The stability of HPK VUV4 SiPMs following a large dose of VUV radiation

Lucas Darroch, David Gallacher, Chloe Gingras, and Thomas Brunner,

on behalf of the nEXO collaboration

CPAD 2022
November 30

- Neutrino Osc. $\Rightarrow \; m_\nu \neq 0$
- Dirac mass $\Rightarrow \; \nu_R$

Dirac mass term for neutrino:

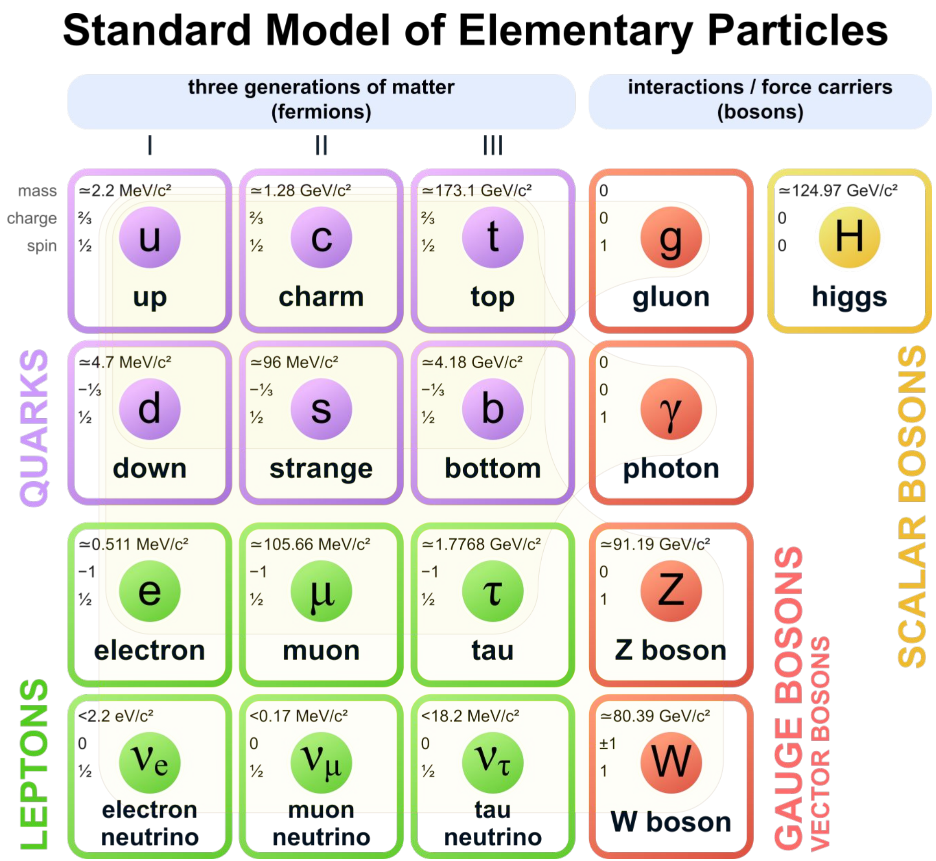
$$L_D = -m_D(\bar{\nu}_R \nu_L + \bar{\nu}_L \nu_R)$$

Why is the Dirac mass so small?

Majorana mass term for neutrino:

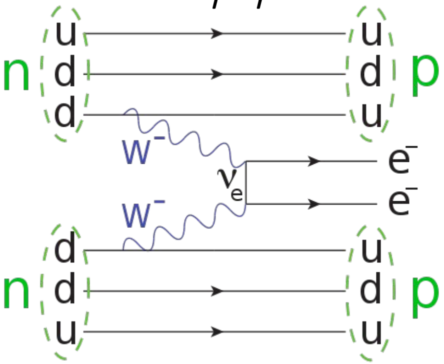
$$L_M = -\frac{1}{2} M(\bar{\nu}_R^C \nu_R + \bar{\nu}_R \nu_R^C)$$

$$\Psi^C = \hat{C}\hat{P}\Psi \; = \; i\gamma^2\gamma^0\Psi^\star$$

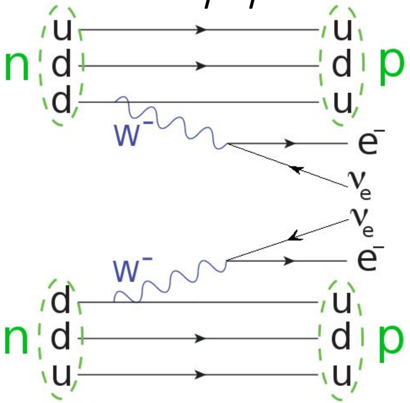


- $0\nu\beta\beta \Rightarrow \nu$: Majorana particle
- $2\nu\beta\beta$ SM process

$0\nu\beta\beta$



$2\nu\beta\beta$



$\beta\beta$ - Decay Spectrum

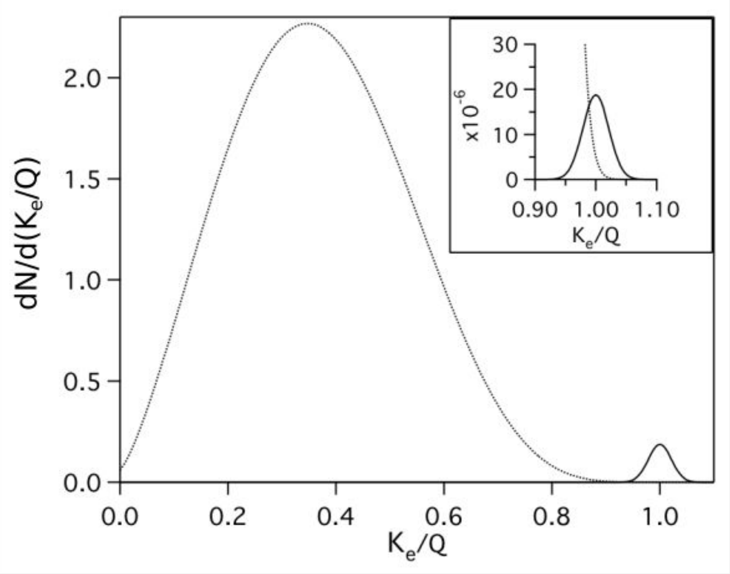
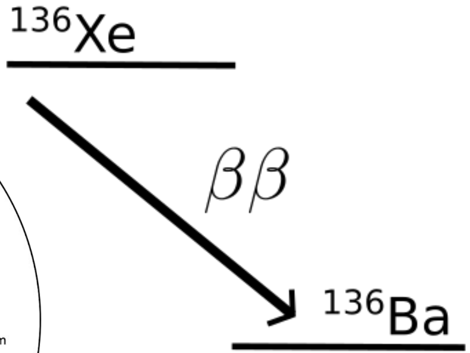


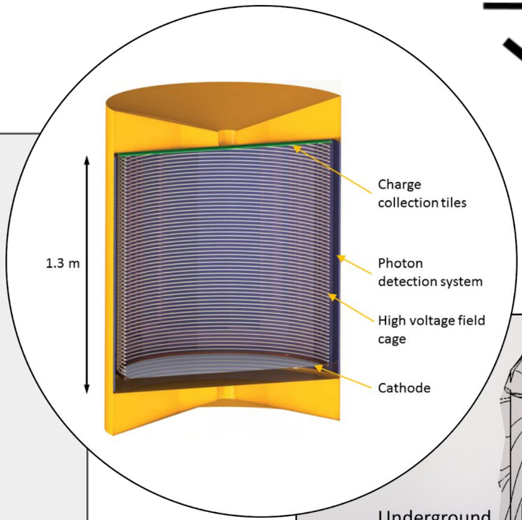
Image from Vogel, Petr. "Neutrinoless double beta decay." *AIP Conference Proceedings*. Vol. 870. No. 1. AIP, 2006.

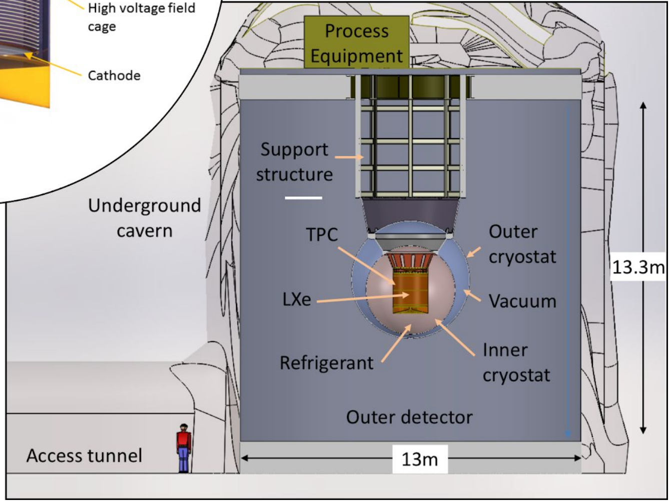
- 2vββ spectrum continuous;
- 0vββ spectrum sharply peaked

nEXO

- Single phase TPC
- 5 tonnes LXe, 90% ^{136}Xe
- Ionization and scintillation signals recorded
- Sensitivity ~10^{28} years for 0νββ half-life[1]







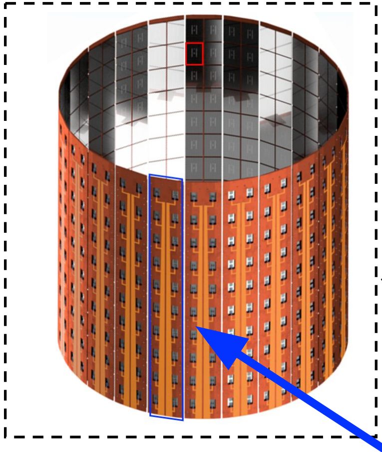
Adhikari, G., et al. "nEXO: neutrinoless double beta decay search beyond 1028 year half-life sensitivity." *Journal of Physics G: Nuclear and Particle Physics* 49.1 (2021): 015104.

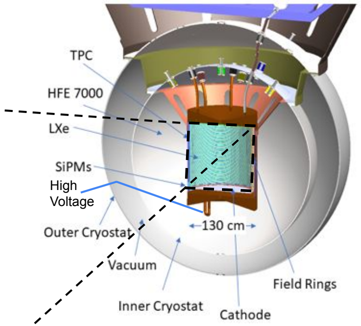
Images from Al Kharusi, S. et al. "nEXO pre-conceptual design report." *arXiv preprint arXiv:1805.11142* (2018).

nEXO photodetector system

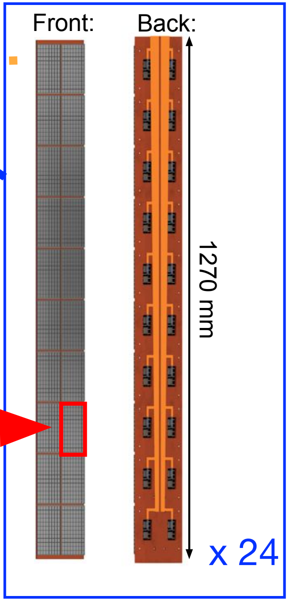
- High gain (single PE resolution)
- Low intrinsic radioactivity
- Low bias voltage
- Prototype SiPMs from two vendors meet nEXO requirements (FBK and HPK)

Photon detector (PD)

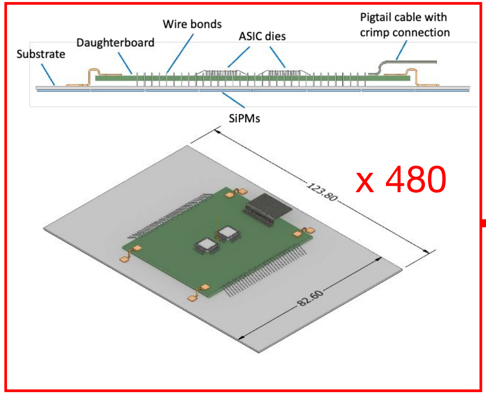




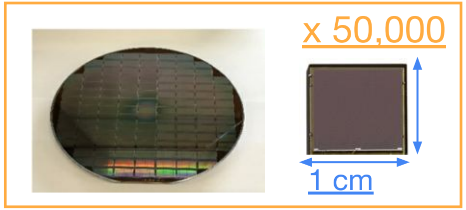
Stave



Tile module



SiPM Devices



Al Kharusi, S. et al. "nEXO pre-conceptual design report." *arXiv preprint arXiv:1805.11142* (2018).

Gallina, G., et al. "Performance of novel VUV-sensitive Silicon Photo-Multipliers for nEXO." *arXiv preprint arXiv:2209.07765* (2022).

Detailed measurements of nEXO candidate SiPMs shown later today

Performance of novel VUV-sensitive Silicon Photo-Multipliers for nEXO

Nov 30, 2022, 4:00 PM
20m
Theater (Wang Center)

Contribution Talk | WG7: Photon Detect... | Early Career Plenary

Speaker

Giacomo Gallina (member@princeton...

Description

Liquid xenon time projection chambers are promising detectors to search for neutrinoless double beta decay ($0\nu\beta\beta$), due to their response uniformity, monolithic sensitive volume, scalability to large target masses, and suitability for extremely low background operations. The nEXO collaboration has designed a five-tonne time projection chamber that aims to search for $0\nu\beta\beta$ of \ce{^{136}Xe} with projected half-life sensitivity of 1.35×10^{28}~yr. To reach this sensitivity, the design goal for nEXO is $\leq$1\% energy resolution at the decay Q-value (2458.07 ± 0.31~keV). Reaching this resolution requires the efficient collection of both the ionization and scintillation produced in the detector. The nEXO design employs Silicon Photo-Multipliers (SiPMs) to detect the vacuum ultra-violet, 175 nm scintillation light of liquid xenon. In this talk, we will show results on the characterization of the newest vacuum ultra-violet sensitive SiPMs by Fondazione Bruno Kessler, the VUVHD3 devices specifically designed for nEXO. We will also present measurements on new test samples of previously characterised Hamamatsu VUV4 Multi Pixel Photon Counters (MPPCs). Various SiPM and MPPC parameters, such as dark noise, gain, direct crosstalk, correlated avalanches and photon detection efficiency were measured as a function of the applied over voltage and wavelength at liquid xenon temperature (163~K). The results from this study are also used to provide updated estimates of the achievable energy resolution at the decay Q-value for the nEXO design.

The European Physical Journal C
Particles and Fields

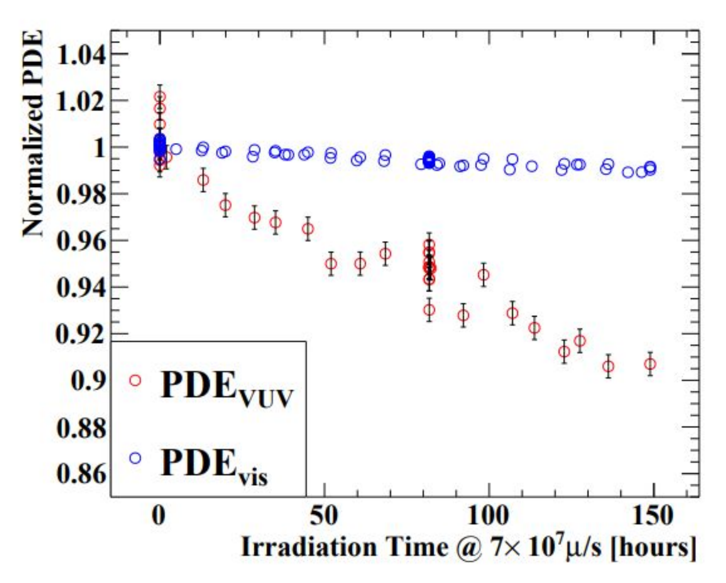
Performance of novel VUV-sensitive Silicon Photo-Multipliers for nEXO

G. Gallina[1,a,c], Y. Guan[2], F. Retiere[1], G. Cao[2,b,e], A. Bolotnikov[3], I. Kotov[3], S. Rescia[3], A.K. Soma[4], T. Tsang[3], L. Darroch[5], T. Brunner[1,5], J. Bolster[6,d], J. R. Cohen[6], T. Pinto Franco[6], W. C. Gillis[6], H. Peltz Smalley[6], S. Thibado[6], A. Pocar[6], A. Bhat[7], A. Jamil[7,c], D. C. Moore[7], G. Adhikari[8], S. Al Kharusi[5], E. Angelico[9], I. J. Arnquist[10], P. Arsenault[11], I. Badhrees[12,f], J. Bane[6], V. Belov[13], E. P. Bernard[14], T. Bhatta[15], P. A. Breur[16], J. P. Brodsky[14], E. Brown[17], E. Caden[5,18,19], L. Cao[20], C. Chambers[5], B. Chana[12], S. A. Charlebois[11], D. Chernyak[21], M. Chiu[3], B. Cleveland[18,19], R. Collister[12], M.Cvitan[1], J. Dalmasson[9], T. Daniels[22], K. Deslandes[11], R. DeVoe[9], M. L. di Vacri[10], Y. Ding[2], M. J. Dolinski[4], A. Dragone[16], J. Echevers[23], B. Eckert[4], M. Elbeltagi[12], L. Fabris[24], W. Fairbank[25], J. Farine[12,18,19], Y. S. Fu[2], D. Gallacher[5], P. Gautam[4], G. Giacomini[3], C. Gingras[5], D. Goeldi[12,i], R. Gornea[12], G. Gratta[9], C. A. Hardy[9], S. Hedges[14], M. Heffner[14], E. Hein[26], J. Holt[1], E. W. Hoppe[10], J. Hößl[27], A. House[14], W. Hunt[14], A. Iverson[25], X. S. Jiang[2], A. Karelin[13], L. J. Kaufman[16], R. Krücken[1,28,h], A. Kuchenkov[13], K. S. Kumar[6] A. Larson[29], K. G. Leach[30], B. G. Lenardo[9], D. S. Leonard[31], G.Lessard[11], G. Li[2], S. Li[23], Z. Li[8], C. Licciardi[12,18,19], R. Lindsay[32], R. MacLellan[15], M. Mahtab[1], S. Majidi[5], C. Malbrunot[1], P. Margetak[1], P. Martel-Dion[11], L. Martin[1], J. Masbou[33], N. Massacret[1], K. McMichael[17], B. Mong[16], K. Murray[5], J. Nattress[24], C. R. Natzke[30], X. E. Ngwadla[32], J. C. Nzobadila Ondze[32], A. Odian[16], J. L. Orrell[10], G. S. Ortega[10], C. T. Overman[10], S. Parent[11], A. Perna[18], A. Piepke[21], N. Pletskova[4], J. F. Pratte[11], V. Radeka[3], E. Raguzin[3], G. J. Ramonnye[32], T.Rao[3], H. Rasiwala[5], K. Raymond[1], B. M. Rebeiro[5], G. Richardson[7], J. Ringuette[30], V. Riot[14], T. Rossignol[11], P. C. Rowson[16], L. Rudolph[5], R. Saldanha[10], S. Sangiorgio[14], X. Shang[5], F. Spadoni[10], V. Stekhanov[13], X. L. Sun[2], A. Tidball[17], T. Totev[5], S. Triambak[32], R. H. M. Tsang[21], O. A.Tyuka[32], F. Vachon[11], M. Vidal[9], S. Viel[12], G. Visser[34], M. Wagenpfeil[27], M. Walent[18], K. Wamba[26], Q. Wang[20], W. Wang[21], Y. Wang[2], M. Watts[7], W. Wei[2], L. J. Wen[2], U. Wichoski[12,18,19], S. Wilde[7], M. Worcester[3], W. H. Wu[2], X. Wu[20], L. Xie[1], W. Yan[2], H. Yang[20], L. Yang[8], O. Zeldovich[13], J. Zhao[2], T. Ziegler[27]

Study on degradation of VUV-sensitivity of MPPC for liquid xenon scintillation detector by radiation damage in MEG II experiment

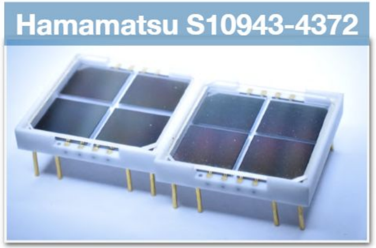
K. Ieki[a], T. Iwamoto[a], S. Kobayashi[a,*], Toshinori Mori[a], S. Ogawa[a], R. Onda[a], W. Ootani[a], K. Shimada[a], K. Toyoda[a]

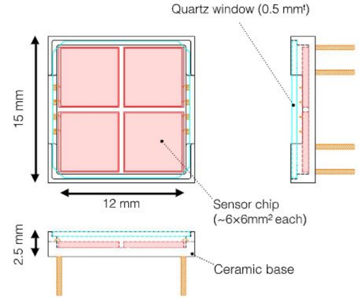
[a]International Center for Elementary Particle Physics (ICEPP), The University of Tokyo, Tokyo, 113-0033 Japan



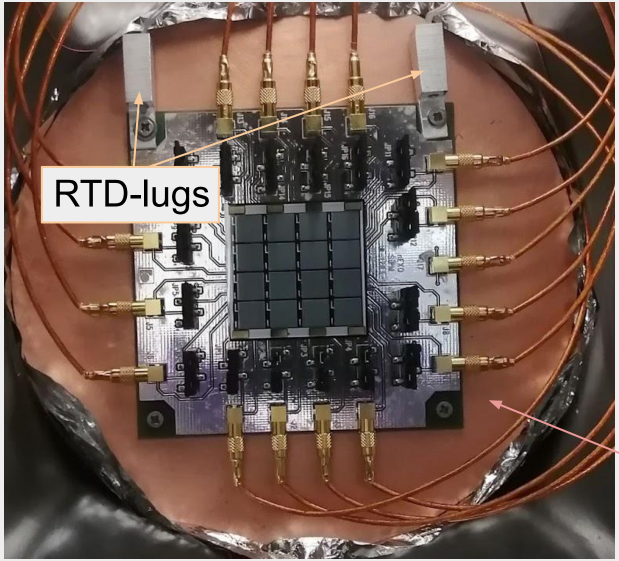
[2211.09882] Study on degradation of VUV-sensitivity of MPPC for liquid xenon scintillation detector by radiation damage in MEG II experiment (arxiv.org)

HPK 'MEG2 Mini-Tile'

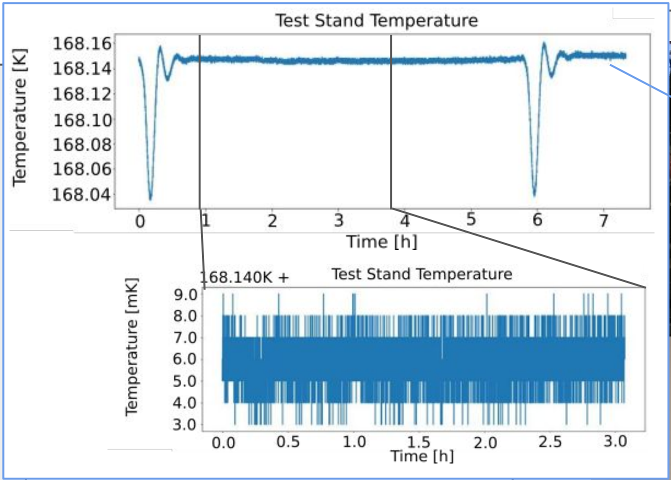




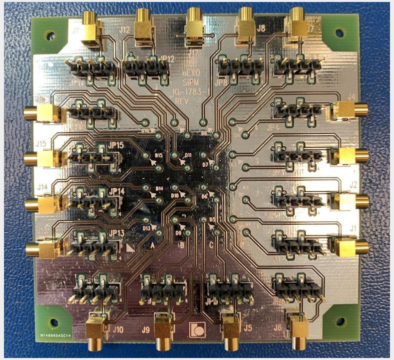
https://hamamatsu.su/files/uploads/pdf/3_mppc/s13370_vuv4-mppc_b_(1).pdf

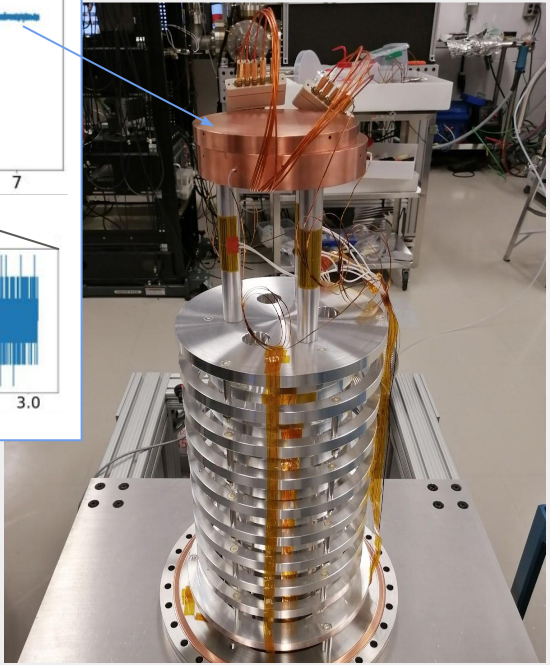


- HPK 4x4 mini tile (VUV4)
- RTD-lugs coupled to PCB



PCB designed at Brookhaven National Lab



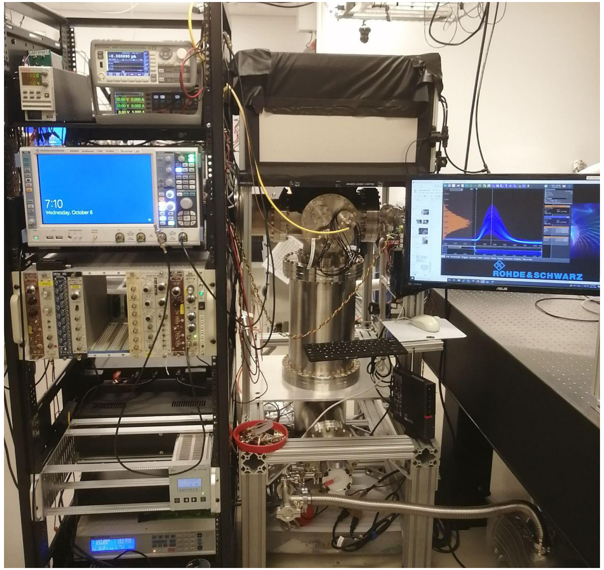


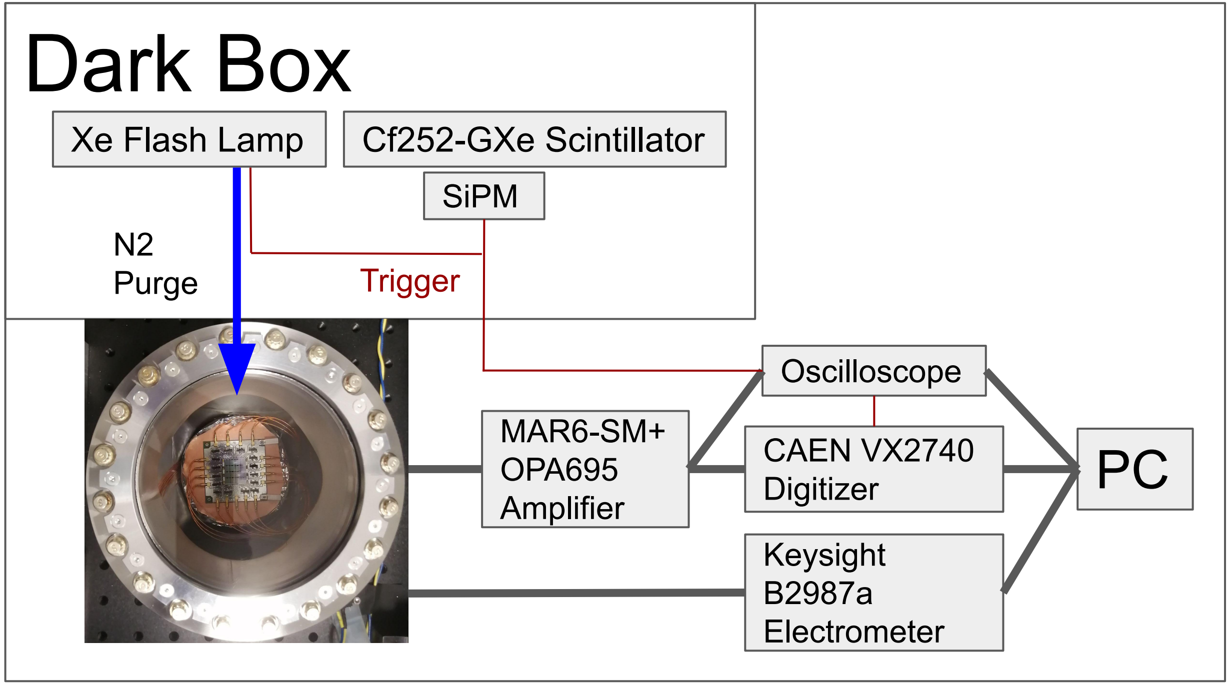
Environmental Test Stand (cryostat):

- Large surface area: A ~ 150 cm^2
- Stable operation: σ_T ~ 1 mK (3h)
- Demonstrated range: 120 - 295 K
- Turnaround time: T ~ 1 day

Characterization measurements:

- PDE
- Gain
- CAs



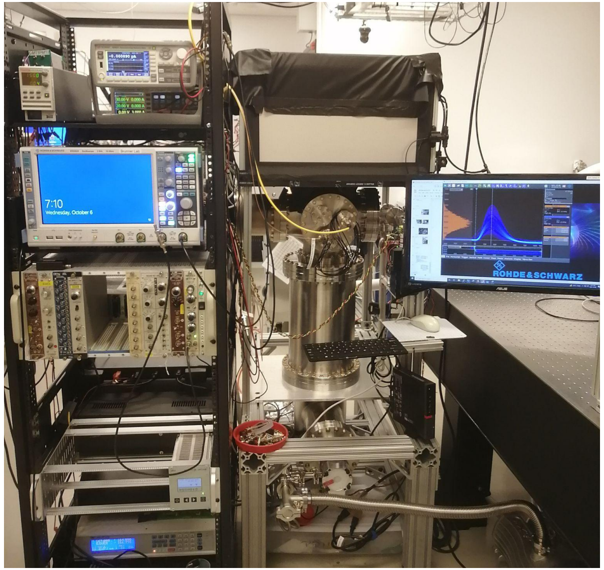


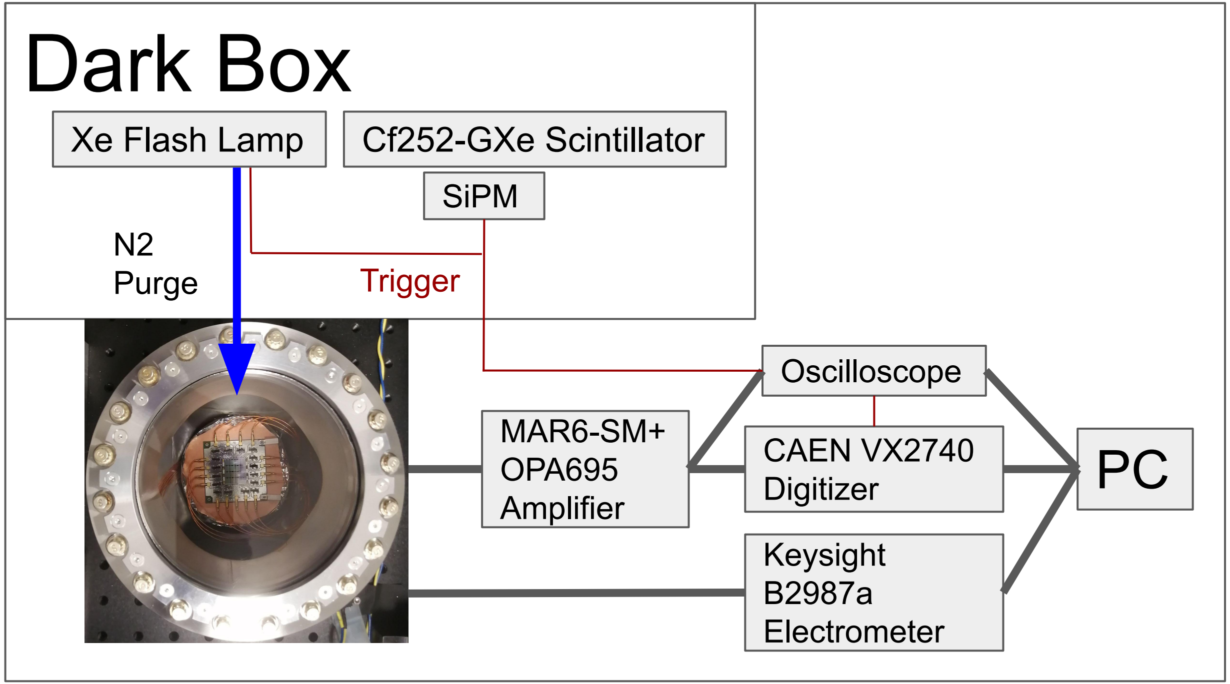
Procedure:

1. Characterization measurements
2. Flash 10^N photons
3. Return to step 1 for increasing N
4. When N >> 10^10 /mm^2:
   - Anneal SiPMs, return to step 1

Characterization measurements:

- PDE
- Gain
- CAs





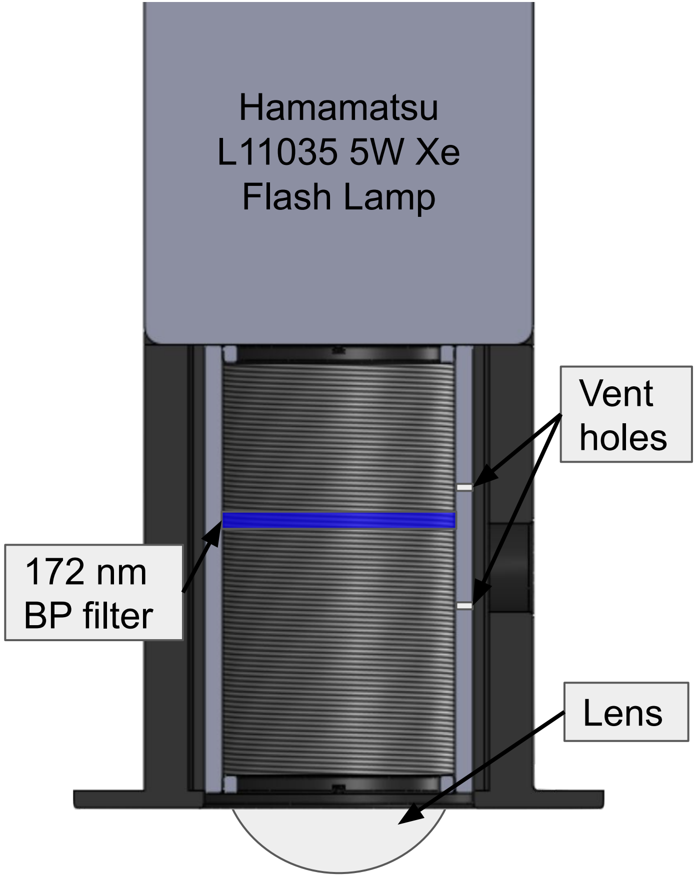
Procedure:

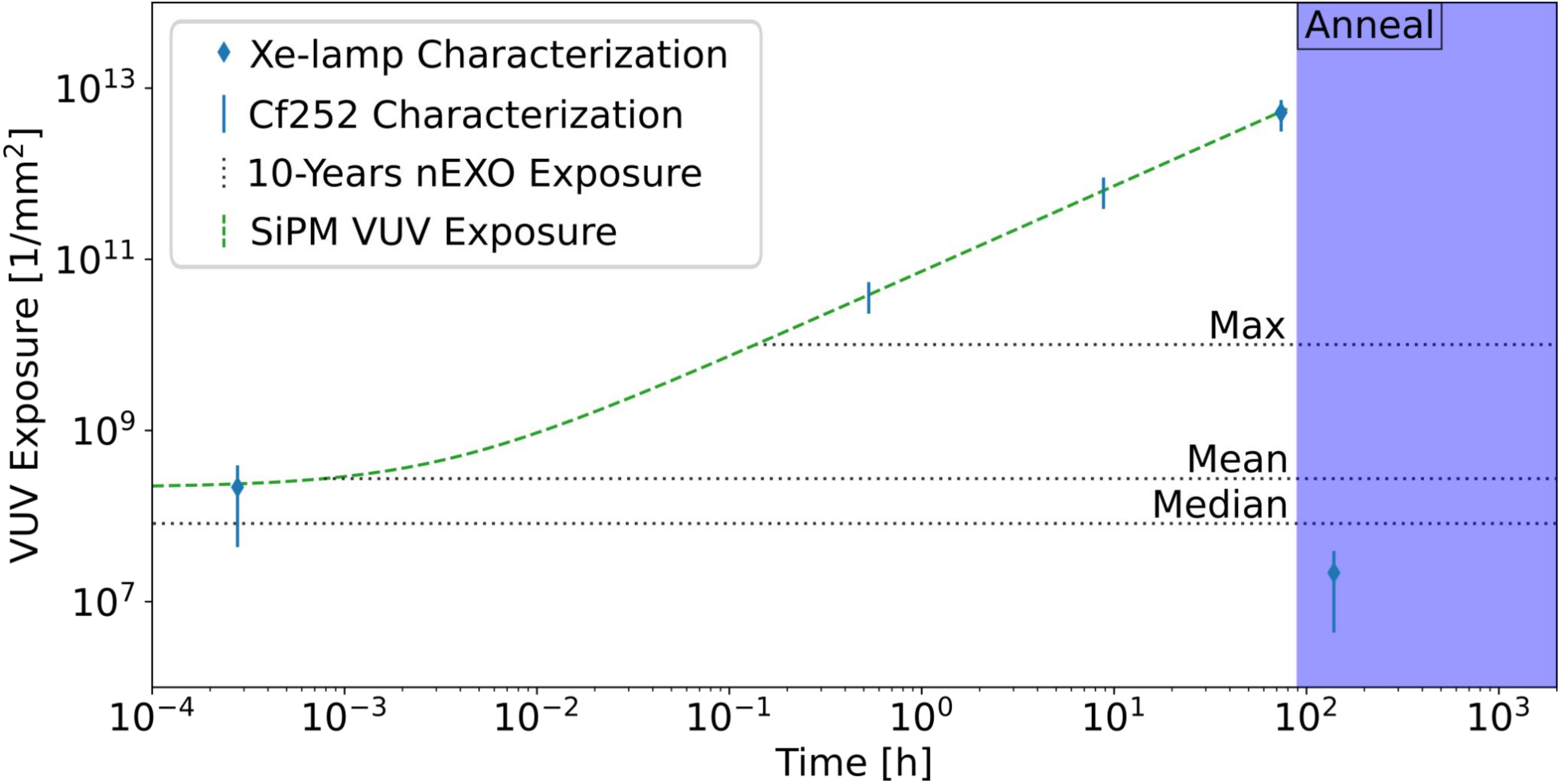
1. Characterization measurements
2. **Flash 10^N photons**
3. Return to step 1 for increasing N
4. When N >> 10^10 /mm^2:
   - Anneal SiPMs, return to step 1

- Lens tube fixed to flash lamp
- 172 nm BP filter and lens
- Flashed at 500 Hz
- Cavities flushed with N2

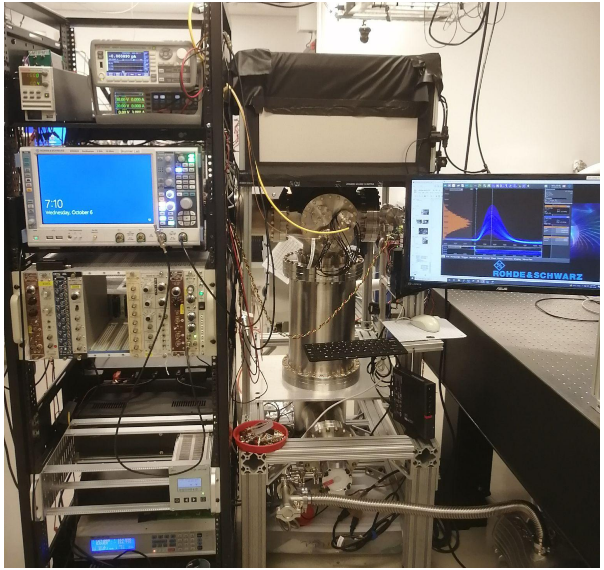
Flash lamp configuration for SiPM VUV irradiation

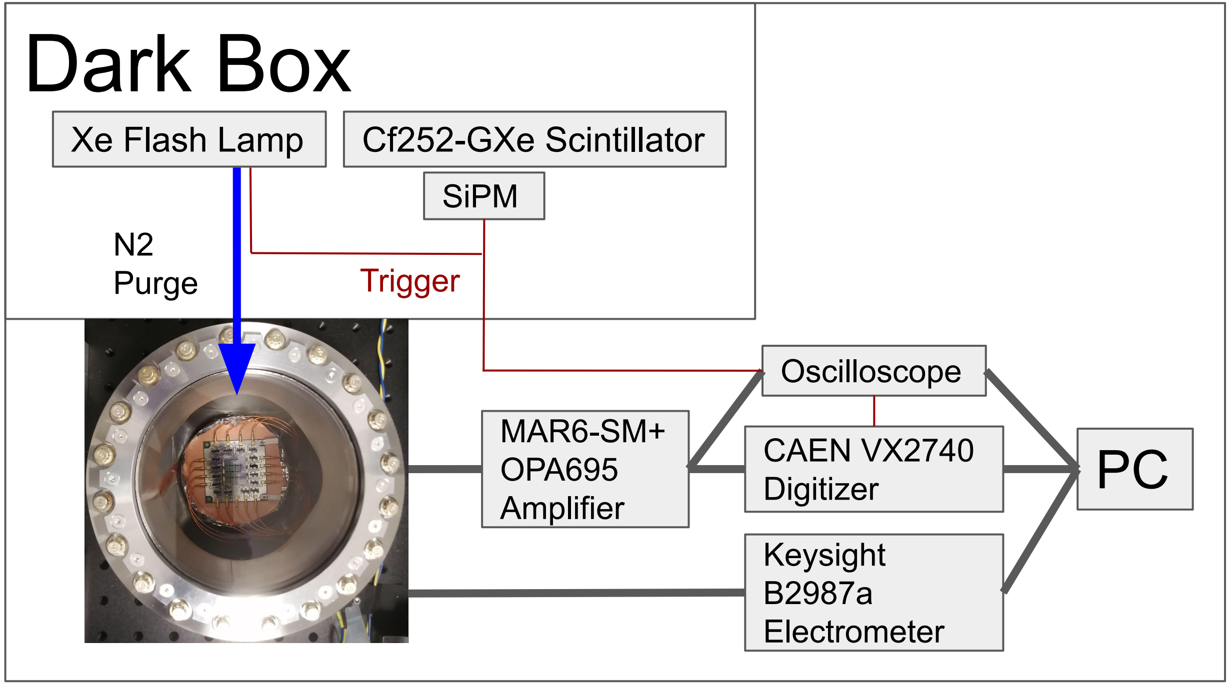



Anneal
Xe-lamp Characterization
Cf252 Characterization
10-Years nEXO Exposure
SiPM VUV Exposure
Max
Mean
Median
VUV Exposure [1/mm^2]
10^{13}
10^{11}
10^{9}
10^{7}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
Time [h]

Characterization measurements:

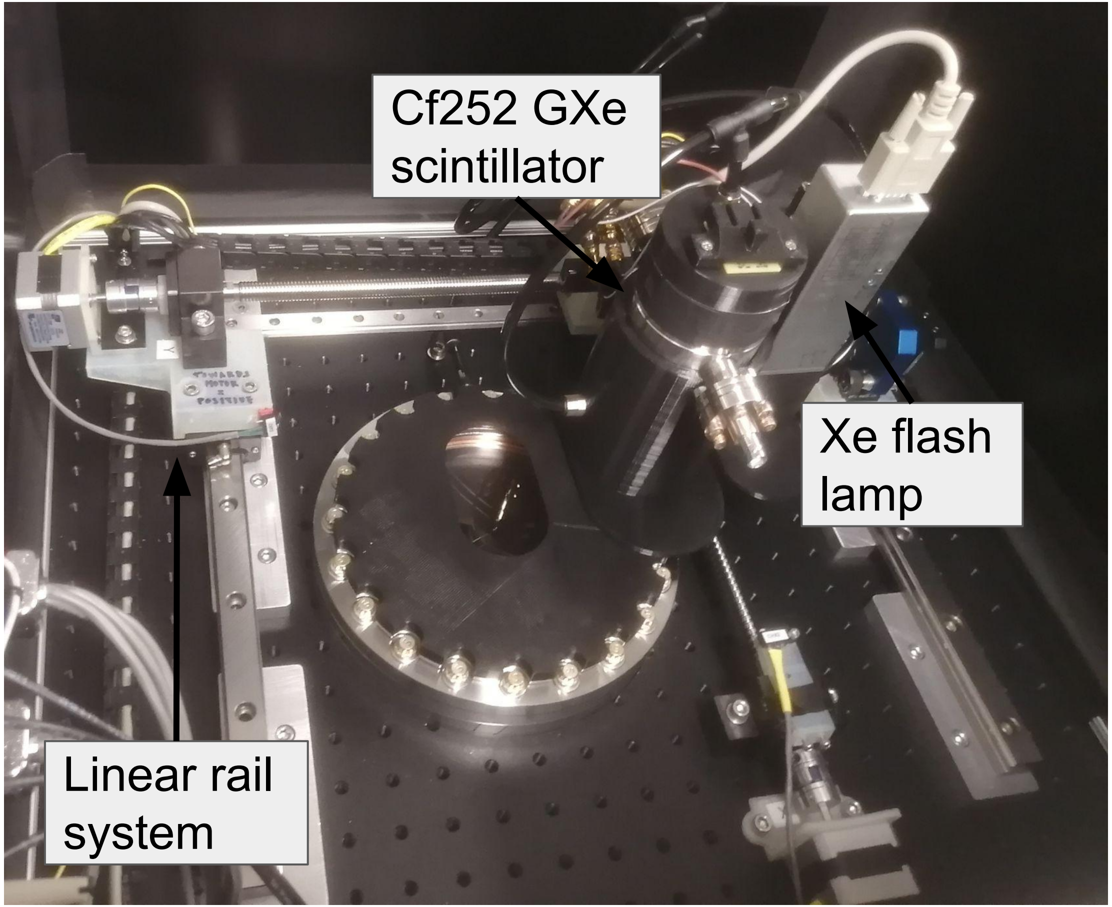
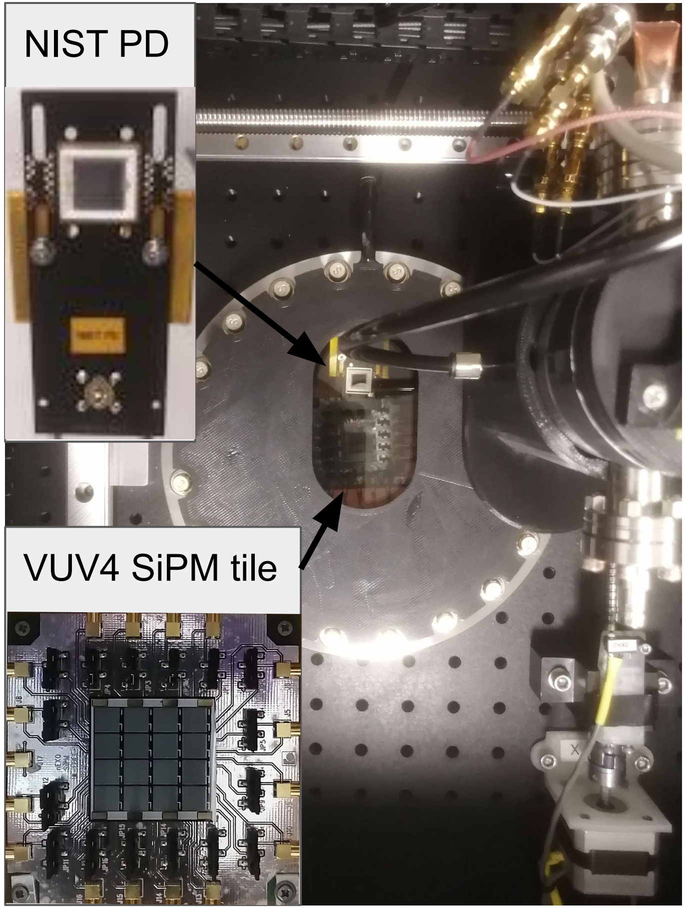
- PDE
- Gain
- CAs





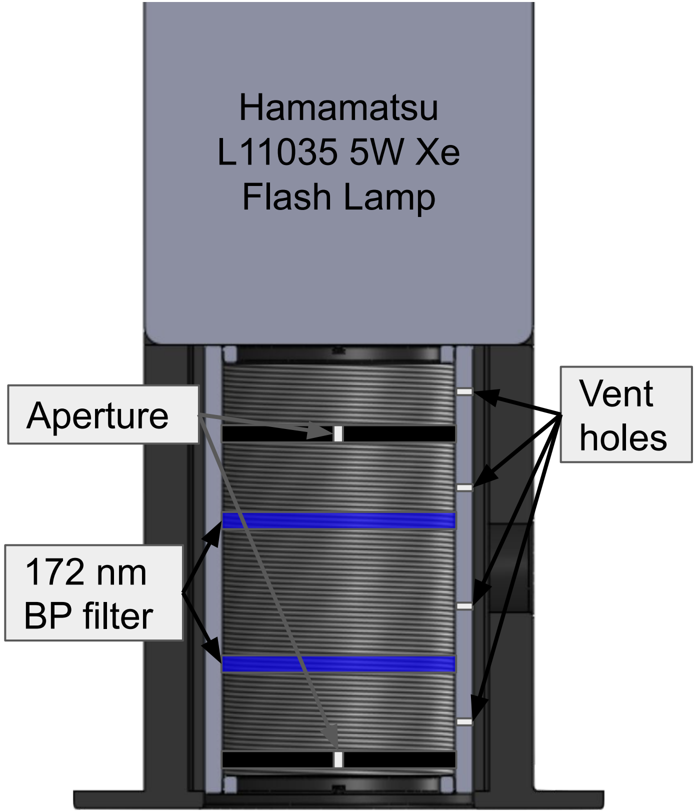
Procedure:

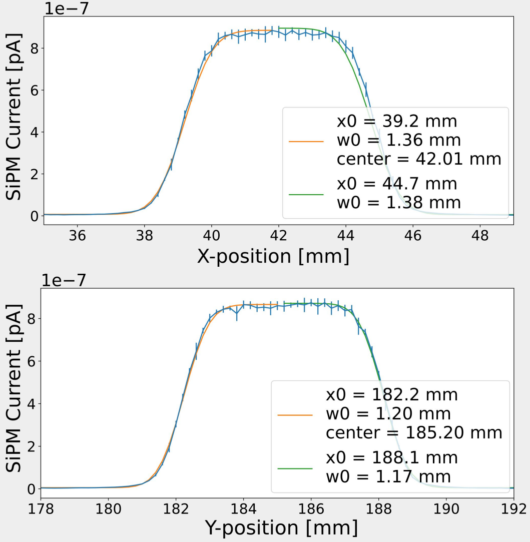
1. **Characterization measurements**
2. Flash 10^x photons
3. Return to step 1
4. When >> 10^10 /mm^2 photons flashed:
   - Anneal SiPMs, return to step 1

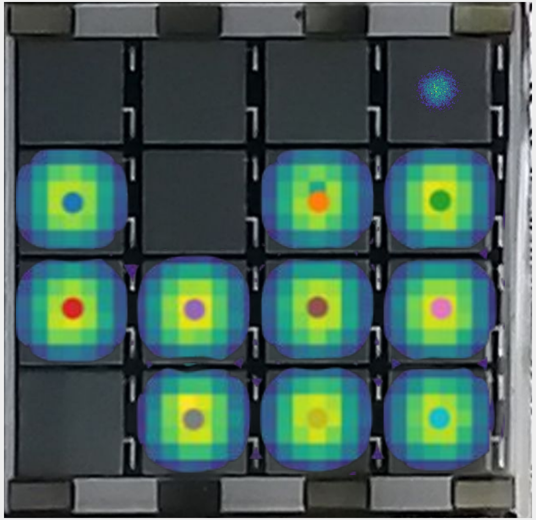

Cf252 GXe scintillator
Xe flash lamp
Linear rail system

NIST PD
VUV4 SiPM tile

- 2x 172 nm BP filter
- Dual apertures eliminate Airy disk
- Flashed at 500 Hz
- Cavities flushed with N2

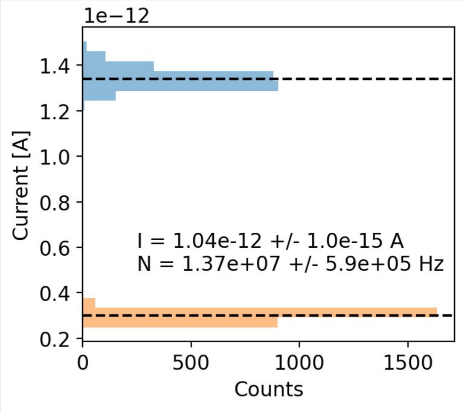
Flash lamp configuration for SiPM characterization

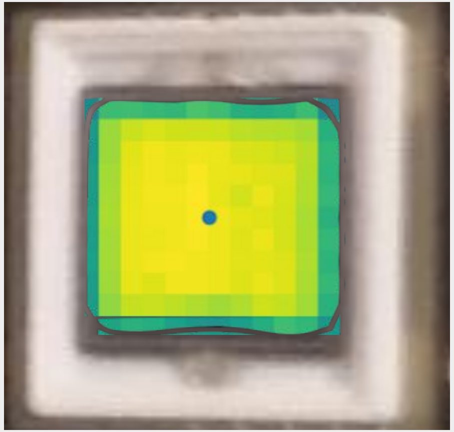




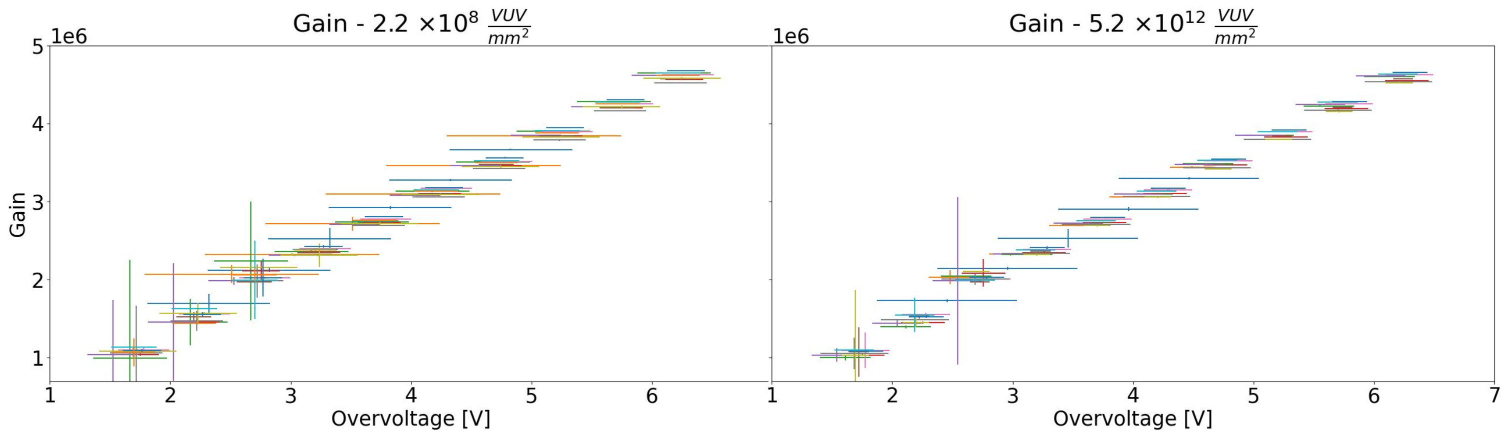


- Raster scan used to position devices
- Device edges and center determined from scan
- Single sweep integrates beam, produces gaussian profile

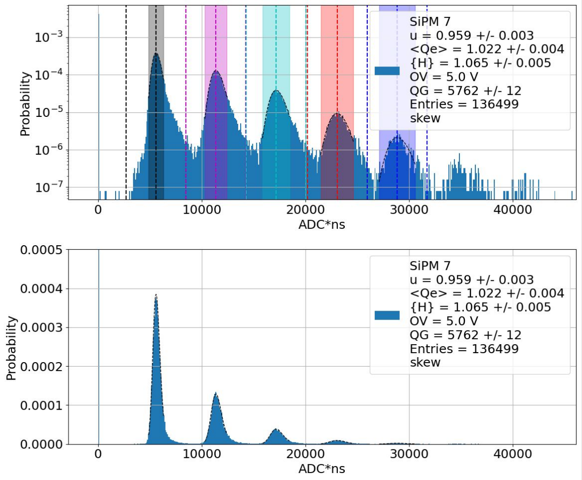


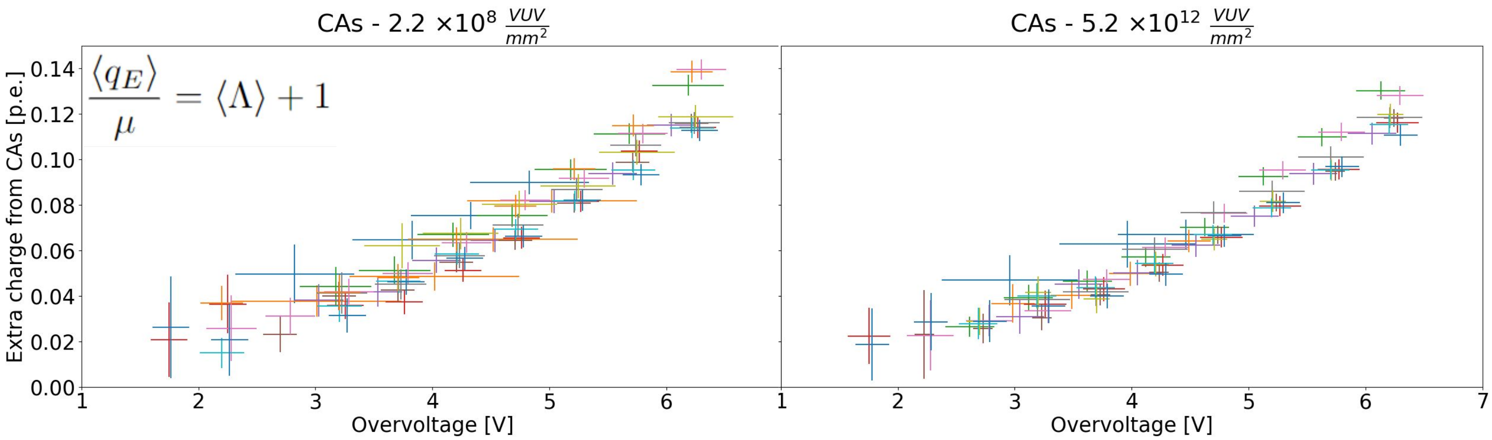


- NIST calibrated XUV photodiode used to determine beam flux
- Flux combined with profile for beam monte-carlo

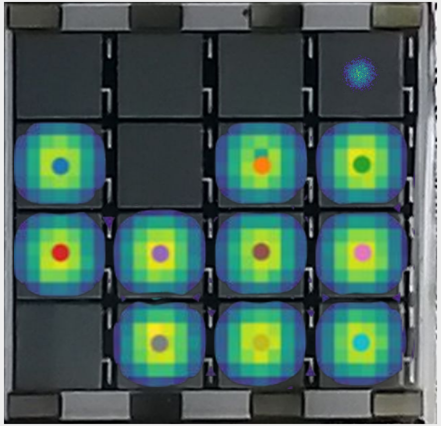


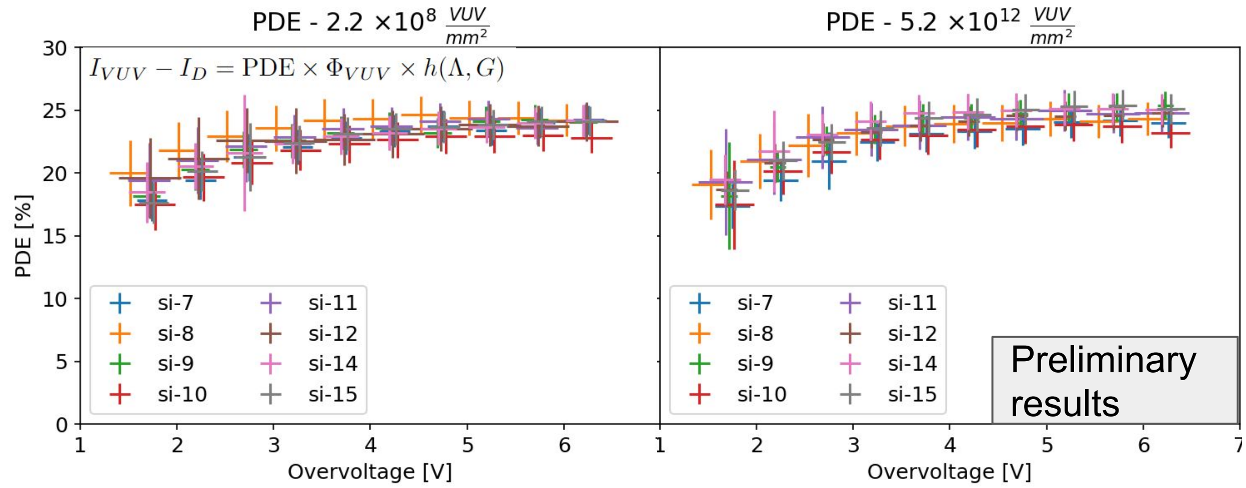
- Gain calculated from charge spectrum 1 PE pulse
- 720 000 1/V single PE gain



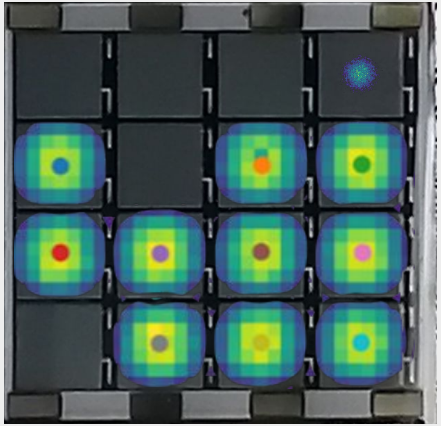


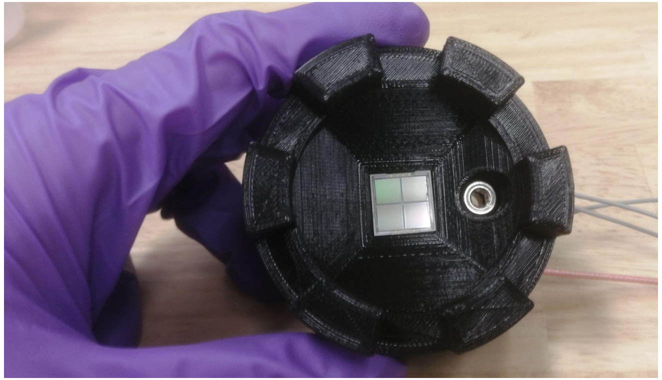
- Zero-count method used to determine mean number of avalanche
- 5% extra charge at 4V OV

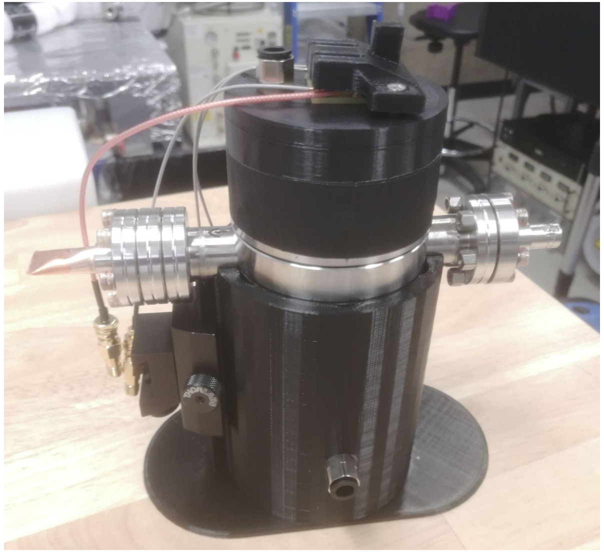


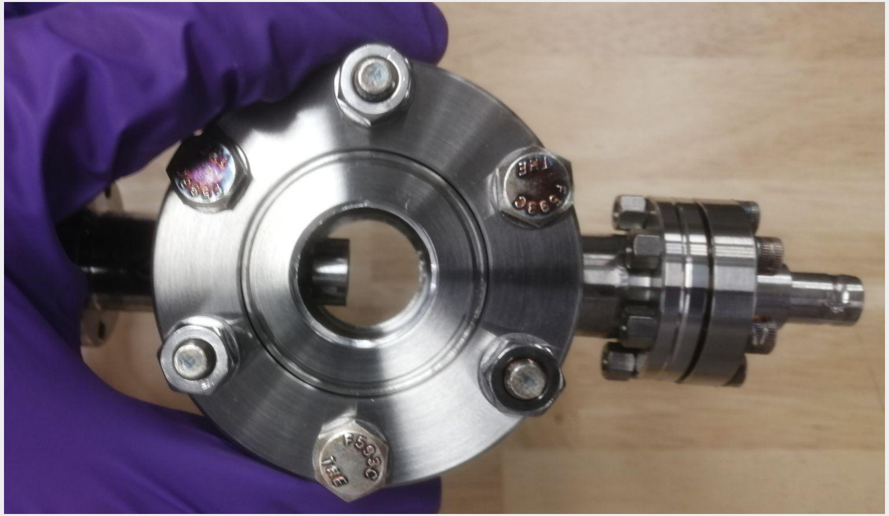


- Xe flash lamp collimated into beam with 172 nm BP filter
- PDE saturation around 23%

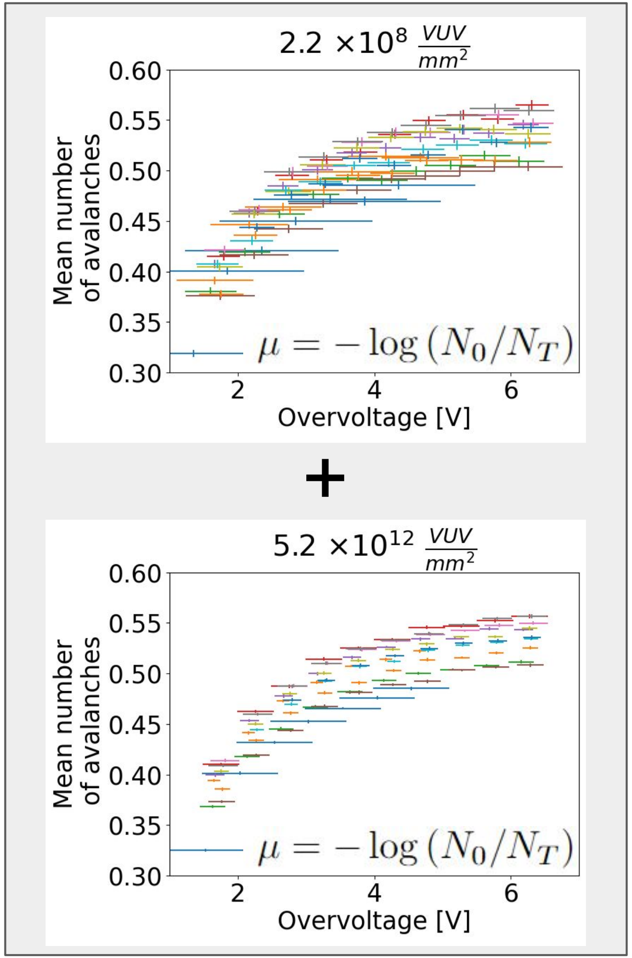






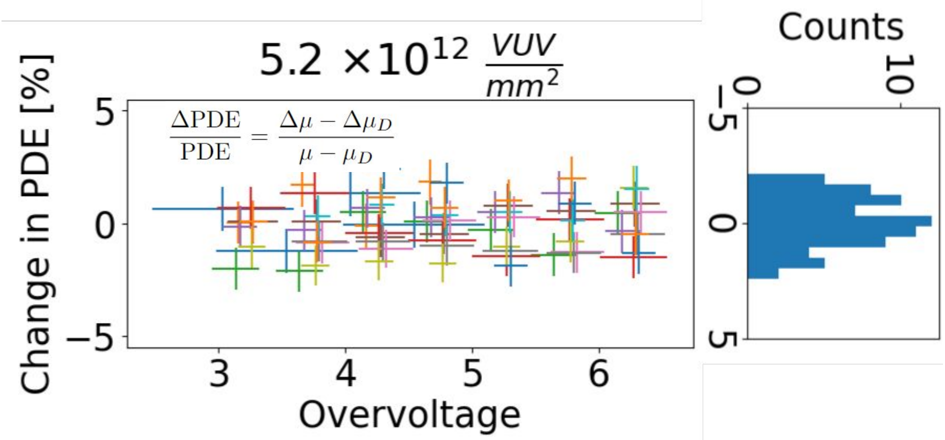


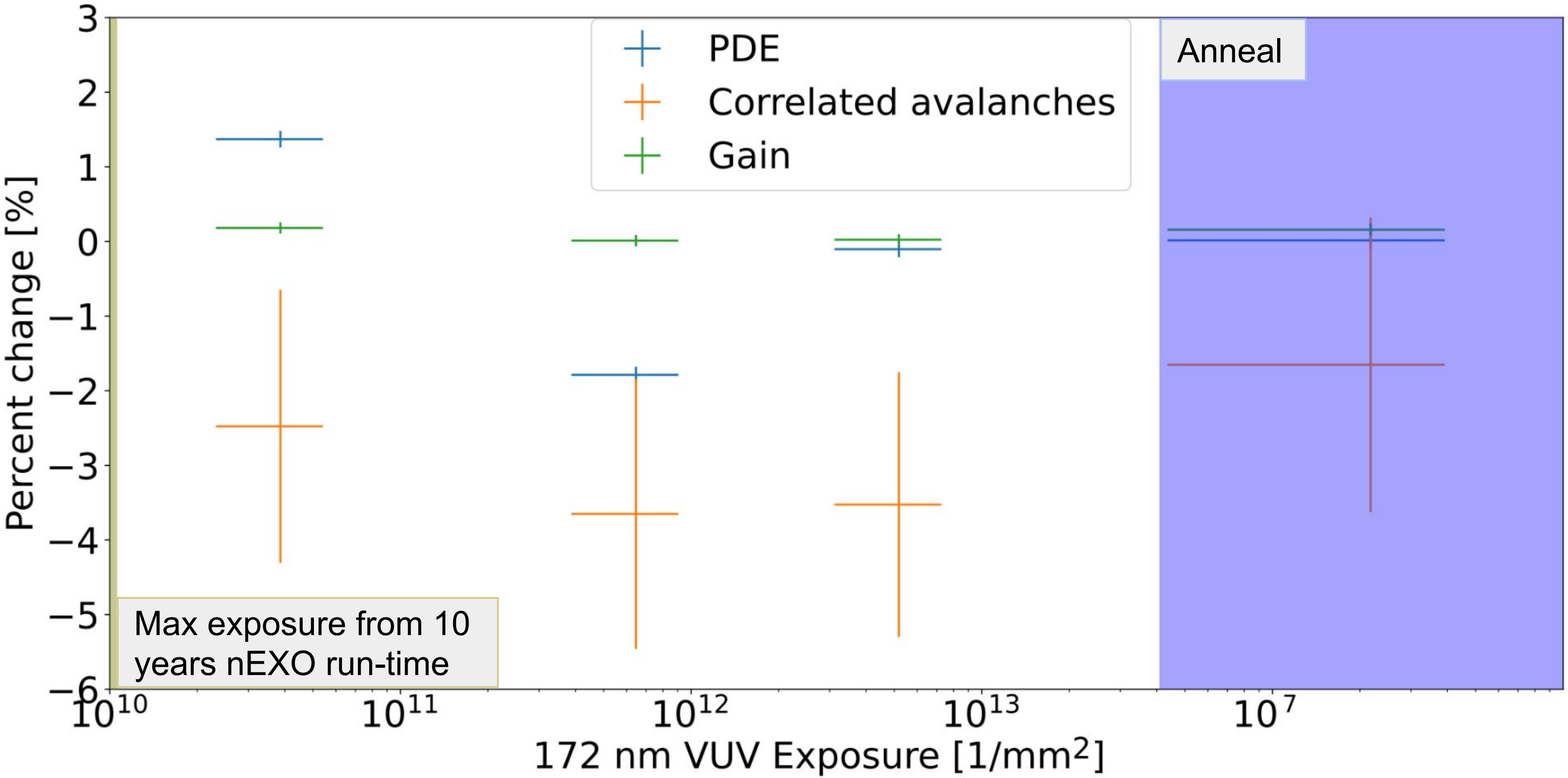
- Cf252-GXe scintillator gives stable VUV light
- SiPM coincidence trigger



- Compare results on point-by-point basis
- Average over fluctuations
- All SiPMs and OVs represented by a single point

$\Rightarrow$





PDE
Correlated avalanches
Gain
Anneal
Max exposure from 10 years nEXO run-time
Percent change [%]
3
2
1
0
−1
−2
−3
−4
−5
−6
10^{10}
10^{11}
10^{12}
10^{13}
10^{7}
172 nm VUV Exposure [1/mm^2]

Conclusion

- HPK VUV4 SiPMs have been tested before/following high VUV exposure
- No change observed for: PDE, Correlated avalanches, or Gain
- Further evidence of SiPM technology readiness for nEXO

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nEXO

NSERC
CRSNG

Fonds de recherche
Nature et
technologies
Québec

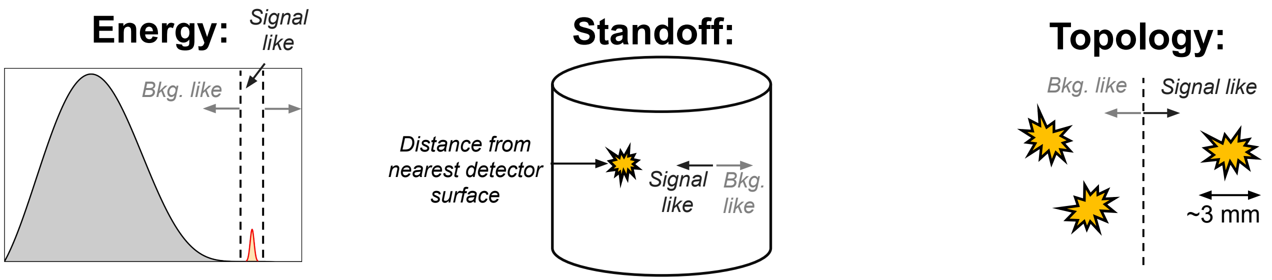
CMC
MICROSYSTEMS

McGill

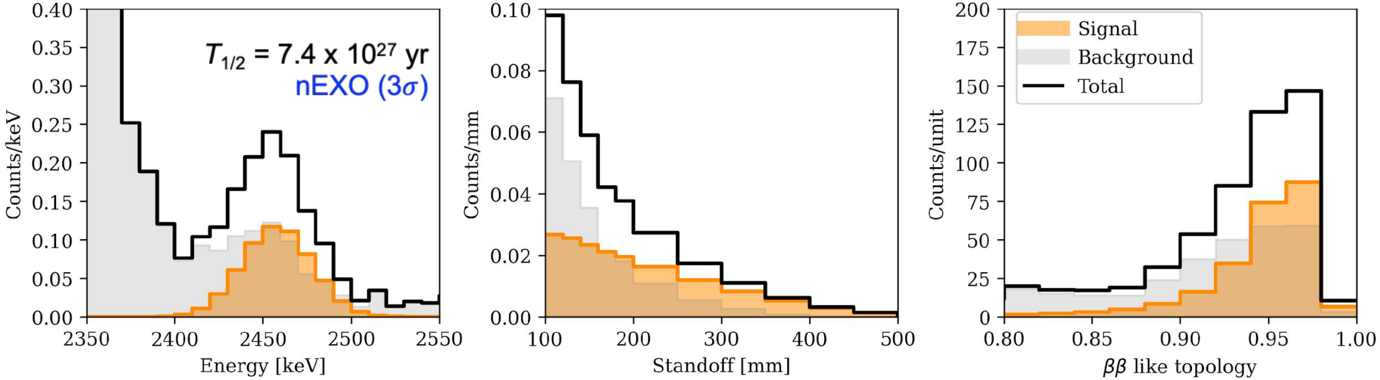
The nEXO Collaboration

nEXO Signal and Background

- nEXO measures multiple parameters for each event to be able to robustly identify a 0νββ signal
- As a fully homogeneous detector, it precisely measures backgrounds in situ
  - No internal materials (other than Xe), making nEXO uniquely robust against unknown backgrounds



1D projections of simulated nEXO signal and backgrounds:



Liquid Xenon Photon Detector with Highly Granular Scintillation Readout for MEG II Experiment

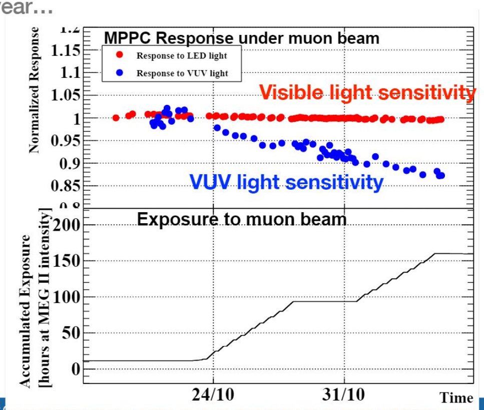
W. Ootani ICEPP, The University of Tokyo
on behalf of MEG II collaboration
Calorimetry for the High Energy Frontier (CHEF2019)
Nov. 25th-29th, 2019, Fukuoka, Japan

A Surprise…

- **Significant degradation of MPPC VUV-sensitivity!**
  - Seems correlated with beam ON/OFF
  - Large degradation for VUV-sensitivity (↔ slight degradation for visible light)
  - Degradation is quite fast: (~0.08%/hour)
  - We can't survive even for one year…
- **Can be a showstopper…**

Radiation	Dose (run2019)
Gamma	~10^{-2} Gy/sensor
Neutron	2.7×10^{6} n_{1MeV}/cm^2
VUV-light	~10^{14} photons/sensor

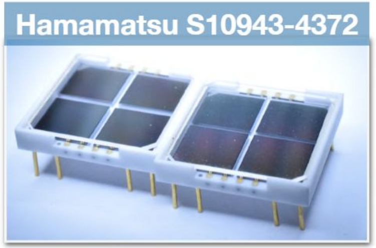
↓
Dose level is quite low

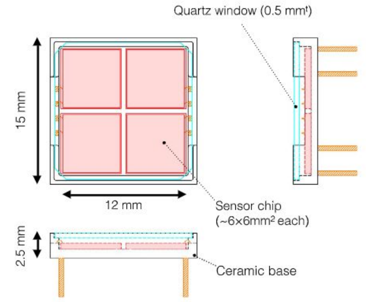


W.Ootani, "Liquid Xenon Photon Detector with Highly … 14

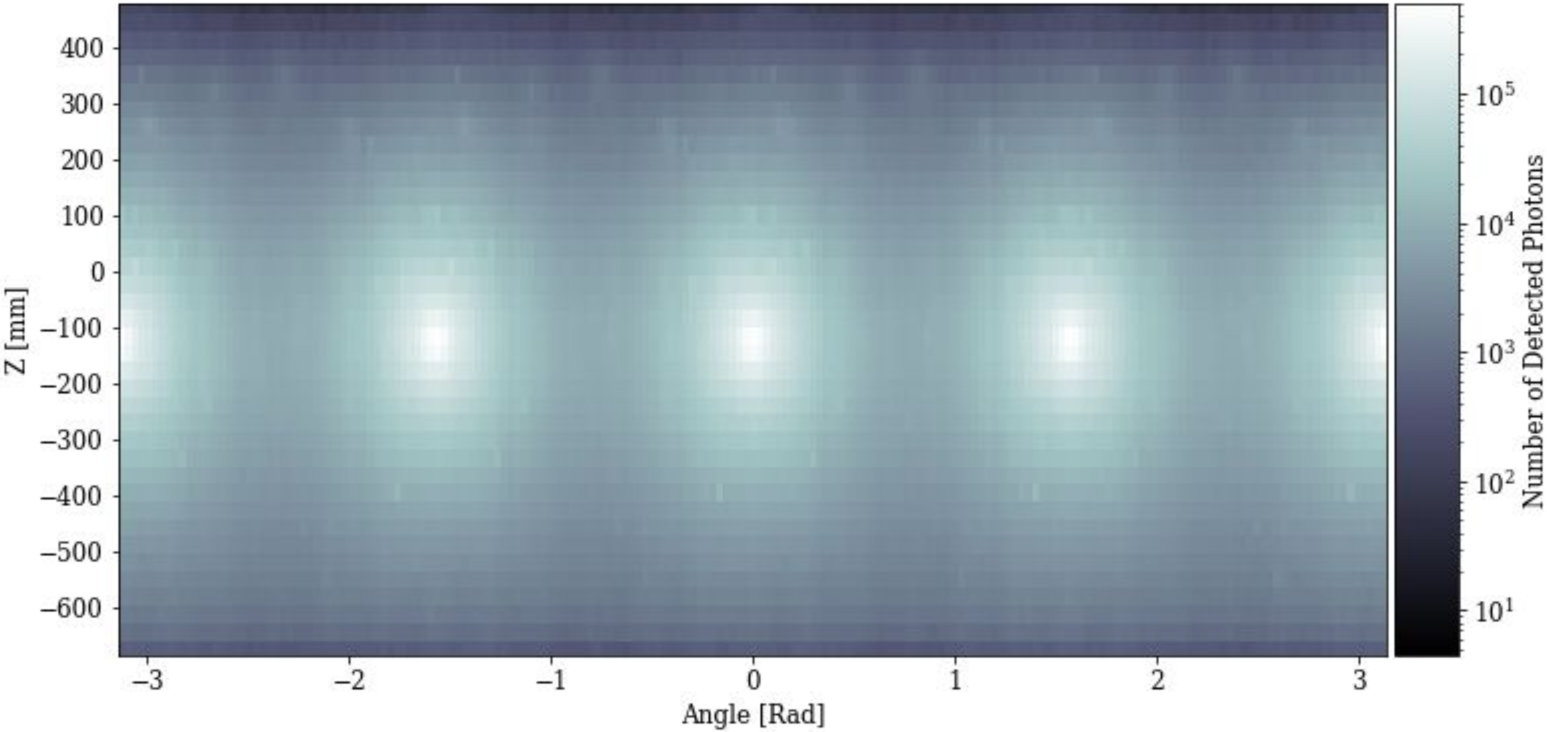
https://indico.cern.ch/event/818783/contributions/3598489/attachments/1950386/3237558/MEG_Ootani191125_compressed.pdf

HPK 'MEG2 Mini-Tile'





https://hamamatsu.su/files/uploads/pdf/3_mppc/s13370_vuv4-mppc_b_(1).pdf



10 Seconds of simulated data from nEXO source calibration, using chroma
Ref: personal correspondence with Sierra Wilde (Yale)