MEGAFRAME: a fully integrated, time-resolved 160×128 SPAD pixel array with microconcentrators

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Outline

- Aims and scope of MEGAFRAME
- Key application: FLIM
- Architecture
- Results
- Conclusions

Aims and Scope of MEGAFRAME

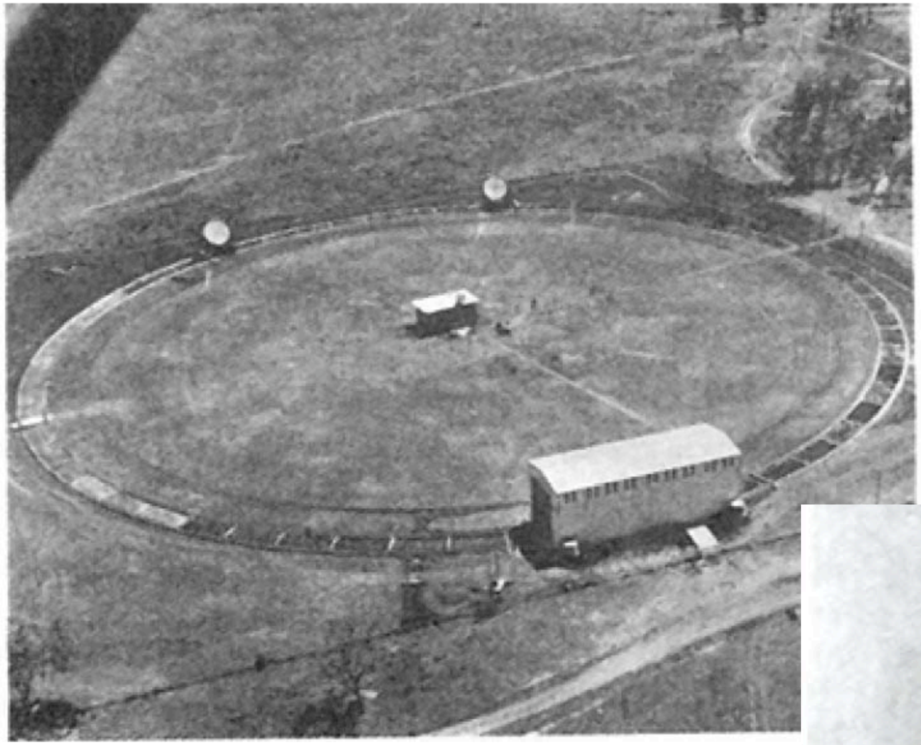
Fully digital,
scalable *sensor* capable
of counting single photons and of
detecting their
time-of-arrival for bioimaging
applications

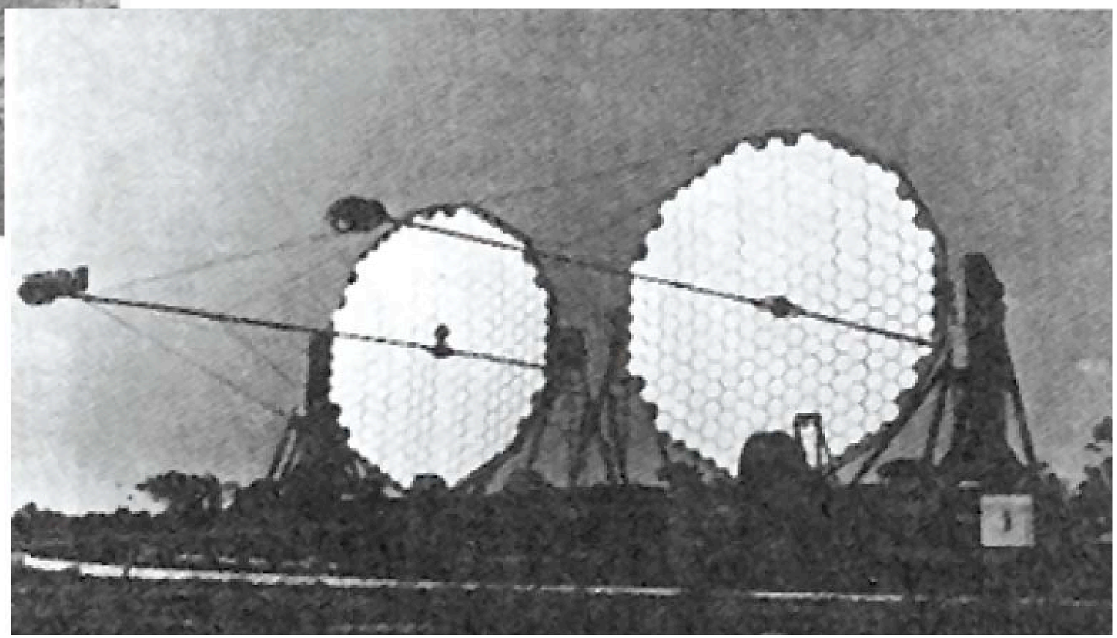
Time-of-arrival and Time-of-flight of Photon Bursts are Useful to…

- compute distances
- reconstruct 3D scenes
- evaluate speed of moving objects
- analyze nuclear reactions
- count molecules
- analyze molecular environment
- “see” subatomic particles and high energy rays

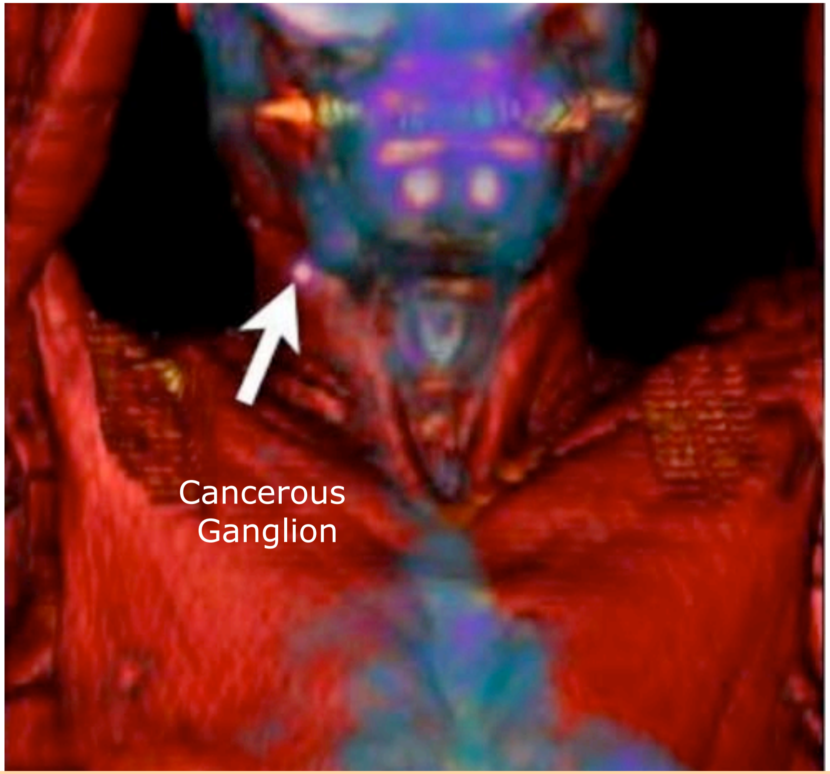
etc.

Stellar Hanbury-Brown Twiss Interferometer





Positron Emission Tomography (PET)



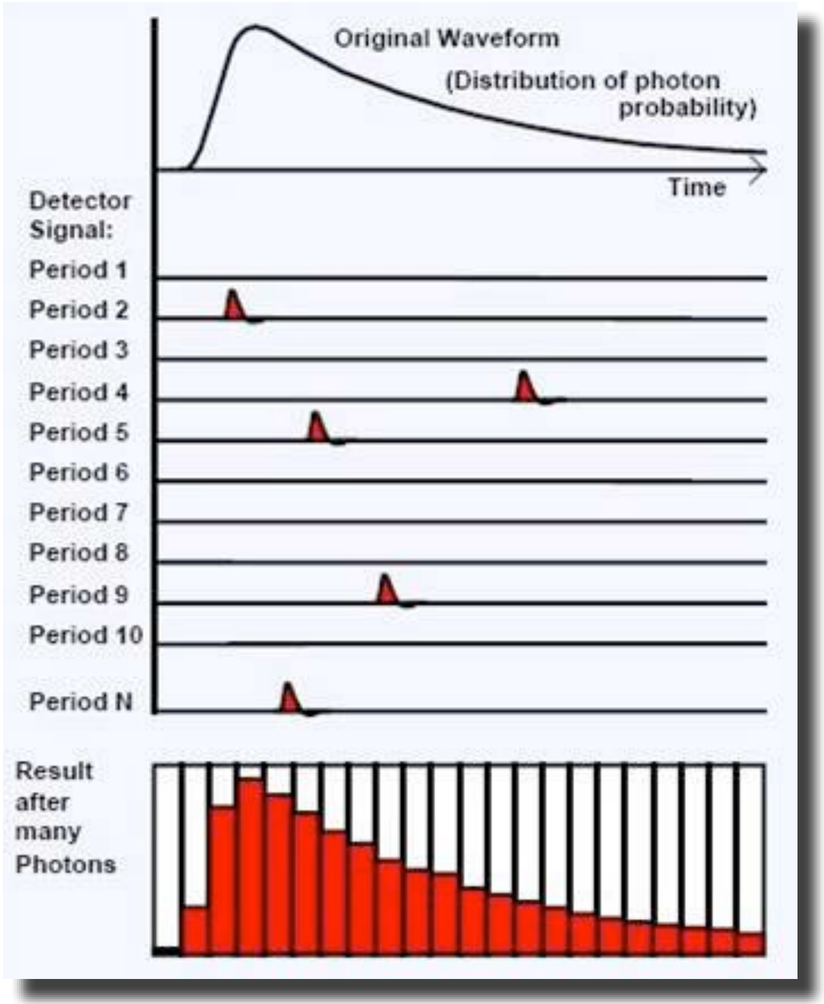
PET visualizes β+ emission from ^{18}FDG metabolized by cancer cells…

in 3D!

Key Application: FLIM

Delft University of Technology

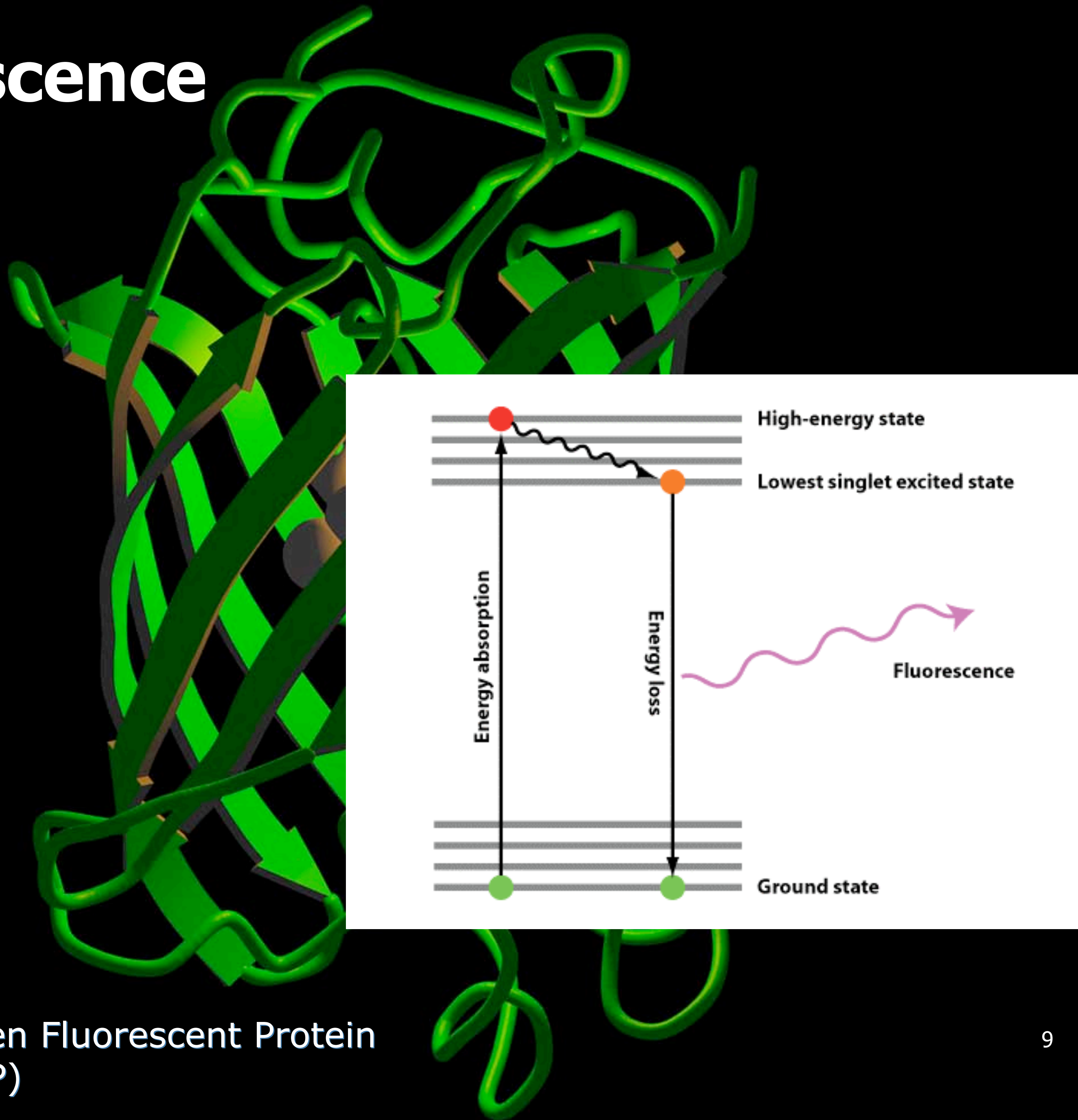
Goal: Time-resolved Imaging ⇒ Fluorescence Lifetime Imaging



Bollinger & Thomas, 1961

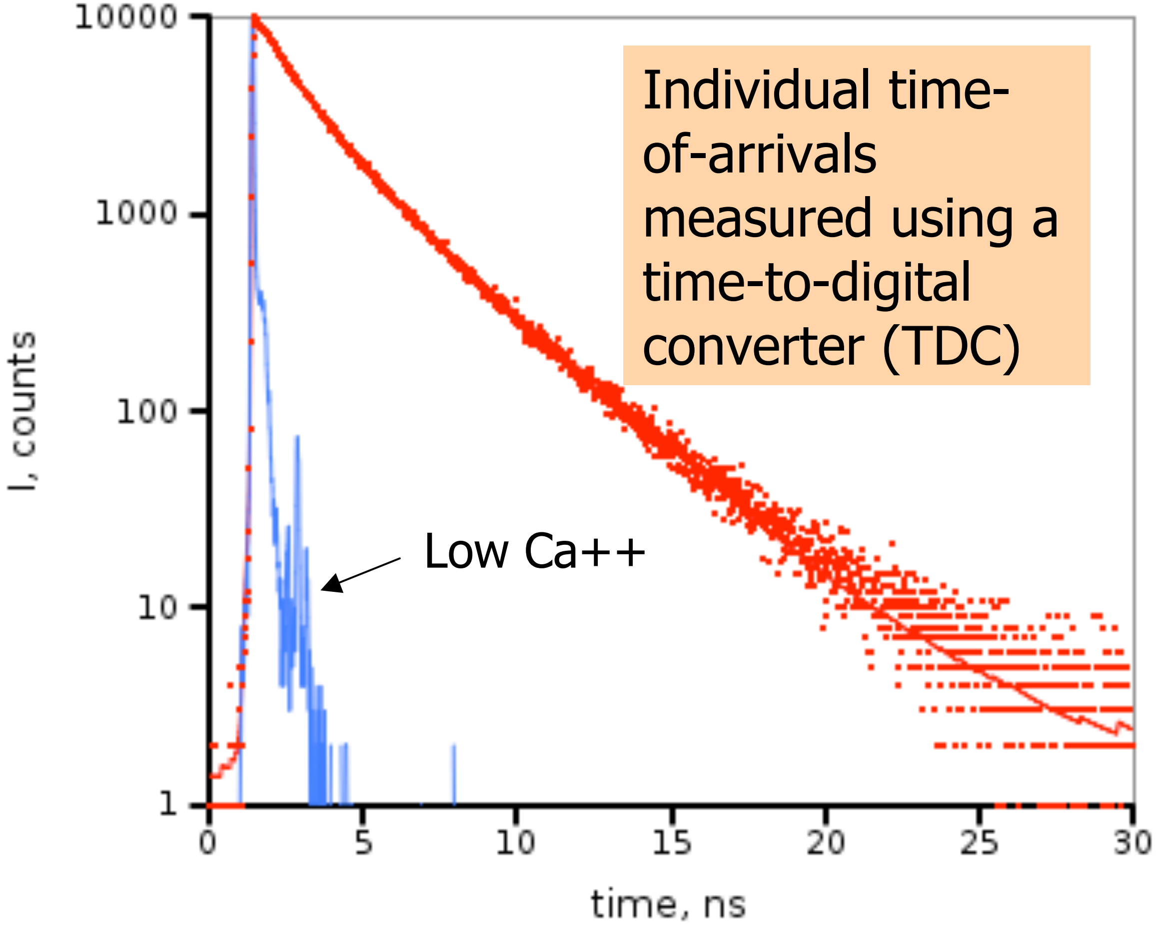
Individual single-photon time-of-arrivals

Fluorescence



Green Fluorescent Protein (GFP)

Fluorescence Lifetime vs. Environment



Novelty of MEGAFRAME

- Use a **massive array** of single-photon avalanche diodes (SPADs) implemented in standard 130nm CMOS imaging process

- Use a TDC **in every pixel**
  - Eliminate scanning, gating/shuttering
  - Increase frame rate
  - Decrease exposure time, fit time
  - Move towards video-rate FLIM

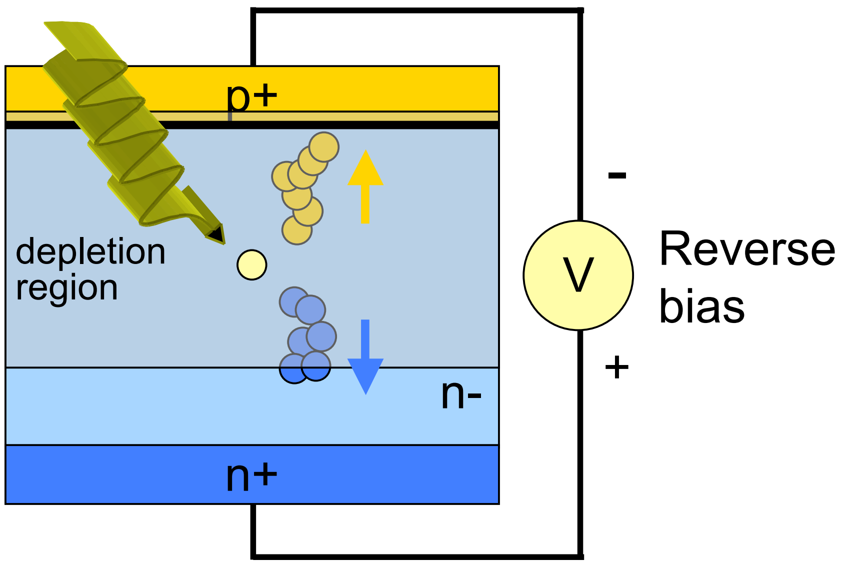
- Recover fill factor losses with **microlenses**

Single-photon Avalanche Diode (SPAD)

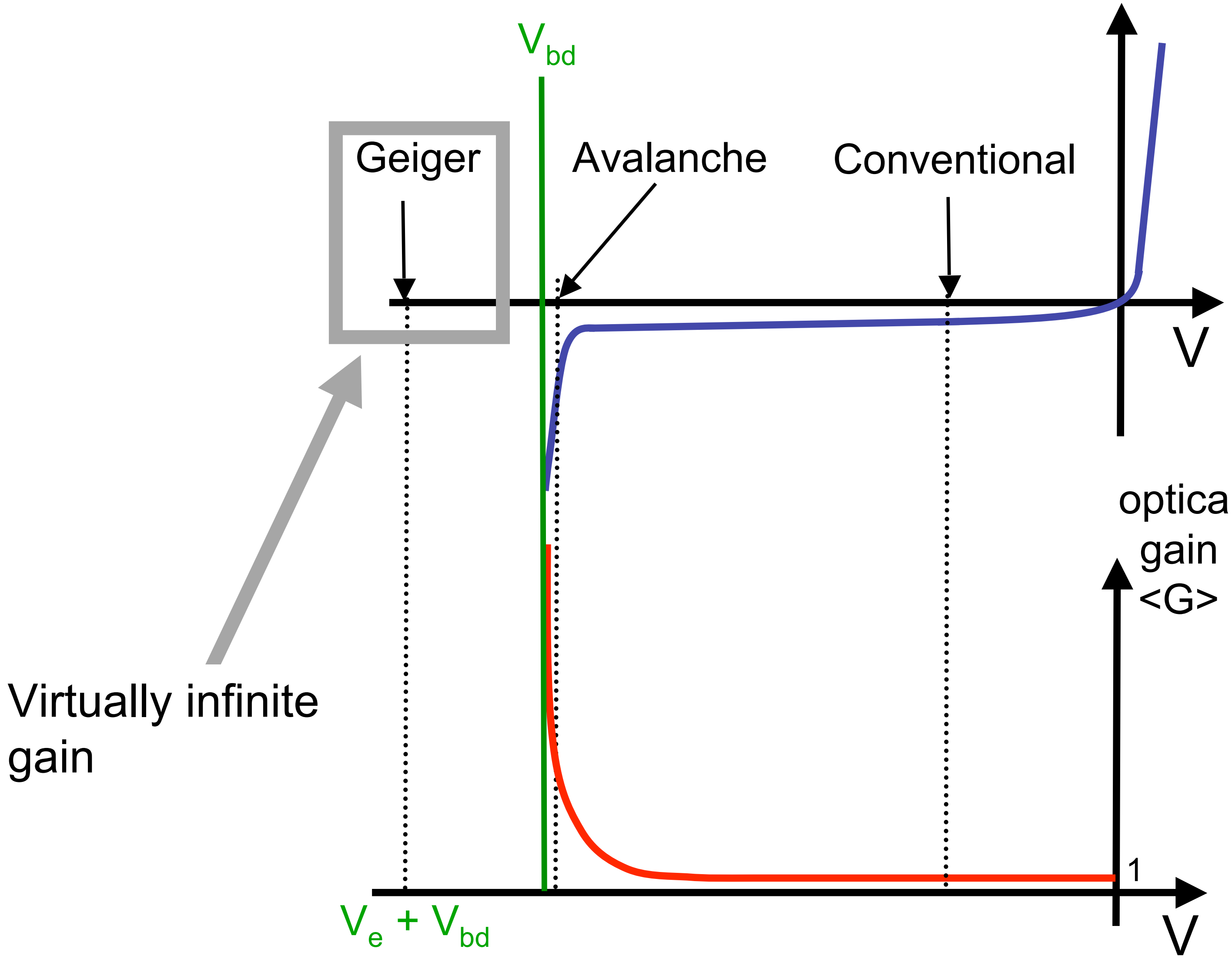
- *Review*:

  Photon to electron - Secondary electron - Multiplication

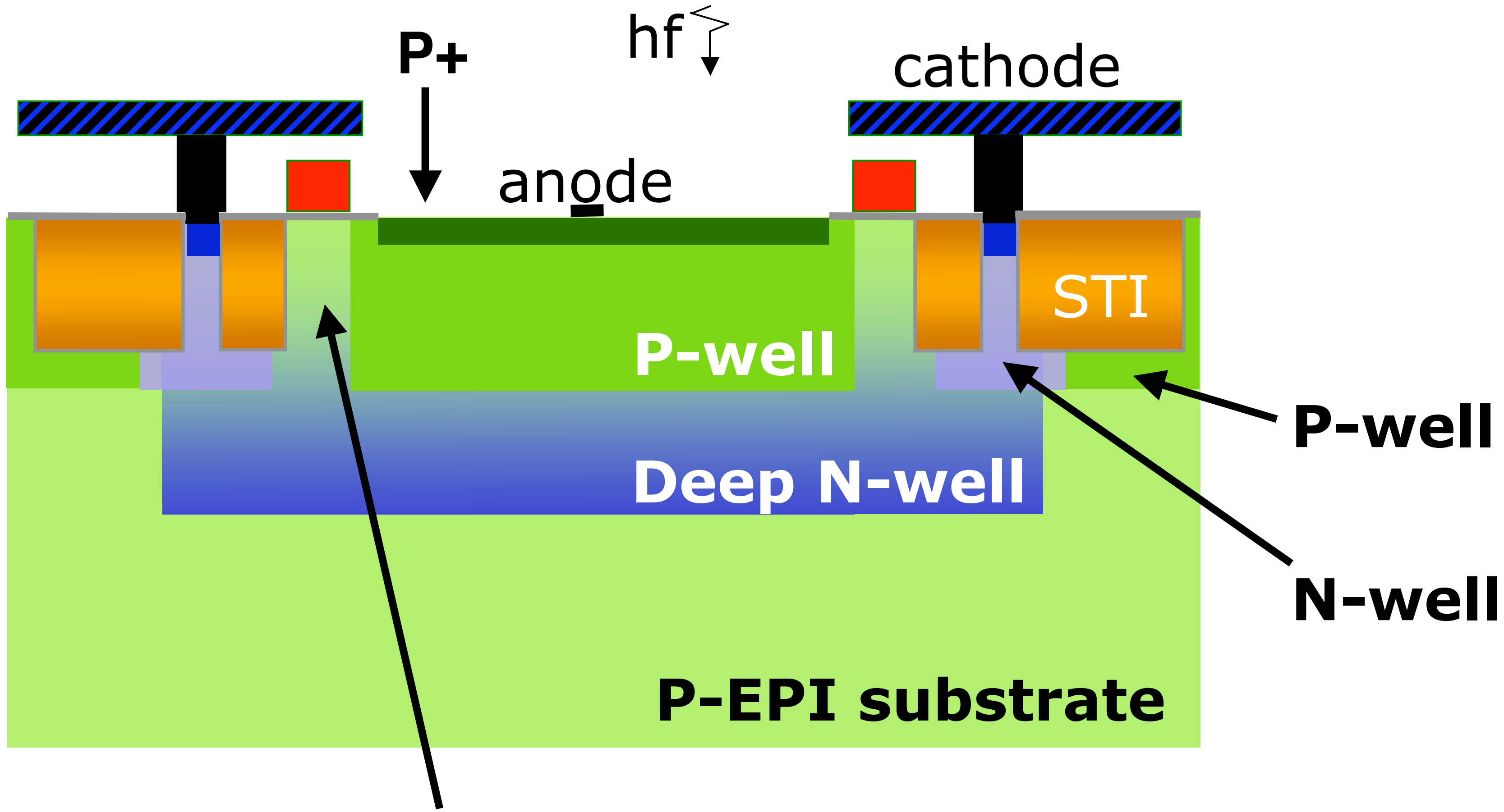
  Multiplication in depletion region by *impact ionization*



SPAD


V bd
Geiger
Avalanche
Conventional
V
optical
gain
<G>
1
V
Ve + Vbd
Virtually infinite
gain

CMOS SPAD

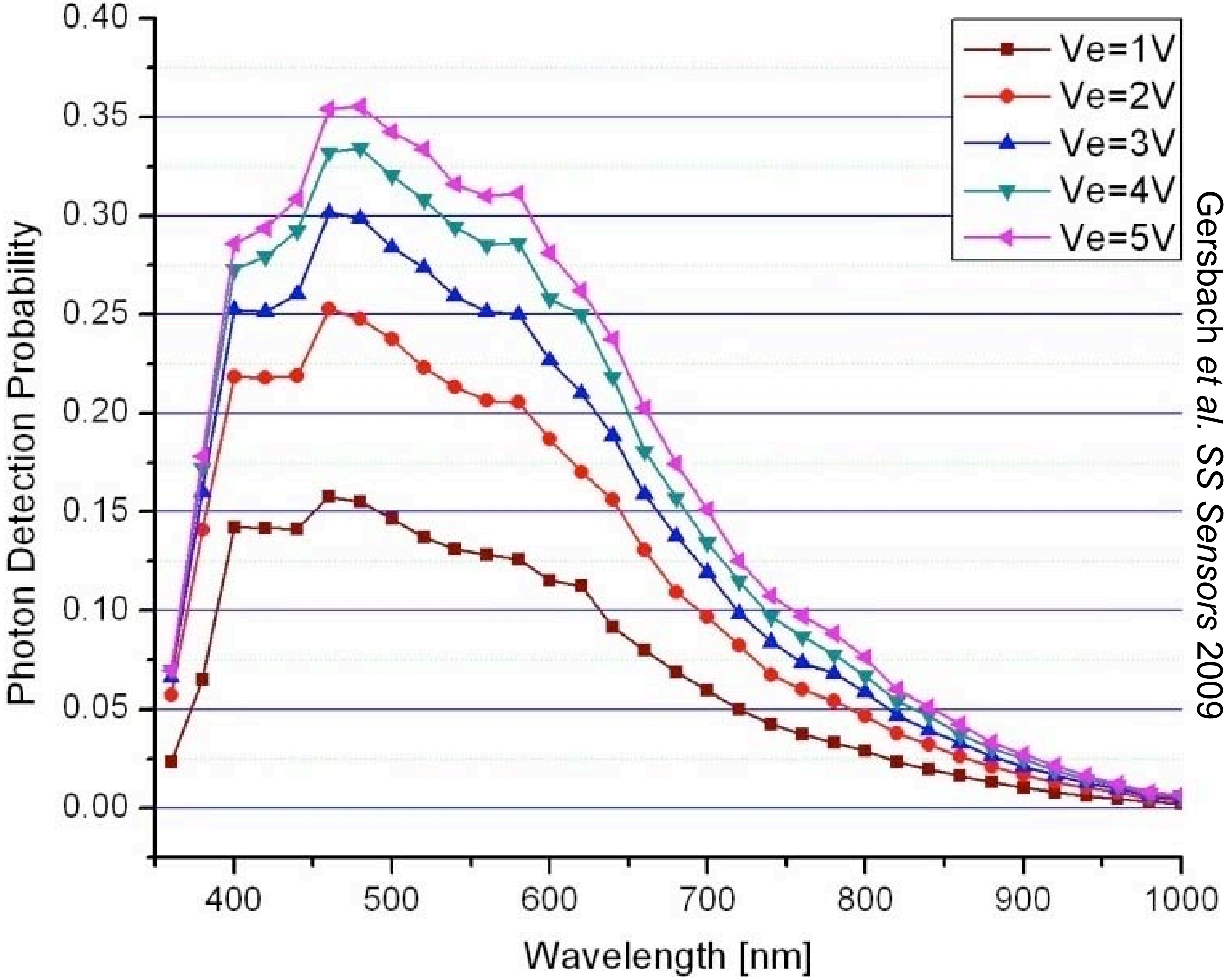


P-EPI/Deep N-well GUARD (no NWELL or PWELL)

Deep-submicron SPAD Performance

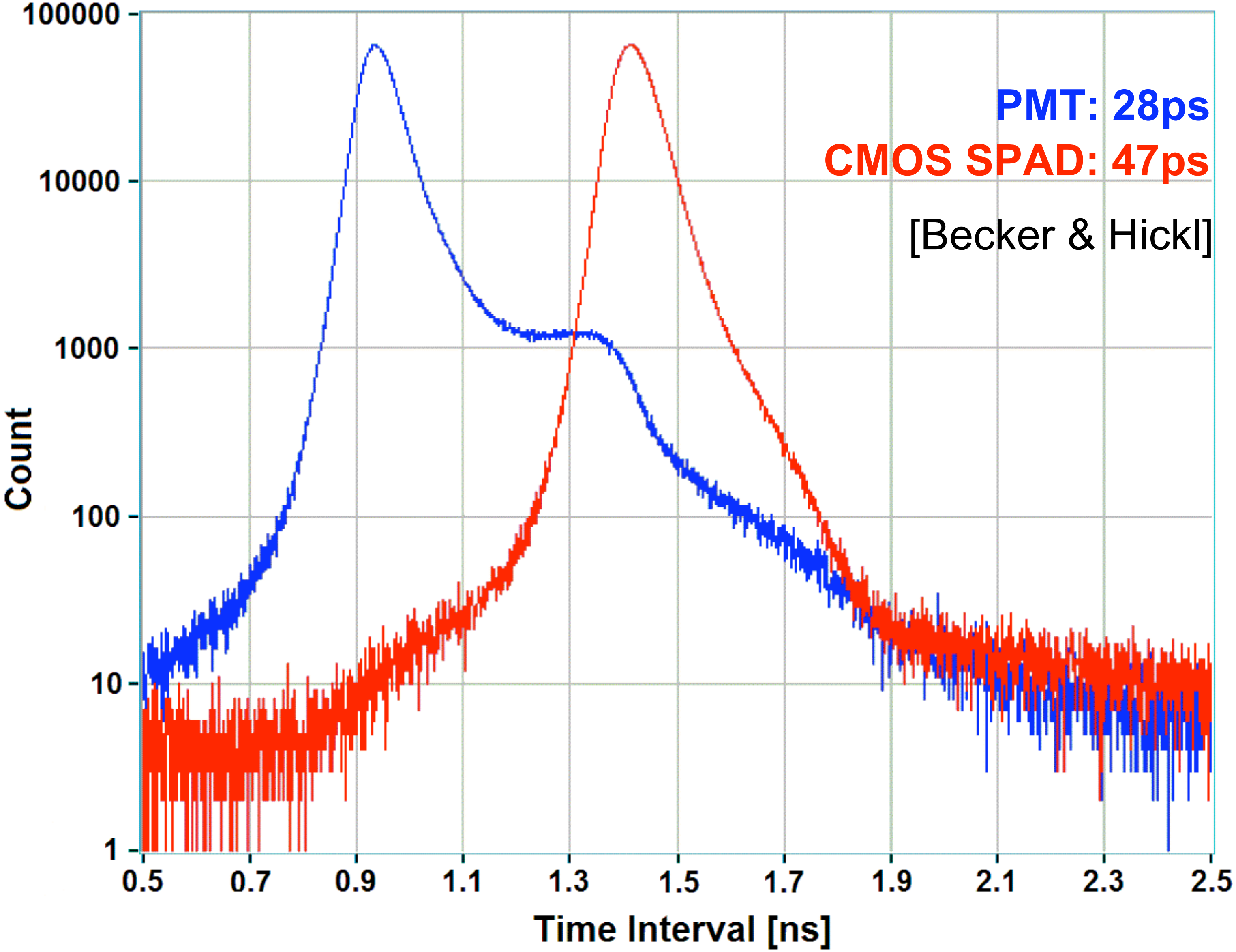
- Technology: 130nm CMOS IS
- Timing uncertainty < 125ps
- DCR (median, RT): 100Hz
- DCR (median, -60C): < 20Hz
- Dead time < 100ns
- PDP (sensitivity): 26% @ 460nm
- Range: 380-900nm

SPAD Spectral Performance



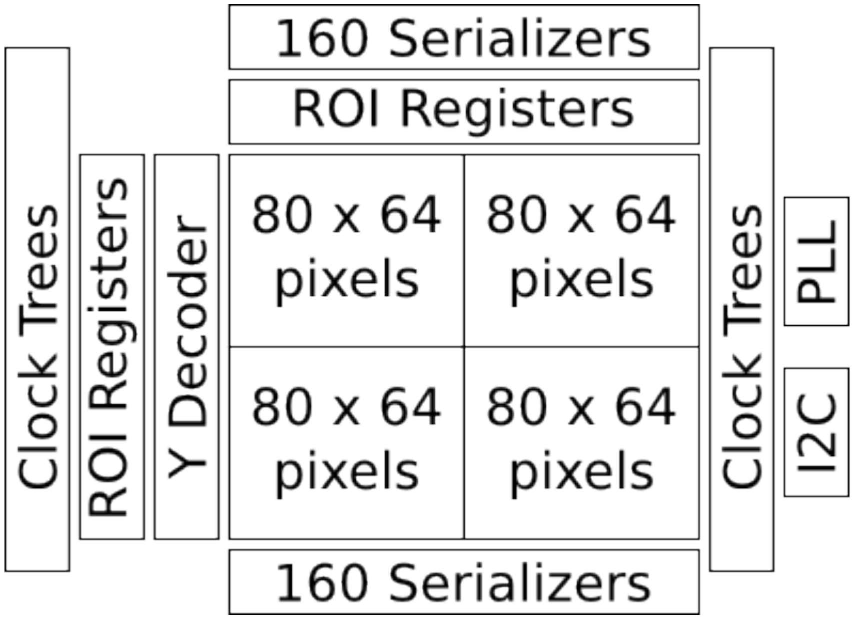
Gersbach *et al. SS Sensors* 2009

SPAD Temporal Performance

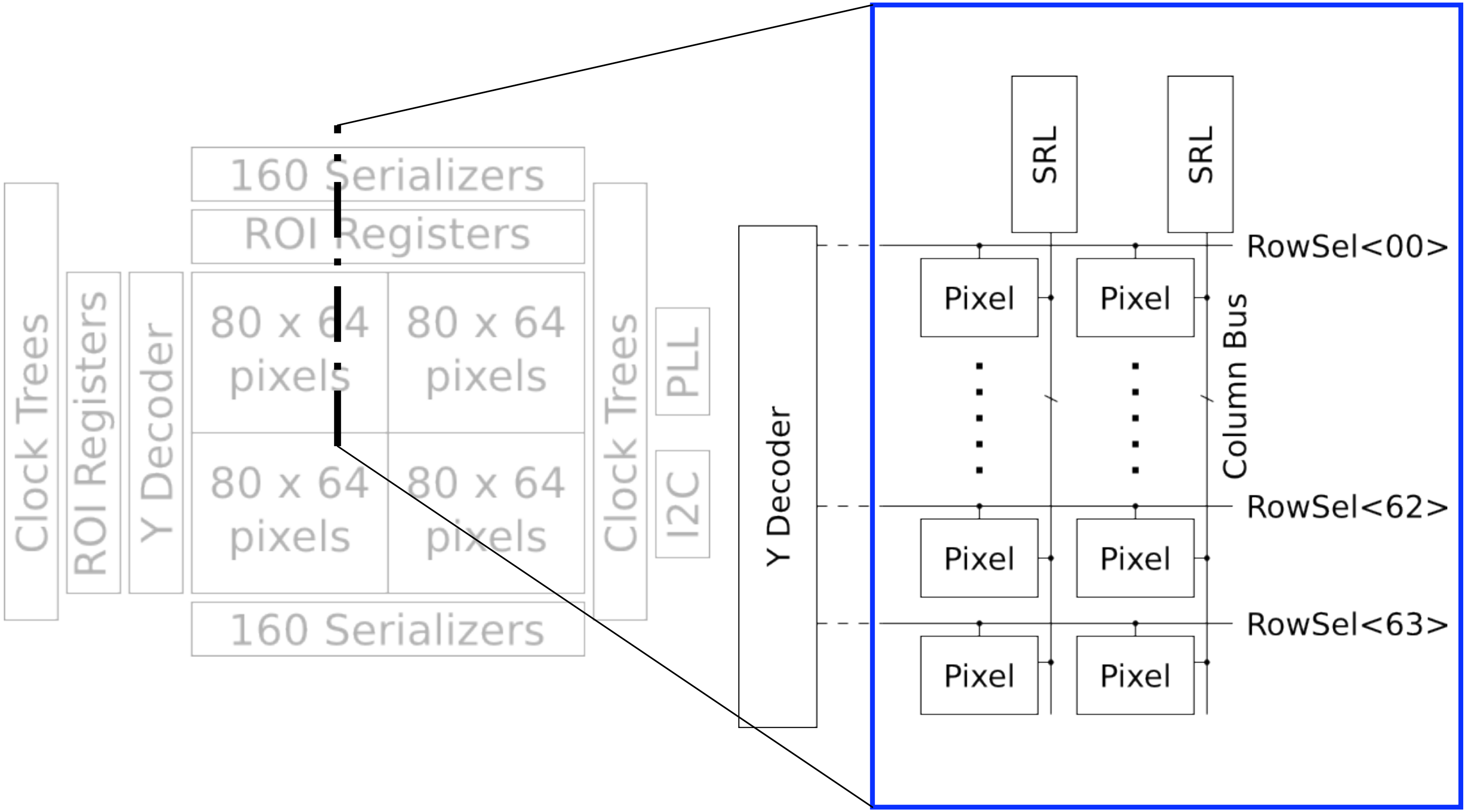


Architecture

Imager Block Diagram

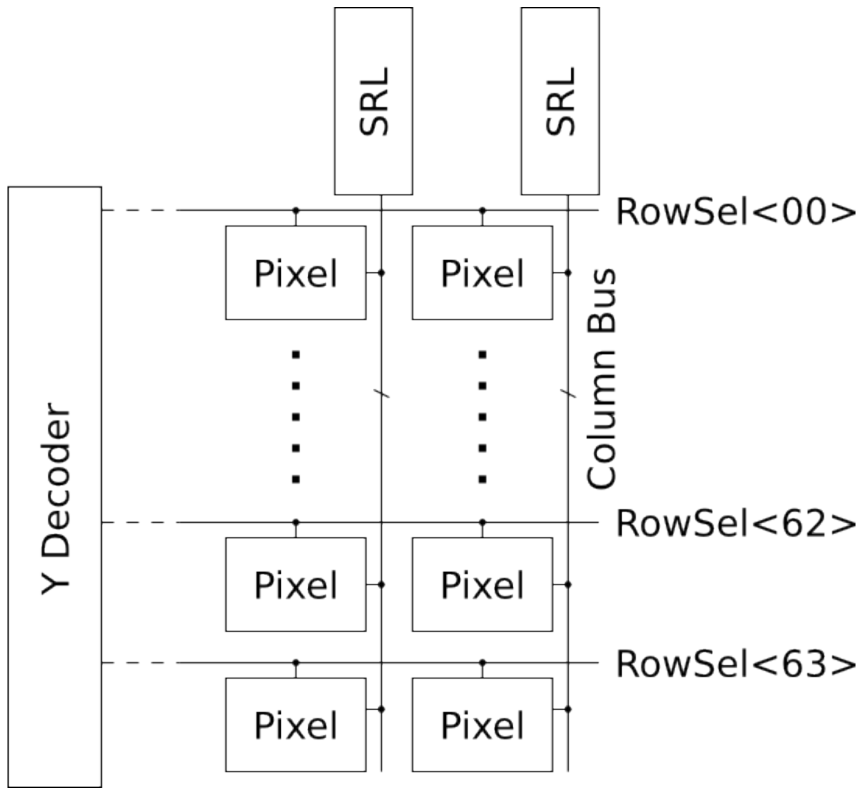


Imager Block Diagram

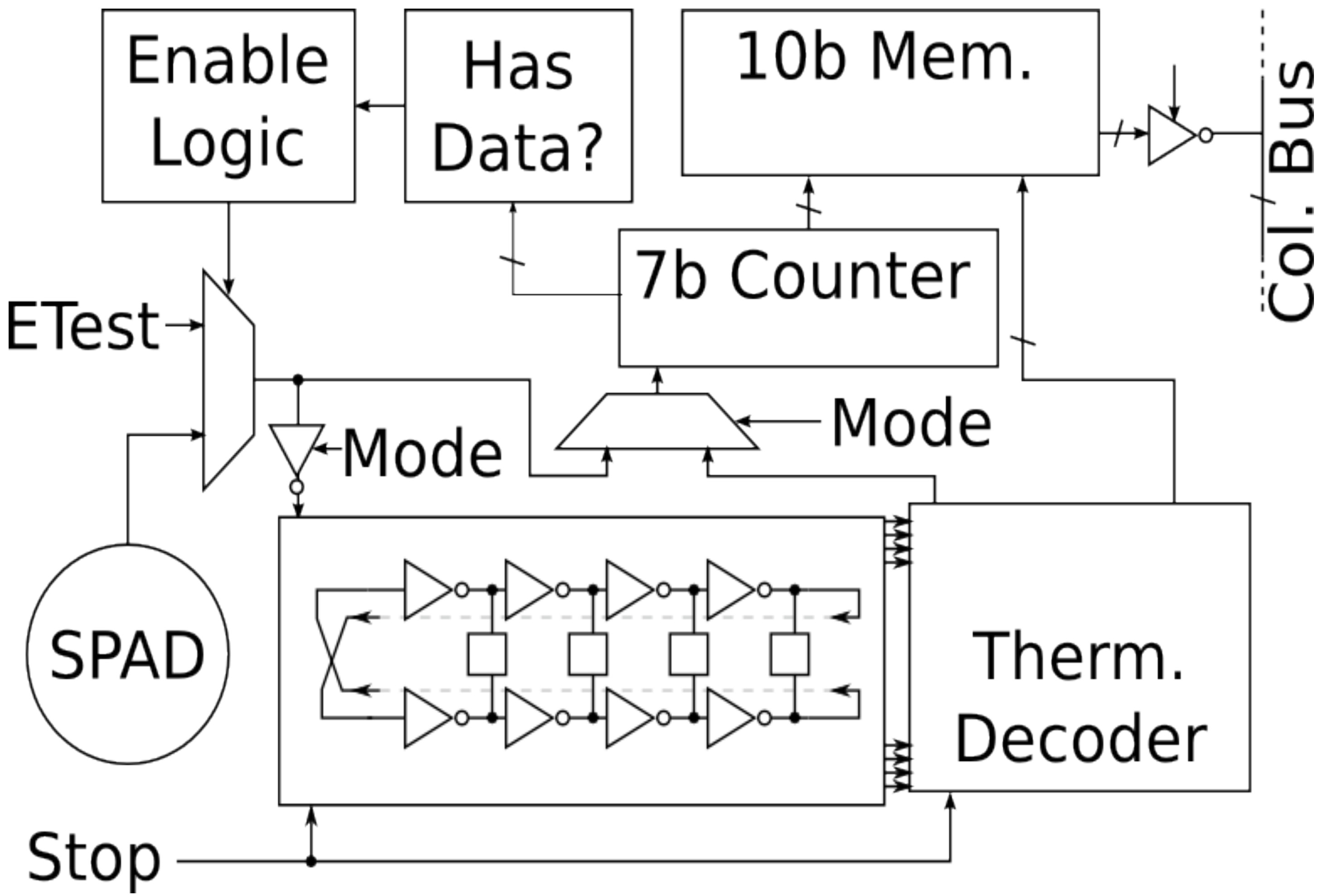


Imager Readout

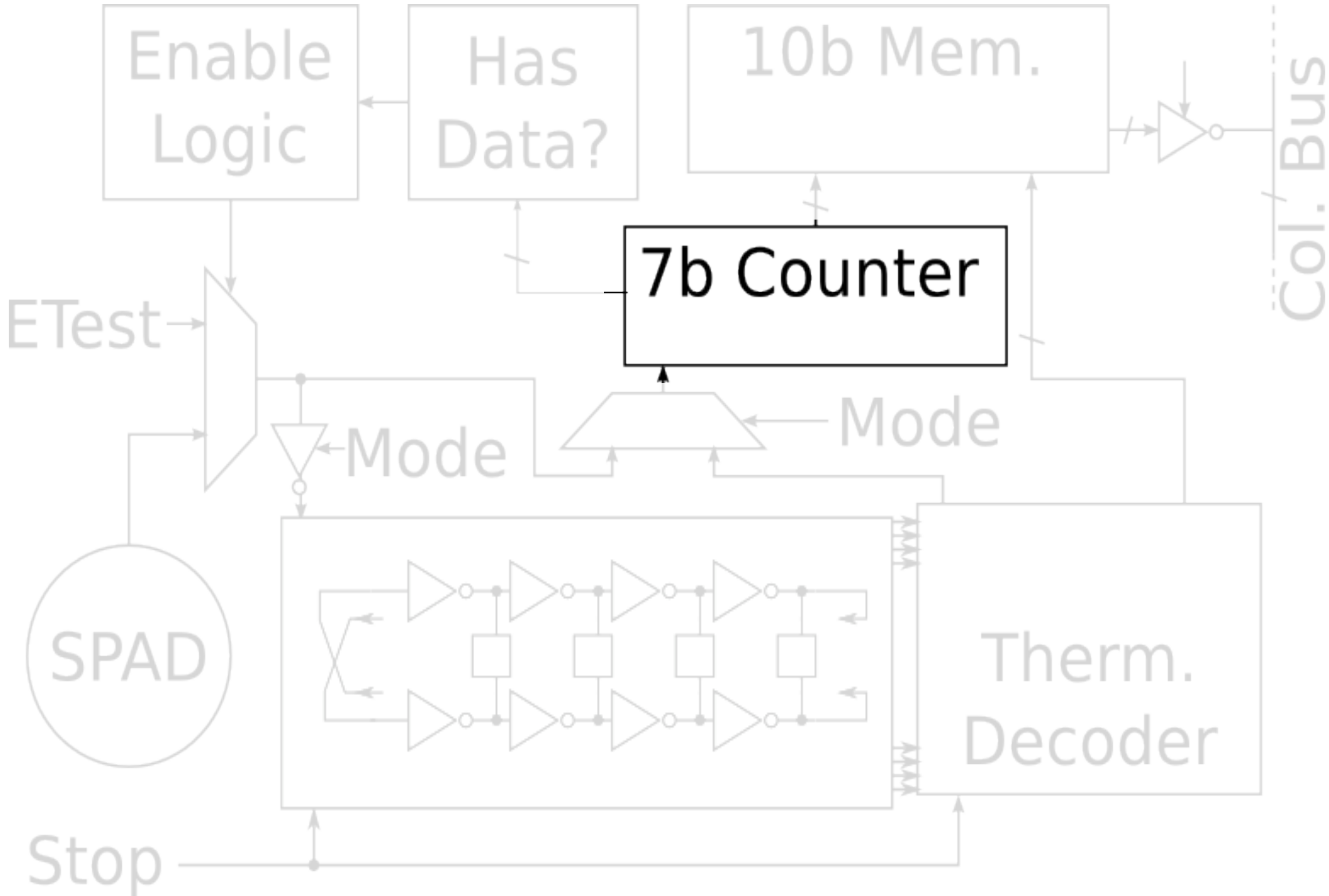
- Rolling shutter with a serializer per half-column
- Region-of-interest registers disable rows or columns to save bandwidth
- 10b on-pixel memory allows acquisition to occur while read-out takes place



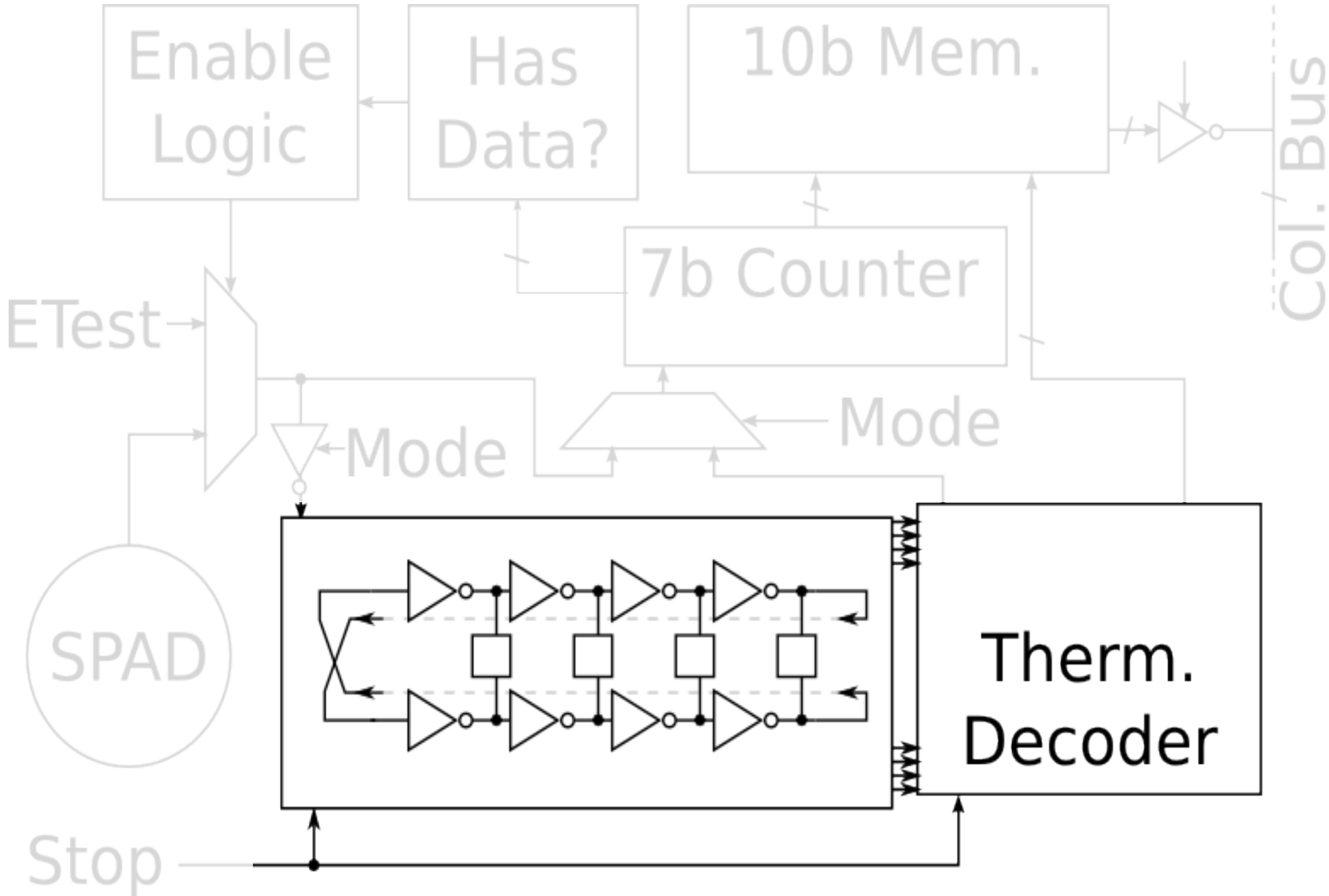
Pixel Architecture



Time-Uncorrelated Photon Counting

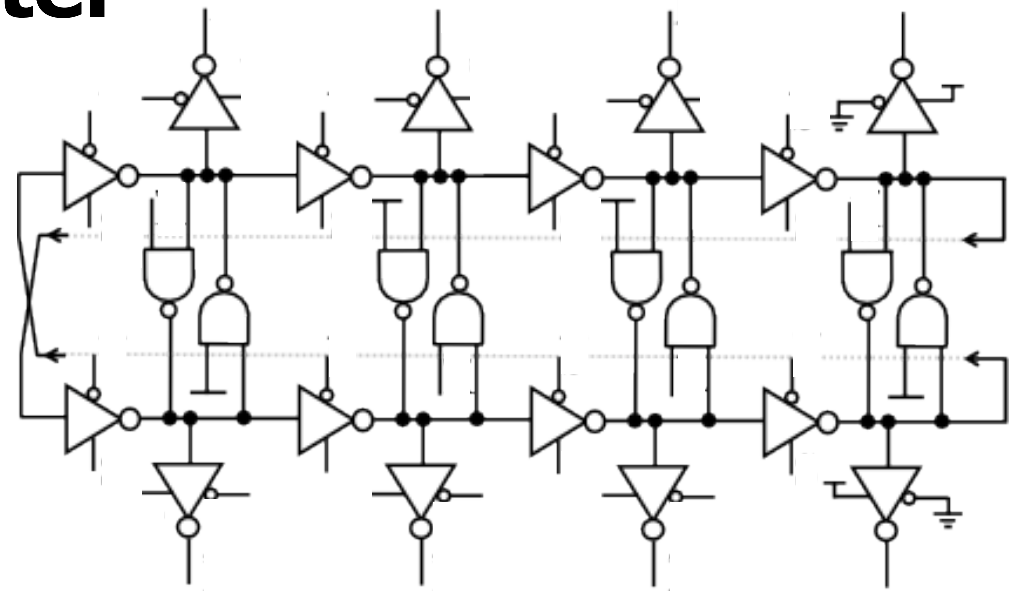


TCSPC



Enable Logic
Has Data?
10b Mem.
Col. Bus
7b Counter
ETest
Mode
Mode
SPAD
Therm. Decoder
Stop

The Core of TCSPC: Time-to-Digital Converter

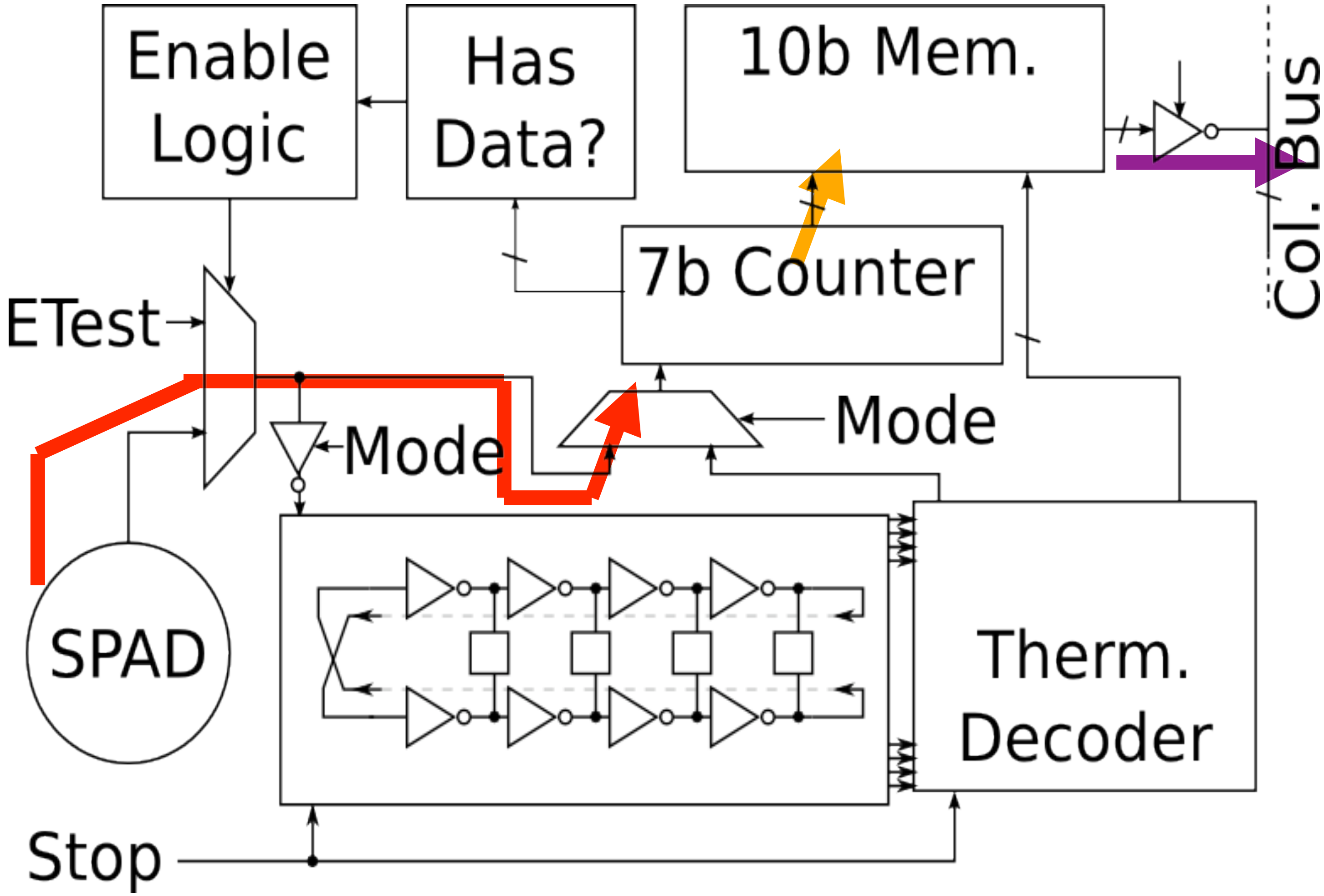


- Ring oscillator based TDC
- START-STOP mode
- Frequency of oscillation 2.27GHz (LOCAL)
- Fine resolution: 55ps
- Range: 55ns (10 bits)

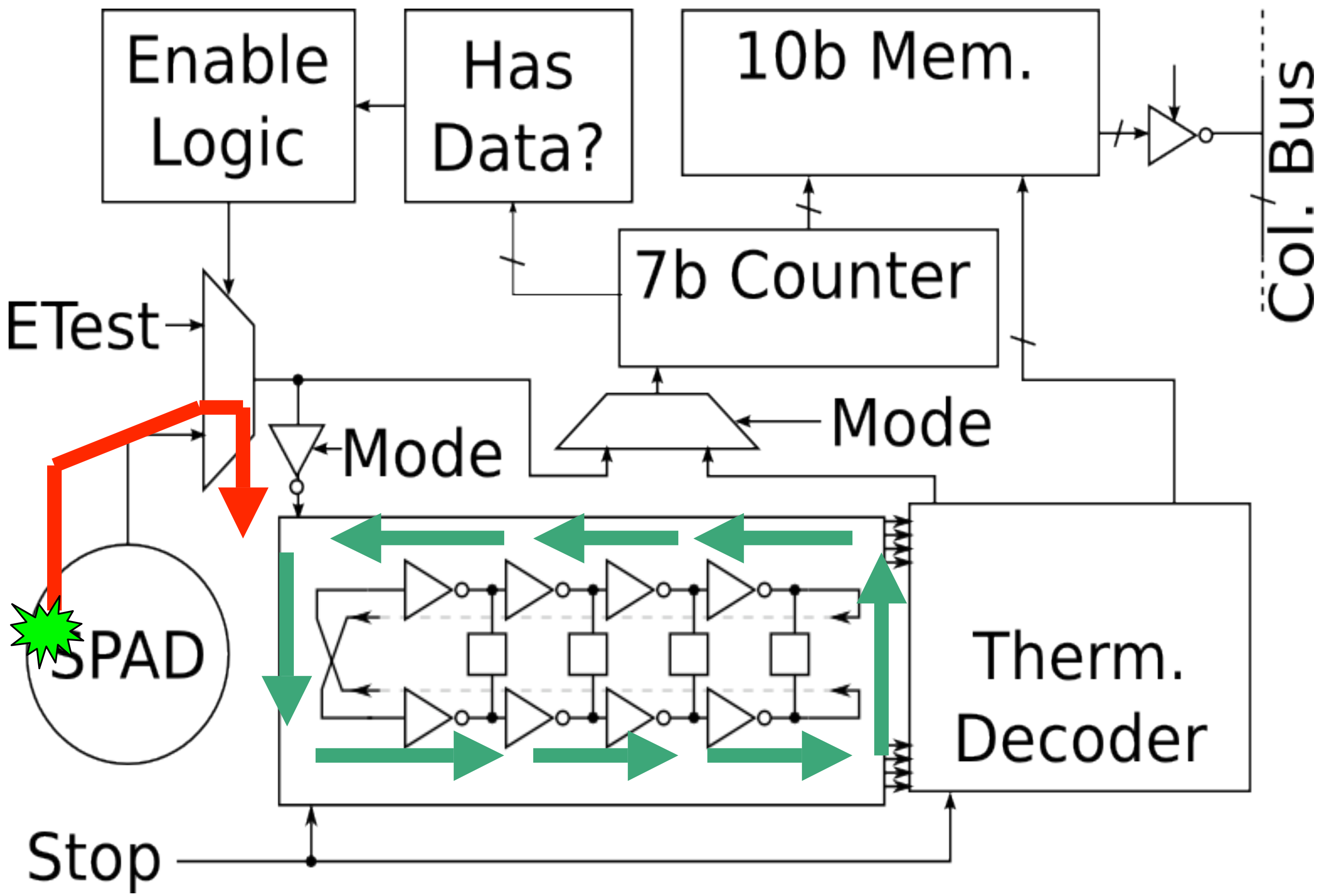
Ring Oscillator (Cont.)

- On-chip PLL contains a copy of the ring oscillator
  - Allows PVT compensation
- Better DNL, INL performance
- Resolution: 55ps -> 75ps

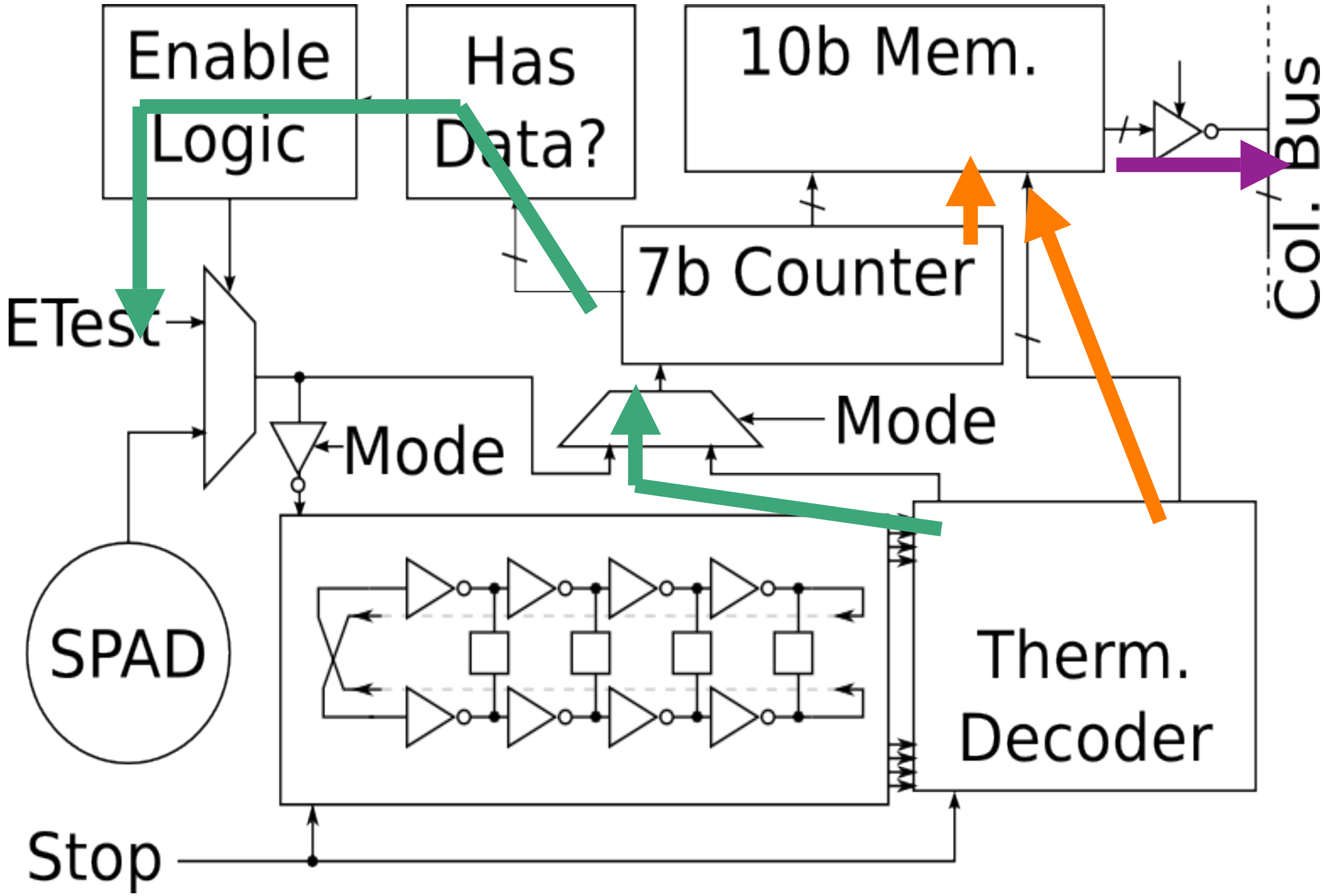
Time-Uncorrelated Photon Counting Operation



TCSPC Operation: Photon Arrival & Ring Oscillator

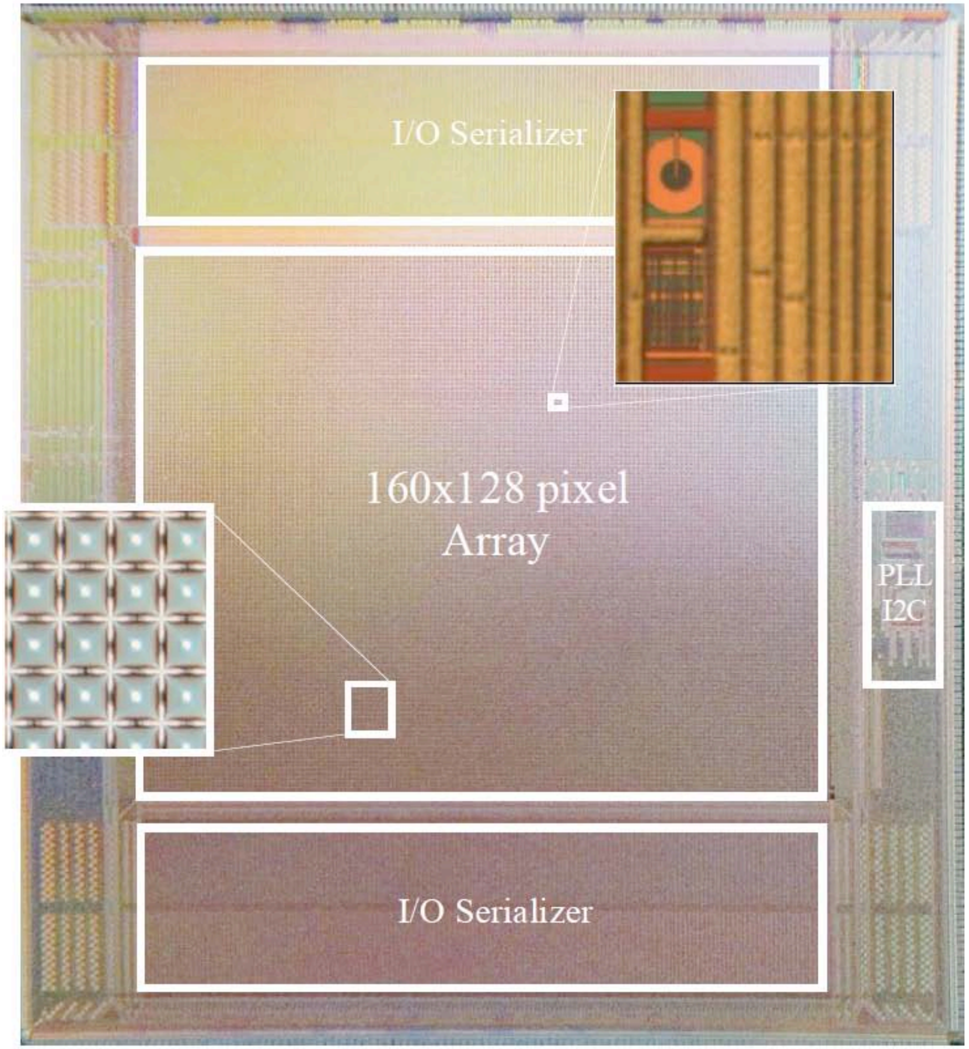


TCSPC Operation: Conversion & Readout



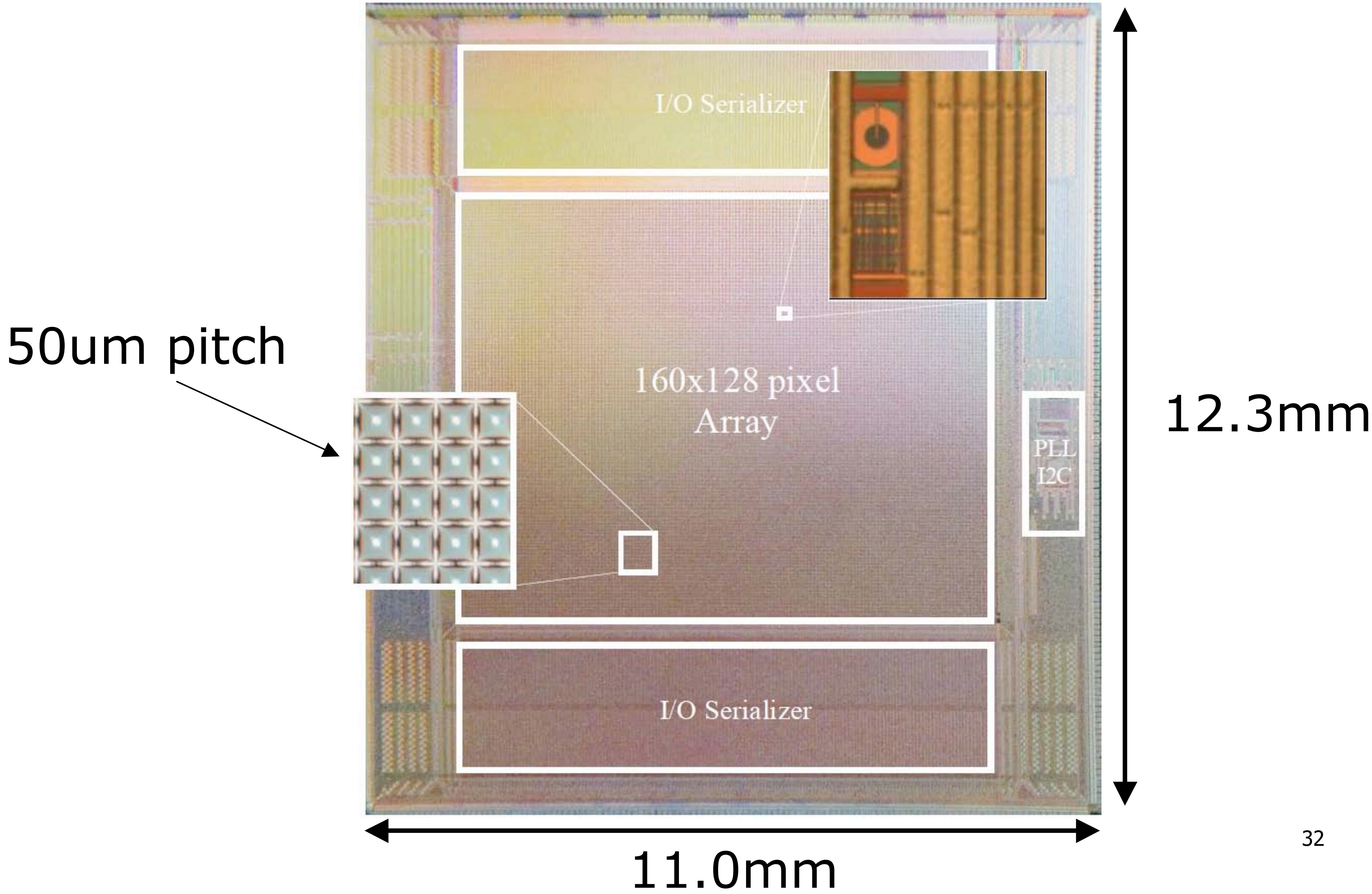
Results

The Megaframe-128 Chip



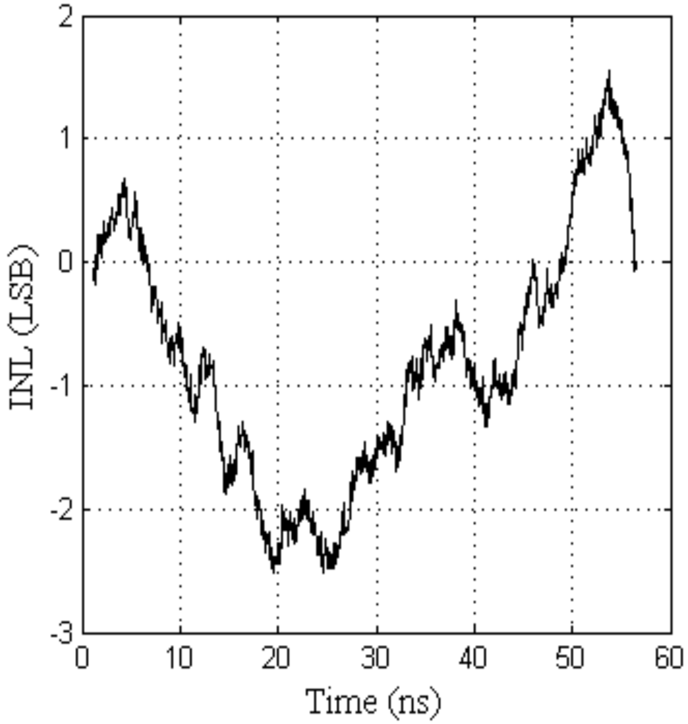
C. Veerappan, J. Richardson, R. Walker, D.-U. Li, M. W. Fishburn, Y. Maruyama, D. Stoppa, F. Borghetti, M. Gersbach, R.K. Henderson, E. Charbon, *ISSCC2011*

The Megaframe-128 Chip

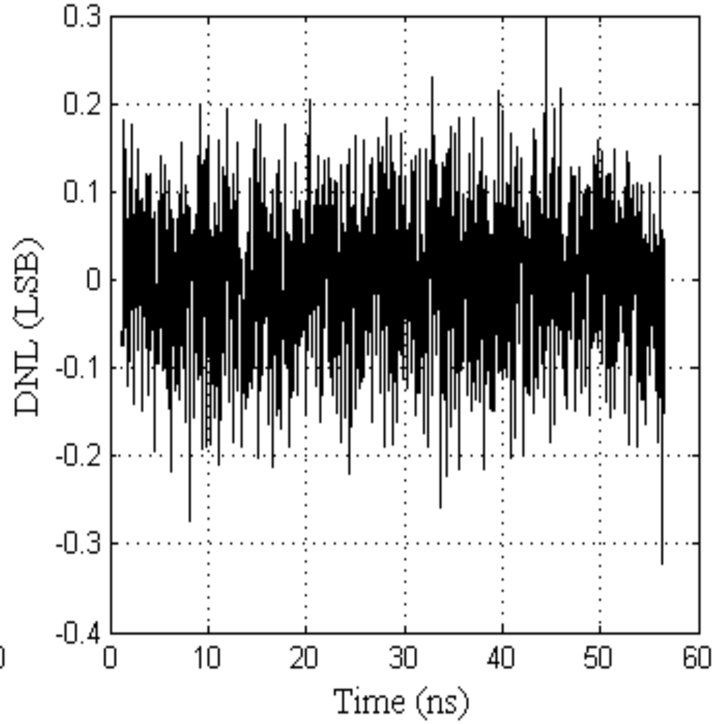


TDC Characterization

INL



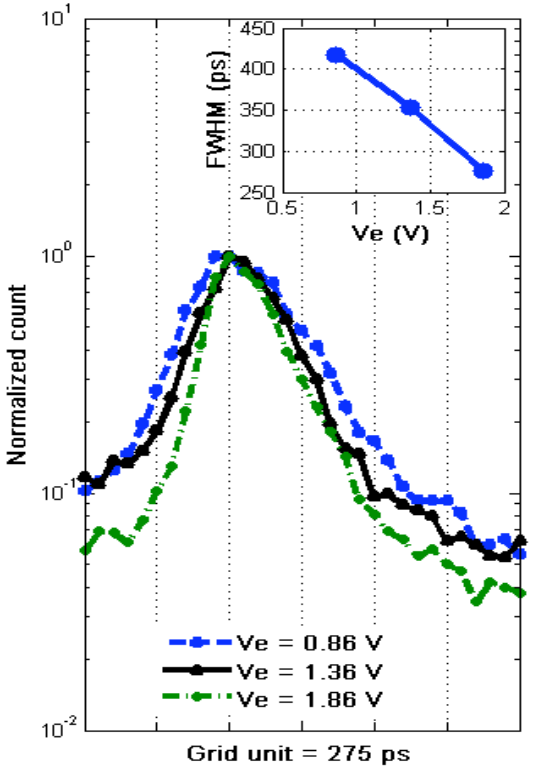
DNL



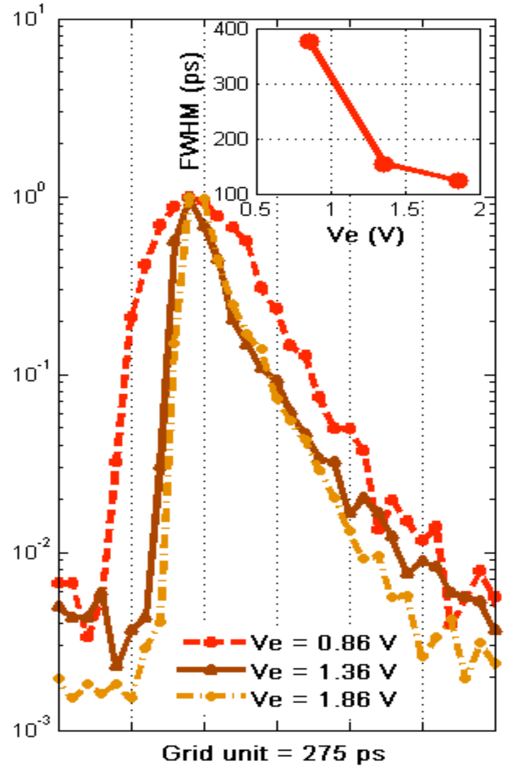
55ps resolution, 55ns range

System-level Timing Uncertainty

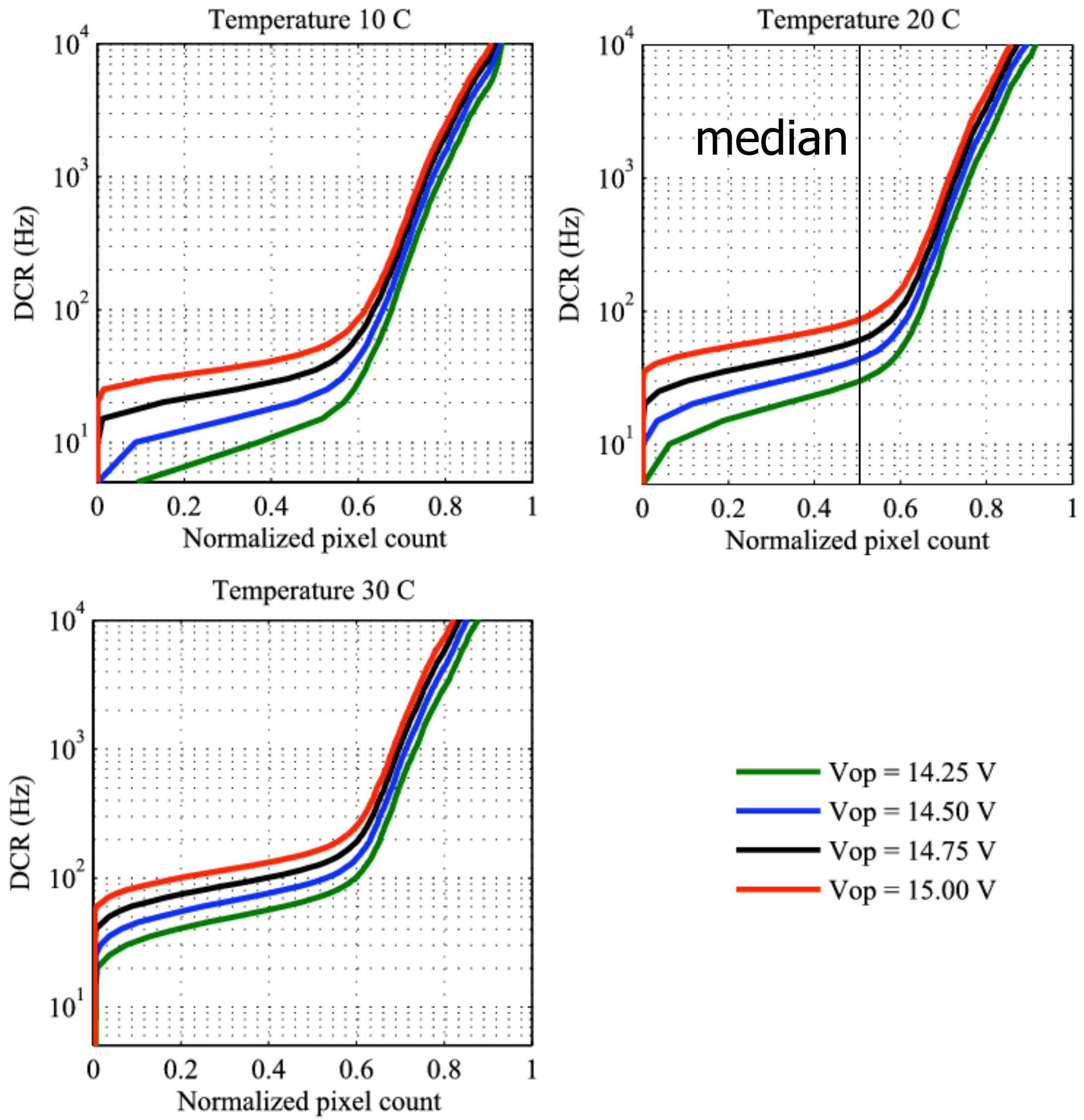
Blue laser



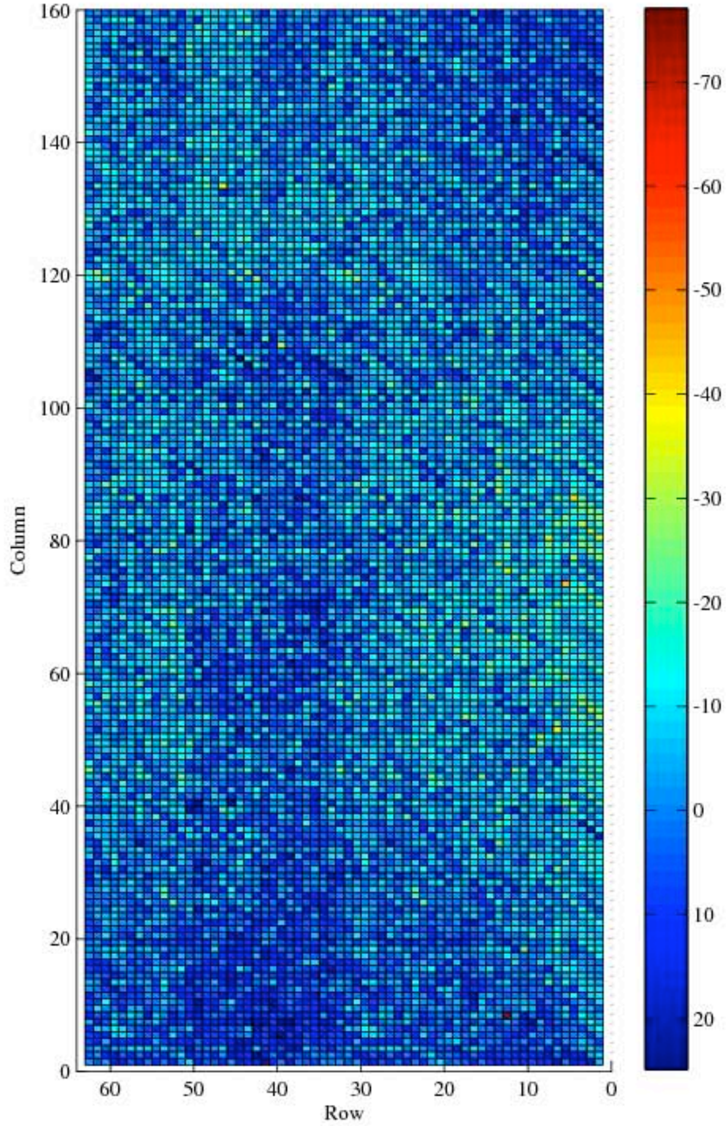
Red laser



Cumulative Noise

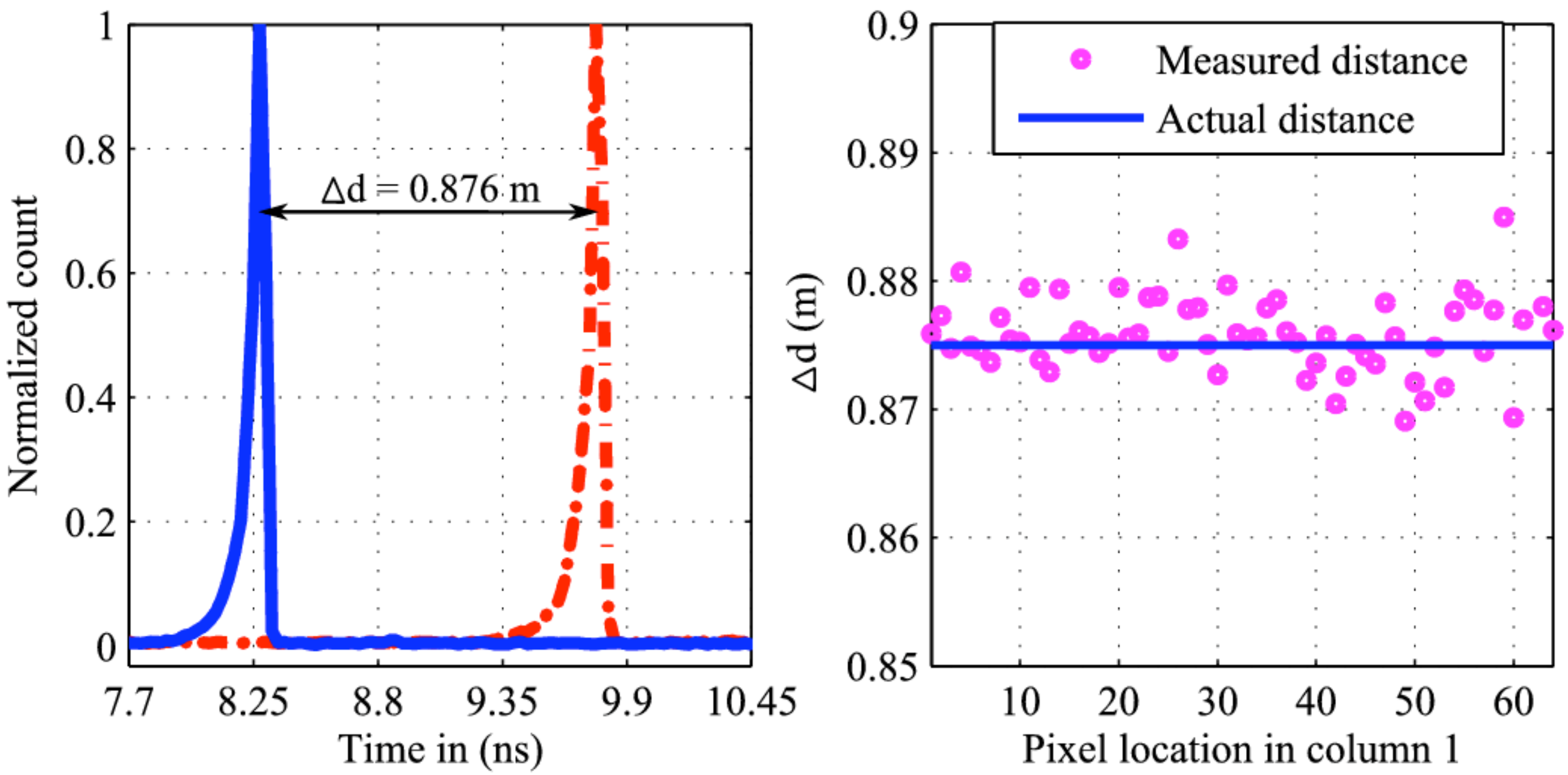


INL Uniformity



TDC INL

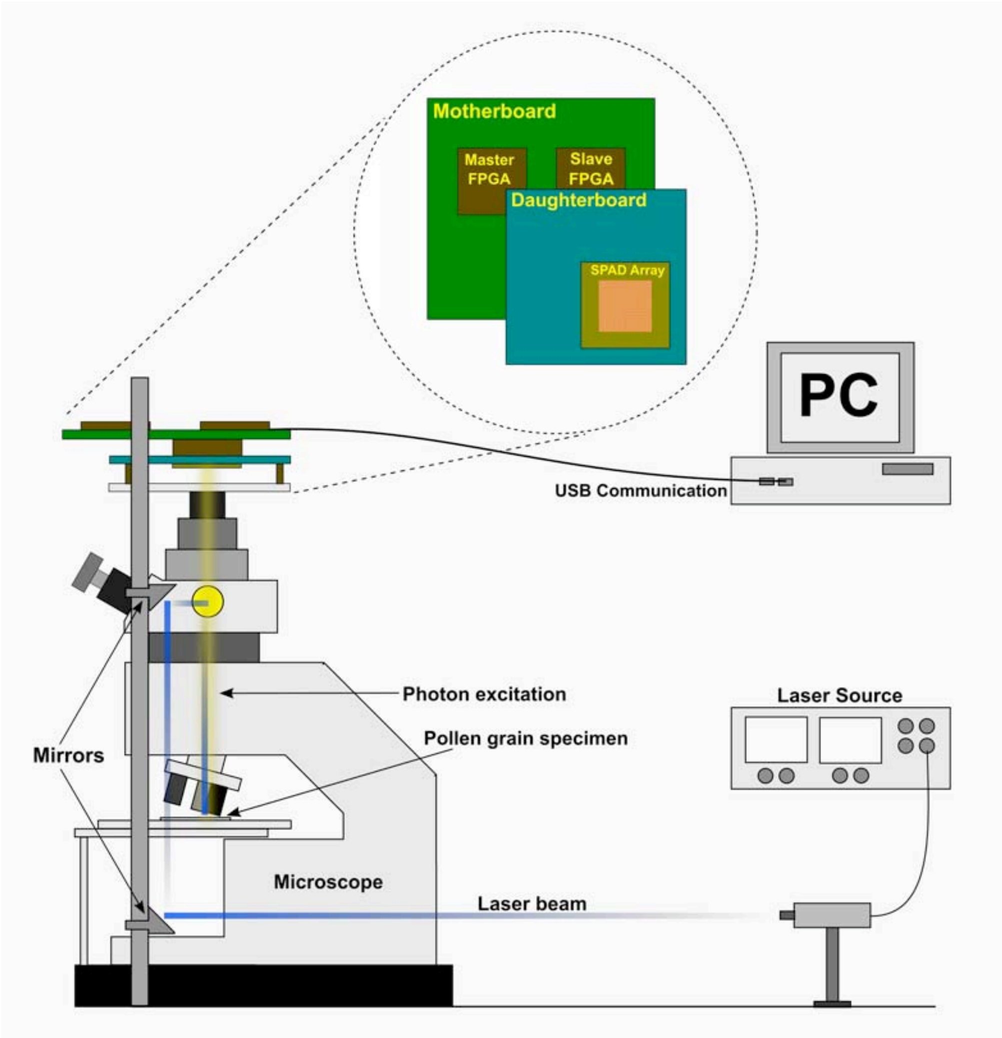
Optical Burst Detection Uniformity



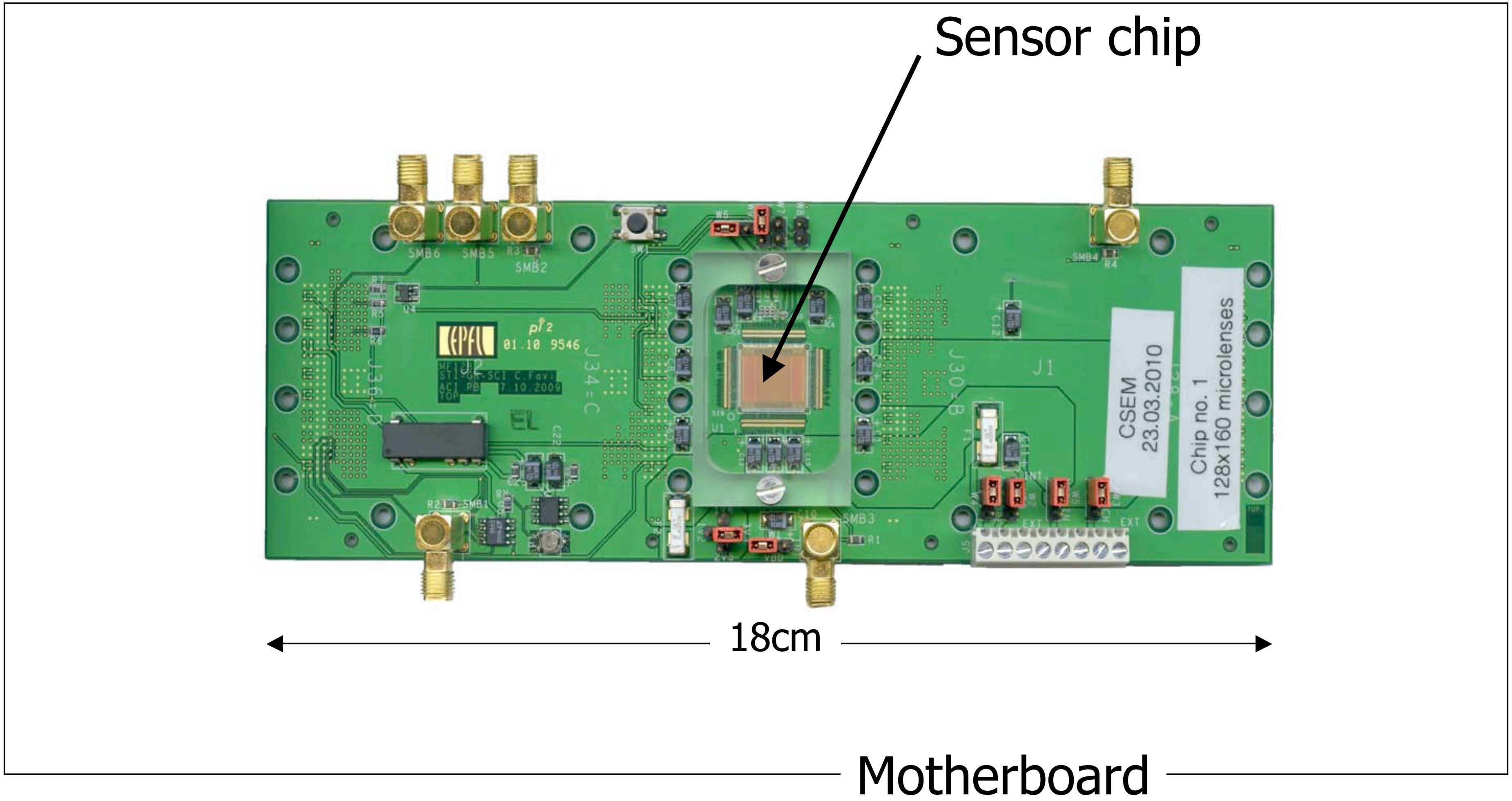
Performance Summary

	Parameter	Condition	Min.	Typ.	Max.	Unit
Pixel	Photon detection probability	V_e=0.62V	3		19	%
	Photon detection probability	V_e=1.40V	3		27.5	%
	Sensitivity spectrum		350		900	nm
	Dead time			100		ns
	TDC measurement range			55		ns
	TDC resolution (1 LSB)			55		ps
	Measurement rate			1		MS/s
	TDC DNL / INL			±0.3 / ±2		LSB
	Nominal fill factor			1		%
System	Clock frequency			16	32	MHz
	Chips size			11.0x12.3		mm^2
	Total I/O bandwidth			51.2		Gbps
	Power dissipation			550		mW
	CMOS Process			130nm		-
	Median DCR	V_e=0.73V		50		Hz
	Mean FWHM jitter	λ=637nm		140		ps
	1σ jitter non-uniformity	λ=637nm, PLL on, count rate = 50kHz		27		ps
FLIM Experiment	Number of measurements per pixel			$3x10^5$		-
	Frame rate			25	50	kfps
	Laser source average power			2		mW
	Average count rate per pixel			15		kc/s
	Target area			125x50		μm^2

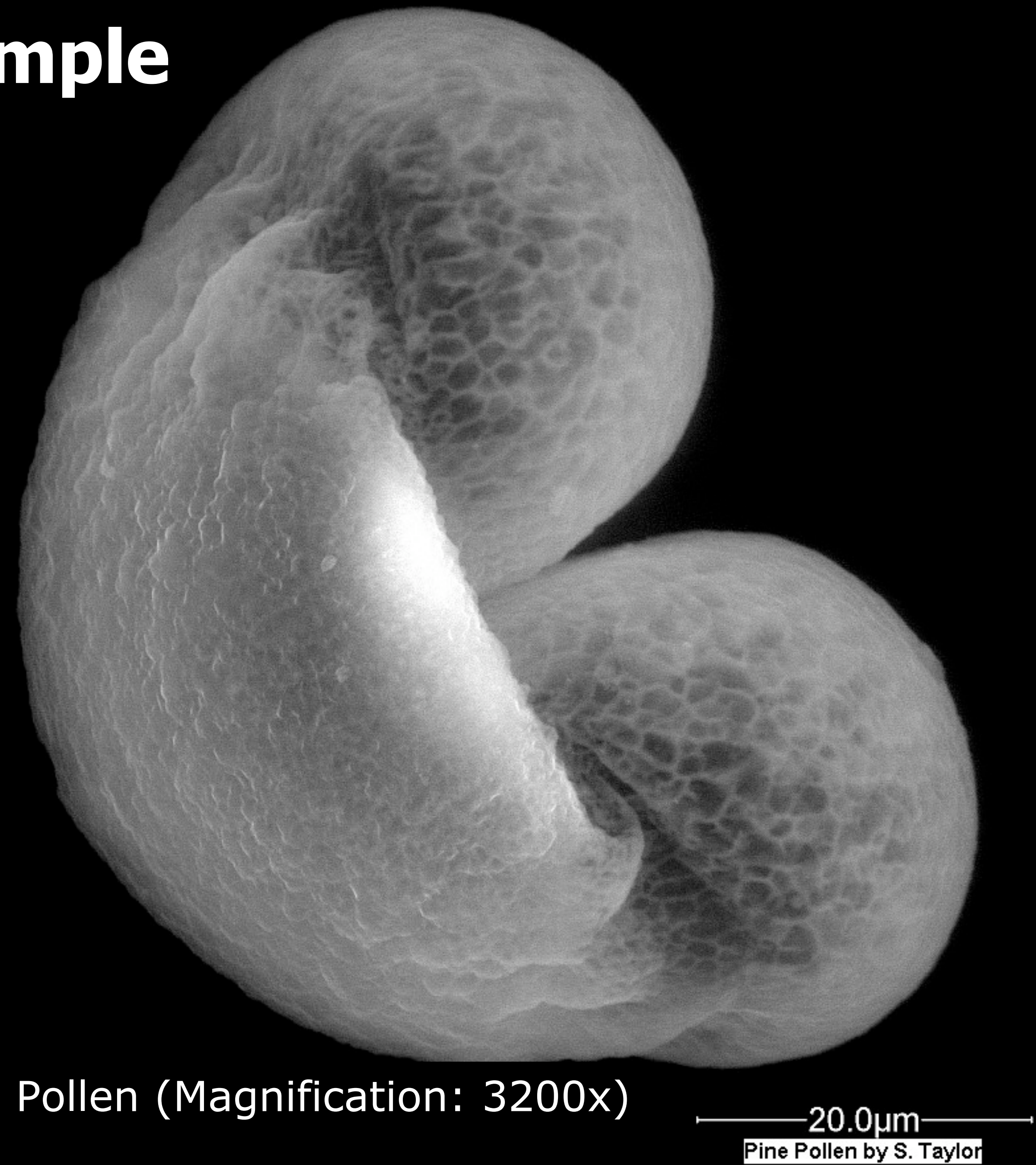
FLIM Experiment



Megaframe-128 Daughterboard



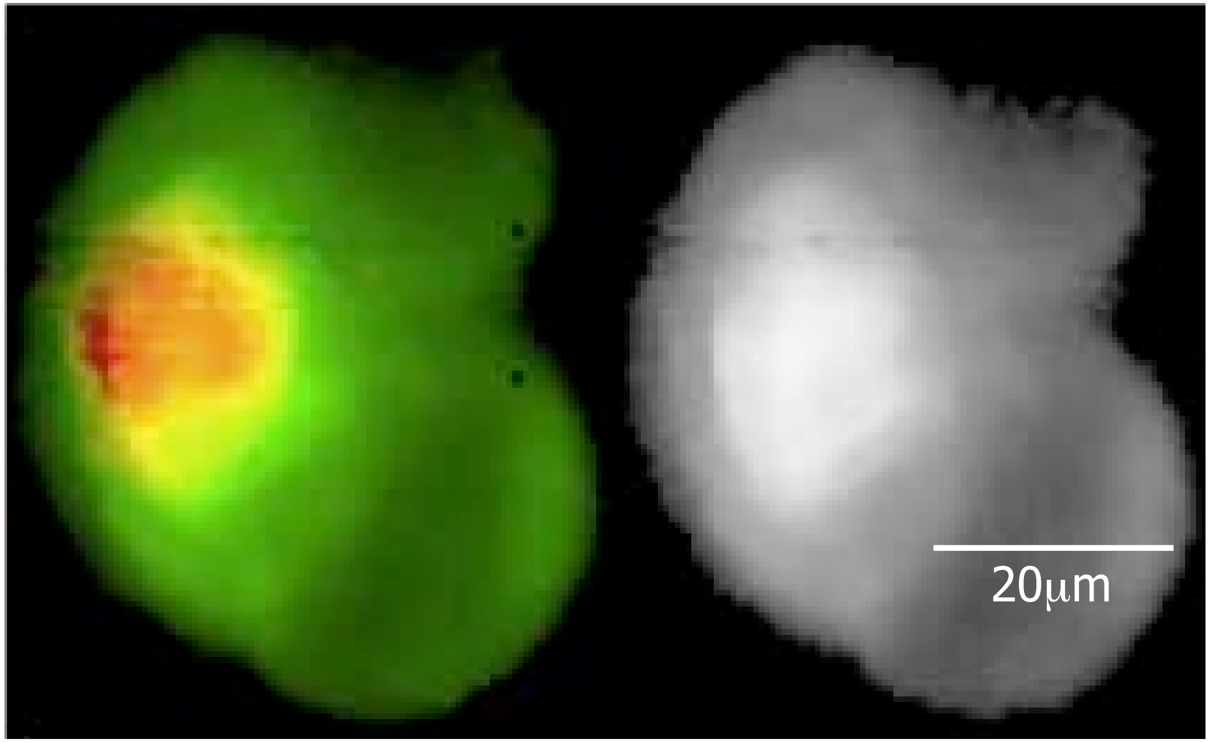
The Sample



Bisaccate Pine Pollen (Magnification: 3200x)

Source: West Georgia Microscopic Center

FLIM Image



- 300,000 frames over 12 second exposure time
- 40MHz laser
- Lifetimes ranging from ~500ps to ~5ns

Conclusions

- Target application, requirements are critical for selecting trade-offs
- Avalanche diodes show competitive performance in a 130nm imaging process
  - <1kHz noise, >30% PDP

Future Directions

- Video-rate FLIM
- SPAD scaling trends
  <1kHz noise
  >30% PDP in 90nm
  UDSM: 65nm? 45nm?
- 3D integration
- Microlens work
- TDC sharing (positron emission tomography)

http://www.megaframe.eu

TU Delft

Delft University of Technology