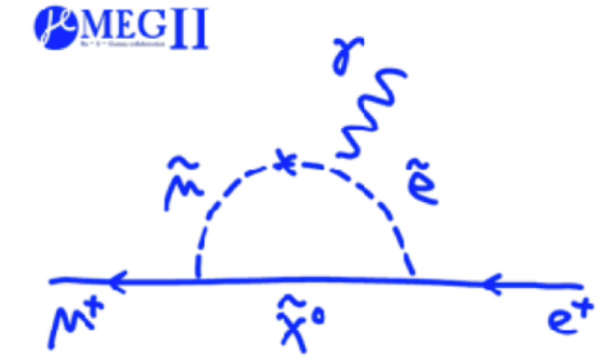
東京大学
素粒子物理国際研究センター
International Center for Elementary Particle Physics
The University of Tokyo



MEG II
Liquid Xenon Detector
and
Simulation

Sei Ban (ICEPP, U.Tokyo), for the MEG II collaboration
7th Oct. 2022, Rare Pion Decay Workshop at UC Santa Cruz

Outline

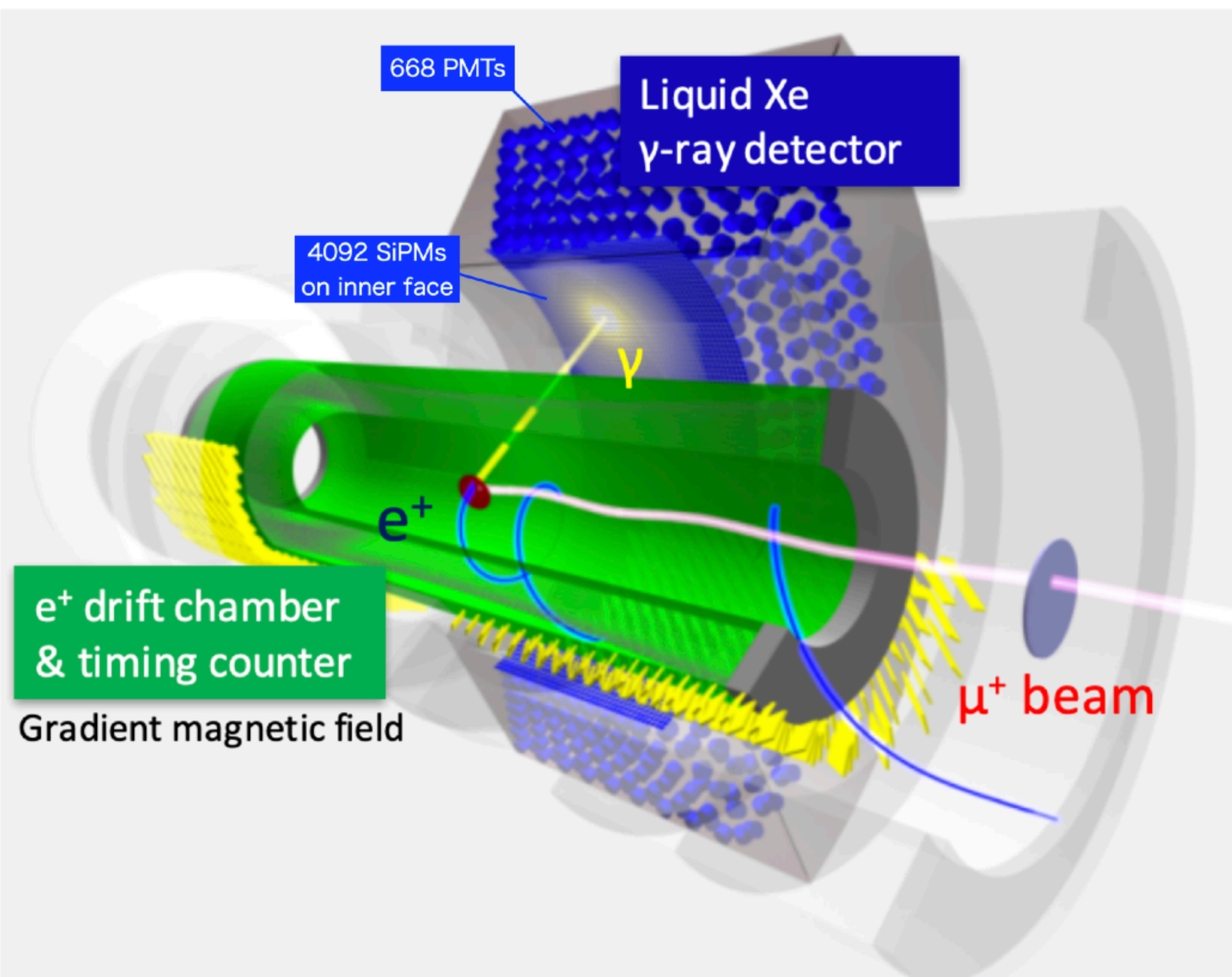
- MEG II : Liquid xenon detector and VUV-sensitive MPPC

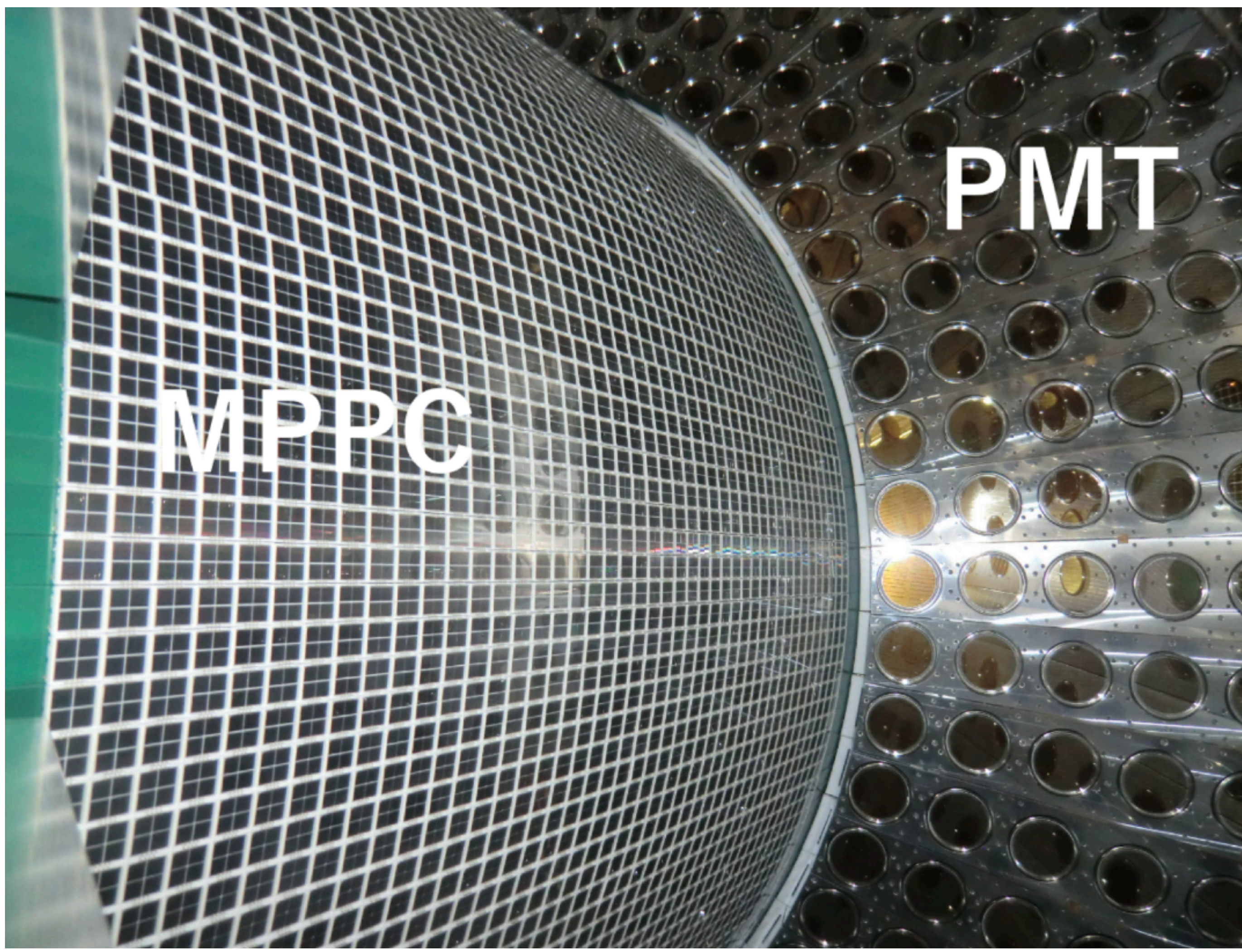
- Simulation of the liquid xenon detector for PIONEER
  - (Just plan)

- Operation and calibration of the liquid xenon detector
  - Presented by Ayaka. M, the next speaker

MEG II : Liquid xenon detector

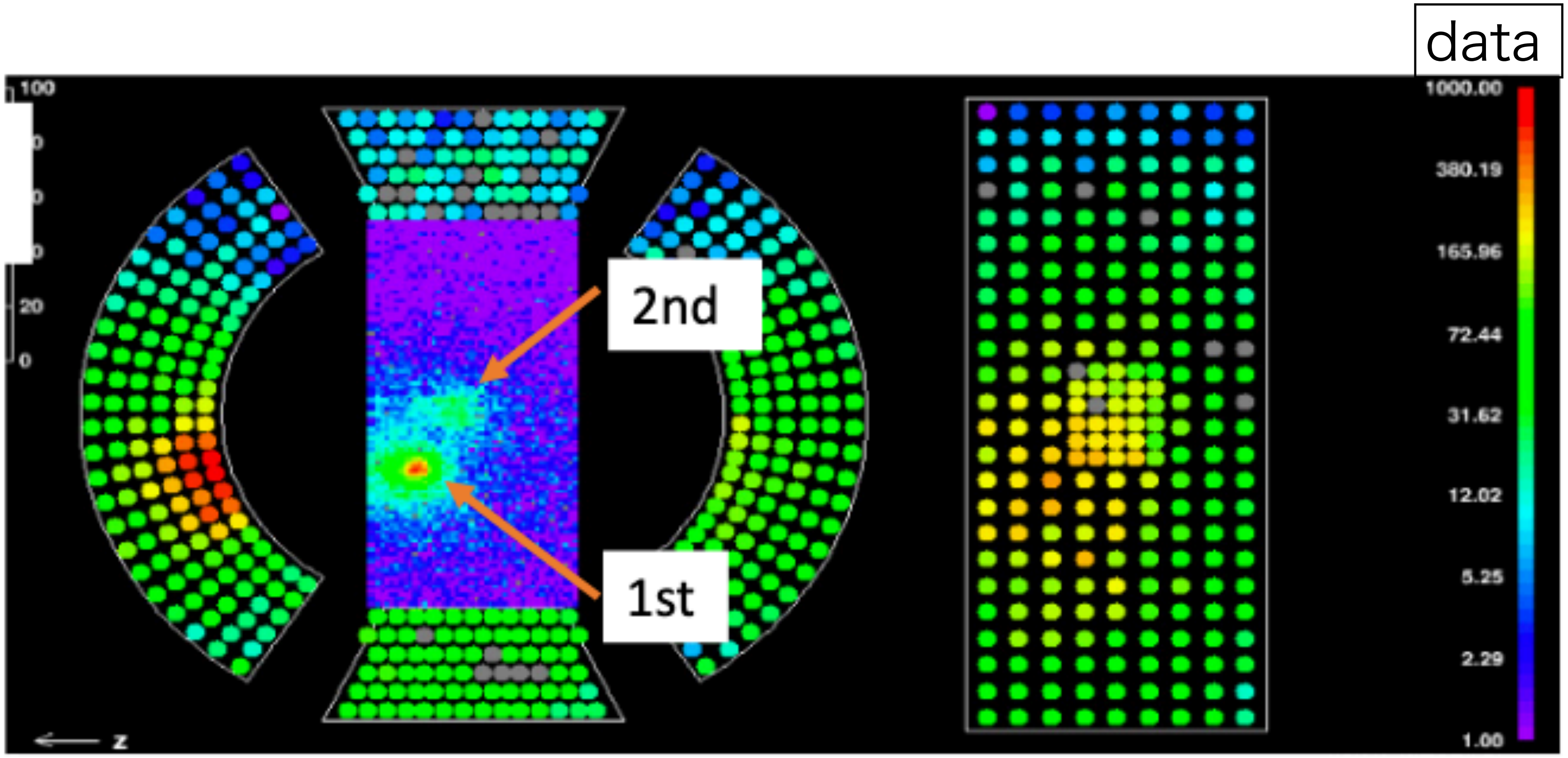
- MEG II experiment searching for charged lepton flavor violation : $\mu^+ \rightarrow e^+ + \gamma$
- Liquid xenon detector for gamma-ray measurement
  - VUV-sensitive MPPCs (x4092) on the inner face
  - VUV-PMTs (x668) on the other faces
- Measuring the energy, position and timing of gamma-rays
- Finer imaging by covering up the inner face tightly with VUV-sensitive MPPCs
  - Improve rejection power for pile up events



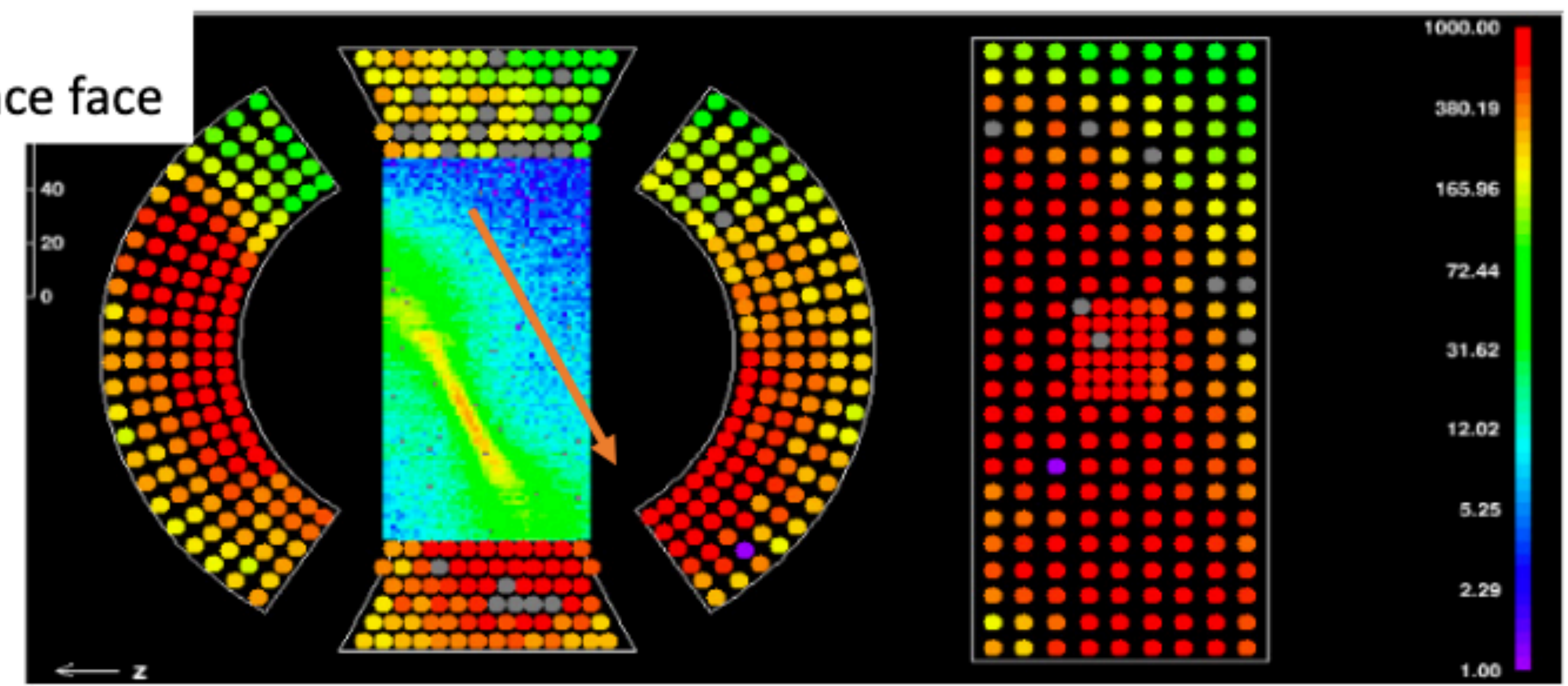


MEG II : Liquid xenon detector

Pileup
gamma-rays

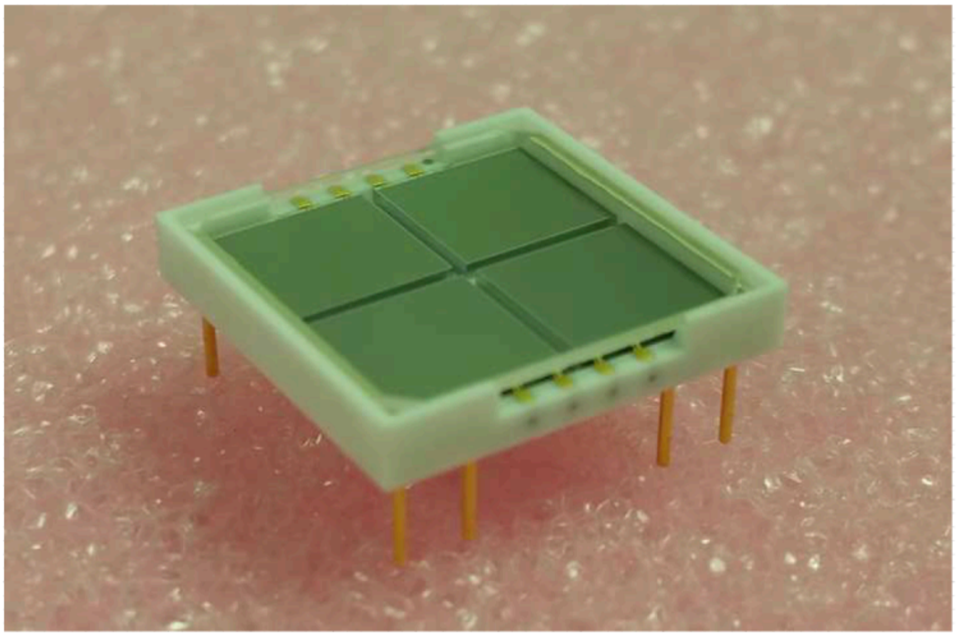


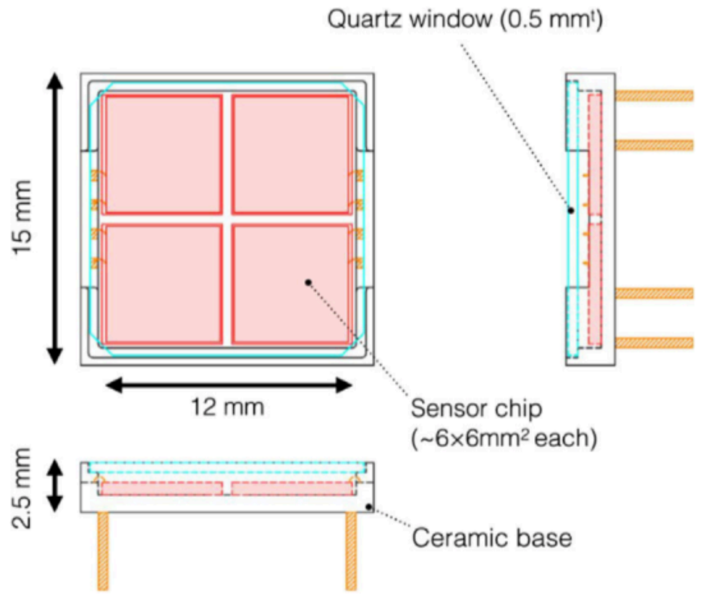
Cosmic-ray
Close to entrance face



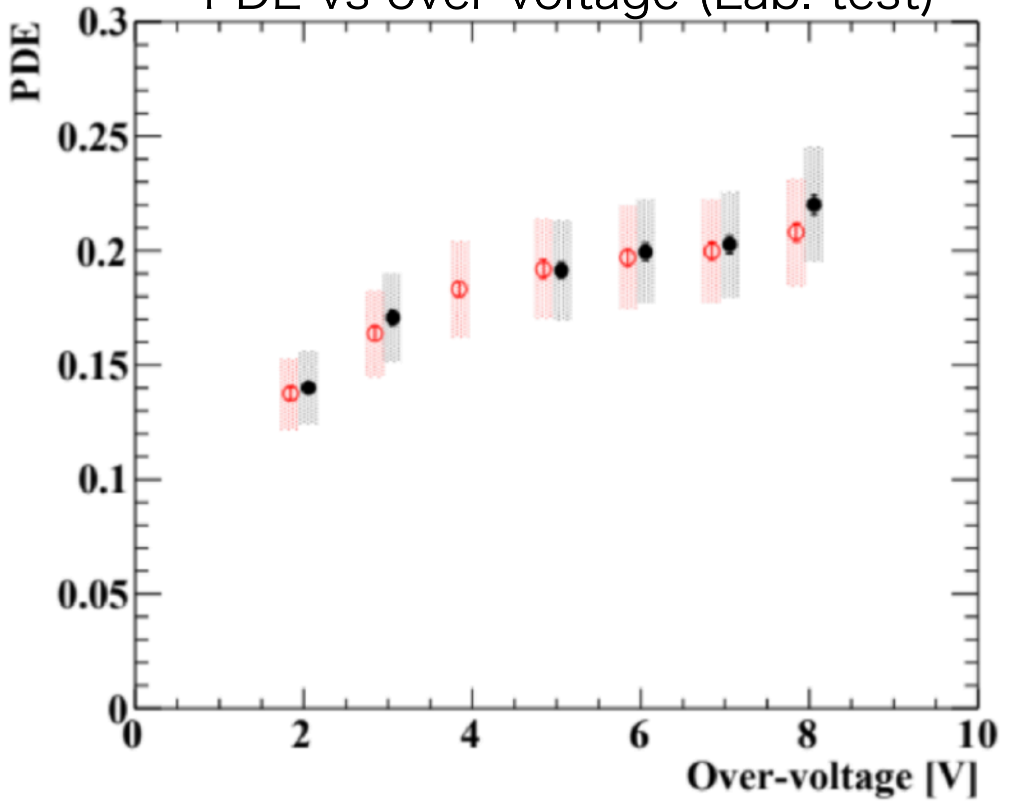
VUV-sensitive MPPC

- VUV-Sensitive MPPC (SiPM) for inner face of the liquid xenon detector
  - Developed by Hamamatsu Photonics for MEG II experiment
- Can be operated
  - at liquid xenon temperature (~165 K)
  - in magnetic field
- Photon Detection Efficiency (PDE) > ~15% for VUV light (λ~170 nm)
  - Evaluated by Lab. test
  - PDE is also monitored by alpha-ray source in the liquid xenon detector during operation



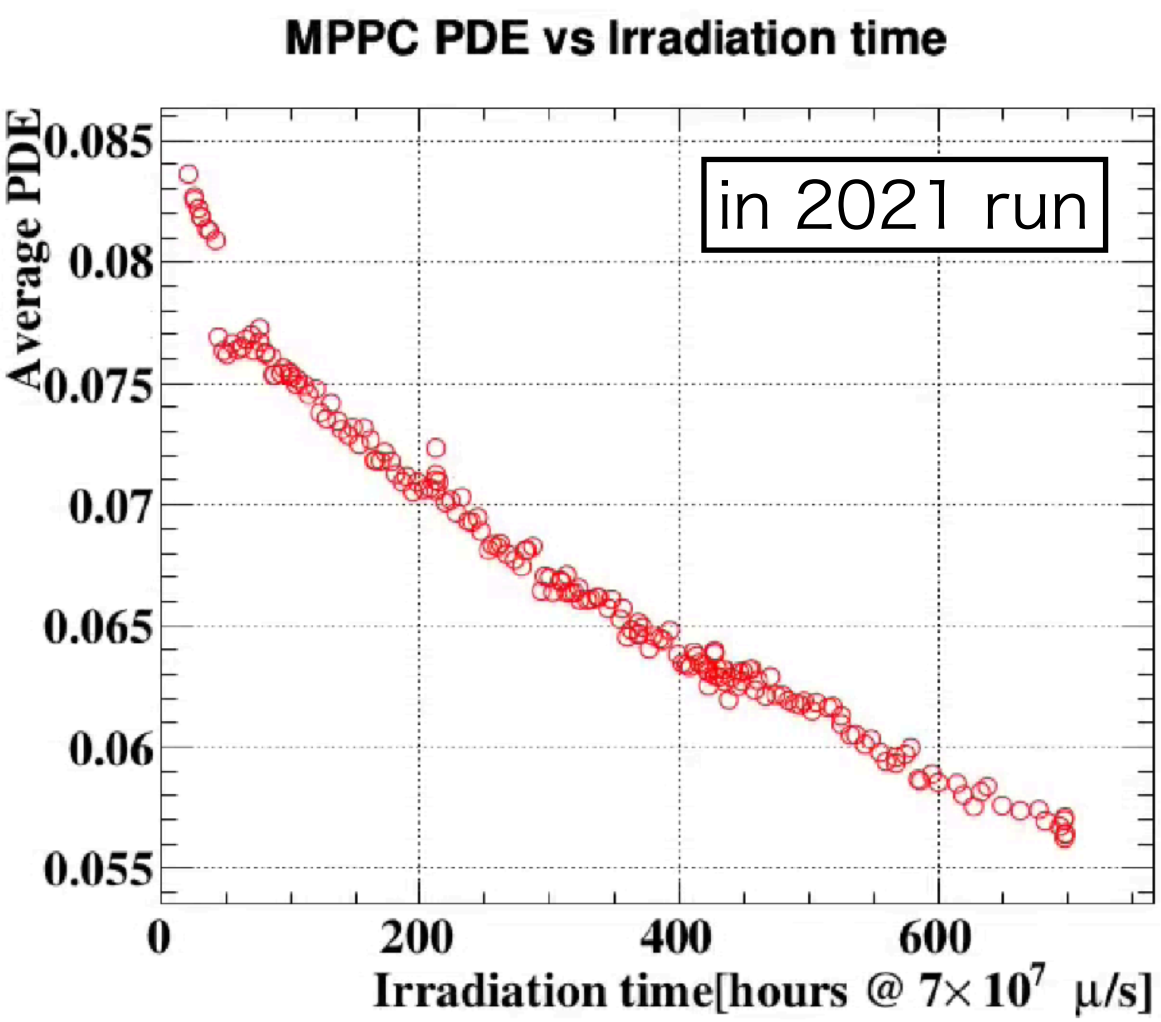


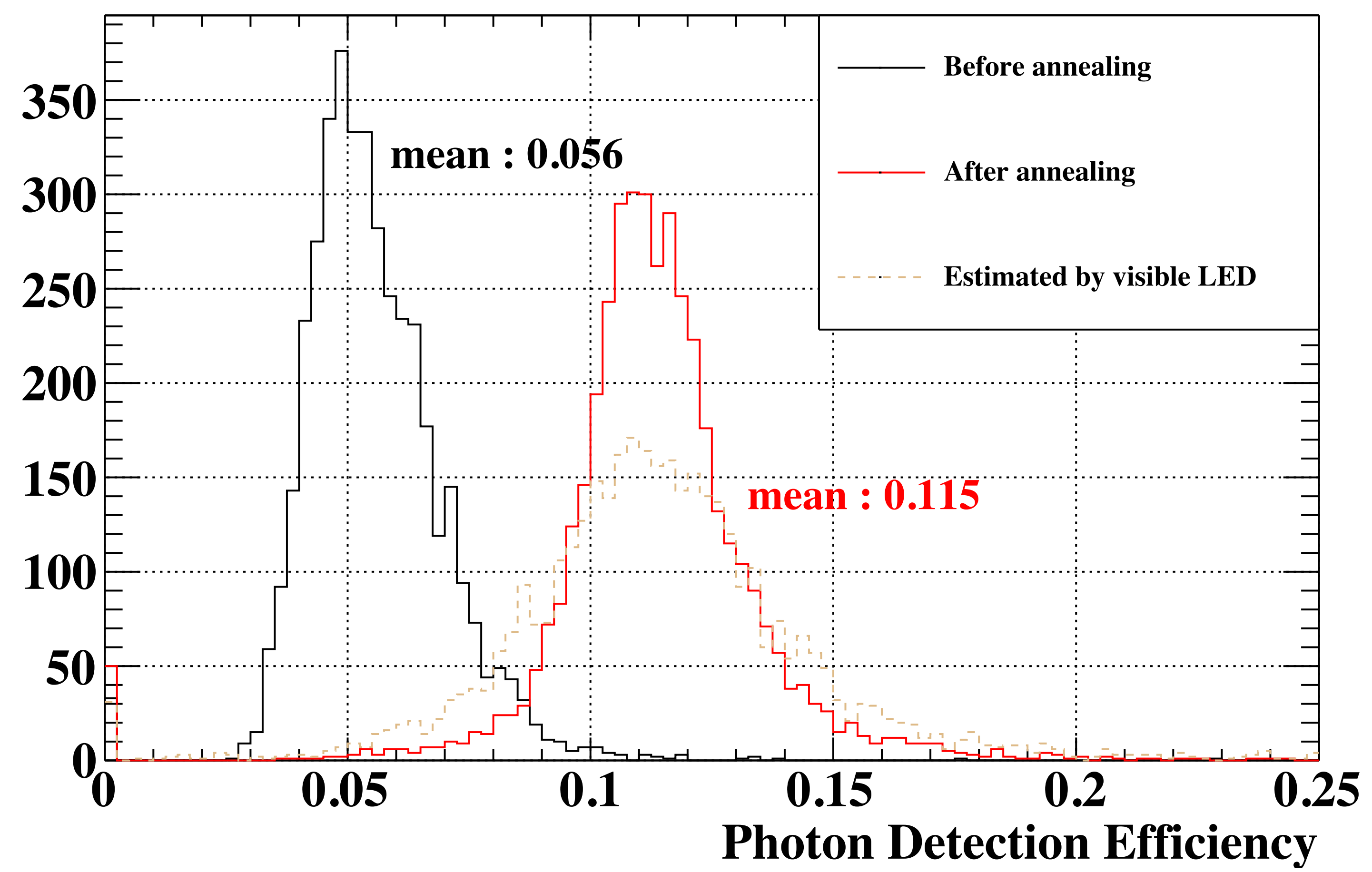
PDE vs over voltage (Lab. test)



VUV-sensitive MPPC : Photon Detection Efficiency

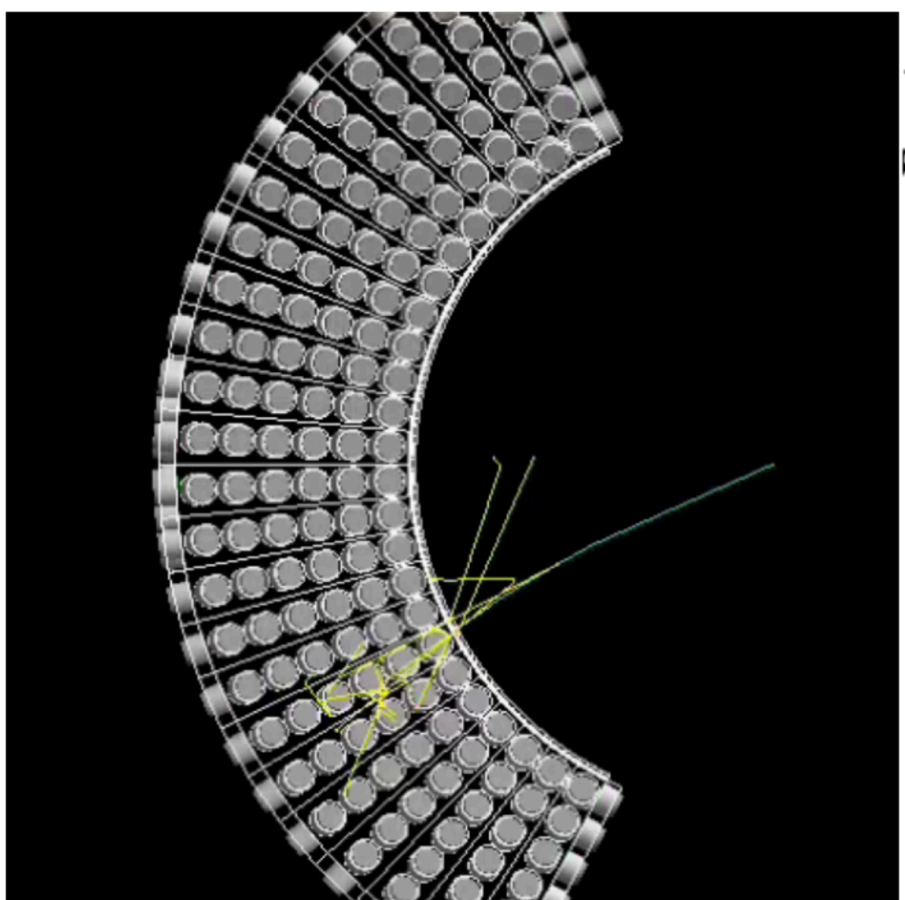
- PDE decrease during beam time was observed
  - The cause of PDE decrease is under investigate (radiation damages?)
  - Averaged PDE : 8.4% → 5.6% in 2021 run
- PDE recovery was attempted by annealing during beam off period
  - Annealing by Joule heating of MPPC itself
  - PDE value after the annealing : ~11.5% in average (still work in progress)
- **Established long term operation scheme in high intensity beam**

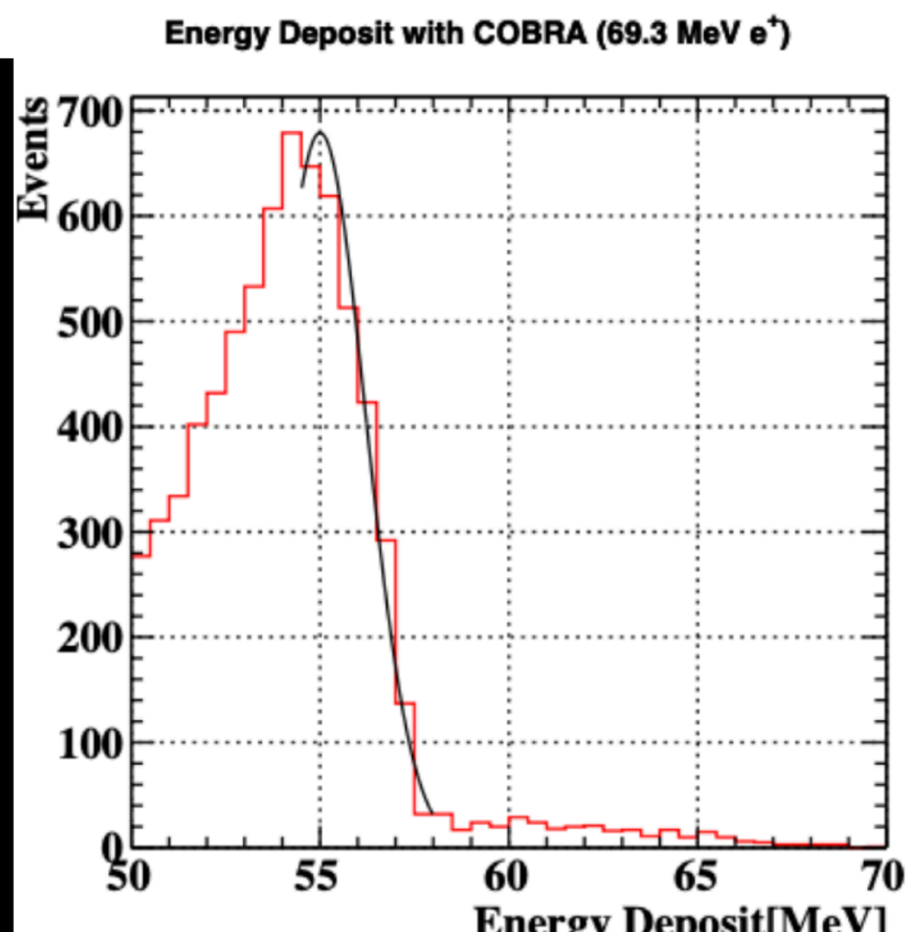


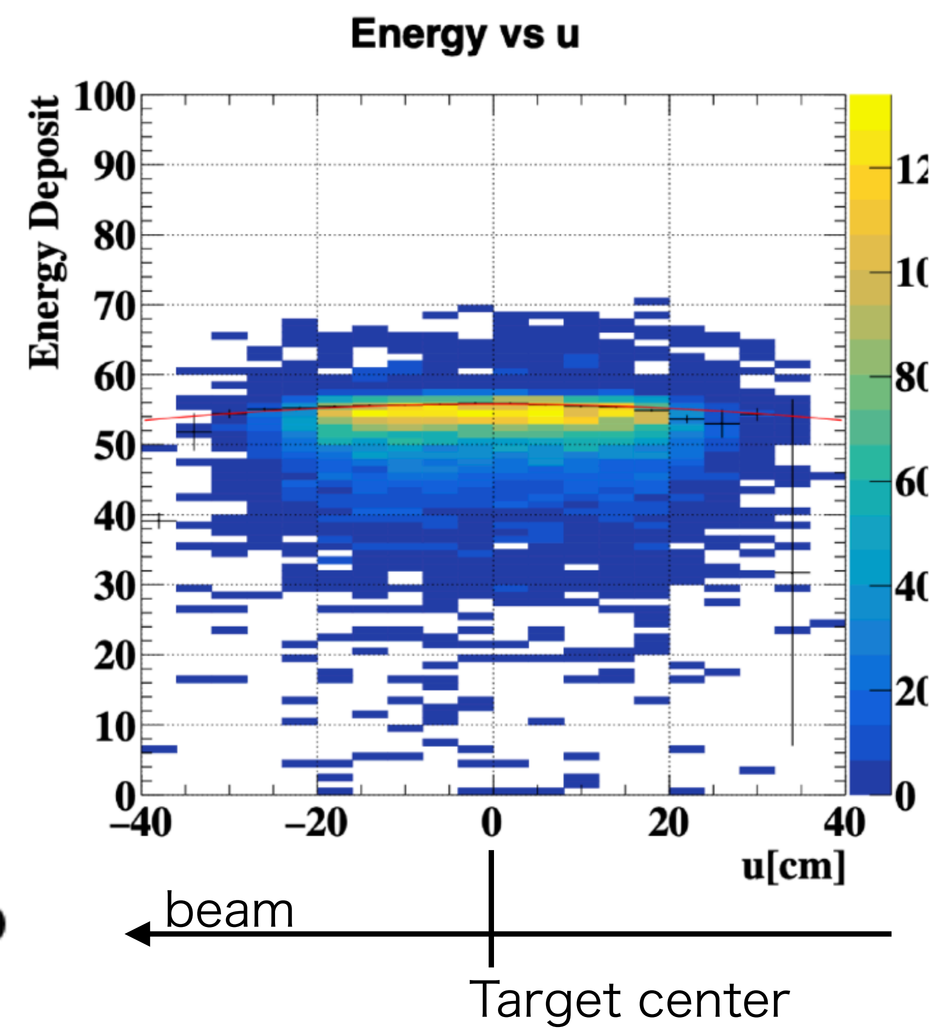


Simulation study for PIONEER

- Simulation study of the liquid xenon detector for PIONEER calorimeter
  - Response for detection of 69.3 MeV e^+ from $\pi^+ \rightarrow e^+ + \nu$
  - To understand : Energy resolution, low energy tail (due to materials)
  - Mott scattering is considered
- Energy loss at the material budget of the liquid xenon detector itself : ~7 MeV
  - Explainable the position dependence of deposit energy (right bottom figure)



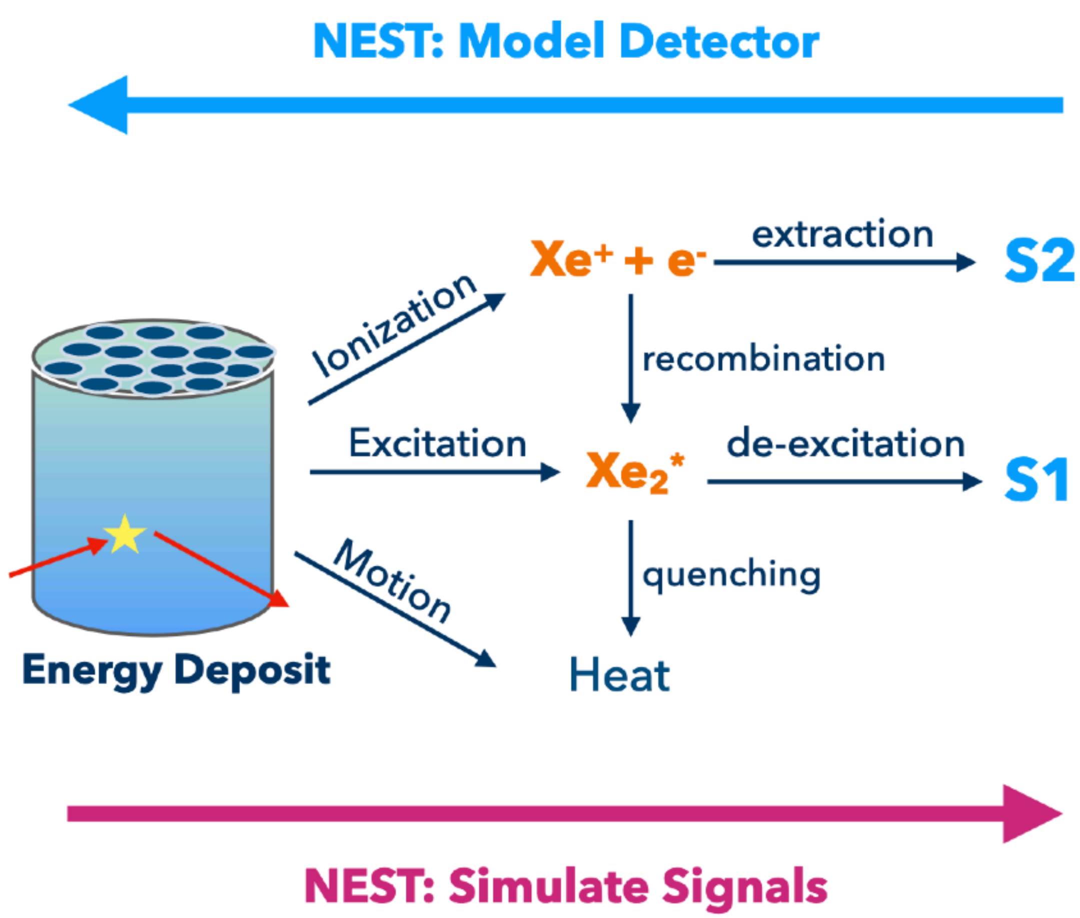




Simulation study for PIONEER : Introduce of NEST

- Introduce "Noble Element Simulation Technique (NEST)" to the simulation
  - https://nest.physics.ucdavis.edu/
  - Comprehensive, accurate, and precise simulation of liquid noble elements
  - Investigate the detector response more precisely at low energy region

- First, we'll introduce NEST to our detector simulation
  - Compare with the current results



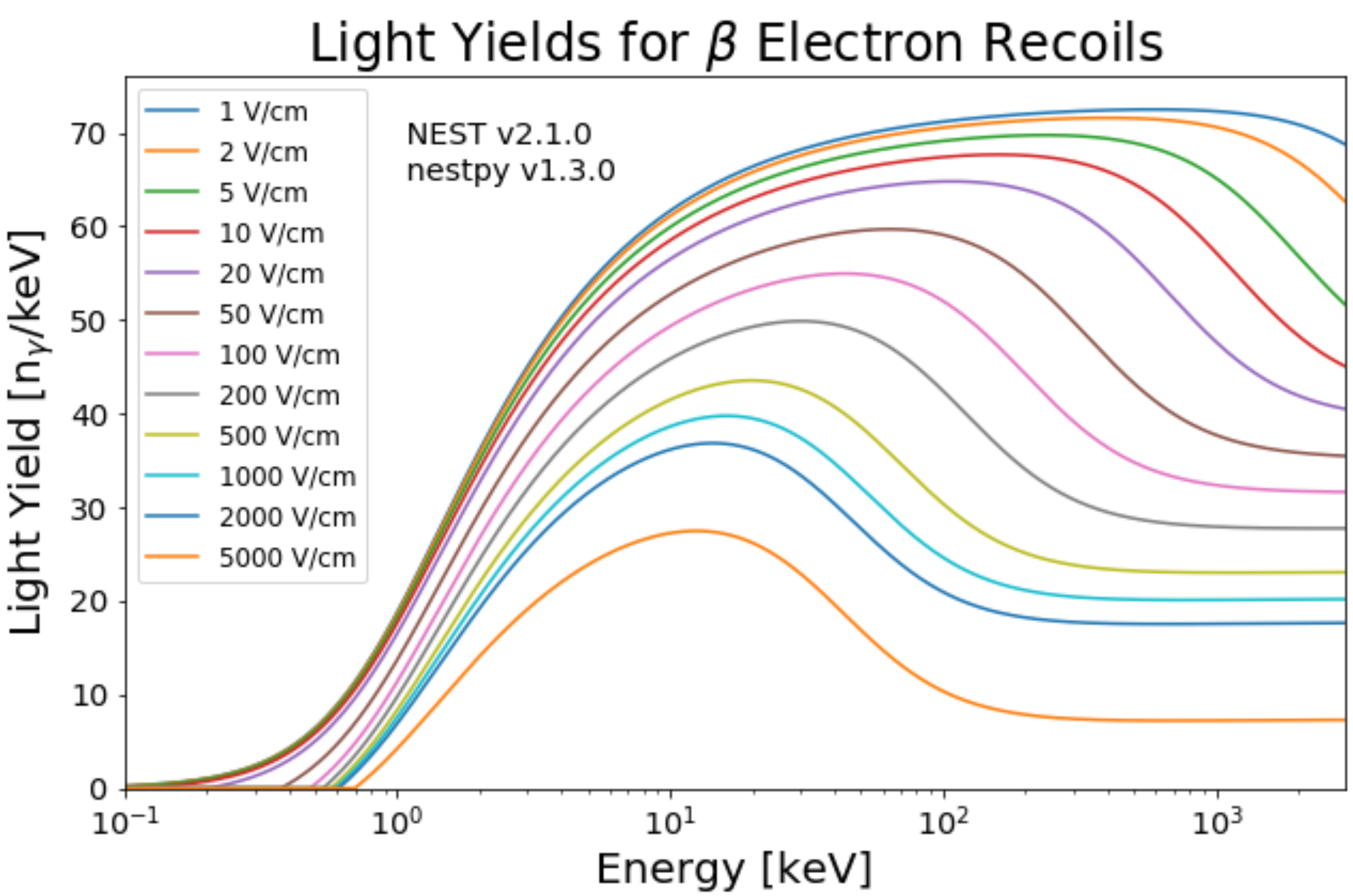


Figure from : https://nest.physics.ucdavis.edu/application/files/8916/1904/0486/APS_April2021_NEST_Andaloro.pdf

DOI:10.5281/zenodo.1314669

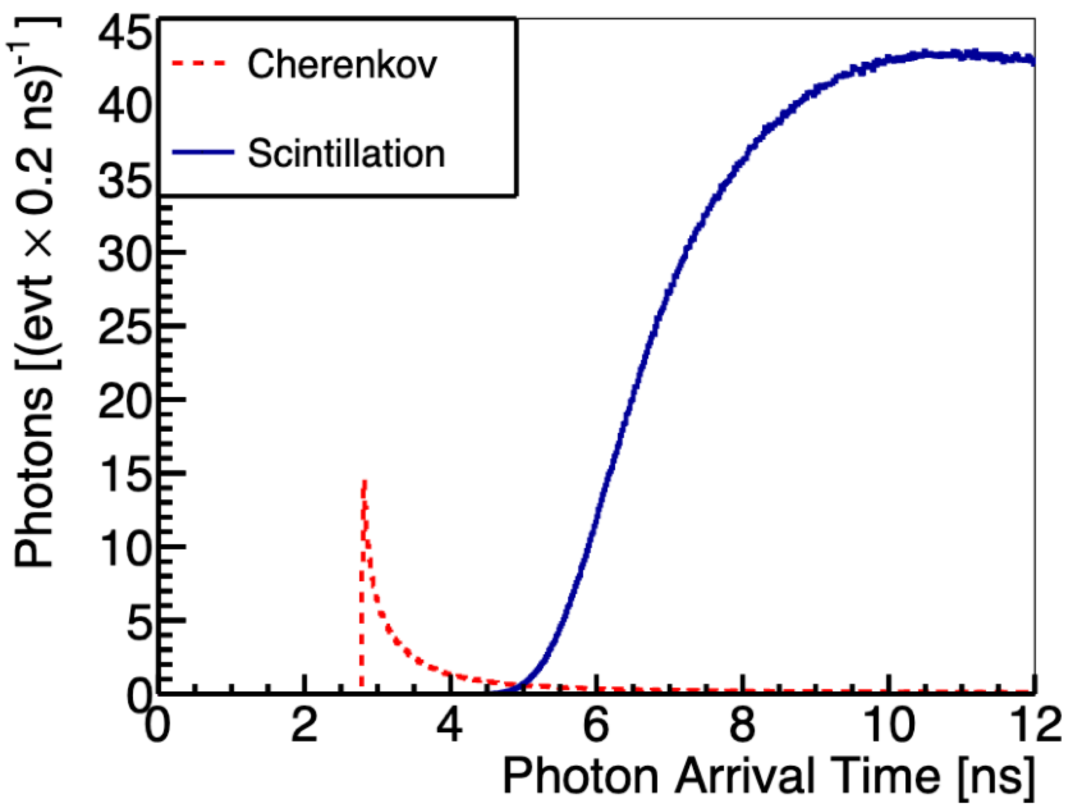
Simulation study for PIONEER : Cherenkov light

- Use Cherenkov light to reconstruct the angular information
  - can be used for background rejection
- Distinguish from scintillation light by “timing” and “event distribution”

	Scintillation	Cherenkov
Timing	Decay time of Xe	Promptly
Distribution	Isotropic	Directive

- We’ll try to detect Cherenkov lights by
  - Simulation study
  - Data (charge exchange reaction of π^0)

Simulated photon arrival time by nEXO group



From : https://arxiv.org/pdf/1812.05694.pdf

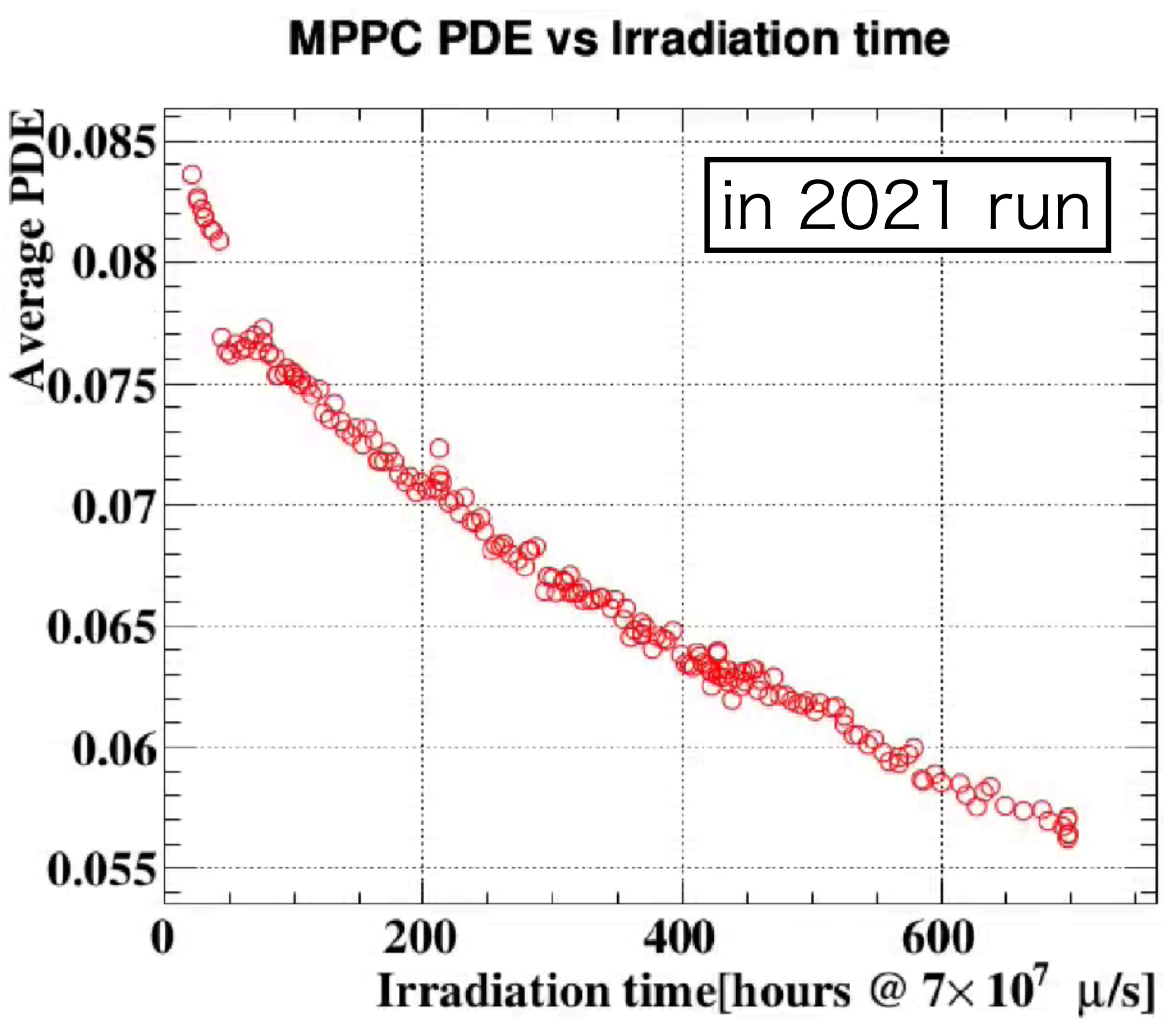
Summary

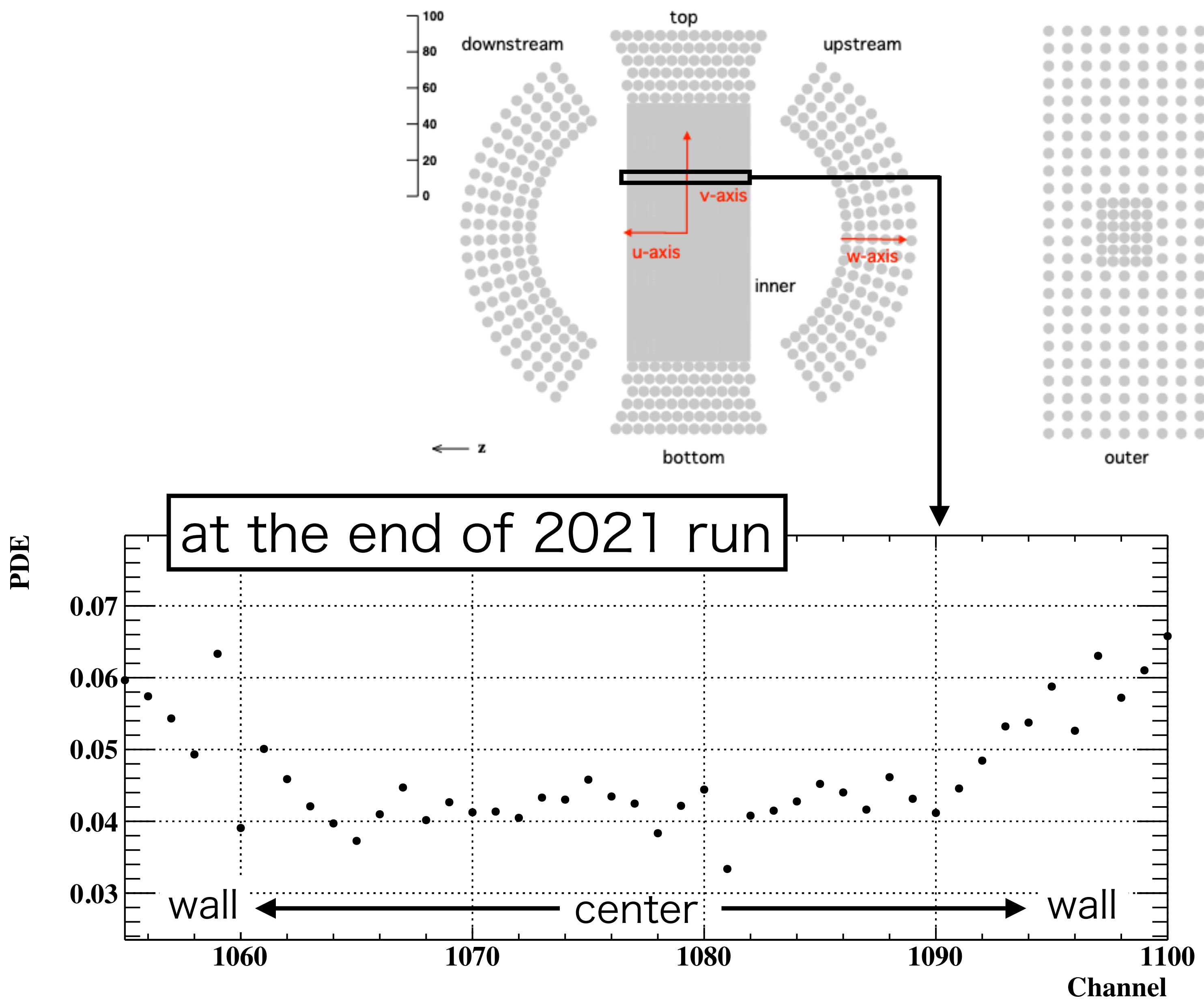
- MEG II experiment searches for charged lepton flavor violation : $\mu^+ \to e^+ \gamma$
  - Liquid xenon detector is used to detect gamma-ray
- VUV-sensitive MPPC (SiPM) was developed by Hamamatsu
  - Photon Detection Efficiency (PDE) for VUV > 15% (at manufactured)
  - PDE decrease during beam time was observed
  - PDE recovery process by annealing was conducted successfully
- Some simulation plan for PIONEER using the liquid xenon detector are shown
  - Introducing NEST physics list
  - Study for using Cherenkov light to reconstruct the angular information

Backup

PDE decrease during beam time in 2021

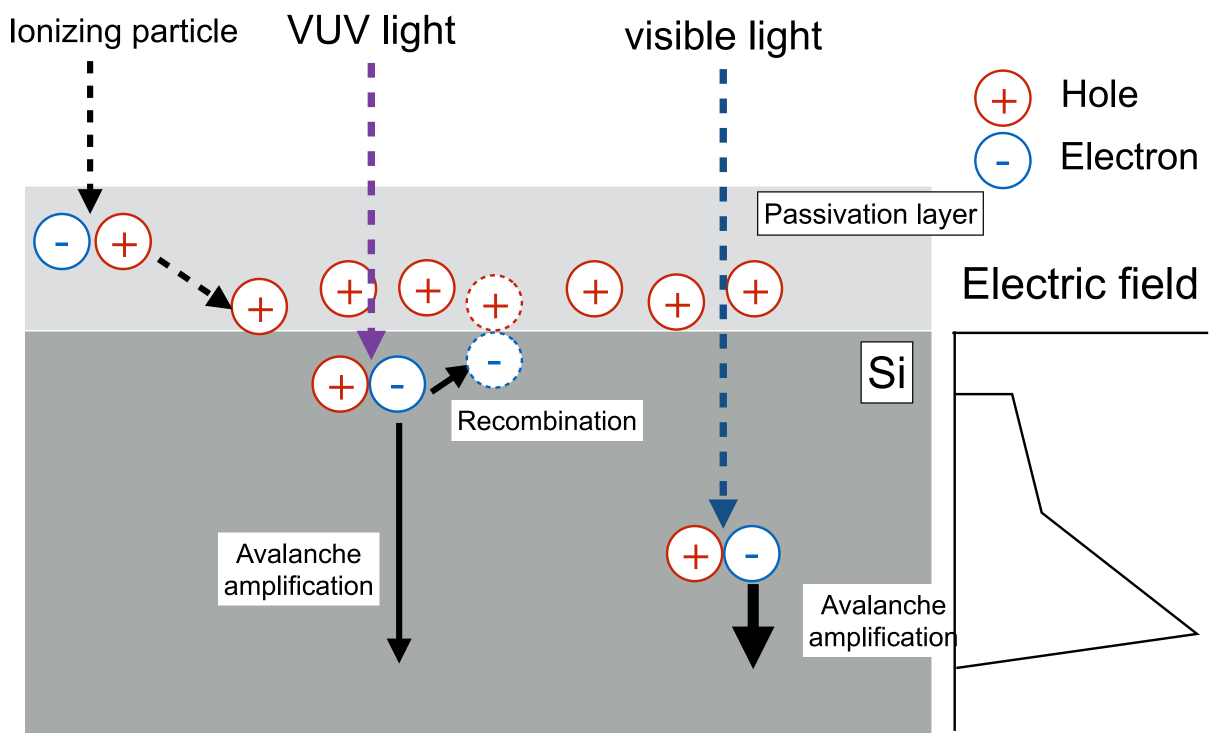
- Photon Detection Efficiency (PDE) of MPPCs was monitored using Alpha-ray
  - ^{241}Am source inside the liquid xenon detector, generating VUV-light
  - Mean PDE value decreased from ~8.5% to ~5.6%
  - Position dependences were observed : larger PDE decrease at the center
    - Radiation damage by beam may be an issue



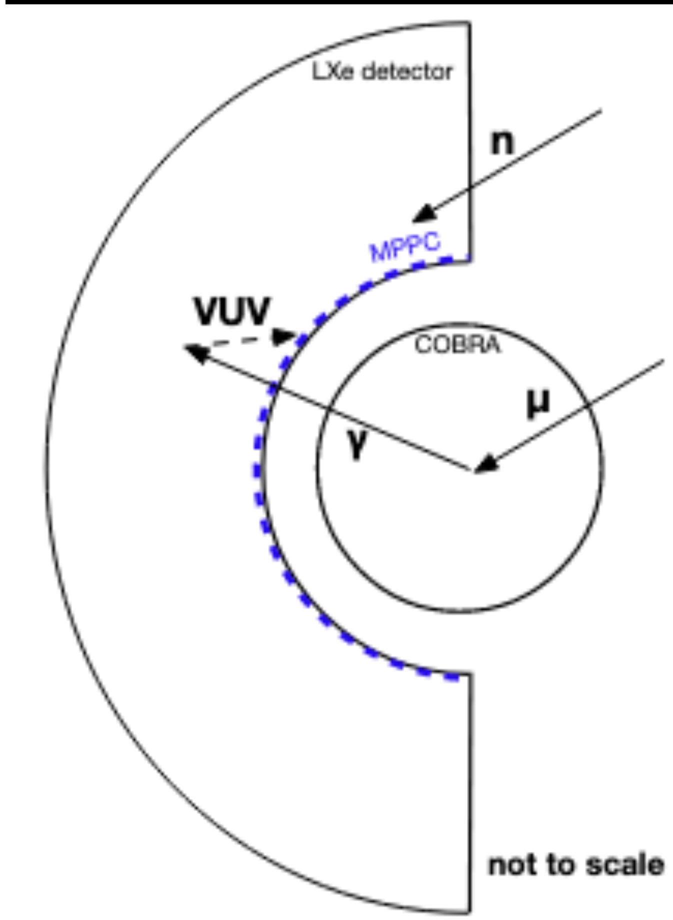


Surface damage of MPPC

- Possible cause of PDE decrease
- Gamma-ray, VUV-light, neutron are incoming to the LXe detector in beam time
- Ionizing particle or VUV lights interact shallow position (Passivation layer) in MPPC and generate ions
  - The ions may recombine with electrons to vanish the seed of avalanche
- It should be reproduced in Lab. by irradiating ionizing particle or VUV
  - We tried to reproduce it to specify the cause of PDE decrease



Radiation environment



expected dose with 160h MEG II intensity

irradiation source	dose/fluence
γ	0.01 Gy
VUV photon	$4.6\text{–}5.8 \times 10^{10}$ /mm^2
neutron	2.9×10^6 n/cm^2

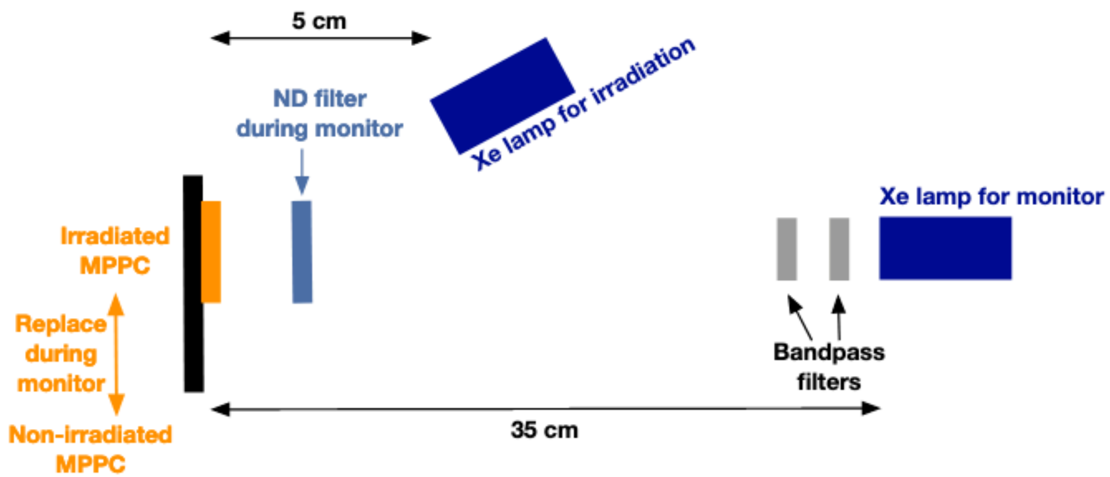
expected dose in 2021
(with ~700h MEG II intensity)

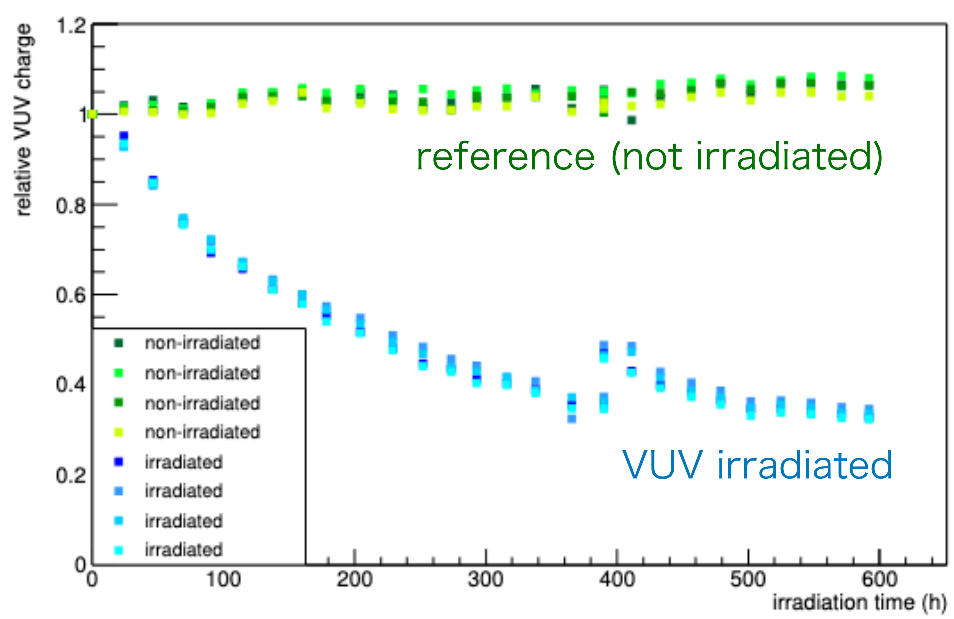
Gamma : 0.04375 Gy
VUV : 2.0-2.5 x 10^{11} /mm^2
neutron : 1.27 x 10^7 n/cm^2

Reproduction of PDE decrease at Lab.

- Radiation damage by VUV-light
  - Irradiation test of VUV-lights both at room temperature and LXe temperature
    - low temperature may enhance the accumulation of the stationary charge

VUV irradiation at room T. (25°C)

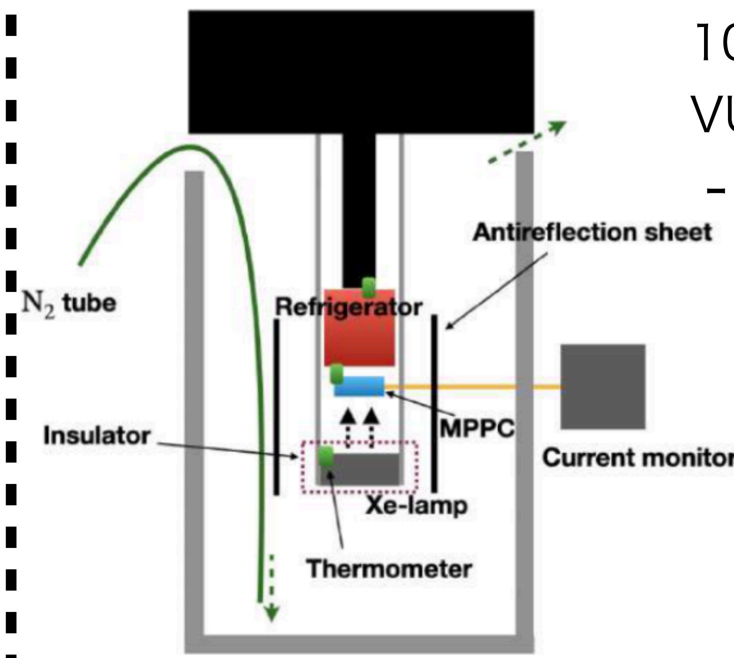


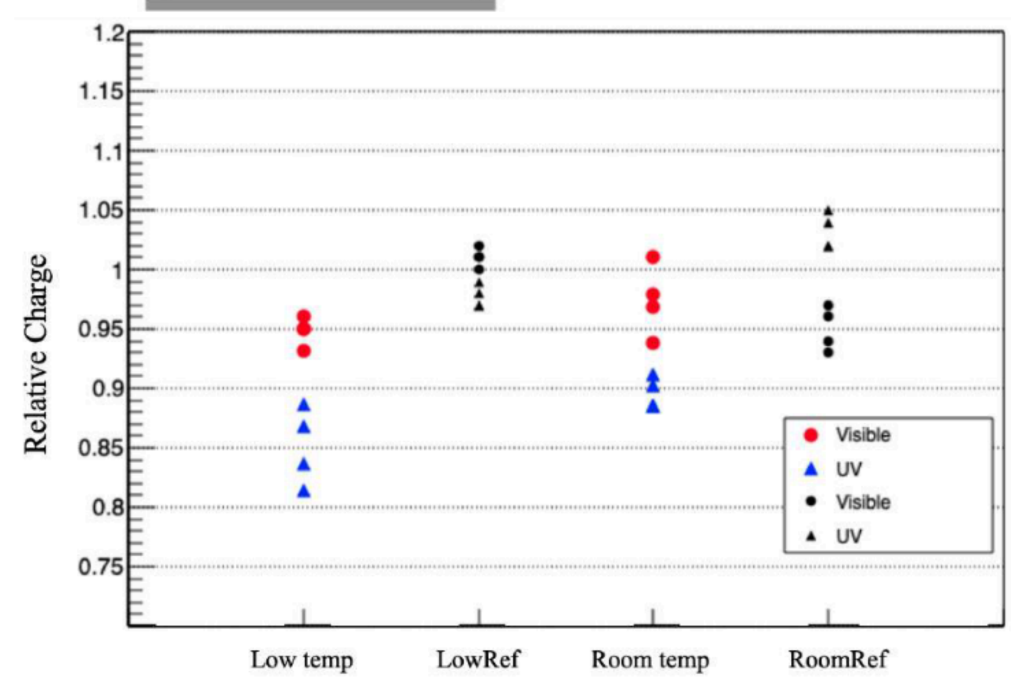


- charge degraded by 65% in total after 3e+16 /mm^2 VUV irradiation
  - Slower by O(10^4) than that in the LXe detector : 9% degradation with 4.6e+10 /mm^2

VUV irradiation at LXe T. (~170K)

- Charge decreased by 10-20% with 1.5e+15 /mm^2 VUV irradiation in total
  - Still slower by O(10^4)

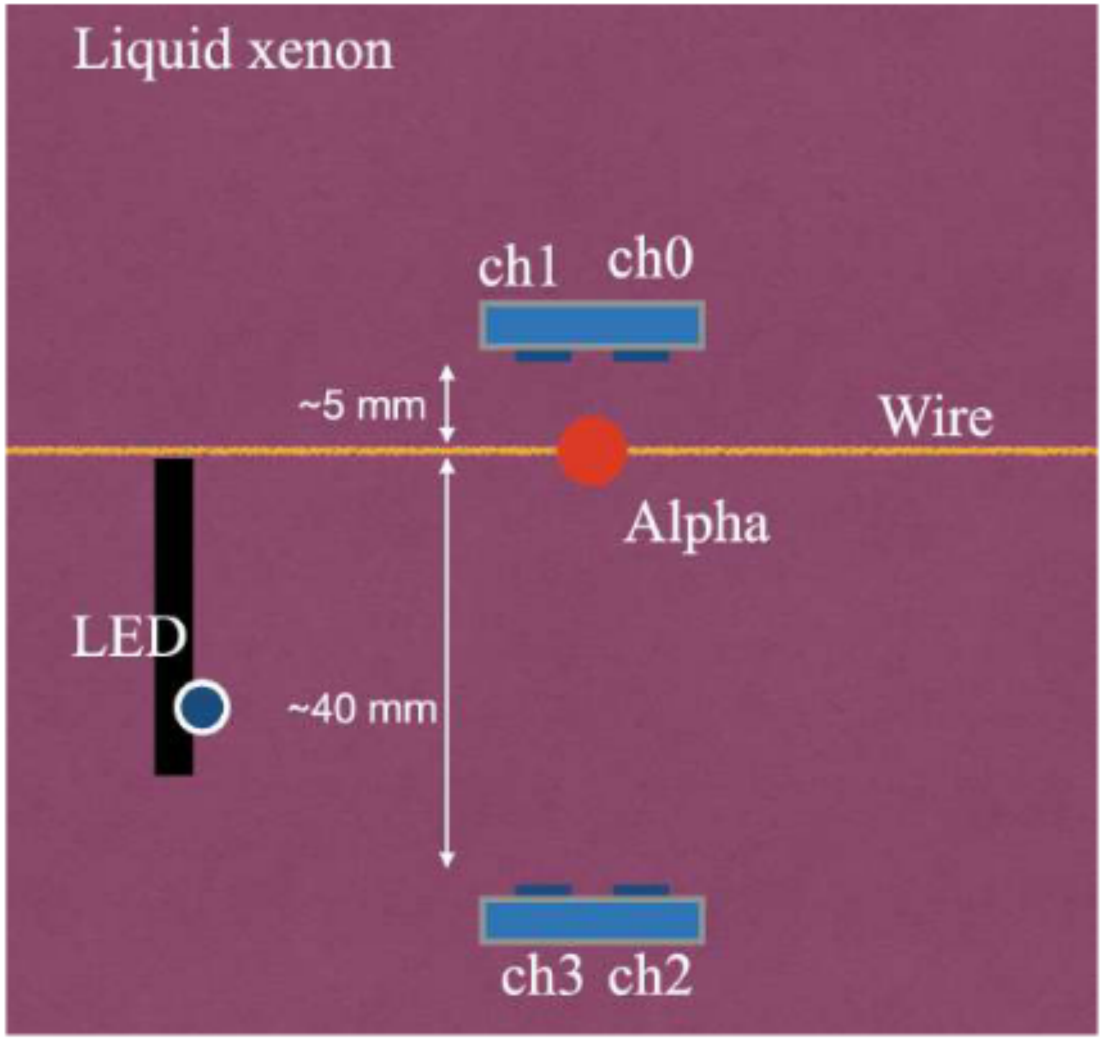




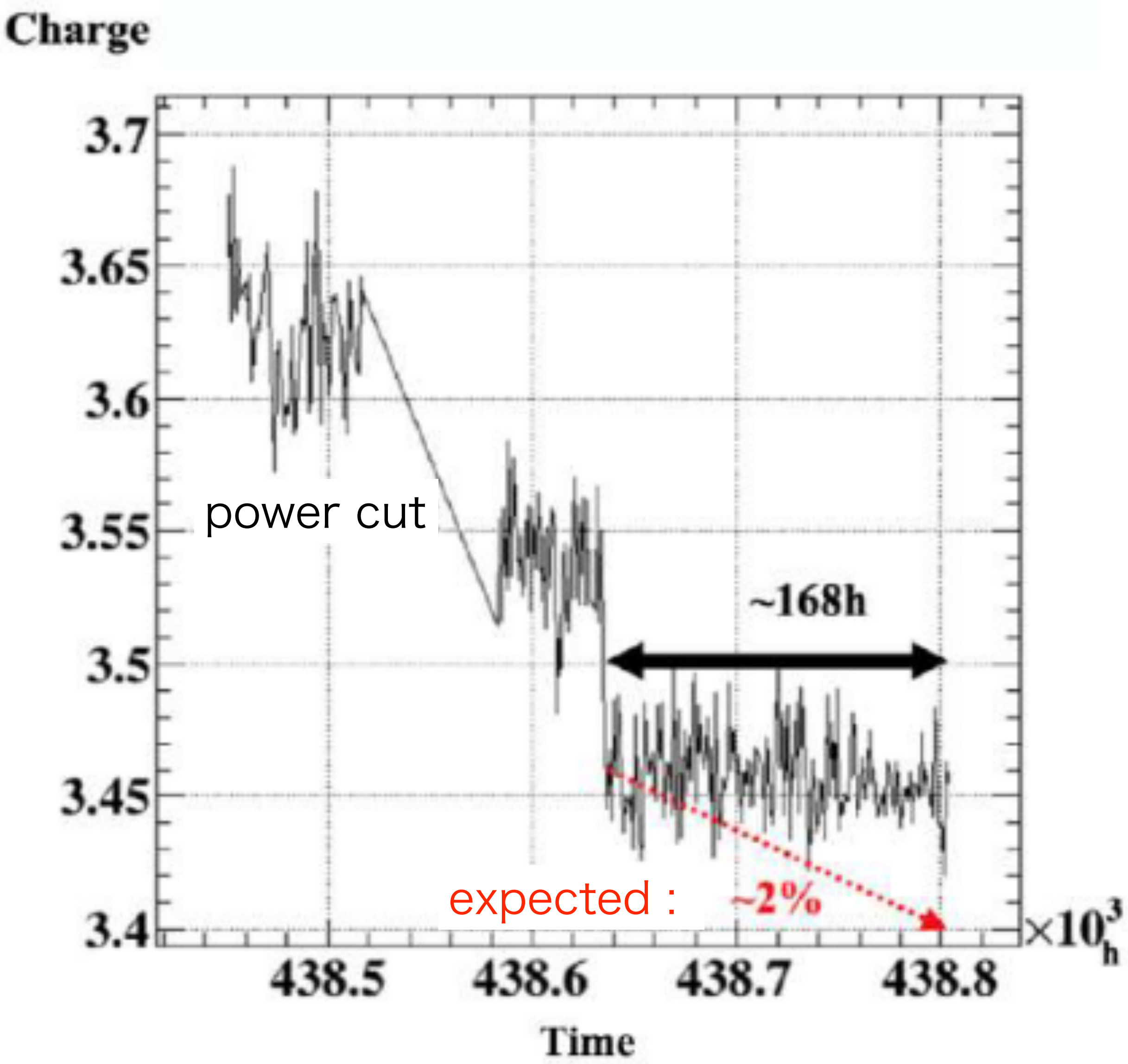
Reproduction of PDE decrease at Lab.

- Radiation damage by VUV-light
  - Scintillation by alpha-ray in LXe was used as light source
    - Exact same wavelength and temperature with the LXe detector
    - HV for MPPC was applied during the irradiation
  - Expected decrease was relatively 2% (w/ 168h dose) but it was not observed

Schematic of setup



Charge history for VUV light

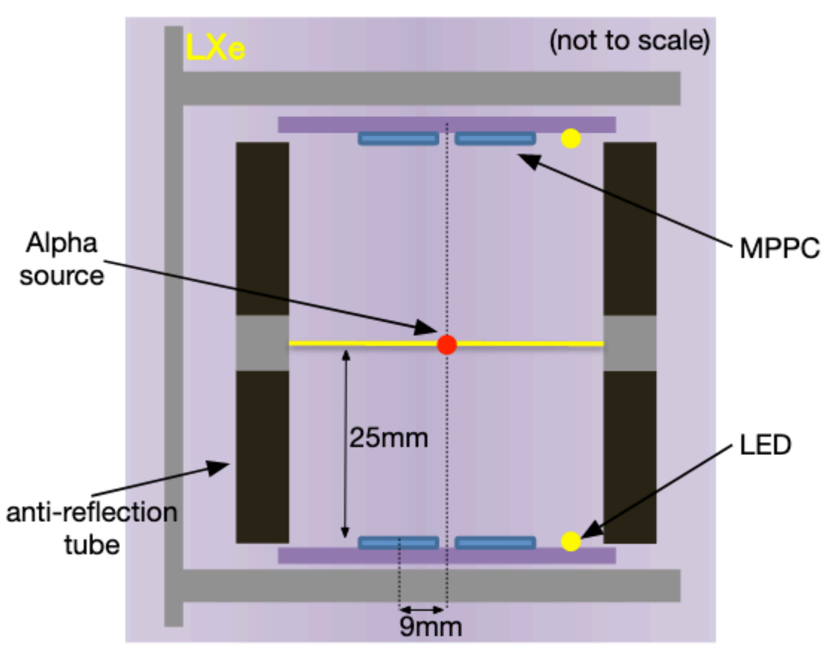


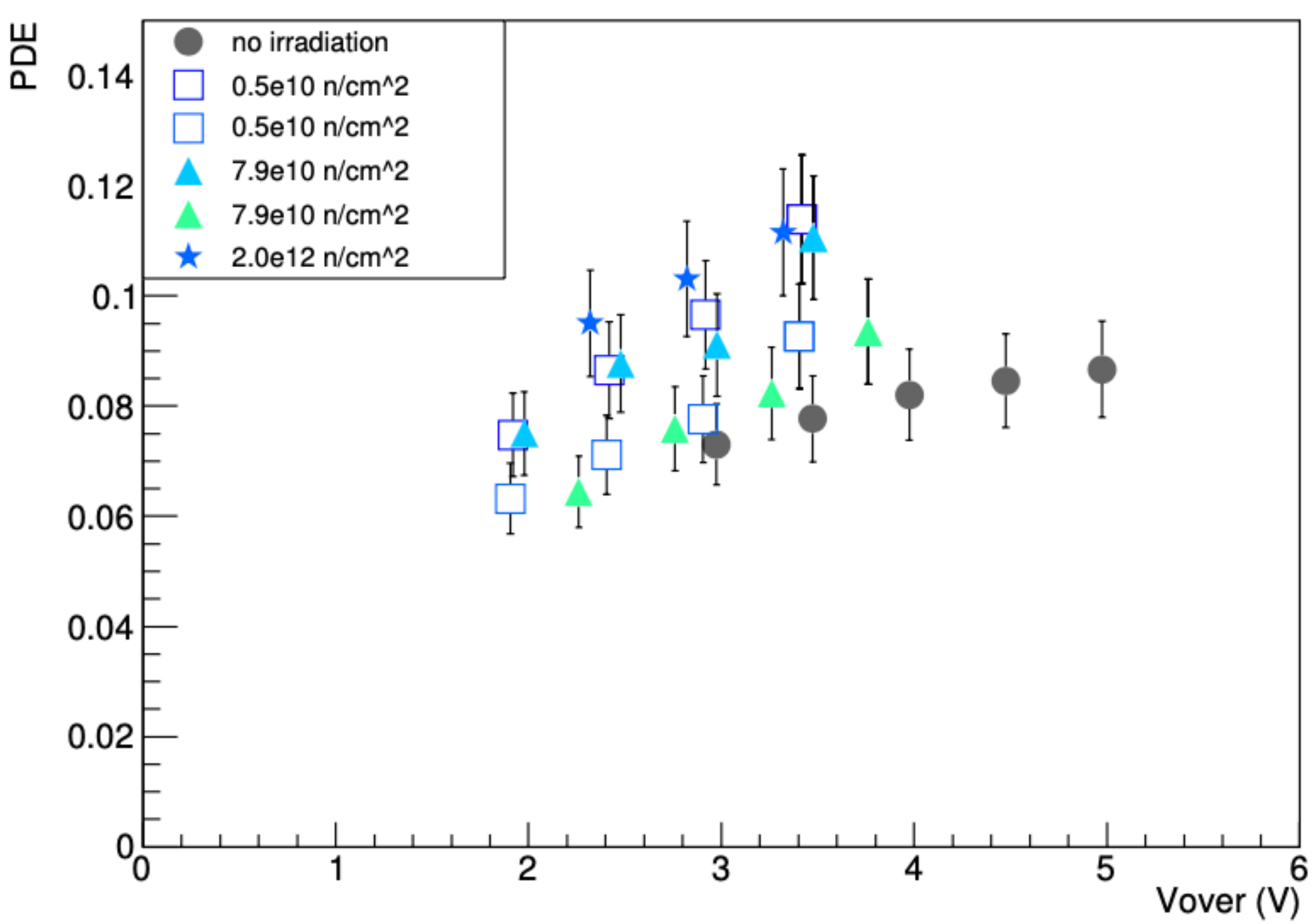
Reproduction of PDE decrease at Lab.

- Radiation damage by neutron
- Neutron irradiation by Tandem electrostatic accelerator at Kobe Univ. in 2015
  - In total, 5e+9 — 2e+12 n/cm^2 irradiation depending on the time and distance
  - No effect of irradiation was observed
  - 4 years gap exists between irradiation and evaluation
    - Annealing effect at room temperature cannot be ignored

- Neutron irradiation in 2015

- PDE was measured in 2019
  - using VUV-light in LXe



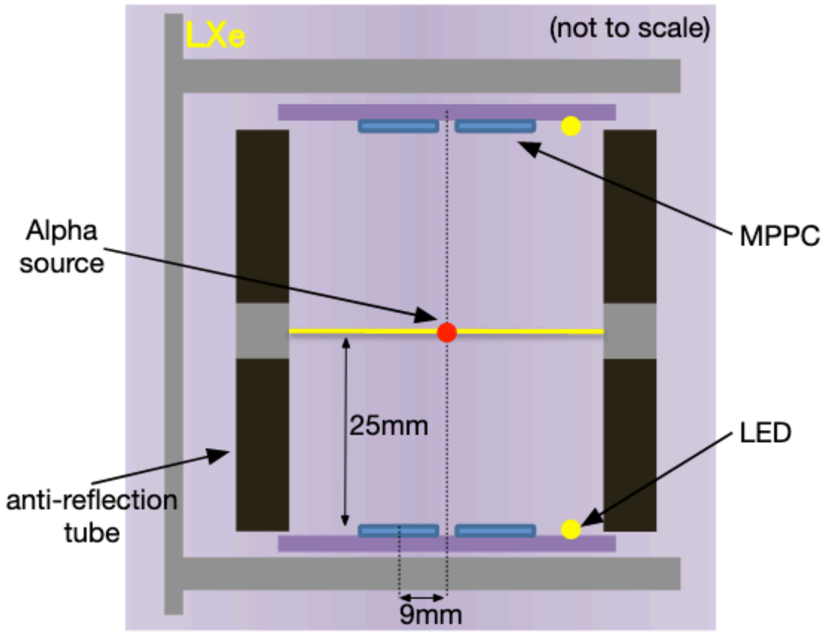


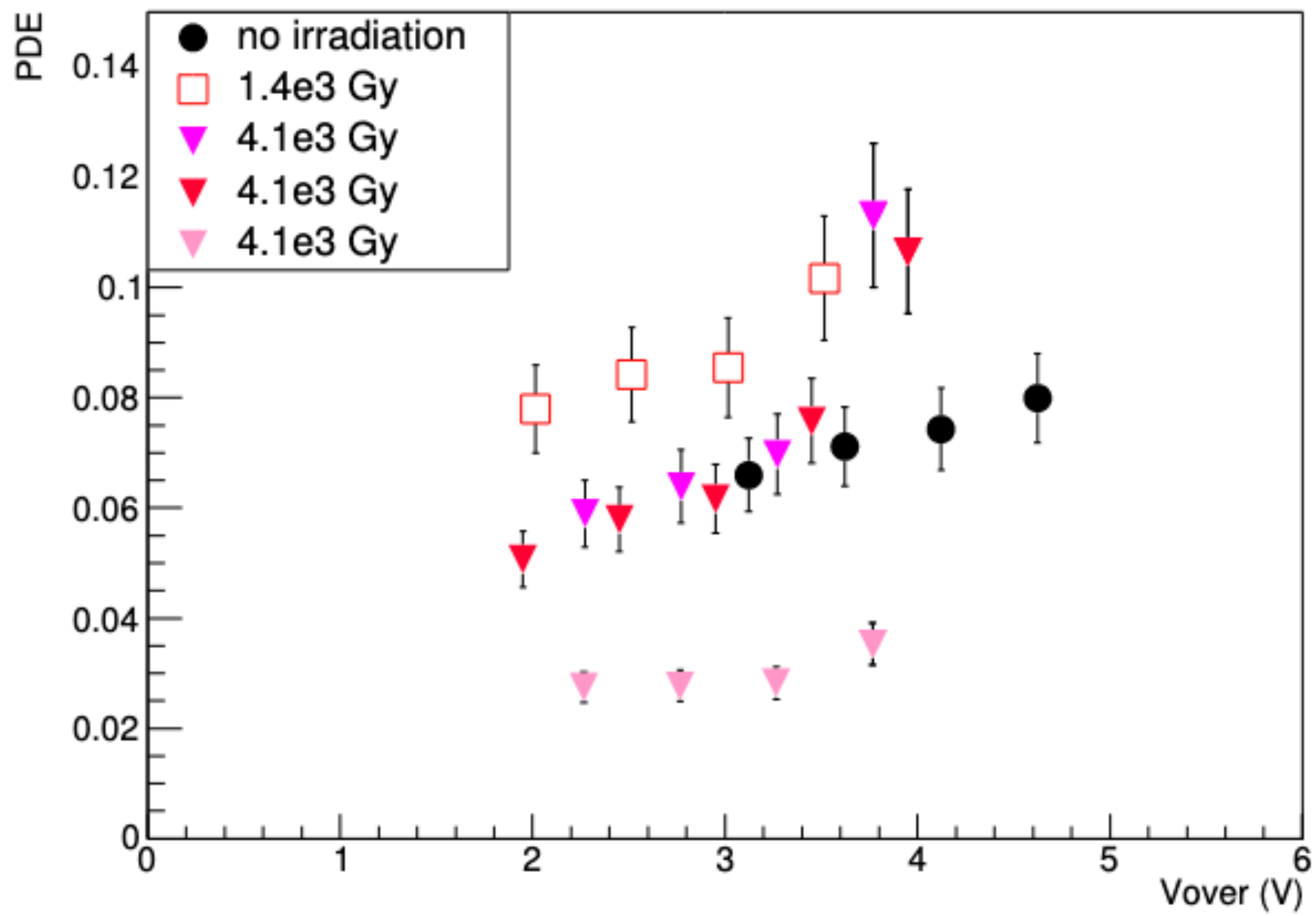
Reproduction of PDE decrease at Lab.

- Radiation damage by gamma-ray
- Gamma-ray in total 4.1e+3 Gy was irradiated and the PDE was evaluated
  - No significant decrease was observed
  - 4 years gap exists between irradiation and evaluation
    - Annealing effect at room temperature cannot be ignored

- Gamma-ray from ^{60}Co (1.1 MeV, 1.3 MeV)
  - In total 4e+3 Gy was irradiated in 2015
  - 0.6 Gy is expected in whole MEG II

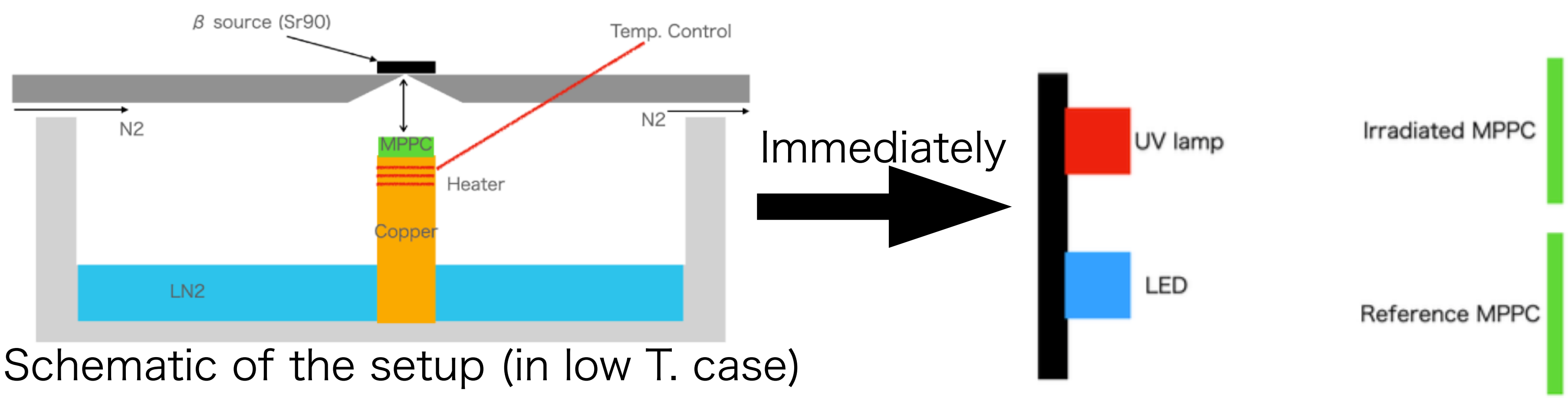
- PDE was measured in 2019
  - using VUV-light in LXe



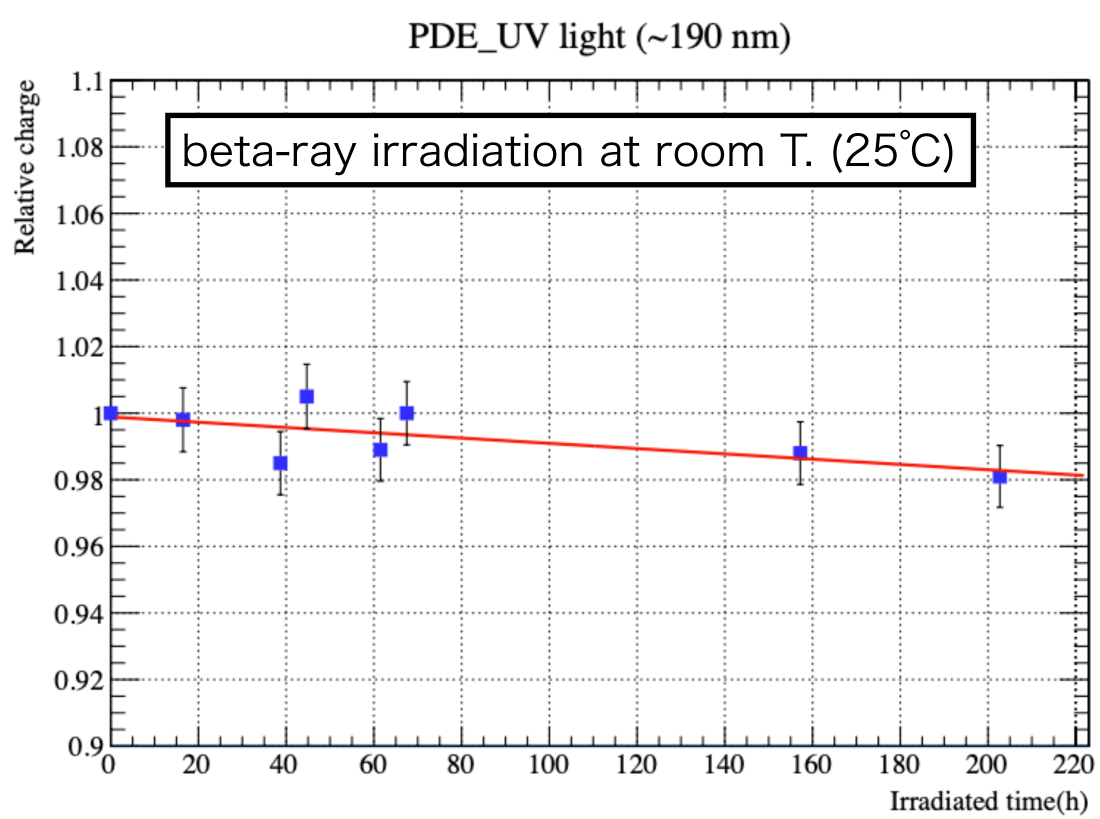


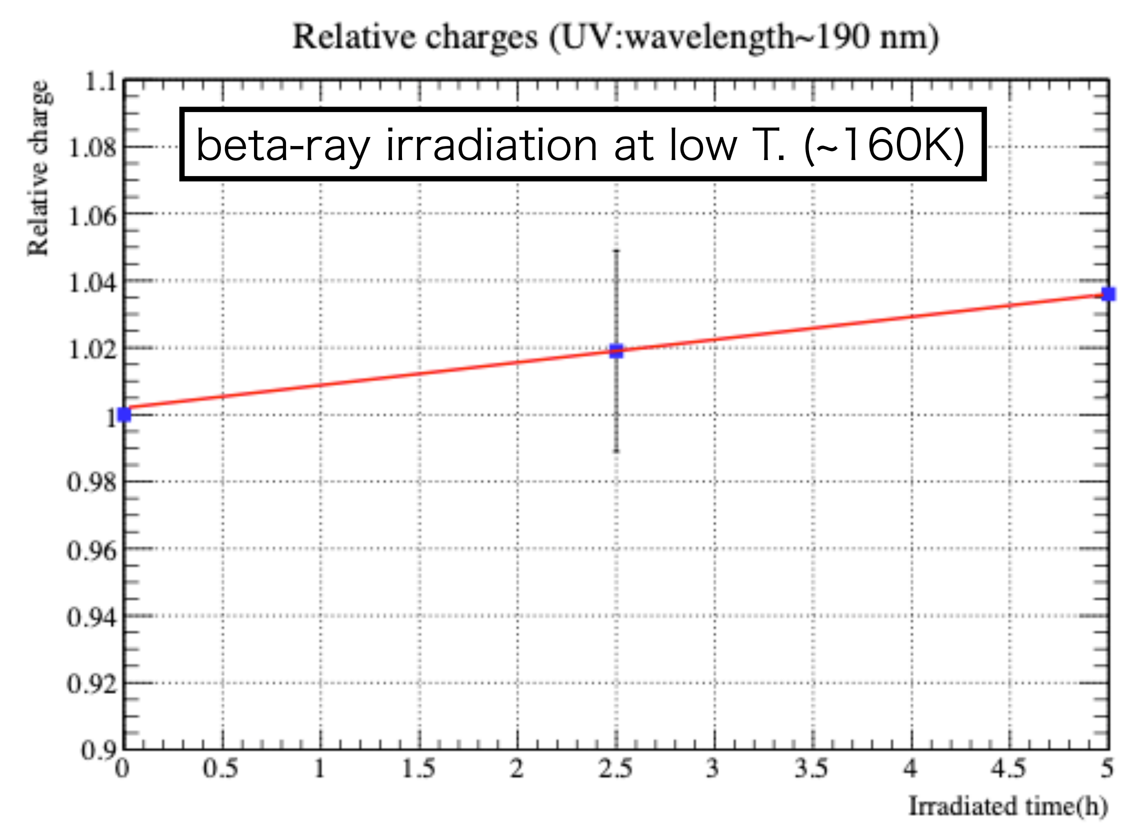
Reproduction of PDE decrease at Lab.

- Radiation damage by gamma-ray was again evaluated using beta-ray source
  - equivalent effect in the charged particle aspect
  - Evaluation both at room T. and low T.
  - Equivalent amount of dose with MEG II 3-year run
  - PDE decreases were not observed



Schematic of the setup (in low T. case)

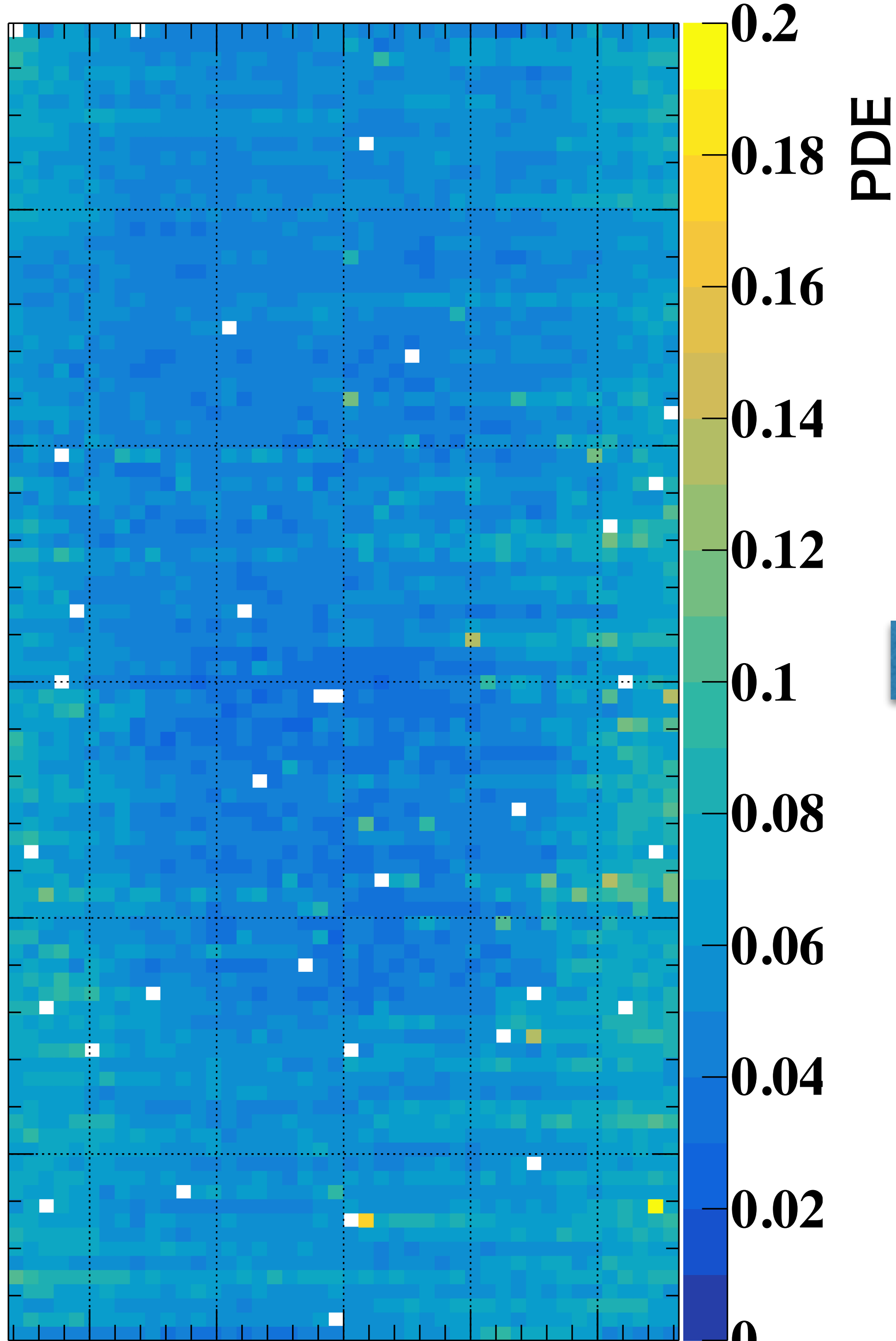




PDE recovery : Evaluation of the recovery

- PDE value before/after the annealing (Hot water and Joule)
- Calculated using alpha-ray data with liquid xenon filling (VUV-light)

PDE map at the end of 2021 run



PDE map after the annealing