Photon detection solutions for next generation experiments

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nEXO collaboration

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UNIVERSITÉ DE SHERBROOKE

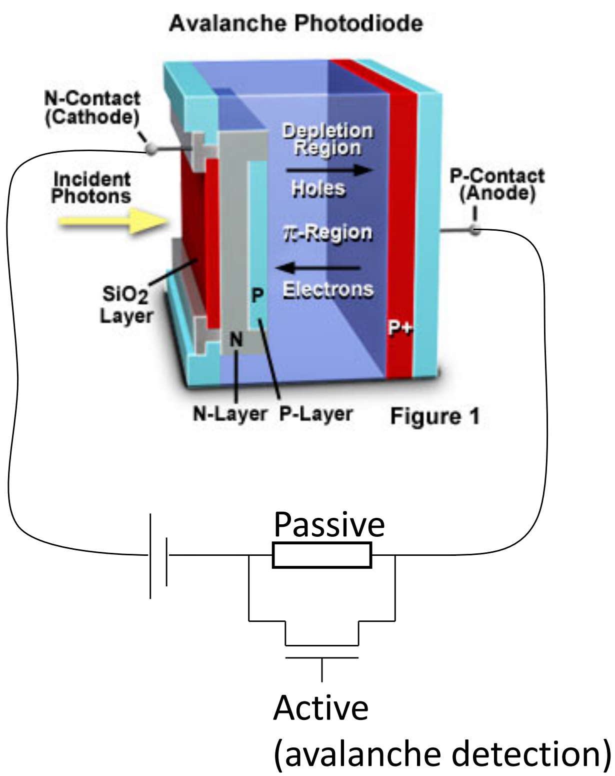
Motivations. Physics

- Light detection driving discoveries
  - Liquid Xenon scintillation in nEXO
    - Require 4-5 m^2 of photo-detector area
    - And may be Cerenkov light detection
  - Liquid Argon scintillation light
    - DarkSide-20k require 15 m^2 of photo-detector area
    - Need 100 m^2 of photo-detector for a 200-ton single phase detector, while DEAP-3600 is about 8 m^2
  - LAB scintillation light in SNO+
    - Enhanced light detection efficiency greatly enhance sensitivity
  - And beyond SNOLAB
    - Cerenkov light in IceCube, Hyper-K,…
    - Liquid Argon scintillation light in DUNE
- Future experiments are requiring ever larger areas, with high efficiency and low radioactivity

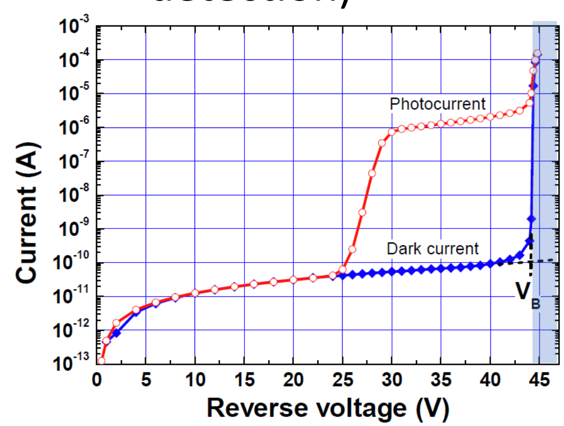
Motivation. The PMT shortfalls

- Not very efficient
  - 35% at most at 420nm
- Large gain fluctuations
  - Though mostly a calibration nuisance
- Fairly to very radioactive
- Fragile and bulky
- Don’t work well cold
  - Especially at liquid Argon temperature
- Sensitive to magnetic field
  - Need compensating coil
- Expensive > 20$/cm^2
- Some after-pulsing and dark noise

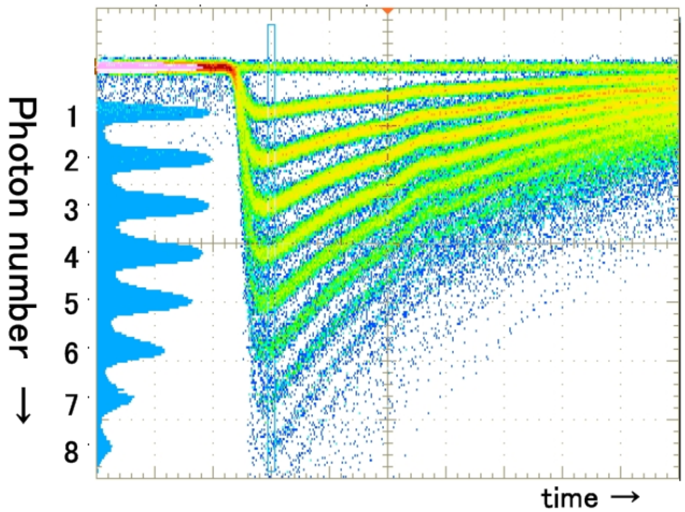
The solution? Single Photon Avalanche Detector?



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



The solution? Silicon Photo-multipliers



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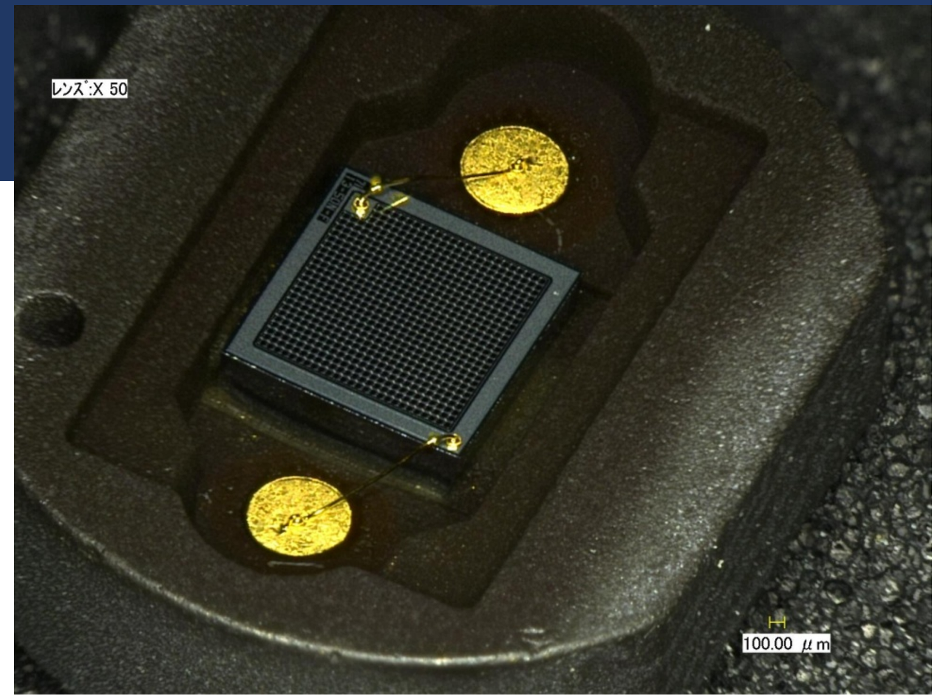

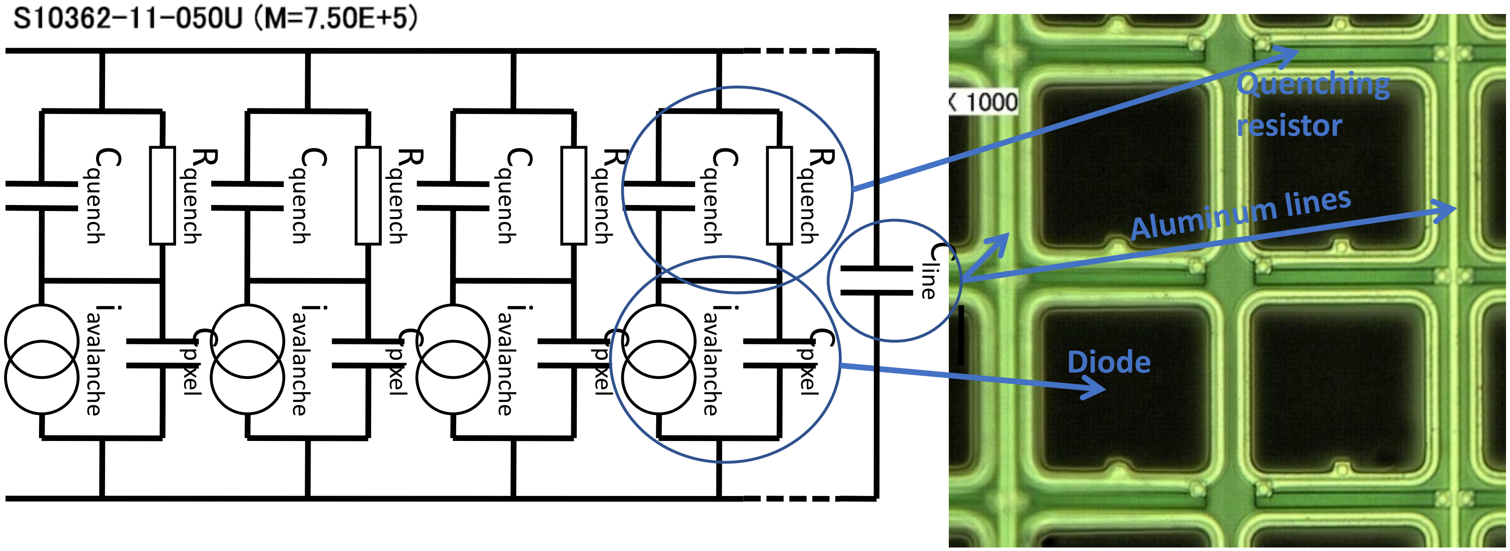

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The solution. SiPMs? Not really

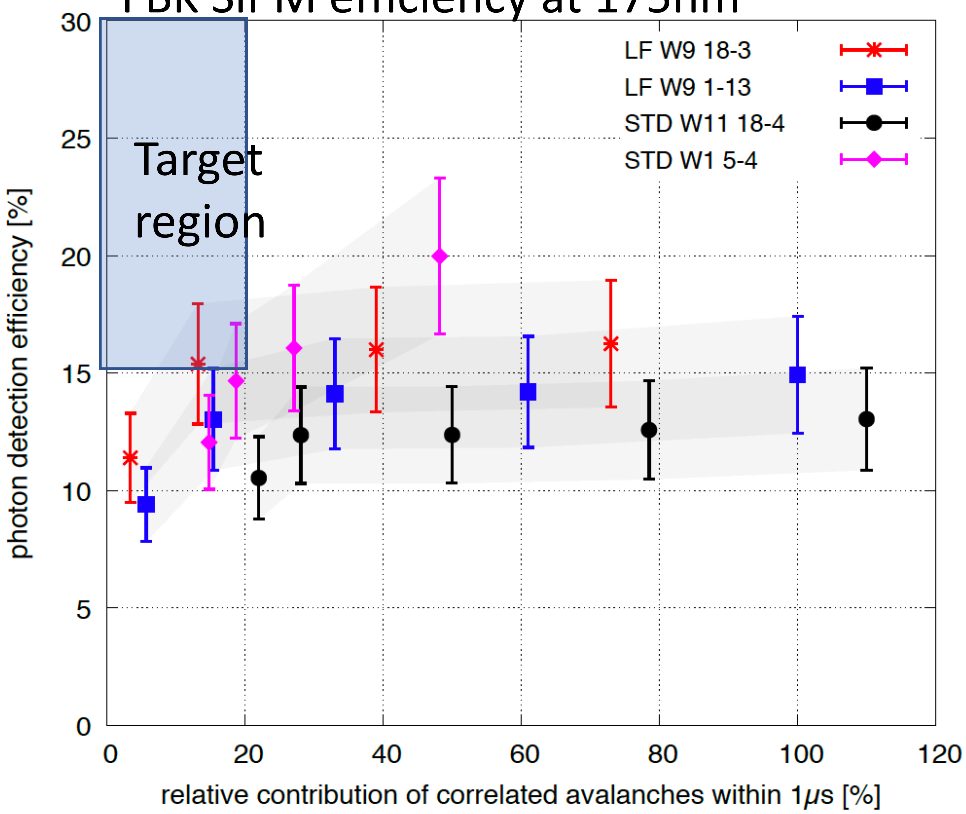
- Pros
  - Low radioactivity
  - High efficiency > 50% at 420nm
    - And improvement foreseen
  - Work better cold
    - Gain unaffected down to liquid nitrogen
    - Dark noise rate <100Hz/cm^2 at -100℃, <1Hz/cm^2 at -160℃
  - Insensitive to magnetic field, compact, robust
- Cons
  - Dark noise rate >1MHz/cm^2 at room temperature
    - After-pulsing is also significant
  - Large capacitance per unit area complicates electronics
  - Cost > 100$/cm^2
    - Though this depends on scale

Then what?

- Below <-100℃. SiPMs!
  - Analog SiPMs are the baseline for nEXO and DarkSide-20k
  - Overcoming electronics and cost issue with 3D integrated digital SiPMs
- At room temperature. Be creative
  - Optimize light transport
  - Keep the same photo-cathode but enhance the collection and gain stages

nEXO preliminary

FBK SiPM efficiency at 175nm



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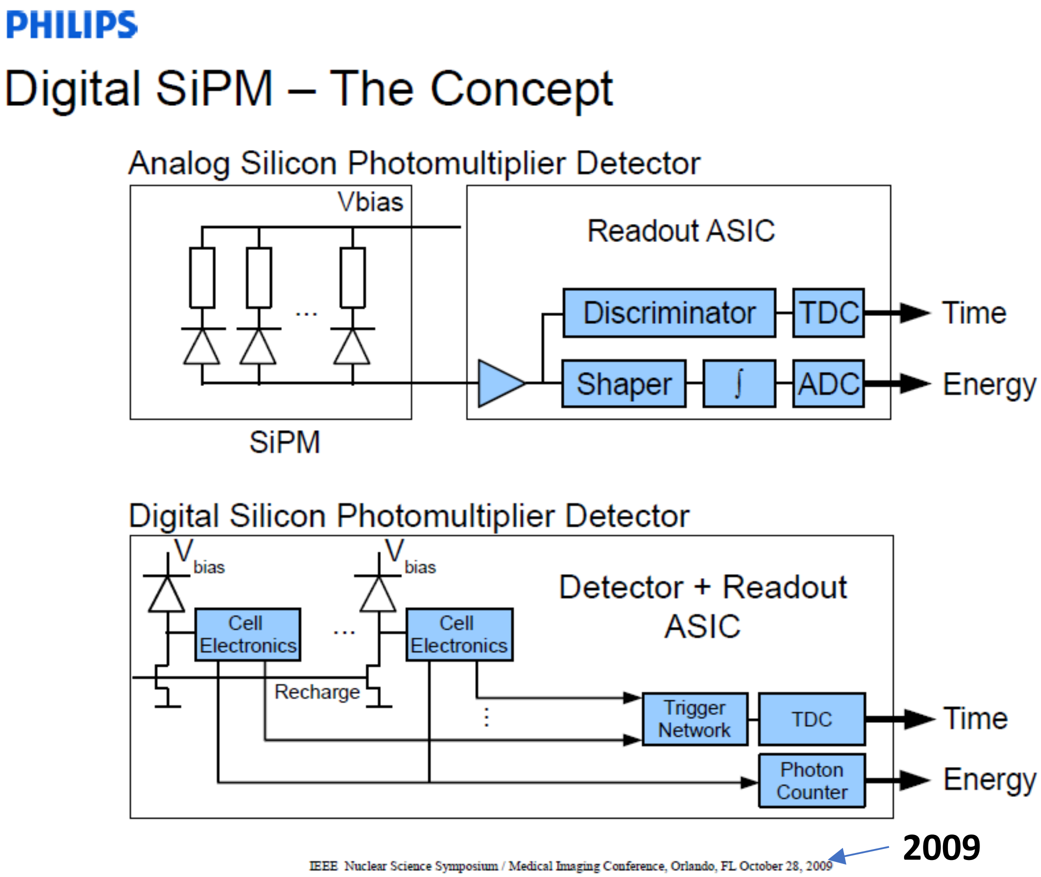
The digital SiPM concept



- 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
    - Can suppress almost all after-pulses
  - Time tag and count the avalanche

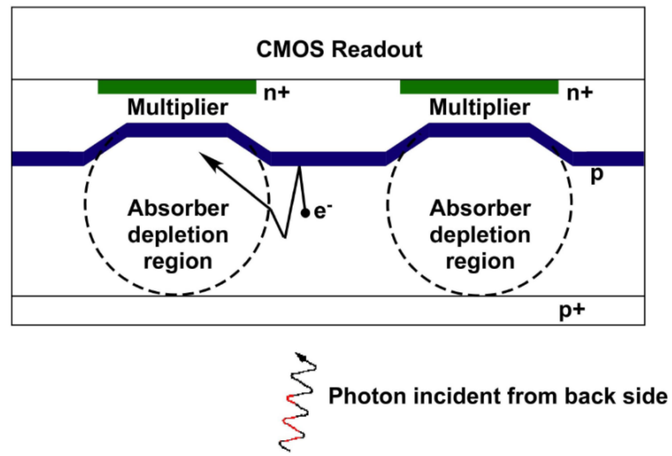
From monolithic digital SiPM to 3DdSiPM

- 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

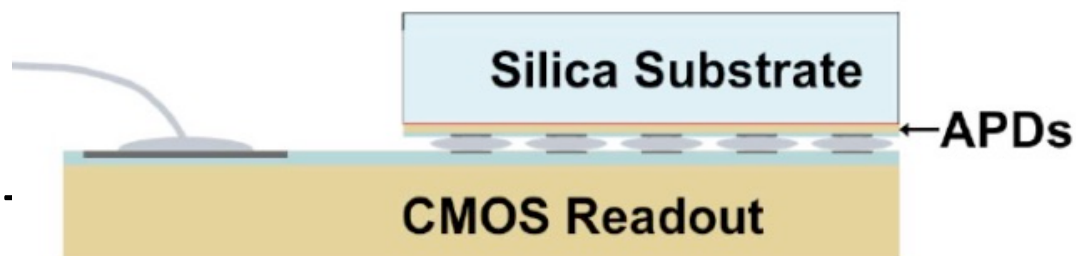
1a 1b 1c 1d

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

Pioneer work at MIT Lincoln Lab

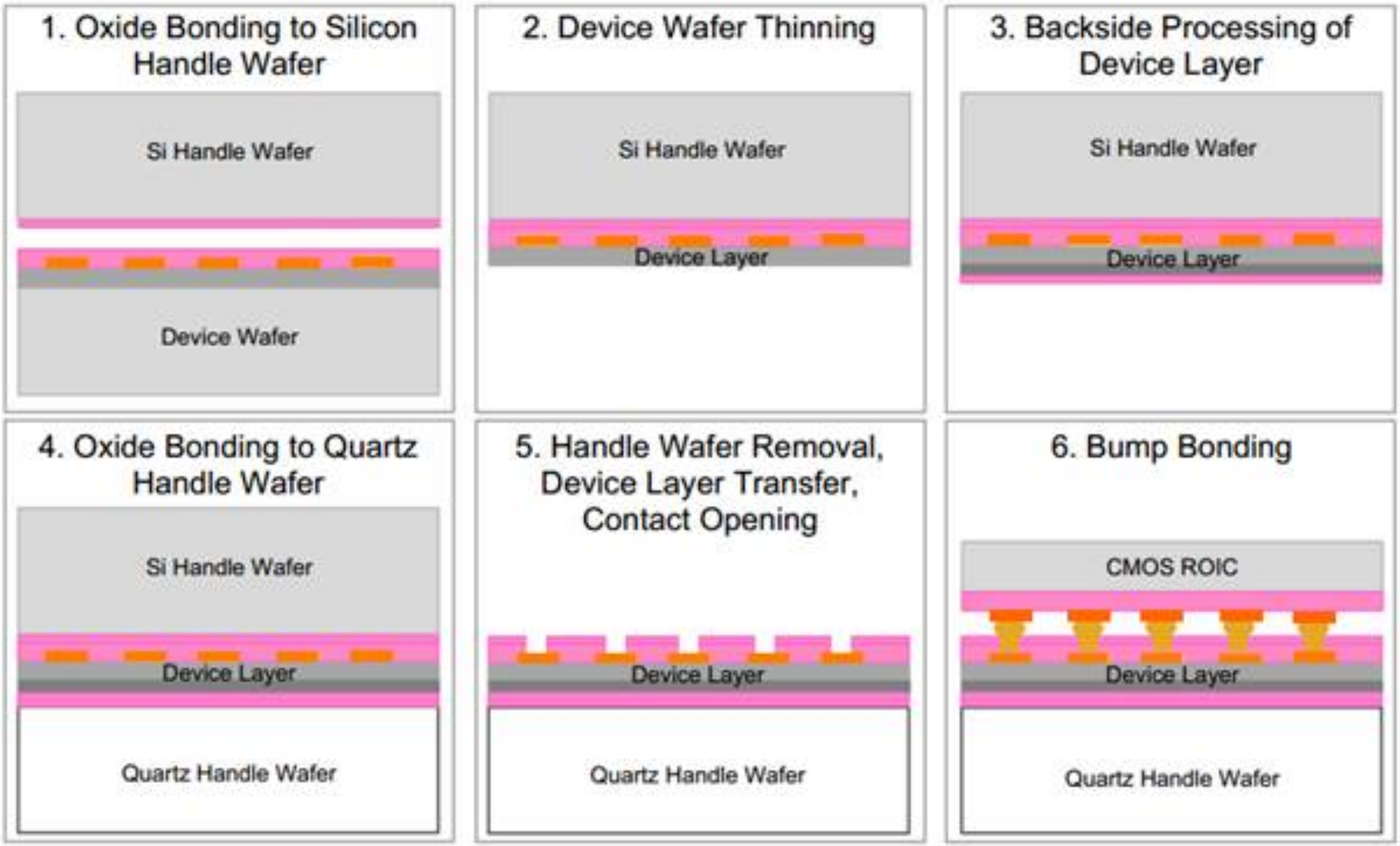
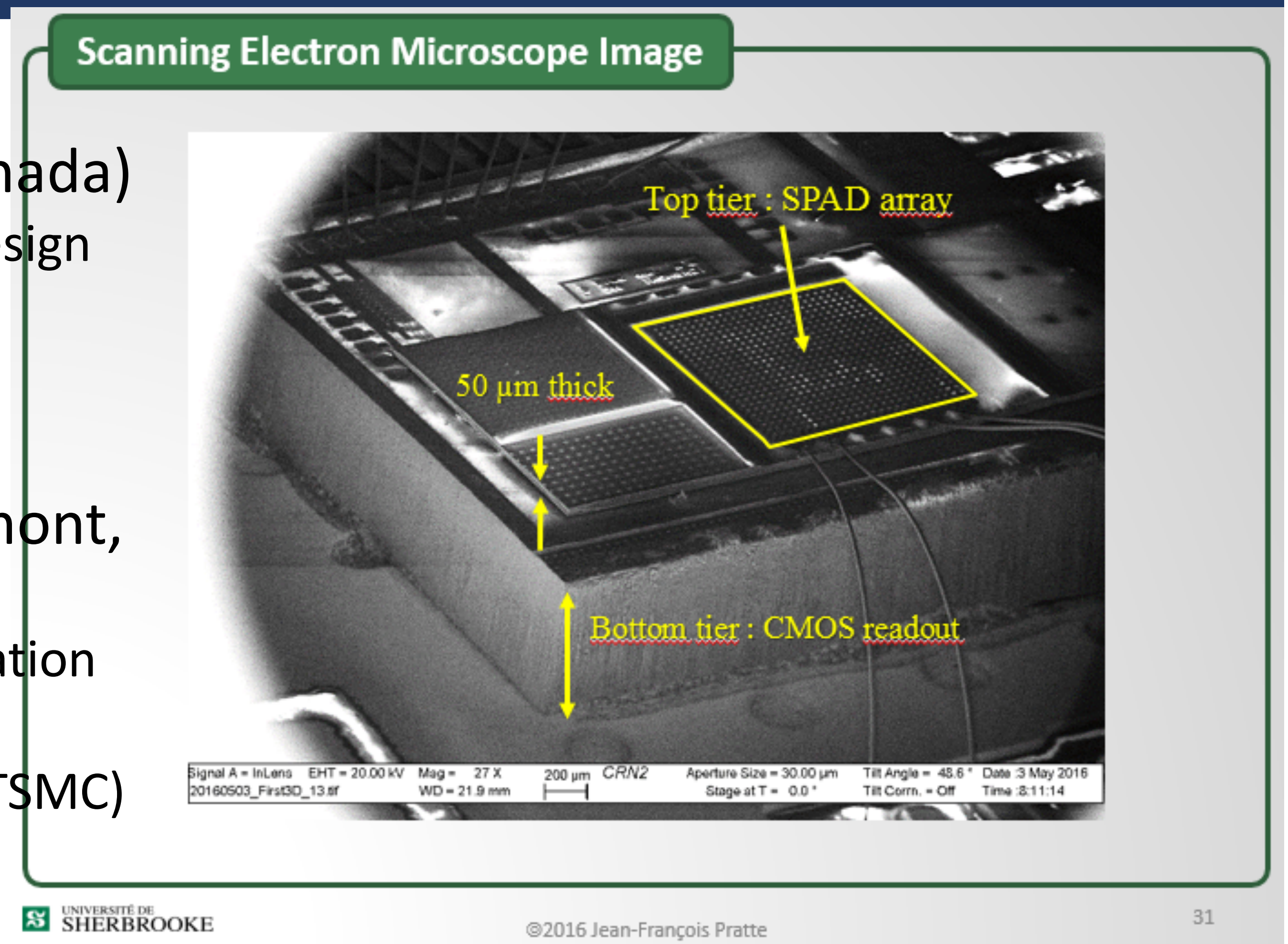


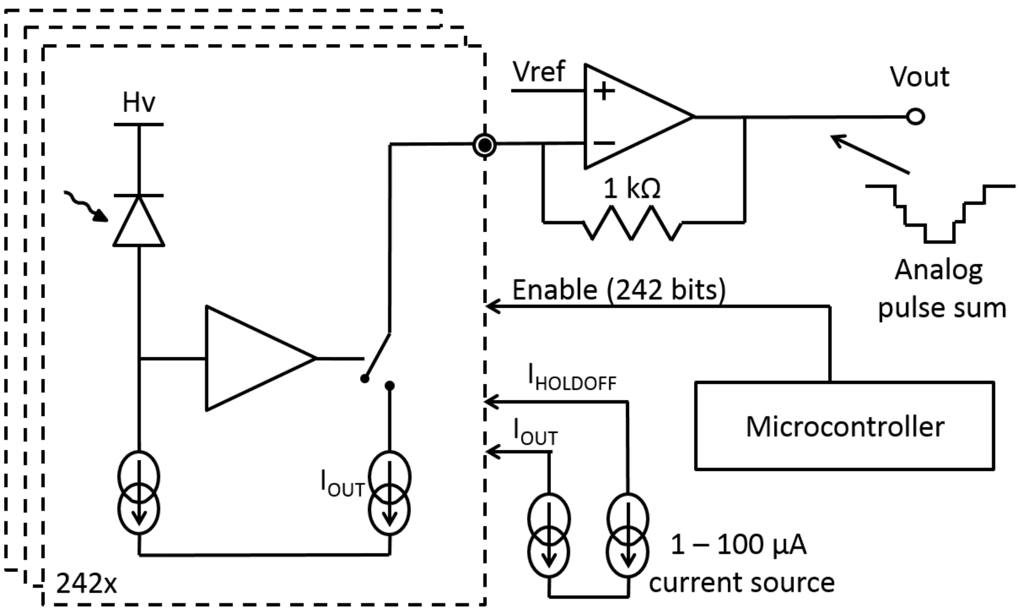
Figure 3: GM-APD back-illumination process flow illustrating the major steps to process a wafer of GM-APD devices that has completed front-side processing through to hybridization with a CMOS ROIC. To simplify the illustration, the relative positions of the components of the bonded wafer stack are maintained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

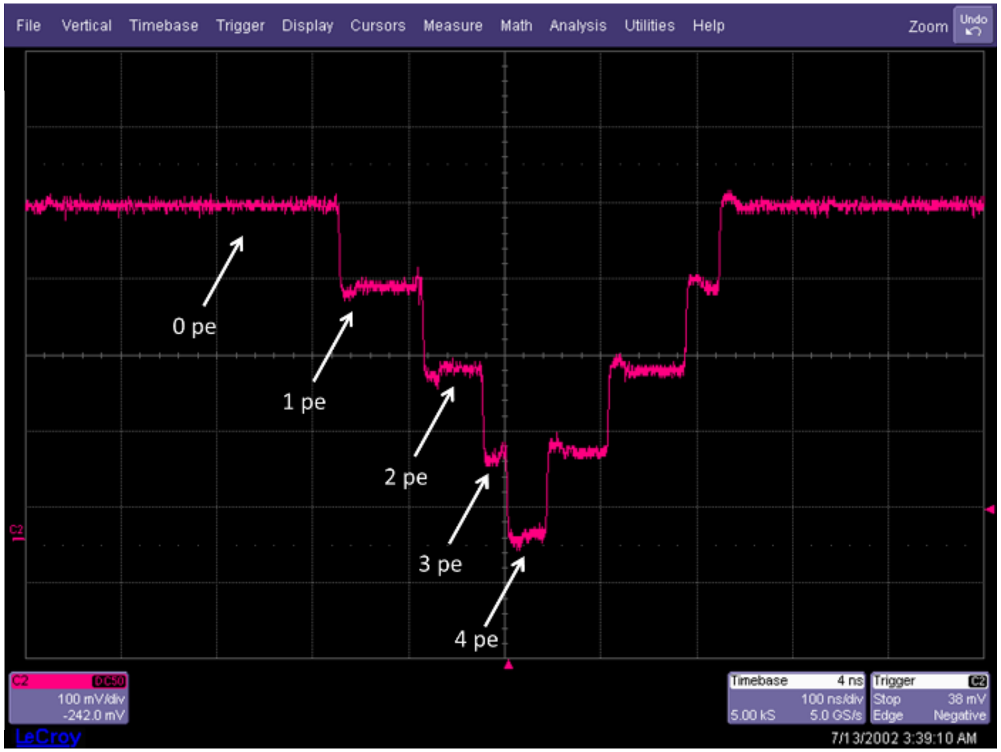
And in Canada

- 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





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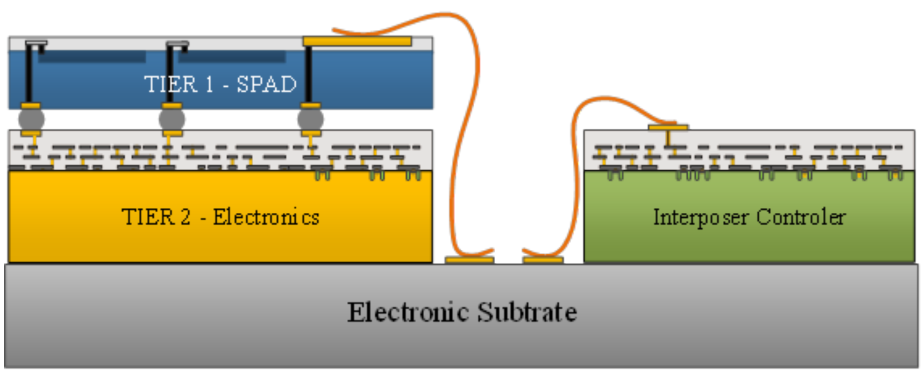
Development of 3DdSiPMs for LXe and LAr applications in Canada

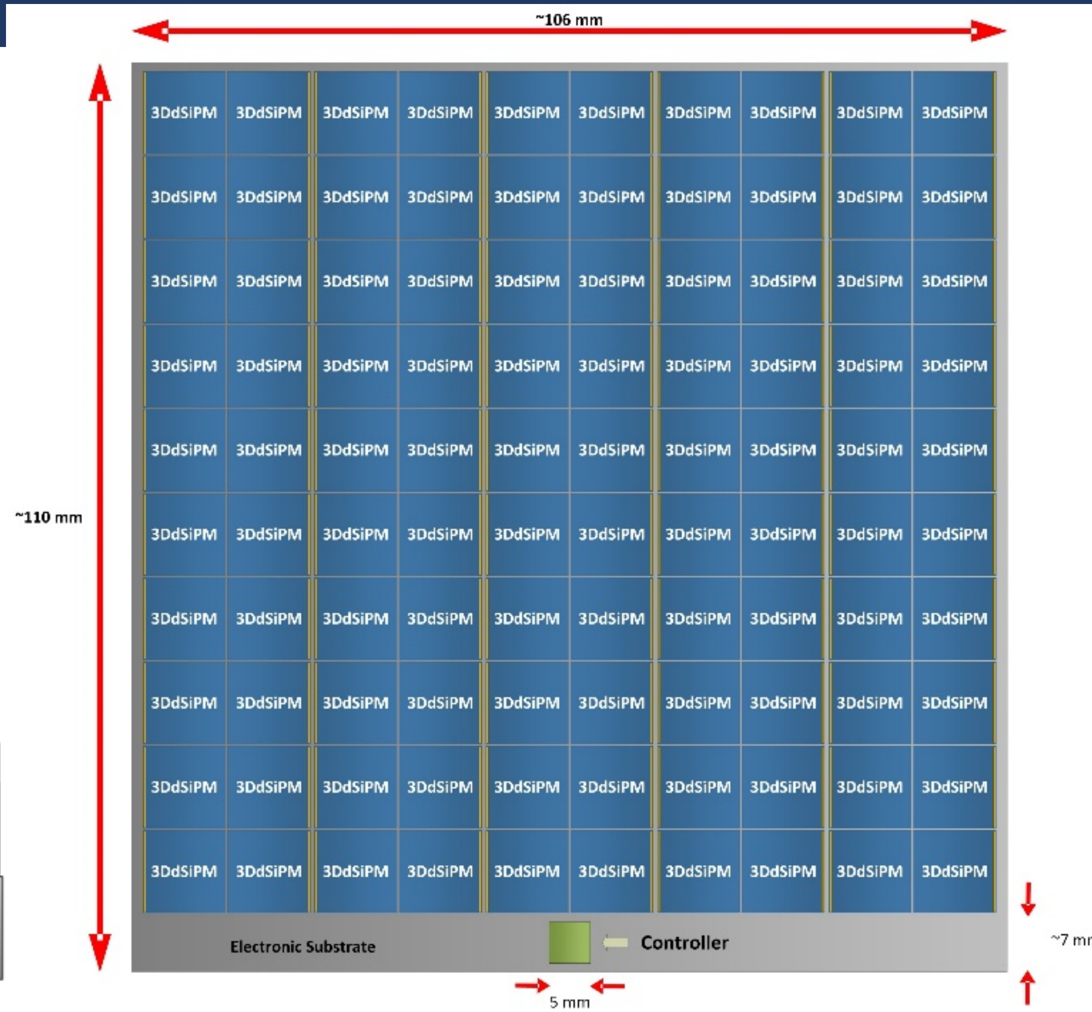
- Expertise in Canada
  - Sherbrooke + TRIUMF
- Facilities in Canada
  - Teledyne-DALSA
  - U.Sherbrooke C2MI, 3IT
  - CMC
  - SFU 4Dlabs?
- Funding
  - NSERC through EXO
  - CFREF through Queens
  - CFI through M.Boulay's LAr/Lxe development infrastructure

Parameters	Requirement	Comments
nEXO barrel photo-detectors	*Specifications at -104 ˚C*	
Photo-detection efficiency at 175nm	>15%	Hamamatsu VUV4 MPPC (analog SiPM) ~23%. Specification assumes SiPMs reflects about 60% of the VUV photons
Correlated avalanche rate (0-1μs)	<20%	Achieved by FBK and Hamamatsu though limit the over-voltage
Dark noise rate	<50Hz/mm^2	Achieved by FBK and Hamamatsu
Readout electronics power dissipation	<20W/m^2	Conceptually possible for analog SiPMs with μs scale shaping and large gain
Time sampling	<1μs	
Radioactivity (Combined Th and U)	<10nBq/cm^2	Achieved by unpackaged FBK SiPMs
Single channel area	<100cm^2	Assembly of several SiPMs
Total area	4-5m^2	
nEXO-EL end-cap photo-detectors	*Same as nEXO barrel photo-detector except*	
Correlated avalanche rate (0-2μs)	<5%	
Time sampling	50ns	
Granularity	5×5mm^2	
Total area	~1m^2	
nEXO-ELT (Cerenkov)	*Upgrade of the nEXO barrel and end-cap photo-detectors*	
Time sampling	1ns	
Granularity	1cm^2	
DEAP-200t (200ton LAr)	*Specifications at -186 ˚C*	
Photo-detection efficiency at 125nm Photo-detection efficiency at 420nm	>15% >40%	Hamamatsu VUV4 MPPC (analog) ~10% Require a VUV to blue wavelength shifter
Correlated avalanche rate (0-5μs)	<10%	For PSD
Dark noise rate	<0.1Hz/mm^2	For triggering and PSD
Time sampling	5ns	For PSD
First photon timing resolution	250ps	For position resolution with time of flight
Radioactivity (Combined Th and U)	?	Driven by neutrons
Granularity	1cm^2	For position reco. especially on surface
Total area	150m^2	

R&D towards nEXO

- Tailor photo-detector tier for VUV detection
- Demonstrate scalability
  - In particular power dissipation
- Demonstrate cost <2M$/m^2
- CFI funds for R&D secured through M.Boulay at Carleton





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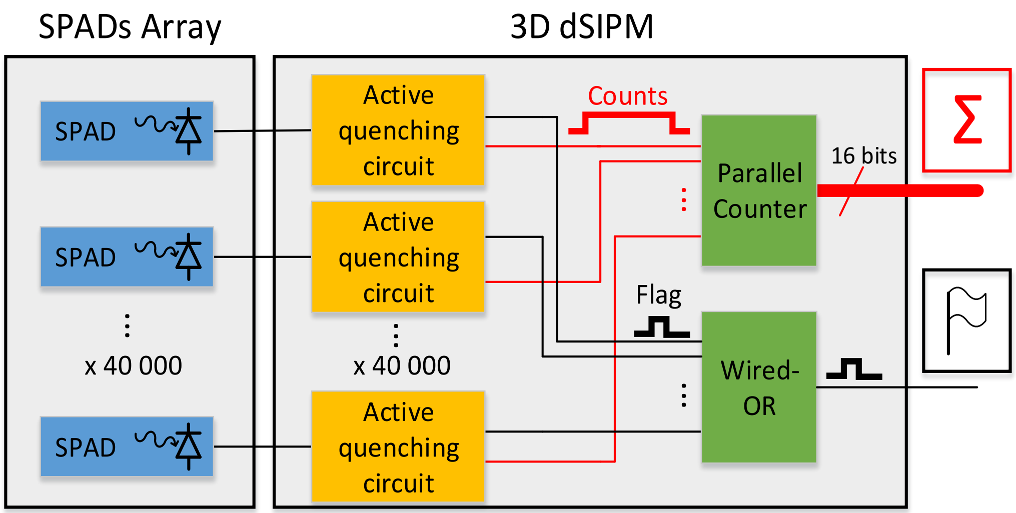
3DdSiPM ”schematics”

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



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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
- **So… for 4 m^2, the digitization cost ~0.7 W! About x20 less than estimates for analog SiPMs**

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

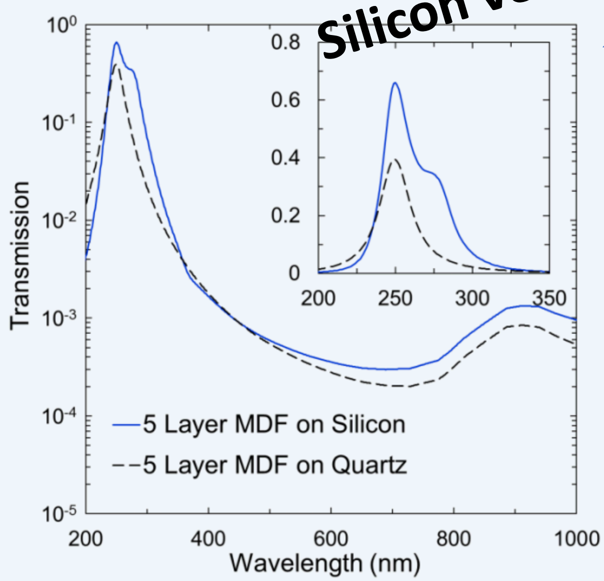
- Timing resolution < 1ns (towards 10ps) overall large area
  - Without huge power dissipation
  - May allow separating Cerenkov and scintillation photons
    - Possible background rejection handle in $0\nu\beta\beta$ experiment
- Fine granularity (at no extra cost)
  - mm^2 scale possible
  - Combined 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$

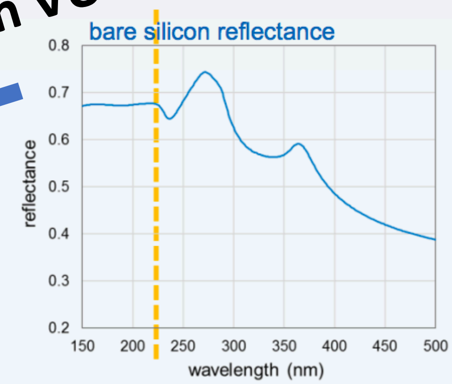
Further challenge. VUV issue 1.

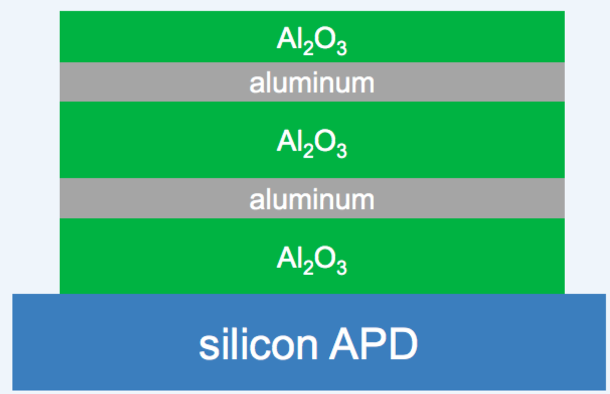
Metal-dielectric UV bandpass filters

- Conventional low-loss dielectric filters are not available in this wavelength range
  - Lack of high refractive index transparent materials
- Bandpass filters in this range are metal dielectric (aluminum)
  - Commercial filters have peak transmission ~30-35%
- High Si UV reflectance now beneficial

Silicon very reflective in VUV





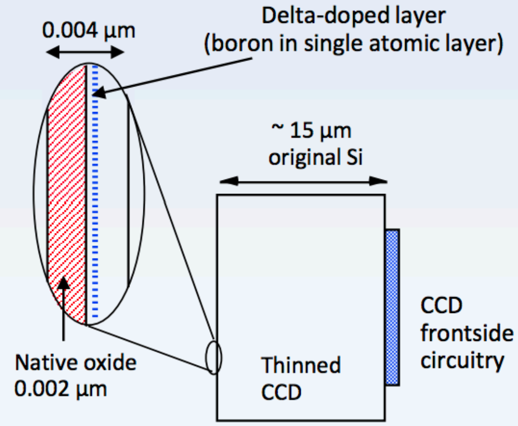


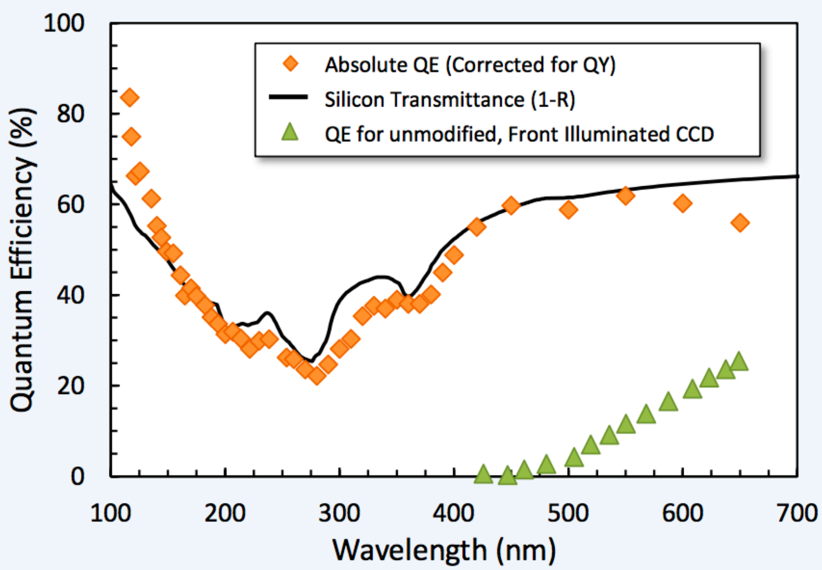
Further challenge. VUV issue 2.

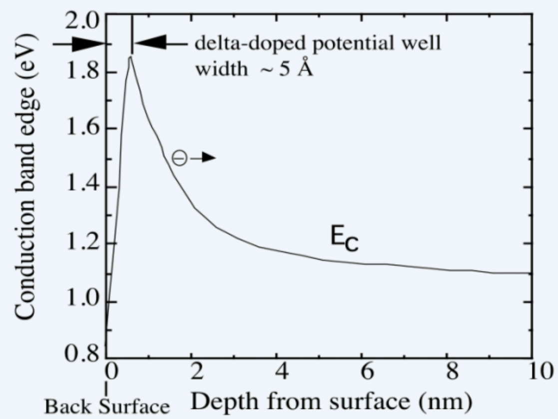
Silicon attenuation length very short in VUV

Two-dimensional doping by MBE

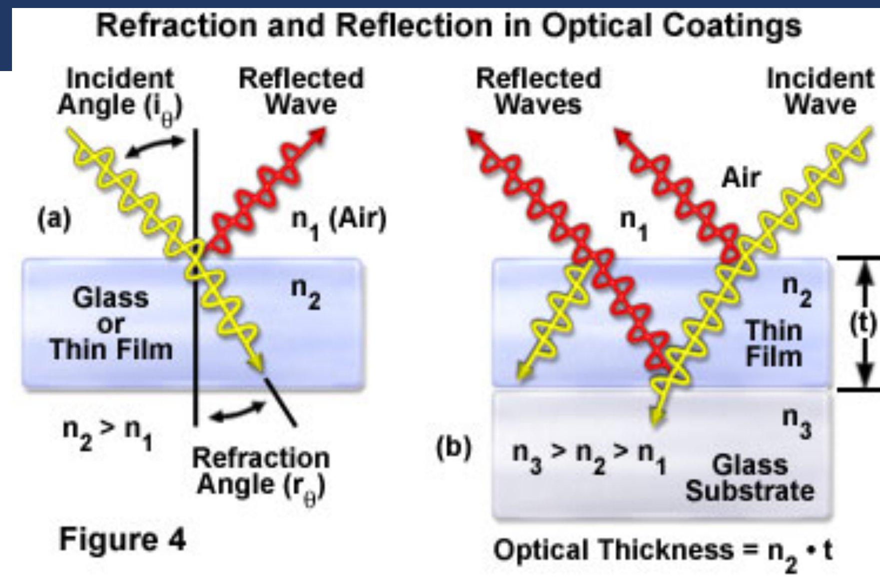
- Delta doping and superlattice doping optimizes surface band structure
- Stable, uniform back surface passivation
- 100% internal QE, 100% fill factor, low dark current
- Ultrathin back surface contact

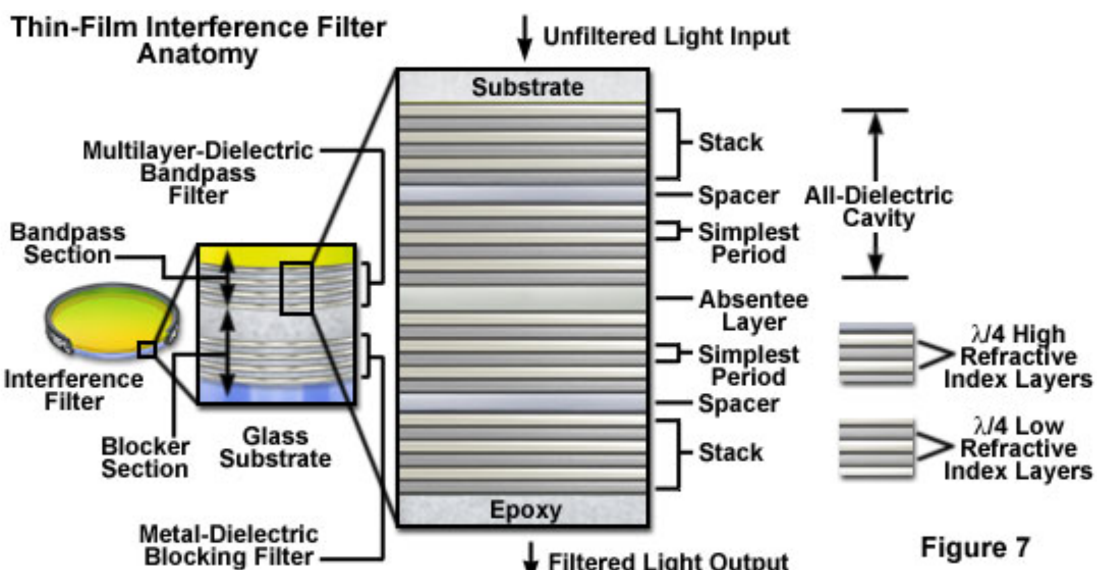


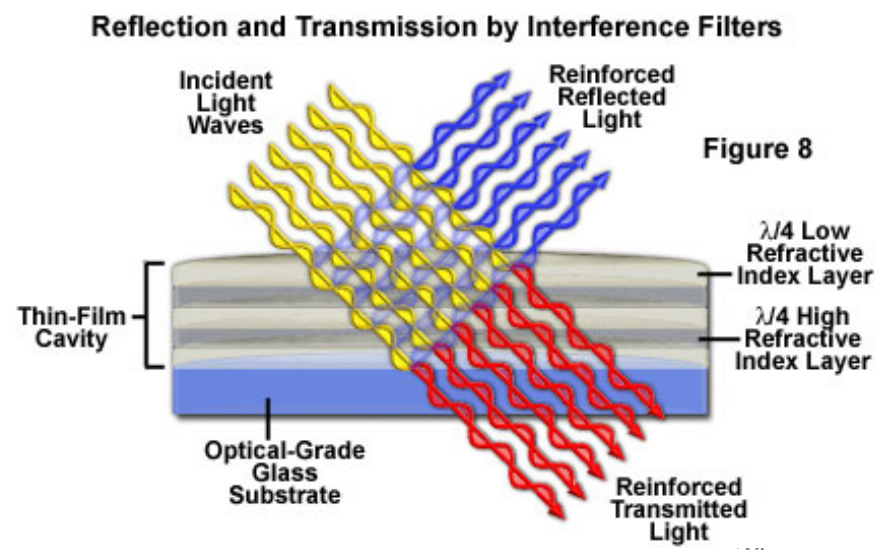




Harnessing the power of interference filters



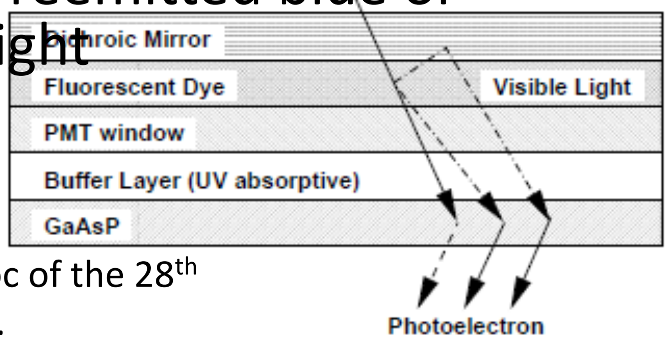




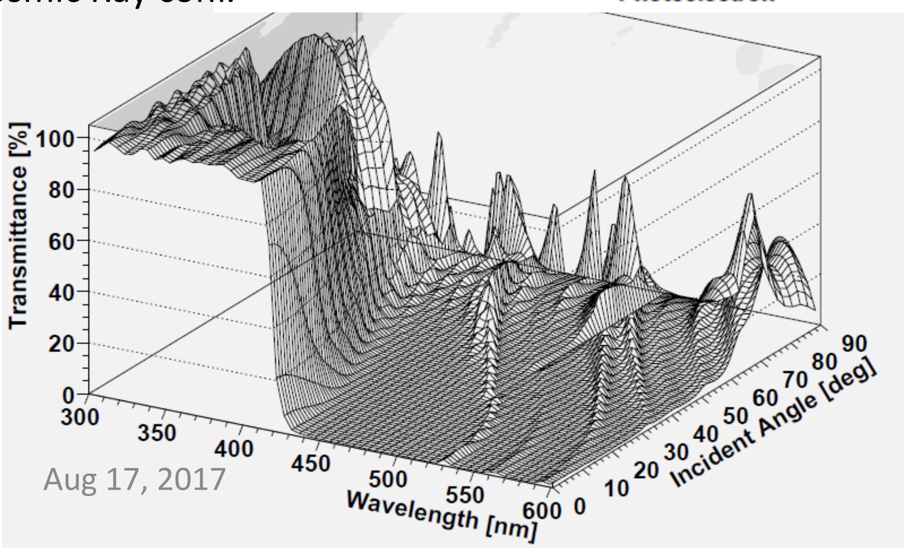
Use this technique to separate scintillation and Cerenkov light in liquid Xenon?

At room temperature, Winston cone + dichroic mirror + wavelength shifter

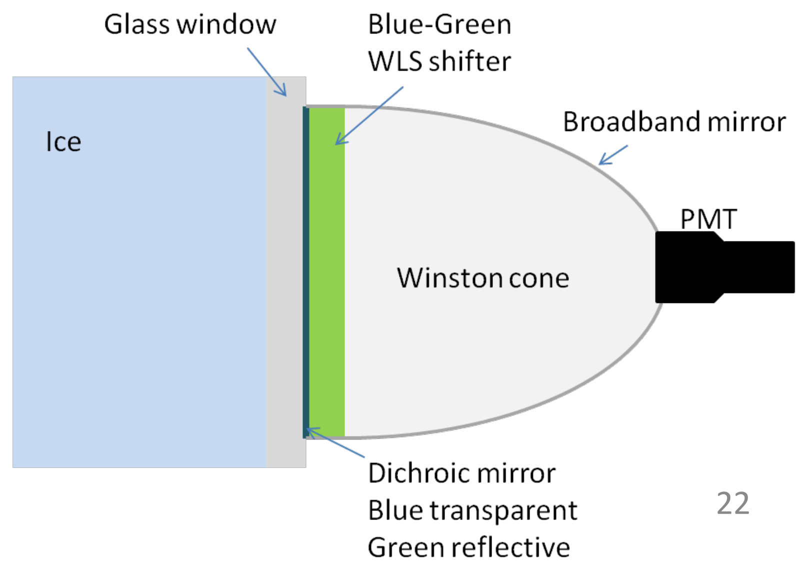
- Concept patented by RIKEN
  - Let UV/Blue light through
  - Reflect reemitted blue or green light



M. Takeda et al., proc of the 28th Int. Cosmic Ray conf.

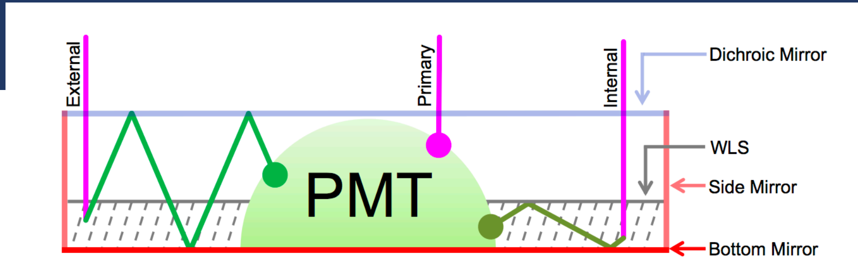


- This concept for large area
  - Reemitted light is completely trapped
  - Focus the light to PMT using Winston cone
    - Make the cone of acrylic for radioactivity shielding
    - Use SiPM rather than PMT?

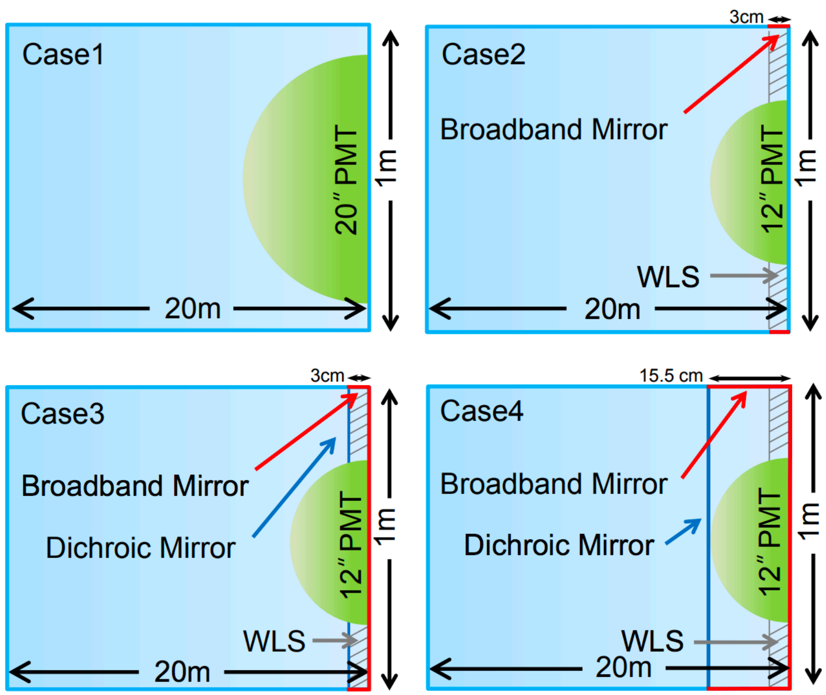


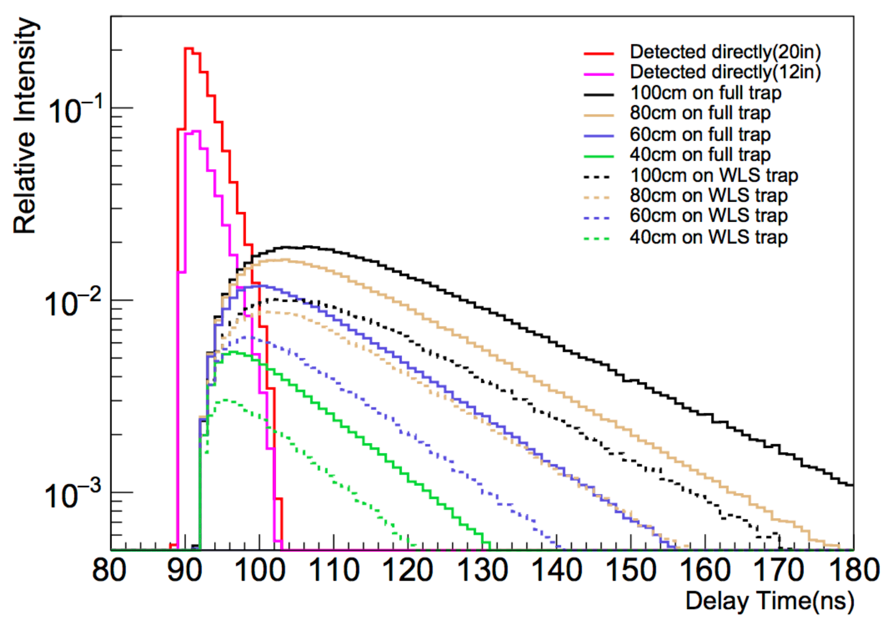
Photon trap for large area

- Configuration investigated for Hyper-K by simulations
  - Aim of reducing cost
- Using a realistic dichroic mirror from Iridian SpectralTechnologies (Ottawa, Canada)



	Relative detection efficiency			
Configuration	**Primary**	**Internal**	**External**	**Total**
Case 1	1.000	0	0	1.000
Case 2	0.379	0.358	0	0.737
Case 3	0.378	0.396	0.099	0.874
Case 4	0.316	0.412	0.344	1.071





C. Rott, S. In, F.R., P. Gumplinger, arXiv:1708.01702

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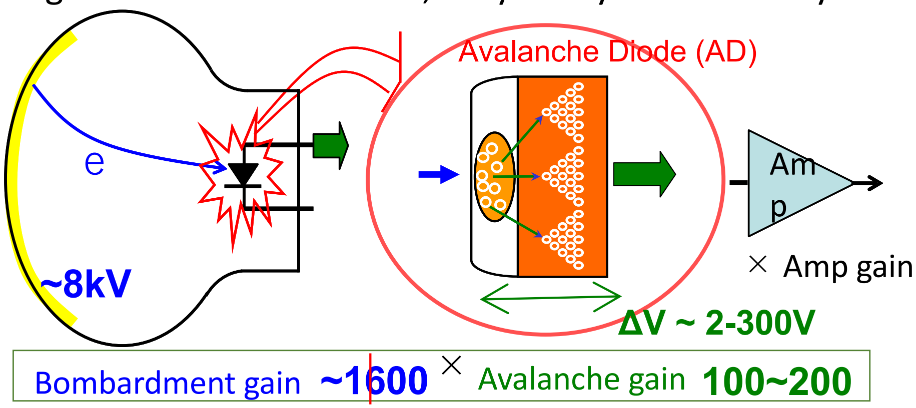
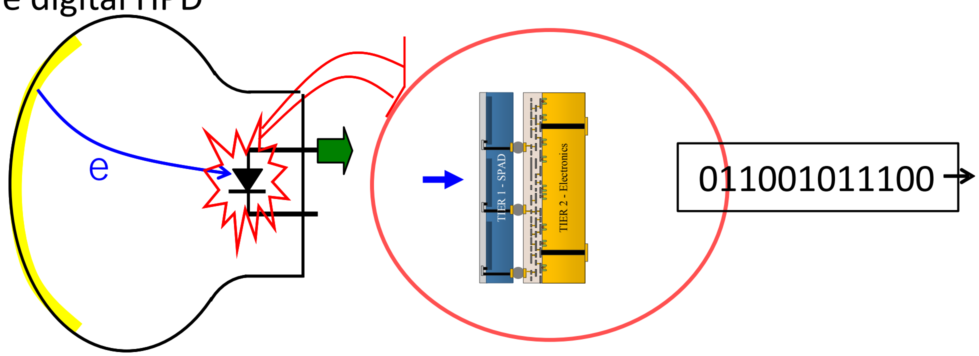
At room temperature: the Digital Hybrid Photo-Detector

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
- Development foreseen in collaboration with U.Alberta

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Summary

- Compelling physics goals demand new technologies
  - Enhance overall light collection in SNO+
  - High spatial granularity and timing resolution while decreasing radioactivity content for DEAP
- Compelling technologies to meet physics demand
  - 3D integrated digital SiPMs
  - Hybrid photo-detectors using an electron detector relying on 3D integratedd technology
  - Interference filters and wavelength shifters
- Compelling technologies “benefitting Canadians” and beyond
  - Time of flight PET
  - LIDAR systems

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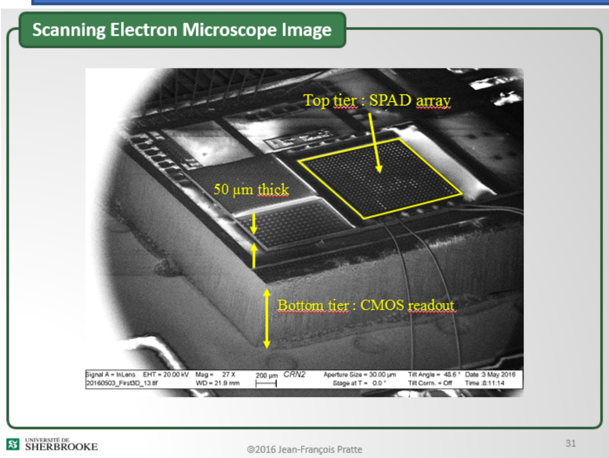
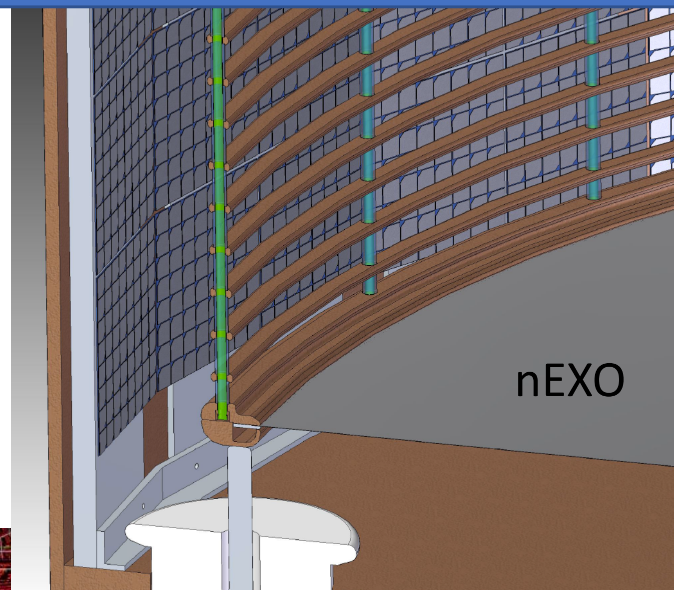
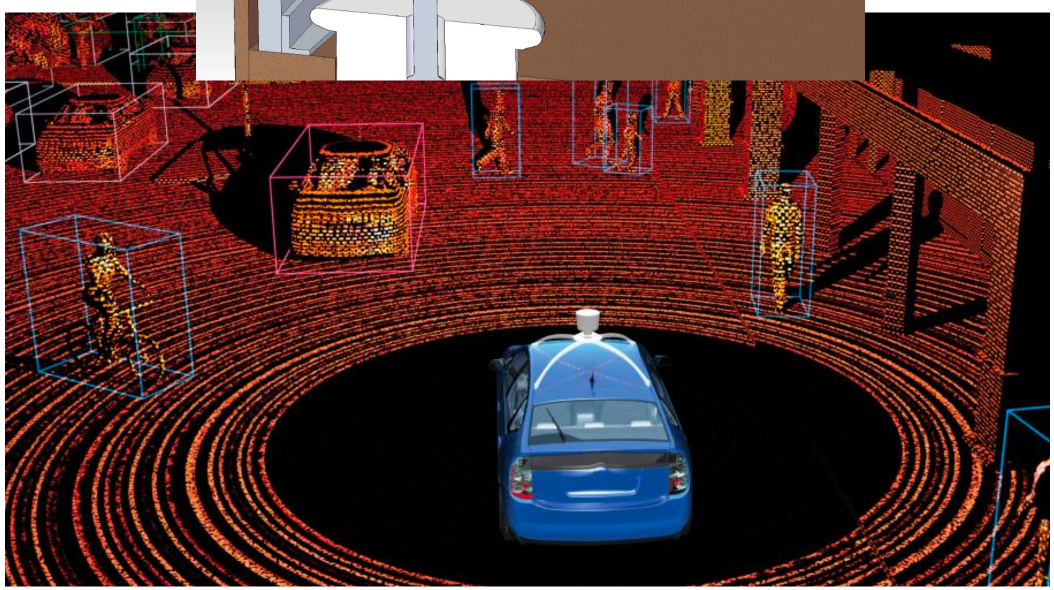
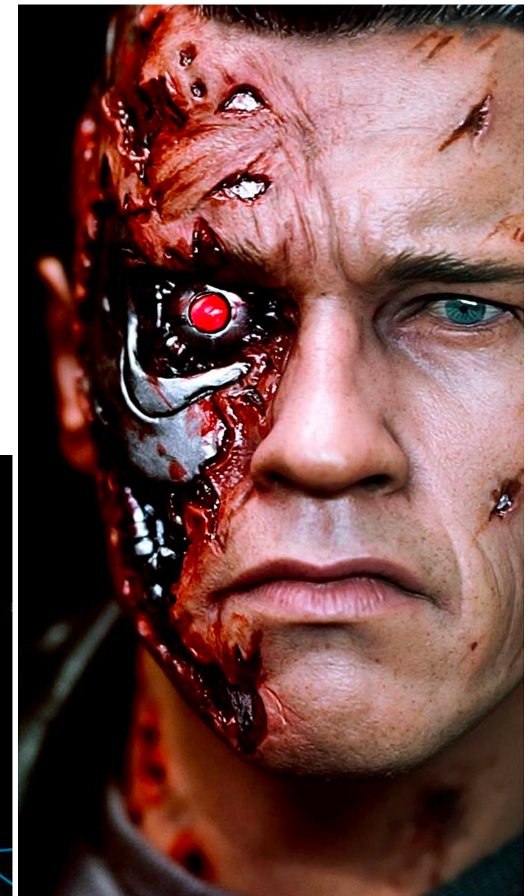
Long term outlook

2015 2025 2035



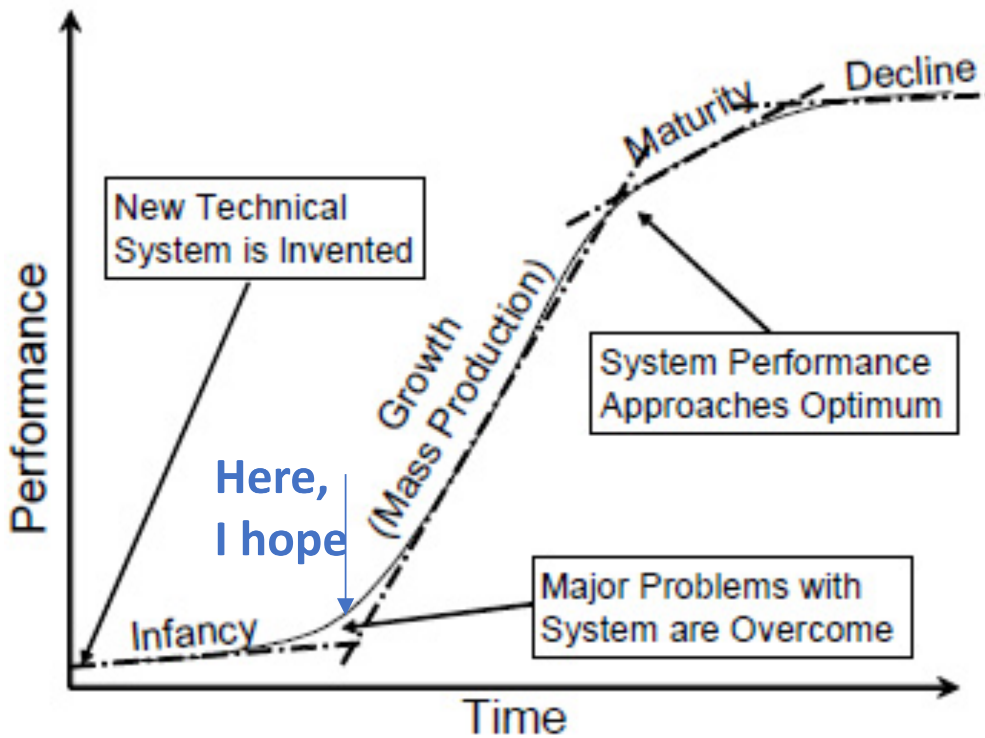






A more sobering outlook

- Where are we?



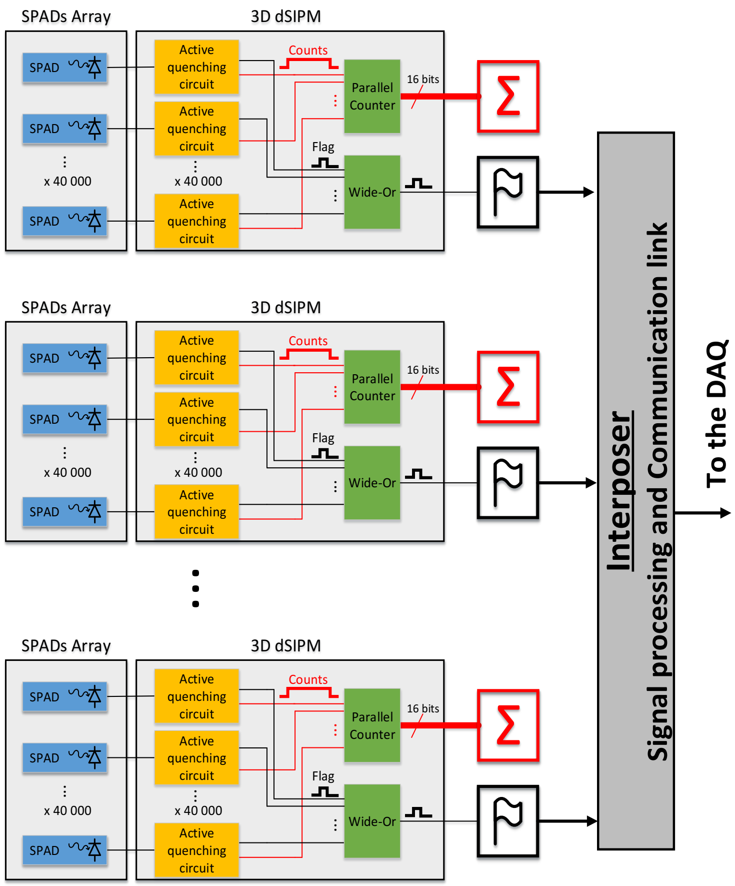
Technology life-cycle curve

- Mitigating risks through an expanded collaborative effort?
- Some independent challenges:
  - 3D integration
  - Delta doping (for VUV)
  - Interference filter (and Atomic Layer Deposition facility)
  - Wavelength shifter

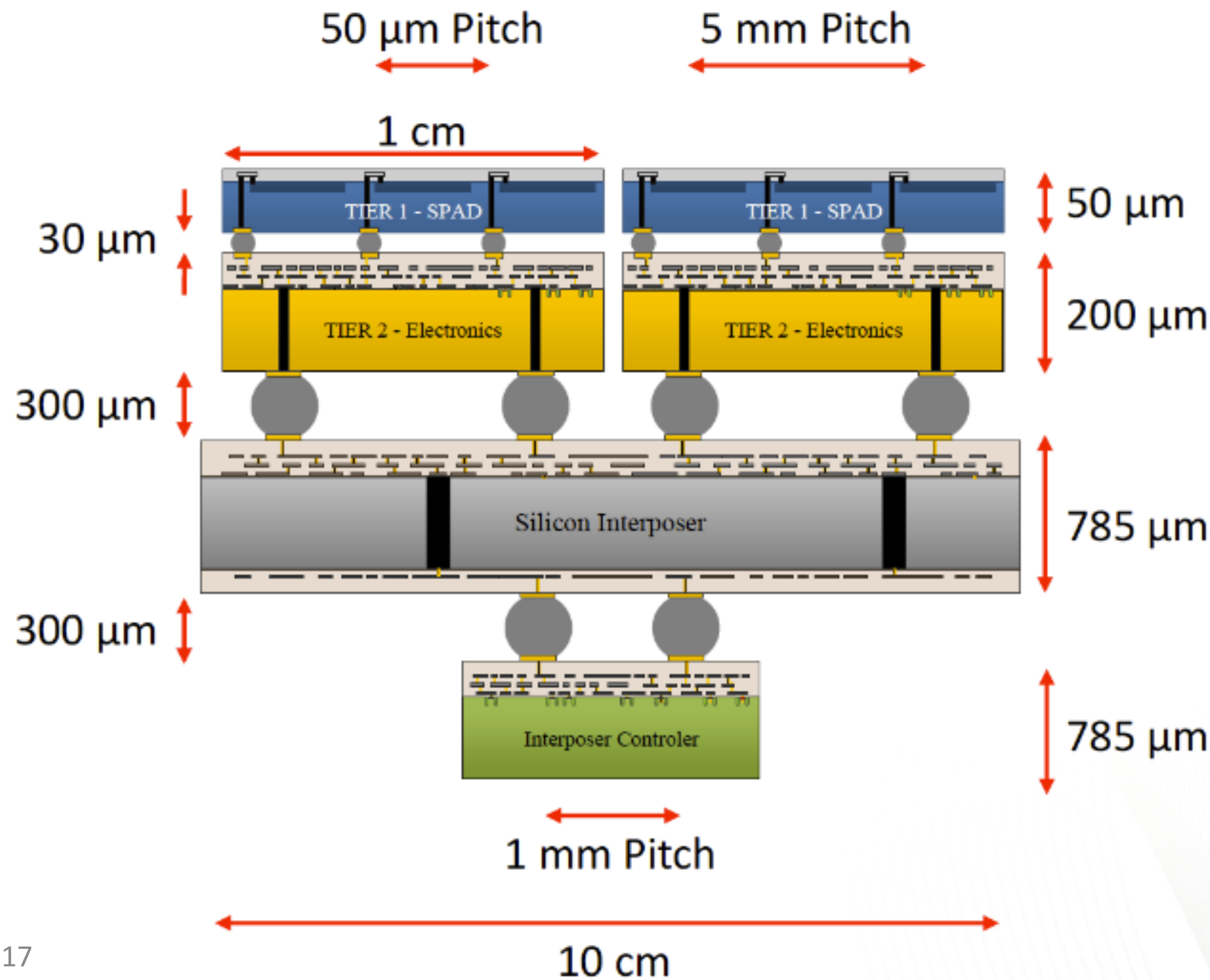
Thank you

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



3 dimensional digital SiPM for nEXO



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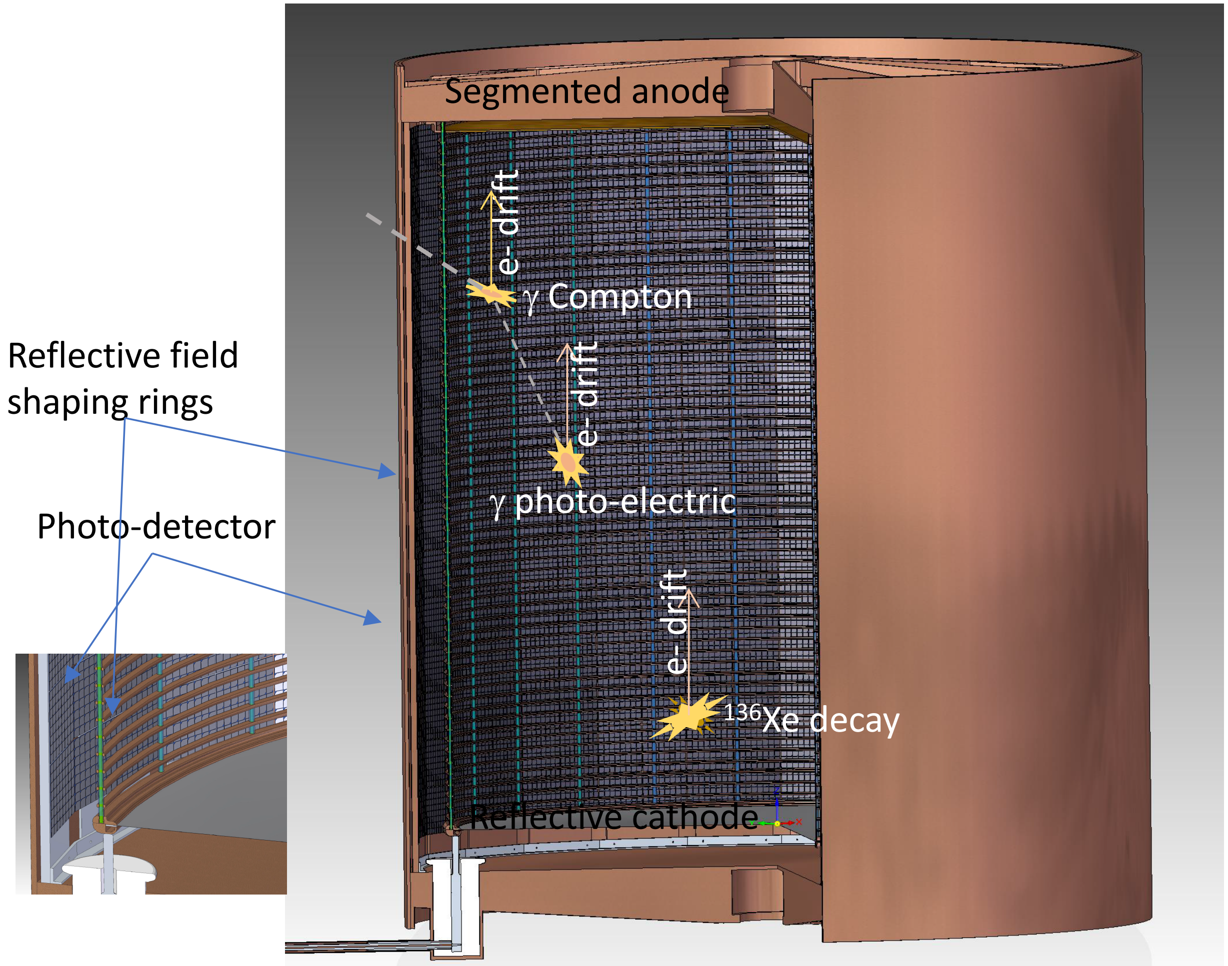
Motivation. nEXO

- 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**



![TRIUMF]

Prototyping the buffer stage

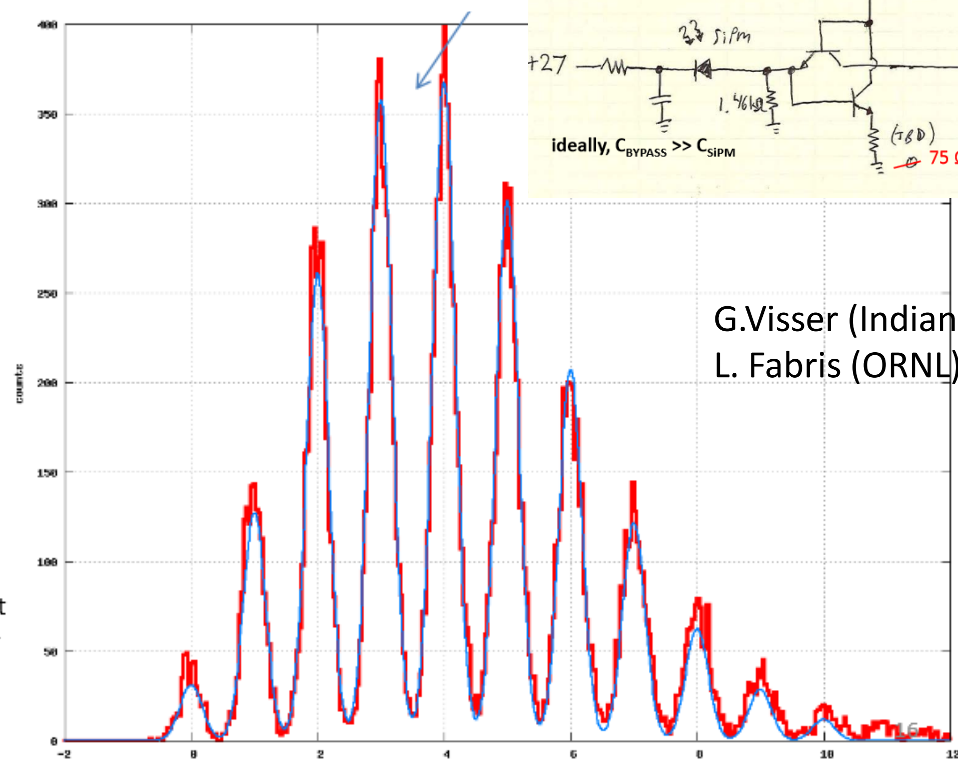
- Avalanche pulses visible!

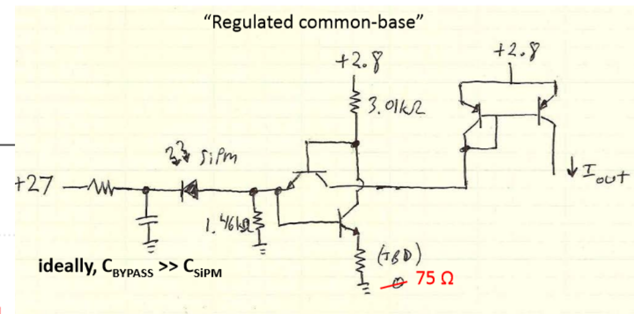
16 SiPM elements
(13.6 nF , 1.44 cm^2)
−30 °C
1 element illuminated

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

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

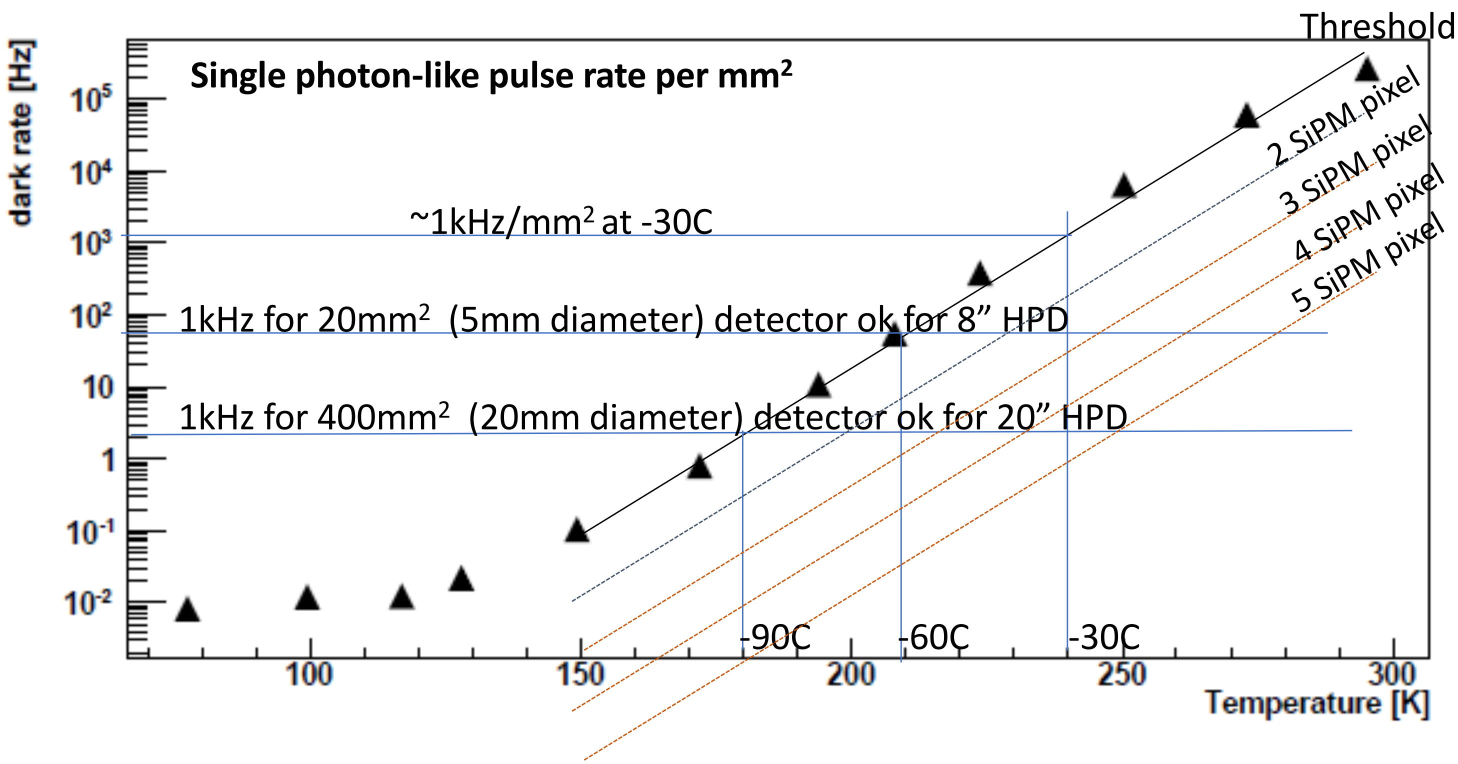
The shaper function here is not optimized, only a guess. Better resolution may be possible.





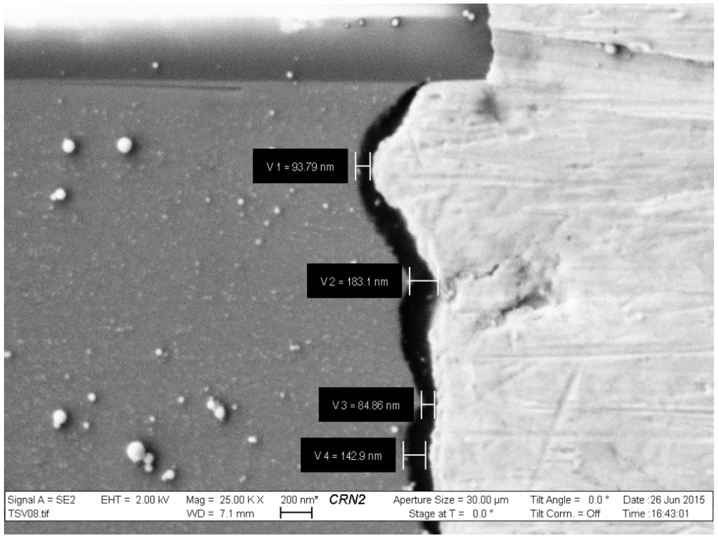
G.Visser (Indiana U.),
L. Fabris (ORNL)

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

TRIUMF

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, …