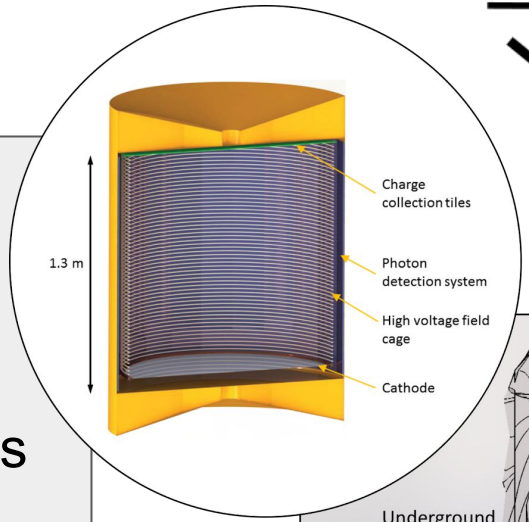
The stability of HPK VUV4 SiPMs following a large dose of VUV radiation

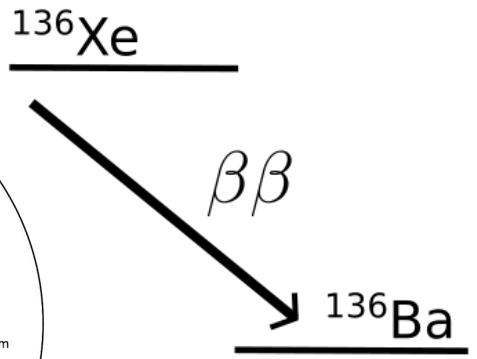
Lucas Darroch, David Gallacher, Chloe Gingras, and Thomas Brunner,
on behalf of the nEXO collaboration

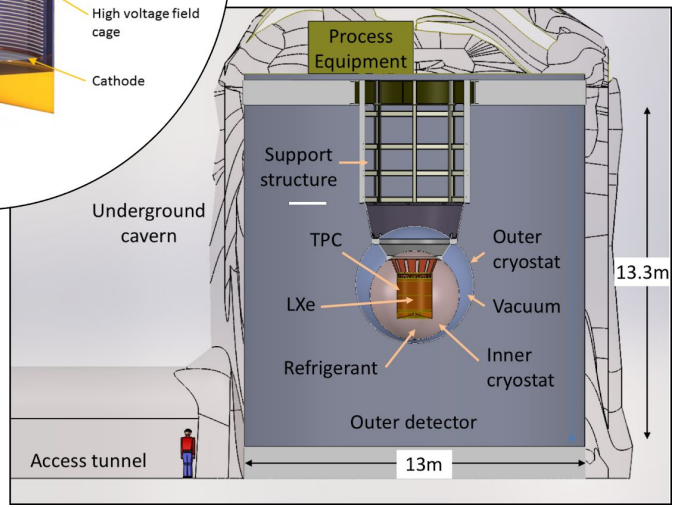
CAP Congress 2023
June 21

McGill

- Plenary talk on nEXO: https://indico.cern.ch/event/1191895/contributions/5361632/
- Single phase TPC
- 5 tonnes LXe, 90% ^{136}Xe
- Ionization and scintillation signals recorded
- Sensitivity ~10^{28} years for 0νββ half-life[1]





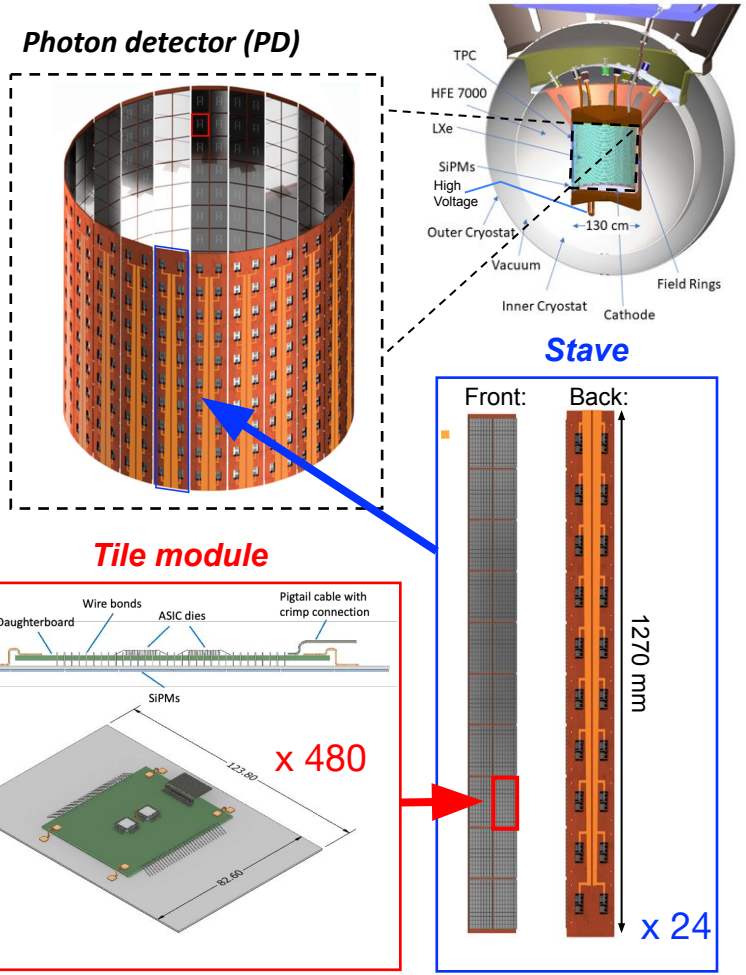


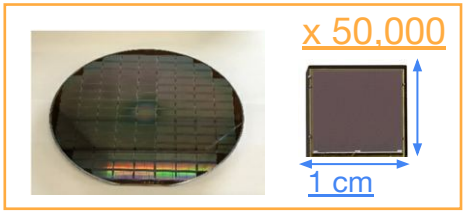
Adhikari, G., et al. "nEXO: neutrinoless double beta decay search beyond 1028 year half-life sensitivity." *Journal of Physics G: Nuclear and Particle Physics* 49.1 (2021): 015104.

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

nEXO photodetector system

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





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

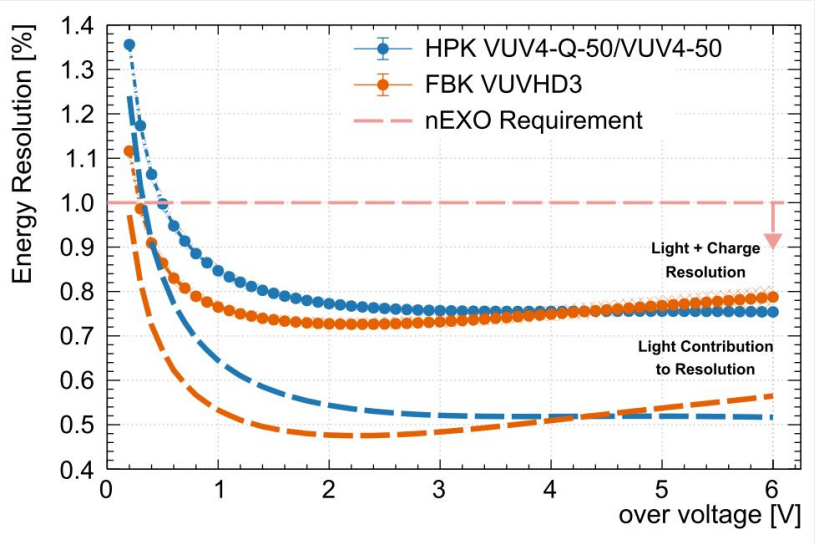
Gallina, G., et al. "Performance of novel VUV-sensitive Silicon Photo-Multipliers for nEXO." *arXiv preprint arXiv:2209.07765* (2022).

Recent publication on VUV-sensitive SiPM performance for nEXO

The European Physical Journal C
Particles and Fields

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

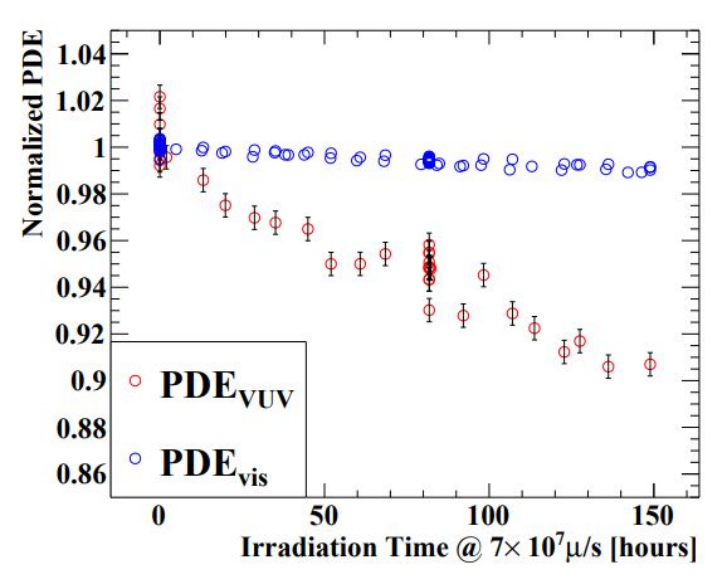
G. Gallina[1,a,c], Y. Guan[2], F. Retiere[1], G. Cao[2,b,c], A. Bolotnikov[3], I. Kotov[3], S. Rescia[3], A.K. Soma[4], T. Tsang[3], L. Darroch[5], T. Brunner[1,3], J. Bolster[6,d], J. R. Cohen[6], T. Pinto Franco[6], W. C. Gillis[6], H. Peltz Smalley[6], S. Thibado[6], A. Pocar[6], A. Bhat[7], A. Jamil[7,e], D. C. Moore[7], G. Adhikari[8], S. Al Kharusi[9], E. Angelico[9], I. J. Arnquist[10], P. Arsenault[11], I. Badhrees[12,f], J. Bane[9], 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[9], 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[3], 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[3], 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. Höfl[27], A. House[14], W. Hunt[14], A. Iverson[23], 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[20], K. G. Leach[30], B. G. Lenardo[9], D. S. Leonard[31], G.Lessard[11], G. Li[2], S. Li[23], Z. Li[5], C. Licciardi[12,18,19], R. Lindsay[32], R. MacLellan[15], M. Mahtab[1], S. Majidi[5], C. Malbrunot[3], P. Margetak[1], P. Martel-Dion[11], L. Martin[3], J. Masbou[33], N. Massacret[1], K. McMichael[17], B. Mong[16], K. Murray[3], 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[3], 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[1], 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

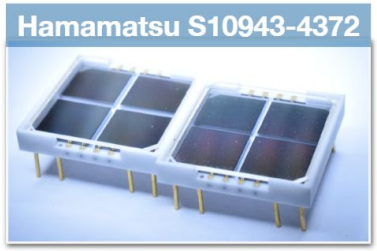
K. Ieki[a], T. Iwamoto[a], S. Kobayashi[a,*], Toshinori Mori[a], S. Ogawa[a], R. Onda[a], W. Ootani[a], K. Shimada[a], K. Toyoda[a]

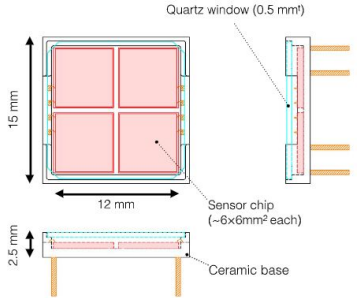
[a]International Center for Elementary Particle Physics (ICEPP), The University of Tokyo, Tokyo, 113-0033 Japan



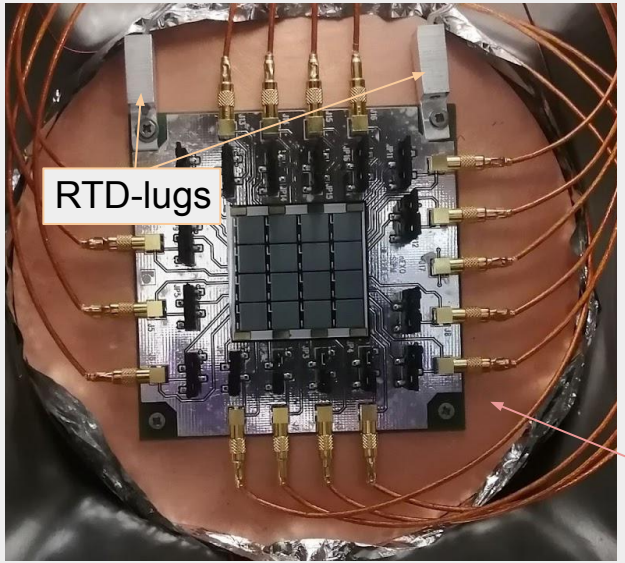
[2211.09882] Study on degradation of VUV-sensitivity of MPPC for liquid xenon scintillation detector by radiation damage in MEG II experiment (arxiv.org)

HPK ‘MEG2 Mini-Tile’

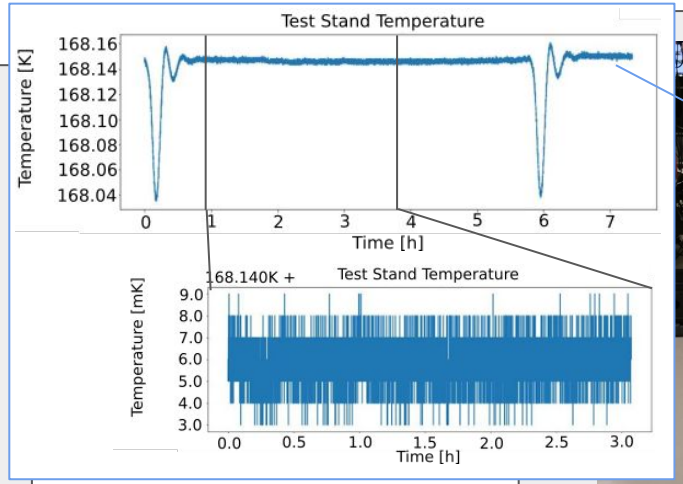




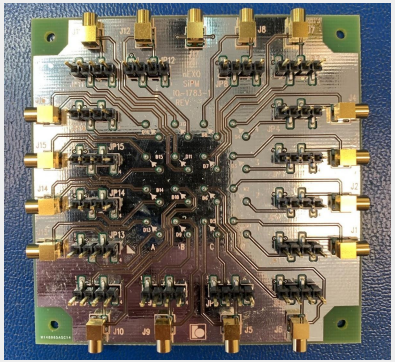
https://hamamatsu.su/files/uploads/pdf/3_mppc/s13370_vuv4-mppc_b_(1).pdf

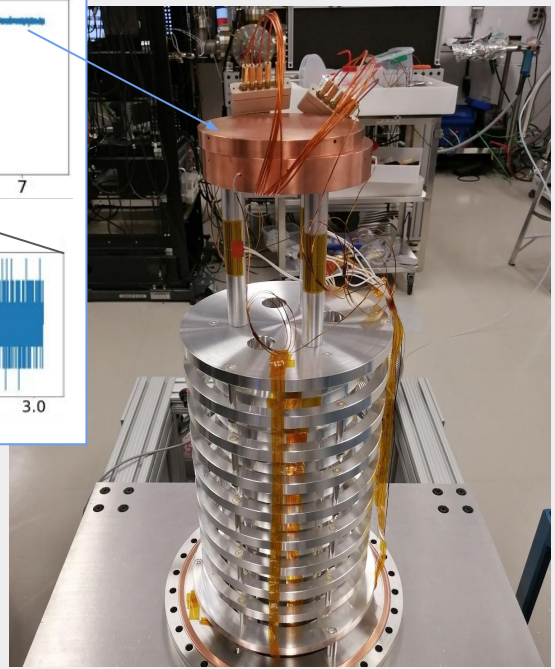


- HPK 4x4 mini tile (VUV4)
- RTD-lugs coupled to PCB



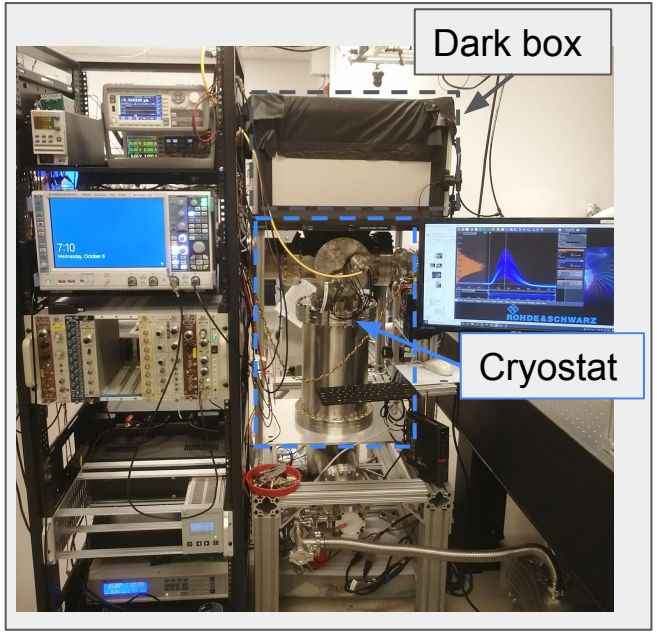
PCB designed at Brookhaven National Lab

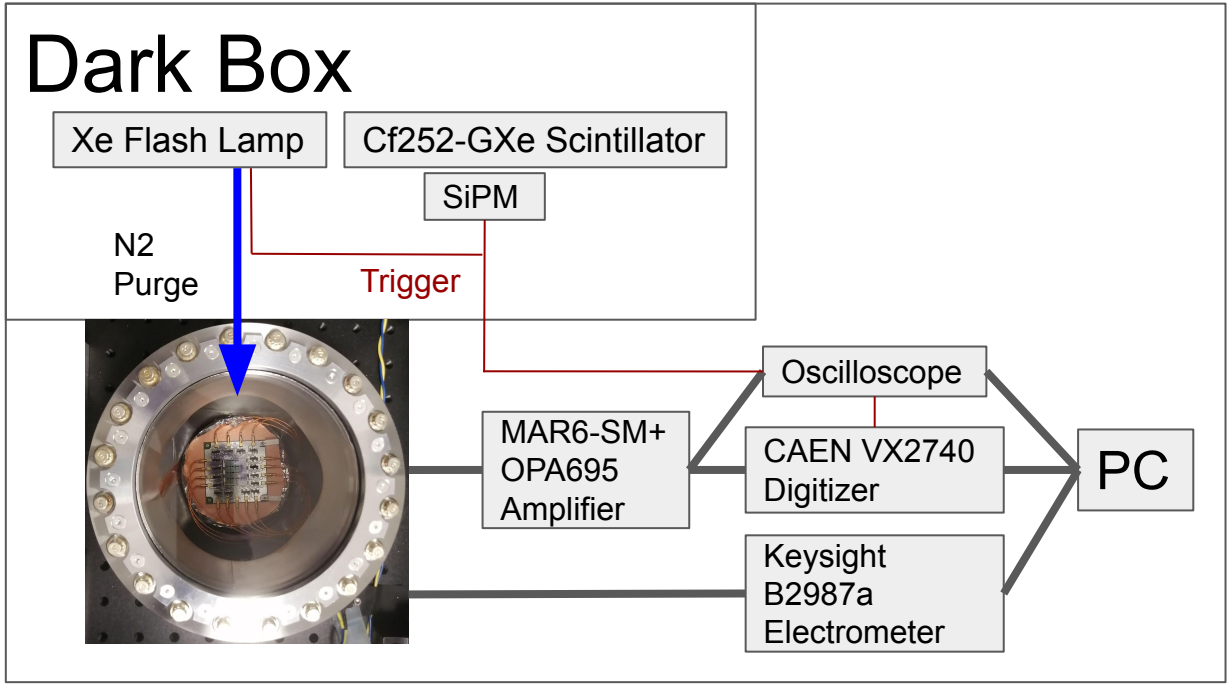




Environmental Test Stand (cryostat):

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



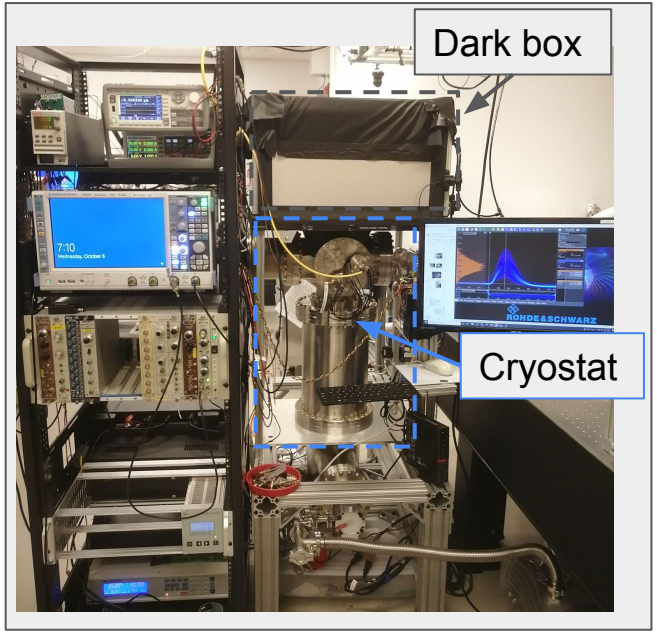


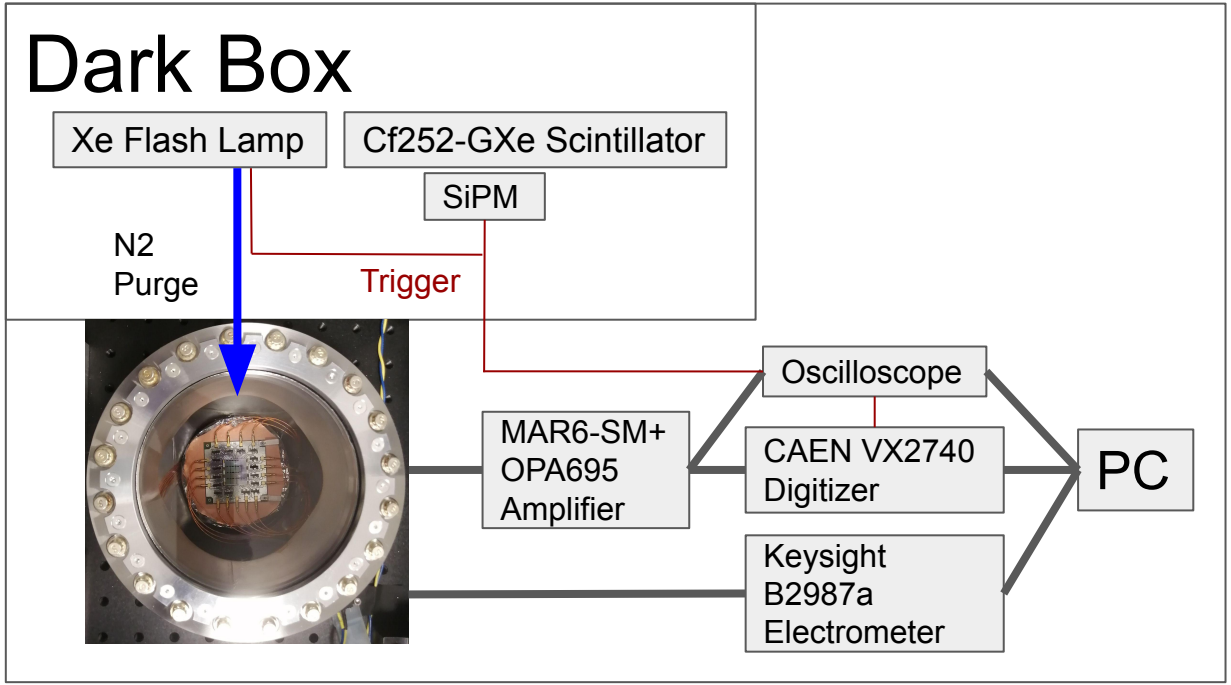
Characterization measurements:

- Gain
- CAs
- PDE

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





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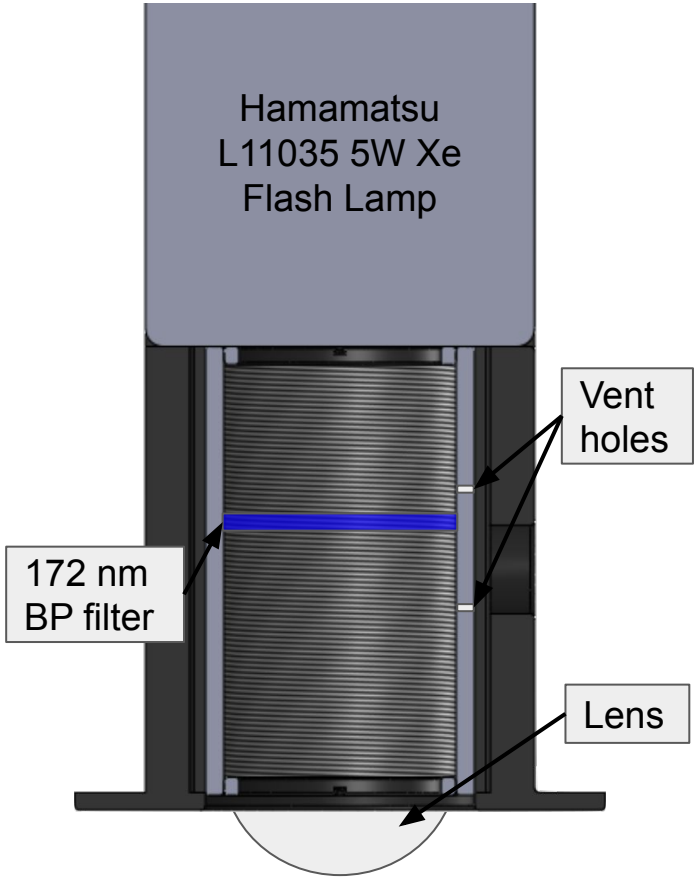
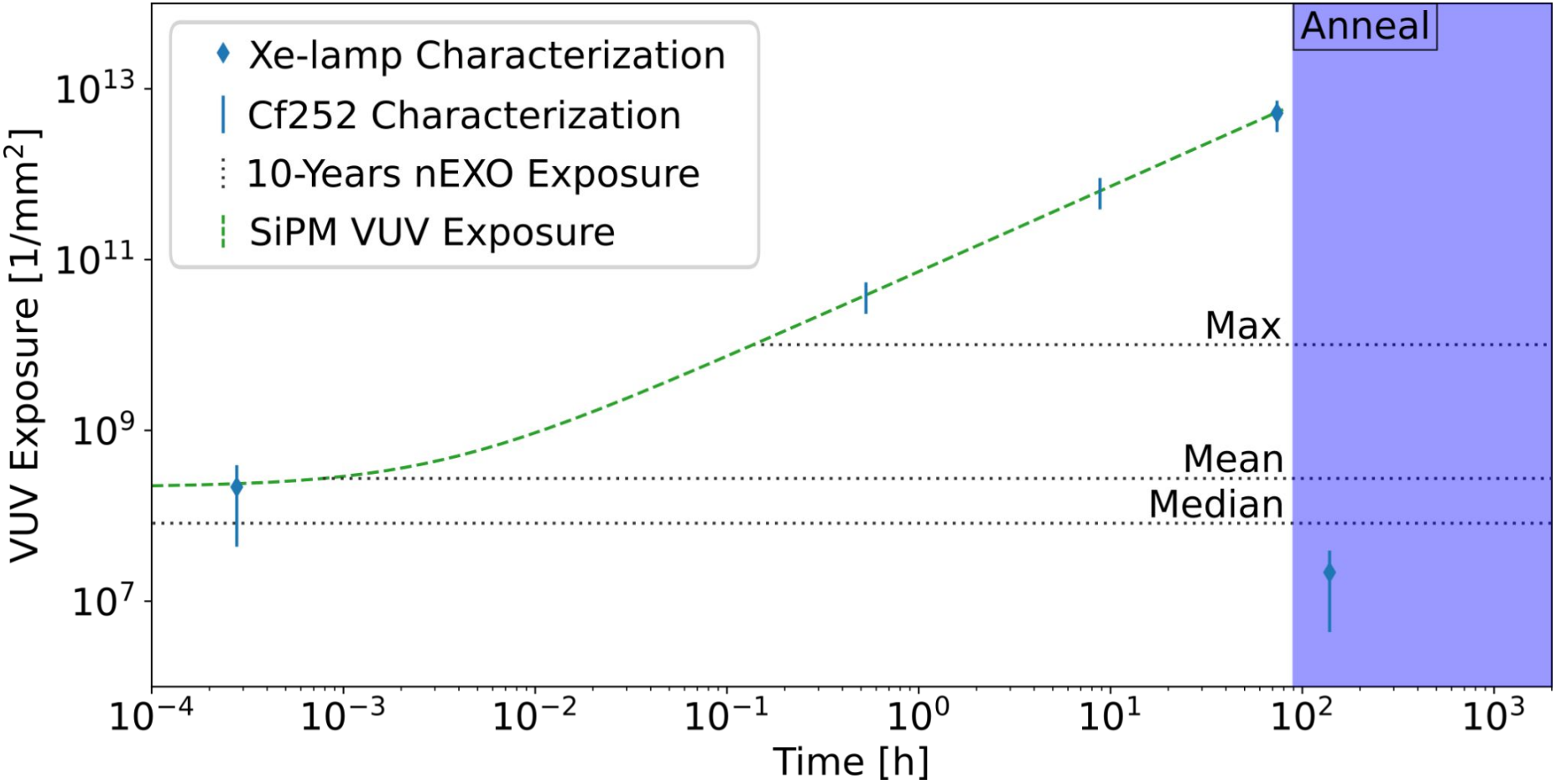
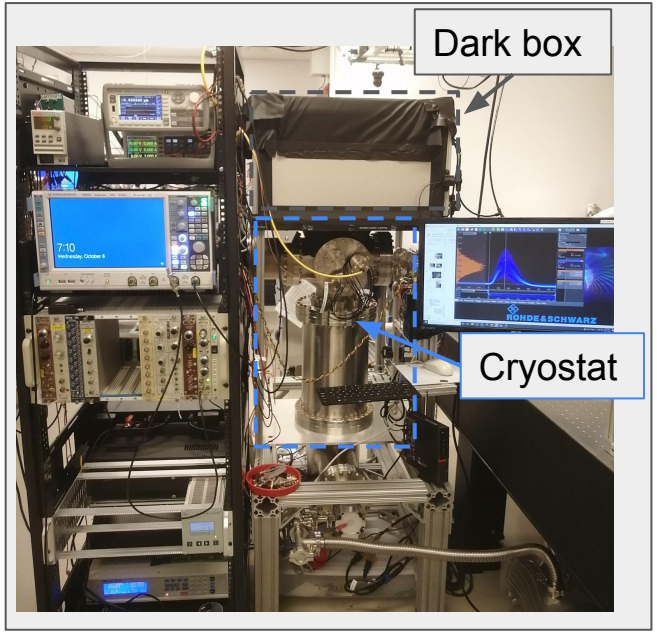
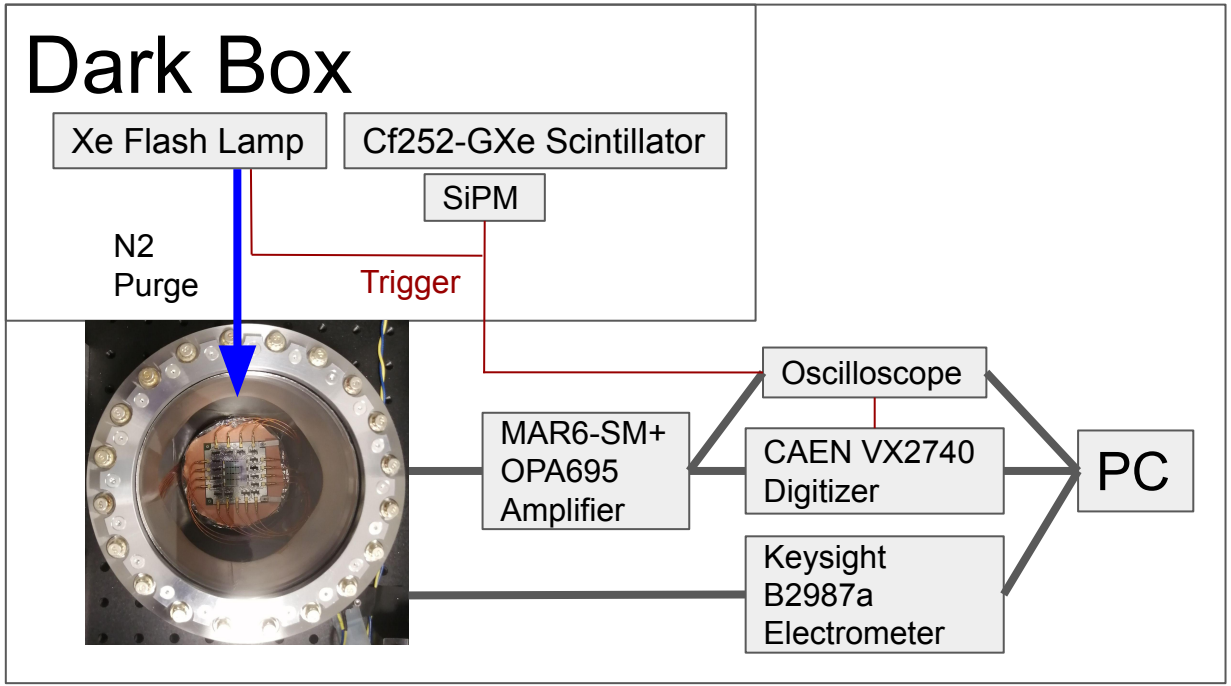
- Lens tube fixed to flash lamp
- 172 nm BP filter and lens
- Flashed at 500 Hz
- Cavities flushed with N2

Flash lamp configuration for SiPM VUV irradiation




Xe-lamp Characterization
Cf252 Characterization
10-Years nEXO Exposure
SiPM VUV Exposure
Anneal
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]





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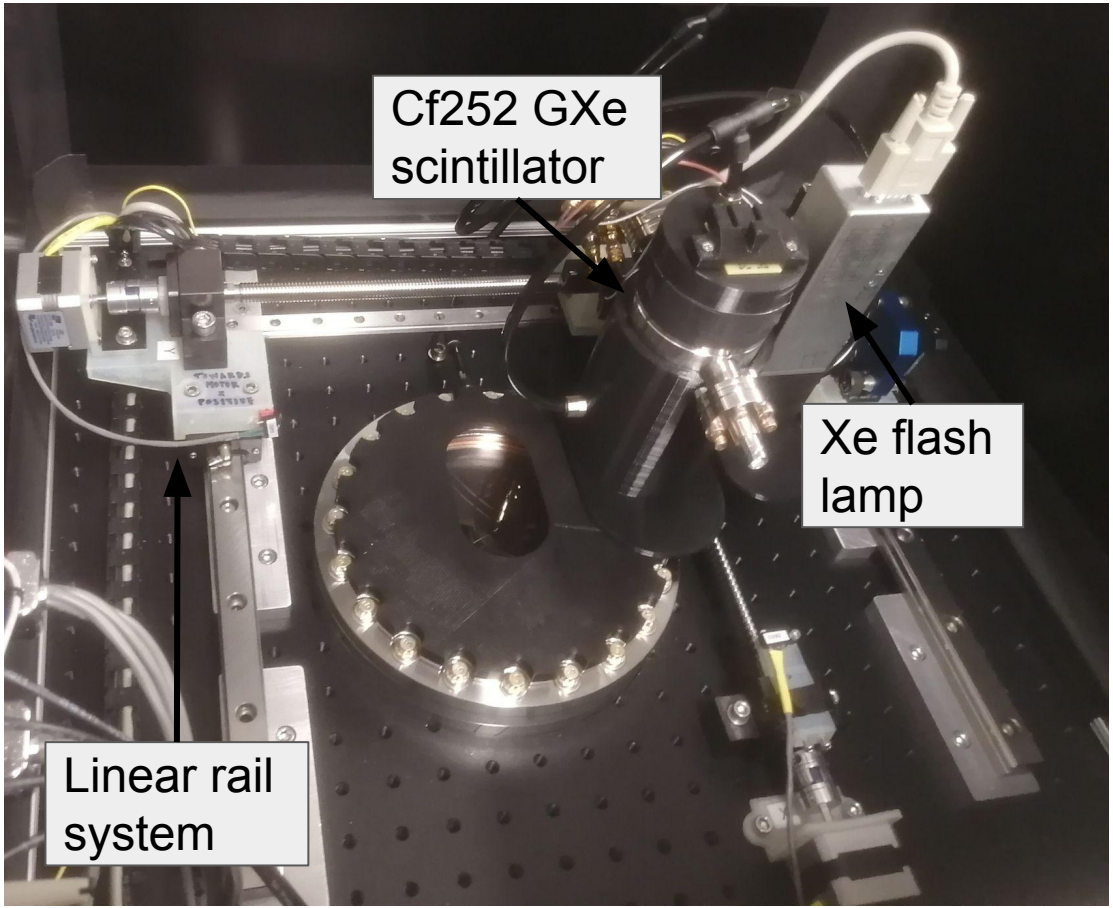
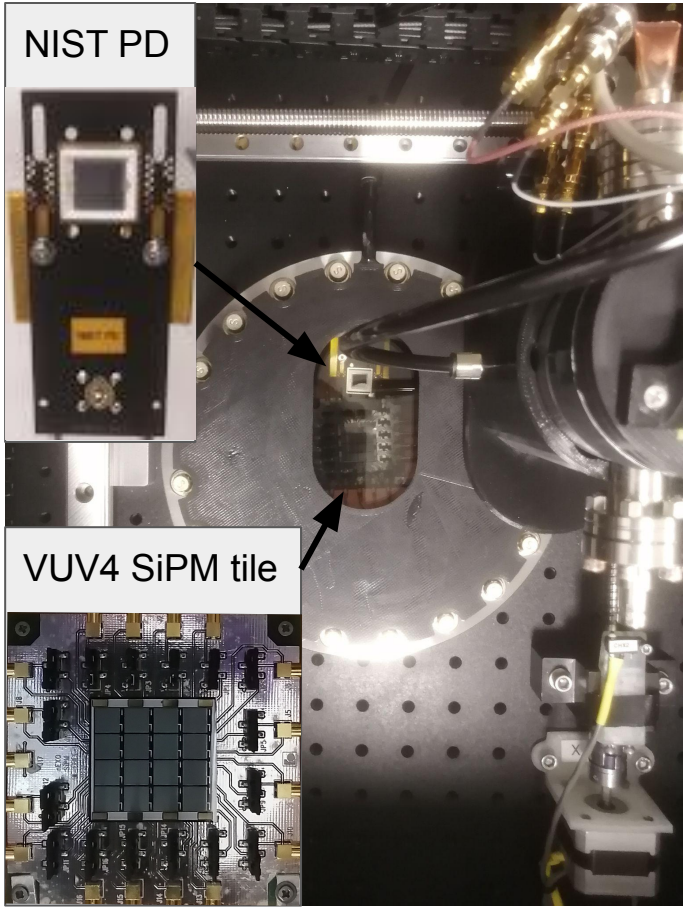
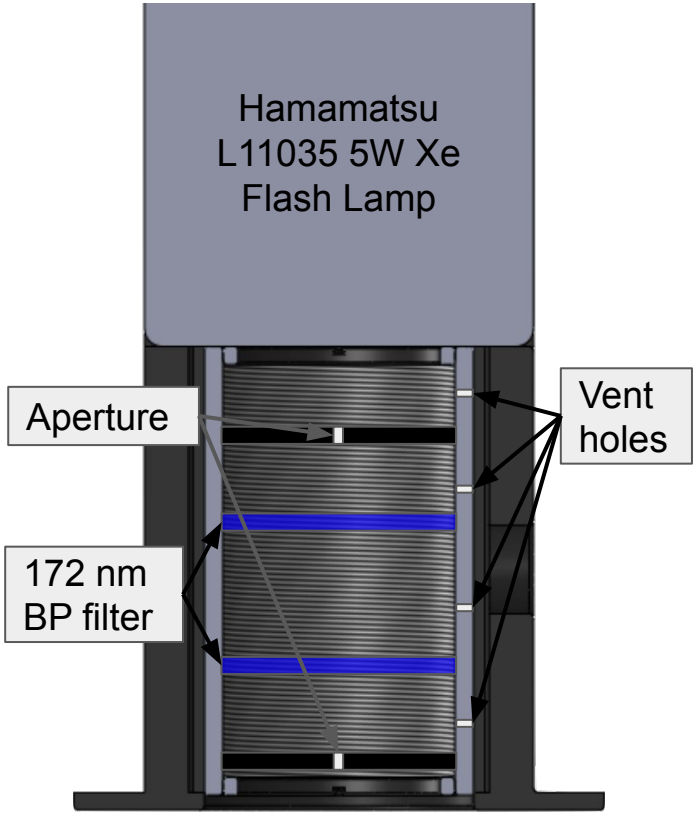
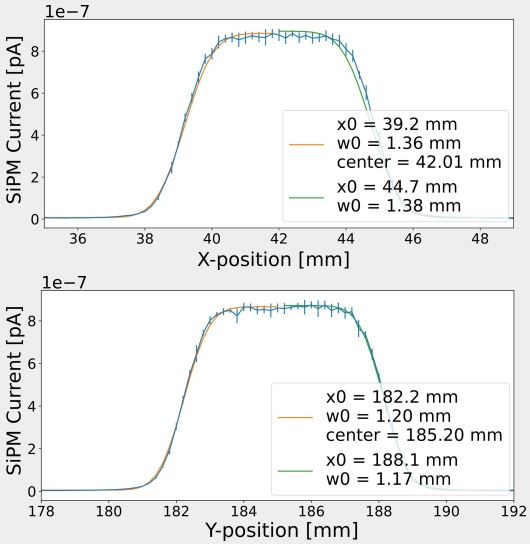

Cf252 GXe scintillator
Xe flash lamp
Linear rail system

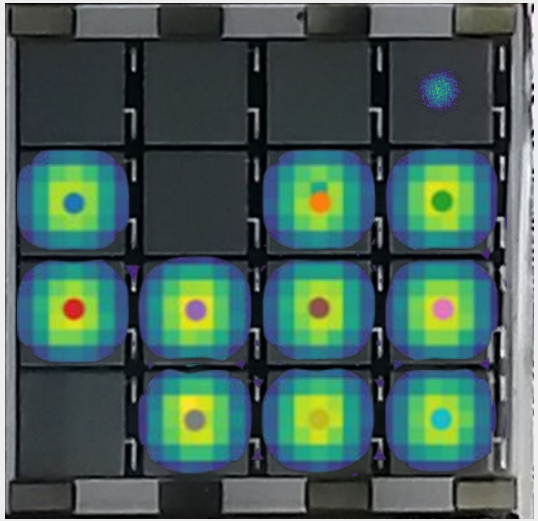

NIST PD
VUV4 SiPM tile

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

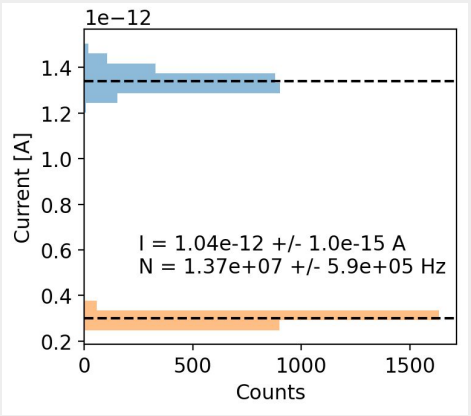
Flash lamp configuration
for SiPM characterization

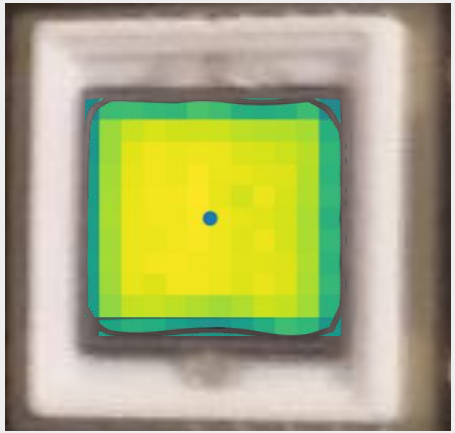




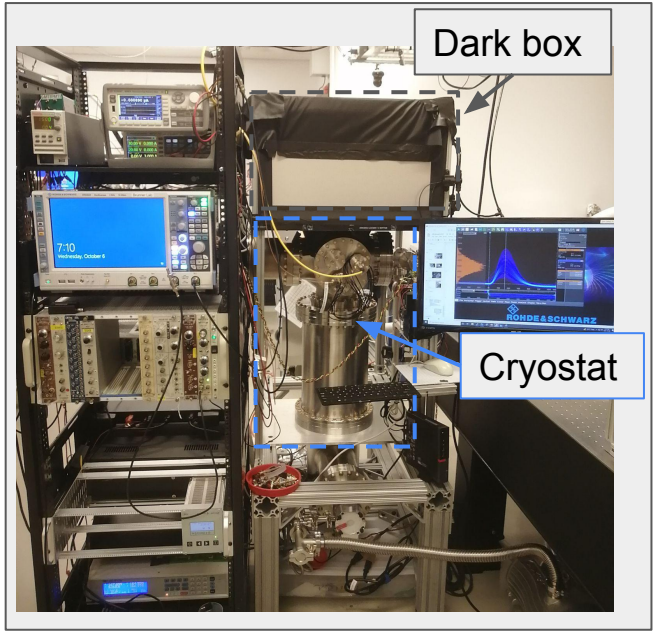


- Raster scan used to position devices
- Device edges and center determined from scan
- Single sweep integrates beam, produces gaussian profile

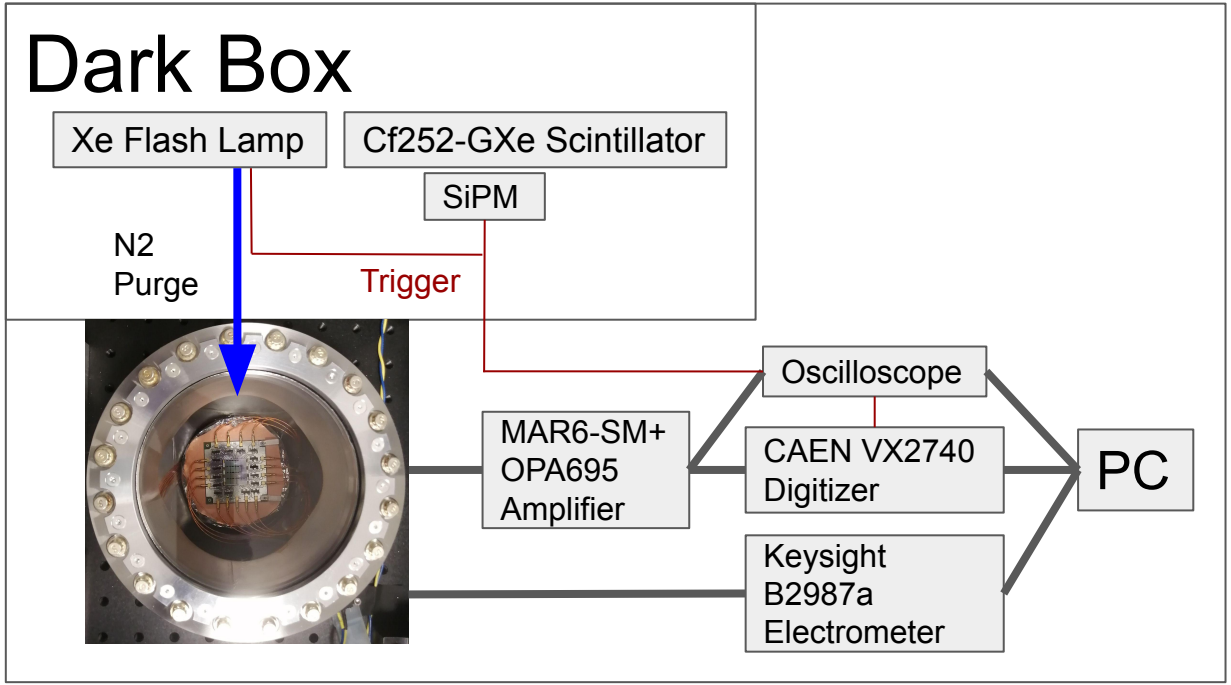




- NIST calibrated XUV photodiode used to determine beam flux
- Flux combined with profile for beam monte-carlo



Dark Box



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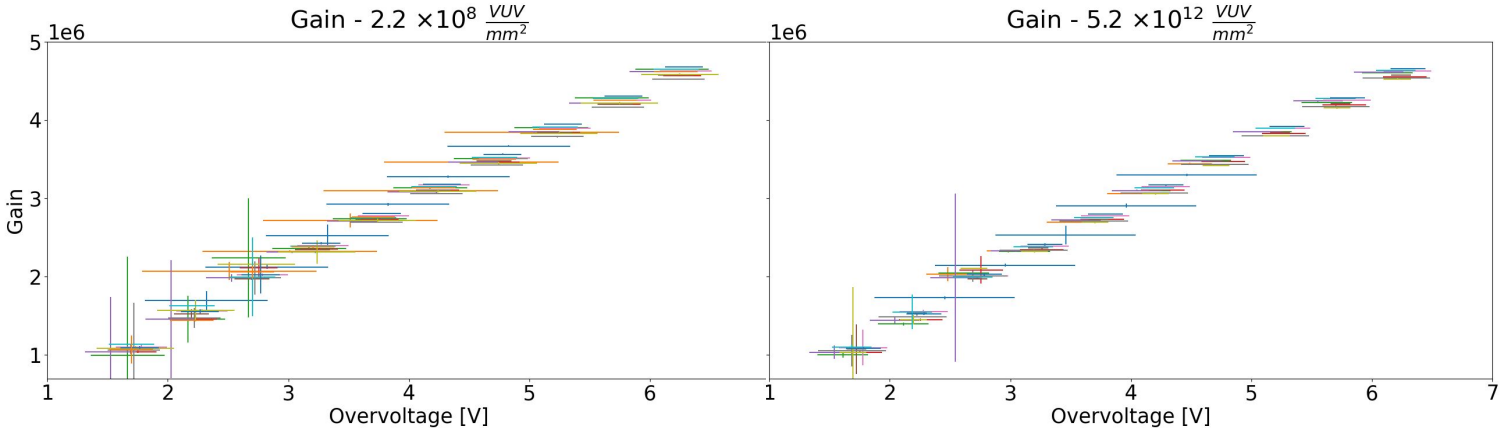
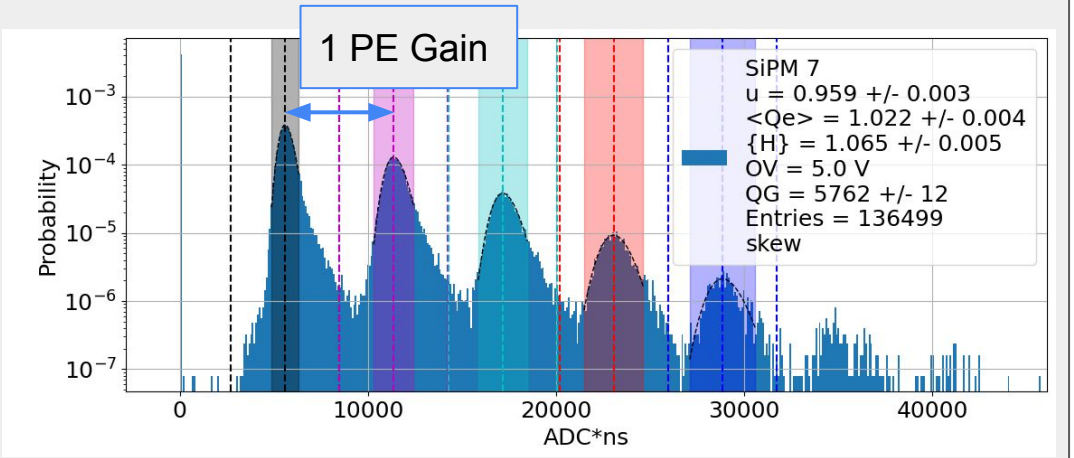
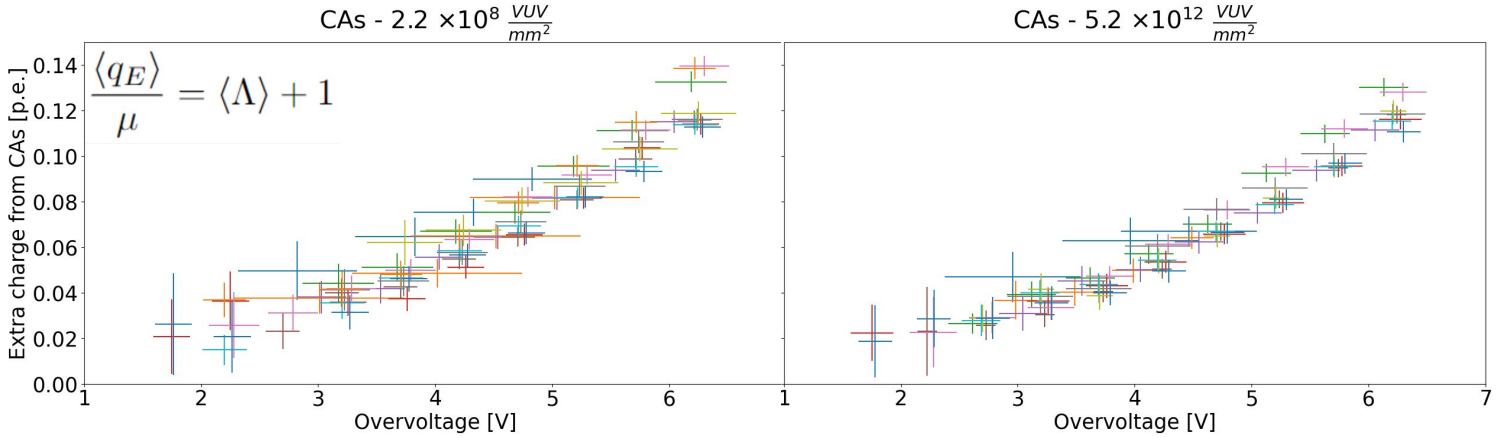
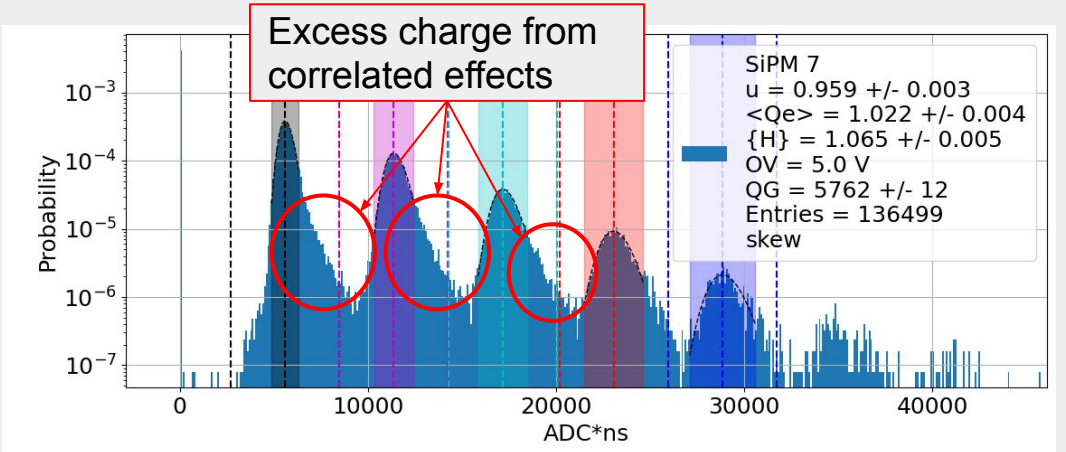


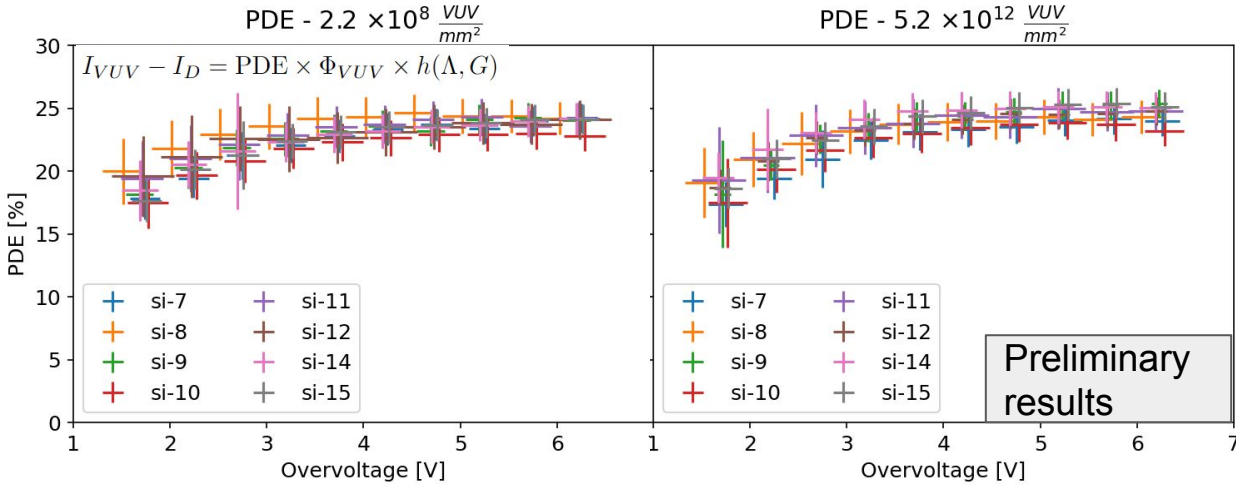
- Gain calculated from charge spectrum (Integrated waveforms)
- 720 000 1/V single PE gain

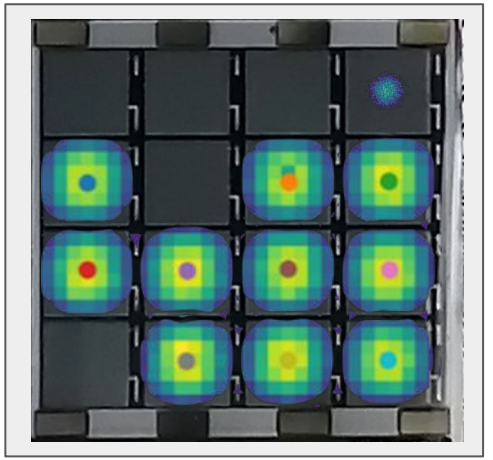




- Zero-count method used to determine mean number of avalanche
- 5% extra charge at 4V OV

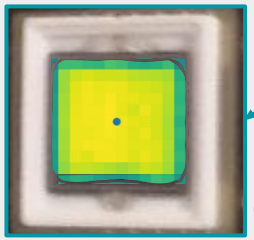




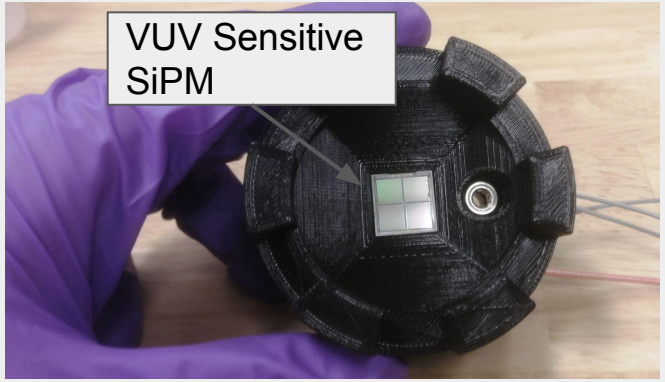


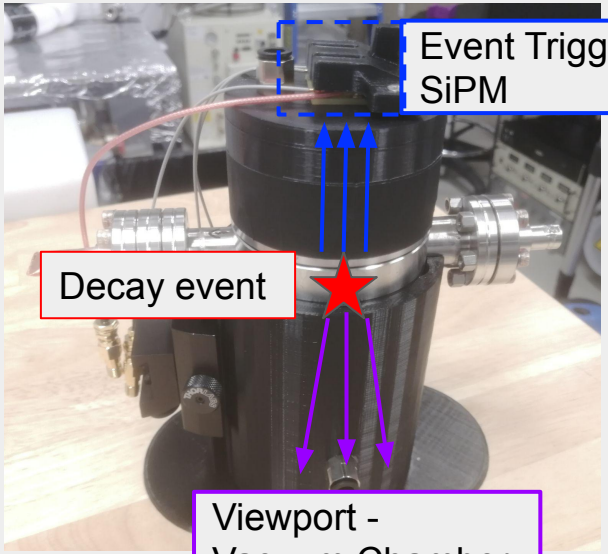
- Xe flash lamp collimated into beam with 172 nm BP filter
- PDE saturation around 23%

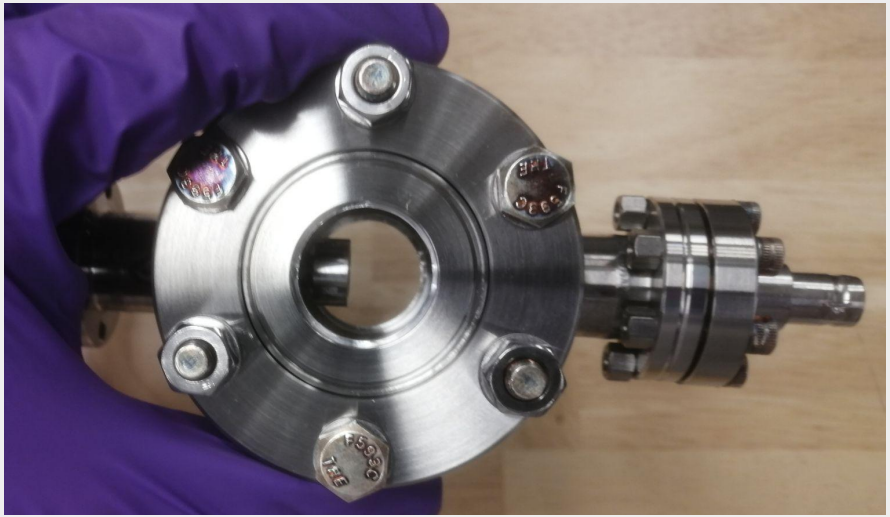
$$I_{VUV} - I_D = \mathrm{PDE} \times \Phi_{VUV} \times \frac{\langle q_E \rangle}{\mu} Ge$$



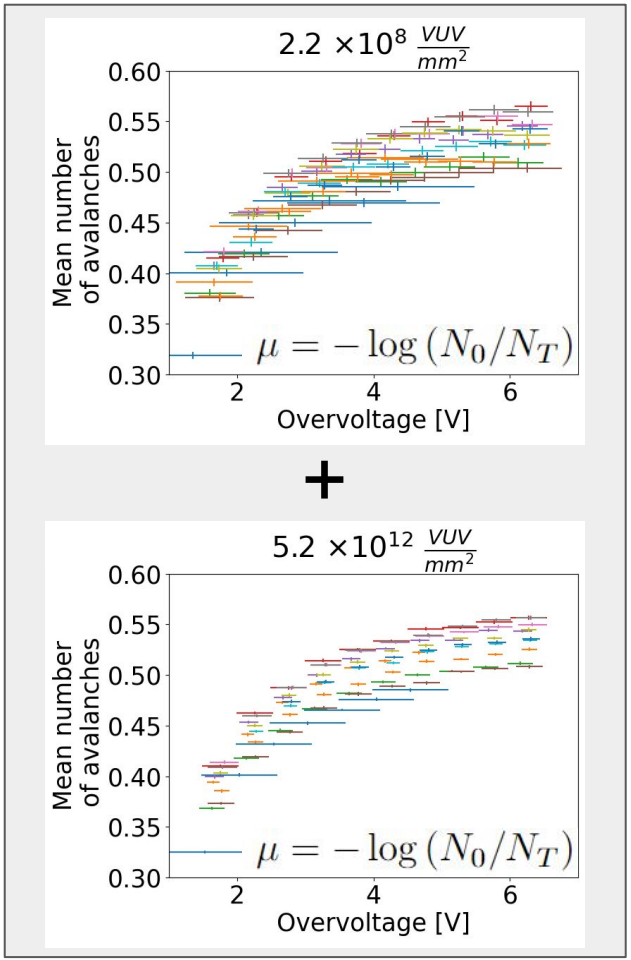
Calibrated photodiode





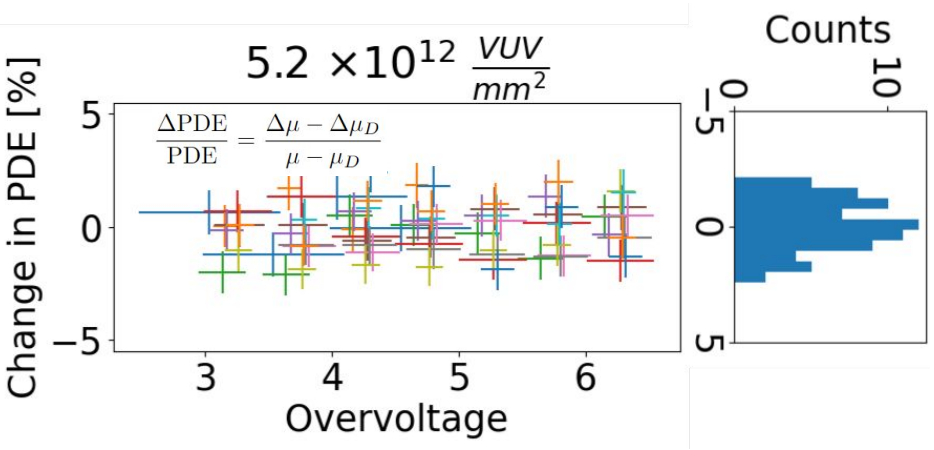


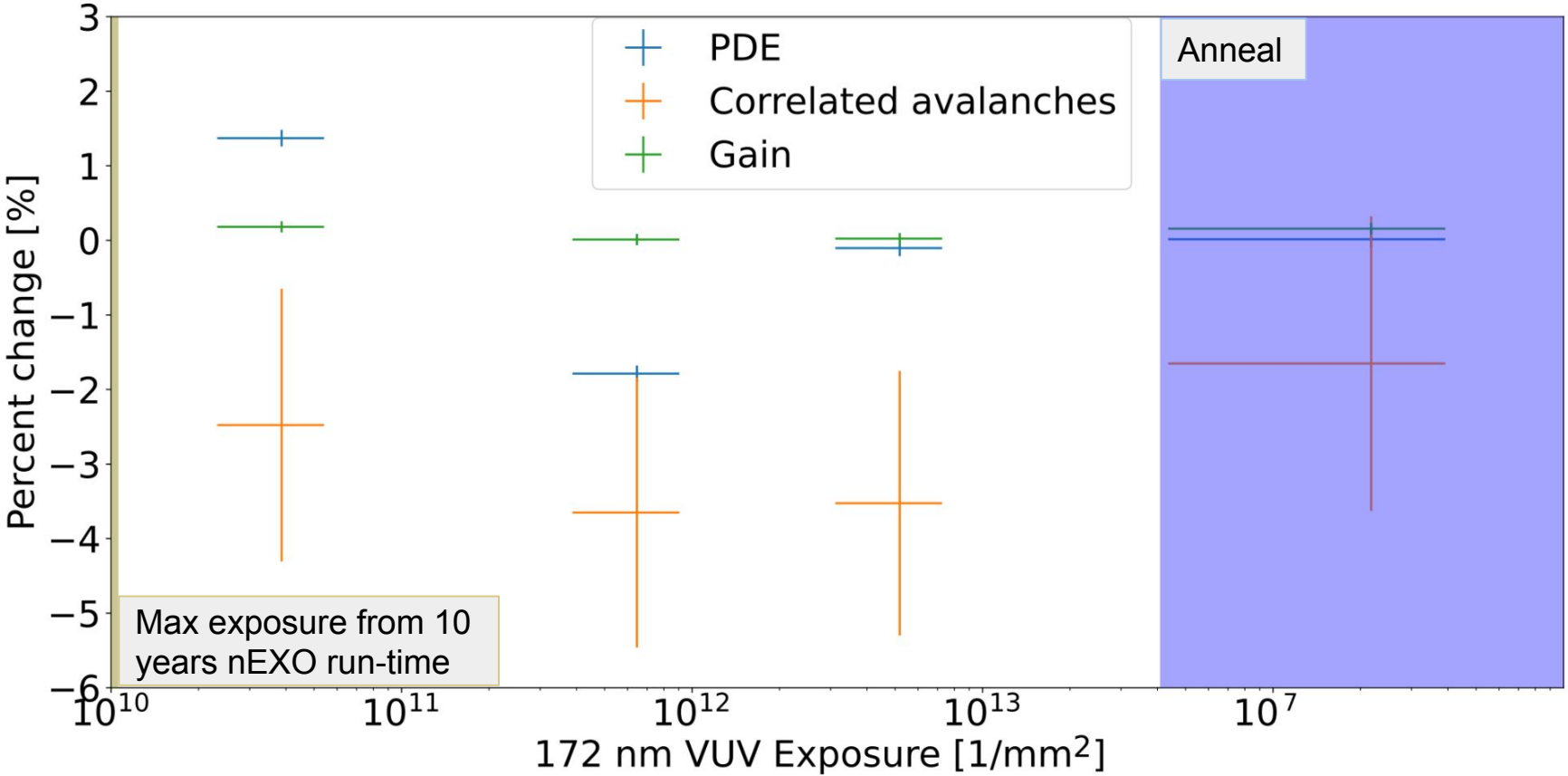
- Xenon gas sealed in chamber with Cf252 radioactive source
- Cf252 decay causes ~172 nm scintillation in xenon
- Coincidence trigger with SiPM



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

⇒




PDE
Correlated avalanches
Gain
Anneal
Max exposure from 10 years nEXO run-time
Percent change [%]
172 nm VUV Exposure [1/mm²]
3
2
1
0
−1
−2
−3
−4
−5
−6
10¹⁰
10¹¹
10¹²
10¹³
10⁷

Conclusion

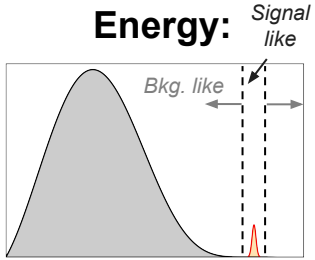
- HPK VUV4 SiPMs have been tested before/following high VUV exposure
- No change observed for: PDE, Correlated avalanches, or Gain
- Further evidence of SiPM technology readiness for nEXO

The nEXO Collaboration

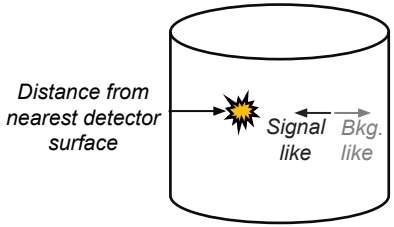
nEXO Signal and Background

- nEXO measures multiple parameters for each event to be able to robustly identify a $0\nu\beta\beta$ 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

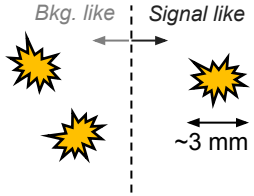
Energy:



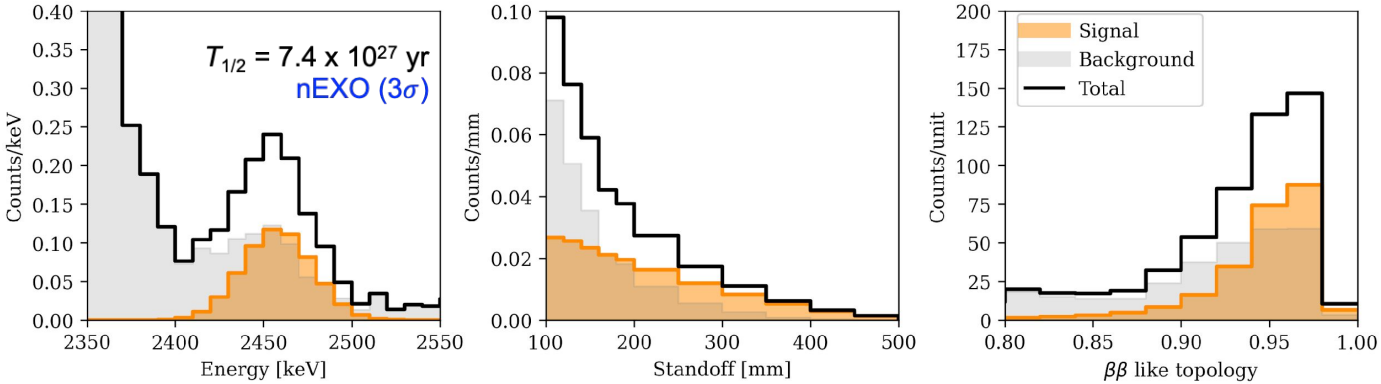
Standoff:



Topology:



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

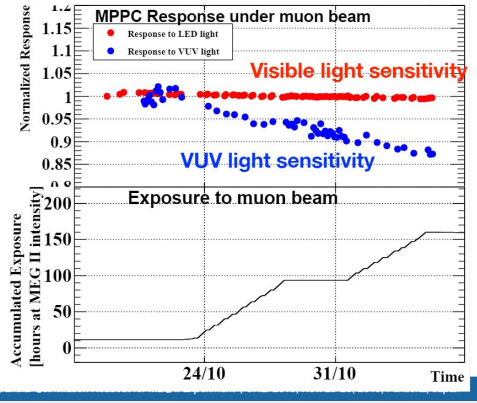
A Surprise…

- **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

↓

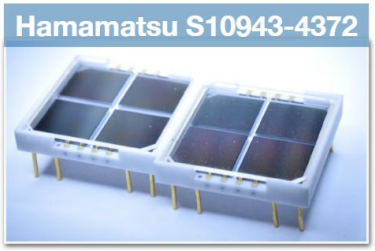
Dose level is quite low

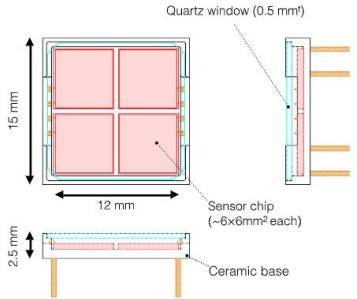


W.Ootani, "Liquid Xenon Photon Detector with Highly … 14

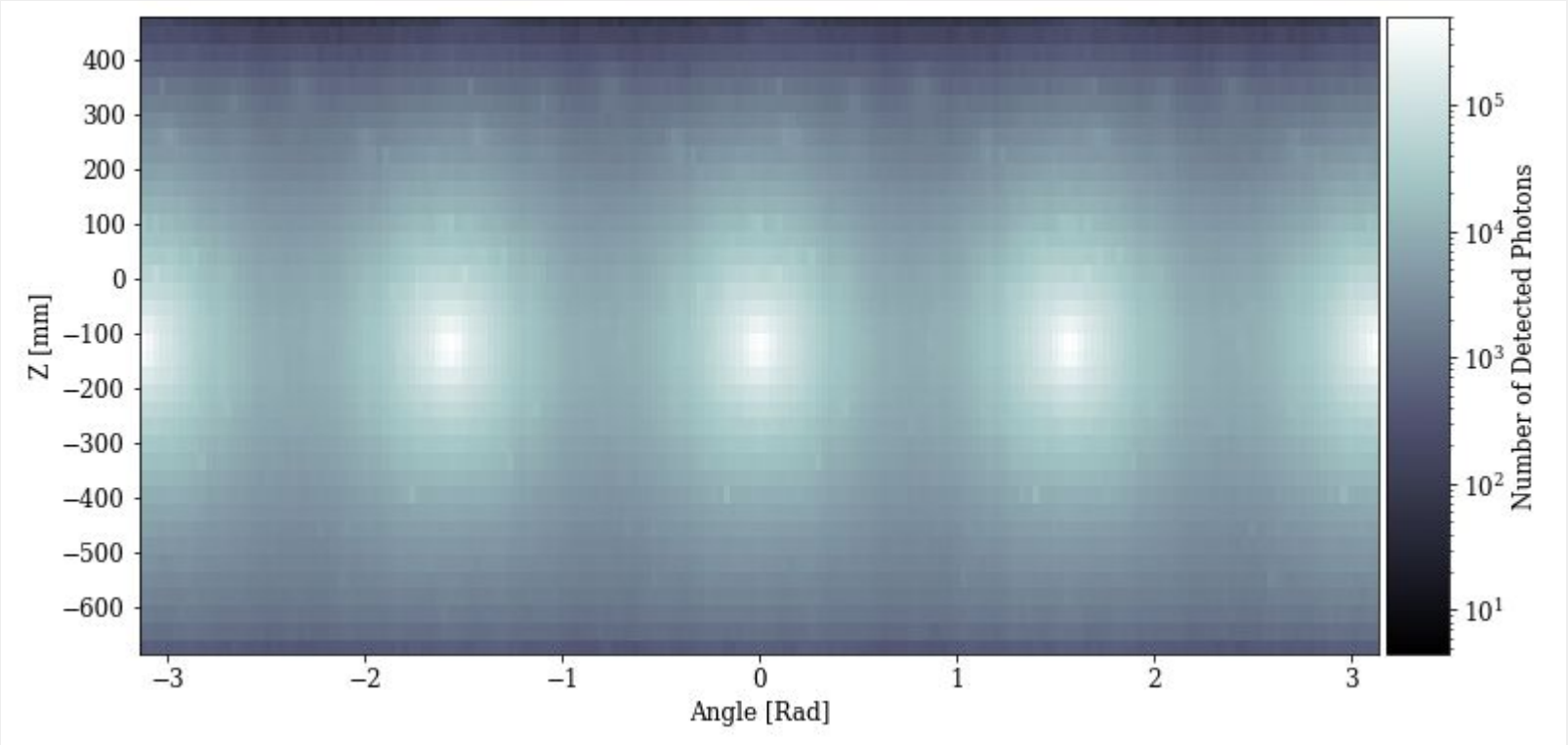
https://indico.cern.ch/event/818783/contributions/3598489/attachments/1950386/3237558/MEG_Ootani191125_compressed.pdf

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 external source calibration. The areas of maximum VUV flux is centered on the external sources. Sierra Wilde (Yale).