Light detection in liquid Xenon

F. Retière

Disclaimer 1. I ran out of time to properly cite everyone. Sorry if there is only an arxiv link attached to material
Disclaimer 2. Sorry if I am not mentioning your work. Being fully inclusive is very tough!

TRIUMF

Present and future liquid Xenon detector

Experiment	Application	Status	Mass	Type
XMASS	DM	Operation	832kg	Scint.
XENON-1T	DM	Operation	1,042kg	Scint. + charge → elum.
LUX	DM	Operation	370kg	Scint. + charge → elum.
PANDAX-II	DM	Operation	580kg	Scint. + charge → elum.
XENON-nT	DM	Construction	6,000kg	Scint. + charge → elum.
LZ	DM	Construction	7,000kg	Scint. + charge → elum.
DARWIN	DM++	Design	50,000kg	Scint. + charge → elum.
EXO-200	$0\nu\beta\beta$	Operation	250kg	Scint. + charge
nEXO	$0\nu\beta\beta$	Design	5,000kg	Scint. + charge → elum.
RED-100	Coherent ν	Limbo?	200kg	Scint. + charge → elum.
XEMIS2	PET	Construction	200kg	Scint. + charge

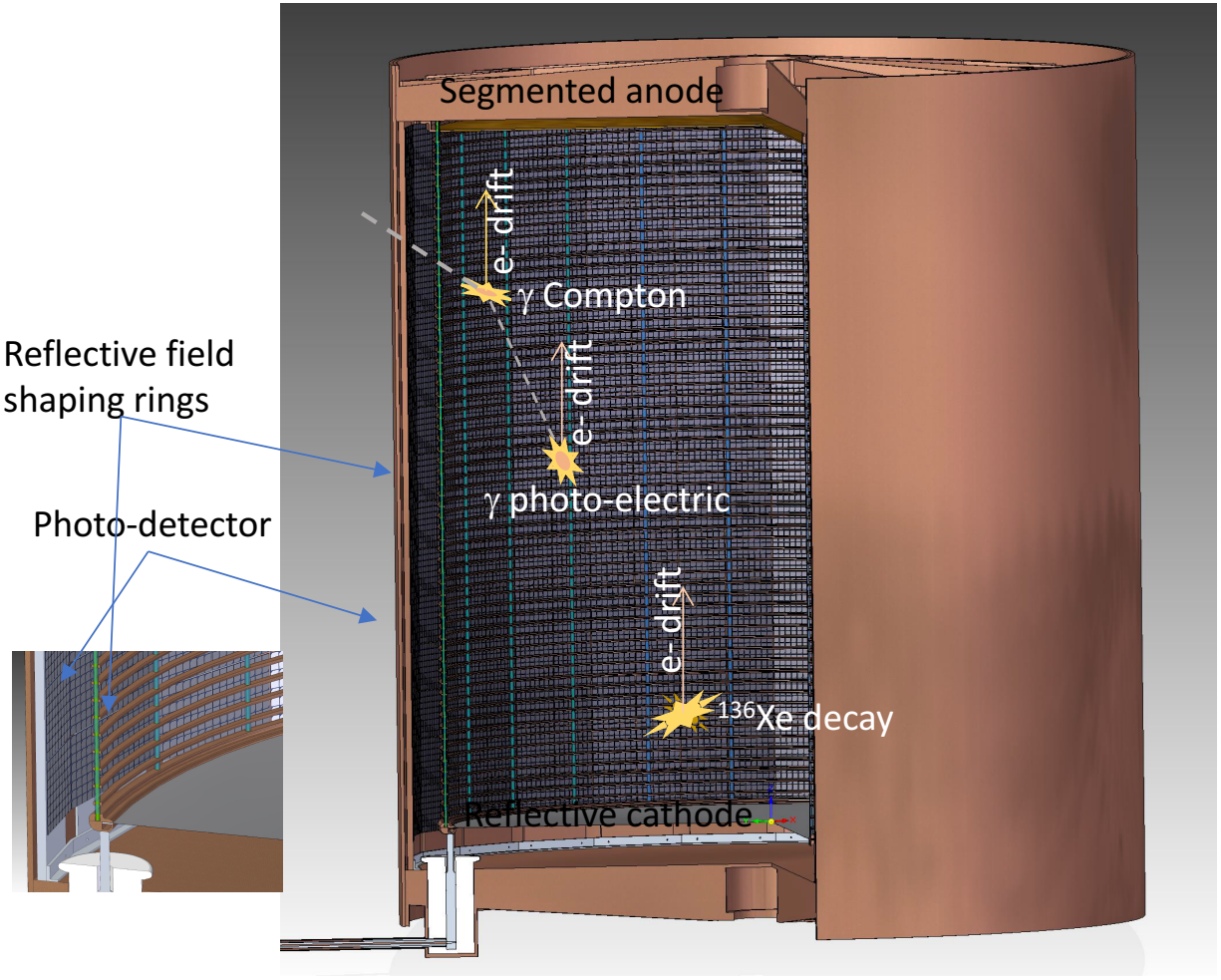
Light detection in selected experiments

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!

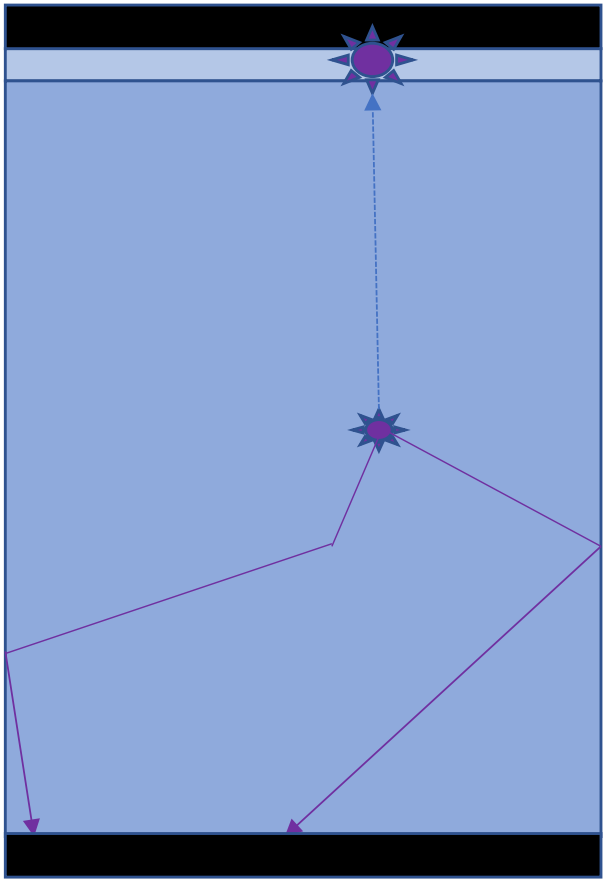
Digression about nEXO

- 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**



Outline

- Light production
  - Scintillation
  - (Electroluminescence)
  - Cerenkov
- Light transport
  - Bulk property
  - Surfaces
- Light detection
  - PMTs
  - SiPMs
  - Others…



Scintillation 1. Wavelength

arXiv:1511.07723v1

Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment
Volume 763, 1 November 2014, Pages 533-537

Time profile of the scintillation from liquid and gaseous xenon

Ikuko Murayama, Shogo Nakamura

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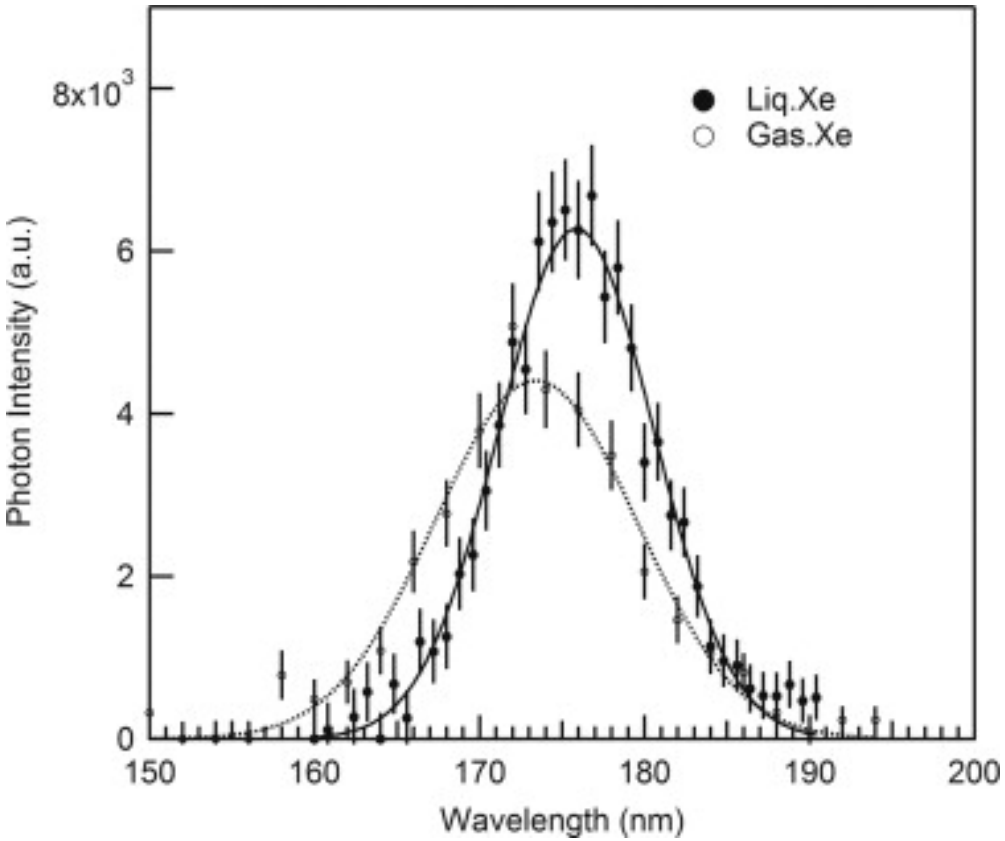
https://doi.org/10.1016/j.nima.2014.07.003 Get rights and content

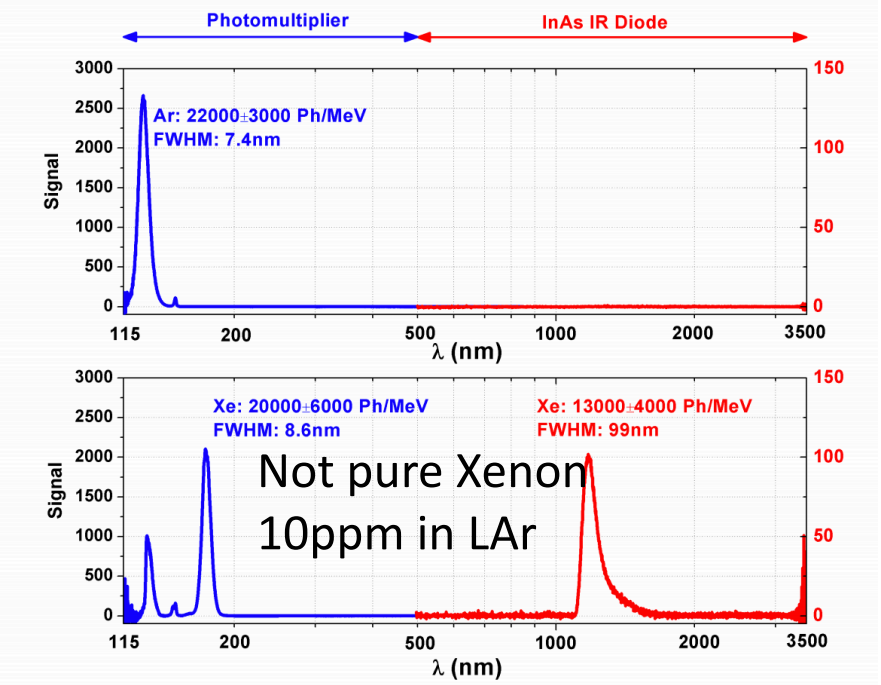


Intense Vacuum-Ultraviolet and Infrared Scintillation of Liquid Ar-Xe Mixtures

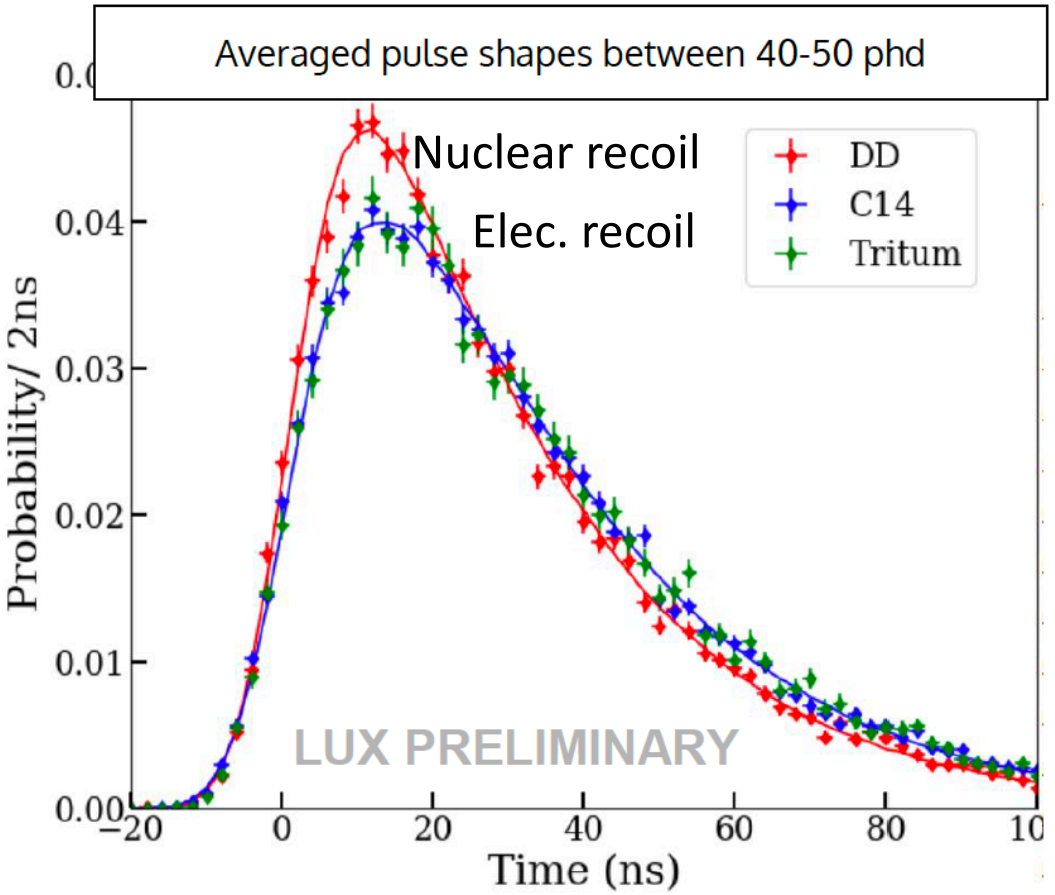
A. Neumeier[1], T. Dandl[2], T. Heindl[2], A. Himpsl[2], L. Oberauer[1], W. Potzel[1], S. Roth[1], S. Schönert[1], J. Wieser[3], and A. Ulrich[2a]

[1] Technische Universität München, Physik-Department E15, James-Franck-Str. 1, D-85748 Garching, Germany
[2] Technische Universität München, Physik-Department E12, James-Franck-Str. 1, D-85748 Garching, Germany
[3] excitech GmbH, Branterei 33, 26419 Schortens

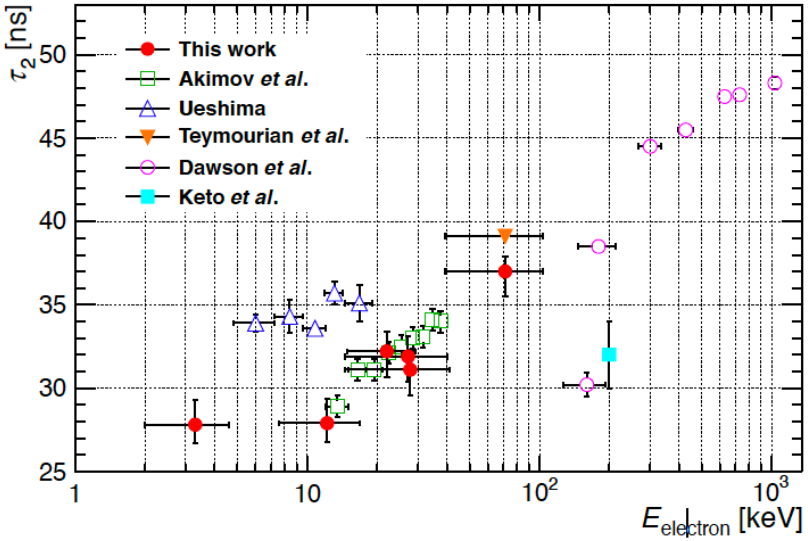
Published in EPL (2015)



Scintillation 2 Time scales



arXiv:1604.01503v3

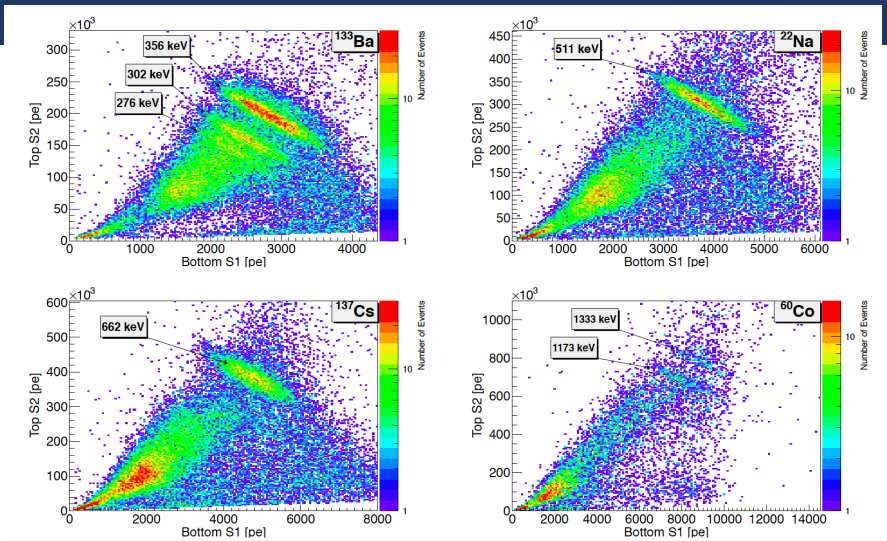


Parameter	Expected	Best fit ± stat.	Fit sys. err.	Optical sys. err.
$(C_1\tau_1)$ / $(C_3\tau_3)$ for ER	~0.1	0.042 ± 0.006	± 3.1%	+75% / -66%
$(C_1\tau_1)$ / $(C_3\tau_3)$ for NR	1.52 (at ~100 MeV)	0.269 ± 0.034	± 3.1%	+20% / -10%
τ_1	2.2 - 4.3 ns *	3.27 ± 0.66 ns	± 1%	+11% / -70%
τ_3 for ER	21 - 27 ns *	25.89 ± 0.06 ns	± 1.9%	+0.5% / -0.6%
τ_3 for NR	21 - 27 ns *	23.97 ± 0.17 ns	± 1.9%	+0.1% / - 1.1%
σ	≥ 3.1 ns	3.59 ± 0.09 ns	± 1.1%	± 1.2%

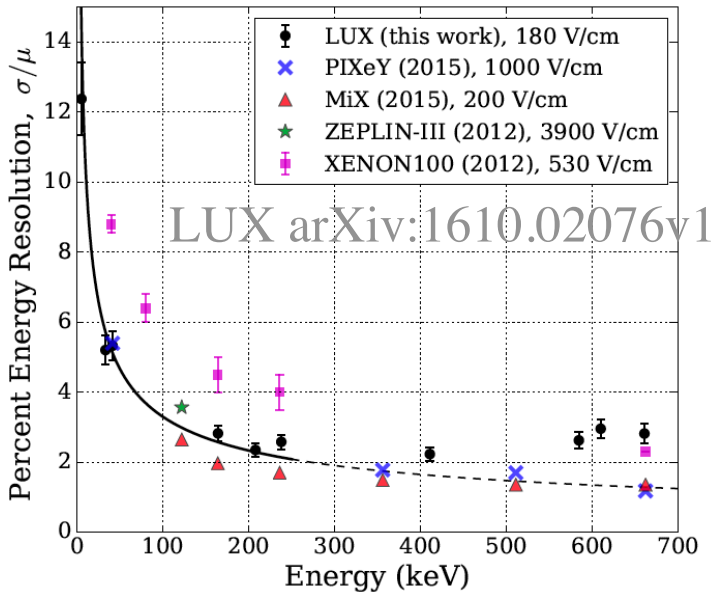
* Range of measured values from Kubota (1978 & 1979), and Hitachi (1983)

PMT + electronics single photon timing resolution

Scintillation 3. Fluctuations

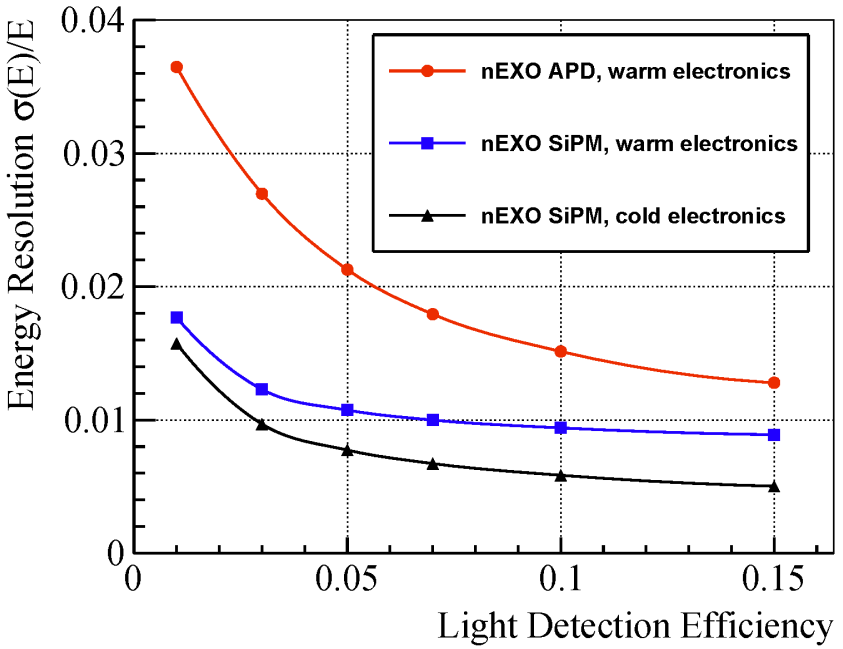


MiX arXiv:1507.01310v2



LUX arXiv:1610.02076v1

Energy resolution projected for nEXO
2456 keV electron recoil
Noise on ionization ~ 800e- (cold)

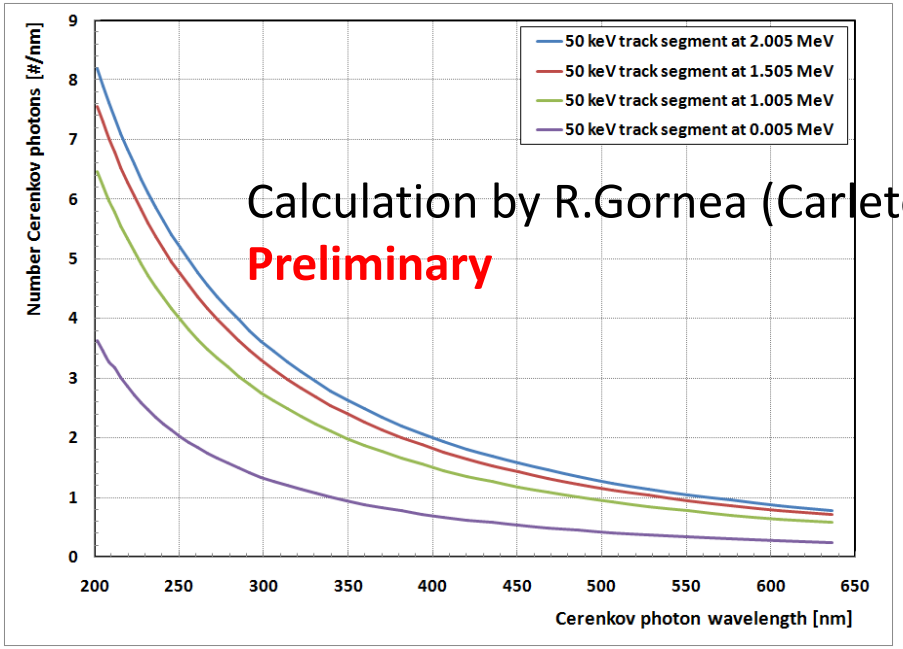


Cerenkov

Contents lists available at ScienceDirect
Nuclear Instruments and Methods in Physics Research A
journal homepage: www.elsevier.com/locate/nima

Possible usage of Cherenkov photons to reduce the background in a ^{136}Xe neutrino-less double-beta decay experiment

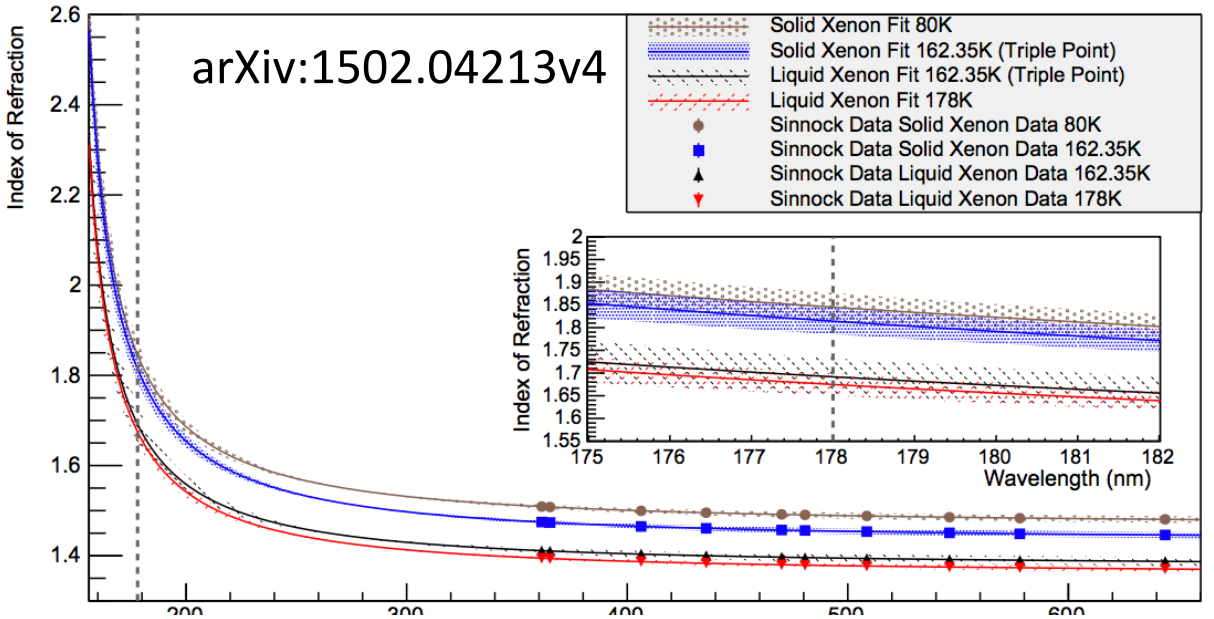
G. Signorelli*, S. Dussoni
INFN Sezione di Pisa, Largo B. Pontecorvo 3, 56127 Pisa, Italy

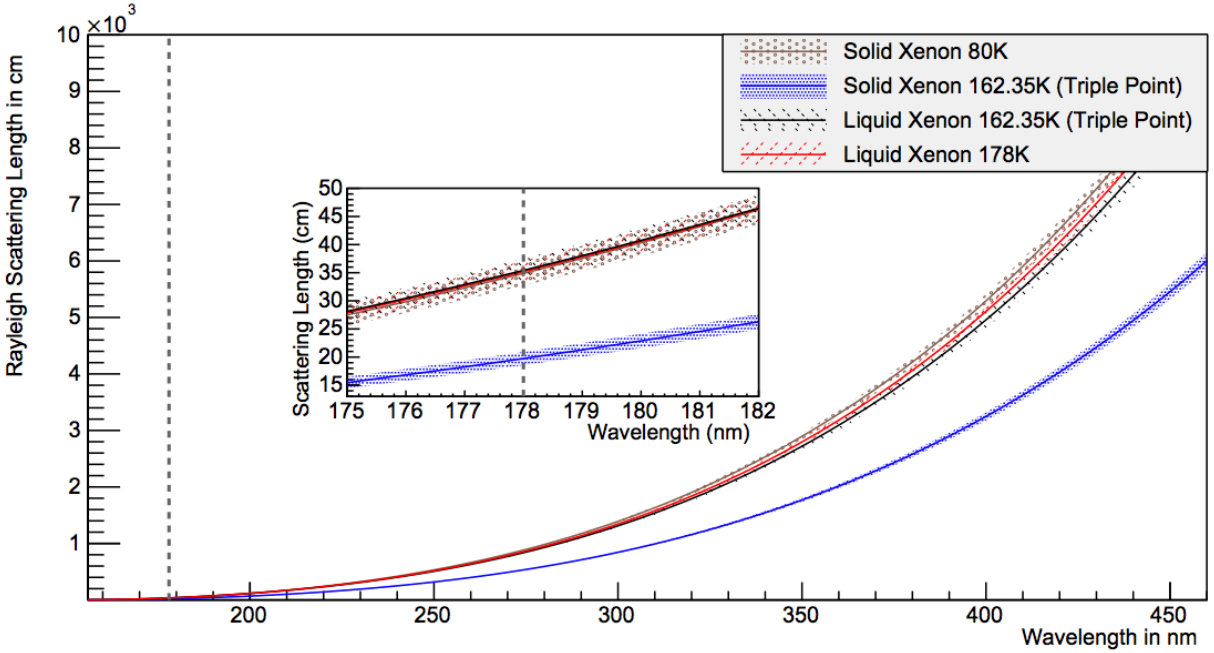


- Should be lots of photons because LXe is transparent down to 175nm
  - >10,000?
- Separate Cerenkov from scintillation
  - Bandpass filter (absorb scintillation)
  - Notch filter (reflect scintillation)
  - Use timing (need <1ns resolution)
- Useful for background rejection in $0\nu\beta\beta$?
- Starting a new program to study light only liquid Xenon

Photon transport through liquid Xenon

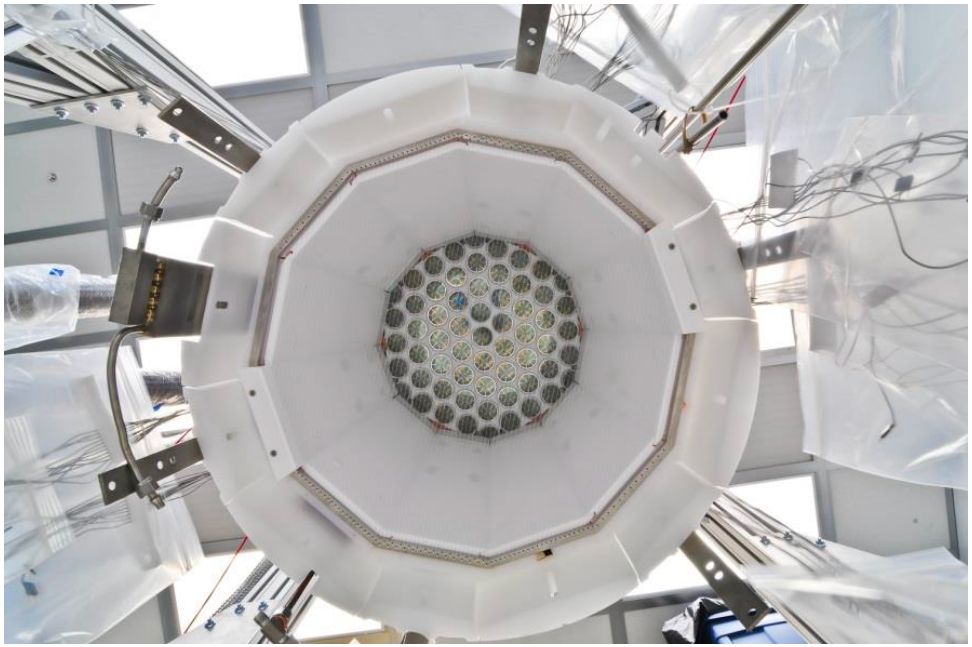
- Attenuation length, ~4m but dependent on purity
- Is the index of refraction measured well enough?





The wonder of teflon

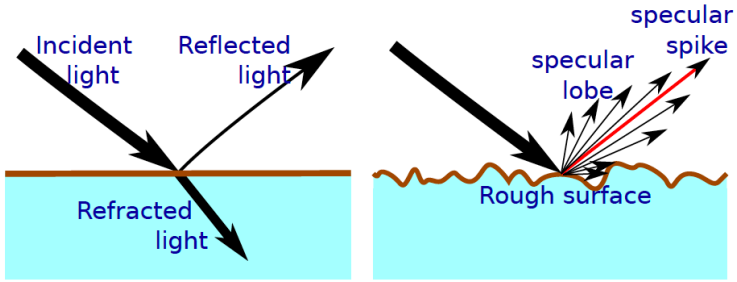
- The inside of LUX



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

Is Teflon well understood?

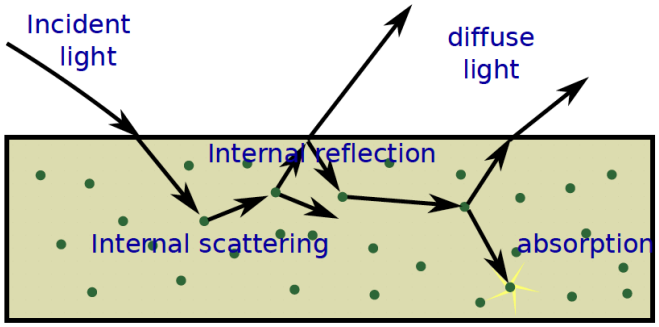
- Specular:

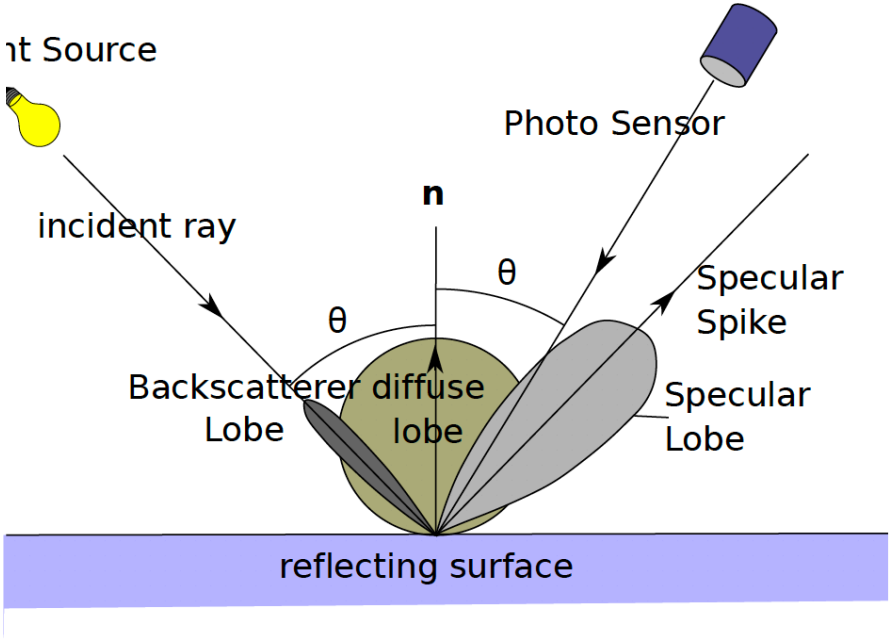


	Diffuse model (D)		Diffuse + Specular model (DS)			
	A	λ (mm)	A	n_{PTFE}	λ (mm)	BHR
807NX	0.972 (> 0.97)	4800	0.961 (> 0.955)	1.73	4600	0.961 (> 0.955)
NXT85	0.986 (> 0.984)	3600	0.975 (> 0.973)	1.8	4600	0.975 (> 0.973)
LUX	0.987 (> 0.985)	4200	0.978 (> 0.975)	1.79	3000	0.978 (> 0.975)

arXiv:1608.01717v2

- Diffuse:

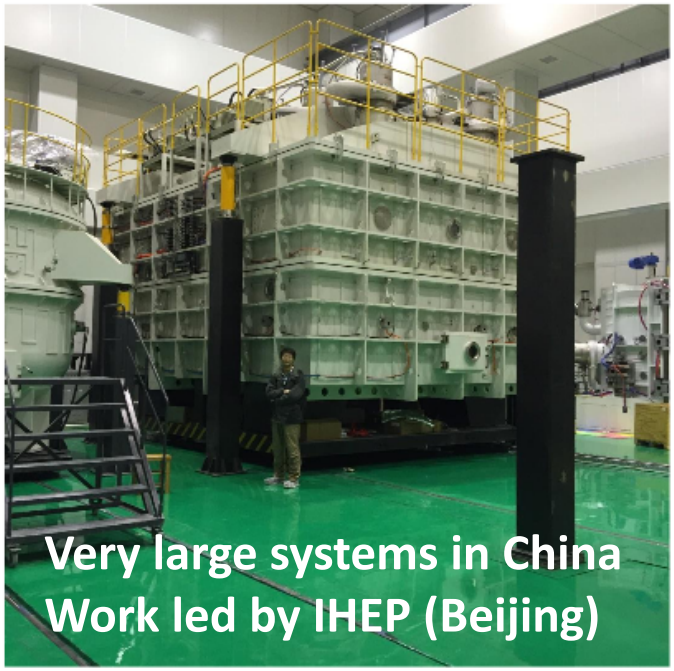


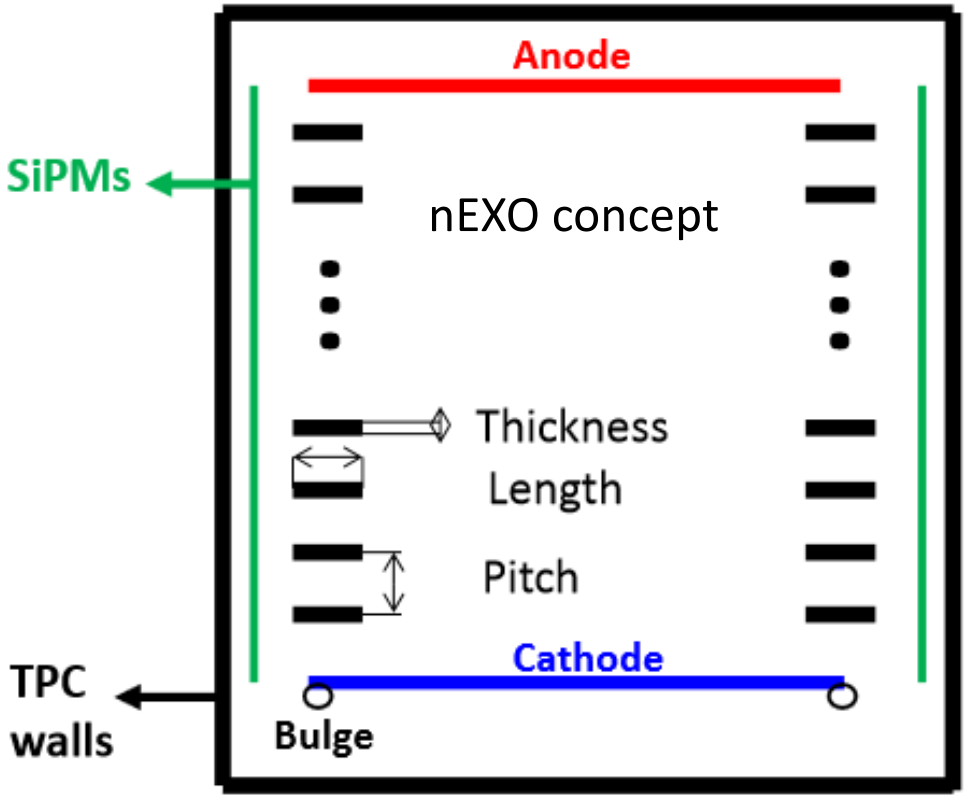


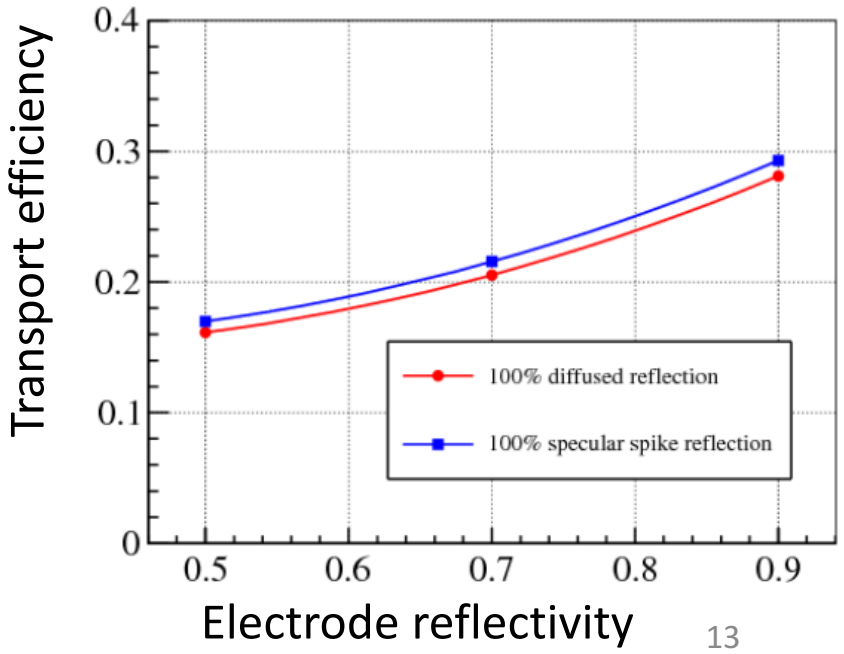
- No thickness dependence from 1 to 9.5mm

Photon transport without teflon

- nEXO would like to do without Teflon
  - … At its own risk!
- Developing VUV mirror
  - Al-MgF2



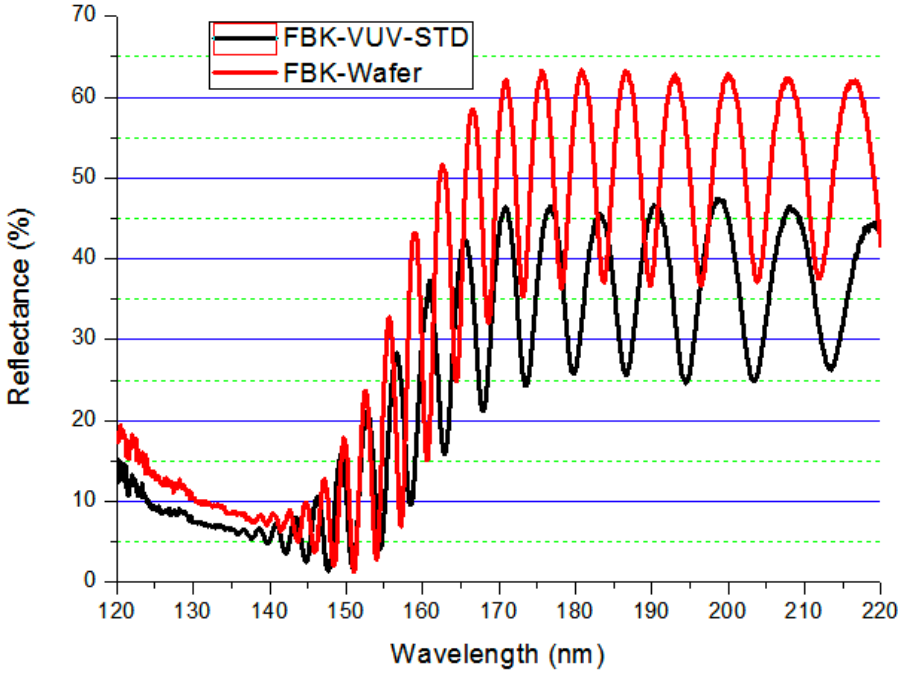




Photon transport and photo-detectors

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

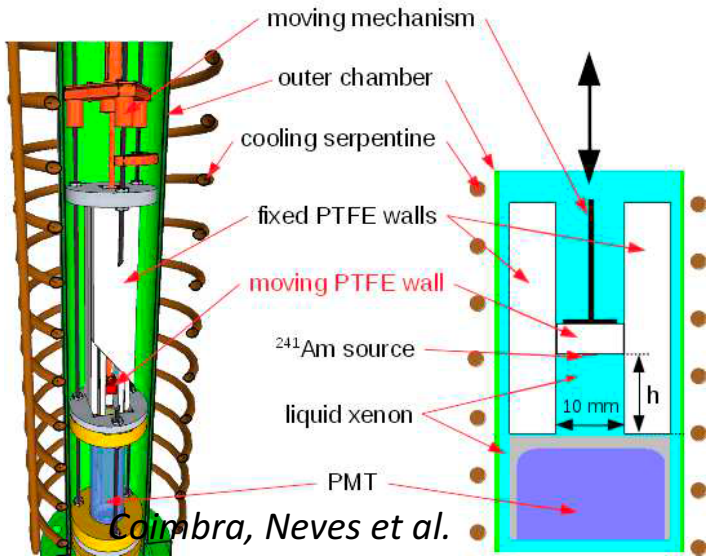
10 degree specular reflectance
For FBK SiPM and bare wafer



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%

New setups for photon transport characterization

- In vacuum
  - Differential vs wavelength and angle
  - Useful for material characterization
- In liquid Xenon integrating
  - Coimbra
  - MiX (Michigan)



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)

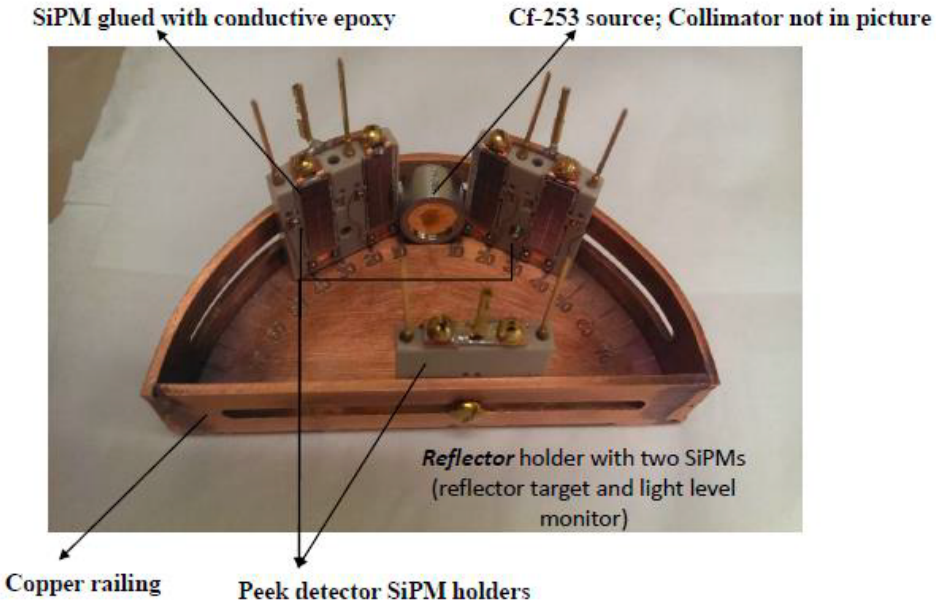
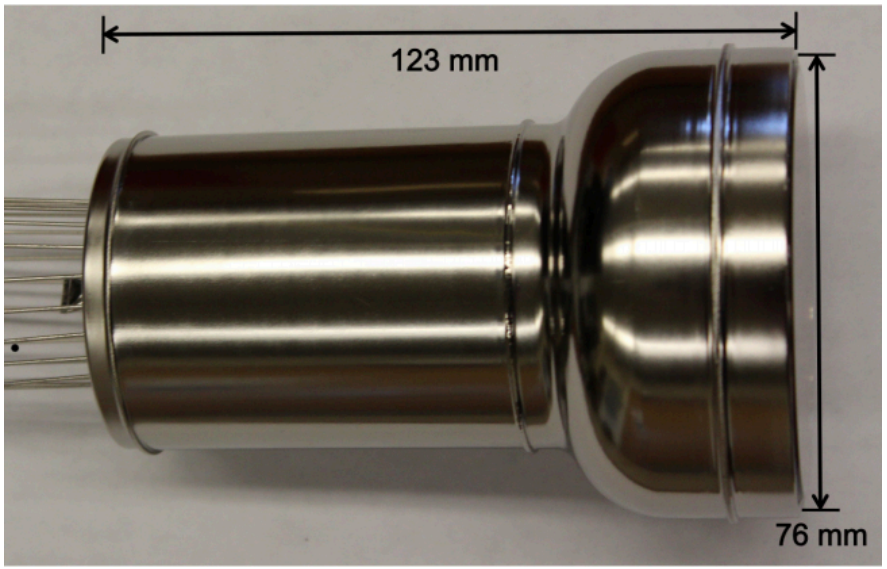
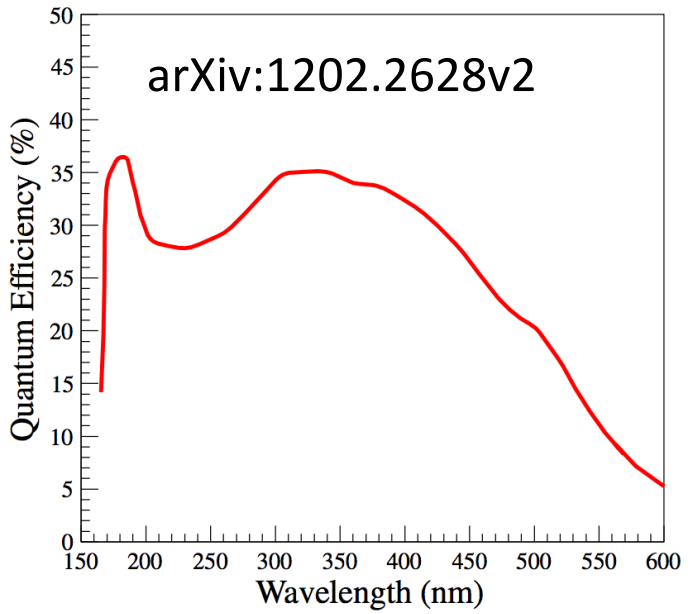
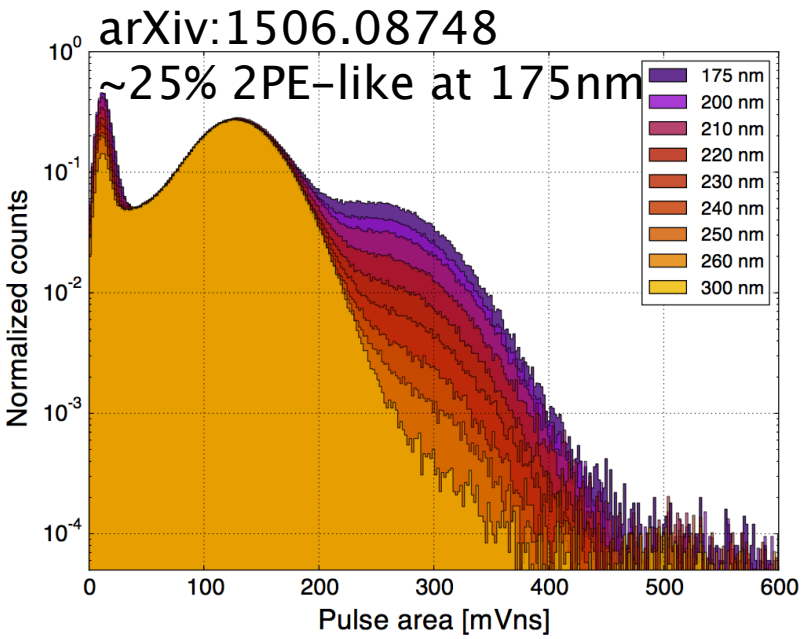


Photo-detector. The PMT workhorse

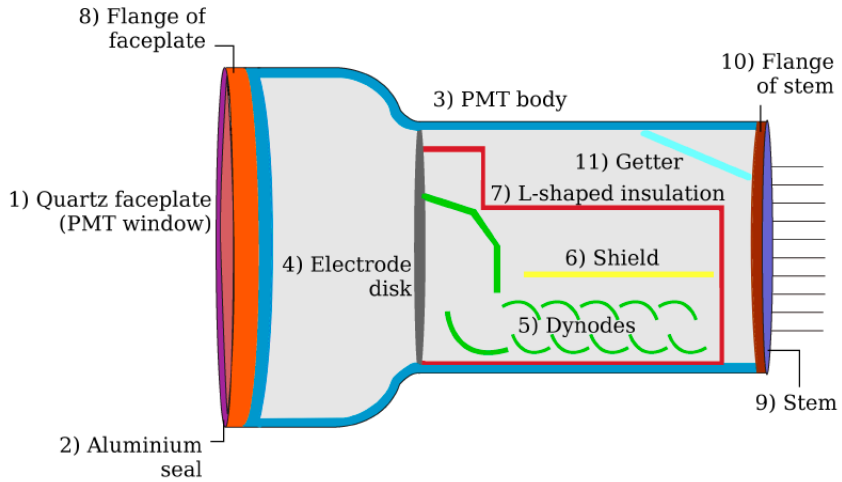
- Hamamatsu R11410
  - Used by all DM experiments
  - Efficiency ~30%
    - But some possible double counting
  - Dark noise ~50Hz at -100C
  - After-pulse ~20%





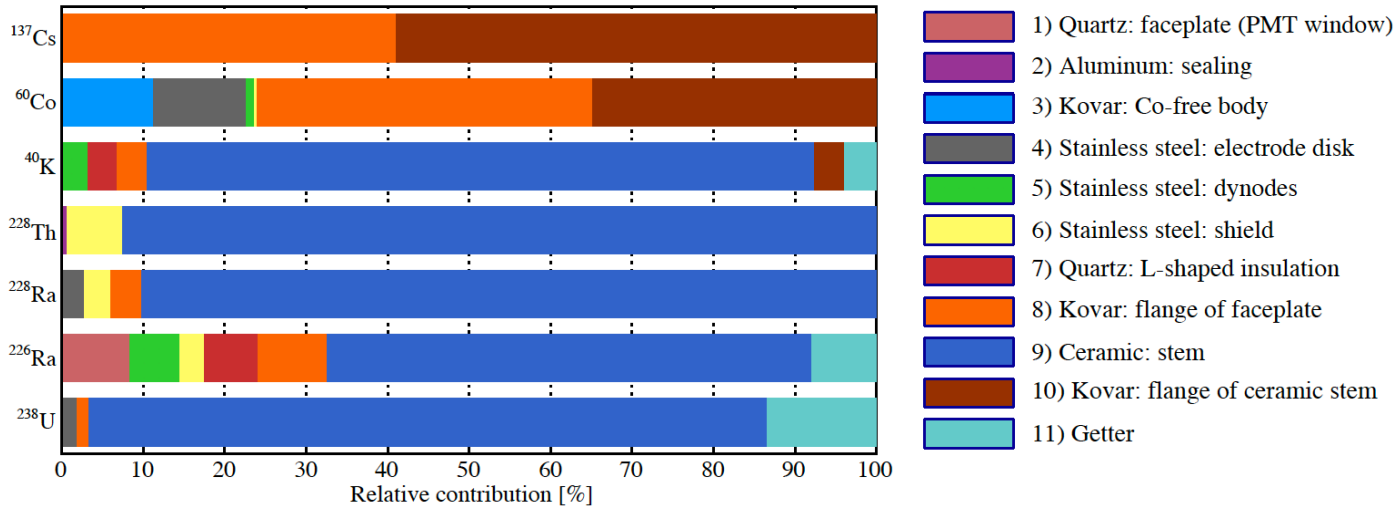


Radiopurity



arXiv:1503.07698v1

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]



Silicon detector 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.
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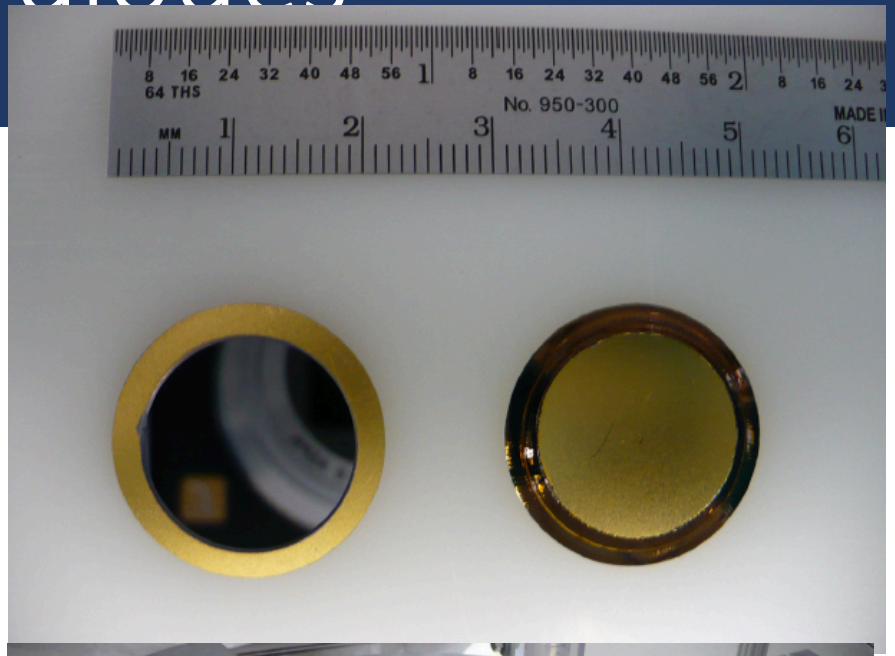
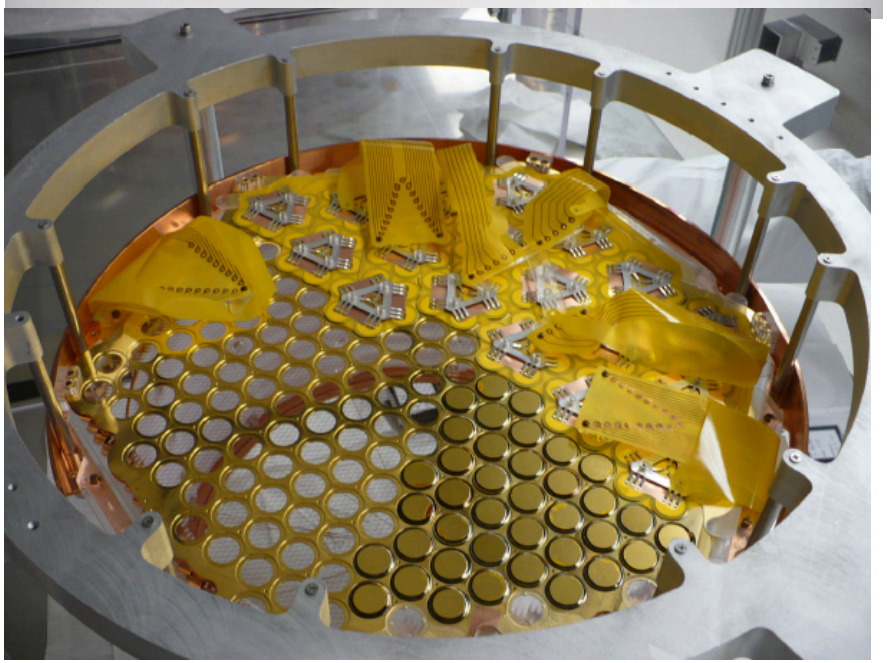
R8520	< 0.33	0.029(2)	0.026(2)	0.009(2)	1.8(2)	0.13(1)	[20]

Avalanche photo-diodes

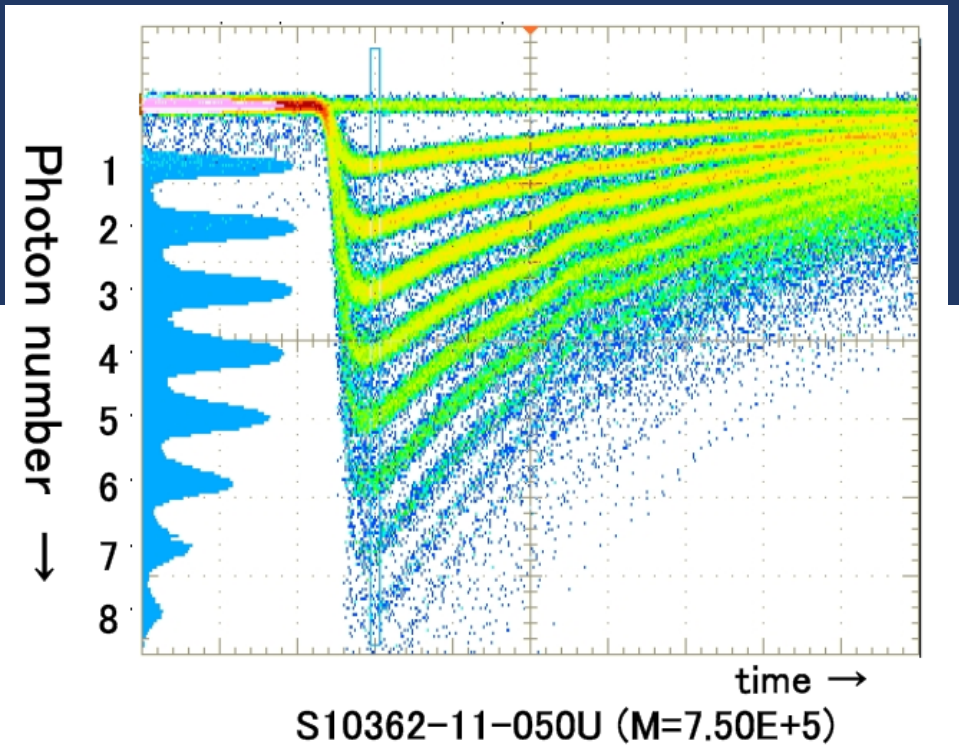
- Used in EXO-200
- Efficient ~50%
- Low radioactivity
- High noise ~ 10 PE equivalent per APD
  - Because of low gain & high capacitance
  - Dominate the energy resolution of EXO-200
- Not scalable to nEXO without heroic electronics effort
- Also concerns about large scale production

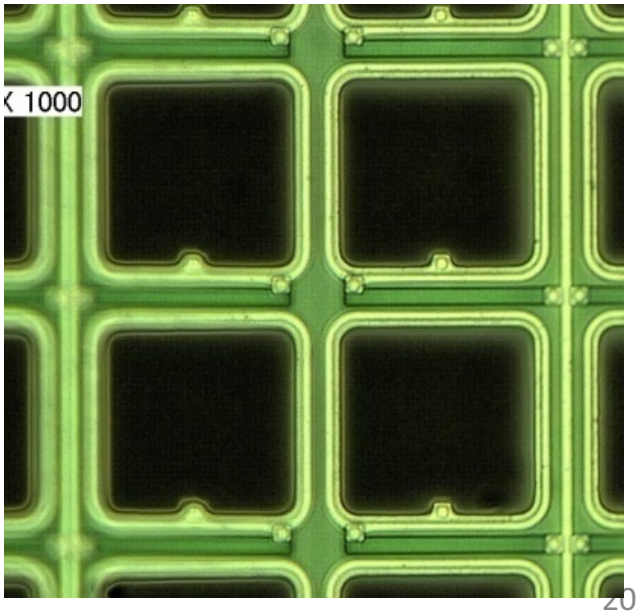




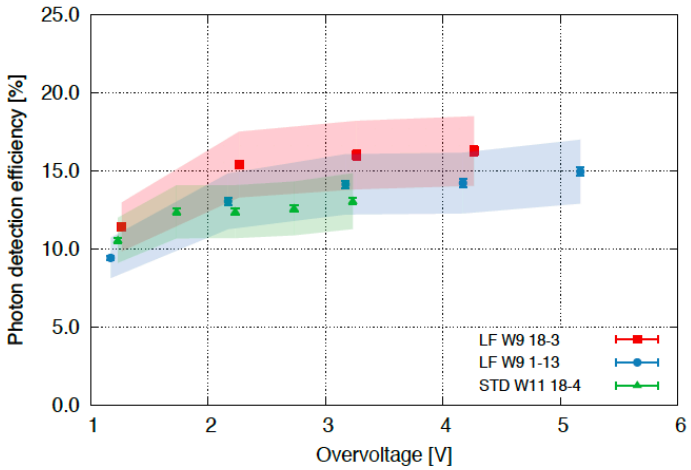
SiPMs

- High gain ~ 10^6
  - Also high capacitance but can be handled to get negligible noise
- Radiopure
- Low dark noise when cold
- Efficiency at 175nm was a question mark

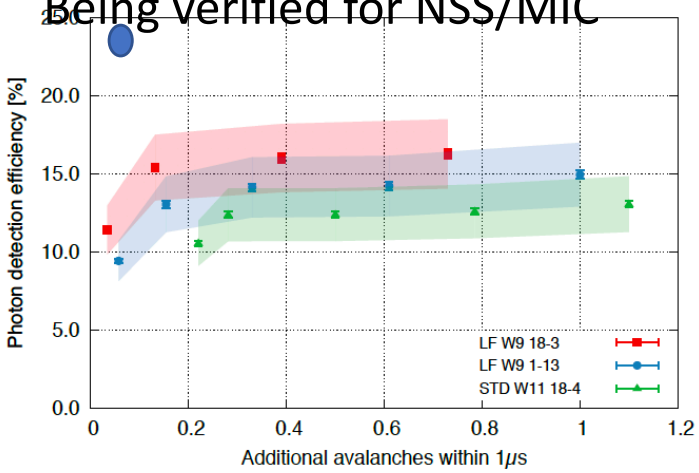




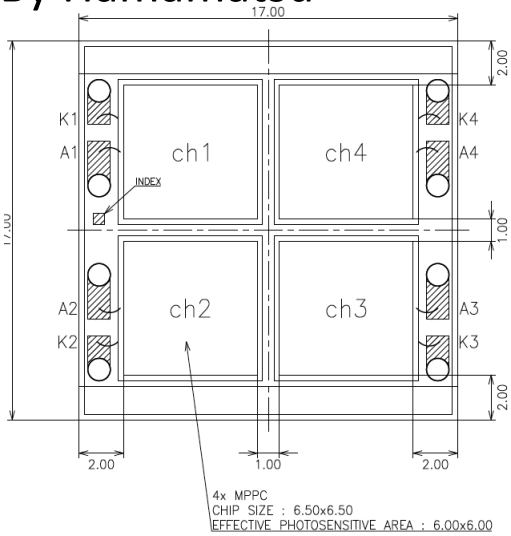
Analog SiPM R&D status



Hamamatsu VUV4
Being verified for NSS/MIC



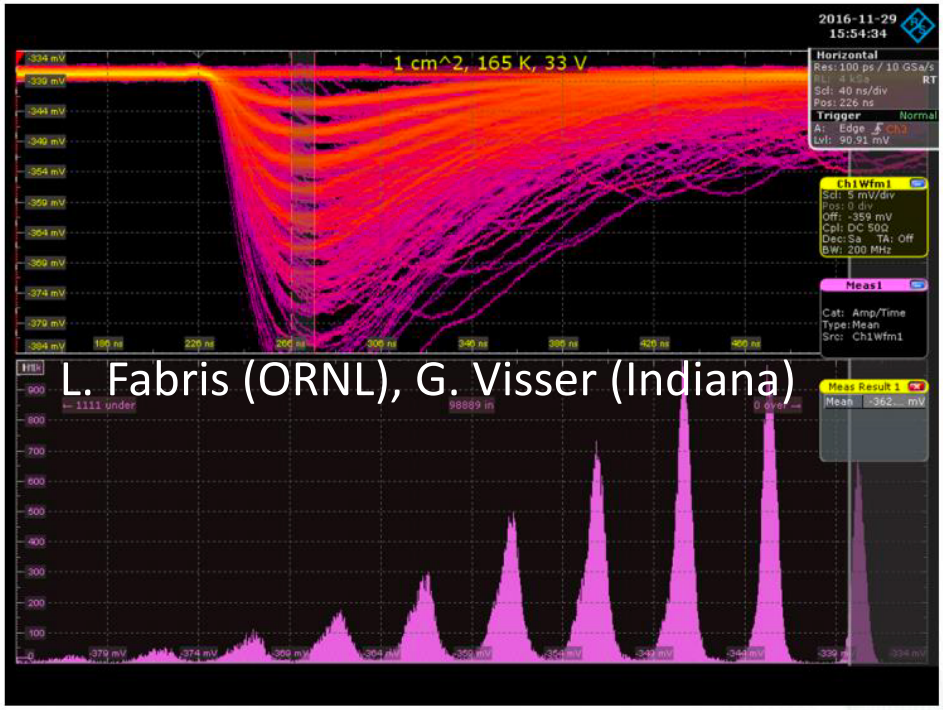
Preliminary quartz package
By Hamamatsu



- Efficiency
  - 15% for FBK
  - 24% for Hamamatsu though need independent measure
  - Meet minimum specification for nEXO (15%)
- Dark noise < 1Hz/mm^2 for both FBK and Hamamatsu
- Cross-talk and after-pulse under control
  - Though may still be limiting

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

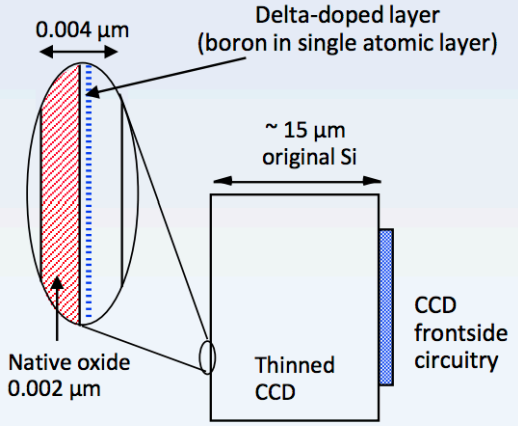
TRIUMF

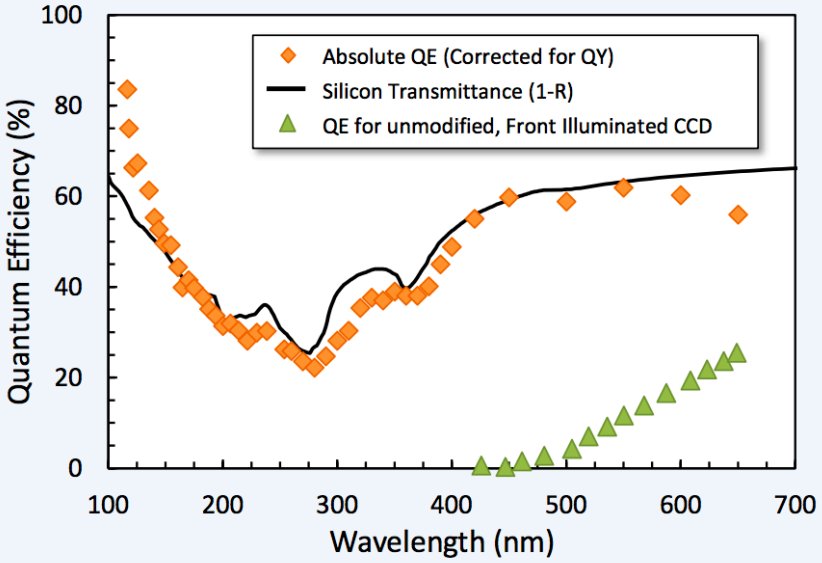
Making VUV SiPM better. Issue 1.

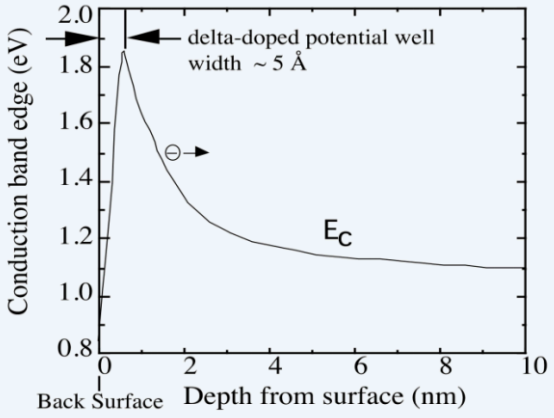
Silicon attenuation length very short in VUV

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





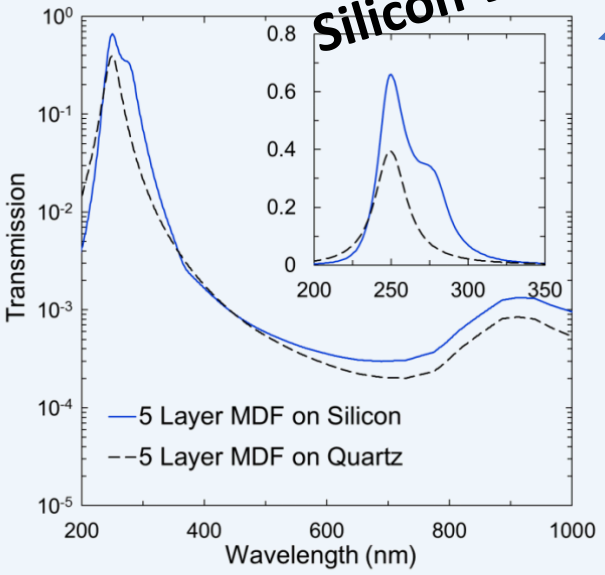


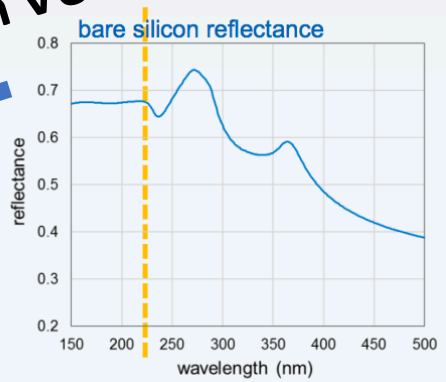
Making VUV SiPM better. issue 2.

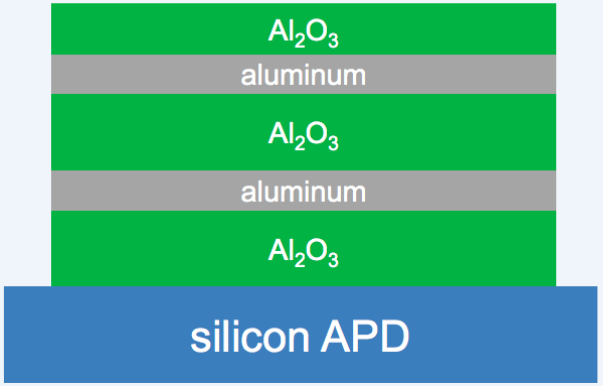
Metal-dielectric UV bandpass filters

- 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

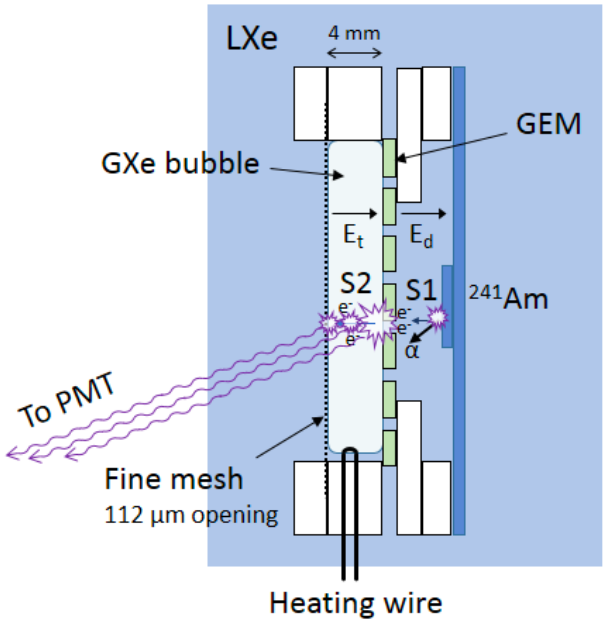


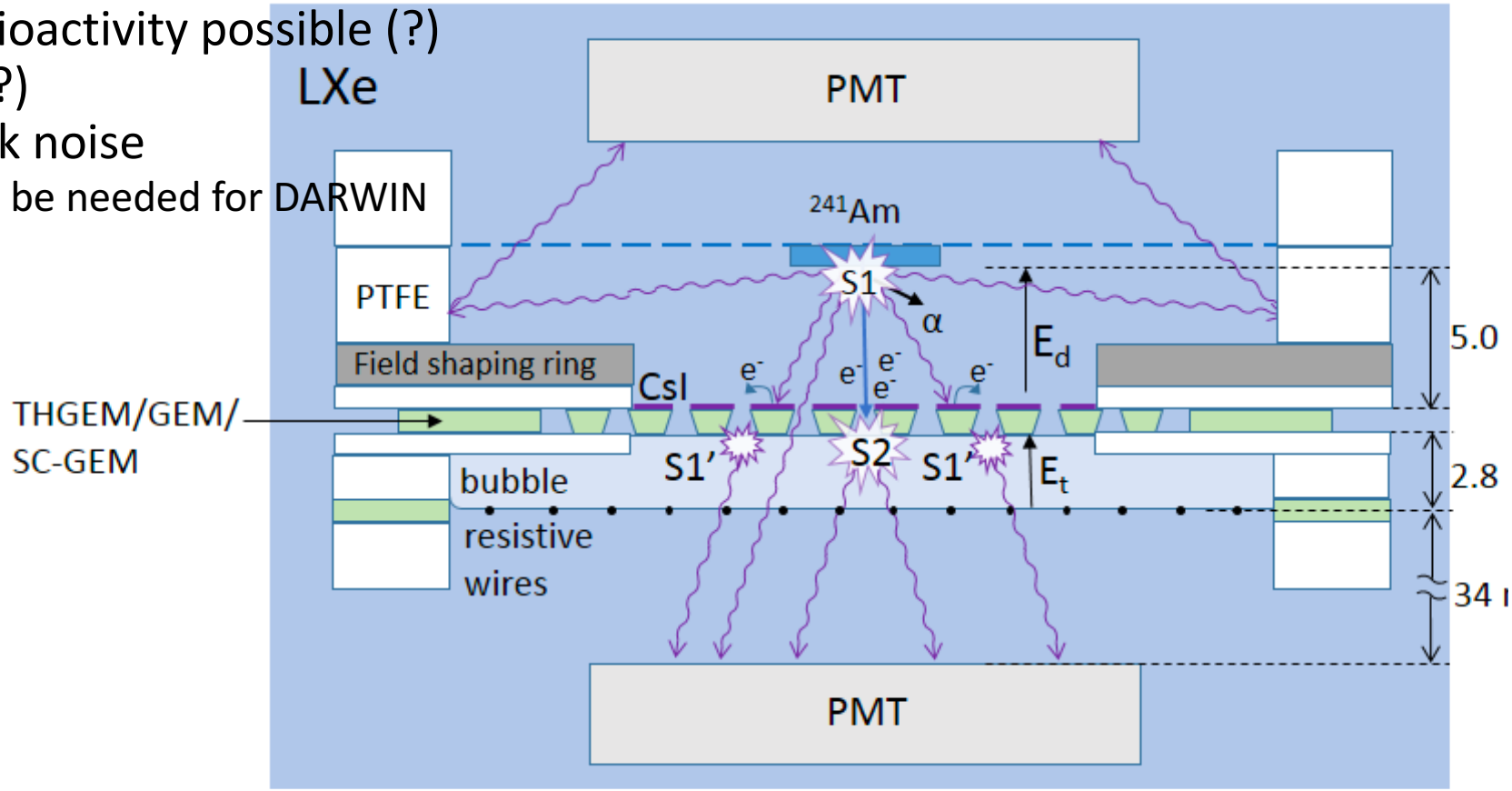




THGEM. Another promising avenue

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





Summary and outlook

- Light detection in liquid Xenon is a key to future discovery
- The R11410 PMT + Teflon combo yield amazing overall light detection efficiency
  - Performance fully understood?
- Future R&D driven by group who don't want or cannot use PMTs and don't like Teflon
  - SiPMs are very promising
    - Analog SiPM are already good enough for nEXO with the caveat that they reflectivity is only partially understood
    - On paper >50% efficiency at 175nm is possible
  - Thick GEMs are competitive performance wise.
    - Can they be low radioactivity and low cost?
  - Development of VUV optics is needed to move away from Teflon
    - Interference filters may prove useful for separating Cerenkov and scintillation light