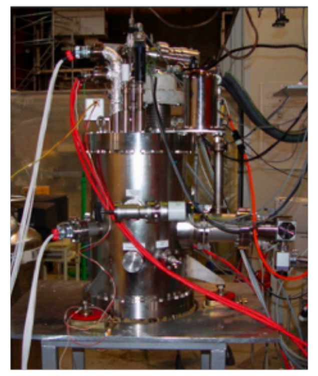
Photodetectors for future LXe experiments

Shingo Kazama (Nagoya University, KMI)

September 15th, 2022 @ MPIK

XENON/DARWIN



XENON10

Total Xe: 25 kg

Target: 14 kg

Fiducial: 5.4 kg

XENON100

Total Xe: 162 kg

Target: 62 kg

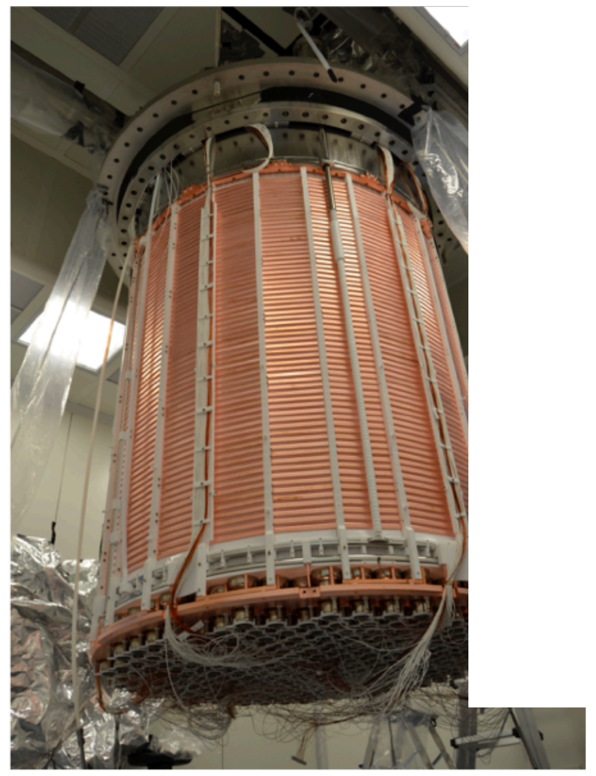
Fiducial: 48 kg

XENON1T

Total Xe: 3.2 ton

Target: 2.0 ton

Fiducial: 1.3 ton

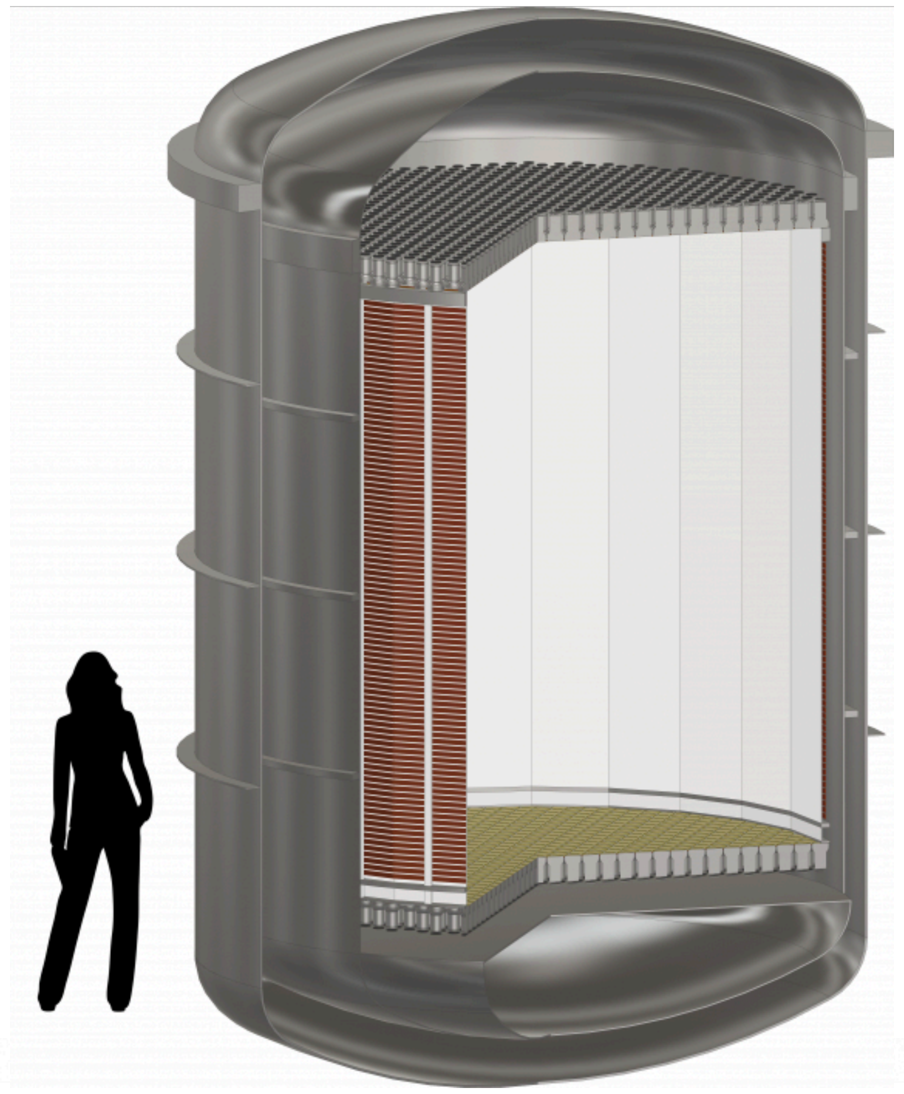


XENONnT

Total Xe: 8.6 ton

Target: ~5.9 ton

Fiducial: ~4 ton



DARWIN

Total Xe: ~50 ton

Target: ~40 ton

Fiducial: >30 ton

XENON1T

DARWIN

XENON10

XENON100

XENONnT

2005

2010

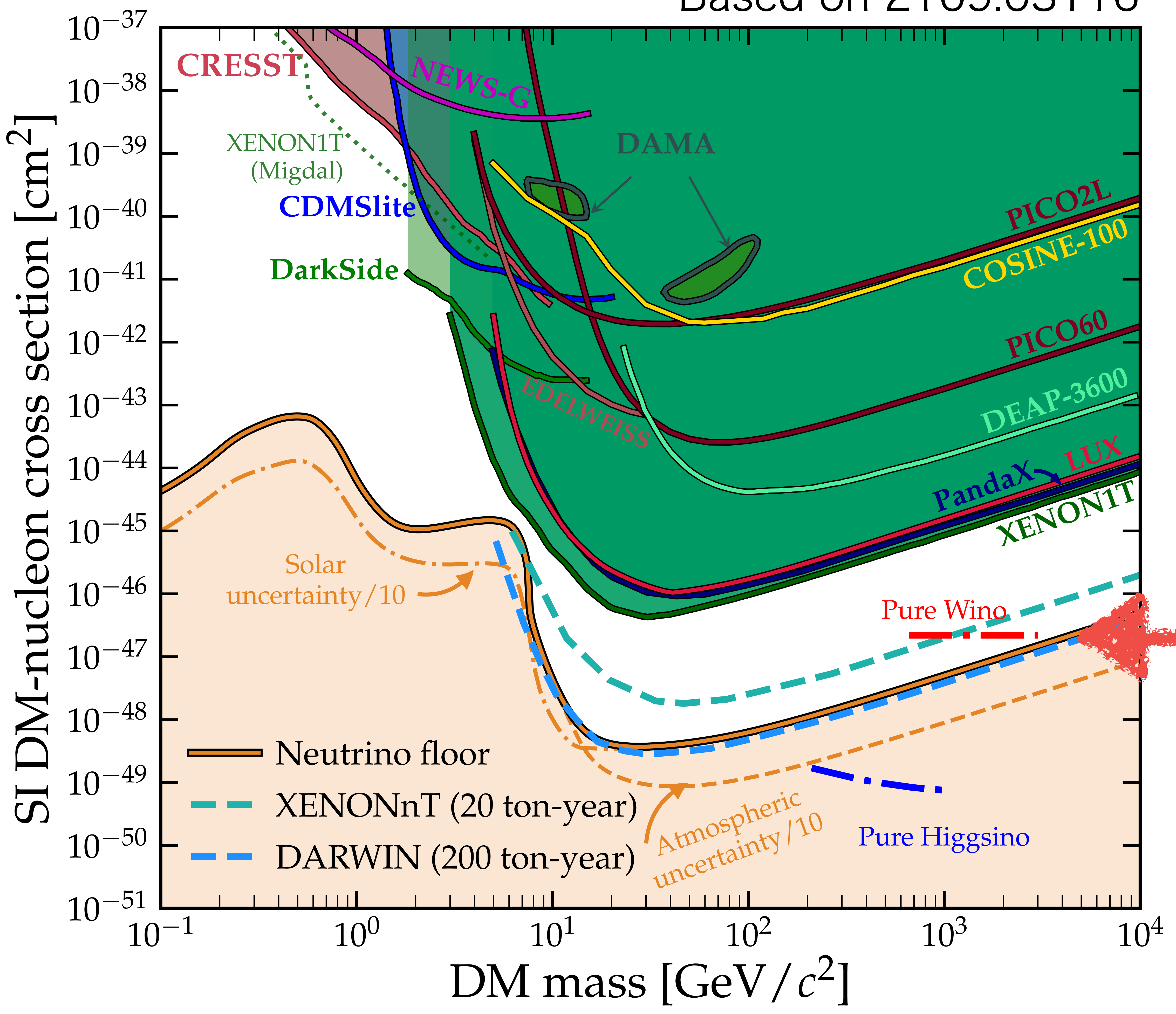
2015

2020

2027

Wino DM@DARWIN

Based on 2109.03116



Slide by Hisano-san

Summary (A dream)

- At 202X, finite values for EDMs are discovered.
- At 202X, peak on gamma ray spectrum from galactic center are discovered around 3TeV at CTA.
- At 202X, DARWIN finds excess of counting rate, which is larger than neutrino BGs.
- At 20XX, wino is discovered at 100TeV pp collider.

Pure wino DM scenario can be fully explored by the DARWIN experiment

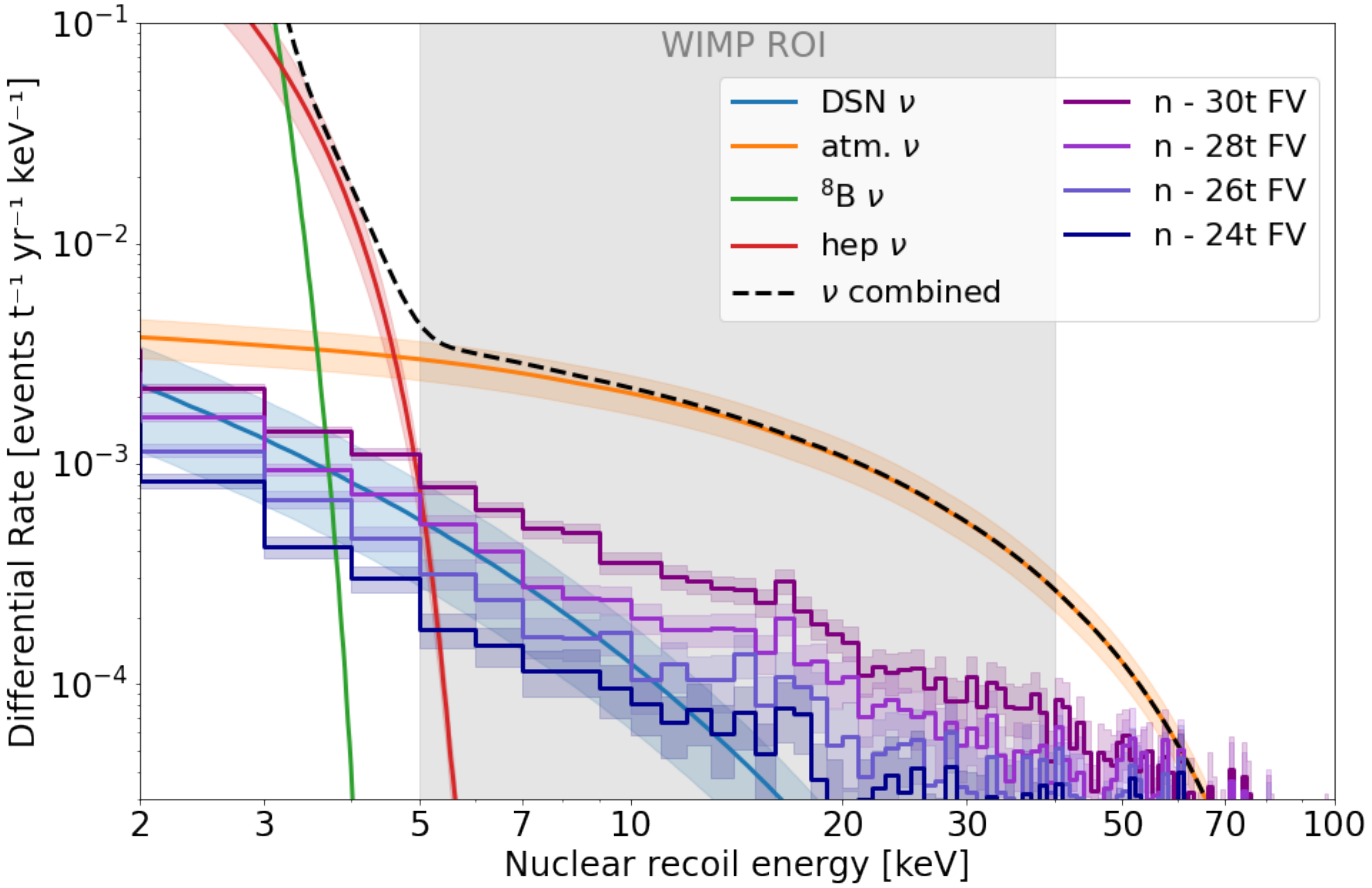
Nuclear Recoil BG

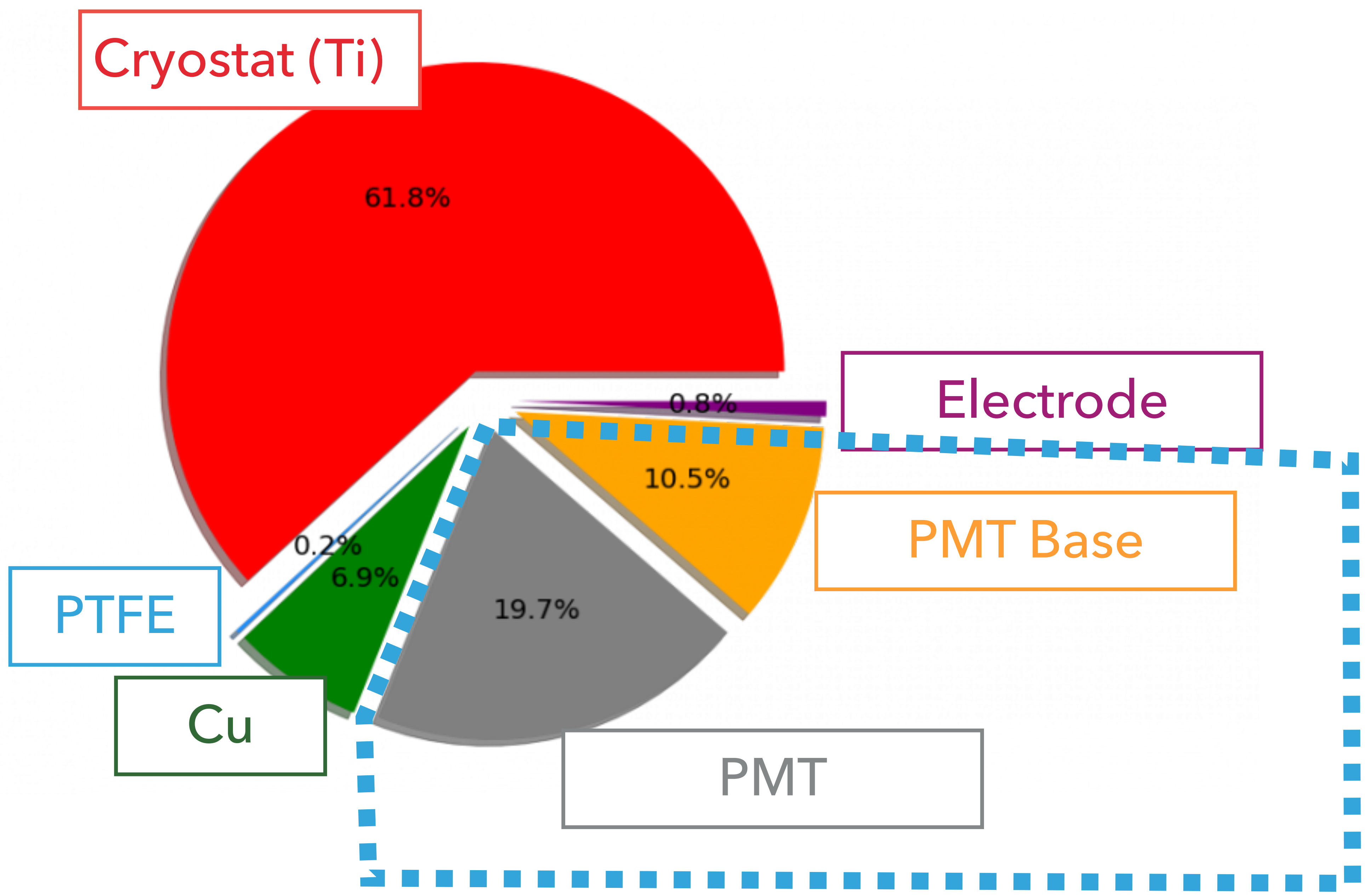
- **Radiogenic neutrons**: spontaneous fission or (α, n) reaction from the U and Th: ~ 2 events/(200 t・year)

- **Coherent v-N scattering (irreducible)**
  - XENONnT(20 t ・year) ~1 neutrino
  - DARWIN (200 t・year) ~ 10 neutrinos

- **Cosmogenic/Radiogenic neutrons**: ~ 0.4 events/(200 t・year) with 12m diameter water tank

From Ph.D thesis for J.Dierle



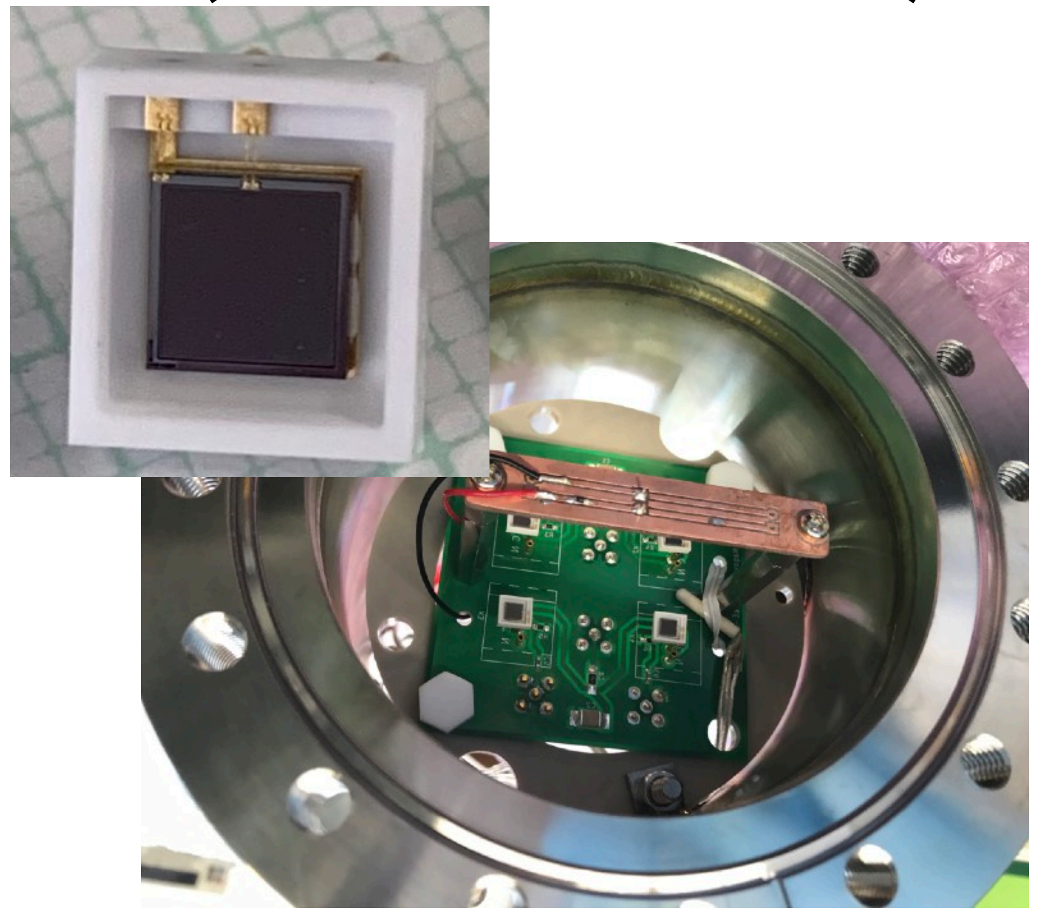


New Photosensor R&Ds @ Nagoya Univ.

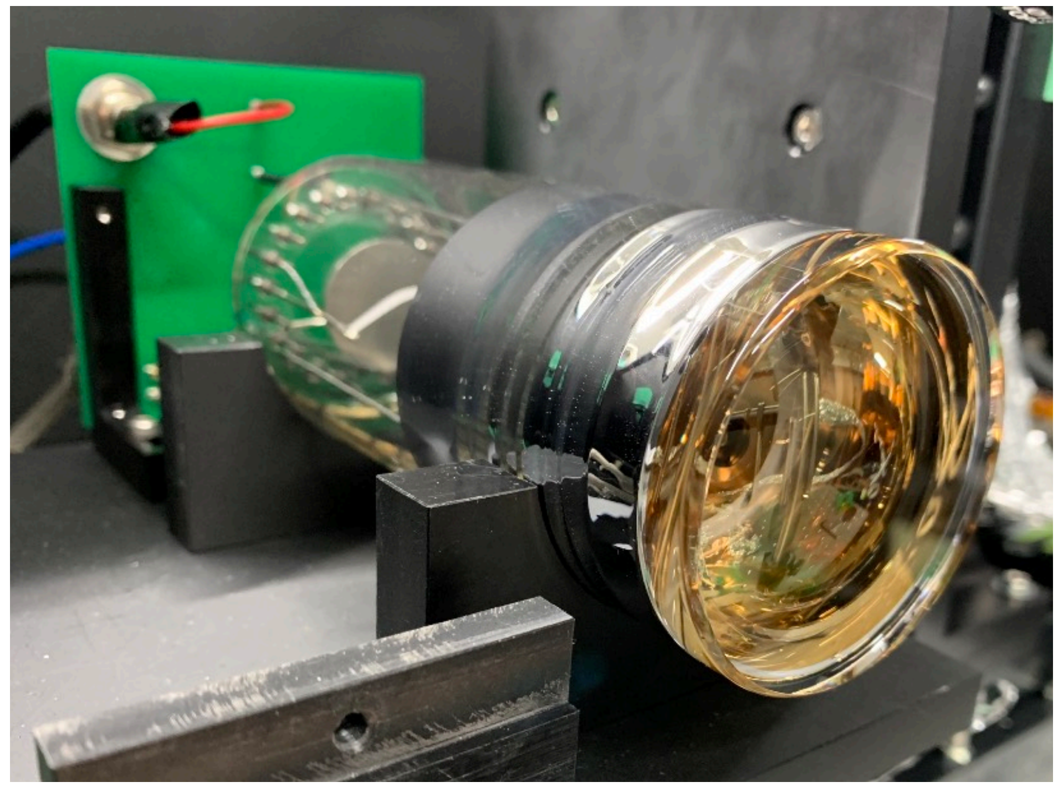
1. Ultra low-radioactive PMT: 3inch R13111 developed by XMASS (XMASS collaboration, JINST 16 P03014)
   - Lowest radioactivity ever achieved
2. SiPM with lower DC rate (~ 0.01Hz/mm^2) (Ozaki et al, JINST 15 P09027)
   - A dedicated SiPM with less DC rate available: ~50 times less @ LXe temperature
3. Hybrid-detector (PMT/SiPM): XE5859
   - Photocathode (converts a photon to an photoelectron) + SiPM (photoelectron detector)

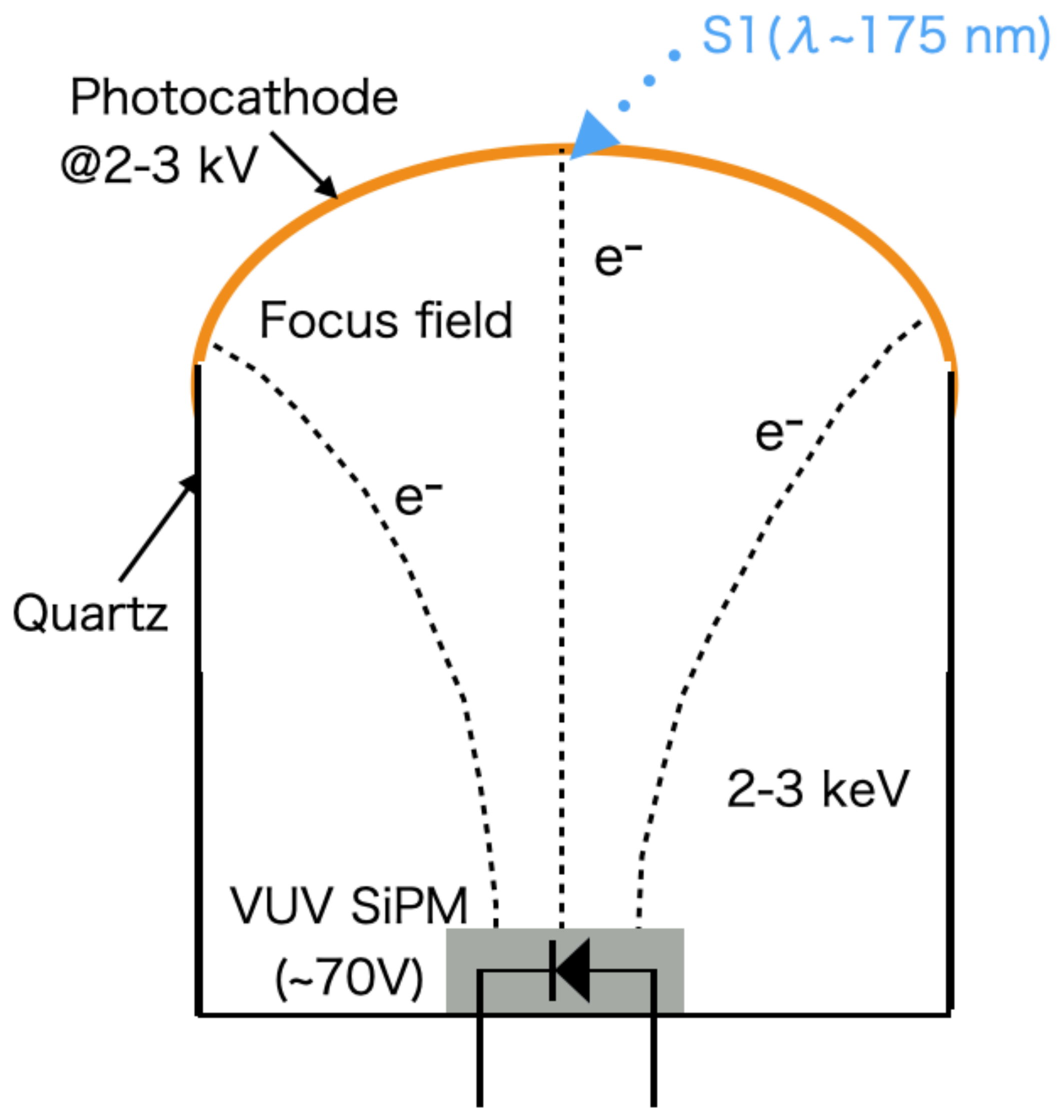
PMT (R13111)

SiPM (S12572-015C-STD)



Hybrid (XE5859)



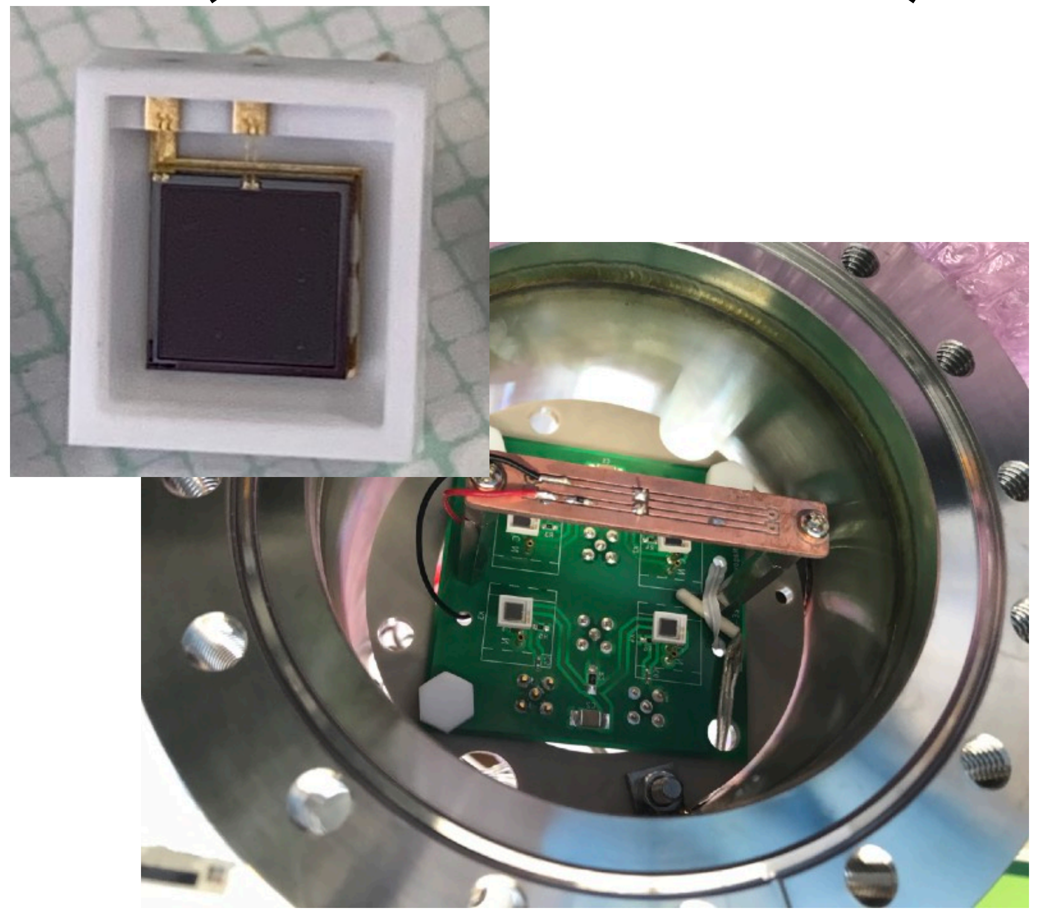


New Photosensor R&Ds @ Nagoya Univ.

	PMT	SiPM S13370 (VUV4)	Hybrid **XE5859**
Operation voltage	~1500V	~50V	Photocathode: < 2 kV SiPM: 50-60 V
Single Photon Gain	$\sim 5 \times 10^6$	$\sim 2 \times 10^6$	$\sim 2 \times 10^6$
DC rate@165 K	~0.01 Hz/mm^2	~1Hz/mm^2	~0.01 Hz/mm^2
Radioactivity	High	Very low	Very low
QE	30 - 40%	25%	?

PMT (R13111)

SiPM (S12572-015C-STD)



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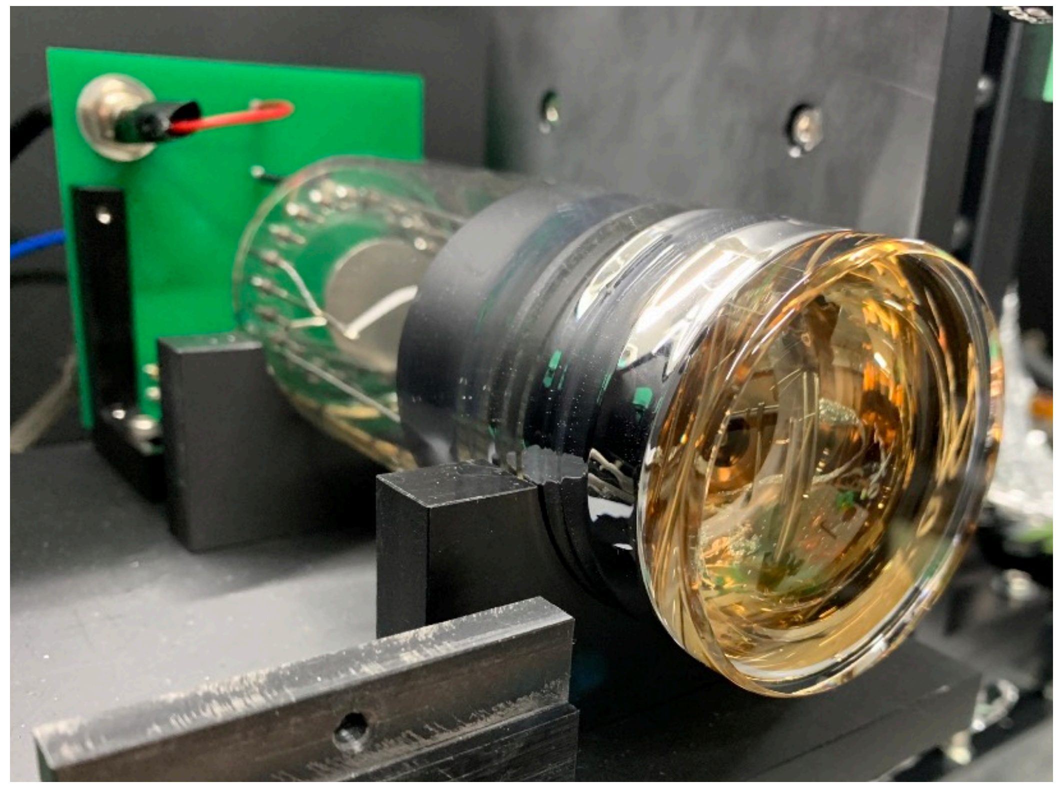
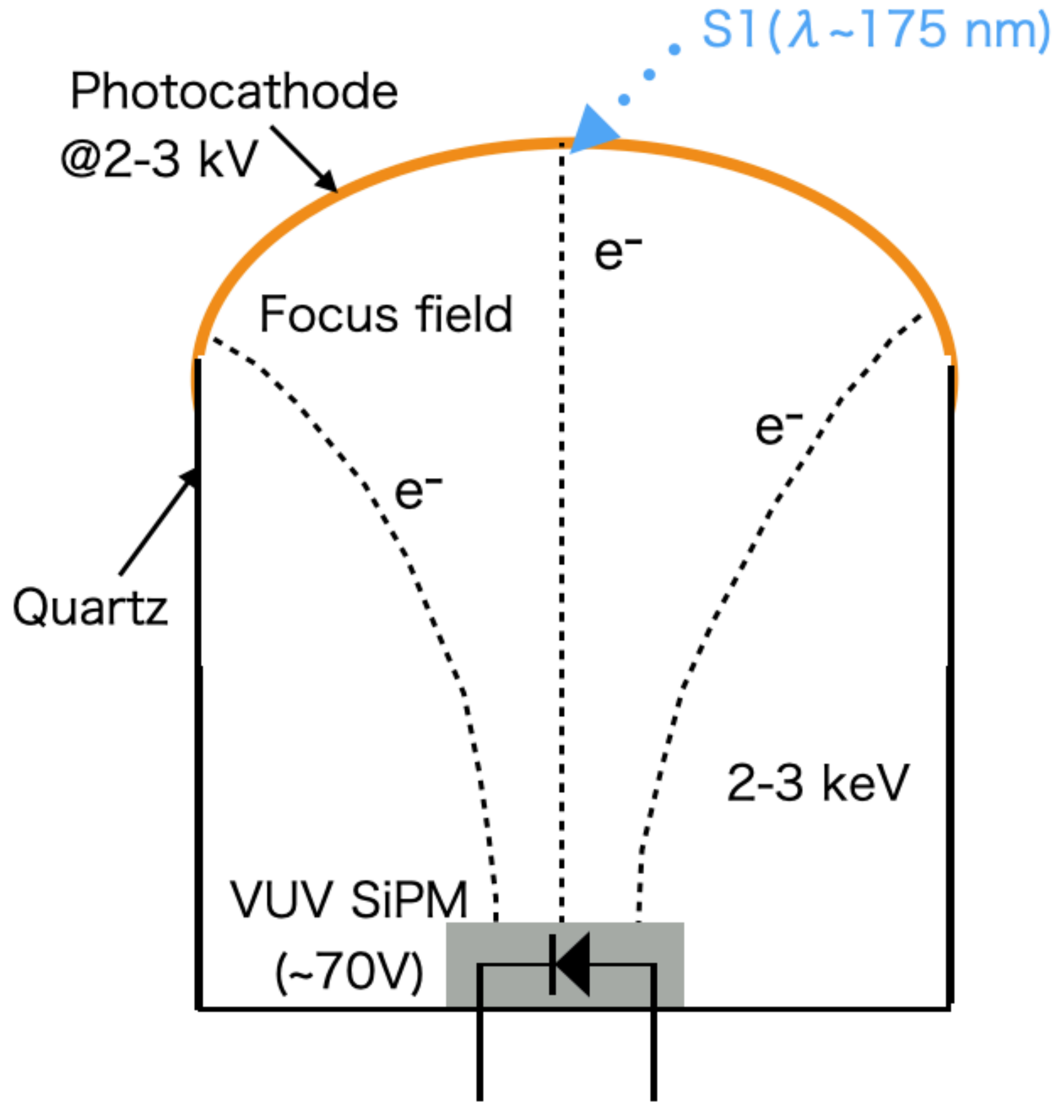




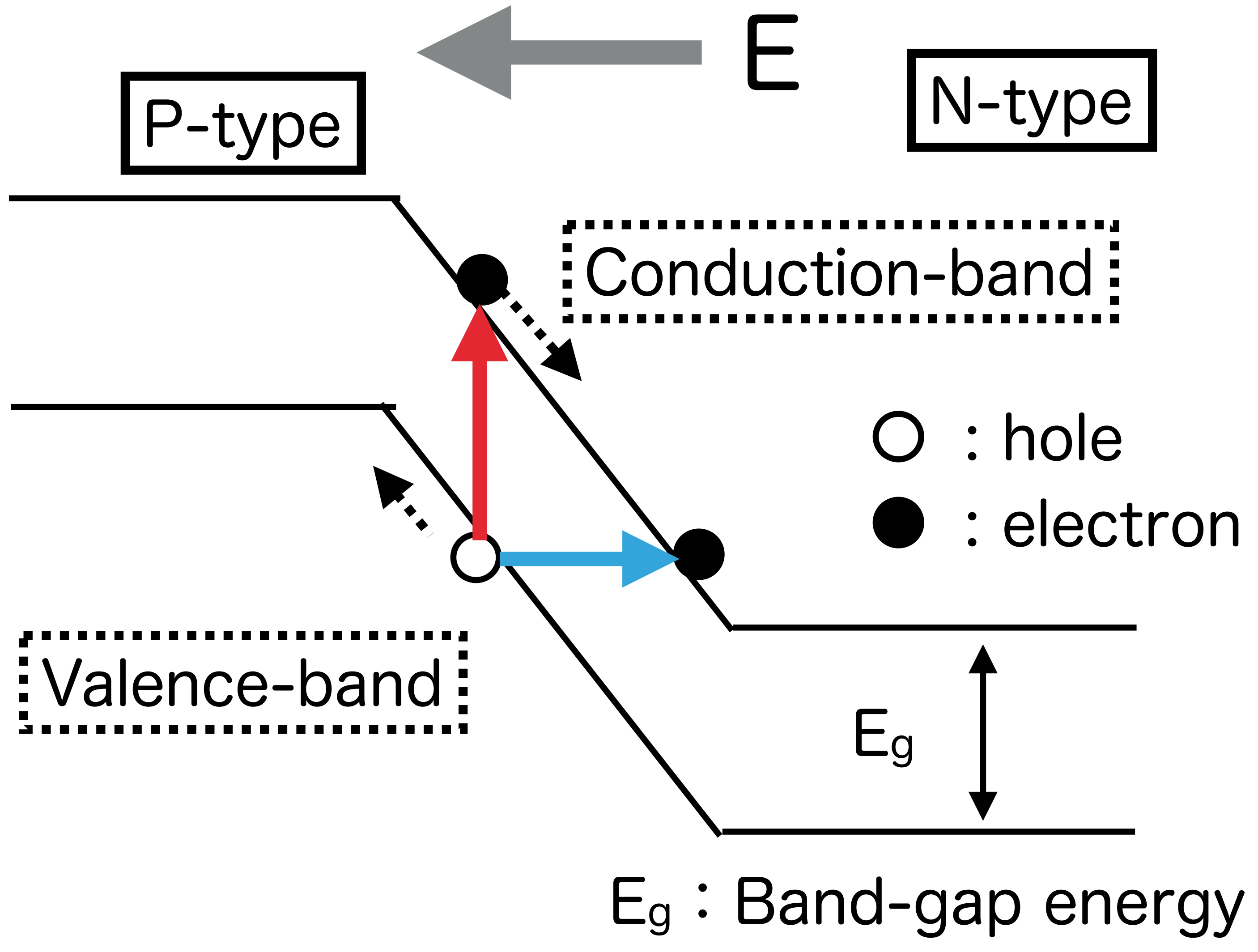
Low DC Rate SiPM

Dark pulses of SiPMs originate from

1. Thermally generated carriers: strong temperature-dependence

$$n_i \propto \times T^{\frac{3}{2}} \times exp(-\frac{E_g}{2k_B T})$$

2. Band-to-band tunneling effect: weak temperature dependence



- At LXe temperature (-100℃), high DC rate is mainly from band-to-band tunneling effect

- To suppress the tunneling effect, we have developed a new SiPM with lowered electric field strength with Hamamatsu

	S12572-015C-SPL **SPL**	S12572-015C-STD **STD**
Operation Voltage	～100V	～65V
Gain	$\sim 1.4\times 10^5$	$\sim 2.3\times 10^5$
Size	3mm×3mm	
Number of pixels	40000	
Pixel piches	15μm	
Fill factor	53%	
Package	Ceramic	
Trench	No trench	
Wavelength	300 - 900 nm	

Low DC Rate SiPM

- To suppress the tunneling effect, we have developed a new SiPM with lowered electric field strength with Hamamatsu
    - E-field(↘)、depletion layer(↗)、 Doping concentration(↘)
- Breakdown voltage becomes larger a bit, but no significant changes in other performances.

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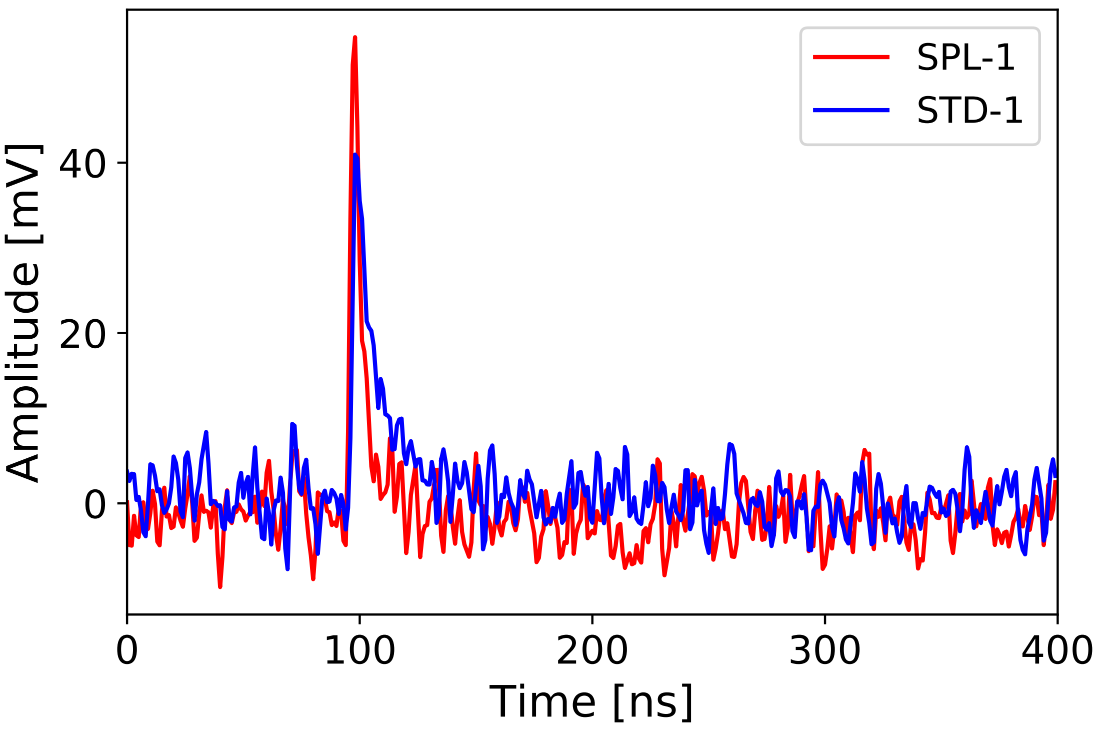
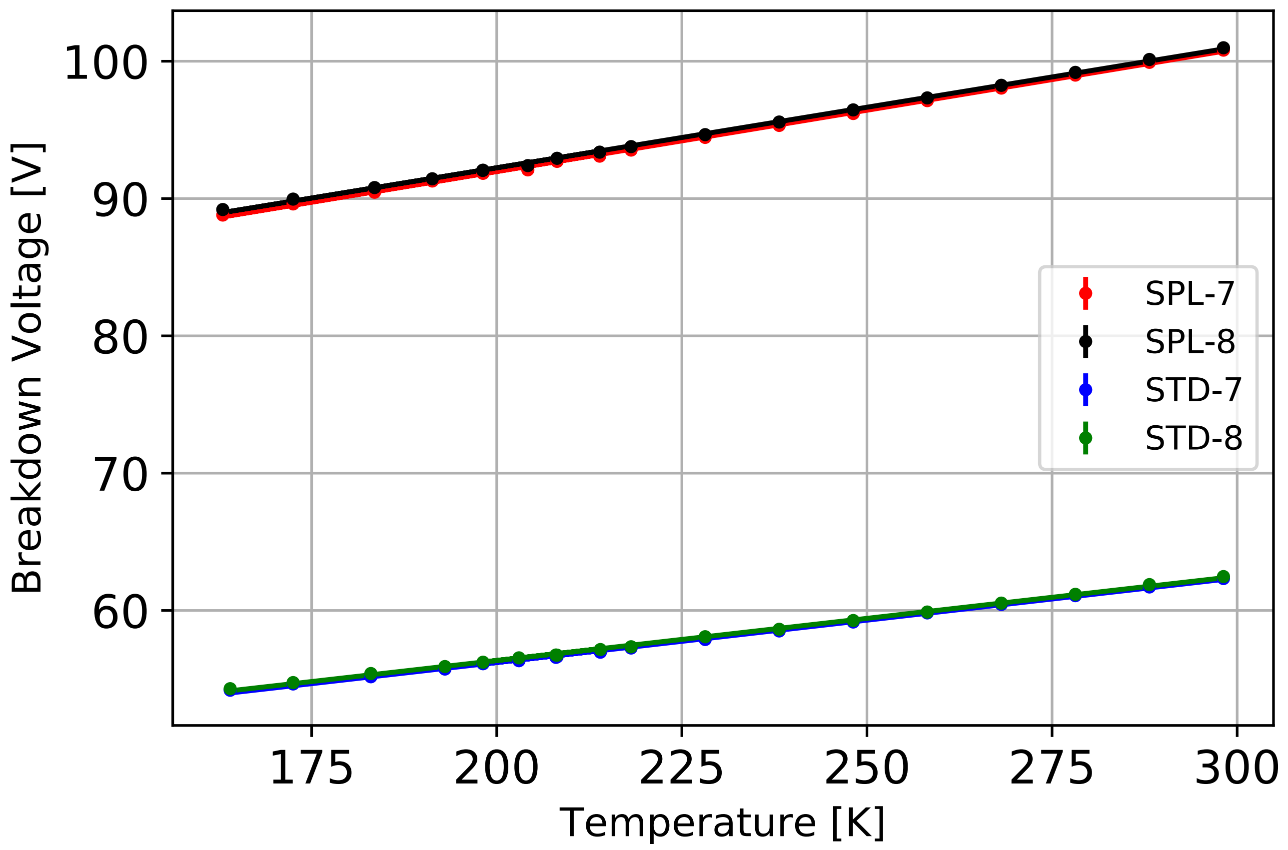
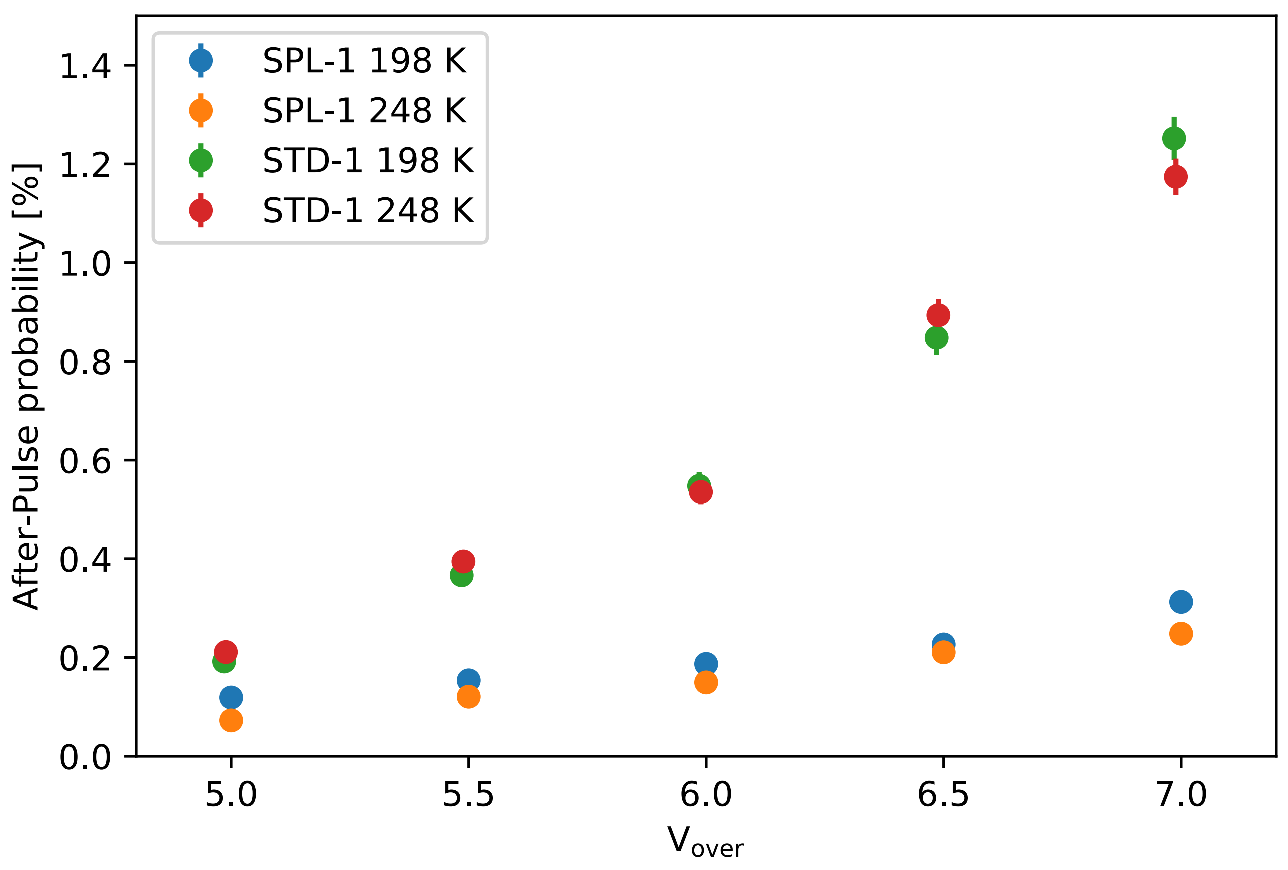
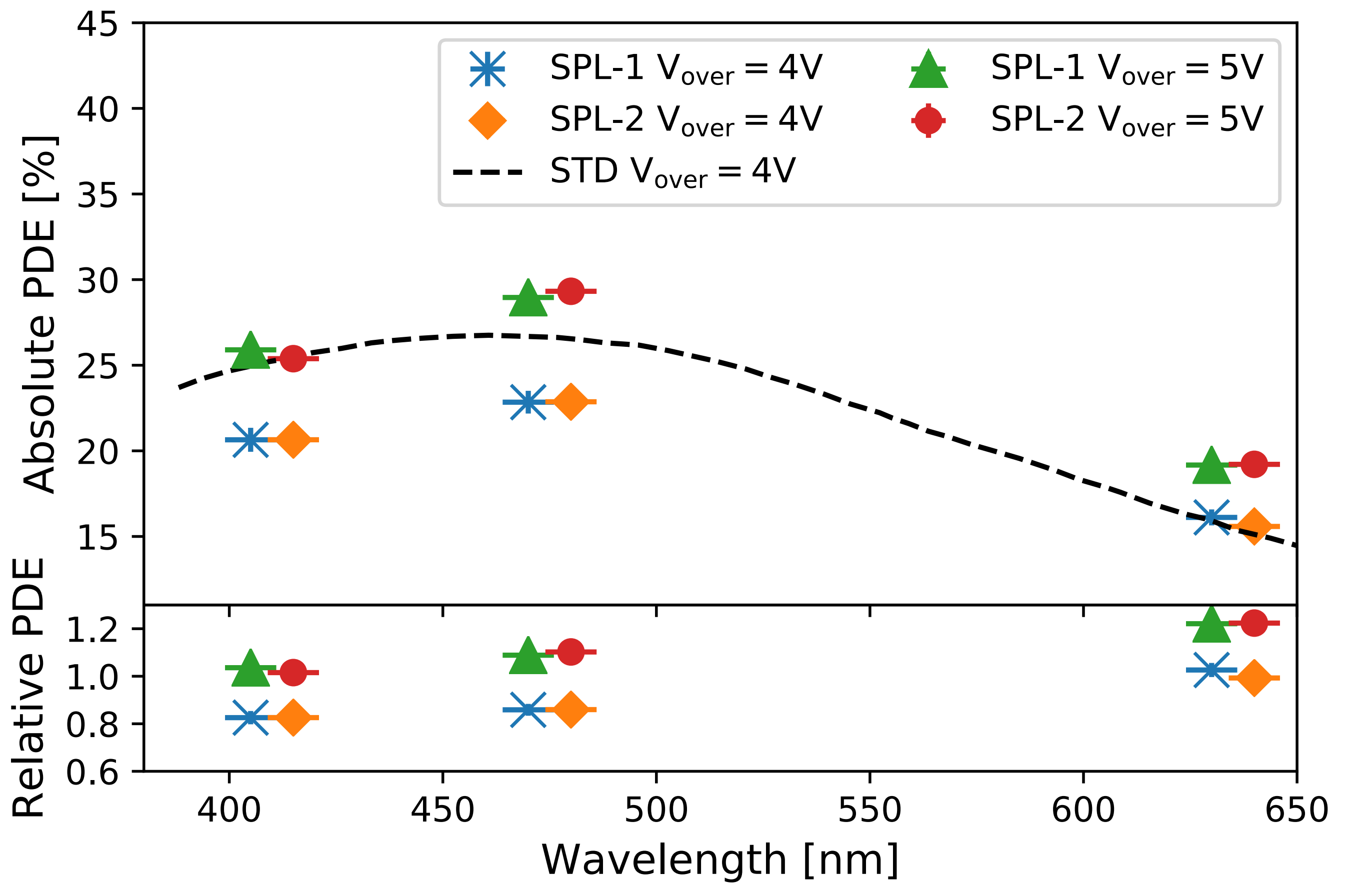




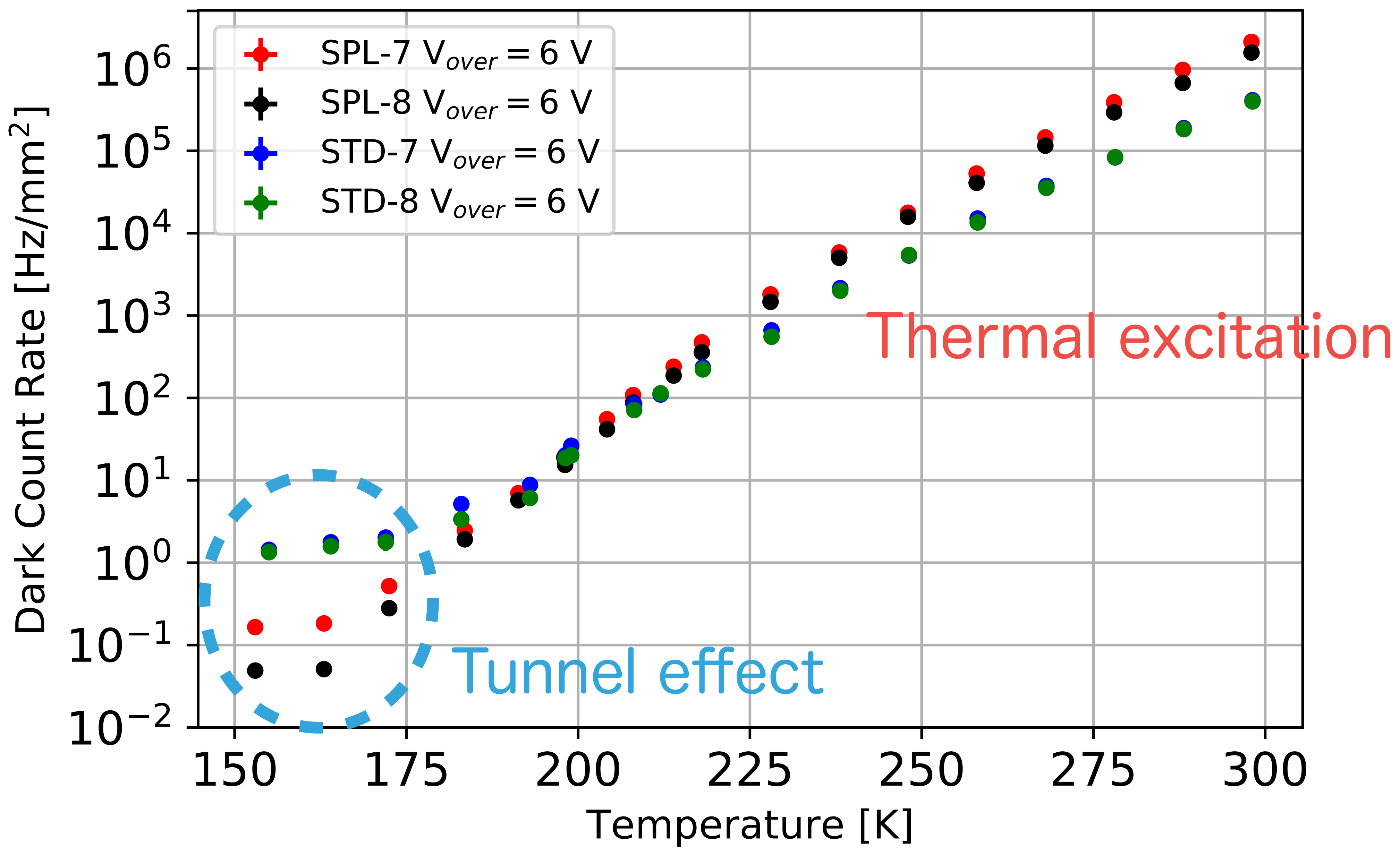


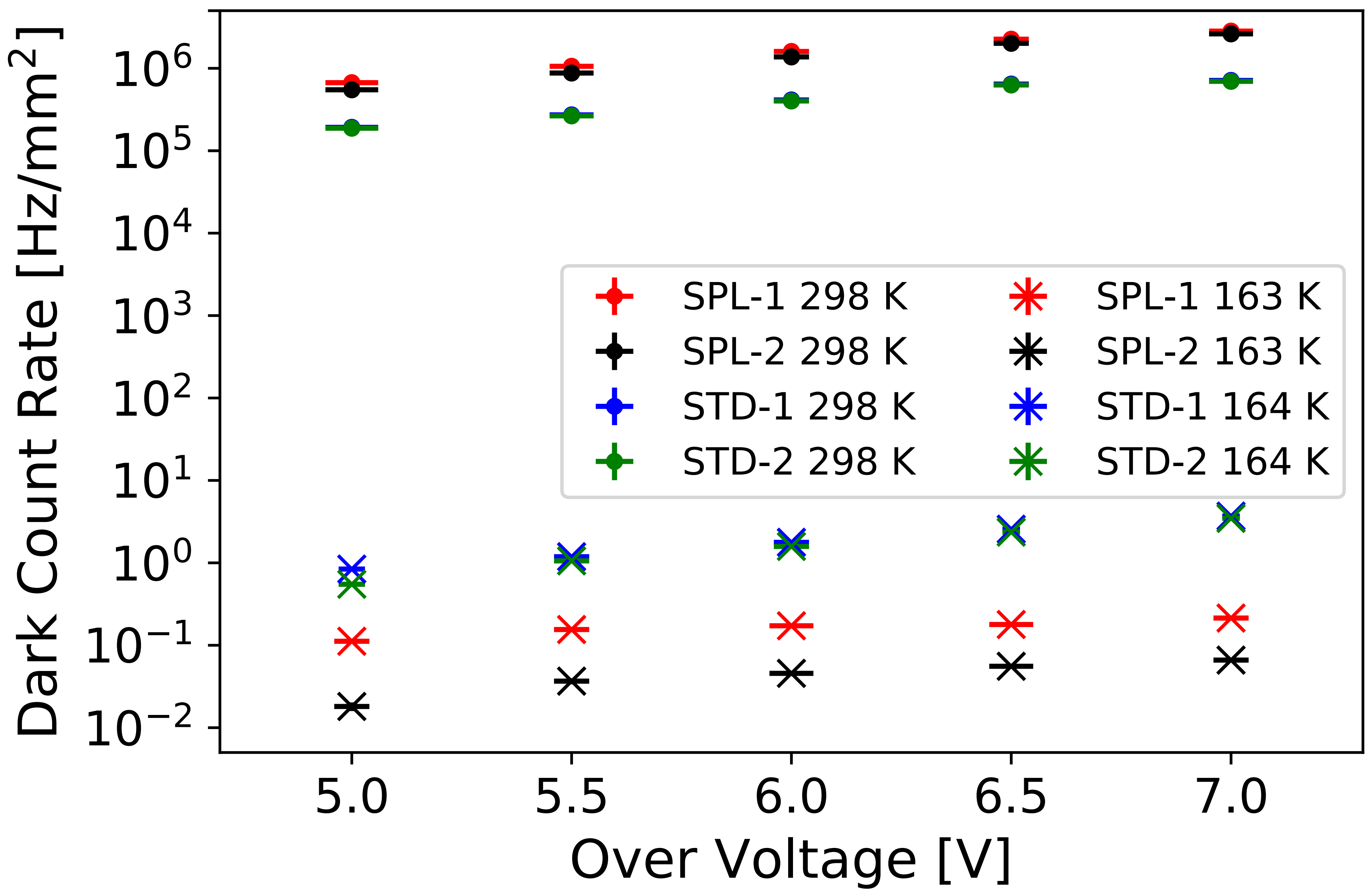


Low DC Rate SiPM

- To suppress the tunneling effect, we have developed a new SiPM with lowered electric field strength with Hamamatsu
  - E-field(↘)、depletion layer(↗)、 Doping concentration(↘)
- Breakdown voltage becomes larger a bit, but no significant changes in other performances.
- By modifying inner field configuration, DC rate can be reduced by a factor of 6-60 w.r.t. a standard SiPM
- Recently developed a SiPM dedicated for VUV light. Both Gain and PDE are similar level that achieved for VUV4 SiPMs.

	VUV 4 S13360	New
V(break down)	~53V	~93V
Gain	～1.4×10⁵	～2.3×10⁵
Active area	3×3mm2	
Pixel piches	50/100μm	
Package	Ceramic	
Trench	With Trench	

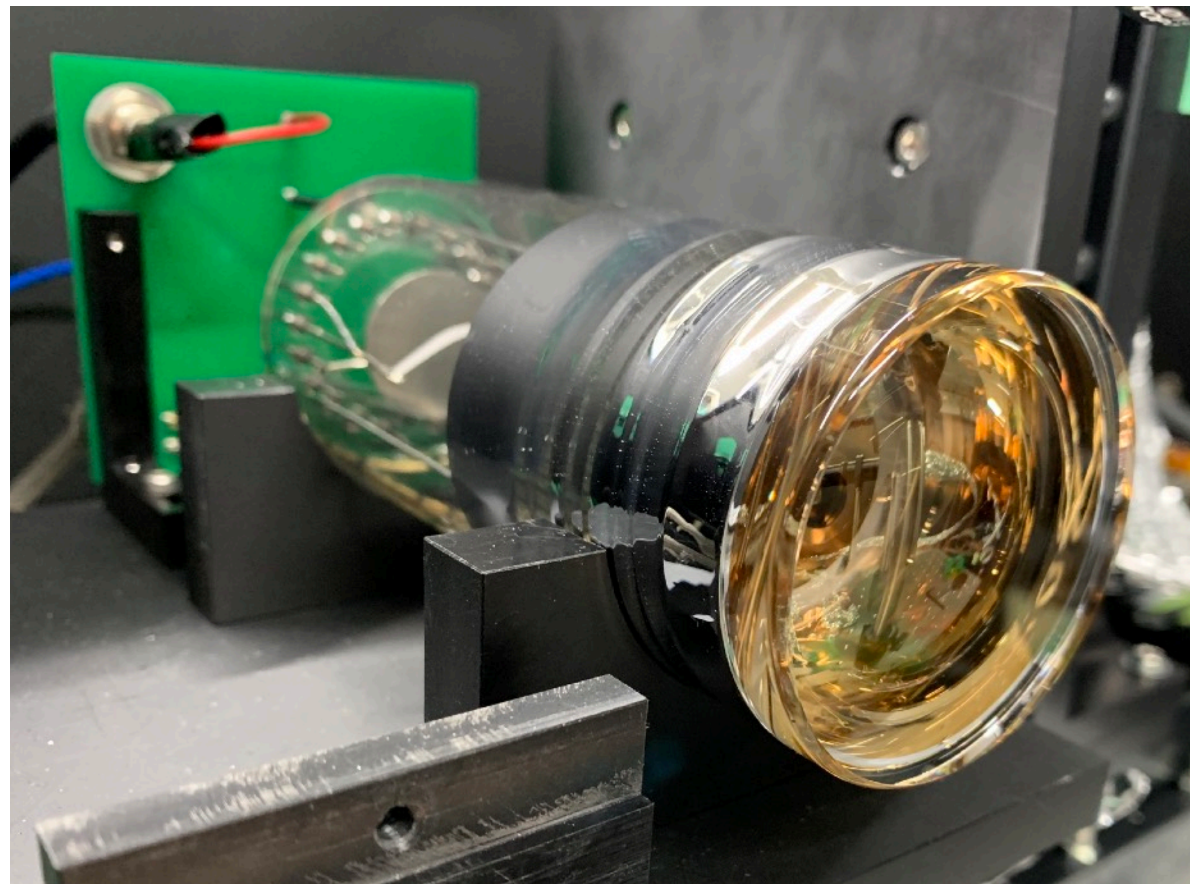


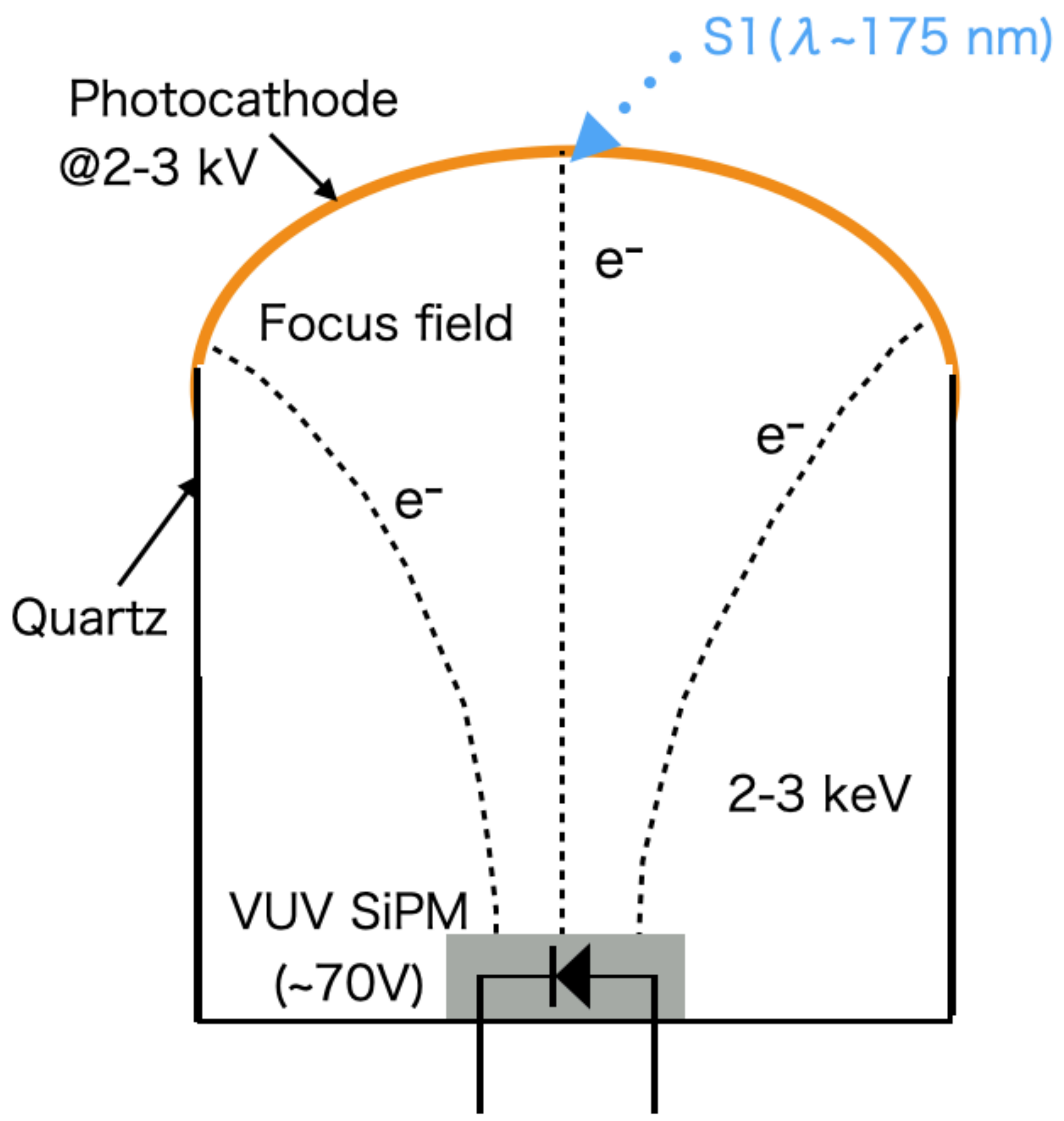


Hybrid Photosensor (= PMT + SiPM)

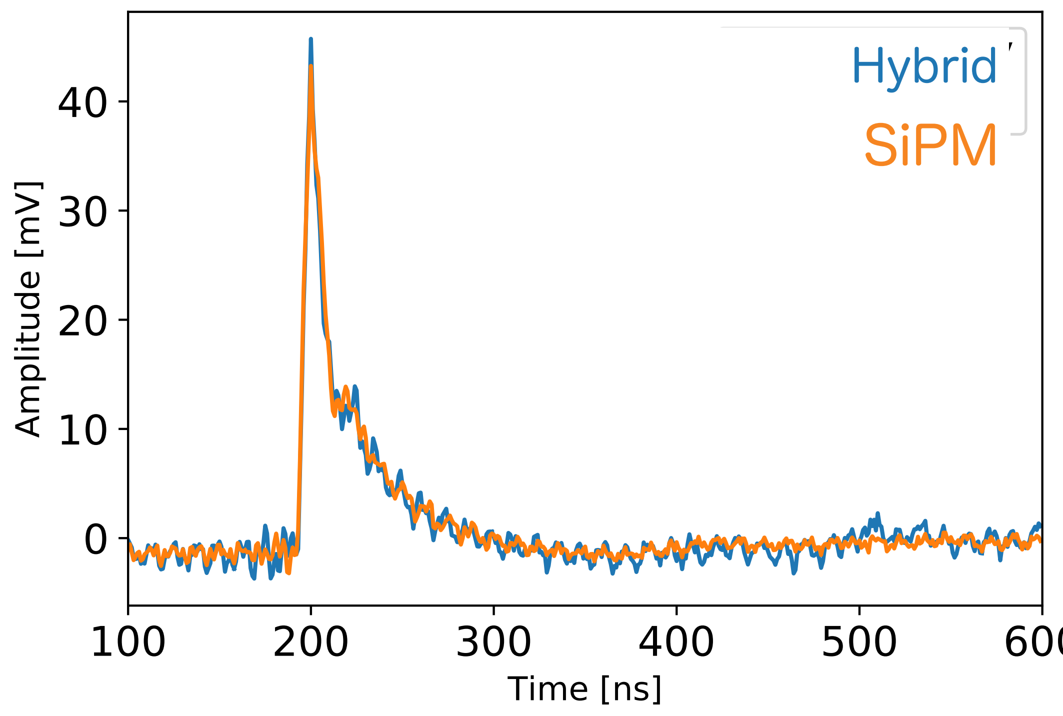
- SiPM: for detecting photo-electron (not photon!)
- O(100) times less DC rate is possible w.r.t. SiPM because of photo-sensitive area difference
- Goal: Quartz + Photocathode + SiPM only
  —> lower # of neutron and material BGs (ideal also for 0νbb)

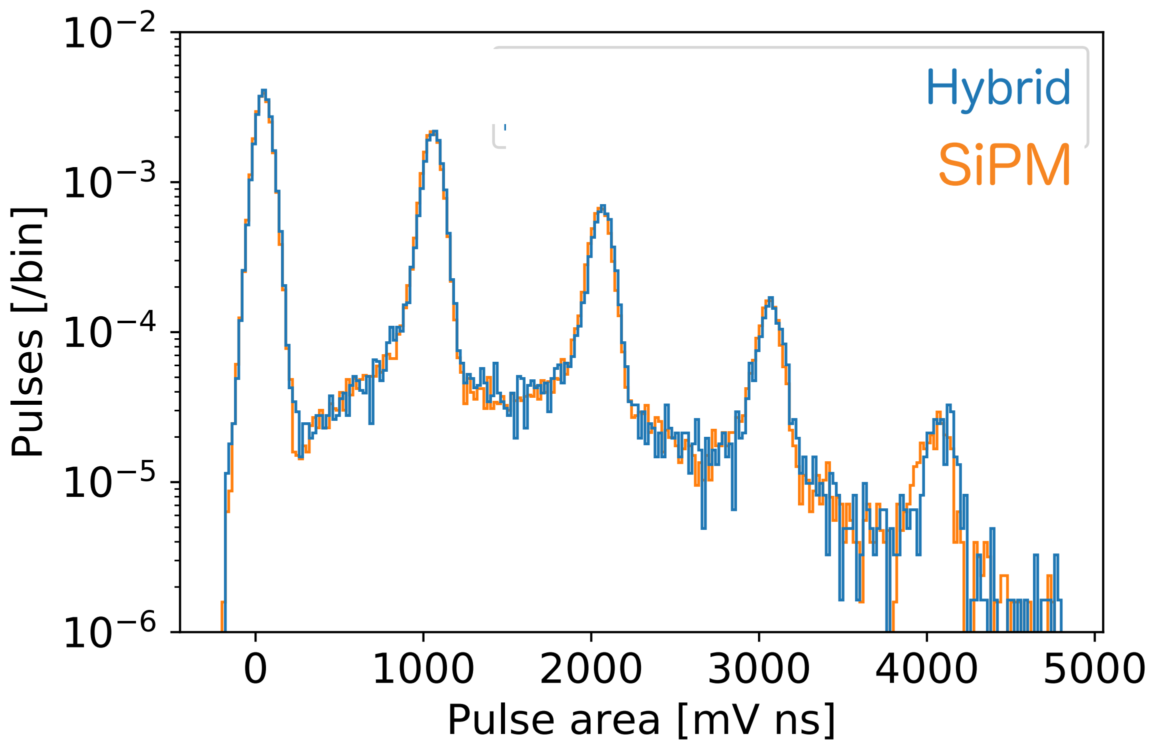
Hybrid (XE5859)

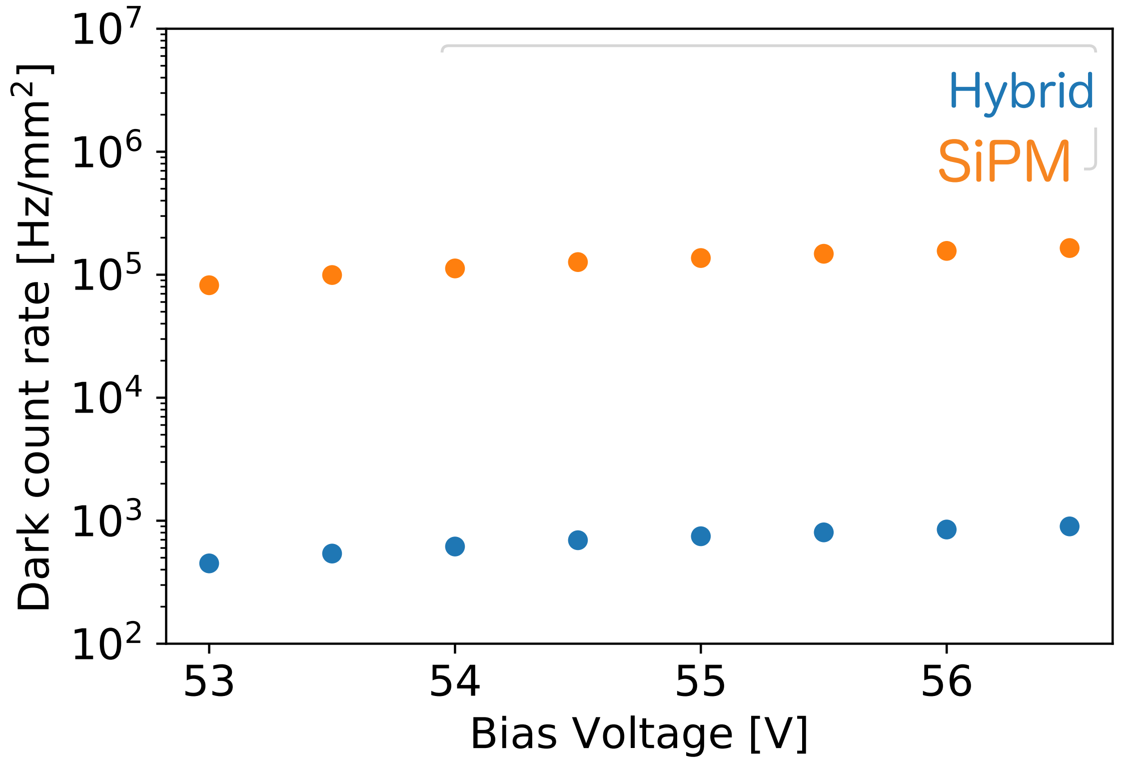




	Hamamatsu XE5859
Photocathode	Bialkari (ϕ 46 mm)
Window	Quartz
SiPM	S13370 (VUV4): 3 mm×3 mm
SiPM pixel size	50 μm × 50 μm (fill factor = 60%)
Photocathode HV	< 2kV







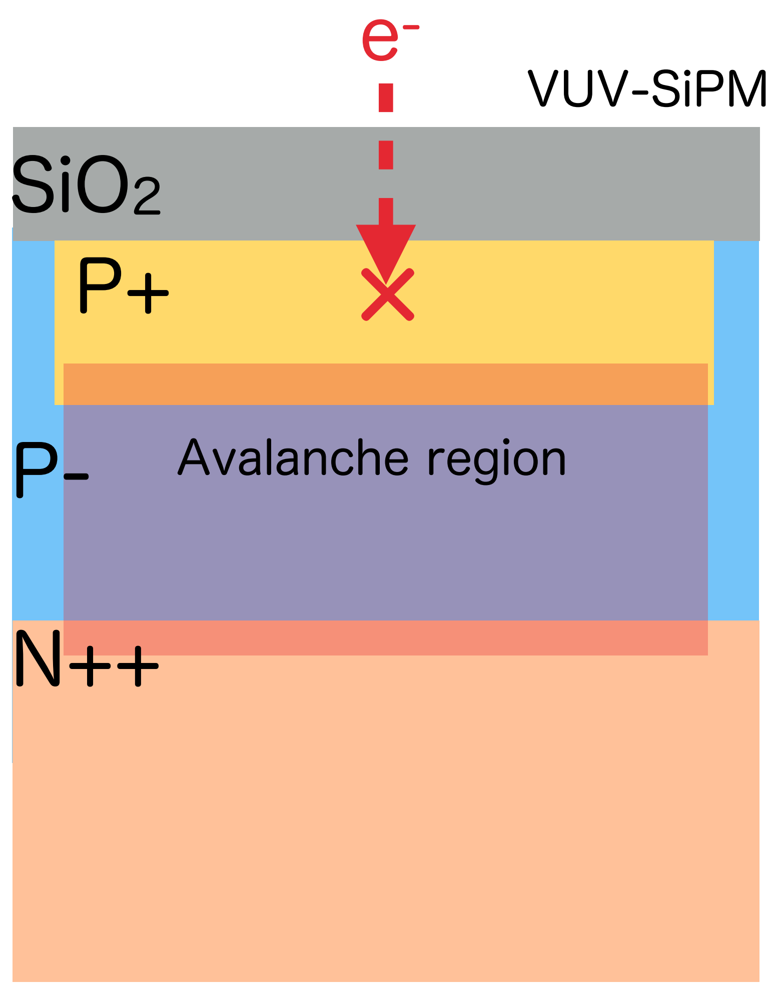
PDE for Hybrid Photosensor

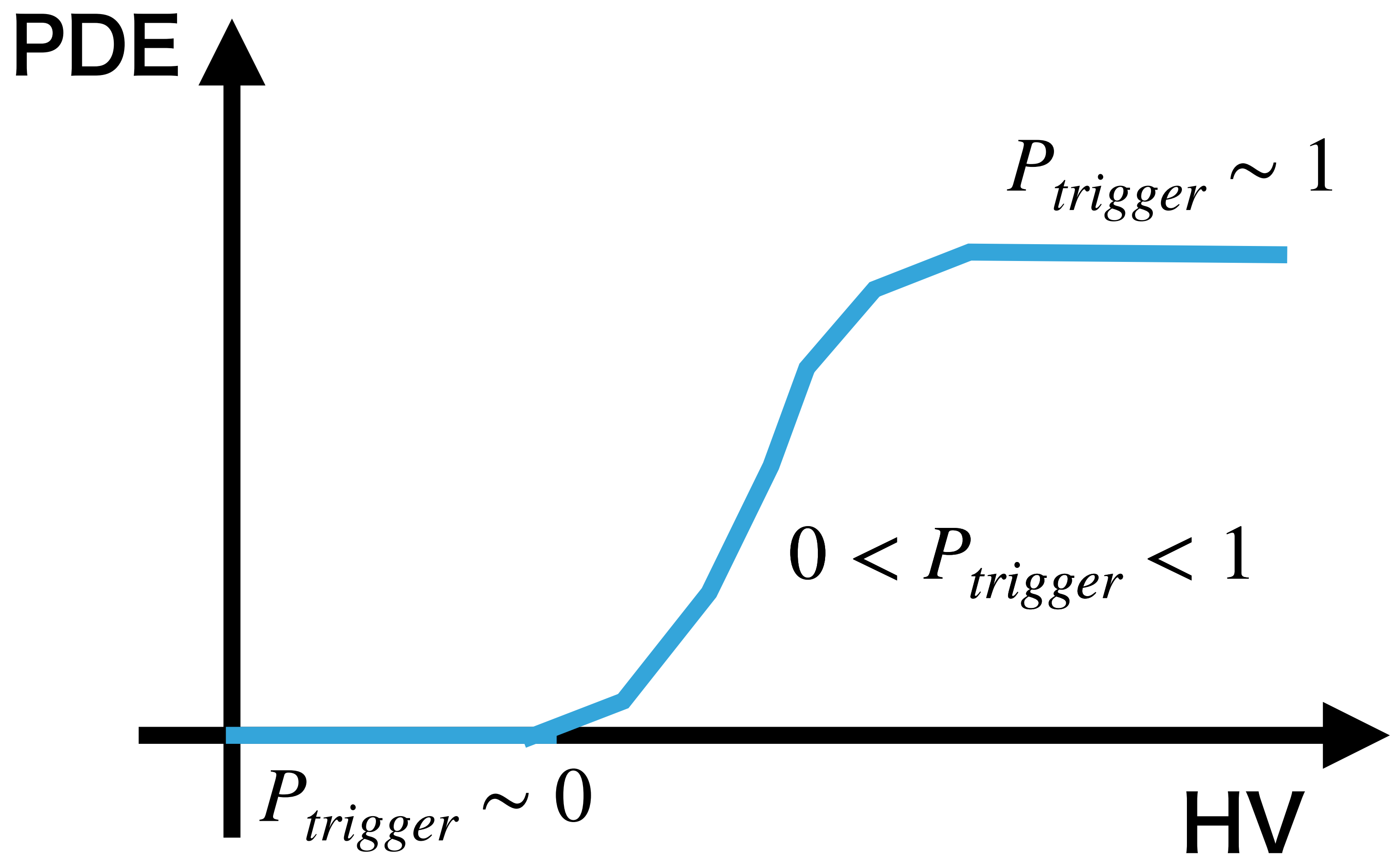
$$\mathrm{PDE} = \mathrm{QE} \cdot \epsilon_{\mathrm{collection}} \cdot \mathrm{FF} \cdot \mathrm{P}_{\mathrm{trigger}}$$

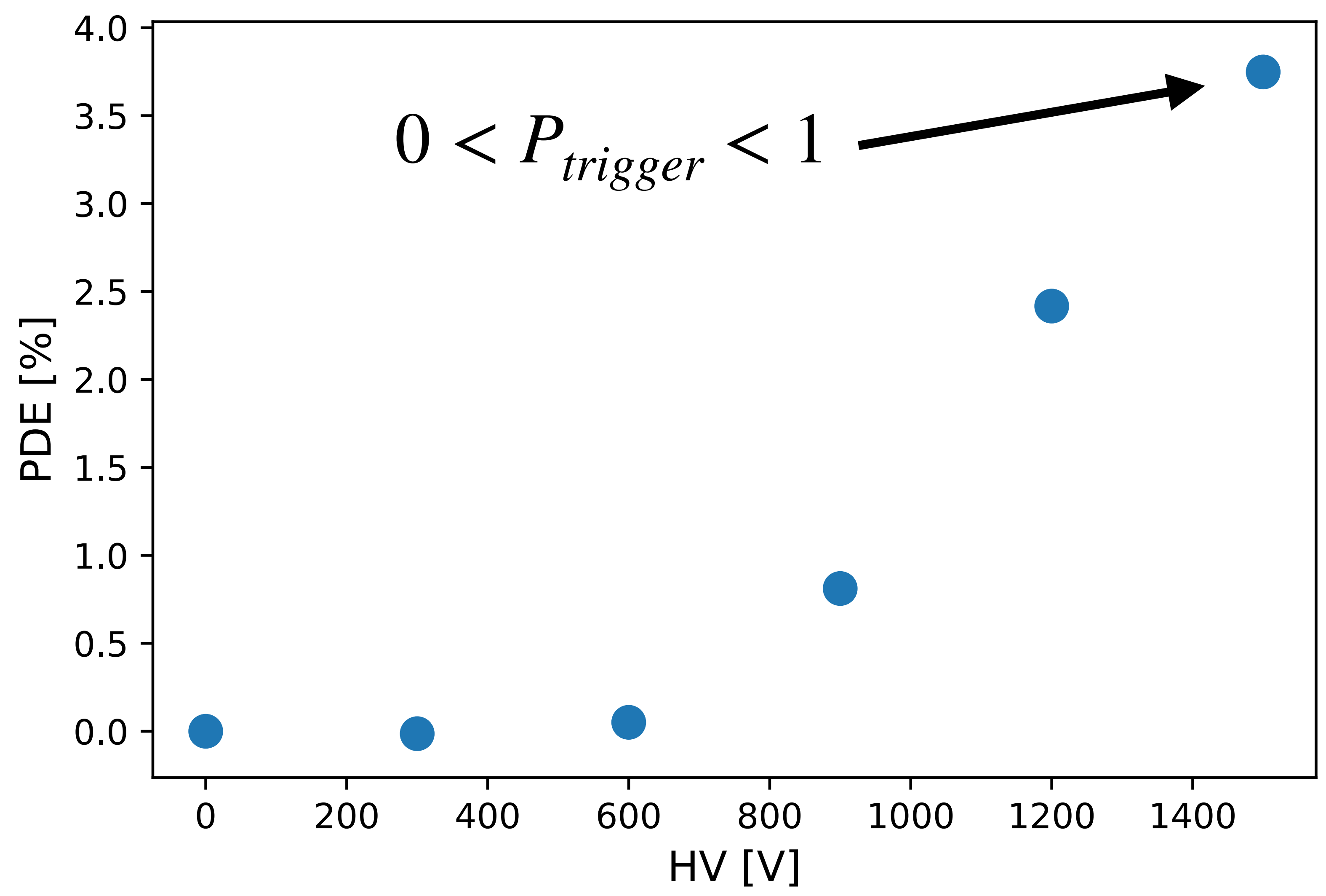
QE	Bialkali	35%
ε (collection)	Collection eff. for photoelectron	~100%
FF	fill factor for SiPM (50μm pixel)	60%
P(trigger)	Probability for a photoelectron to reach an avalanche layer	?

- Photoelectrons need to reach avalanche layer
- Penetration depth depends on kinetic energy of electrons

- $P_{trigger} \sim 0$: electrons mostly stop in SiO2 or P+ layer
- $0 < P_{trigger} < 1$: some electrons can reach avalanche layer
- $P_{trigger} \sim 1$: All electrons can reach avalanche layer



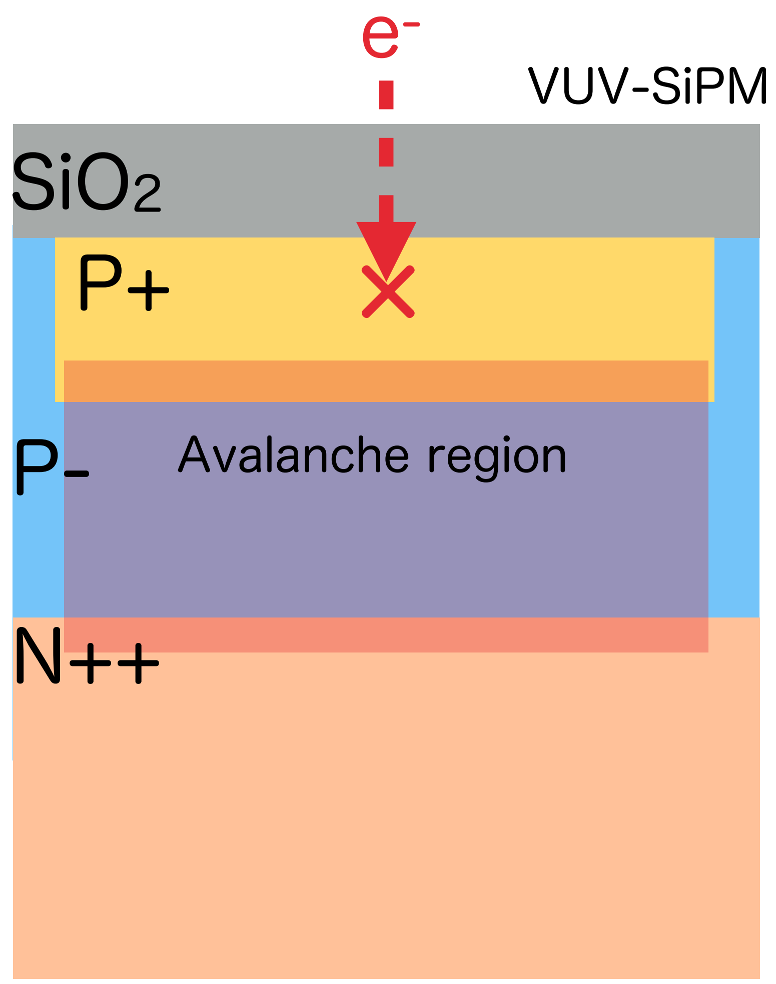


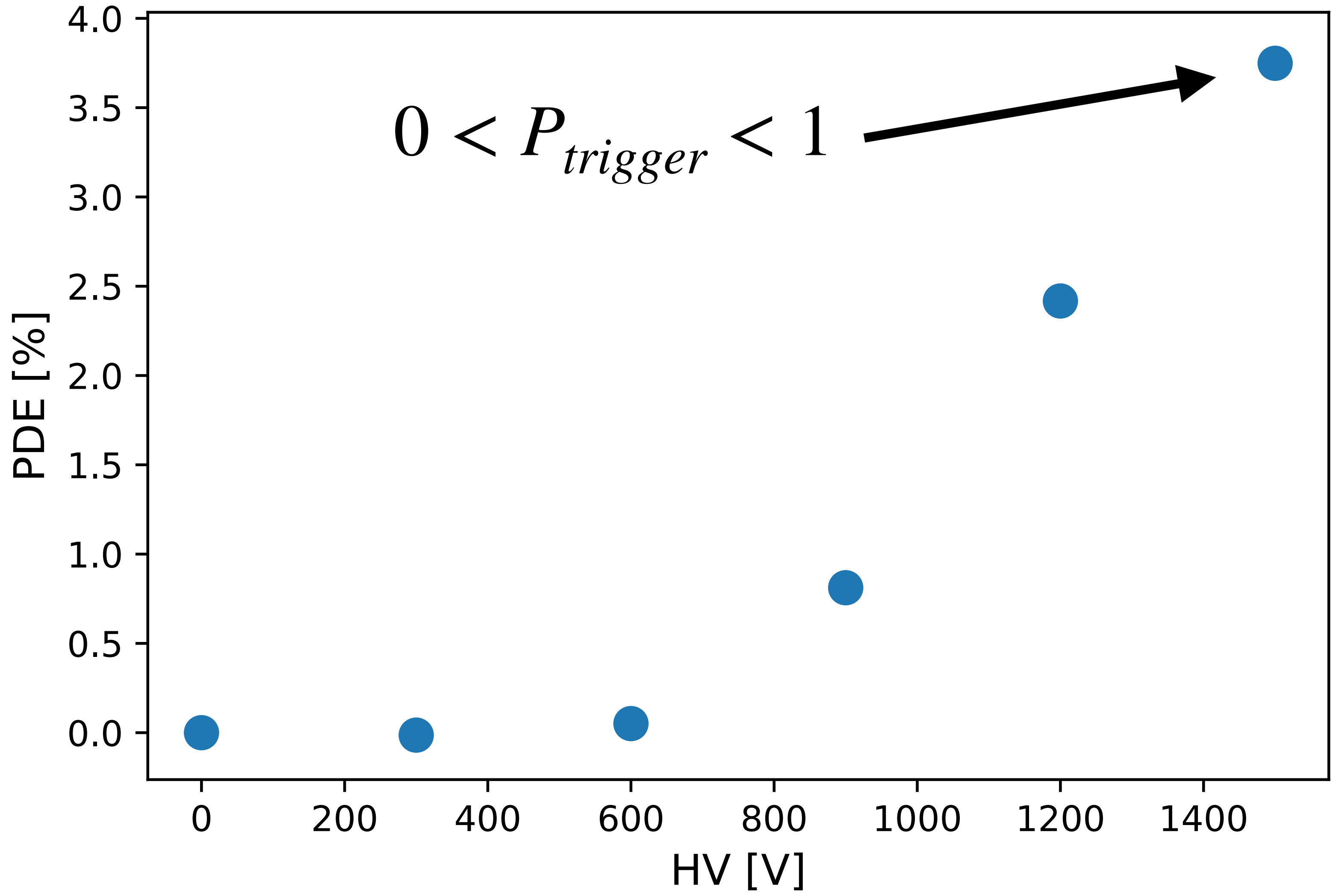


PDE for Hybrid Photosensor

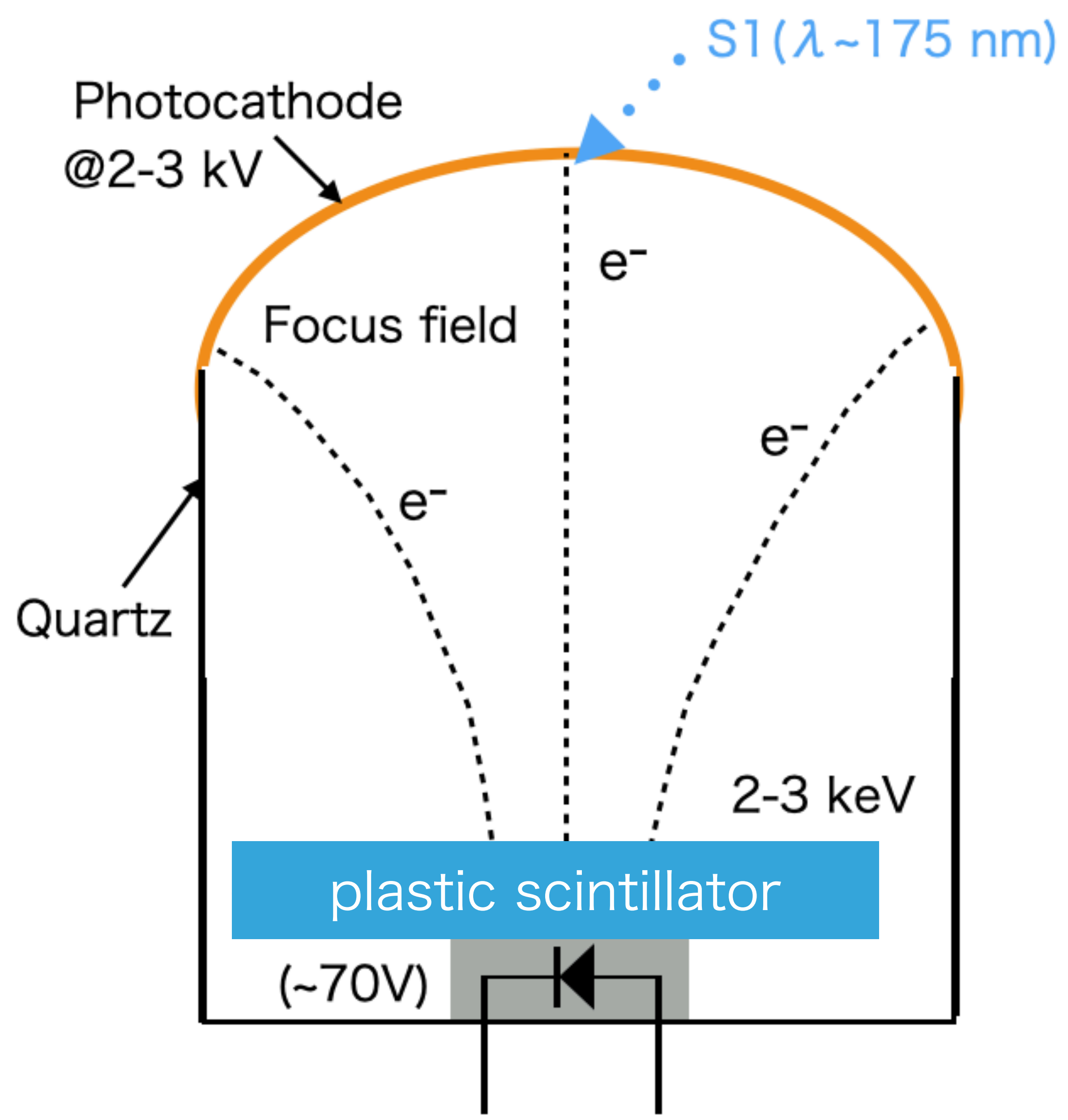
Why P(trigger) < 1 ?

- Kinetic energy of photoelectron: 1.5 keV (low-energy)
  —> Range in Si = O(10) nm
- Cannot reach avalanche layer because of thick SiO2/P+ layer





How can we improve PDE?



Put a thin plastic scintillator in front of SiPM to convert a photoelectron into O(10) UV photons (ABALONE-like detector)

(VUV photon -> photoelectron -> UV photons)

Plastic scintillator candidates:

- EJ-212(t=100 um): ~10 photons/keV
  - Wavelength: 400 - 550 nm
  - Currently testing the concept with a dedicated detector

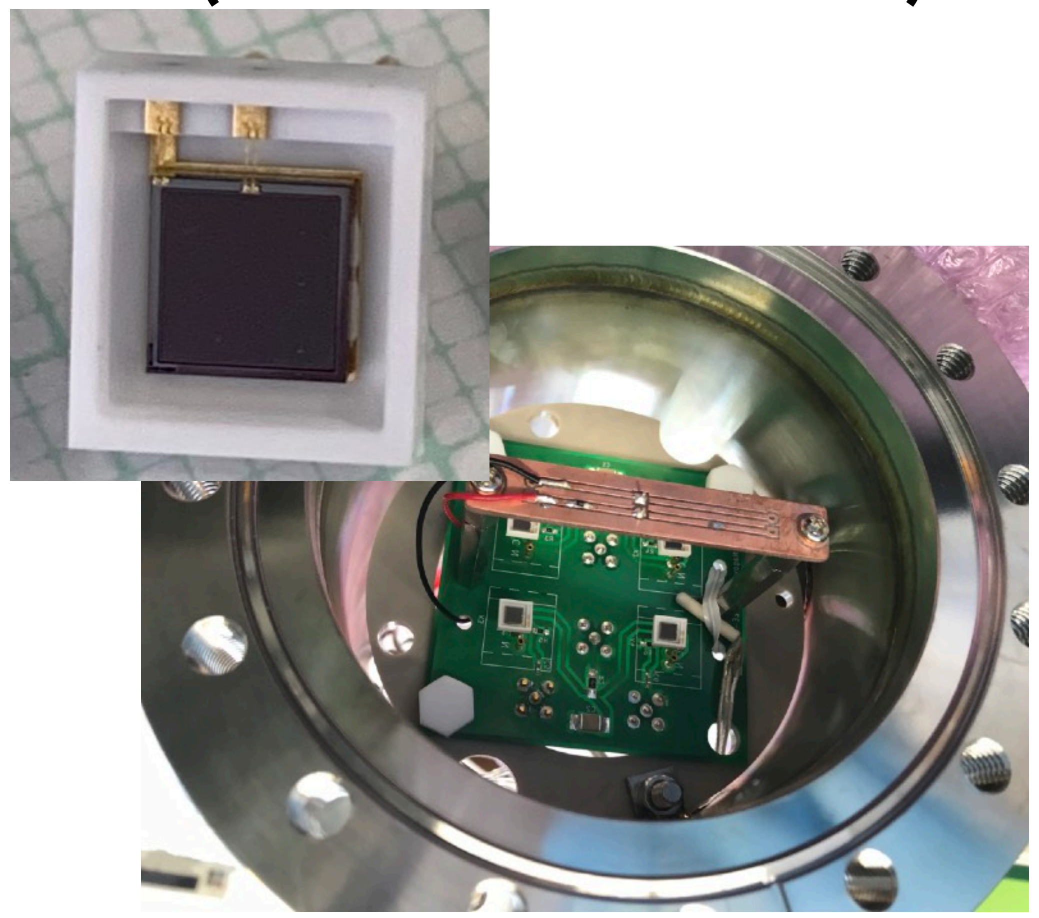
Summary

For future direct DM experiments such as DARWIN, we are developing three different types of photodetectors:

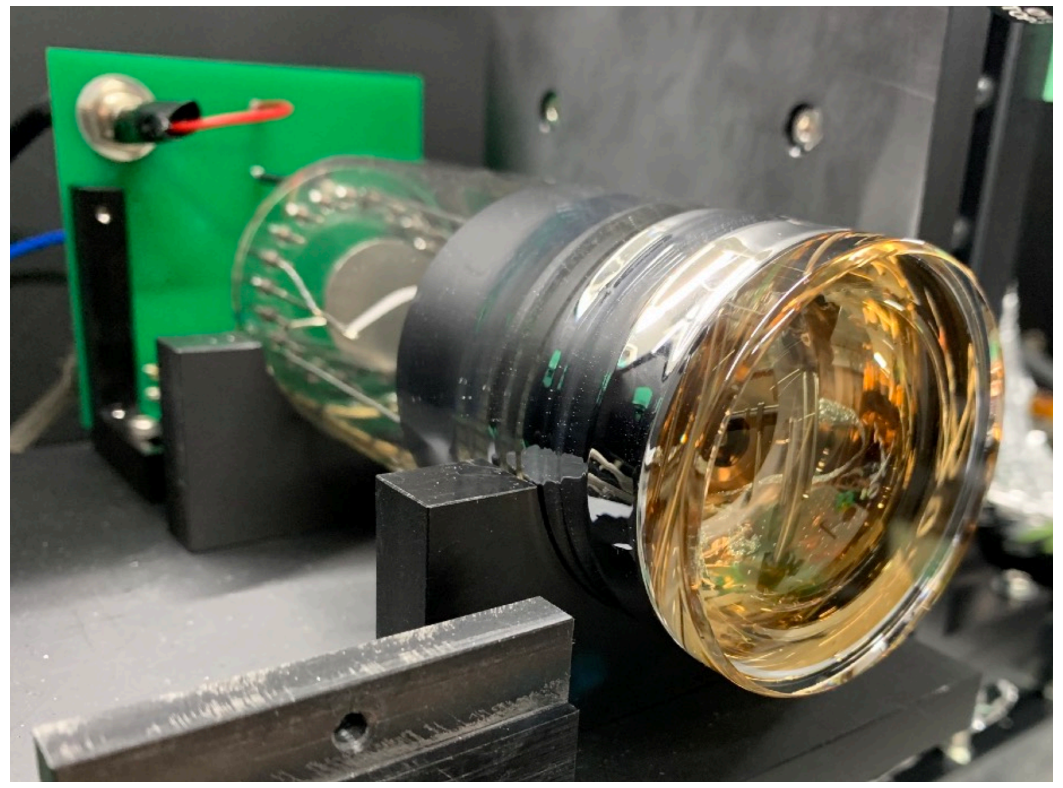
1. Ultra low-radioactive PMT: 3-inch R13111 developed by XMASS already available
2. SiPM with lower DC rate: currently characterizing a dedicated VUV SiPM
3. Hybrid-detector (PMT/SiPM): currently developing a new hybrid photodetector with plastic scintillator

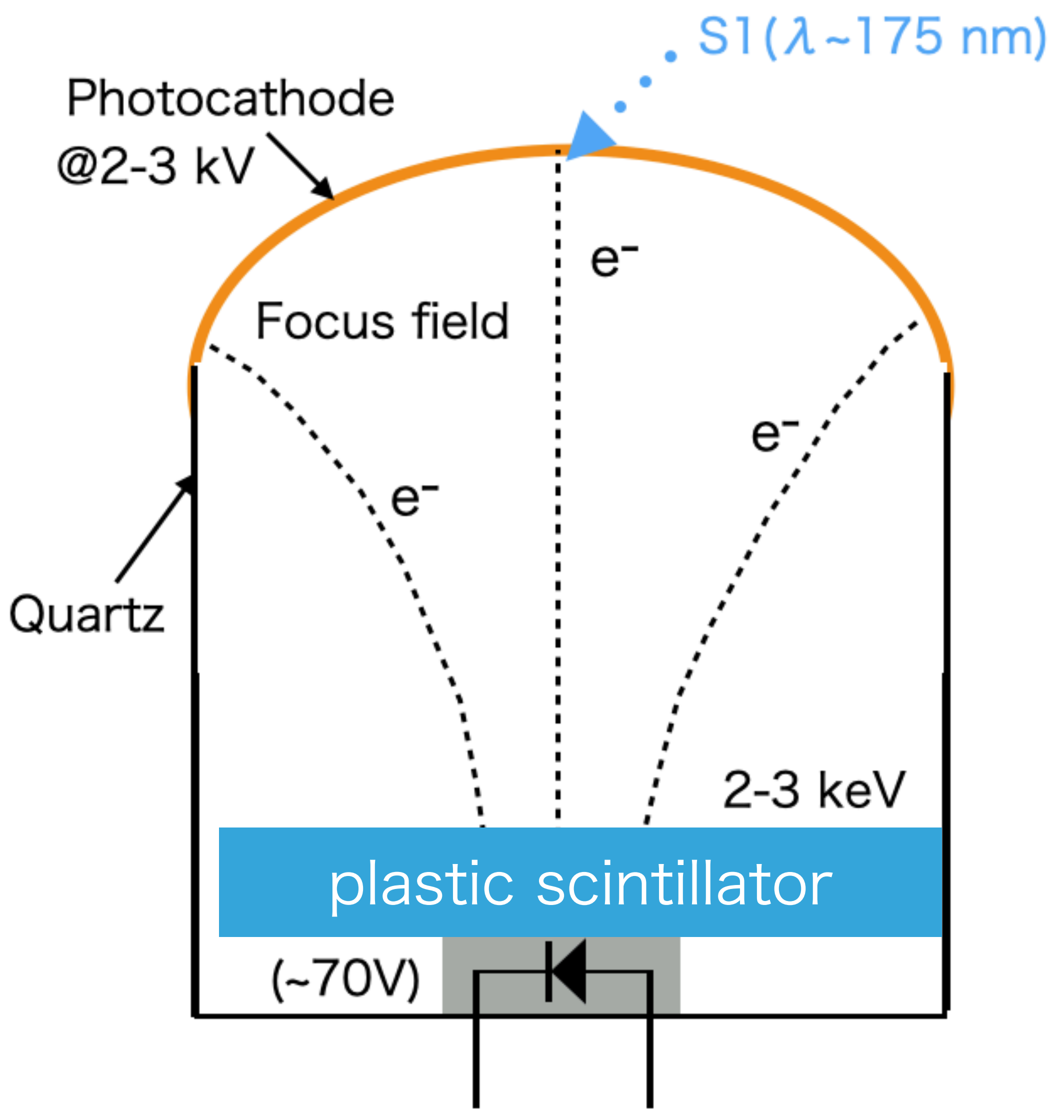
PMT (R13111)

SiPM (S12572-015C-STD)



Hybrid (XE5859)





Back Up

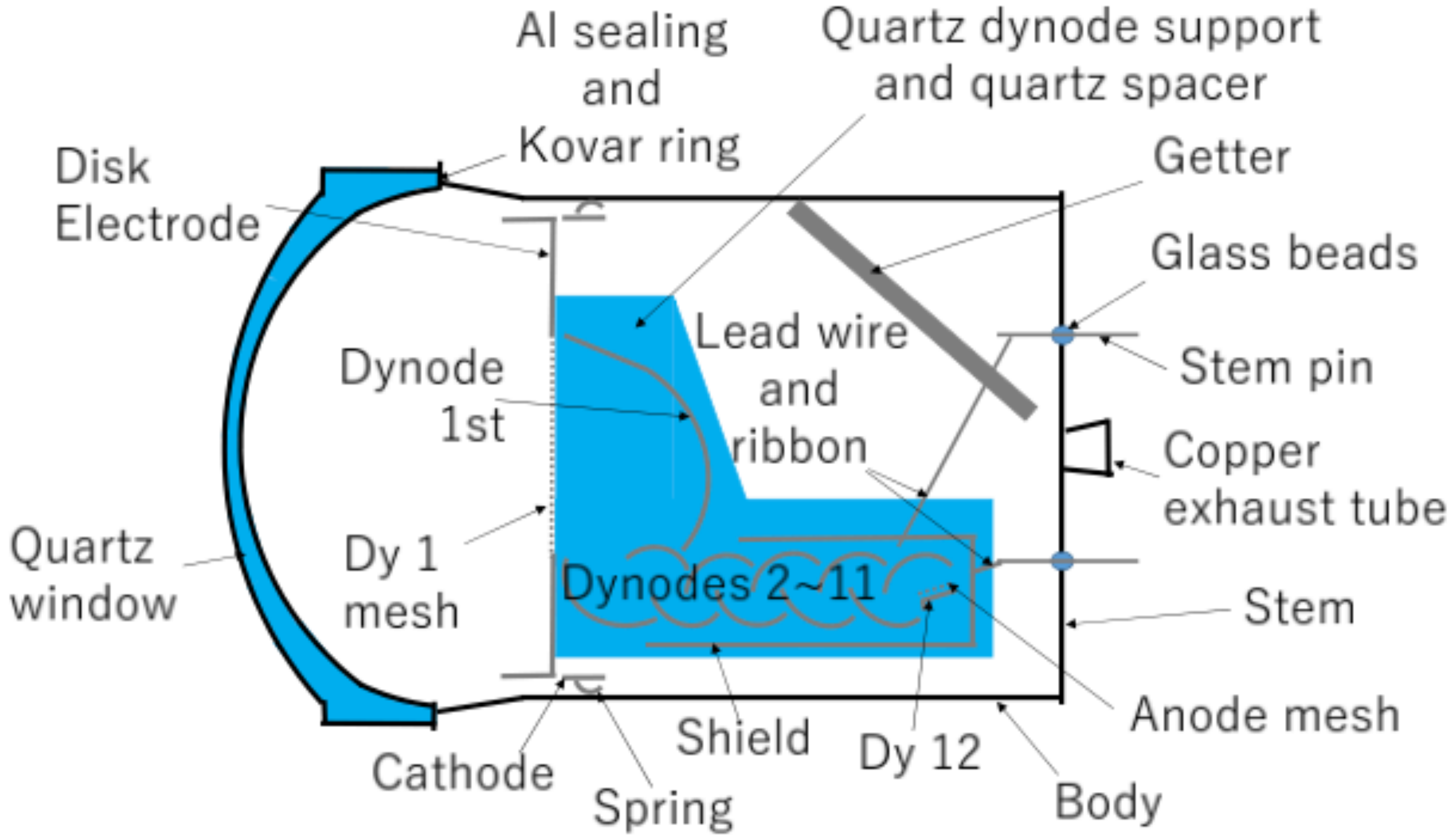
Low BG PMTs: R13111

JINST 15 P09027

Lowest radioactivity among PMTs for LXe DM detector.

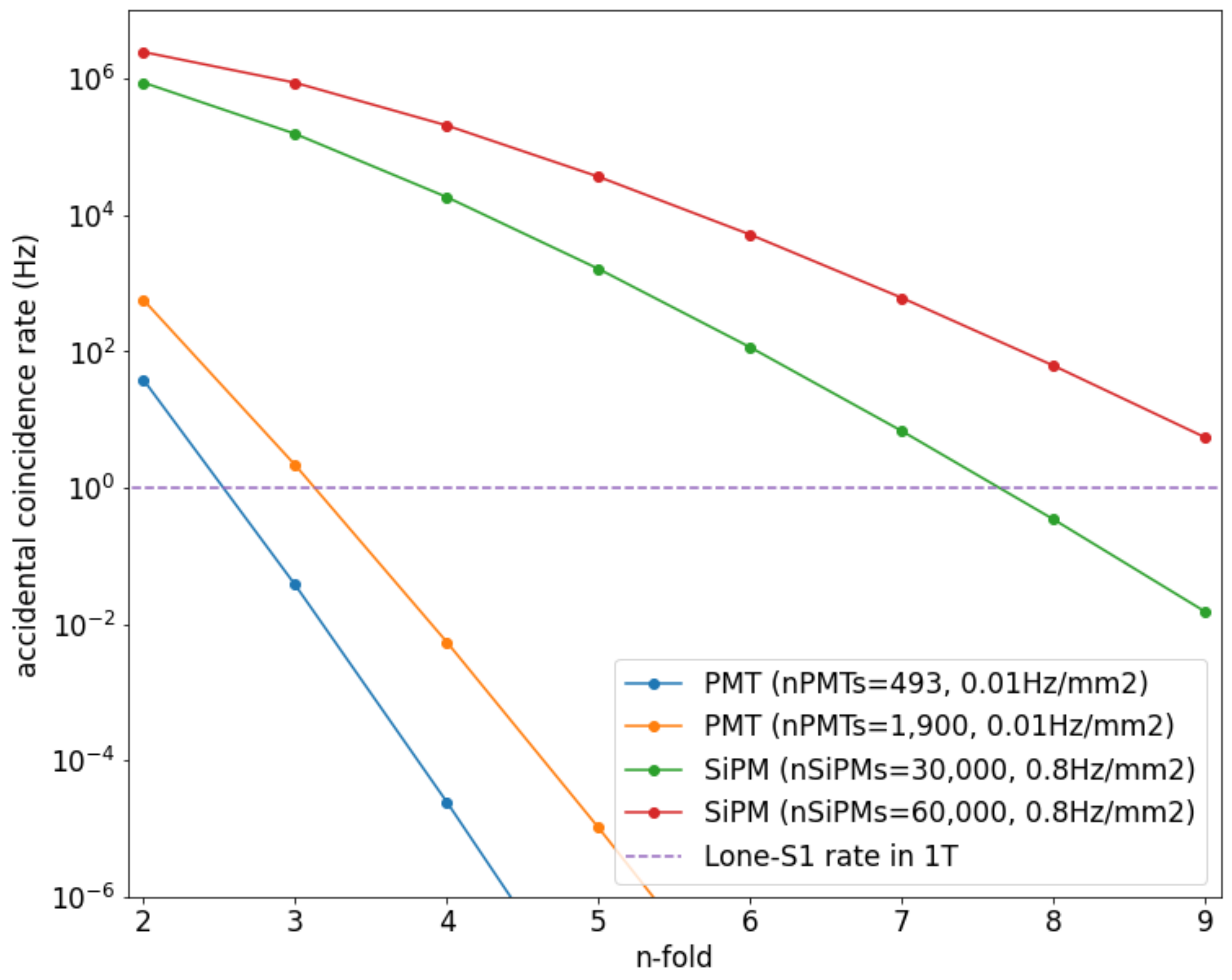
- Glass material was synthesized using low-radioactive-contamination material
- Photocathode was produced with 39K-enriched potassium
- Purest grade of aluminum material used for the vacuum seal.
- TTS is ~2 ns, better than other PMTs for LXe DM detector

μBq/PMT	^{226}Ra	^{238}U	^{228}Ra	^{40}K	^{60}Co
R13111 in 2015	$(3.8 \pm 0.7)\cdot 10^2$	$<1.6 \cdot 10^3$	$(2.9 \pm 0.6)\cdot 10^2$	$<1.4 \cdot 10^3$	$(2.2 \pm 0.5)\cdot 10^2$
R13111 in 2016	$(4.4 \pm 0.6)\cdot 10^2$	$<1.4 \cdot 10^3$	$(2.0 \pm 0.6)\cdot 10^2$	$(2.0 \pm 0.5) \cdot 10^3$	$(1.3 \pm 0.4)\cdot 10^2$
R11410-21(XENON1T) [15]	$(5.2 \pm 1.0)\cdot 10^2$	$<1.3 \cdot 10^4$	$(3.9 \pm 1.0)\cdot 10^2$	$(1.2 \pm 0.2) \cdot 10^4$	$(7.4 \pm 1.0) \cdot 10^2$
R11410-10(PandaX) [3]	$<7.2\cdot 10^2$	—	$<8.3\cdot 10^2$	$(1.5 \pm 0.8) \cdot 10^4$	$(3.4 \pm 0.4) \cdot 10^3$
R11410-10(LUX) [19]	$<4.0\cdot 10^2$	$<6.0 \cdot 10^3$	$<3.0 \cdot 10^2$	$<8.3 \cdot 10^3$	$(2.0 \pm 0.2) \cdot 10^3$



What's the Target DC Rate for DARWIN?

N-fold accidental coin. rate	12×12mm² SiPM 0.8 Hz/mm2	3-inch PMT 0.01 Hz/mm2	
	60,000 channels	1,900 channels	493 channels
3-fold	8.8×10^5 Hz	2.2 Hz	0.04 Hz
6-fold	5.2×10^3 Hz	<< 1	<< 1
9-fold	5.5 Hz	<< 1	<< 1



- Lone-S1 rate in 1T&nT ~ 1 Hz.
- 3-fold accidental coincidence rate with 100 ns window for 1,900 PMTs is ~2.2Hz, while it is ~ 10^6 Hz for 60,000 SiPMs
    - need to increase from 3-fold to 8/9-fold to achieve O(1) Hz
- DC rate for new photosensor should be less than 0.01Hz/mm2 if we want to keep 3-fold coincidence