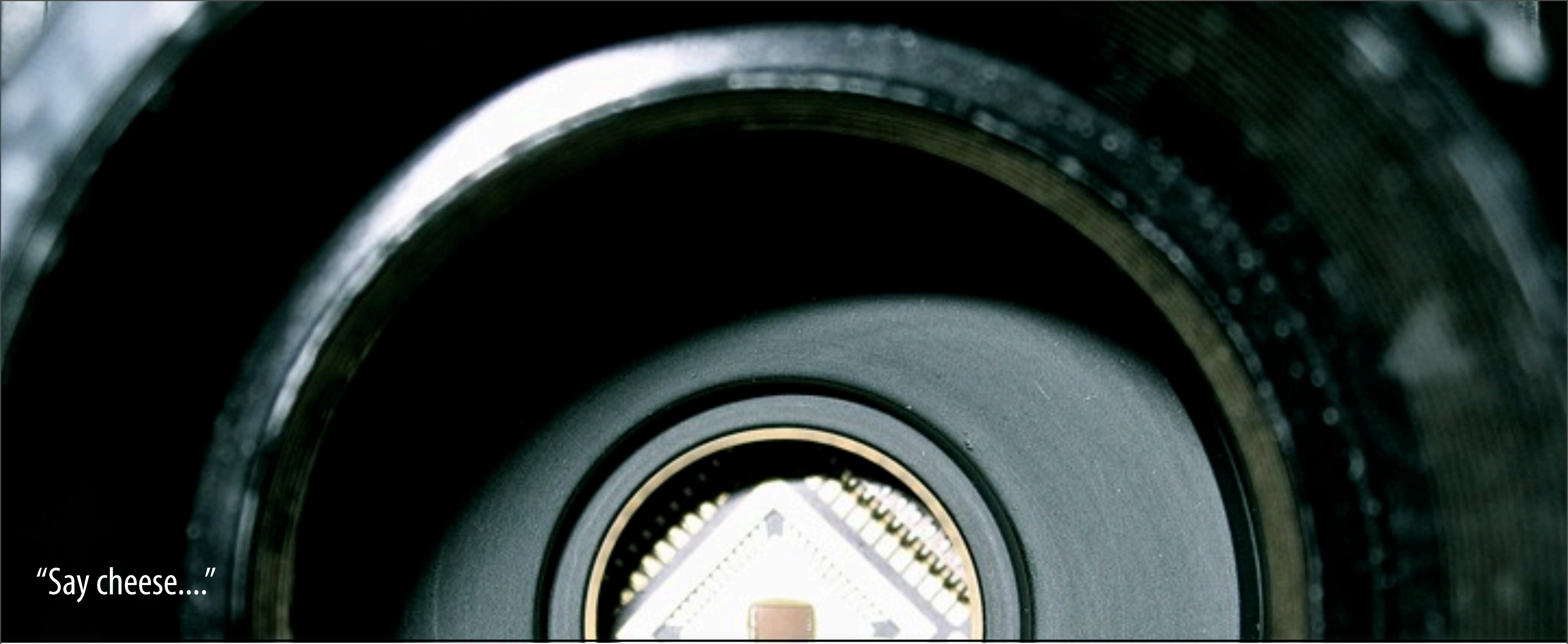
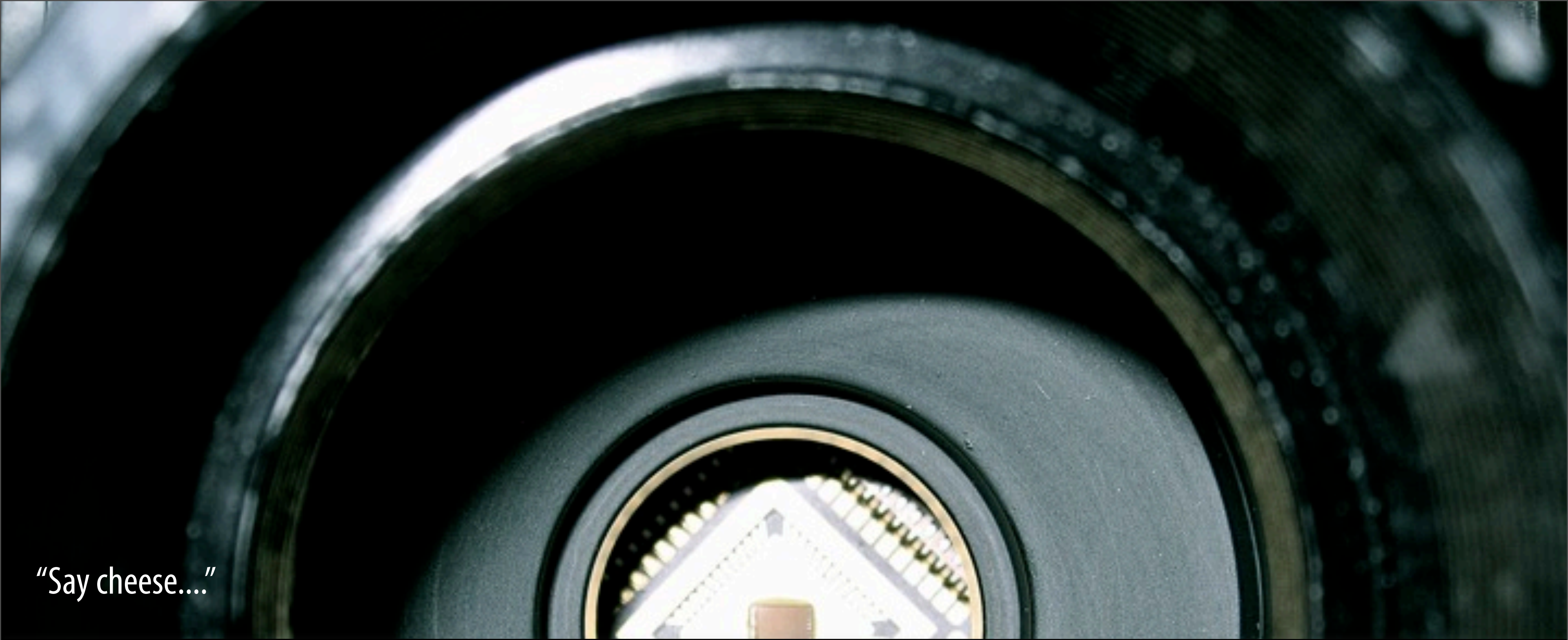


High-Speed Single-Photon Camera

Fabrizio Guerrieri

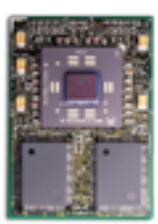
Advisor: Prof. Franco Zappa
Co-advisor: Dr. Simone Tisa

Tutor: Prof. Angelo Geraci



What am I going to talk about?

MOTIVATIONS
& IDEAS




THE MAKING OF
THE SPAD CAMERA

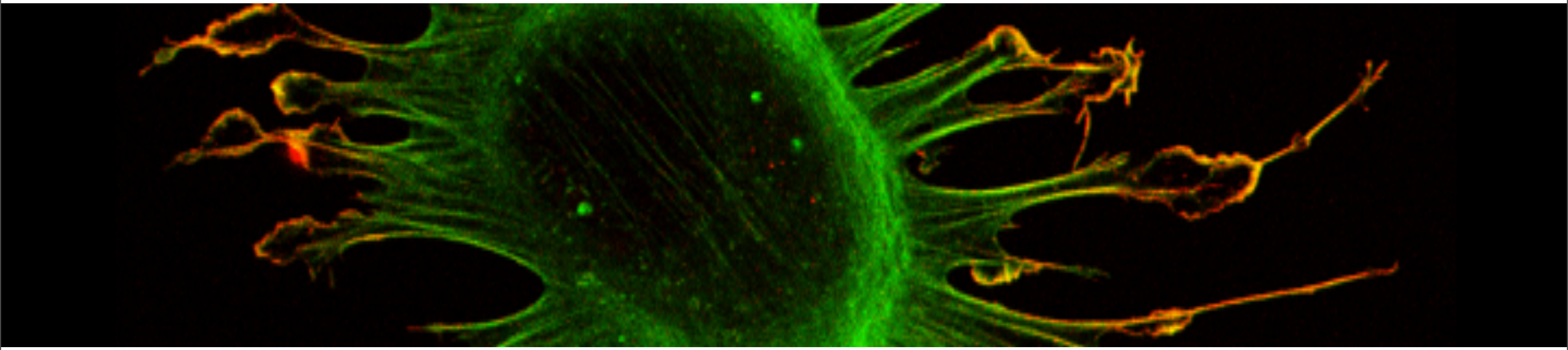


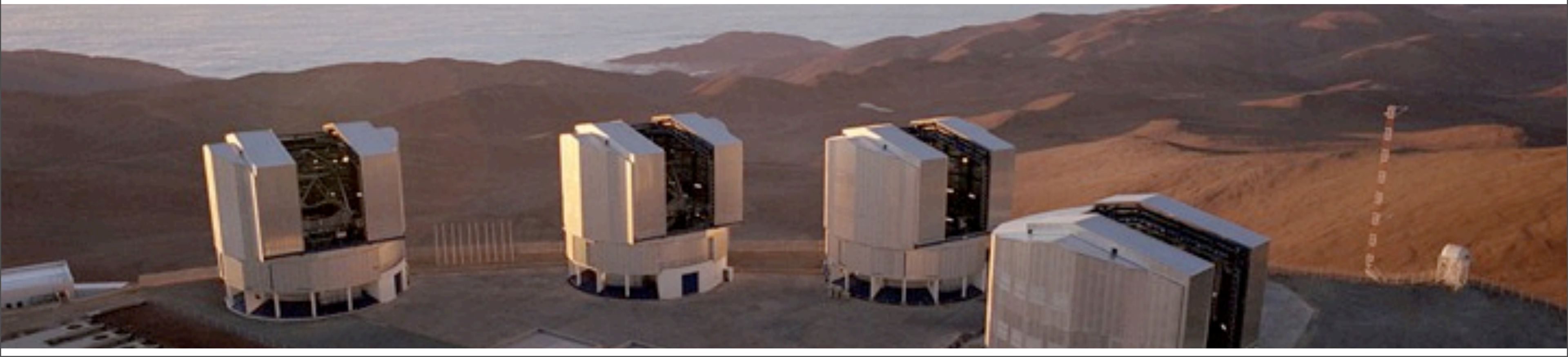
FROM THE DEVICE...
... TO THE APPLICATIONS (3)

MOTIVATIONS

Demanding imaging applications require

Extreme sensitivity AND high-speed

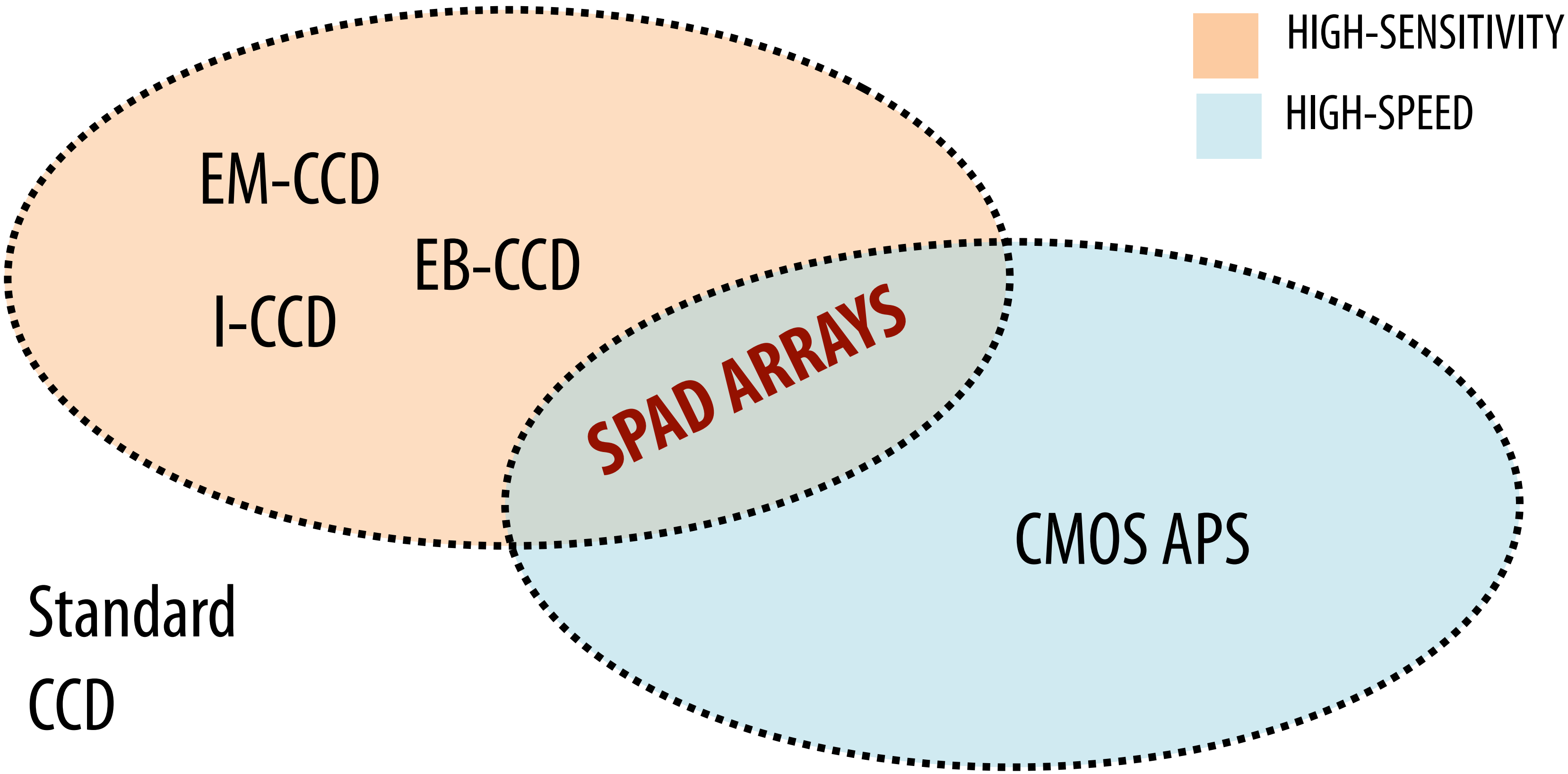




MOTIVATIONS

Demanding imaging applications require

Extreme sensitivity **AND** high-speed



Standard
CCD

IMAGER SPECIFICATIONS

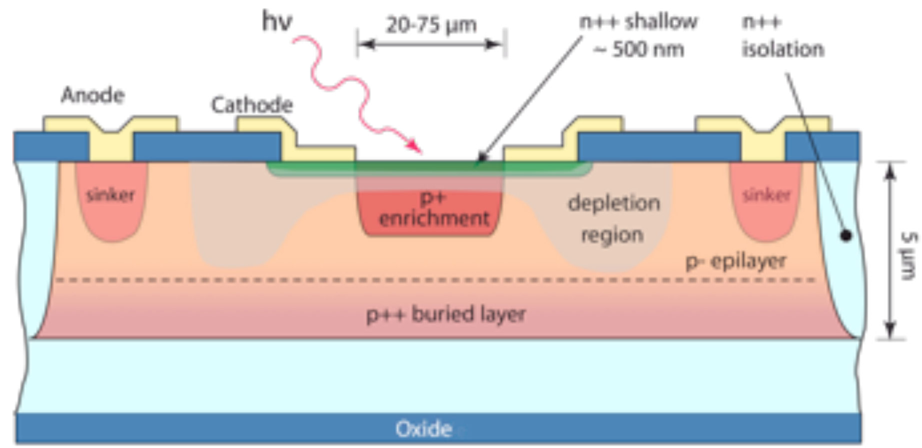
REQUIREMENT	PROPOSED SOLUTION	RISK
Single-Photon sensitivity	SPAD detector	
High-speed (> 10 kframe/s)	Completely independent pixels	
High pixel number	> 100	
Compactness	Use of HV-CMOS compatible tech	
Additional features	Global shutter, programmability...	

Increasing risk:

SPAD ARRAYS

HIGH PERFORMANCE ARRAY

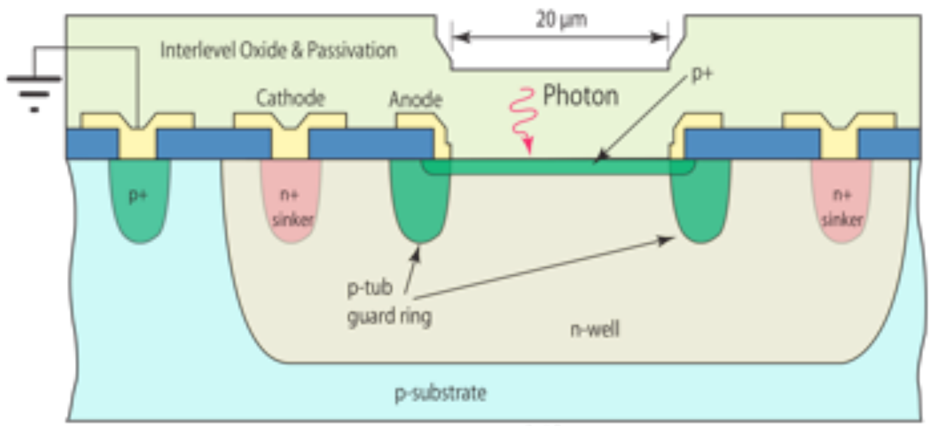
- Large pixel diameter
- Moderate number of pixels
- Limited by the ext. Electronics



CUSTOM TECH

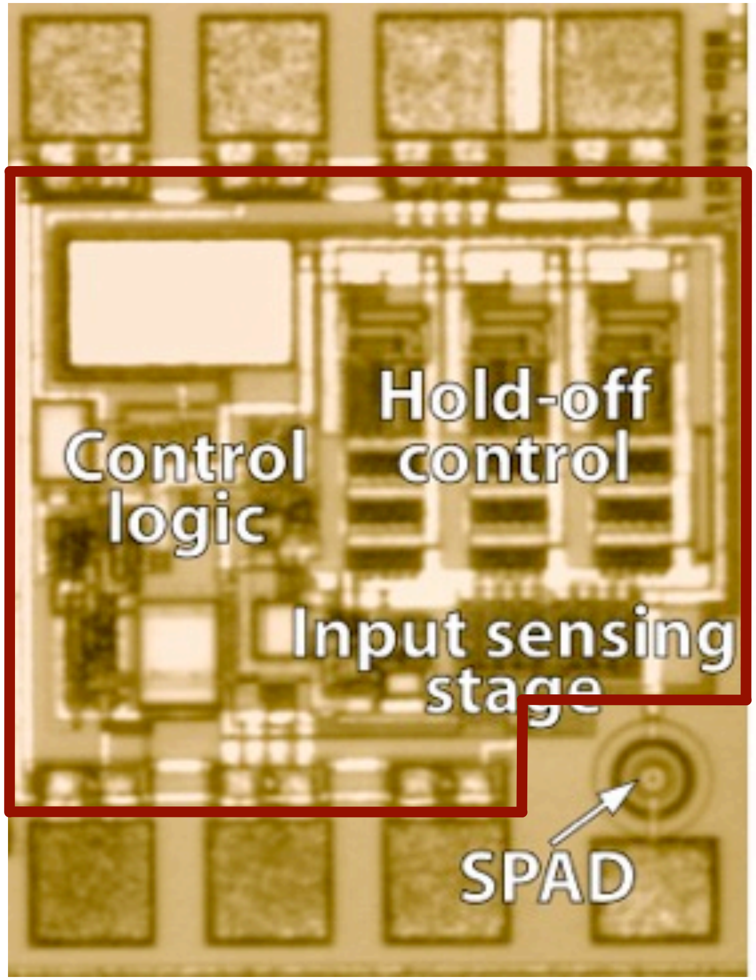
DENSE ARRAY

- Small pixel diameter
- Large number of pixels
- Possibility of smart pixels

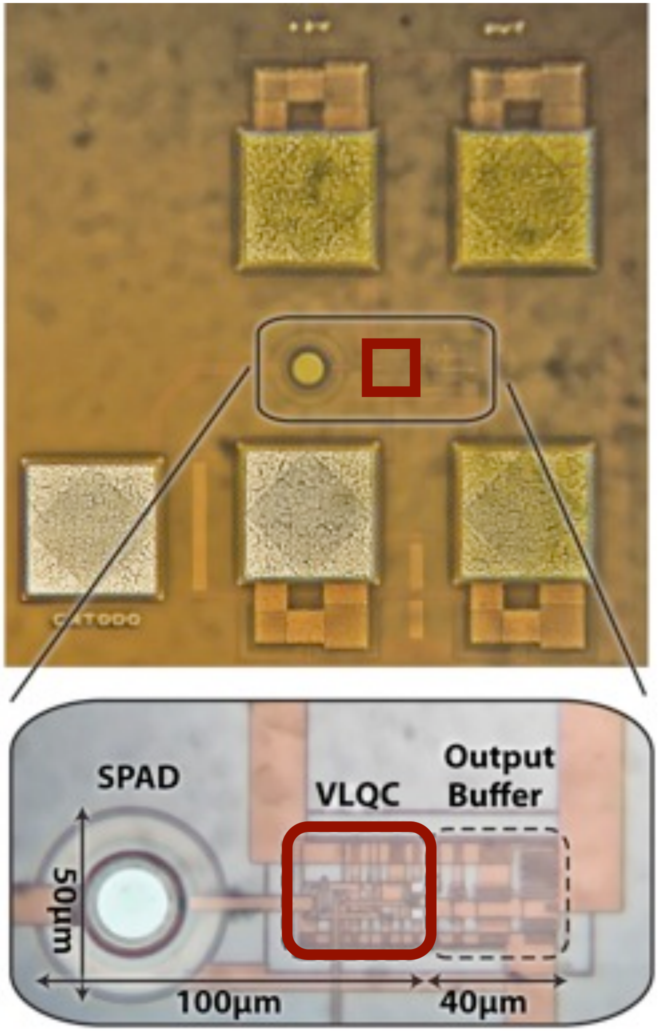


STANDARD CMOS TECH

ACTIVE QUENCHING CIRCUIT

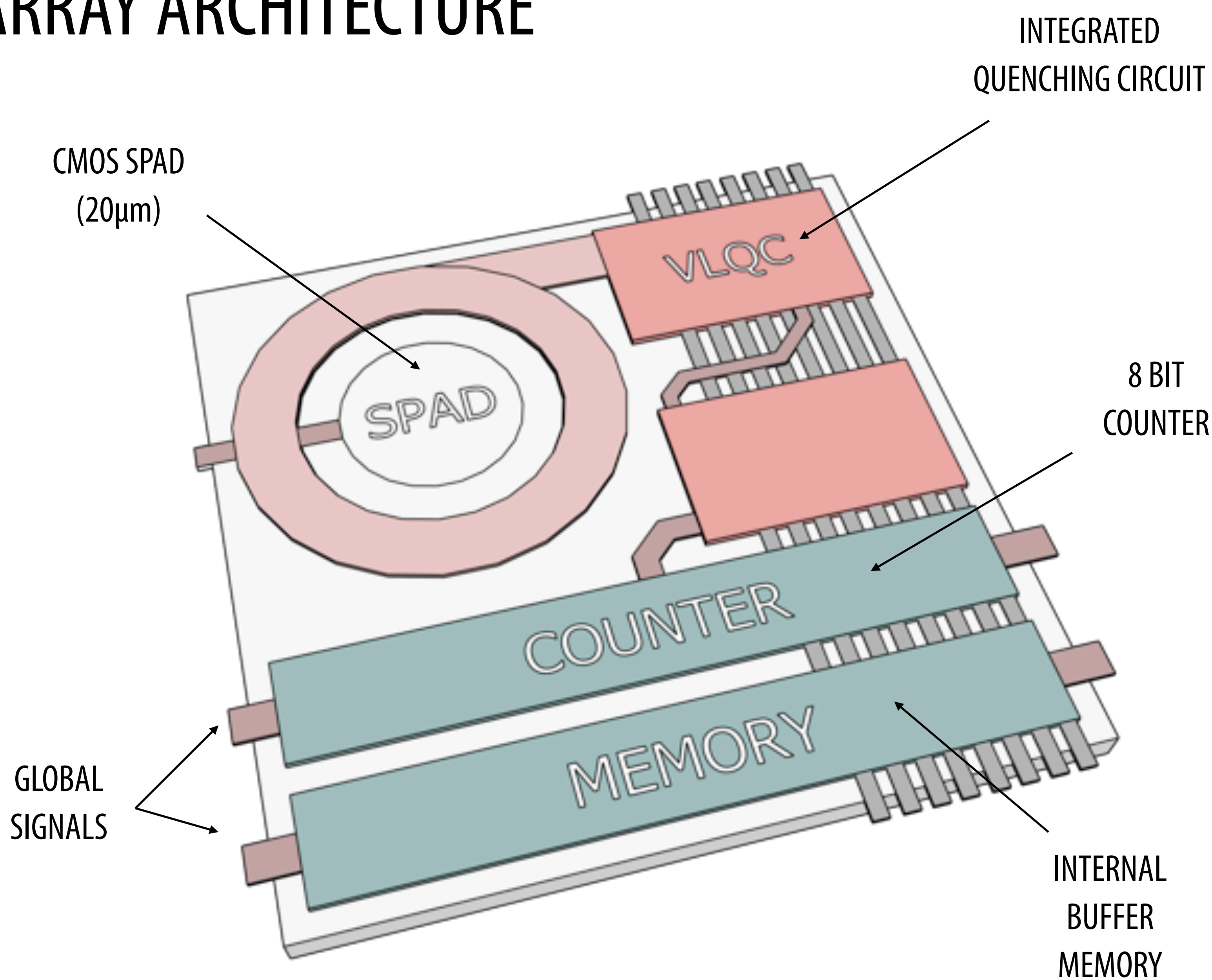


Group’s State-of-the-Art

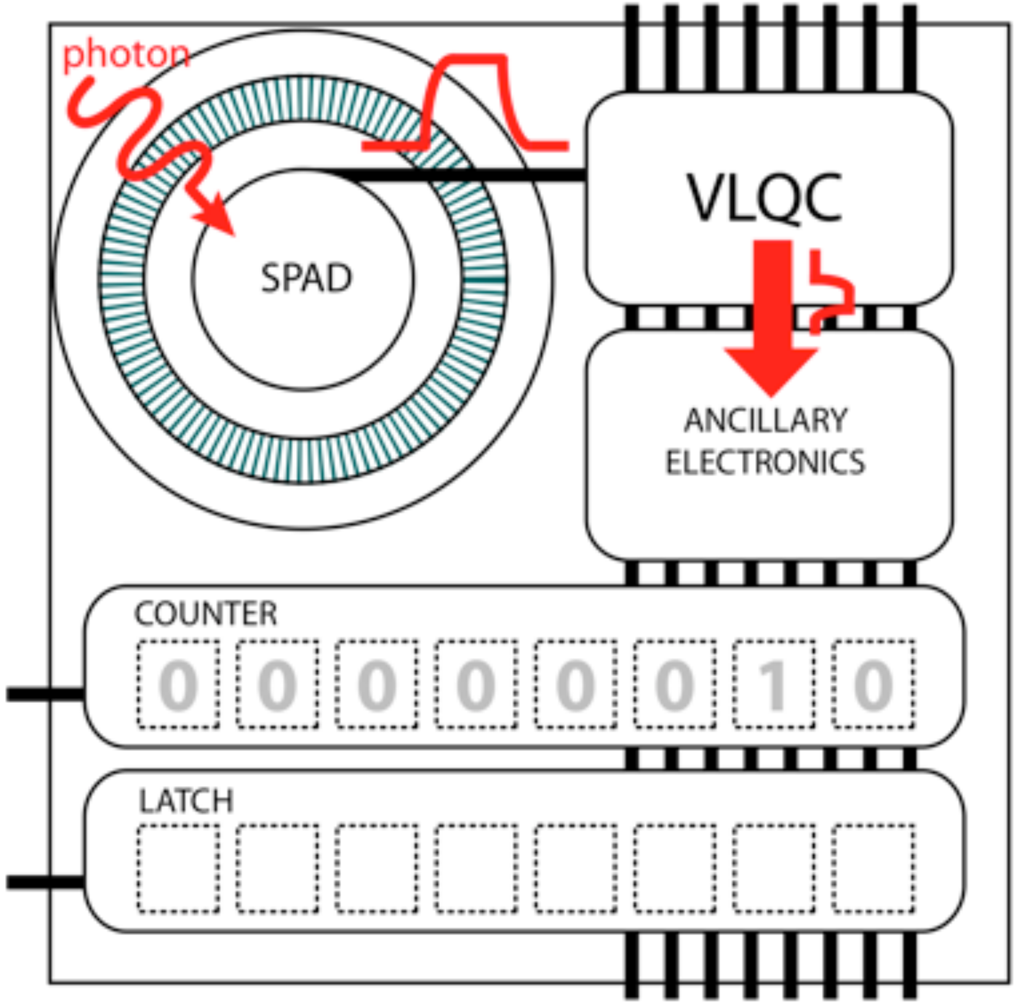


VLQC

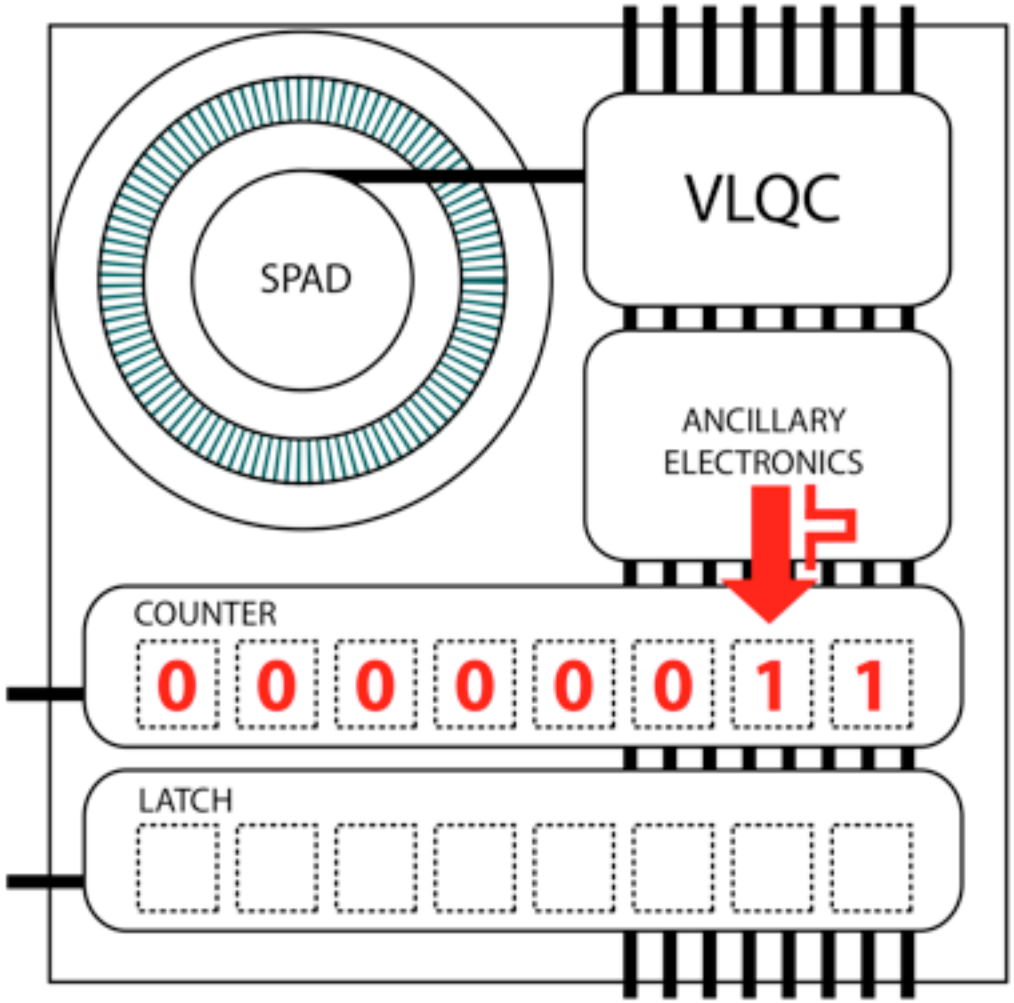
ARRAY ARCHITECTURE



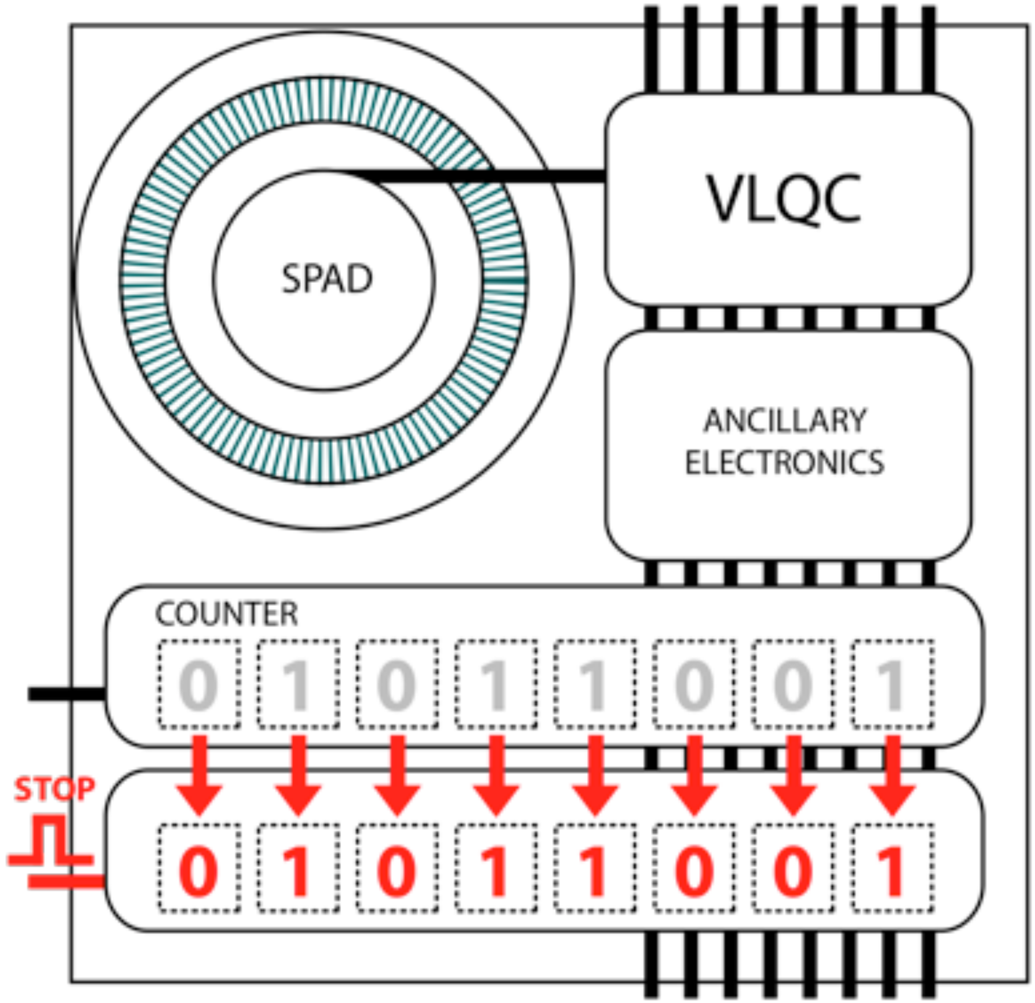
ARRAY OPERATIONS



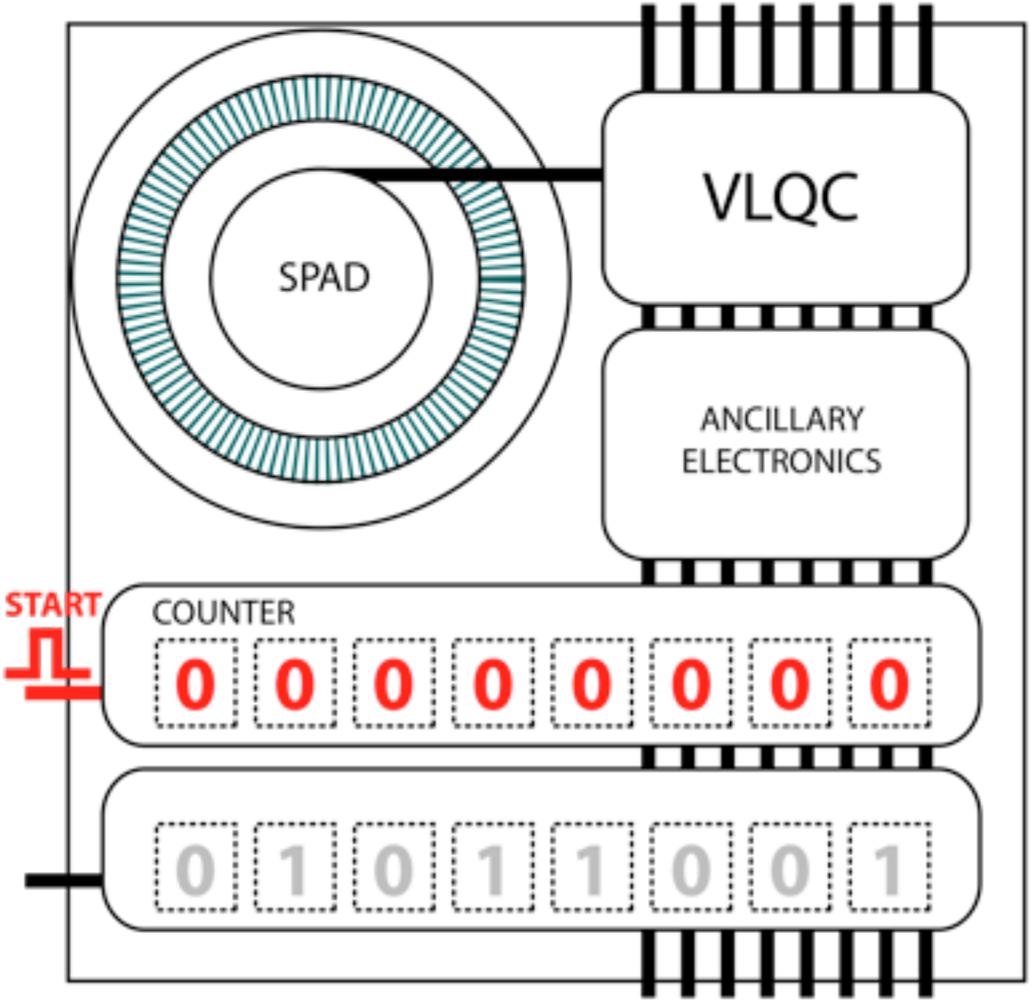
ARRAY OPERATIONS



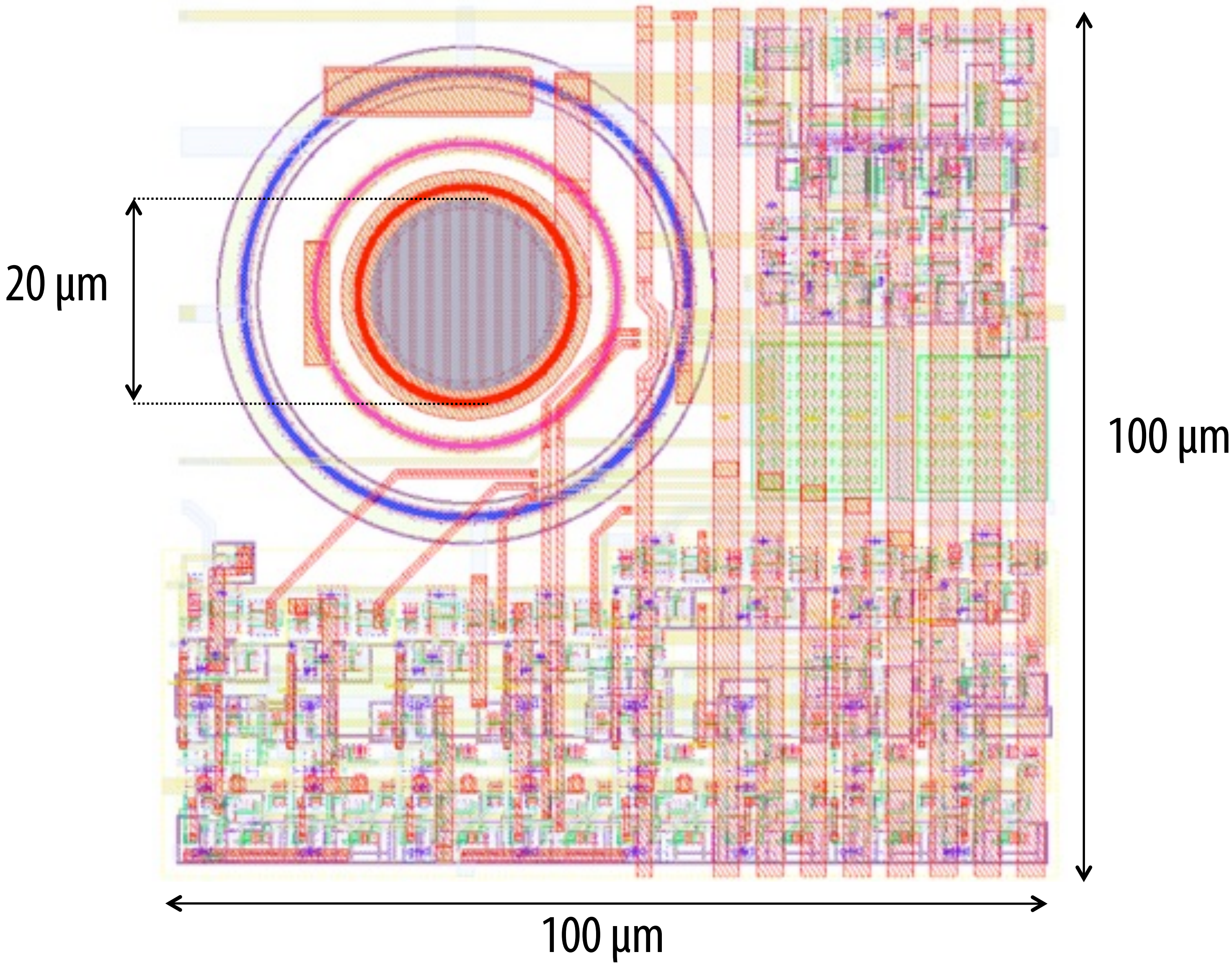
ARRAY OPERATIONS



ARRAY OPERATIONS



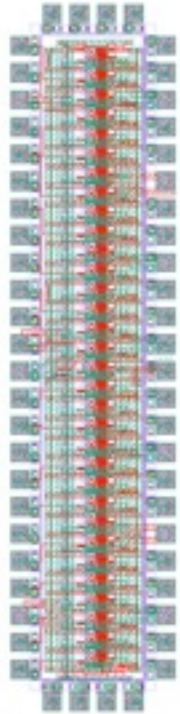
PIXEL LAYOUT

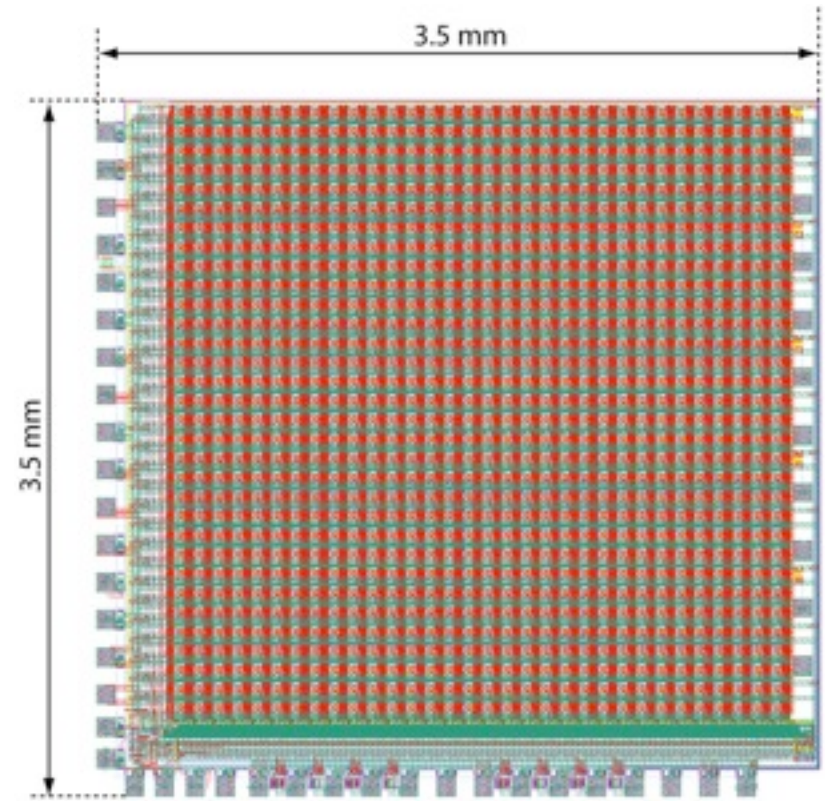


SPAD ARRAYS

VLQC

SMART PIXEL





LINEAR 32x1 ARRAY

32 counting and timing channels

Single-photon sensitivity

Up to 312.5 kframe/s

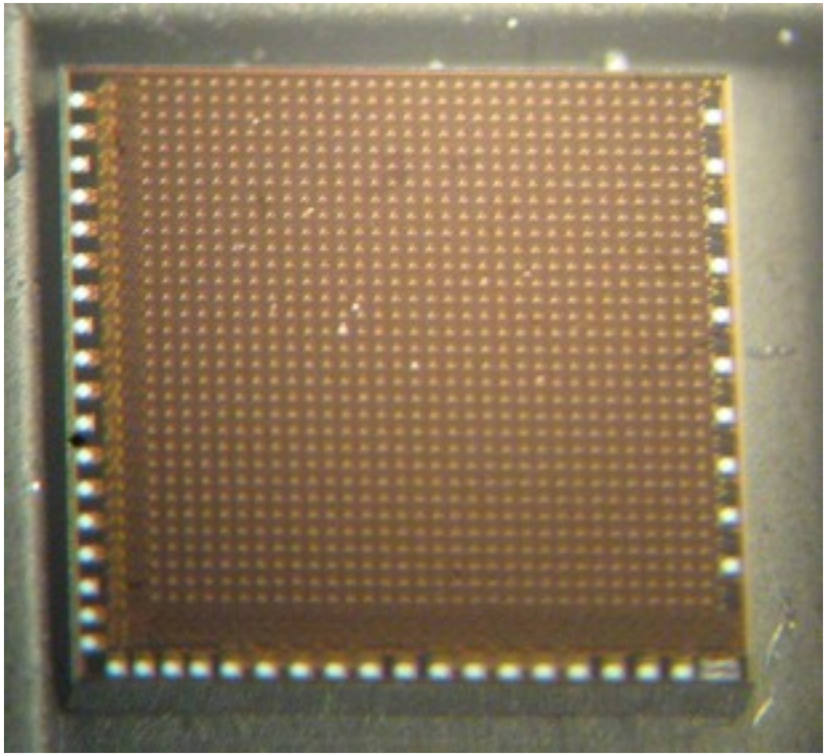
32x32 SPAD IMAGER

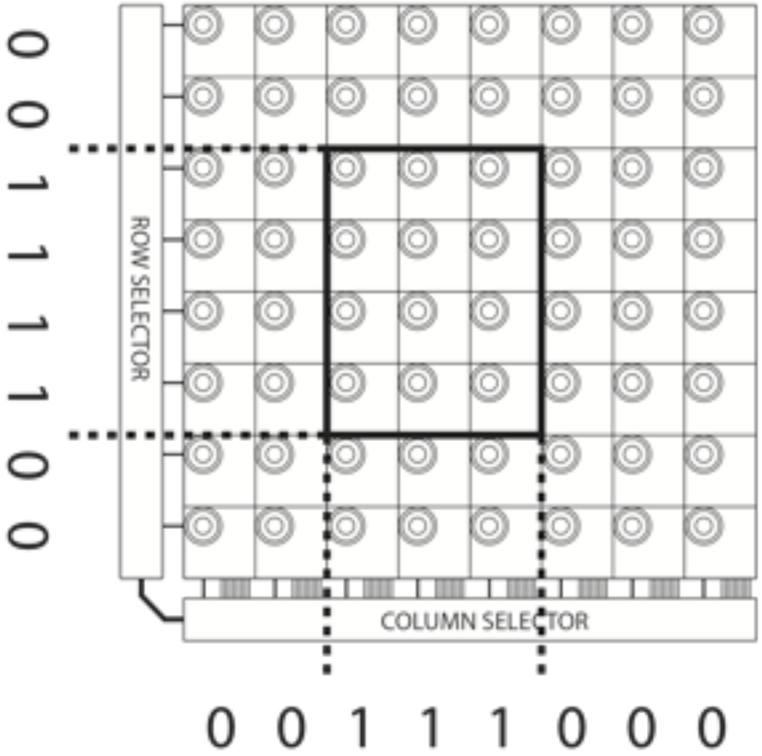
1,024 parallel counting channels

Single-photon sensitivity

Up to 100 kframe/s

SPAD IMAGER



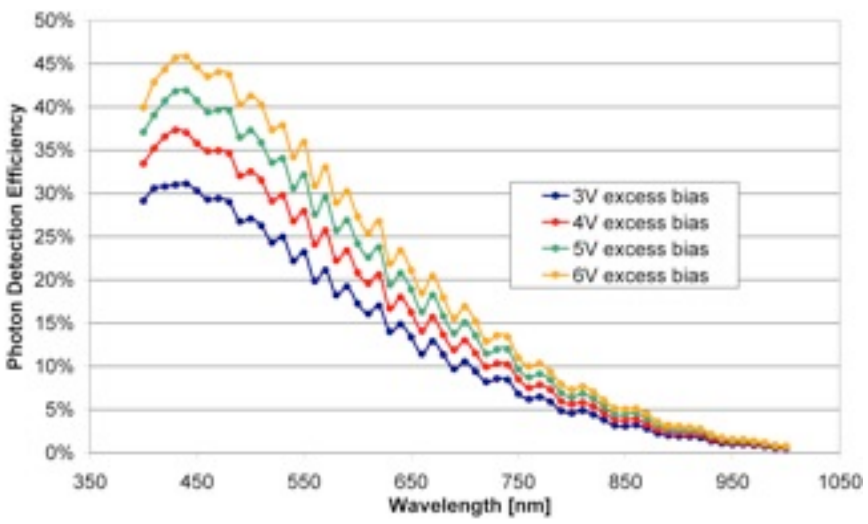


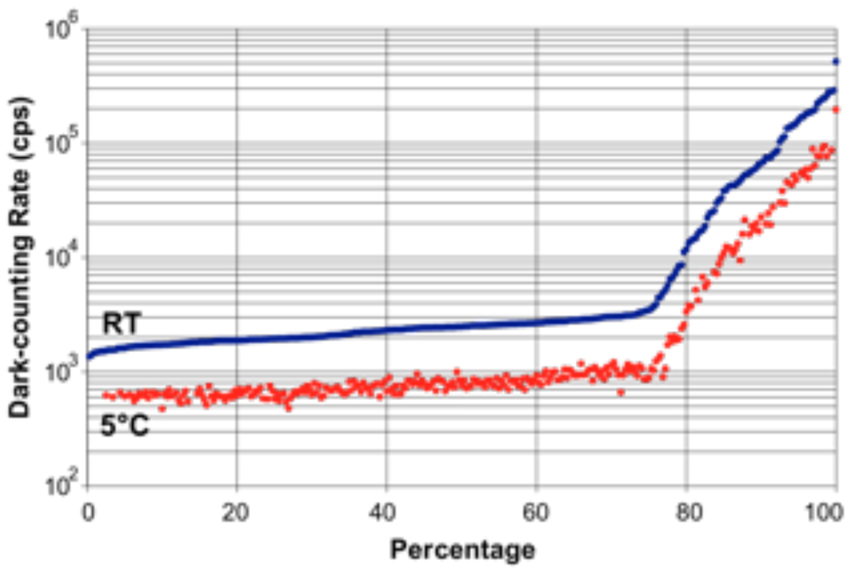
- 1024 parallel channels
- Global shutter
- Up to 100 kframe/s

- Programmable to read-out any pixel sub-portion to increase max frame-rate

SPAD IMAGER

Experimental measurements





Up to 45% Single-Photon Det. Efficiency

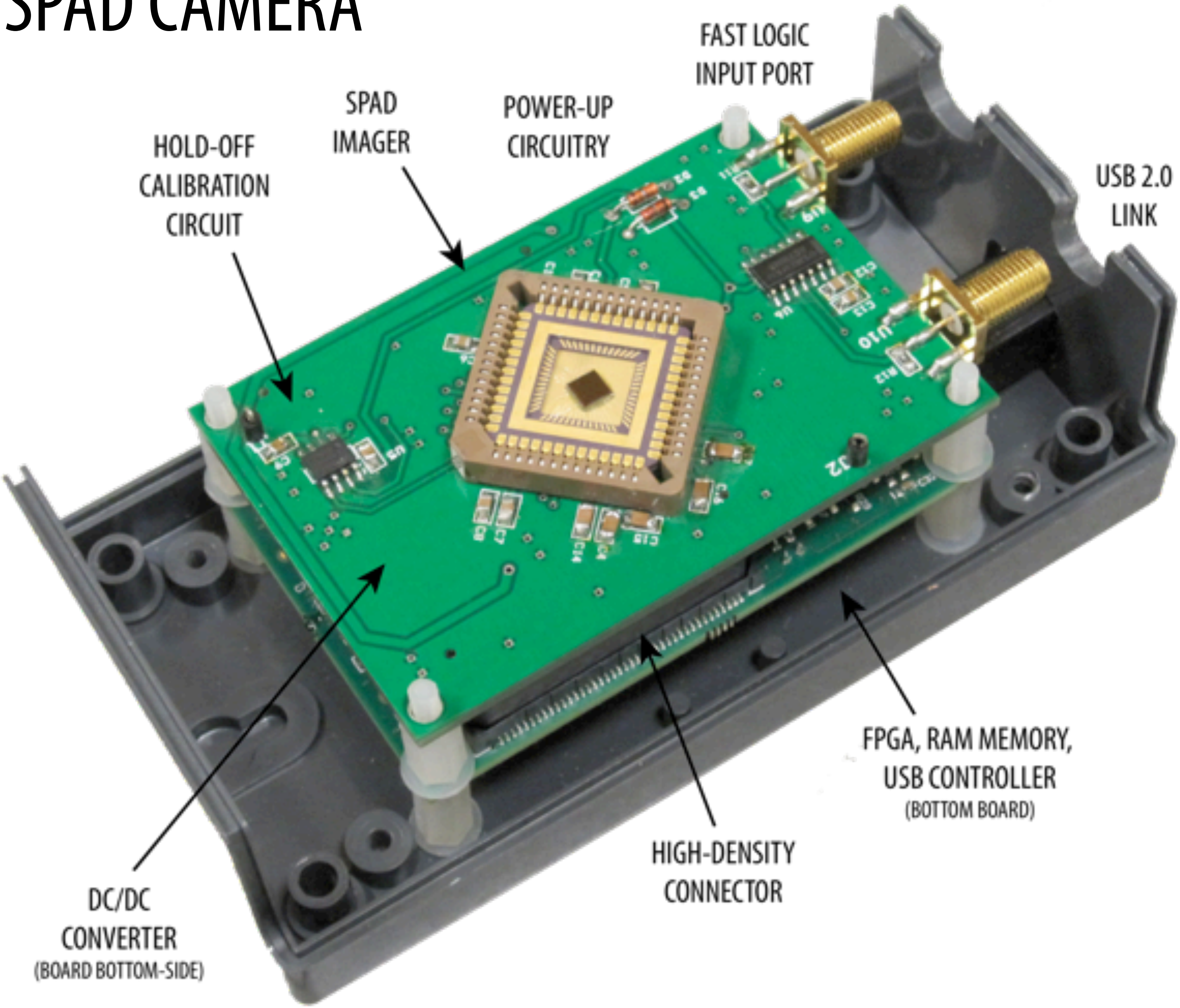
75% DCR < 4 kcps at room temperature

Negligible crosstalk probability

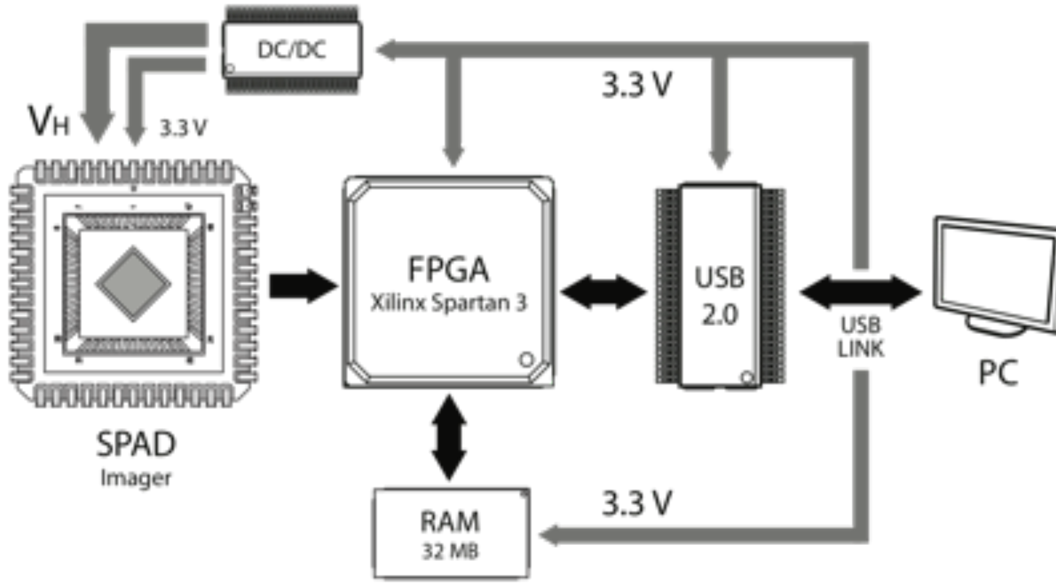
IMAGER SPECIFICATIONS

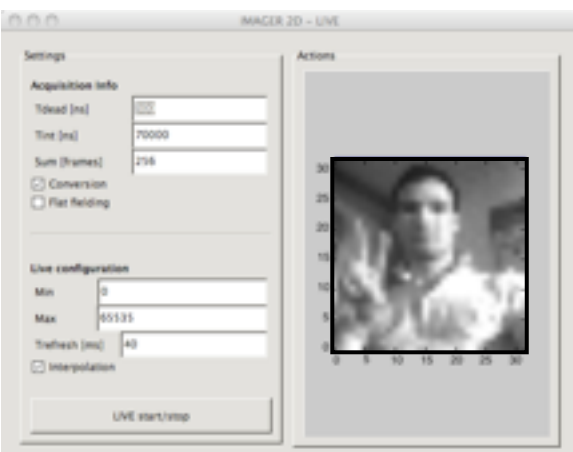
REQUIREMENT	IMPLEMENTED SOLUTION	
Single-Photon sensitivity	CMOS SPAD detector	✔
High-speed (> 10 kframe/s)	"Smart" pixel comprising everything necessary to count photons	✔
High pixel number	32x32 CMOS imager	✔
Compactness	100x100 µm pixel dimension	✔
Additional features	Global shutter, programmability…	✔

SPAD CAMERA


FAST LOGIC INPUT PORT
SPAD IMAGER
POWER-UP CIRCUITRY
HOLD-OFF CALIBRATION CIRCUIT
USB 2.0 LINK
FPGA, RAM MEMORY, USB CONTROLLER (BOTTOM BOARD)
HIGH-DENSITY CONNECTOR
DC/DC CONVERTER (BOARD BOTTOM-SIDE)

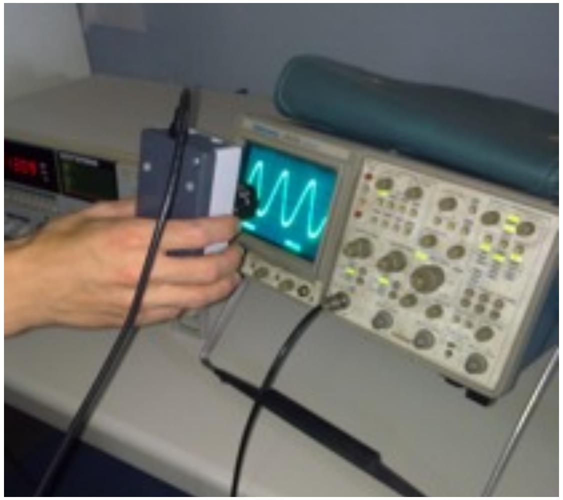
SPAD CAMERA



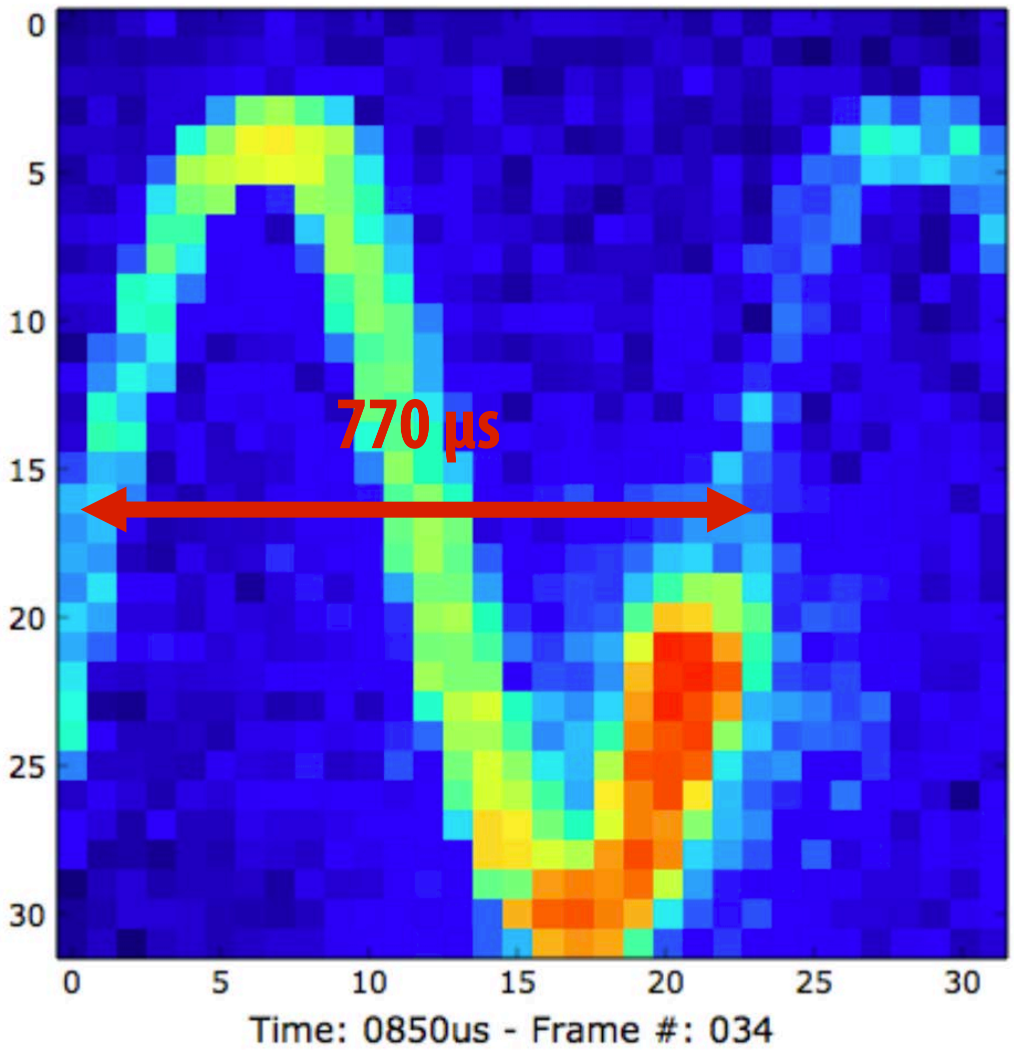


- FPGA-based high-speed electronics
- Requires only USB cable to work: Plug’n’Play
- Developed cross-platform software

SPAD CAMERA

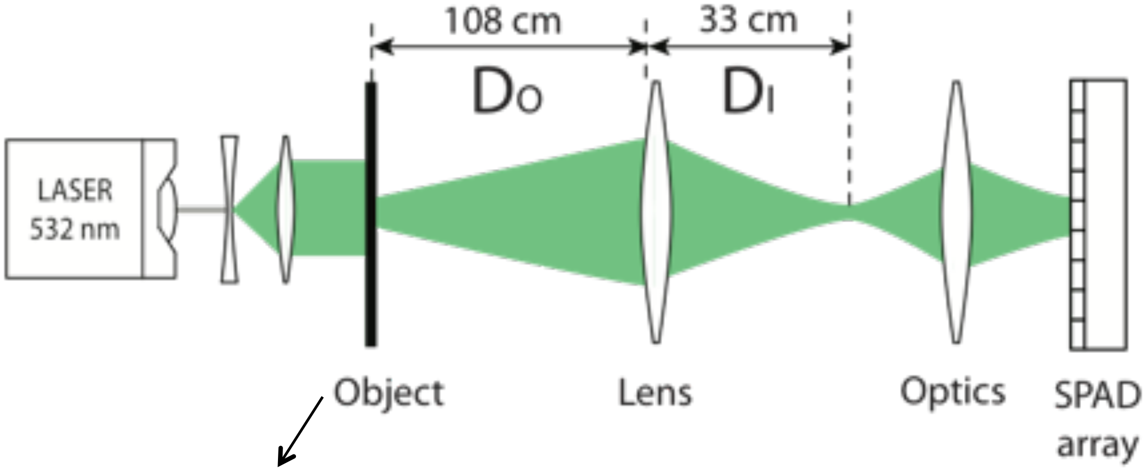


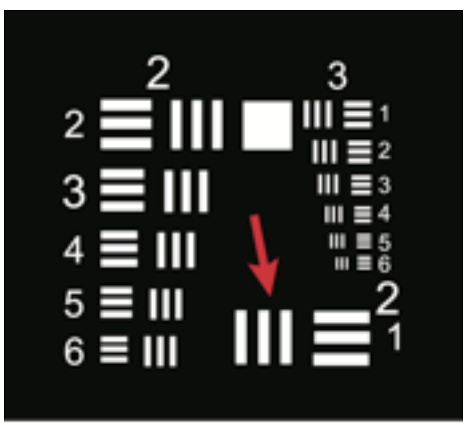
- Easy to use
- 40 kframe/s
- Low light level at such a high speed

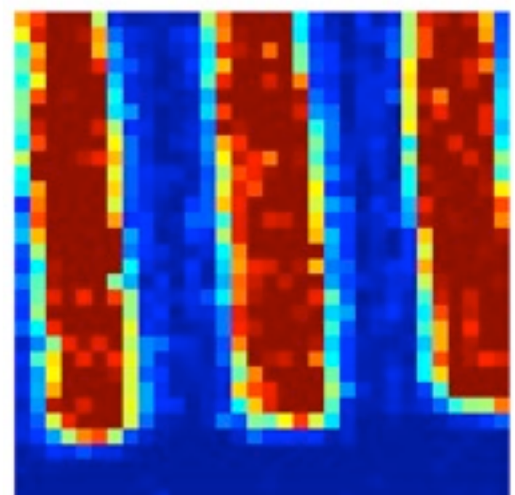


SUB-RAYLEIGH IMAGING @ MIT

Conventional imaging with non-diffraction limited optics

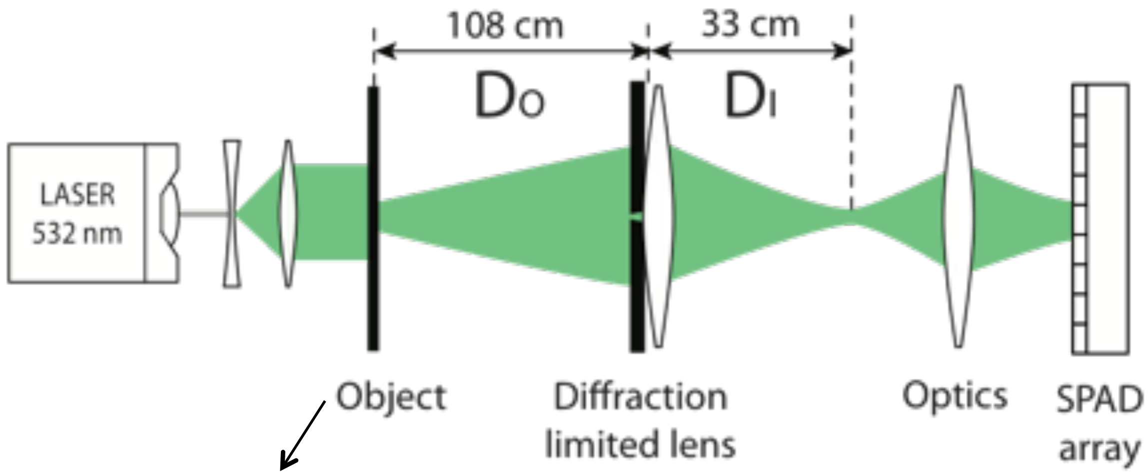


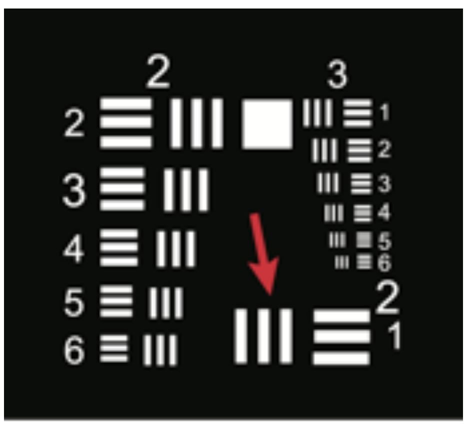




SUB-RAYLEIGH IMAGING @ MIT

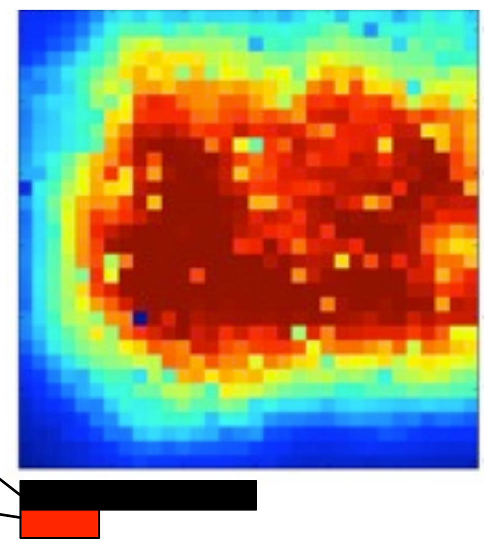
Conventional imaging with diffraction limited optics





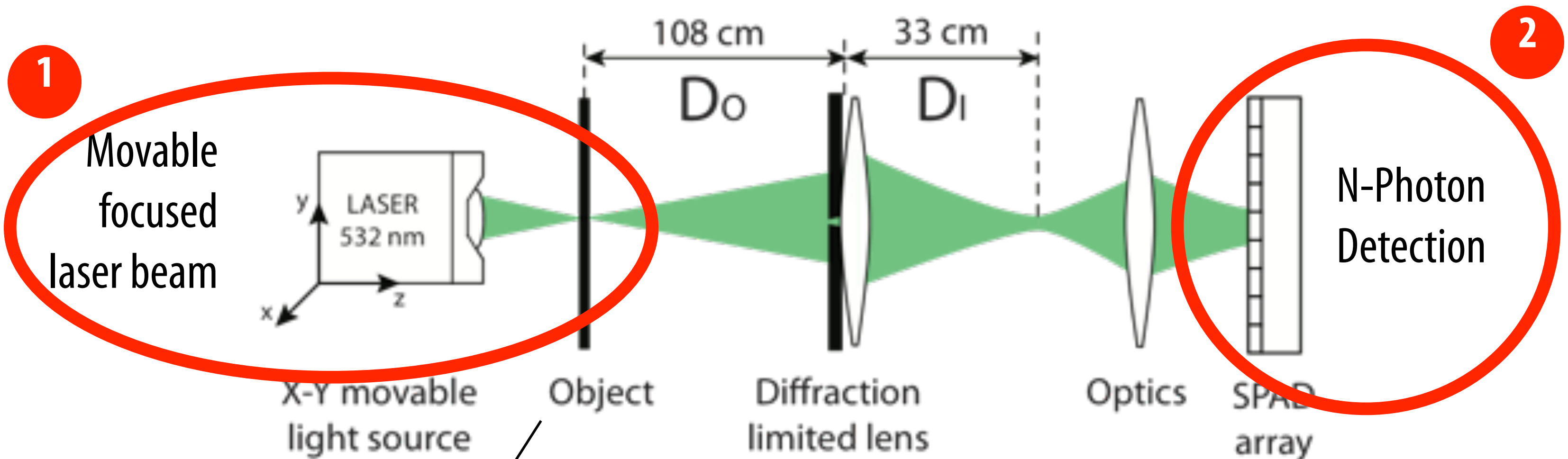
Rayleigh bound

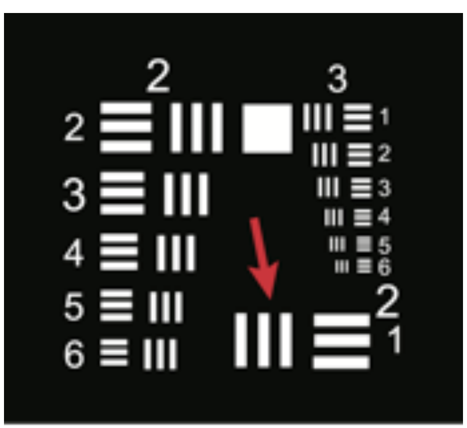
Stripe size

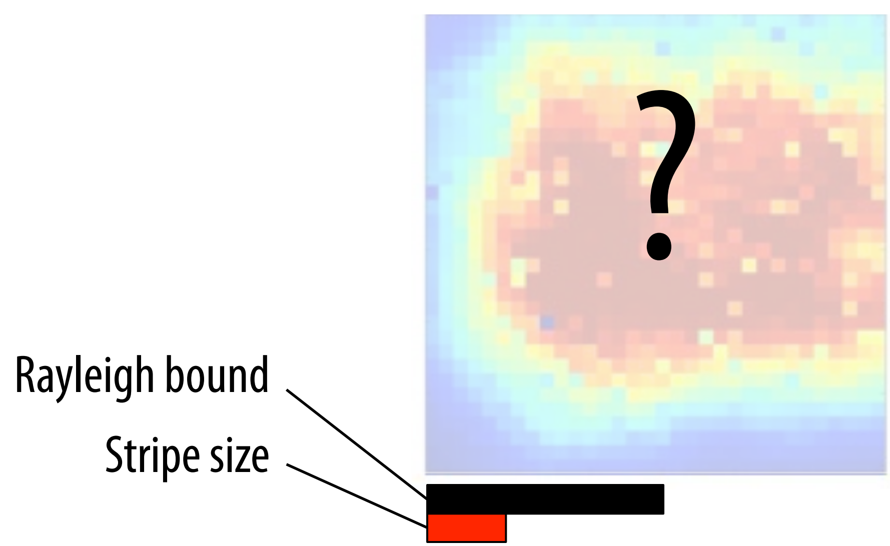


SUB-RAYLEIGH IMAGING @ MIT

Setup modifications to apply the Sub-Rayleight technique

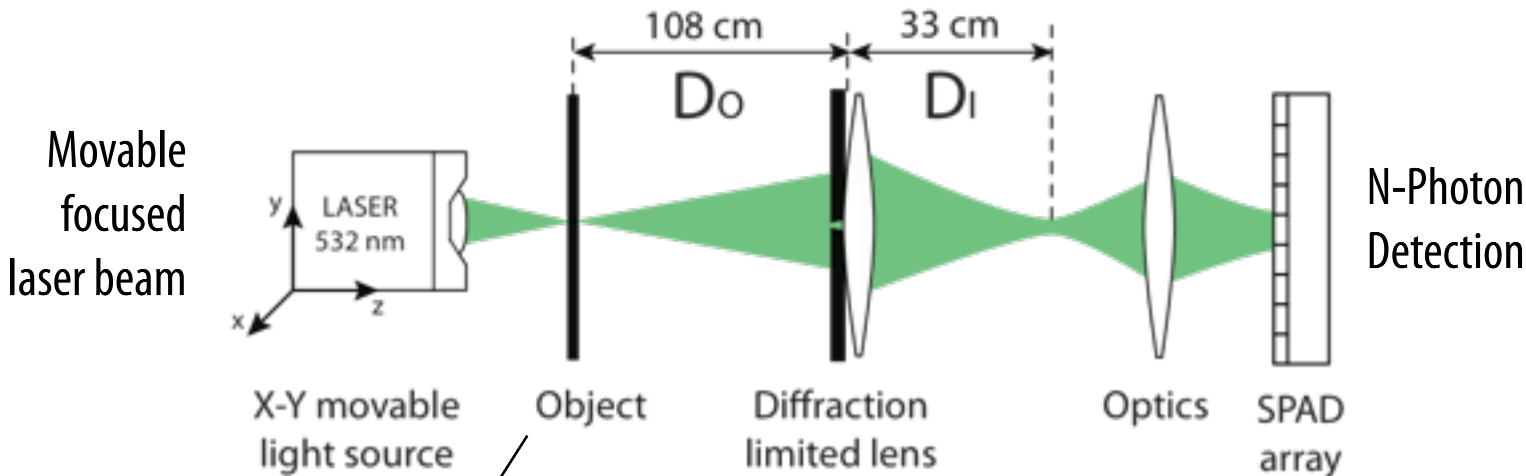


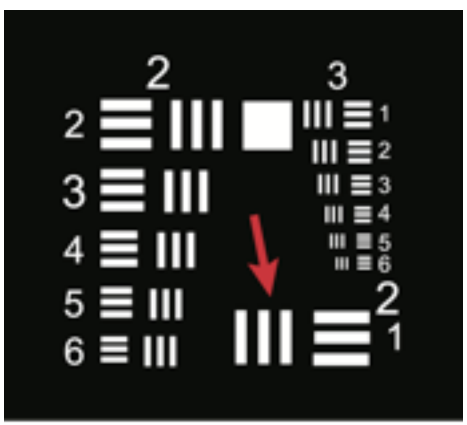


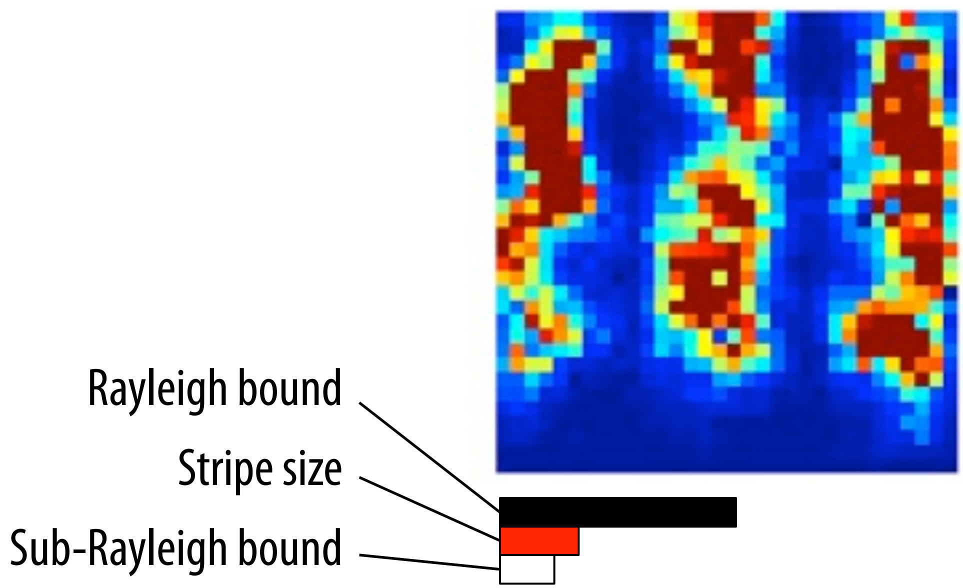


SUB-RAYLEIGH IMAGING @ MIT

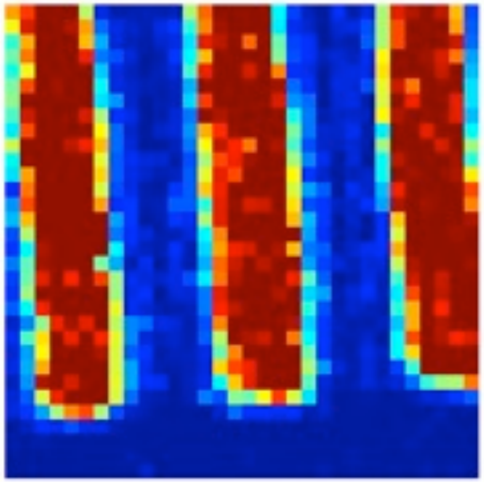
Sub-Rayleigh imaging with diffraction limited optics



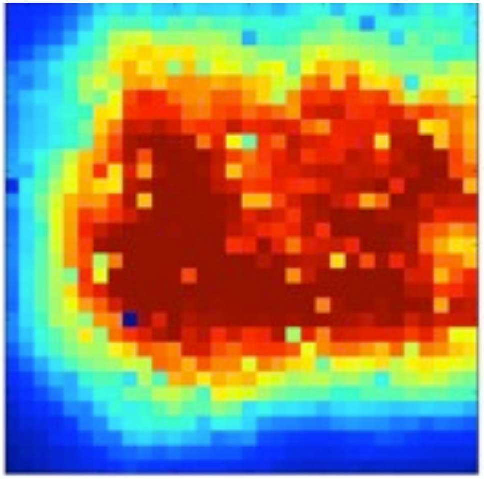




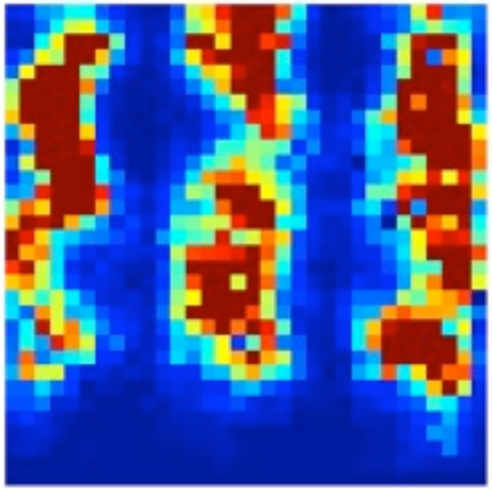
SUB-RAYLEIGH IMAGING @ MIT



Good optics
+
Conventional imaging



Bad optics
+
Conventional imaging

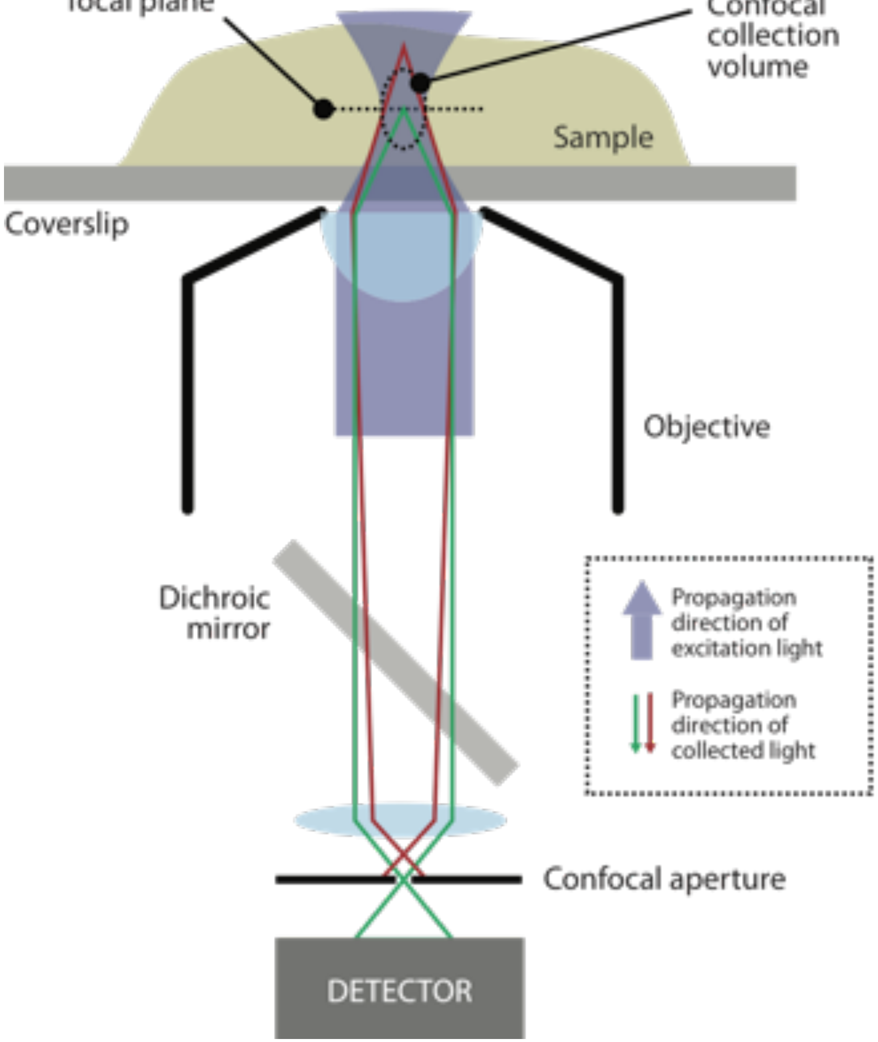


Bad optics
+
Sub-Rayleigh imaging

Imaging beyond the Rayleigh limit is possible by
- Scanning the object by a focused light spot
- Employing N-Photon detection strategy

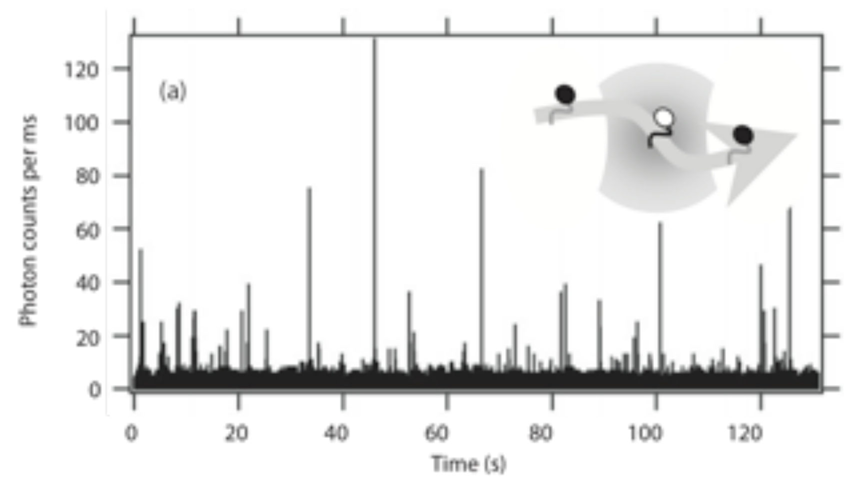
Improvement goes as about the square root of N

HIGH THROUGHPUT FCS @ UCLA



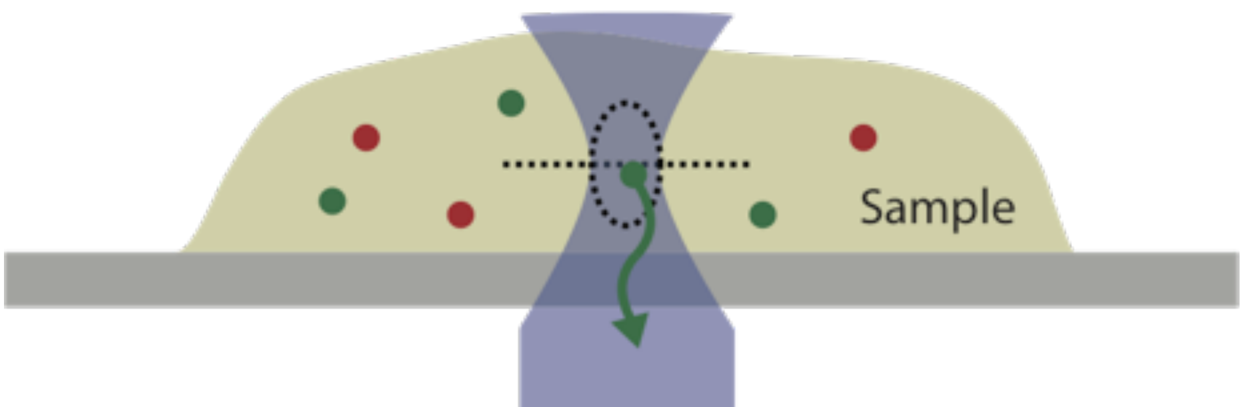
Fluorescent analyte flows or diffuses through a small excitation volume emitting fluorescence bursts

Fluorescence Correlation Spectroscopy (FCS) analyses the fluorescence intensity fluctuations using temporal autocorrelation



HIGH THROUGHPUT FCS @ UCLA

To work well only one particle at time should enter the excitation volume ➡ **PROBLEM!** Long acquisition times! ➡ Need faster acquisition of FCS data ➡ **SOLUTION!** Multi-spot parallel FCS acquisitions

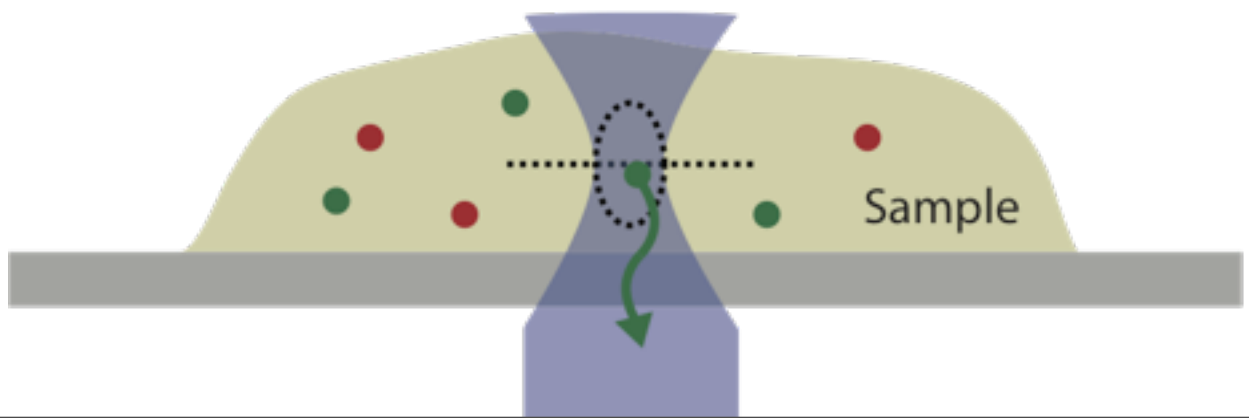


HIGH THROUGHPUT FCS @ UCLA

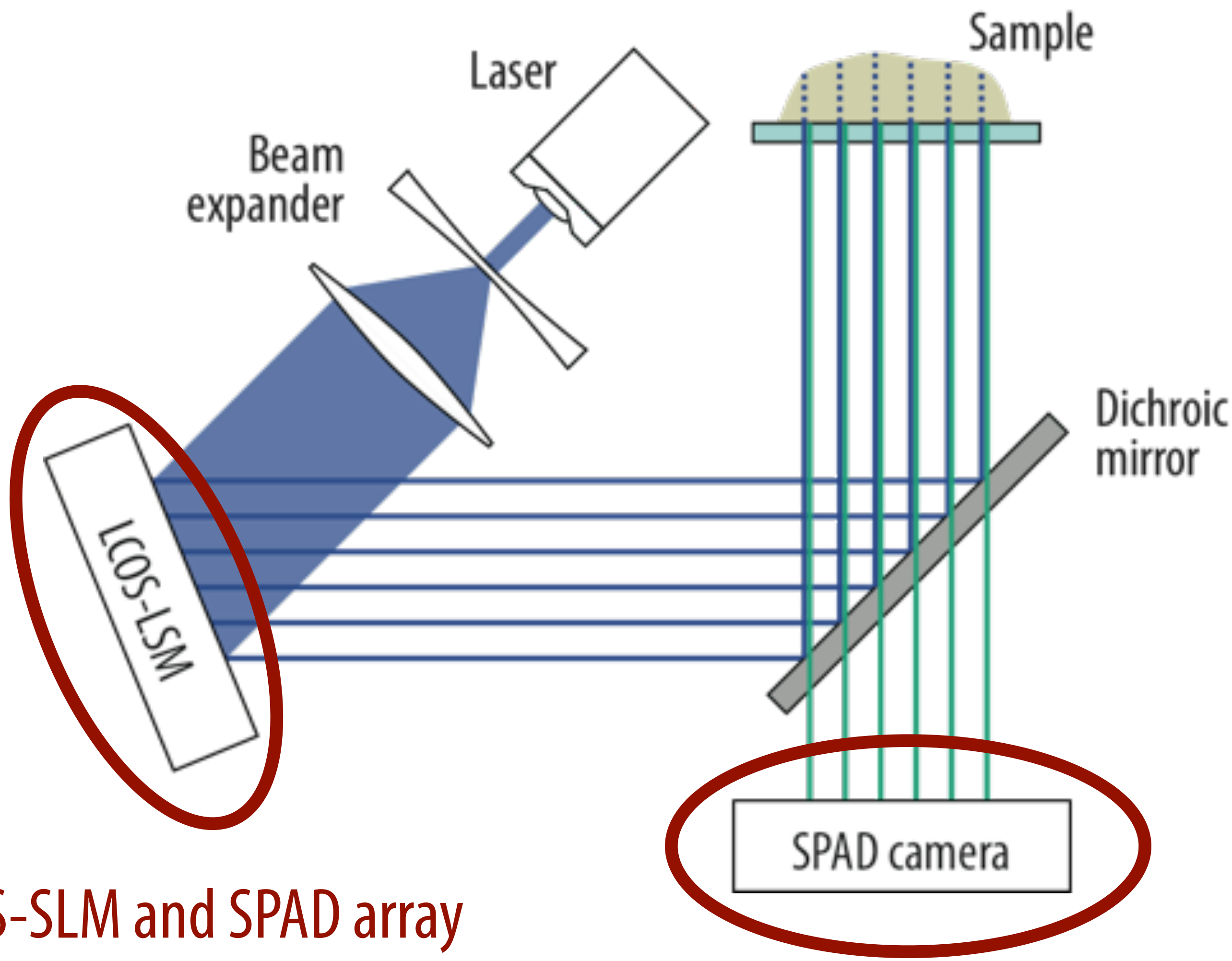
To work well only one particle at time should enter the excitation volume ➡ **PROBLEM!** Long acquisition times! ➡ Need faster acquisition of FCS data ➡ **SOLUTION!** Multi-spot parallel FCS acquisitions

A very sensitive and high-speed device is required!

SPAD arrays as enabling technology

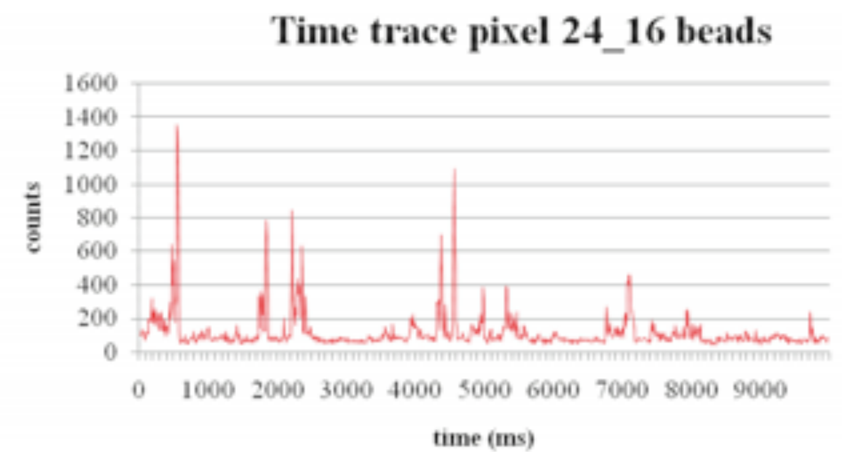


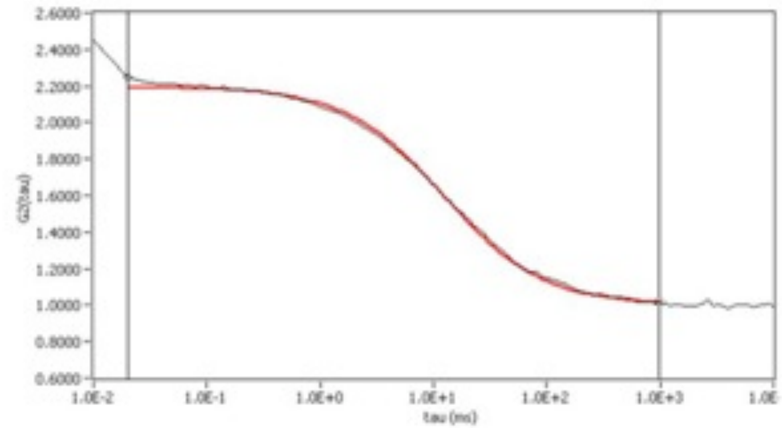
HIGH THROUGHPUT FCS @ UCLA

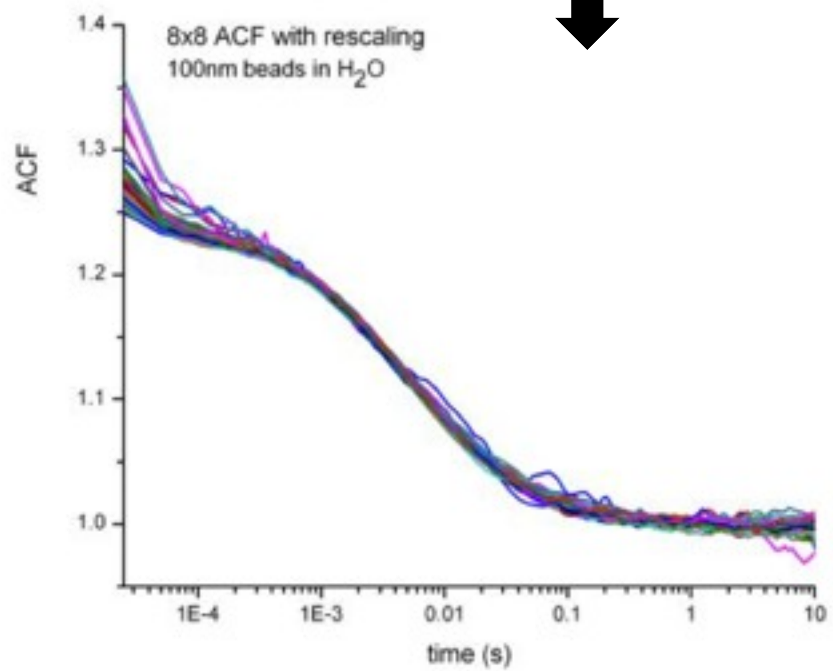


LCOS-SLM and SPAD array enabling technologies

HIGH THROUGHPUT FCS @ UCLA







8x8 ACF with rescaling
100 nm beads in H_2O

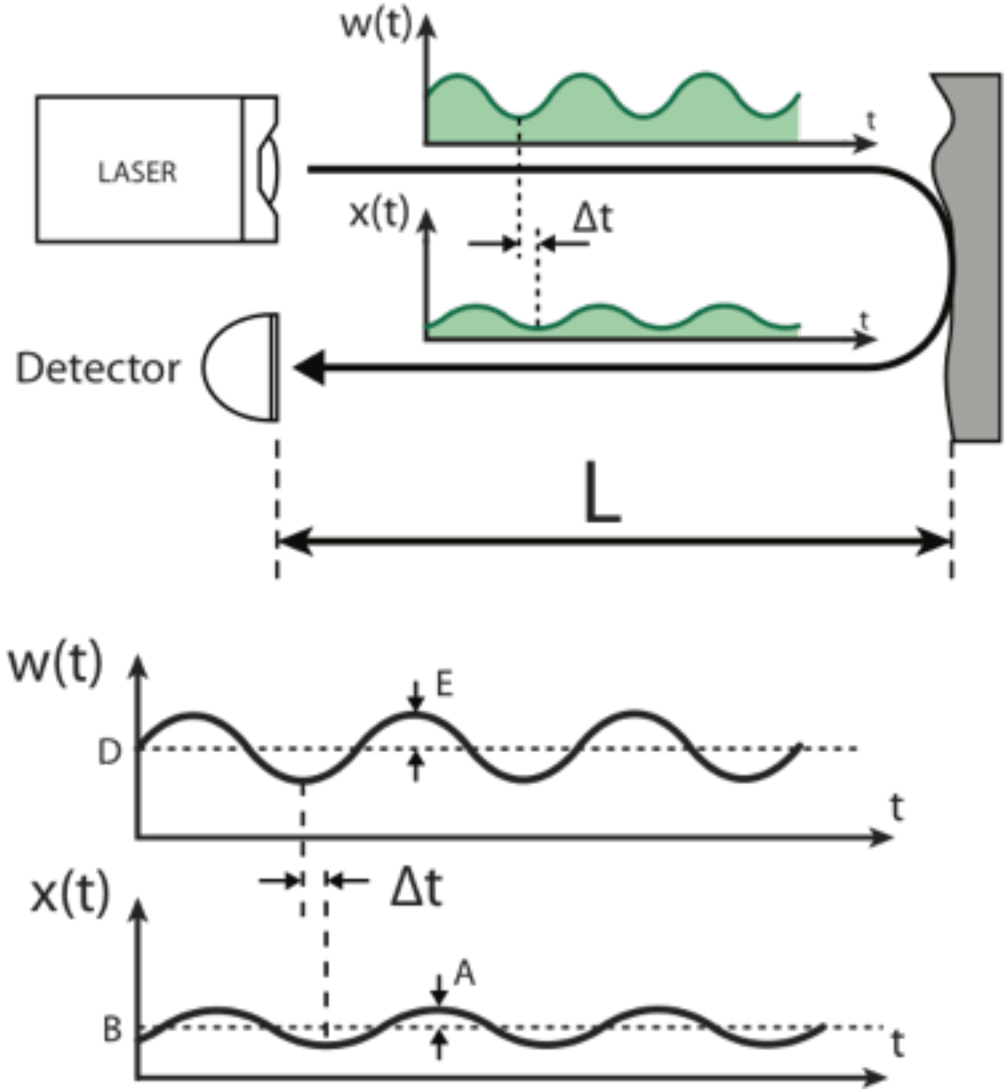
Curves overlap and can be fitted

3D IMAGING

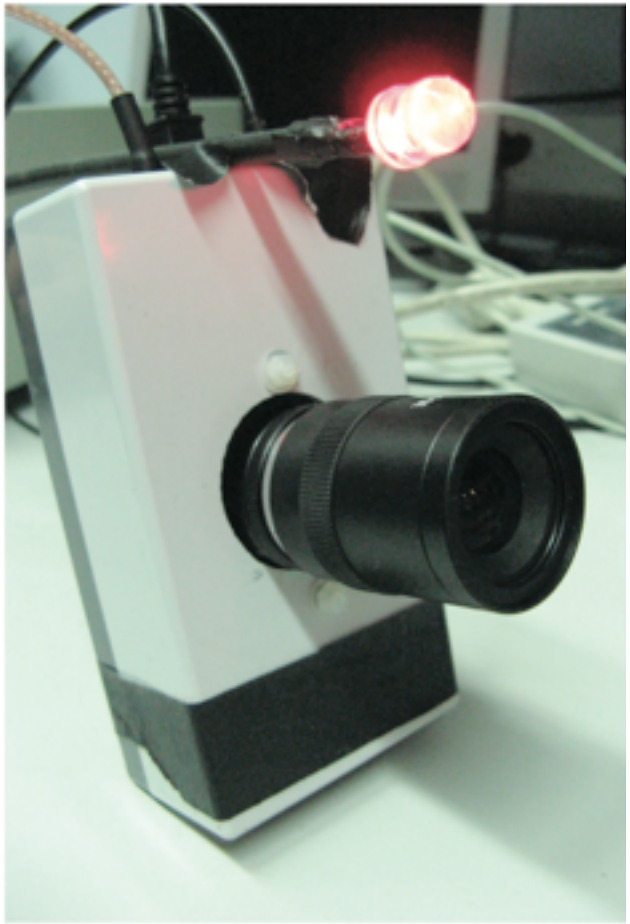
Indirect-ToF

- Modulated light illuminates the scene
- A very sensitive detector measure the reflected light
- Depth information can be extracted calculating the waveform phase shift:

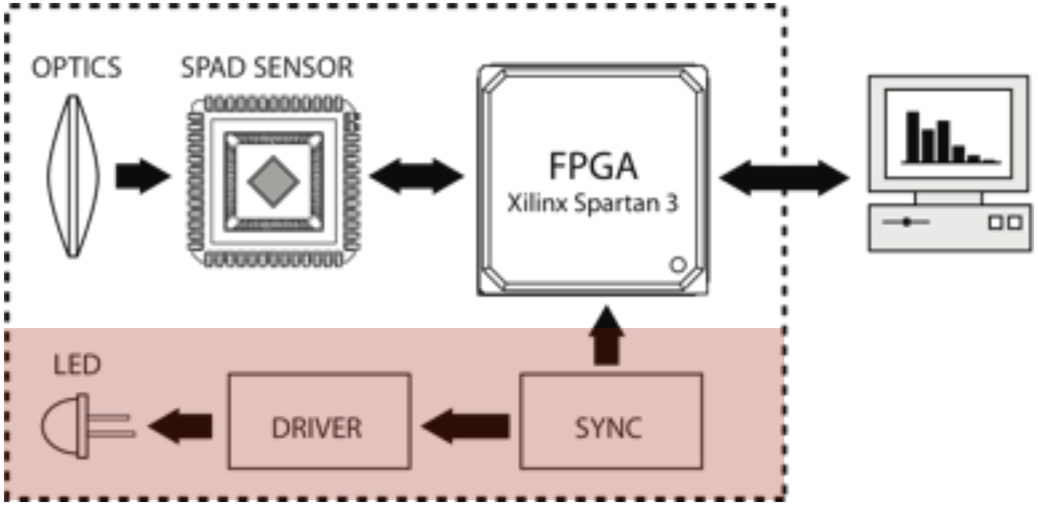
$$L = \frac{\Delta t}{2} c$$



3D IMAGING

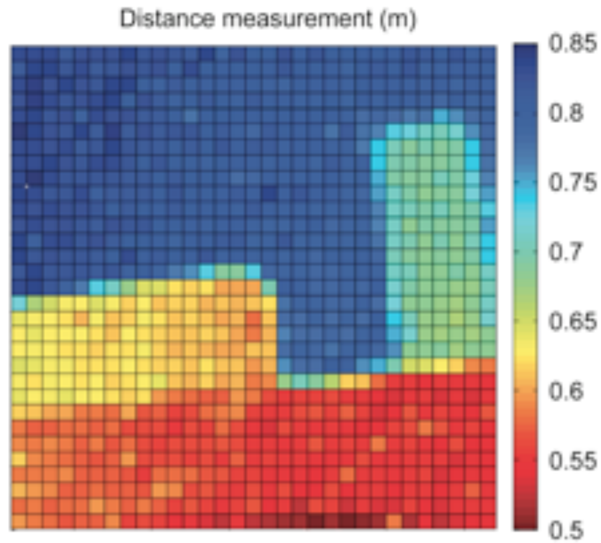


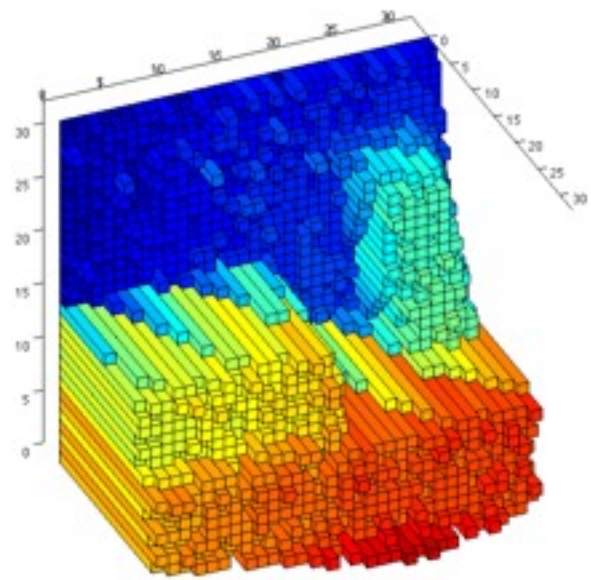
How did a 2D camera become "3D capable"?



Light source + driver + waveform generator + new FPGA firmware

3D IMAGING





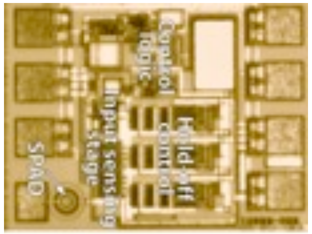
Depth resolution:
3 – 9 mm

Scene depth:
30 cm

Measurement time:
10 s

Good results but need to speed the acquisition up to get movie-like 3D imaging

CONCLUSIONS

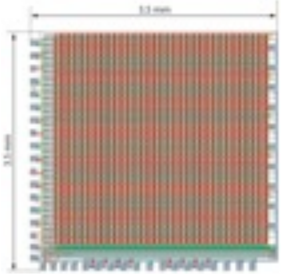


Group SoA

My work

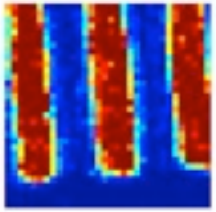
VLQC

Pixel



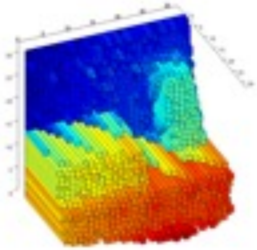
32x32
Array

SPAD
Camera



Sub-Rayleigh
Imaging

FCS



3D
Imaging

PHD FACTS

Achievements/Awards

- Physical Review Letters as first author (IF=7.33)
- Progetto Rocca fellowship
- My research helped the group to submit and win an European grant.
- Laser Focus World Award "Commendation for excellence in technical communications"
- Co-author of 2 invited conference papers
- ESSDERC08: special congratulation by conference committee
- PhDay 2008 1° year student award

PhD doctoral school

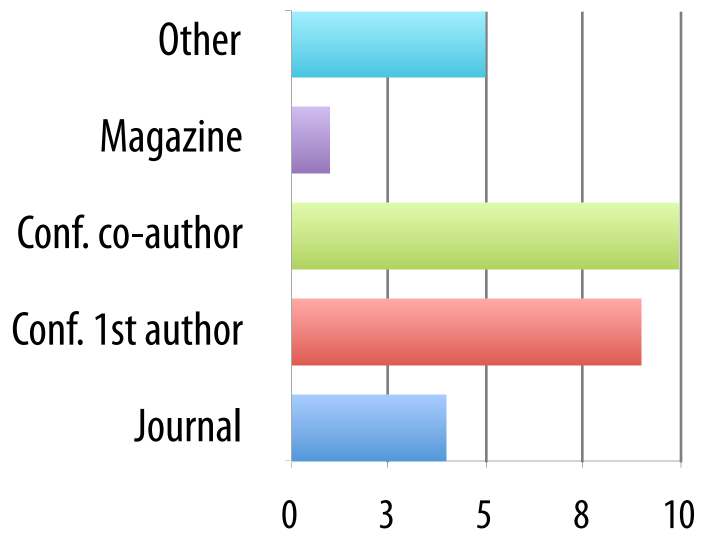
Courses' grade: all A (8 courses)

Attended extra non-mandatory courses

Publications

Total papers: **29**

Conference talks: **6**

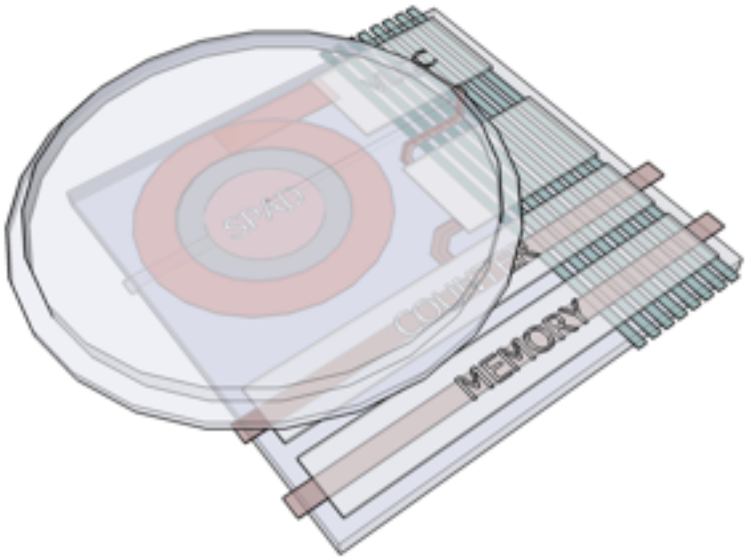


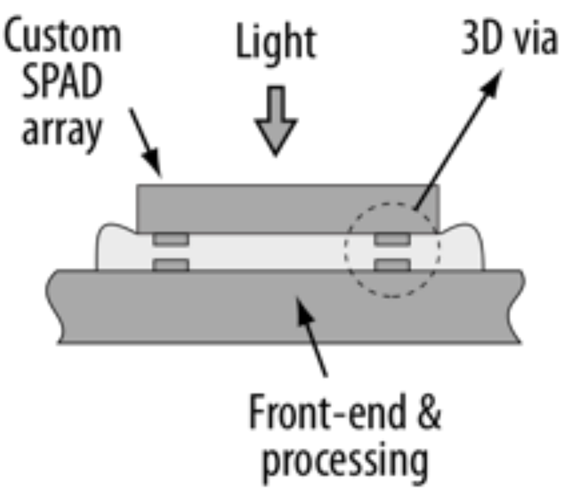
FUTURE DEV

- Improve fill-factor
- Improve detector
- Parallel TCSPC
  with 32x1 array
- Timing array with embedded TDC

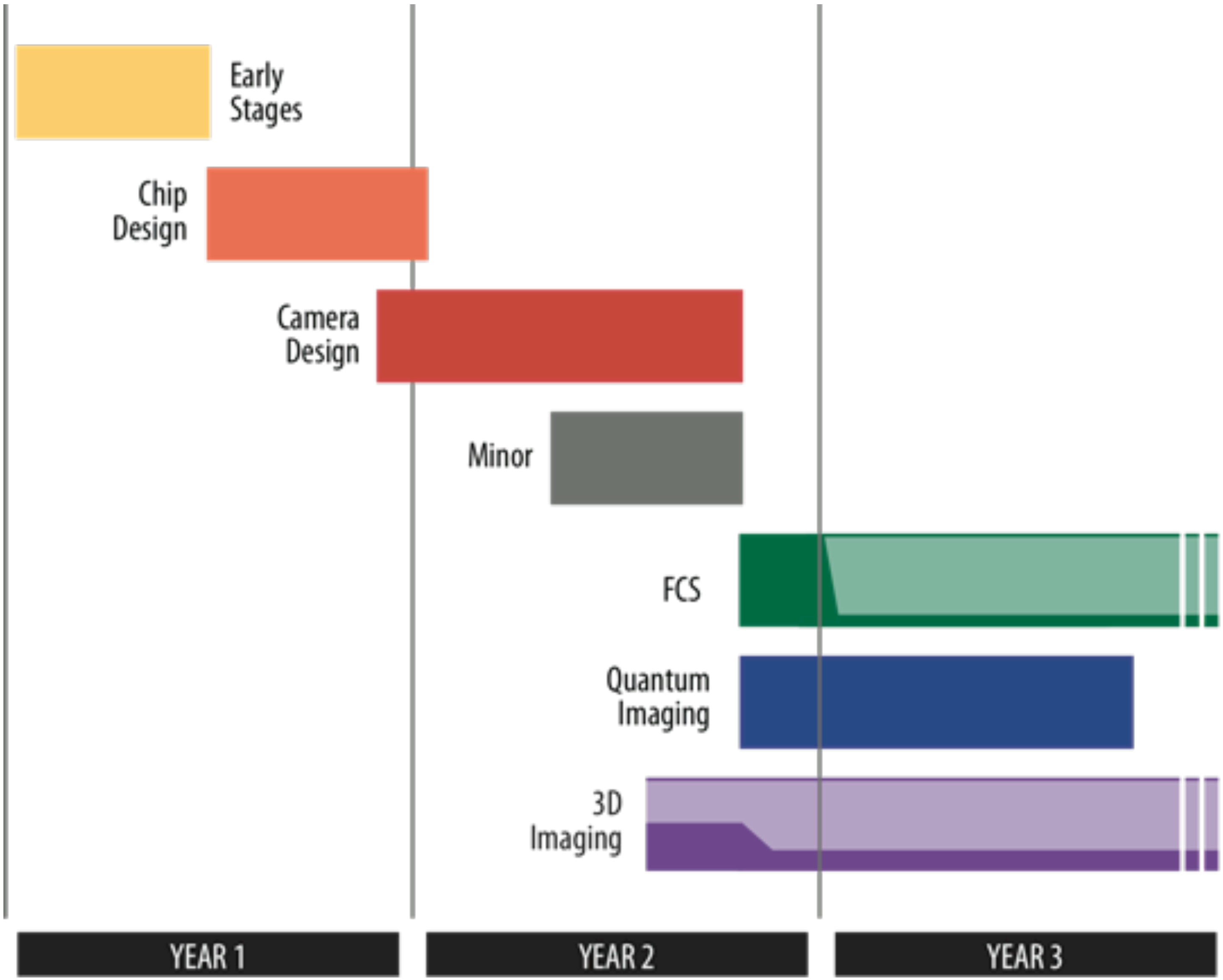
⬇

We are already working on them!





PHD TIMELINE



JOURNAL PUBLICATIONS

F. GUERRIERI, L. Maccone, F. N.C. Wong, J. H. Shapiro, S. Tisa, F. Zappa
"Sub-Rayleigh Imaging via N-Photon Detection"
Physical Review Letters (PRL), vol. 105 nr. 16, Ottobre 2010.

F. GUERRIERI, S. Tisa, A. Tosi, F. Zappa
"Two-Dimensional SPAD Imaging Camera for Photon Counting"
IEEE Photonics Journal, vol. 2 nr. 5, Ottobre 2010.

S. Tisa, *F. GUERRIERI*, F. Zappa
"Monolithic array of 32 SPAD pixels for single-photon imaging at high frame-rates"
Nuclear Instruments and Methods in Physics Research, A 610 (2009) 24-27.

S. Tisa, *F. GUERRIERI*, F. Zappa
"Variable-Load Quenching Circuit for single-photon avalanche diodes"
Optics Express 2232, vol. 16 no. 3, 2008.

EUROPEAN PROJECT: MiSPIA

needed to overcome complexity. Engineering large distributed systems increasingly requires cooperative networked control systems, and optimisation and decision support methods and tools which are used to modernise physical infrastructures, to control complex processes in manufacturing, or to monitor and control systems performance.

Research addressing this Challenge in particular will encourage international cooperation under the Intelligent Manufacturing Systems (IMS) scheme.

Technologies developed under this Challenge are expected to be tailored to meet key societal and economic needs.

Objective ICT-2009.3.7 Photonics

Target outcomes

a) Photonics technologies, components and (sub)systems driven by key applications/social needs. Cost-effective innovative device and system integration, including electronics/photonics integration

technologies, components, (sub)systems and disciplines for medical and biological applications of photonics.

4) *Cost-effective high-performance imaging for Safety & Security:* specific targeted actions on (i) CMOS-compatible low-power uncooled image sensors with high dynamic range and single-photon imaging capability at video-rate readout speed and/or (ii) compact multi-feature imaging systems based on advanced smart pixel detector arrays with sub-picosecond timing precision, pixel-level hyper-/multi-spectral resolution, polarisation sensitivity, and intra-pixel on-chip pre-processing capabilities.

5) Specific targeted actions on *highly integrated components* for high average and high peak power lasers for ICT and industrial applications: (i) novel concepts for fibres and fibre lasers with integrated functions, such as filters, polarisers, frequency shifters, q-switches, etc.; (ii) diode lasers with new functions integrated in the semiconductor e.g. epitaxial structures for mode selection, Bragg gratings, integrated q-switches and saturable absorbers, etc.

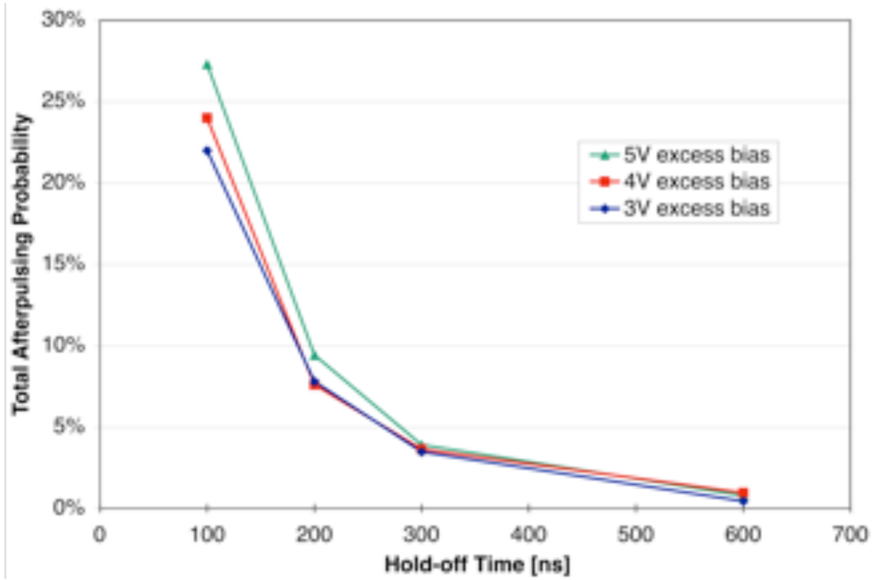
HIGH THROUGHPUT FCS @ UCLA

Device	Pattern	Pixel	n	d (ms)	
SPAD camera	Single	B	0.53	12.5	Good
SPAD camera	Single	C	0.616	11.8	Good
SPAD camera	8x8	A	1.55	7.35	
SPAD camera	14x14	A	3.74	7.42	
SPAD camera	32x32	A	17.7	1.78	
SPAD camera	32x32	C	138	2.86	
SPAD camera	32x32	D	95.6	2.87	
Custom SPAD array		1	0.472	14.1	Reference
Custom SPAD array		4	0.703	14.3	Reference

PERFORMANCES 1/2

20-μm CMOS SPAD

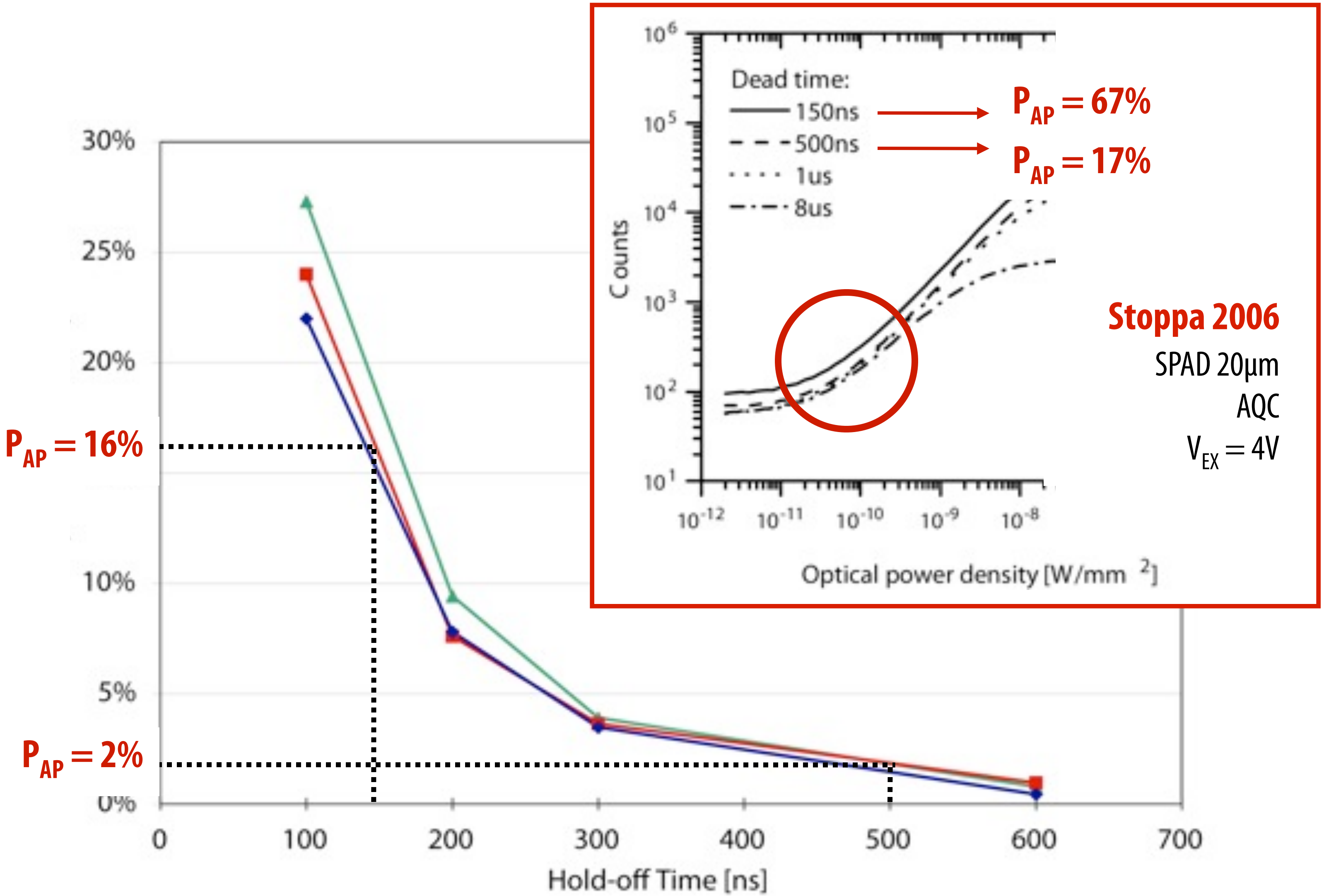
Distance	Crosstalk Probability
100 μm	3.53×10^{-5}
200 μm	4.33×10^{-6}
300 μm	2.86×10^{-5}
400 μm	7.15×10^{-7}



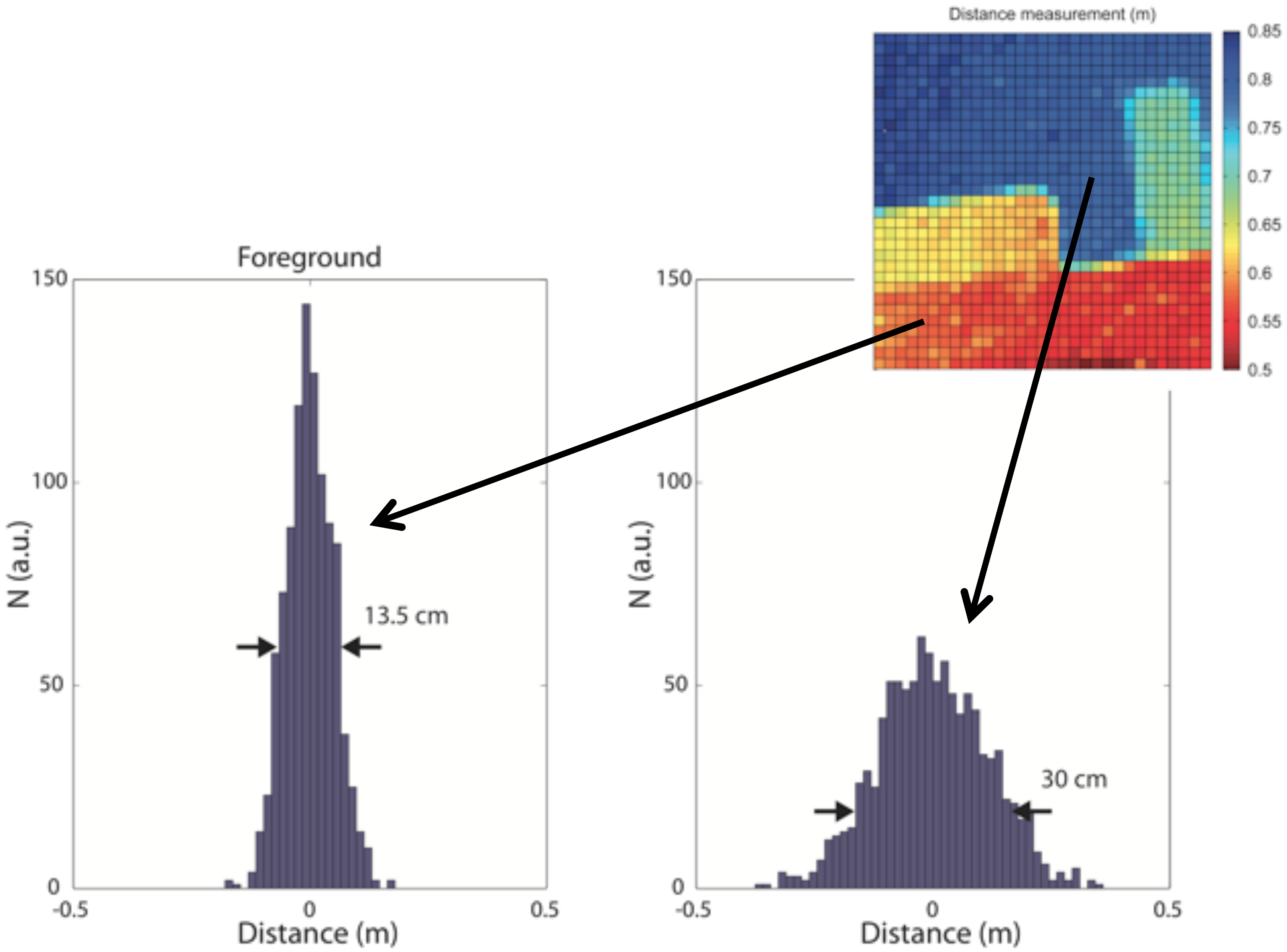
V_{EX}	DCR	PDE_{PK}	AP*
3V	2000cps	31%	0,45%
4V	3000cps	37%	0,90%
5V	4900cps	42%	0,96%

VLQC

Afterpulsing performances

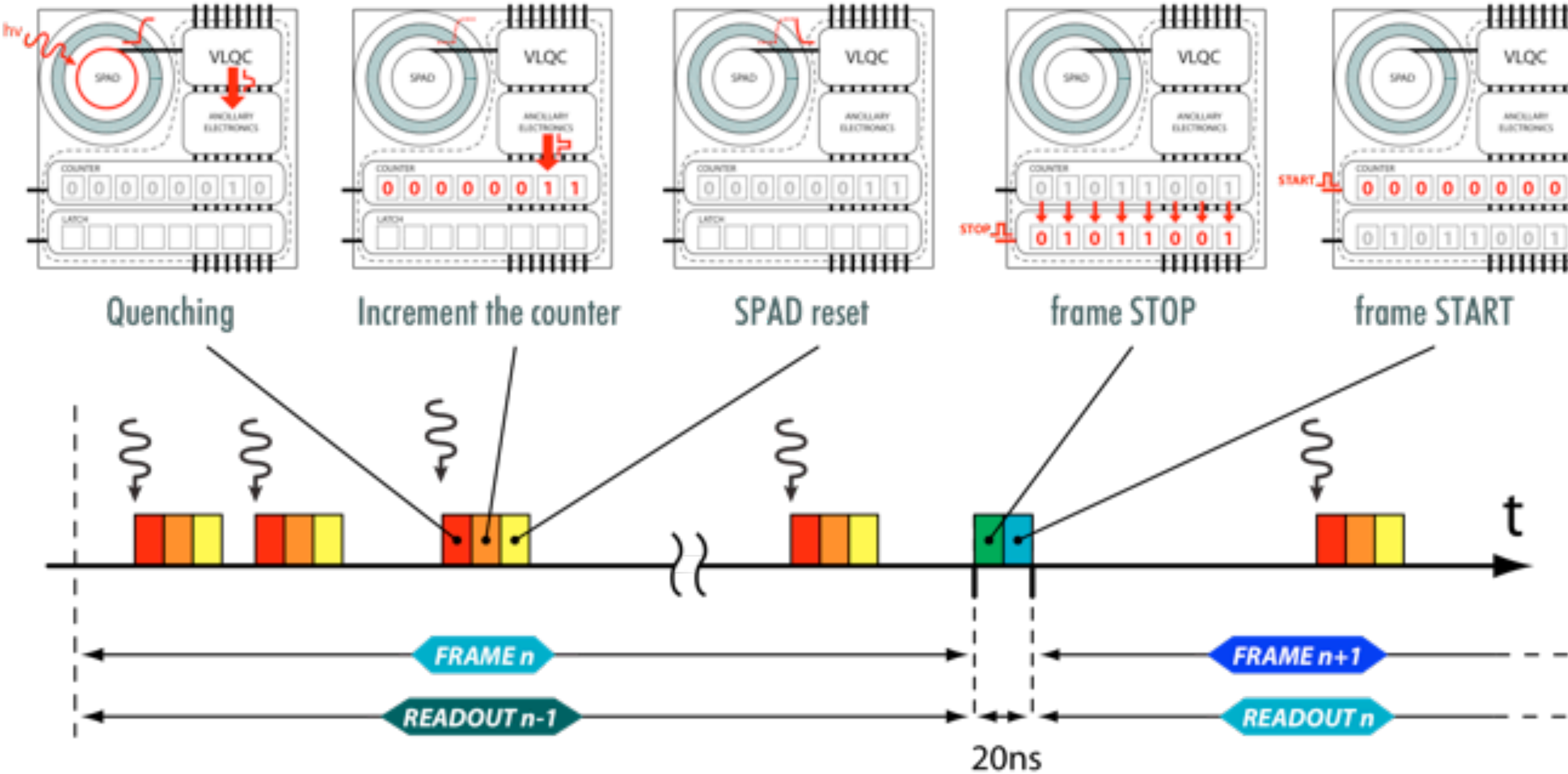


3D IMAGING



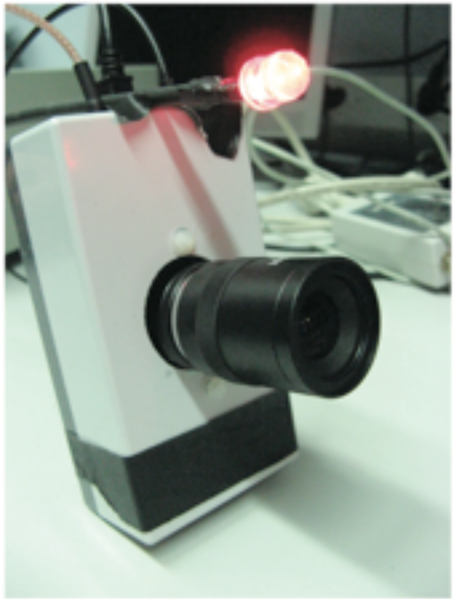
Distance measurement (m)
0.85
0.8
0.75
0.7
0.65
0.6
0.55
0.5
Foreground
150
100
50
0
N (a.u.)
13.5 cm
-0.5
0
0.5
Distance (m)
150
100
50
0
N (a.u.)
30 cm
-0.5
0
0.5
Distance (m)

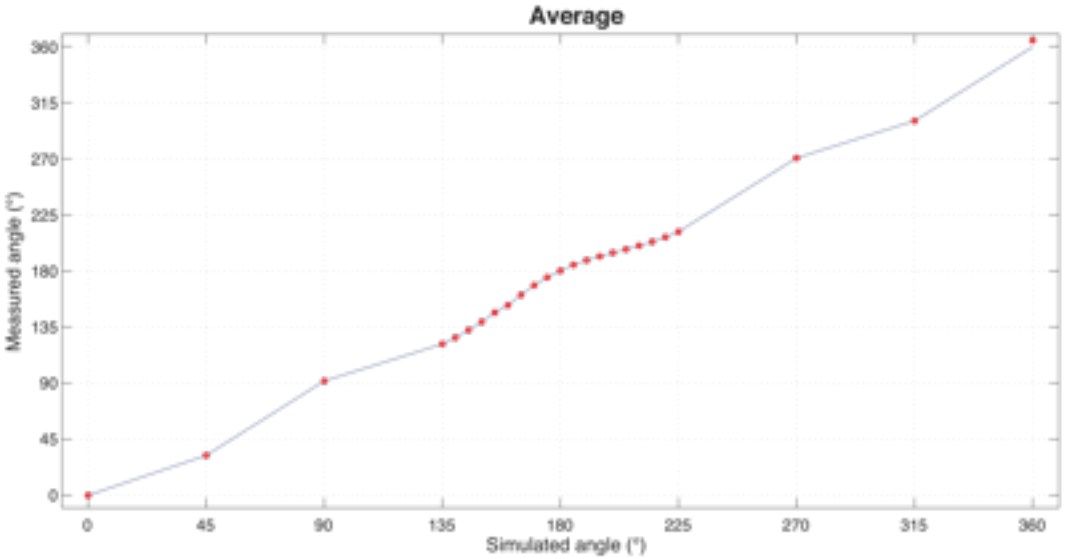
ARRAY OPERATIONS



- 2-level pipeline architecture
- Only 20ns interframe dead time

3D IMAGING





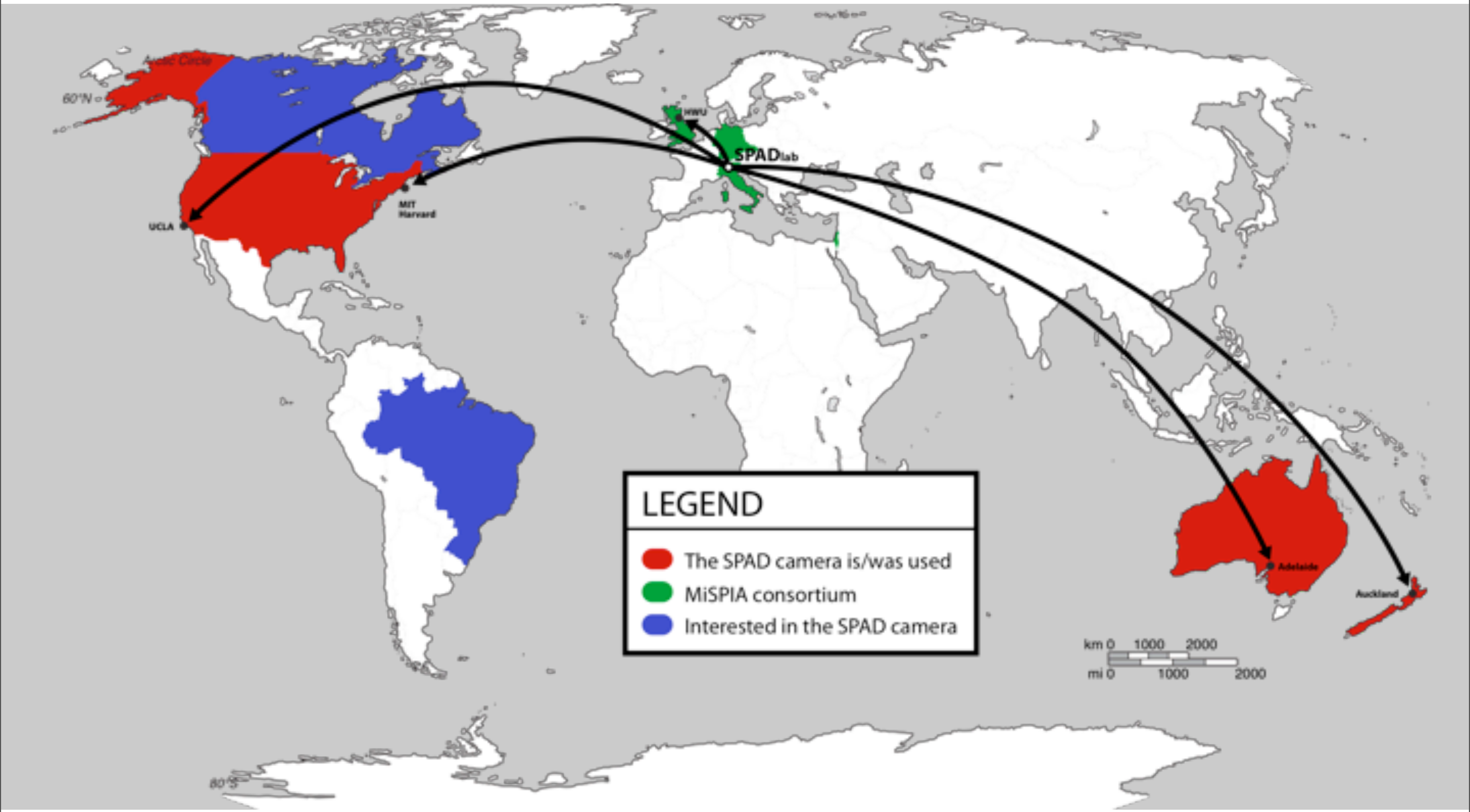
Light modulation manually with fixed camera input trigger

Phase (°)	Measure (°)	Dev.std. (°)
0	0	1.27
45	31.98	1.17
90	91.71	1.24
135	121.34	1.15
180	180.17	2.91

NOTES

- Prepare slide on competitors (arrays)
- Slides on comparison ToF with iToF
- Slide with fast imaging example (oscilloscope)
- Bring the fonts!!!
- Slide with new FCS pattern (did they solve? What’s the current status?)
- Slides to explain better MIT stuff?
- Slide on microlenses

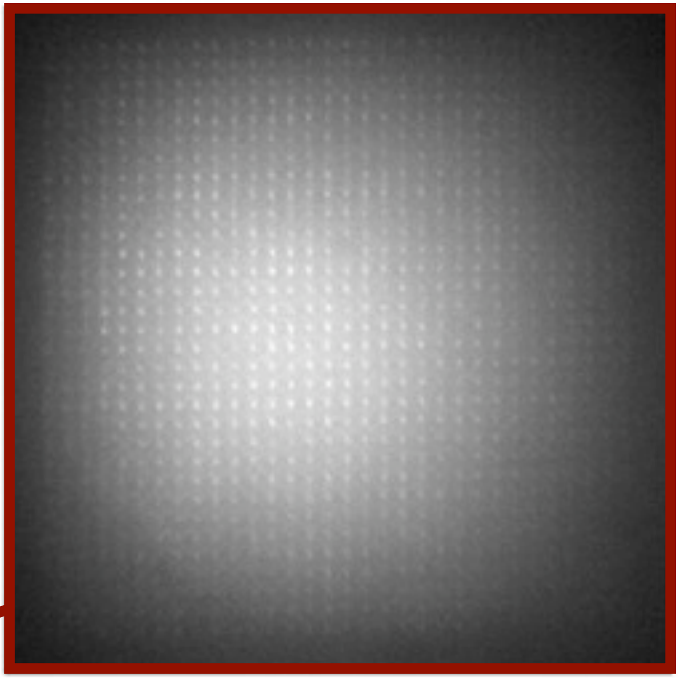
INTERNATIONAL SUCCESS



HIGH THROUGHPUT FCS @ UCLA

PRELIMINARY CONCLUSIONS

- Demonstrated feasibility of 64X throughput improvement with 8x8 sub-array
- Future steps:
    - Use different samples
    - Improve optics to extend the technique to bigger patterns



With 32x32 pattern the spots are not well defined and ACF could not be fitted

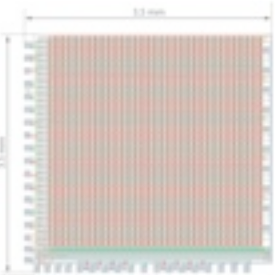
CONCLUSIONS

Novel SPAD quenching circuit

- Small footprint
- Small parasitic capacitance
- Compatible with CMOS SPAD technology
- Reduced afterpulsing and good timing

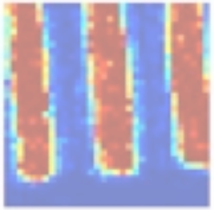
VLQC

Pixel



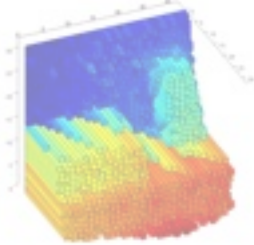
32x32
Array

SPAD
Camera



Sub-Rayleigh
Imaging

FCS



3D
Imaging

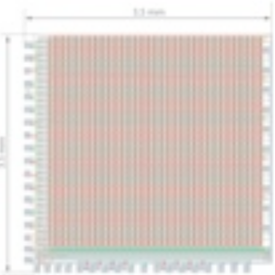
CONCLUSIONS

Smart pixel architecture

- 20-µm CMOS SPAD detector
- Front-end electronics (VLQC)
- Counting and buffer digital logic

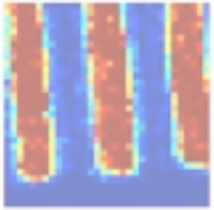
VLQC

Pixel



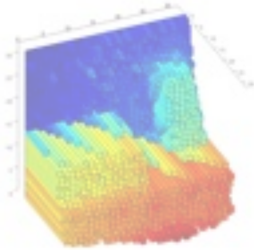
32x32
Array

SPAD
Camera



Sub-Rayleigh
Imaging

FCS



3D
Imaging

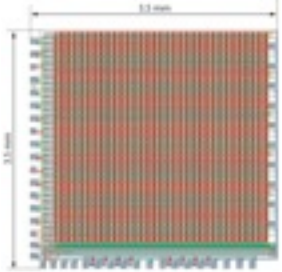
CONCLUSIONS

32x32 CMOS SPAD imager

- 1,024 indipendent photon counting channels
- Single-photon sensitivity
- Up to 100 kframe/s

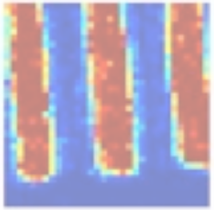
VLQC

Pixel



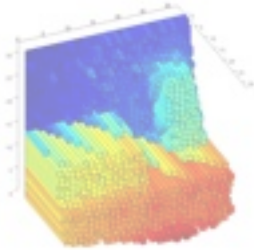
32x32 Array

SPAD Camera



Sub-Rayleigh Imaging

FCS

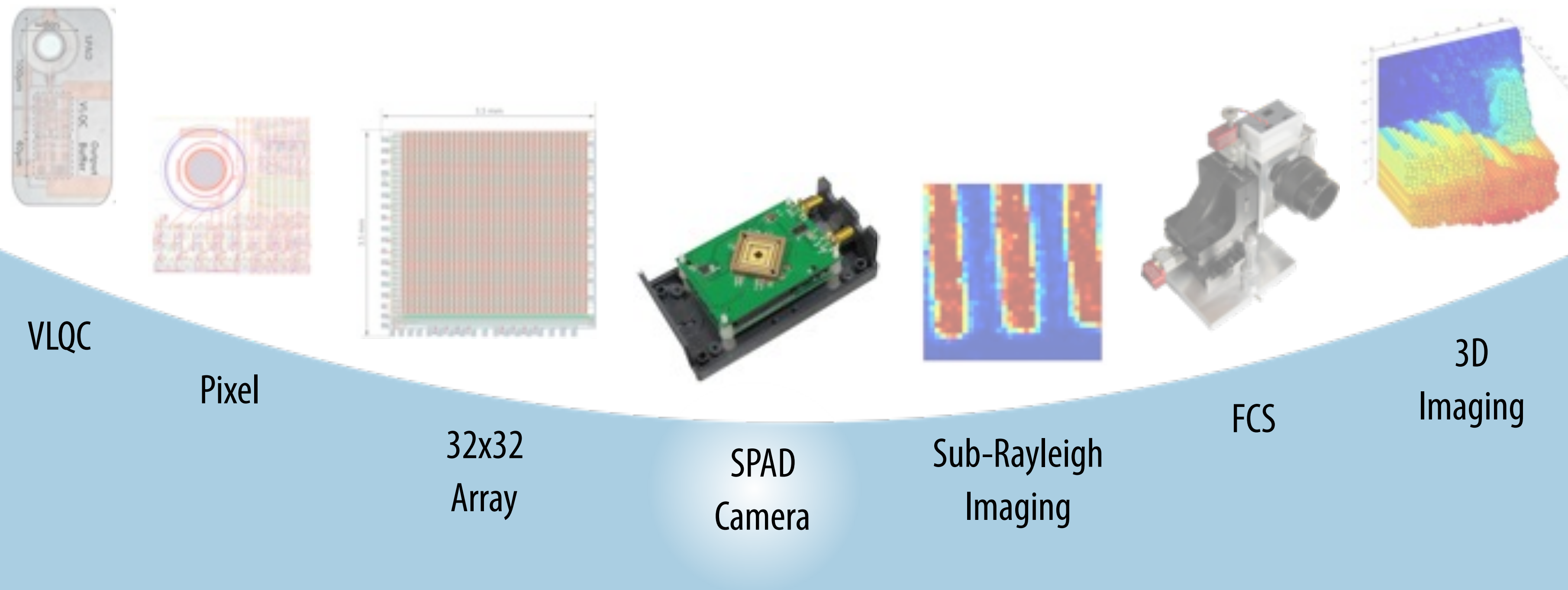


3D Imaging

CONCLUSIONS

SPAD camera

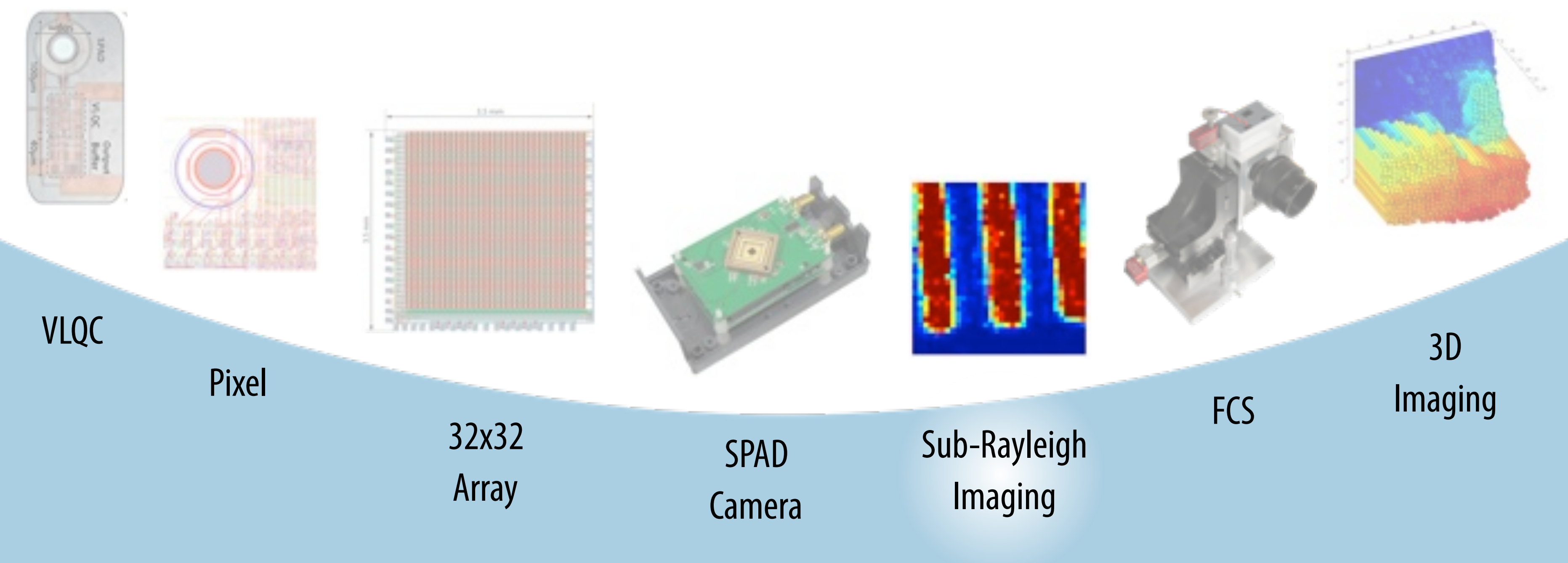
- High-speed digital FPGA-based system electronics
- Plug'n'play device. Power supplies from USB
- Cross-platform user-friendly user interface
- Optics



CONCLUSIONS

Sub-Rayleigh imaging @

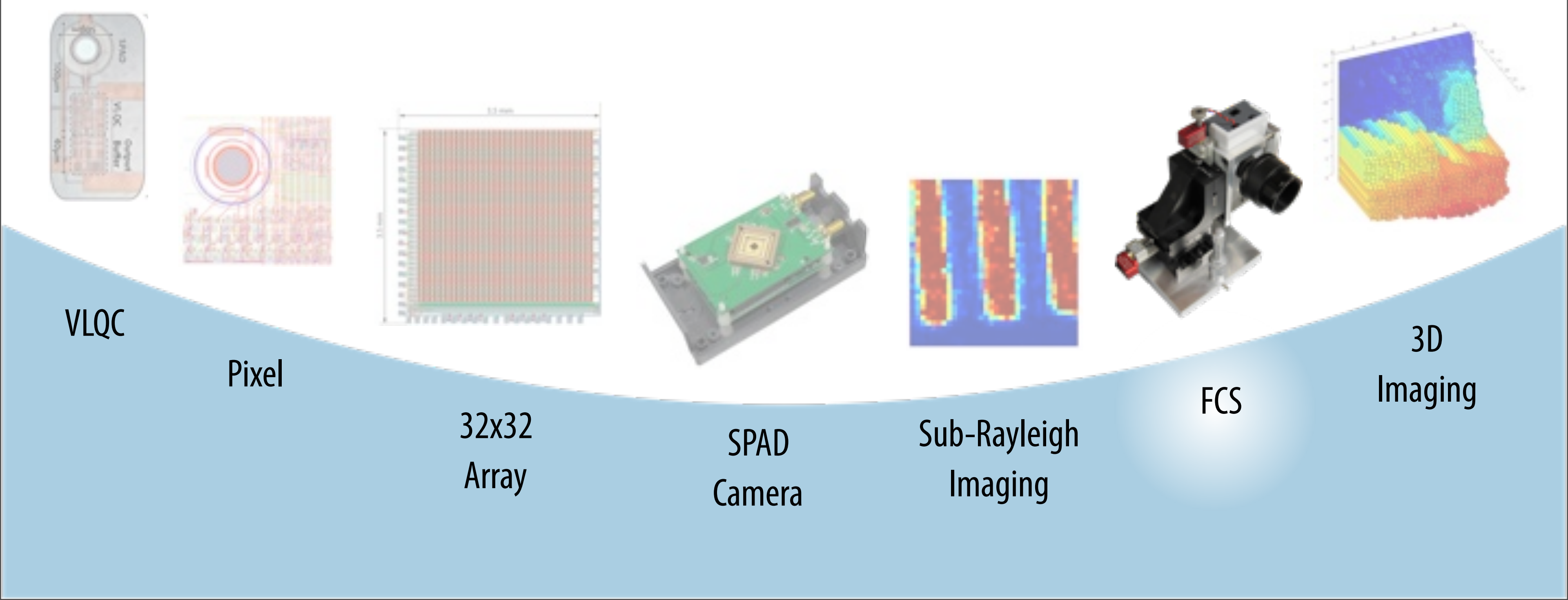
- Experimentally demonstrated and developed novel imaging technique
- Full project responsability
- SPAD camera as enabling technology



CONCLUSIONS

Fluorescence Correlation Spectroscopy @ Ucla

- Proof of concept for high-troughput FCS on 1,024 parallel channels
- Customization of SPAD camera for FCS
- Promising preliminary experimental results



CONCLUSIONS

3D imaging @ Polimi

- Developed and conceived technique to use SPAD camera in 3D imaging
- Very good preliminary experiments