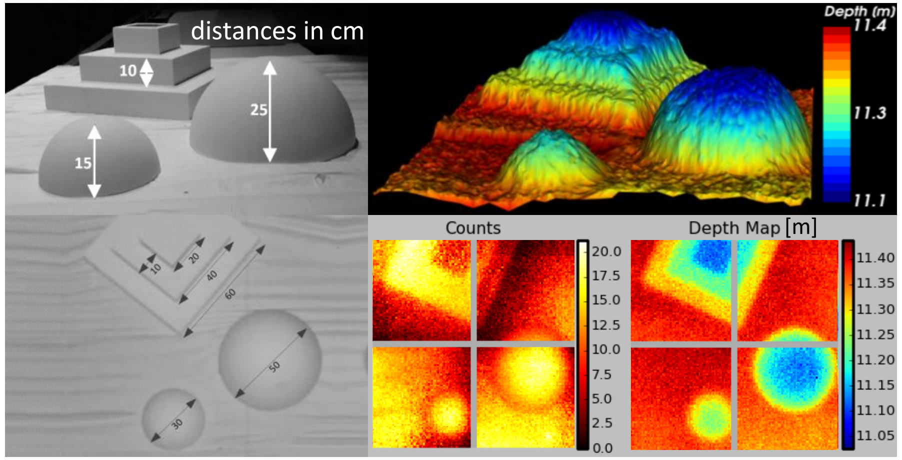
1st generation of Flash LiDAR imager based on CMOS SPAD technology

csem

CSEM sensor board based on 2x2 MILA imagers

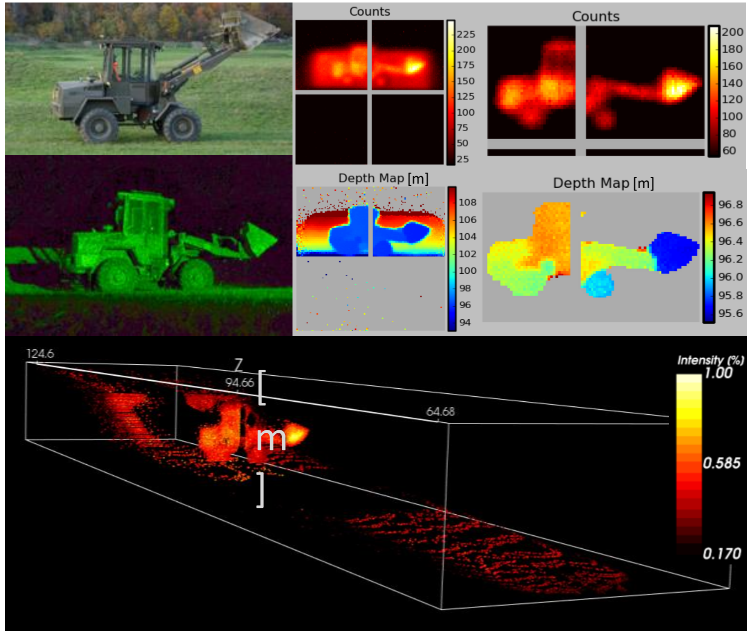


Short distance measurements



CSEM LiDAR system

Long distance measurements



CMOS SPAD Arrays Flash LiDAR in Space

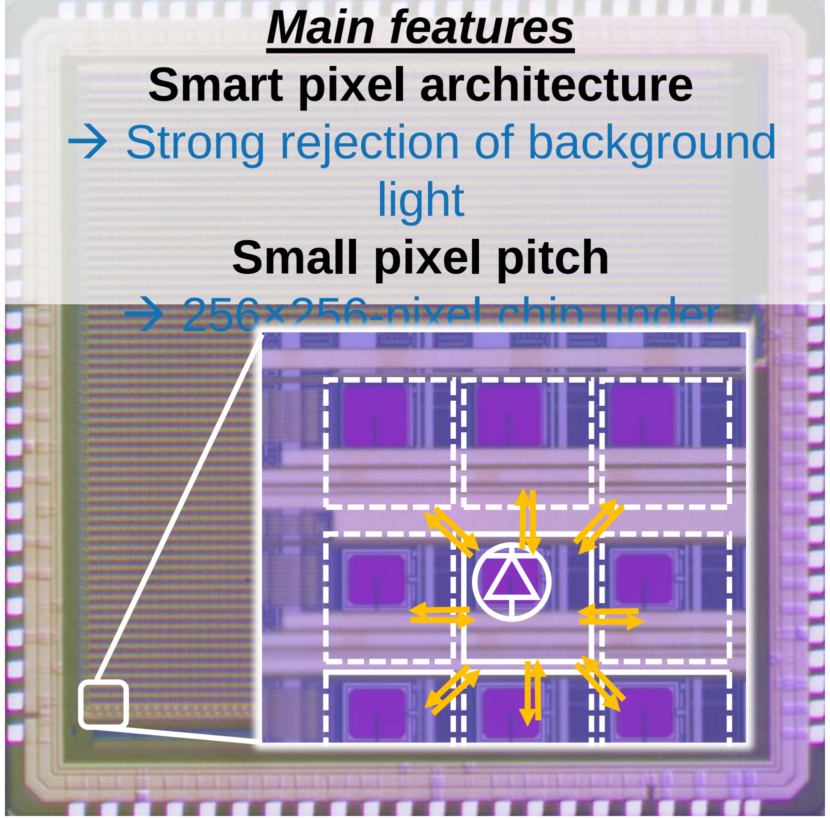
FBK technology over the years – Results

WALLIE

Wide range high-resolution LiDAR Imager

2nd generation of Flash LiDAR imager based on CMOS SPAD technology

Specifically designed to acquire **depth maps** of the scene over **long distances** even in presence of **strong background light.**



Main features

Smart pixel architecture

→ Strong rejection of background light

Small pixel pitch

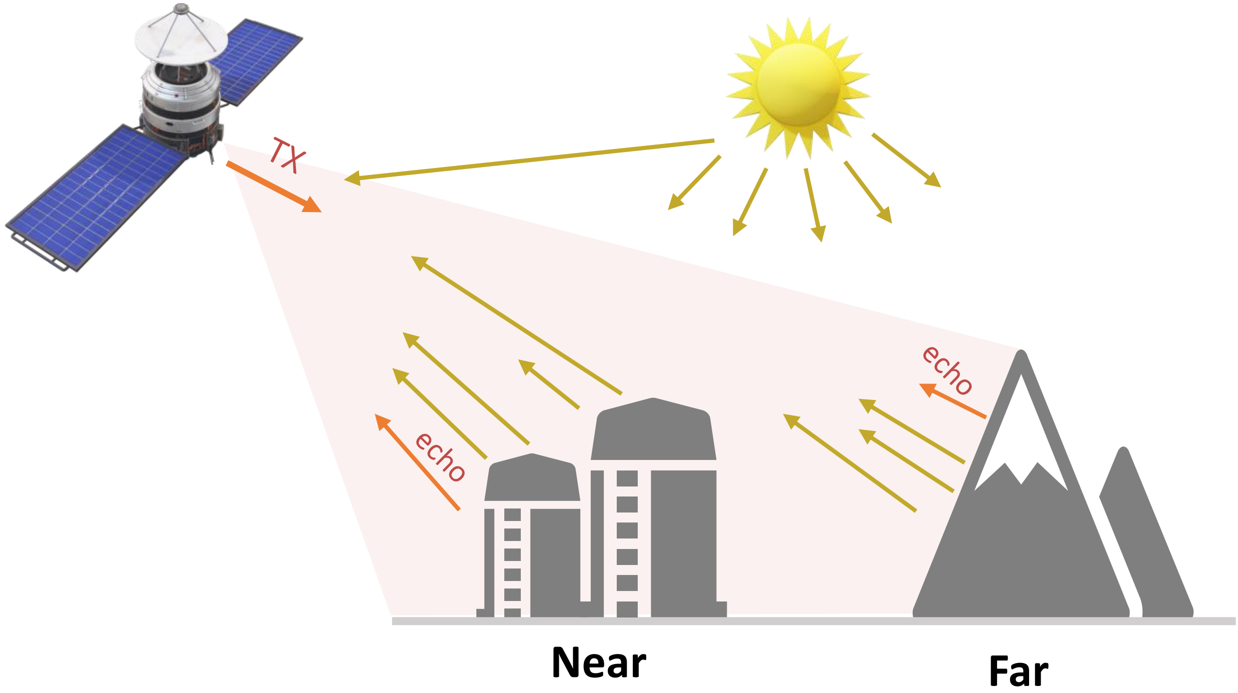
→ 256×256-pixel chip under

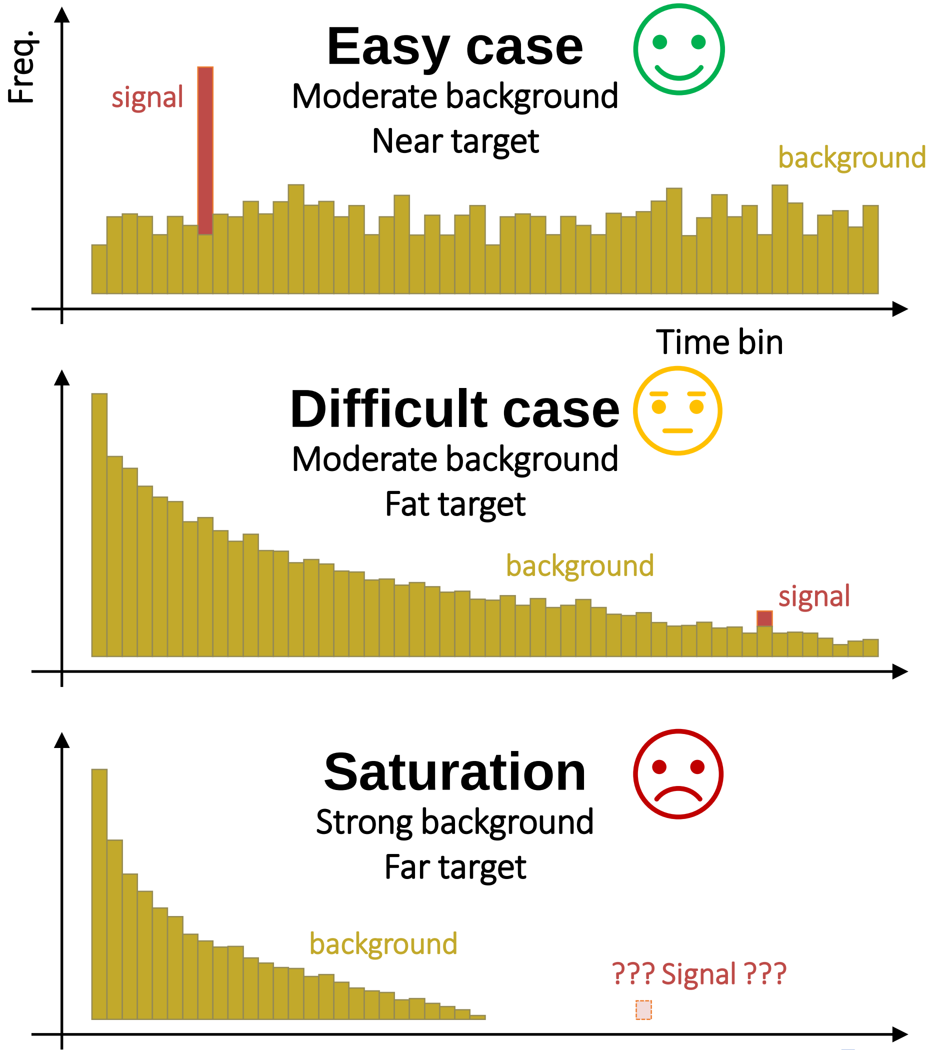
Based on FBK patented

csem

Current prototype: 64×64-pixel Flash LiDAR sensor

In-pixel background rejection

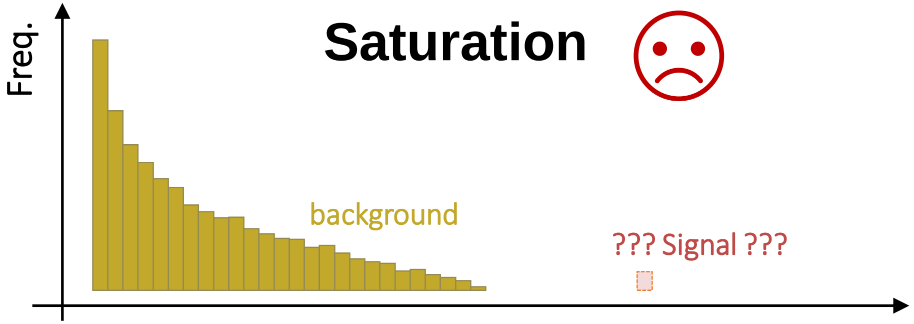




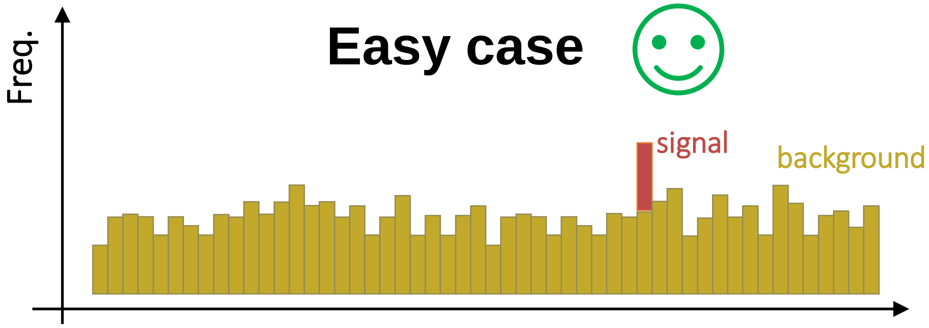
Goal: develop an architecture that **avoids saturation** and **turns difficult cases into easy cases.**

Current prototype: 64×64-pixel Flash LiDAR sensor

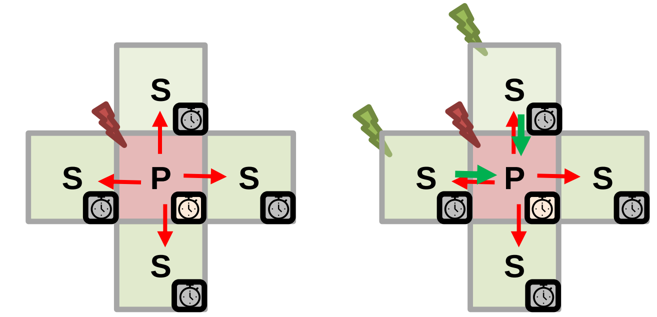
Smart pixel architecture



CMOS → In-pixel smart features



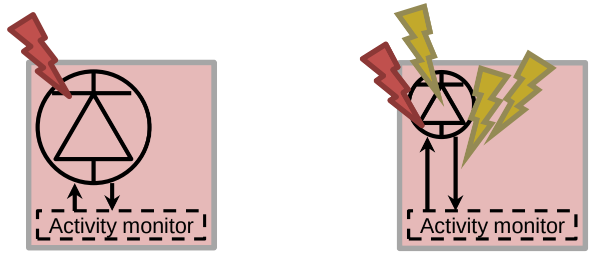
- Distributed correlation mechanism
    - Patented technology



Uncorrelated photon → Discarded

Correlated photons → Recorded

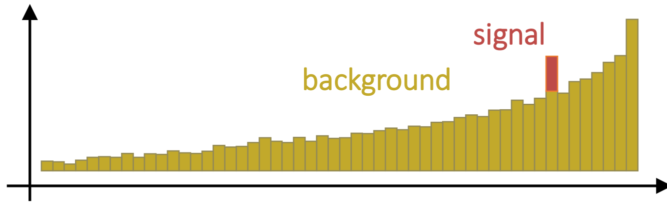
- Automatic sensitivity adjustment



Weak background
→ PDP enhancement
High sensitivity

Strong background
→ PDP reduction
Low sensitivity

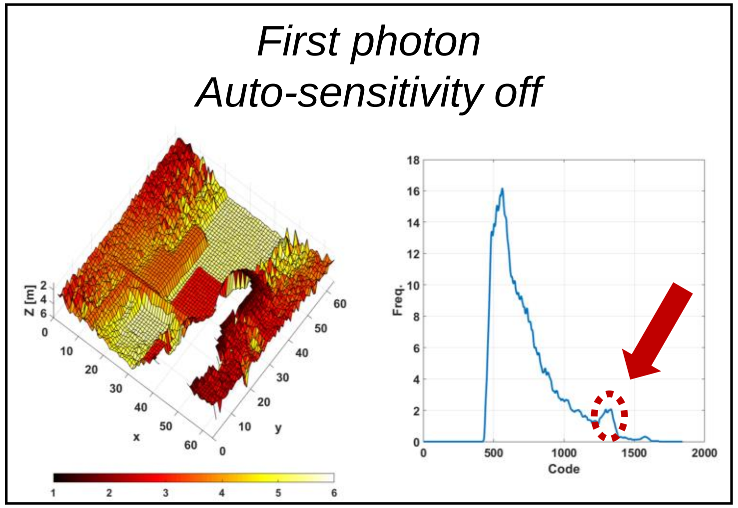
- Multi-photon and last-photon acquisition

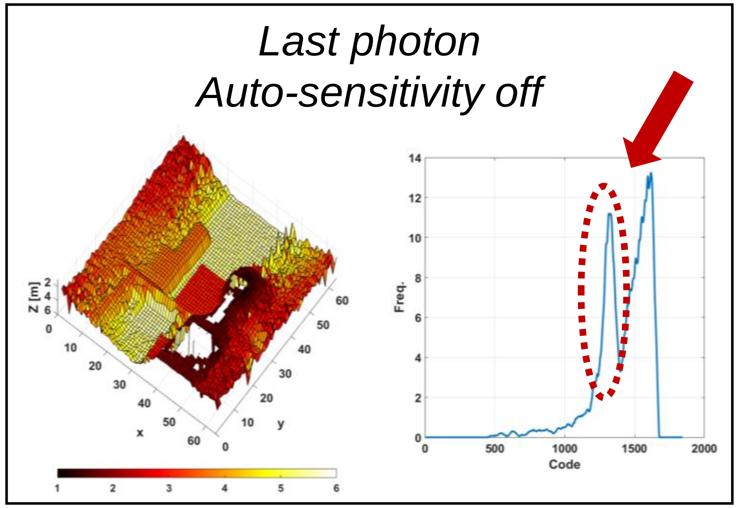


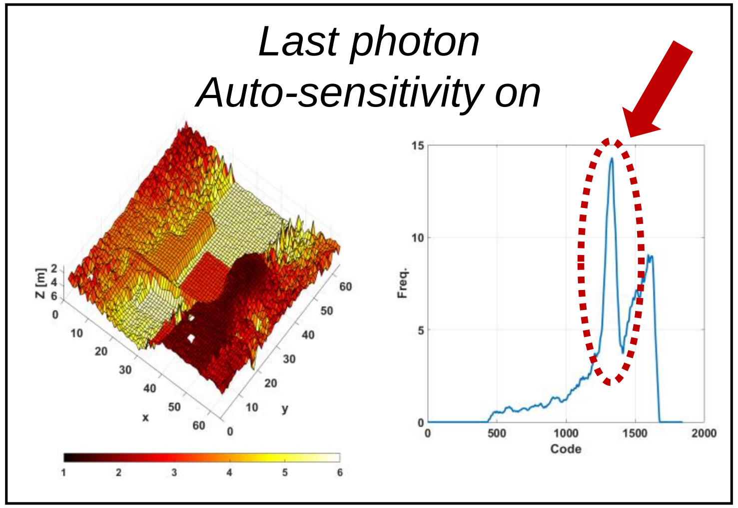
Current prototype: 64×64-pixel Flash LiDAR sensor

Sample images – Indoor & outdoor (based on a low-cost system)

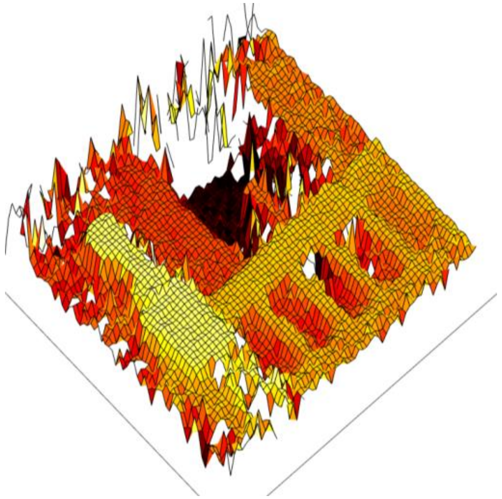
Correlation always on


First photon
Auto-sensitivity off


Last photon
Auto-sensitivity off


Last photon
Auto-sensitivity on

Main sensor parameters		
Parameter	Unit	Value
Technology	nm	110
Pixel Array	pixel	64x64
Pixel Pitch	µm	48
Fill-factor	%	12.9
PDP @ V_{ex}	%	54.5 @ 6.6 V
Median DCR	Hz	388@6.6 V
Timestamping resolution	ps	250 – 10.000
Measurement range	m	1536-12288



3D imaging performance		
Parameter	Unit	Value
Wavelength	nm	905
Avg optical power	mW	5.8-9.3
FoV	deg	25.0x25.0
Max measured distance	m	8.2
Accuracy	m	±0.15
Precision(σ)	m	0.03…0.27
Frame rate	Hz	25
Power consumption	mW	205.7

Future perspectives and challenges

ESA project → Increase the TRL

esa Contract No. 4000126705/19/NL/AR/zk

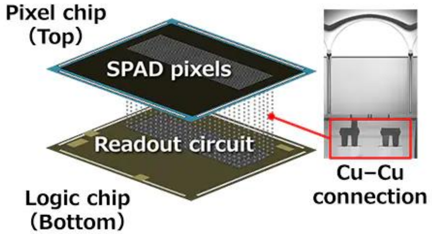
- Fabrication of a large area prototype
- Radiation tests
- Integration into a complete LiDAR system
- Validation over large distances

Future perspectives and challenges

Challenges

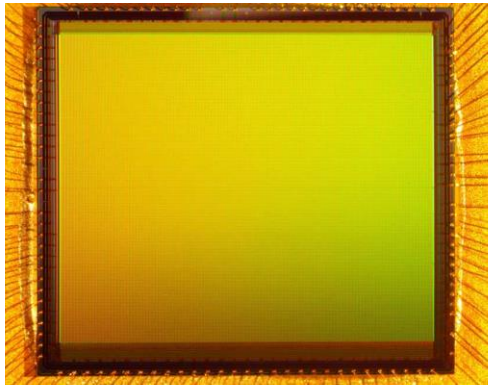
3D stacking with FBK SPADs & advanced CMOS processing

Optimized sensing + optimized readout



[Sony, news 2021]

- Higher sensitivity + smaller pixels
- Microlenses
- Higher level of integration (processing layer in 40 nm tech. node or below)



Pairing sensors with AI processors

Reduced memory requirements
More efficient processing

[Opal Kelly 2021]

- Accurate statistical models of the photon flux
- Development of AI models for the processing in real time of the timestamps
- Integration into FPGAs or custom processors

Thank you

The work is carried out under a program funded by the **European Space Agency**.
We thankfully acknowledge the **Sensing & Control group at CSEM** for the fruitful discussions.

IRIS unit – Intregrated Readout ASICs and Image Sensors

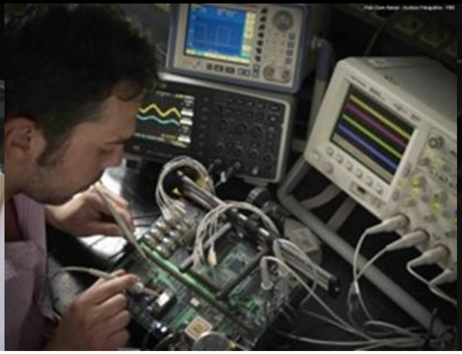
Mission and value proposition

Fully customized design of image sensors & readout ASICS in CMOS standard technology

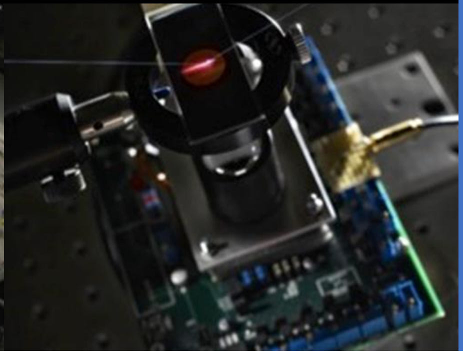
Our mission is to leverage the potential of image sensors and the level of integration of radiation detectors with highly optimized electronic design in CMOS standard technology. We cover the entire set of development stages, including feasibility studies & architecture definition, mixed-signal IC design, electro-optical testing & characterization, FPGA / microcontroller-based prototyping and setup of a supply chain with wafer-level tests.

Architecture Definition & Mixed Signal IC Design

Manufacturing in 350nm-40nm CMOS Std



Electro-optical Testing & Characterization



Prototyping & Setup of a Supply Chain

8
researchers

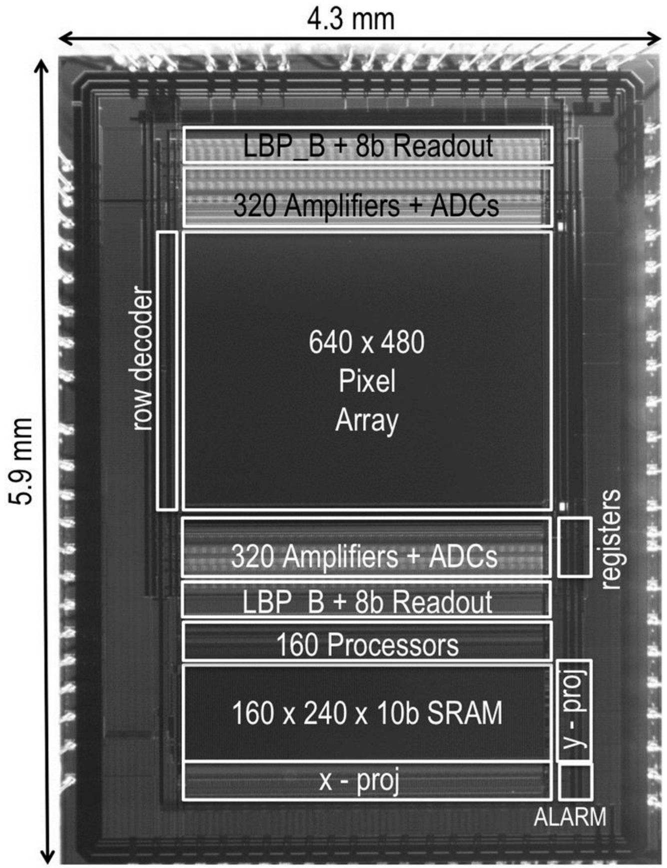
1
PhD student

1
Technician

Laboratories for functional verification, electro-optical testing & characterization.

IRIS – Intregrated Readout ASICs and Image Sensors

Research lines



Example of a low-power vision sensor for battery-operated surveillance systems.

Single-photon Imagers

They combine single-photon detectors and high-speed electronics to count photons and measure their arrival time in parallel for each pixel.

Low-Power Vision Sensors

They gather extra information from the scene at chip- or pixel-level to perform complex tasks using a small amount of power.

Monolithic Active Pixel Sensors

MAPS exploit the interaction of charged particles with matter to measure their energy, position and direction with a low energy budget.

Multispectral, X-ray and THz

They add the wavelength as another variable capable of increasing the information carried by an image, to see things our eye cannot see.

Readout ASICs

They extract the useful signal from custom detectors (SiPM, SDD, strip detectors, 3D SiPM, …), minimizing noise and distortions.

IRIS – Intregrated Readout ASICs and Image Sensors

Technology - Application matrix

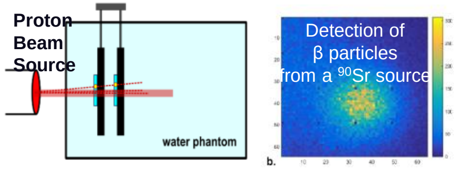
	Quantum S&T	Space S&T	Science	Bio-/Medical Food, Health	Security	Industrial / Automotive	Consumer / IoT
Single-Photon imagers	Quantum & ghost QRNG Quantum comm.	[1] **Solid-state LiDAR** Scientific imaging HDR imaging	Time-resolved img Quanta imaging	FLIM, PET, hadron therapy Raman, SPECT, …		LiDAR/d-ToF	3D imaging Depth sensing 2D imaging
Low-Power Vision Sensors		Star-tracker			[3] **Low-power video-surveillance**	High-speed vision	AI-enhanced imaging, HDR
Multispectral, X-ray and THz			Multi-spectral (THz) imaging	X-ray imaging for dental appl.	THz / MIR sensing	[4] **Quality control with THz**	
MAPS			Particle tracking for HEP	[2] **Particle tracking for hadron therapy**			
Readout ASICs	Readout ASICs for quantum detectors & photonic circuits	Readout ASICs for SiPM, SDD, InGaAs	Readout ASICs for SiPM, SDD, InGaAs	Air quality monitoring		Self-mixing interferometry	Self-mixing interferometry

TRL LEVEL

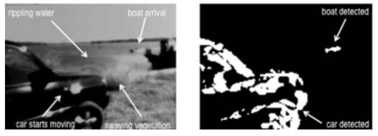
Examples

[1] **Solid-State LiDAR**
Direct Time-of-Flight depth sensing based on single-photon detectors

[2] **Particle tracking for hadron therapy**
Direct detection of charged particles with a low material budget

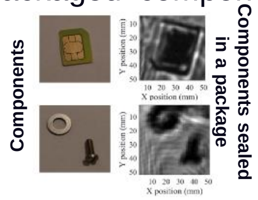


[3] **Low-power video-surveillance**
Surveillance of large areas with battery operated devices



Smart motion detection insensitive to standard background variations (sea waves, trees moving)

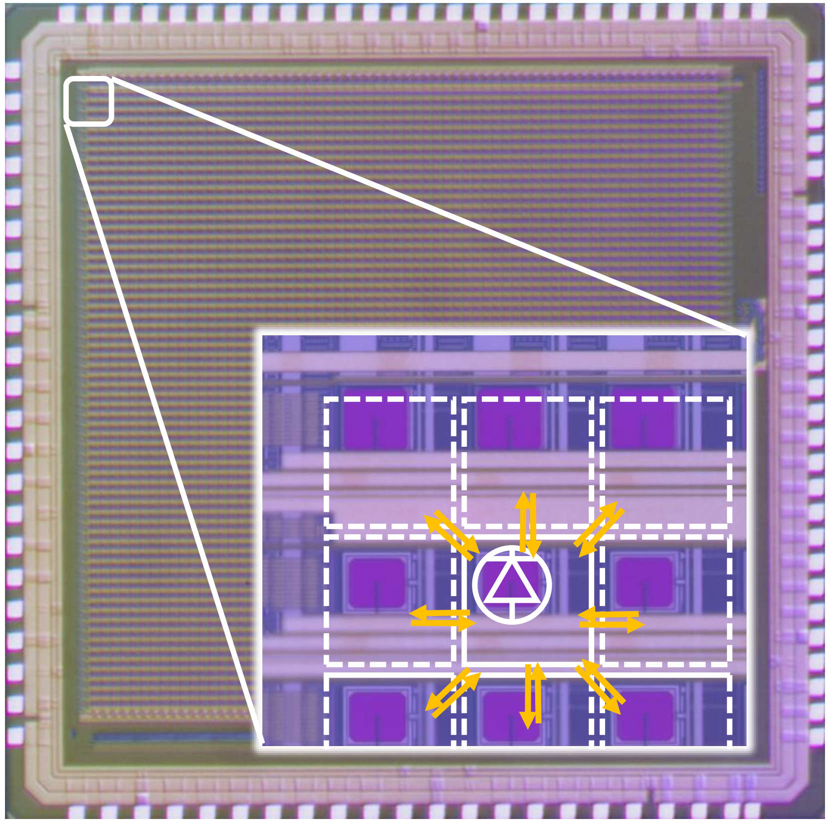
[4] **Quality control with THz**
Multi-spectral analysis of packaged components



Current prototype: 64×64-pixel Flash LiDAR sensor

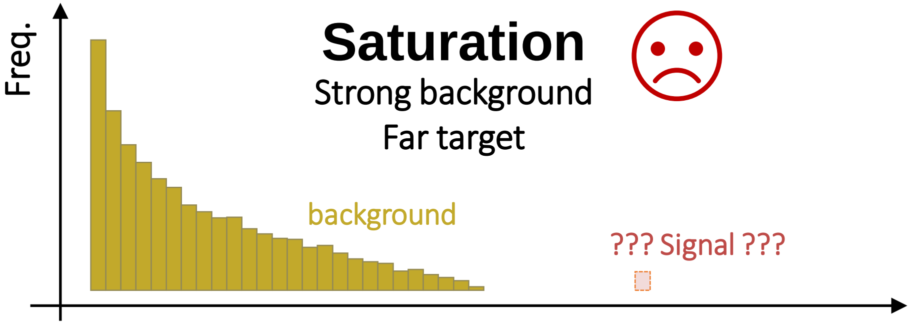
DToF sensor as a smart device - High level of integration

- In-pixel logic
  - Distributed correlation mechanism
    - Background rejection without loss of spatial resolution
    - *Patent application publication US 2022/208825 A1*
  - Automatic sensitivity adjustment
    - To prevent device saturation
  - Multi-photon and last-photon acquisition
    - High priority to late photons → improved measurement range
- Global features
  - Region of Interest (ROI) based readout
  - Fast serialized for data output in DDR on 8-bit LVDS
  - SPI for sensor configuration and external sensitivity programming
  - PLL locked TDC for PVT compensation
- Implemented with Rad-Hard Techniques

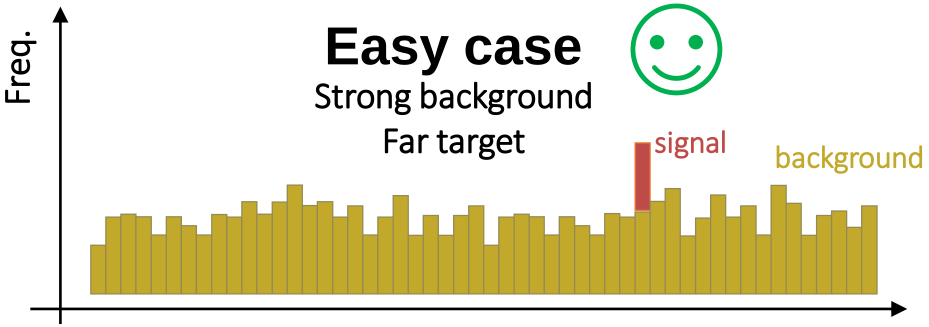


Current prototype: 64×64-pixel Flash LiDAR sensor

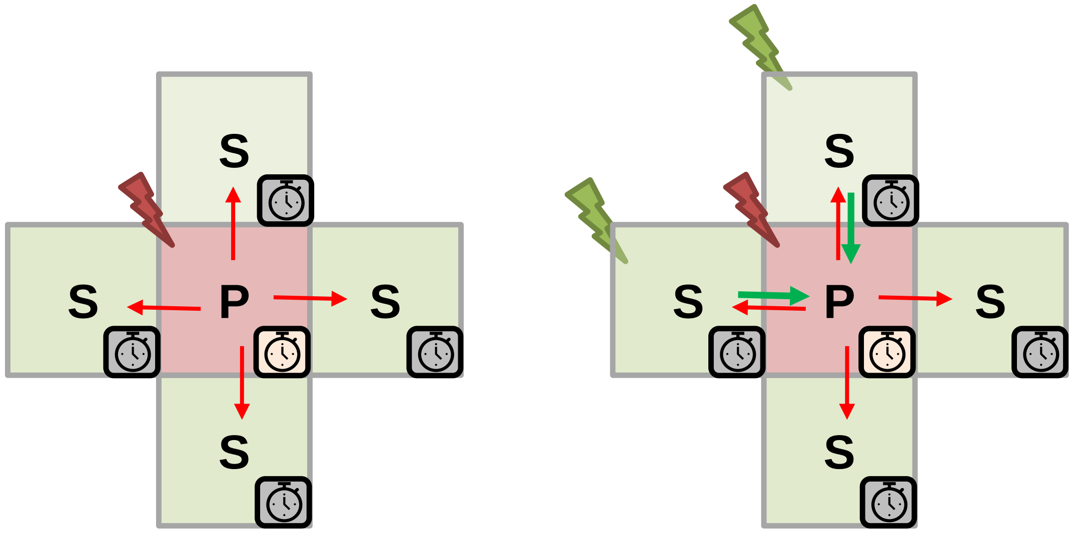
Distributed correlation mechanism



CMOS → In-pixel smart features



- Background rejection **without loss of spatial resolution**
- *Patent application publication US 2022/208825 A1*

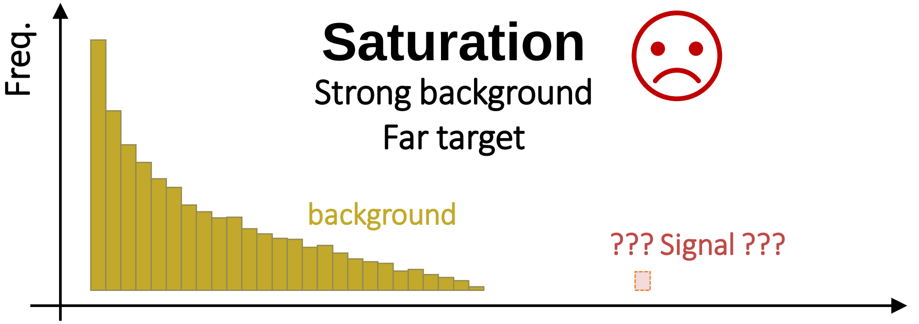


Uncorrelated photon → Discarded

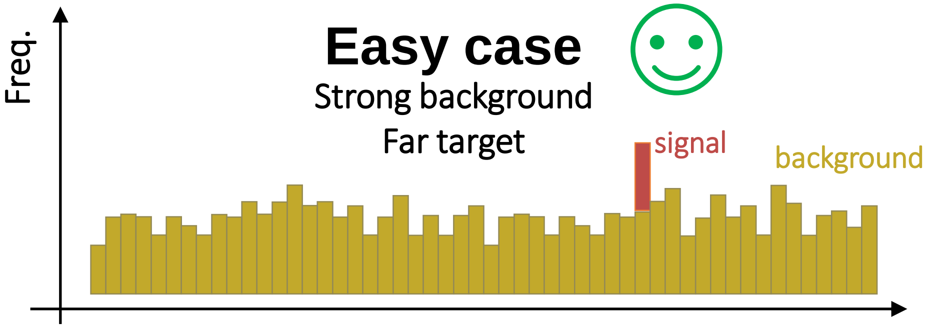
Correlated photons → Recorded

Current prototype: 64×64-pixel Flash LiDAR sensor

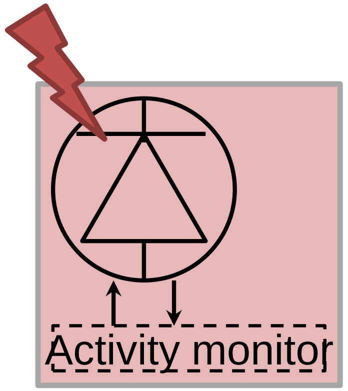
Automatic sensitivity adjustment



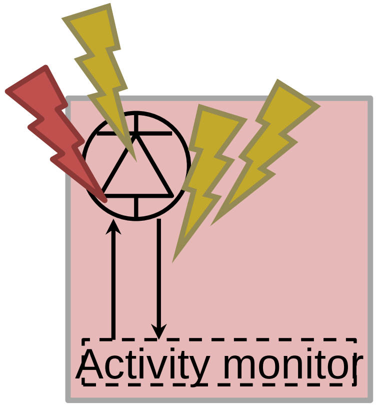
CMOS → In-pixel smart features



- SPAD PDP is automatically tuned depending on the triggering rate
- This prevents device saturation



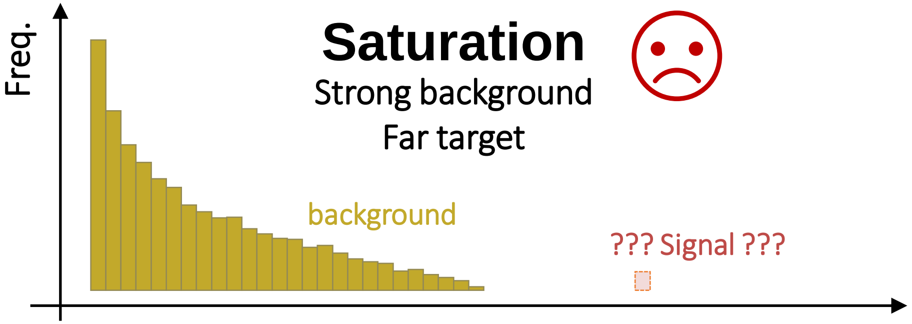
Weak background
→ PDP enhancement
High sensitivity



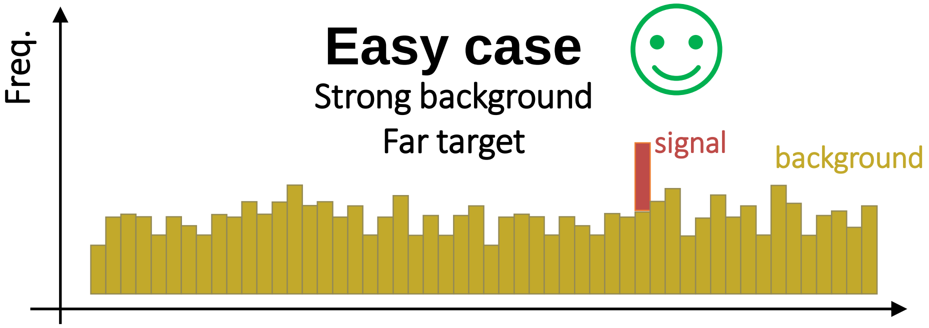
Strong background
→ PDP reduction
Low sensitivity

Current prototype: 64×64-pixel Flash LiDAR sensor

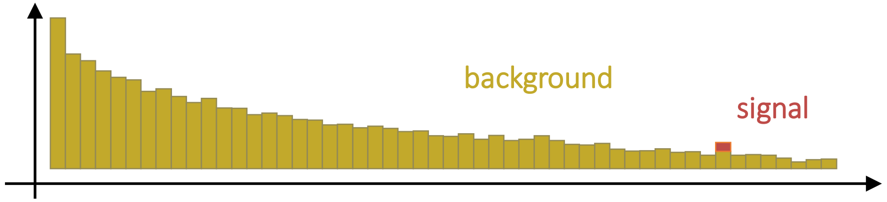
First-photon vs last-photon acquisition



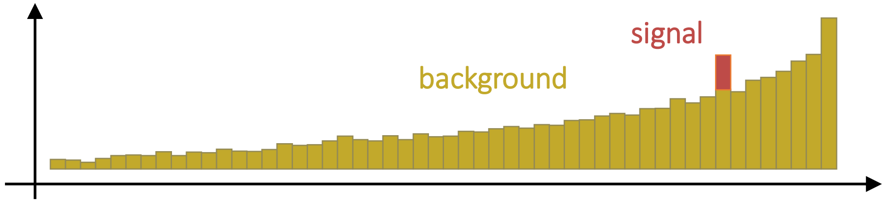
CMOS → In-pixel smart features



- Each channel can typ. record 1 or 2 photons
- Late photons are penalized



→ First-photon acquisition gives priority to early photons



→ Last-photon acquisition gives priority to late photons (when signal is weaker → SNR advantage)

- Our chip supports both acquisitions