3D integrated digital SiPM

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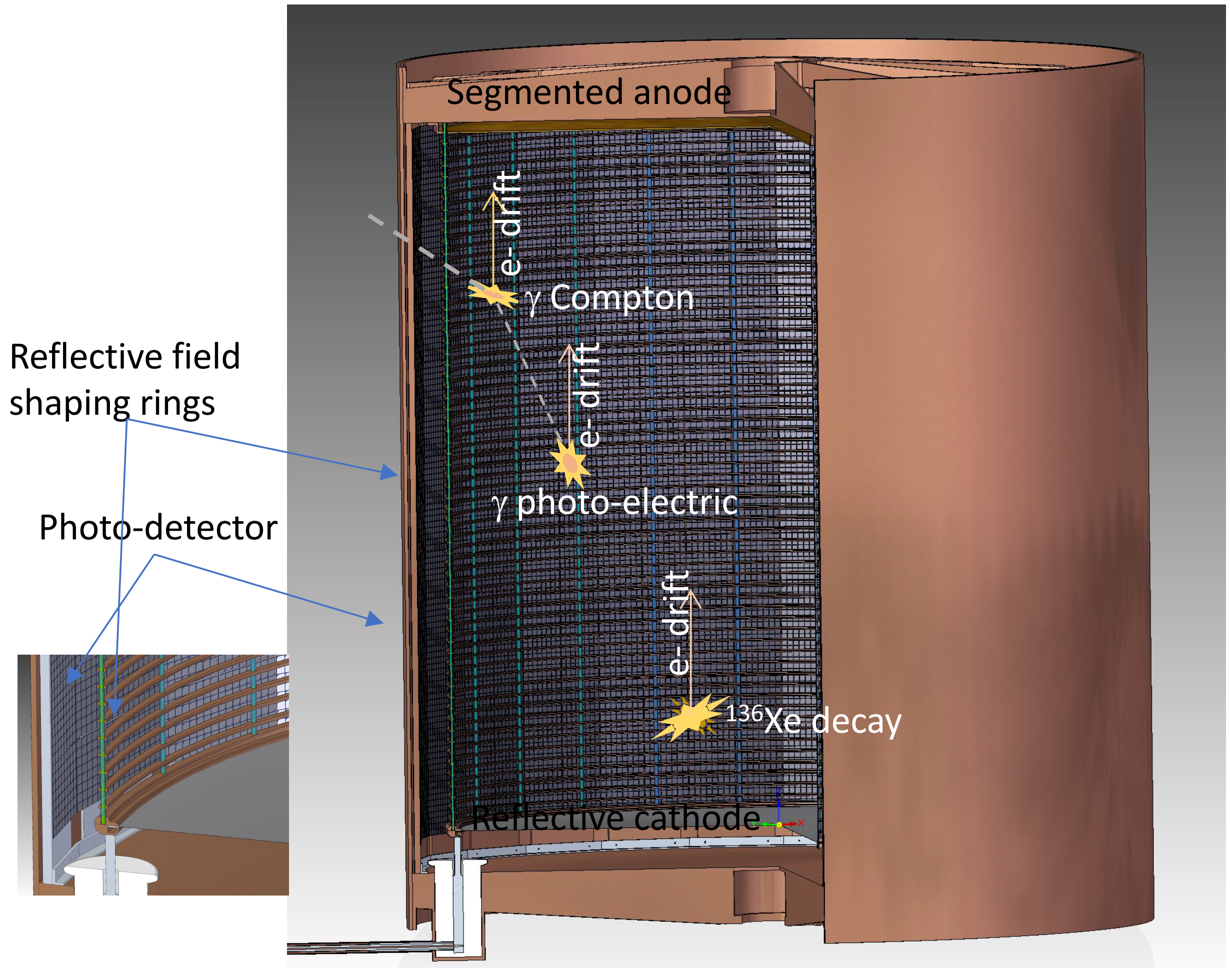
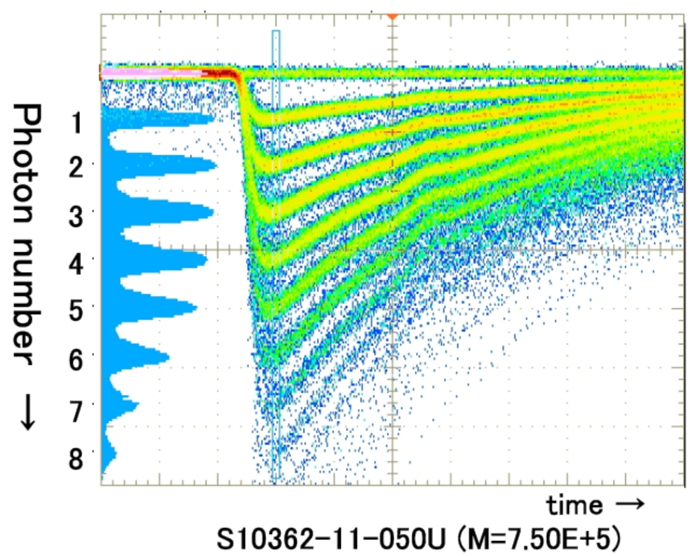
nEXO collaboration

Motivation. nEXO

- 4-5 m^2 SiPM
  - Single VUV photon sensitive
    - >15% efficiency
  - Very low radioactivity
    - Silicon is generally very radiopure
- SiPM electronics in liquid Xenon
  - Power dissipation < 100W
  - Challenging to achieving noise < 0.1PE per channel of 1-10cm^2 because of large capacitance
    - With analog electronics need to limit bandwidth
    - **Digital SiPM promise better performance and lower power**

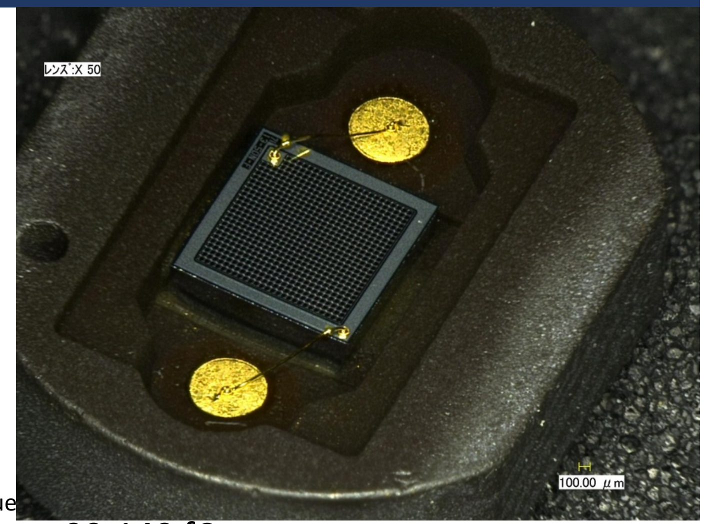


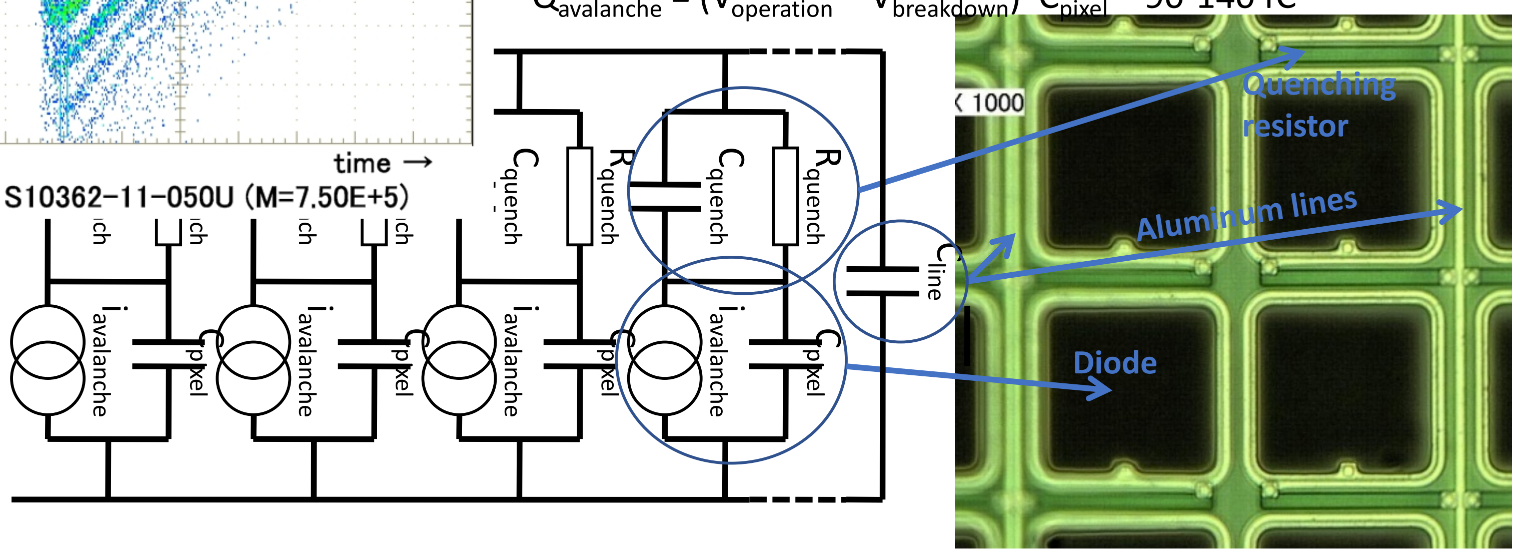
Analog Silicon Photo-multipliers



Parameters for T2K MPPC

C_{pixel} = 90 fF
R_{quench} = 150 kΩ
C_{quench} ~ 4 fF (parasitic)
C_{line} ~ 10 pF (parasitic)
$I_{avalanche} = (V_{operation} - V_{breakdown}) / R_{que}$
$Q_{avalanche} = (V_{operation} - V_{breakdown})\ C_{pixel}$ ~ 90-140 fC





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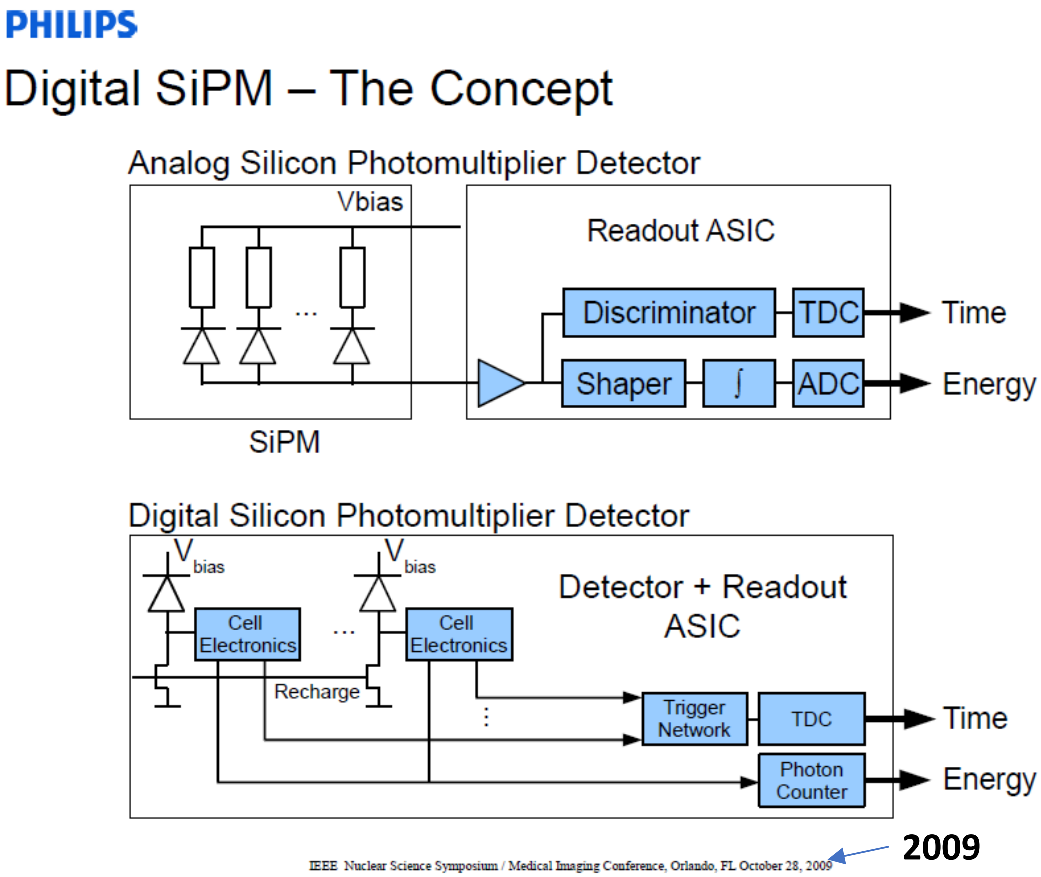
The digital SiPM concept

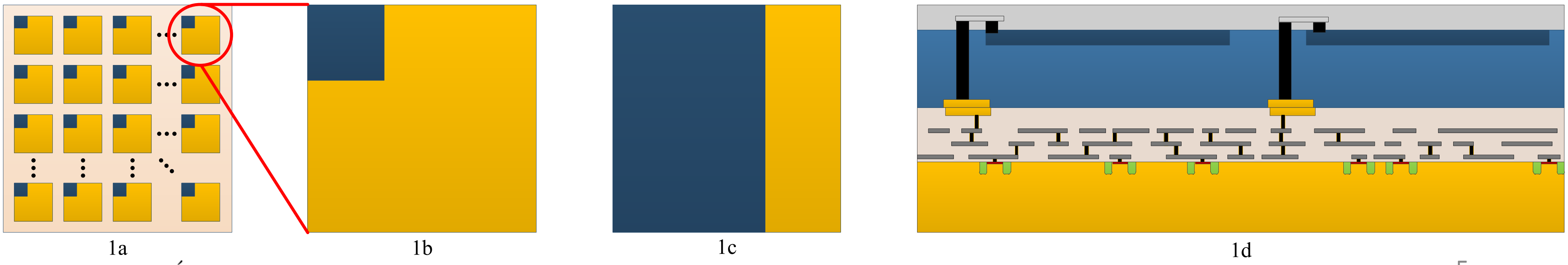


2009

- Photon to bit conversion
  - As opposed to photon to analog to bit conversion
- Quenching scheme
  - Current sense per diode
  - Quench upon discharge
    - Control quench time
  - Time tag and count the avalanche

From monolithic digital SiPM to 3DdSiPM

- Monolithic issues
  - Electronics circuit limits the active area
    - Trade off between active area (1b) or performance (1c)
  - Compromise between photo-detector and electronics technology
- 3D solves most issues
- Main challenge
  - Connect each diode on photo-detector chip to quenching electronics chip



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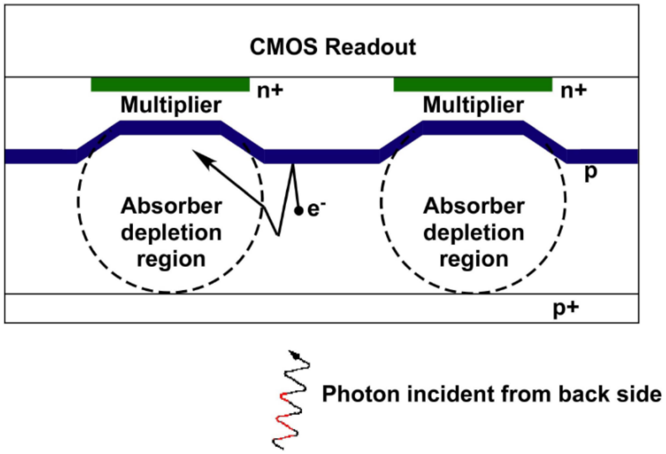
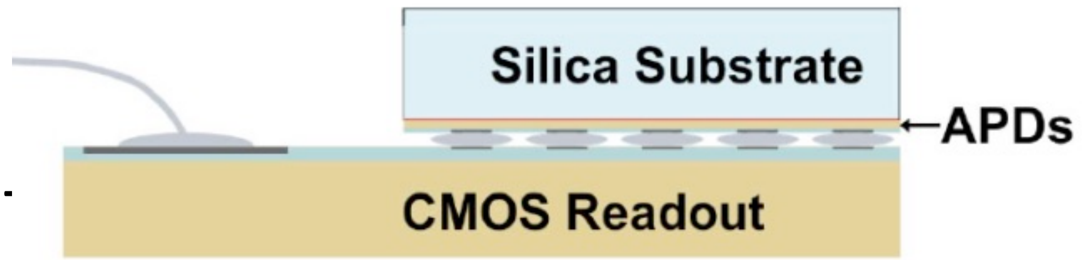
Pioneer work at MIT Lincoln Lab

- 25µm pitch
- 180nm CMOS + custom (APDs)
- 7-bit counter/pixel
- Backside illumination



- **10 - 20% detection efficiency**
  (limited by optical cross-talk)



B. Aull et al., IEEE Sensors J., 2015

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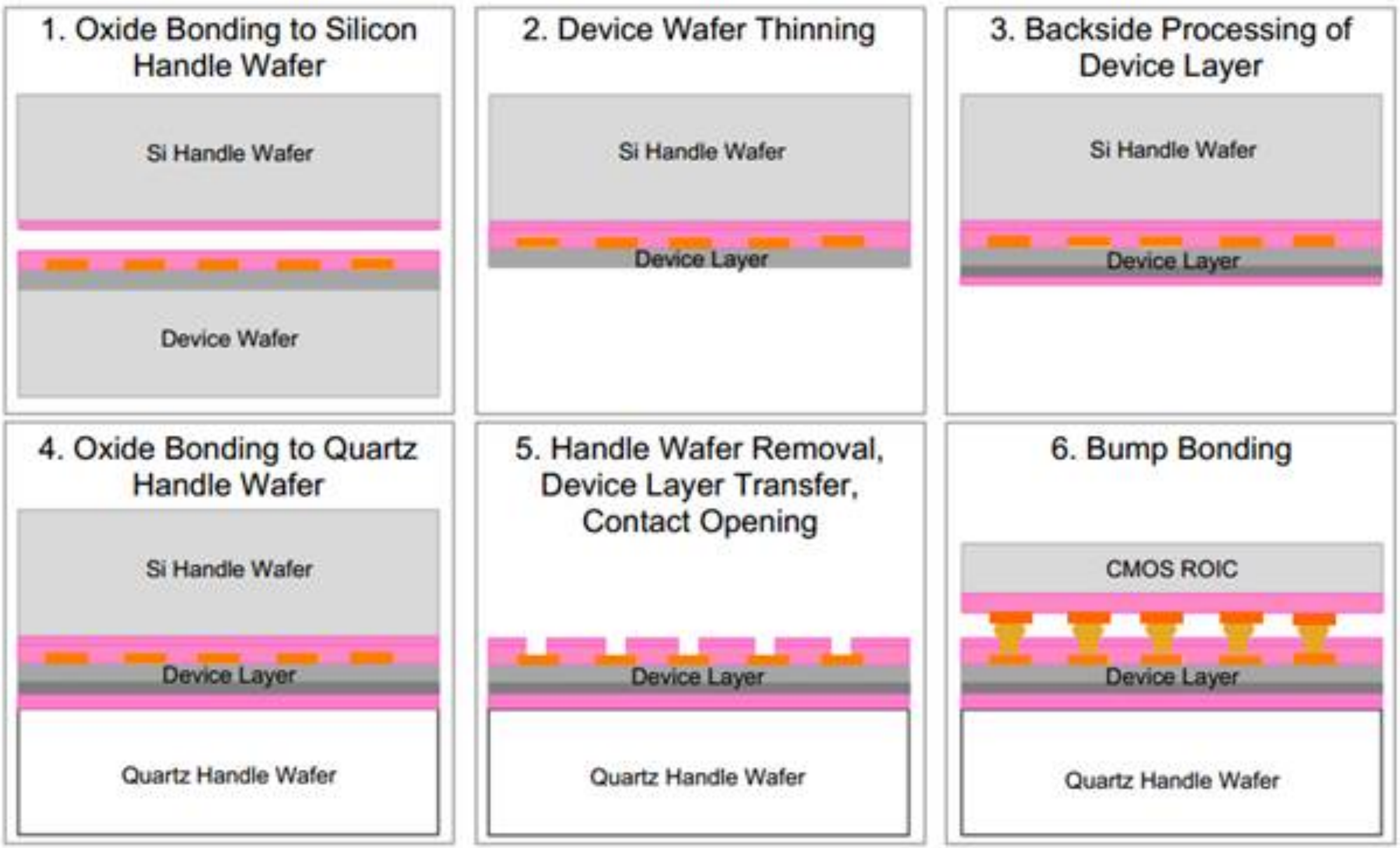
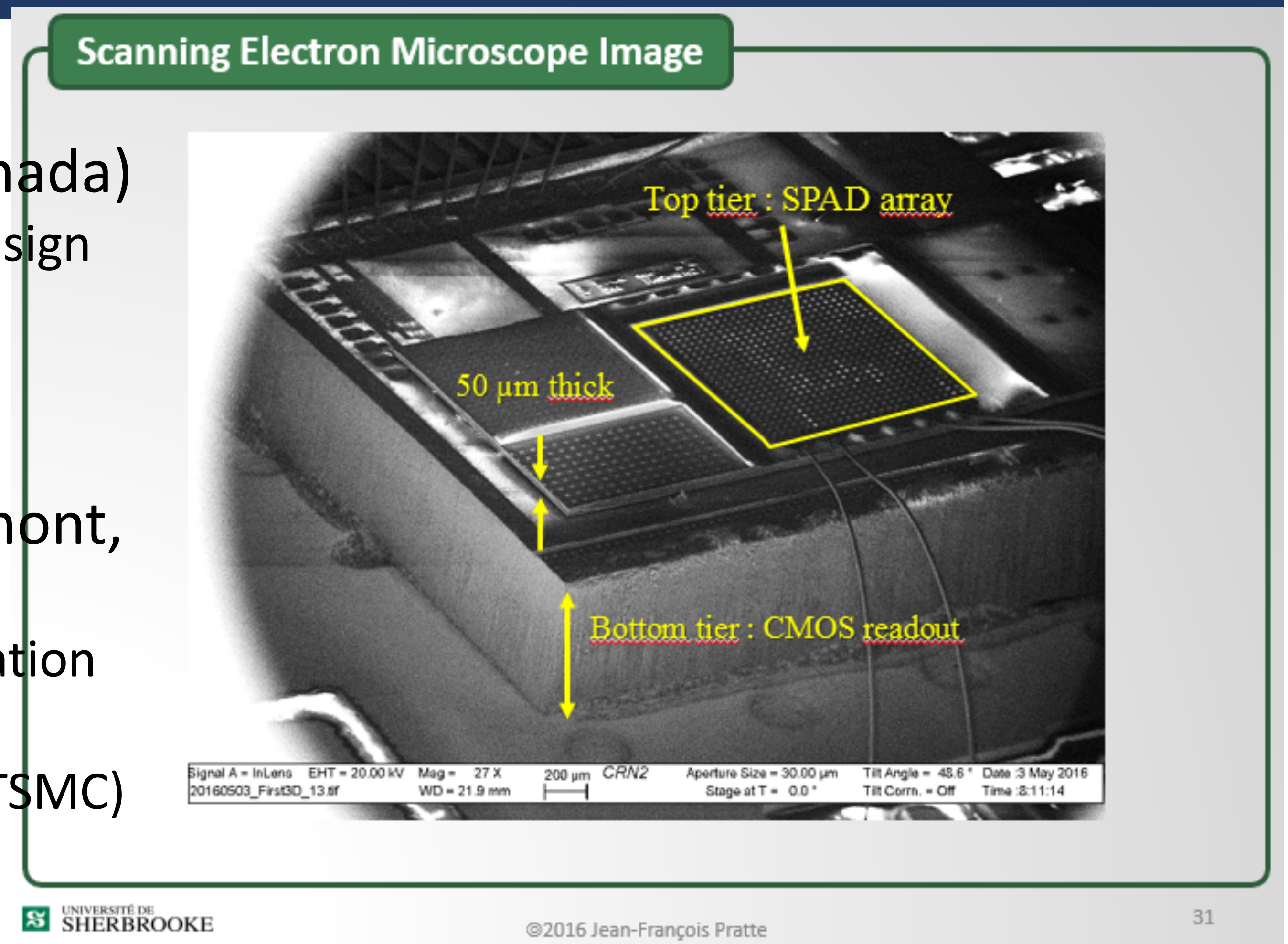


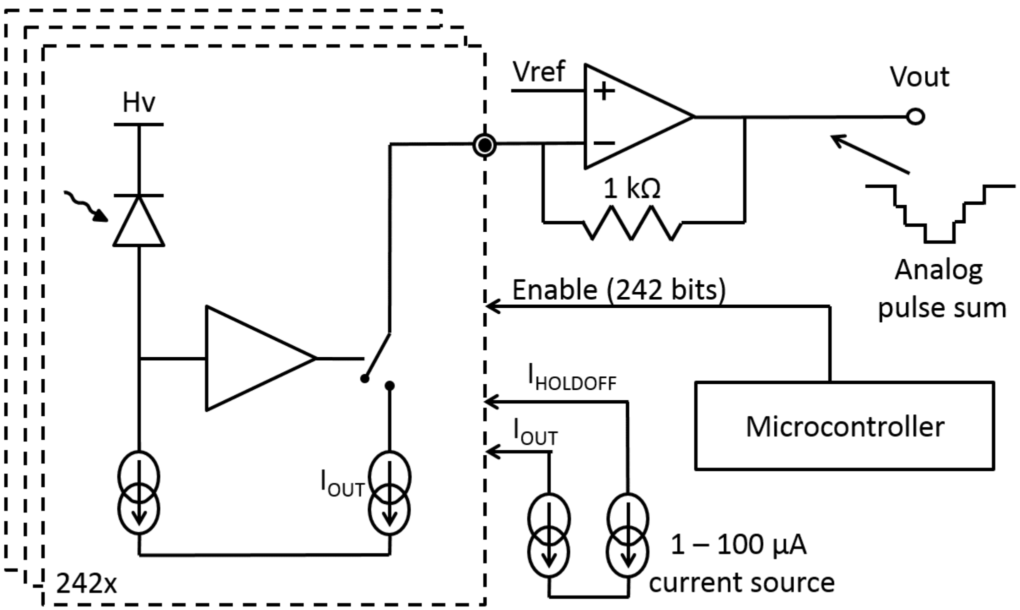
Figure 3: GM-APD back-illumination process flow illustrating the major steps to process a wafer of GM-APD devices that has completed front-side processing through to hybridization with a CMOS ROIC. To simplify the illustration, the relative positions of the components of the bonded wafer stack are maintained in all process description panels.

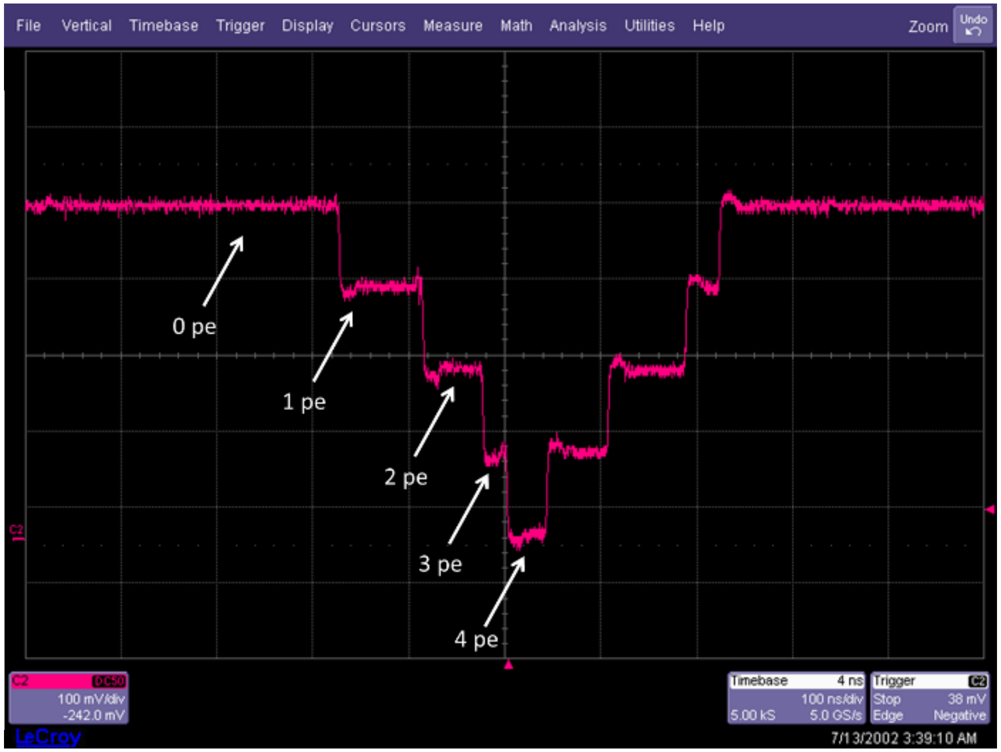
And in Canada

- U.Sherbrooke (QC, Canada)
  - Photo-detector tier design
  - Electronics tier design
  - 3D assembly
- In collaboration with Teledyne-DALSA (Bromont, QC, Canada)
  - Photo-detector fabrication
  - 3D assembly
  - (CMOS chip made by TSMC)

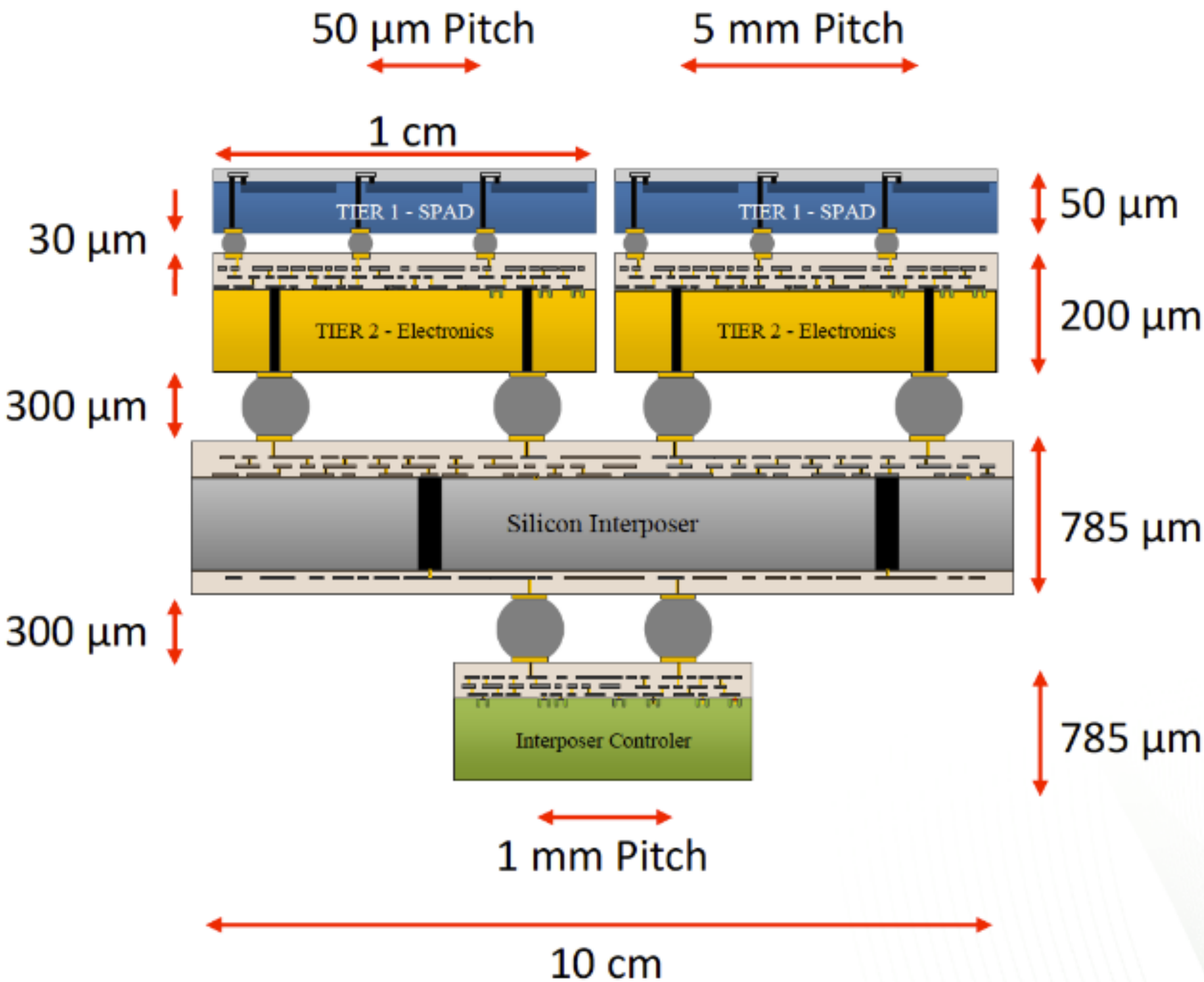


It works! Sherbrooke's proof of concept





3 dimensional digital SiPM for nEXO



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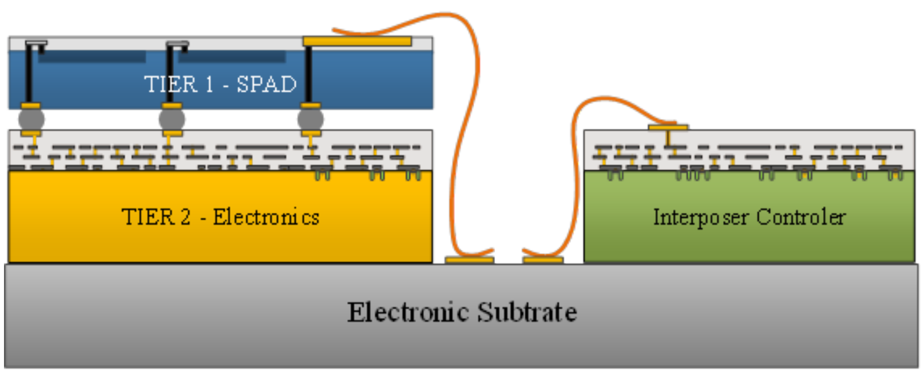
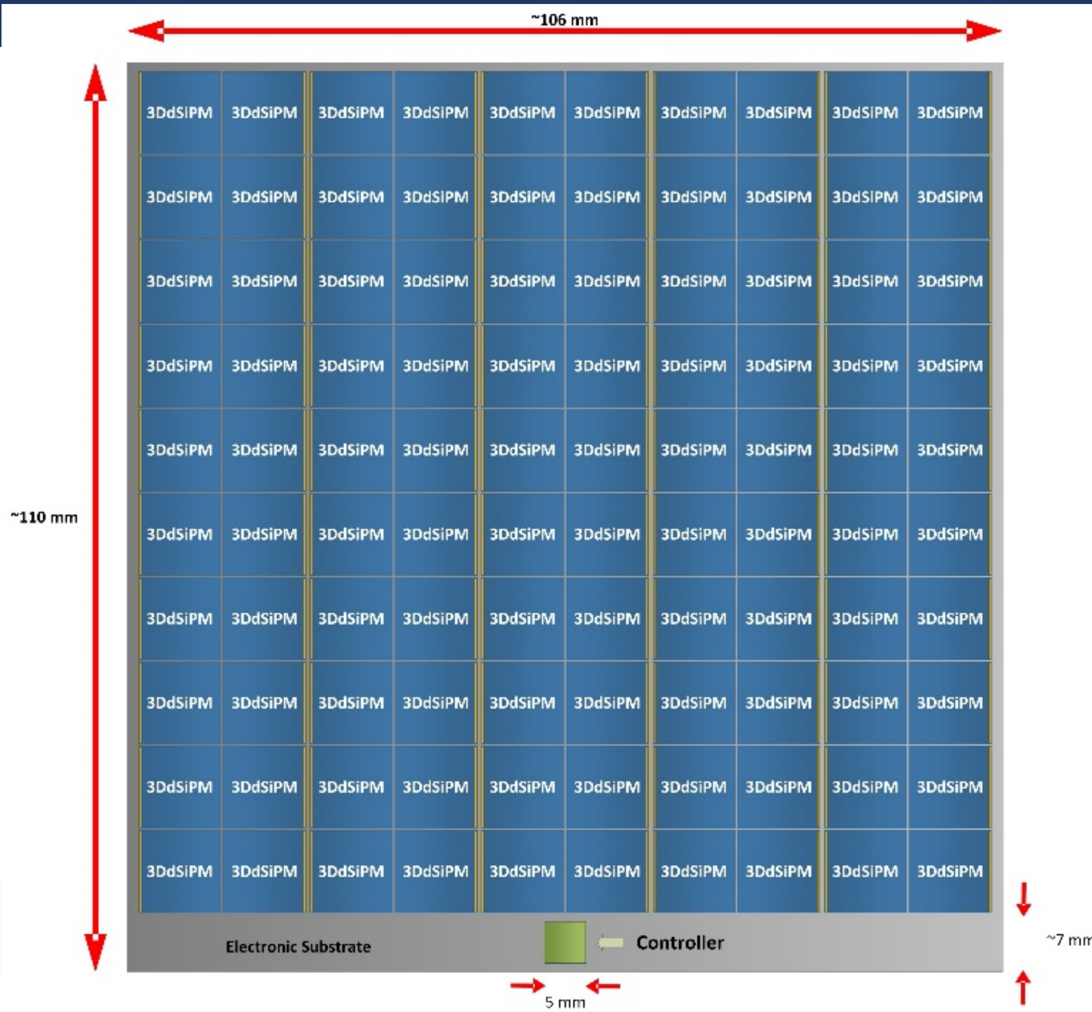
R&D towards nEXO

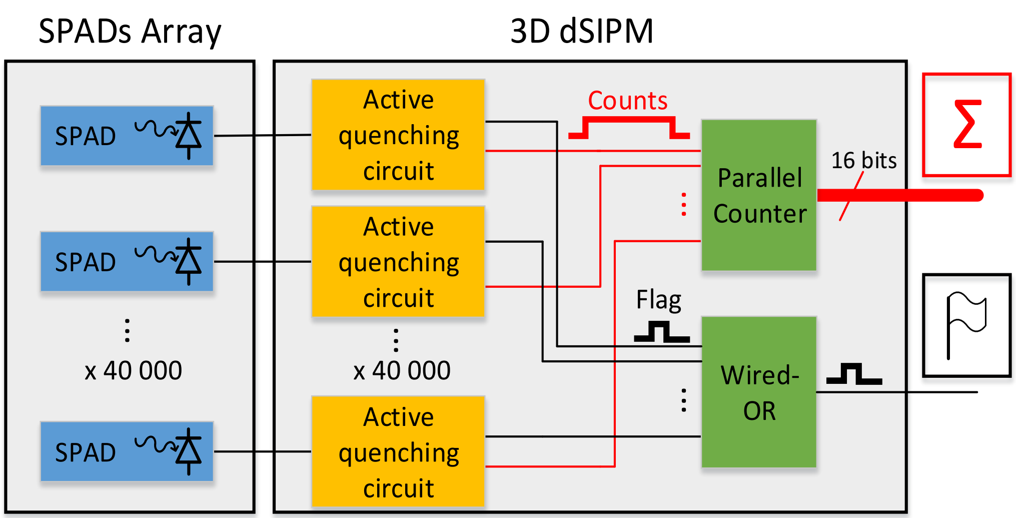
- Tailor photo-detector tier for VUV detection
- Demonstrate scalability
  - In particular power dissipation
- Demonstrate cost <2M$/m^2
- Funds requested for proof of concept





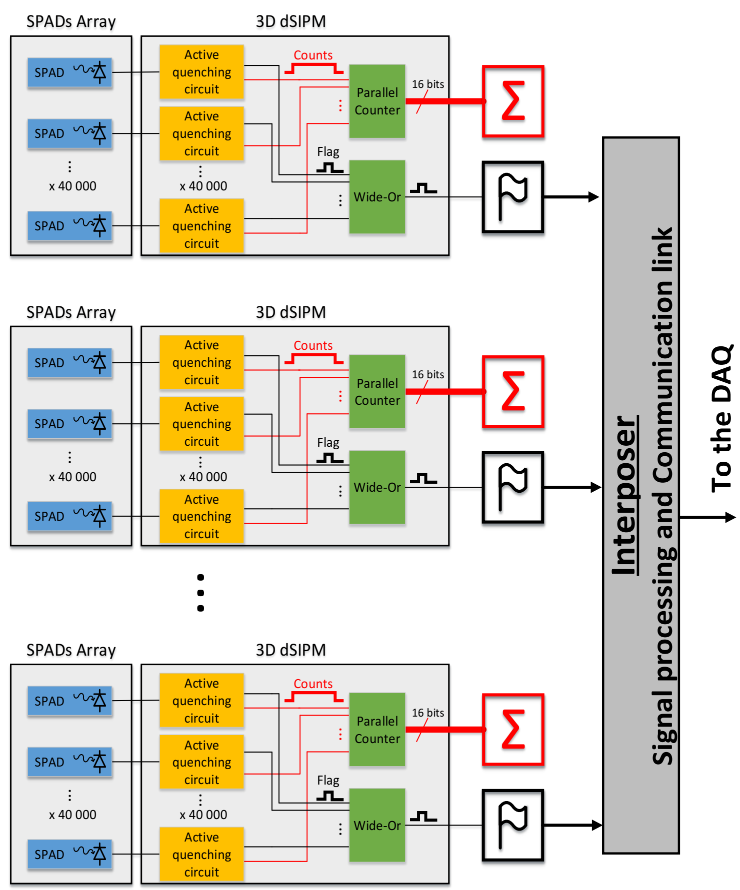
3DdSiPM "schematics"

- About 1x1cm^2
- Wired-OR
- Parallel adder provides the number of SPAD fired upon interposer request
- Low power digital asynchronous logic (no clock)



Tile for coincidence and triggering

- Adjustable coincidence window
- Adjustable threshold
- A trigger is generated when:
  - Flag count > threshold
  - Inside the coincidence window
- The parallel adder of each 3DdSiPM is activated for the duration of the scintillation
- Data transmission logic



Power consumption

- The proposed 3DdSiPM has a total area of 1 cm^2 and is composed of three modules.
  - 40 000 quenching circuits to individually quench the SPAD
  - A wired-or for the flag
  - A parallel adder for the sum
- Power consumption of the 3DdSiPM depends on the event rates
  - Power consumption evaluated for a DCR of 5k s^{-1} /cm^2
- **<u>So… for 4 m^2, the digitization cost ~0.7 W! About x20 estmimated for analog SiPMs</u>**

Consumption per 3DdSiPM (1 cm^2)			
	Static (µW)	Dynamic (µW)	Total (µW)
Quenching circuit (40k)	10	1	11
Wired-OR	0.3	1.3	1.6
Adder	5.2	1E-3	5.2
Total	15.5	2.3	**17.8**

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Other advantages of 3DdSiPMs in LXe and LAr

- Timing resolution < 1ns (towards 10ps) overall large area
  - Without huge power dissipation
  - May allow separating Cerenkov and scintillation photons
    - Possible background rejection handle in $0\nu\beta\beta$ experiment
- Fine granularity (at no extra cost)
  - mm^2 scale possible
  - Combined with electro-luminescence allows exquisite charge cloud reconstruction in liquid Xenon. Another possible background rejection handle in $0\nu\beta\beta$ experiment
  - Allow tagging activity on the photo-detector surface
- Zero after-pulsing due to active quenching
  - Enhance energy resolution and pulse shape discrimination
  - Though does not eliminate cross-talk (including delayd cross-talk)
- Push cost down to allow $>100m^2$ coverage for ~10M$

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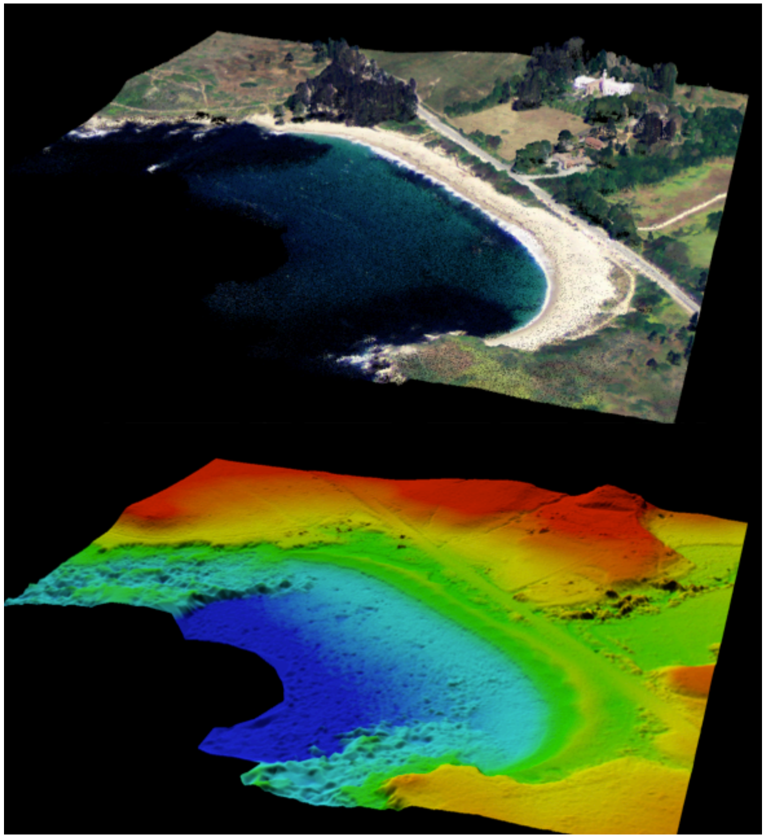
Other applications of 3DdSIPMs

- TOF PET revolution
  - 10 ps ~ few mm
- Many particle physics applications
  - Plastic scintillator
  - Calorimeters with inorganic scintillators
- LiDAR
  - High precision (10ps~mm)
  - High rate
  - Possible imaging capabilities
  - Huge market: self driving cars, …



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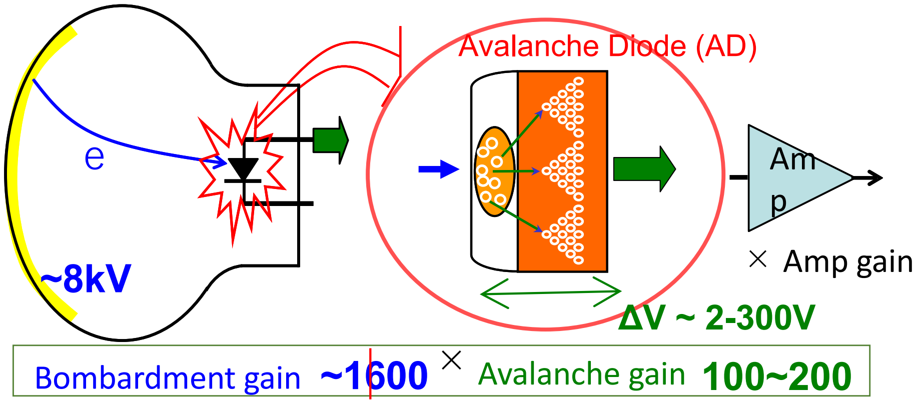
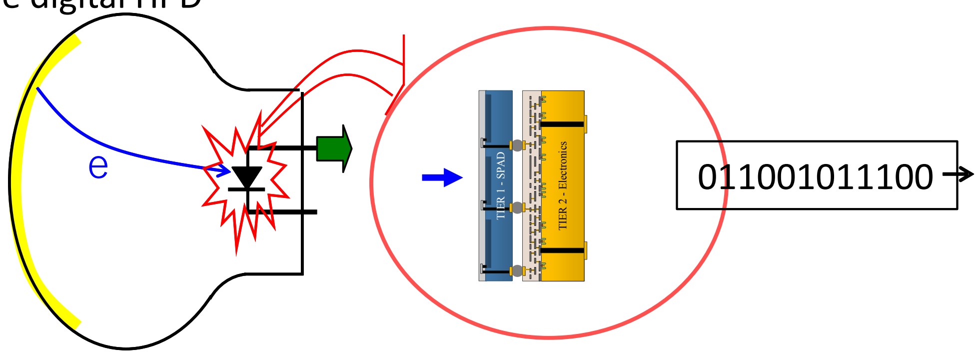
Another application: Digital Hybrid Photo-Detector

Analog HPD from Hamamatsu, Tokyo & Kyoto University



The digital HPD



- Use 3D Geiger-mode avalanche diode array for gain stage
  - Size 0.1-1 cm^2 with photocathode 100-1000cm^2
- May be cheaper than very large 3DdSiPM plane
  - 1/1000 reduction of Si area
- Dark noise
  - Not an issue cold, e.g. in LAr
  - Need to play some tricks at room temperature. Same as detecting charge particles

Summary and outlook

- The photon to bit converter has arrived
- Relying on two key technologies
  - Geiger-mode avalanche allowing the detection of single charge carriers
  - Directly coupled to electronics in 3D for maximum performance and flexibility
- Compelling solution for nEXO providing very low power dissipation
- In general compelling solution whenever dark noise can be overcome
  - For small area (e.g. PET)
  - For small time window (e.g. LiDAR)
  - Operated cold, e.g. in liquid Xenon and liquid Argon
- This technology can also be used for charge particle detection
- It is not an easy technology and it is expensive at the R&D stage
  - Help and $$$ are welcome!

Thank you

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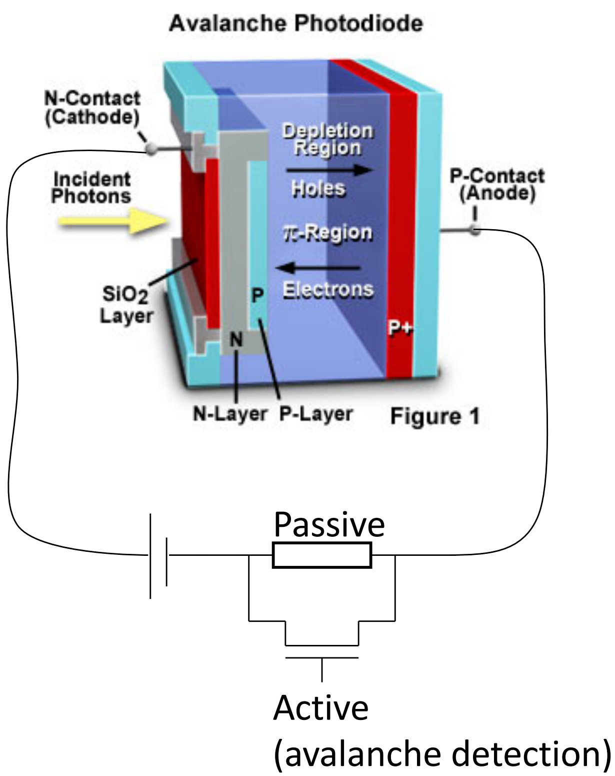
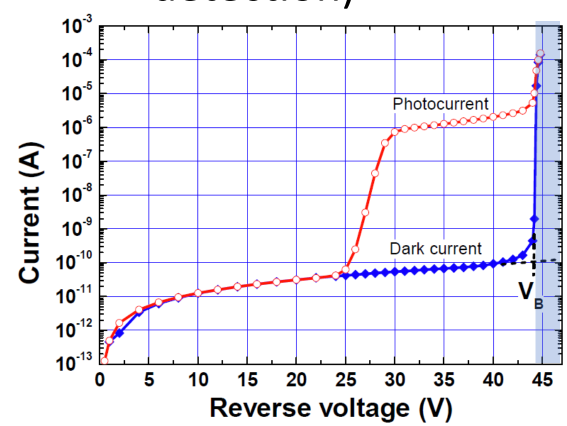
Single Photon Avalanche Detector



- Avalanche photo-diode operated above breakdown
  - Runaway avalanche due to impact ionization
- with quenching circuit
  - Passive (resistor)
  - Active (transistor + quenching detection)



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Prototyping the buffer stage

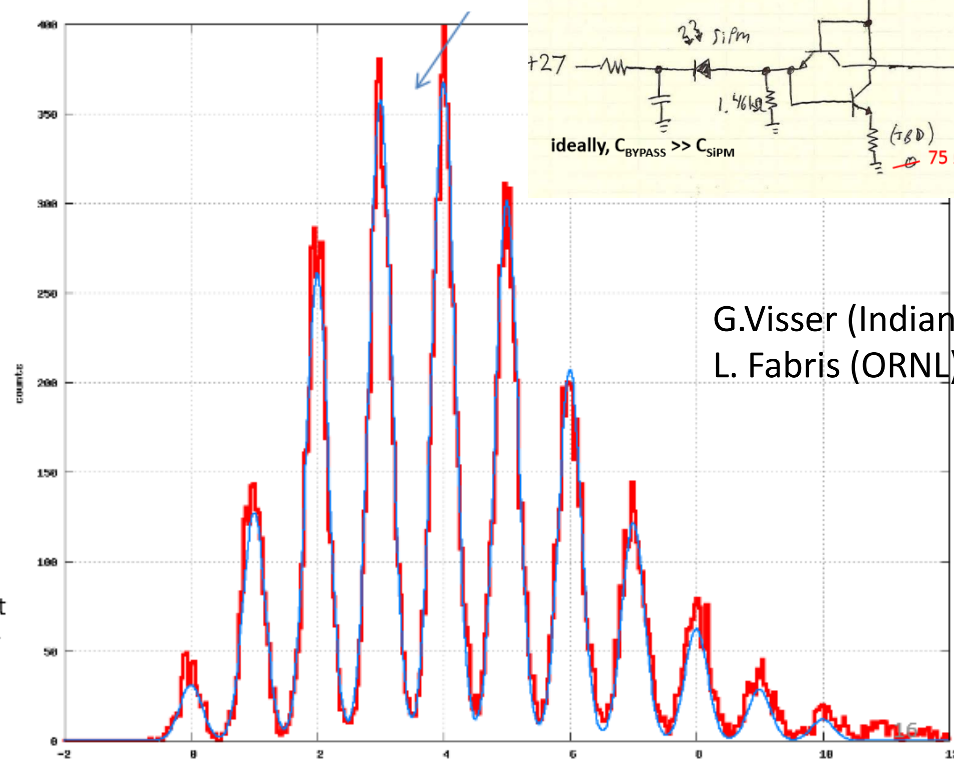
- Avalanche pulses visible!

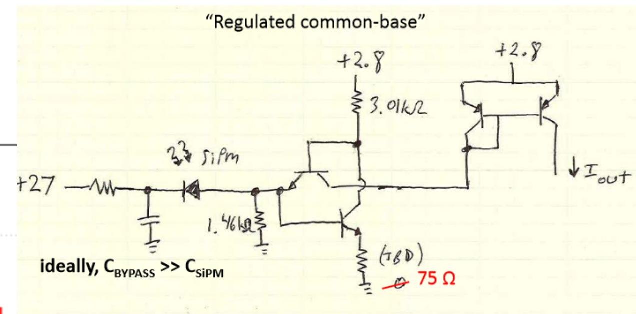
16 SiPM elements
(13.6 nF , 1.44 cm^2)
−30 °C
1 element illuminated

fit σ = 0.176 pixels
fit λ = 4.11 pixels
22856 events

(fit curve is simply a Poisson-weighted sum of Gaussians)

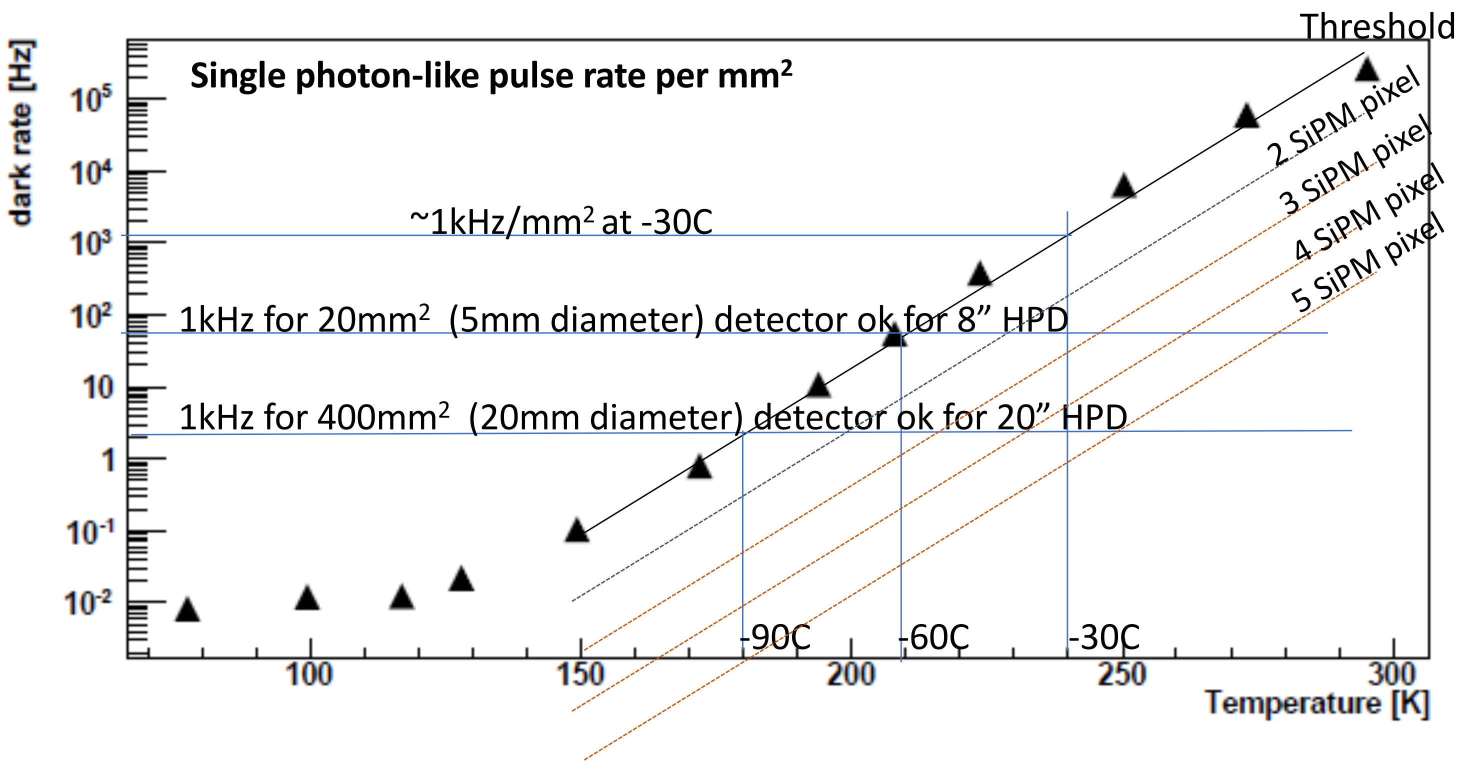
The shaper function here is not optimized, only a guess. Better resolution may be possible.





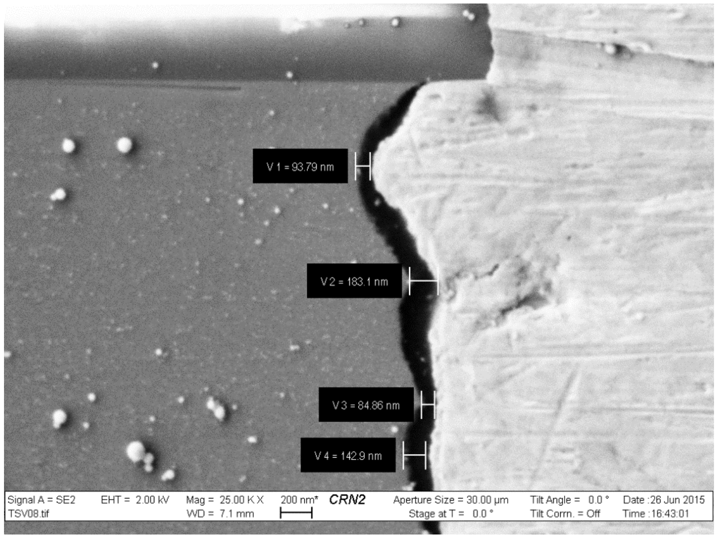
G.Visser (Indiana U.),
L. Fabris (ORNL)

Dark noise issue



Issues

- Through Silicon Via backside isolation with substrate
- Under bump metallization connection to TSV end cap (Ti/Cu interface)
- …



➢ 3D integration process related: will not be an issue when process moved to C2MI