Cryogenic applications of SiPMs

F. Retière

TRIUMF

Domain of application

- Temperature < -50C
  - Dark noise tend to be overwhelming at higher temperature
- Temperature > 5K
  - Superconducting sensors are superior for very cold appliaction
- Applications
  - Liquid Xenon
  - Liquid Krypton
  - Liquid Argon

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

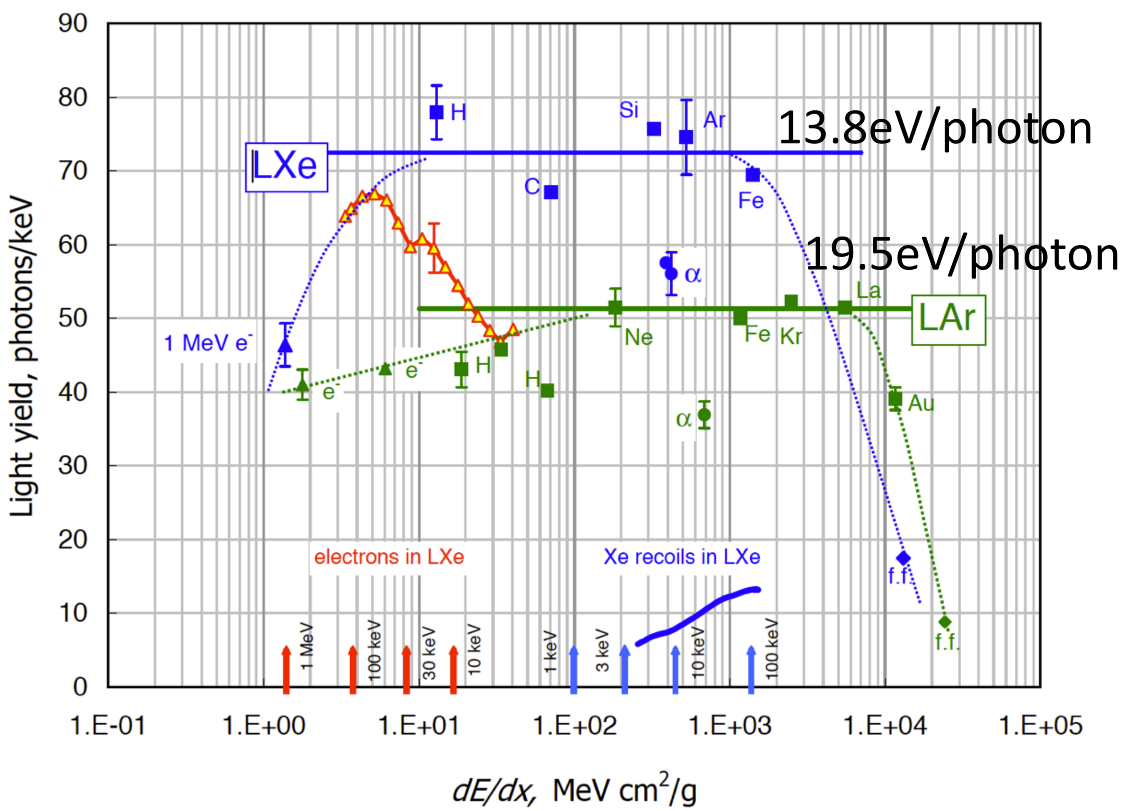
Present and future liquid Krypton detector

Experiment	Application	Status	Mass	Signal type	PD type
NA62	K decay	Operation	25,000kg	Charge	N/A

Present and future liquid Argon detector

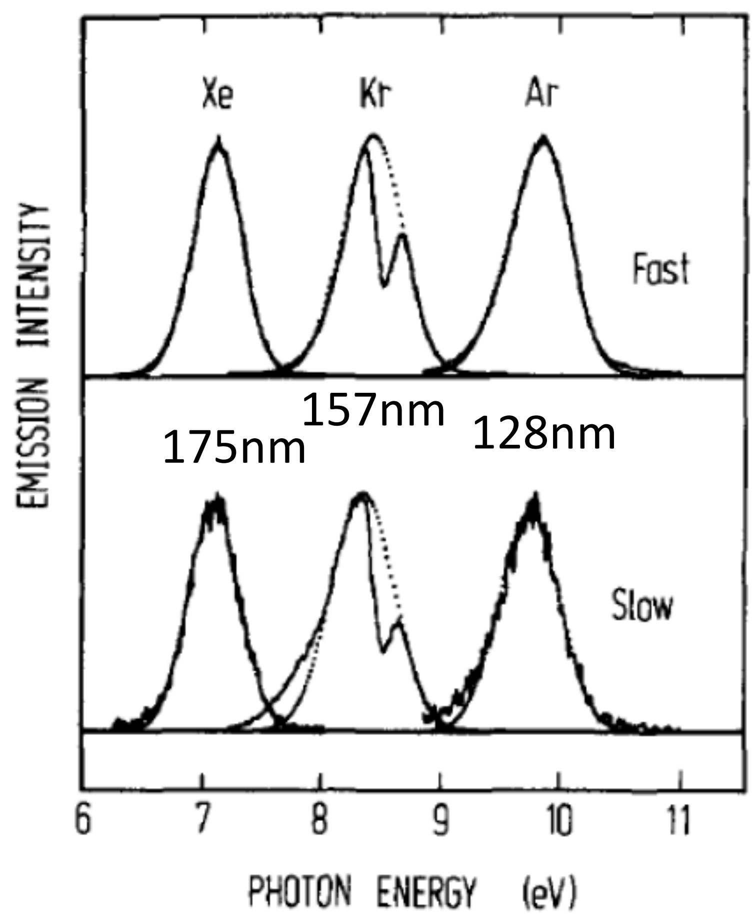
Experiment	Application	Status	Mass	Signal type	PD type
DarkSide-50	DM	Operation	50kg	Scint+charge→elum	PMT
DEAP-3600	DM	Operation	3,300kg	Scint	PMT
DarkSide-20k	DM	Design	20,000kg	Scint.+charge→elum	SiPM
DEAP-300t	DM	Concept	300,000kg	R&D	R&D
ANKOK	DM	Design	?	?	SiPM
CENNS-10	Coherent ν	Construction	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

Scintillation in LXe and LAr



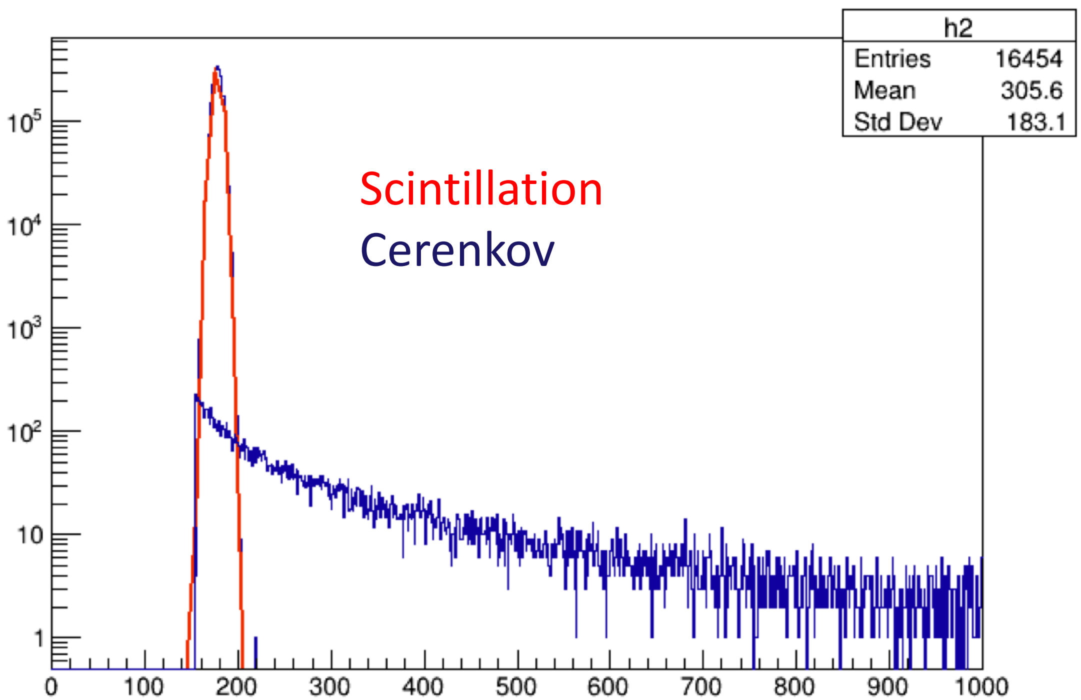
arXiv:1207.2292v3

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

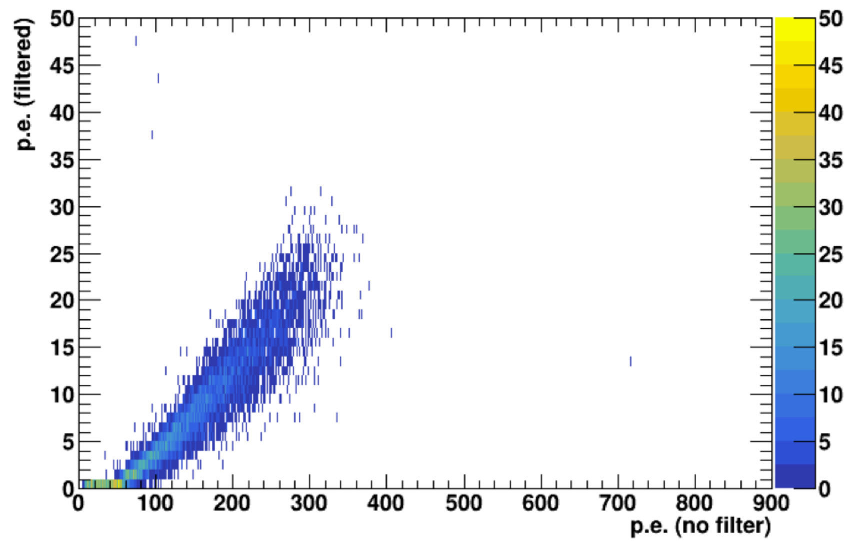


Cerenkov …

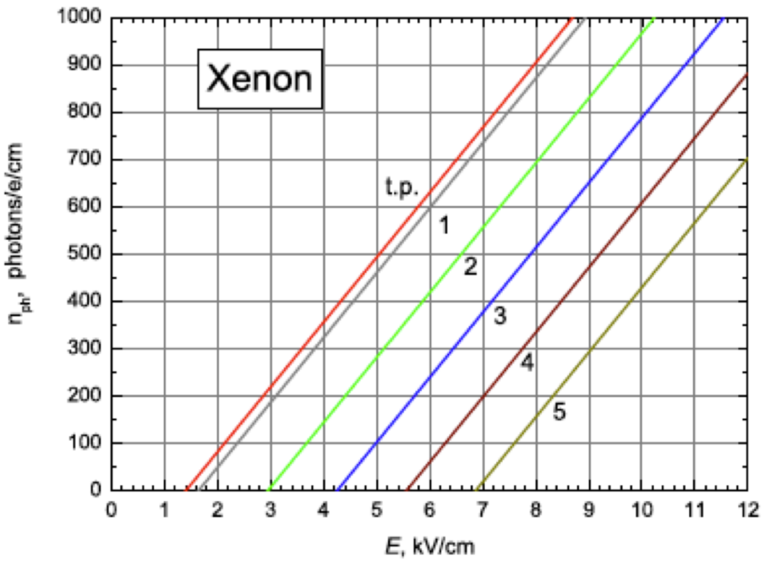
- 1/10000 Cerenkov/scintillation in LXe

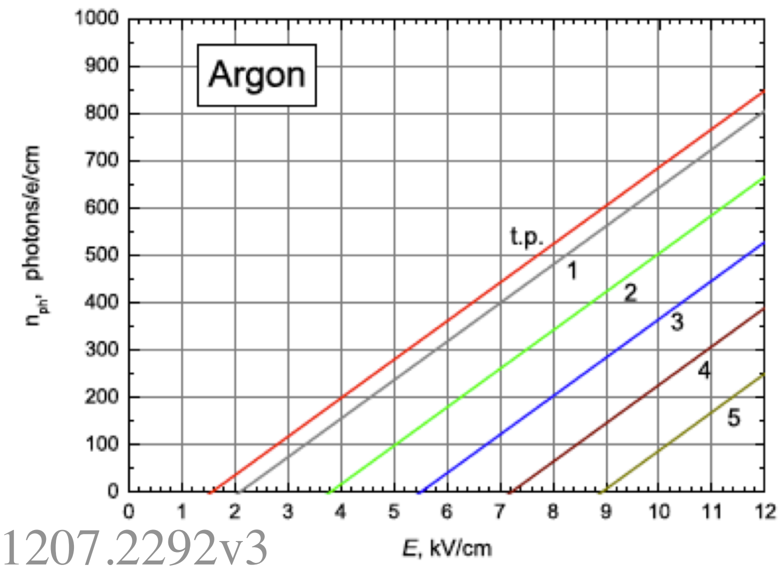


- Filter out with a cut of at 225nm using a 90Sr source



Electro-luminescence



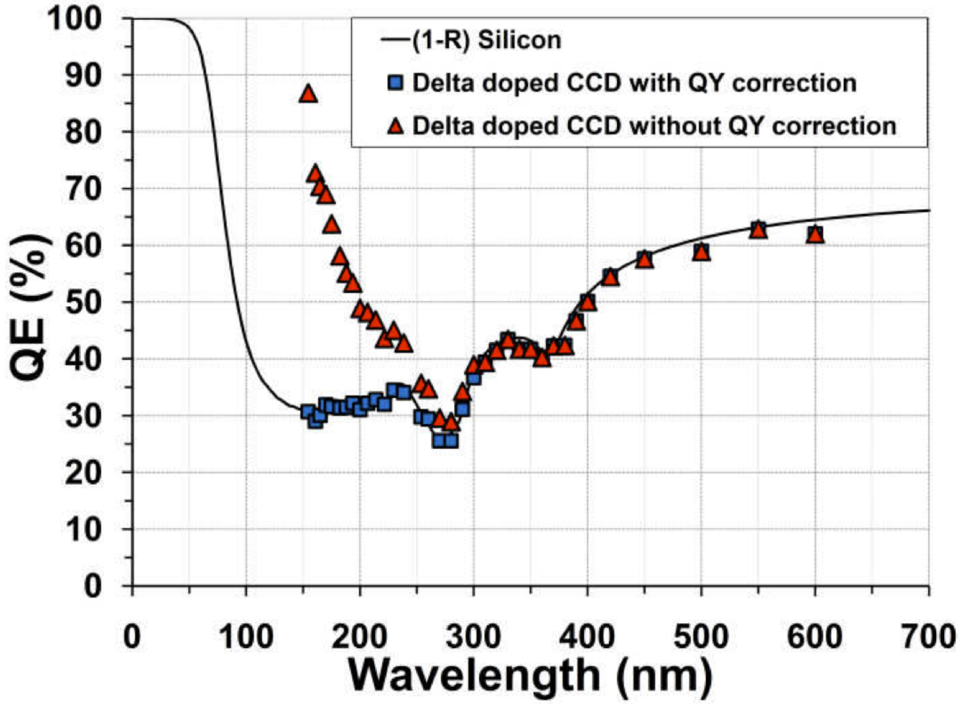


- Convert e- into photon
  - Smaller fluctuations than with charge amplification
- Used to detect charge with light sensors

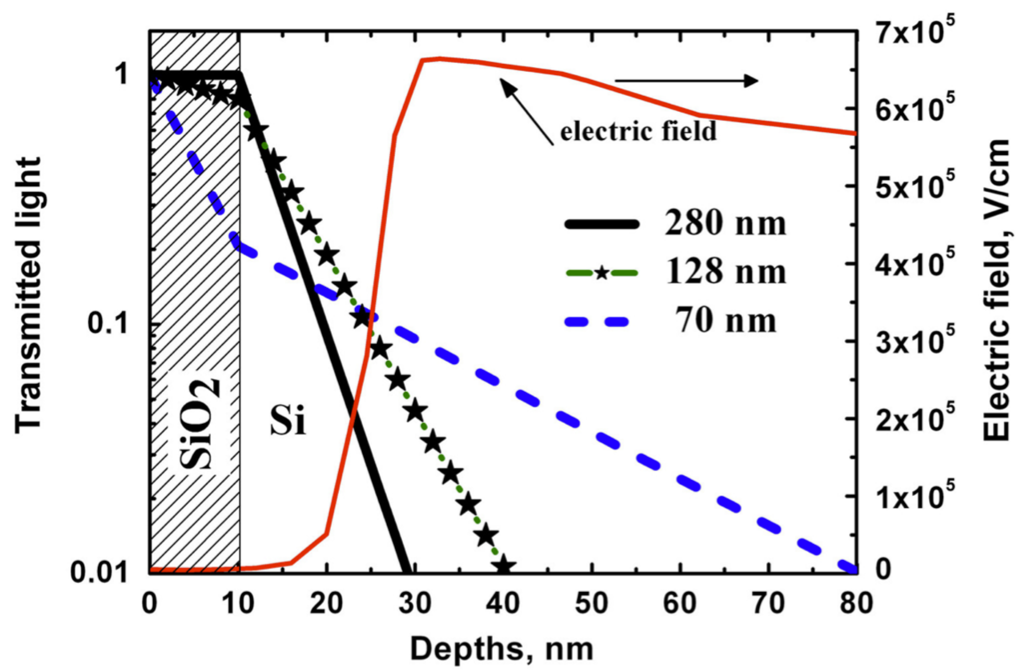
arXiv:1207.2292v3

VUV light detection challenges

- Reflections



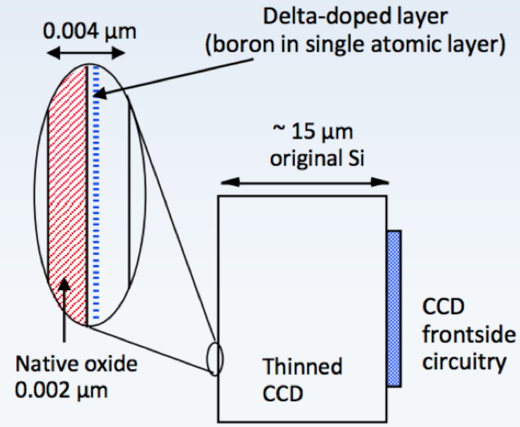
- Shallow absorption depth

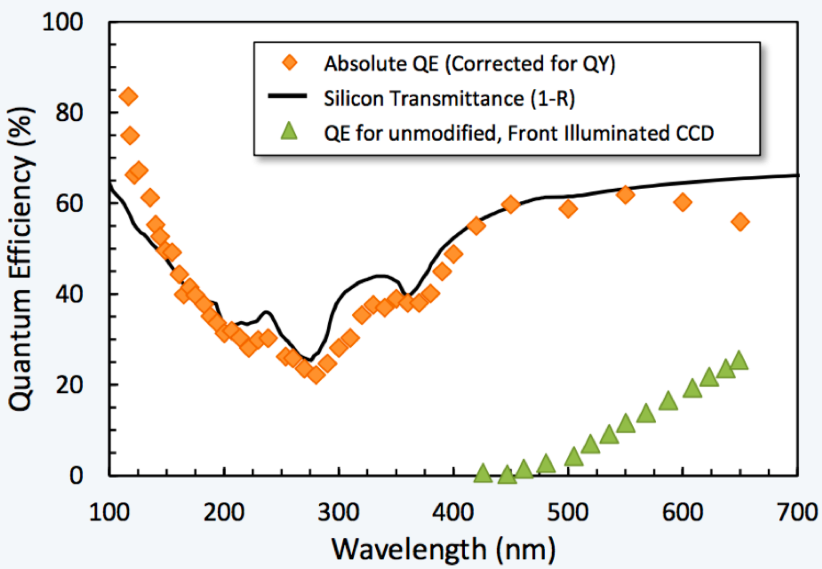


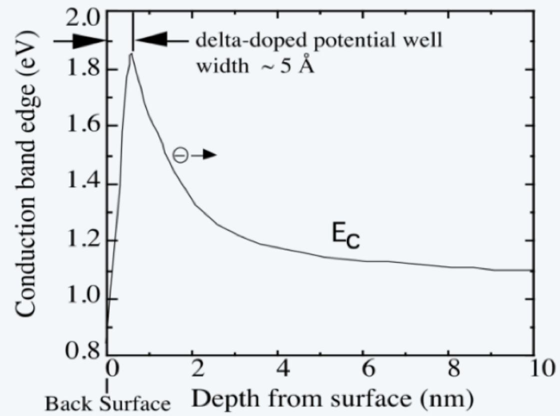
Shallow junction for VUV CCD

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



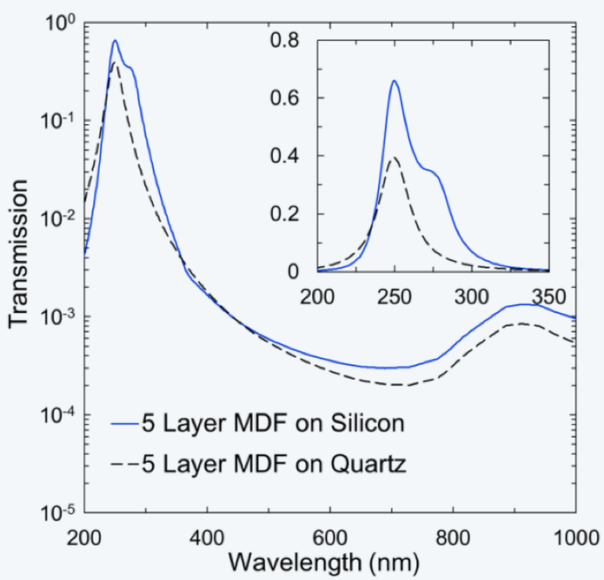


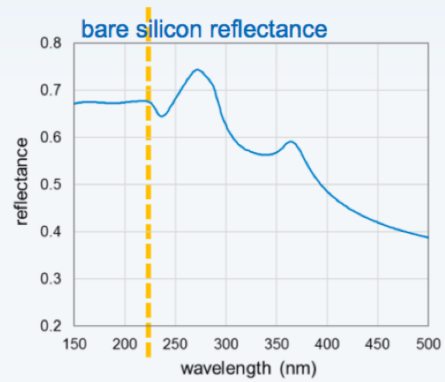


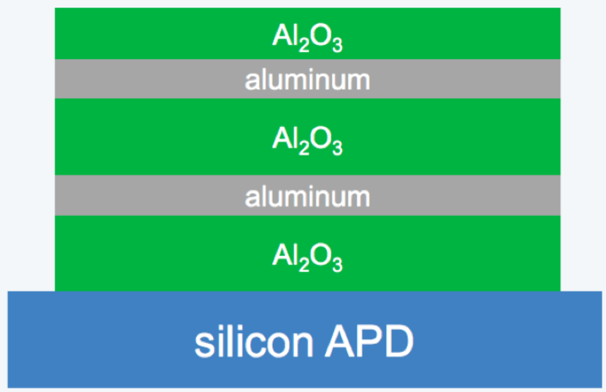
Anti-reflective coating

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



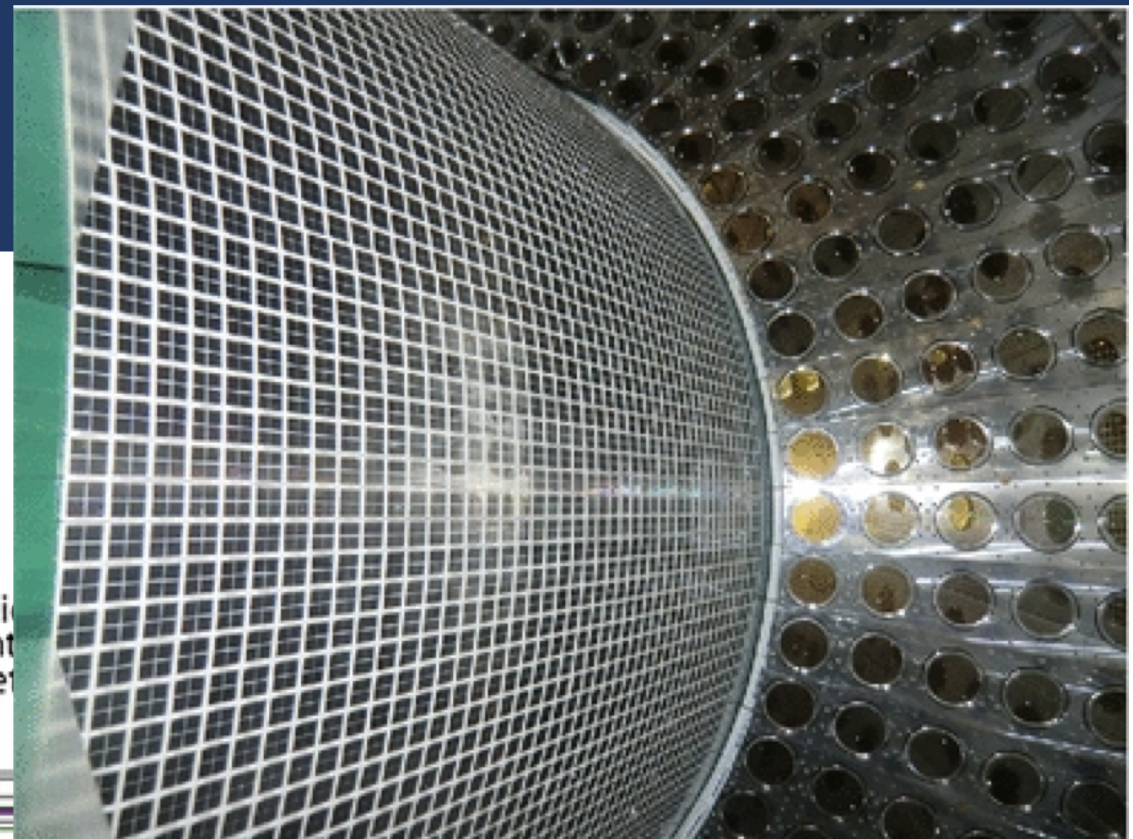


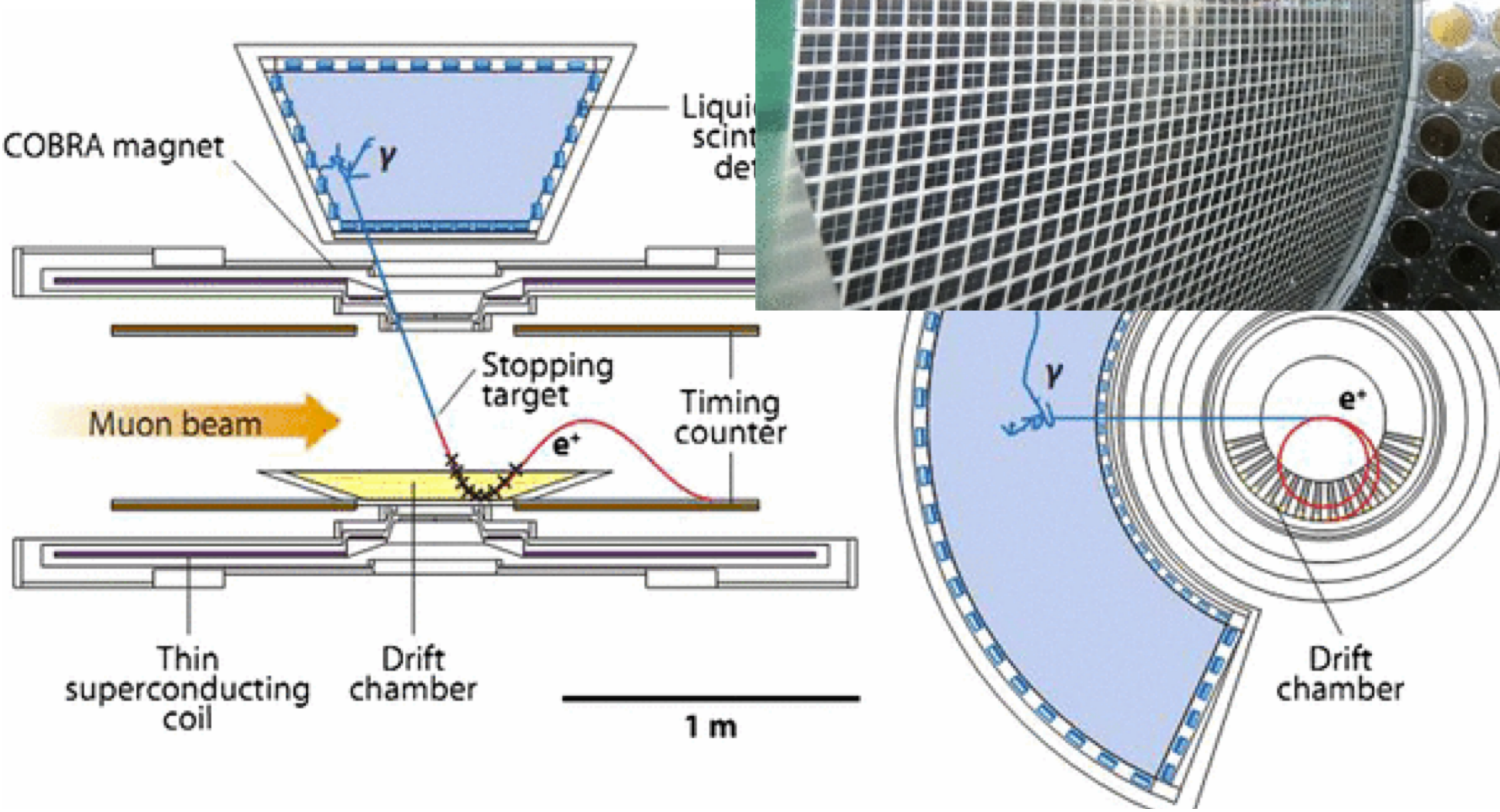


SiPM in LXe and LAr, sorted by photo-detection area

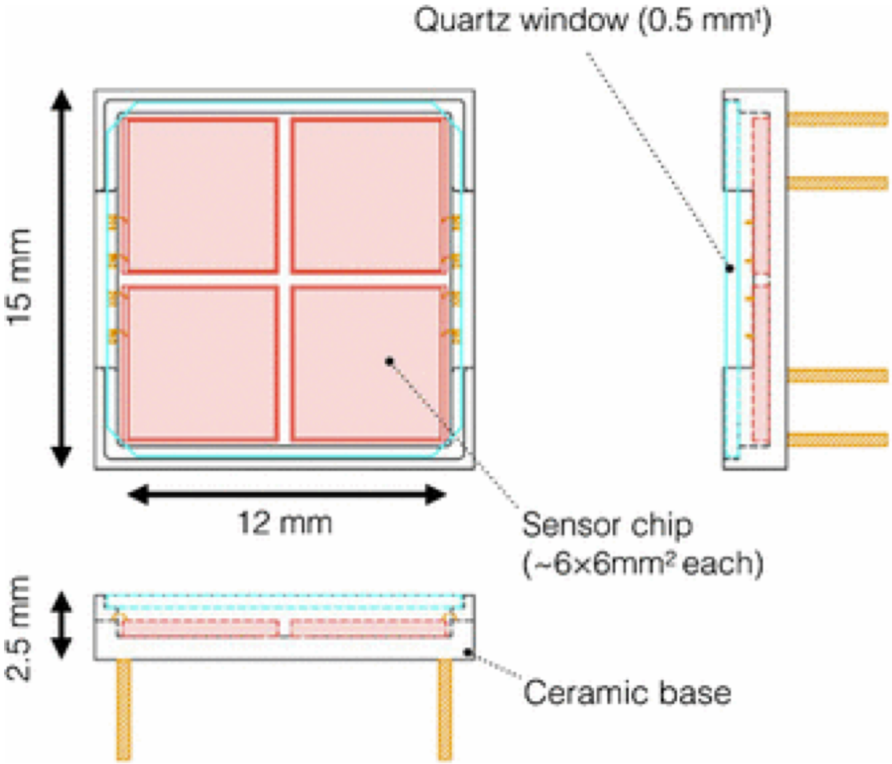
Experiment	Type	Photo-detector solution	Area
MEG-II	LXe	Hamamatsu VUV2	0.6 m2
nEXO	LXe	FBK, Hamamatsu, 3DdSiPM	~5 m2
DARWIN	LXe	SiPM is one option	~8 m2
DarkSide-20k	LAr	FBK NUV-HD triple dopant	15 m2
DEAP-300t	LAr	SiPM is baseline option	~200 m2
Proto-DUNE-SP	LAr	Light guide or trap + SiPM	
DUNE	LAr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

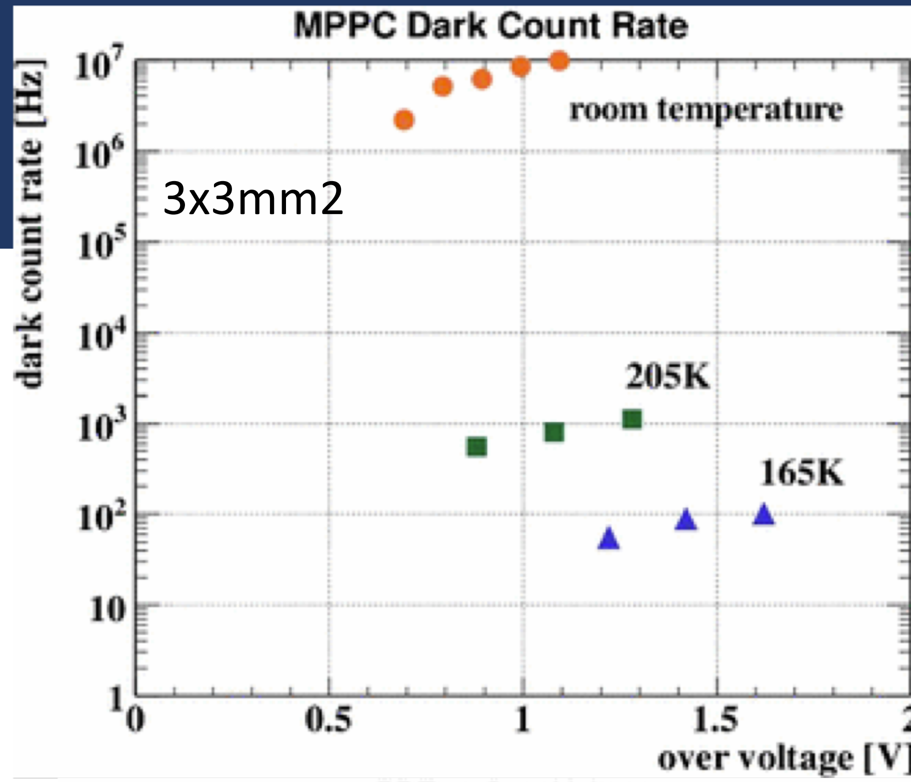
MEG-II – The pioneer

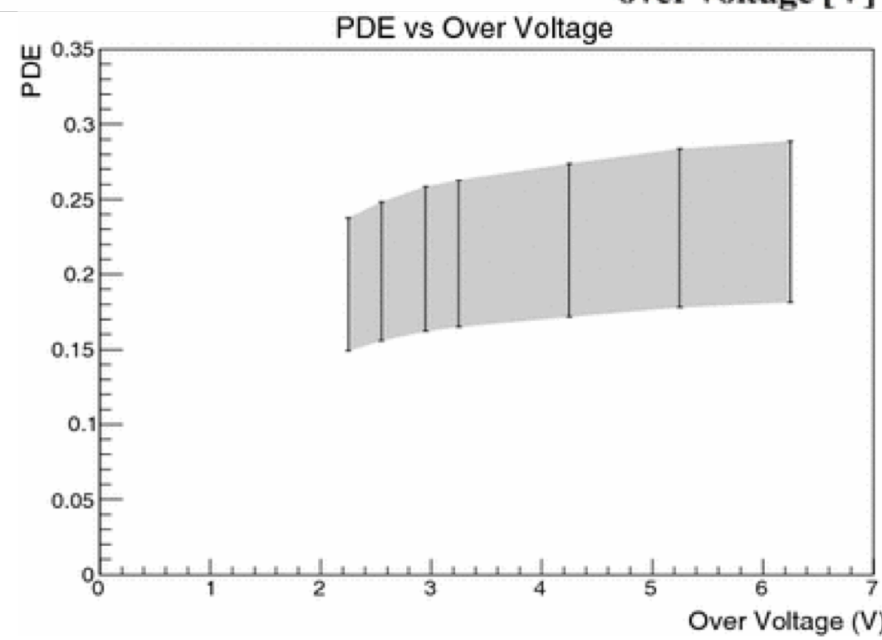




MEG-II MPPCs


Quartz window (0.5 mm^t)
15 mm
12 mm
Sensor chip
(~6x6mm² each)
2.5 mm
Ceramic base


MPPC Dark Count Rate
dark count rate [Hz]
room temperature
3x3mm2
205K
165K
over voltage [V]


PDE vs Over Voltage
PDE
Over Voltage (V)

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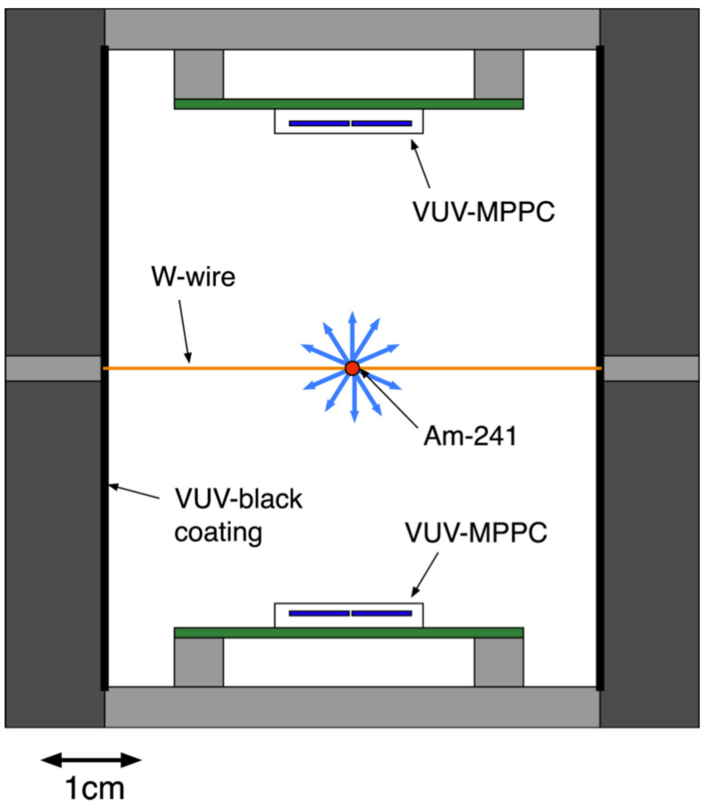
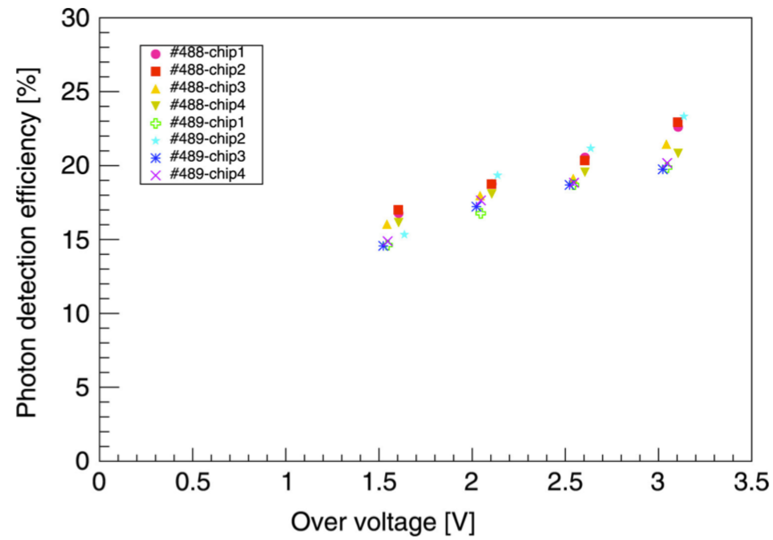
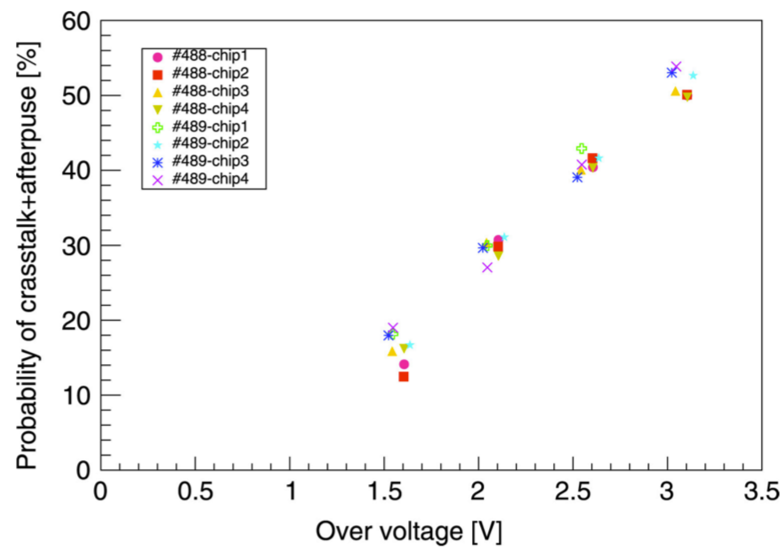
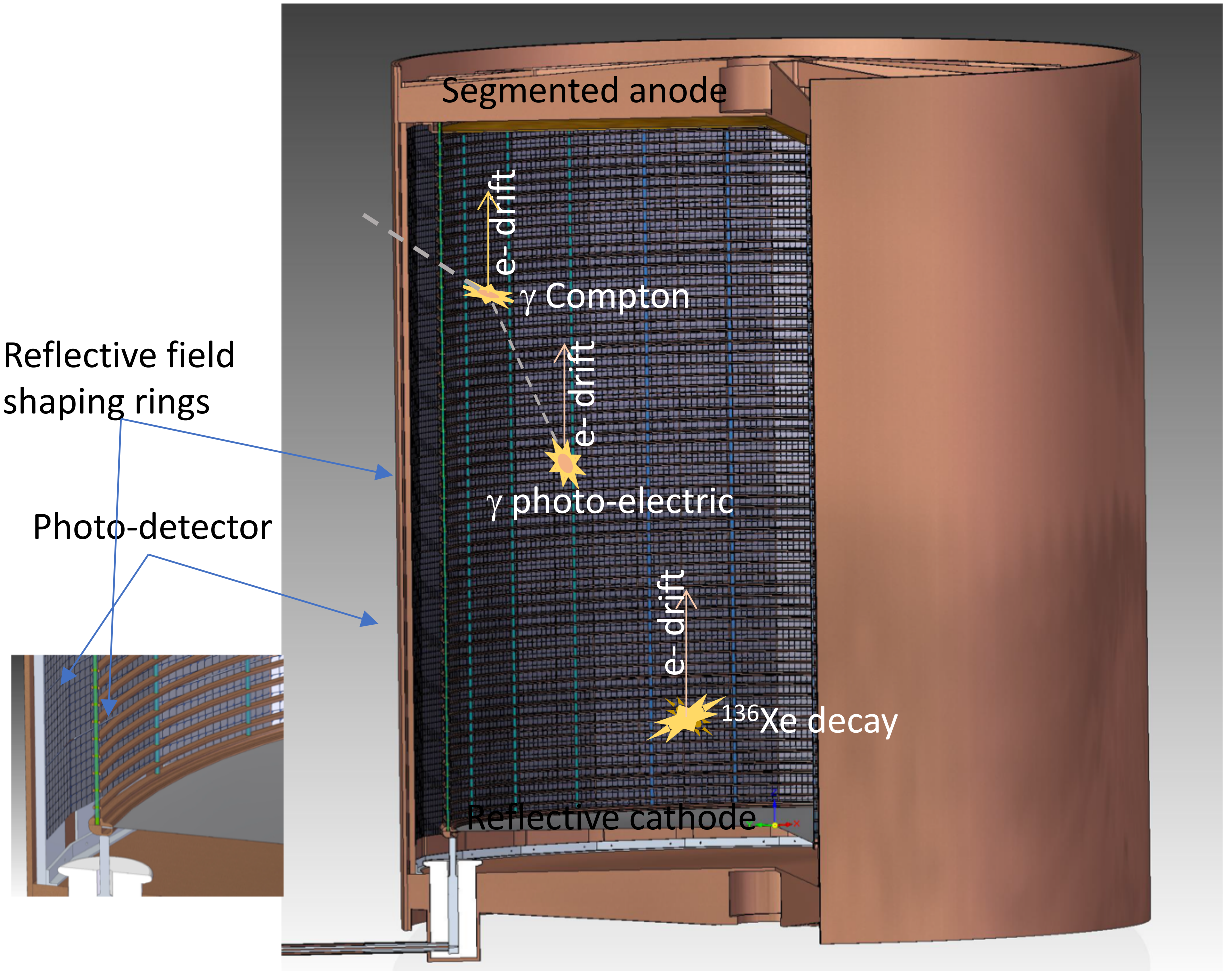

VUV-MPPC
W-wire
Am-241
VUV-black
coating
VUV-MPPC
1cm


#488-chip1
#488-chip2
#488-chip3
#488-chip4
#489-chip1
#489-chip2
#489-chip3
#489-chip4
Photon detection efficiency [%]
Over voltage [V]


#488-chip1
#488-chip2
#488-chip3
#488-chip4
#489-chip1
#489-chip2
#489-chip3
#489-chip4
Probability of crasstalk+afterpuse [%]
Over voltage [V]

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**



SiPM for lower 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

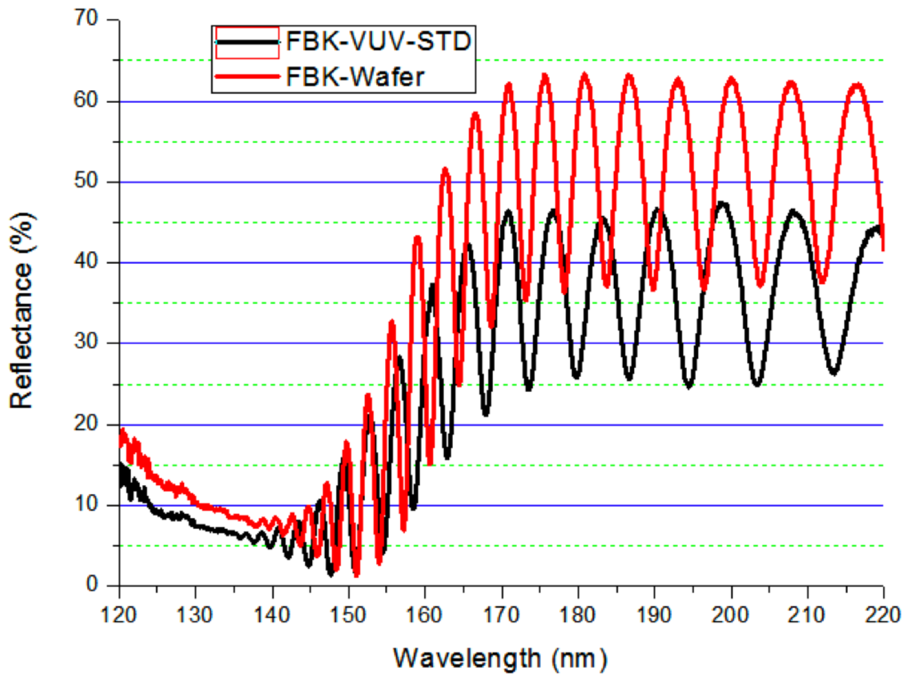
[C] NEXT Ge counting. http://arxiv.org/abs/1411.1433

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]

nEXO – photon transport

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

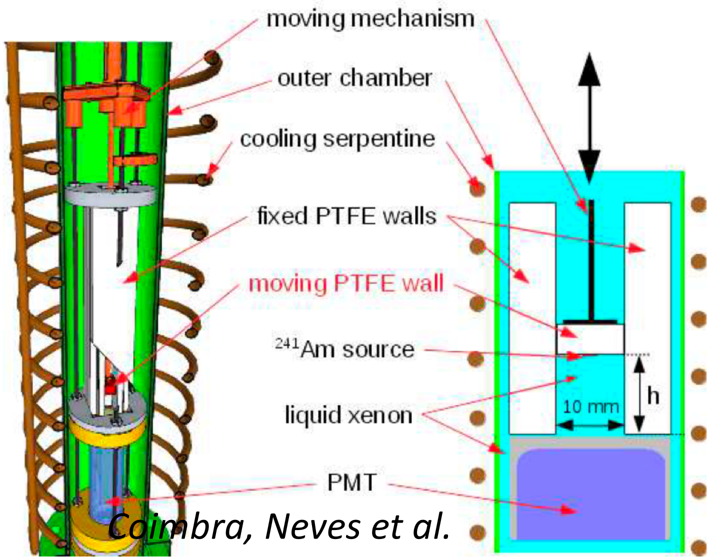
10 degree specular reflectance
For FBK SiPM and bare wafer



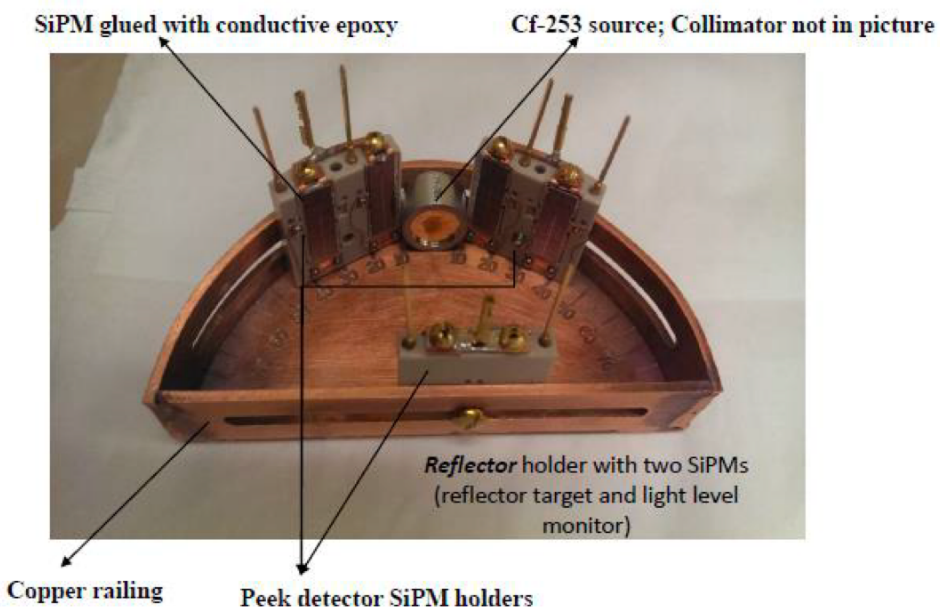
Device	Specular (177nm, 10 degree)	Diffuse(193 nm)
FBK-VUV-STD	35%	11.5%
FBK-VUV-LF	40%	12.3%
FBK-RGB	38%	17%
FBK wafer*	50%	0.16%

Photon transport characterization in general

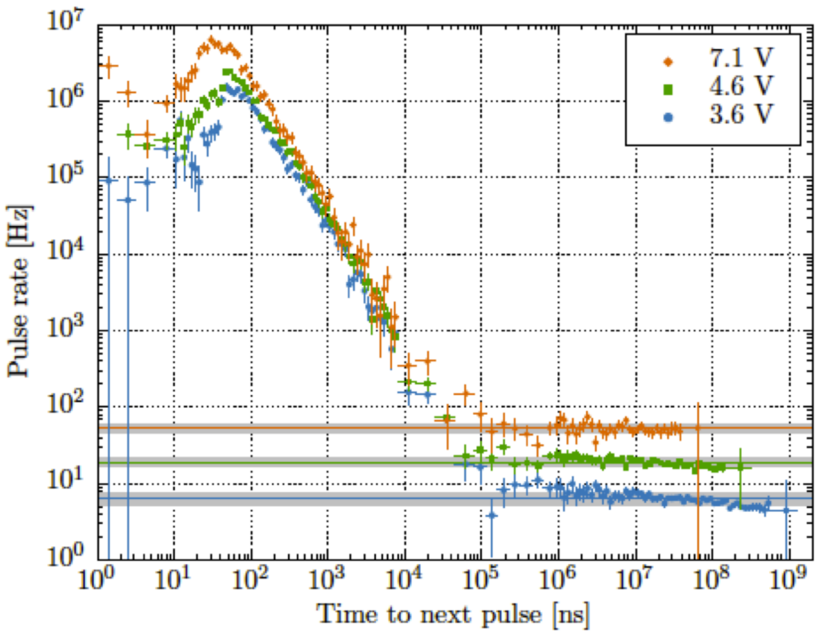
- In vacuum
  - Differential vs wavelength and angle
  - Useful for material characterization
- In liquid Xenon integrating
  - Coimbra
  - MiX (Michigan)
- In liquid Xenon differential (in angle)
  - Muenster
  - Optics characterization at U.Alabama
    - Key element very absorptive VUV material (e.g. Actar)

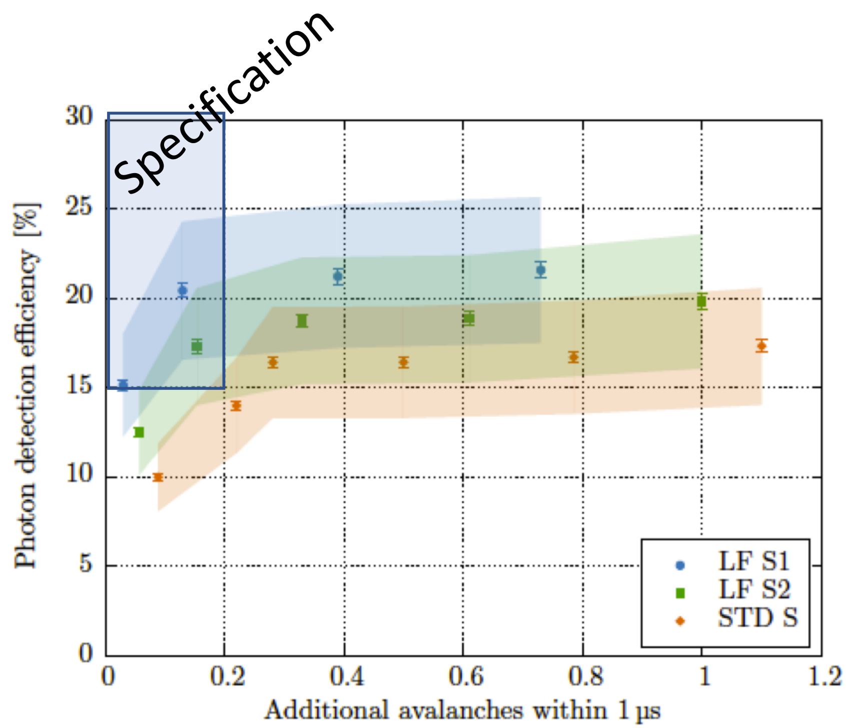


Coimbra, Neves et al.



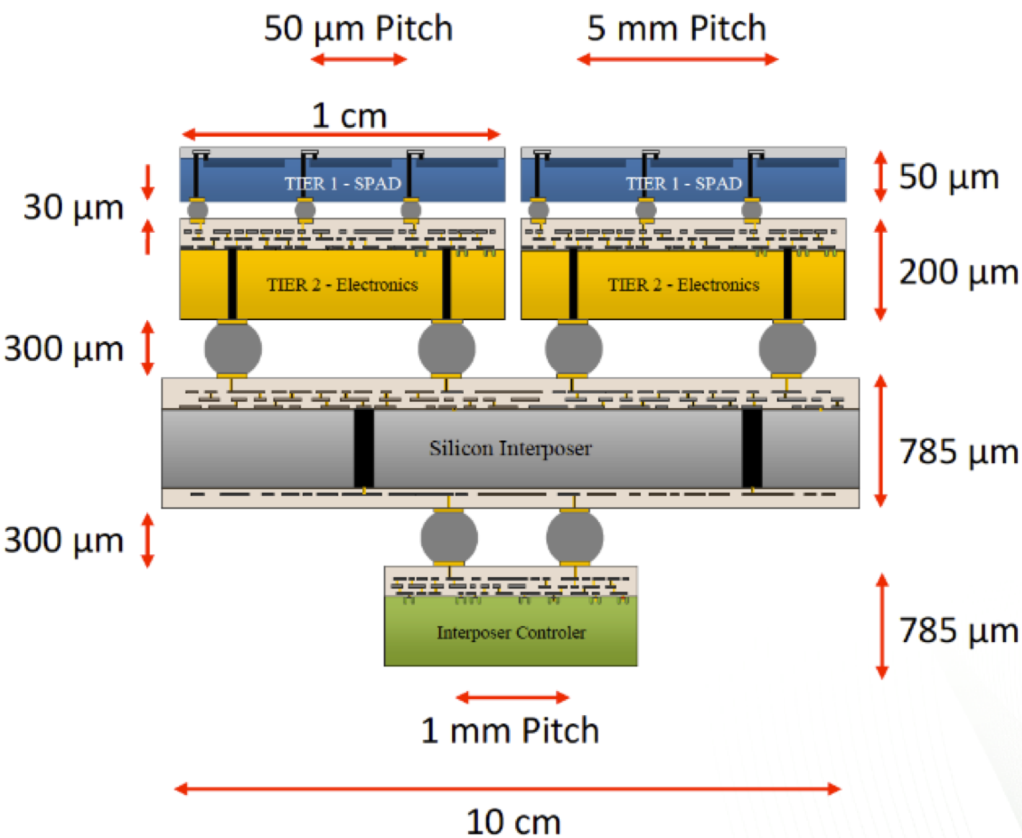
nEXO –SiPM





Also, Hamamatsu VU4 meets specifications

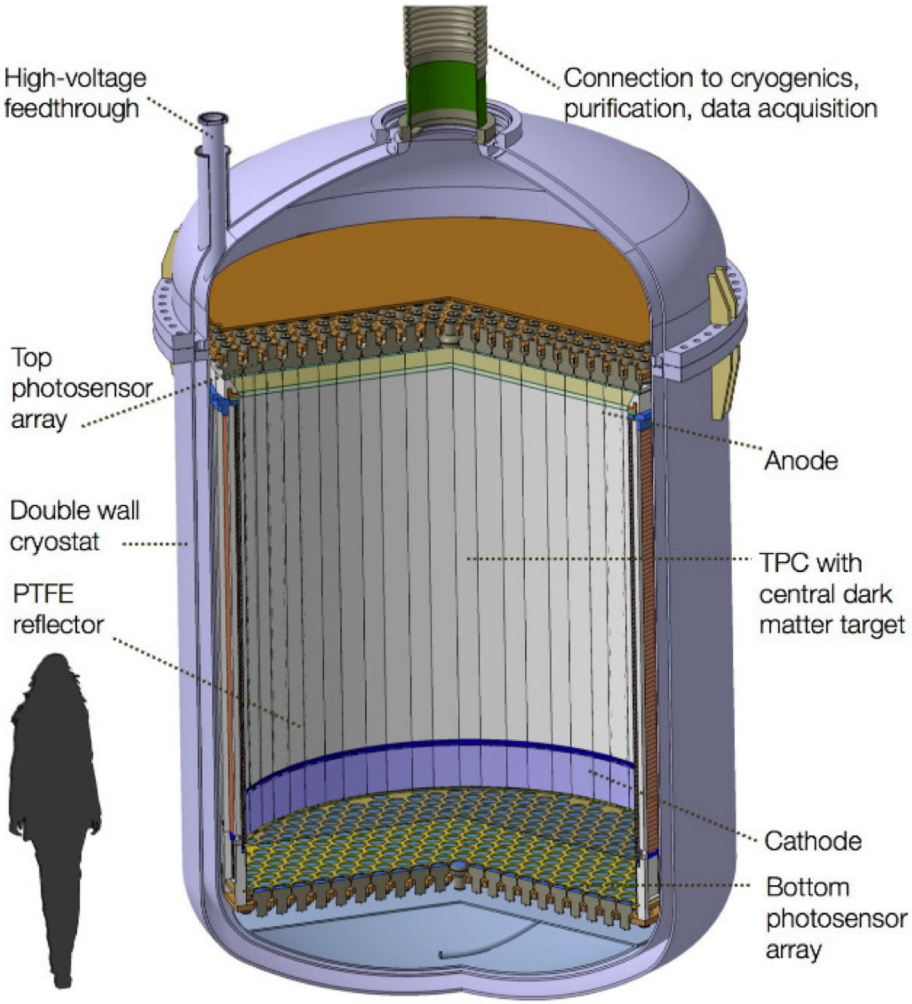
nEXO - 3DdSiPM



U. Sherbrooke (QC, Canada)

- 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

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?

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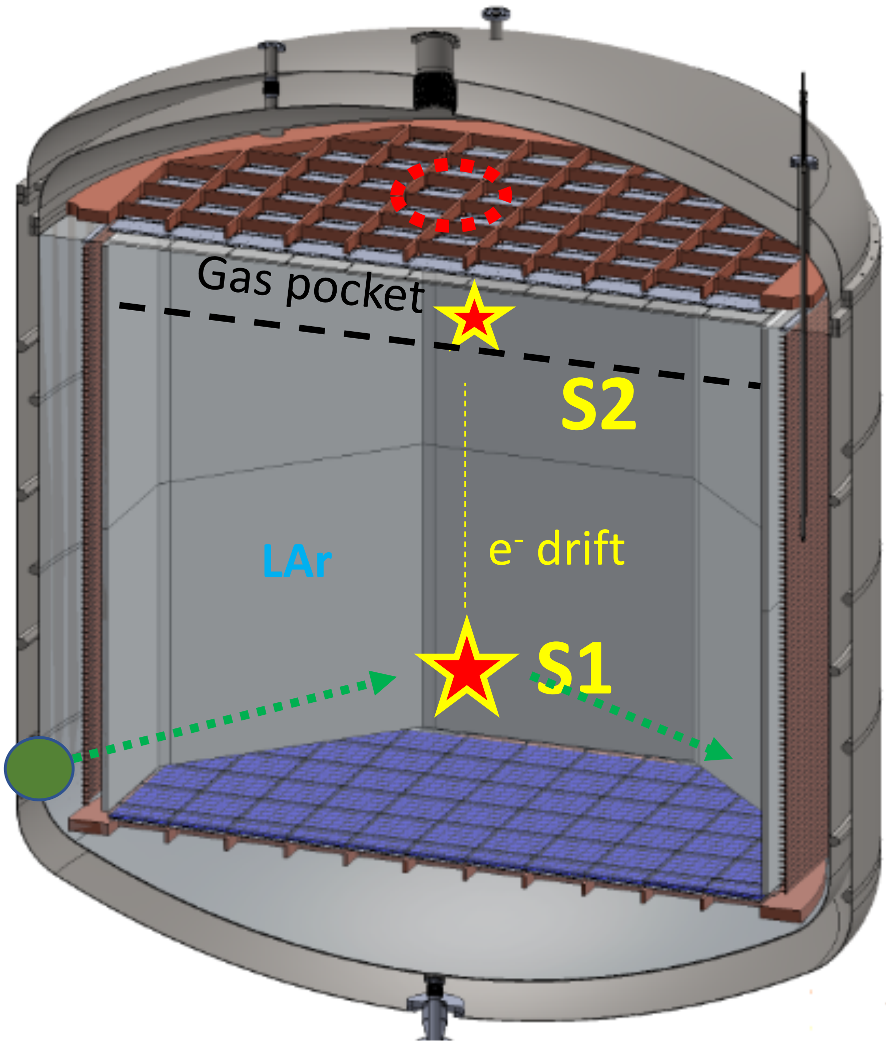
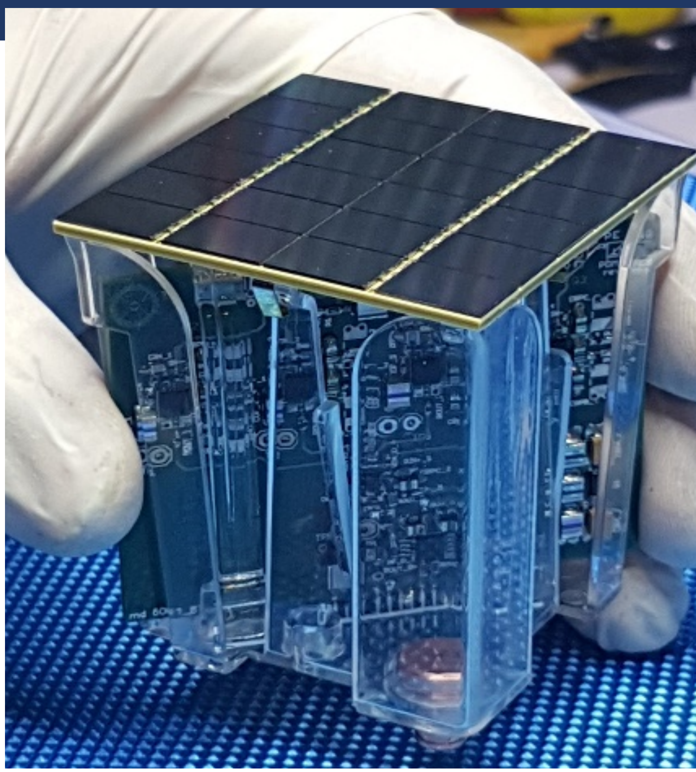
Dark Matter – DarkSide-20k

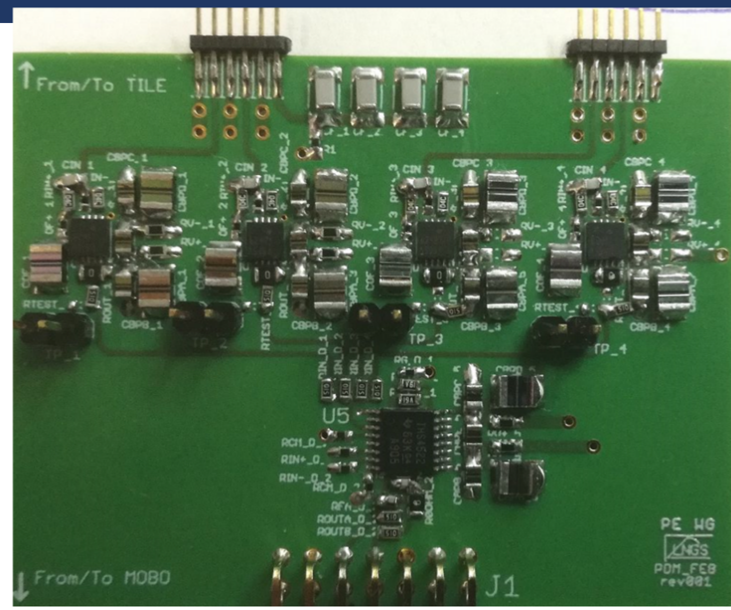


- Dark matter search experiment with 20t of LAr depleted in LAr
- 15 m2 of SiPM in TPC
  - + xxx m2 of SiPM in veto
- Blue light detection with WLS (TPB)
- Granularity not needed
- Small after-pulsing needed

DarkMatter – DarkSide-20k SiPM

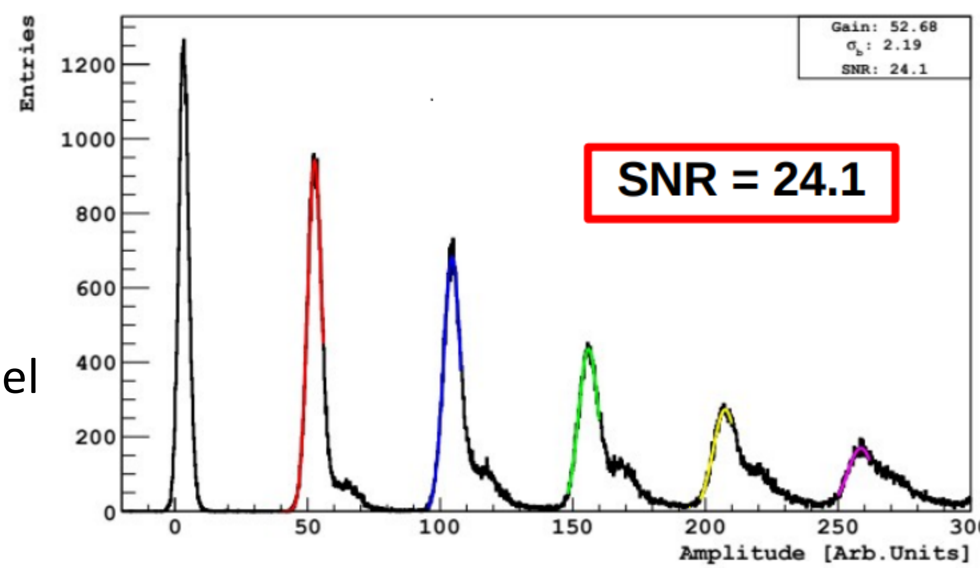


SiPM tile conectors



4 TIASs (6 SiPMs each)

Summing stage



FBK NUV-HD triple dose

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

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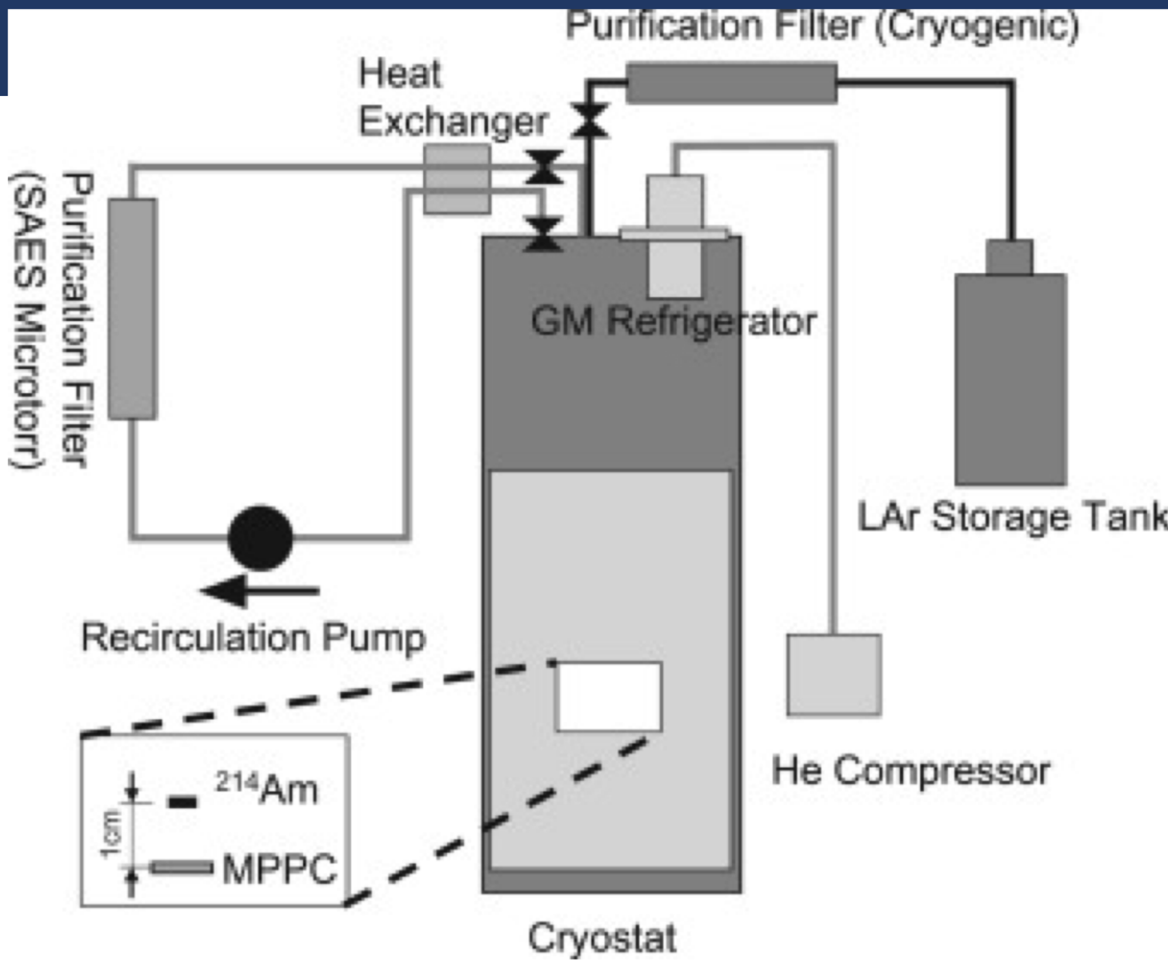
DarkMatter - >200t of LAr

- Physics case for another x10-x20 detector beyond DarkSide-20k is compelling
  - Reach neutrino floor
- Technology single phase vs double phase not decided
  - Very long drift may be challenging for double phase
  - But synergy with DUNE
- With single phase, need 100-200 m^2 of SiPM along walls
  - Low radioactivity
  - Timing resolution for single-site (WIMP, beta) vs double site (neutron, gamma) rejection?
  - Fine granularity for surface event rejection?
  - 3DdSiPMs have a lot of pros: no after-pulsing, excellent timing, low power consumption. But scalable?
- Time scale > 2025

Direct detection of 128nm light



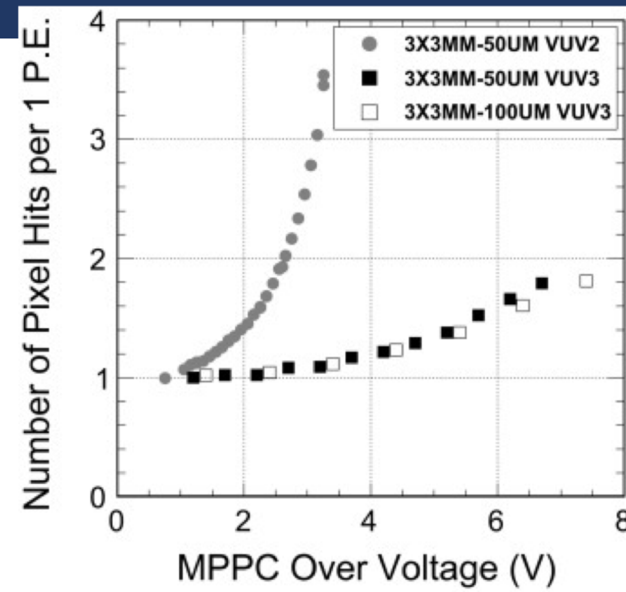
Performance of VUV-sensitive MPPC for liquid argon scintillation light

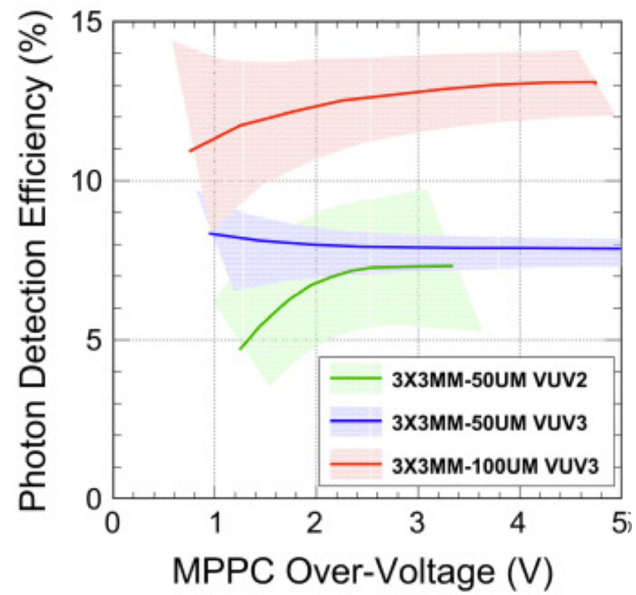
T. Igarashi, M. Tanaka, T. Washimi, K. Yorita

Show more

https://doi.org/10.1016/j.nima.2016.07.008

Get



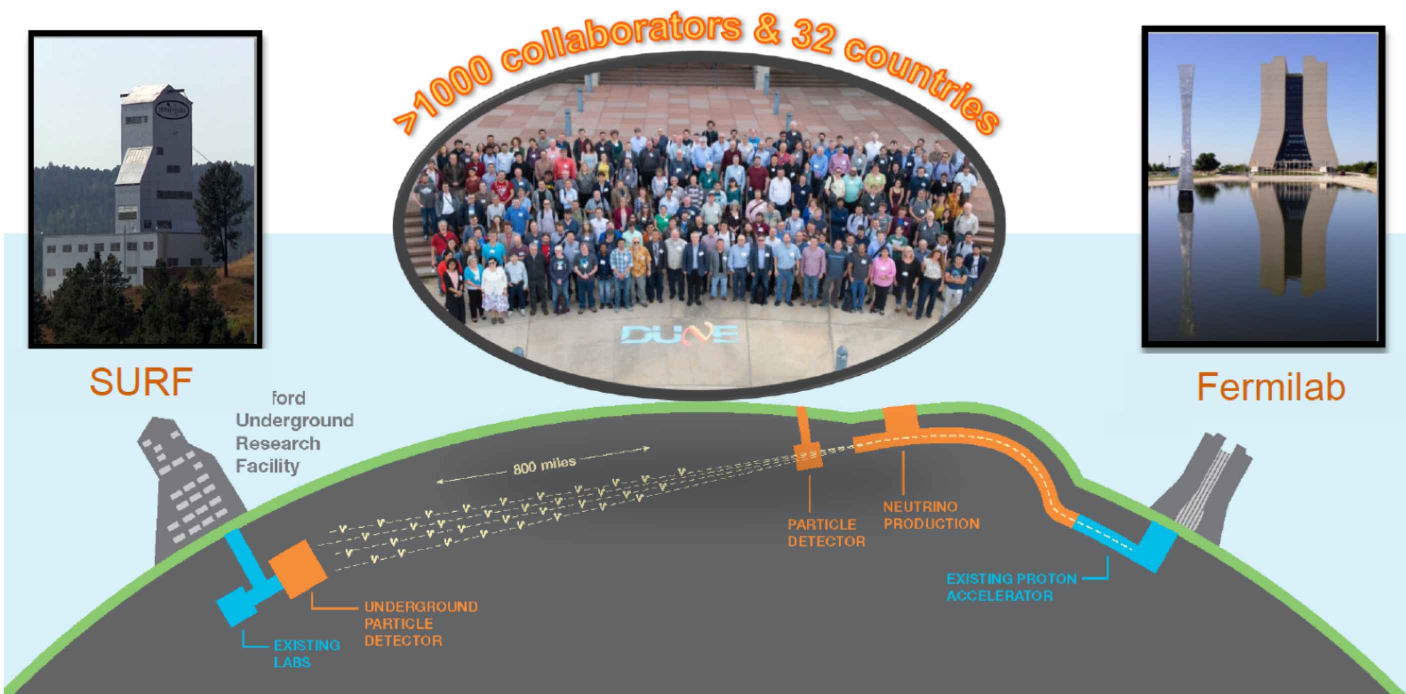


DUNE – liquid Argon

DEEP UNDERGROUND NEUTRINO EXPERIMENT

DUNE Experiment

Observe ν_e appearance and ν_μ disappearance at long baseline in wideband beam to measure MH, CPV, and neutrino mixing parameters in a single experiment. Deep underground location reduces cosmogenic background and enables sensitivity to low-energy physics.



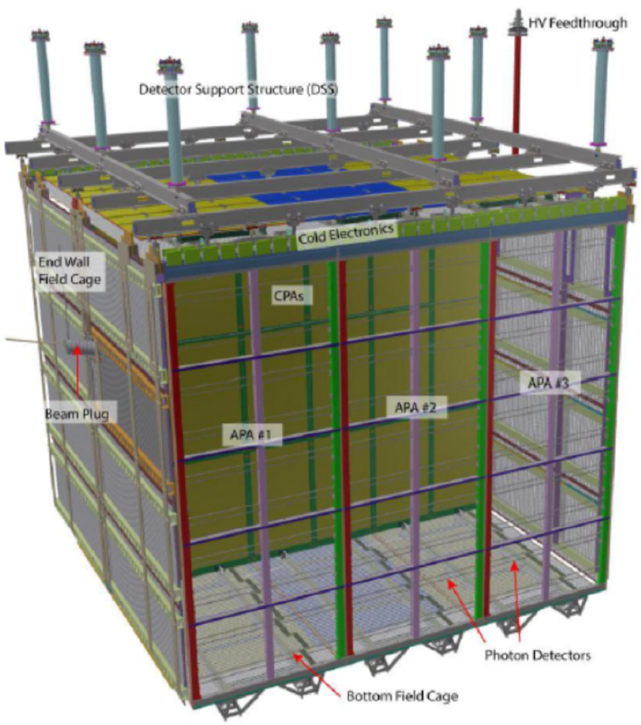
DUNE prototyping

DEEP UNDERGROUND NEUTRINO EXPERIMENT

Single & Dual Phase Prototypes

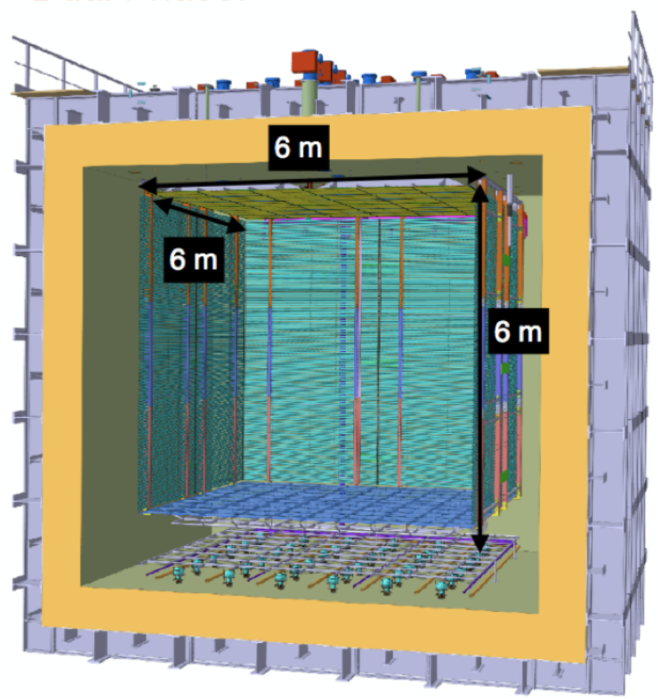
Enabled by CERN Neutrino Platform

Single Phase:



Active volume 6.9 x 7.2 x 6 m^3

Dual Phase:



Active volume 6 x 6 x 6 m^3

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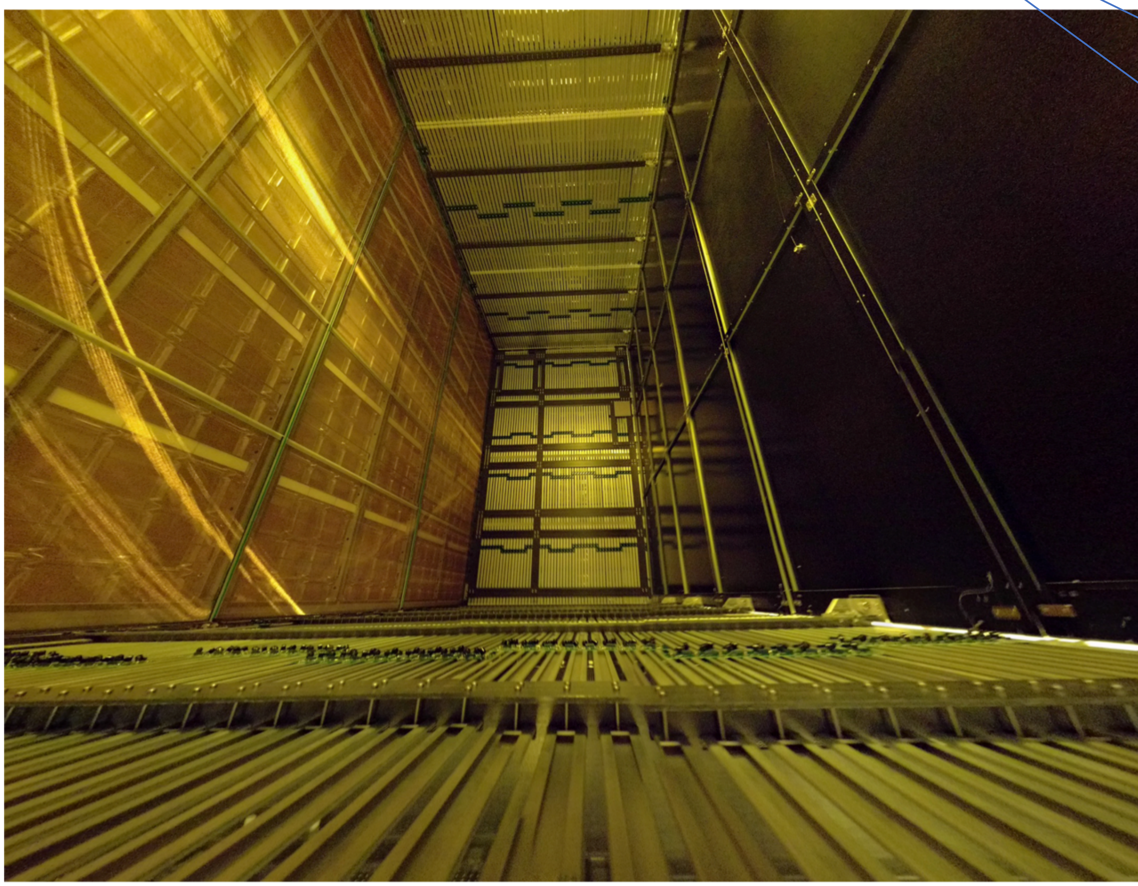
DUNE single phase

Photo-detector plate



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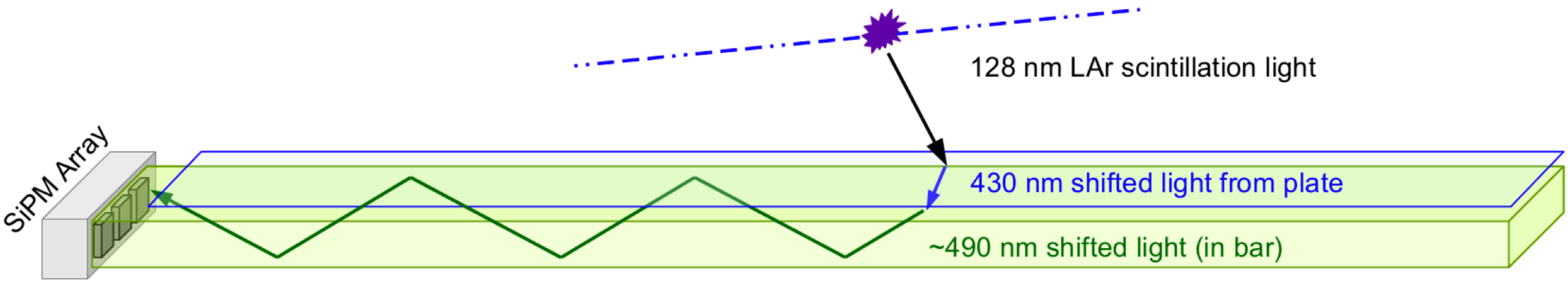
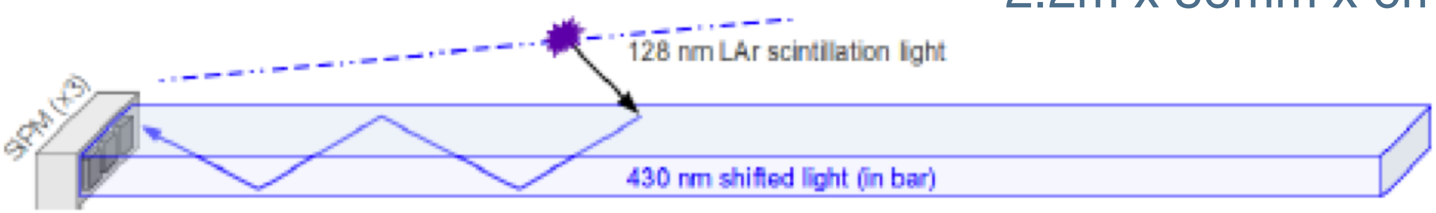
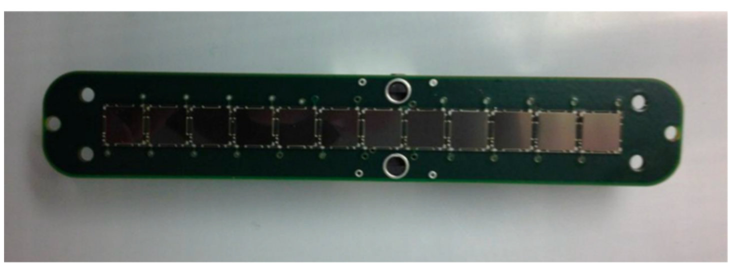
Wavelength shifter concept



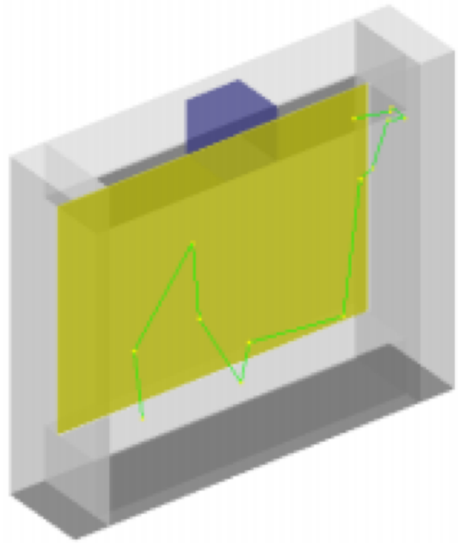
2.2m x 86mm x 6mm (groups of 10)

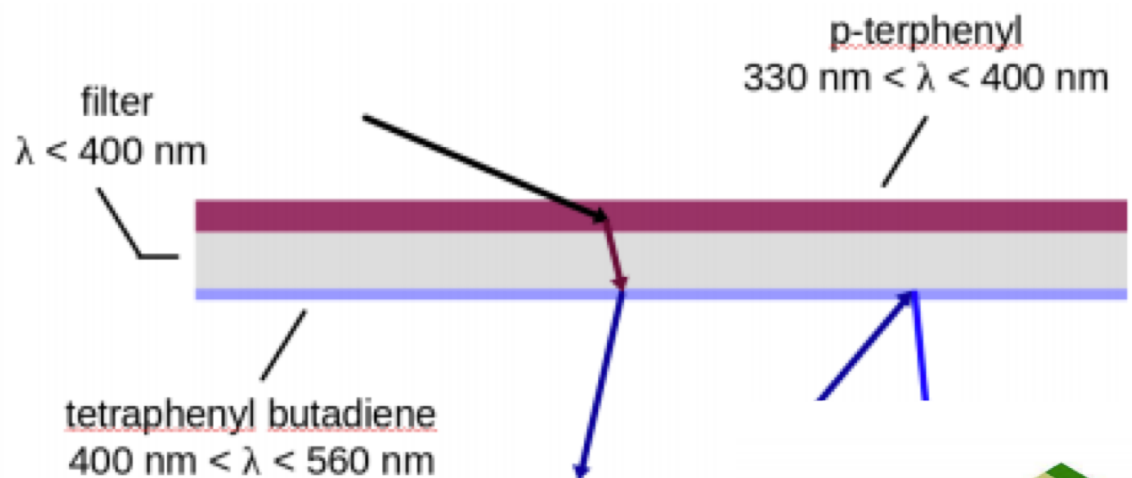


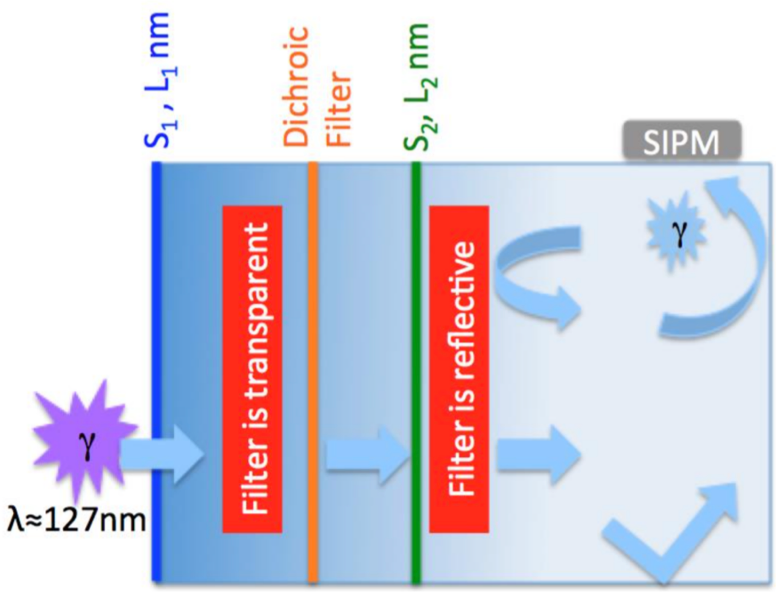


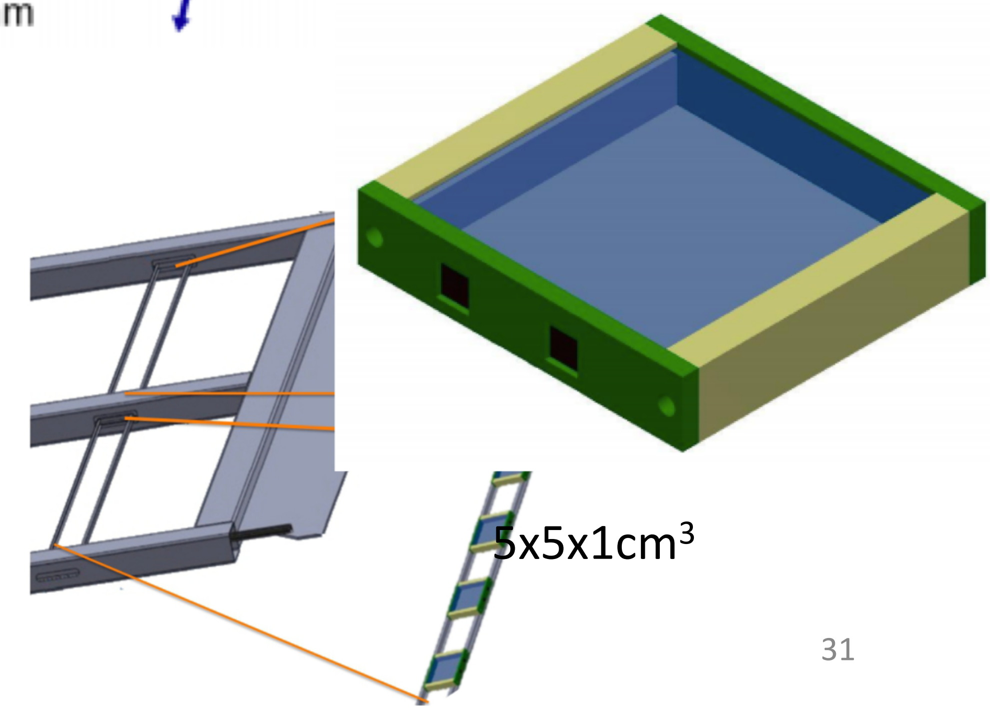
12 SensL 6x6 mm2 SiPMs
Ganged together -> 4.32cm^2 per electronics channel

Alternate option. ARAPUCA

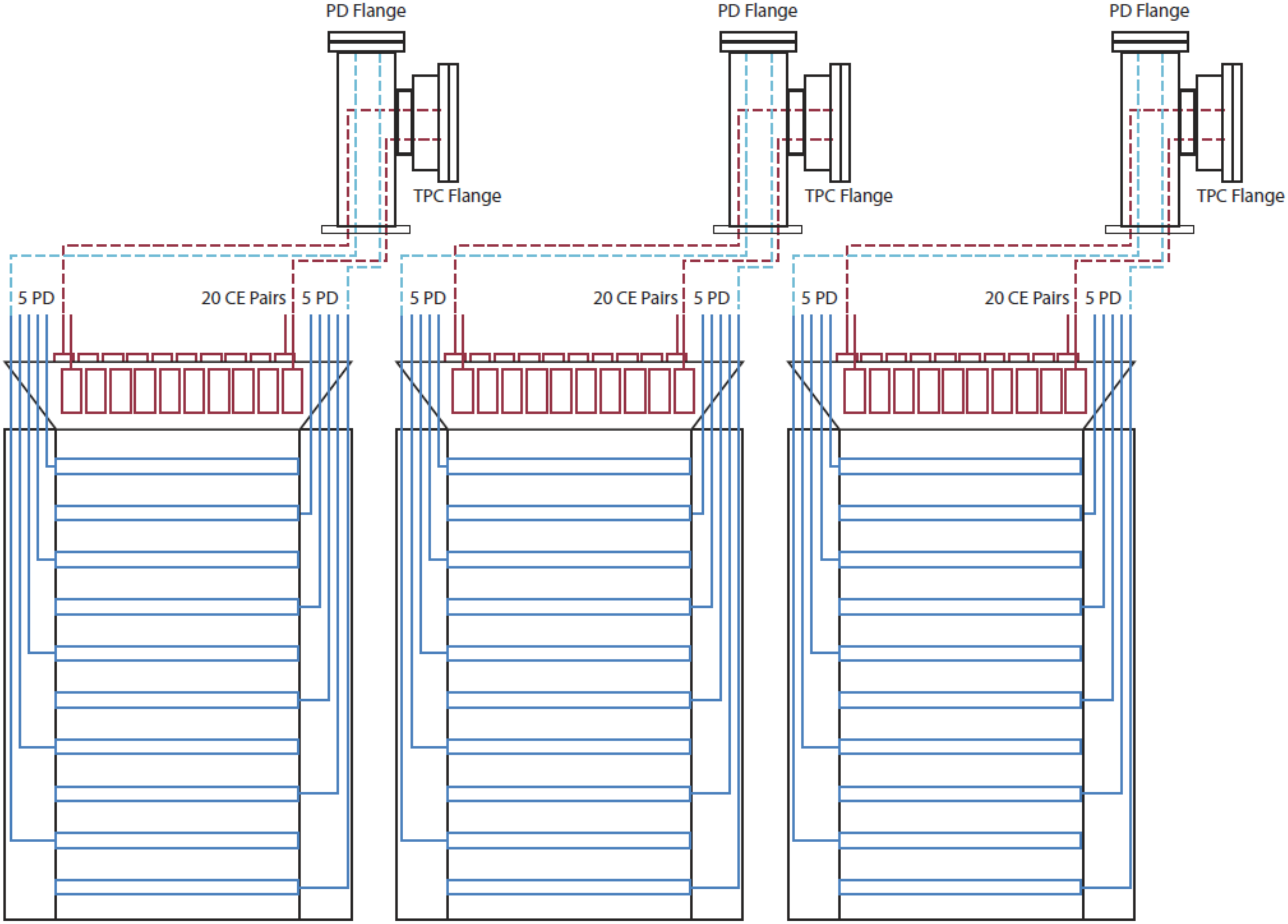








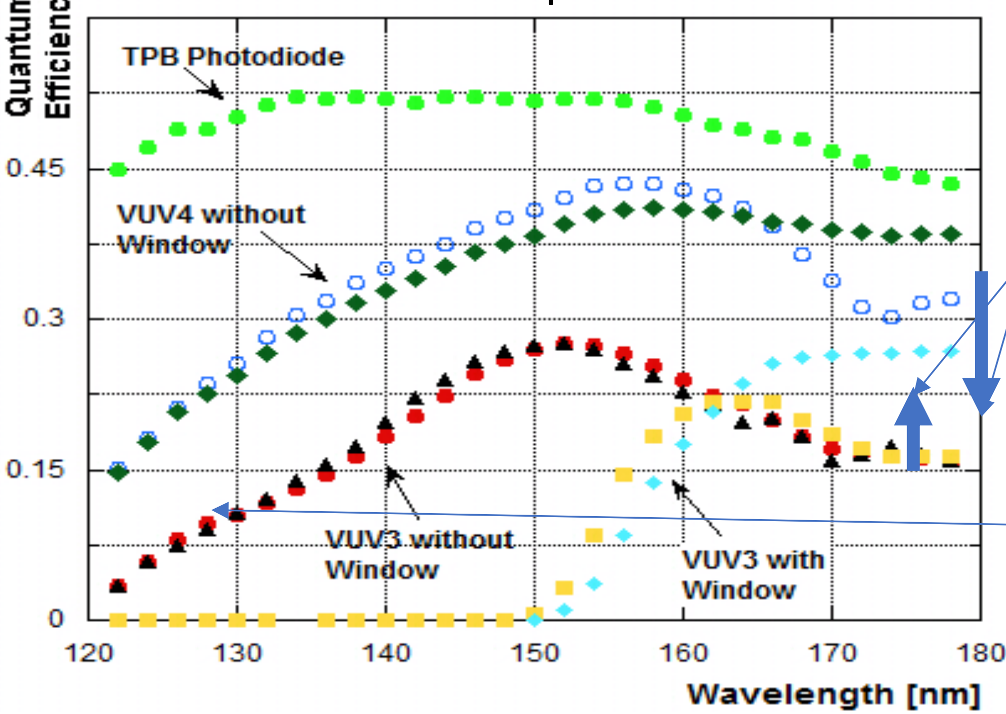
Proto-DUNE-SP lay out

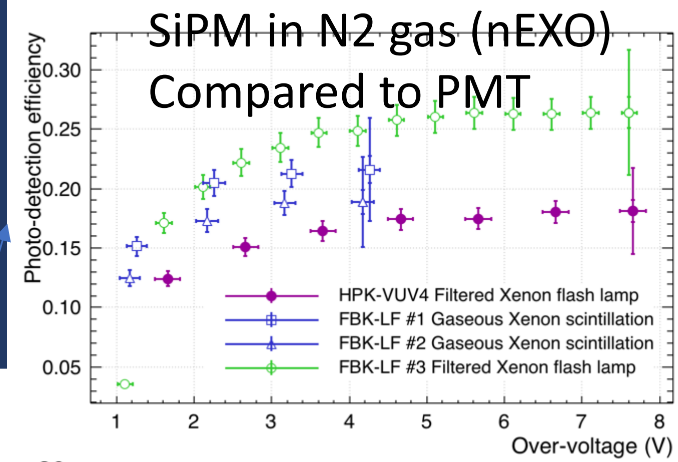


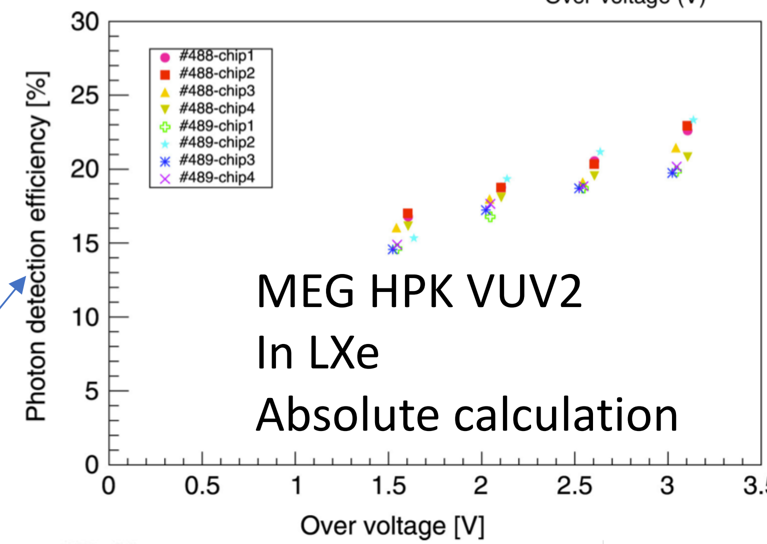
The PDE issue?

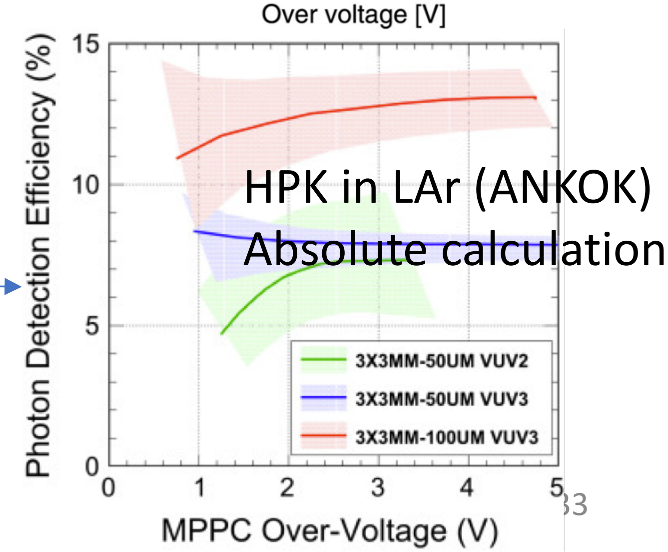
M. Bonesini[1], T. Cervi[2], A. Menegolli[2], M. C. Prata[2], G.L. Raselli[2], M. Rossella[2], A. Falcone[2], M. Torti[1]
[1]Istituto Nazionale di Fisica Nucleare, Sezione di Milano Bicocca
[2]Istituto Nazionale di Fisica Nucleare, Sezione di Pavia and Università degli Studi di Pavia

Reference to photodiode









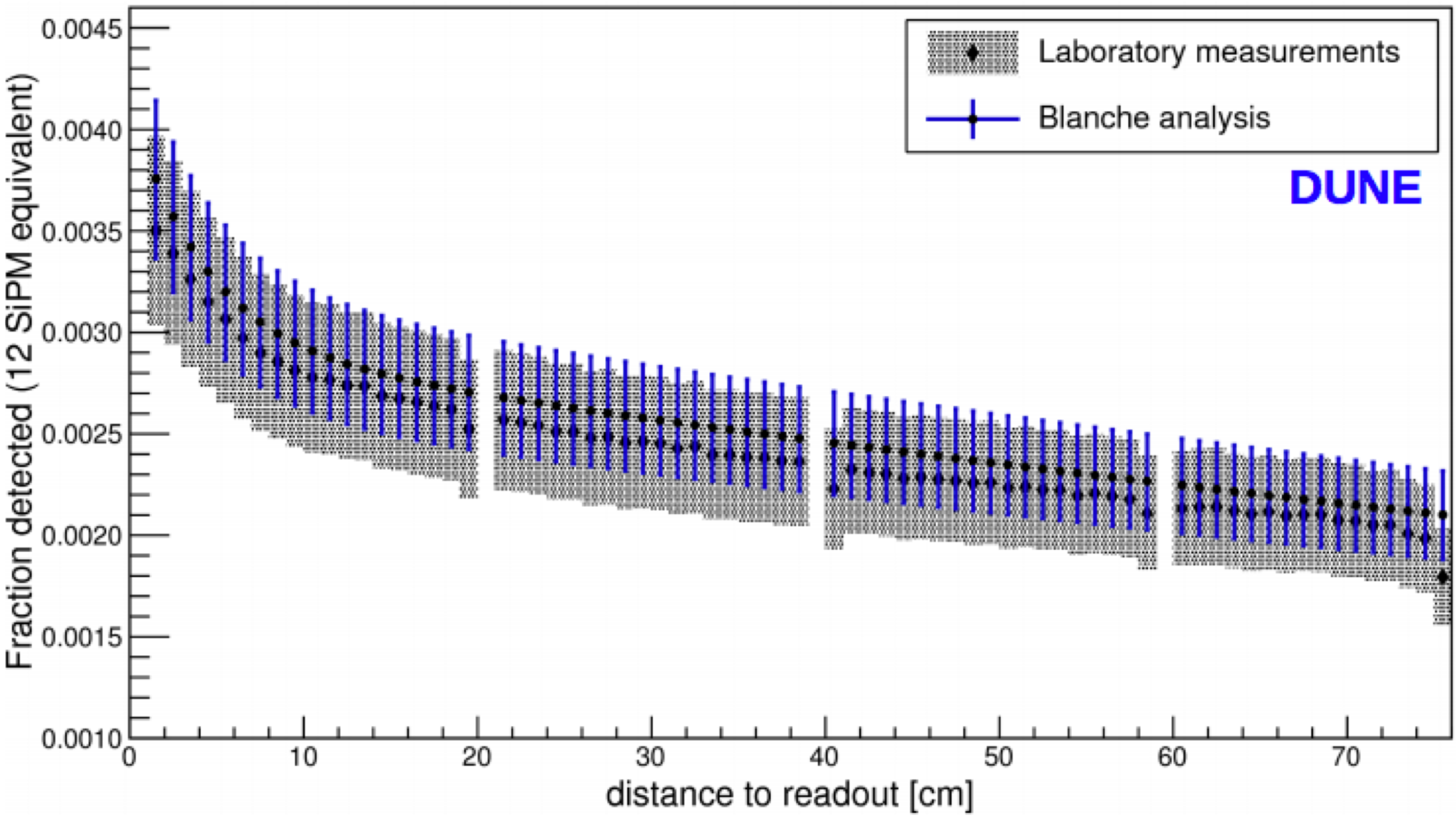
TRIUMF

Summary and comments

- Lots of experiments looking into using SiPMs in LXe and LAr
  - Low temperature enables large area
- Good efficiency (>20%) established at 175nm (LXe)
  - Though some remaining controversies
  - >50% is achievable in principle with anti-reflective coating
- Baseline for LAr is to use wavelength shifting materials
  - Direct detection is emerging
- Photon transport in LAr and LXe should be more extensively studied
- Beyond 2020, digital SiPMs may overtake analog SiPMs

The end

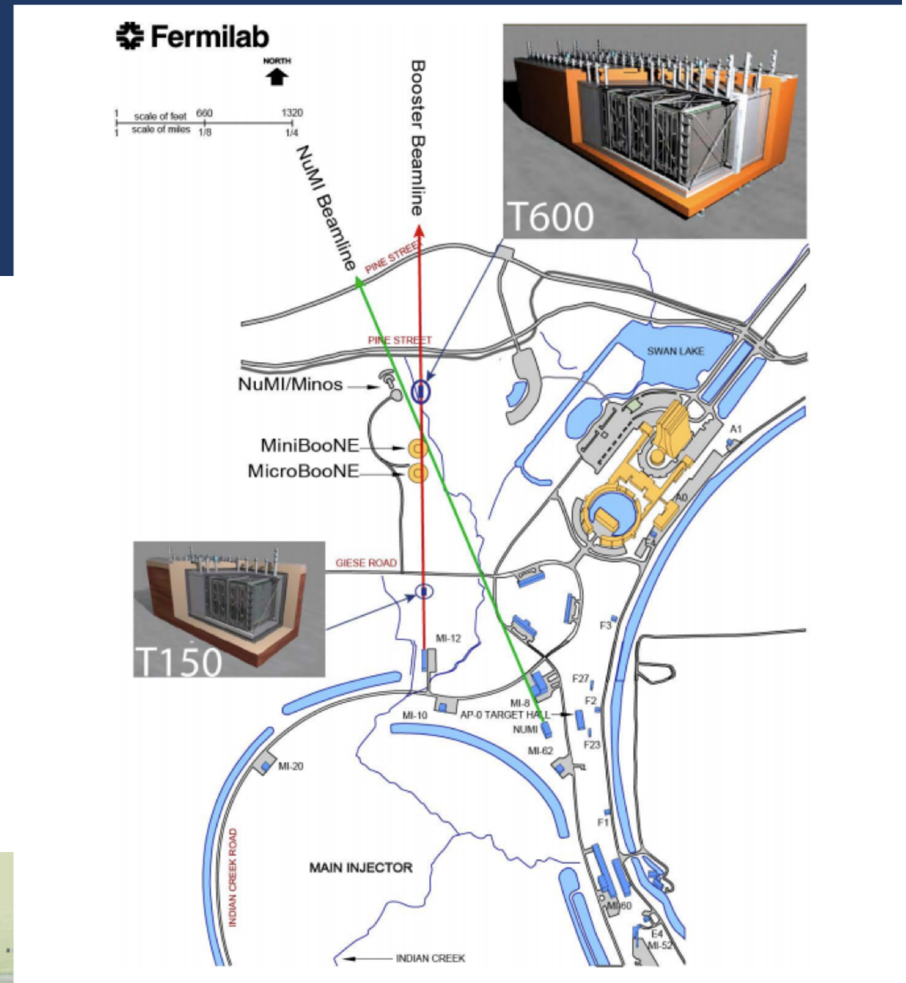
TRIUMF

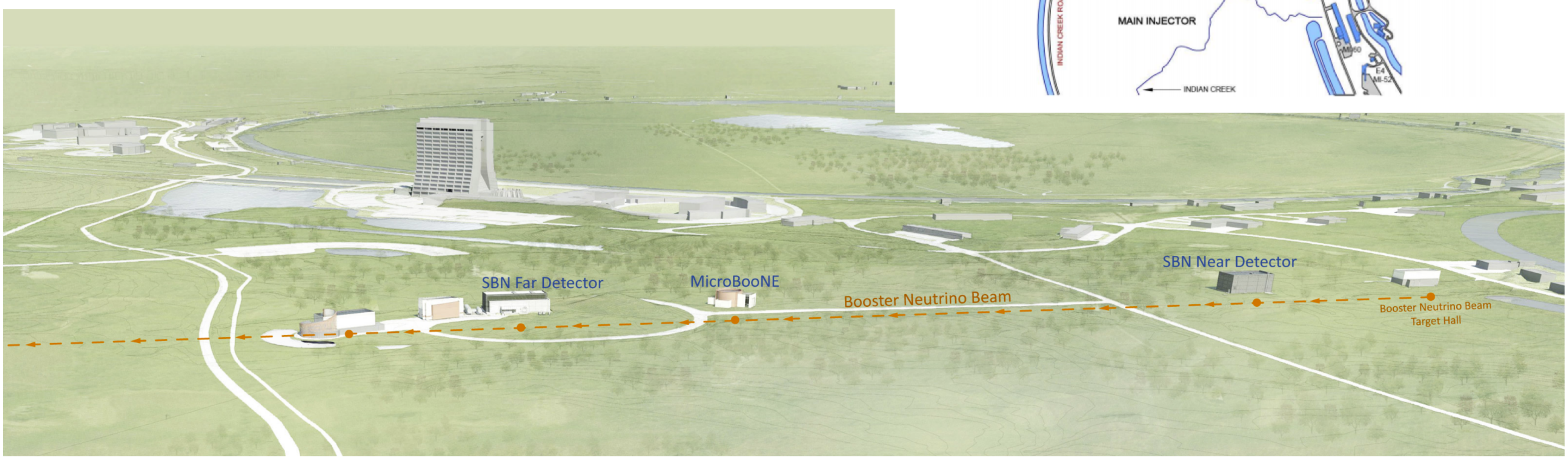


Laboratory measurements
Blanche analysis
DUNE
Fraction detected (12 SiPM equivalent)
distance to readout [cm]
0.0010
0.0015
0.0020
0.0025
0.0030
0.0035
0.0040
0.0045
0
10
20
30
40
50
60
70

TRIUMF

DUNE prototyping





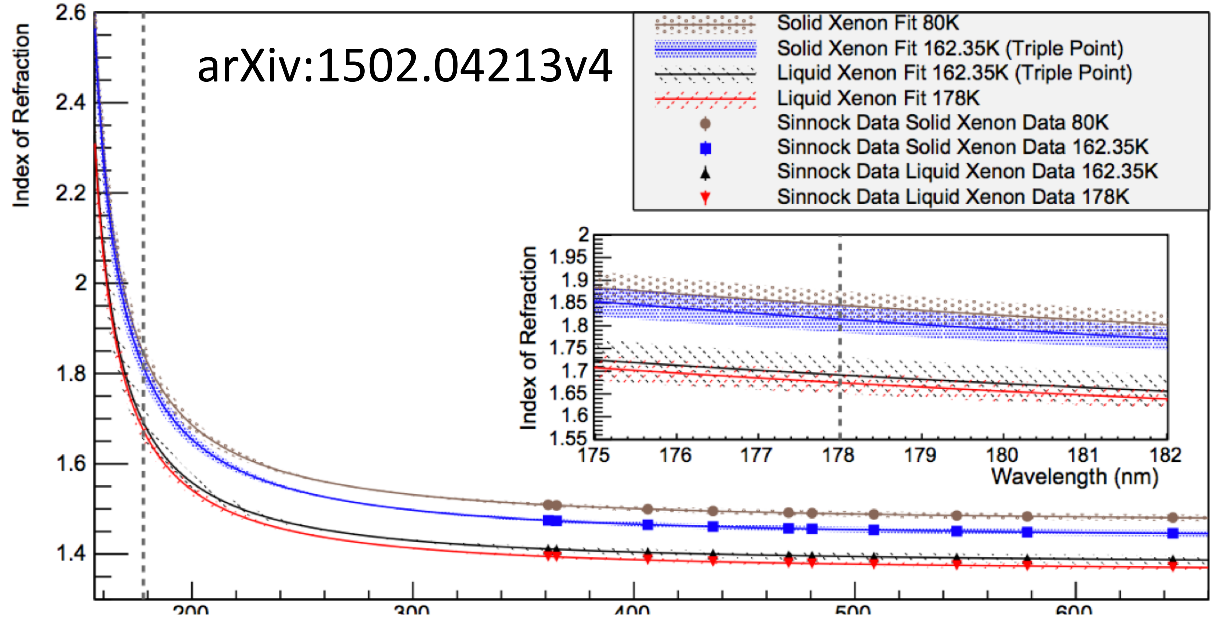
Light detection in selected experiments

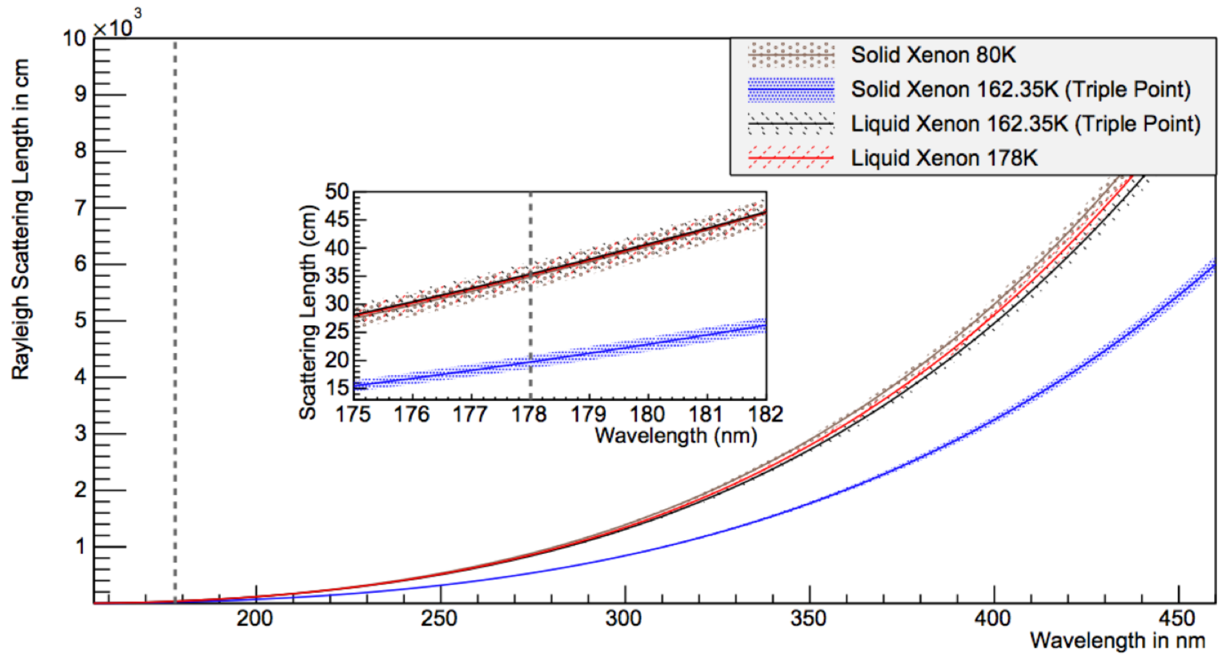
Experiment	Inferred overall efficiency (g1) Photoelectron/photon	Comment
XMASS	~15%	PMTs + high coverage
LUX	11.7 +- 0.3 %	Teflon + PMTs
PANDAX-II	11.3 +- 0.5 %	Teflon + PMTs
XENON-1T	14.4 ± 0.7 %	Teflon + PMTs
EXO-200	7-9%	Teflon + APDs
nEXO	>3%	SiPM barrel
MIX	23.9 ± 1.2 %	PMTs + Teflon
PIXeY	9.7+-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

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

Photon transport through liquid Xenon

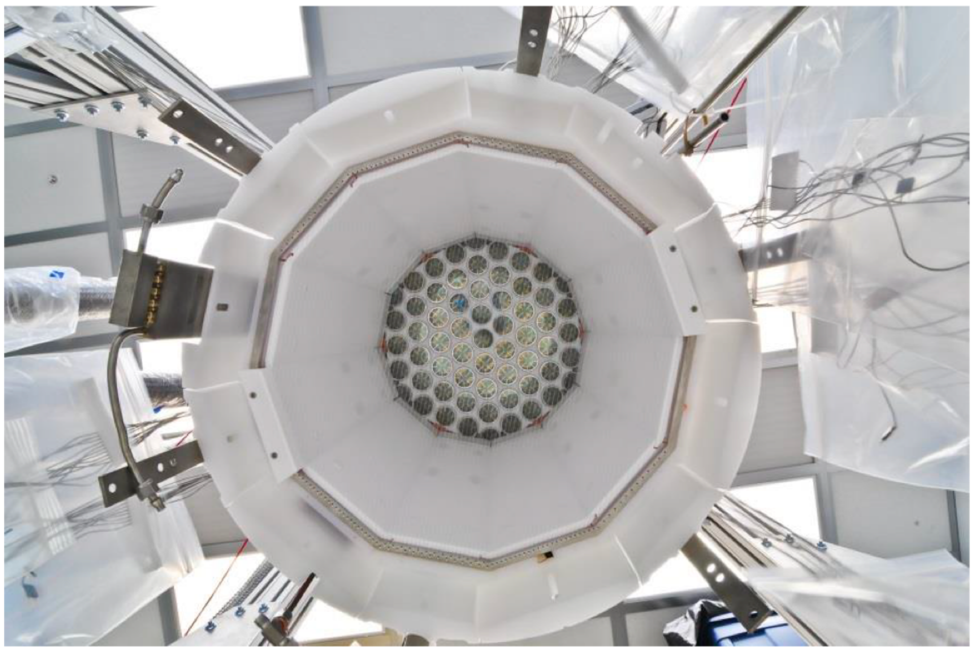
- Attenuation length, ~4m but dependent on purity
- Is the index of refraction measured well enough?





The wonder of teflon

- The inside of LUX

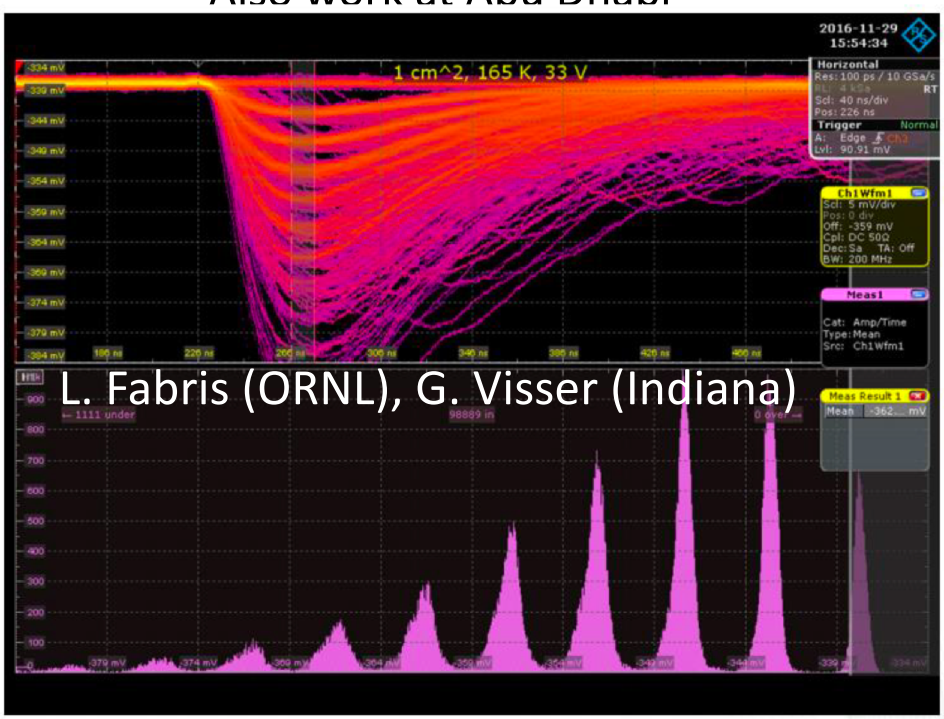


- 10% overall detection efficiency with a 35% efficiency PMT means the transport efficiency is ~30%
- 30% efficiency is outstanding with a photo-coverage <10%

TRIUMF

Gain/noise and digital SiPMs

- Noise specifications < 0.2PE
- Power specification ~100W for 4 m2
- Capacitance ~nF/cm^2
- Tough but it works
  - nEXO R&D
  - Also work at Abu Dhabi

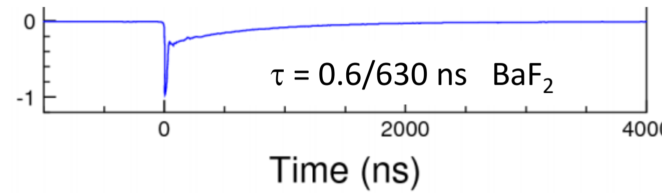


L. Fabris (ORNL), G. Visser (Indiana)

- 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

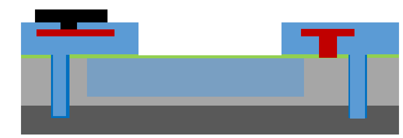
D. G. Hitlin, Lauritsen Laboratory, Caltech
M. Hoenk, J. Hennessey, A. Jewell, Jet Propulsion Laboratory, Caltech
G. Paternoster, A. Gola, FBK



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

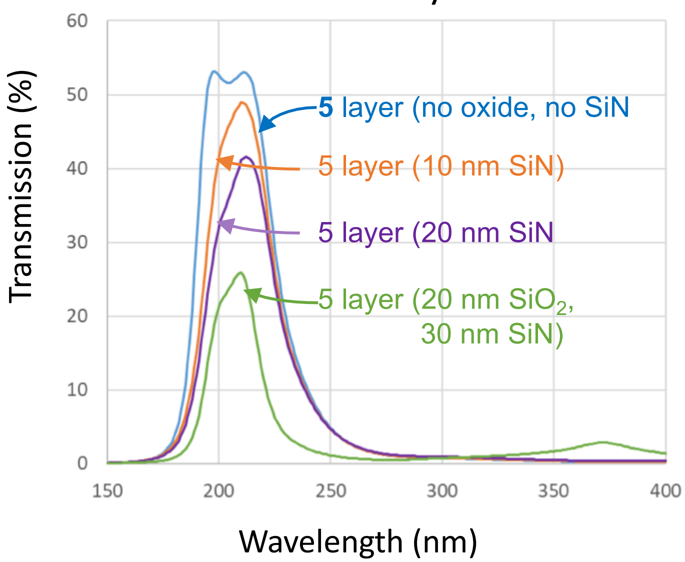
Caltech/JPL and FBK are developing a SiPM with an integrated interference filter for this purpose

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

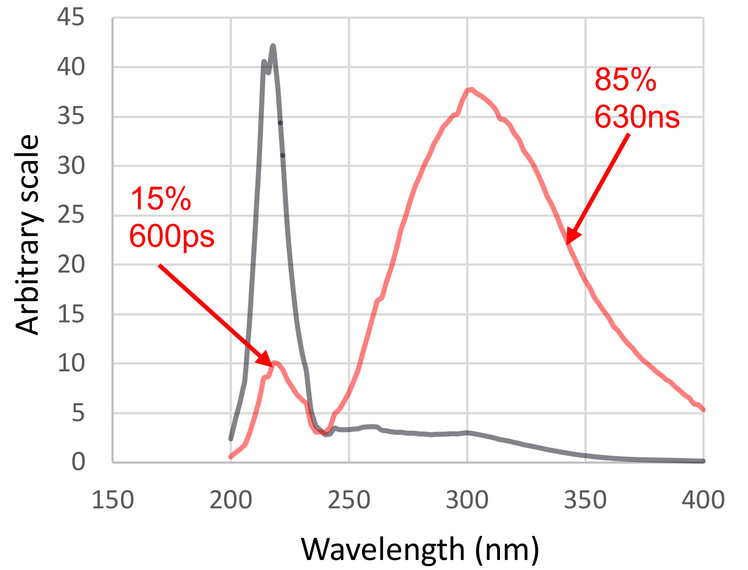


SiPM with thin entrance window and guard ring structure

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