3-dimension integrated digital Silicon Photo-multiplier (3DdSiPM)

For astro-particle physics and beyond

F. Retière

TRIUMF

UNIVERSITÉ DE SHERBROOKE

GRAMS

Outline

- Motivations
  - Dark Matter search with DarkSide-20k
  - Neutrinoless double beta decay with nEXO
  - Quick review of other experiments
- Digital SiPMs the final stage of evolution for single photon detectors
- 3DdSiPM development in Canada
- Future prospect

The dark matter paradigm

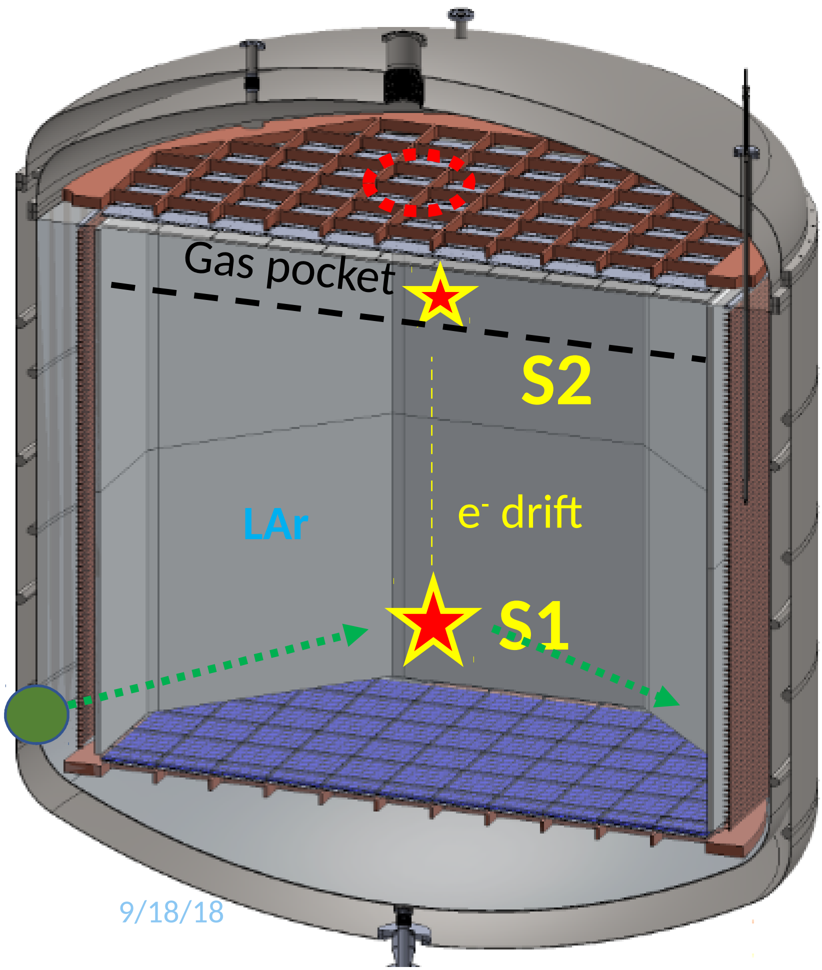
- Matter that is invisible
  - For electromagnetic and strong interactions at least
  - Could be one or more particle types
- And is massive enough to explain
  - Clumpiness of the universe as seen by CMB and baryonic matter distribution
  - Rotation velocity of stars within galaxies, dwarf galaxies around galaxies and galaxy clusters
    - Diffuse
  - And possibly bullet cluster

Searching for Dark Matter with liquid Argon

- Pros
  - Excellent “electron recoil” rejection
    - WIMP yield nuclear recoil
  - “cheap”
  - Ultra-low radioactivity with underground argon and distillation

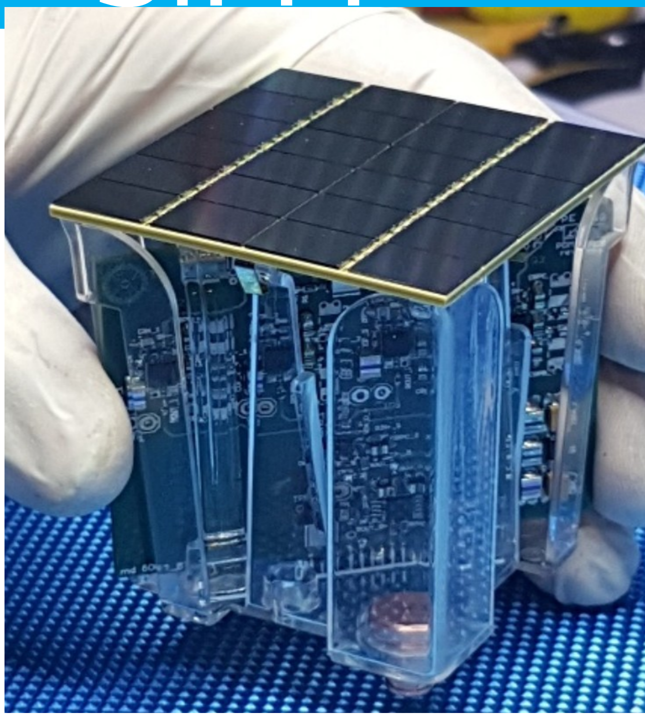
- Cons
  - Not that dense. Need about 3 times more mass than Xenon for same sensitivity
  - Scintillate at ~128nm
    - Requires wavelength shifting
    - Or new development
  - Large natural radioactivity: 39Ar beta decay

Dark Matter – DarkSide-20k

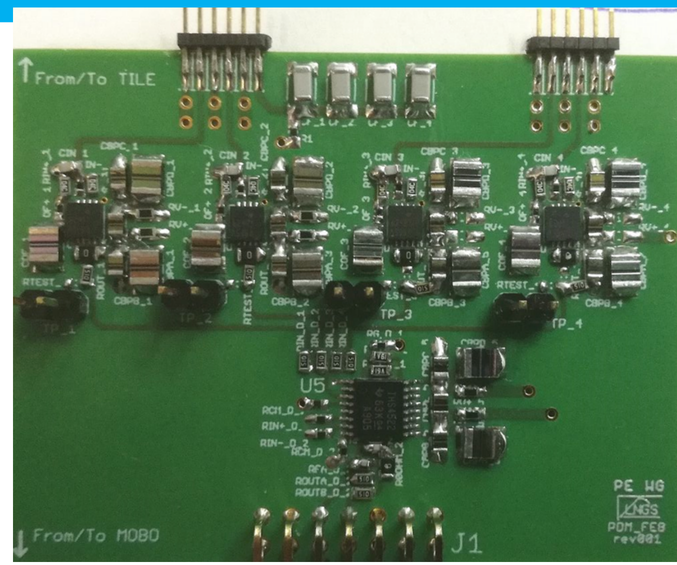


- Dark matter search experiment with 20t of LAr depleted in LAr
- 15 m2 of SiPM in TPC
  - + xxx m2 of SiPM in veto
- Blue light detection with WLS (TPB)
- Granularity not needed
- Small after-pulsing needed

DarkMatter – DarkSide-20k SiPM

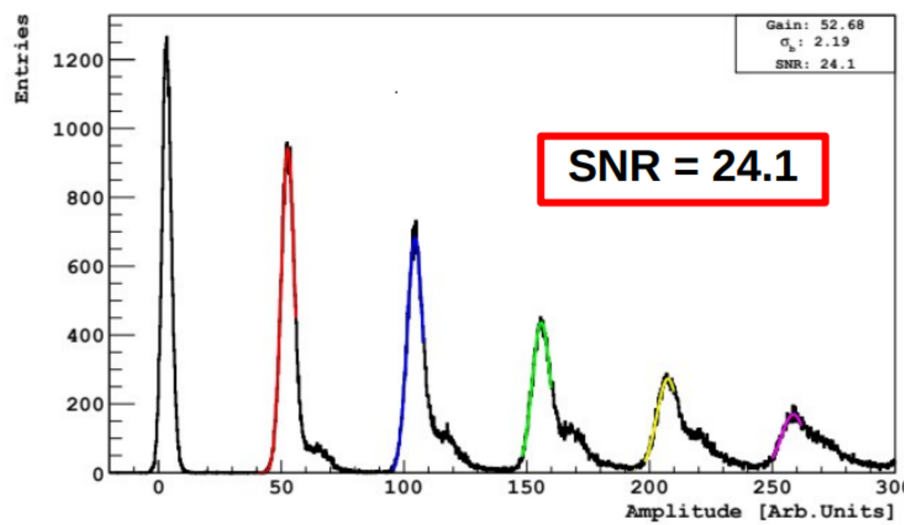


SiPM tile conectors



4 TIASs (6 SiPMs each)

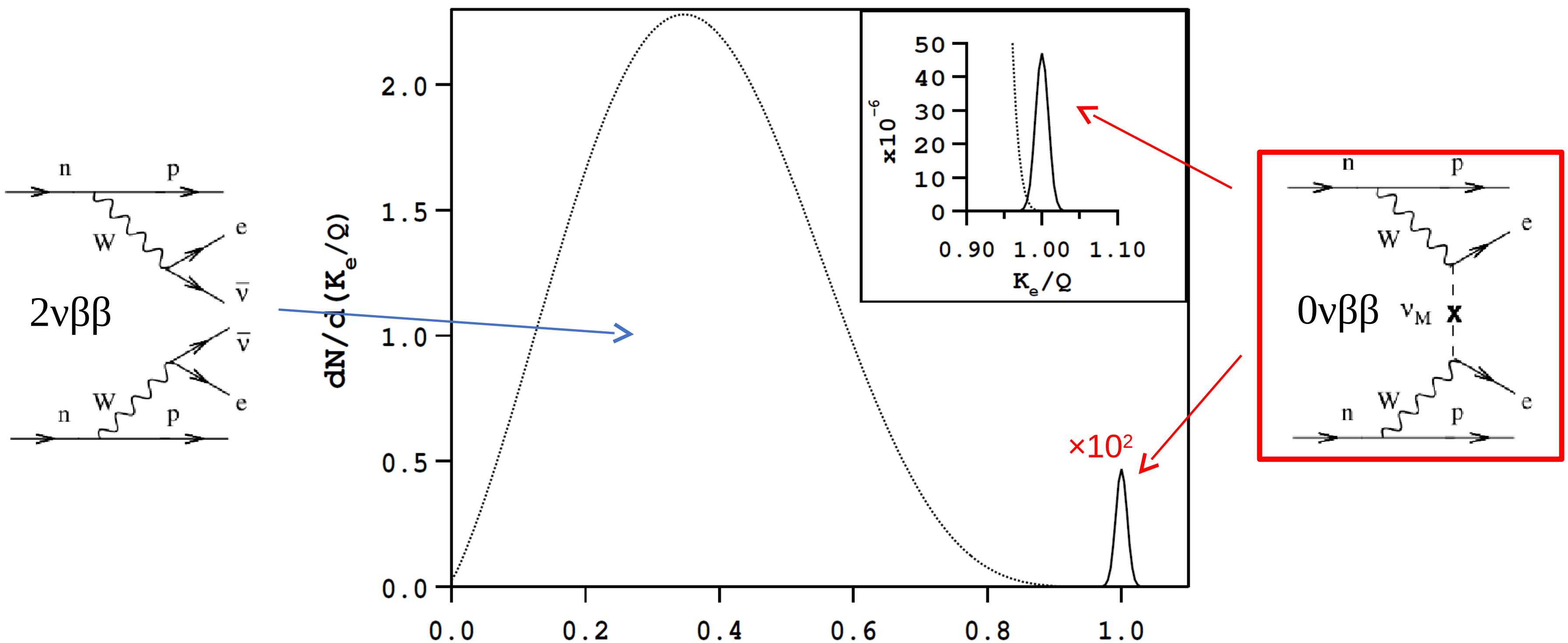
Summing stage



FBK NUV-HD triple dose

Single PE sensitivity for 25cm^2 chanı
enabled by operation at DV~7V

Neutrinoless double beta decay



kinetic energy K_e of the two electrons
in units of kinematic endpoint (Q)

The problem:

- ^{136}Xe 2νββ lifetime ✉ 2.165×10^{21} y
- ^{136}Xe 0νββ lifetime ✉ $> 3.7 \times 10^{25}$ y

The universe is 14×10^{9} y

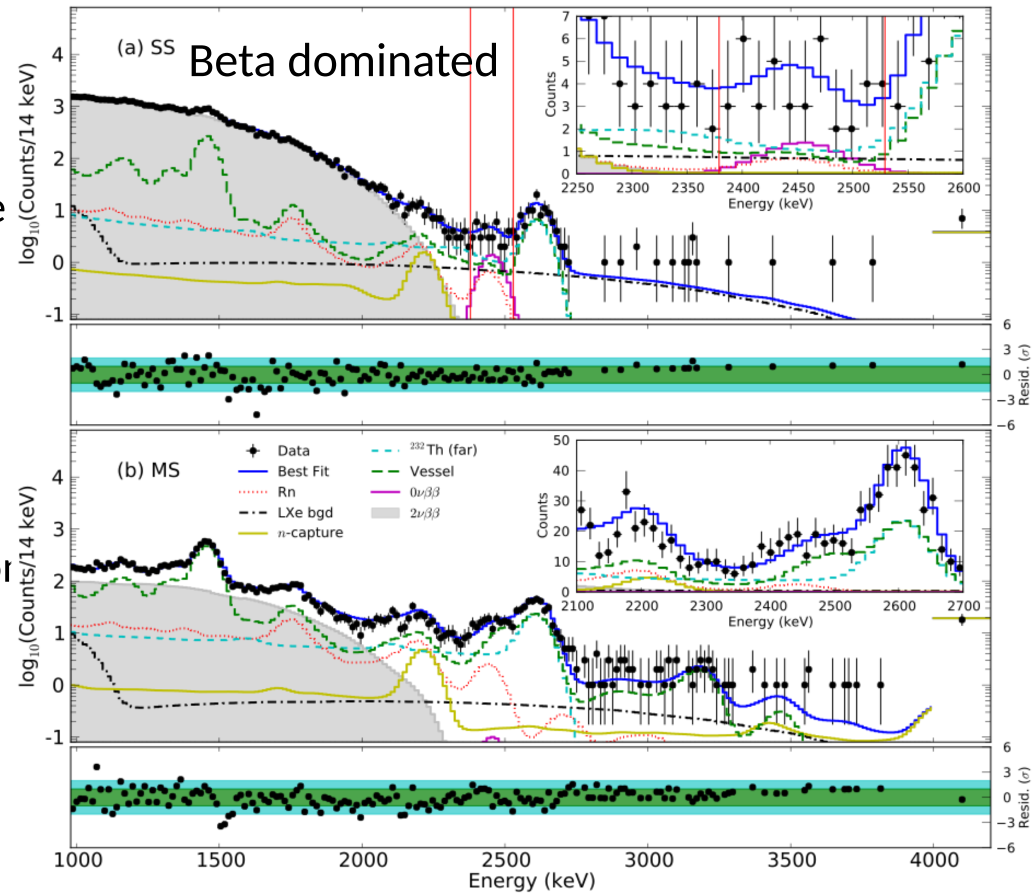
[arXiv:hep-ph/0611243]

TRIUMF · UNIVERSITÉ DE SHERBROOKE · 3IT · GRAMS

Neutrinoless double beta decay with liquid Xenon

- Pros
  - High-Z + monolithic + fine granularity
    - Gamma ray cannot penetrate without detection
  - Can be re-purified
- Cons
  - Fair energy resolution
    - Requiring combined ionization and scintillation detection
    - Requiring excellent light detection efficiency
  - Expensive

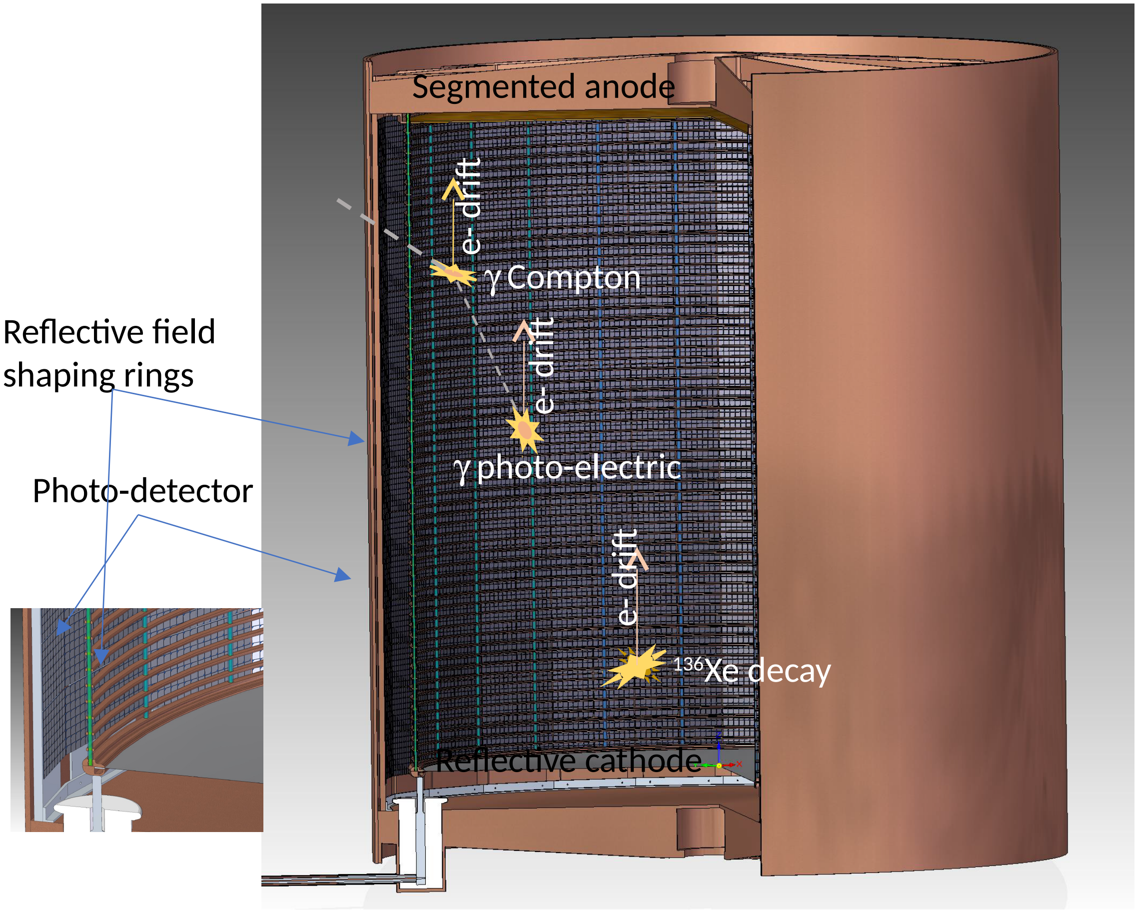
EXO-200



Gamma dominated

nEXO - 0νββ with LXe

- 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 · UNIVERSITÉ DE SHERBROOKE · 3IT · GRAMS

Present and future liquid Xenon detector

Experiment	Application	Status	Mass	Signal type	PD type
XMASS	DM	Operation	832kg	Scint.	PMT
XENON-1T	DM	Operation	1,042kg	Scint.+charge→elum.	PMT
LUX	DM	Operation	370kg	Scint.+charge→elum.	PMT
PANDAX-II	DM	Operation	580kg	Scint.+charge→elum.	PMT
XENON-nT	DM	Construction	6,000kg	Scint.+charge→elum.	PMT
LZ	DM	Construction	7,000kg	Scint.+charge→elum.	PMT
DARWIN	DM++	Design	50,000kg	Scint.+charge→elum.	R&D
EXO-200	$0\nu\beta\beta$	Operation	250kg	Scint.+charge	APD
nEXO	$0\nu\beta\beta$	Design	5,000kg	Scint.+charge→elum.	SiPM
RED-100	Coherent ν	Limbo?	200kg	Scint.+charge→elum.	SiPM
MEG-2	$\mu\to e\gamma$	Construction		Scint.	SiPM
XEMIS2	PET	Construction	200kg	Scint.+charge	PMT
PETALO	PET (TOF)	Concept	200kg	Scint.	SiPM

TRIUMF UNIVERSITÉ DE SHERBROOKE 3IT GRAMS

Present and future liquid Argon detector

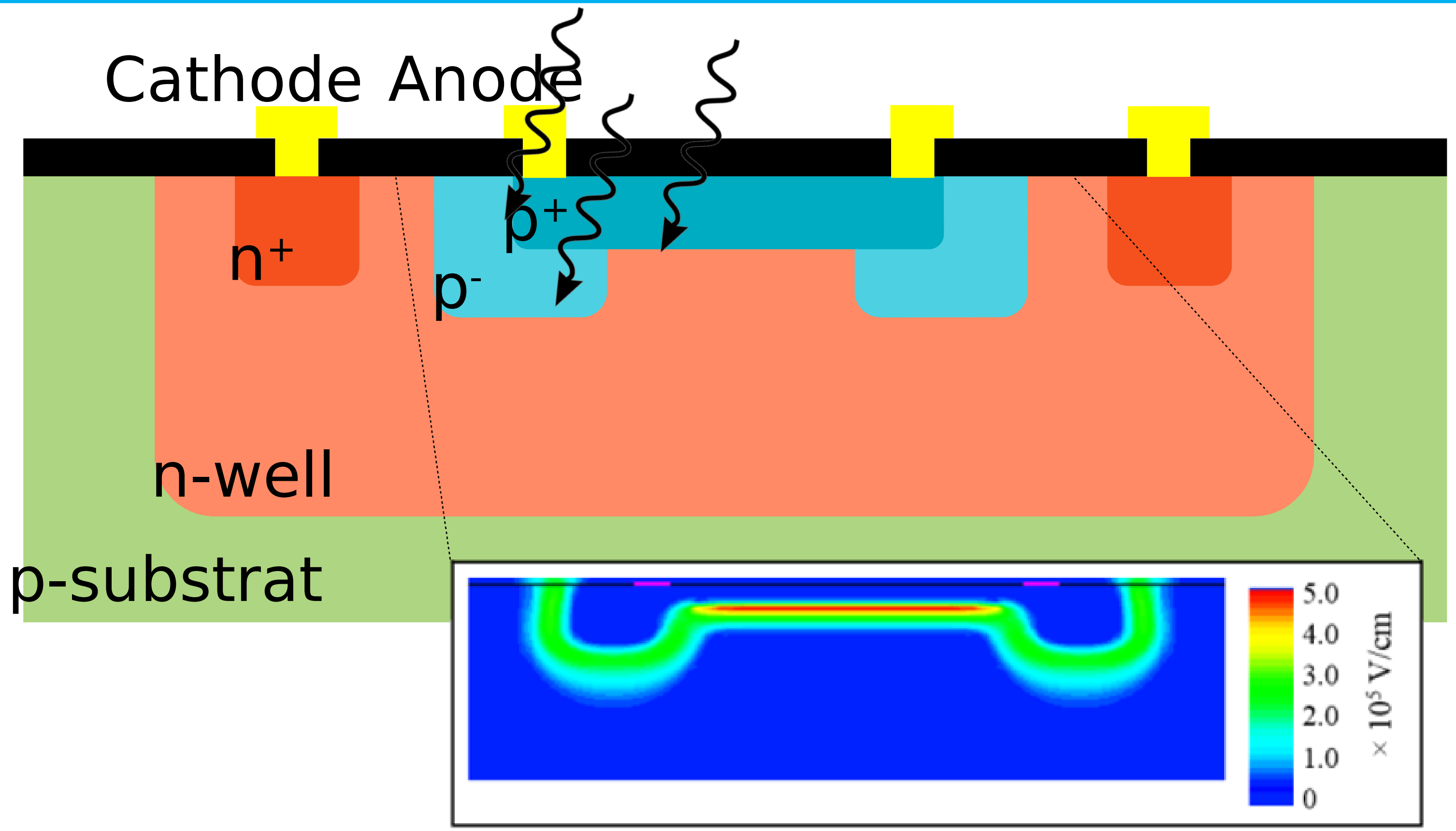
Experiment	Application	Status	Mass	Signal type	PD type
DarkSide-50	DM	Operation	50kg	Scint+charge→elum	PMT
DEAP-3600	DM	Operation	3,300kg	Scint	PMT
DarkSide-20k	DM	Design	20,000kg	Scint.+charge→elum	SiPM
DEAP-300t	DM	Concept	300,000kg	R&D	R&D
ANKOK	DM	Design	?	?	SiPM
GERDA veto	$0\nu\beta\beta$	Operation		WLS fiber → SiPM	SiPM
CENNS-10	Coherent ν	Construction	10kg	Scint	PMT
SBND	ν oscillation	Design	112,000kg	Scint+charge	PMT
microBOONE	ν oscillation	Operation	80,000kg	Scint+charge	PMT
ICARUS	ν oscillation	Construction	760,000kg	Scint+charge	PMT
ProtoDUNE-SP	ν oscillation	Operation	77,000kg	Scint+charge	LG+SiPM
ProtoDUNE-DP	ν oscillation		10,000kg	Scint+charge→elum	PMT
DUNE module	ν osc. +	Concept	17,000t	Scint+charge	SiPM

SiPM in LXe and LAr, sorted by photo-detection area

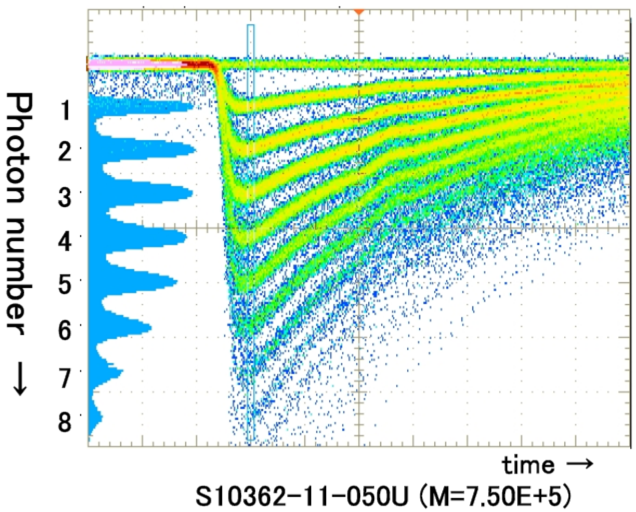
Experiment	Type	Photo-detector solution	Area
MEG-II	LXe	Hamamatsu VUV2	0.6 m2
GERDA – veto	LAr		
nEXO	LXe	FBK, Hamamatsu, 3DdSiPM	~5 m2
DARWIN	LXe	SiPM is one option	~8 m2
DarkSide-20k	LAr	FBK NUV-HD triple dopant	15 m2
DEAP-300t	LAr	SiPM is baseline option	~200 m2
Proto-DUNE-SP	LAr	Light guide or trap + SiPM	
DUNE	LAr	Light guide or trap + SiPM	

Switching to SiPMs because of lower radioactivity (nEXO, GERDA) or due to difficulty to operated PMTs in LAr (DarkSide-20k)

Single Photon Avalanche Photo-Diode (SPAD)



SPAD array = Silicon Photo-multipliers



Parameters for T2K MPPC

C_{pixel} = 90 fF

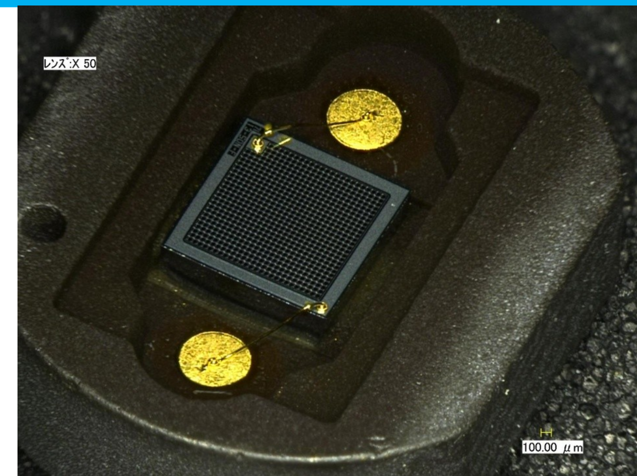
R_{quench} = 150 kΩ

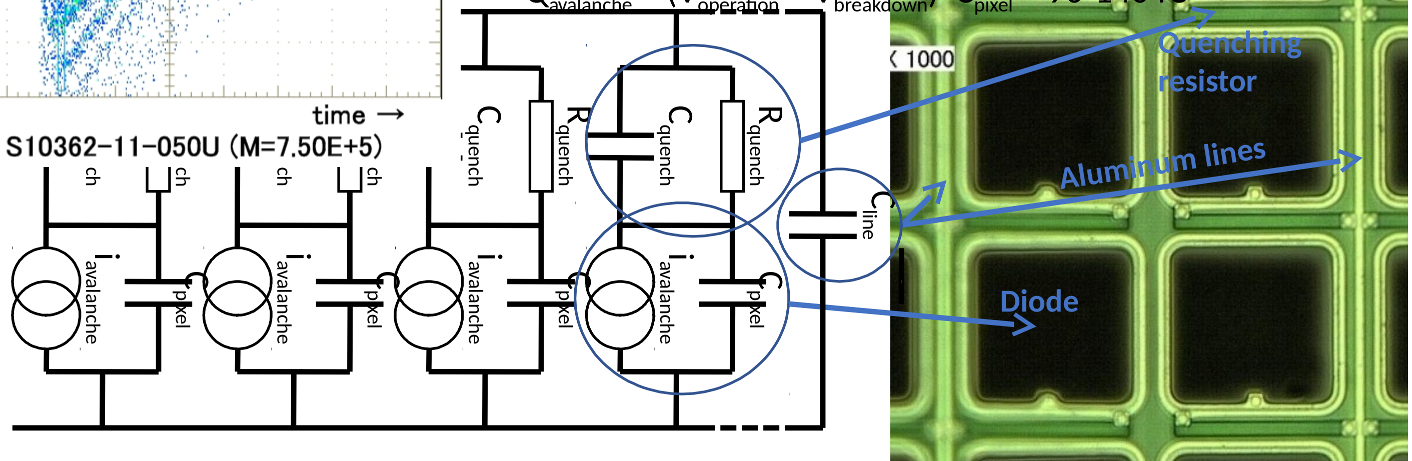
C_{quench} ~ 4 fF (parasitic)

C_{line} ~ 10 pF (parasitic)

$I_{avalanche} = (V_{operation} - V_{breakdown}) / R_{quench}$ ~ 5-10 µA

$Q_{avalanche} = (V_{operation} - V_{breakdown})\ C_{pixel}$ ~ 90-140 fC





TRIUMF UNIVERSITÉ DE SHERBROOKE 3IT GRAMS

SiPM vs PMT. Radioactivity

Newer ICPMS measurements pending

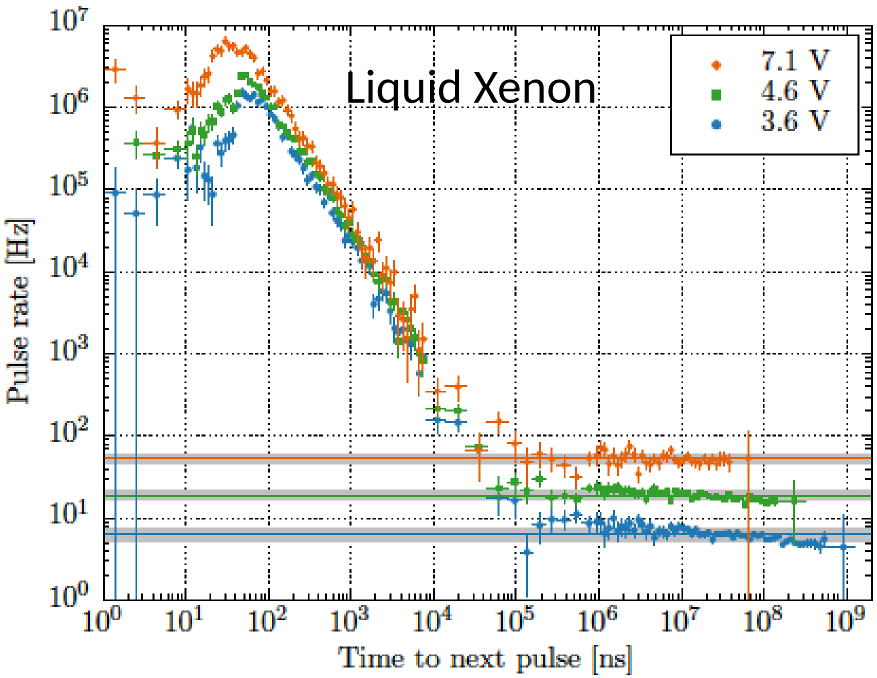
	^{238}U	^{232}Th	^{40}K
Prelim. nEXO requirements for 4m^2	< 0.1 nBq/cm^2	<1 nBq/cm^2	< 10 nBq/cm^2
FBK SiPM (bare wafers) [A]	<0.4 nBq/cm^2	~0.6 nBq/cm^2	~3 nBq/cm^2
Hamamatsu MPPC (packaged) [B]	<7 µBq/cm^2	<3 µBq/cm^2	<3 µBq/cm^2
SensL SiPM (packaged) [C]	<1.1 mBq/cm^2	<33 µBq/cm^2	<69 µBq/cm^2

[A] Counting at U.Alabama after nuclear activation at MIT shown at this meeting
[B] Hamamatsu Ge counting in house. Assume 300µm SiPM thickness. Confidential
[C] NEXT Ge counting. http://arxiv.org/abs/1411.1433

PMT type	Normalized activity [mBq/cm^2]						Ref.
	^{238}U	^{226}Ra	^{228}Th	^{235}U	^{40}K	^{60}Co	
R11410-21	< 0.4	0.016(3)	0.012(3)	0.011(3)	0.37(6)	0.023(3)	this work
R11410-20	< 0.56	< 0.03	0.028(6)	< 0.025	0.37(6)	0.040(6)	this work
R11410-10	< 3.0	< 0.075	< 0.08	< 0.13	0.4(1)	0.11(2)	[20]
R11410-10 (PandaX)	–	< 0.02	< 0.02	0.04(4)	0.5(3)	0.11(1)	[12]
R11410-10 (LUX)	< 0.19	< 0.013	< 0.009	–	< 0.26	0.063(6)	[21]
R11410	1.6(6)	0.19(2)	0.09(2)	0.10(2)	1.6(3)	0.26(2)	[20]
R8778 (LUX)	< 1.4	0.59(4)	0.17(2)	–	4.1(1)	0.160(6)	[21]
R8520	< 0.33	0.029(2)	0.026(2)	0.009(2)	1.8(2)	0.13(1)	[20]

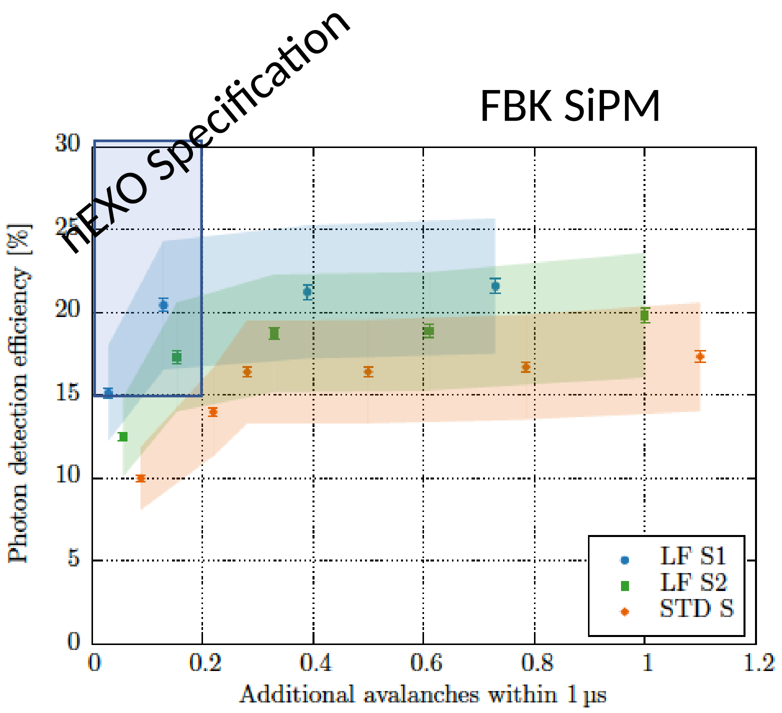
SiPM vs PMT. Nuisance

- Gain fluctuations much lower for SiPMs
- Dark noise
  - PMT ~ 0.1-1Hz/mm2
  - Best SiPM
    - 50kHz/mm2 at 20C
    - 0.1-1Hz/mm2 at LXe temp.
    - 0.01-0.1Hz/mm2 at Lar temp.
- After-pulsing
  - Comparable ~20% at reasonable voltage
  - SiPM AP can be very slow when cold



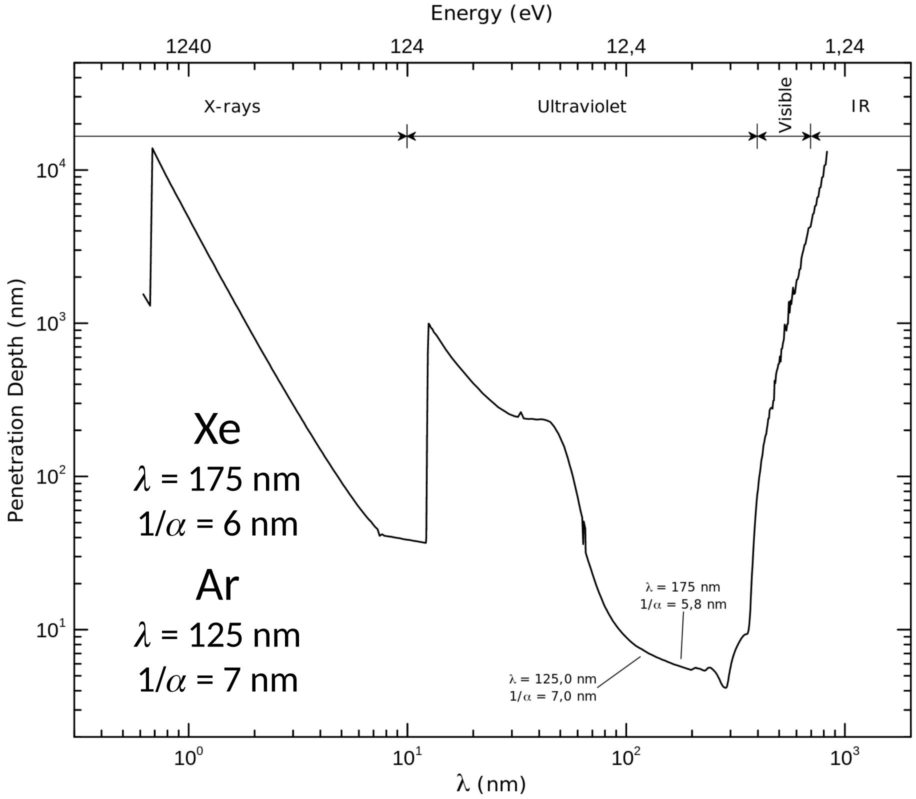
SiPM vs PMT. Efficiency

- At 175nm
  - Best PMT ~ 35%
  - Best SiPM ~ 20%
    - But working on it
- At 420nm (wavelength shifter)
  - Best PMT ~ 35%
  - Best SiPM ~ 60%

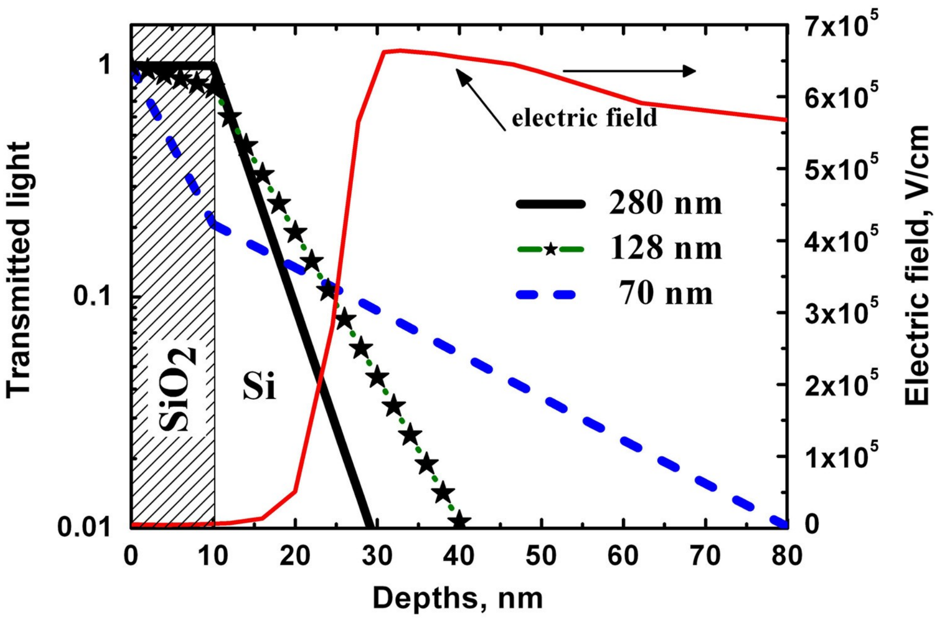


VUV light detection challenges

- Reflections



- Shallow absorption depth

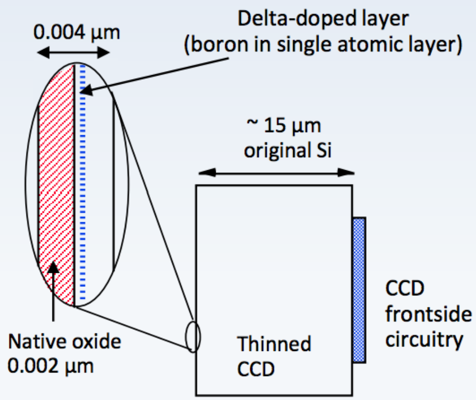


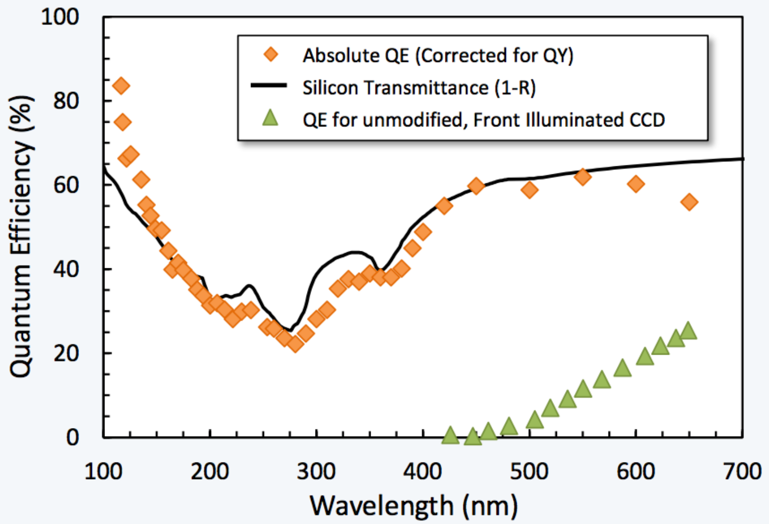
TRIUMF UNIVERSITÉ DE SHERBROOKE 3IT GRAMS

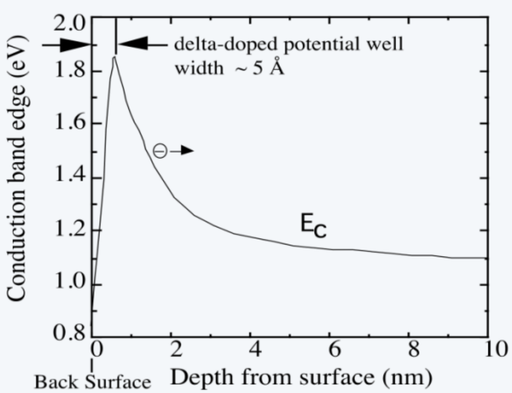
Shallow junction for VUV CCD

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







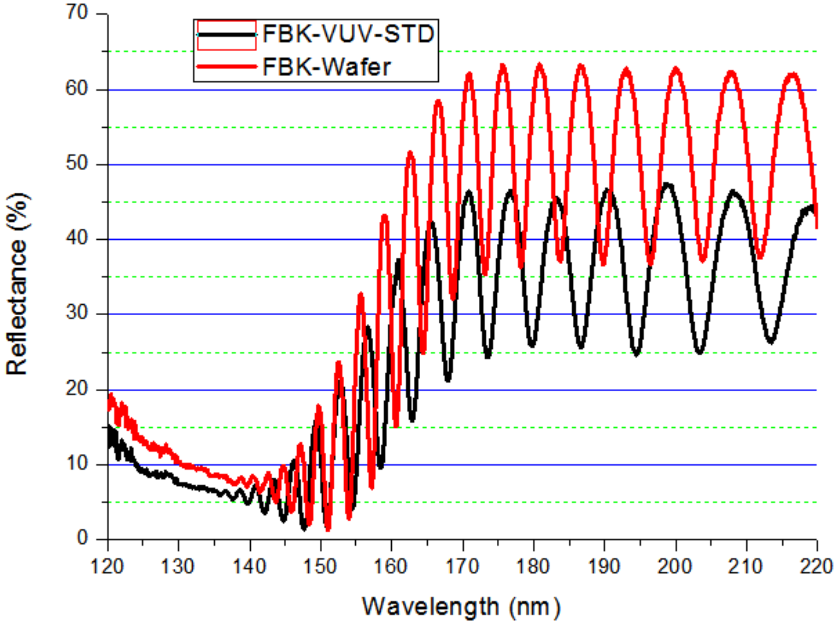
LBNL

TRIUMF UNIVERSITÉ DE SHERBROOKE 3IT GRAMS

SiPM reflectivity

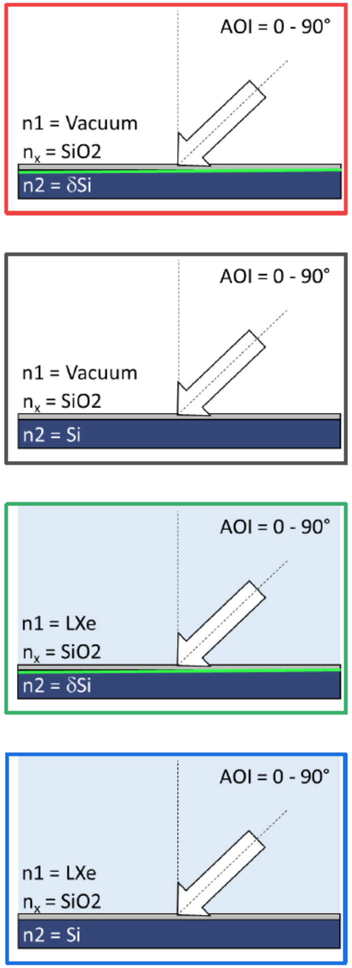
- VUV light can reflect on photo-detectors
- This is a serious issue for silicon based photo-detectors

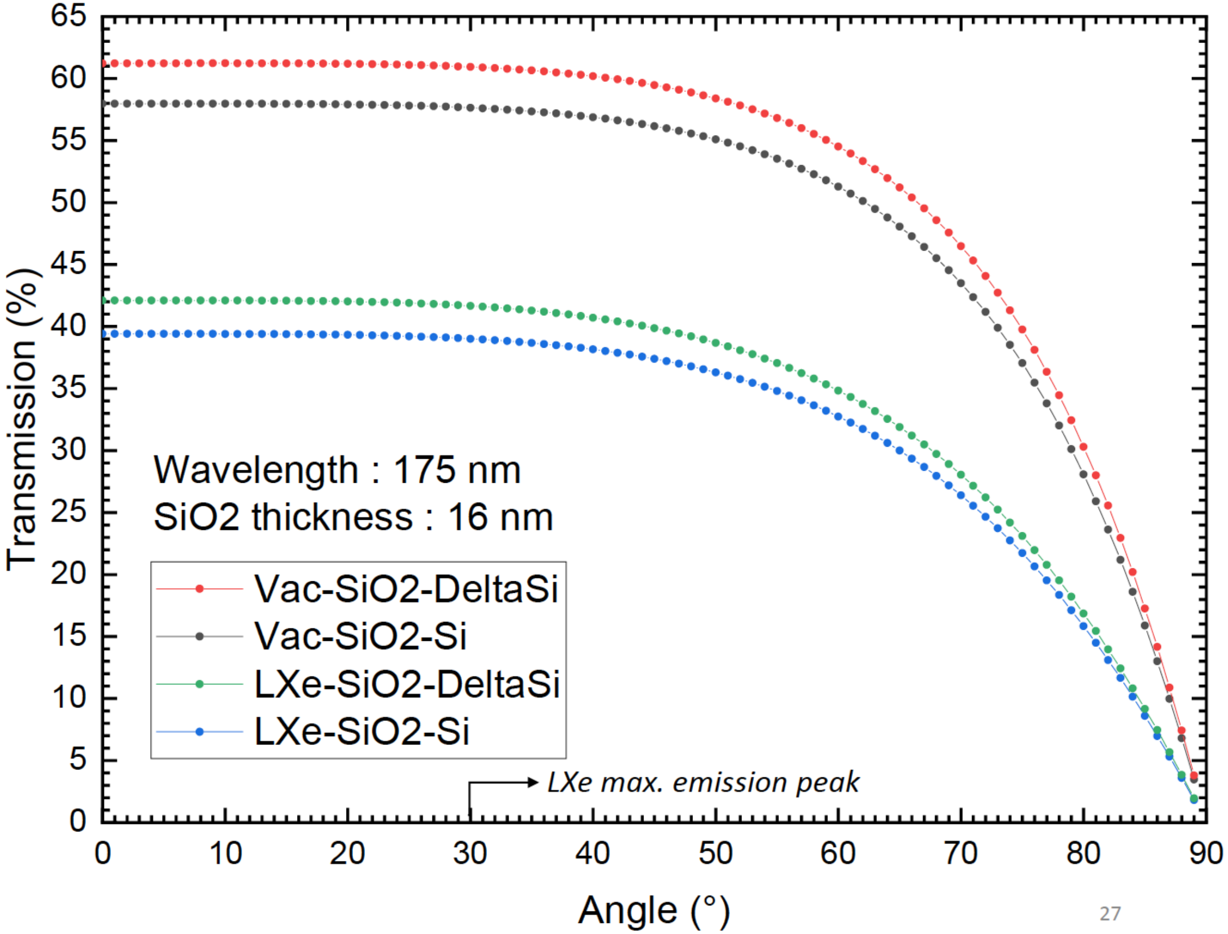
10 degree specular reflectance
For FBK SiPM and bare wafer



Device	Specular (177nm, 10 degree)	Diffuse(193 nm)
FBK-VUV-STD	35%	11.5%
FBK-VUV-LF	40%	12.3%
FBK-RGB	38%	17%
FBK wafer*	50%	0.16%

Si-SiO2 stack does not work in LXe



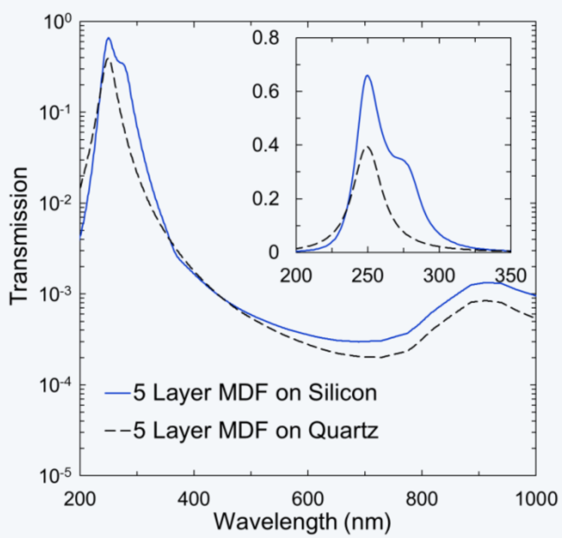


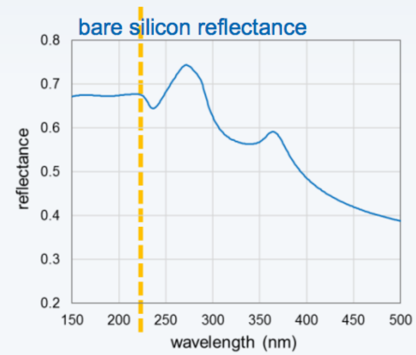
F. Vachon (Sherbrooke)

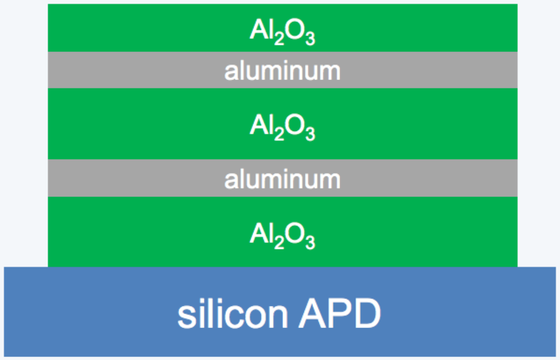
Anti-reflective coating

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



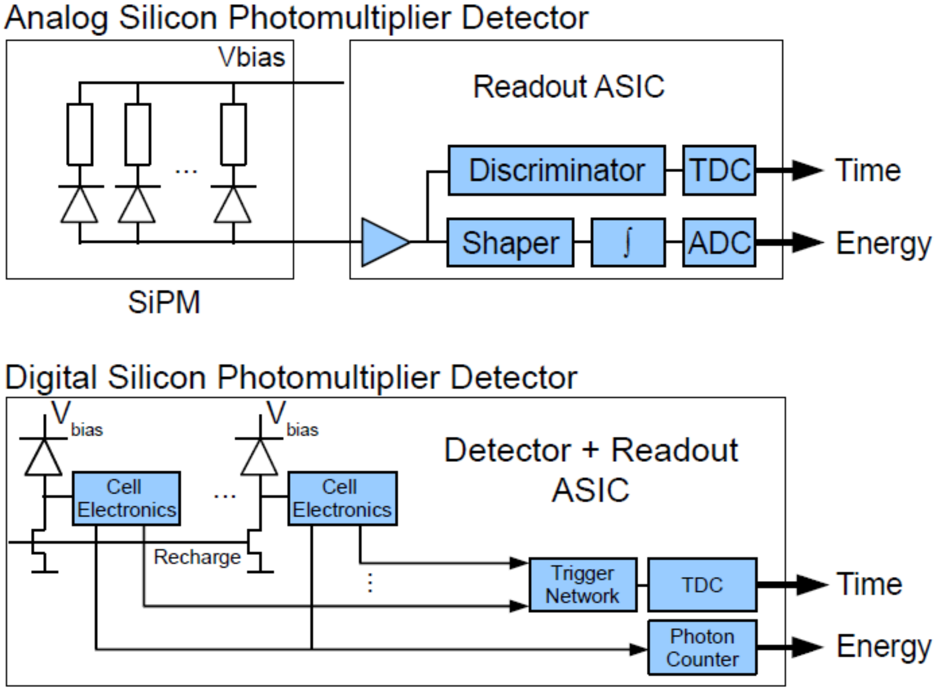




The digital SiPM concept

PHILIPS

Digital SiPM – The Concept



IEEE Nuclear Science Symposium / Medical Imaging Conference, Orlando, FL October 28, 2009

2009

Photon to bit conversion

- As opposed to photon to analog to bit conversion

Quenching scheme

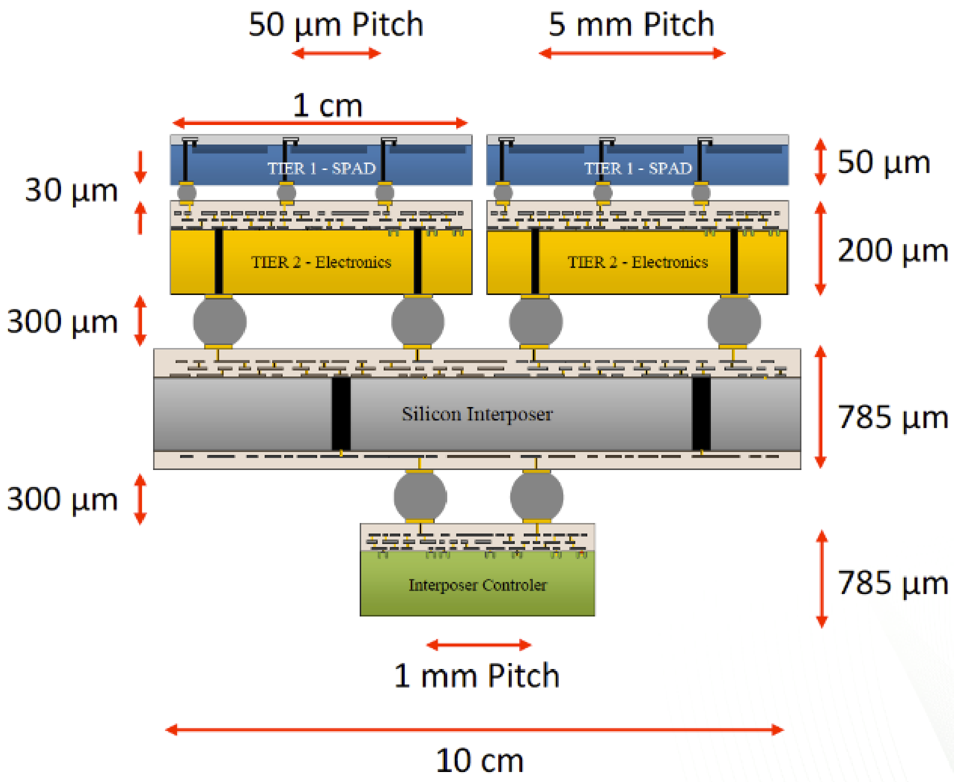
- Current sense per diode
- Quench upon discharge
  - Control quench time
- Time tag and count the avalanche

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

1a 1b 1c 1d

The dream 3DdSiPM for nEXO



- In nEXO 100ns sampling rate is sufficient
- Main motivation
  - Lowest power dissipation
  - Ease of integration
  - No after-pulsing
- Main challenge
  - Achieving >15% PDE at 175nm (the reason why we are here!)

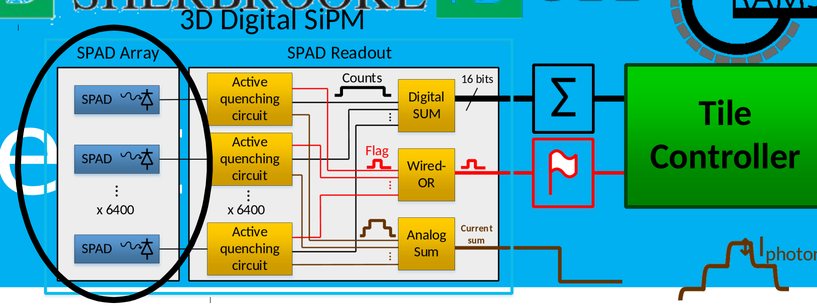
Update on 3DdSiPM readout ASIC and cryogenic CMOS modeling

Serge A. Charlebois,
Tommy Rossignol, Nicolas Roy, Gabriel St-Hilaire,
Nicolas Viscogliosi, Caroline Paulin,
Leo Caussan, Frédéric Vachon, Samuel Parent,
Jean-François Pratte
Interdisciplinary Institute for Technological Innovation (3IT),
Université de Sherbrooke

September 2018

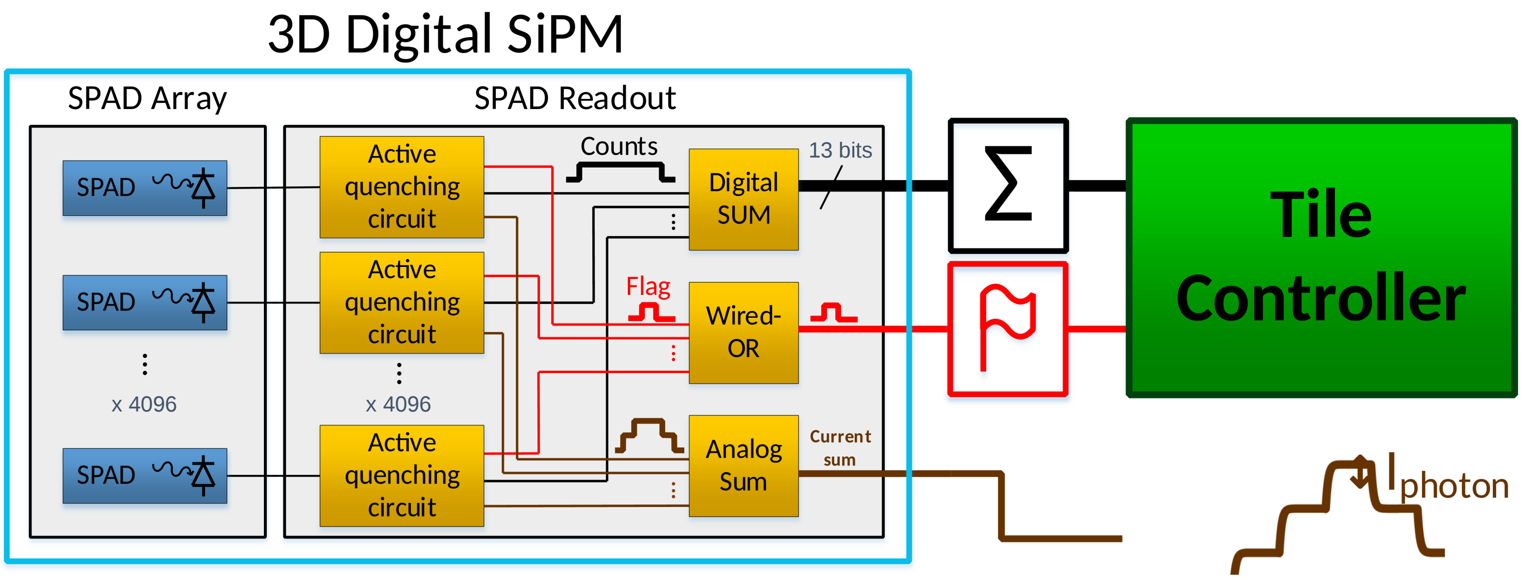
TRIUMF

SPAD development



- Generation 1. Die level bonding
  - Functional SPAD
  - Fairly high dark noise and some flashing SPADs
- Generation 2. Currently funded
  - Testing with 2D single SPAD
  - 3D SPAD array in 2019
- Generation 3.
  - Still more or less a dream

CMOS Readout for 3DdSiPM - Architecture

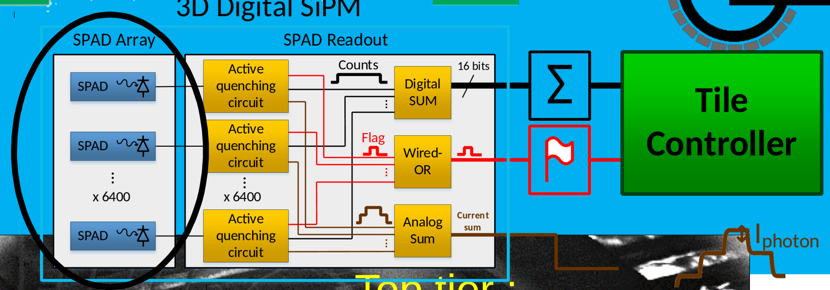


- Digital Sum
- Wired-OR (first detected photon Flag)
- Analog Sum

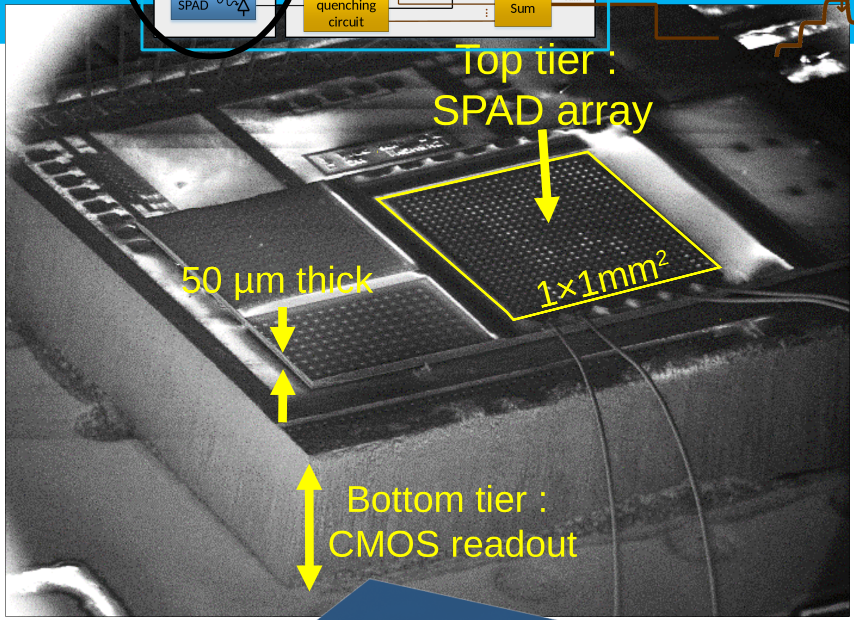
TRIUMF

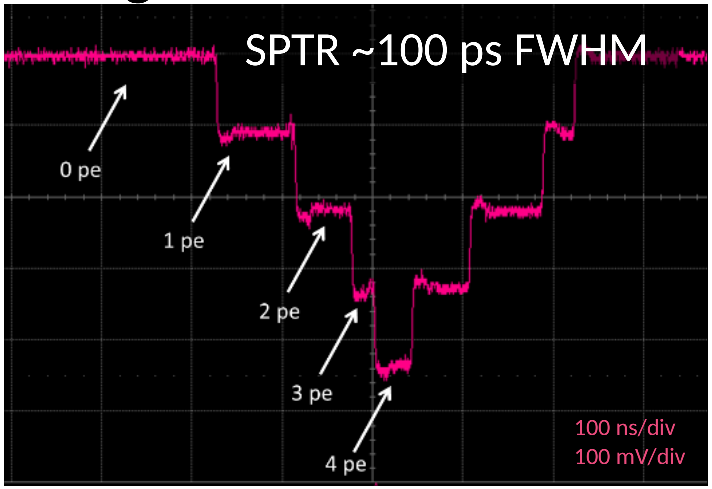
UNIVERSITÉ DE SHERBROOKE 3IT GRAMS

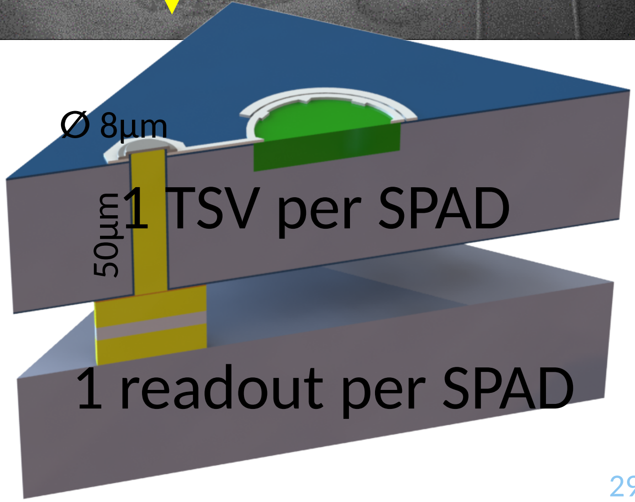
Sherbrooke's 3D digital SiPM. Gen 1



- 1st proposal in 2010*
- Prototype completed
- Embedded features
  - adjustable hold-off time
  - adjustable dynamic range
  - single SPAD enable/disable

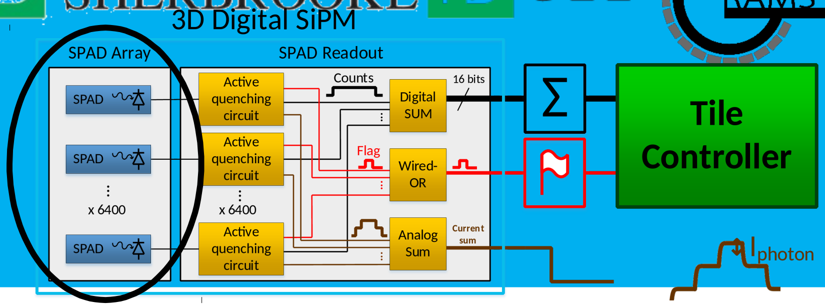




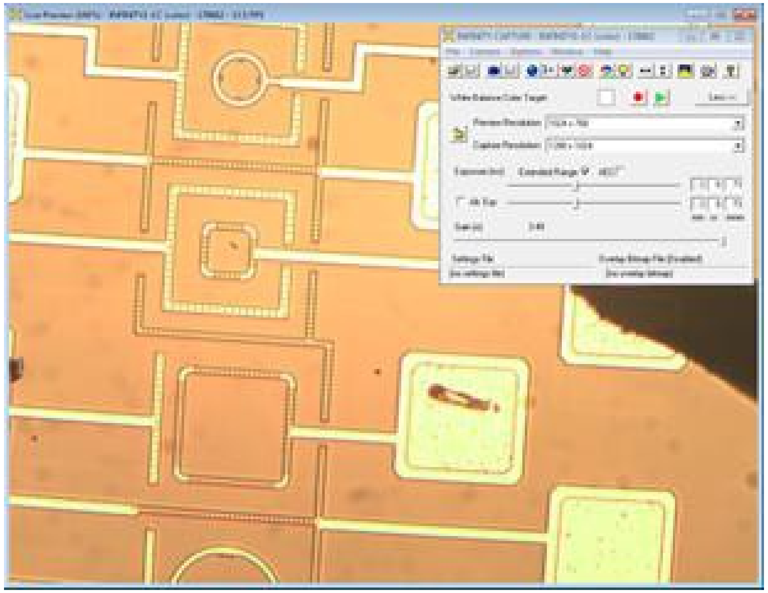


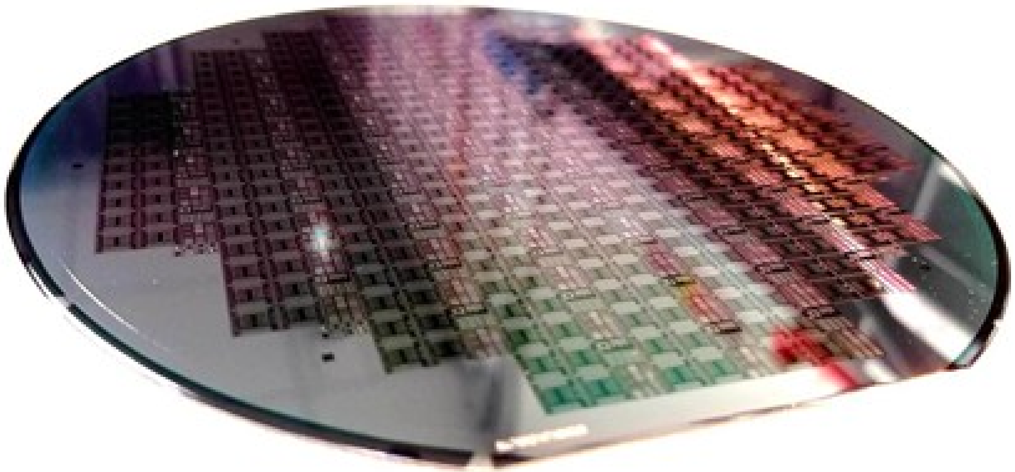
*Pratte et al. « High sensitivity fully digital photodetector », 3D Systems Integration Conf. 2010 IEEE Inter. (3DIC), Germany

SPAD Gen 2.

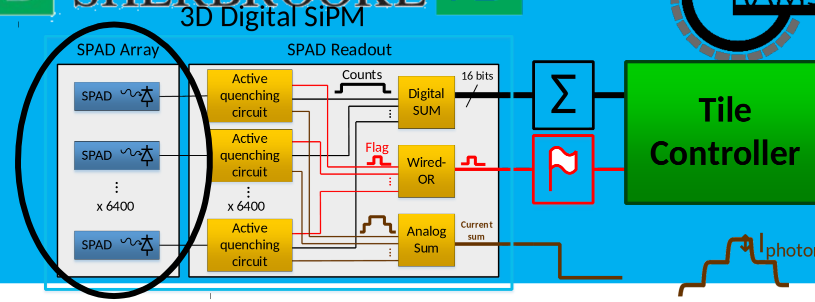


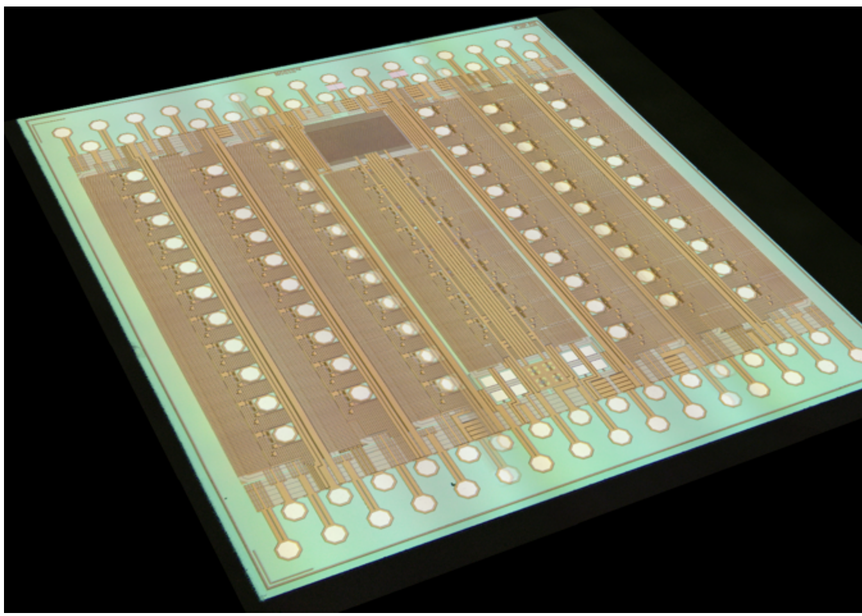
- Single SPAD testing



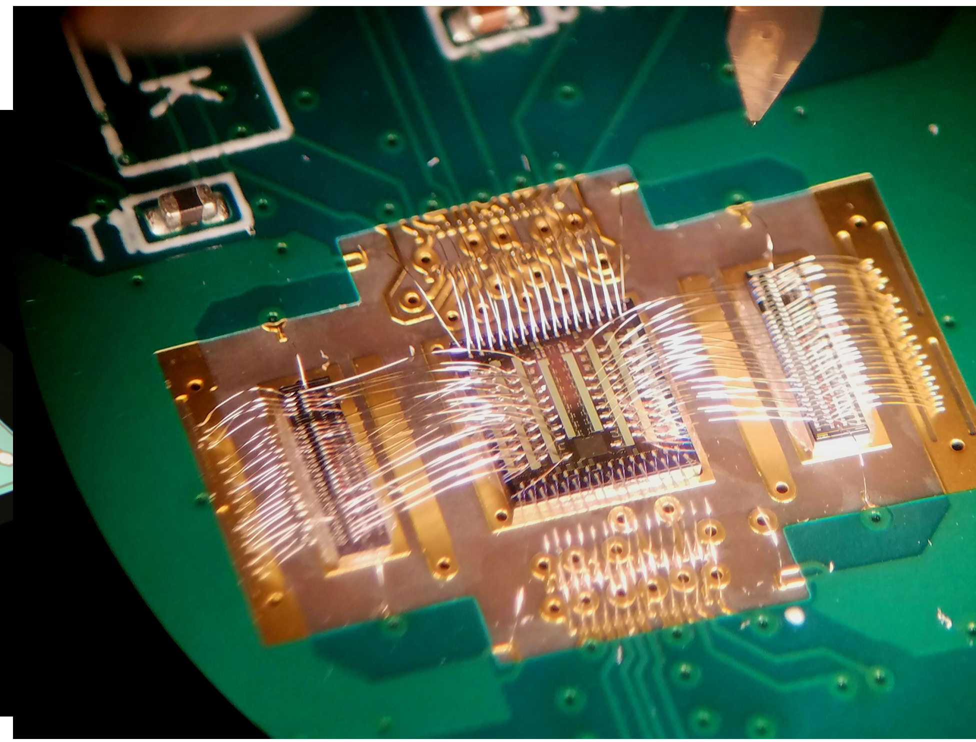


Chipprobe testing single SPADs



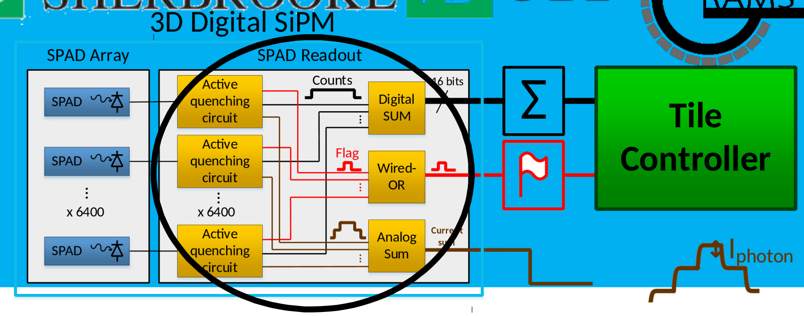


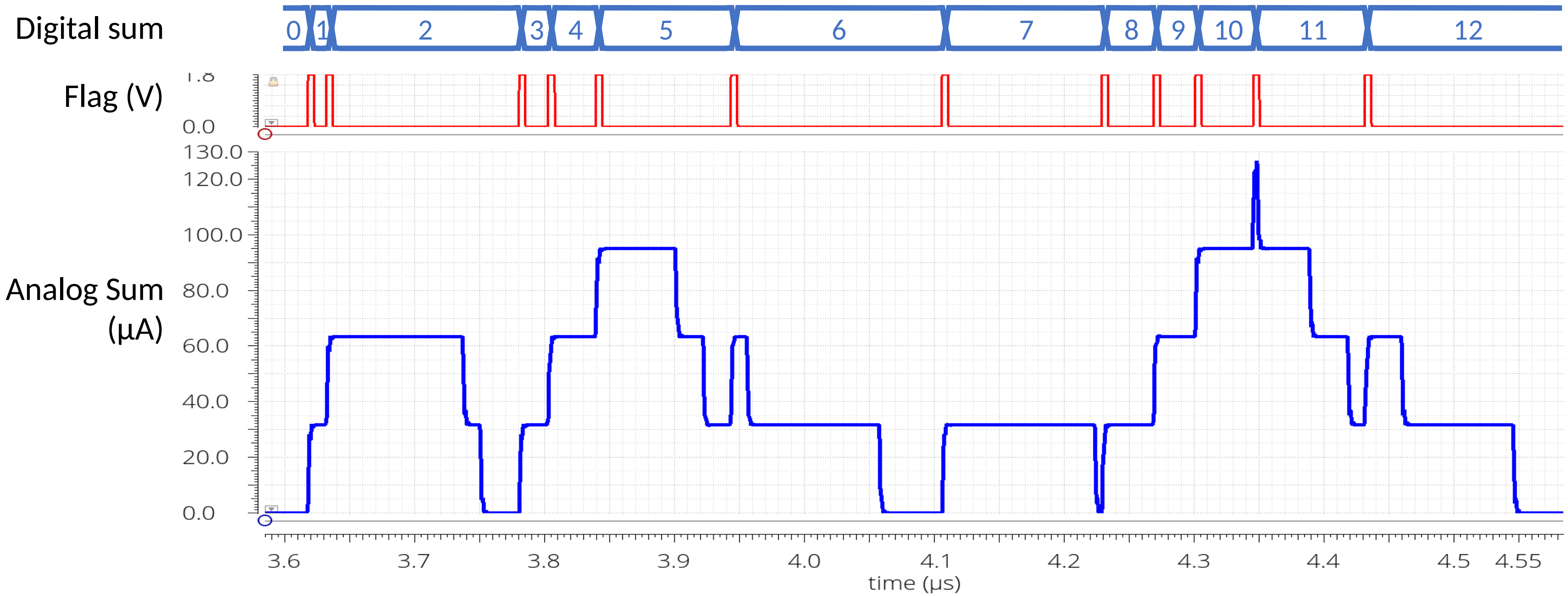
Enhenced micrograph of the chip.
Top-bottom: I/O pads
Left-right: pads to external SPADs



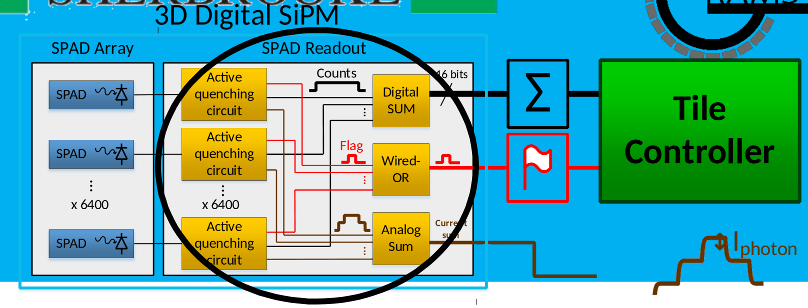
Promising performances achieved

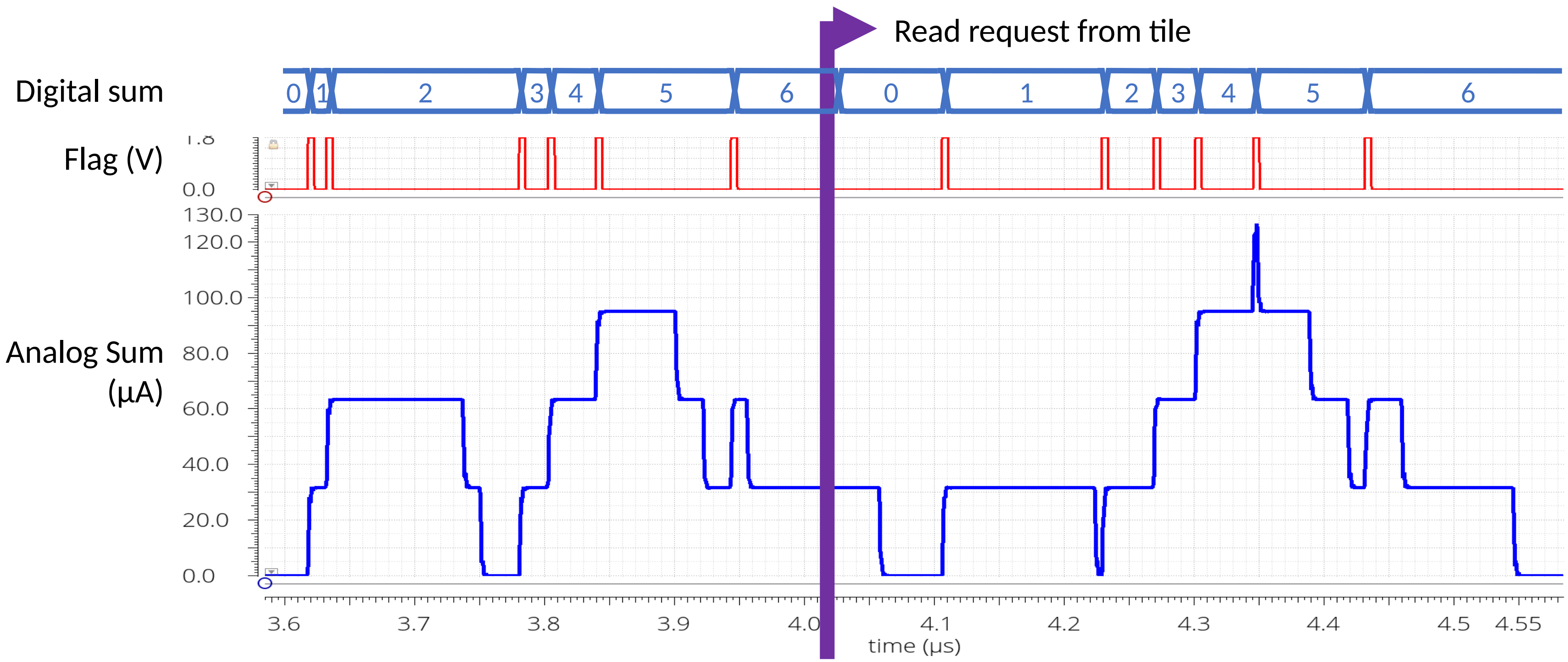
CMOS Readout Simulated Outputs



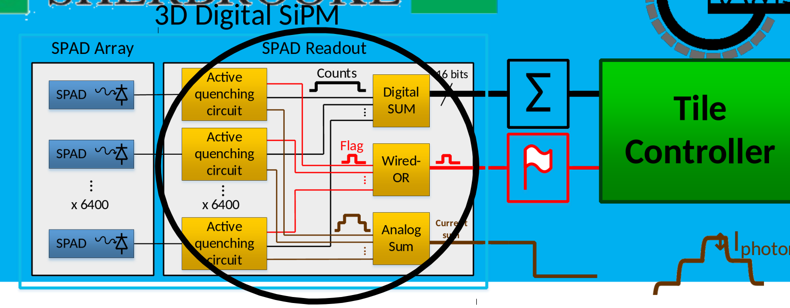


CMOS Readout Simulated Outputs





CMOS Readout for 3DdSiPM

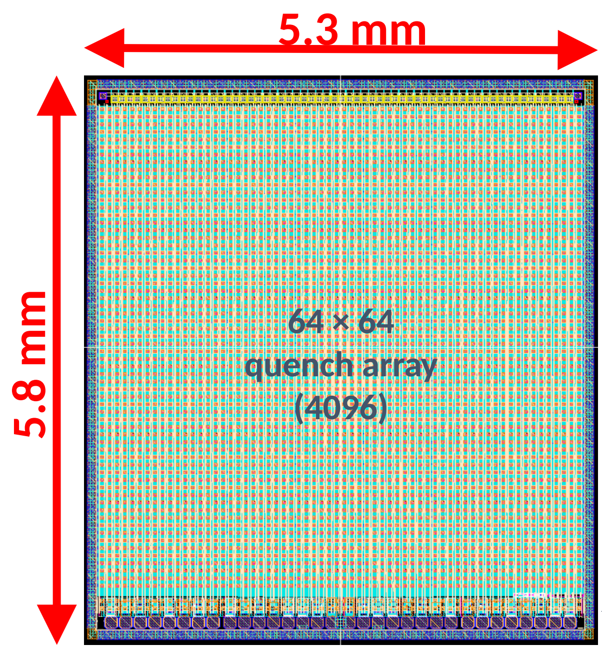


Advancement

- ✓ Design Review (Winter 2018)
- ✓ ASIC architecture completed
- ✓ Floorplan
- ✓ Digital-on-Top design flow
- ✓ Test bench simulations
- ✓ Top level simulations
- ✓ Submitted Sept. 2018

On going

- ❑ Physical test bench (PCBs, codes, etc.)
- ❑ ASIC Characterization (start Nov. 2018)



- **Active area: 5 × 5 mm²**
- **ASIC Fill Factor: 82.7 %**

One row of SPADs to provide for functional testing

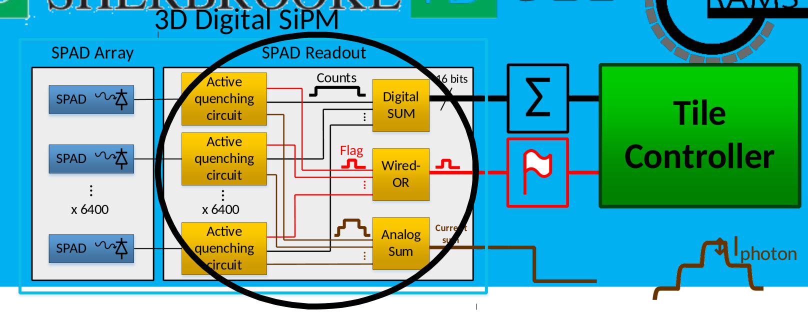
13 bits digital sum

Low jitter wired or

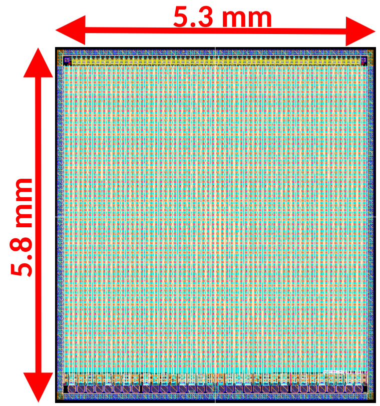
Analog monitor

32 I/O pads in single row

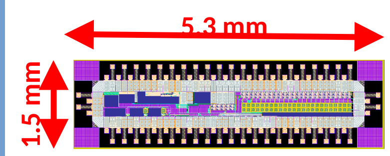
Specifications



nEXO mode	-	Event driven
	-	Flags the controller to signal counts
	-	Transmission on request by controller
	-	Integration time 200 ns (10 ns – 1 µs)
	-	Analog monitor
LAr mode	-	Synchronous, short and long frames to allow PSD (Pulse Shape Discrimination) in LAr
	-	10 ns minimum frame, multiples of for long frames
	-	128 FIFO depth for transmission on request
	-	Flags the controller to signals counts
	-	Flag jitter <500 ps for time-of-flight reconstruction
Test structures ($7.95\ mm^2$)	-	All elemental components of the design have been submitted in a test chip without digital interface to allow tests of:
	-	Quenching circuit w/wo SPADs
	-	2D SiPM with analog monitor
	-	Timing jitter



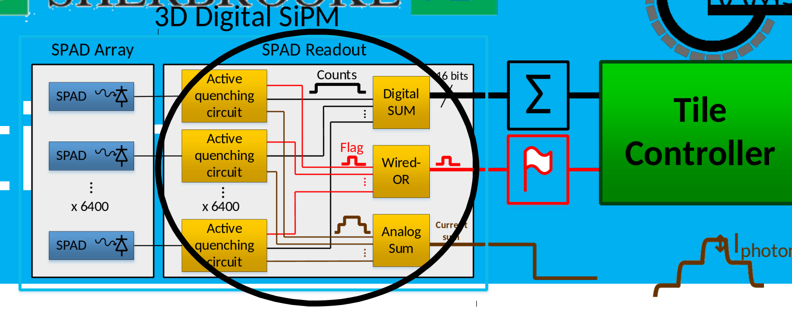
Active area: $5 \times 5\ mm^2$



Serge.Charlebois@USherbrooke.ca

TRIUMF · UNIVERSITÉ DE SHERBROOKE · 3IT · GRAMS

Power consumpti

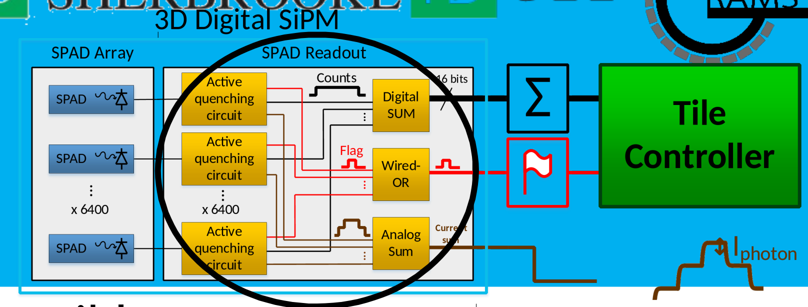


- The proposed 3DdSiPM has a total area of 1 cm^2 and is composed of three modules.
  - 40 000 quenching circuits to individually quench the SPAD
  - A wired-or for the flag
  - A parallel adder for the sum
- Power consumption of the 3DdSiPM depends on the event rates
  - Power consumption evaluated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

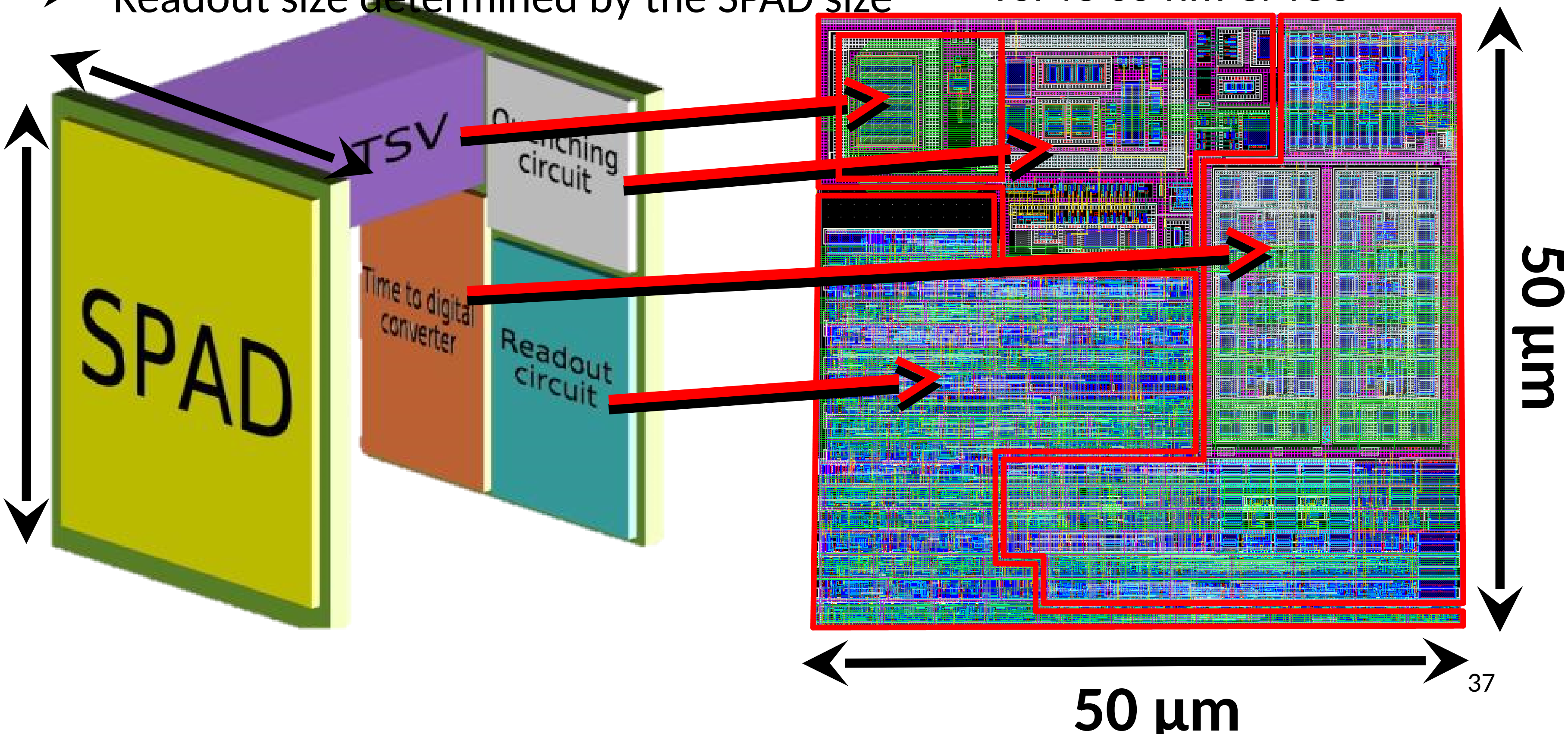
UNIVERSITÉ DE SHERBROOKE 3IT GRAMS

CMOS for high speed applications



- Need to timestamp as many prompt photons as possible
  - 1 TDC per SPAD
- 3D SPAD readout to eliminate timing skew
  - Readout size determined by the SPAD size

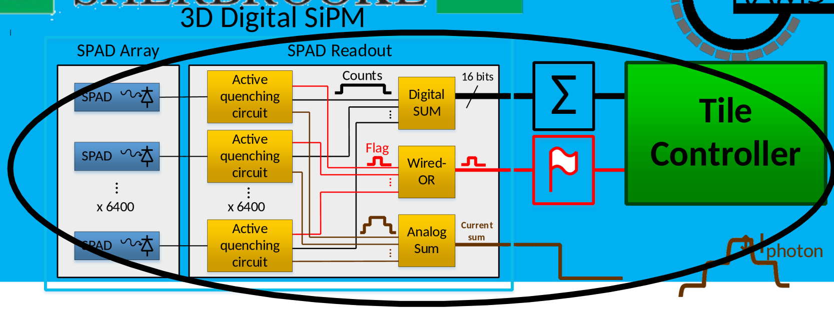
TSMC 65 nm CMOS



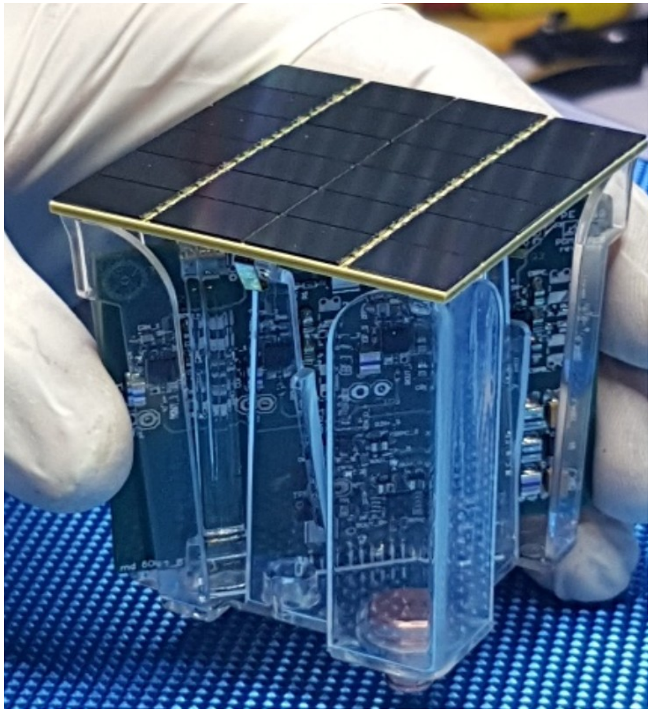
TRIUMF

UNIVERSITÉ DE SHERBROOKE 3IT GRAMS

Tile assembly



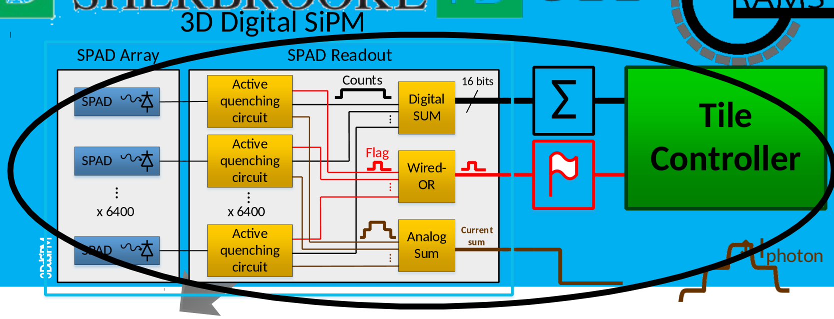
- DarkSide ”tile”



- nEXO tile
  - Radioactivity constraints greatly limit material for “PCB”
    - Two options: quartz or silicon
  - Silicon interposer is ideal
    - Low radioactivity
    - Thermal expansion match
    - Interest in the industry
      - Institute of MicrElectronics (IME) in China
      - Fraunhoffer in Germany

TRIUMF UNIVERSITÉ DE SHERBROOKE 3IT GRAMS

Tile



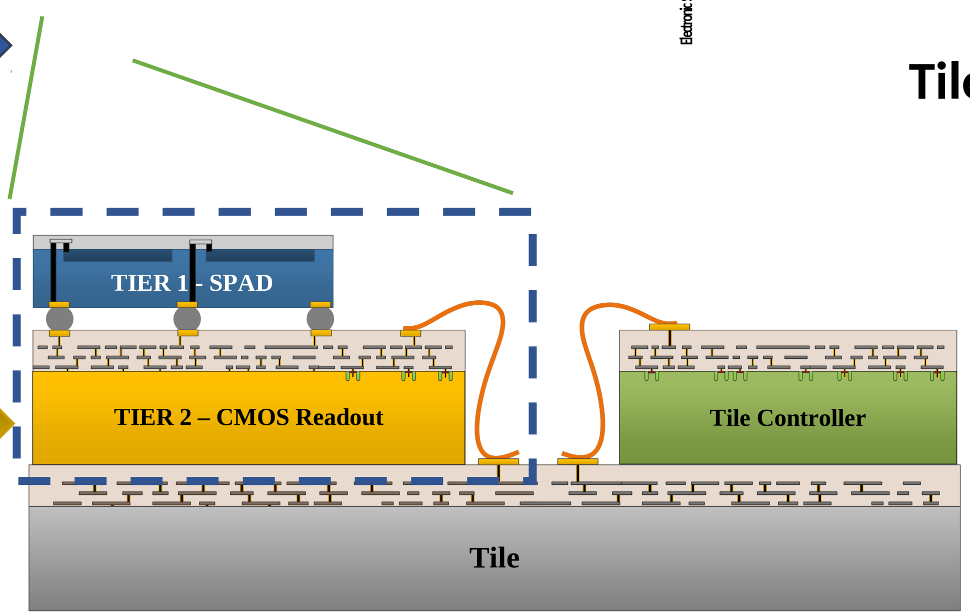
3D digital SiPM

SPAD Array
(DALSA)

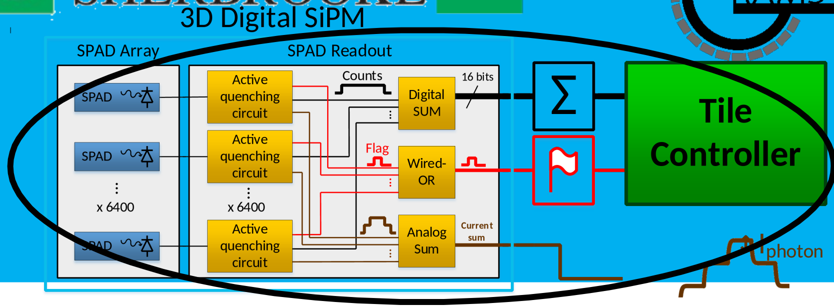
CMOS Readout
(TSMC 180 nm)

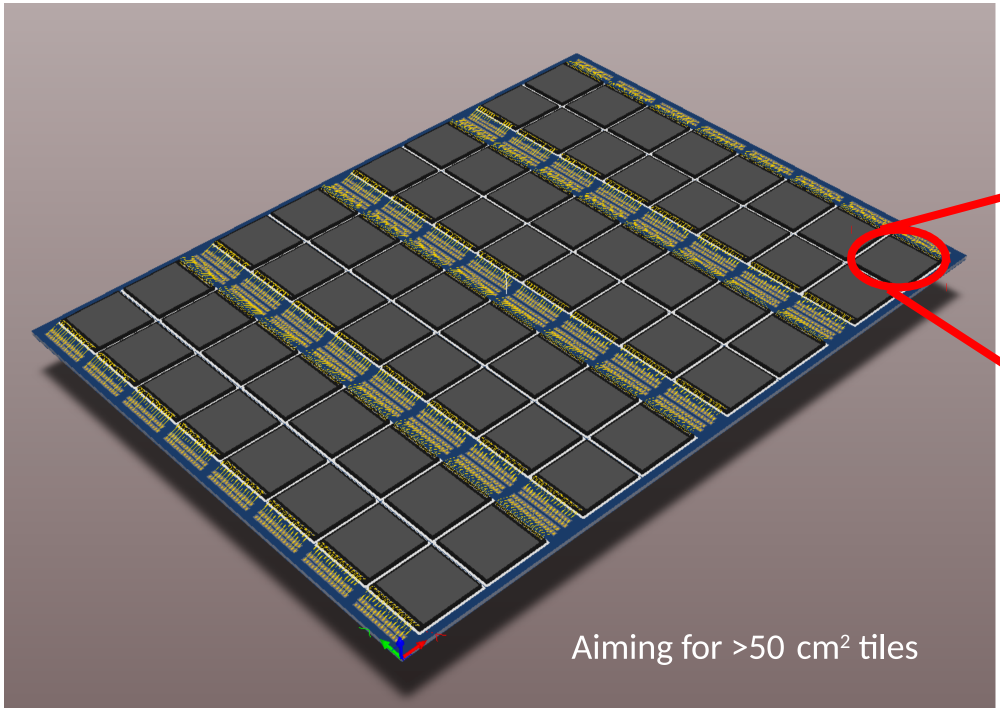
Tile

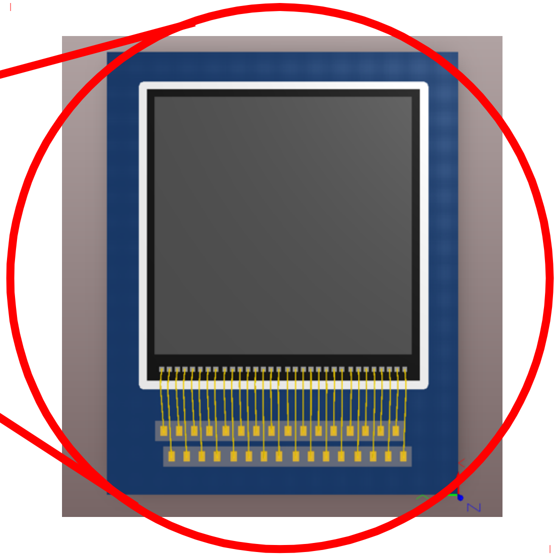
Tile Controller



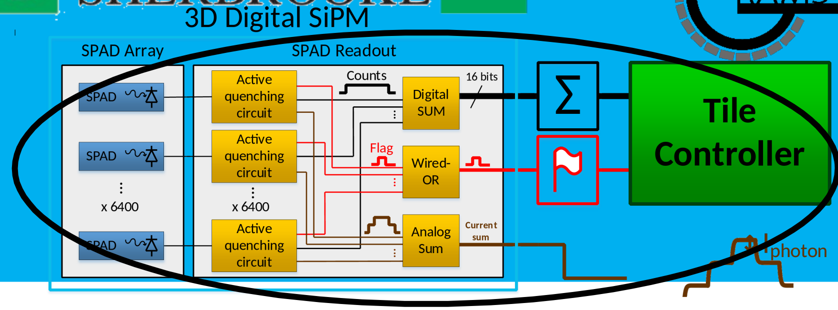
3DdSiPM Tile Assembly





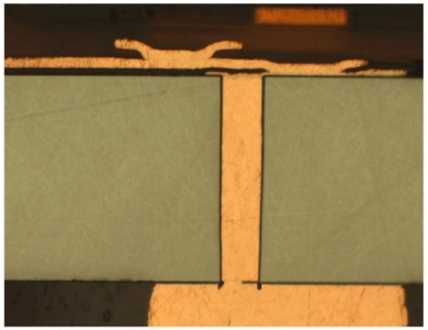


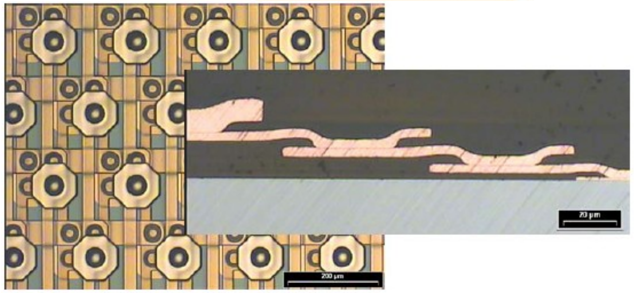
Fraunhofer IZM (Berlin) technology



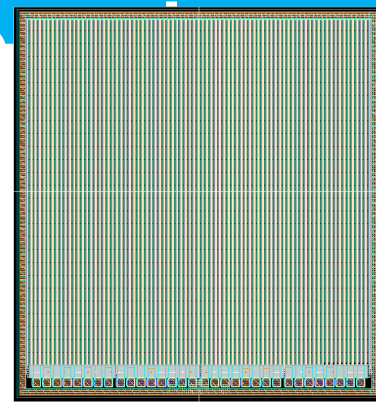
- Focusing on 3DdSiPM tile requirements (digital)
  - 4 metal/TSV/4 metal
  - Digital transmission over ~5 cm distance
    - rate to be determined
    - 4 metal layers per side enable proper transmission line design
- Phase 1:
  - Signal transmission simulations
  - Routing mockup (how many layers are really needed)
- Phase 2: Design rules validation and prototypes
- Phase 3: Full size implementation
- Seed funding to be requested in 2 weeks

Fraunhofer IZM



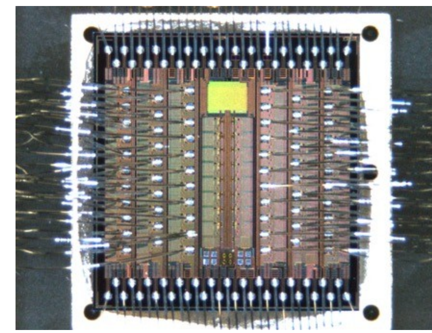


Overview of 3DdSiPM readout electronics development



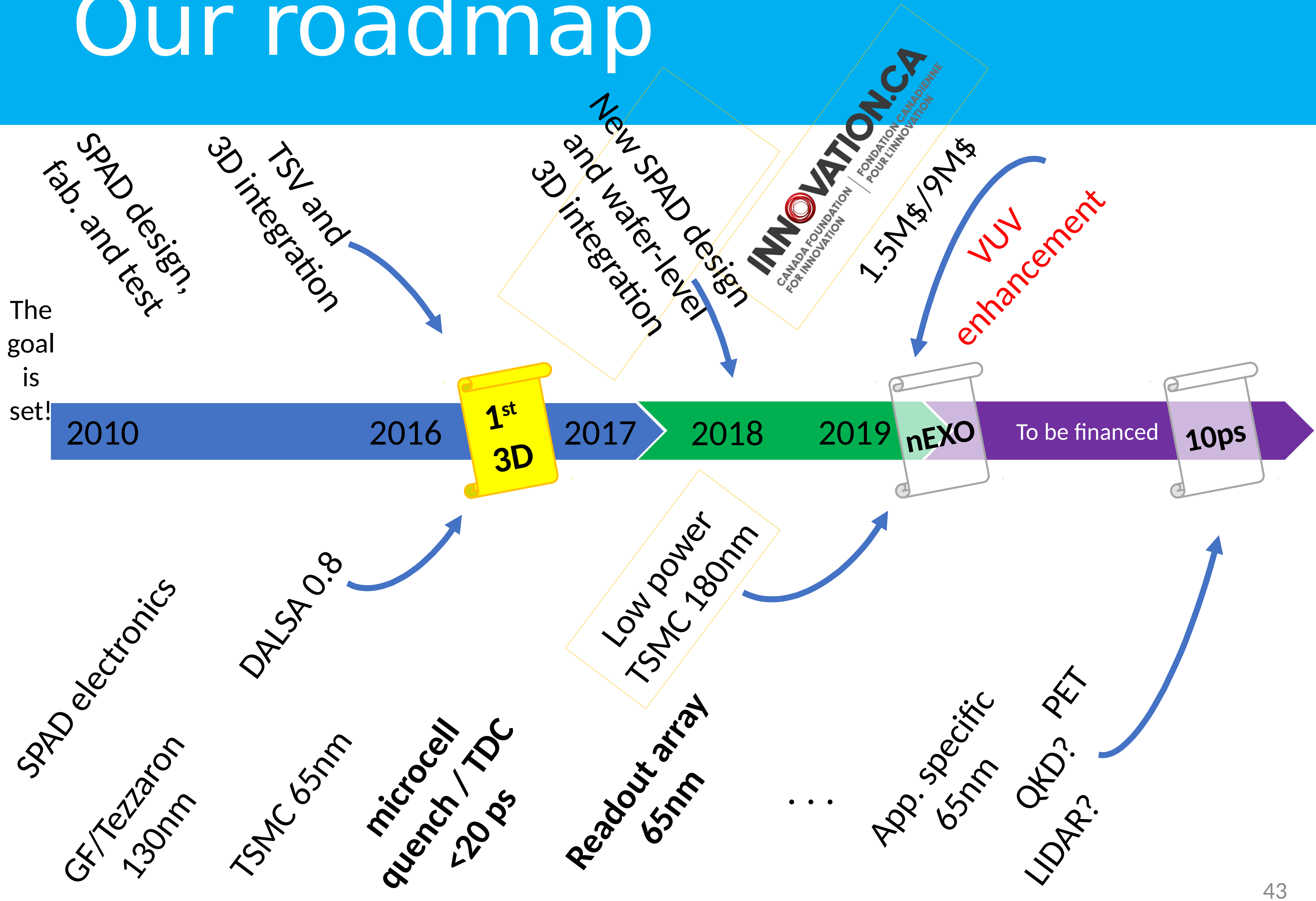
Full readout ASIC

- 3DdSiPM readout electronics
  - Design submitted (Sept. 2018)
  - Testbenches in design:
    - Validate the design
    - Prepare for ASIC testing
- Cryogenic CMOS modeling
  - Completed design (Fall 2017), fabrication (Feb. 2018)
  - Transistors under testing and modeling has started
  - Need to feed these models into simulator for final validation of 3DdSiPM readout design
- Large size silicon interposer for the tile structure
  - Discussions with DarkSide electronics’ group to develop this (potential CERN support)



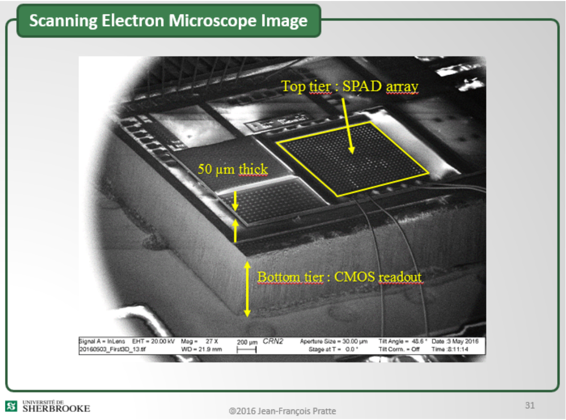
- ChipProbe
  - Completed design (Fall 2017)
  - Fabrication (Feb. 2018)
  - Now used to test SPADs for photodetector development (can quench external SPADs)

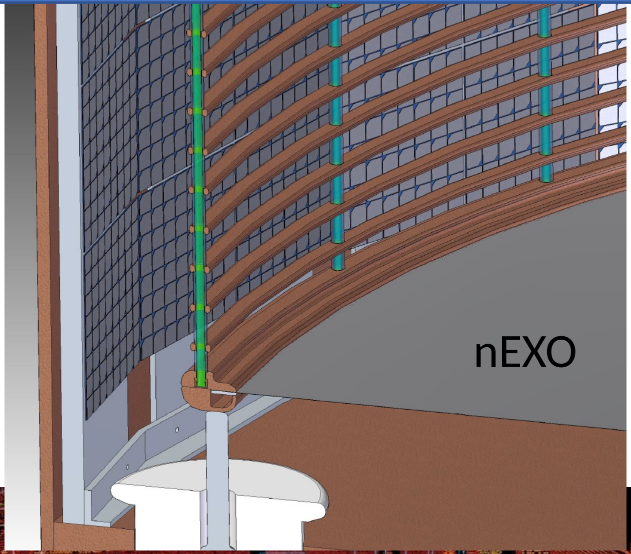
Our roadmap


The goal is set!
SPAD design, fab. and test
TSV and 3D integration
New SPAD design and wafer-level 3D integration
INNOVATION.CA
CANADA FOUNDATION FOR INNOVATION
FONDATION CANADIENNE POUR L'INNOVATION
1.5M$/9M$
VUV enhancement
2010
2016
1st 3D
2017
2018
2019
nEXO
To be financed
10ps
SPAD electronics
GF/Tezzaron 130nm
DALSA 0.8
TSMC 65nm
microcell quench / TDC <20 ps
Low power TSMC 180nm
Readout array 65nm
. . .
App. specific 65nm
PET
QKD?
LIDAR?

Long term outlook

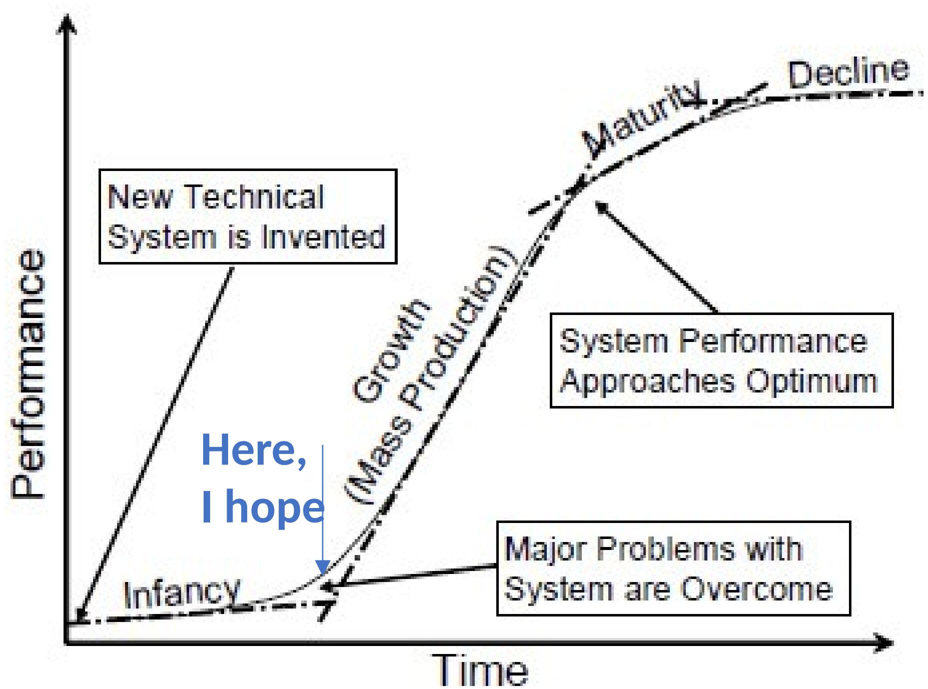
2015 2025 2035





A more sobering outlook

- Where are we?



Technology life-cycle curve

- Mitigating risks through an expanded collaborative effort?
- And challenges that I glanced over
  - Optimum SPAD array configuration for 3D?
  - VUV sensitivity
  - IR sensitivity
    - Silicon or something else?

Summary

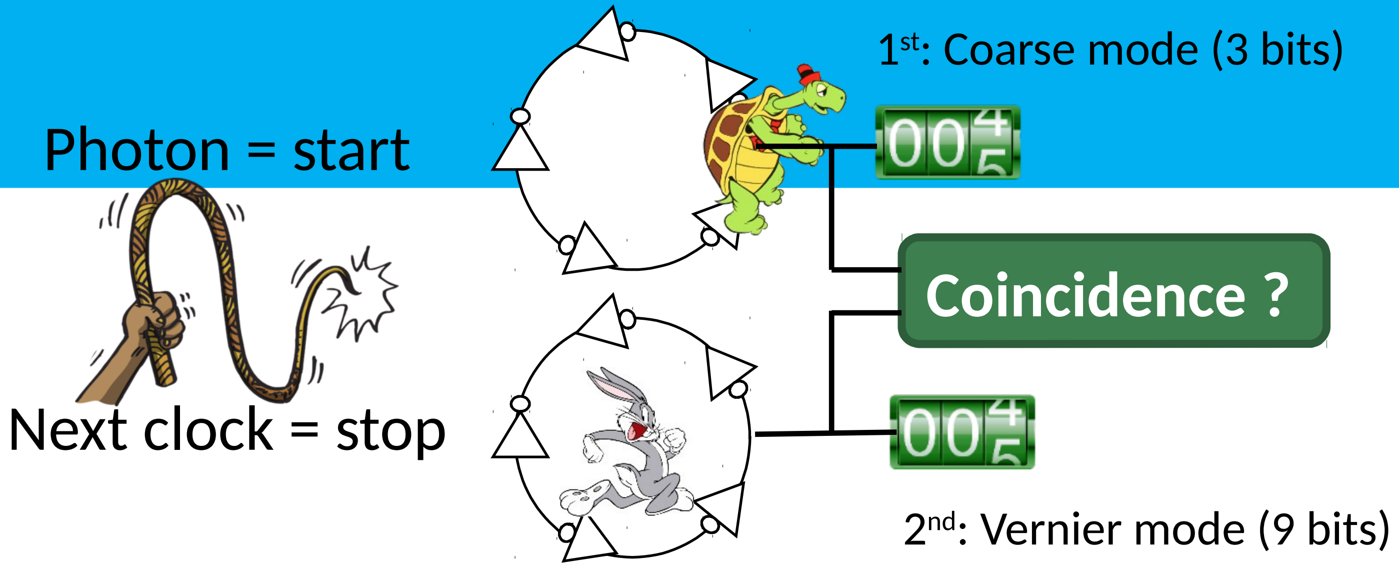
- SiPMs are a compelling solution in LXe and LAr
  - Need LBL MBE to achieve desired VUV sensitivity
- 3DdSiPM is the “ultimate” SiPM solution
  - Combining photon detection and electronics
  - Potential to achieve highest performances
    - Efficiency, After-pulsing suppression
- Many applications outside particle physics
  - Photon detection is very versatile

The end

TRIUMF

Single Stage Vernier Ring TDC in CMOS 65 nm

UNIVERSITÉ DE SHERBROOKE 3IT GRAMS

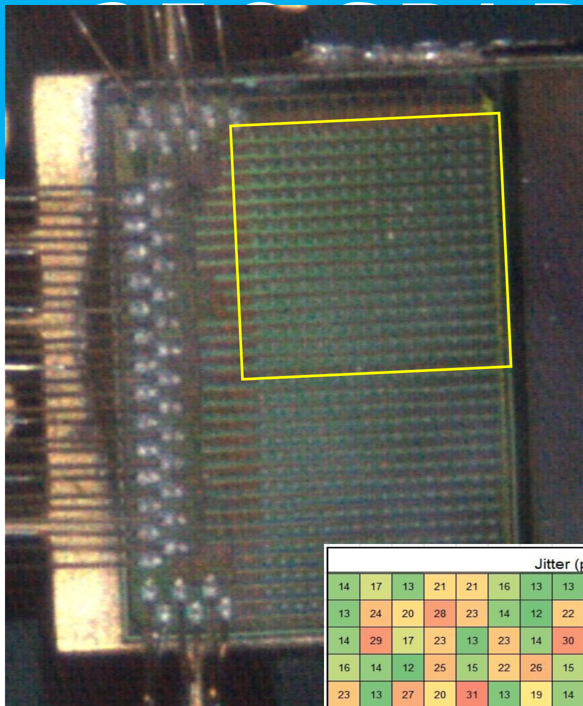


Dual Phase-Locked Loop:

- To stabilize each ring
  - Temperature, bias voltage
- To provide uniformity
  - Pixel-to-pixel variation
  - Chip-to-chip variation

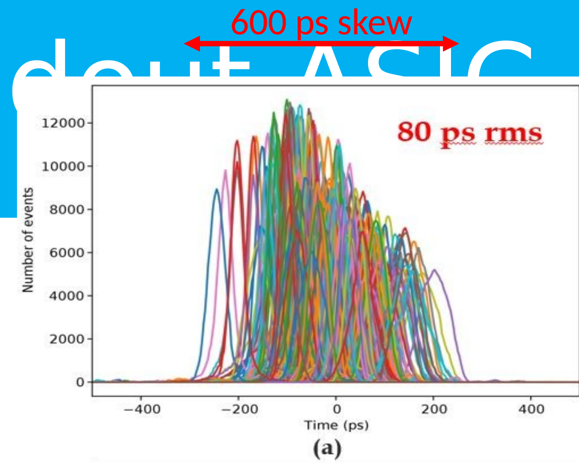
- Jitter: 16.2 ps (mean)
- Resolution: 15 ps
- DNL max: 0.37 LSB, INL max: 3.3 LSB
- 162 µW up to 100 kcps
- Very small area

pixels readout ASIC



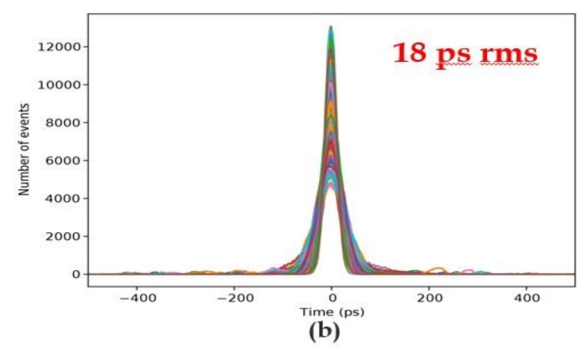
Jitter (ps rms)															
14	17	13	21	21	16	13	13	27	28	18	15	14	12	15	16
13	24	20	28	23	14	12	22	21	13	14	20	12	15	17	20
14	29	17	23	13	23	14	30	22	24	21	23	19	17	15	20
16	14	12	25	15	22	26	15	16	21	21	24	19	20	17	22
23	13	27	20	31	13	19	14	18	15	16	16	20	22	20	18
18	24	28	23	24	17	13	13	27	17	12	16	22	14	17	26
17	15	19	12	18	12	23	30	18	17	17	19	24	31	23	15
16	13	13	19	19	12	15	12	19	22	15	17	15	22	19	18
16	12	21	33	18	18	16	24	22	20	16	20	18	32	16	17
15	17	17	16	19	32	29	36	23	23	12	17	22	21	15	14
15	22	13	20	21	18	24	11	25	13	22	15	13	16	25	26
16	21	22	14	19	19	26	13	19	18	22	14	21	33	21	17
21	20	22	20	20	17	16	30	14	16	18	16	15	16	19	18
16	19	19	23	14	18	18	17	17	14	22	23	25	13	17	23
21	20	16	28	25	26	23	23	23	12	14	22	28	12	22	20
18	21	24	13	15	26	21	12	22	17	20	16	17	17	29	13

The timing jitter of each pixel as a function of the position in the array.



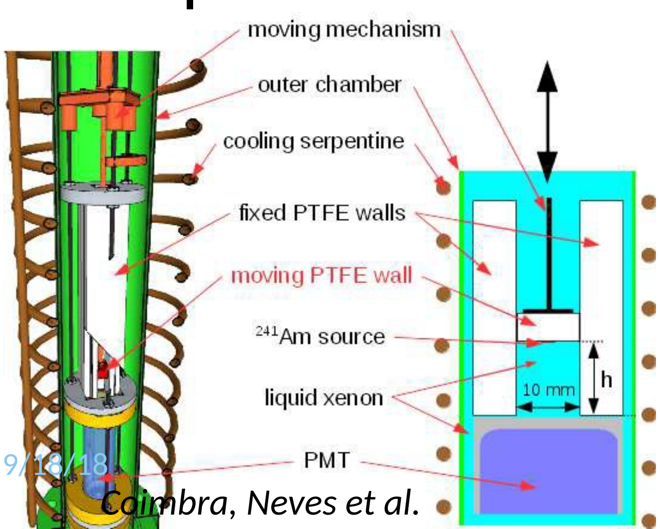
256 histograms of timing jitter of each pixel.

Calibration and correction



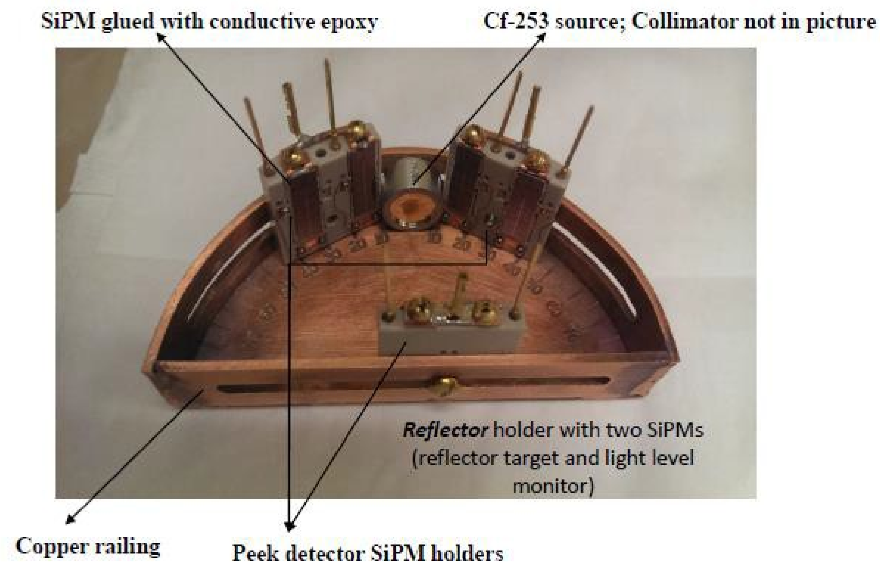
Photon transport characterization in general

- In vacuum
  - Differential vs wavelength and angle
  - Useful for material characterization
- In liquid Xenon

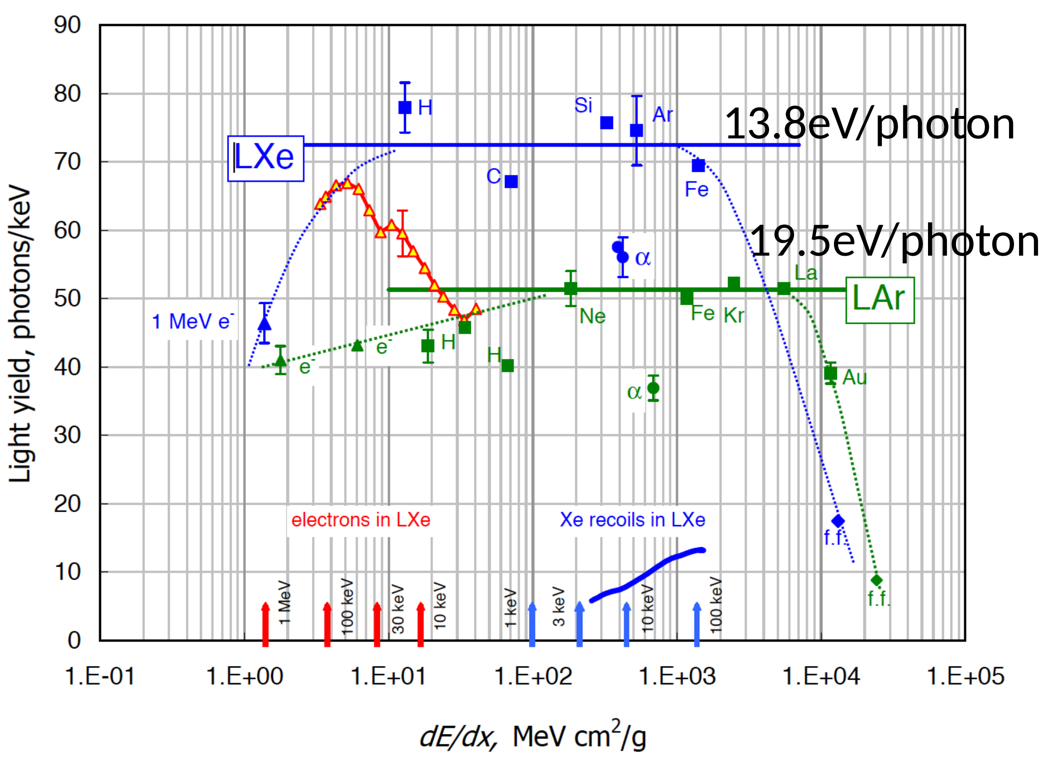


Coimbra, Neves et al.

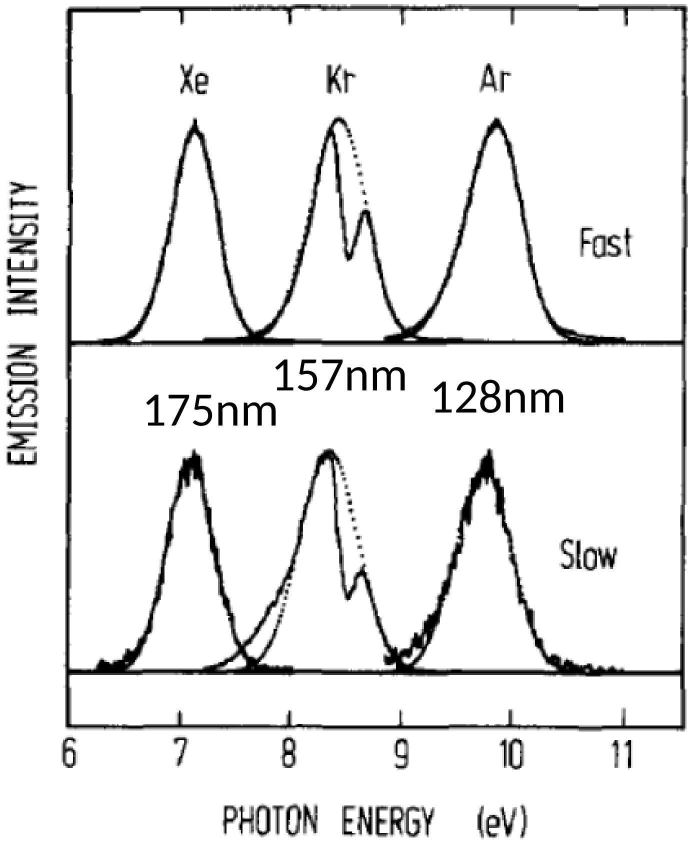
- In liquid Xenon differential (in angle)
  - Muenster
  - Optics characterization at U.Alabama
    - Key element very absorptive VUV material (e.g. Actar)



Scintillation in LXe and LAr

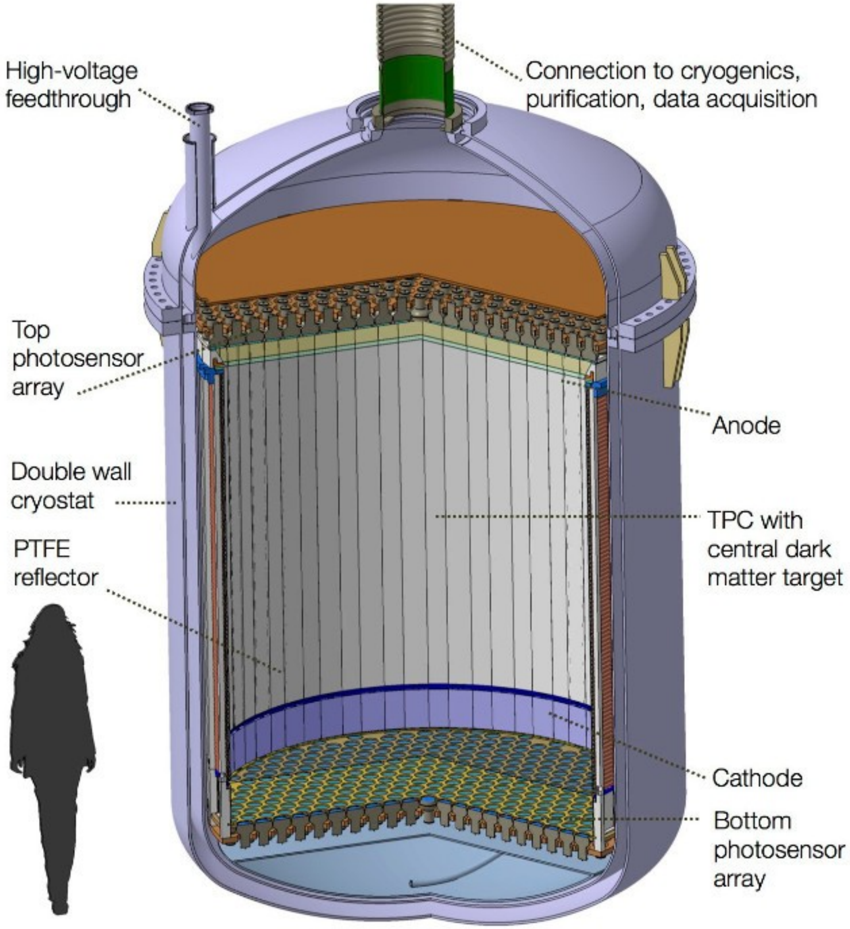


J Chem Phys vol 91 (1989) 1469 E Morikawa et al



arXiv:1207.2292v3

Dark matter - DARWIN

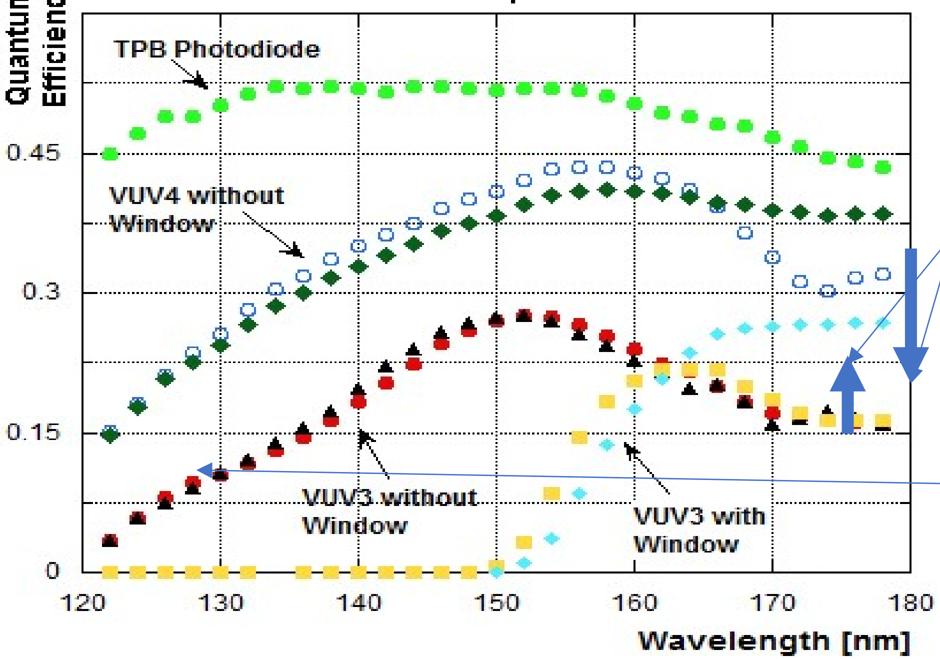


- SiPM investigated among other options
  - PMTs
  - Hyrbid PMT with SiPM for gain stage (CUPID)
  - MPGD (gas)
- Dark noise requirement very low for matching small scintillation flash (1PE) with full drift time ~1ms
  - DN Rate < 10^{-3} Hz/mm^2?

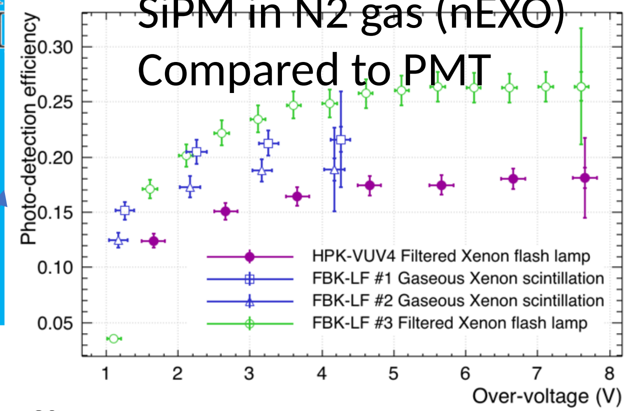
The PDE issue?

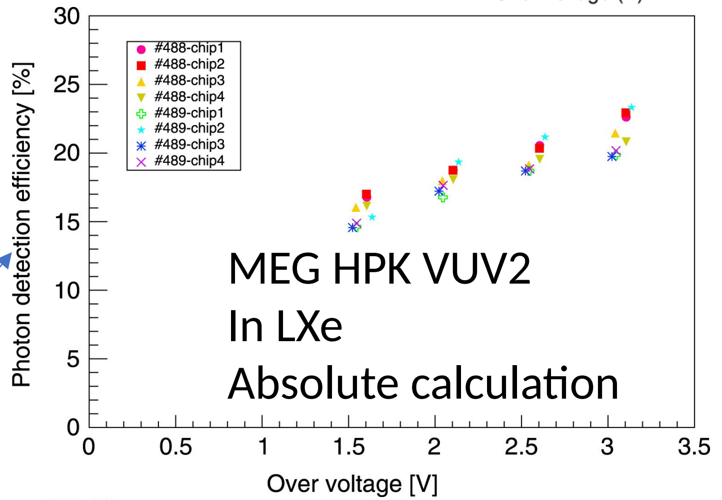
M. Bonesini[1], T. Cervi[2], A. Menegolli[2], M. C. Prata[2], G.L. Raselli[2], M. Rossella[2], A. Falcone[2], M. Torti[1]
[1]Istituto Nazionale di Fisica Nucleare, Sezione di Milano Bicocca
[2]Istituto Nazionale di Fisica Nucleare, Sezione di Pavia and Università degli Studi di Pavia

Reference to photodiode

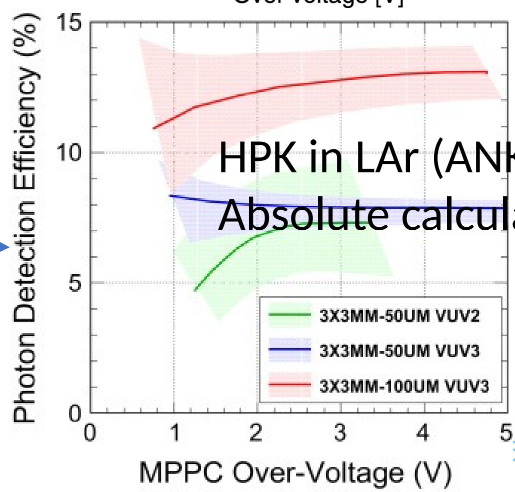


SiPM in N2 gas (nEXO)
Compared to PMT





MEG HPK VUV2
In LXe
Absolute calculation



HPK in LAr (ANKOK)
Absolute calculation

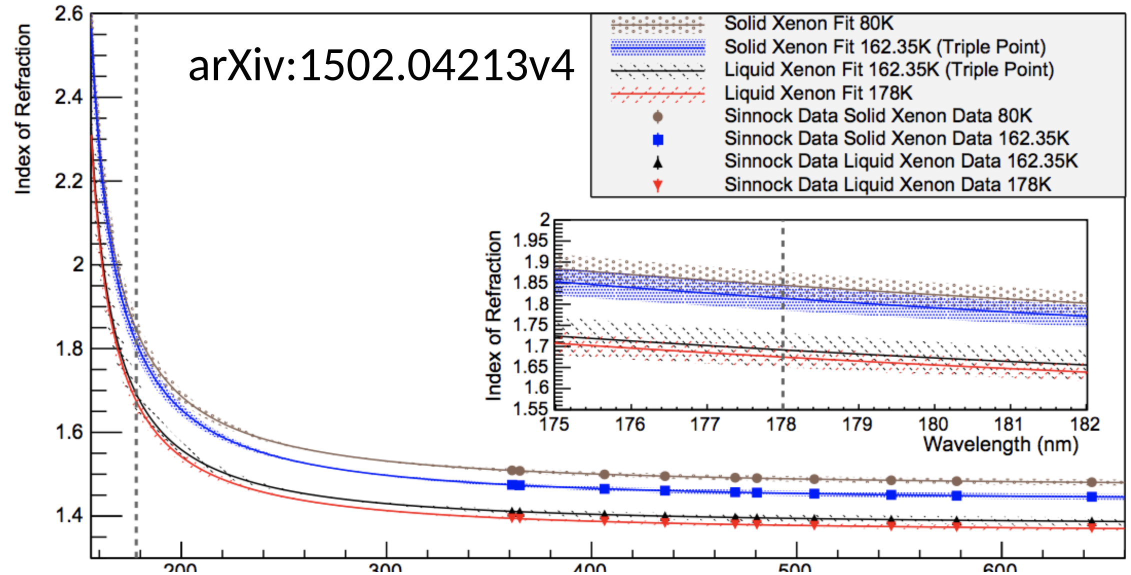
Light detection in selected experiments

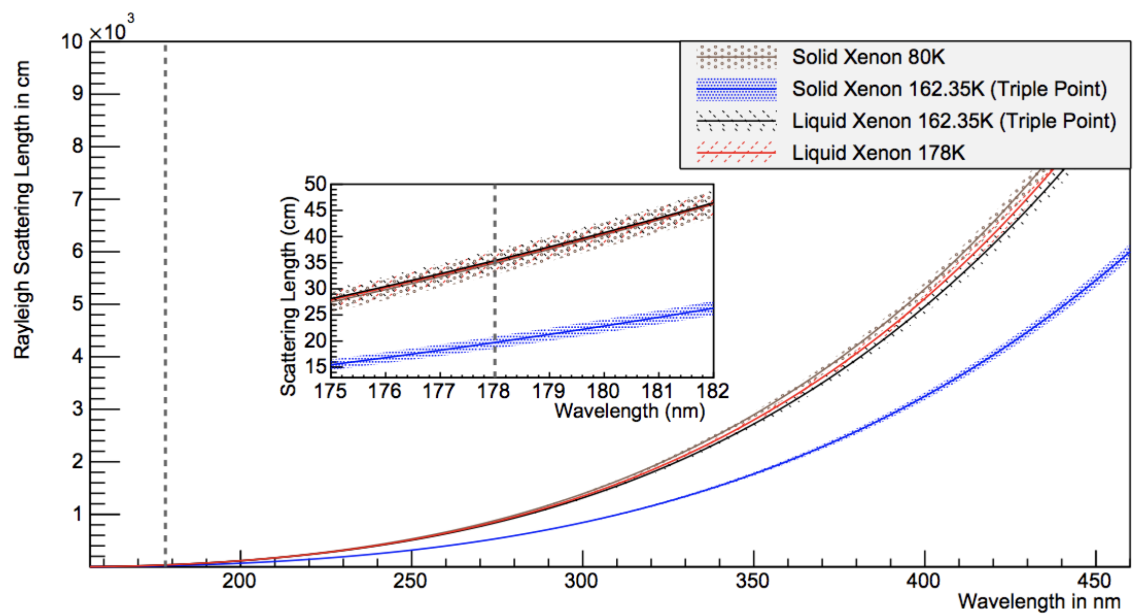
Experiment	Inferred overall efficiency (g1) Photoelectron/photon	Comment
XMASS	~15%	PMTs + high coverage
LUX	11.7 +- 0.3 %	Teflon + PMTs
PANDAX-II	11.3 +- 0.5 %	Teflon + PMTs
XENON-1T	14.4 ± 0.7 %	Teflon + PMTs
EXO-200	7-9%	Teflon + APDs
nEXO	>3%	SiPM barrel
MIX	23.9 ± 1.2 %	PMTs + Teflon
PIXeY	9.7+- 0.2 %	

Are these numbers always true photo-electrons?
Or can they include after-pulse? They should not!

Photon transport through liquid Xen

- Attenuation length, ~4m but dependent on purity
- Is the index of refraction measured well enough?





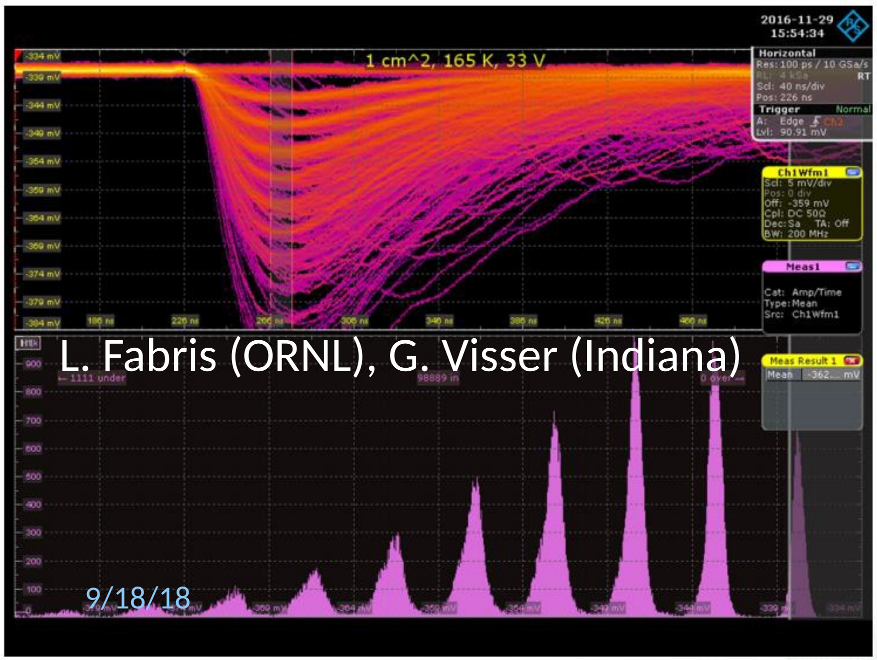
The wonder of teflon

- The inside of LUX

- 10% overall detection efficiency with a 35% efficiency PMT means the transport efficiency is ~30%
- 30% efficiency is outstanding with a photo-coverage <10%

Gain/noise and digital SiPMs

- Noise specifications < 0.2PE
- Power specification ~100W for 4 m2
- Capacitance ~nF/cm2
- Tough but it works
  - nEXO R&D
  - Also work at Abu Dhabi

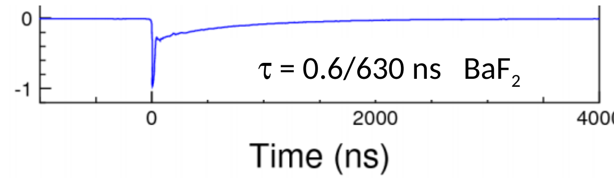


L. Fabris (ORNL), G. Visser (Indiana)

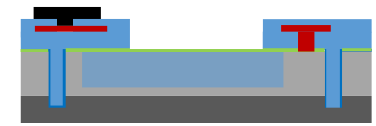
- Power constraints limit the speed
  - Sampling rate for nEXO ~2MHz
  - 10 MHz would be desirable
  - Higher speed would be useful for PSD, Cerenkov detection and using electro-luminescence
- Difficult with analog electronics but “easy” with digital SiPMs
  - See my other talk for details
  - Option being investigated in parallel for nEXO

A large area SiPM for efficient detection of the fast scintillation component of BaF_2

D. G. Hitlin, Lauritsen Laboratory, Caltech
M. Hoenk, J. Hennessey, A. Jewell, Jet Propulsion Laboratory, Caltech
G. Paternoster, A. Gola, FBK

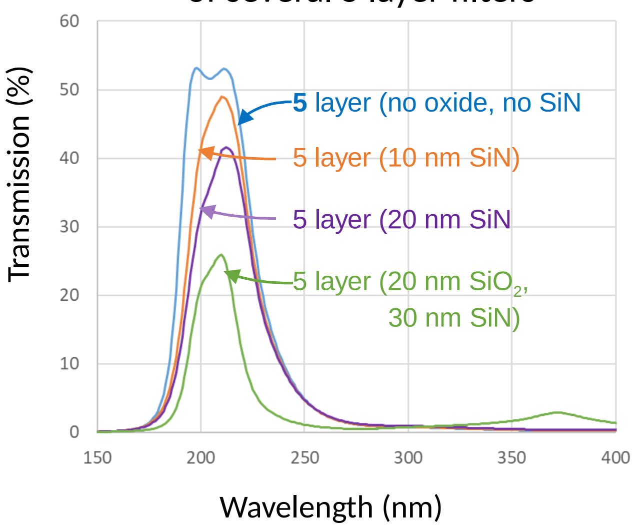


- Making use of the very fast barium fluoride scintillation component at 220nm for fast timing and high rate capability requires a means of suppressing the larger slow component at 300nm
- Caltech/JPL and FBK are developing a SiPM with an integrated interference filter for this purpose
- This requires reduction of SiN passivation layer on an FBK device and fabrication of an integrated metal/dielectric filter, which has higher efficiency than an external filter

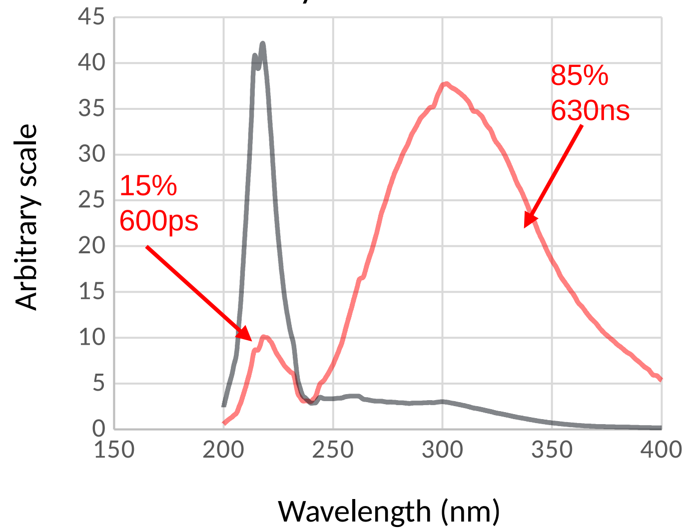


SiPM with thin entrance window and guard ring structure

Calculated transmittance of several 5 layer filters

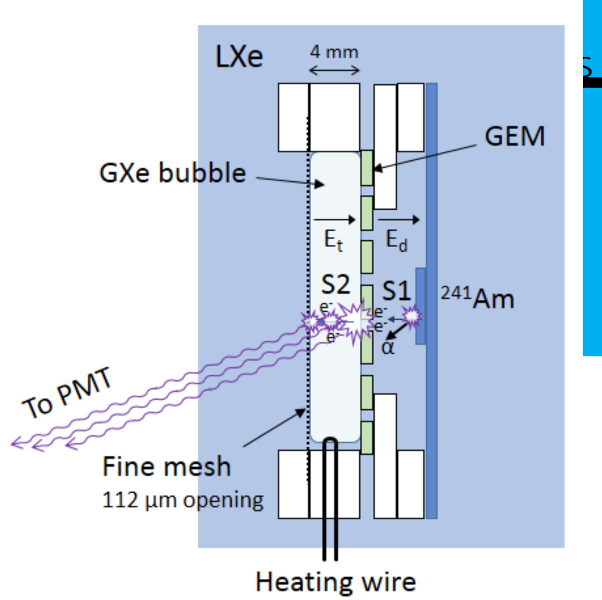


Native BaF_2 spectrum & calculated response with 5 layer filter on 10nm SiN



Test wafers are in production

THGEM. Another promising avenue



- L. Arazi & Weizman group
- Bubble assisted amplification in thick GEM
- Pros:
  - Low radioactivity possible (?)
  - Cheap (?)
  - Low dark noise
    - May be needed for DARWIN