PHOTON COUNTING IMAGE SENSORS

VARIETY OF NEW PROSPECTS

Jennifer Ruskowski

Fraunhofer IMS

CONTENT

- Photon counting AND imaging ?
- Single photons detectable ?
- Counting or Timing ?
- Using AI?

➔ Application examples

➔ Introduction SPAD

➔ Two operating configurations

➔ On sensor raw data level

PHOTON COUNTING AND IMAGING?

- Classical Image

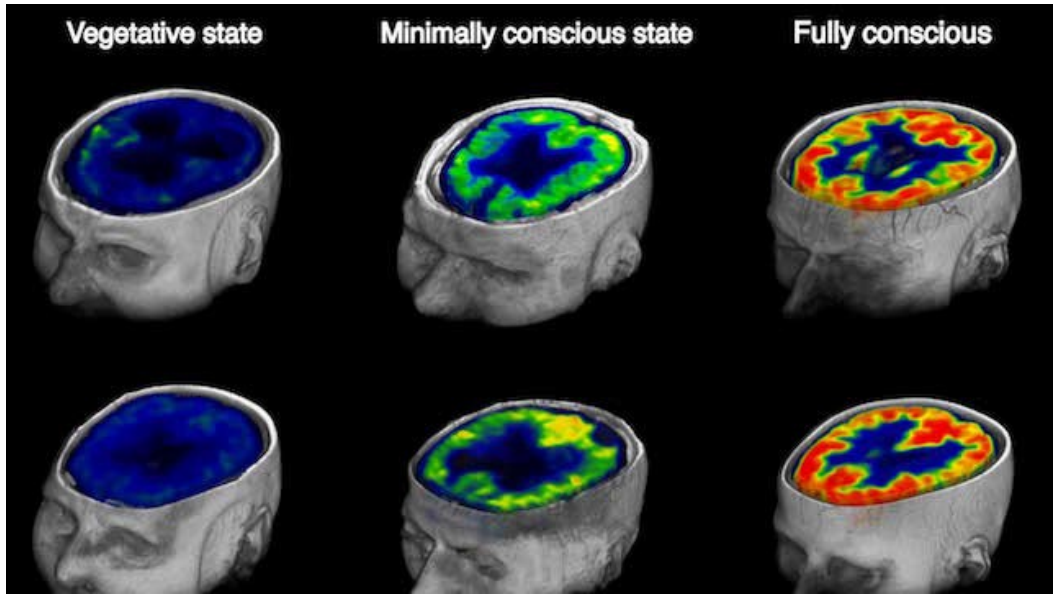
Source: puffer fish (private photo)

- CMOS Image Sensor
- Light → Charge → Voltage → Amplification

- Single Photon “Image” ?

- Sensor → ???
- Single Photon → ???

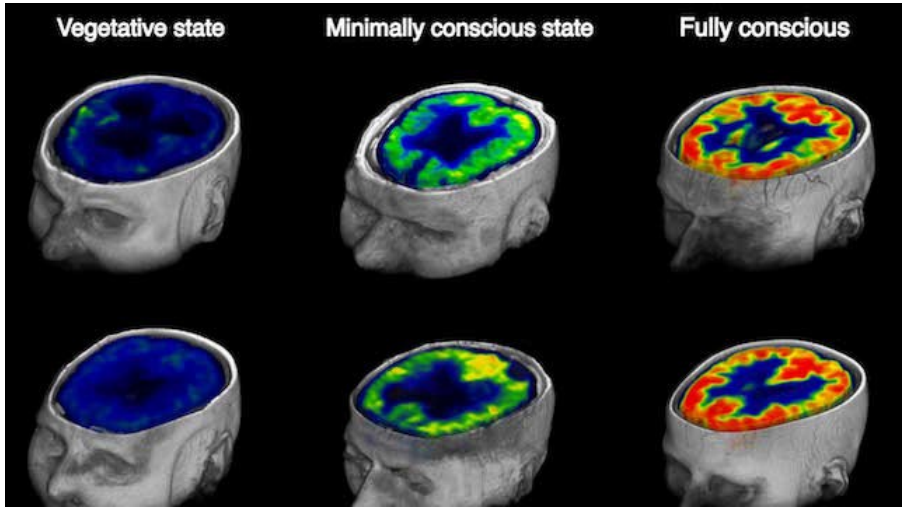
PET



Source: www.medium.com

- **P**ositron **E**mission **T**omography
- Observation of metabolic process of tissue in 3D

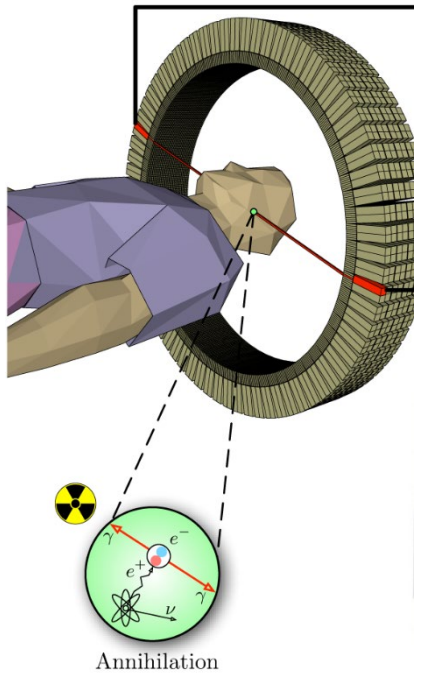
PET



Source: www.medium.com

- Two gamma rays are released in directions approximately 180 degrees apart
- Detection and Correlation of the two gamma photons

Source: Jens Maus, Wikipedia



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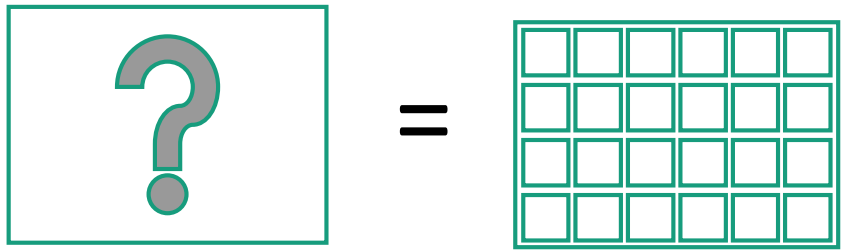
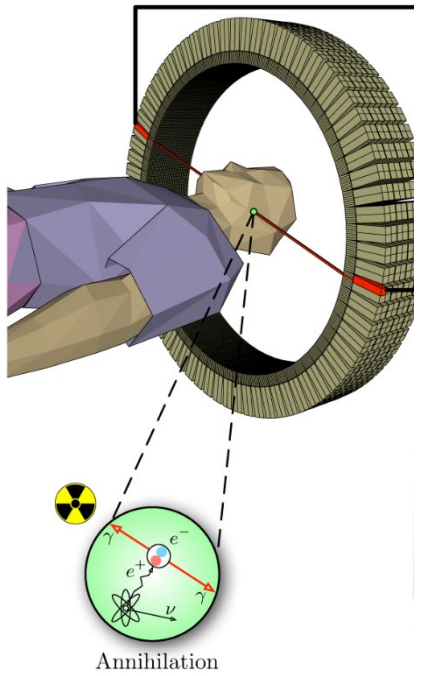


Quantity of correlated single photon events

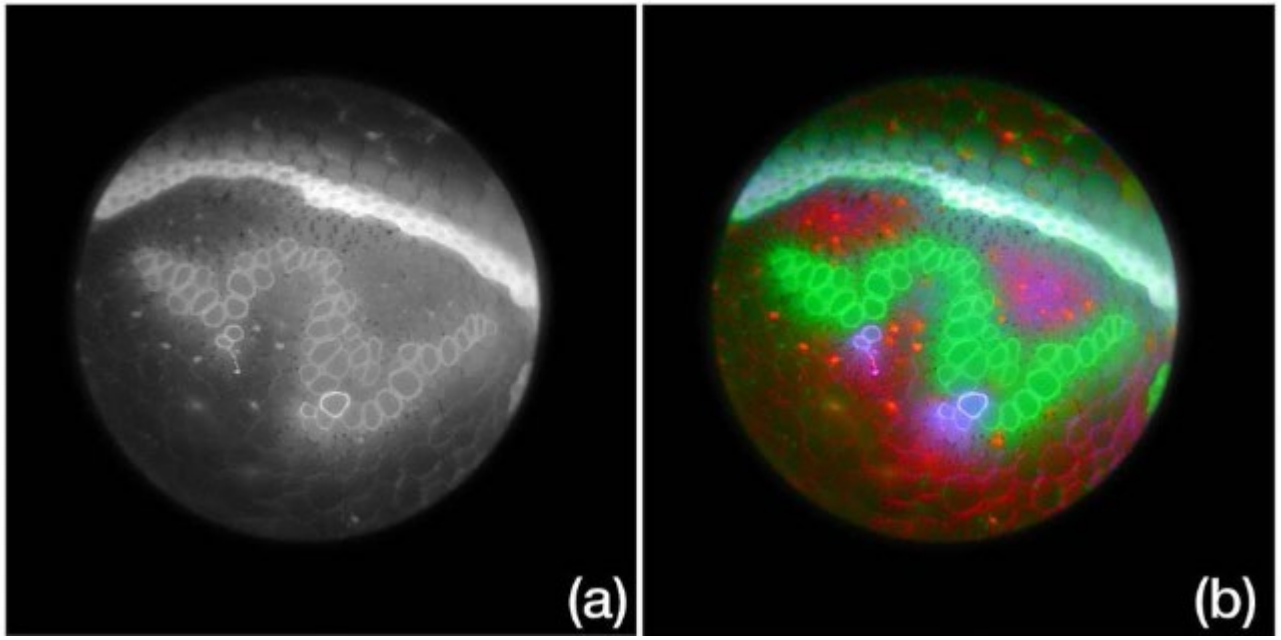
Source: Jens Maus, Wikipedia



- Positron Emission Tomography
- Observation of metabolic process of tissue in 3D

FLIM

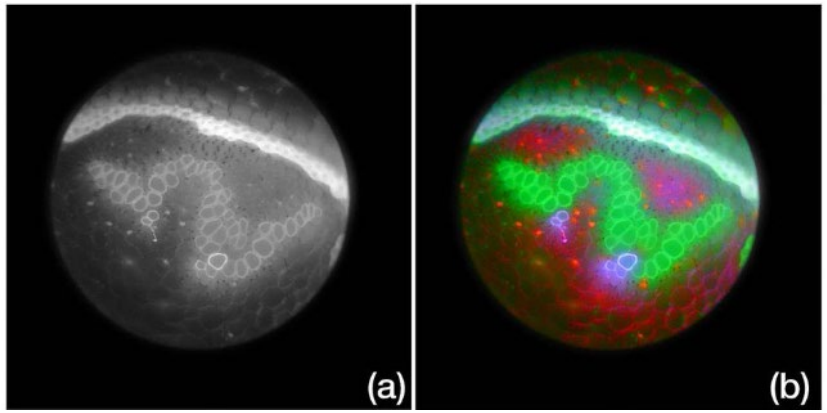
Source: Photonscore



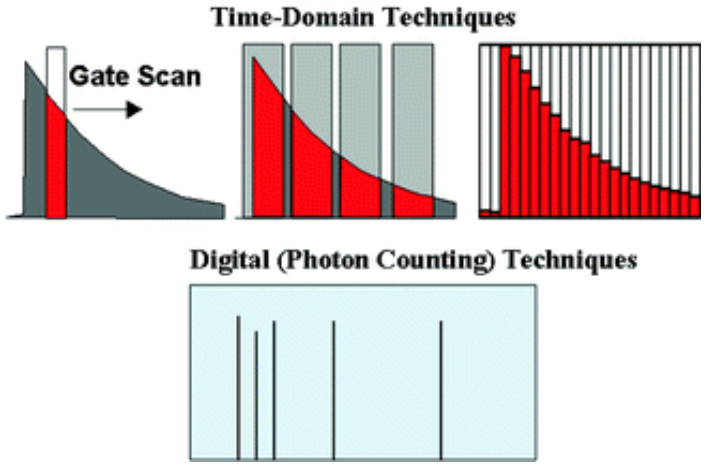
- **F**luorescence-**l**ifetime **i**maging **m**icroscopy
- Detected areas with different exponential decay rates of the fluorescence

FLIM

Source: Photonscore



Source: Springer, K. Suhling et al.



$$I(t) = I_0 \exp\left(-\frac{t}{\tau}\right)$$

Lifetime τ

→ time-correlated single photon counting

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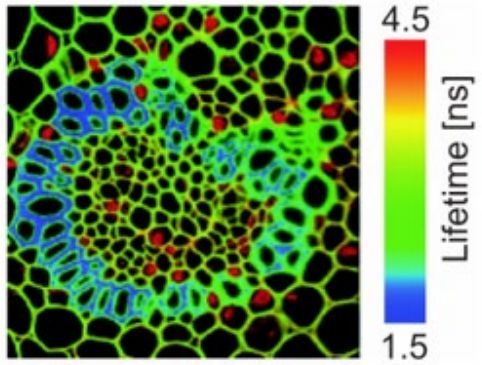
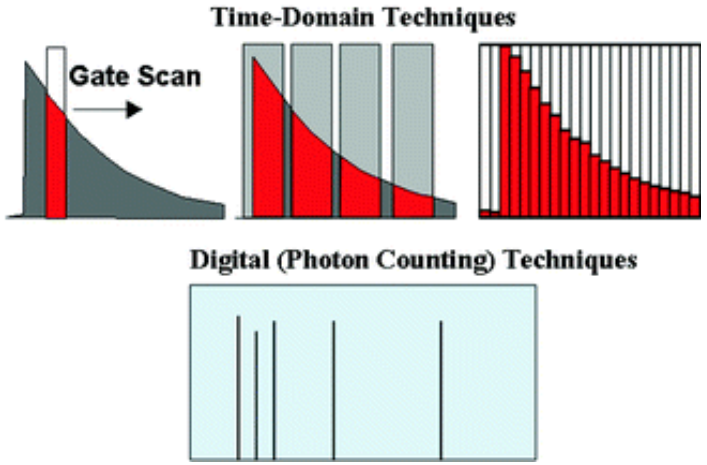
FLIM

=



Source: Picoquant

Source: Springer, K. Suhling et al.



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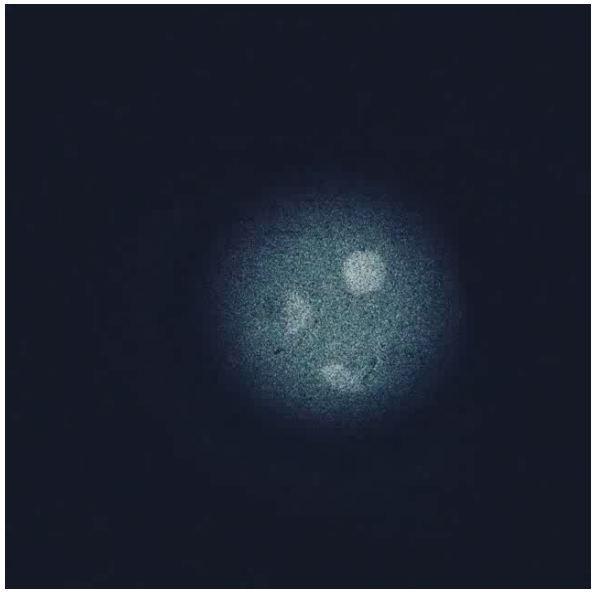
GHOST IMAGING



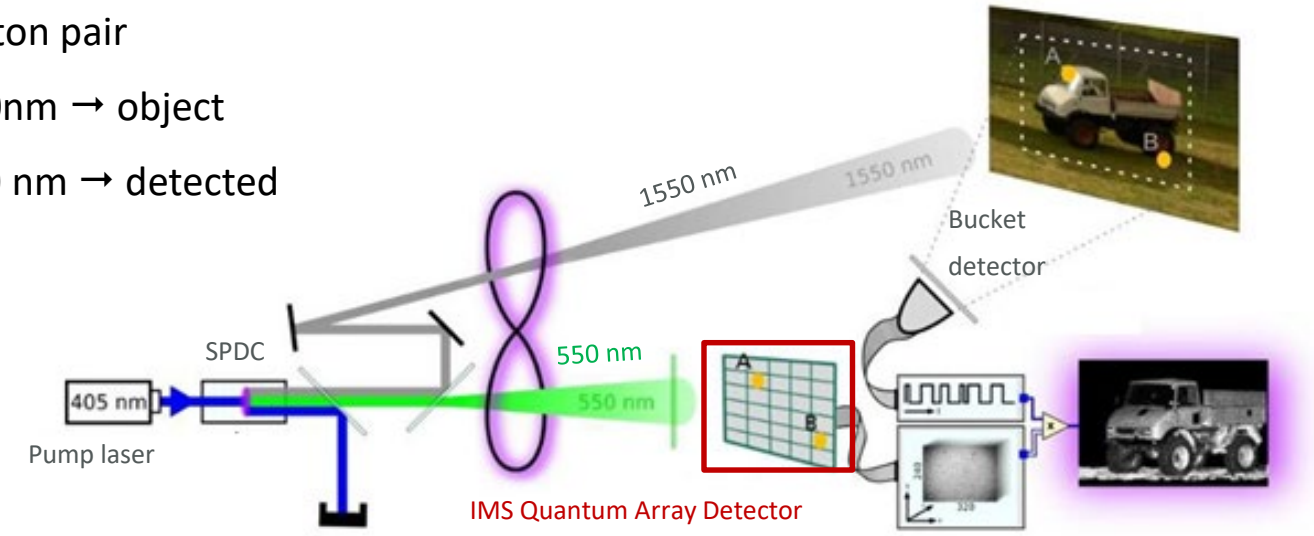
Source: Fraunhofer IOF

- Image of light that has never interacted with the object itself
- Quantum physics with entangled photon pairs

GHOST IMAGING

Source: Fraunhofer IOF

- Entangled photon pair
  - idler: 1550nm → object
  - signal: 550 nm → detected

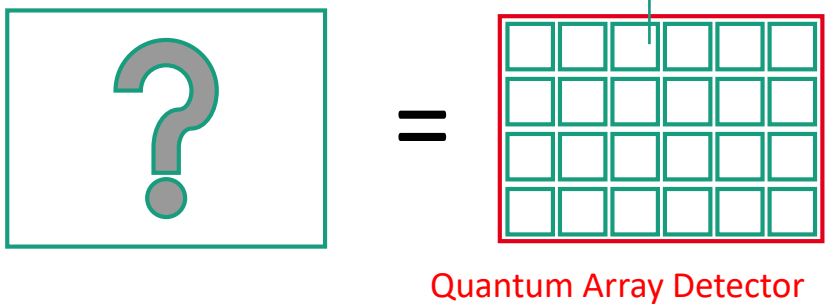


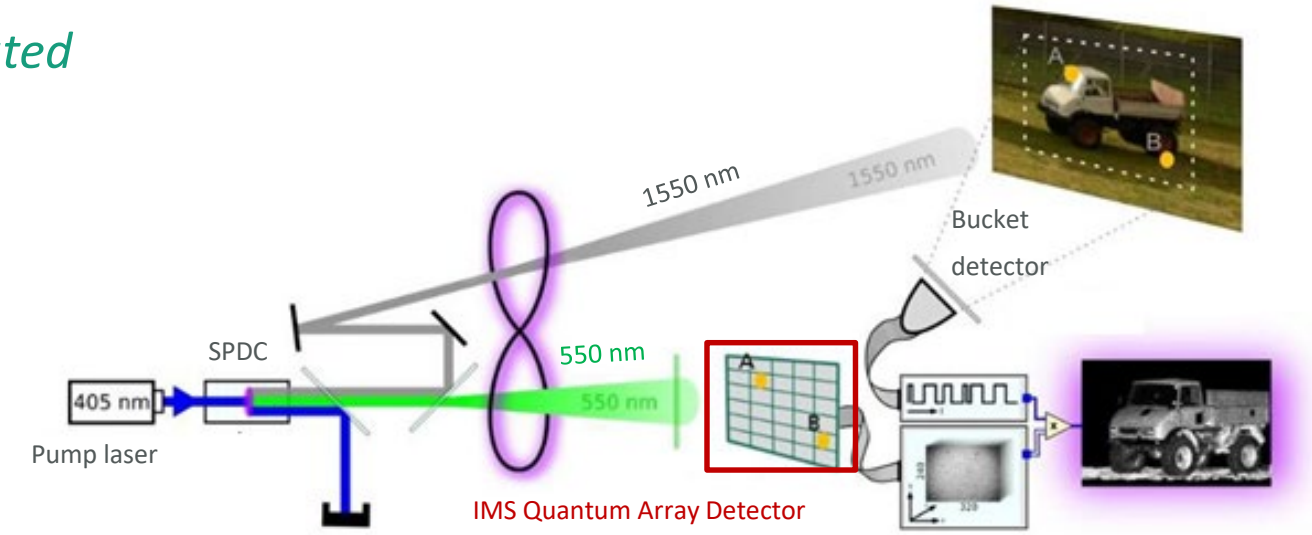
Source: Fraunhofer IOSB

- Image of light that has never interacted with the object itself
- Quantum physics with entangled photon pairs

GHOST IMAGING

With bucket detector correlated events





Source: Fraunhofer IOSB

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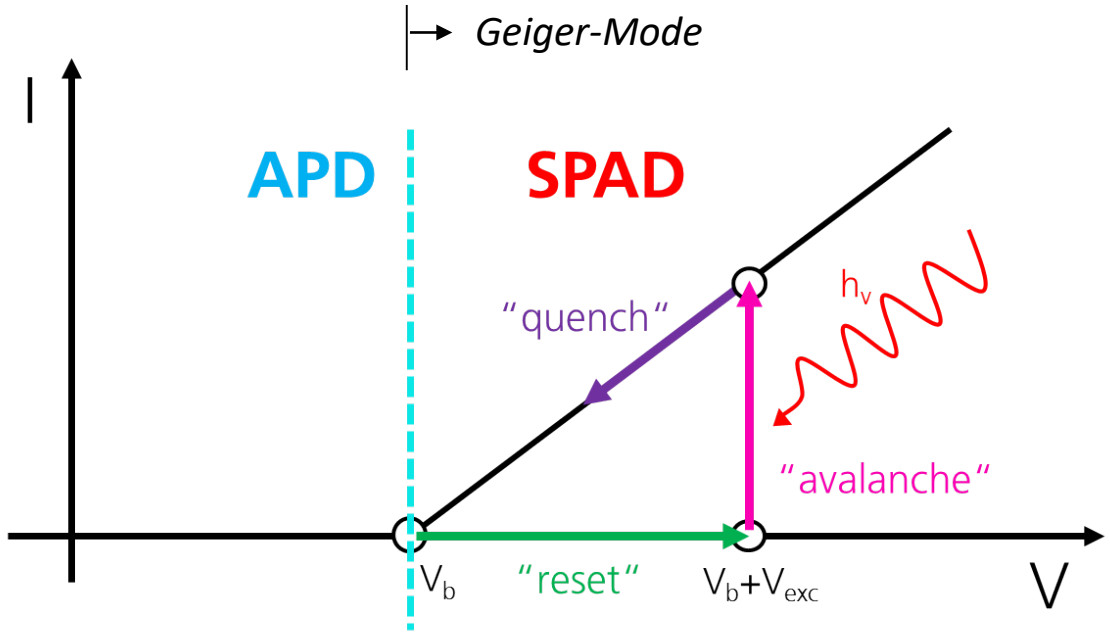
SINGLE PHOTONS DETECTABLE ?

- **S**ingle-**P**hoton **A**valanche **D**iode
- Operation in Geiger-Mode
  - above breakdown voltage V_b
- Digital output signal



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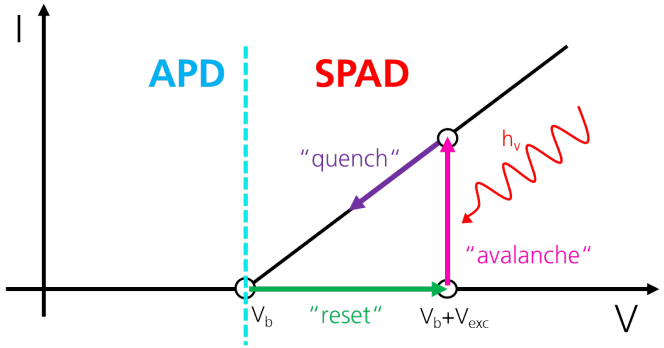
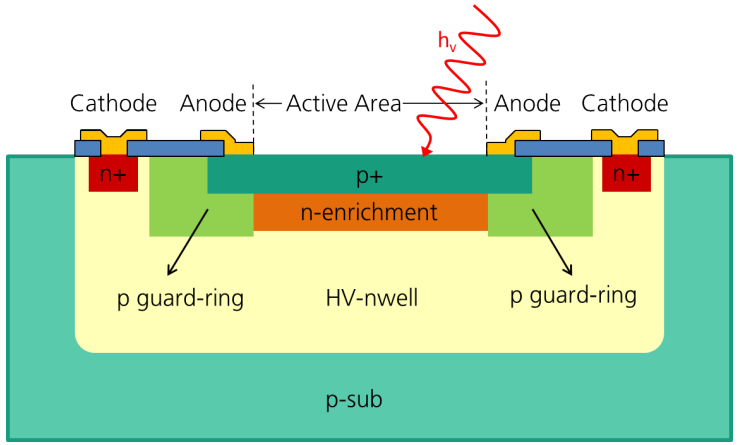




- Due to high non-active area:
  - Lowest pixel size ~ 10 µm (depending on other trade-offs)
- SPAD in CMOS
  - Electrical field with one additional ion implantation (here: n-enchrichment)

SINGLE PHOTONS DETECTABLE ?

PHOTODIODE BENCHMARK

Silicon-based detectors

	PIN-PD	APD	SiPM	SPAD
Gain	1	10^3	10^6	10^6
Single photon detection	No	No	Yes	Yes
Operational Bias	Low	Medium	Medium	Medium
Temperature Sensitivity	Low	High	Low	Low
Array possible	Limited	Limited	Limited	Yes
Readout / Electronics	Complex	Complex	Medium	Simple
Rise time	Medium	Slow	Fast	Fast

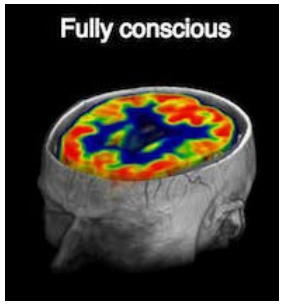
Source: Forschungsfabrik Mikroelektronik

Silicon Photomultiplier: several SPADs connected in parallel → analog device

COUNTING OR TIMING ?

- Different measurement types

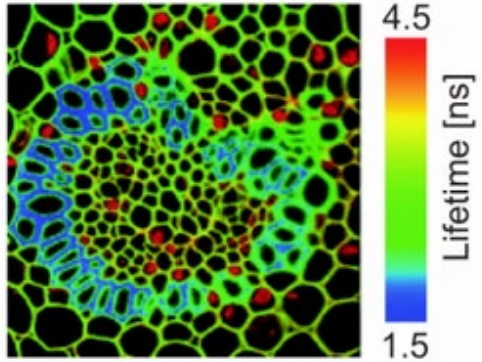
PET



Photon timing & correlation to another event

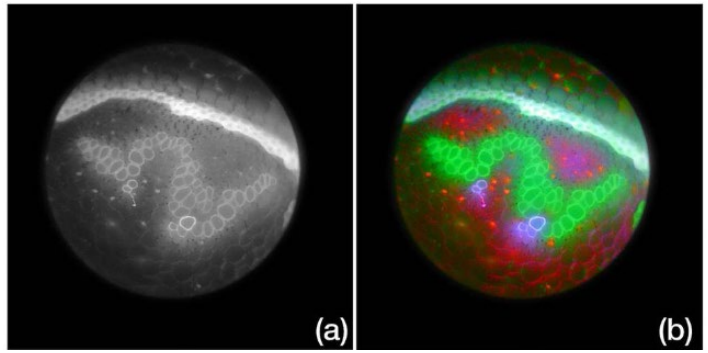
GHOST

FLIM



Photon timing

FLIM – example 2



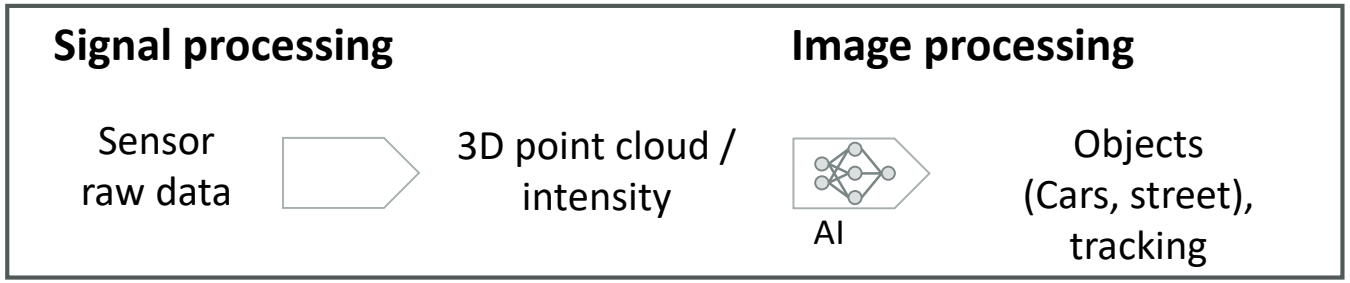
(a) Photon counting

(b) -“- plus lifetime

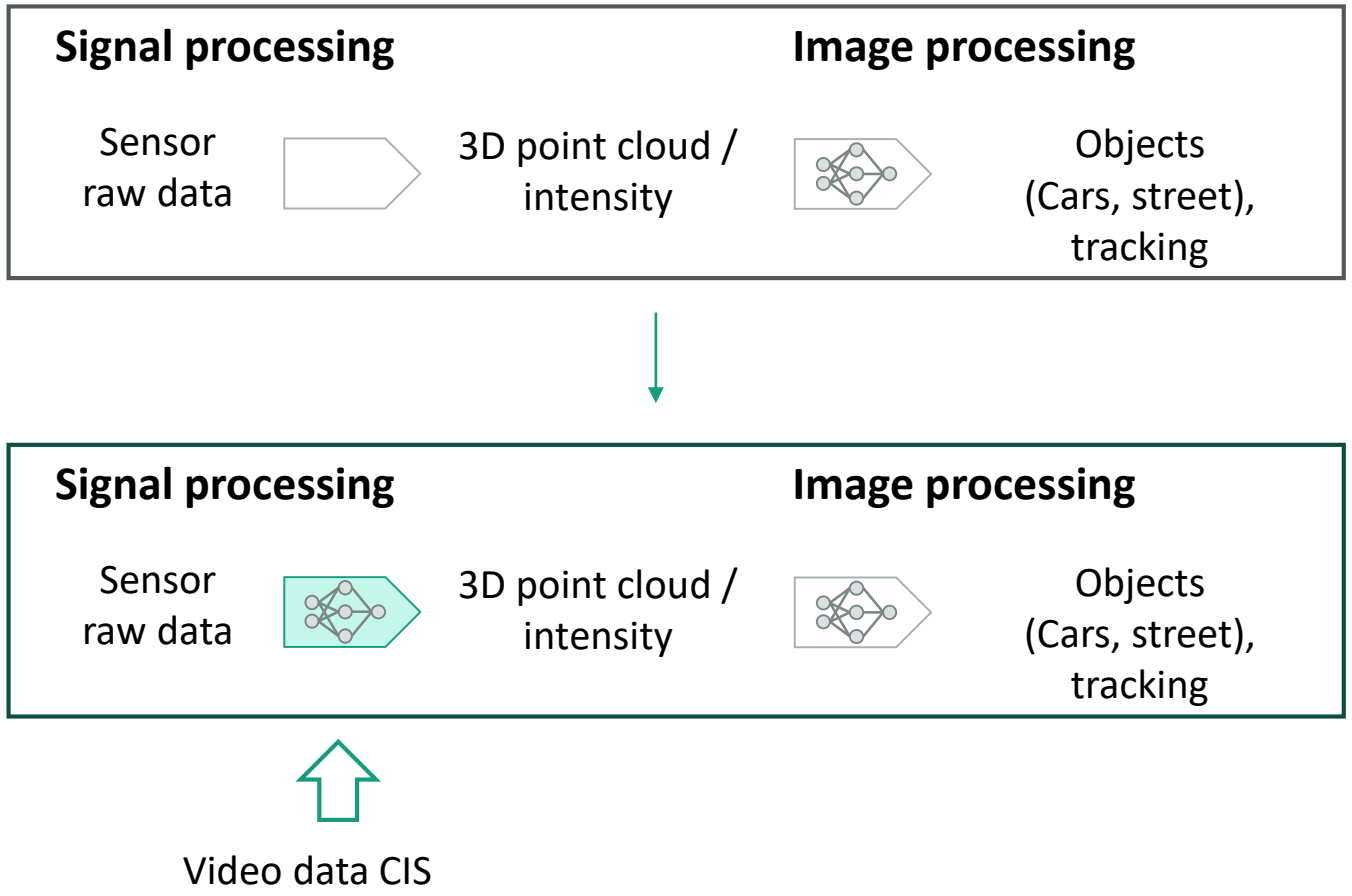
SIGNAL PROCESSING WITH AI?

Source: www.arstechnica.com / Ouster

- Based only on LiDAR data
  - video-like intensity values (Photon counting)
  - 3D data (Photon timing)
- LiDAR – **Li**ght **D**etection **A**nd **R**anging
  - 3D measurement method
  - Round trip time
- Conventional neural networks for object recognition
  - Cars → red
  - Street → yellow



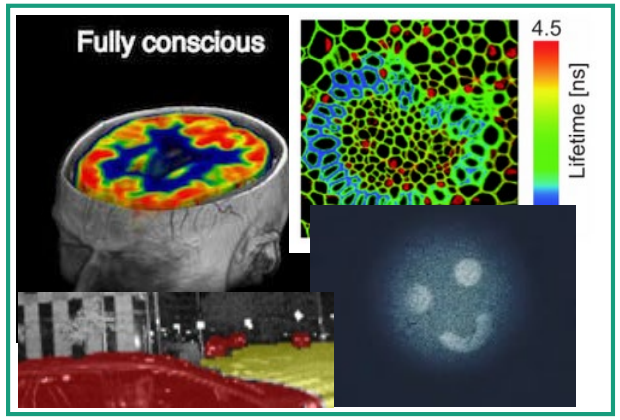
SIGNAL PROCESSING WITH AI?



- Using AI methods on sensor raw data level
- Two main goals
  1. Reduce data traffic
  2. Increase performance
     - For example supporting fast sensor fusion

CONCLUSION

- Single Photon Images



- Photodiode → SPAD or SiPM
- Sensor mode → Photon Timing / Photon Counting
- Single Photon → Yes

- Single photon sensing can be found in different applications and market segments
- SPAD and SiPMs are the photodiode choice to make
- Often the plain signal capture have to be compared to other signal events
- AI will be more and more important to process data from

  Photon Counting Image Sensors

POSTSCRIPTS

- SPAD

  254.

  → Basics: Caironi, Mario, and DARIO ANDREA NICOLA Natali. "Photodetectors, Materials, Devices and Applications." (2015): 195-

- Time-correlated single photon counting

  → O'Connor, Desmond. *Time-correlated single photon counting*. Academic Press, 2012.

- Ghost Imaging

  Metrology, Imaging, and

  → How it works? Start with a book: Simon, David S., Gregg Jaeger, and Alexander V. Sergienko. "Ghost Imaging and Related Topics." *Quantum Communication*. Springer, Cham, 2017. 131-158.

- LiDAR
  heterodyne, FMCW, 1550nm/905nm, VCSEL/edge

  mikroelektronik/de/Unser-

  → different key words, as TCSPC, Scanning/SolidState/ MEMS/Flash, emitting laser diode,

  first overview: https://www.forschungsfabrik- mikroelektronik.de/content/dam/ipms/forschungsfabrik-Angebot/Anwendungsangebot/Transport-und-Mobilitaet/LiDAR/Dokumente/LiDAR_Solutions_for_Automotive_and_Industrial.pdf

PICTURES

- Page 3 - private photo
- Page 4 - https://medium.com/@sullyfchen/mathematical-medicine-positron-emission-tomography-pet-scans-4afd7c7d66e3
- Page 5 - Von Jens Maus (http://jens-maus.de/) - own work - part of master thesishttp://jens-maus.de/ftp/langner_mscthesis.pdfhttp://jens-maus.de/ftp/langner_mscthesis.bib, Gemeinfrei,https://commons.wikimedia.org/w/index.php?curid=401252
- Page 7 - https://photonscore.de/lincam
- Page 8 - https://link.springer.com/chapter/10.1007/978-3-319-14929-5_3
- Page 9 - https://www.picoquant.com/applications/category/life-science/fluorescence-lifetime-imaging-flim
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