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VUV-sensitive MPPC used in the liquid xenon detector for MEG II experiment

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on behalf of the MEG II collaboration
The University of Tokyo

6th International Workshop on New Photo-Detectors (PD24)
Nov 19–22, 2024 Vancouver, Canada

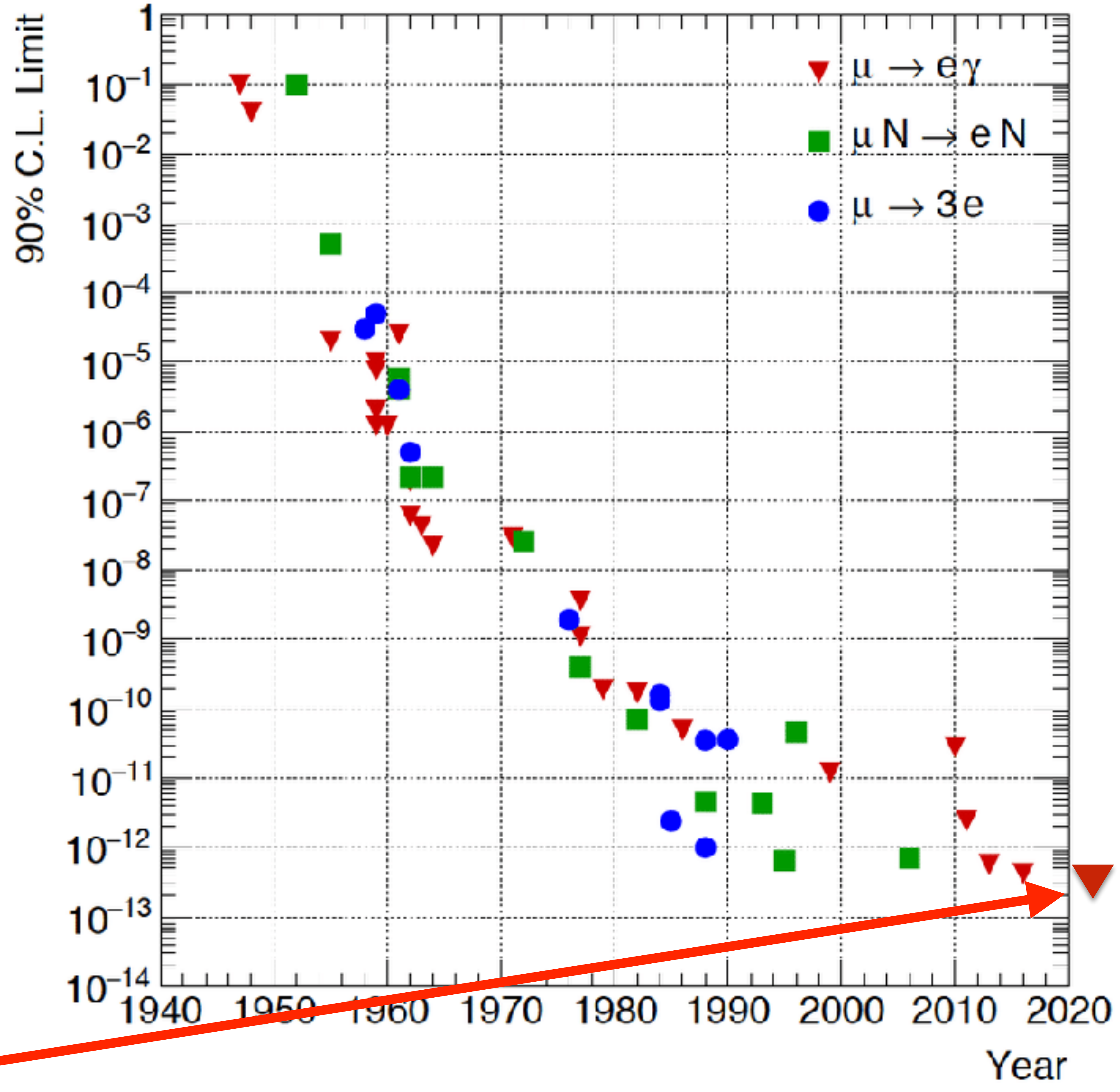
$\mu^+ \to e^+\gamma$

Charged lepton flavor is well conserved in any observations

Prediction from the standard model with neutrino oscillation Br$(\mu \to e\gamma) \sim 10^{-54}$

Discovery of CLFV decay $\mu \to e\gamma$ is clear evidence of BSM physics

- Current best limit:



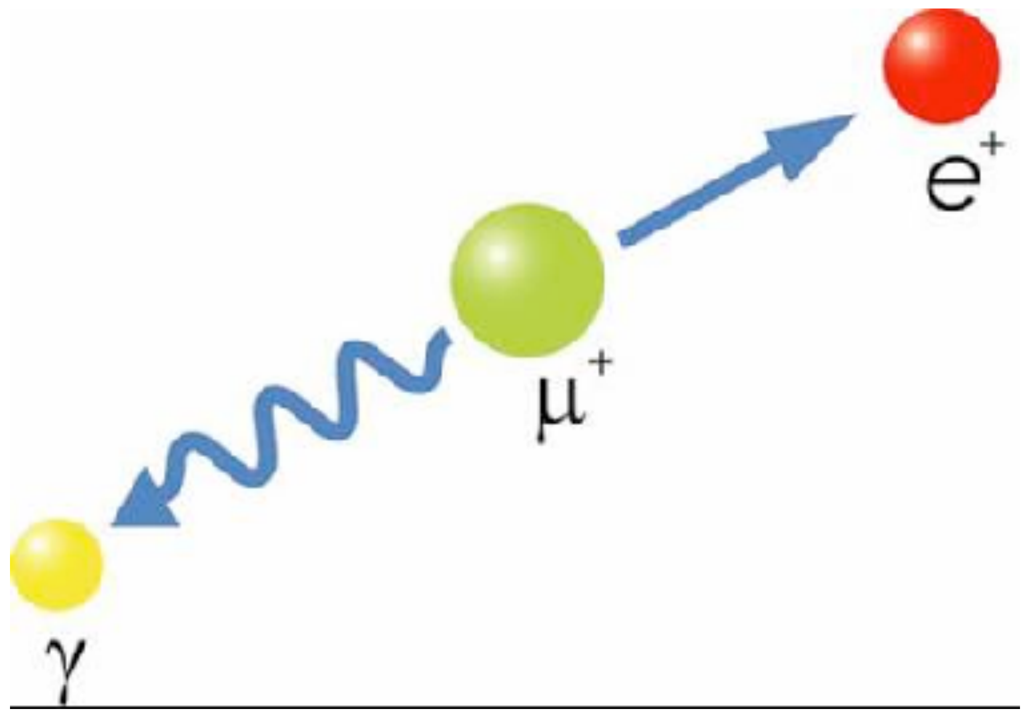
MEG II experiment in 2024

Br$(\mu \to e\gamma) < 3.1 \times 10^{-13}$ at 90%CL

(EPJC 84, 216 2024)

$\mu^+ \to e^+\gamma$ signal & background

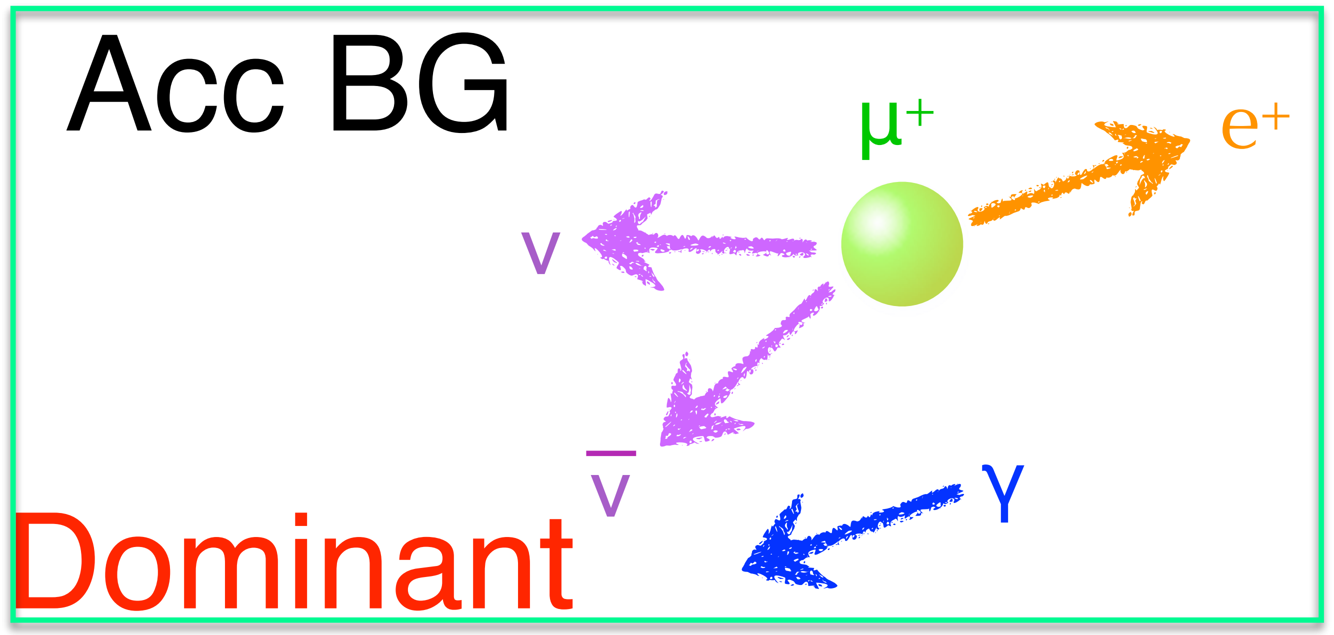
- $\mu \to e\gamma$ signal

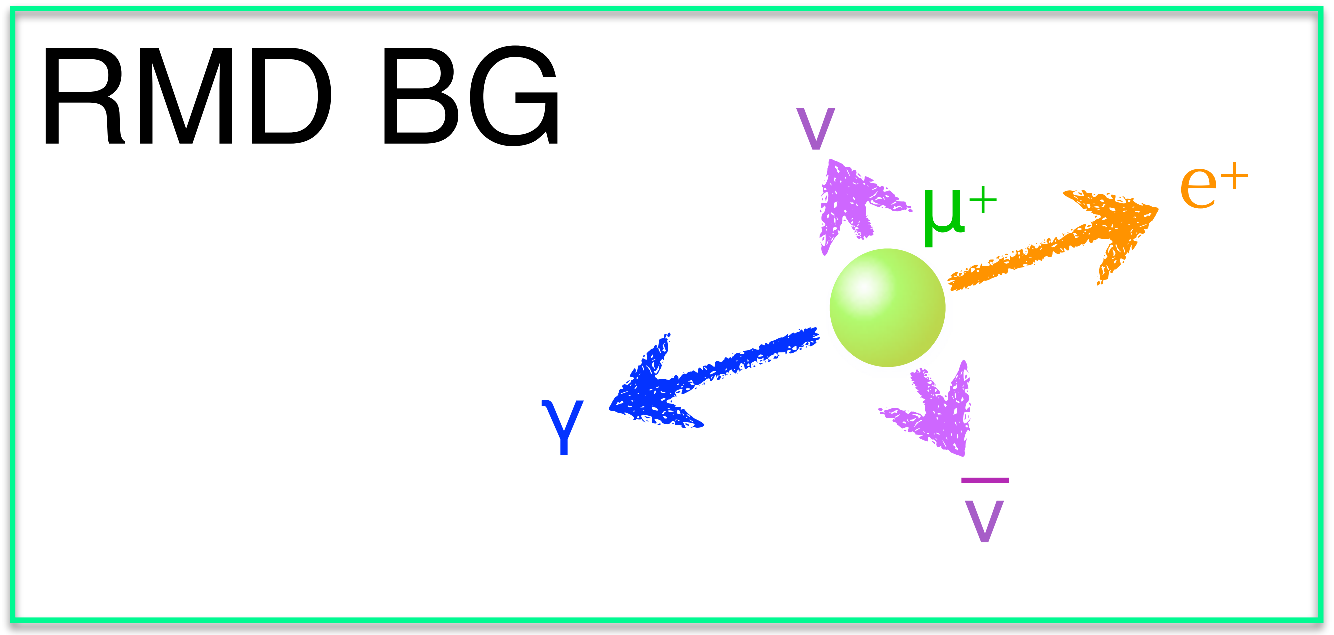


$$E_\gamma, E_e \sim 52.8\ MeV$$

$$\Theta_{e\gamma} = 180°, T_\gamma = T_e$$

- Background
  - Accidental background is our dominant source





$$N_{Sig} \propto R_\mu \times T \times Br(\mu \to e\gamma) \times \varepsilon$$

Efficiency crucial for statistics

$$N_{BG} \propto R_\mu^2 \times \boxed{\Delta E_\gamma^2} \times \Delta E_e \times \Delta\Theta_{e\gamma}^2 \times \Delta t_{e\gamma} \times T$$

Beam rate

Resolutions

Elapsed time

Good resolution crucial to lower the accidental background (N_{BG})

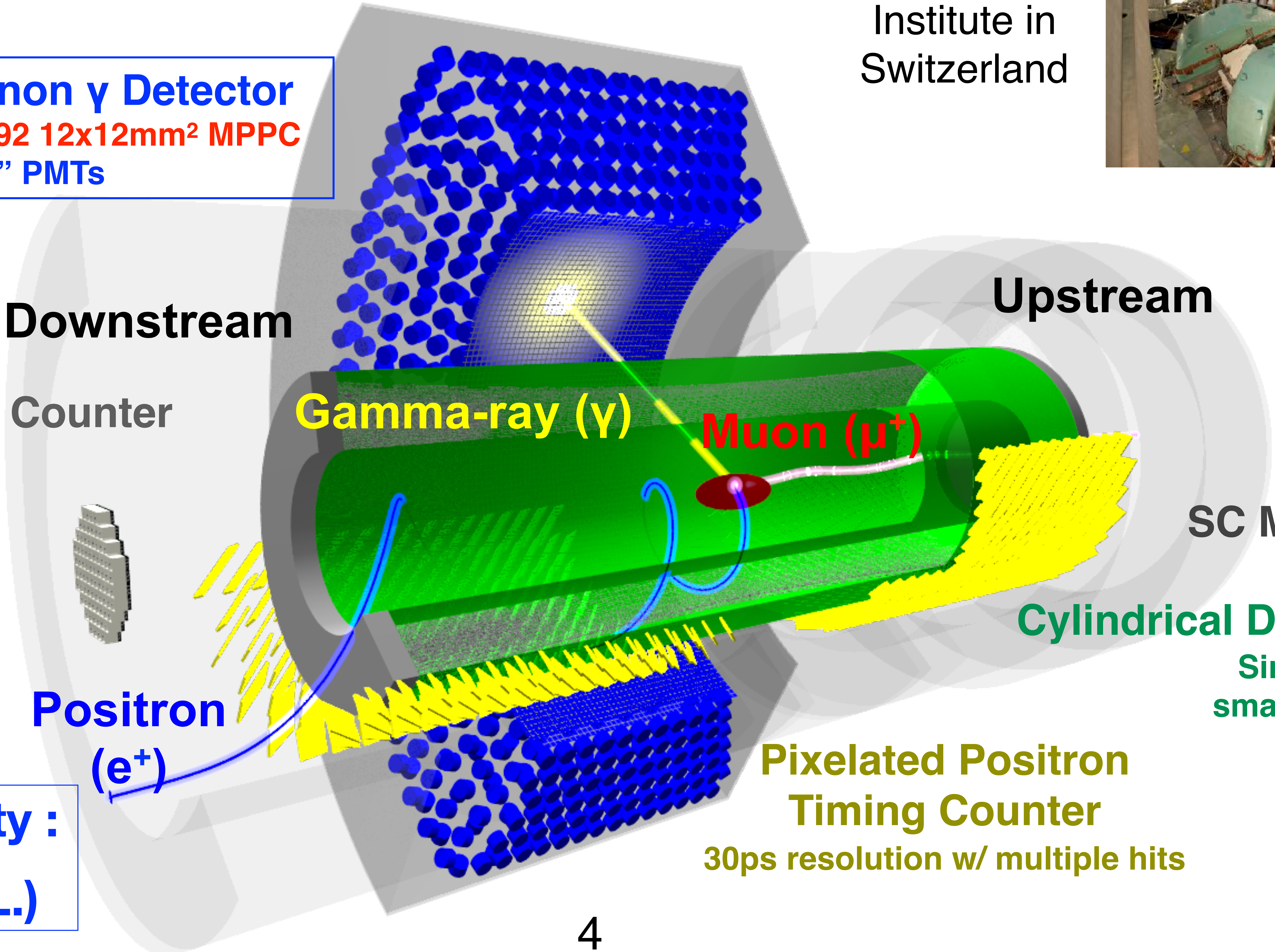
MEG II Experiment

900 l Liquid Xenon γ Detector
w/ VUV-sensitive 4092 12x12mm^2 MPPC
+ 668 2" PMTs

Paul Scherrer
Institute in
Switzerland

590 MeV
2.4mA proton
ring cyclotron

muon rate:
4x10^7/s



Radiative Decay Counter

Further reduction
of radiative BG

SC Magnet

Cylindrical Drift Chamber

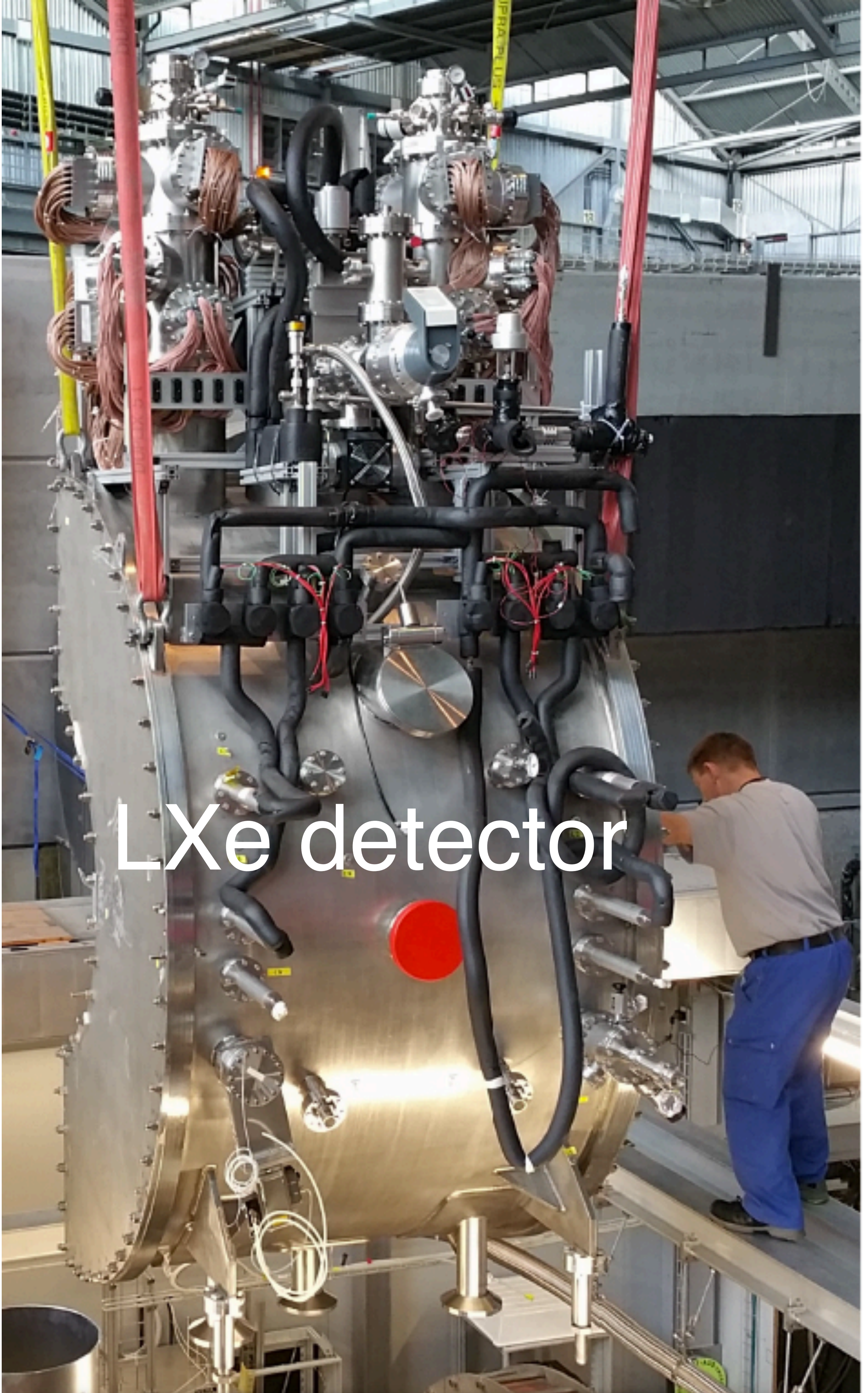
Single volume
small stereo cells
more hits

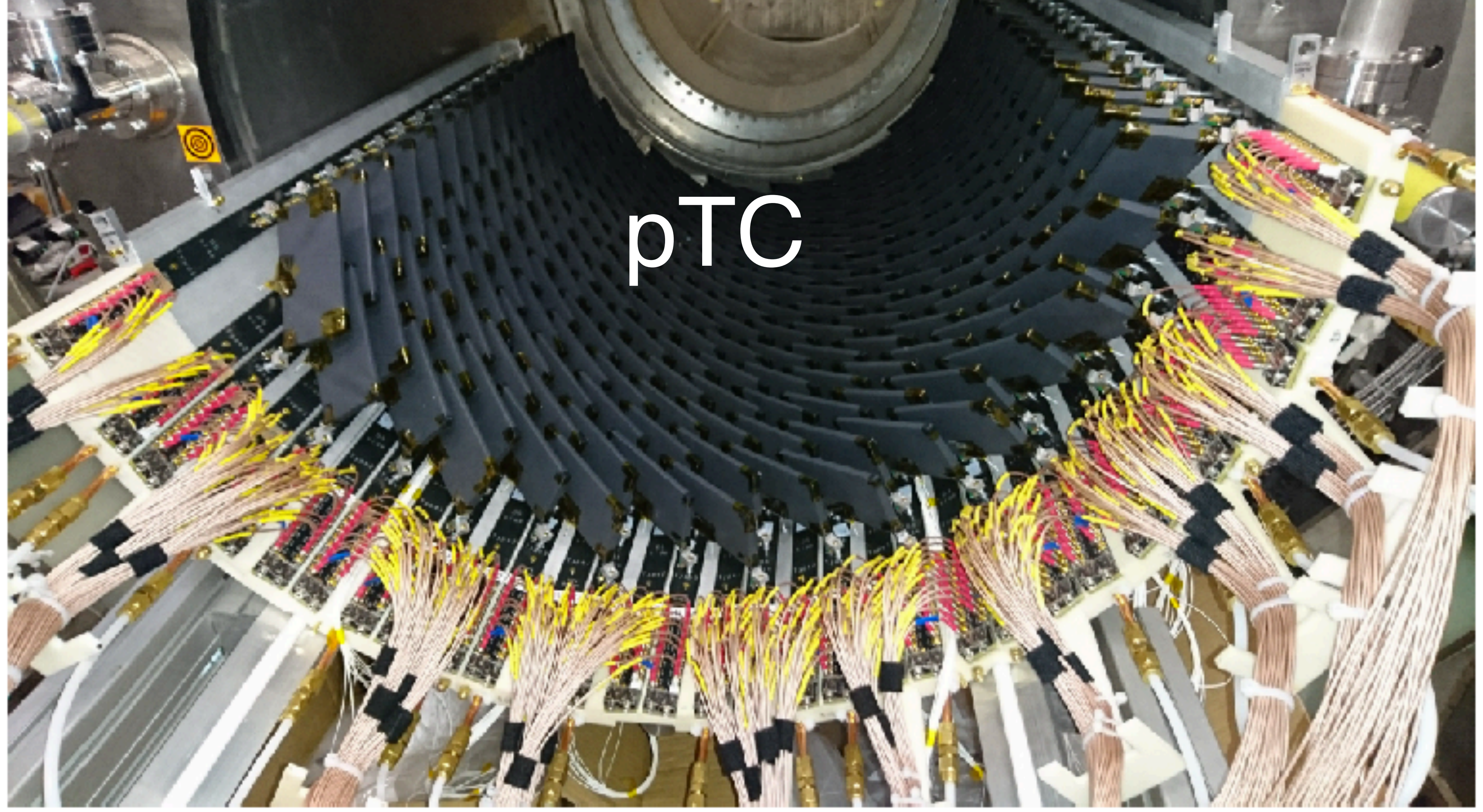
×2 resolution
everywhere

Pixelated Positron
Timing Counter

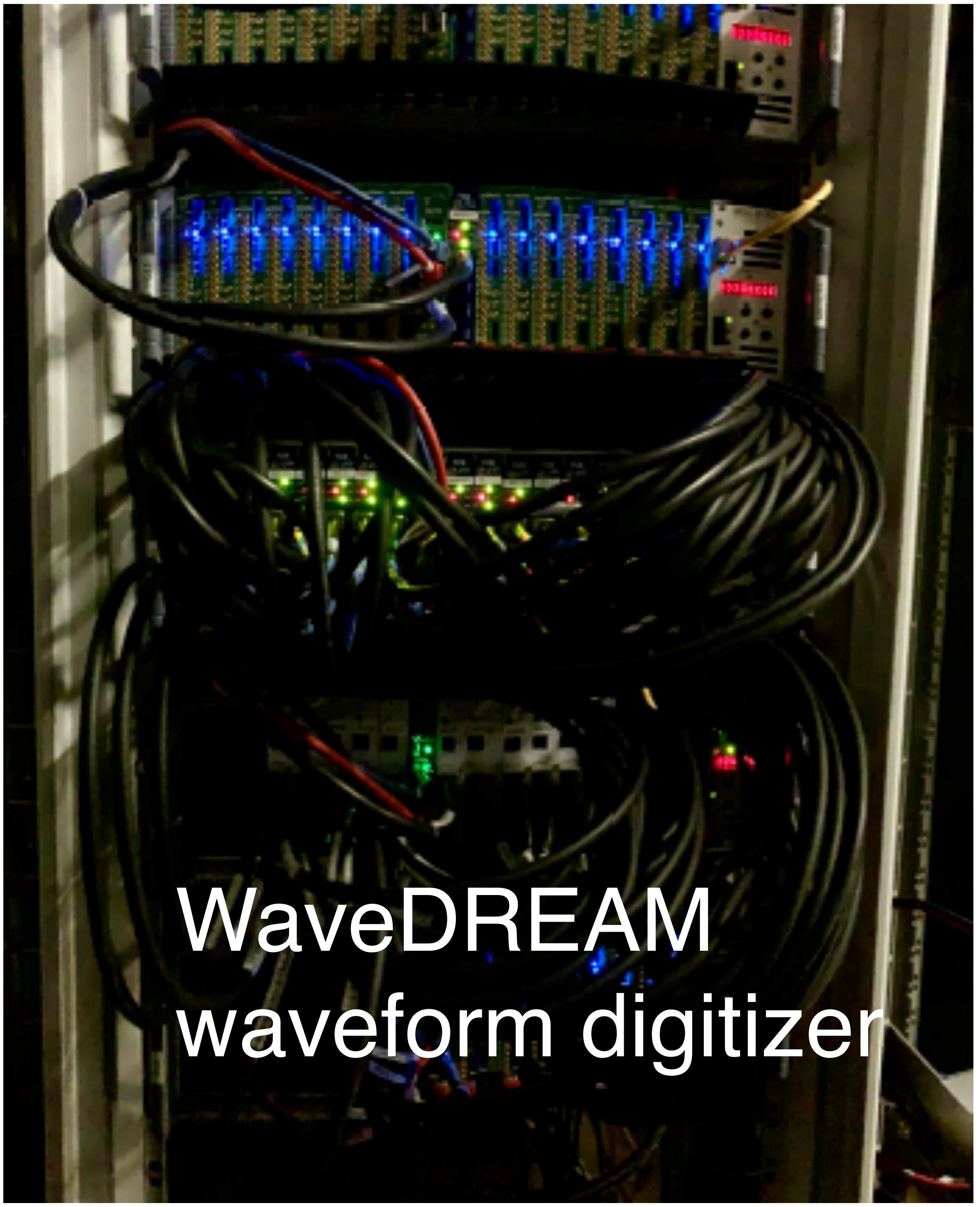
30ps resolution w/ multiple hits

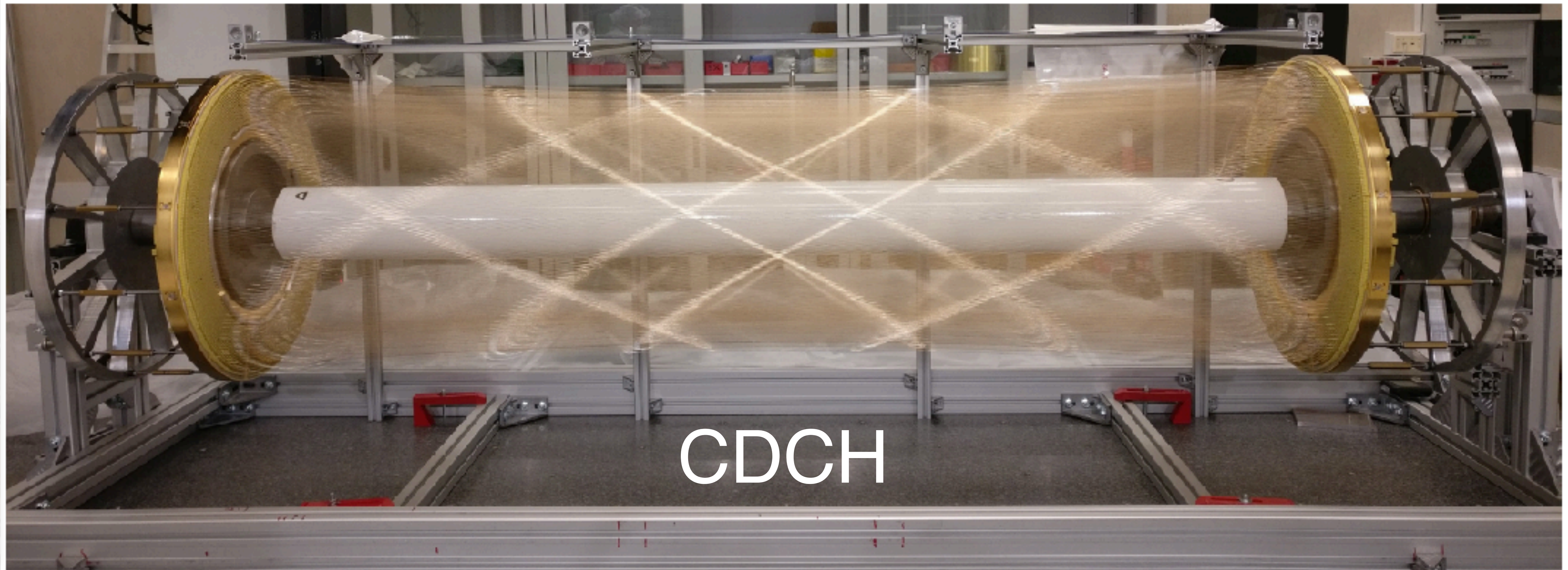
Target sensitivity :
6×10^{-14} (90%C.L.)

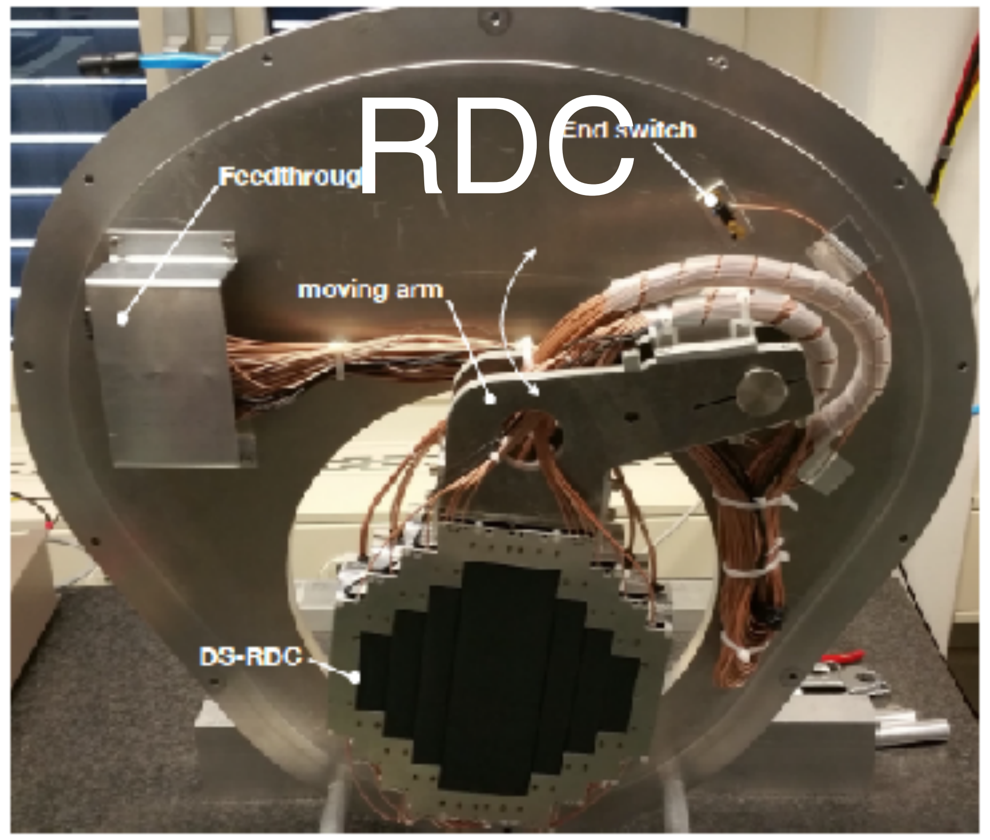




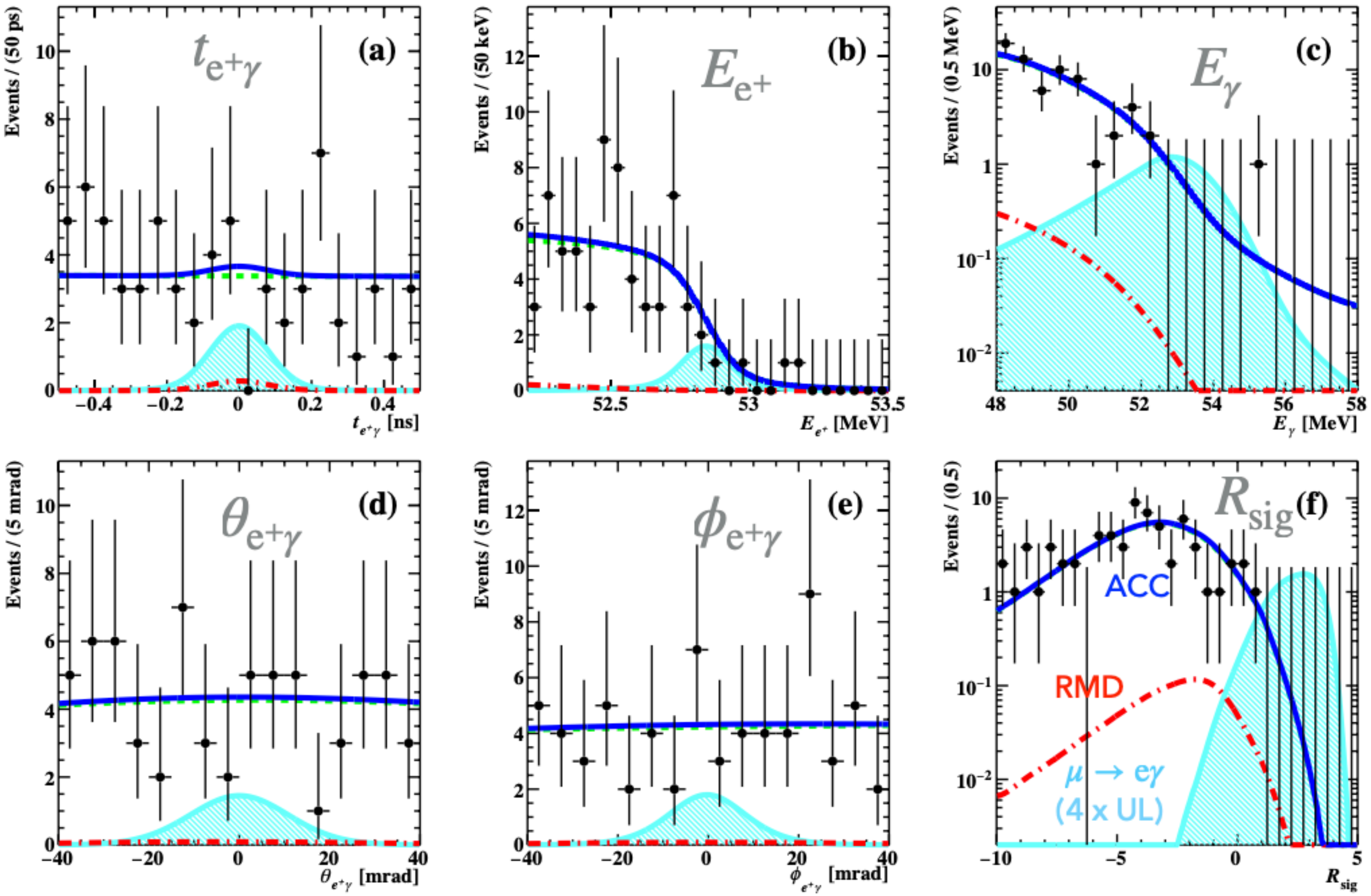
MEG II proposal 2013
Detector R&D 2012-2015
Construction in 2015-2020
Commissioning and physics run 2021-







Data & fit results



Maximum likelihood analysis to estimate $N_{\rm sig}$

- **Signal** and **RMD** PDFs from σ meas.
- **Accidental BKG** PDFs from sideband data

No excess was observed with the first 7-week data in 2021

Combined result of MEG and MEG II 2021 provides the most stringent limit on the Branching ratio $\mathscr{B}(\mu \to e\gamma) < 3.1 \times 10^{-13}$

(f) Relative signal likelihood

$$R_{\rm sig} = \log_{10}\left(\frac{S(x_i)}{f_{\rm RMD}R(x_i) + f_{\rm ACC}A(x_i)}\right)$$

$$f_{\rm RMD} = 0.02,\ f_{\rm ACC} = 0.98$$

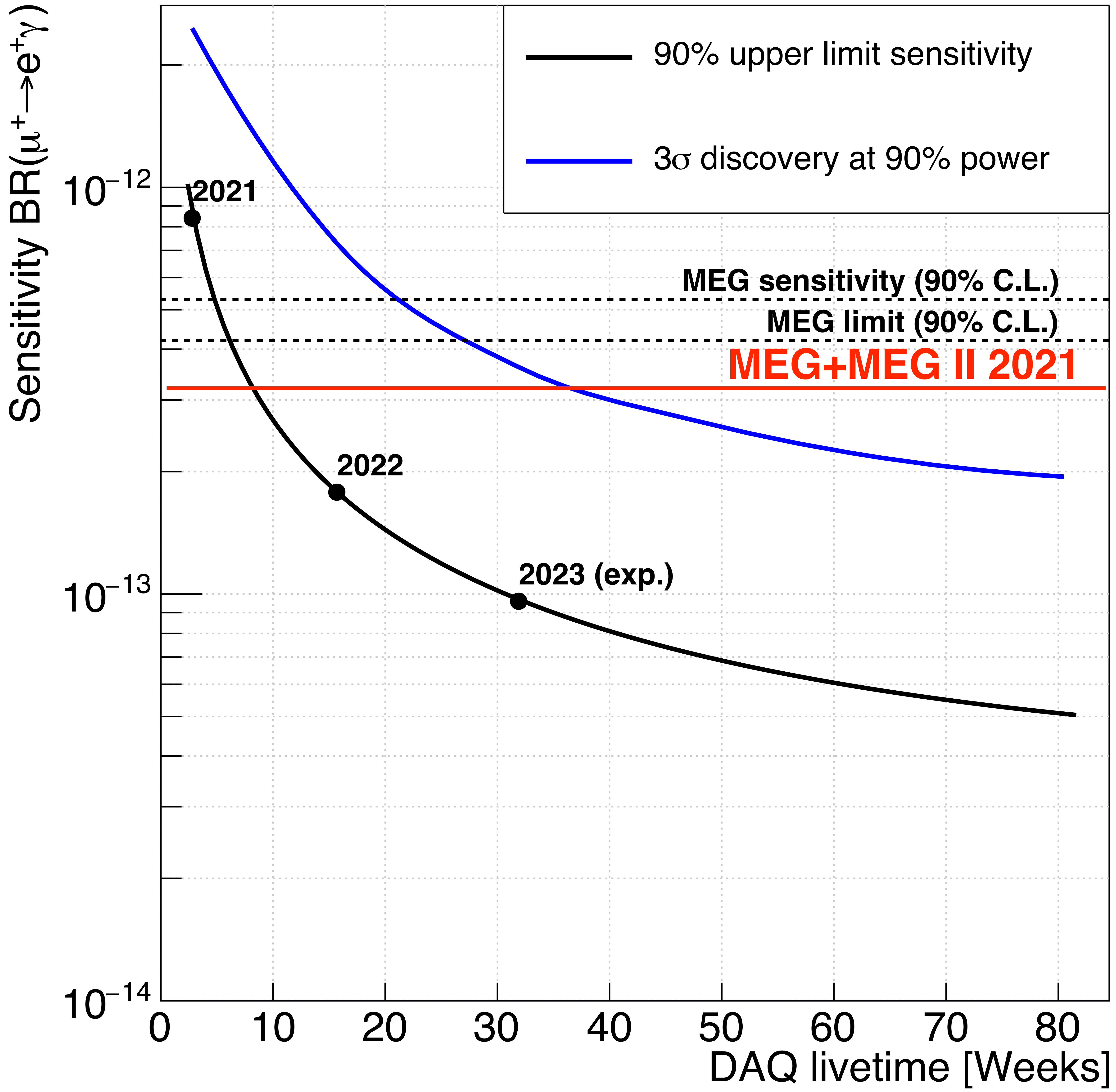
MEG II prospects

MEG II experiment will accumulate the physics data until 2026

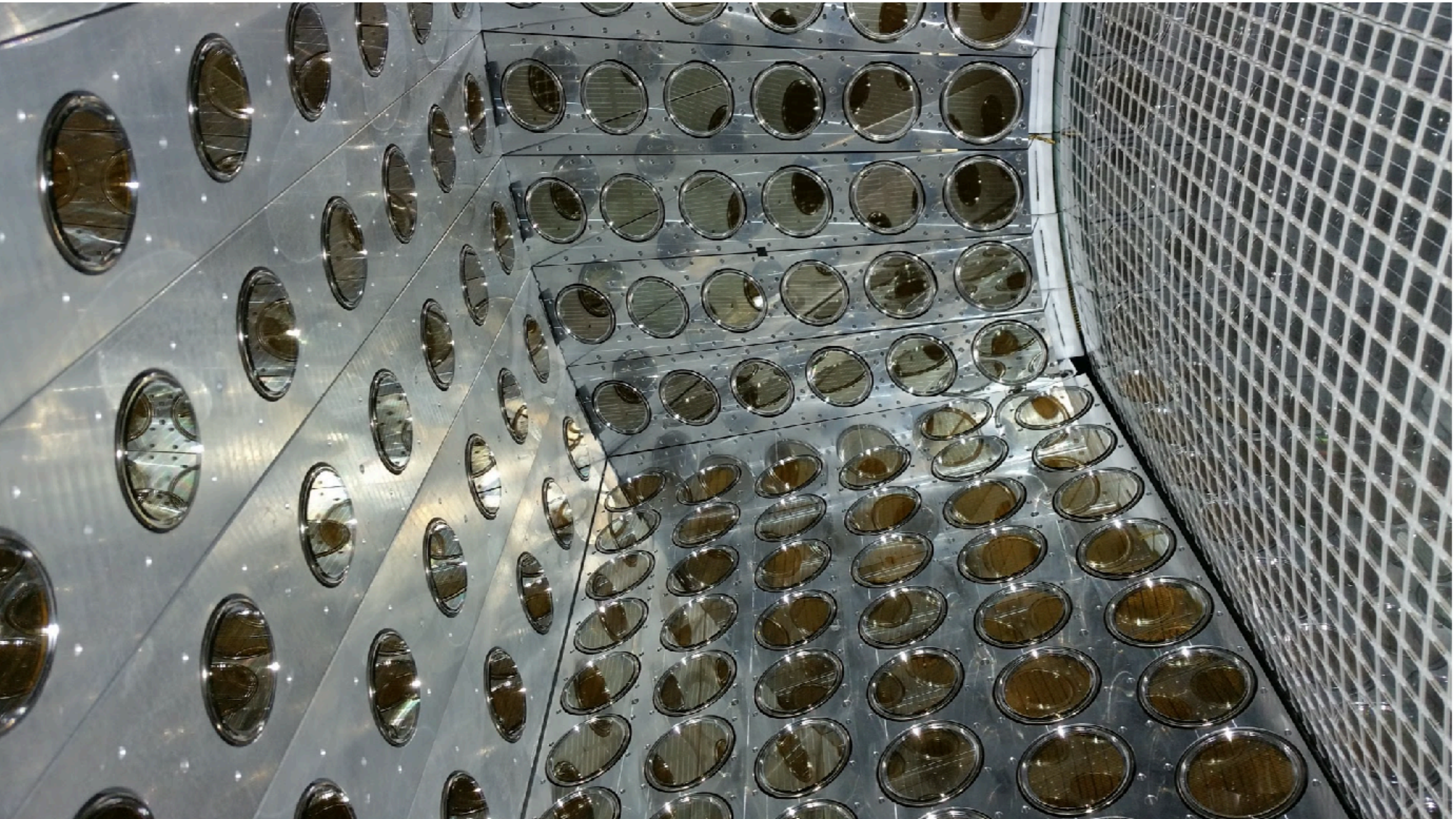
- The PSI accelerator will be in shutdown from 2027 due to an beam line upgrade plan (HiMB) up to 10^{10} μ/s

The target sensitivity of the MEG II: Br(μ→eγ)~(5–6)×10^{-14} @90%C.L.

In parallel, 2022 analysis is ongoing. The results will be published soon better sensitivity than MEG



MEG II Liquid Xenon Detector and MPPC



MEG II Liquid Xenon Detector and MPPC

Position, timing, energy measurements of 52.8 MeV γ

- C-shape to fit the superconducting magnets

900 L Liquid Xenon

Homogeneous

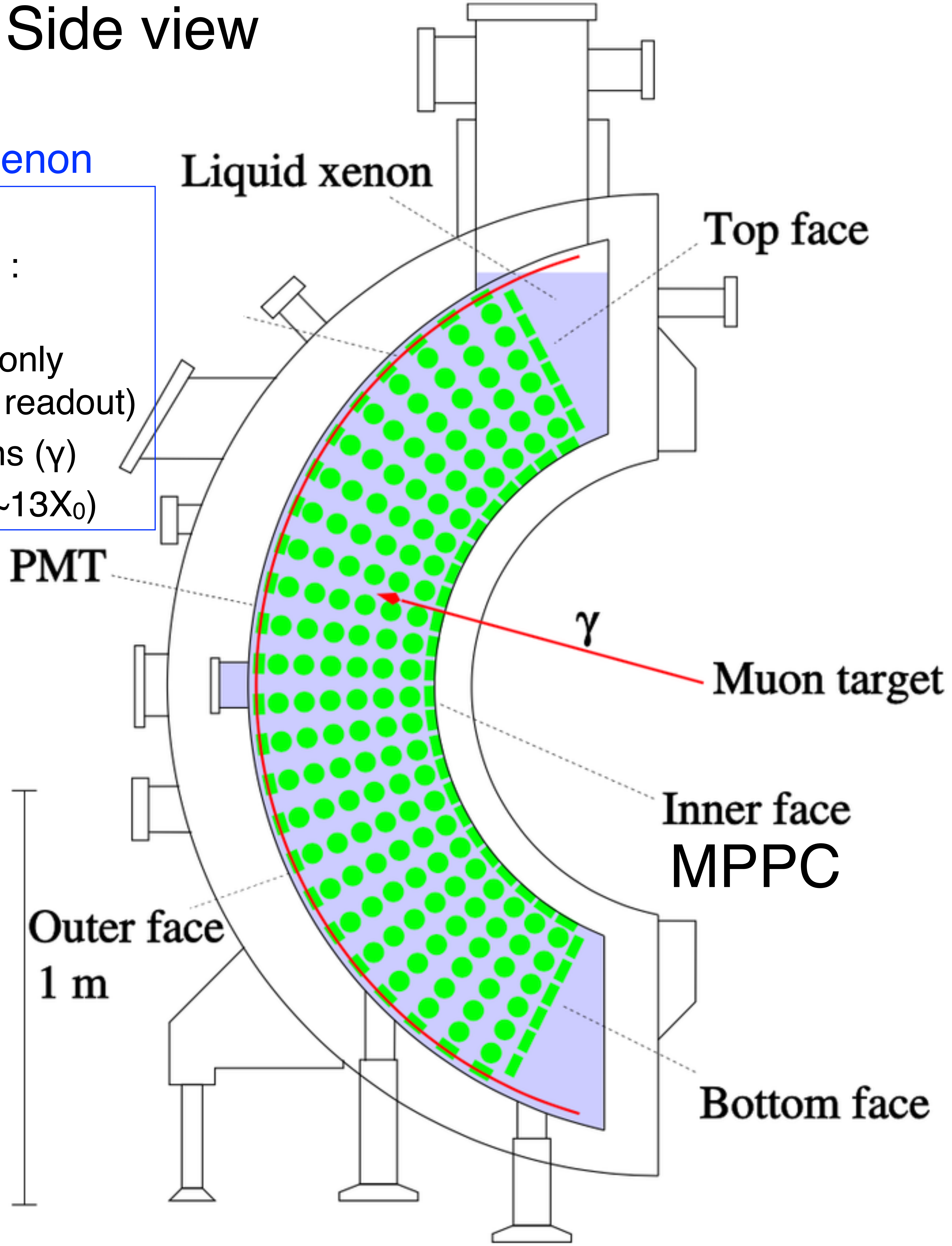
Heavy (3 g/cm^3) : high γ efficiency

High light yield (only scintillation light readout)

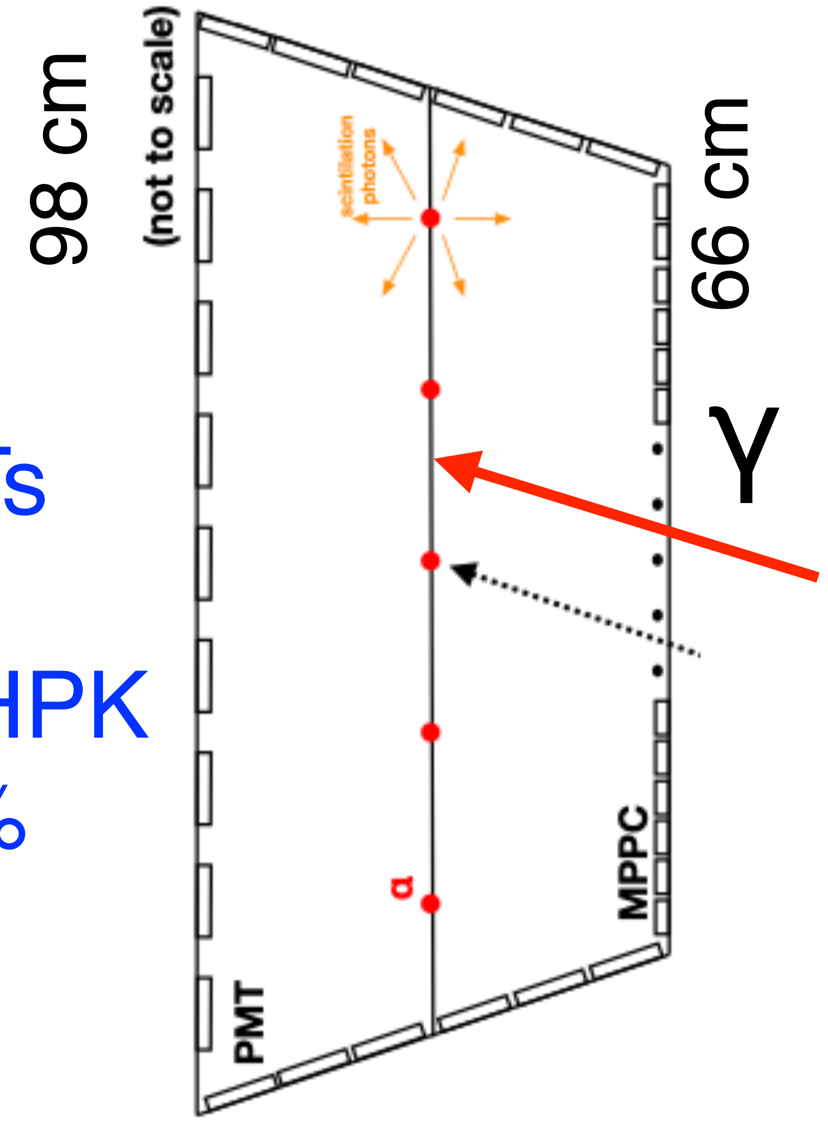
decay time : 45ns (γ)

Depth 38.5cm (~13X_0)

Side view



Top view



Thin entrance window

for γ (honeycomb structure) : 0.075X_0
66 cm (horizontal) × 140 cm (arc)

668 PMTs
51mmϕ
R9869 by HPK
QE~15%

4092 MPPCs (S10943-4372)
15×15mm^2 by HPK

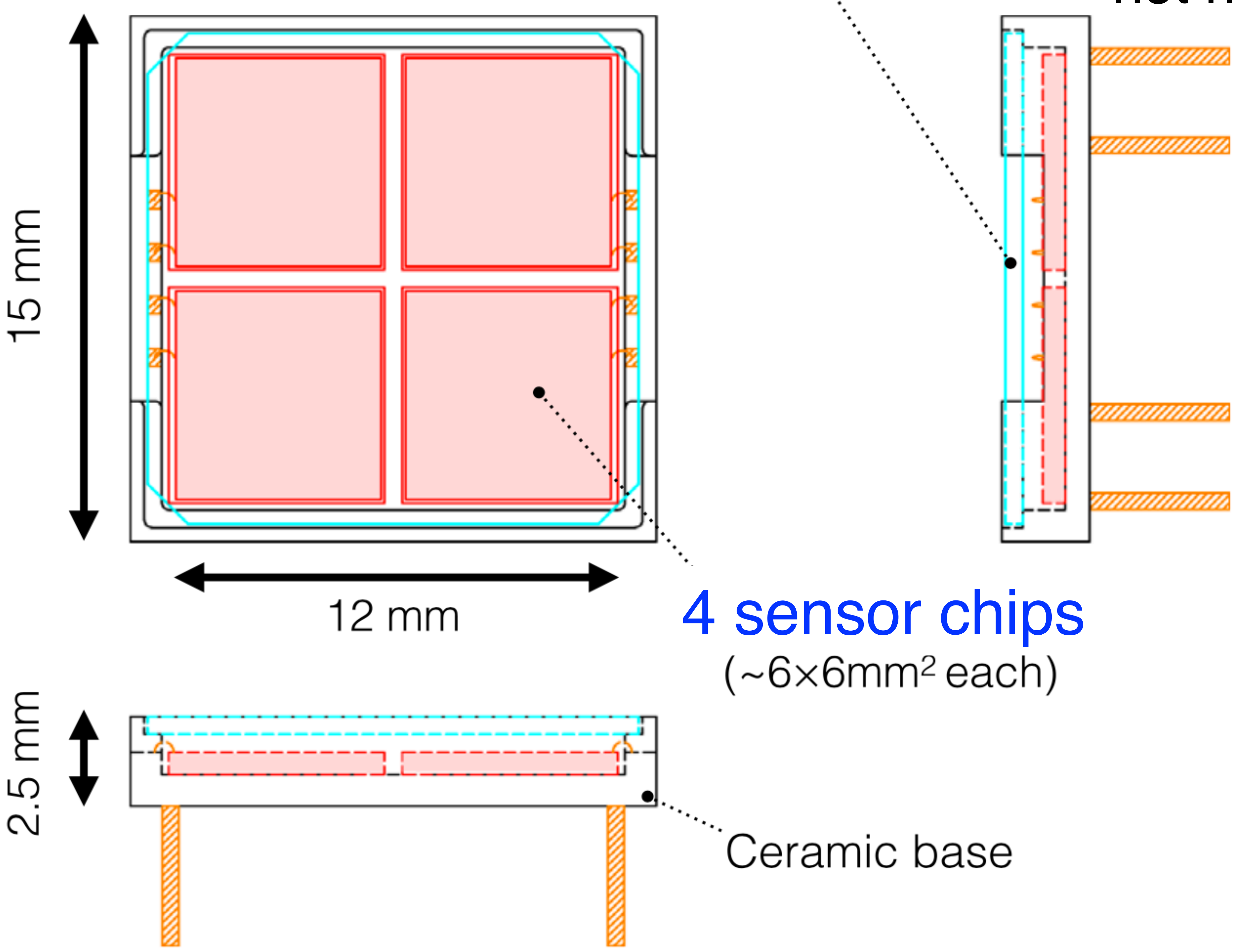
immersed in LXe (0.029X_0 from MPPC)

Sensitive to VUV-light (175nm)

Operational at 165K

All the waveforms are recorded by WaveDREAM (DRS4)

MPPC (SiPM) for MEG II LXe detector



Quartz window (0.5 mm^t) for protection not hermetic

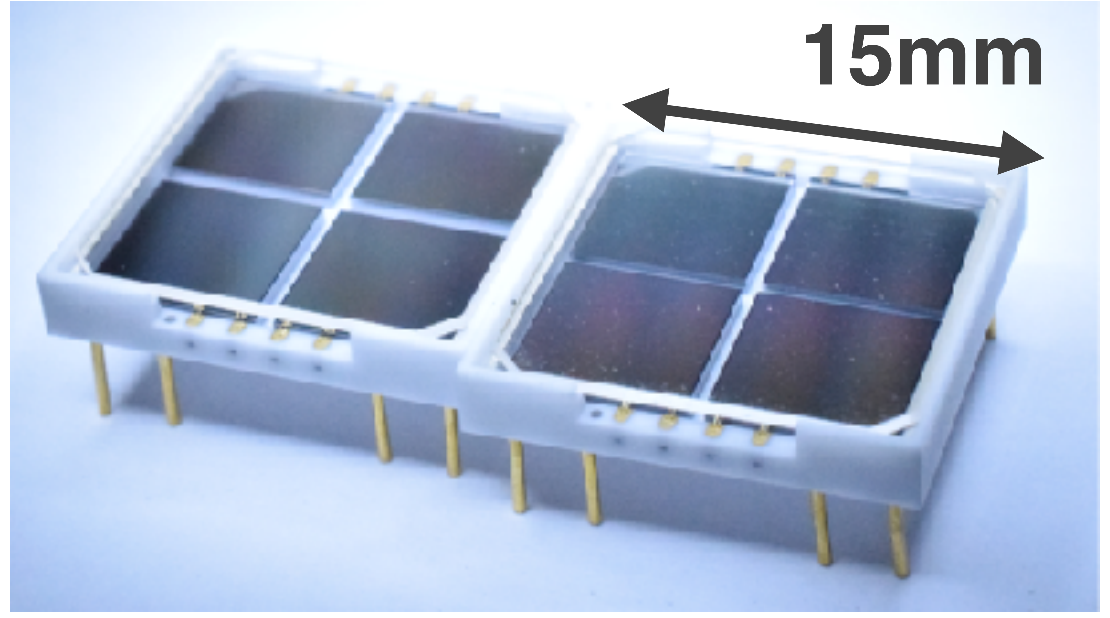
4 sensor chips (~6×6mm^2 each)

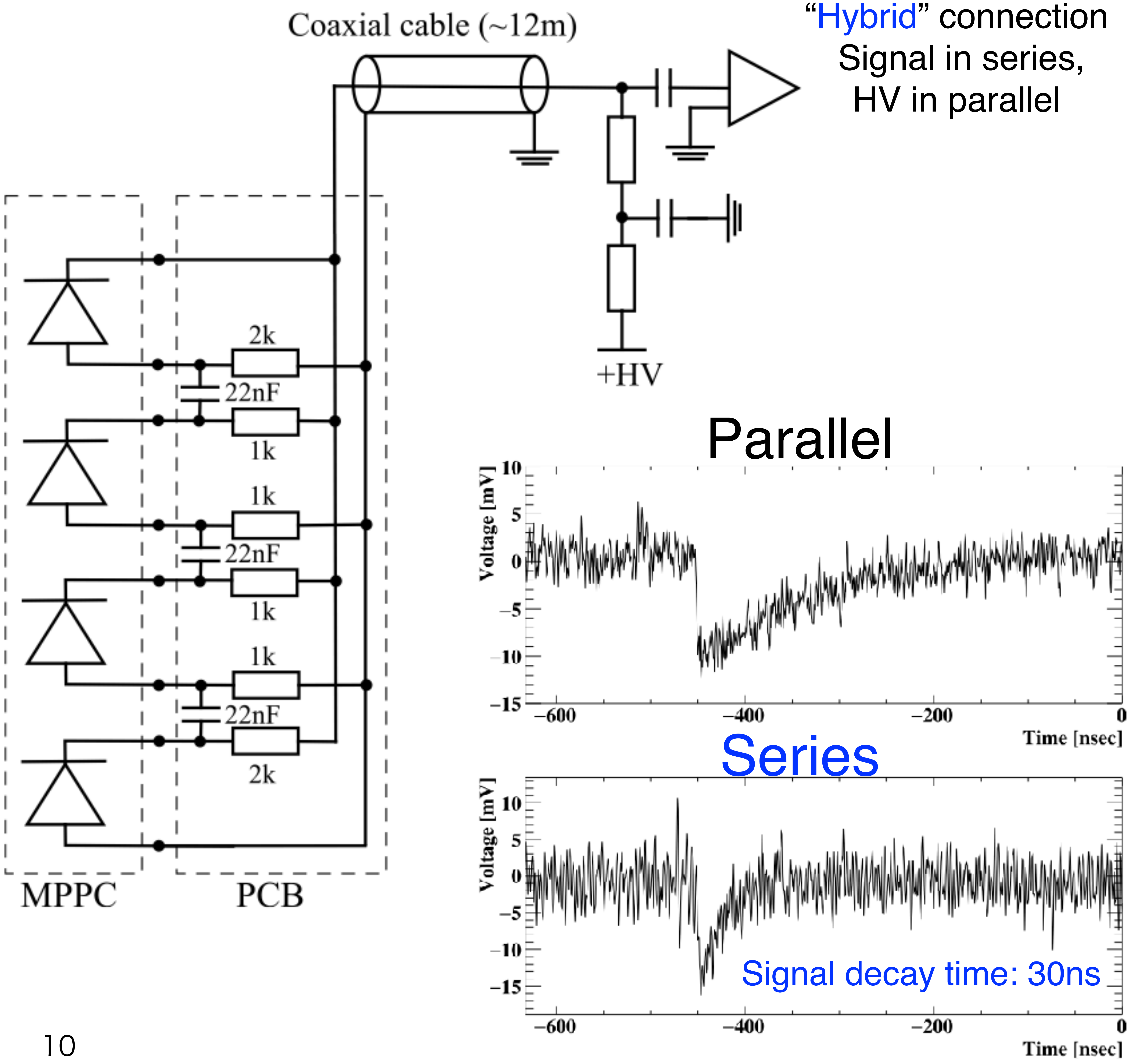
Ceramic base

50μm pixel pitch

No protection layers for VUV-sensitive

Metal quench resistor for low T





"Hybrid" connection
Signal in series,
HV in parallel

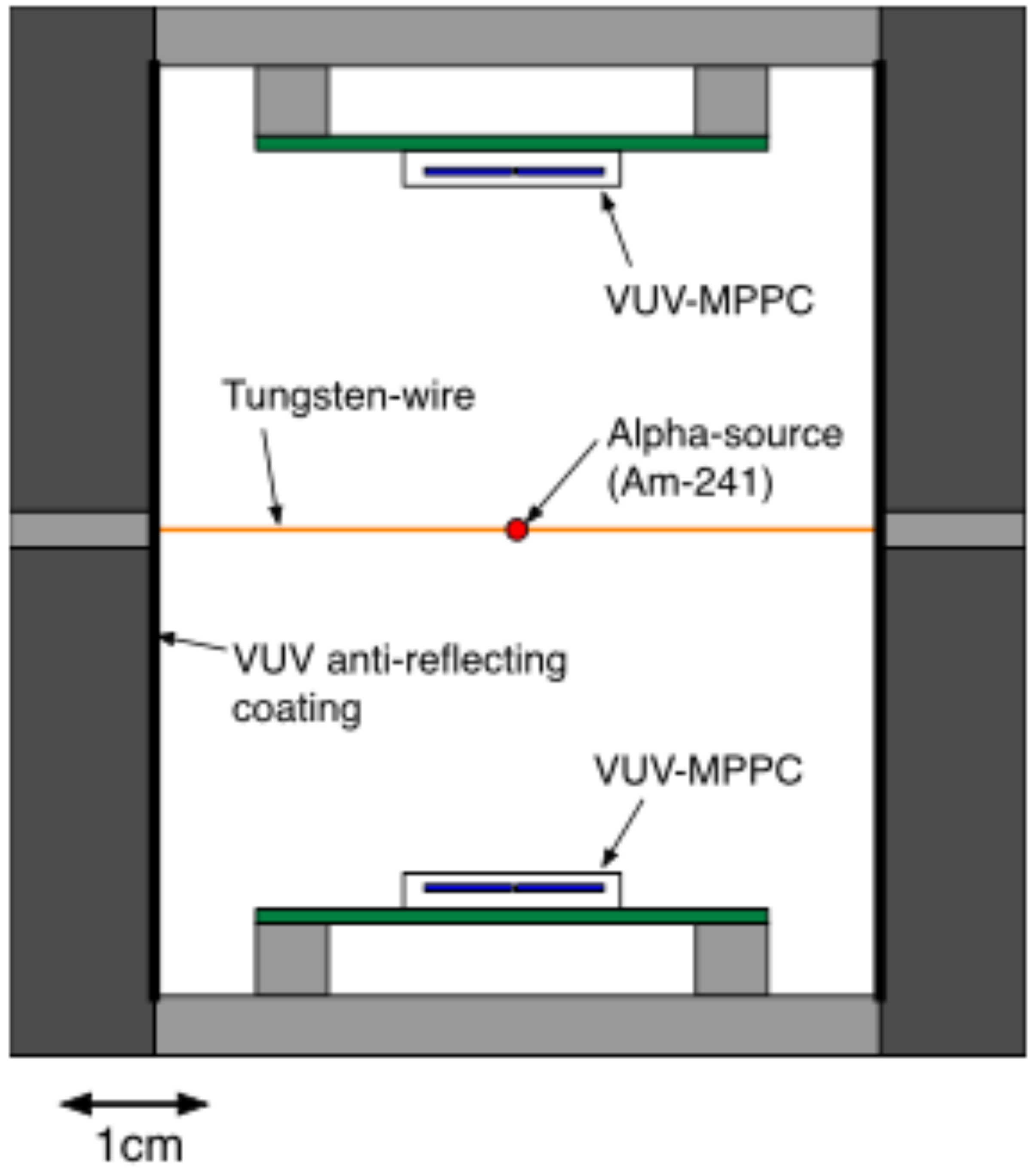
Parallel

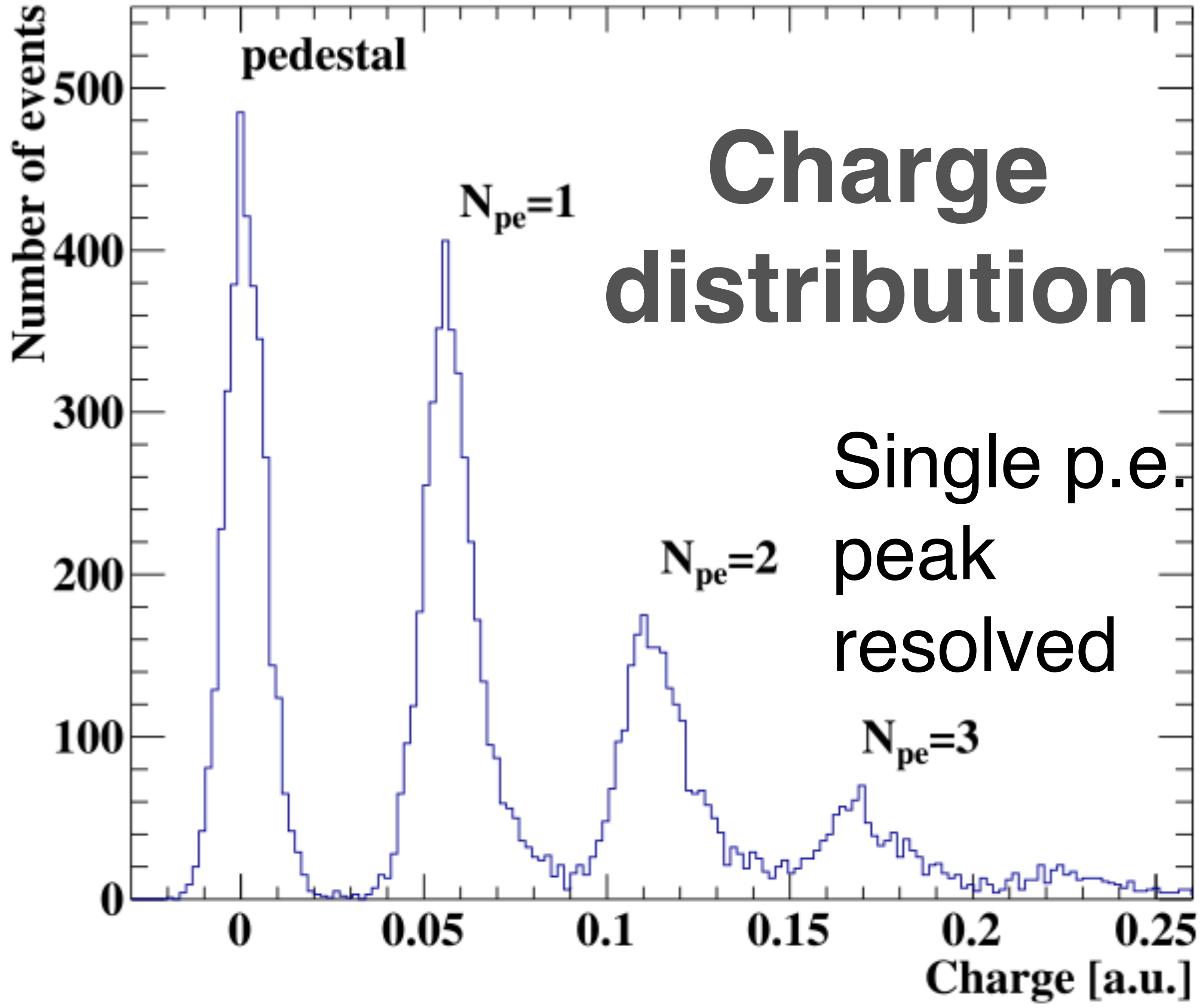
Series

Signal decay time: 30ns

Performance in the test setup

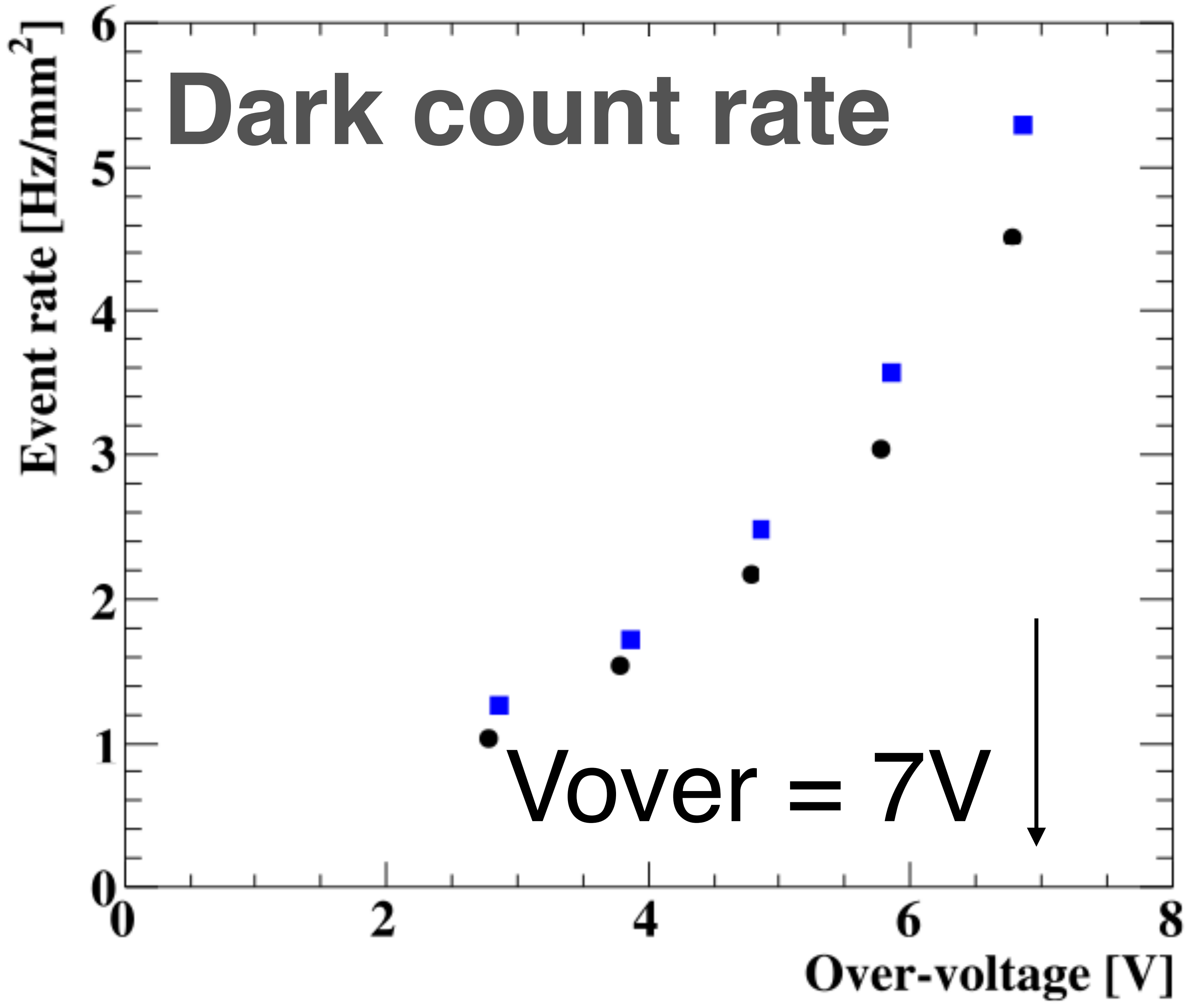
- Evaluated in the test setup with 2l LXe





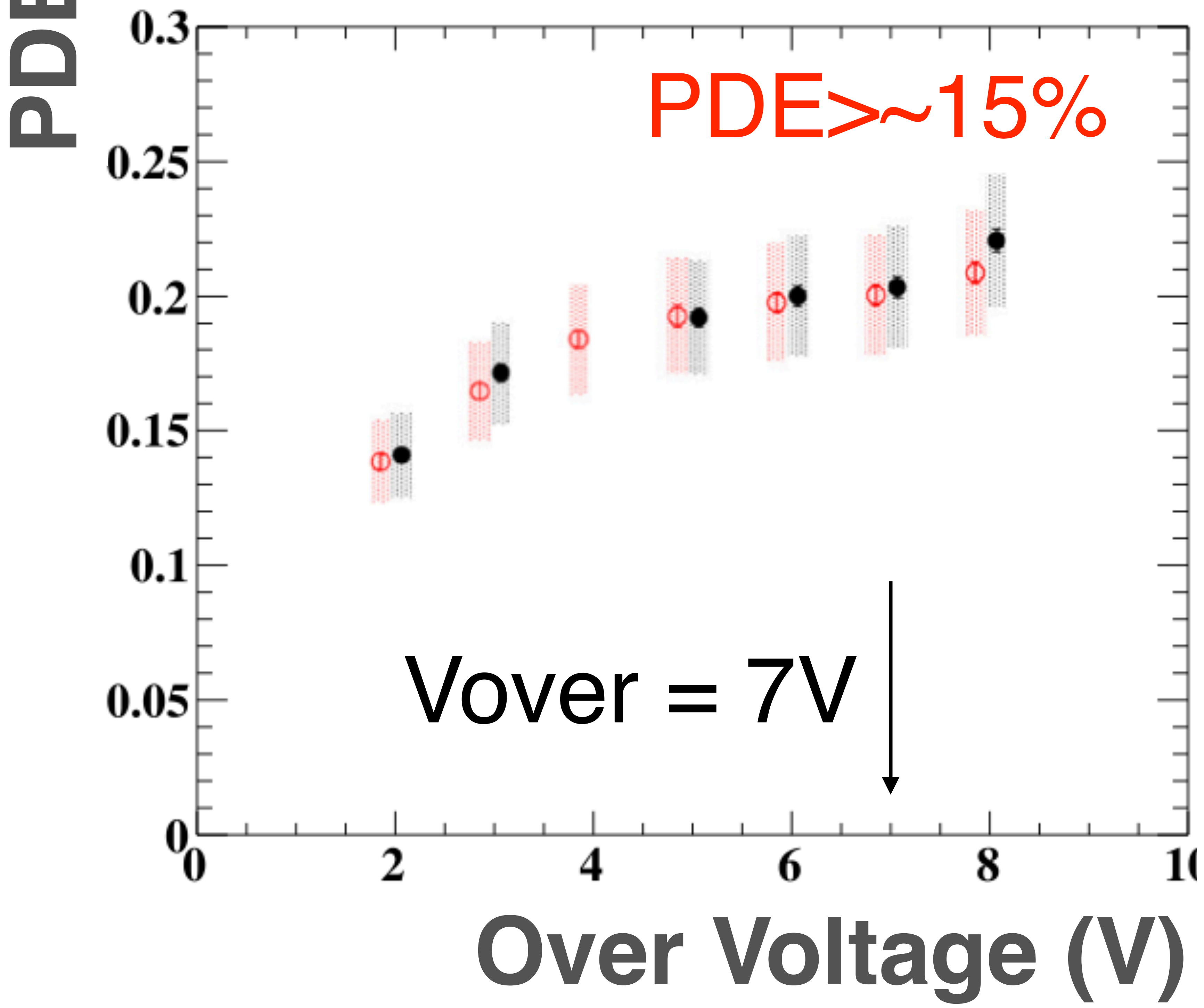
Charge distribution

Single p.e. peak resolved



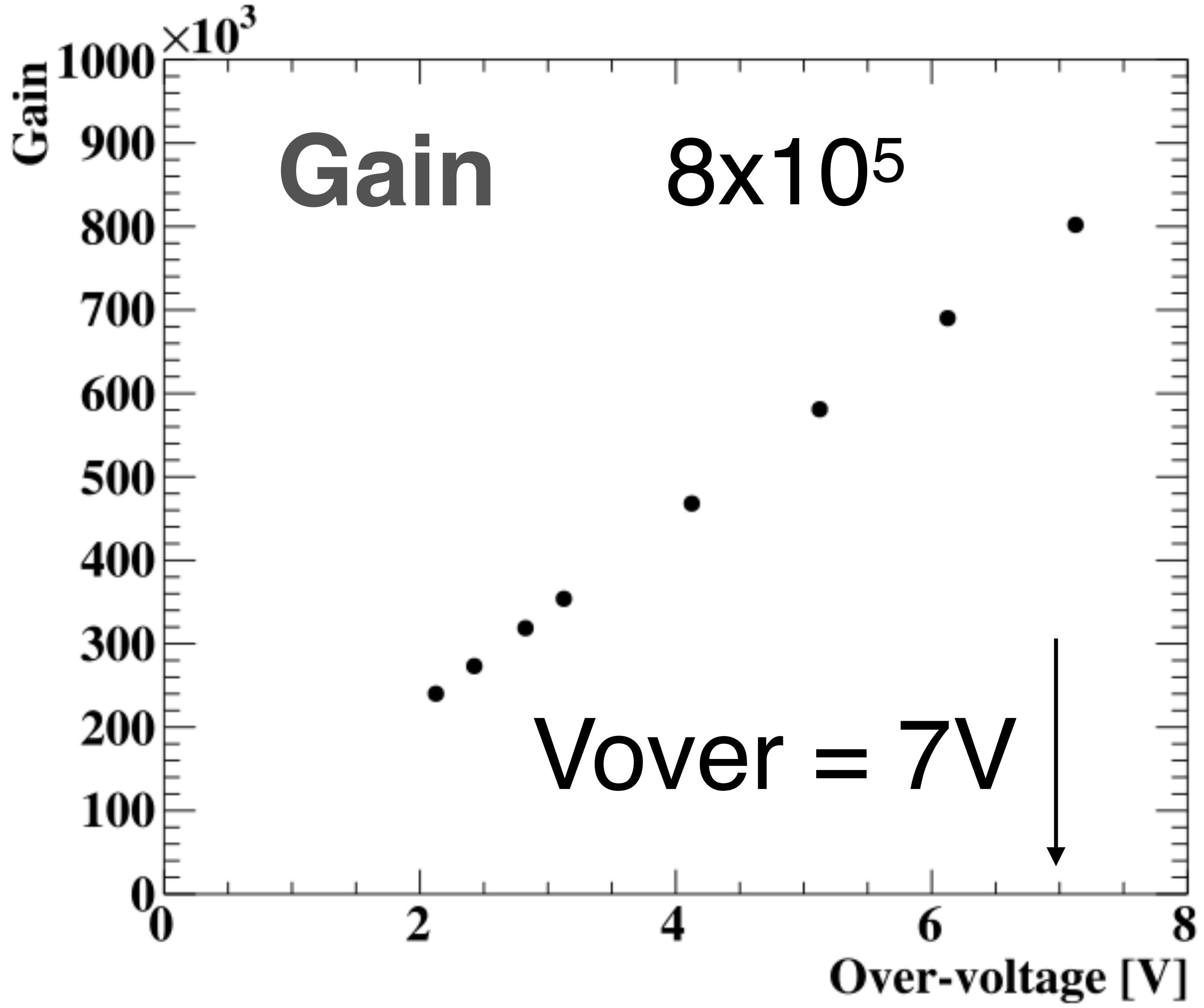
Dark count rate

Vover = 7V



PDE>~15%

Vover = 7V

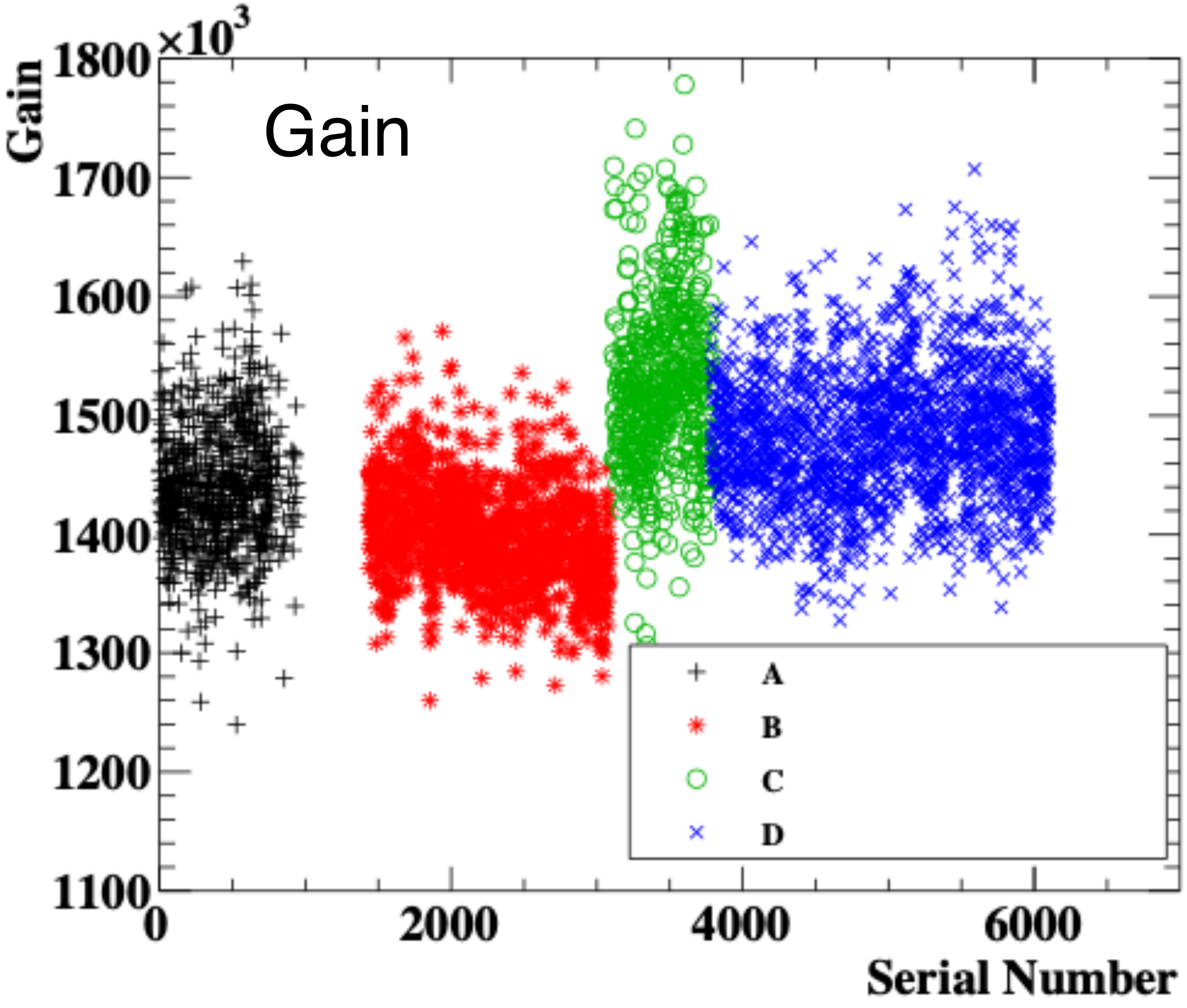


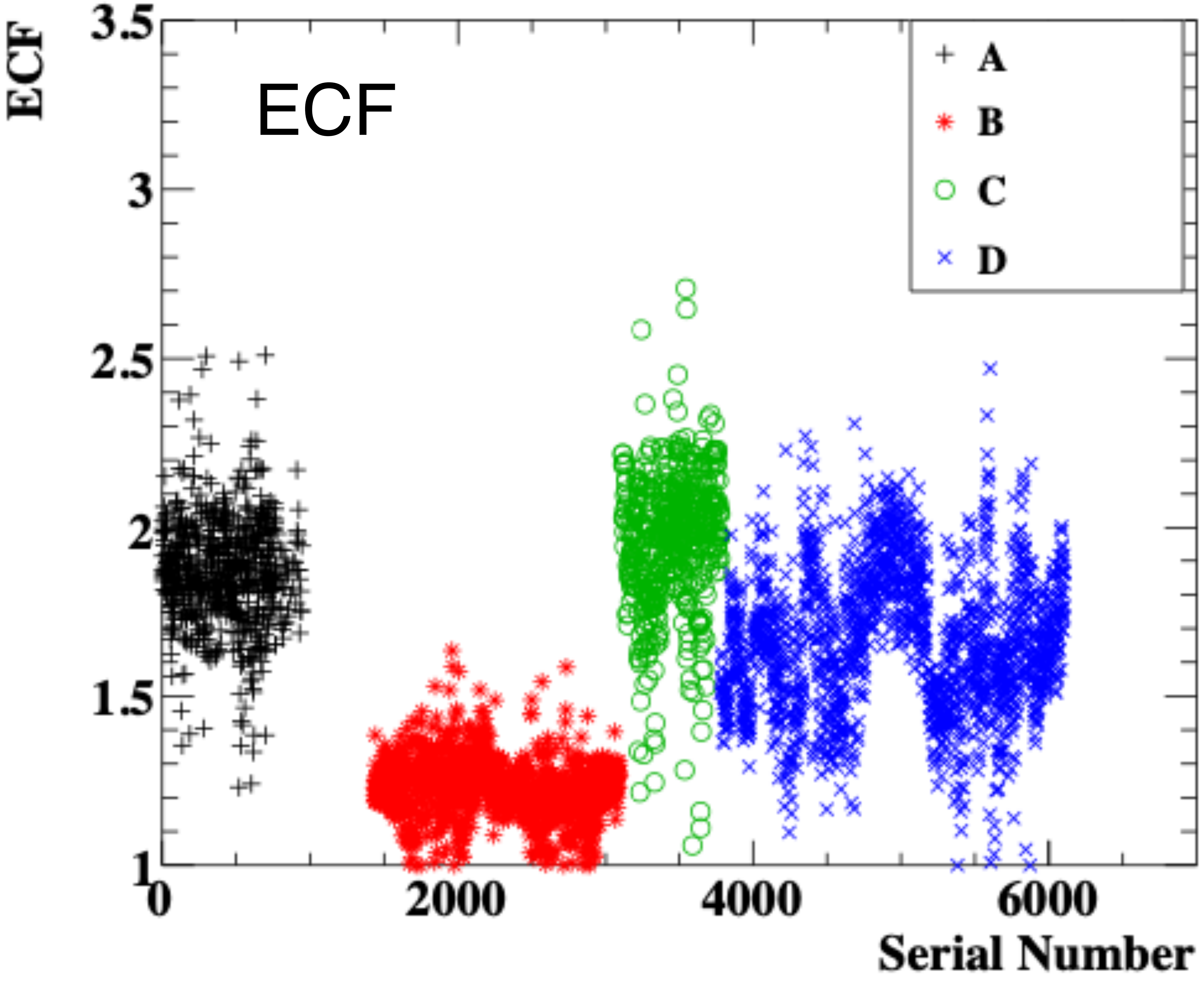
Gain 8×10^5

Vover = 7V

MPPC calibration in the MEG II LXe detector

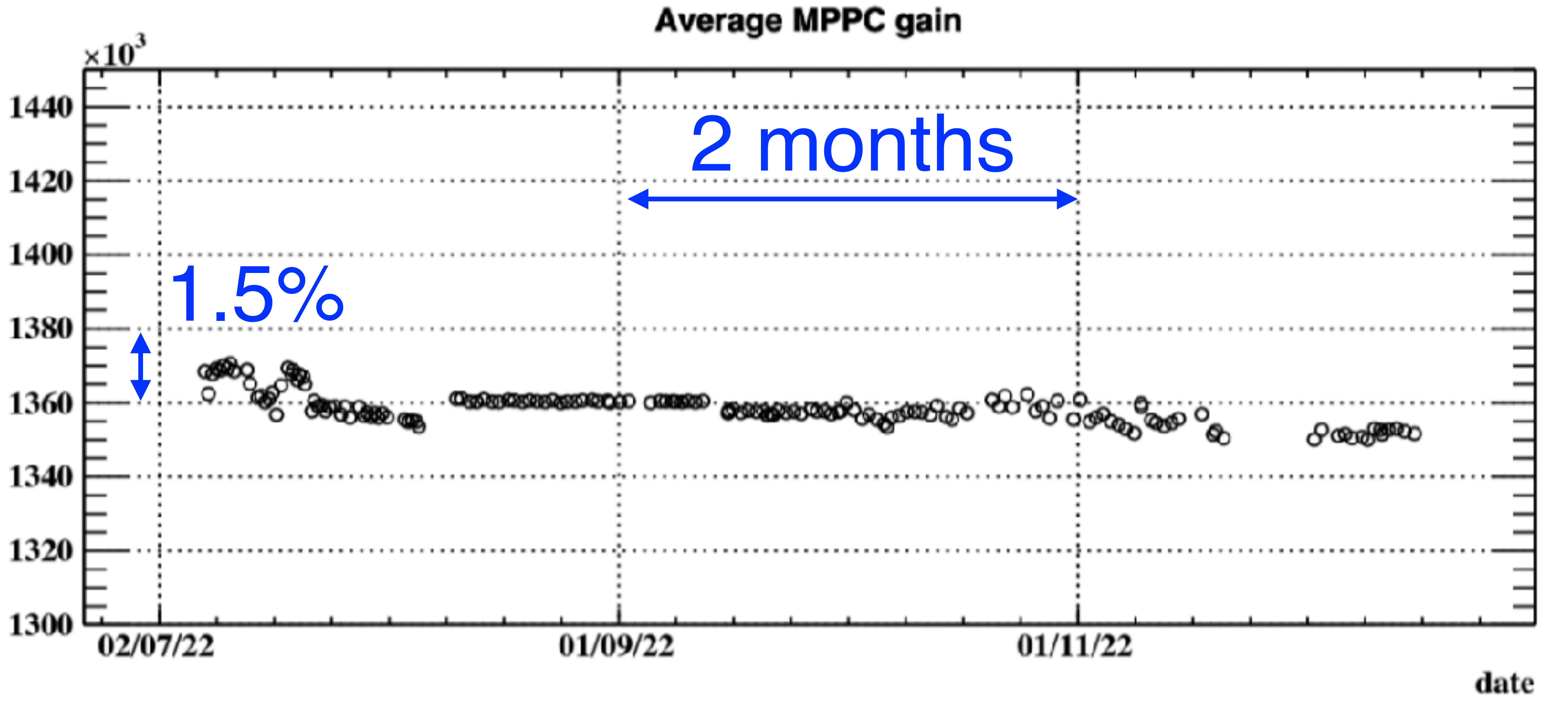
- Measured gain and ECF of 4092 MPPCs as a function of serial numbers
- Production lot dependences observed

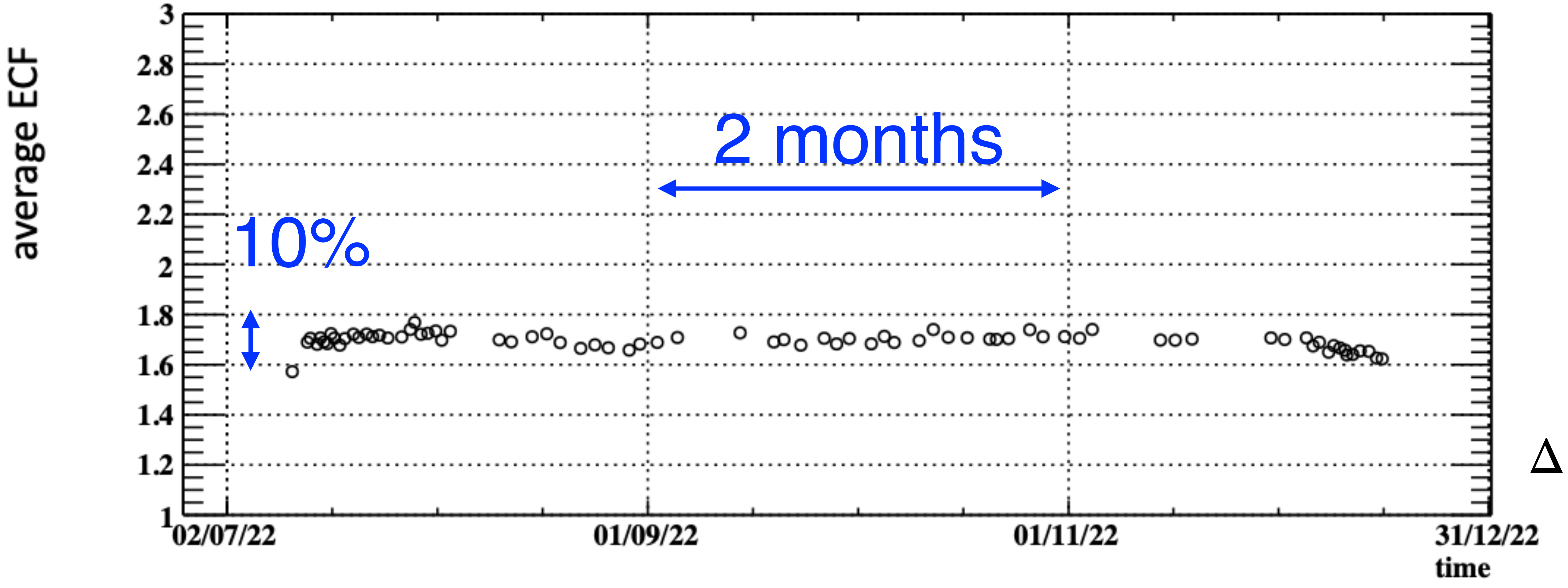




MPPC monitoring (stability over time)

Gain and ECF are sufficiently stable for long term operation

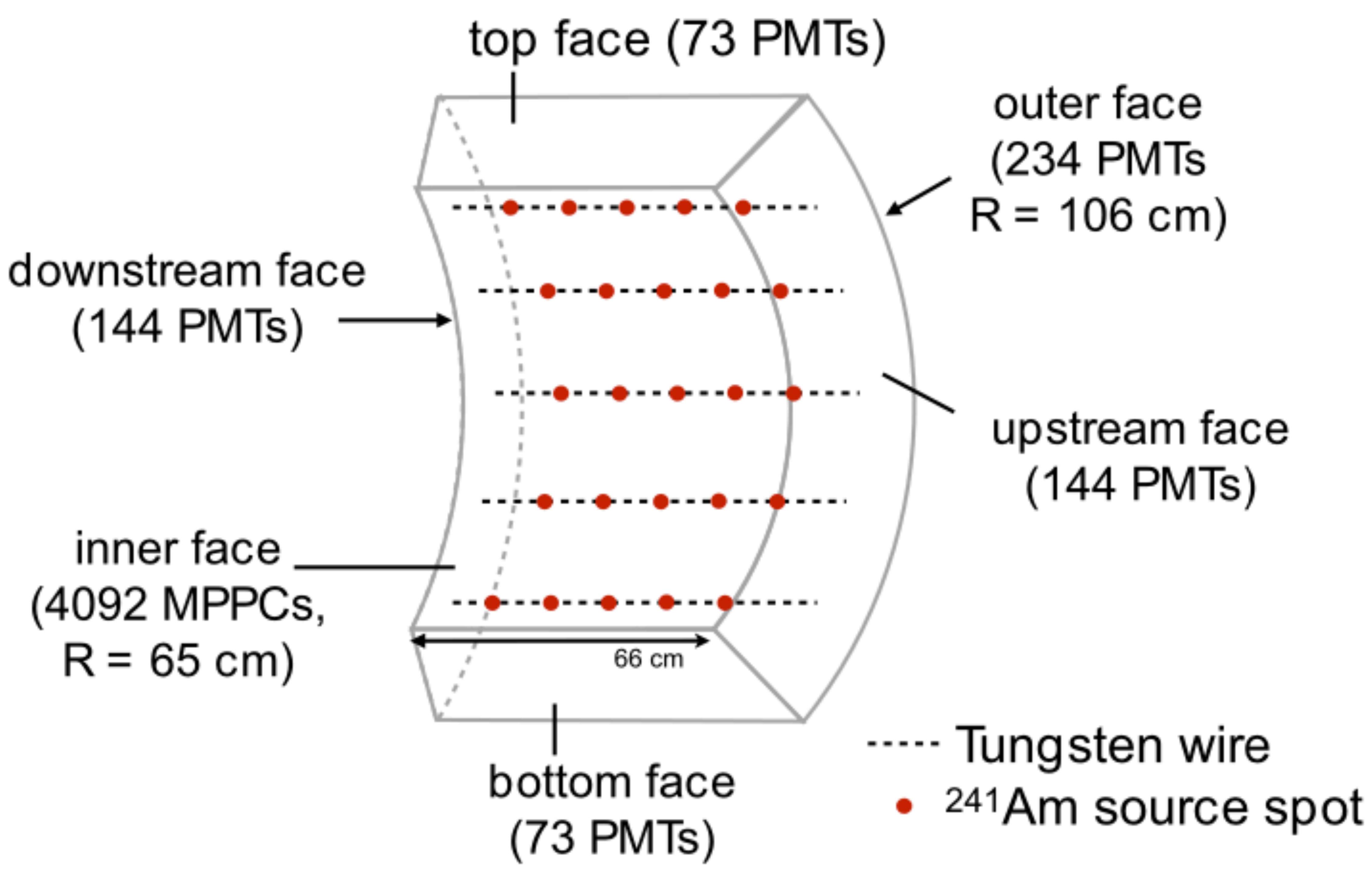


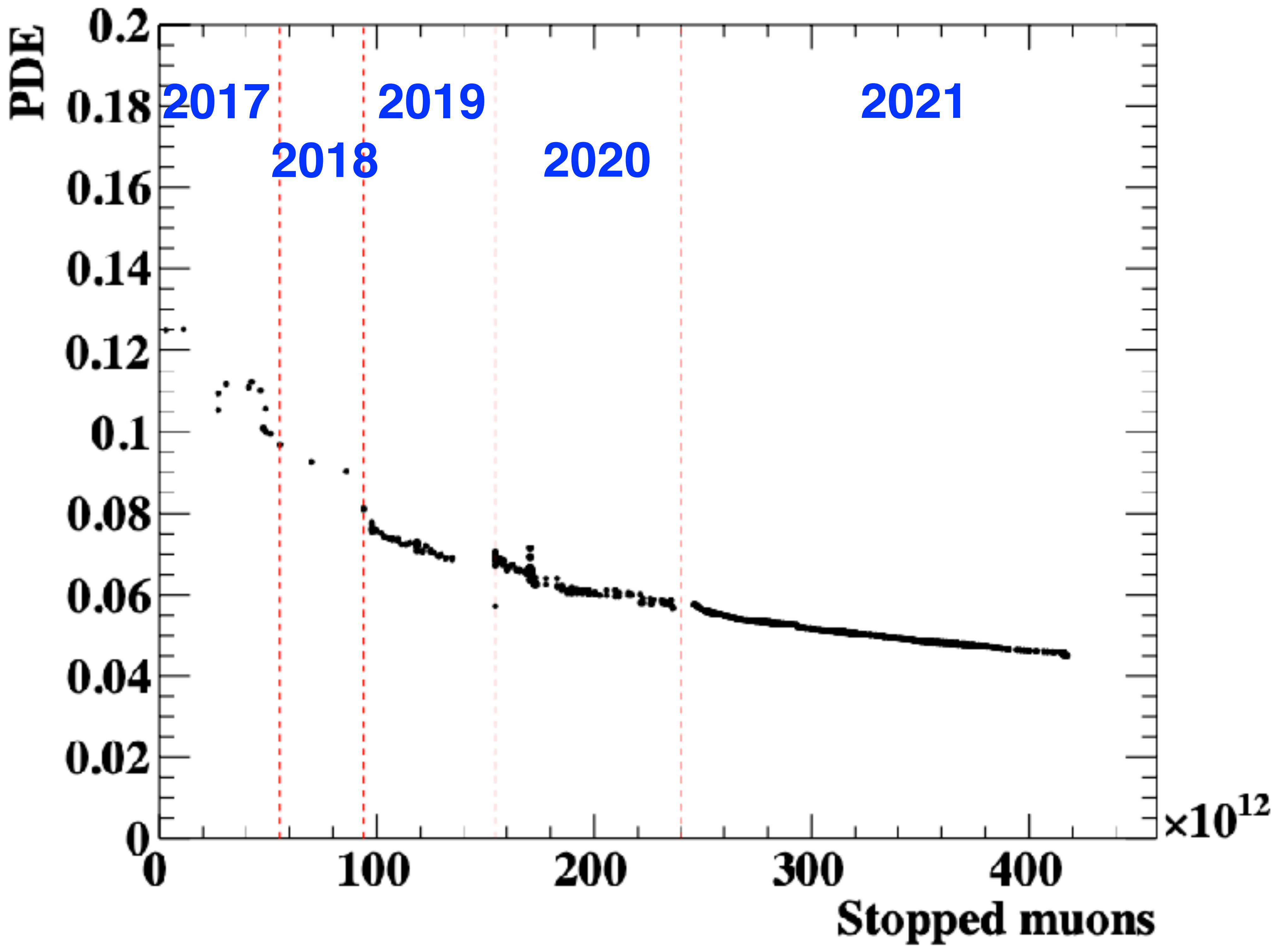


V$_{bd}$: 56mV/K

ΔV_{bd}~ 1% @ΔT_{LXe}~1K

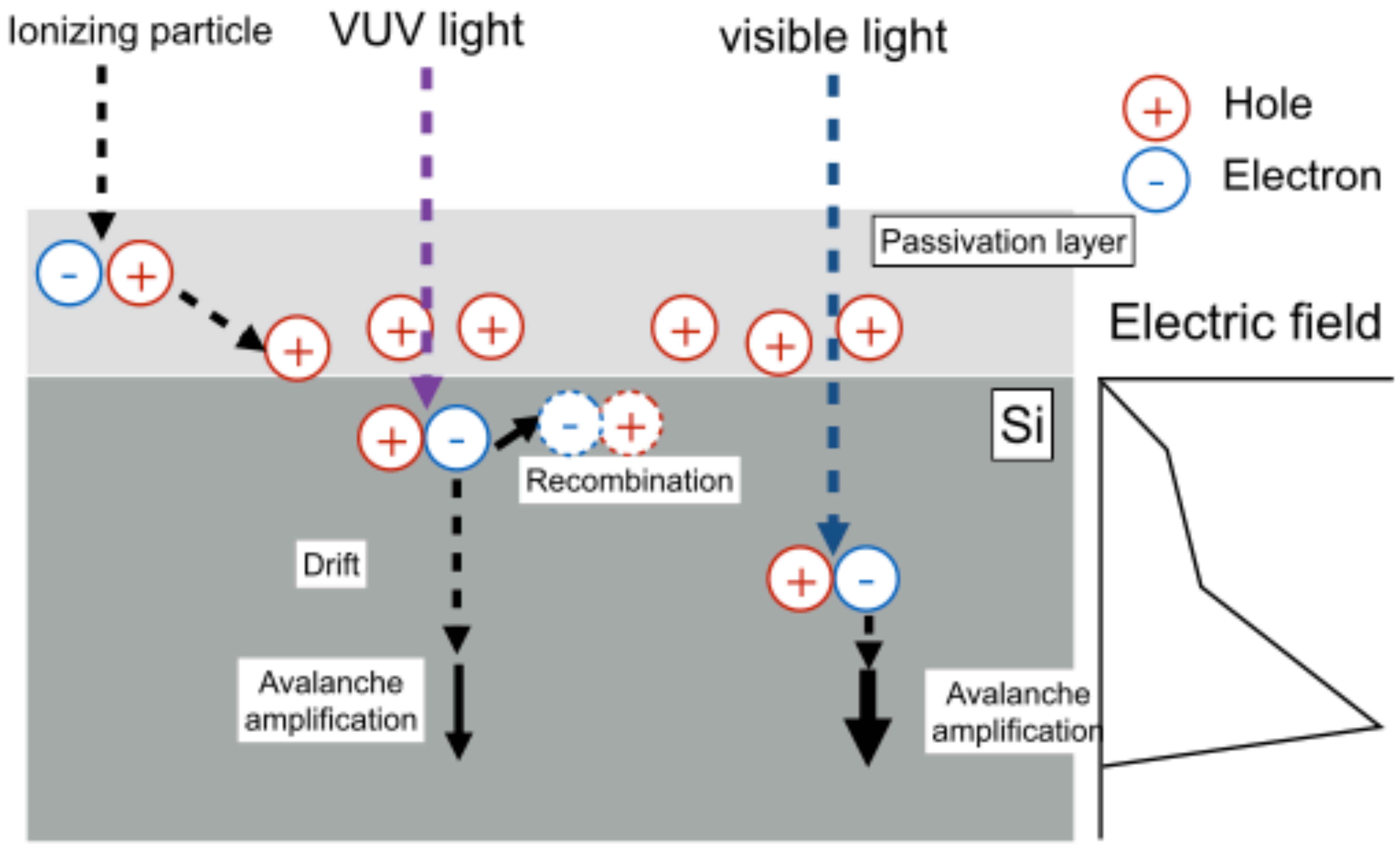
MPPC PDE decrease

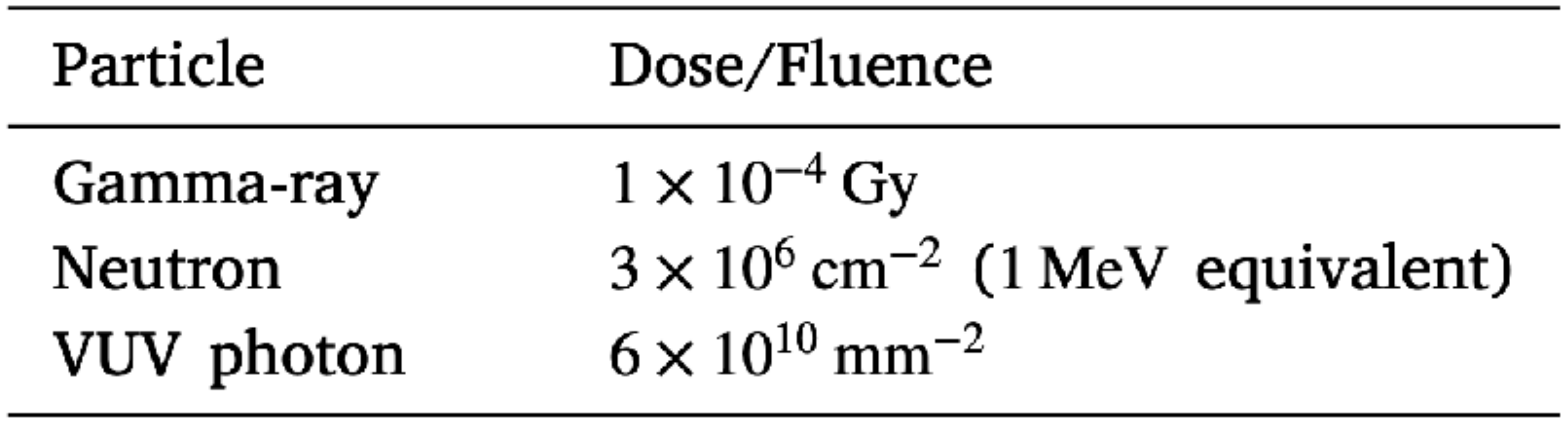




- MPPC PDE monitored by α peaks.
- PDE decrease was observed when we started using muon beam, and was not stopped

PDE decrease mechanism





Particle	Dose/Fluence
Gamma-ray	1×10^{-4} Gy
Neutron	3×10^{6} cm^{-2} (1 MeV equivalent)
VUV photon	6×10^{10} mm^{-2}

<< 240Gy

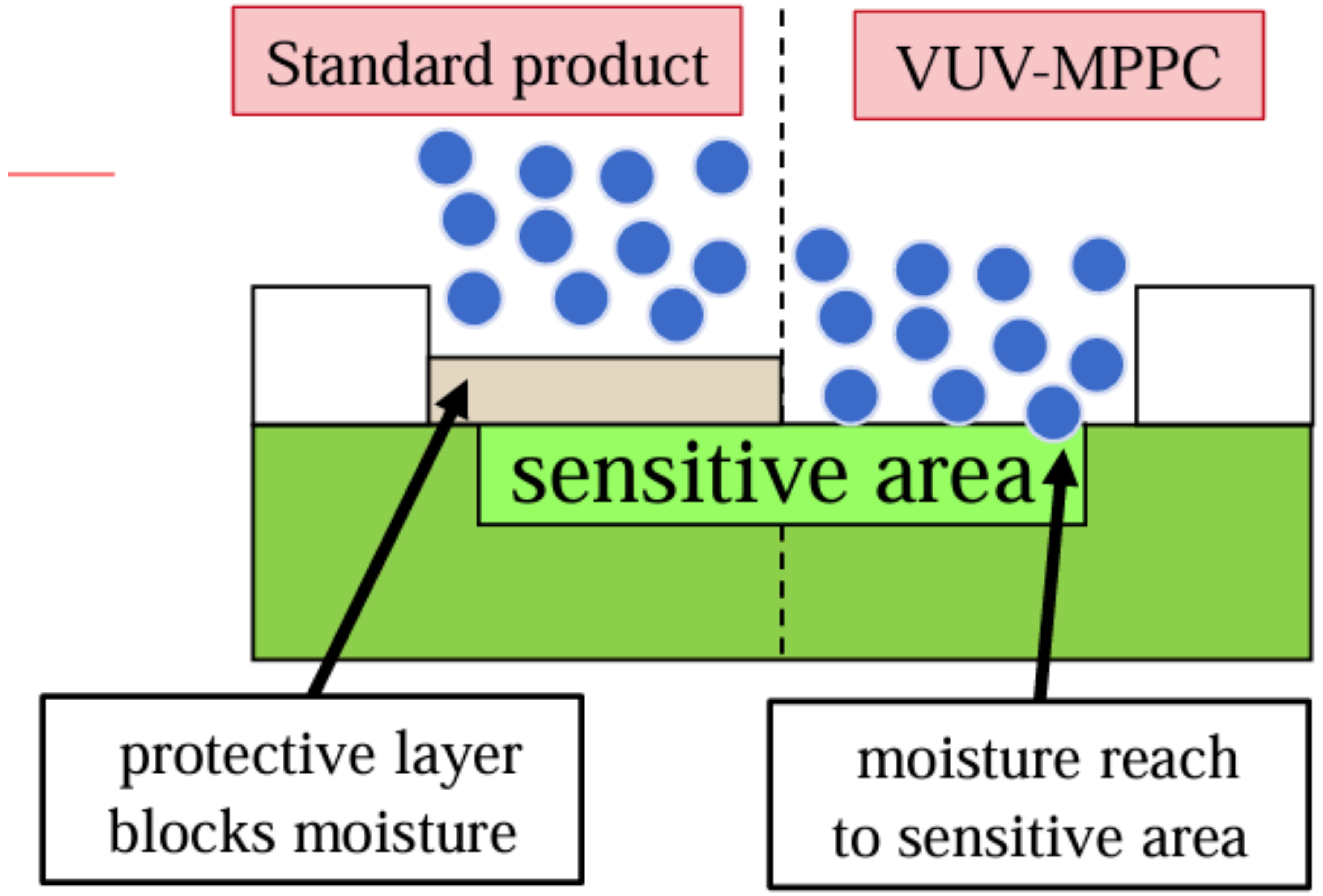
<< 10^9 cm^{-2}

- Possible cause
  - Surface damage by VUV-light
    - Electron-hole pair generated by VUV light at surface of Si, and holes are trapped there.
    - The holes reduce electric field, reducing collection efficiency of electron avalanche
- The mechanism has not been fully understood yet
  - Degradation happens only with much larger amount of VUV light at room T
  - Degradation seems accelerated at low T
- We haven’t reproduced the PDE decrease in lab. measurement yet

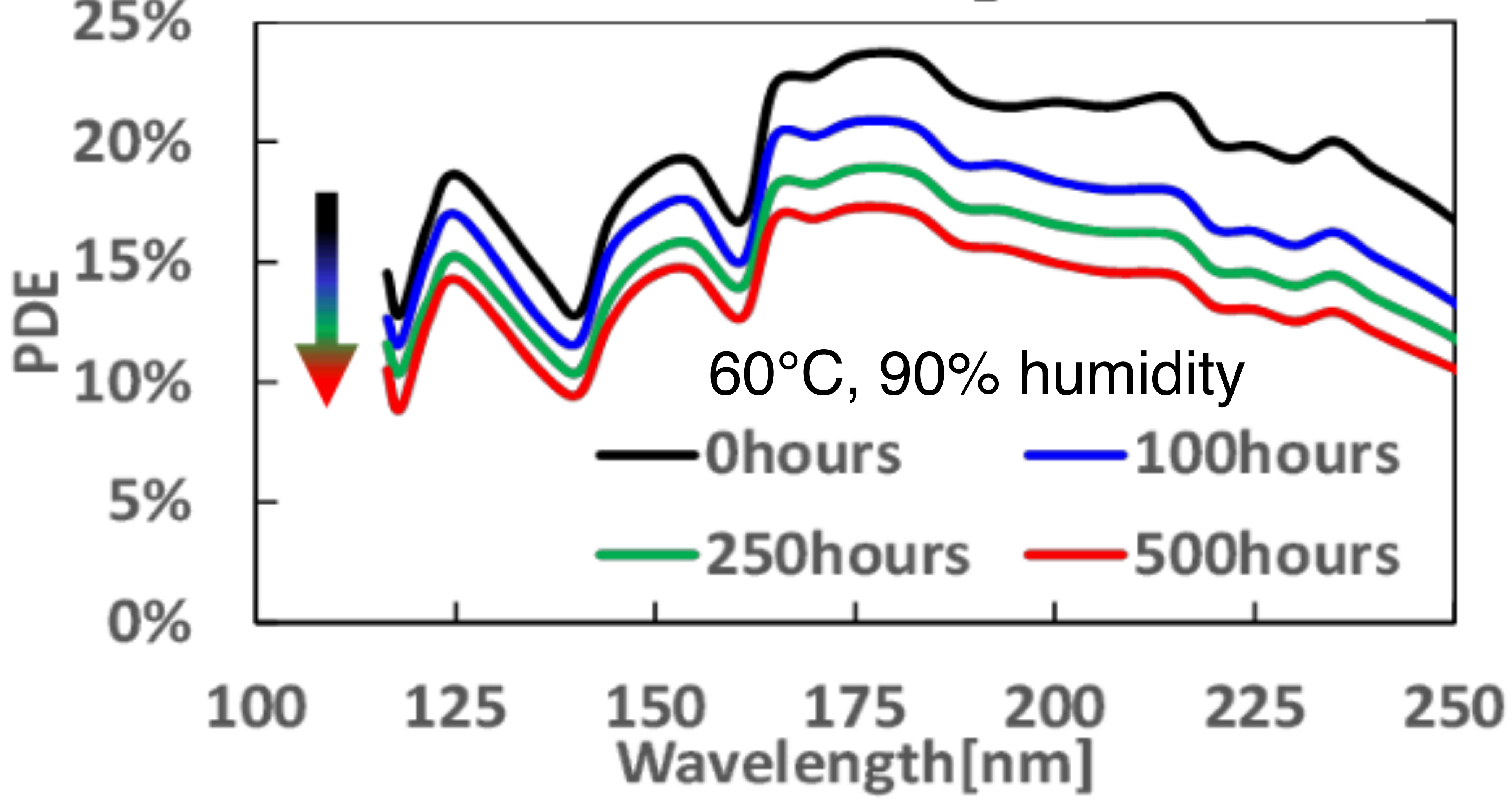
Moisture in VUV-MPPC?

Hamamatsu Photonics K.K.
Symposium University of Tokyo-ETH Zurich-University of Zurich 17 October, 2023

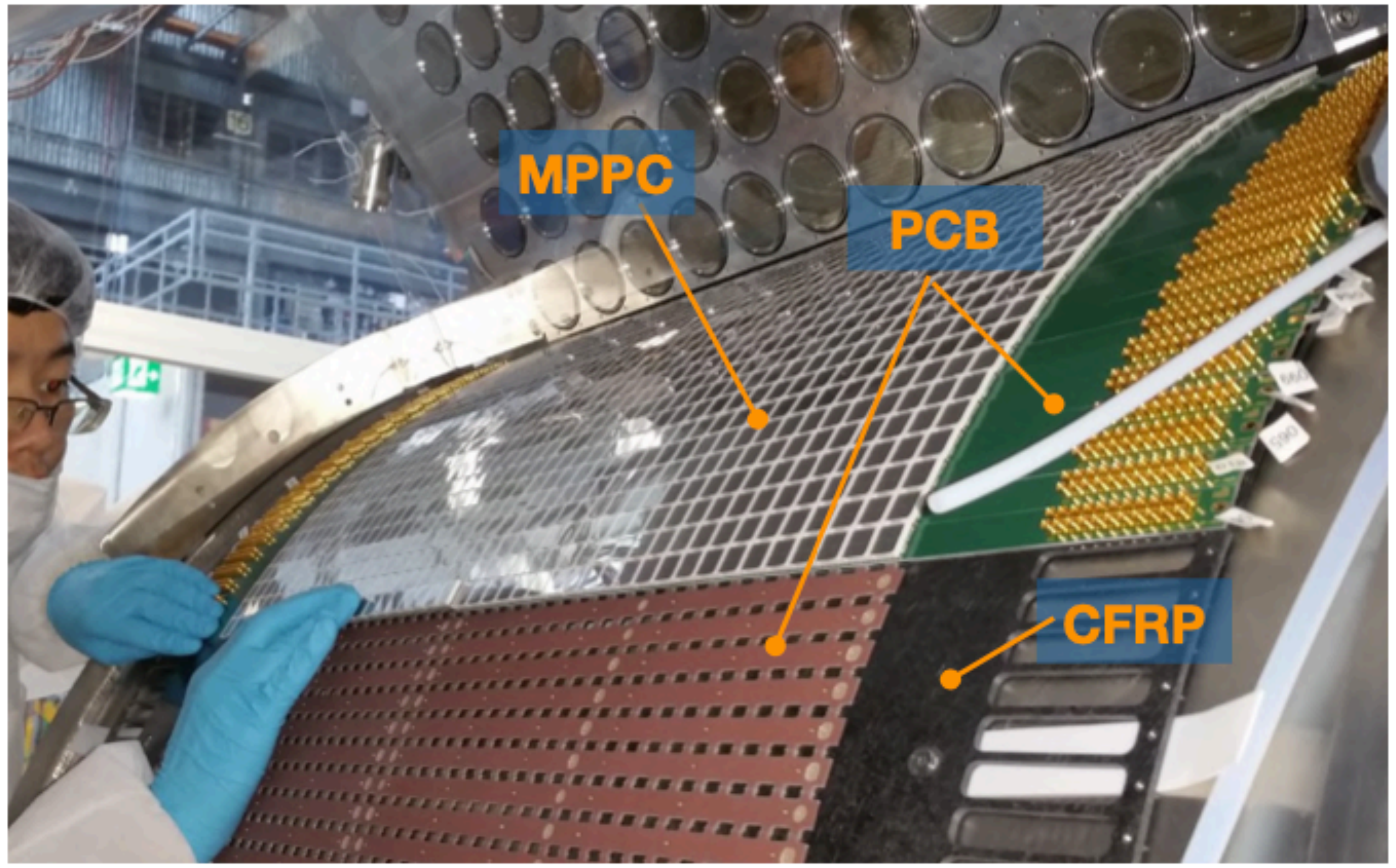
- VUV-MPPC has no protection layer
  - PDE degradation is observed due to moisture
- The PDE decrease were accelerated?
  - The MEG II MPPC were exposed in ambient humidity before/during construction
- VUV light irradiation to humidified VUV-MPPCs are tested in lab to reproduce the observed PDE decrease in the MEG II MPPC
- Hamamatsu has an improved MPPCs
  - Reduction of defects on Si surface
  - The PDE decrease might be reduced



conventional process



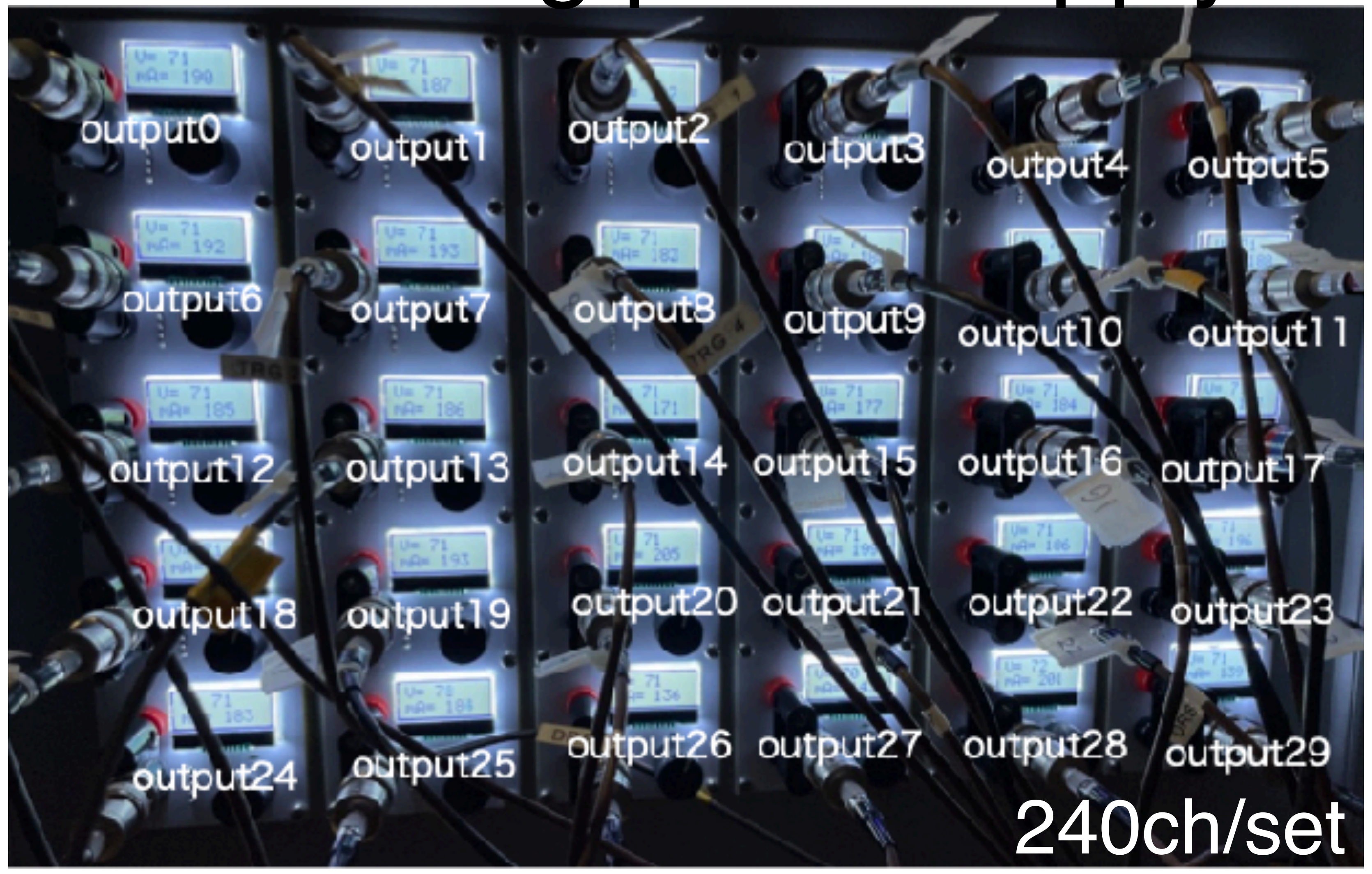
Solution for PDE decrease



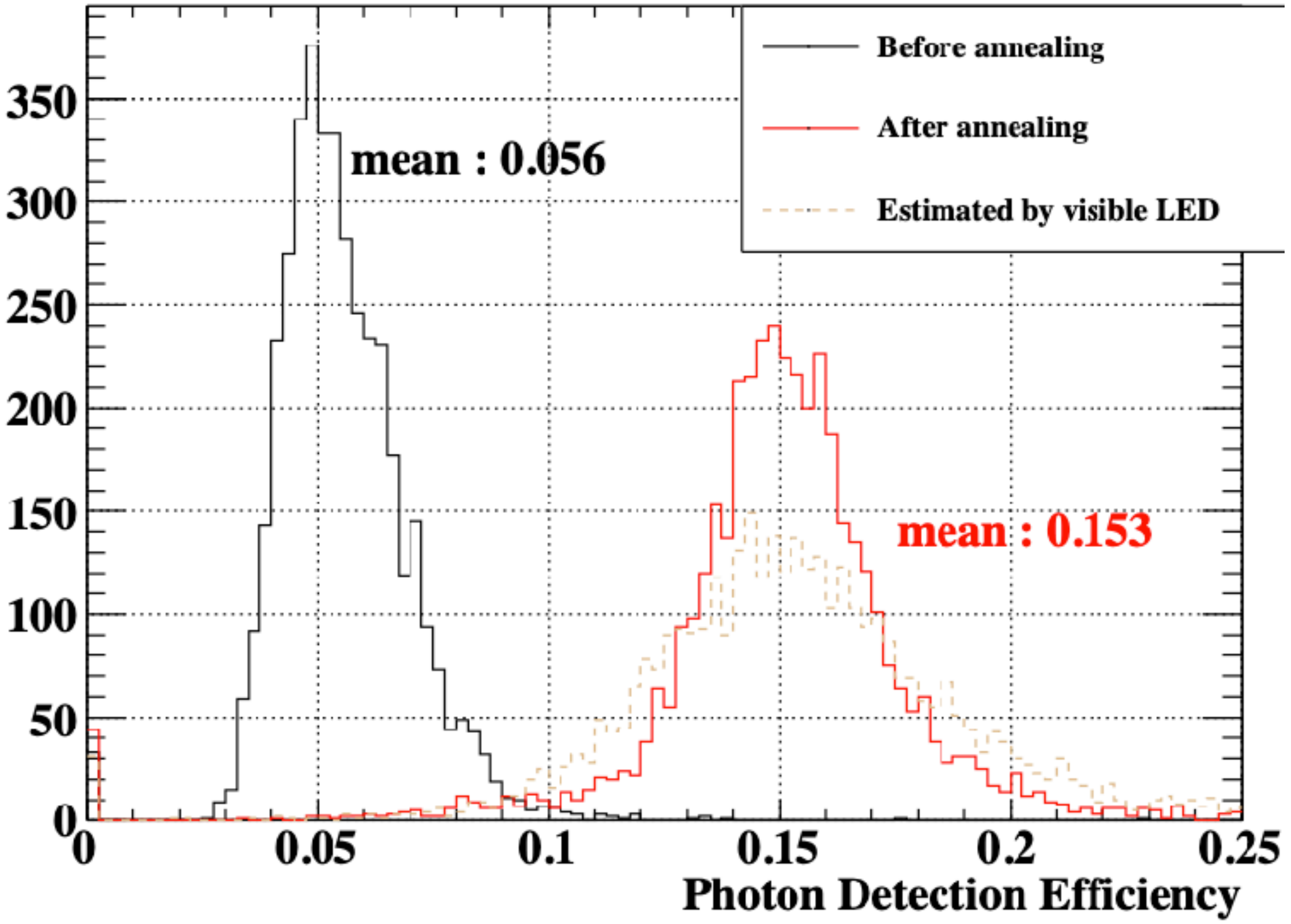
- Temperature limit
  - MPPC: 100°C
  - PCB: 120°C
  - CFRP: 45°C
  - Glue: 65°C

- Joule annealing method
  - Supply ~1.7W per MPPC using high current and LED light
- 30 hours annealing / MPPC → 1.5 month annealing

Annealing power supply



PDE before/after the annealing with LY correction (after annealing)



Summary

- The MEG II experiment looks for new physics BSM by studying the $\mu^+ \rightarrow e^+\gamma$ decay with the target sensitivity of 6×10^{-14} before 2027. The first MEG II results with 2021 data were presented last year.

- The 900 l LXe detector for the γ detection utilizes 4092 VUV-sensitive MPPCs. The full readout of all the photo sensors has been started since 2021.

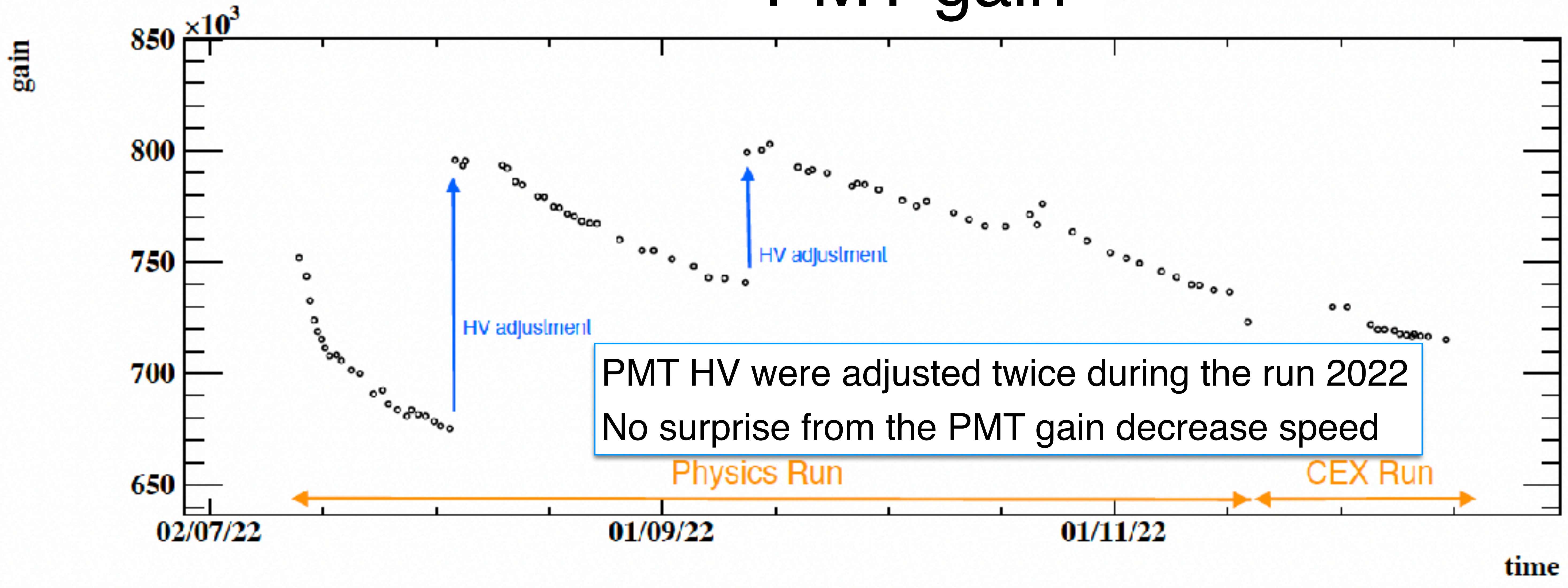
- The sensor calibration and monitoring methods are established for the long run, and the detector performances are evaluated for the physics data analysis.

- The reason of the PDE decrease has to be understood, but the remedy to recover the PDE has been established.

Detector monitoring

- PMT Gain
  - Absolute PMT gain is calculated with LED
  - Constantly gain is decreased under muon beam
  - Twice HVs were adjusted during run 2022
- LXe light yield
  - Monitored by α events by PMTs
  - Assumption of constant PMT QE
  - During the run, the gaseous purification is always on with getter
  - At the beginning, liquid purification with molecular sieves also performed

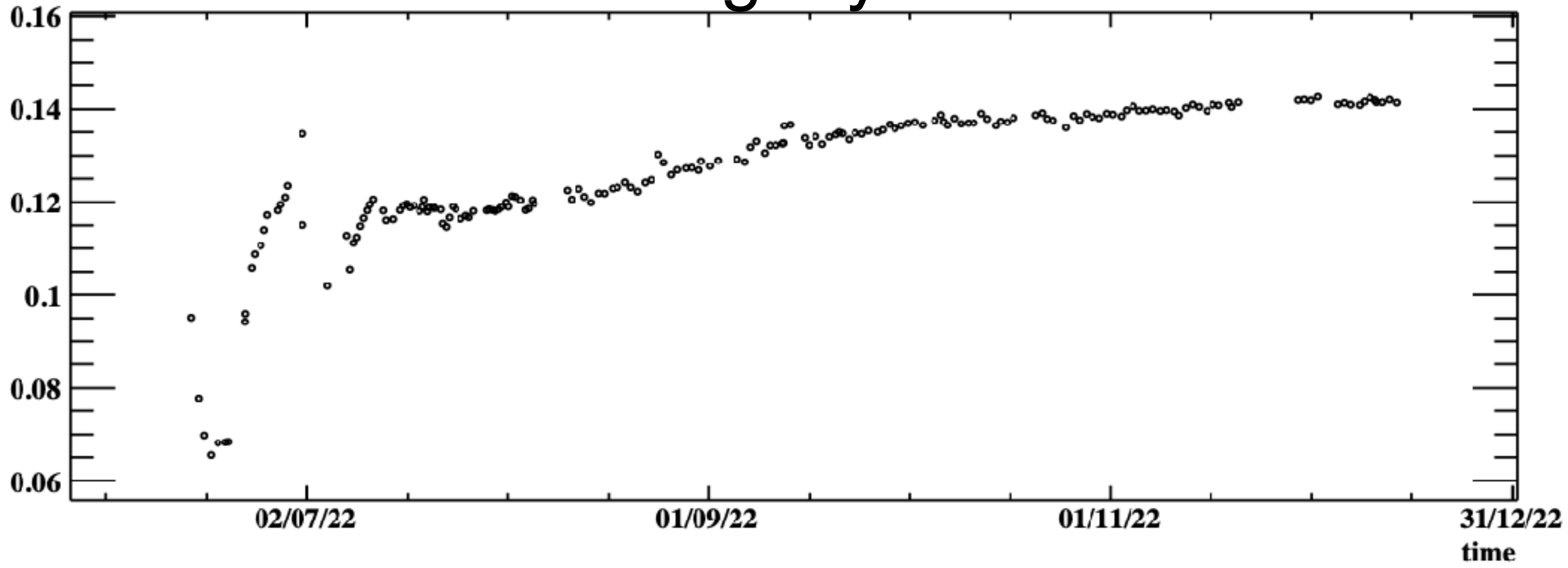
PMT gain



PMT HV were adjusted twice during the run 2022

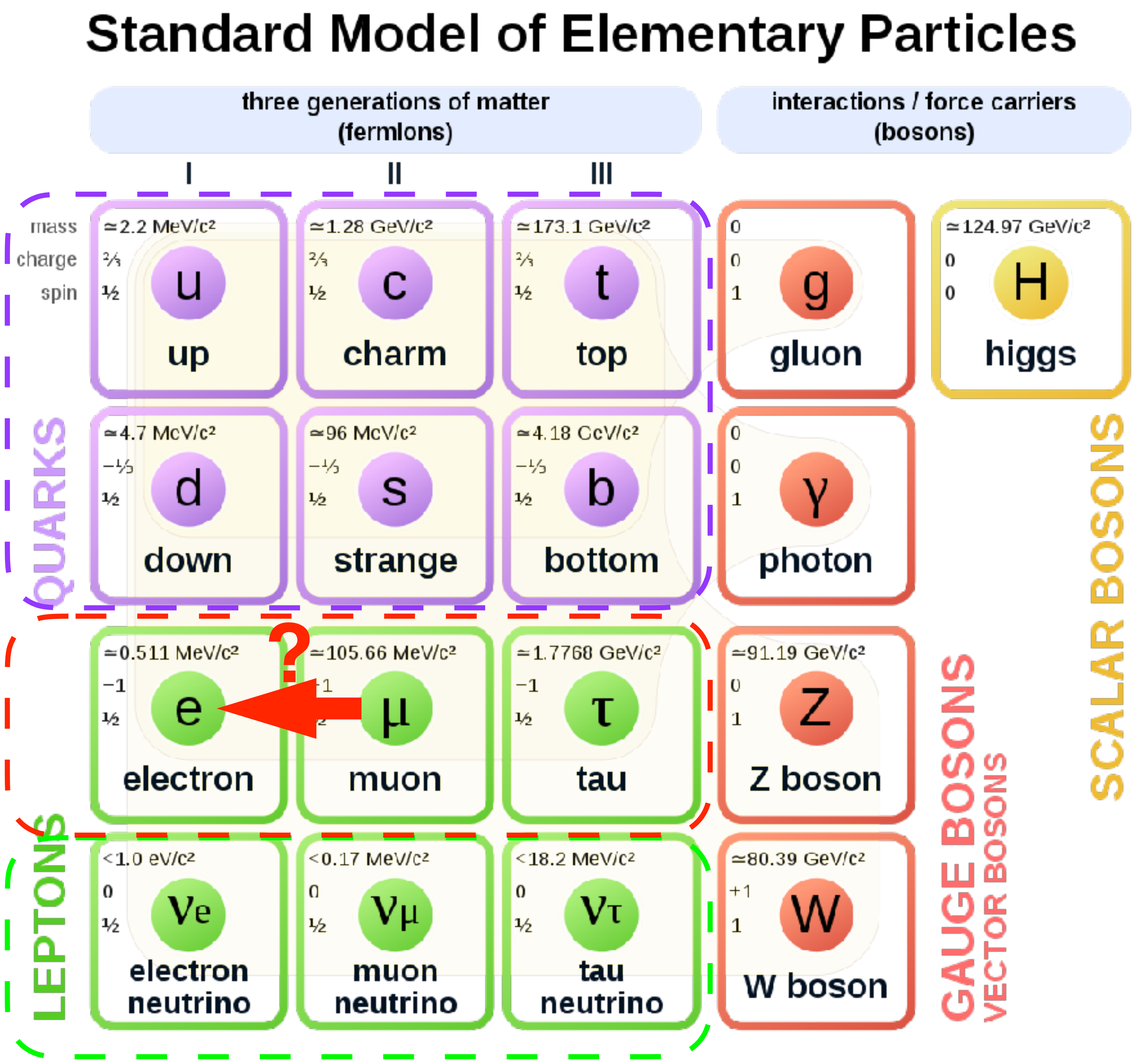
No surprise from the PMT gain decrease speed

Light yield



Monitored by α events by PMTs

Charged Lepton Flavor Violation



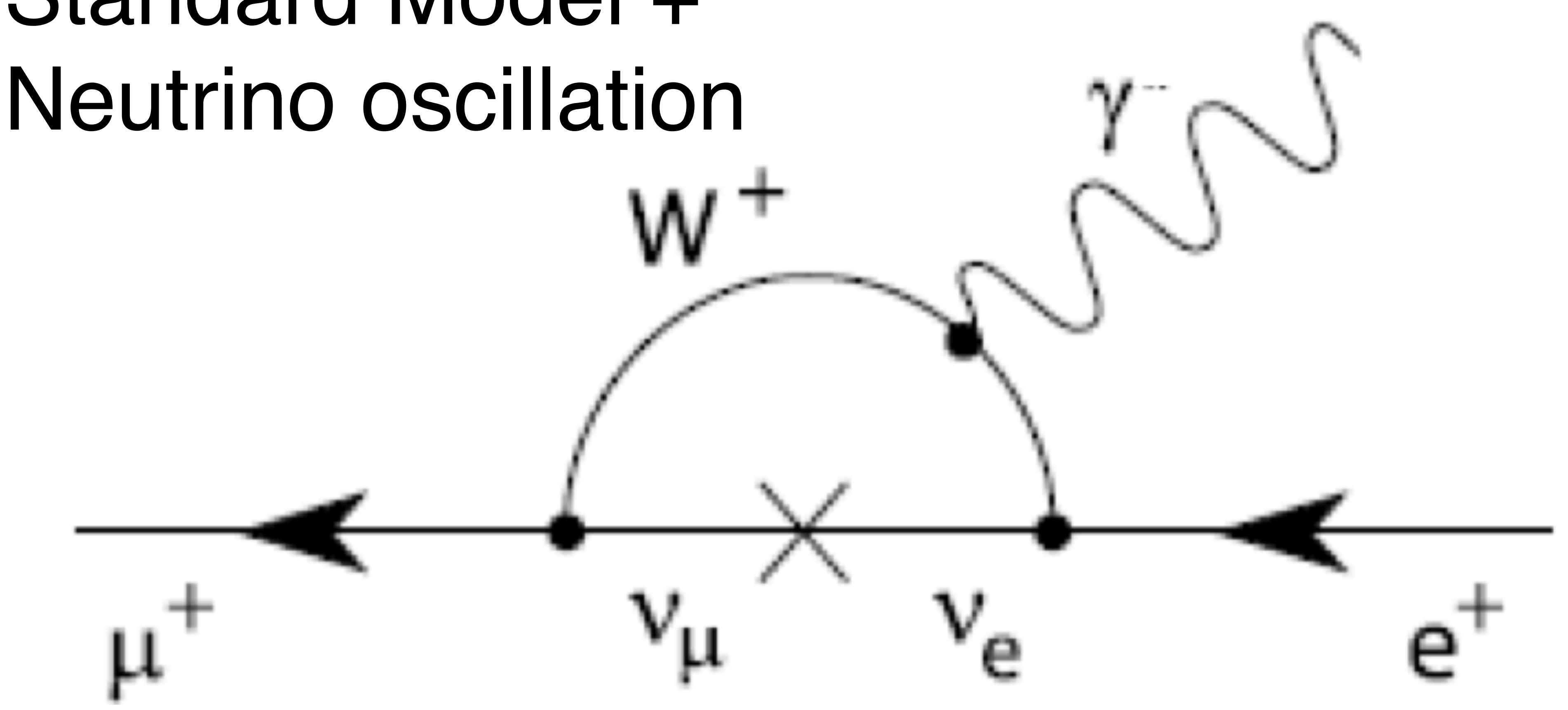
CKM matrix

CLFV

Neutrino Oscillation

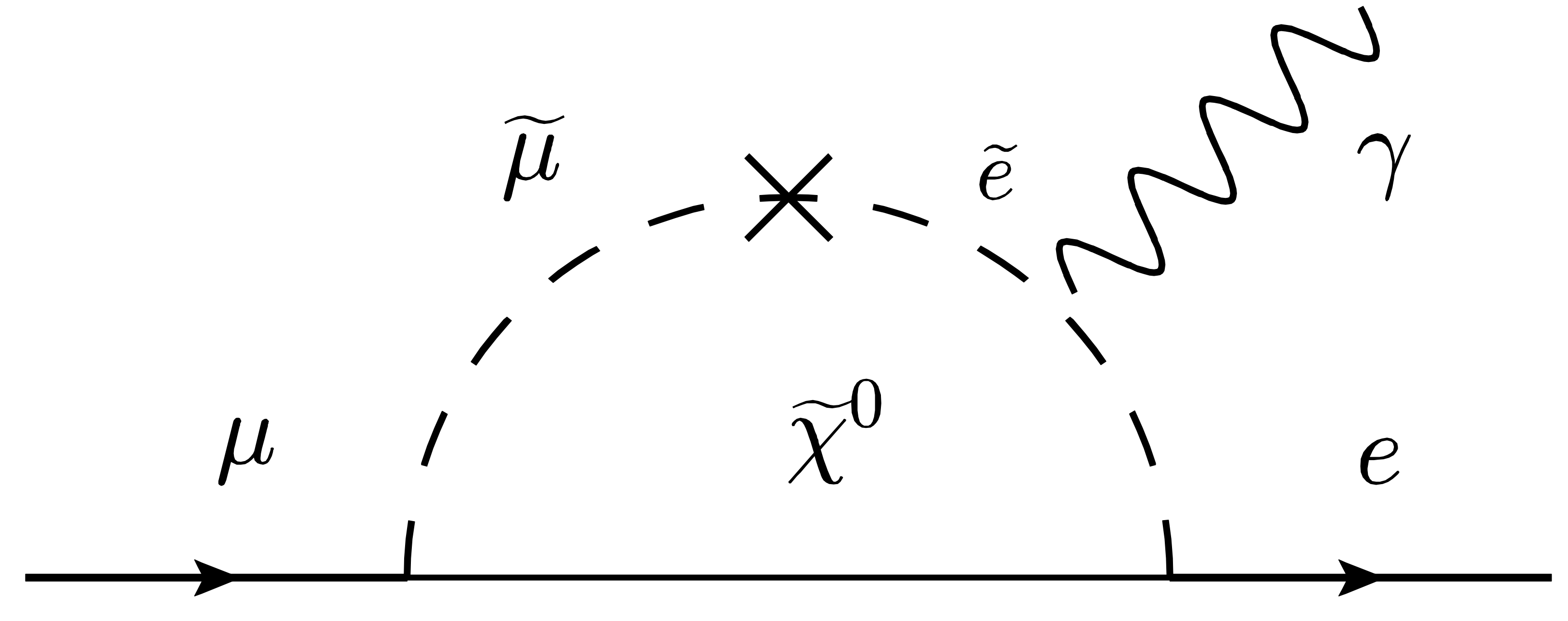
From Wikipedia

Standard Model + Neutrino oscillation



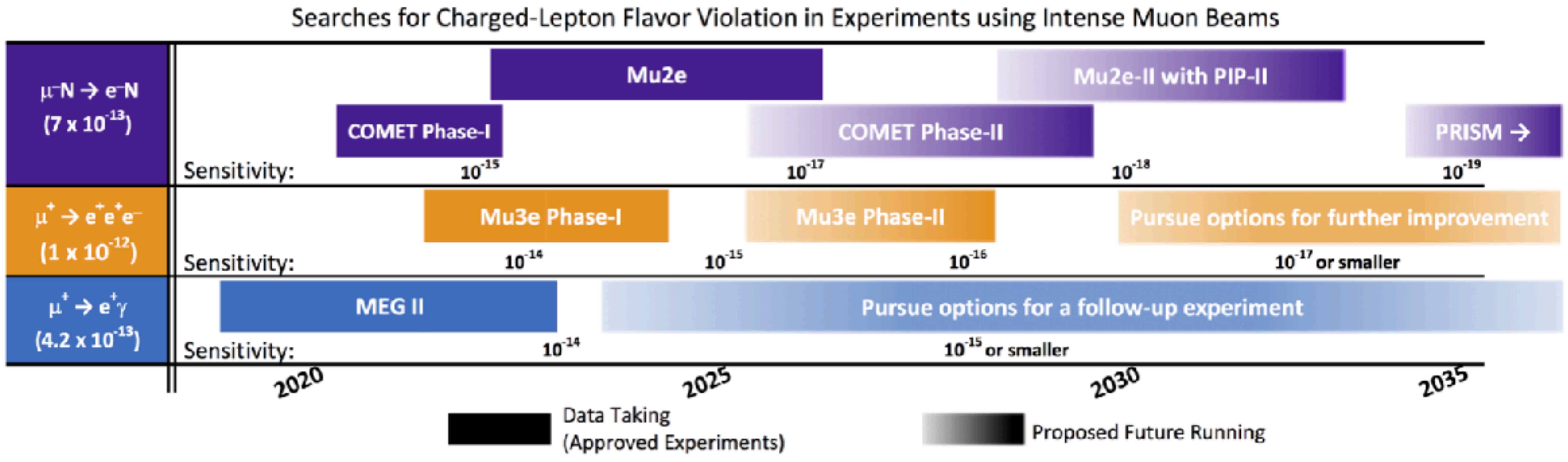
Br(μ→eγ) ~ 10^{-54}

New physics predictions (SUSY-GUT, SUSY-Seesaw etc.)



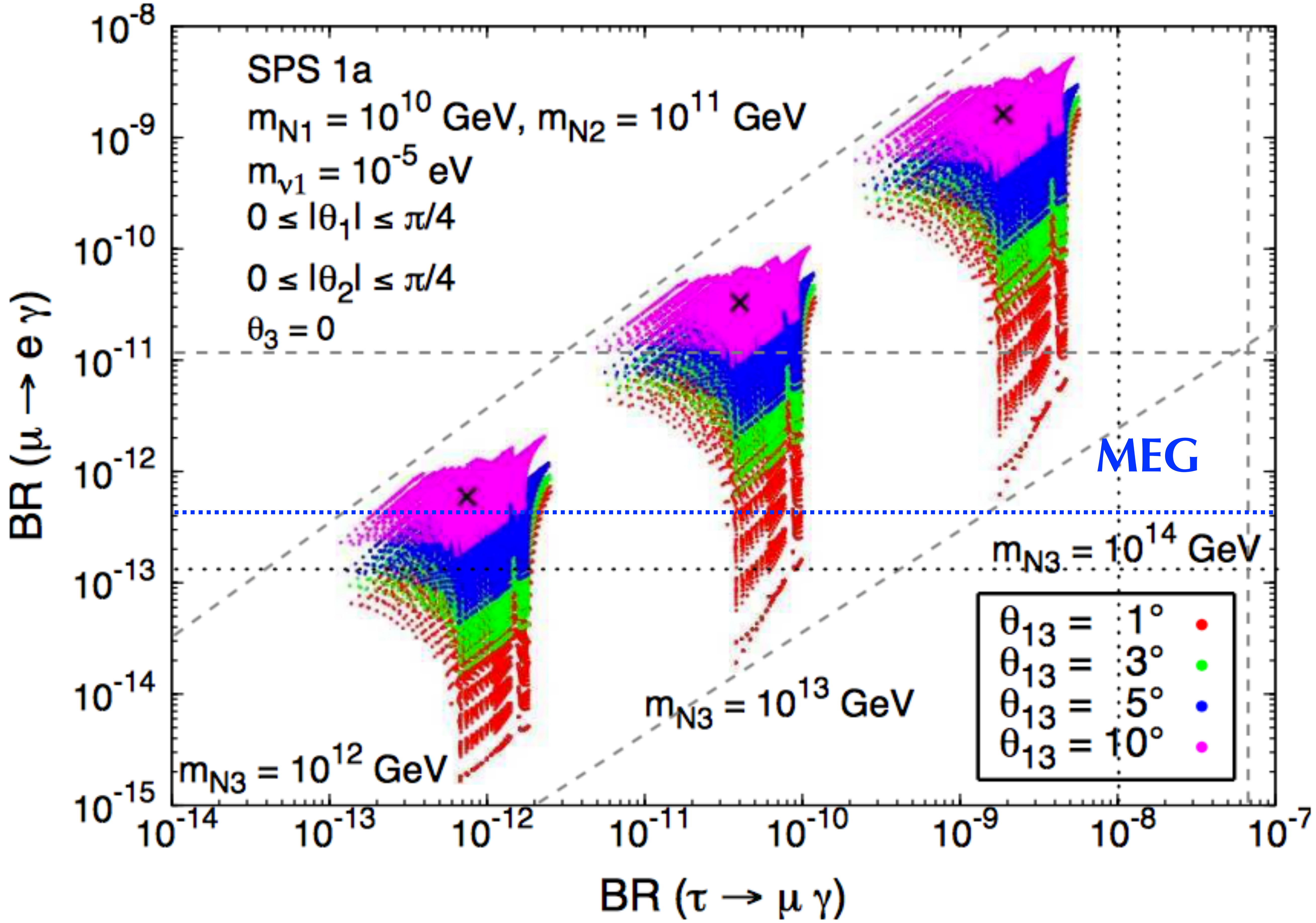
Br(μ→eγ) ~ 10^{-14}

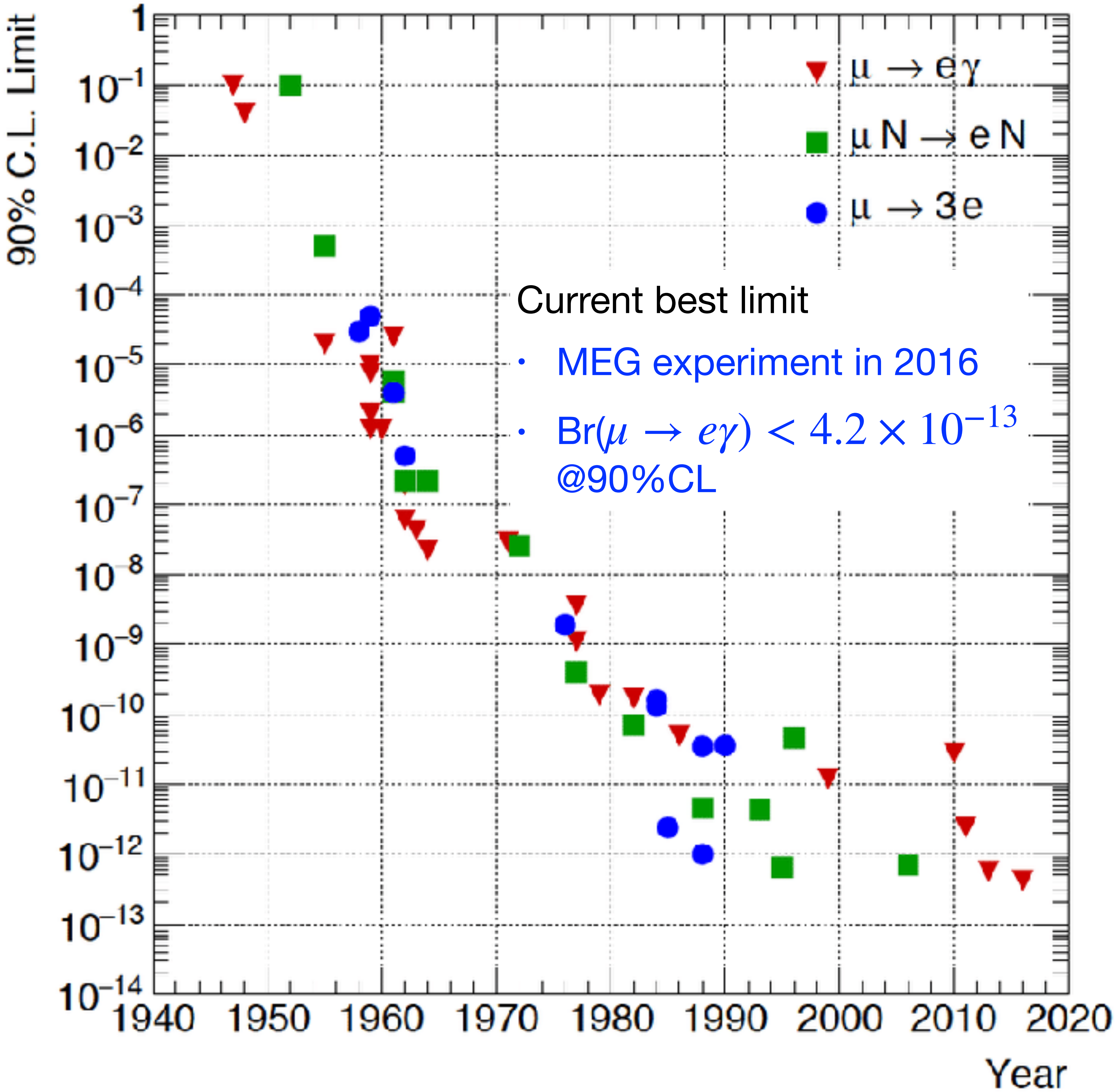
$\mu^+ \to e^+\gamma$



S. Antusch et al, JHEP 0611:090(2006)

SUSY-Seesaw





Current best limit

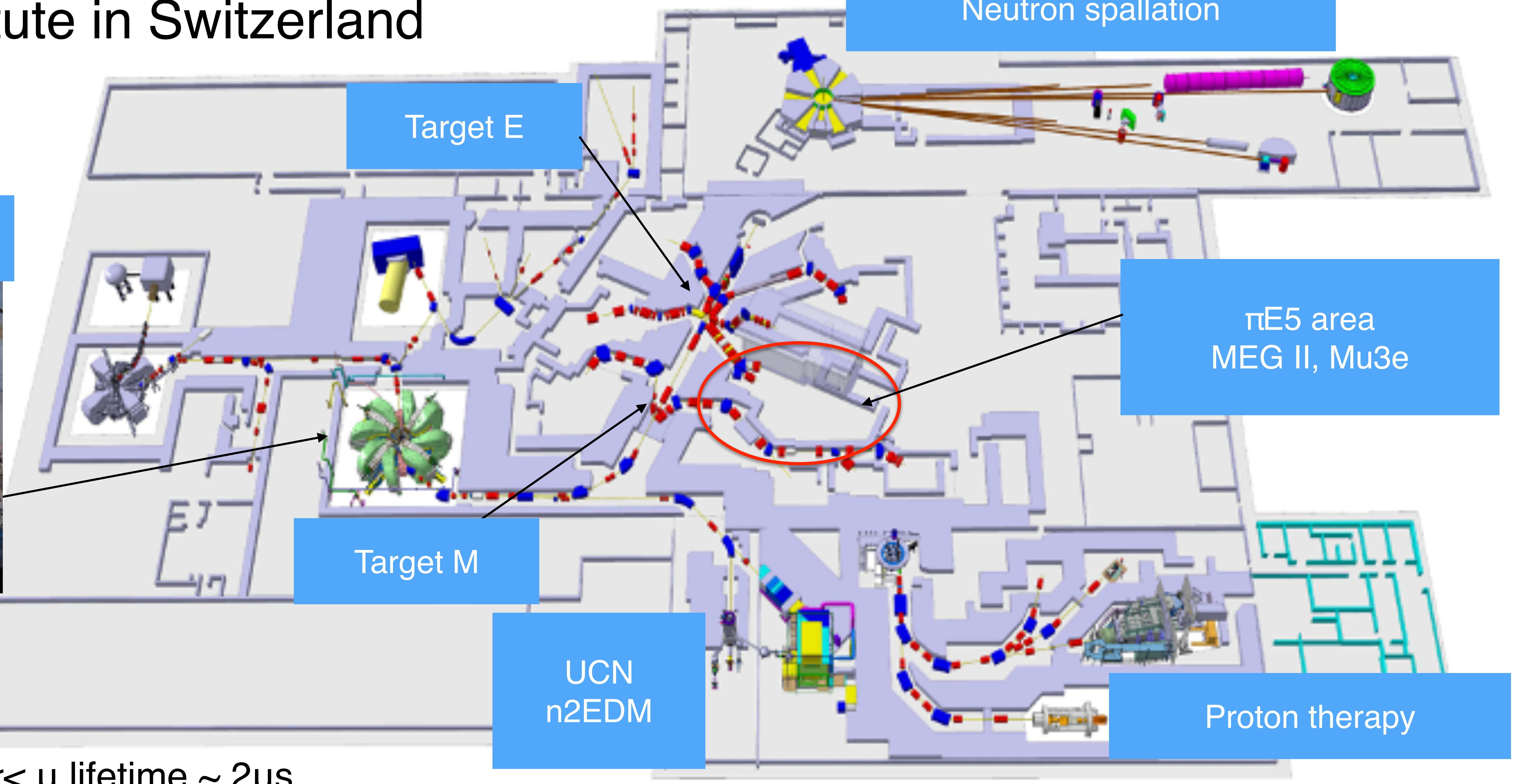
- MEG experiment in 2016
- $Br(\mu \to e\gamma) < 4.2 \times 10^{-13}$ @90%CL

High intensity muon beam (DC)

Paul Scherrer Institute in Switzerland

590 MeV 2.4mA
proton ring cyclotron

Proton accelerator



Neutron spallation

Target E

πE5 area
MEG II, Mu3e

Target M

UCN
n2EDM

Proton therapy

50 MHz RF time structure << μ lifetime ~ 2μs

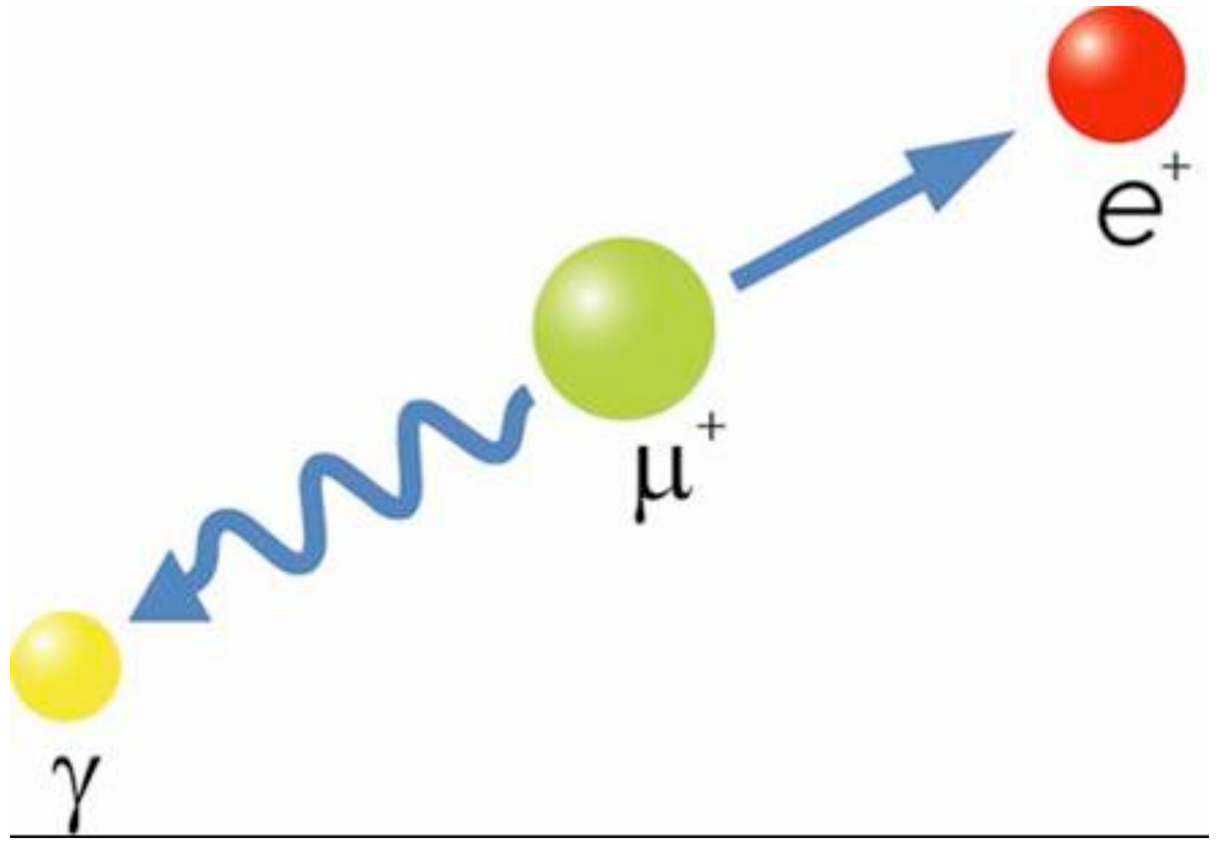
No time structure in muon decay (continuous)

World most intense DC muon beam > 10^8 μ/s

Surface muon beam ~ 29 MeV/c

$\mu \to e\gamma$ signal and background

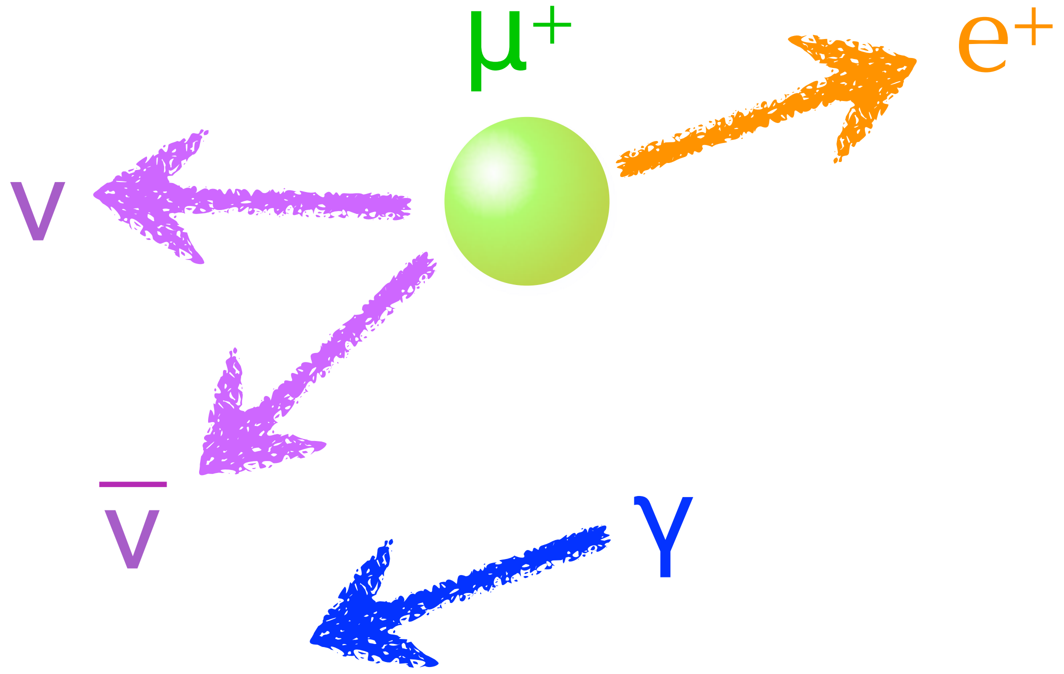
Signal



$$E_\gamma, E_e \sim 52.8\ MeV$$
$$\Theta_{e\gamma} = 180^\circ, T_\gamma = T_e$$

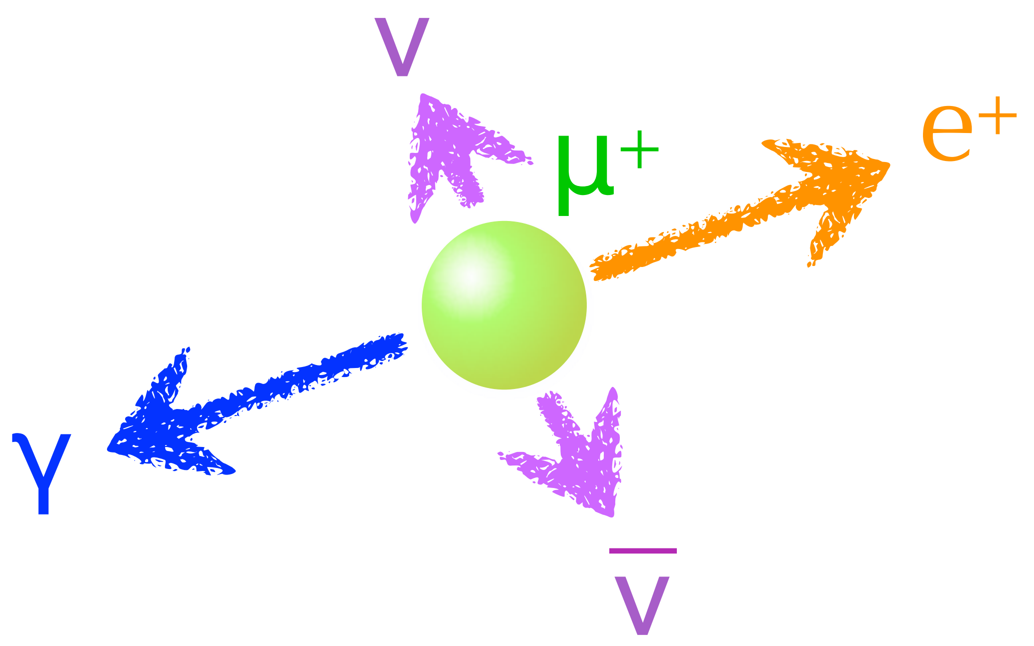
Background

Accidental Dominant BG



Michel e+ + random γ
from RMD/ AIF

Radiative Muon Decay



e+-γ timing coincident

$$N_{acc} \propto (R_\mu)^2 \times (\Delta E_\gamma)^2 \times \Delta E_e \times (\Delta\Theta_{e\gamma})^2 \times \Delta t_{e\gamma} \times T$$

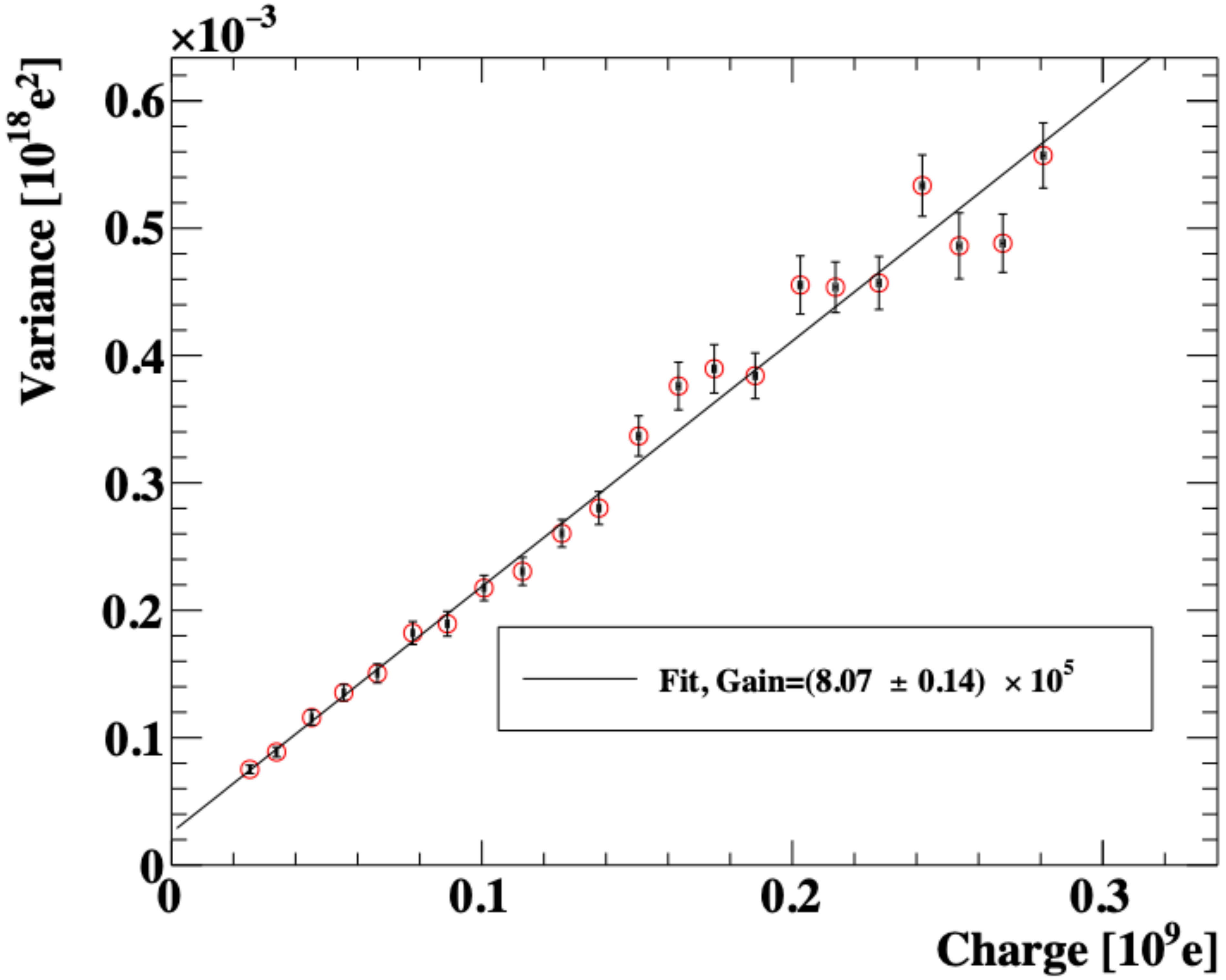
- High statistics: High intensity muon beam
- Low background:
  - Lower instantaneous muon beam rate (DC muon beam, not pulse beam)
  - Good detector resolutions

PMT gain calculation

- Photon statistics relations

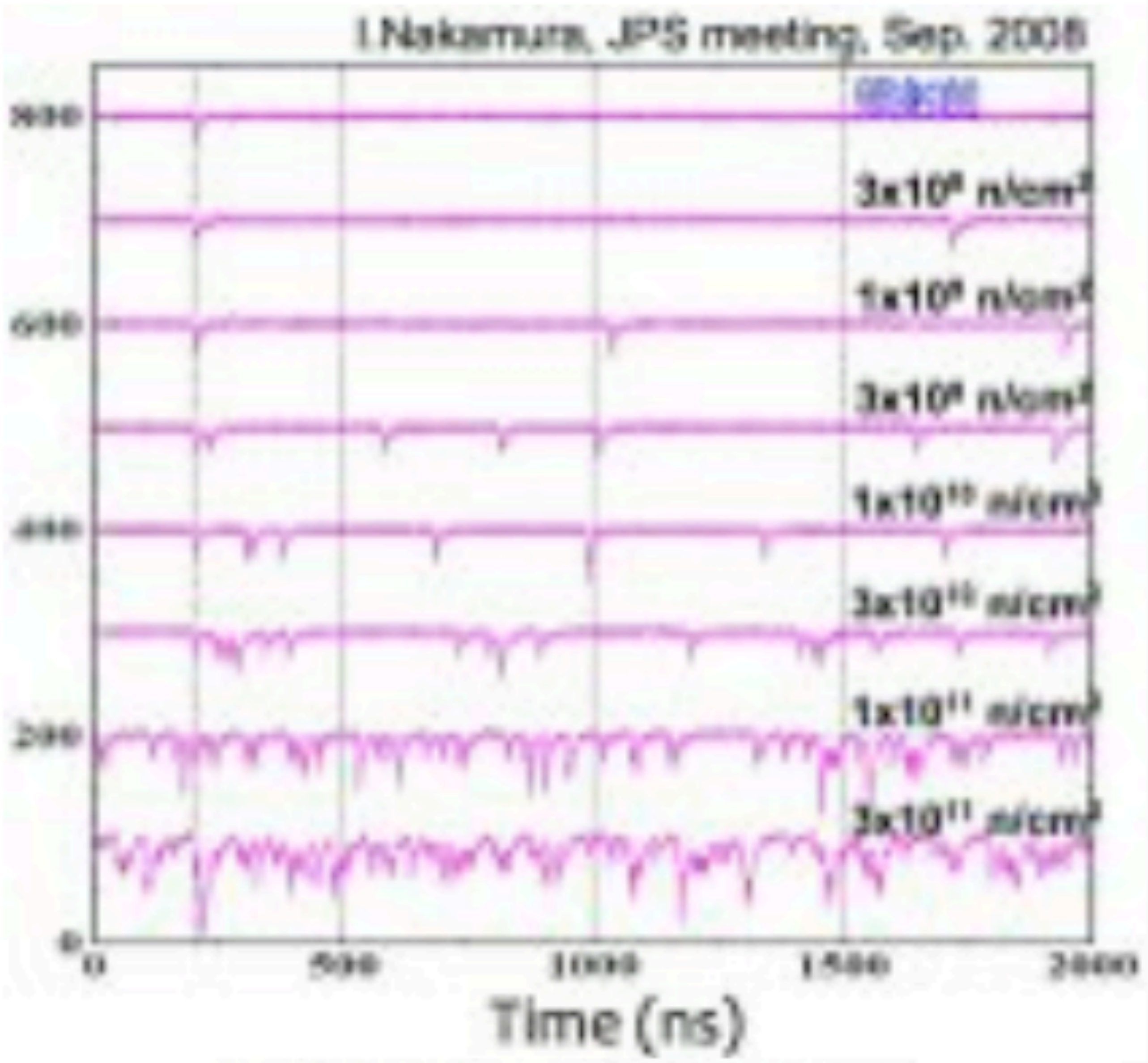
$$\sigma_Q^2 = G \cdot e \cdot \overline{Q} + \sigma_0^2$$

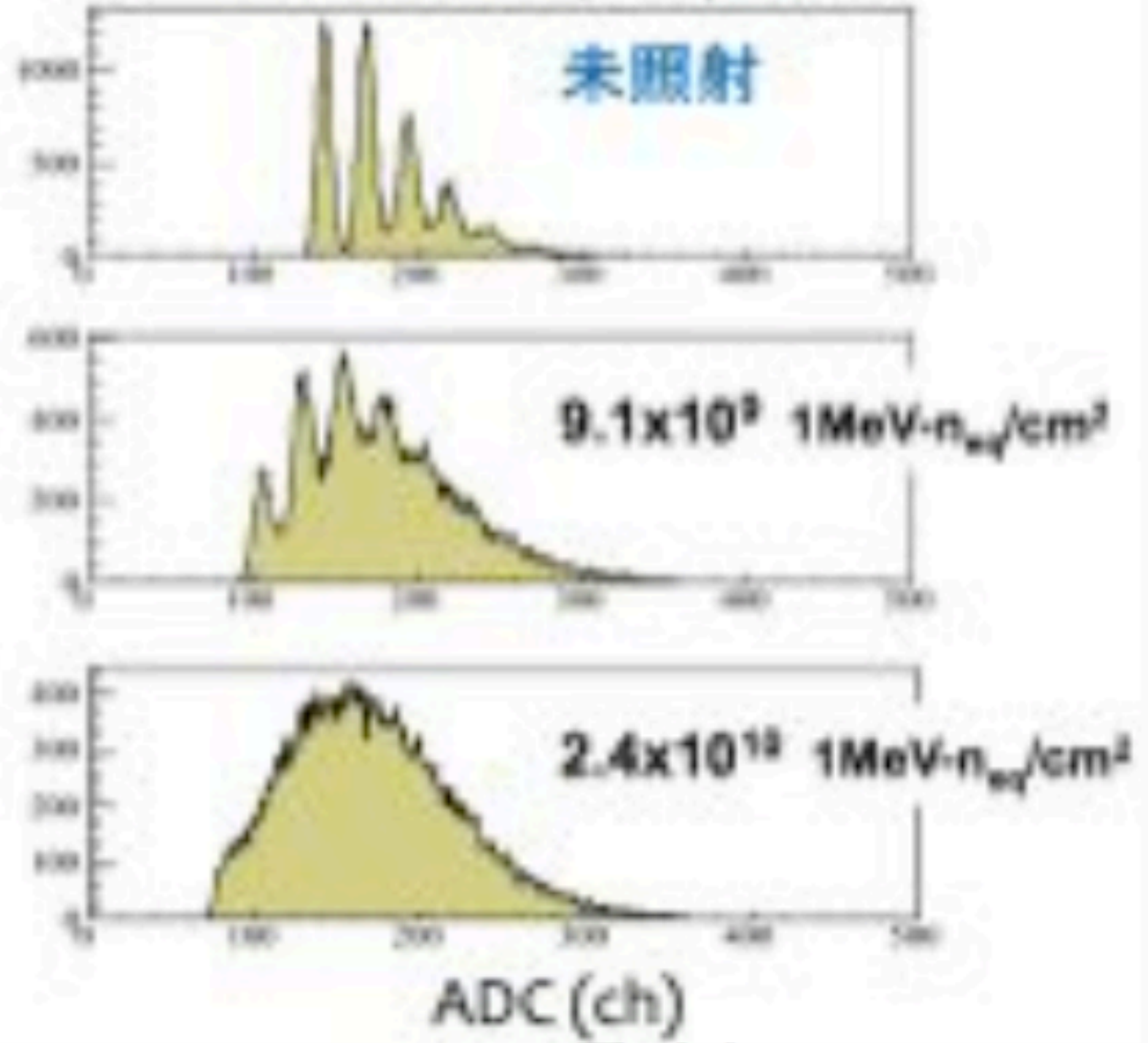
  - σ_Q^2: spread of integrated charge distribution
  - G: gain
  - e: elementary charge
  - $\bar{Q}$: mean of integrated charge



Radiation hardness

- Radiation produces defect in silicon bulk or Si/ SiO_2 interface
  - Dark count rate, leakage current, PDE, ...
- Fast neutron
  - $>10^8$ n/cm^2 Increase of dark count rate
  - $>10^{10}$ n/cm^2 Loss of single p.e. detection capability
  - <1 n/s/cm^2(>0.1MeV) ~ $<1.6x10^8$ n/cm^2 for full 5-years operation in πE5 area in PSI
  - ~3.5n/s/cm^2 ~ 10^7 n/cm^2 for one week CEX run per year for 5-years
- γ-ray
  - 200Gy Increase of leak current
  - MC: 0.58Gy with 10^8 μ/s for 5-years for MEG
- Radiation damage might not be an issue for MEG.

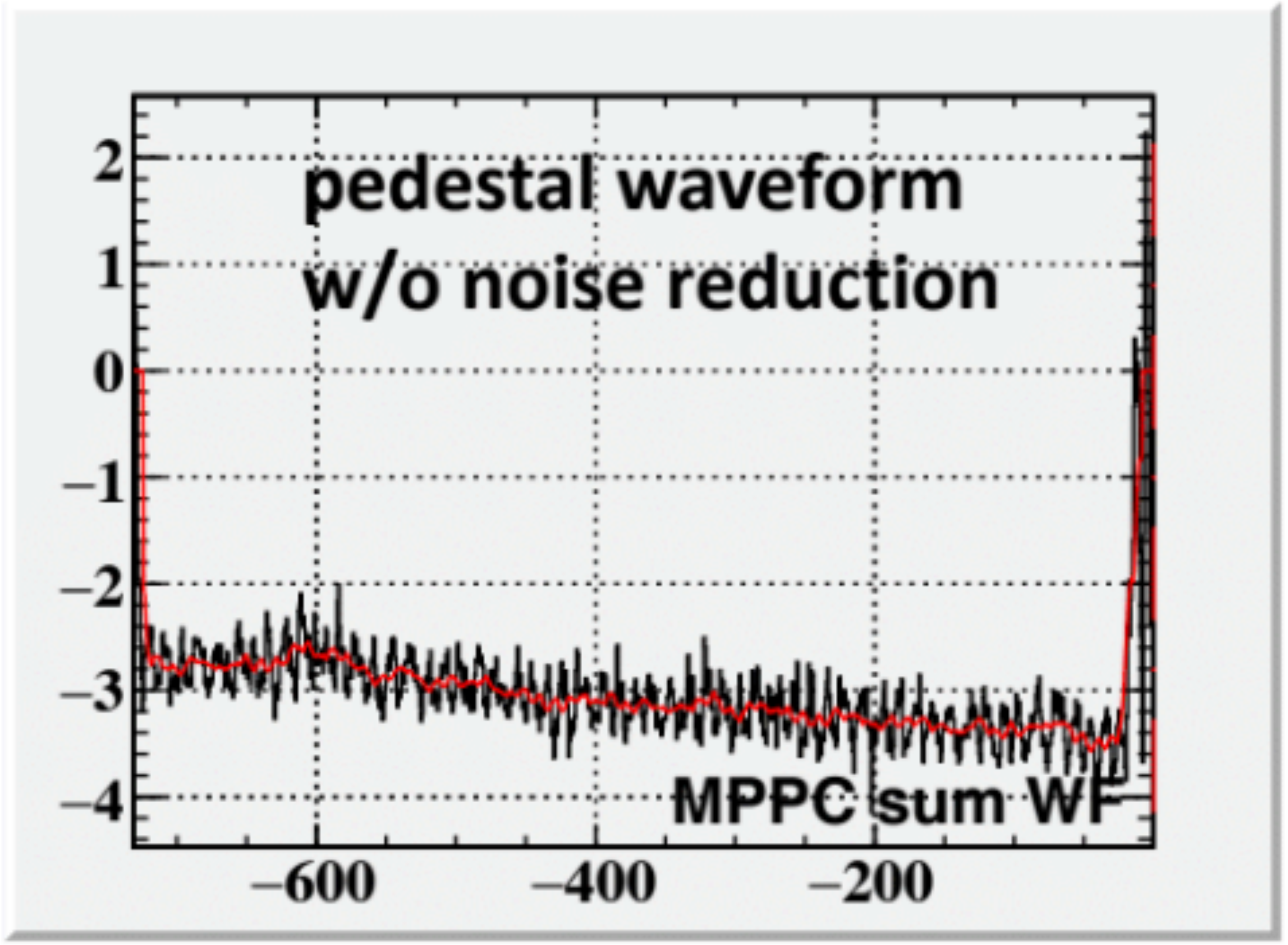

I.Nakamura, JPS meeting, Sep. 2008

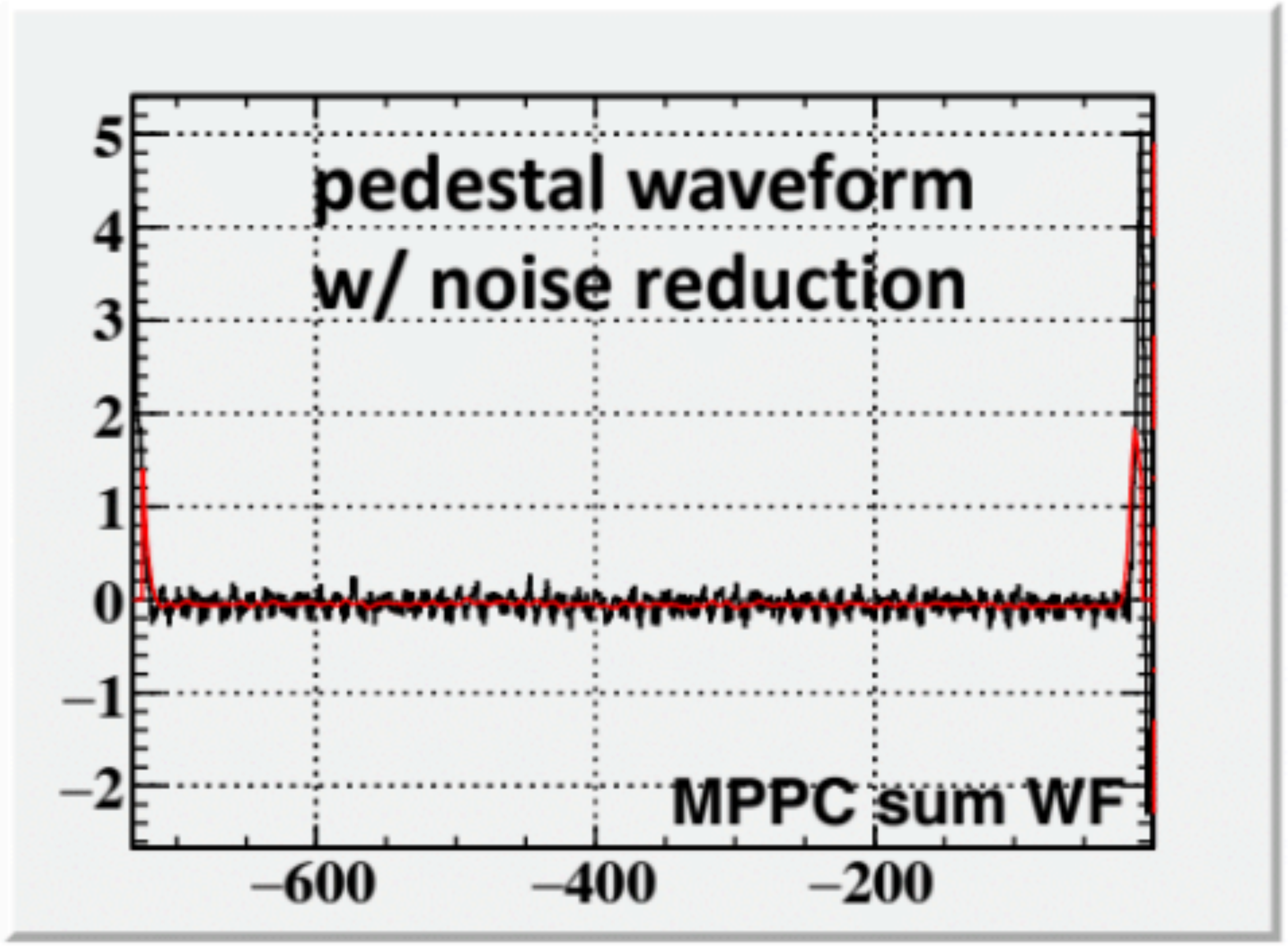

T.M. et al, PoS (PD07)033, 2007

T. Matsumura et al.

Noise reduction

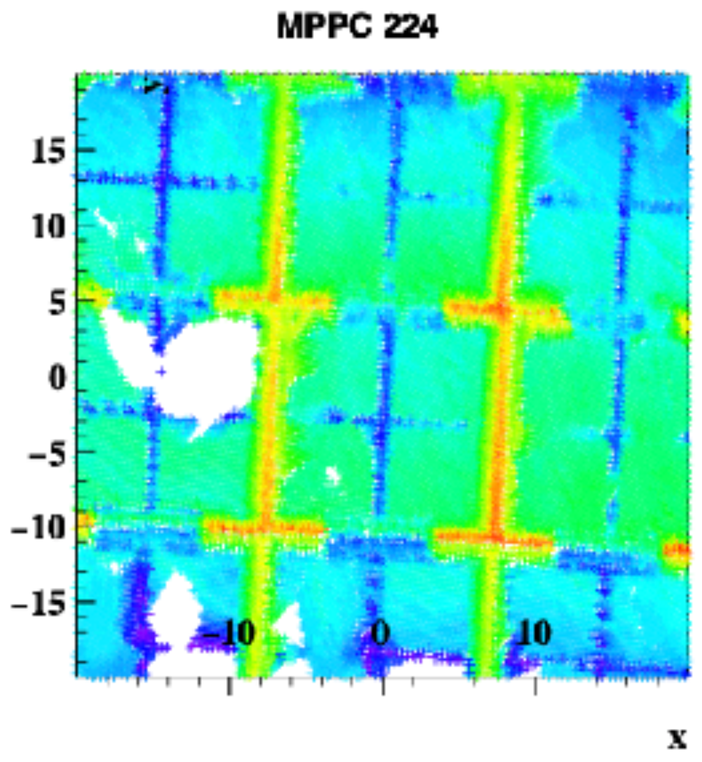
- Temperature dependent template (slope from waveform digitizer)
- Readout electronics voltage offset template
- High frequency noise template (clock signal in waveform digitizer)
- The first cell dependent noise template

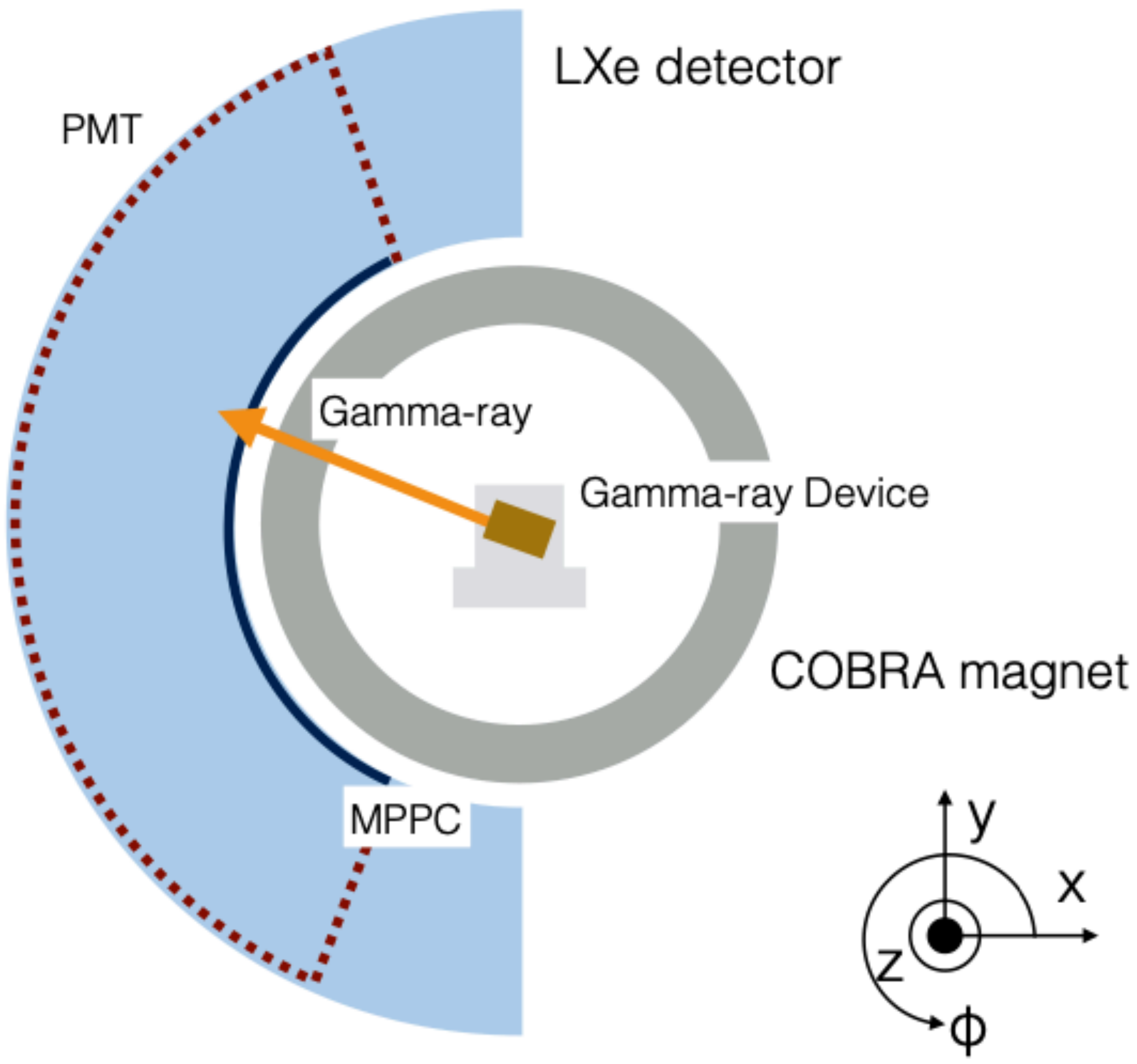


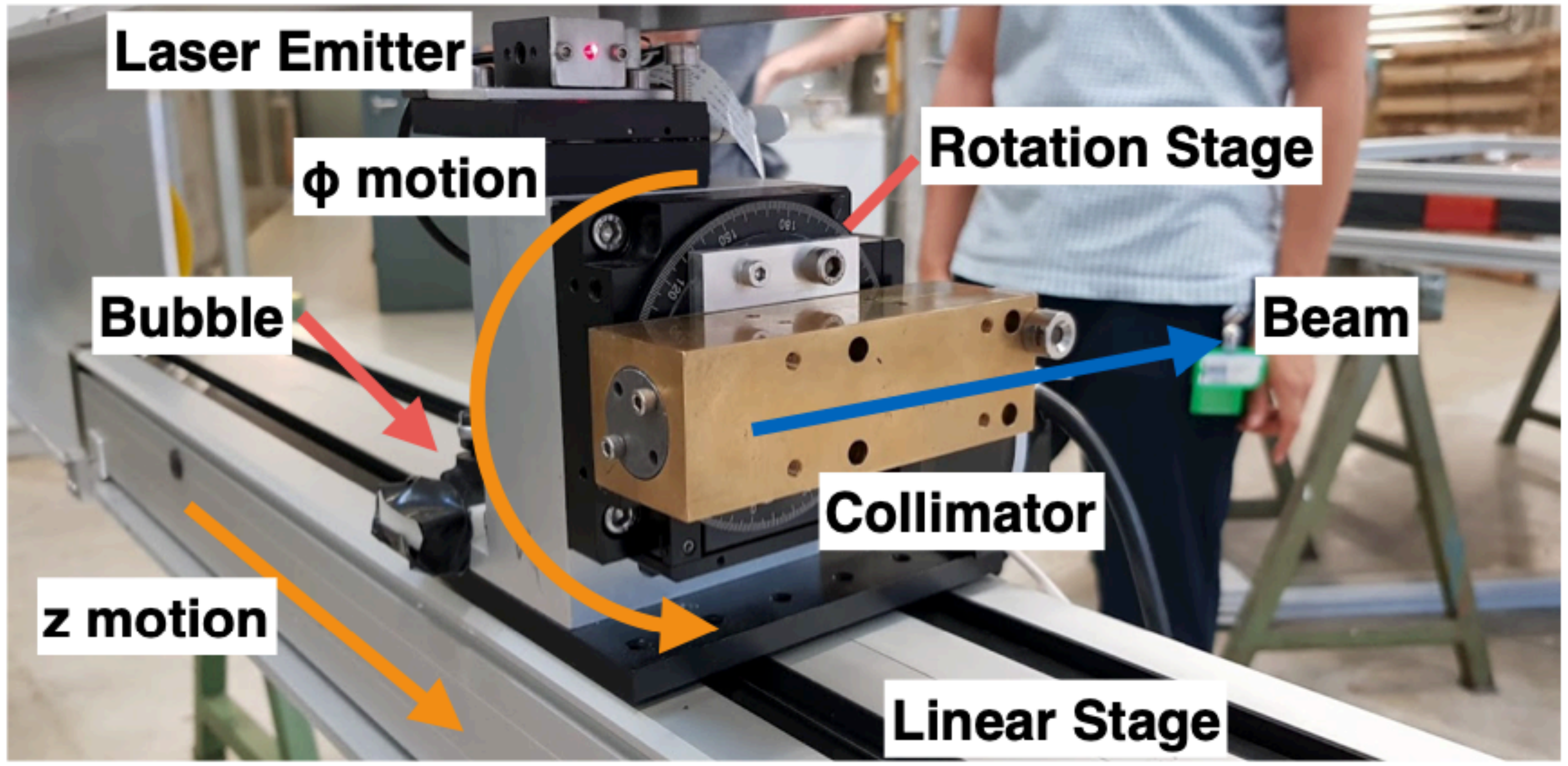


MPPC alignment

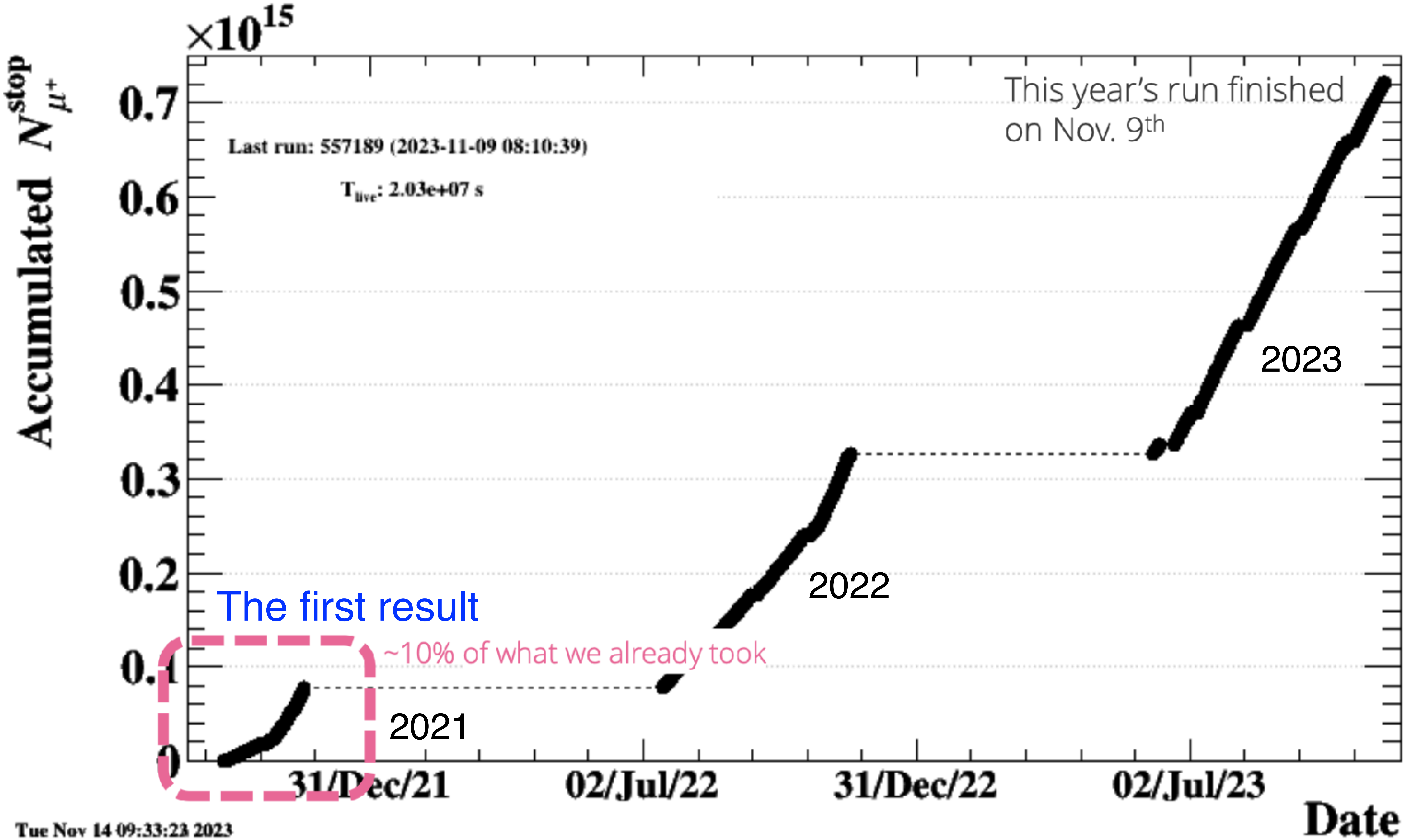
- MPPC position alignment
  - Direct optical alignment at room temperature
  - Collimated γ beam to the detector with LXe
    - To take into account thermal expansion of MPPC supports (CFRP, PCB)
- Combined result
  - position uncertainty 0.6mm in z and 0.75mrad in ϕ







MEG II data

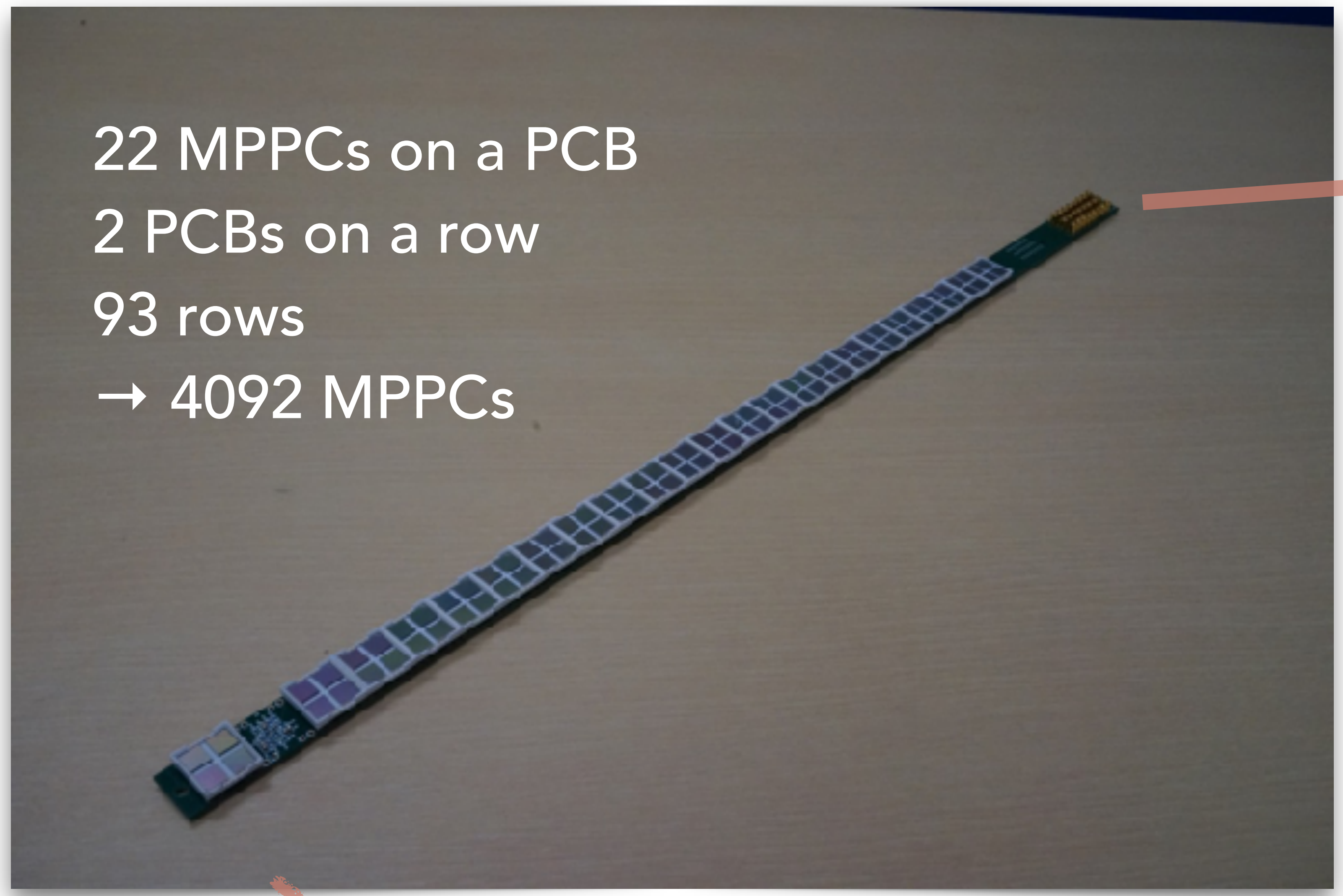


This year's run finished on Nov. 9th

The first result

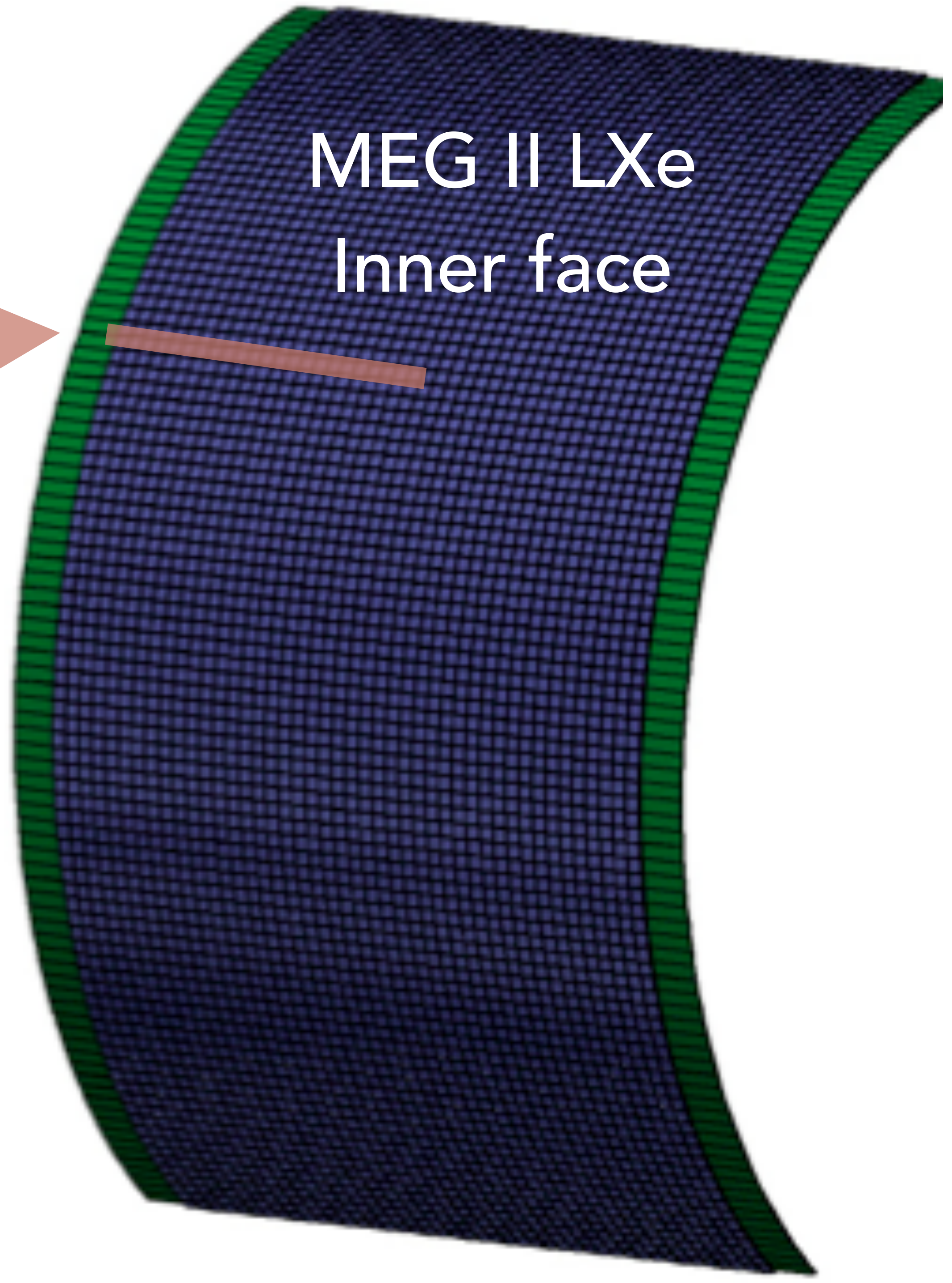
~10% of what we already took

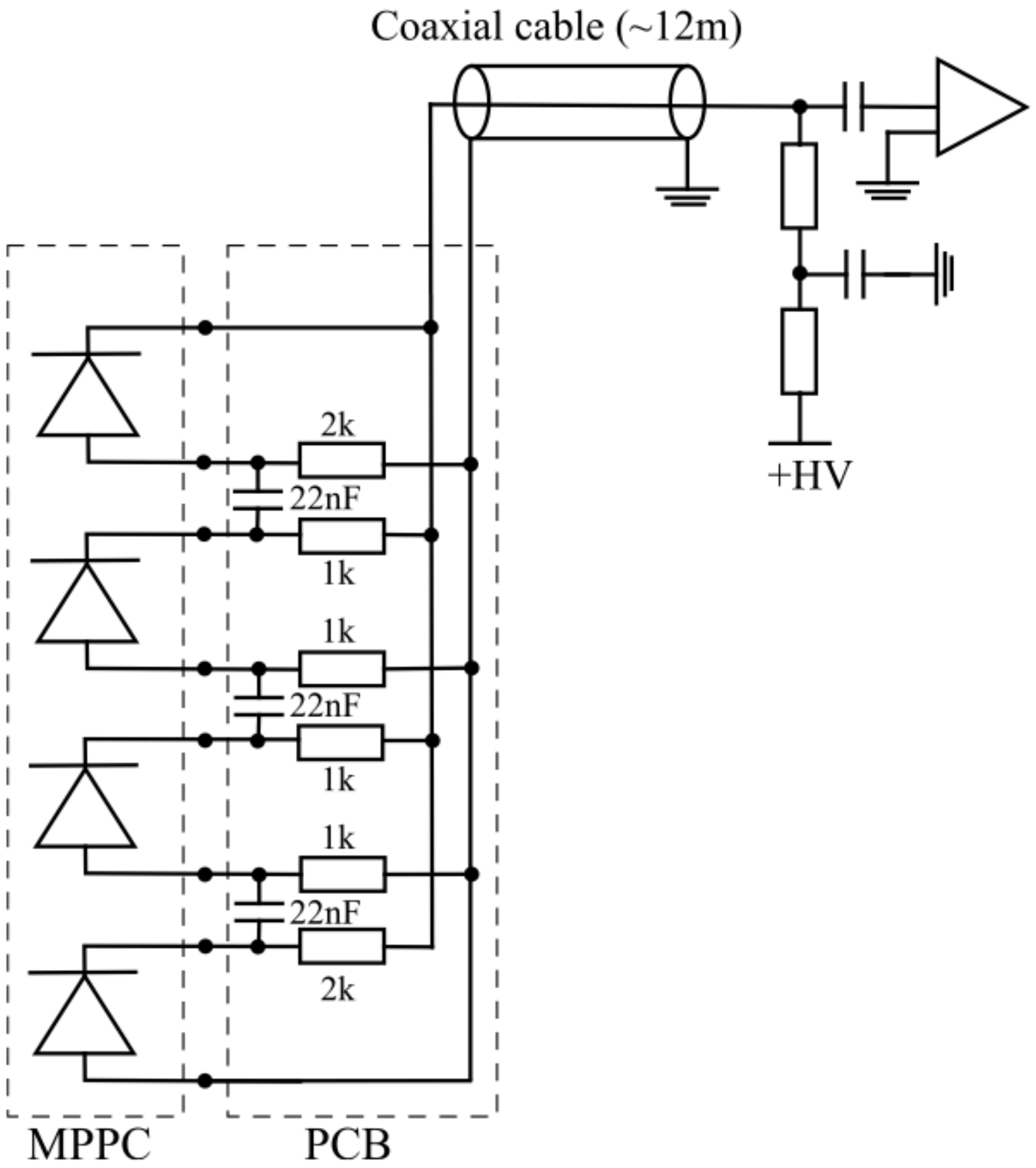
Signal readout scheme



22 MPPCs on a PCB
2 PCBs on a row
93 rows
→ 4092 MPPCs

Coaxial cable (2.5-4.9m)

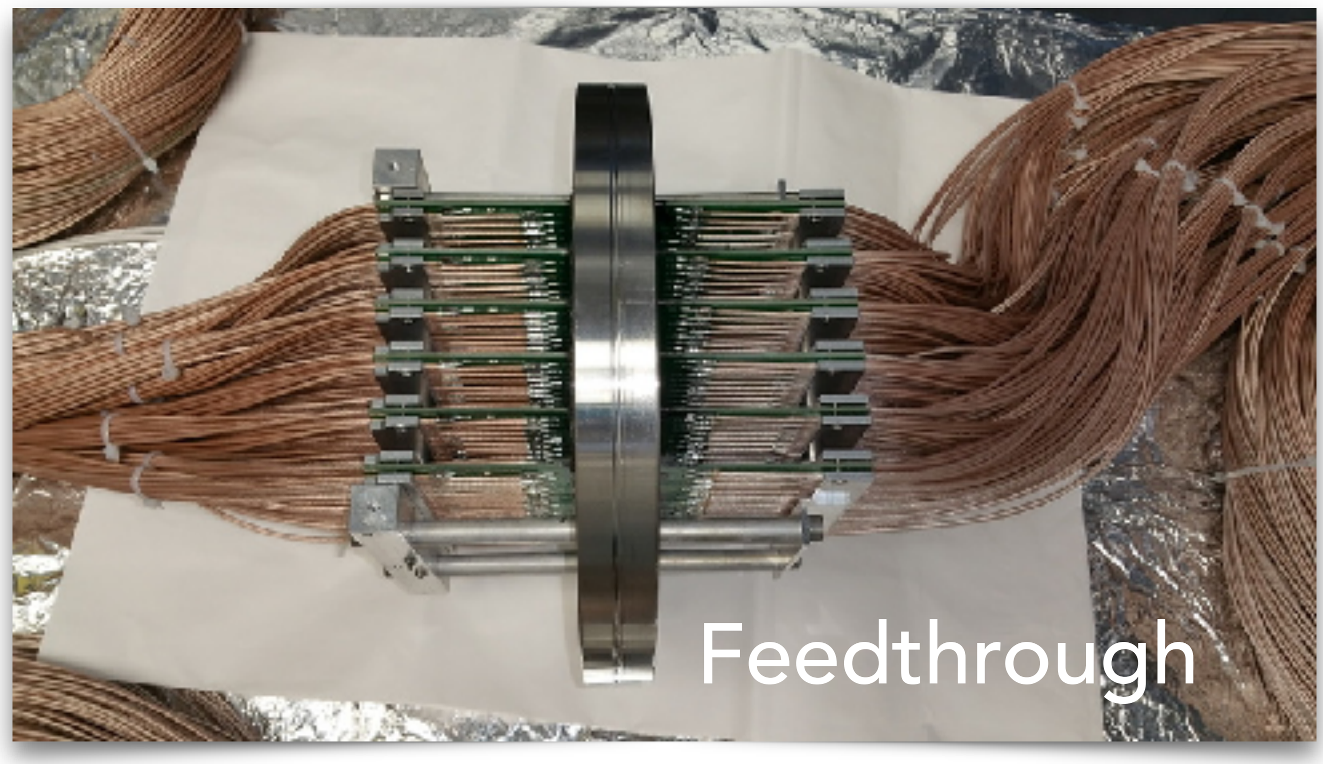




High density
PCB-based
feedthrough
(custom-made)

432ch / flange

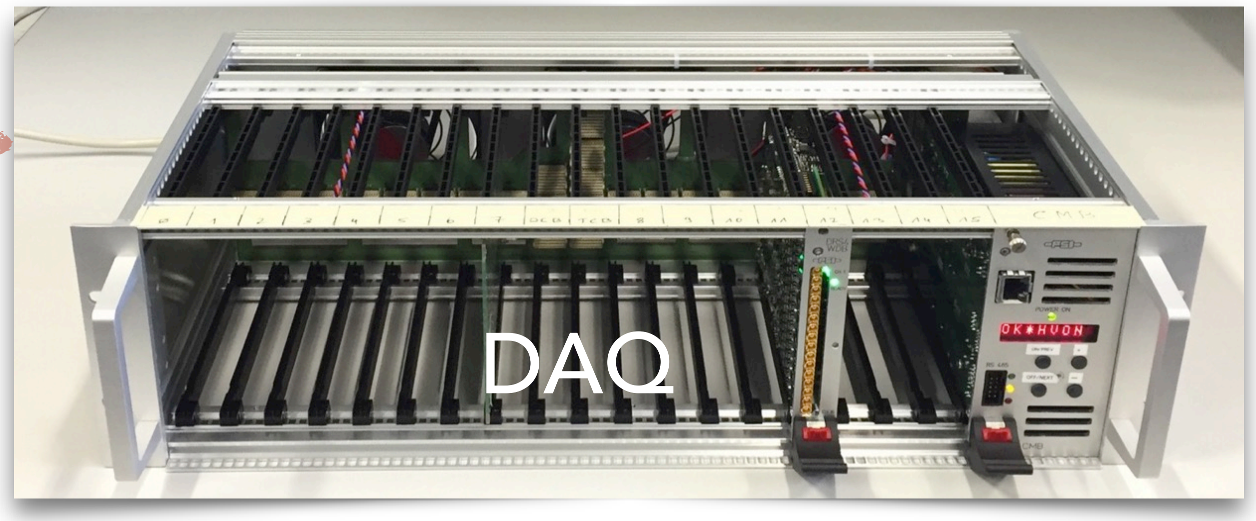
x 10 flanges



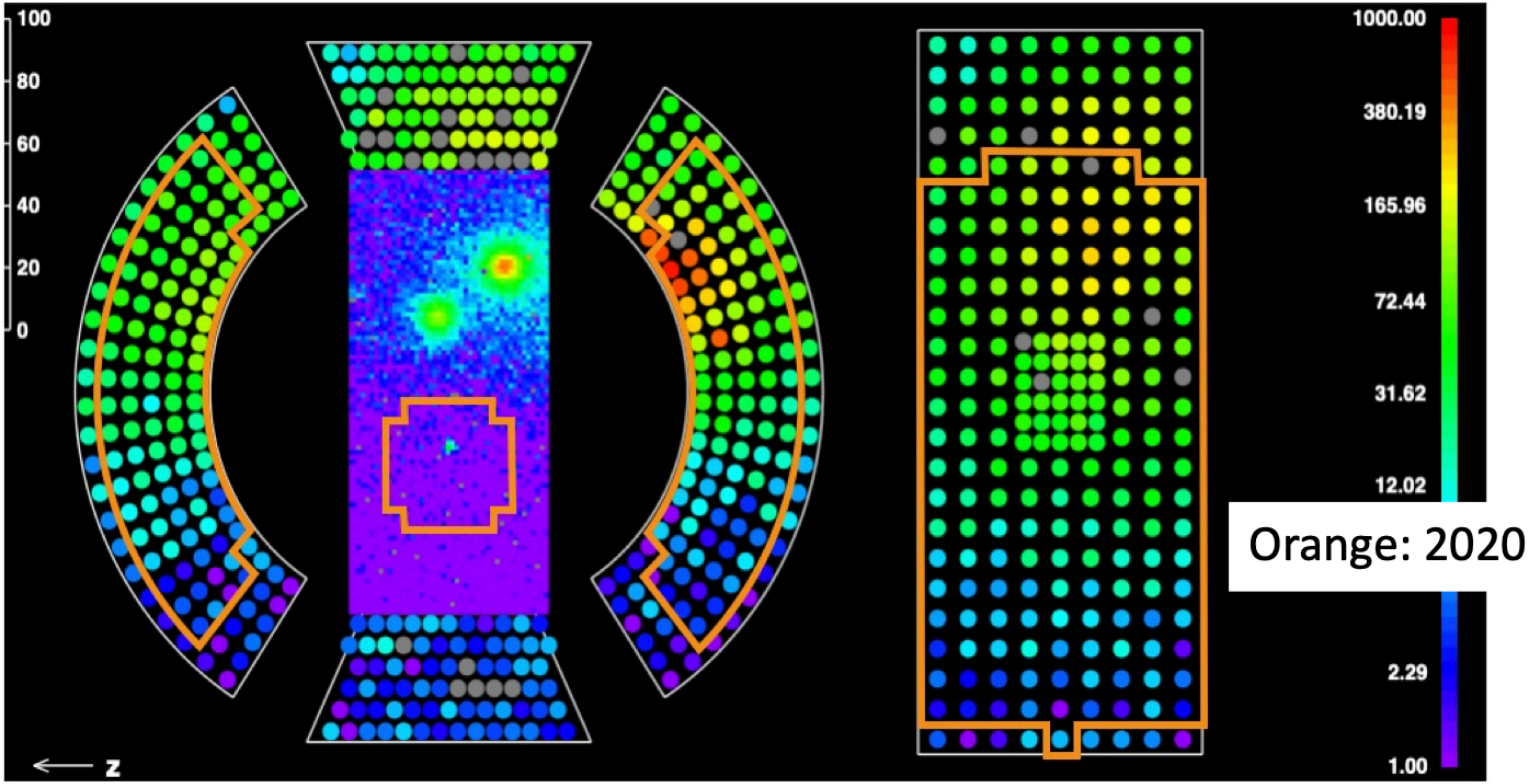
Coaxial cable (8.5m)

Waveform digitizer

Fully integrated DAQ board including bias supply for SiPM, waveform digitizer, FPGA-based trigger (WaveDREAM)



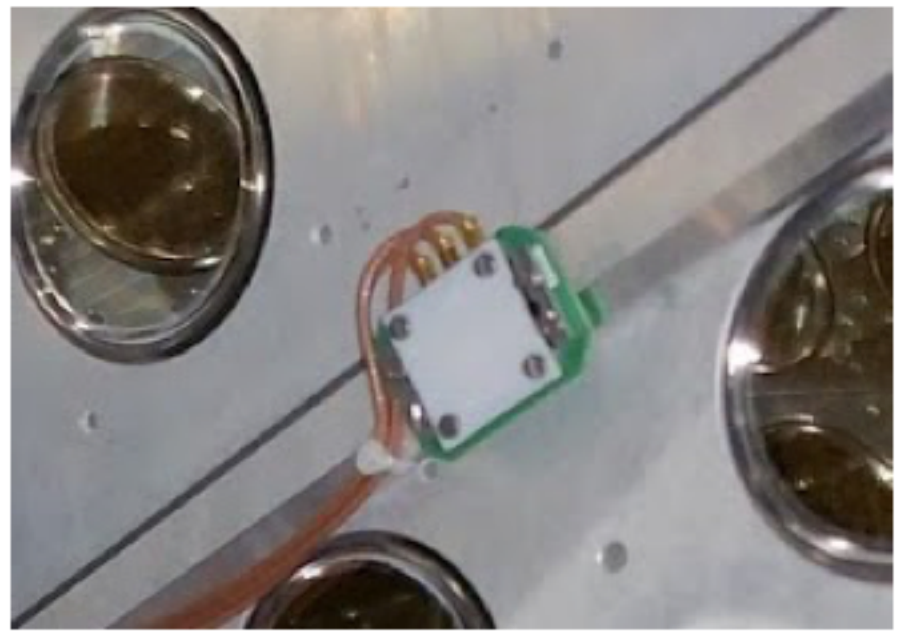
LXe detector commissioning

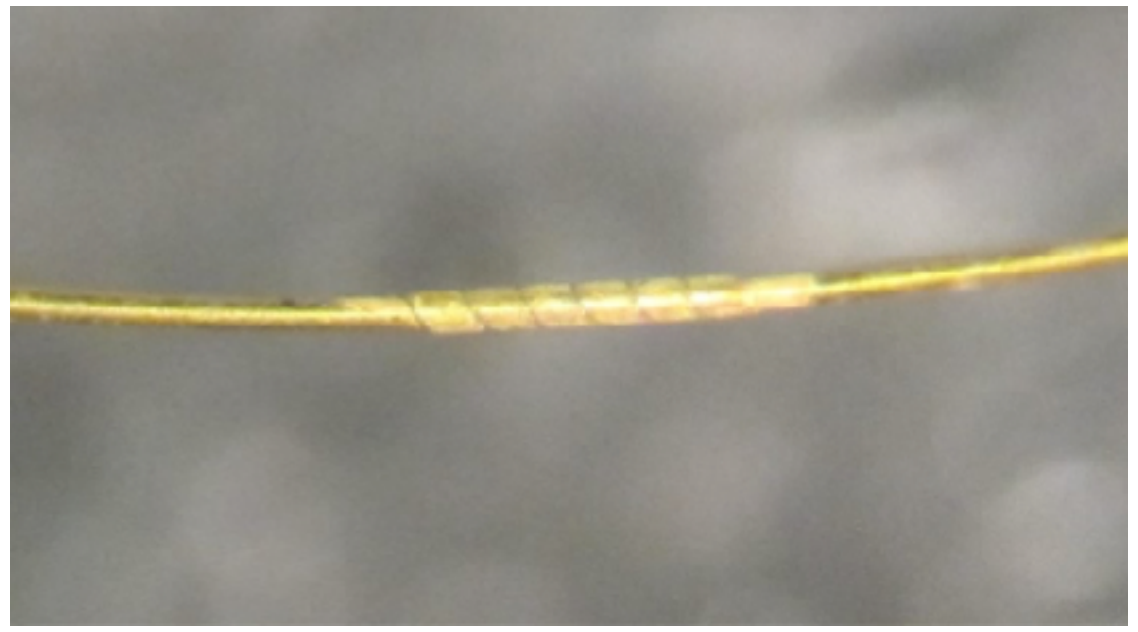


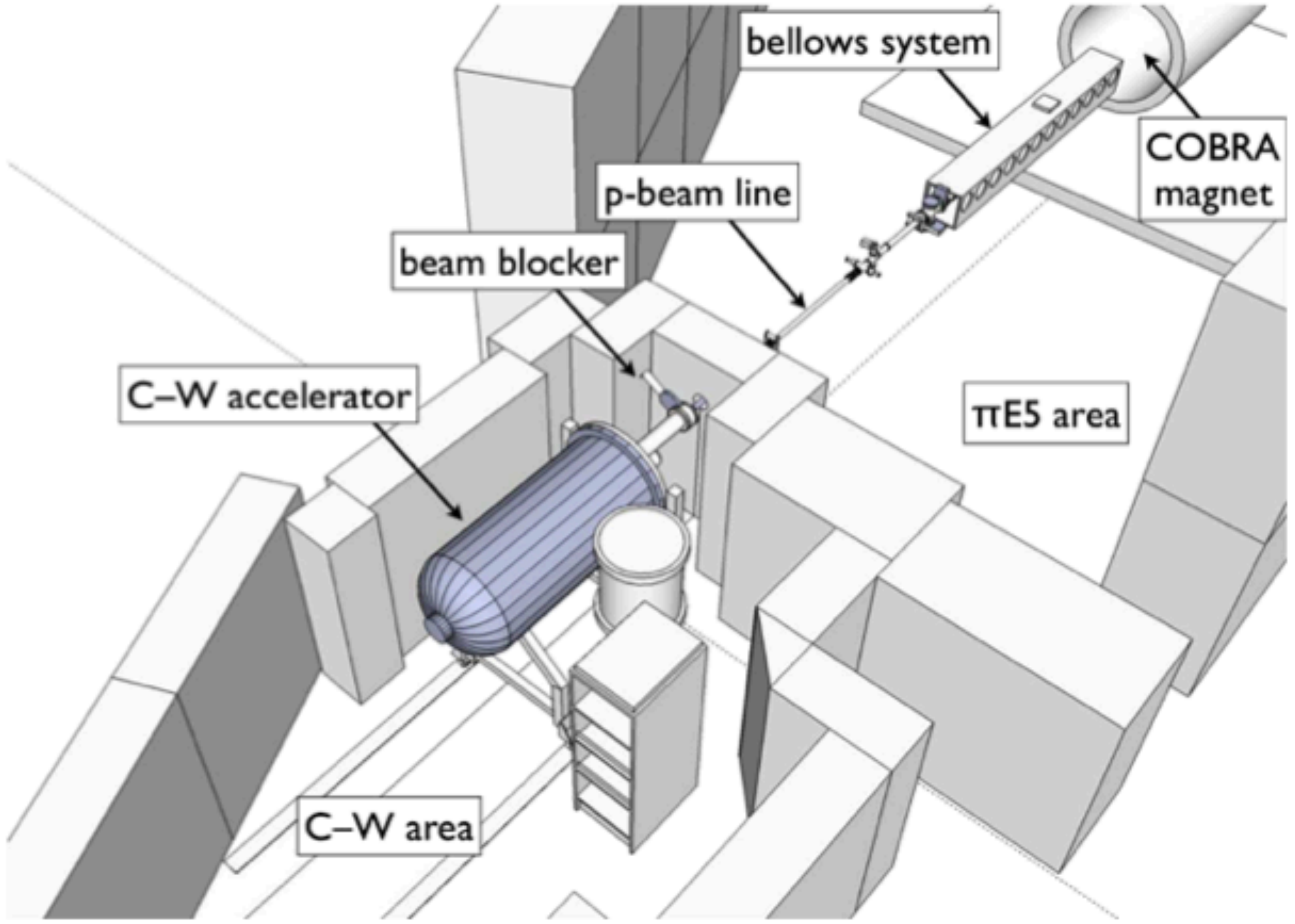
- 2017 Detector construction completed
  - sensor calibration, muon beam run with reduced number of readout sensors
- 2021 Full electronics ready, detector performance evaluation work started

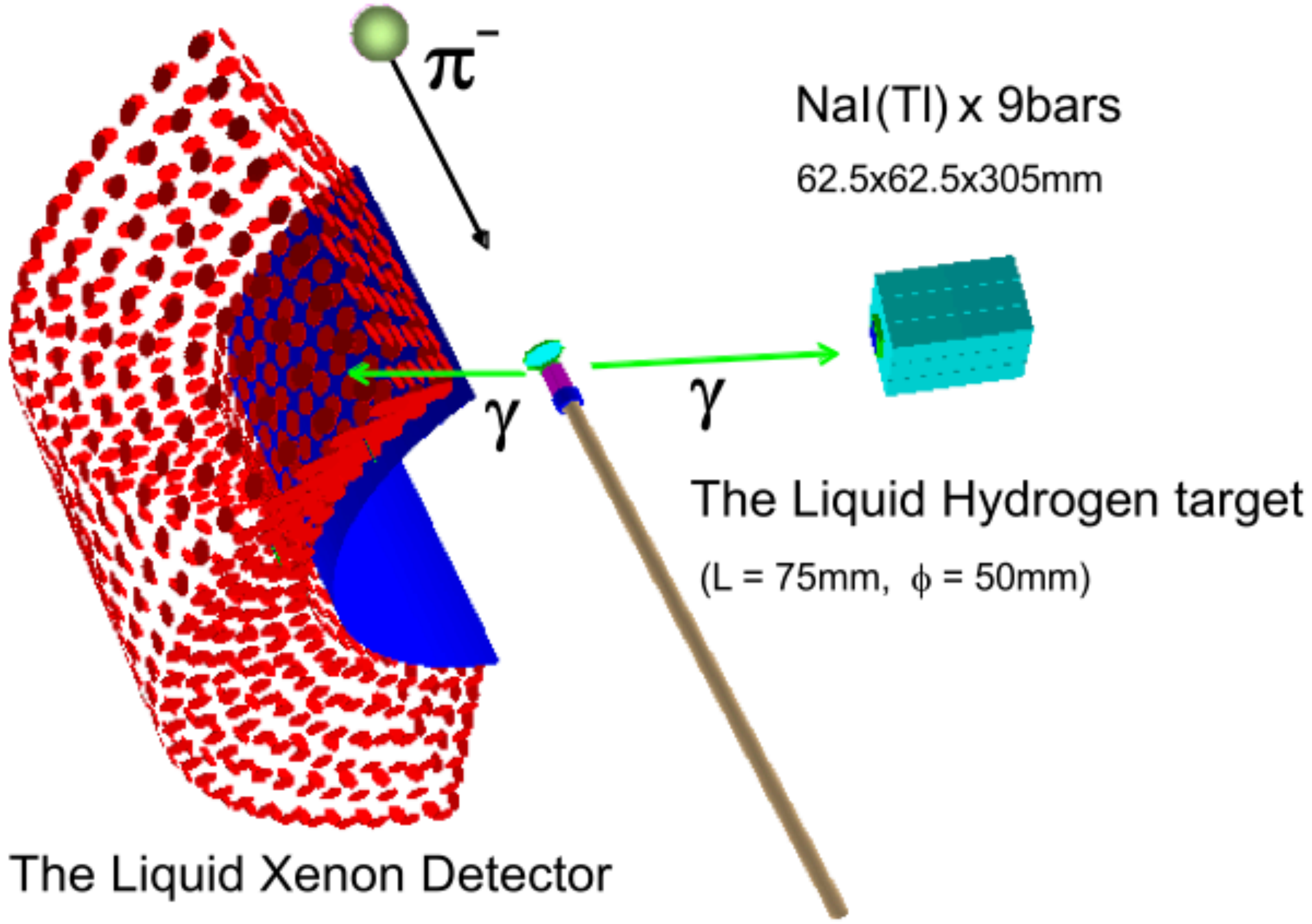
LXe detector event reconstruction & calibration

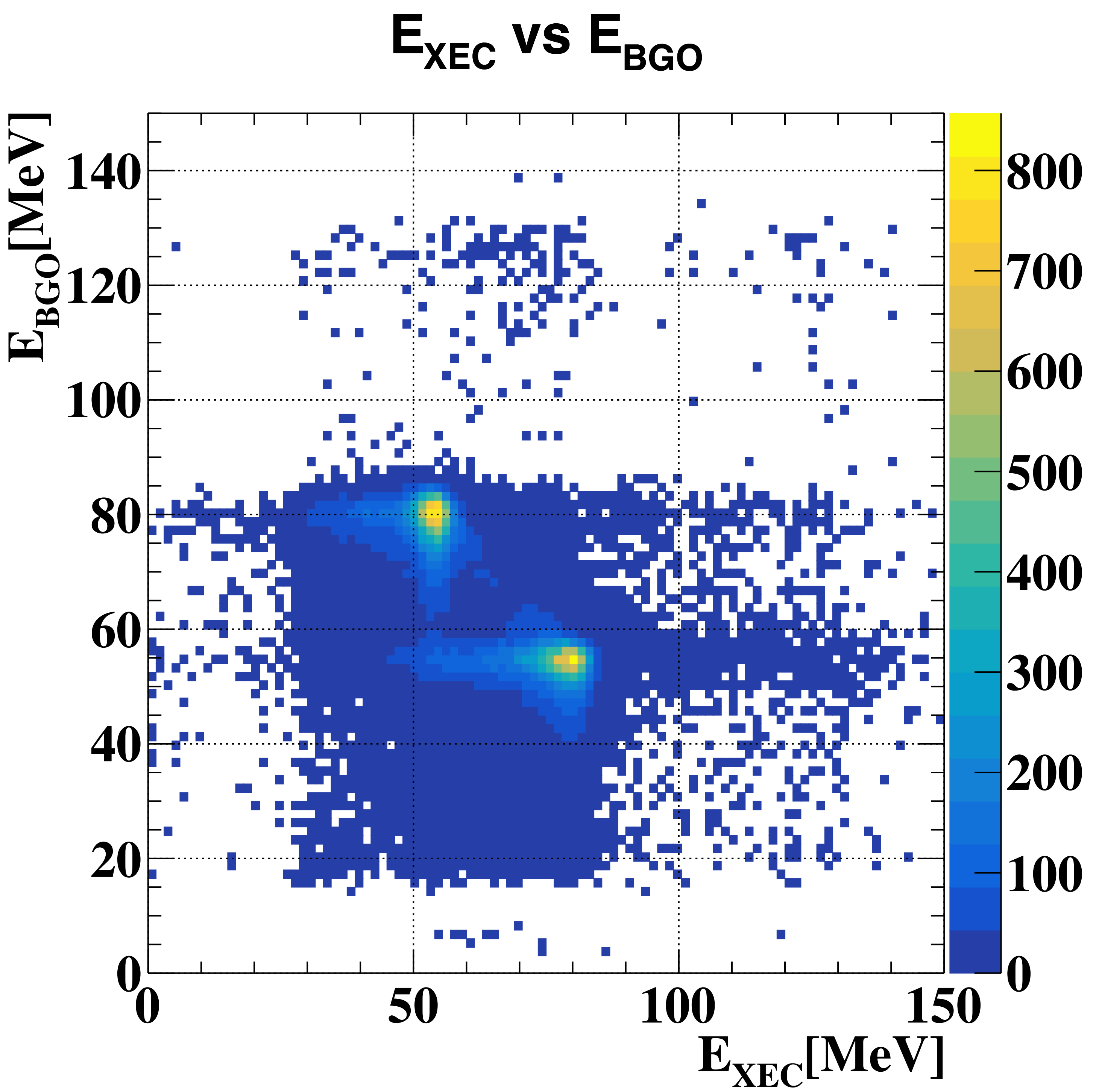
- Reconstruction
  - Energy : sum of MPPC/PMT charges
  - Position (3D) : MPPC/PMT charge distribution
  - Time : average MPPC/PMT time
- Calibration
  - LED for gain, ^{241}Am for PDE, QE
  - 17.6 MeV γ from ^{7}Li(p,γ)^{8}Be reaction
  - 55, 83 MeV γ from $\pi^{-}p \rightarrow \pi^{0}n$ reaction



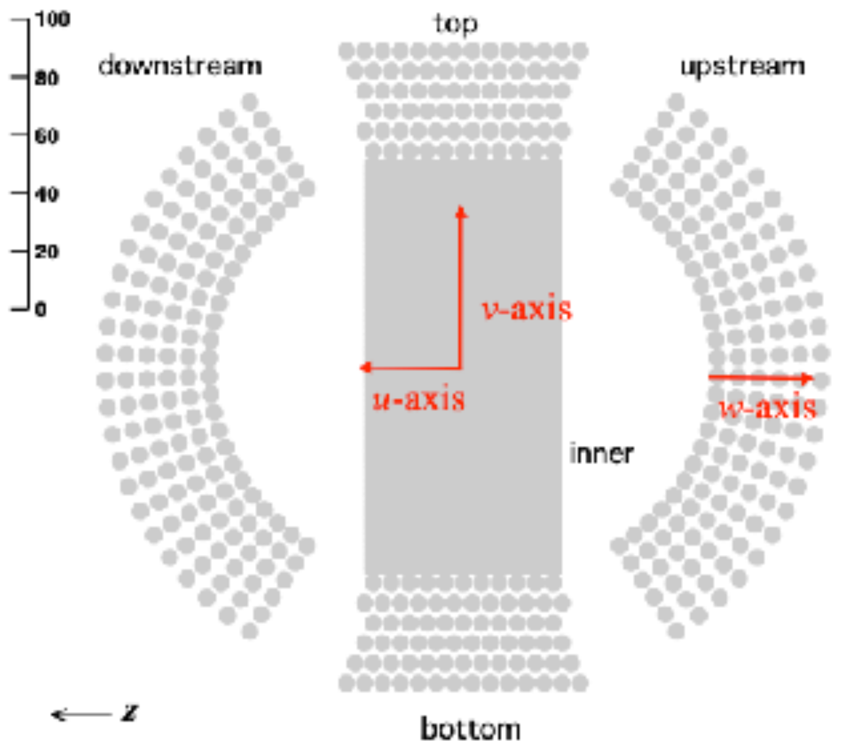


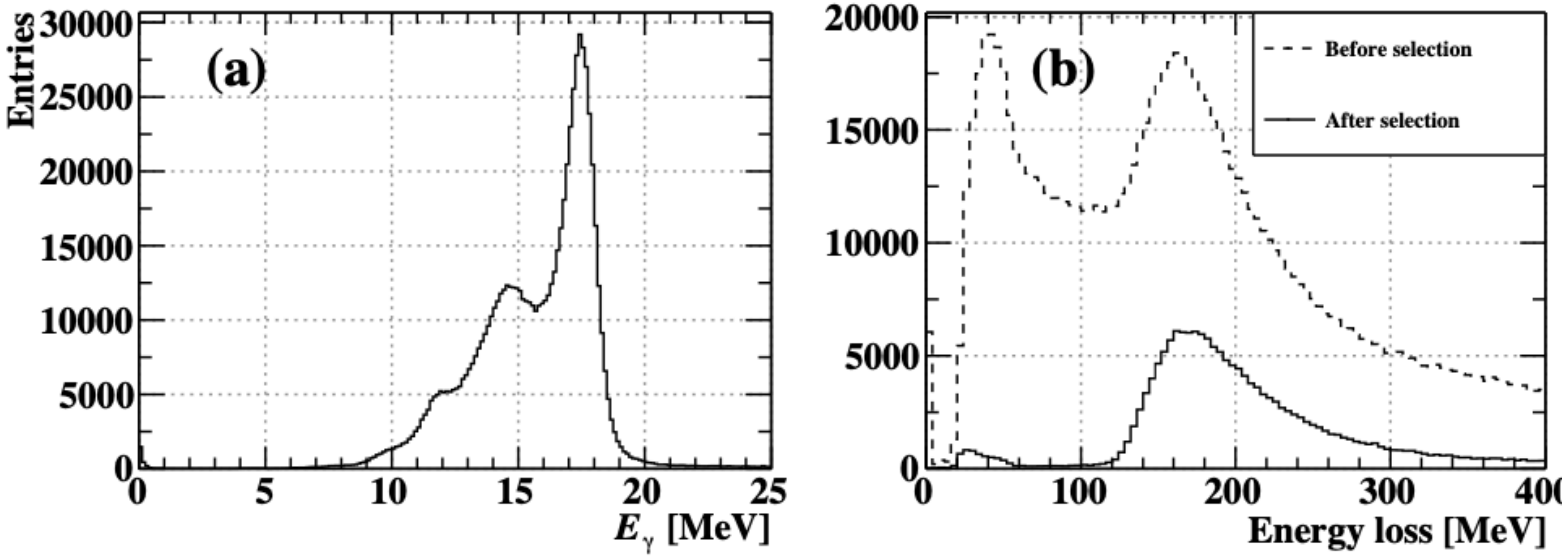




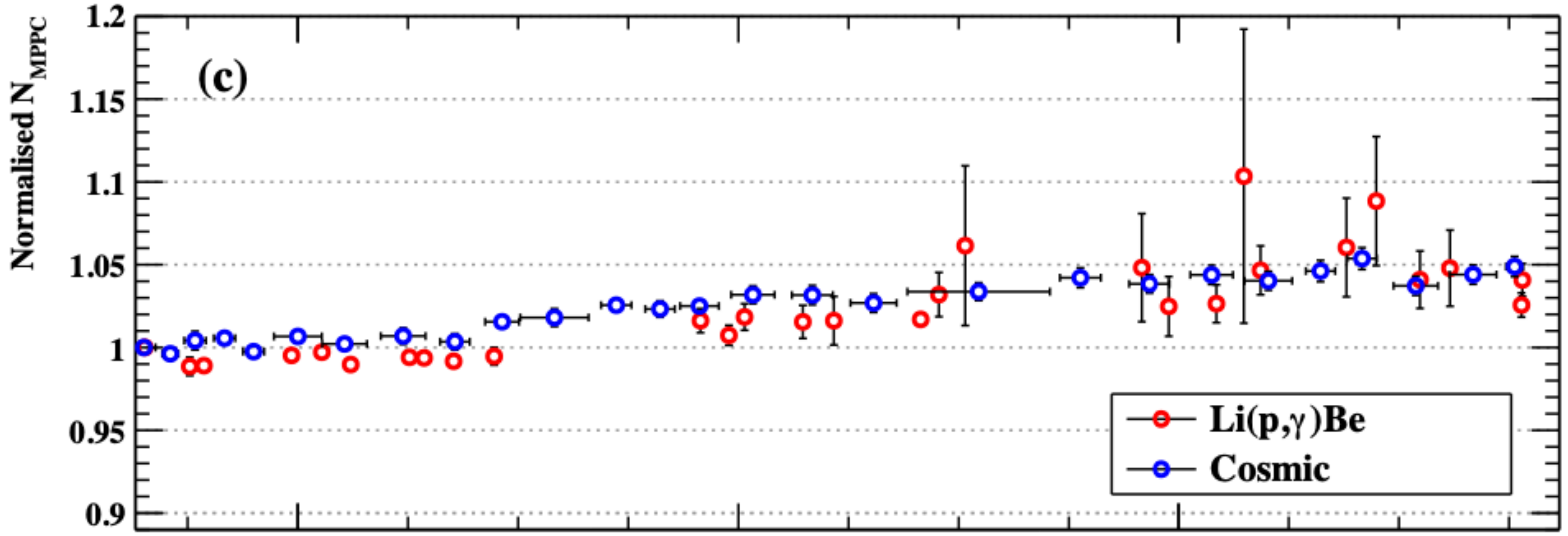


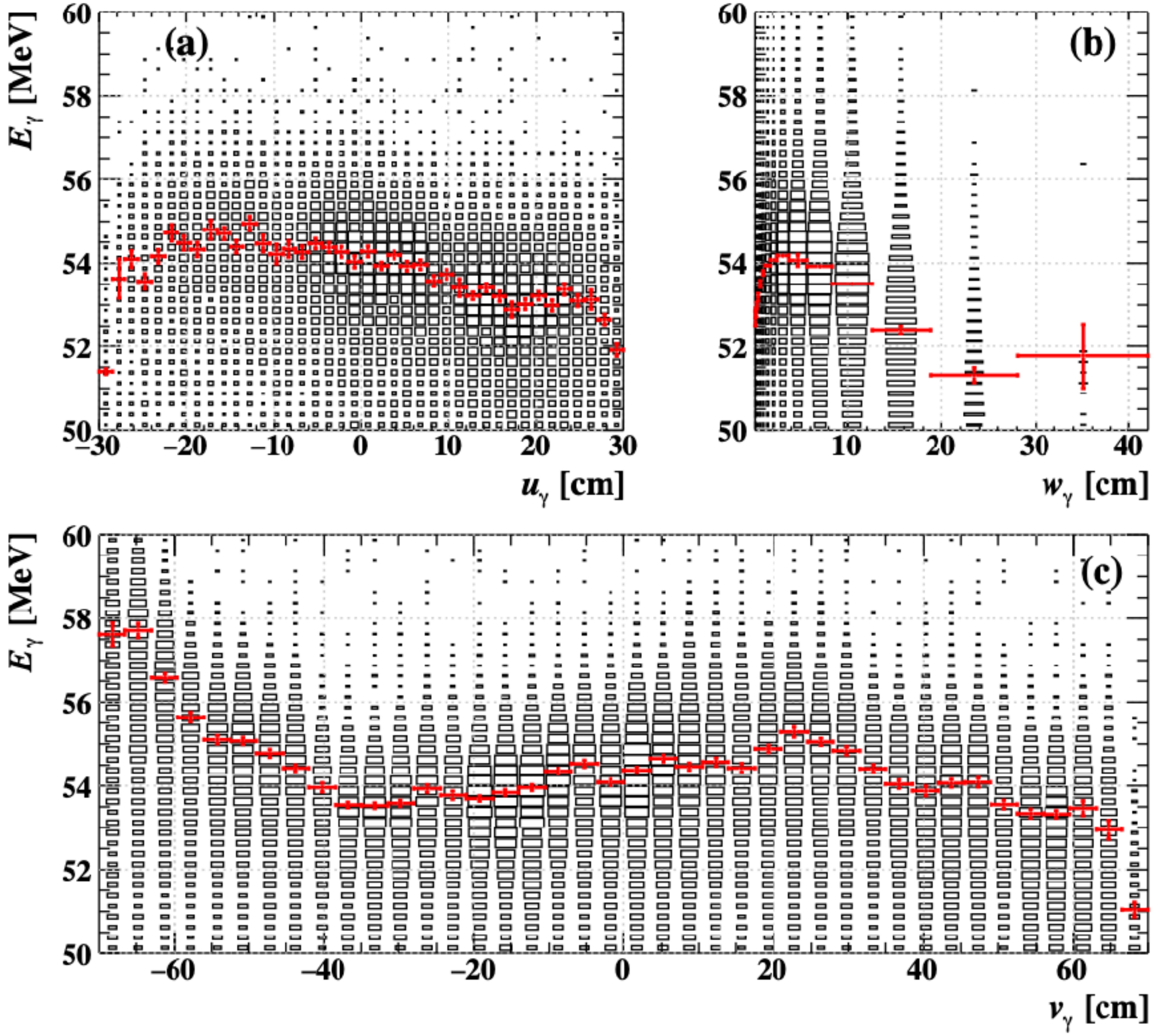
LXe detector stability and uniformity





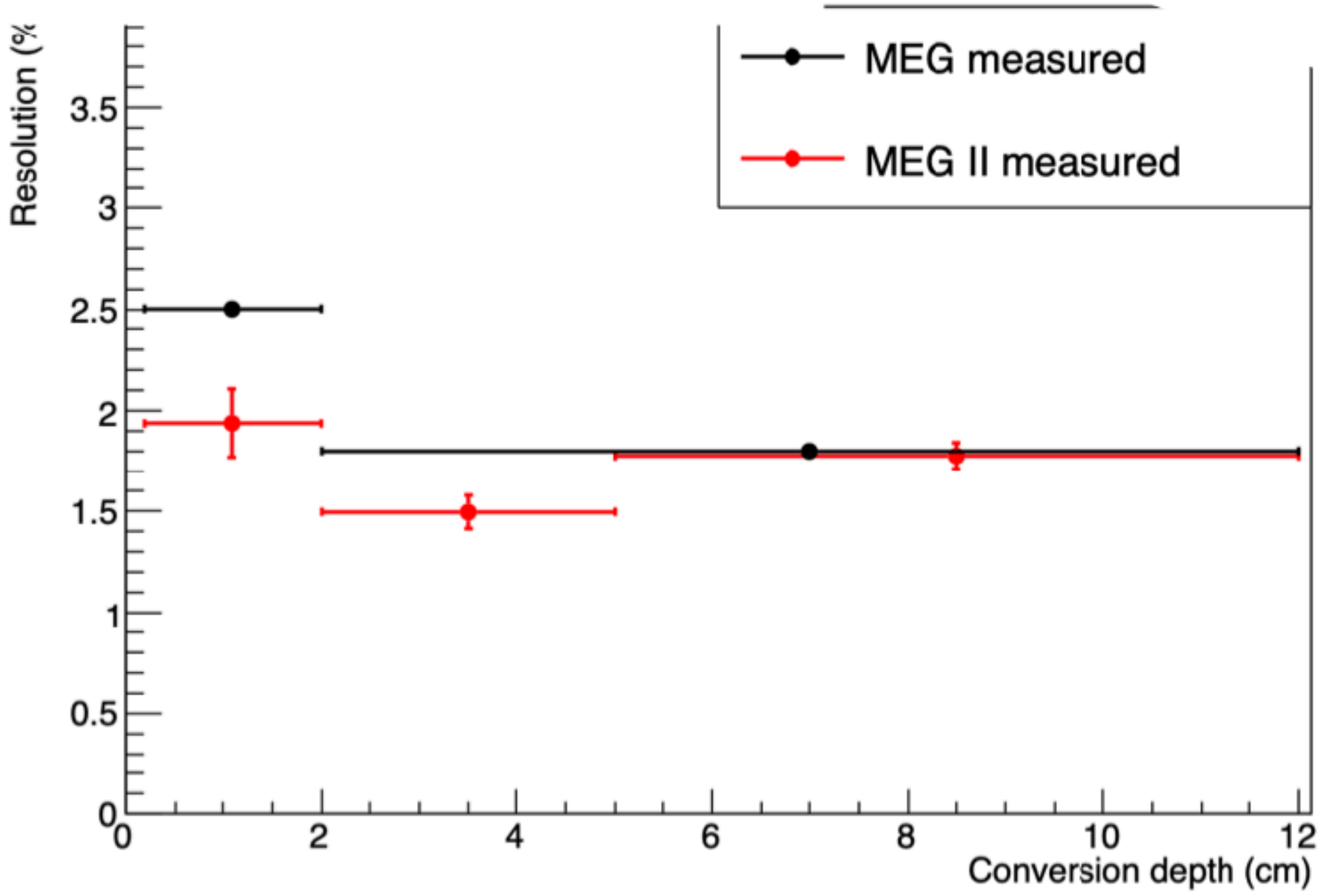
MPPC Q sum



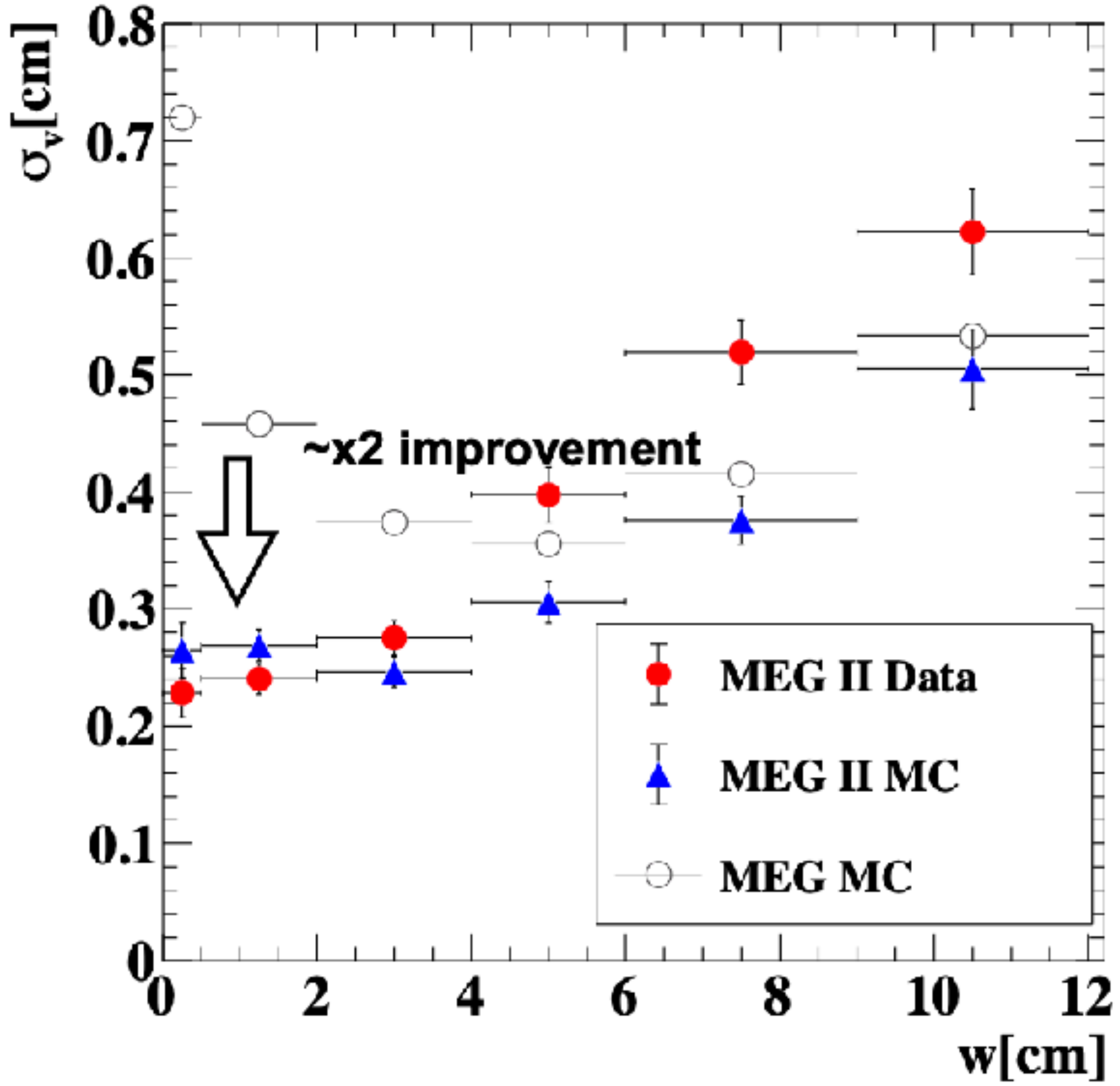


The LXe detector performance evaluation

Energy resolution (for 53MeV γ) vs depth



Position resolution



	MEG (measured)	MEG II (measured)
position resolution $(u/v/w)$(mm)	5/5/6	2.5/2.5/5.0 mm
energy resolution (%)$(w < 2\,\mathrm{cm}/w > 2\,\mathrm{cm})$	2.4/1.8	2.0/1.8 %
timing resolution (ps)	62	~ 65 ps
efficiency (%)	63	62