CMOS Quantum Imagers for Picosecond Sensing Applications

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Emerging Imaging Needs

- *ultra-fast*, *time-correlated*, molecular processes in physics and the life-sciences

- *quantitative* bio-chemistry and molecular biology

- New class of problems addressed by *precision imaging* techniques

Precision Imaging

- Quantum sensitivity *single photon resolution*
- Picosecond *timing accuracy*
- Over 100,000 *frames per second*
- Over 5 decades of *dynamic range*

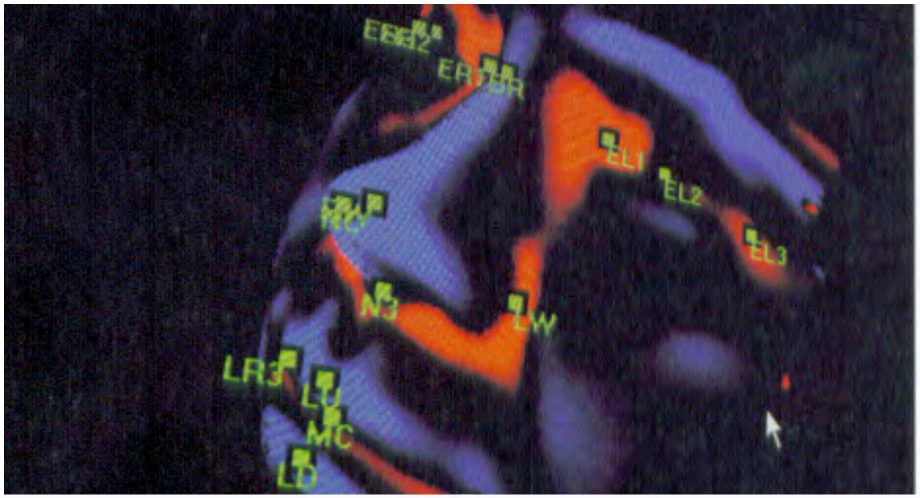
All of the above: *in massive pixel arrays!*

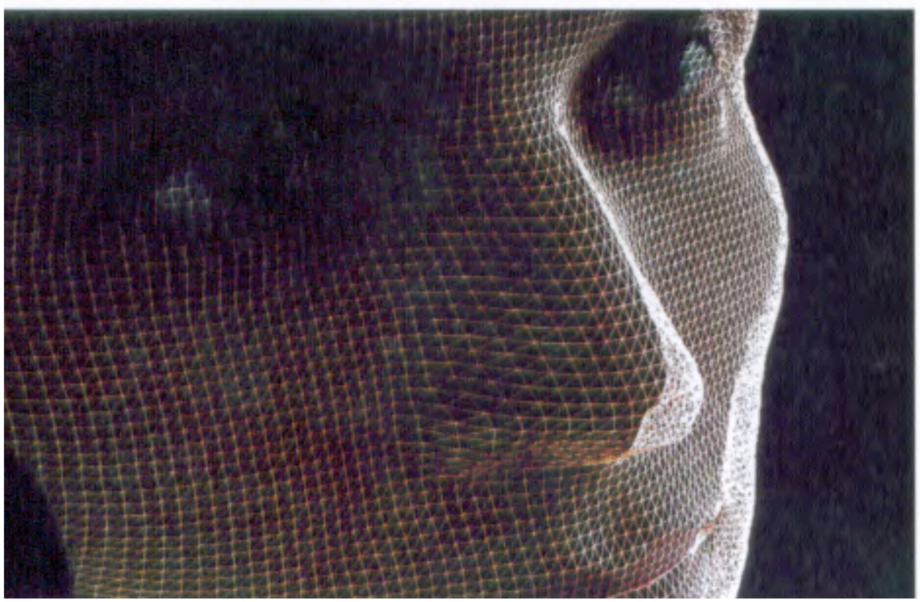
Applications

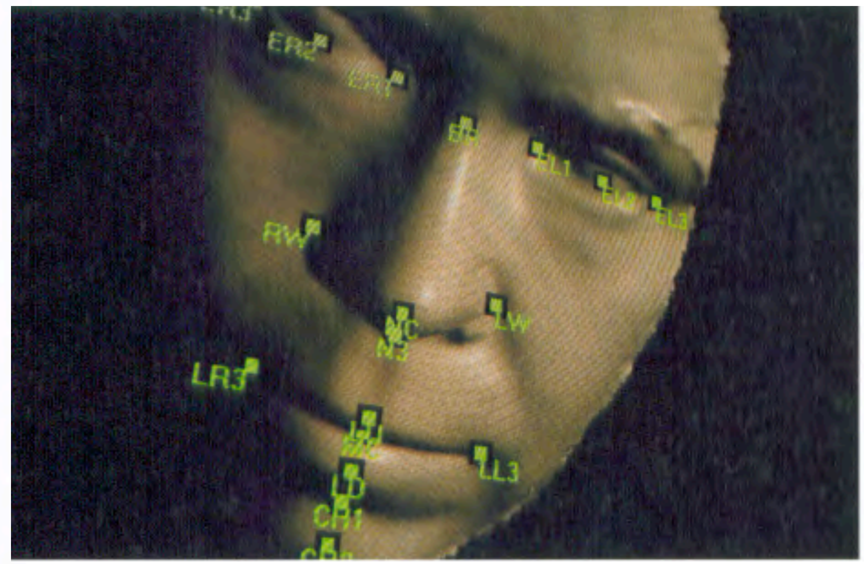
- Vision
  - Nightvision
  - 3D vision, HCIs
  - Security, automotive
- Engineering
  - Fluid-dynamics
  - Energy
  - Bioimaging
- Medical / Research
  - Molecular imaging
  - Functional neuro-scanning
  - Microscopy, spectroscopy

Human-Computer Interfaces

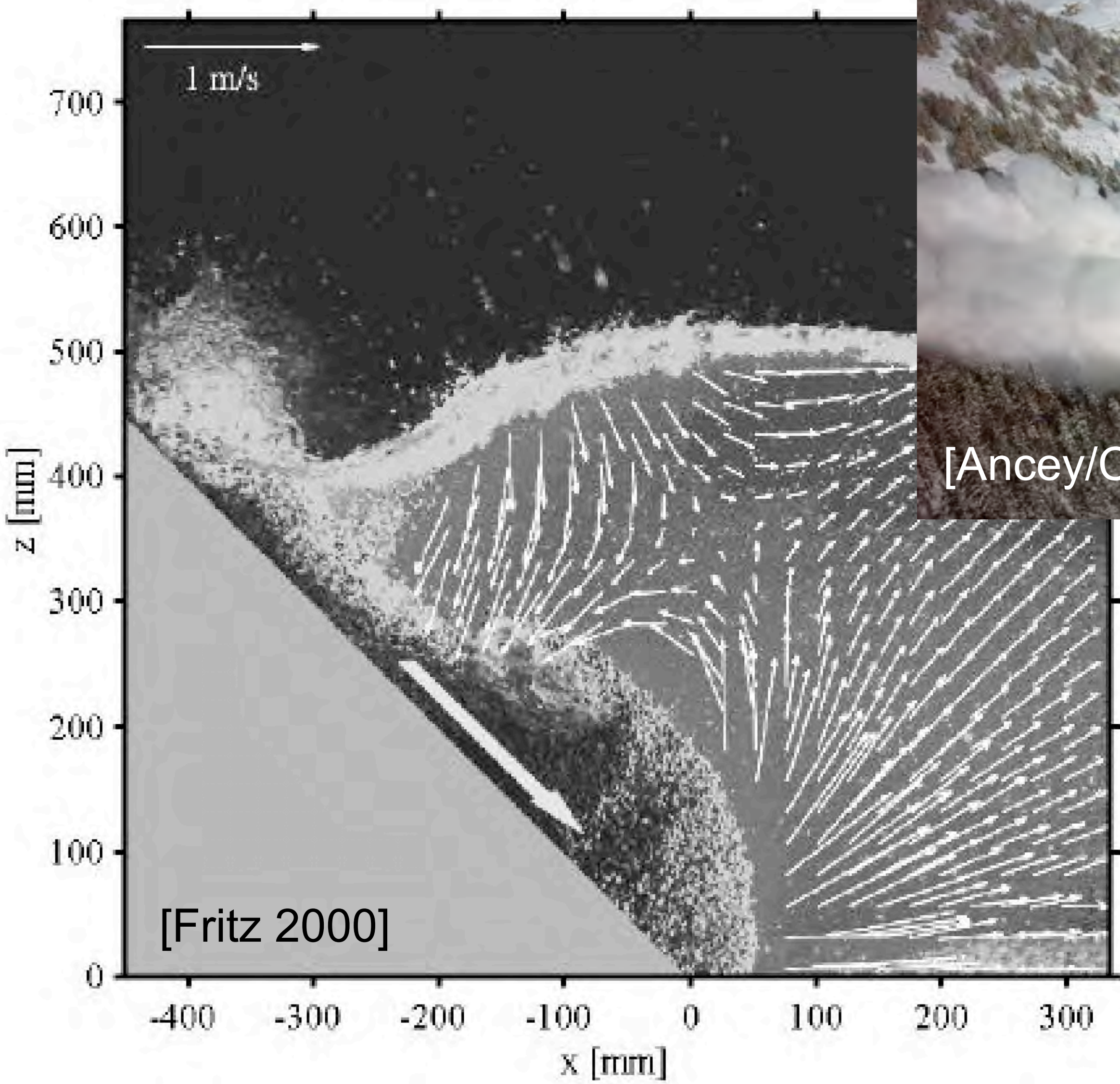
3D Vision: Biometrics & Gaming



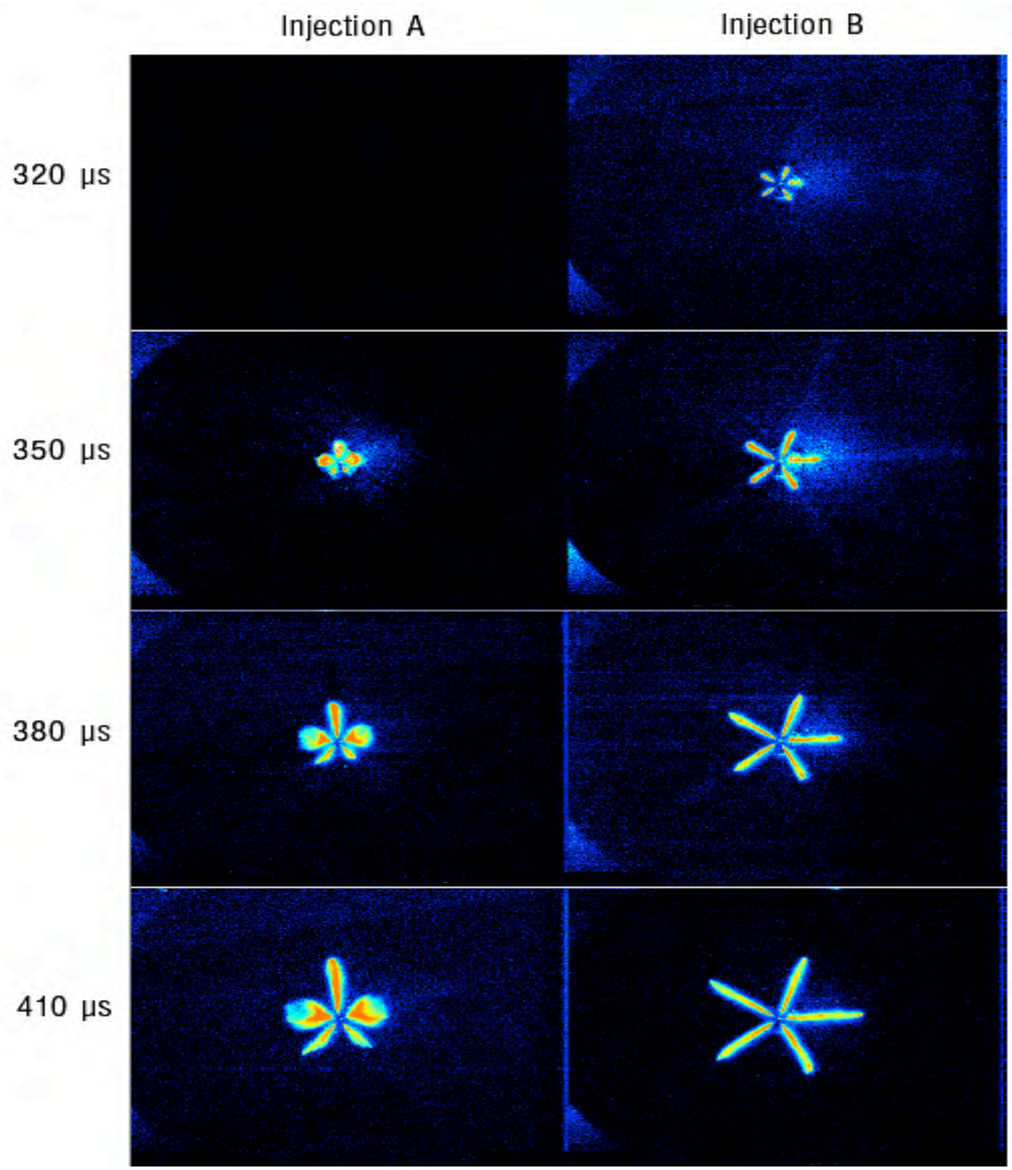




Fluid-dynamics

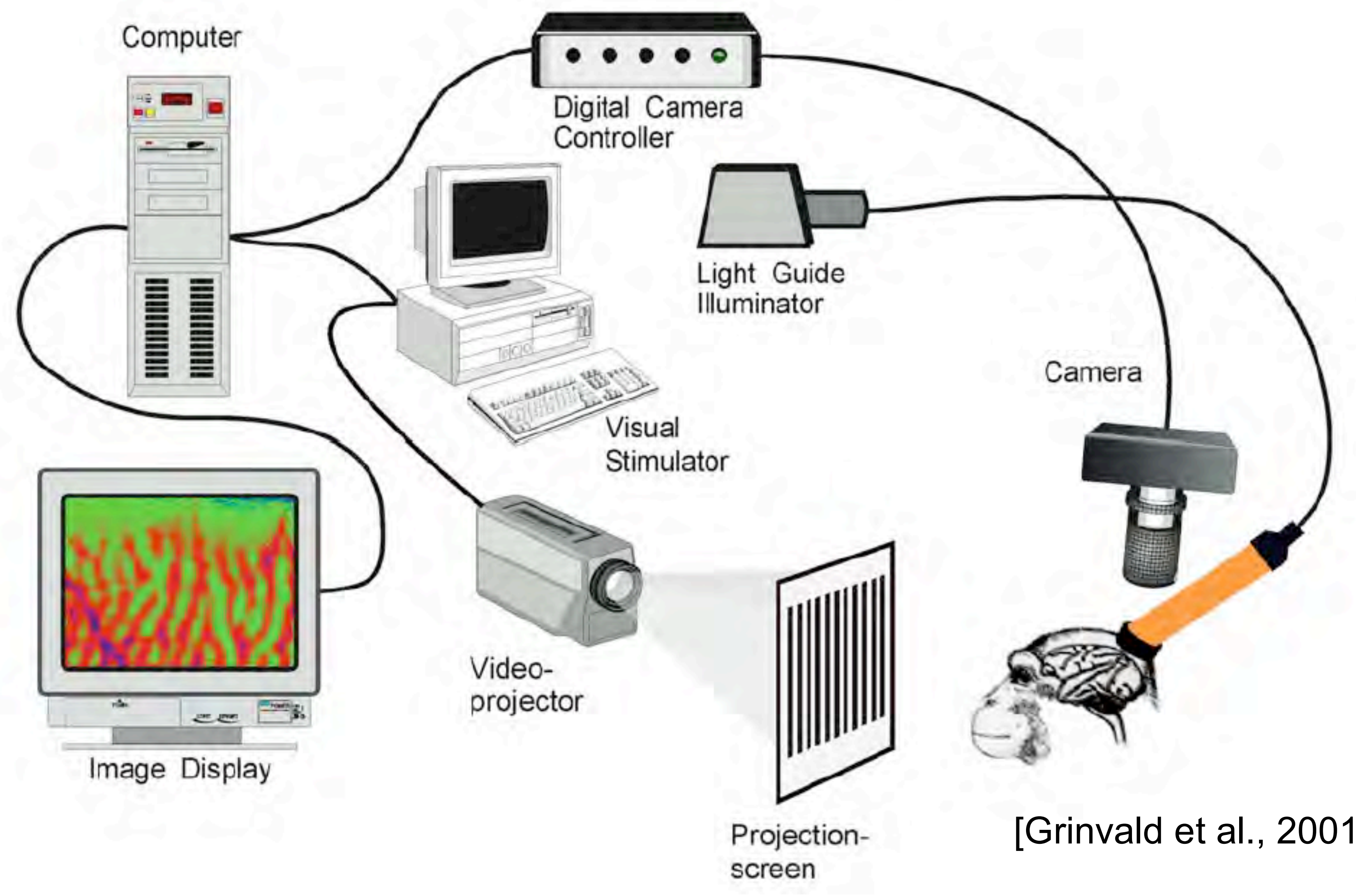


Combustion Engine Dynamics



[Eisenberg 2005]

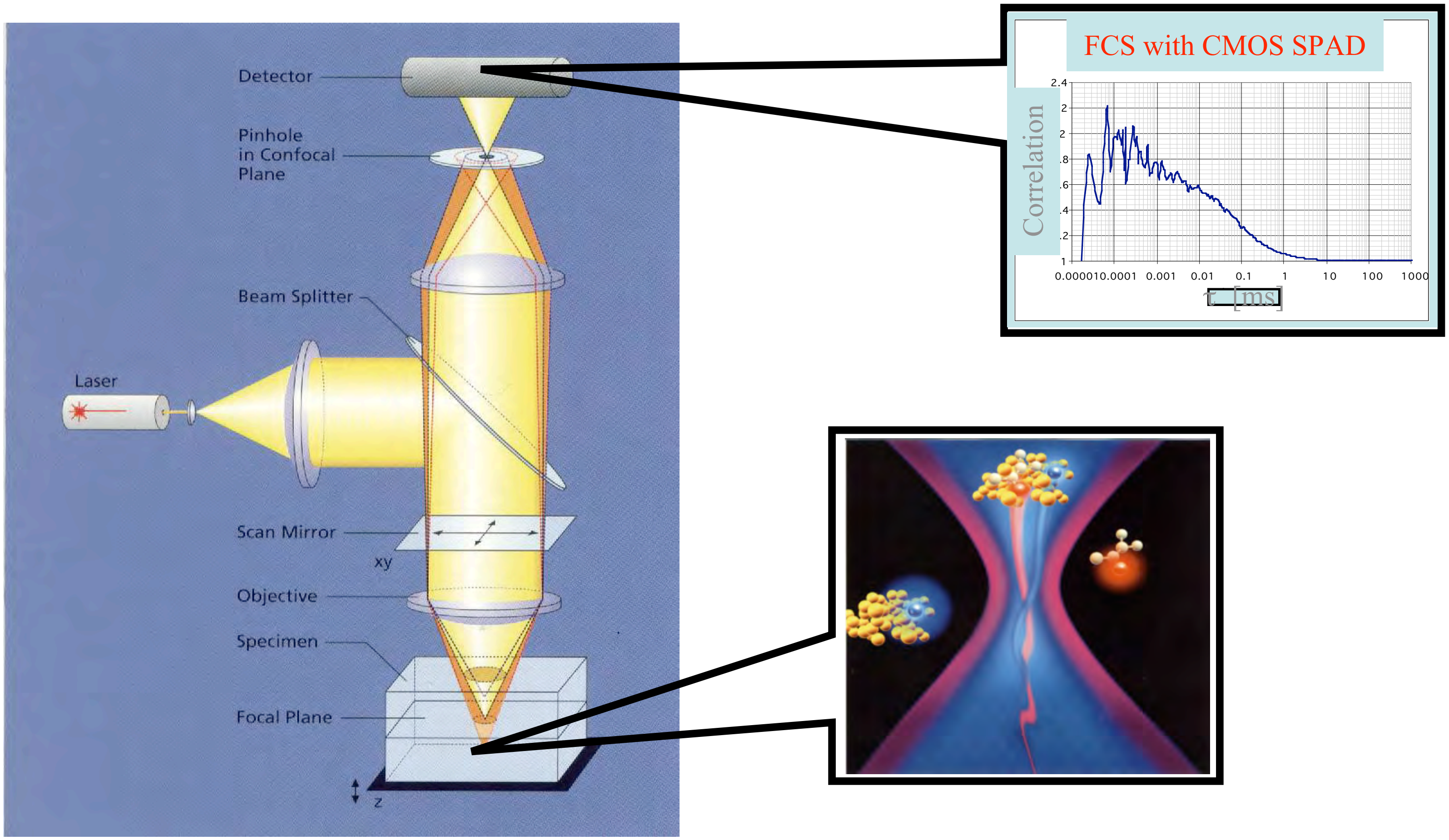
Functional Neuro-scanning



[Grinvald et al., 2001]

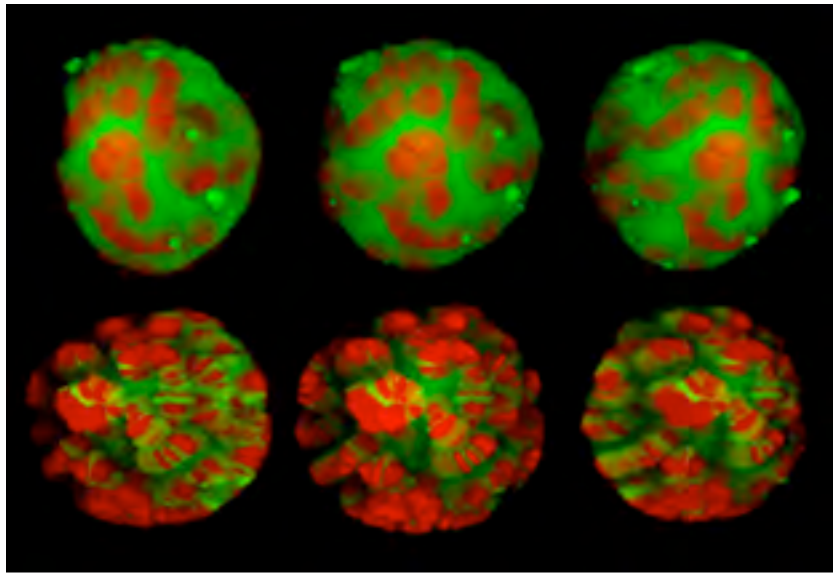
Molecular Imaging

- Fluorescence Correlation Spectroscopy (FCS)



[Gösch, *et al.*, 2003]

In Vivo Bioimaging



[Jie Yao, *Nature* 2006]

- Salivary glands of Drosophila larvae with giant chromosomes
- Two-photon fluoerscence lifetime imaging (FLIM) enables avoiding to break nuclei for “2D spreading”

Outline

- Single Photon Detection
- Single Photon Imagers
- Some Applications
- Next Generation Systems
- Conclusions

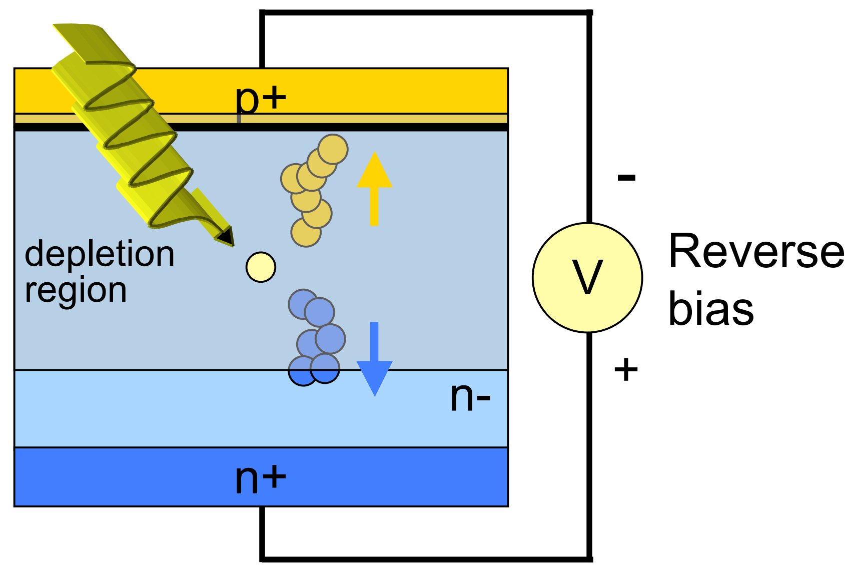
Single Photon Detection

Silicon Avalanche Photodiodes

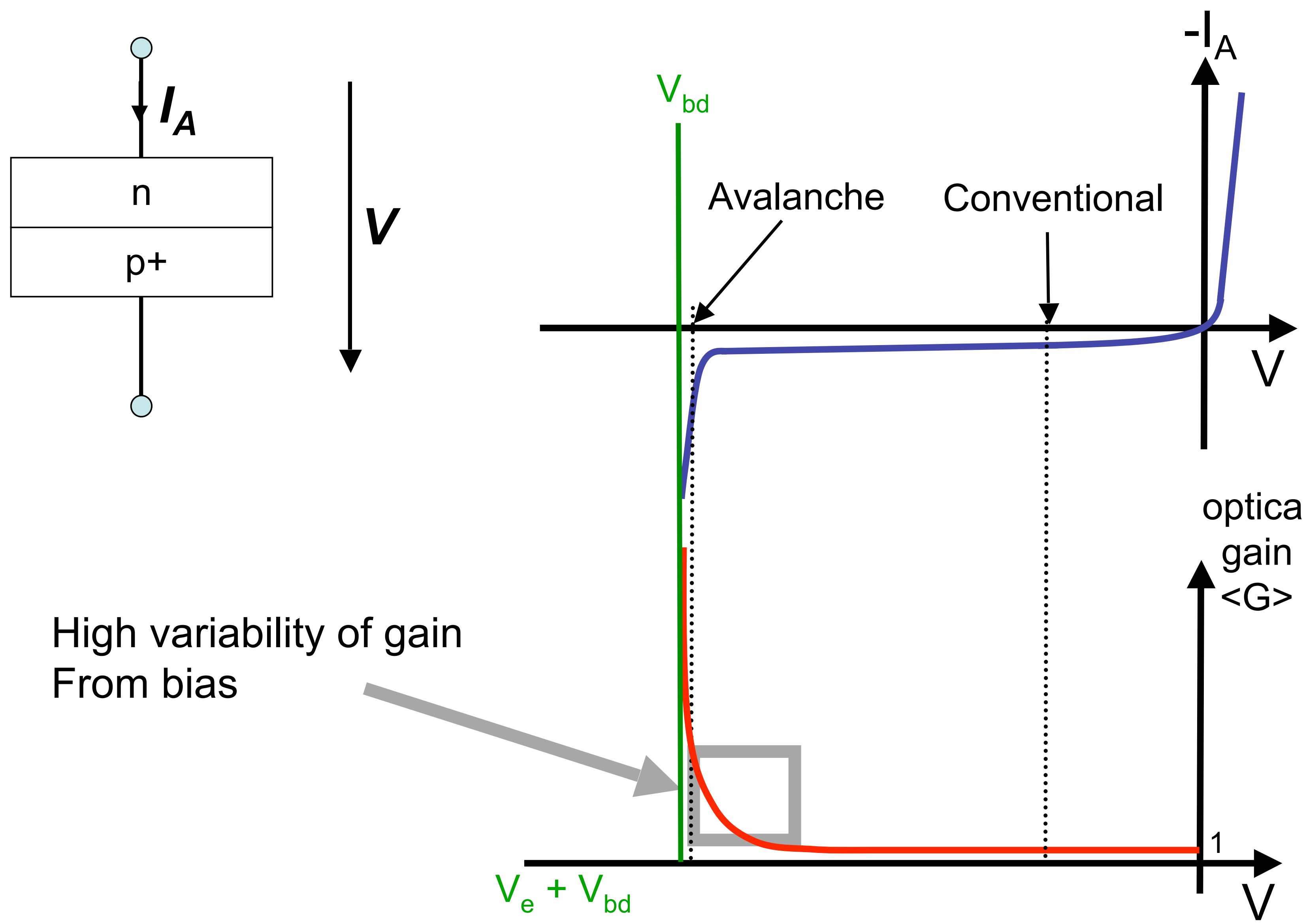
- ***Review***:

  Photon to electron - Secondary electron - Multiplication

  Multiplication in depletion region by ***impact ionization***

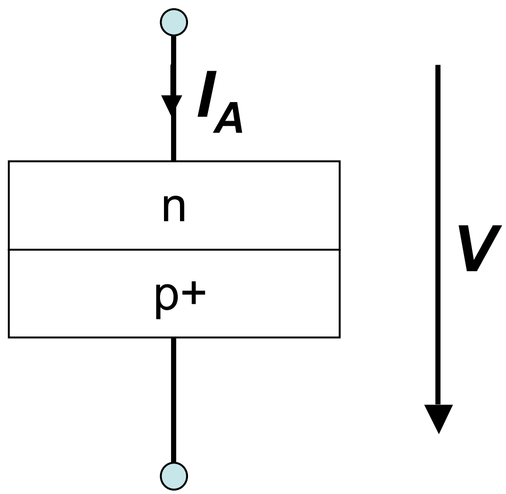


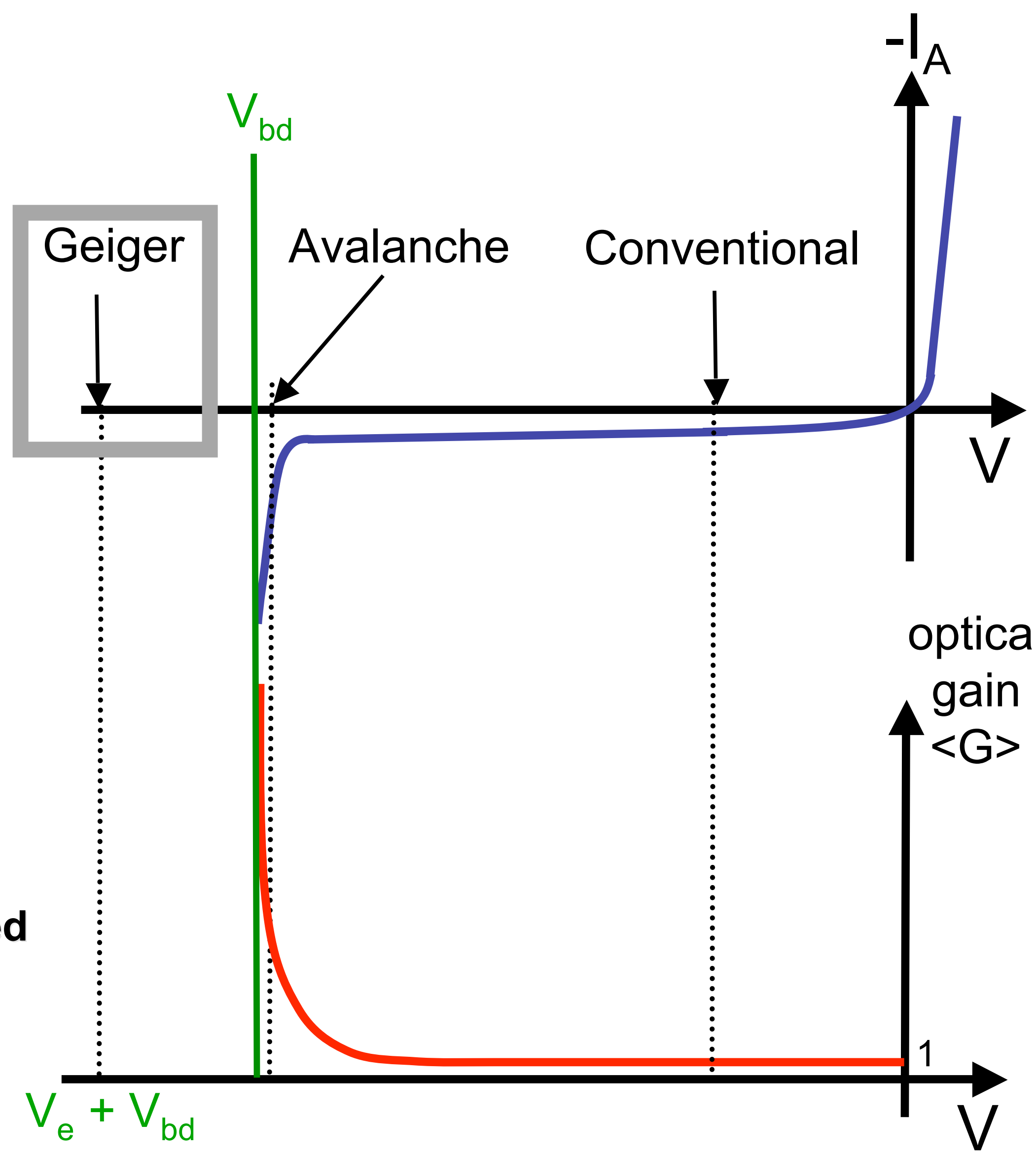
Silicon Avalanche Photodiodes



High variability of gain
From bias

Operating in Geiger Mode

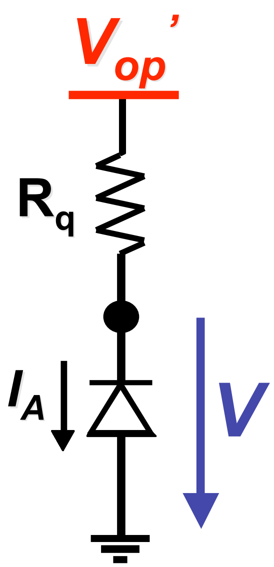




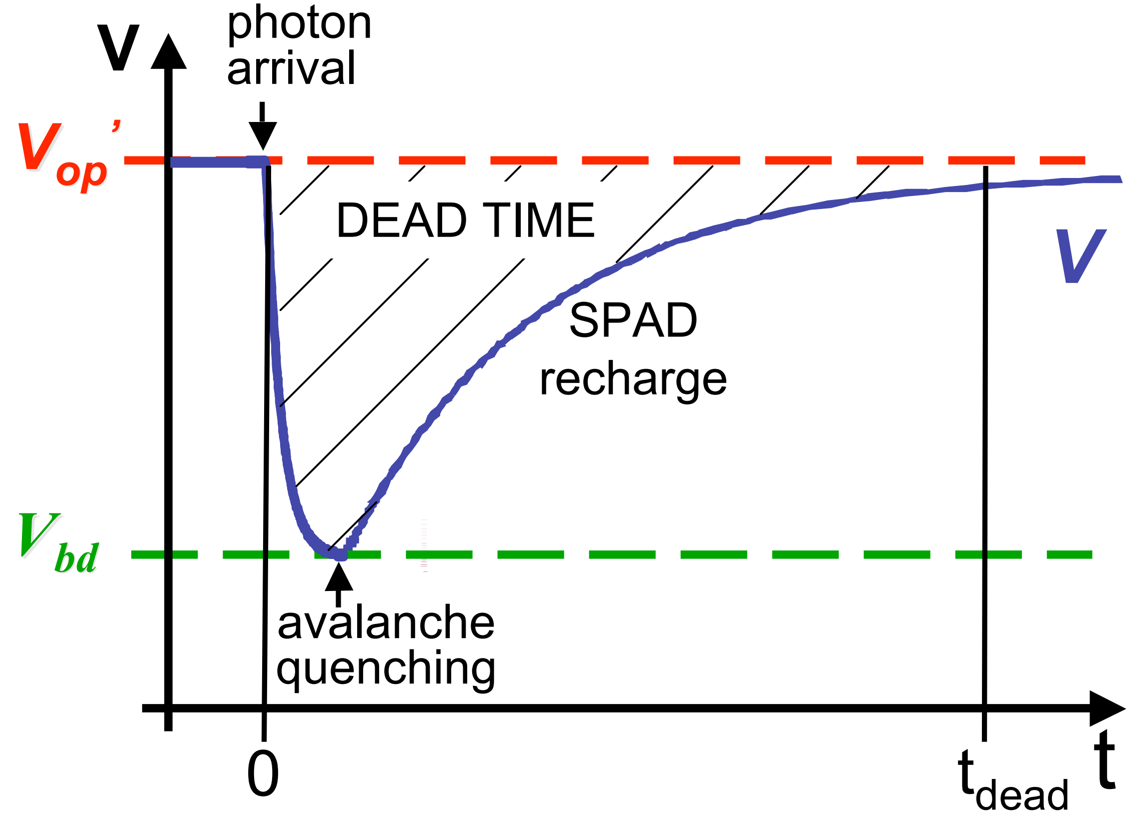
- In avalanche mode:
  <G> ≅ 1000
- In Geiger mode:
  <G> → ∞
  ➔ **avalanche must be stopped**

Quenching the Avalanche

Passive quenching:



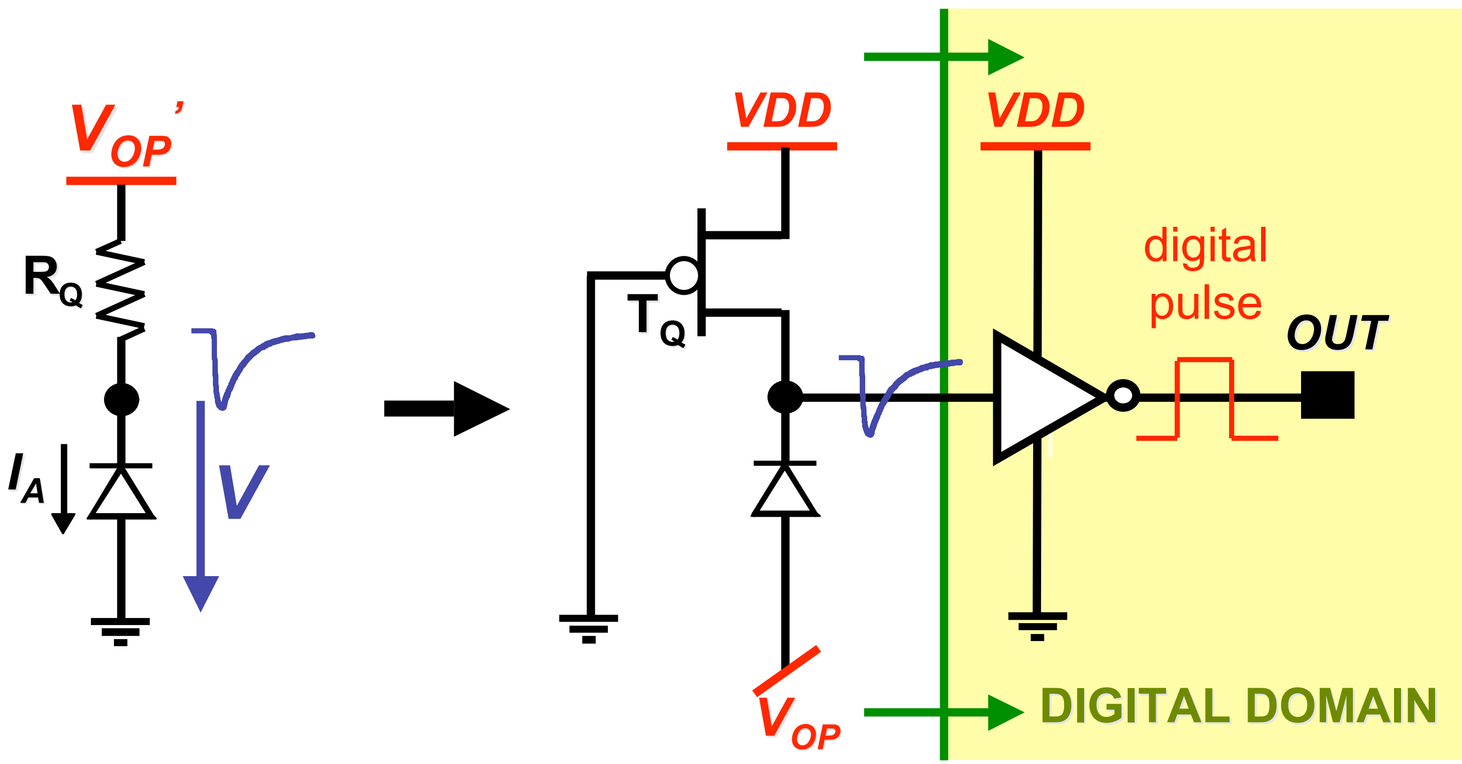
Operation cycle:



— One photon ➡ one cycle (dead time definition)

— Thermally generated carriers ➡ ***dark counts***

SPAD Implementation in CMOS

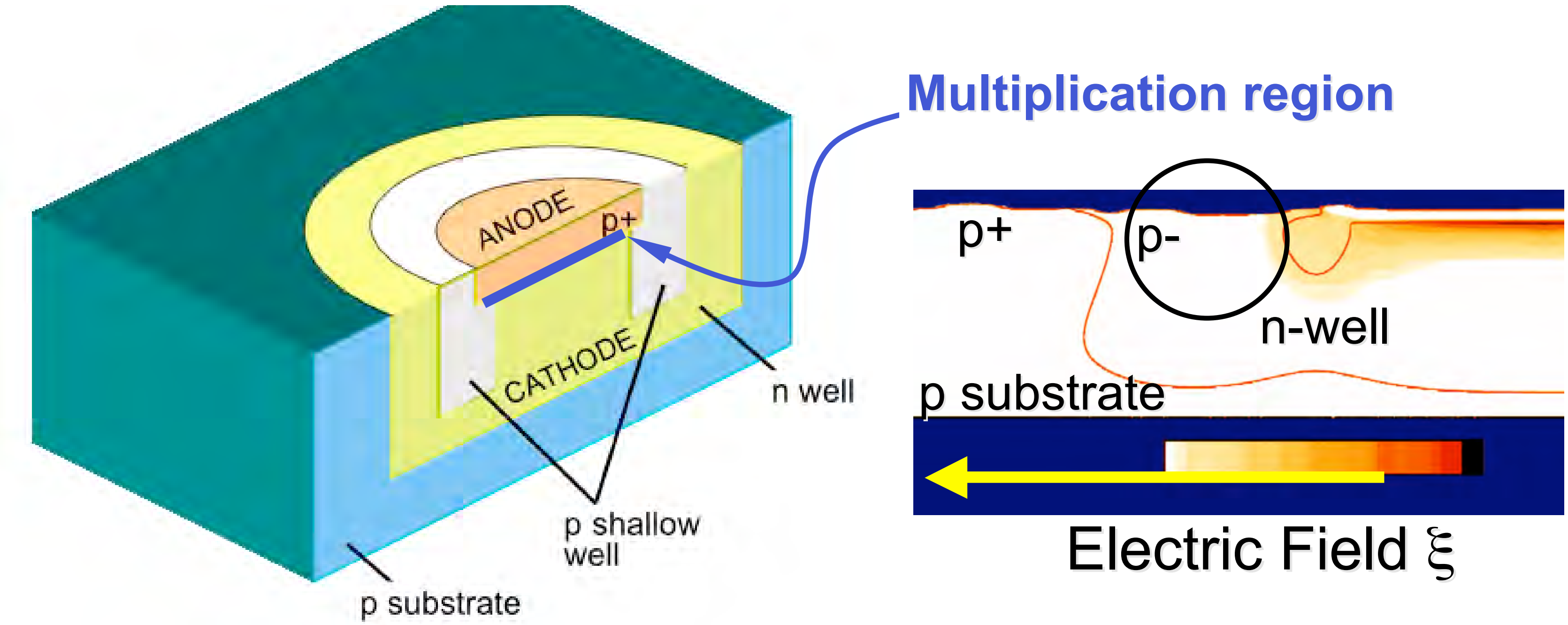


Other quenching techniques exist: e.g. active FB

[Cova *et al.* , Rochas *et al., etc.*]

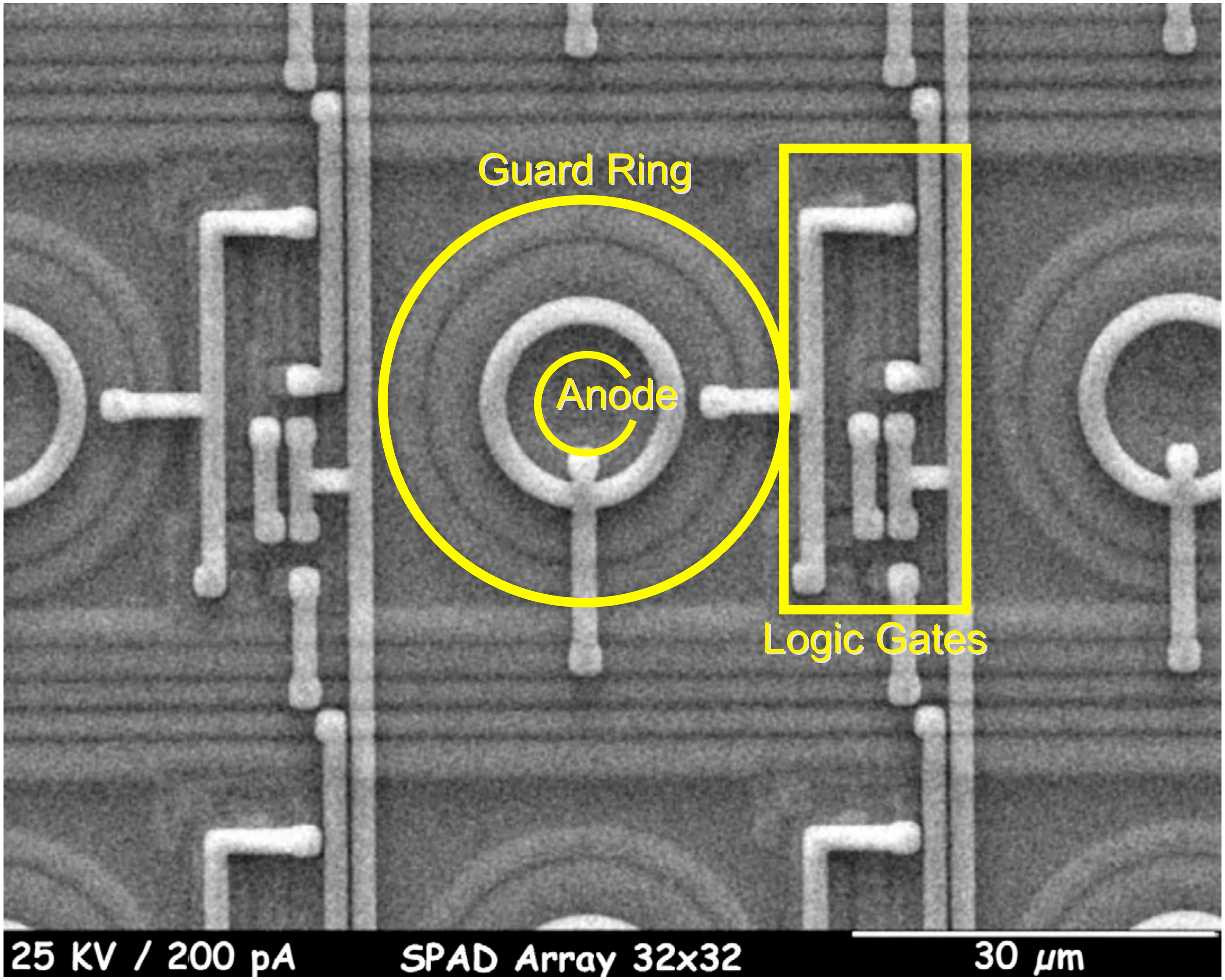
Fabrication Issues

- p- guard ring for electric field reduction in edges
- Prevention of premature edge discharge
- Creation of zone with constant electric field



Original idea proposed in the 1960s by Haitz and others

SEM Micrograph



[Niclass and Charbon, ISSCC05]

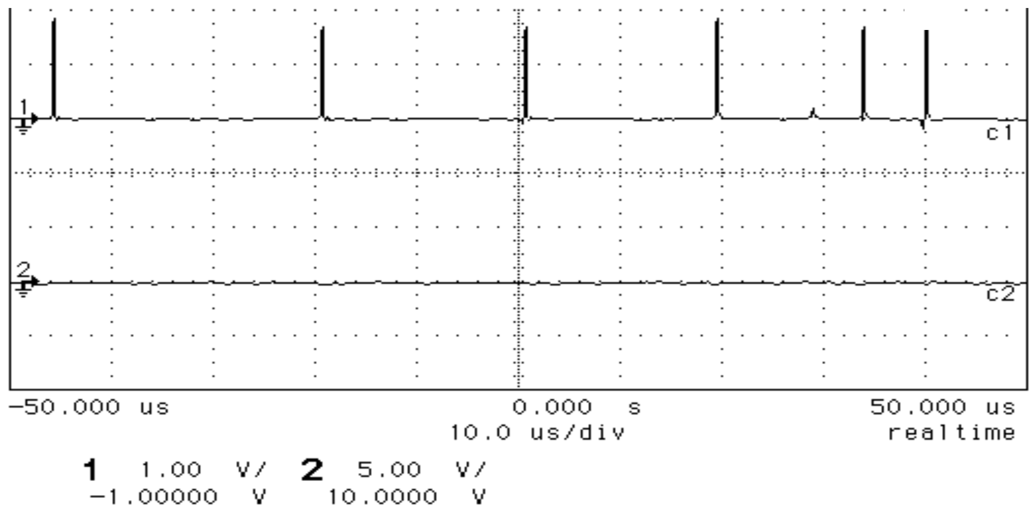
SPAD Salient Parameters

- **Dark counts**
  - Spurious pulses unrelated to photons
- **Photon detection probability** (PDP)
  - Probability of a photon triggering an avalanche
- **Timing resolution**
  - Uncertainty betw. photon arrival and pulse generation
- **Cross-talk**
  - Optical & electrical cross-pixel interference
- **Afterpulsing**
  - Spurious pulses related to photons
- **Dead time**

Dark Counts

Traps capture photocharges and release them randomly

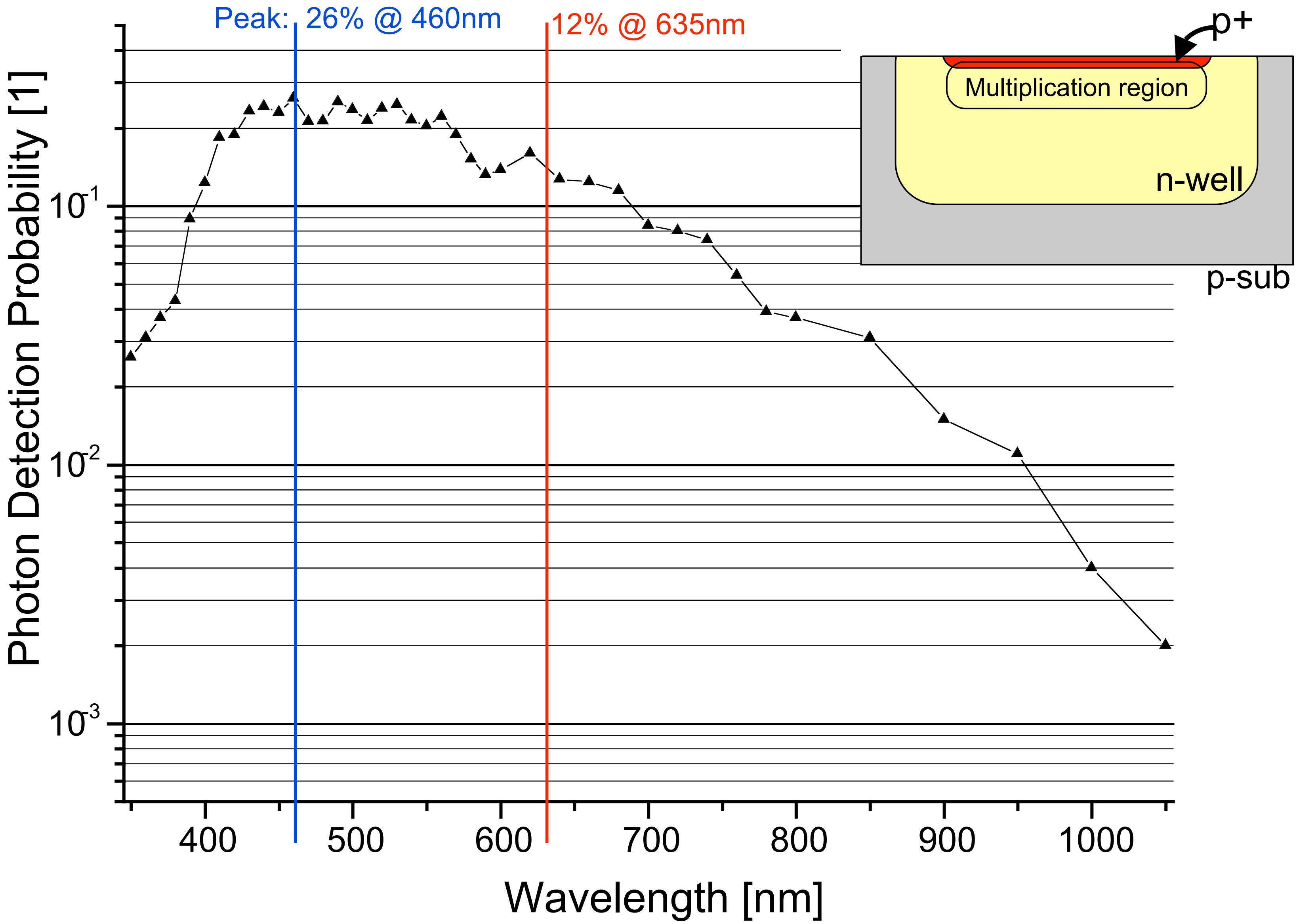
→ avalanche is triggered → spurious pulses



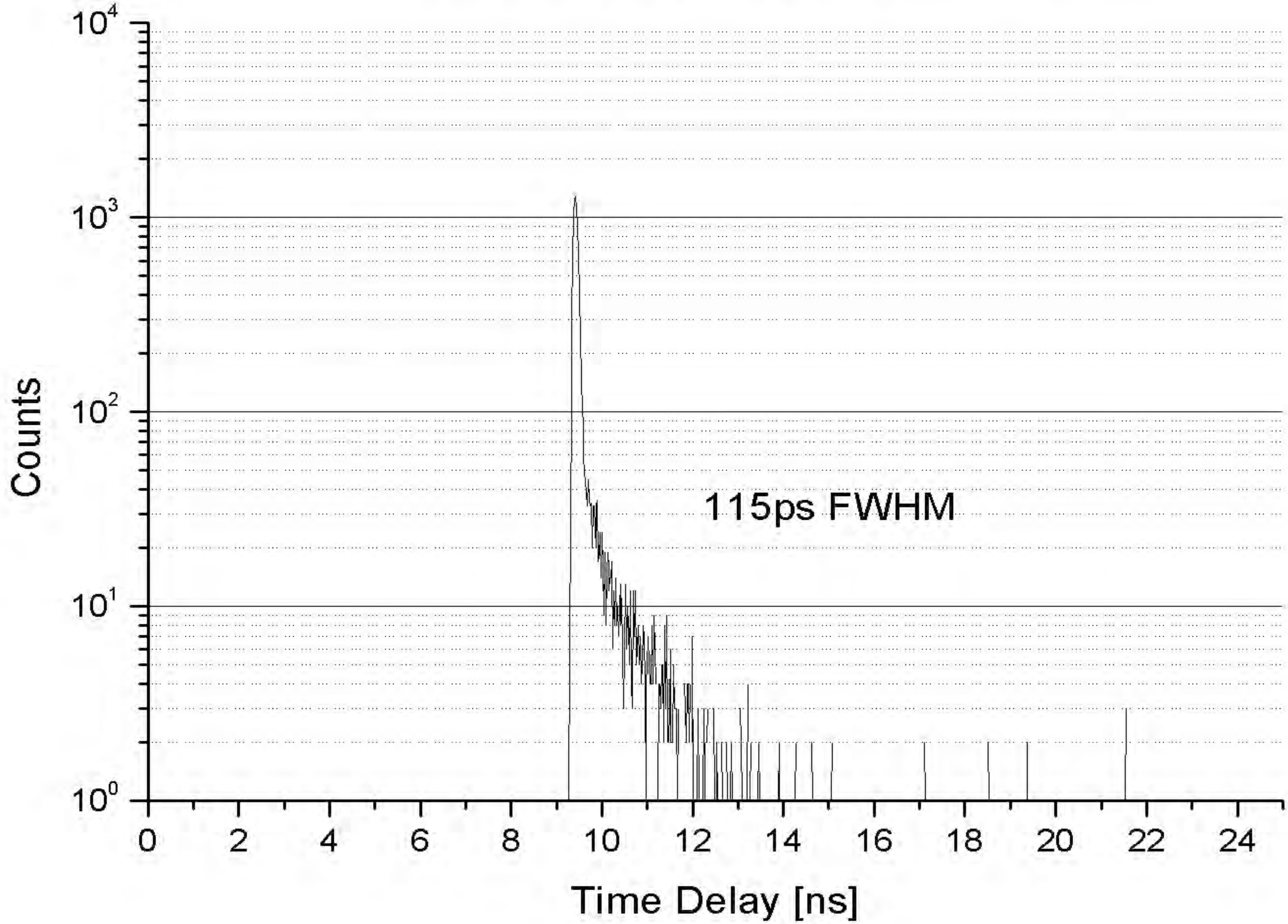
Mechanisms:

- Tunneling generation
- Trap-assisted thermal generation
- Trap/tunneling assisted generation

Photon Detection Probability

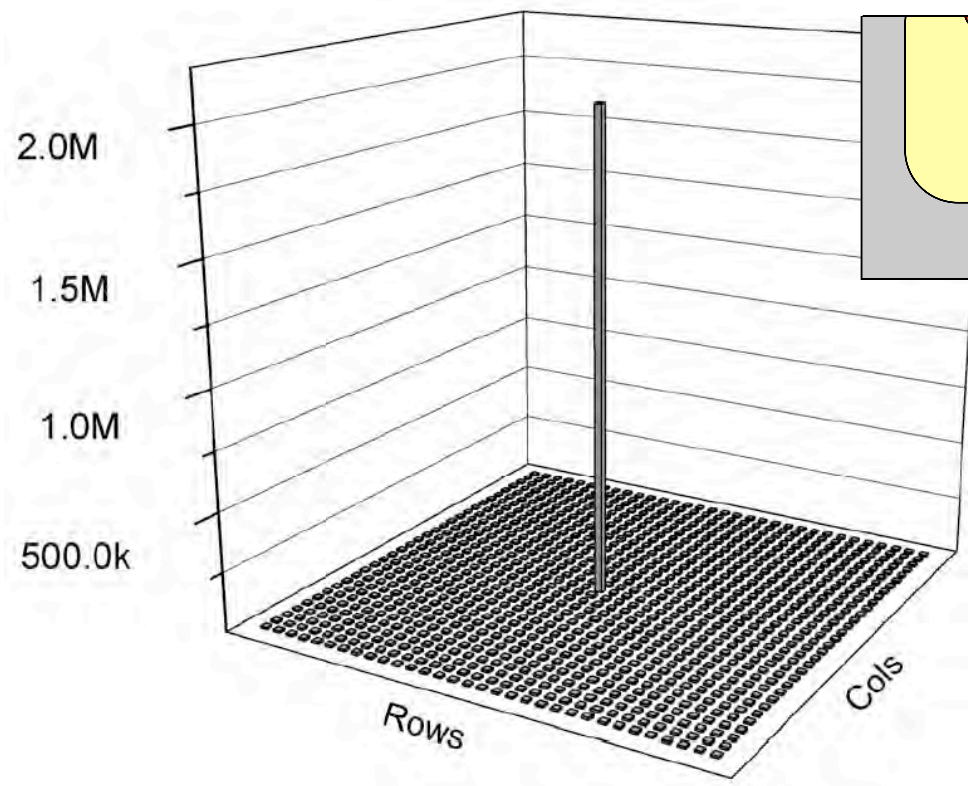


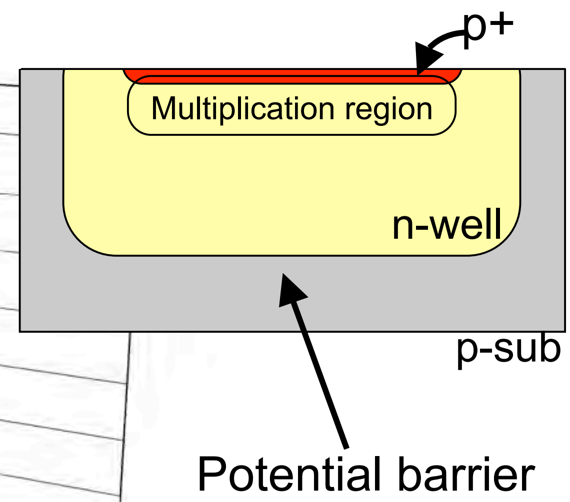
Time Resolution



Crosstalk

- Electrical cross-talk reduced by potential barrier
- Optical cross-talk alleviated by reduced number of carriers in avalanche





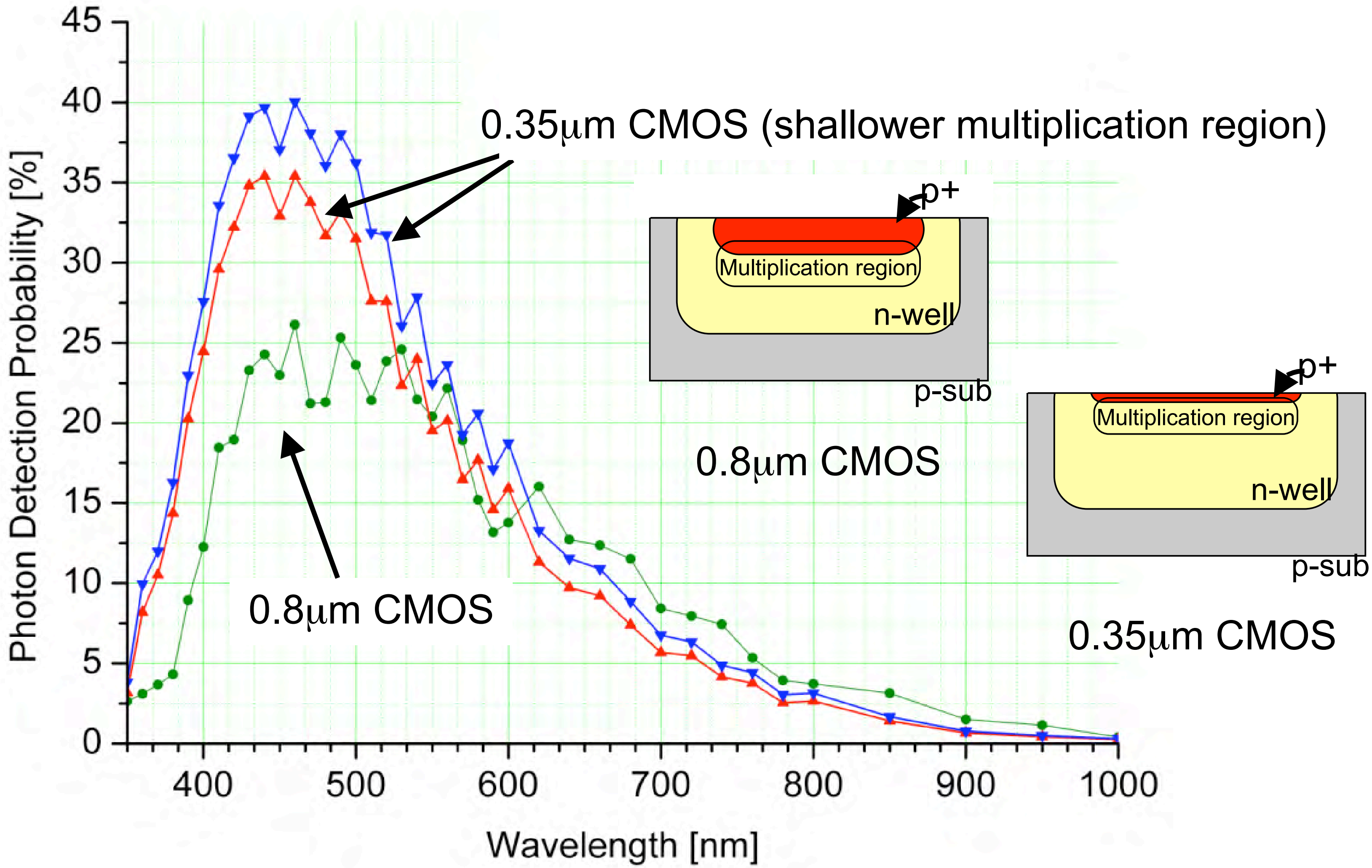
[Niclass, Charbon *et al.*, JSSC 2005]

Effects of Miniaturization

- Single photon counting can be performed on a small surface

- Reduced parasitic capacitance
  – Reduced **dead time**
  – Smaller photoemission due to avalanche, thus reduced probability of secondary avalanches
  – Reduced probability of **afterpulses** and **optical cross-talk**

Technology Migration



Single Photon Imagers

Challenges of Large Arrays

SPADs are digital, dynamical devices, they must be treated as such in designing the sensor architecture

Architectures

- Complexity in pixel
  - Fast (full parallelism)
  - Large pixels, small arrays
  - In general, low post-layout flexibility

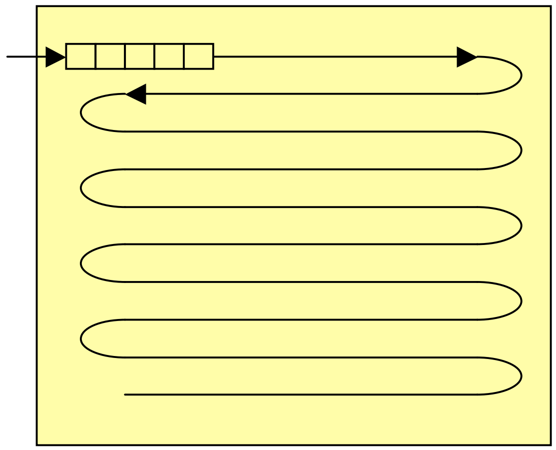
- Complexity in readout
  - Small pixels, large arrays
  - Slower processing
  - More post-layout flexibility

Architectures depend on implementation

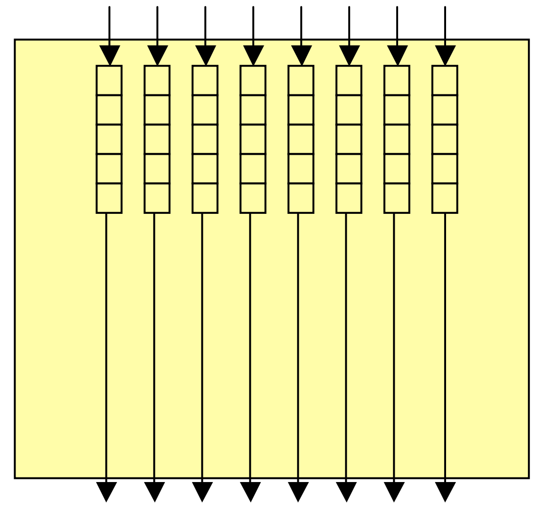
Readout Mechanisms

- Random access (sequential) readout
  - Column parallel
  - Pixel based
- Event-driven readout
- Pipelined readout

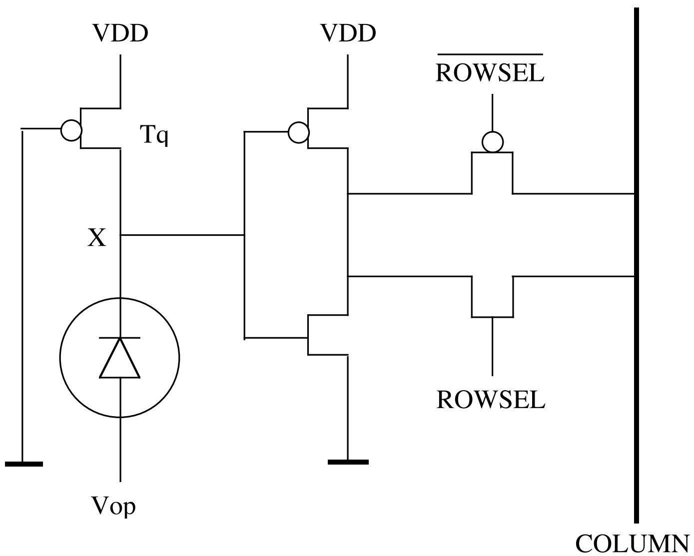
Random Access Readout

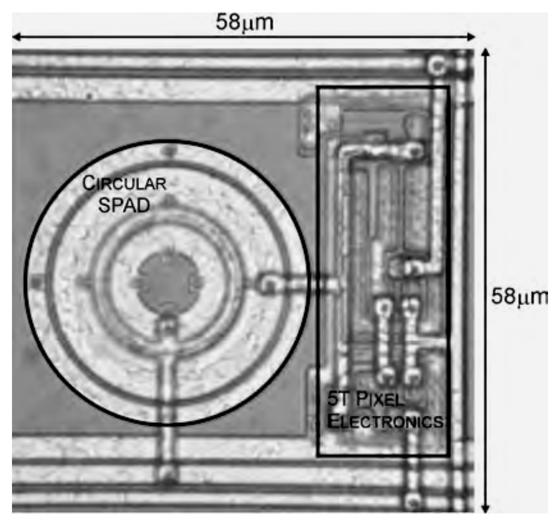


Pixel based readout (no parallelism)

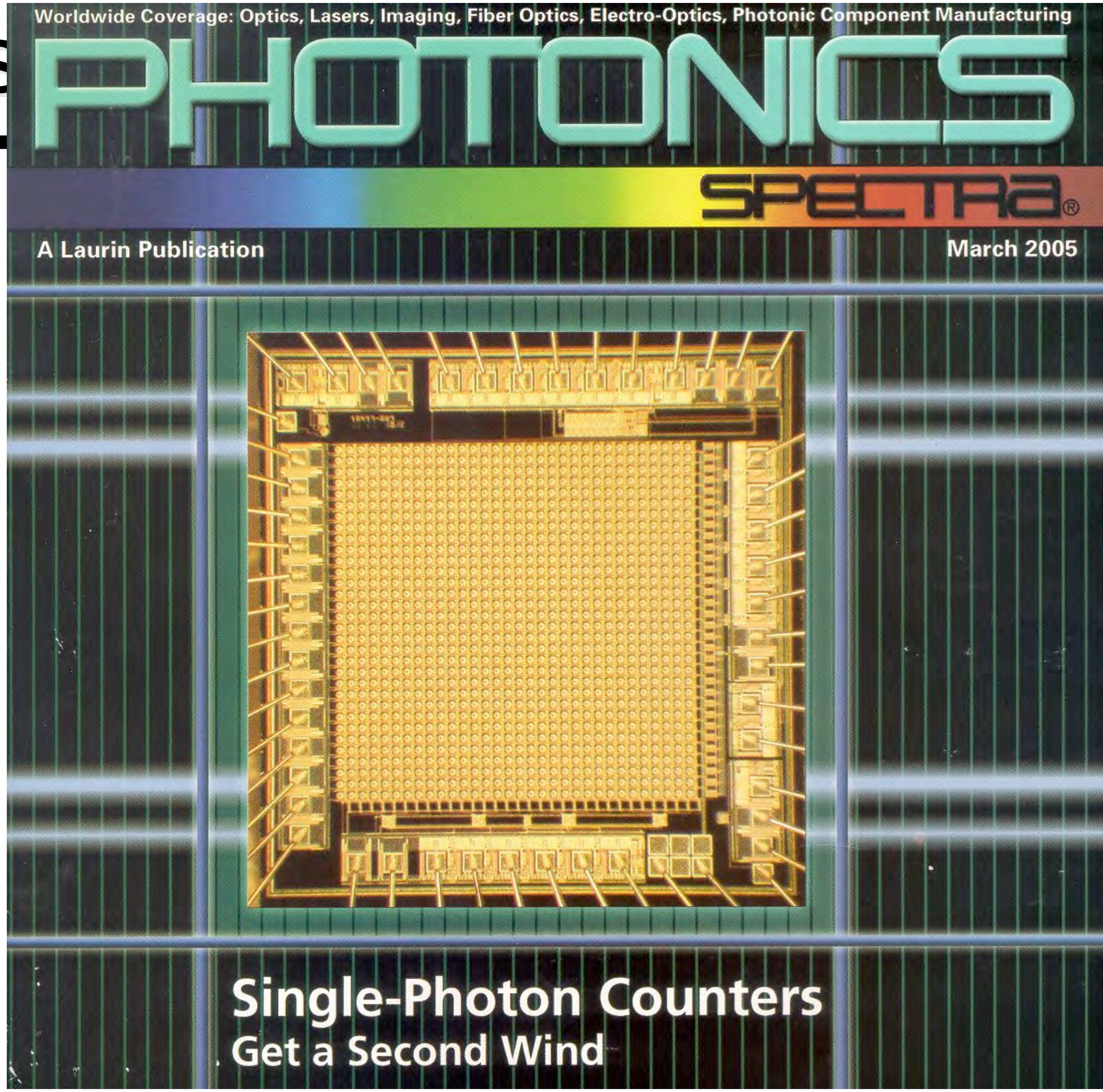


Column parallel readout (lmtd parallelism)





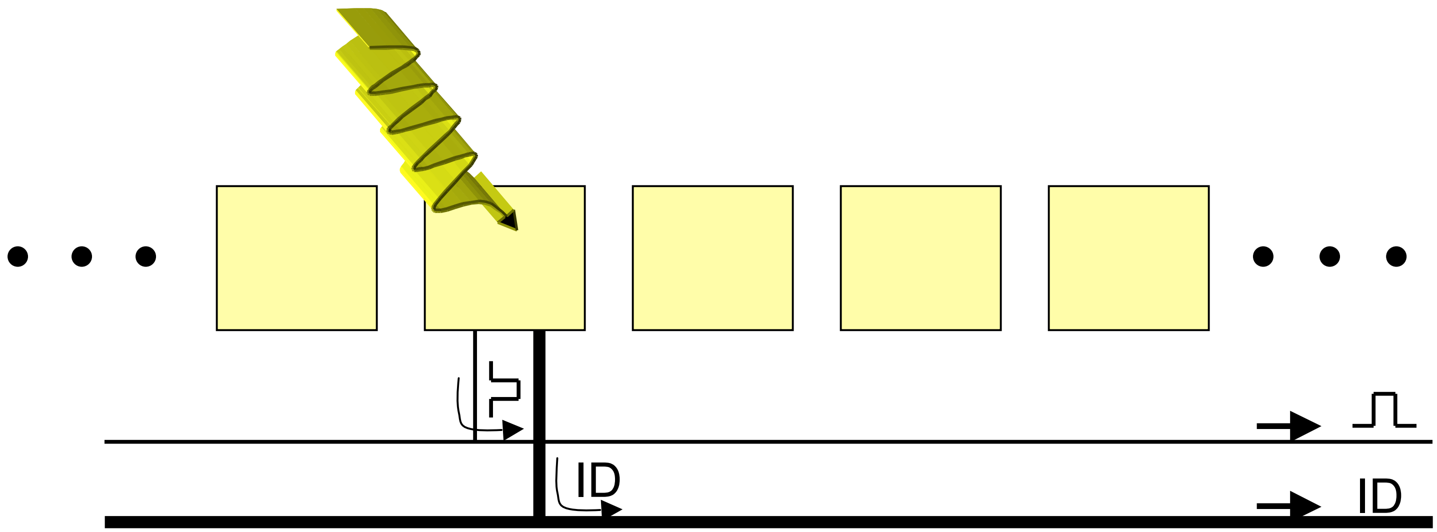
Firs… ray



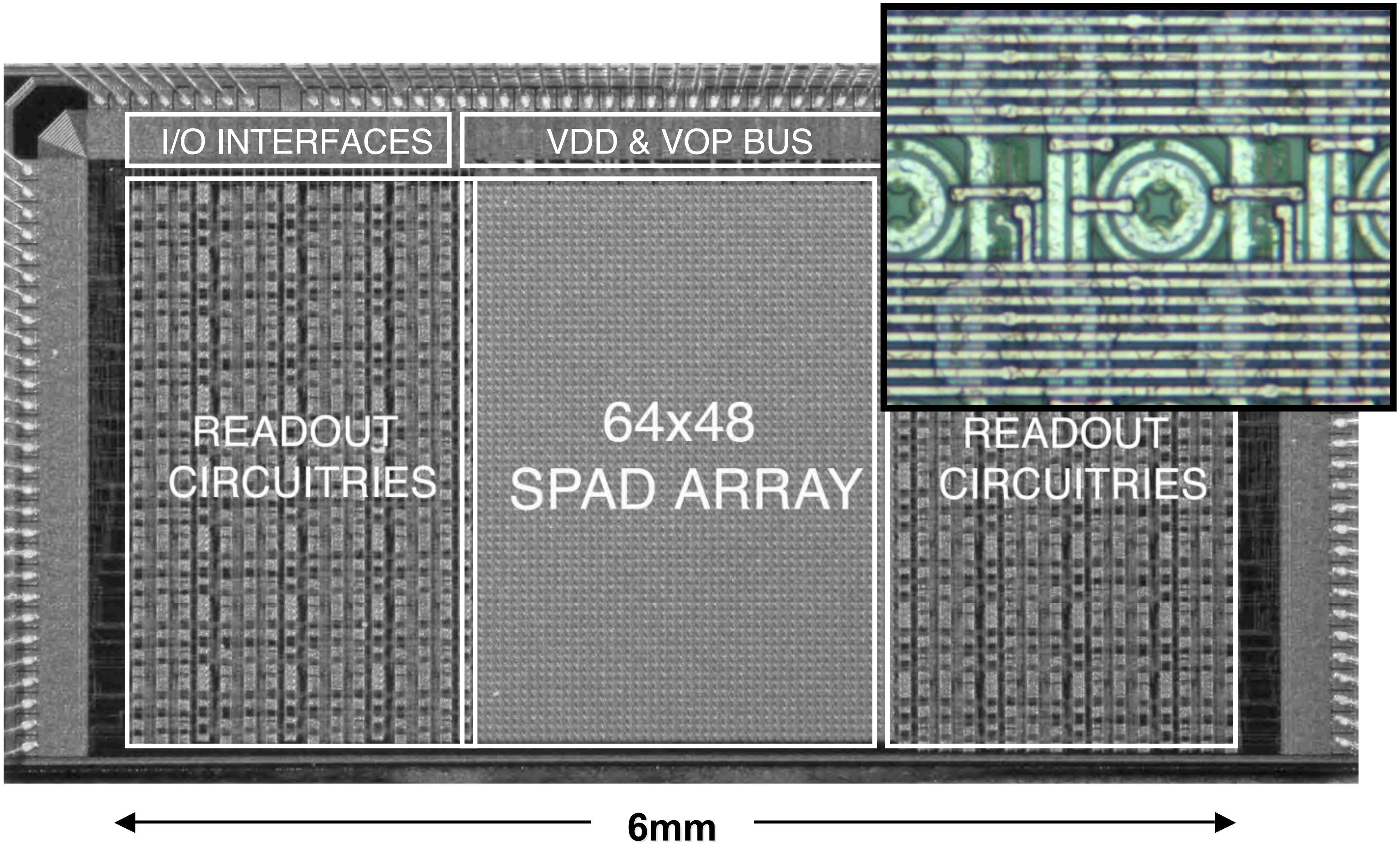
[Niclass, Charbon, ISSCC 05]

Event-Driven Readout

- Principle
  - Column becomes a timing preserving bus
  - A pixel hit by a photon transmits its ID
  - Timing pulse travels through the bus and is measured outside array

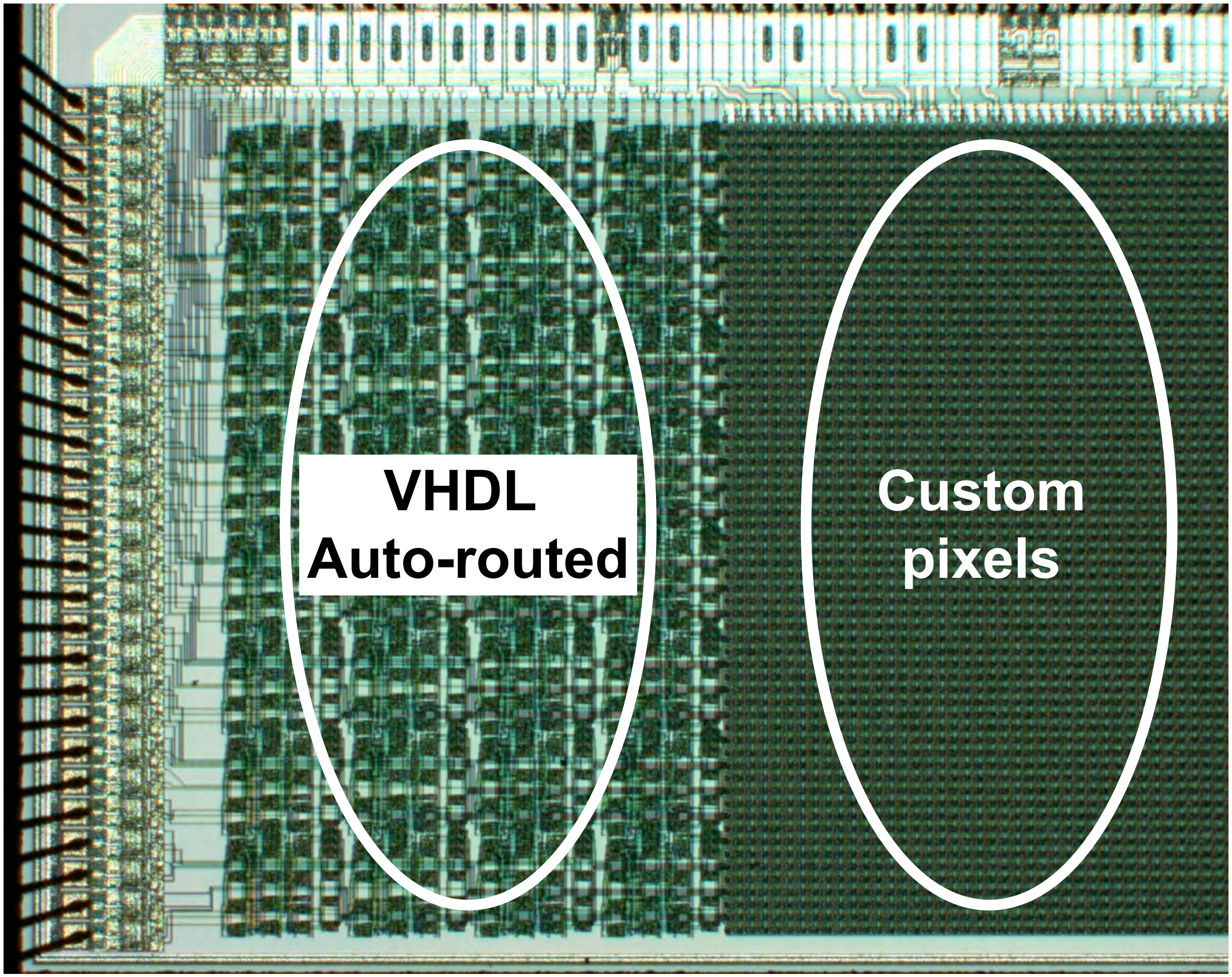


CMOS 64x48 Pixel Array



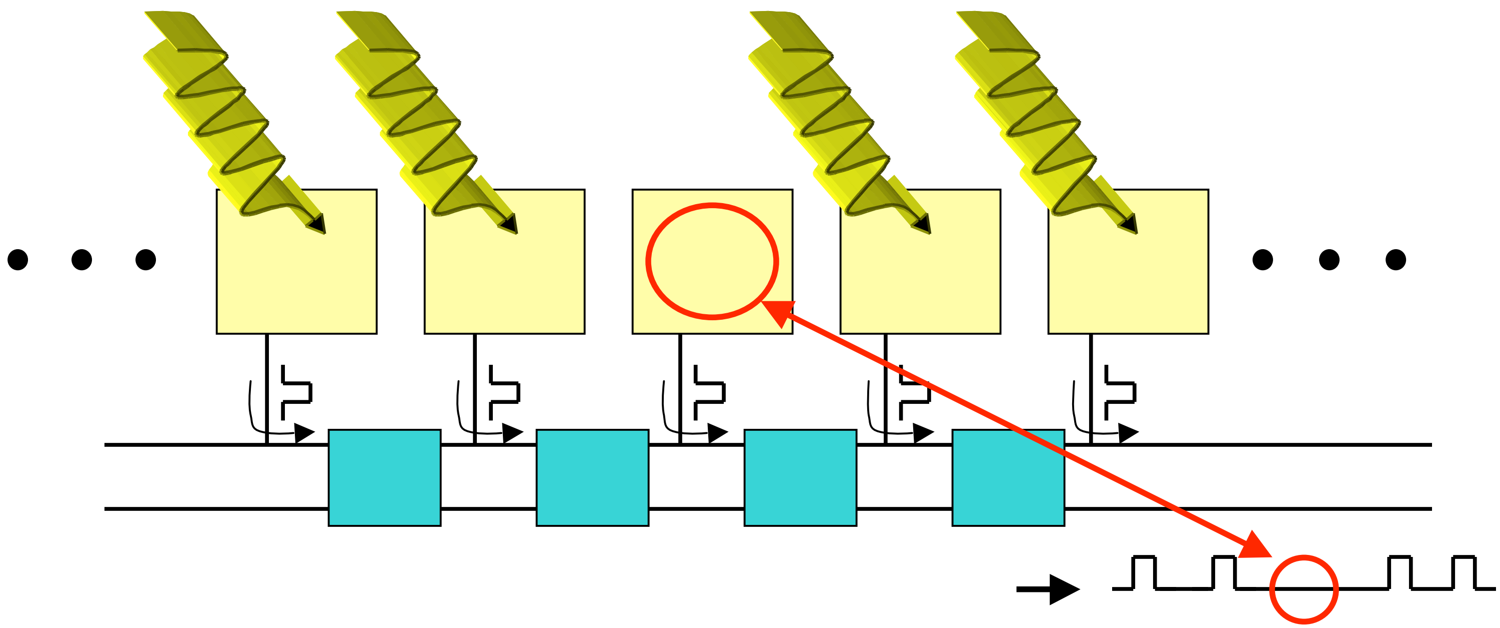
[Niclass, Sergio, Charbon, Esscirc 06]

Digital Pixel vs. Digital Readout

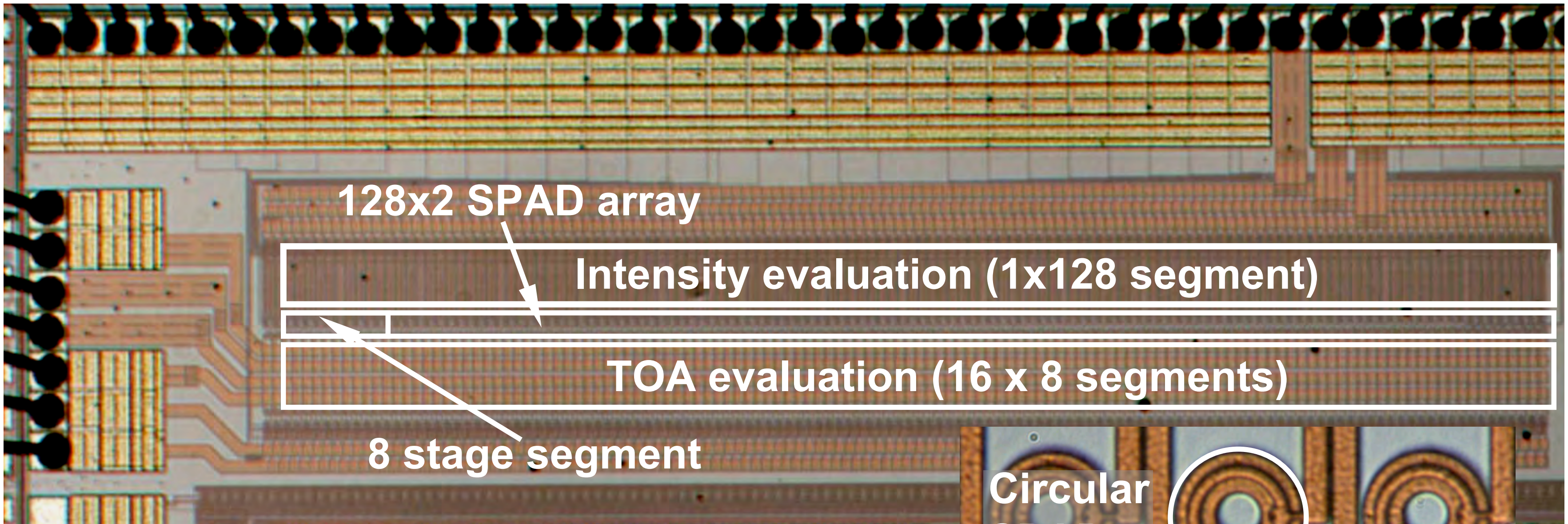


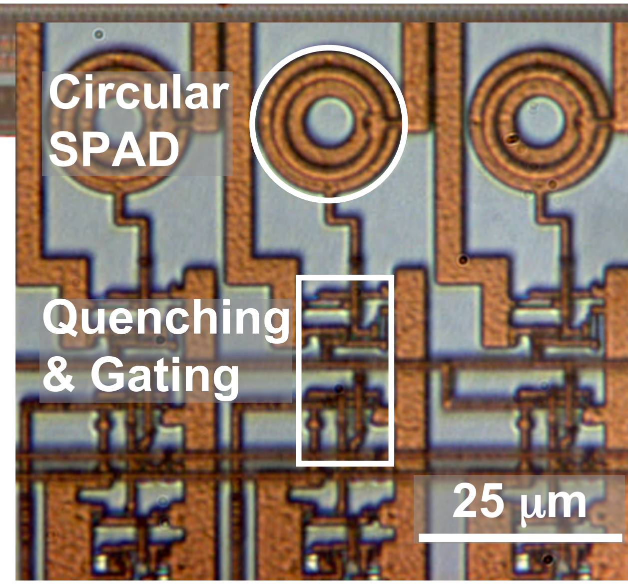
Pipelined Readout

- Principle
  - Column becomes a timing preserving bus
  - A pixel hit by a photon transmits the pulse in TDMA
  - Timing pulse travels through the bus and is measured outside array



CMOS 128x2 Pixel Array



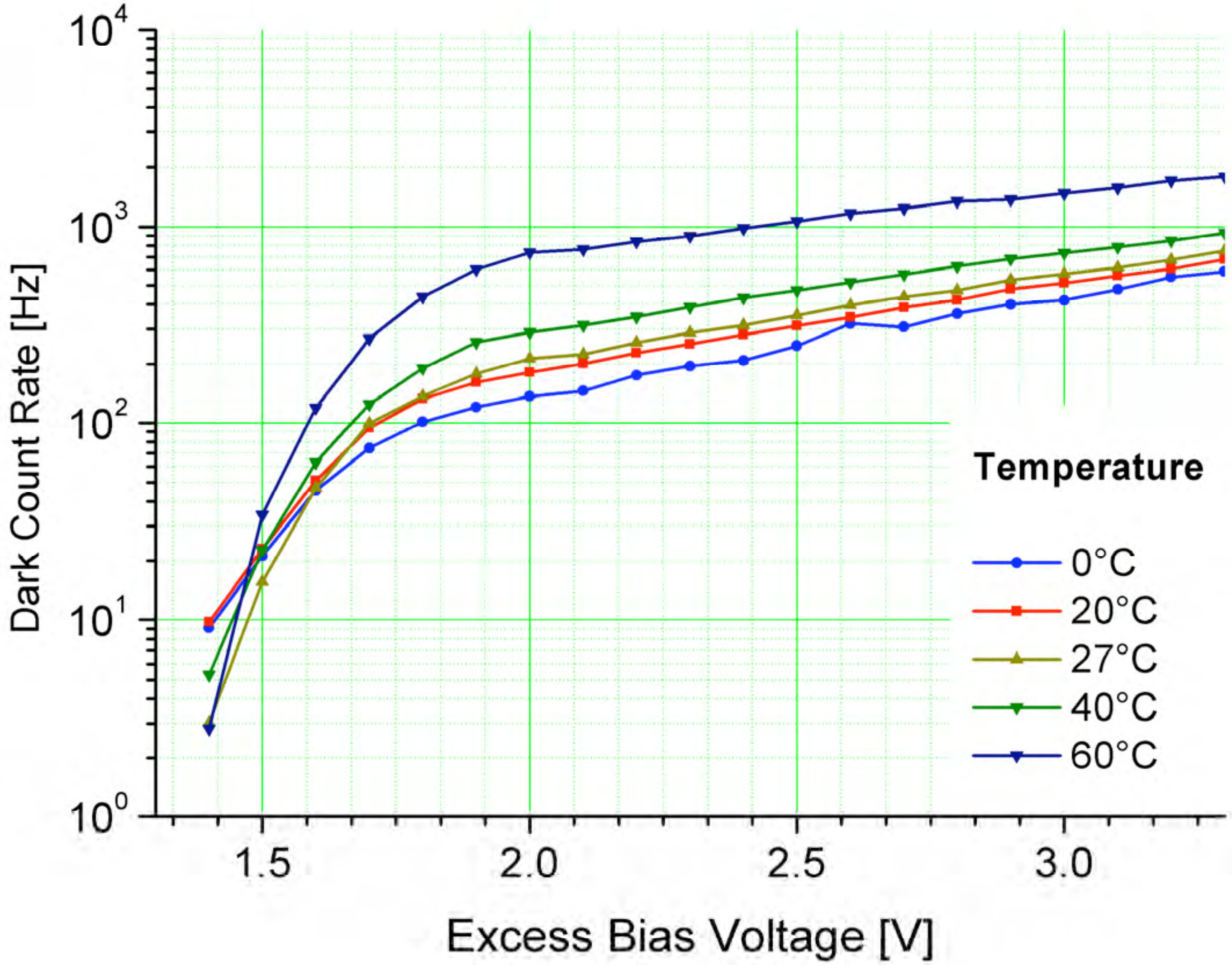


<u>Fabrication:</u>

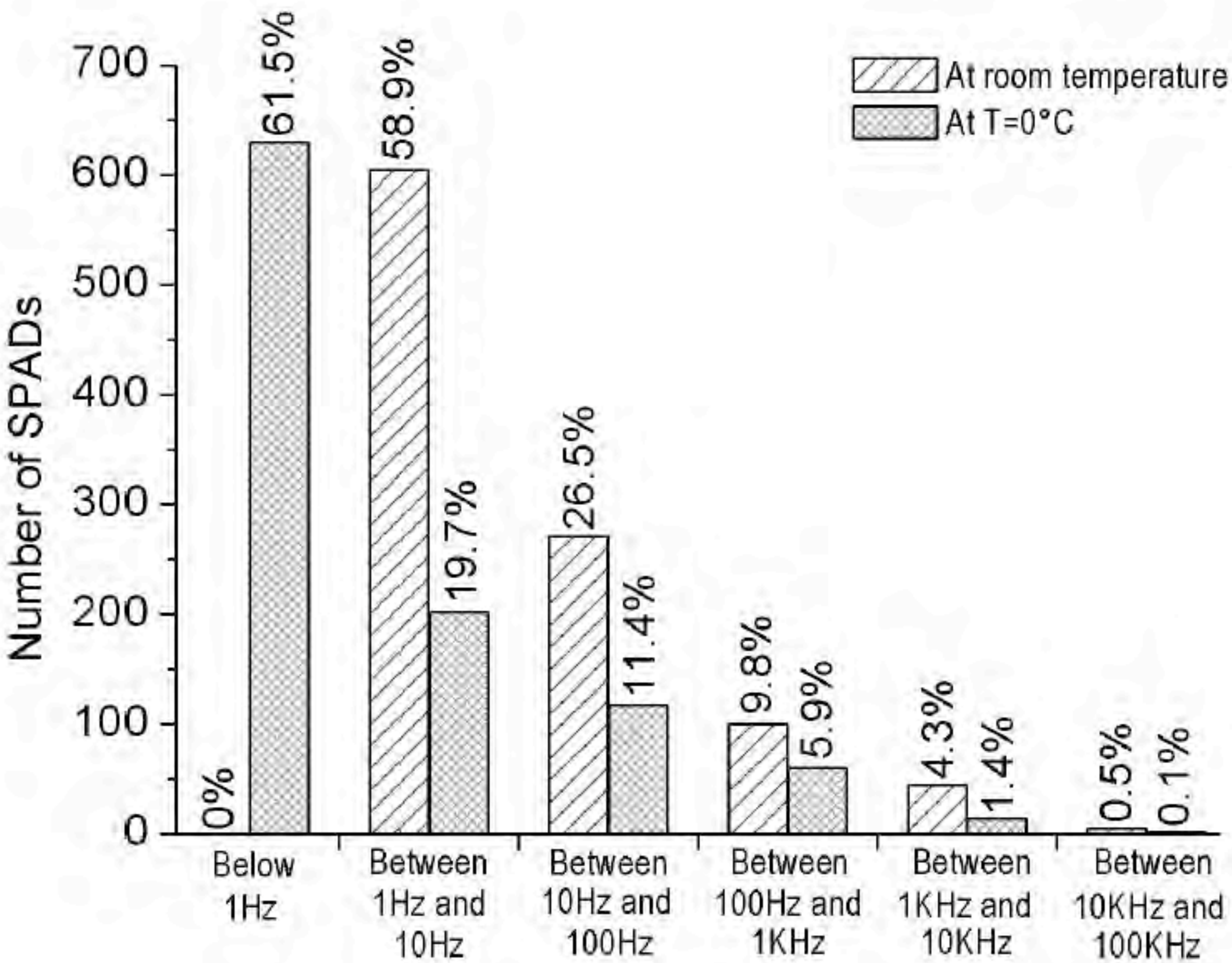
0.35μm CMOS technology
4.1 x 1.1mm^2

[Sergio, Niclass, Charbon, ISSCC 07]

Dark Count Rate (DCR)



DCR Distribution



Some Applications

⇒ 3D Vision

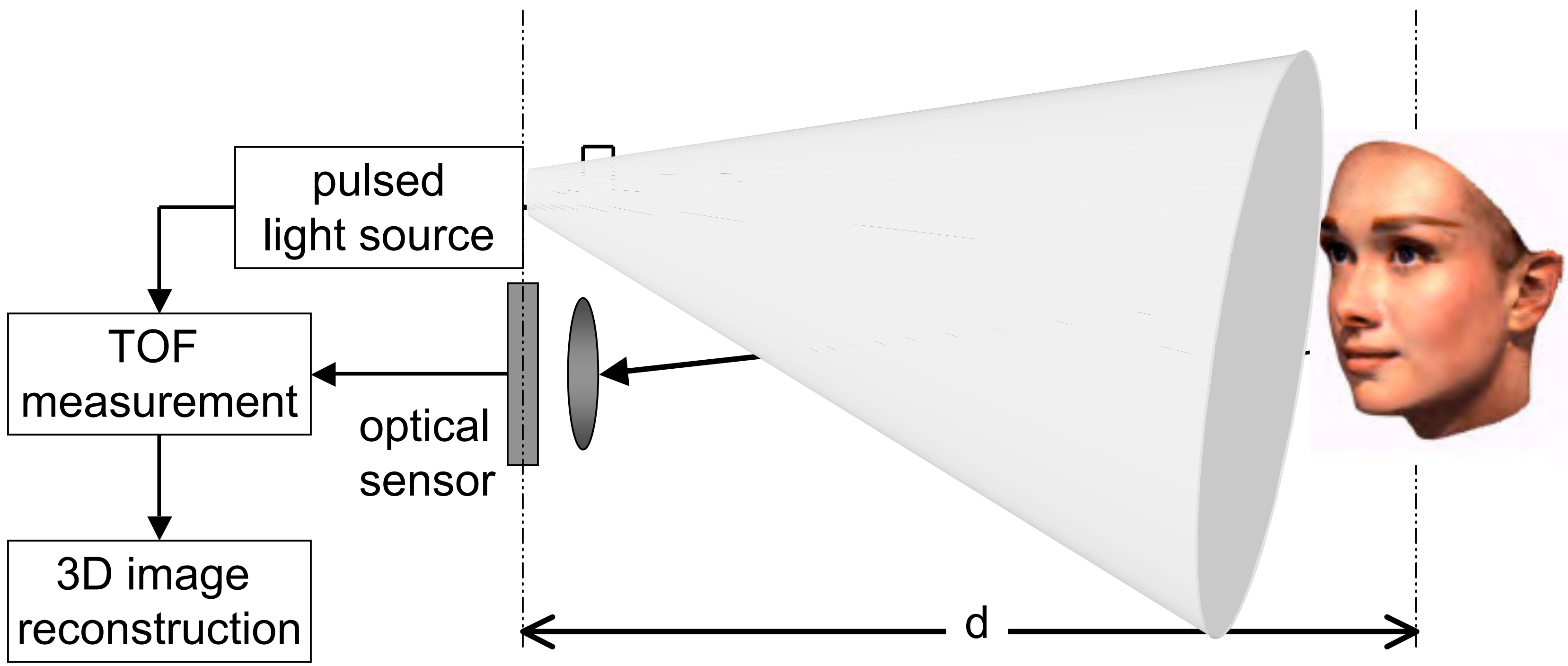
⇒ LLL/Ultrafast cameras

⇒ Room/T chemiluminescence detection

⇒ Multi-photon fluorescence

⇒ *In situ* single-photon counting

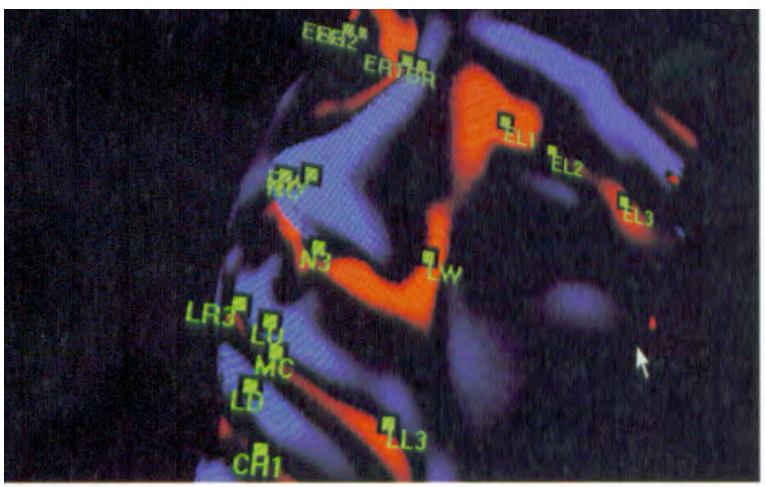
3D Vision: Time-of-Flight



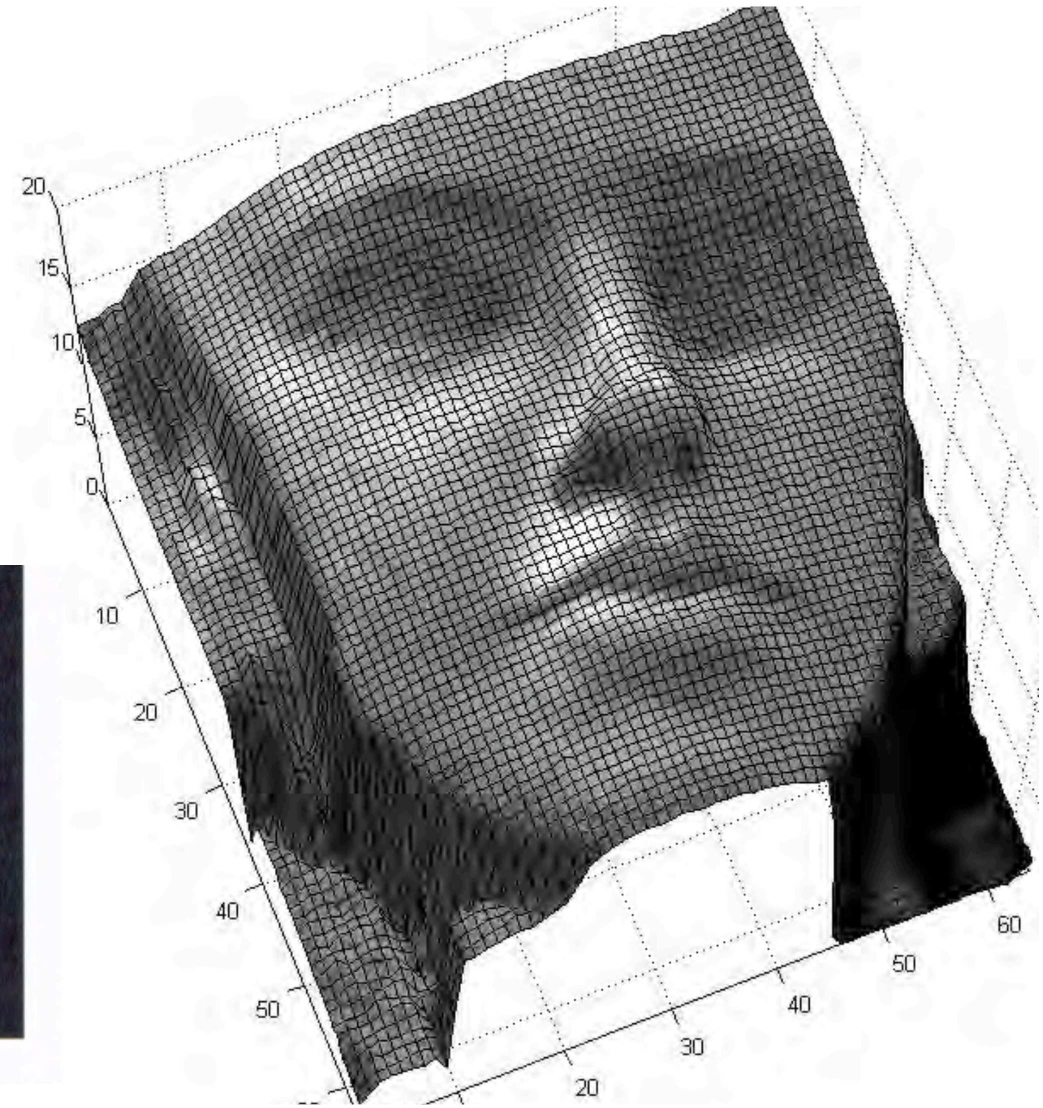
d = (c/2) TOF

Depth Map Example

- Lateral resolution:
  - 64x64 pixels
- Depth resolution:
  - 1.3mm (wc)
- Range:
  - 3.75m



Example: face recognition



[Niclass and Charbon, ISSCC 2005]

High Speed

Features

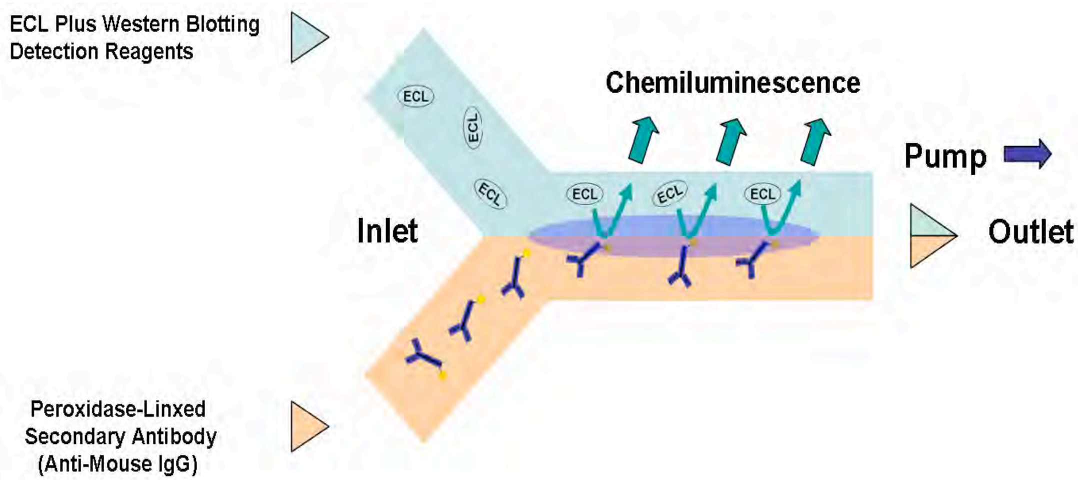
– No measurable thermal noise (Poisson noise dominates)

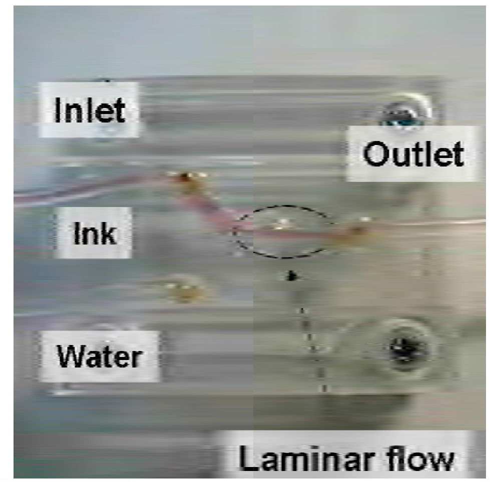
– No measurable cross-talk, blooming, smearing

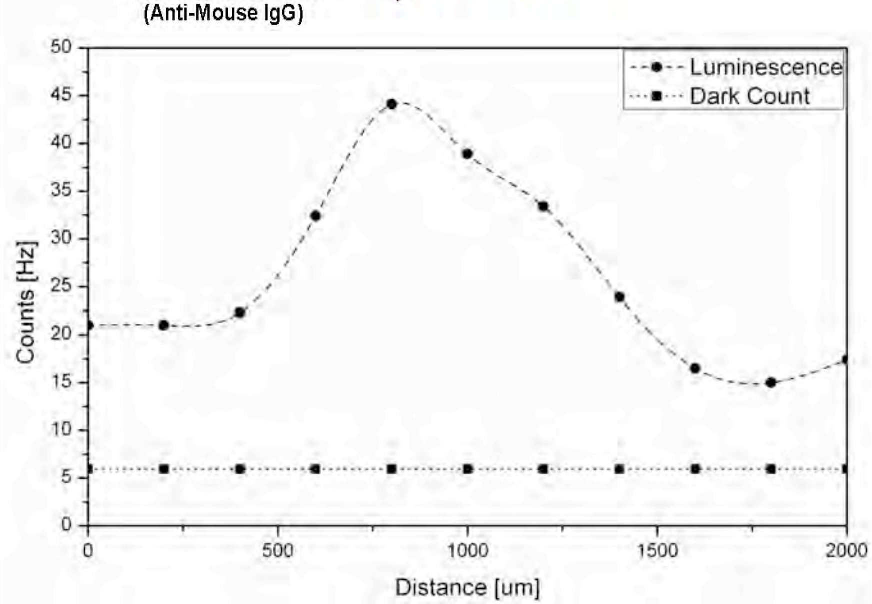
4μs 10μs 25μs 100μs 1ms

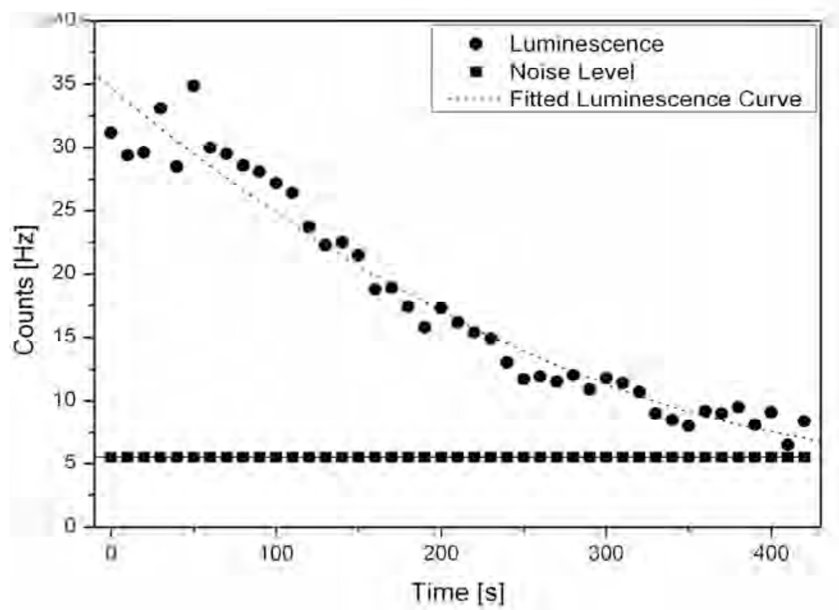
[Niclass, Rochas, Besse, Popovic, and Charbon, Transducers 2005]

Chemiluminescence Reactor





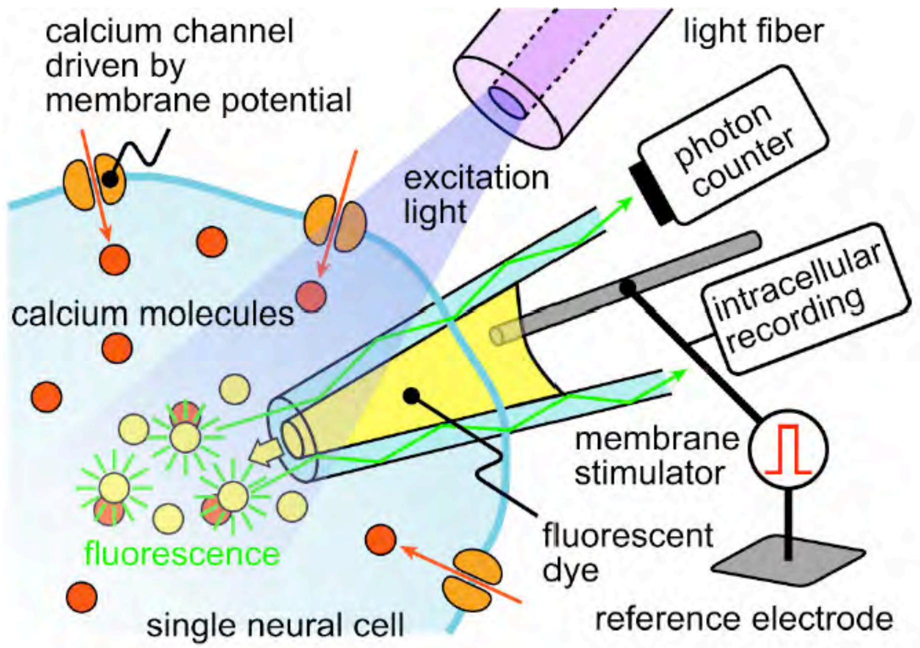




[Gersbach, Maruyama, Sawada, Charbon, μ*TAS*'06]

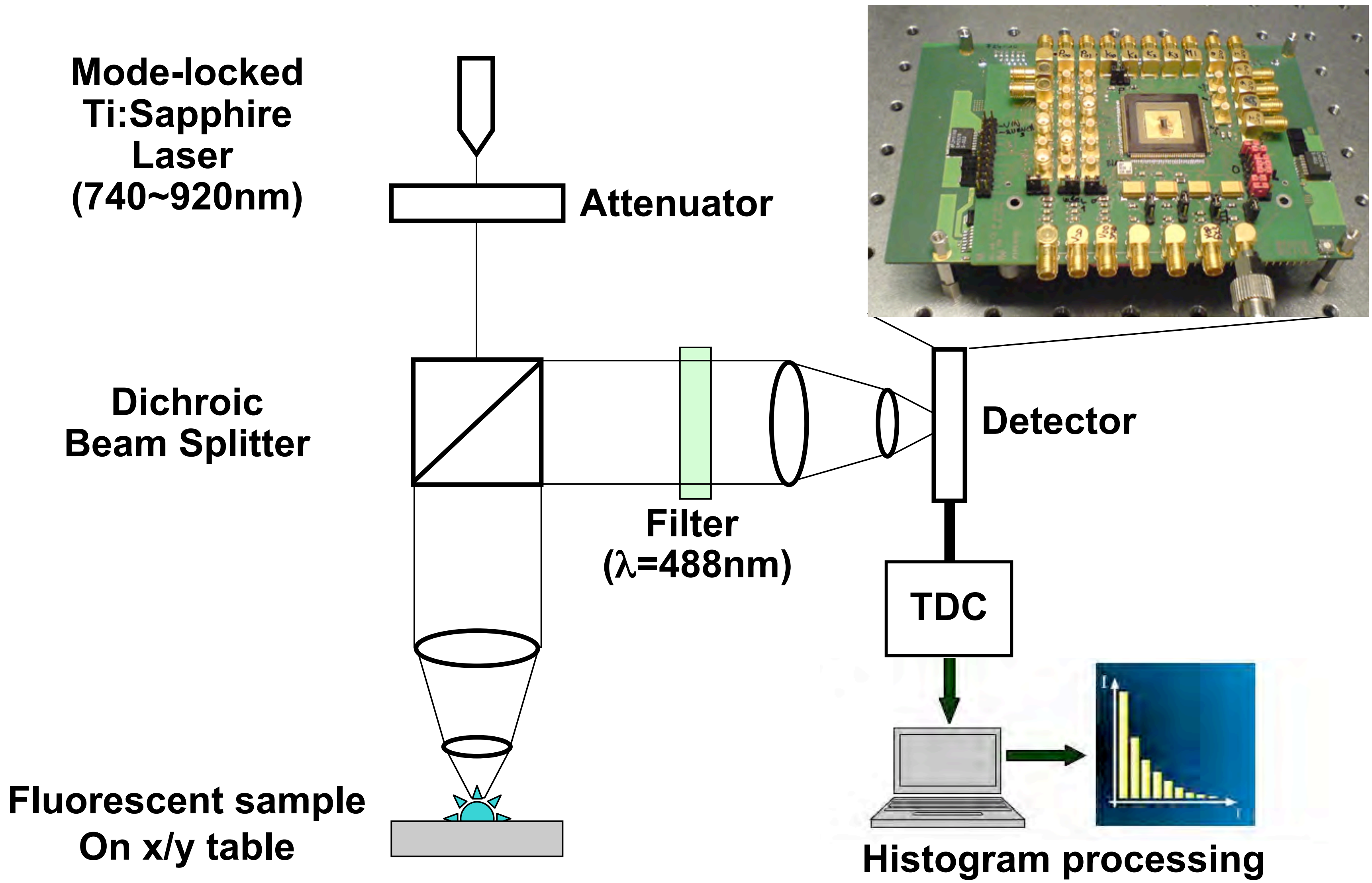
Calcium Signaling / Patch Clamp

- Monitor ion channels in sensory cortex
- Stimulation via patch clamp



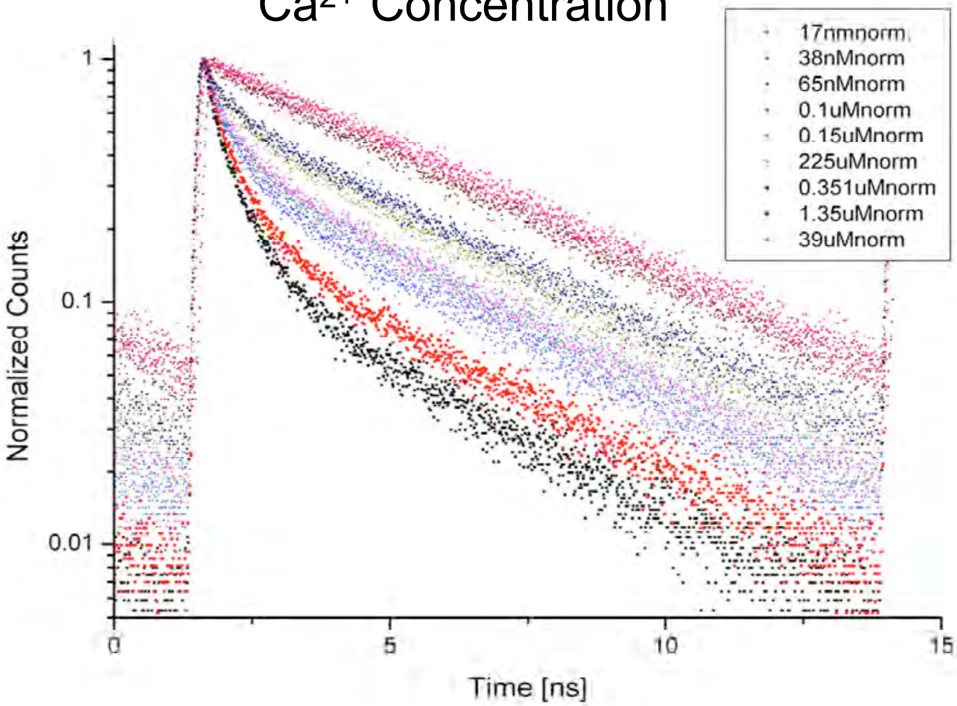
[Nagasawa et al., Transducers 2005]

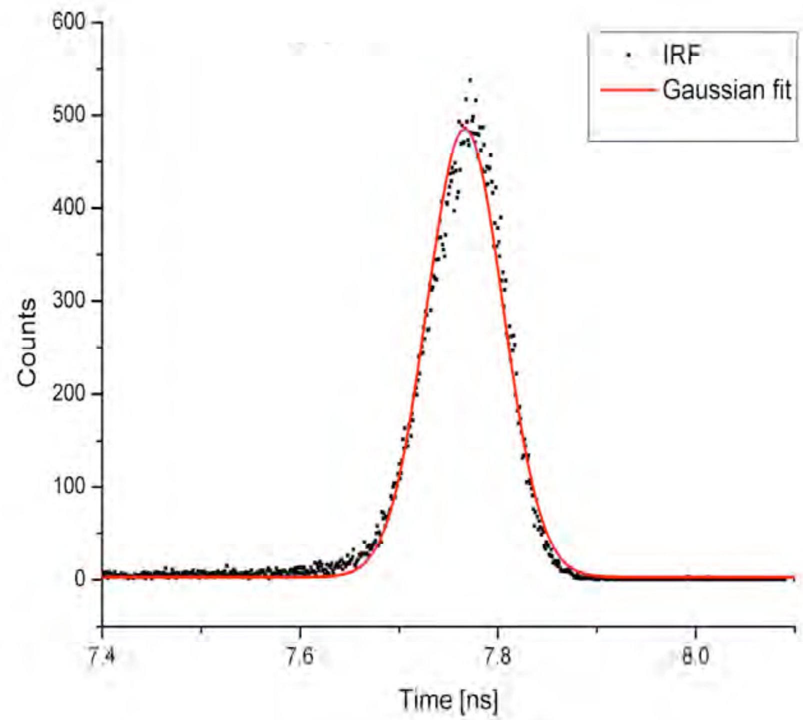
Confocal FLIM Optical Setup



Integrated Two-Photon FLIM

Ca^{2+} Concentration





- X Wavelength: 800nm
- Response: 400~430nm
- Rep. Rate: 80MHz
- Output Freq.: 19kHz
- Avg. power output: 0.5W
- Eff. Avg. power: 35mW

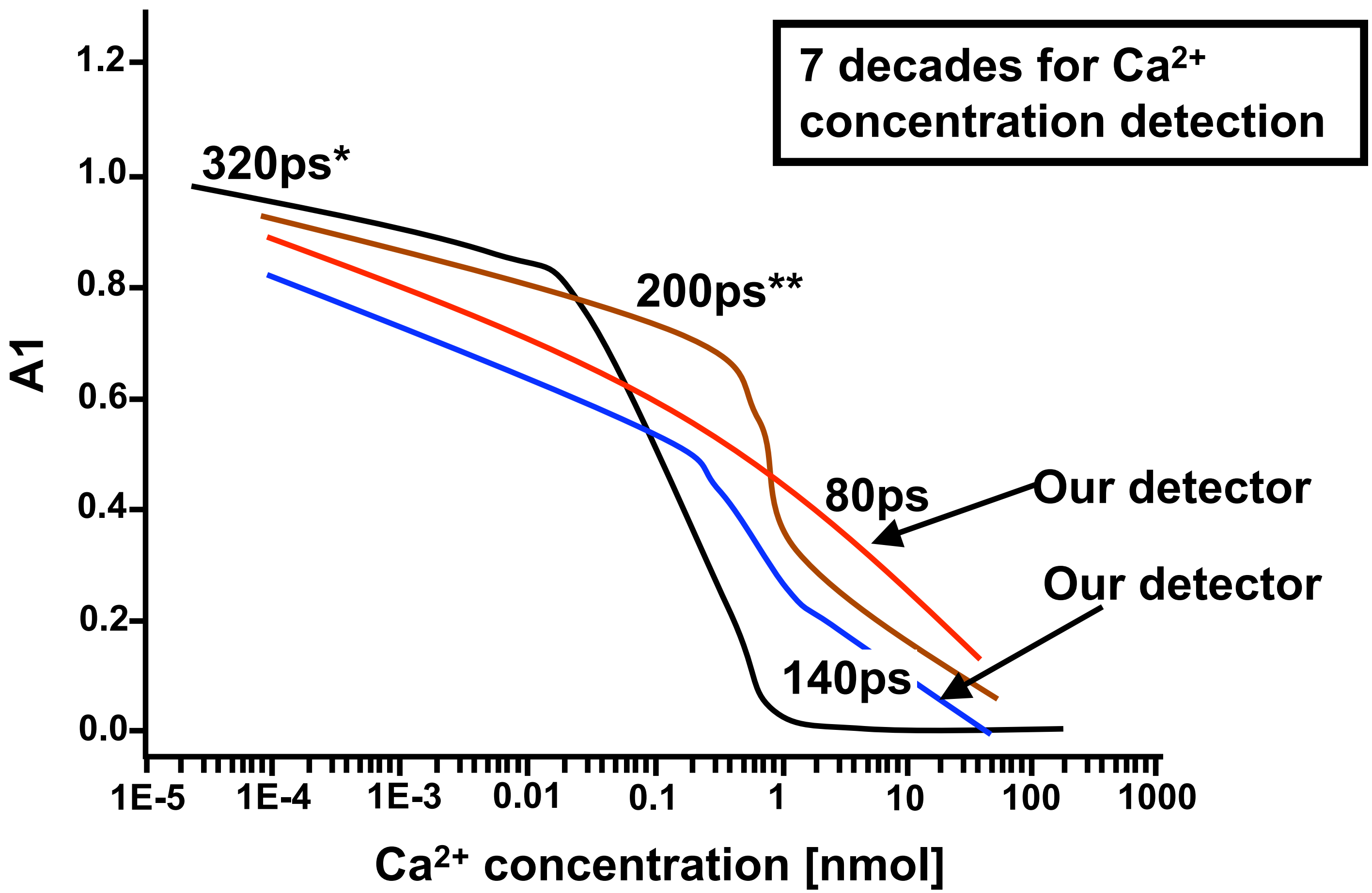
<u>Fluorophore:</u>
Oregon Green Bapta-1

[Gersbach, Charbon, *et al.*, CLEO-Europe, 2007]

New Results

- Thanks to an IRF FWHM of 79ps, we observed a triple-exponential fit for OGB-1 as predicted by Wilms
- Increased dynamic range of Ca^{2+} Signaling

New Results (Cont.)

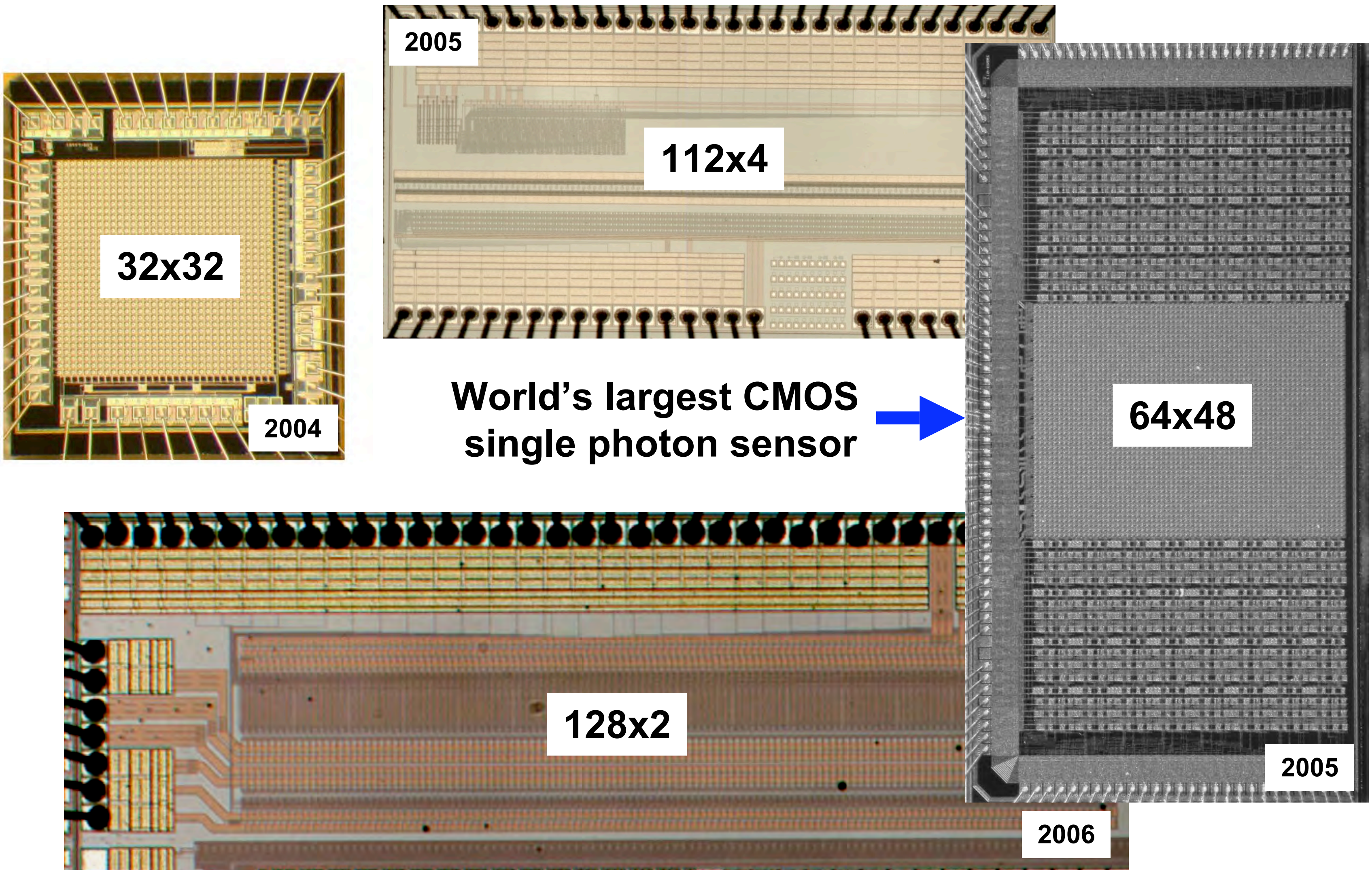


** [Wilms 2006]

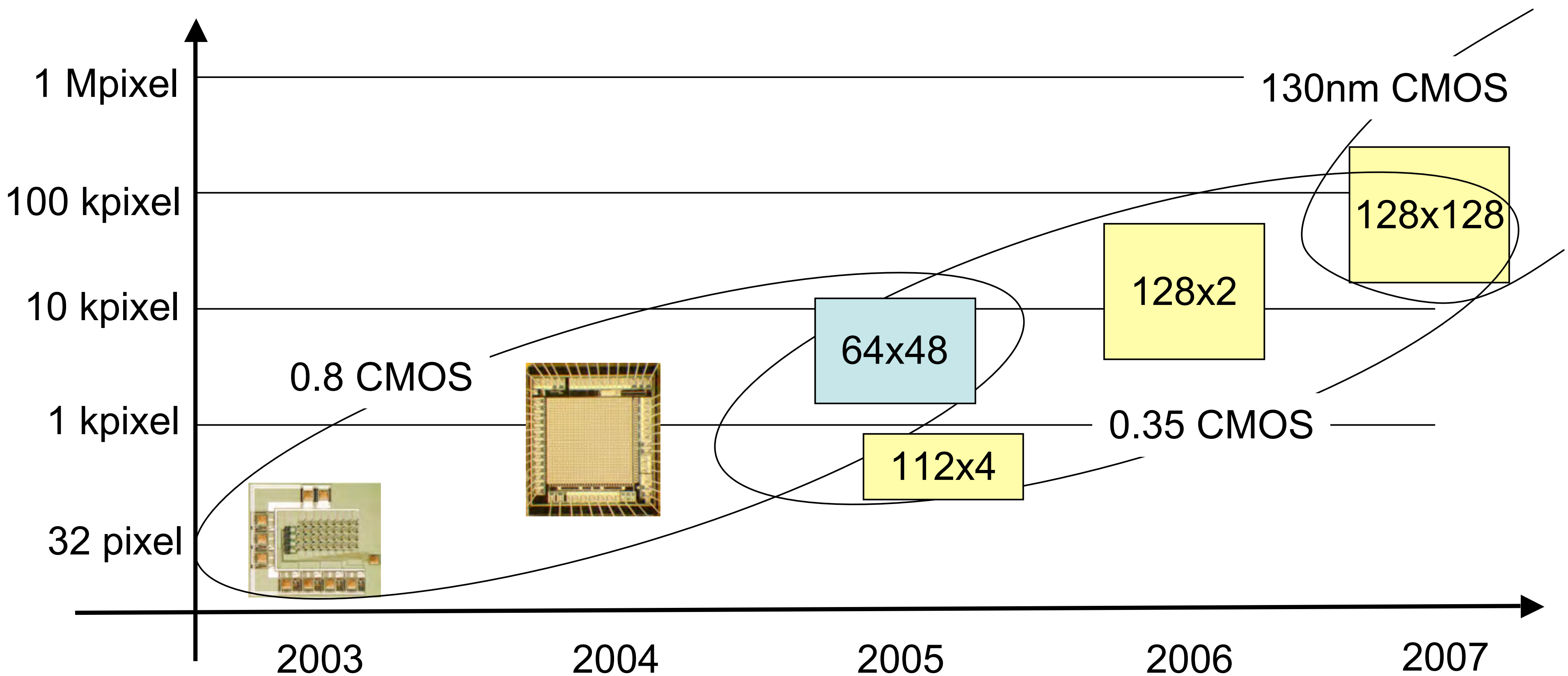
* [Agronskaia 2004]

Next Generation Systems

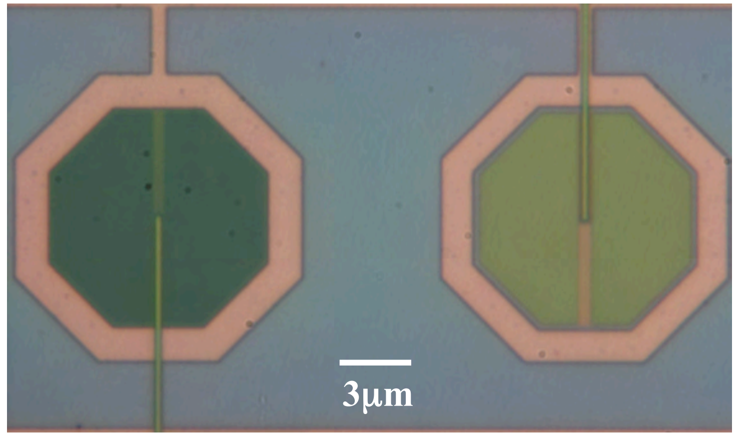
EPFL Single Photon Sensor Family



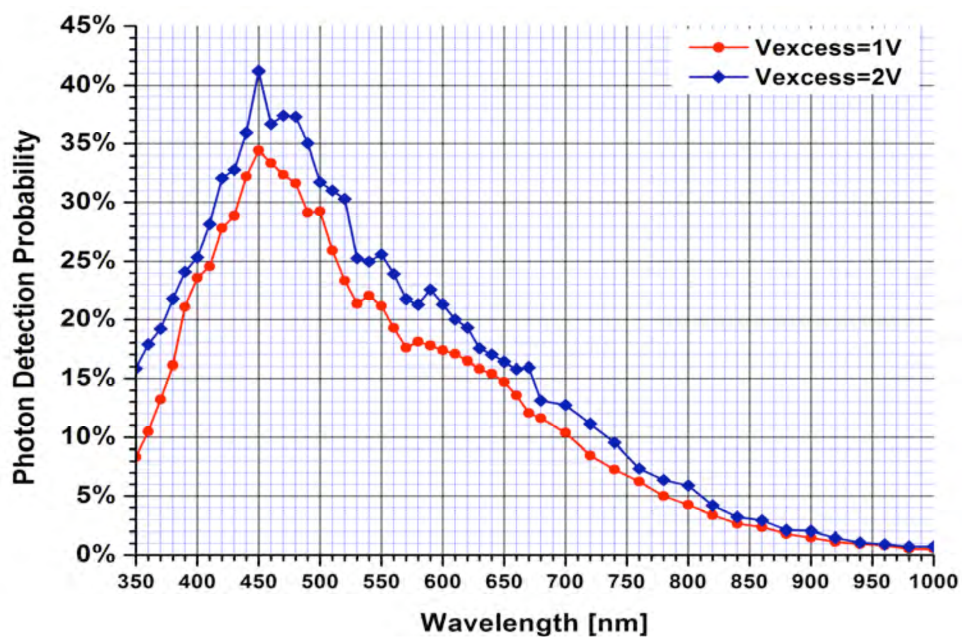
EPFL Imaging Roadmap



Deep Submicron Detectors



CMOS 130nm



[Niclass, Gersbach, Henderson, Grant, and Charbon, JSTQE'07]

Conclusions

- Picosecond time resolution (1~100ps)
- High number of pixels (64x64 ~ 1Mpixels)
- High frame rates (1Mfps in continuous mode)
- High intensity saturation levels (10x improvement)
- High sensitivity (single photon)
- Low power

The AQUA Group

The <u>AQUA Group</u> was started in June 2003. It is funded by the Swiss National Science Foundation, the European Commission, and the European Space Agency.

http://aqua.epfl.ch/