Commissioning of VUV-MPPCs for MEG II Liquid Xenon Detector

ICEPP The University of Tokyo

Core-to-Core Program

ICASiPM

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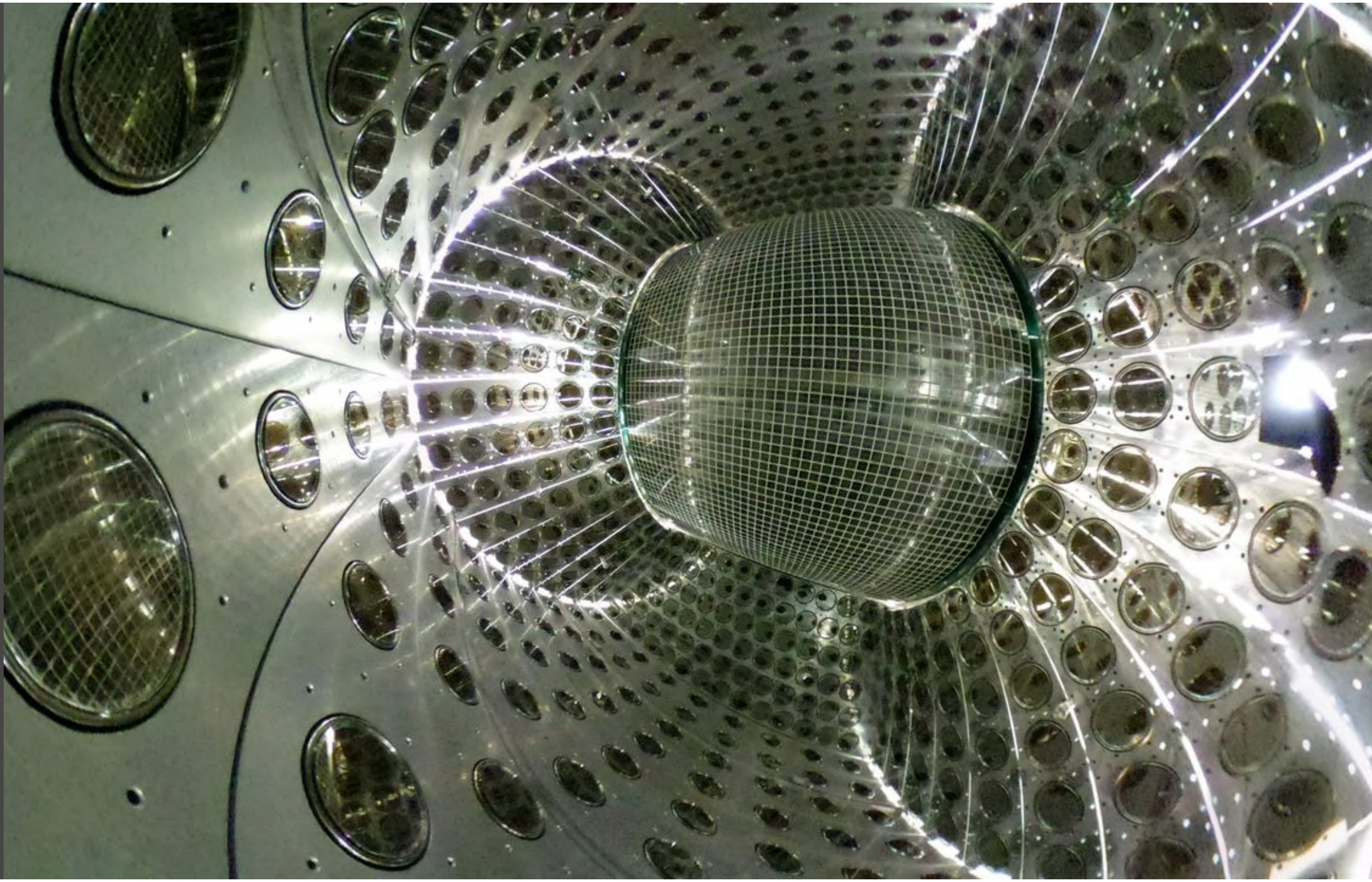
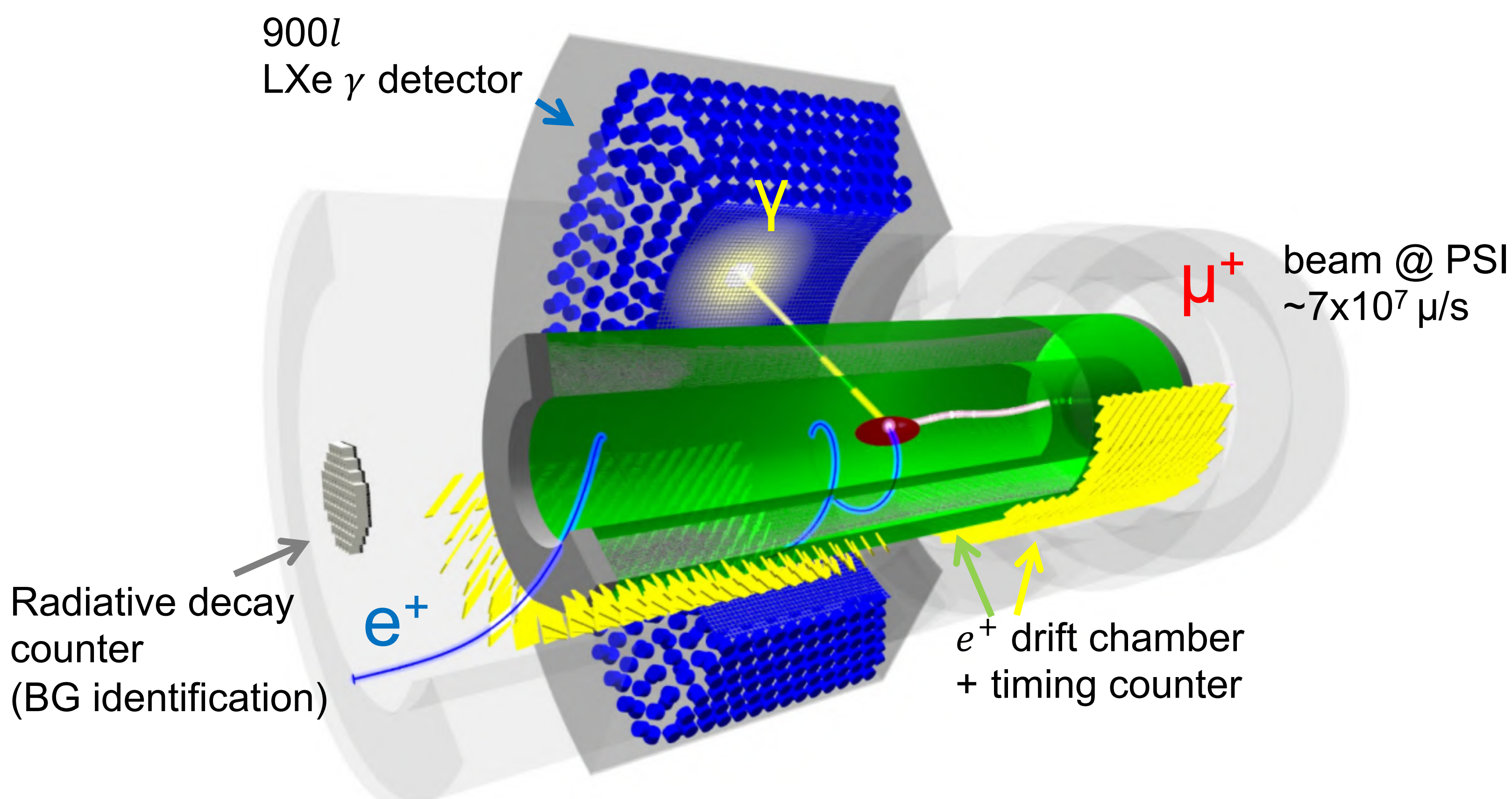
International Conference on the Advancement of Silicon Photomultipliers
Jun. 11th-15th, 2018, Schwetzingen, Germany

- MEG II Experiment
- Upgrade of LXe Photon Detector
- Construction
- Commissioning status
- Summary and Prospects



MEG II Experiment

- **Experimental search for lepton flavour violating decay $\mu^+ \to e^+\gamma$ as an unambiguous evidence of BSM physics**
  - Current bound: $\mathcal{B}(\mu^+ \to e^+\gamma) < 4.2\times10^{-13}$ (90%C.L.) (MEG in 2016)
  - **MEG upgrade (MEG II) with a projected sensitivity of 6×10^{-14} in preparation.**
- **MEG II detectors with significantly improved performance**
  - Much higher resolutions and efficiencies for both photon and positron detectors
  - Twice or higher μ intensity, fully exploiting world's most intense DC μ-beam at PSI up to $\sim10^8$ μ^+ beam



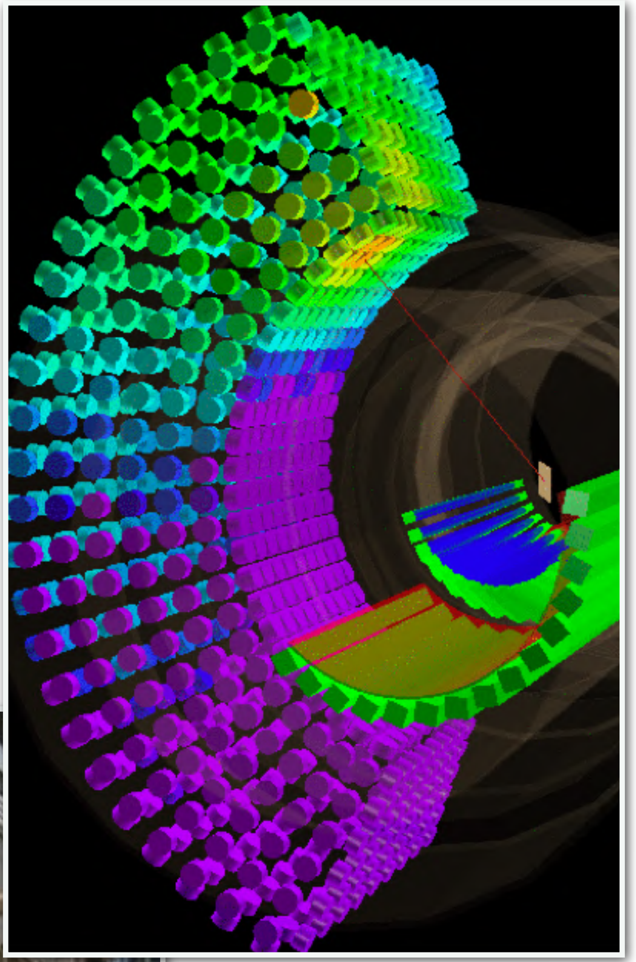
Upgrades from MEG:
- x2 beam rate
- x2 detector resolution and efficiency

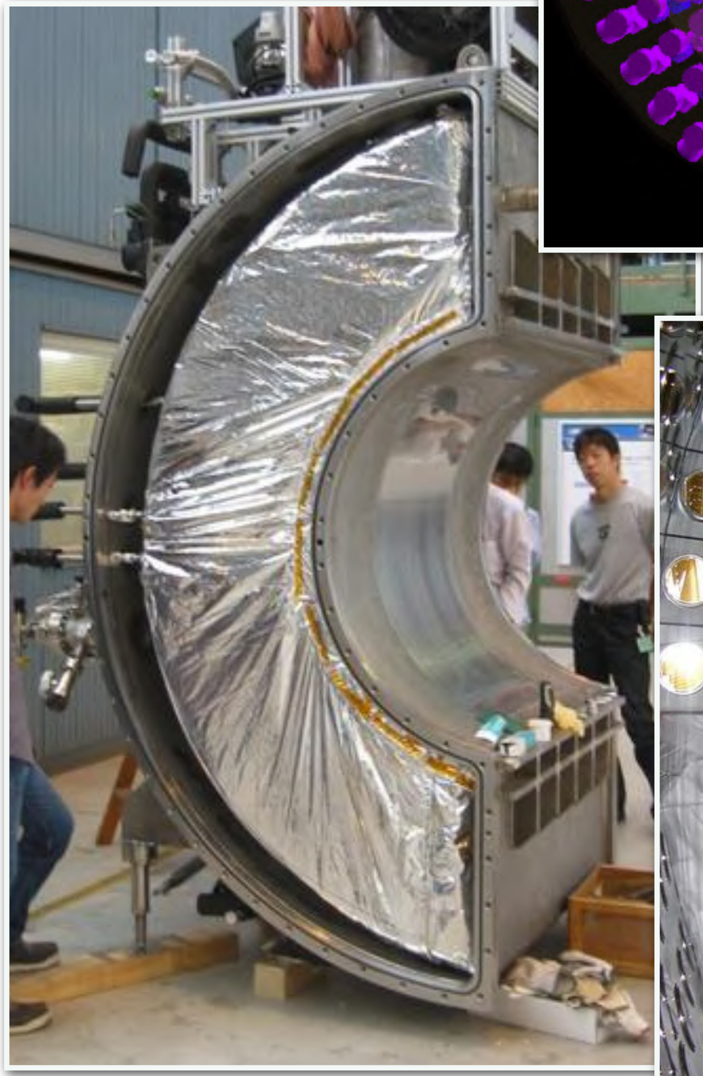
MEG LXe Photon Detector

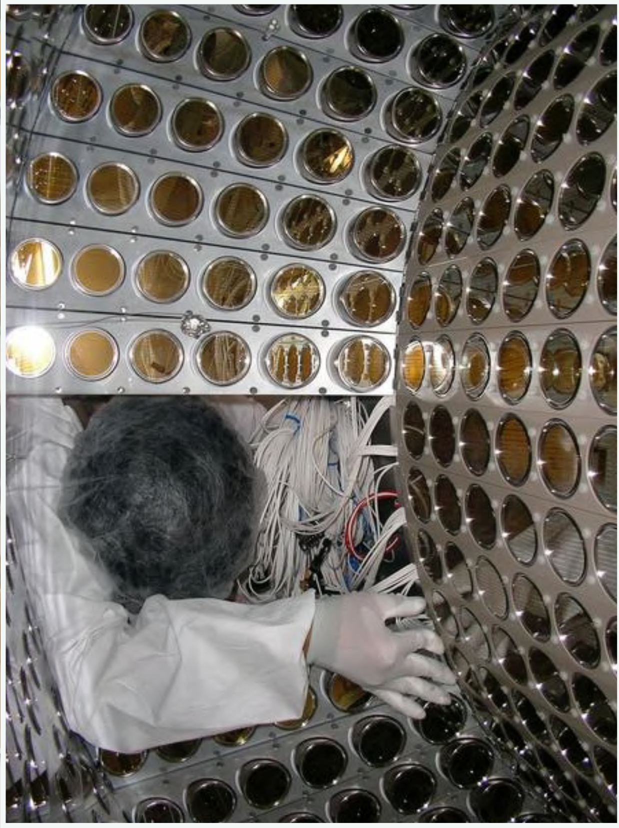
- **900ℓ LXe (~2.7ton) scintillation detector to measure 52.8MeV-photon from μ→eγ**
- **LXe as a detector medium**
  - High stopping power X_0 = 2.77cm
  - High light yield 75% of NaI(Tl)
  - Fast (τ=45ns for e/γ)
- **LXe scintillation light readout by photosensors surrounding LXe active volume**

  MEG: PMT(×846)

  →MEG II: SiPM(×4092) + PMT(×668)
- **Reconstruction**
  - **Energy:** sum of SiPM/PMT charges
  - **Position:** SiPM/PMT charge distribution
  - **Time:** average SiPM/PMT time
- **All channels are readout by waveform digitiser.**
  - Pileup reduction
  - Particle ID

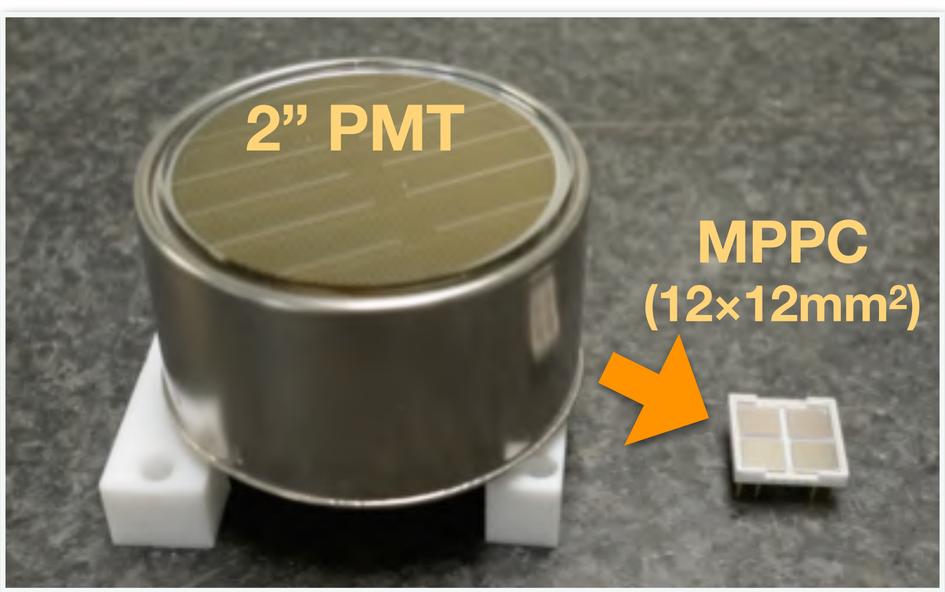


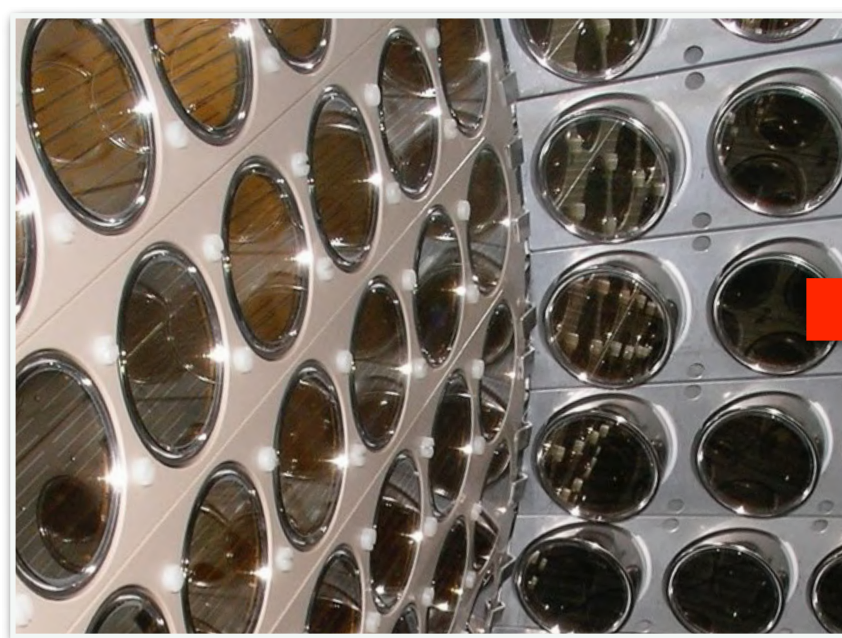


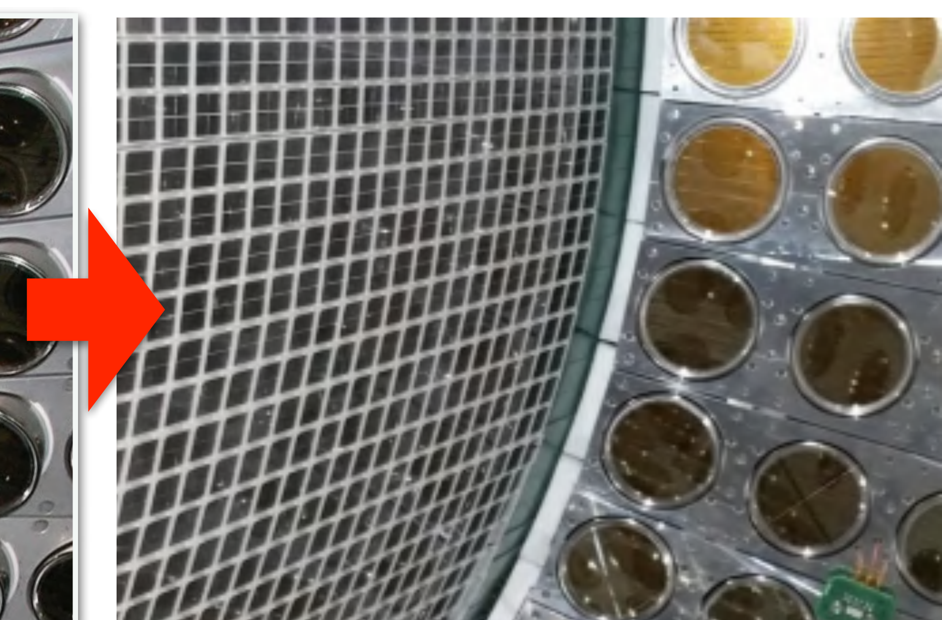


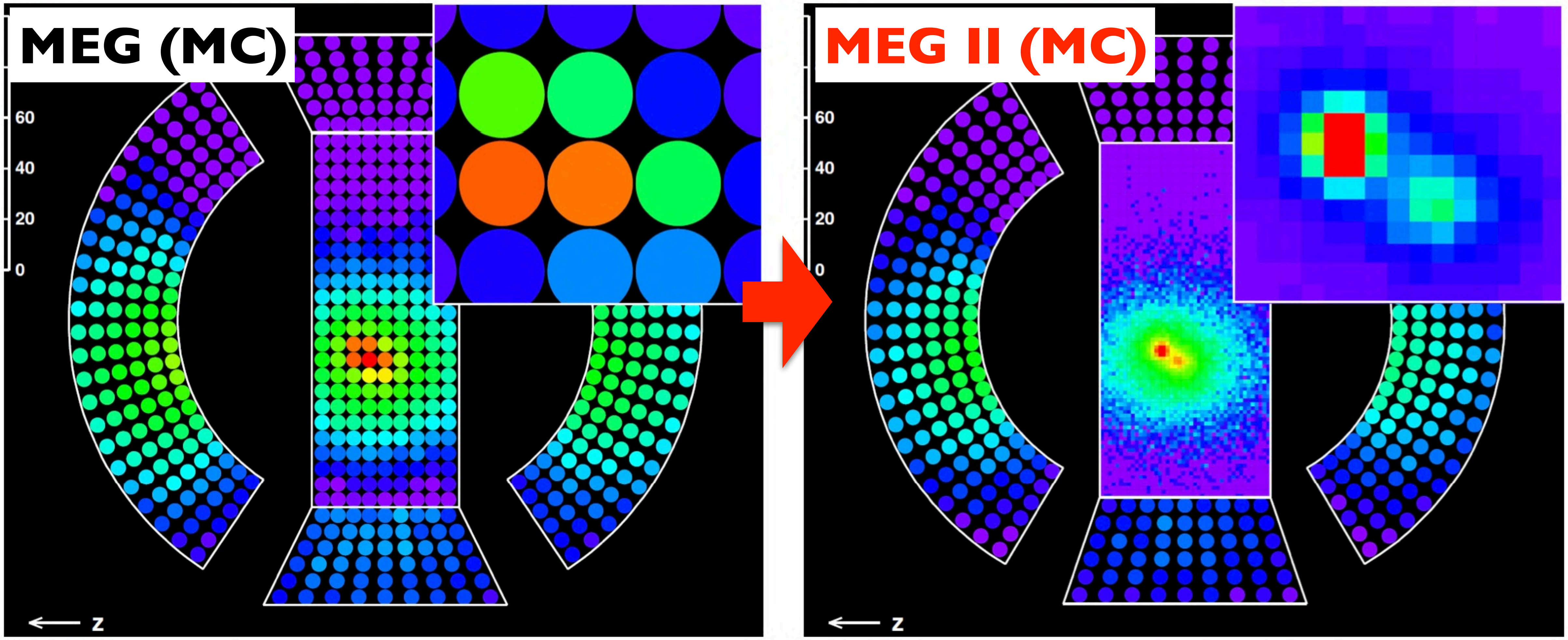
LXe Detector Upgrade for MEG II

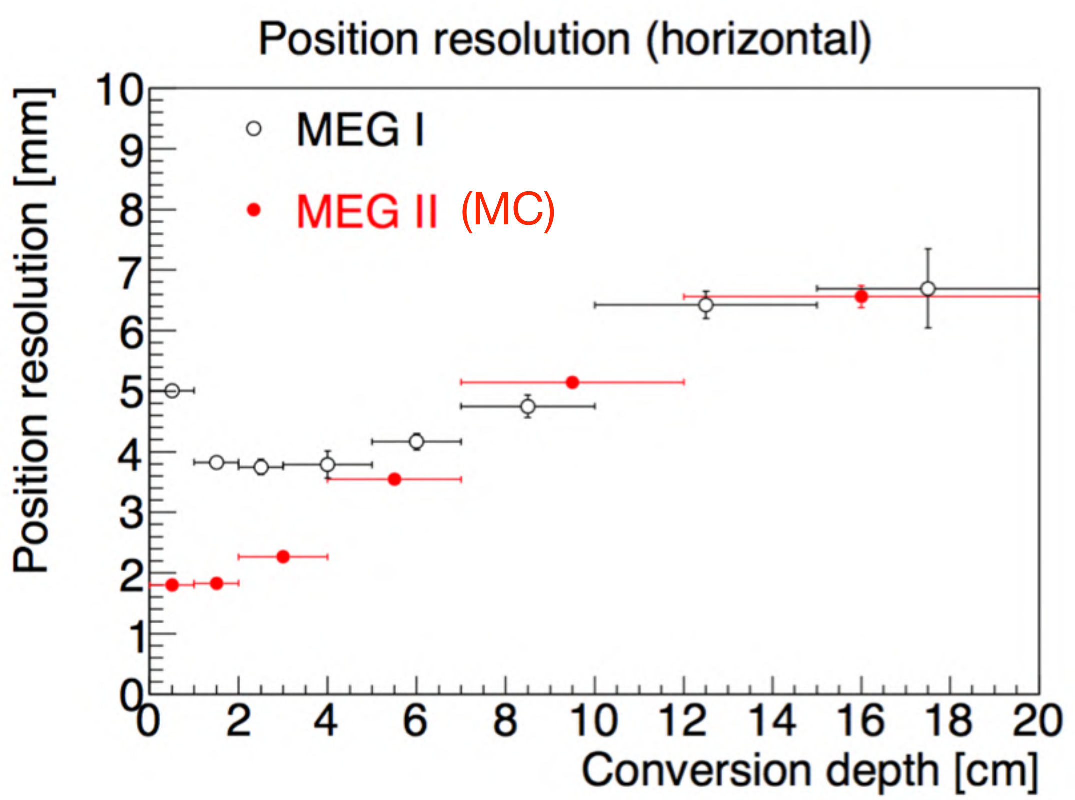
- **Highly granular scintillation readout**
  - 216 × PMTs(2-inch) on γ-entrance face are replaced with **4092 × MPPCs (139mm² each)**
  - γ-entrance face (**0.92m²**) covered by total active sensor area of **0.57m²**
  - **Energy and position resolutions will be improved by a factor of two.**
  - γ-detection efficiency will also be improved by ~10% because MPPC is much thinner than PMT.
  - Modified PMT layout for better response to acceptance edge events

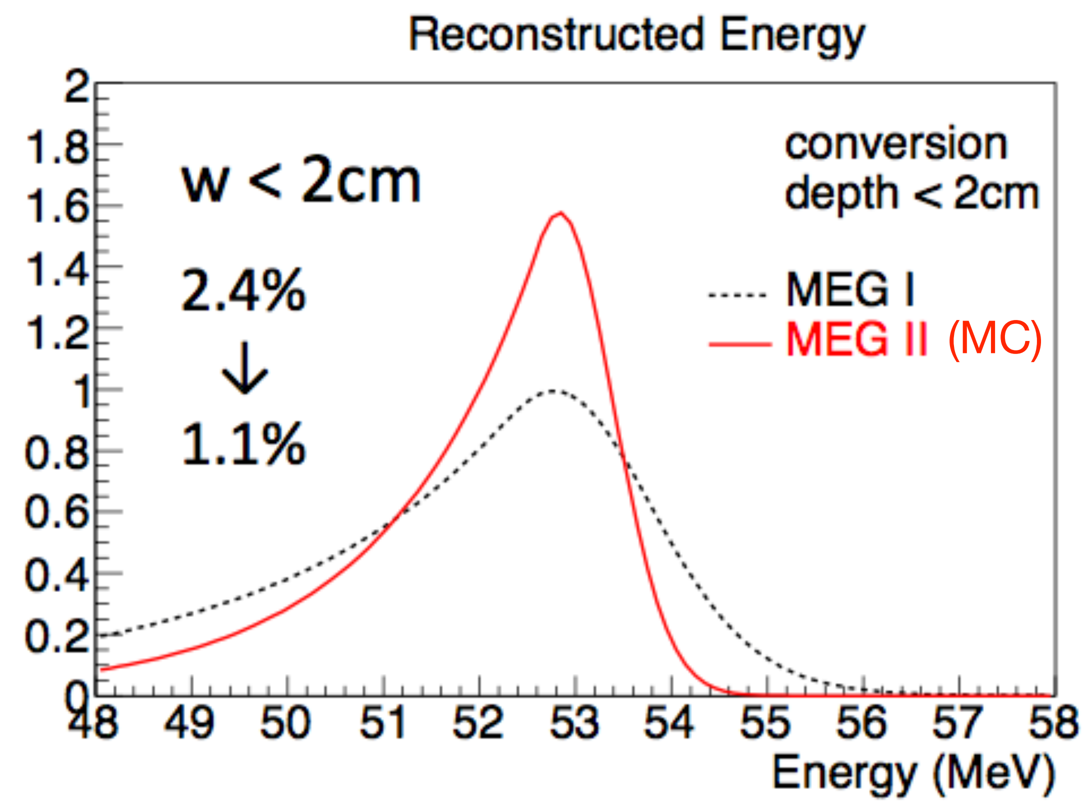







MEG (MC)
MEG II (MC)
60
40
20
0
z

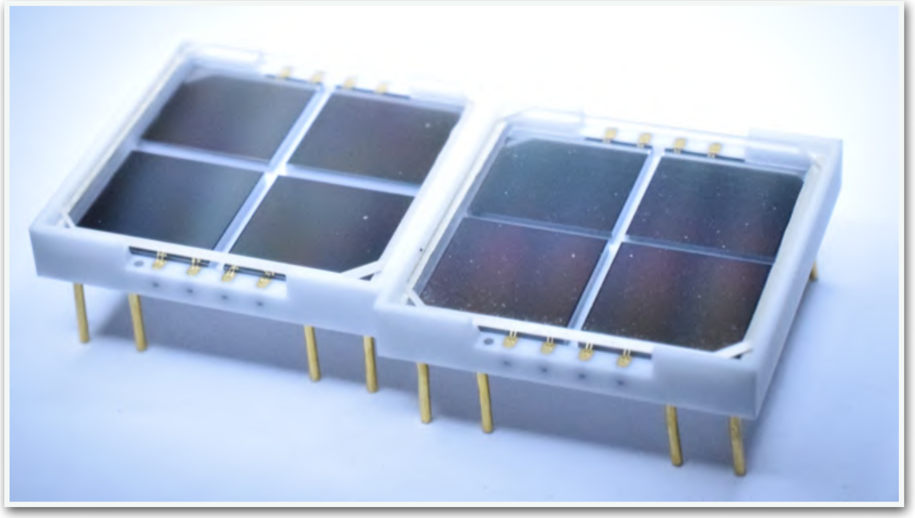

Position resolution (horizontal)
MEG I
MEG II (MC)
Position resolution [mm]
Conversion depth [cm]

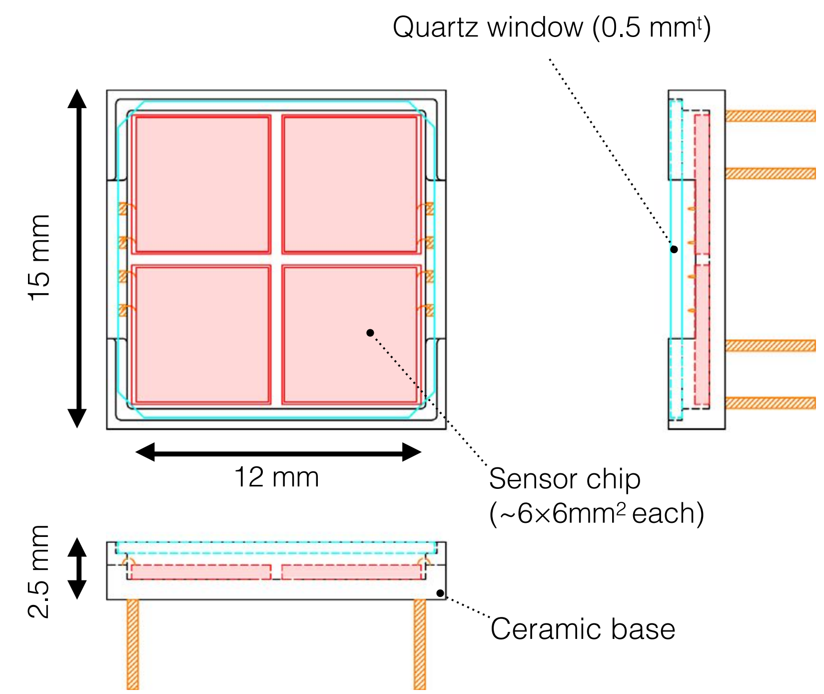

Reconstructed Energy
w < 2cm
2.4%
↓
1.1%
conversion depth < 2cm
MEG I
MEG II (MC)
Energy (MeV)

VUV-sensitive MPPC

- **VUV-sensitive MPPC developed for MEG II in collaboration with Hamamatsu Photonics K.K.**
- **Model S10943-4372**
  - Active area: 139mm^2
  - Discrete array of four independent sensor chips (5.95×5.85mm^2 each)
  - 50μm pixel pitch
  - Metal quench resistor (only 20% change at LXe temp~165K)
  - PDE > 15% for LXe scintillation light (λ=175nm)
  - Gain > 5×10^5 (four chips connected in series)
  - Low cross talk / low after-pulsing
  - Operational with over-voltage up to 7V

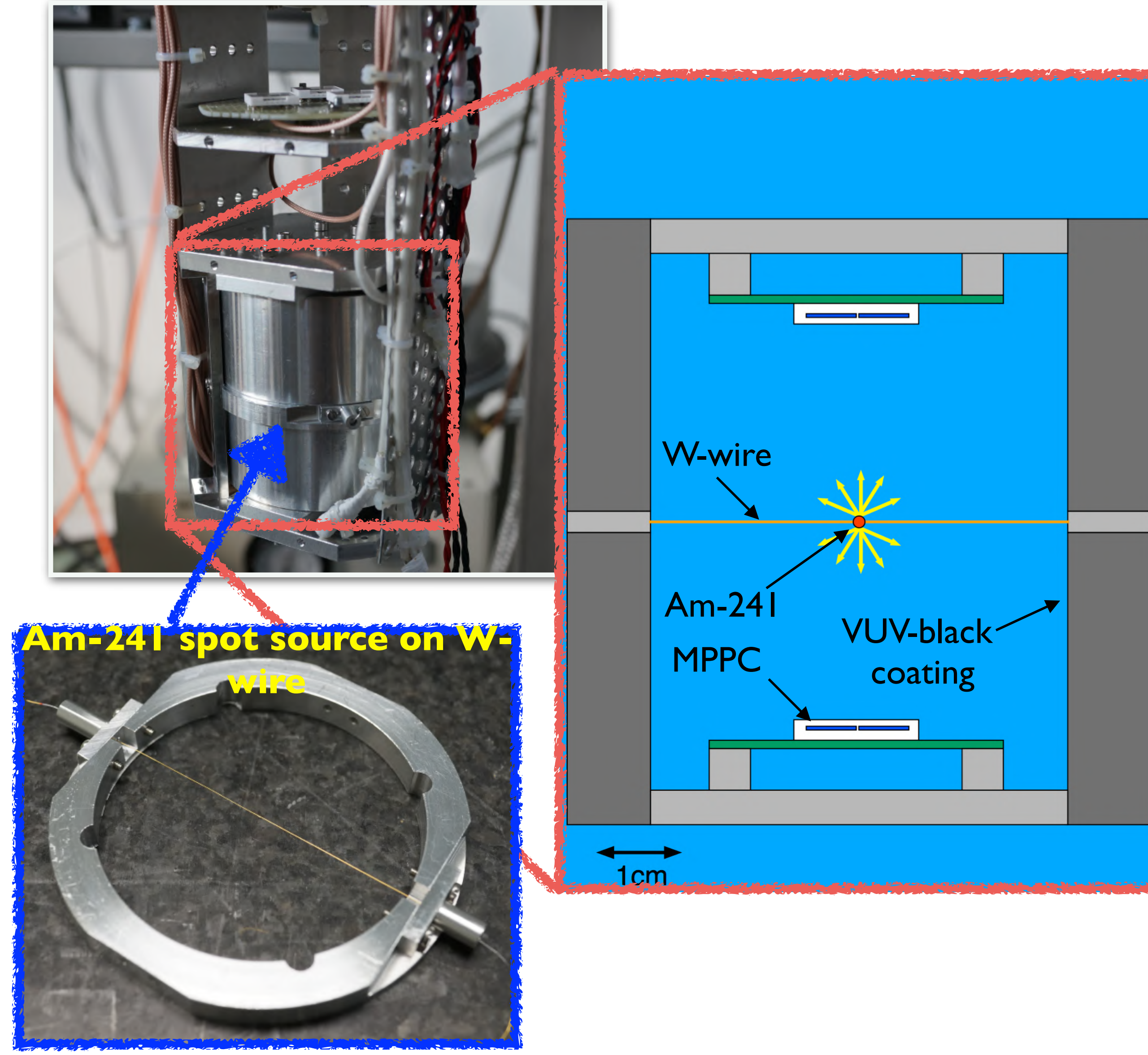
Hamamatsu S10943-4372

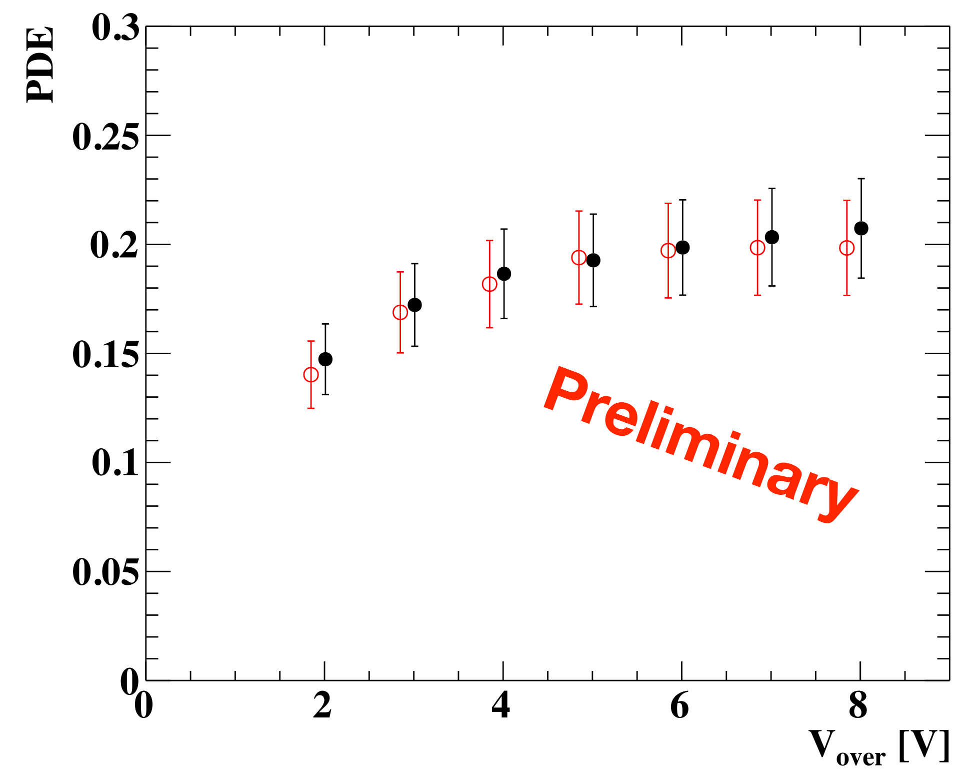




PDE

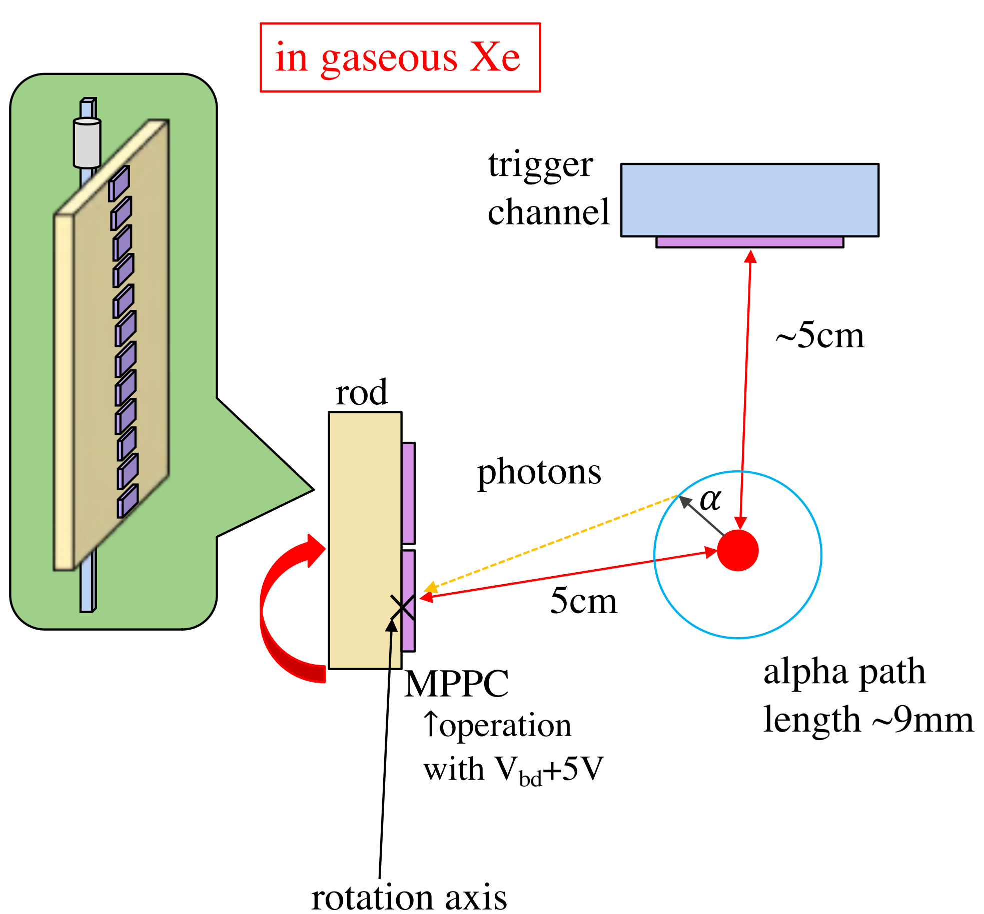
- **PDE measured in a small laboratory setup in LXe**
  - Am-241 spot α-source on W-wire (ϕ100um, gold-plated) as a fixed spot light source
- **PDE = (measured # of photoelectrons)/(expected # of photons)**
  - Uncertainty in estimation of expected # of photons impinging MPPC (W_{ph}, gain, cross-talk, after-pulsing, effect of reflection)
- **PDE > 15%**

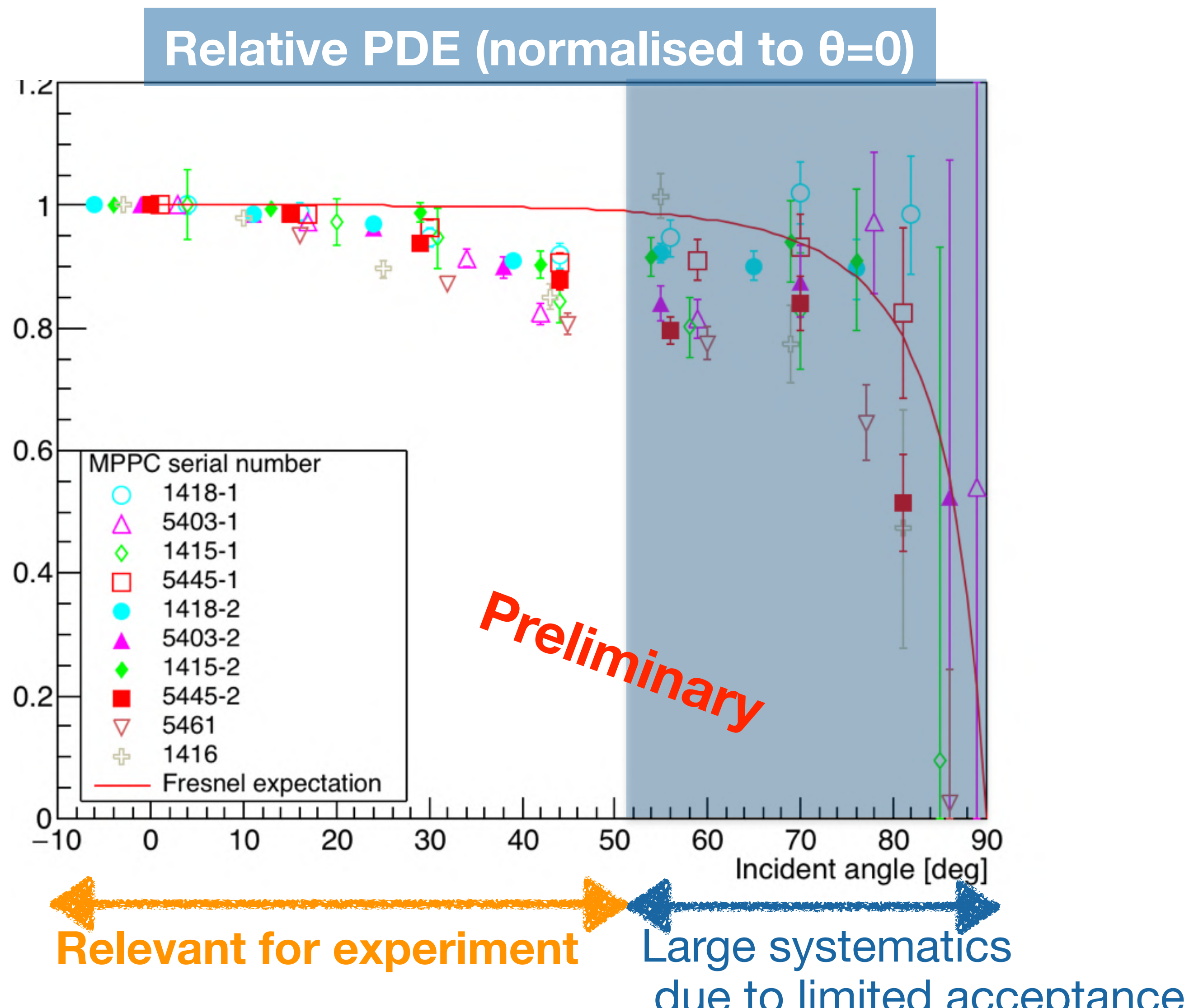




Angular Dependence of PDE

- **Correct knowledge of angular dependence of PDE is required especially for position reconstruction**
- **Angular dependence of PDE was measured in a dedicated setup with gaseous Xe at room temp**
  - **Larger than expected from Fresnel reflection**
  - Consistent result obtained observed also in LXe with the detector, but still with larger uncertainty
- **For VUV light, charge carrier is generated in contact layer within 5nm from top surface**
  - Very thin dead layer in contact layer could cause additional angular dependence





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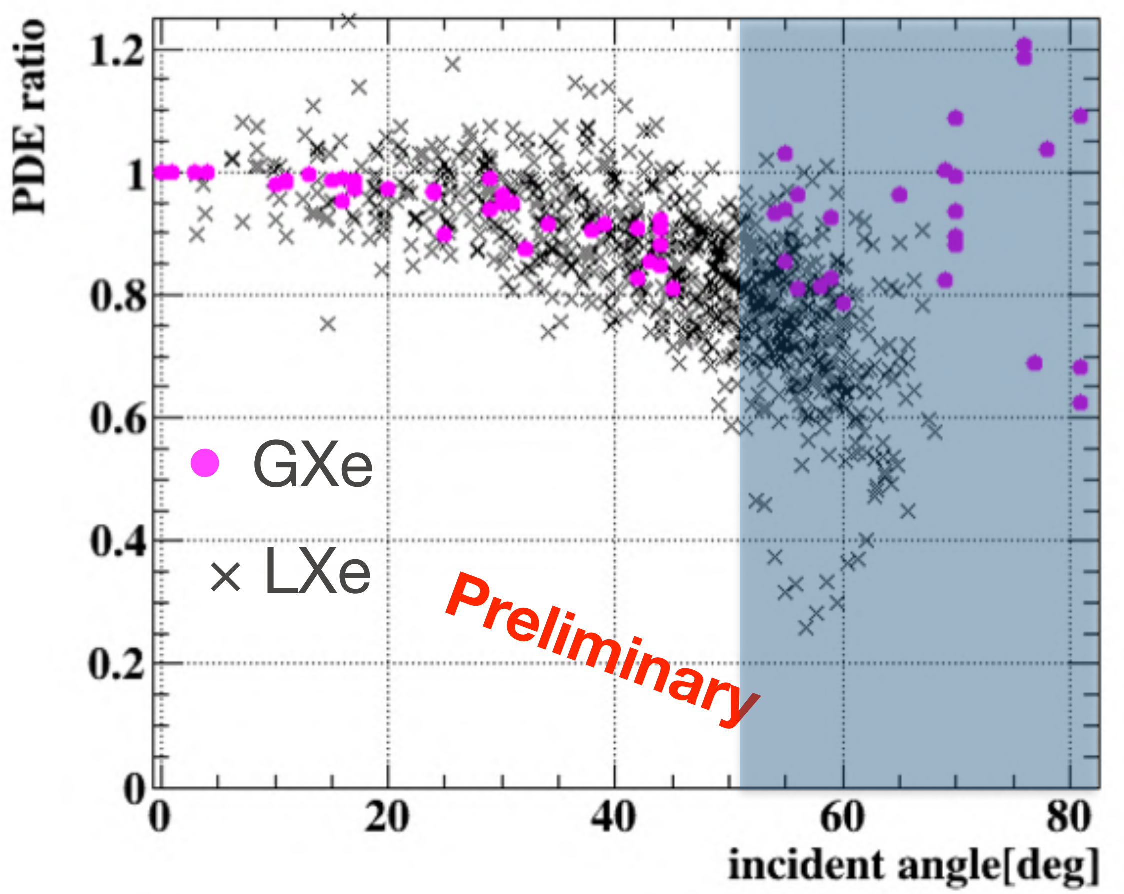
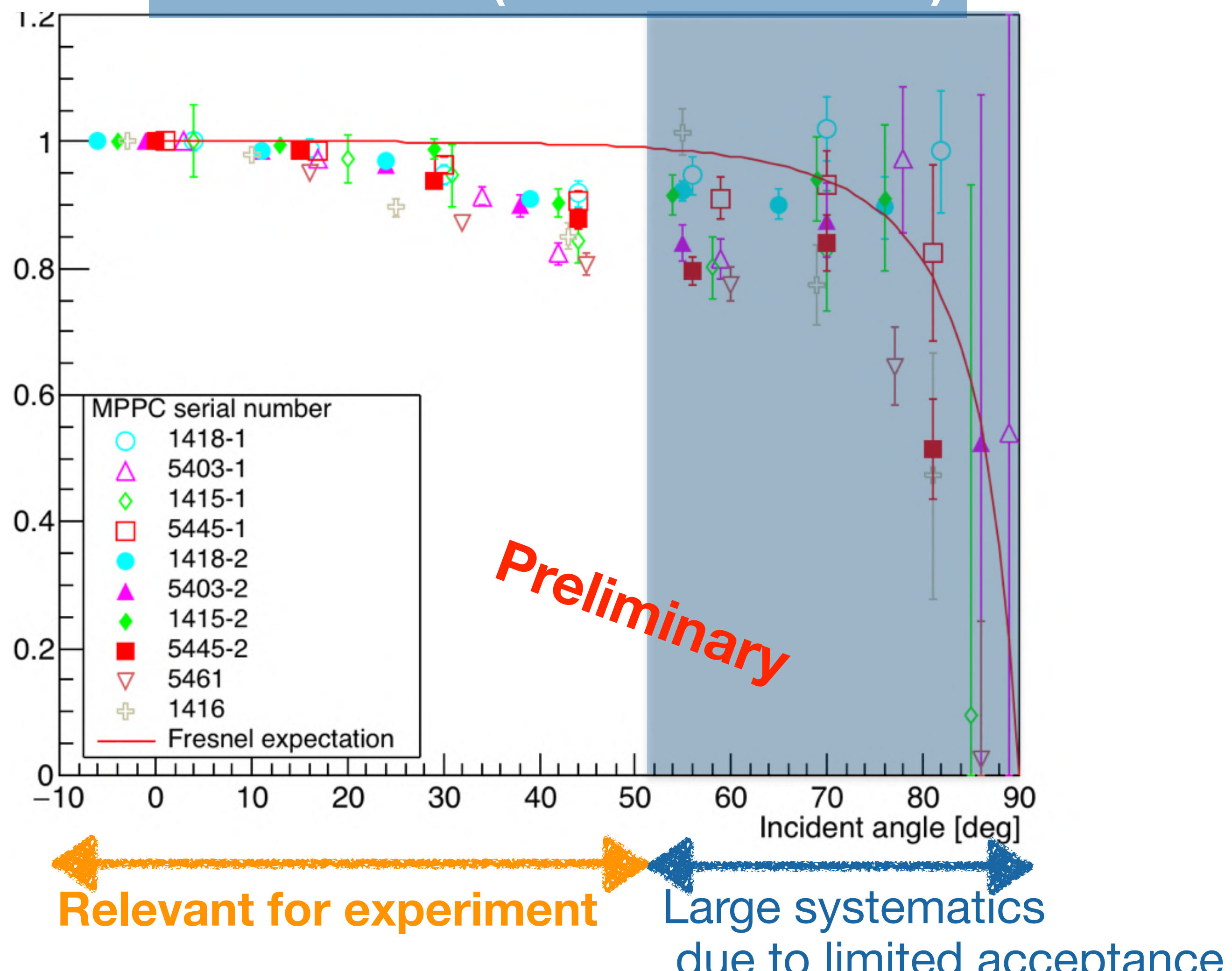
GXe vs. LXe PDE ratio (measured/expected)



Relative PDE (normalised to θ=0)

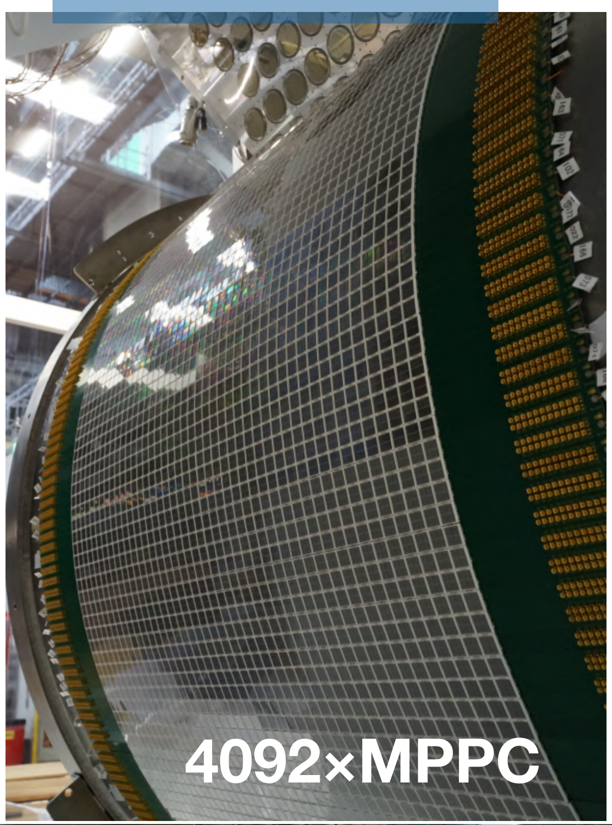


Construction

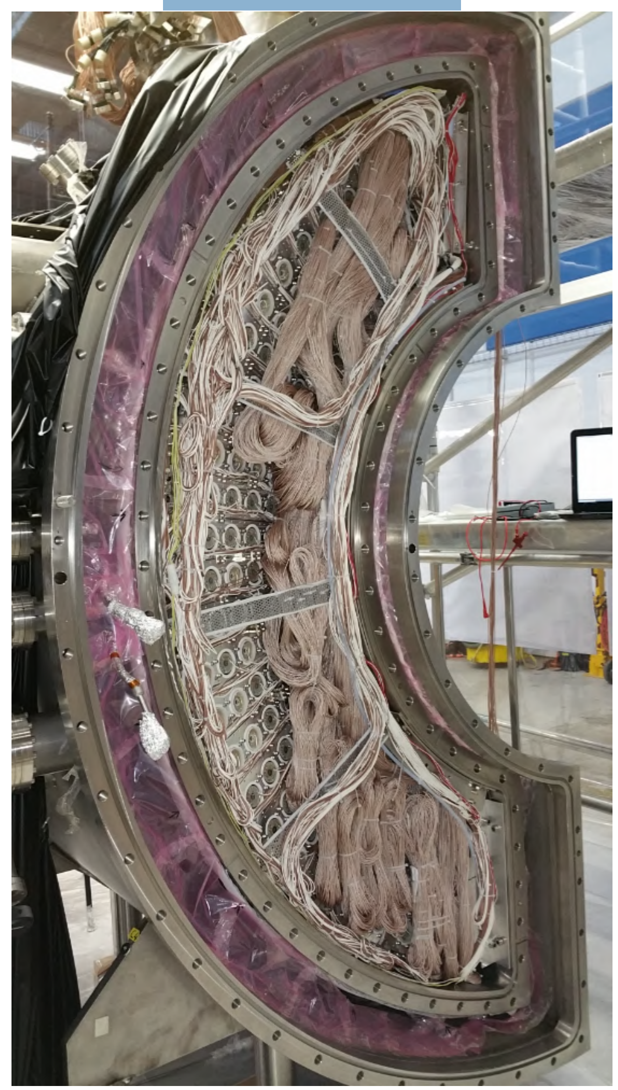
- **Construction completed**

→**Detector now in commissioning phase**

Photosensor installation

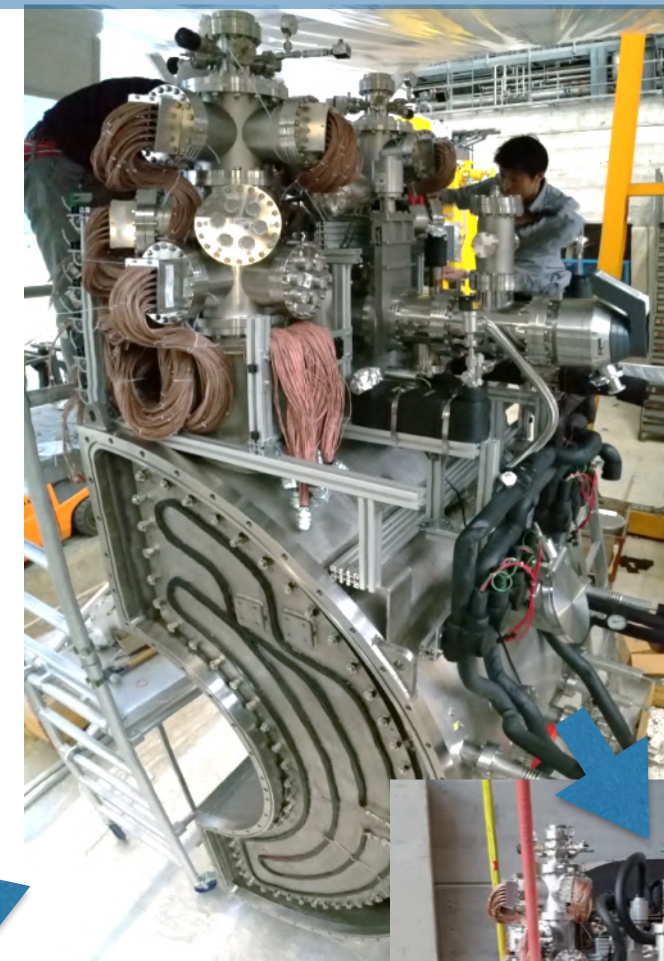


Cabling



Cabling for ~5000 sensors is not an easy task…

Cryogenics/vacuum piping



Installed in PSI πE5

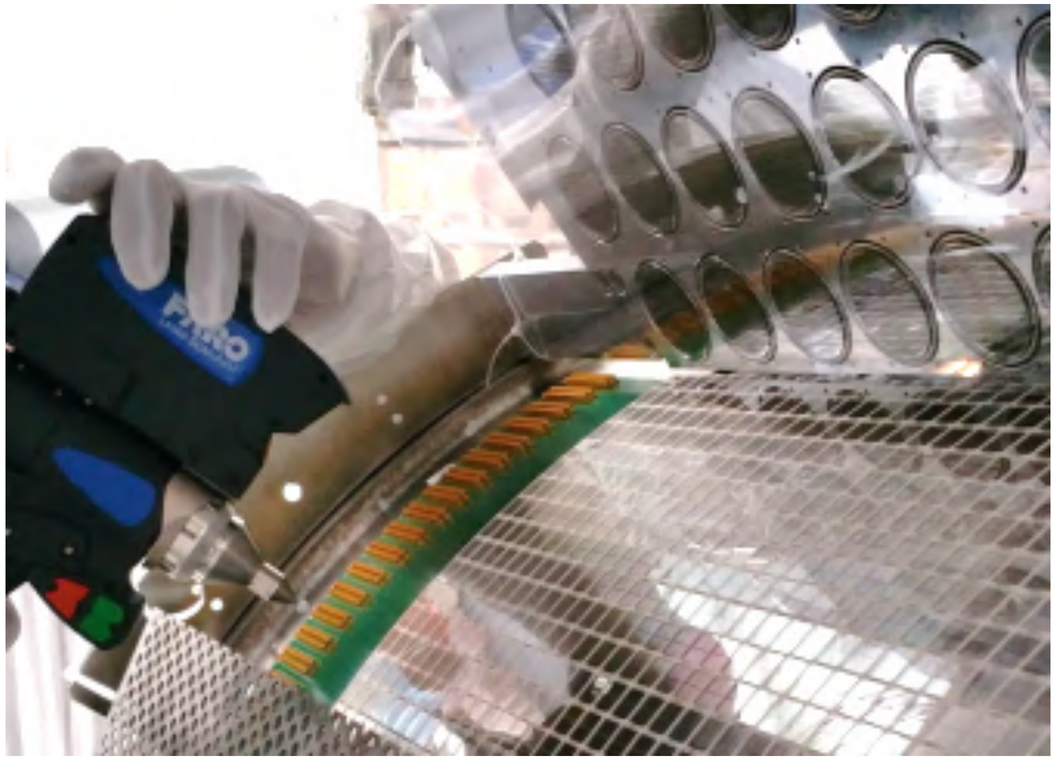
Commissioning

- **Detector commissioning in progress**
  - System check
  - LXe transfer to detector vessel
  - LXe purification
  - Photosensor calibration
  - Detector calibration
- **Not quite ready for full commissioning**
  - Limited number of readout electronics channels. Full electronics will be ready in 2019
  - Suffering higher noise than expected after installed in beam area. Still under investigation

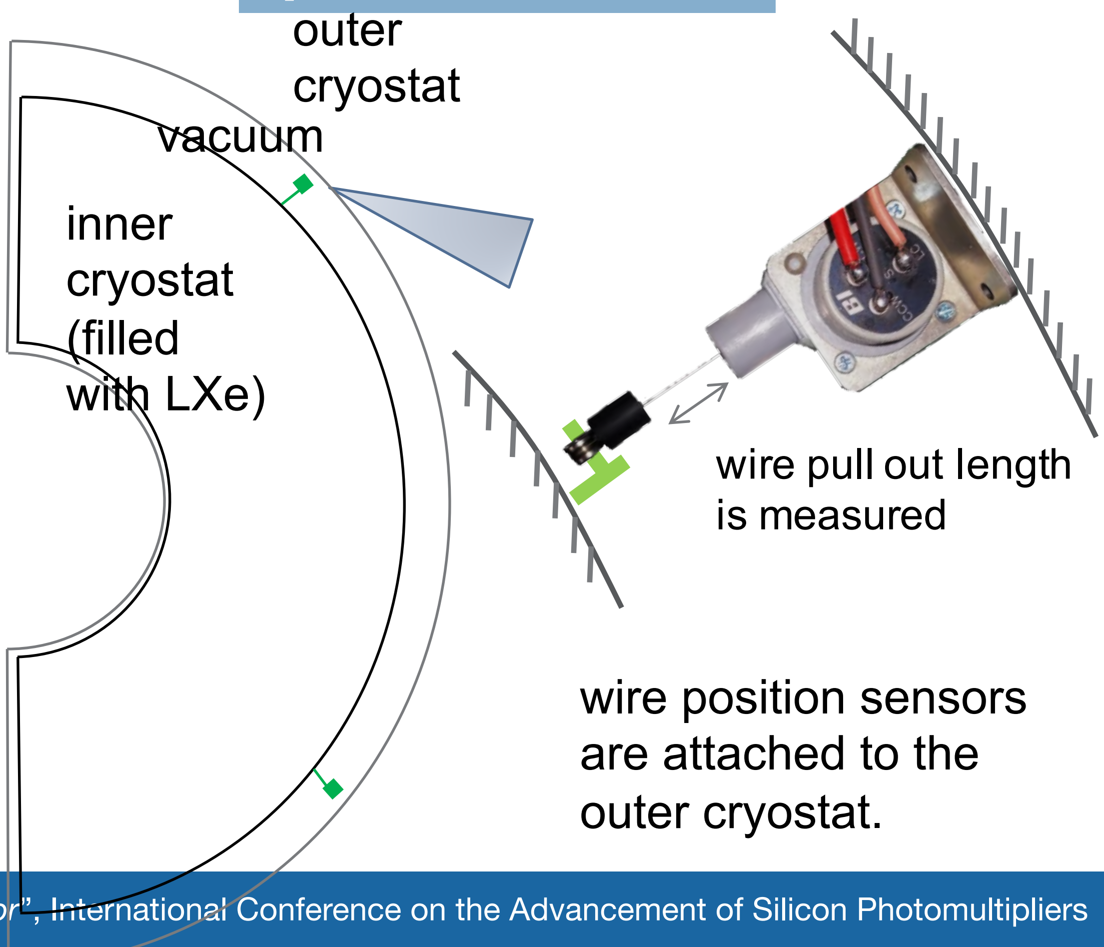
MPPC Alignment

- **Precise alignment of MPPCs is crucial because of significantly improved position resolution down to a few mm**
  - Target alignment precision <0.5mm
- **Multiple redundant methods**
  - 3D survey with 3D-camera and laser tracker at room temp.
  - Position sensor to measure displacement/deformation of inner LXe vessel
  - X-ray survey to measure sensor position in LXe from outside detector vessel

Survey by 3D camera

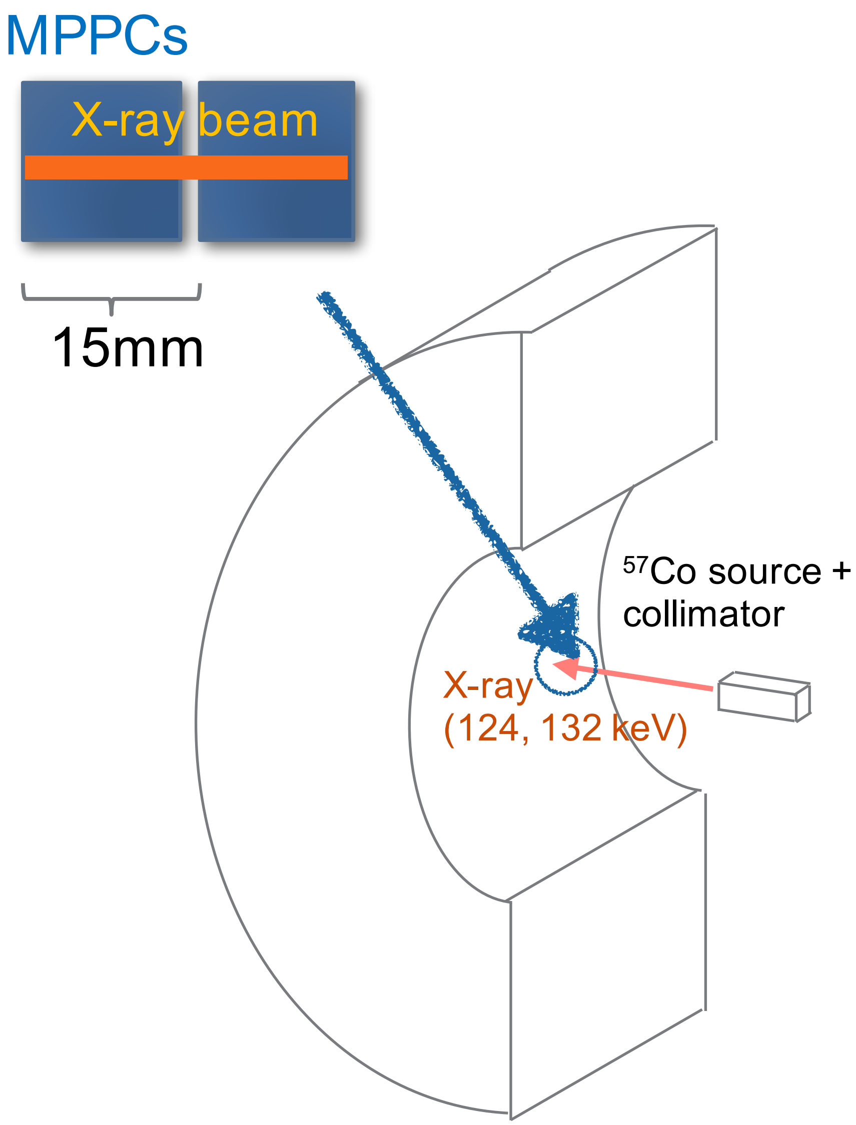


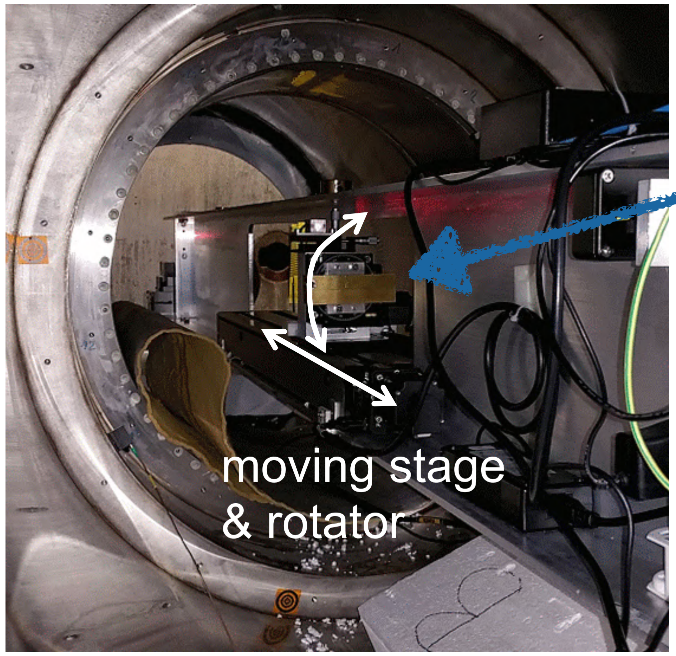
Inner vessel position sensor



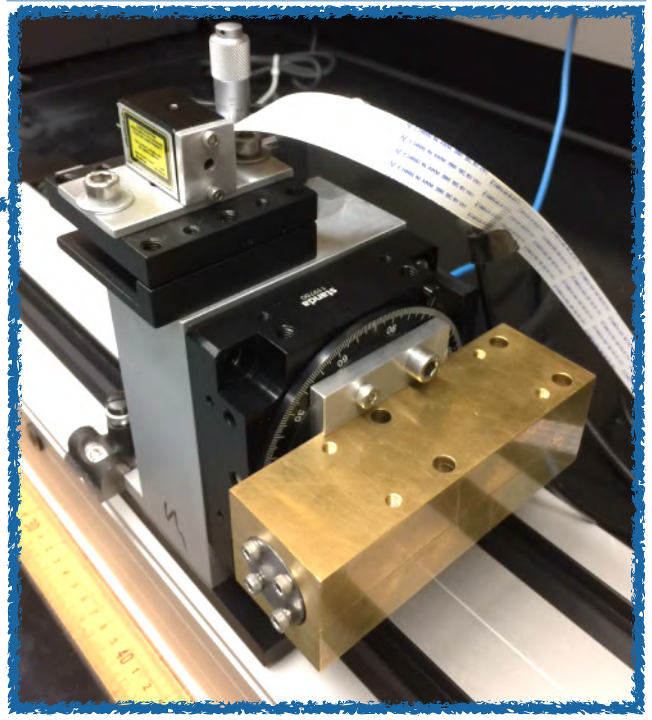
X-ray Survey

- **2D-positions (z & Φ) of MPPCs in LXe are directly measured with collimated X-ray**
  - MPPCs are scanned by slit beam of $2 \times 30 mm^2$ at MPPC
  - Scan in two directions (Z & Φ)



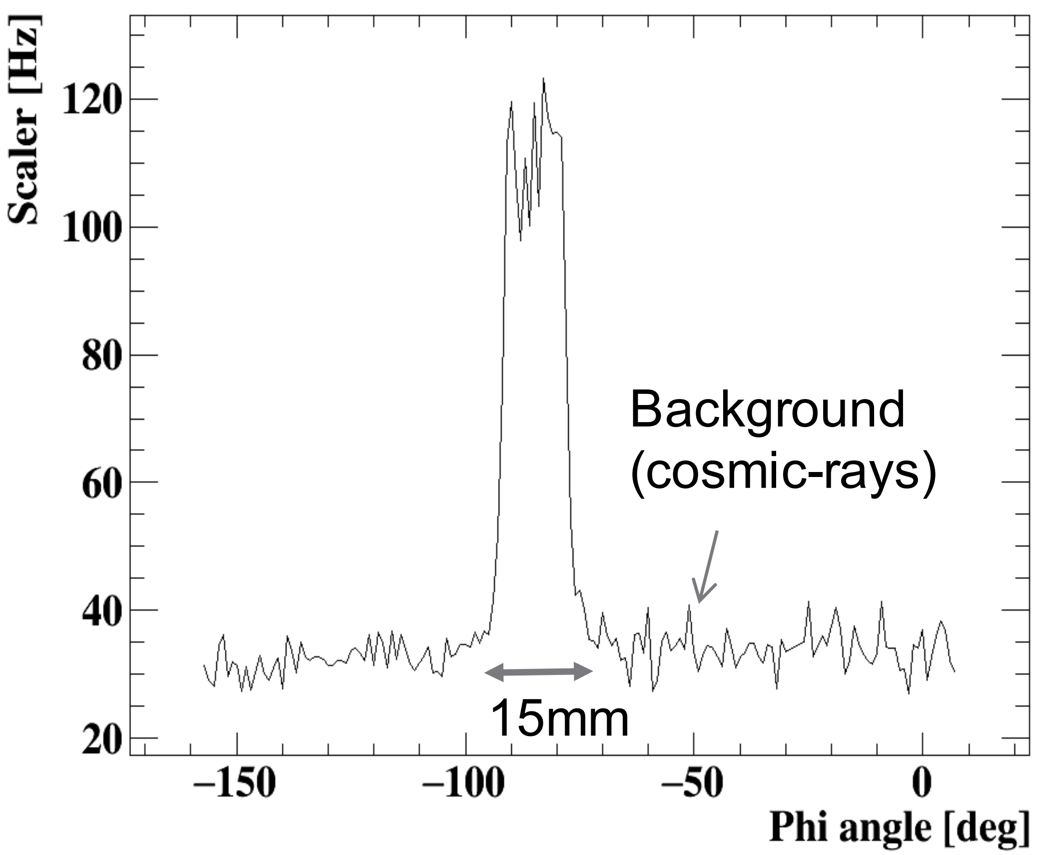


^{57}Co in slit collimator

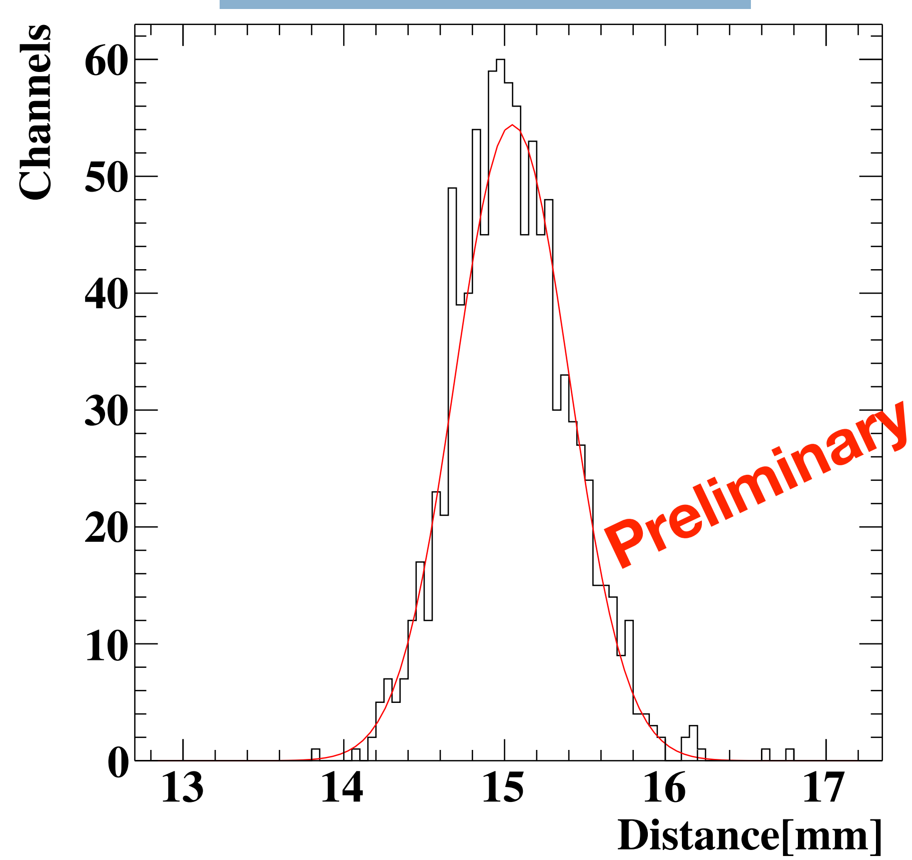


X-ray Survey

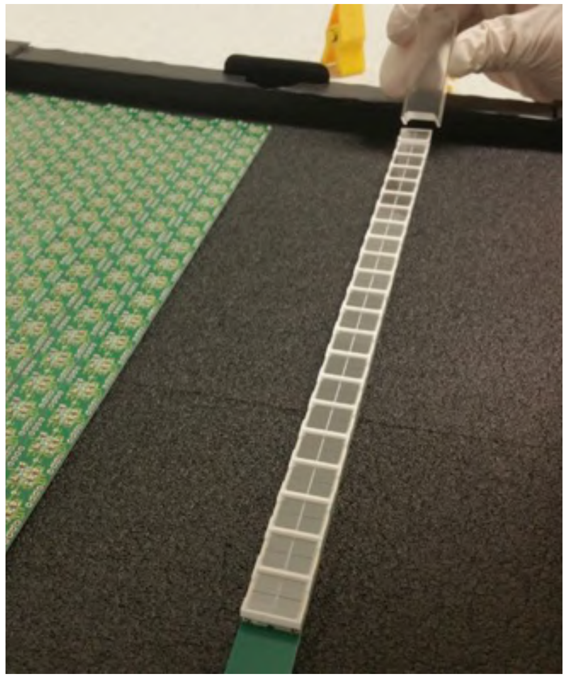
- **Preliminary results from first measurement**
  - **Clear rate variation for each scanned MPPC**
  - MPPC position extracted from rate distribution
- **Validation by checking intervals of MPPCs mounted on the same PCB slab**
  - Expected: 15.07mm (tolerance within ±0.05mm)
  - Measured: 15.05±0.01mm (mean)
    - **Consistent with expectation**
    - **Resolution estimated as 0.4mm,** meeting the requirement
- **Detailed analysis in progress to extract all MPPC positions**



Measured intervals of adjacent MPPCs



MPPC mounted on PCB slab



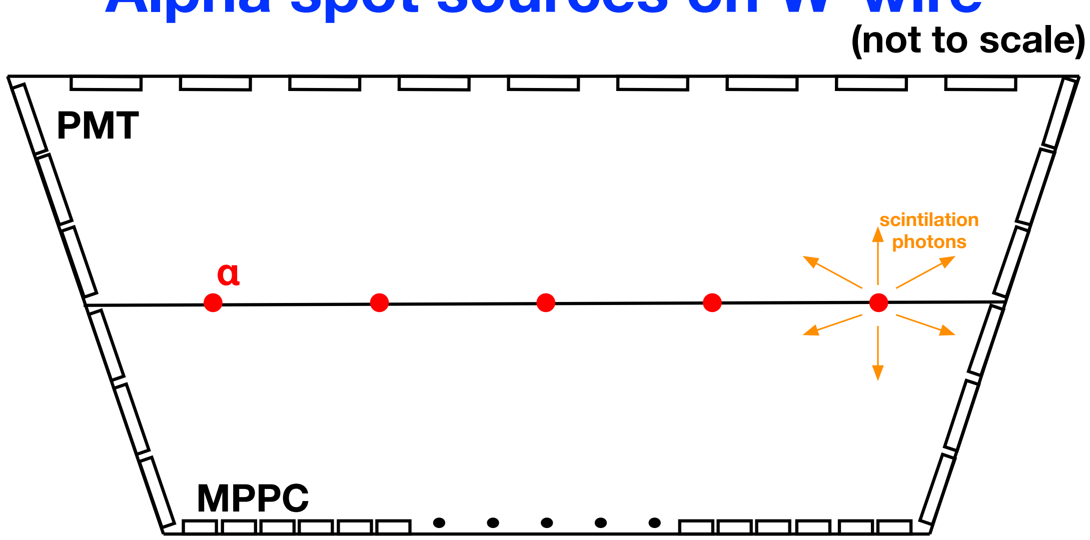
Calibration/Monitoring

- **Various calibration/monitoring methods employed in LXe detector**

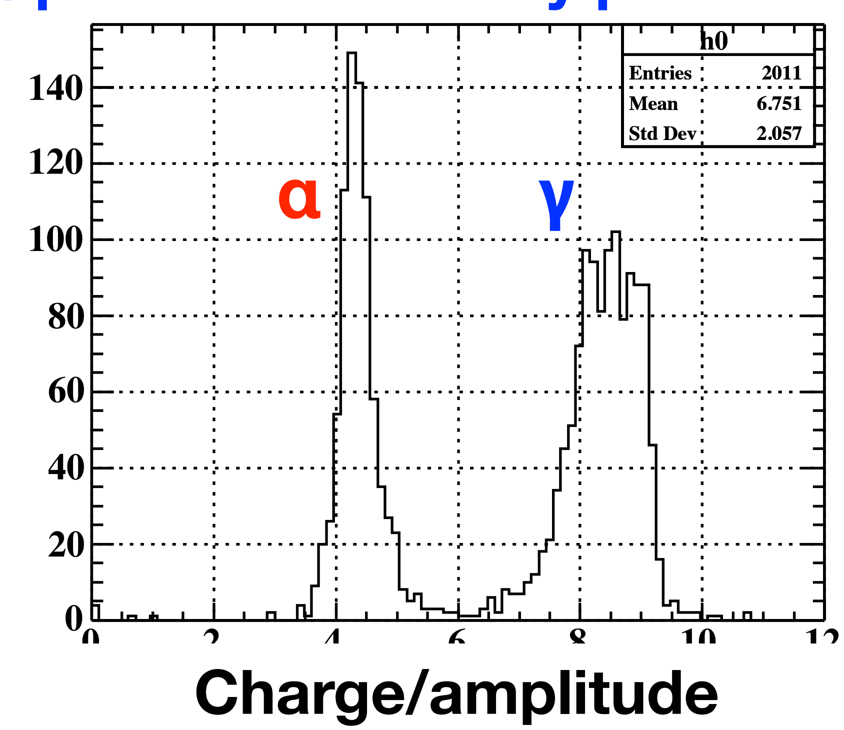
Photosensor calib.

- **LED:** visible photon
- **Alpha source** (^{241}Am spots on W-wire): 5.5MeV-α
  - As a spot light source with constant intensity→abs. calib. of photosensor eff.
  - Easily discriminated from γ-ray events with pulse shape (ex. charge/amplitude)
- **Cosmic ray:** ≲O(GeV)
- **Charge Exchange (CEX):** $\pi^- p \rightarrow \pi^0 n$, $\pi^0 \rightarrow \gamma\gamma$ (55, 83, 129MeV -γ)
- **Cockcroft-Walton proton accelerator:** ^{7}Li(p,γ)^{8}Be (14.8, 17.6MeV- γ), ^{11}B(p,γ)^{12}C(4.4, 11.6, 16.1MeV-γ)
- **AmBe source:** 4.4MeV-γ
- **Neutron generator:** ^{58}Ni(n,γ)^{59}Ni (9MeV-γ)

Alpha spot sources on W-wire



α/γ discrimination by pulse shape

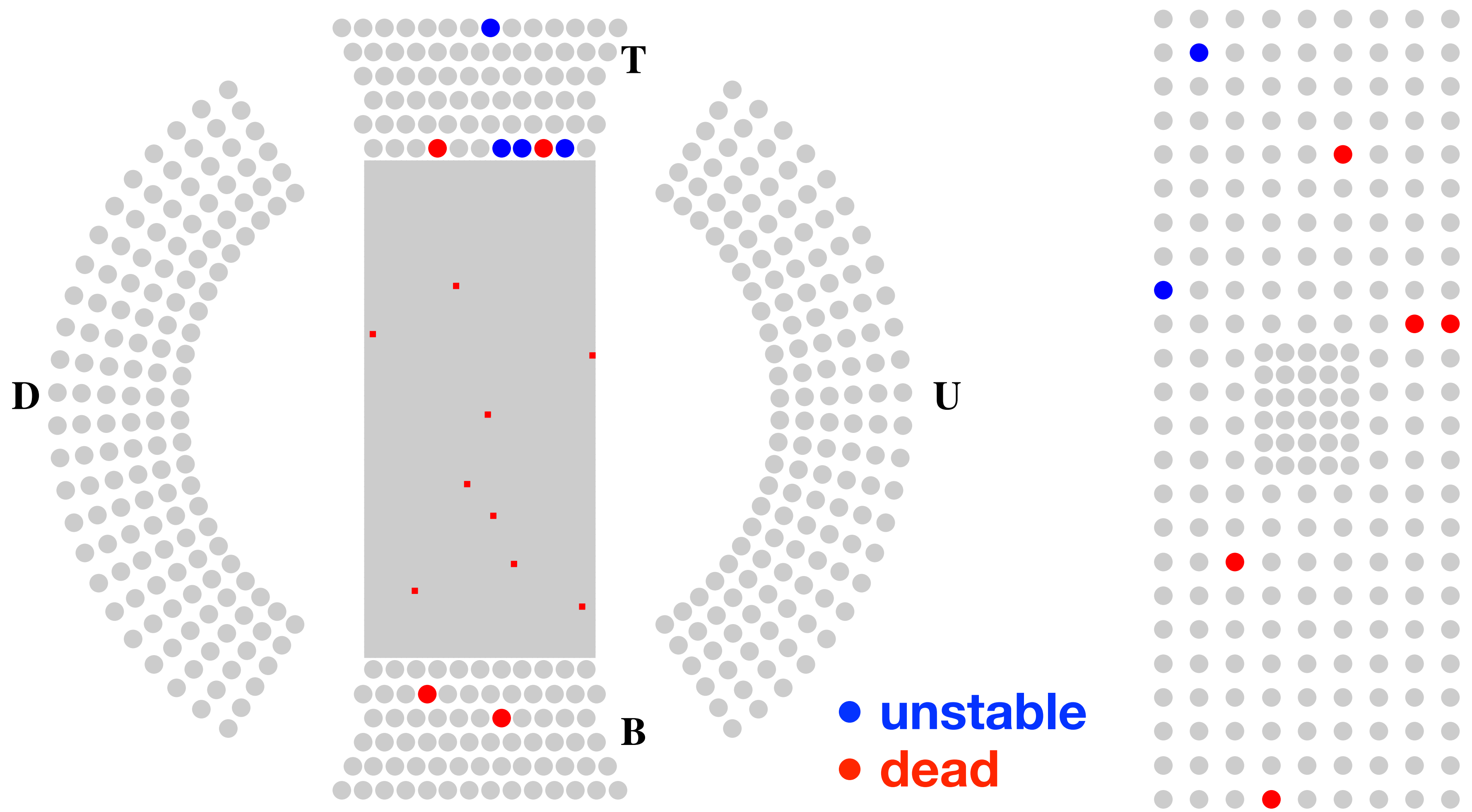


Photosensor Calibration

- **Signal check**
  - MPPC: dead (9ch)
  - PMT dead(9ch), unstable(6ch)

  →Effect on detector performance expected to be negligible (at least for MPPC)
- **Photosensor calibration, with more attention on MPPC**
  - Gain
  - PDE

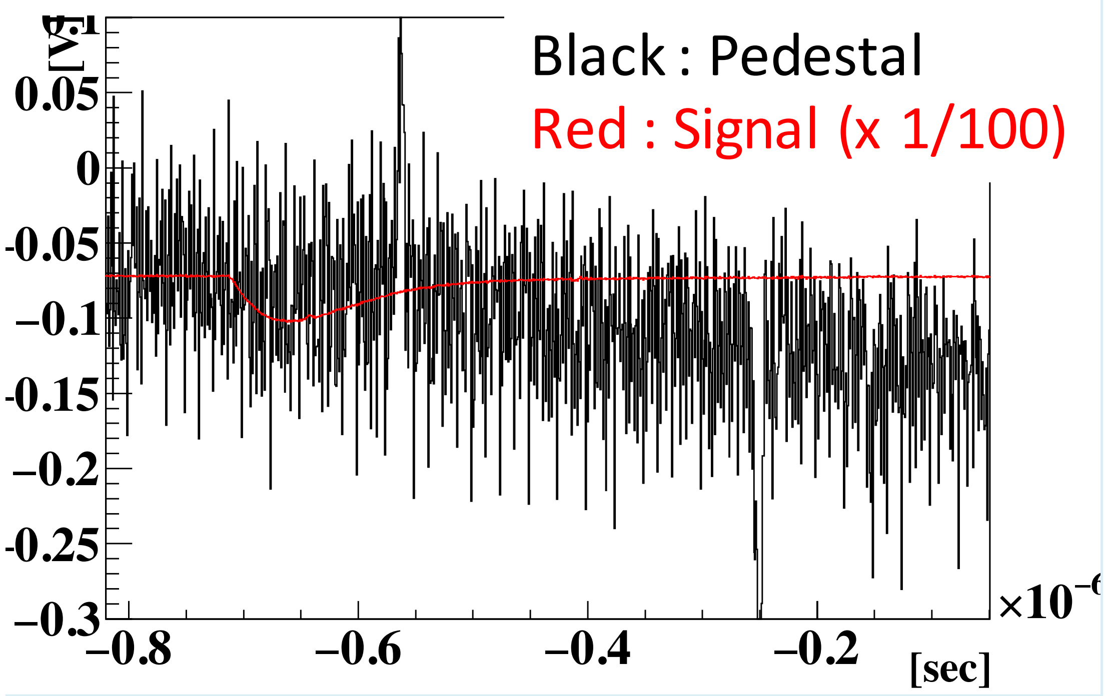
Dead channel map



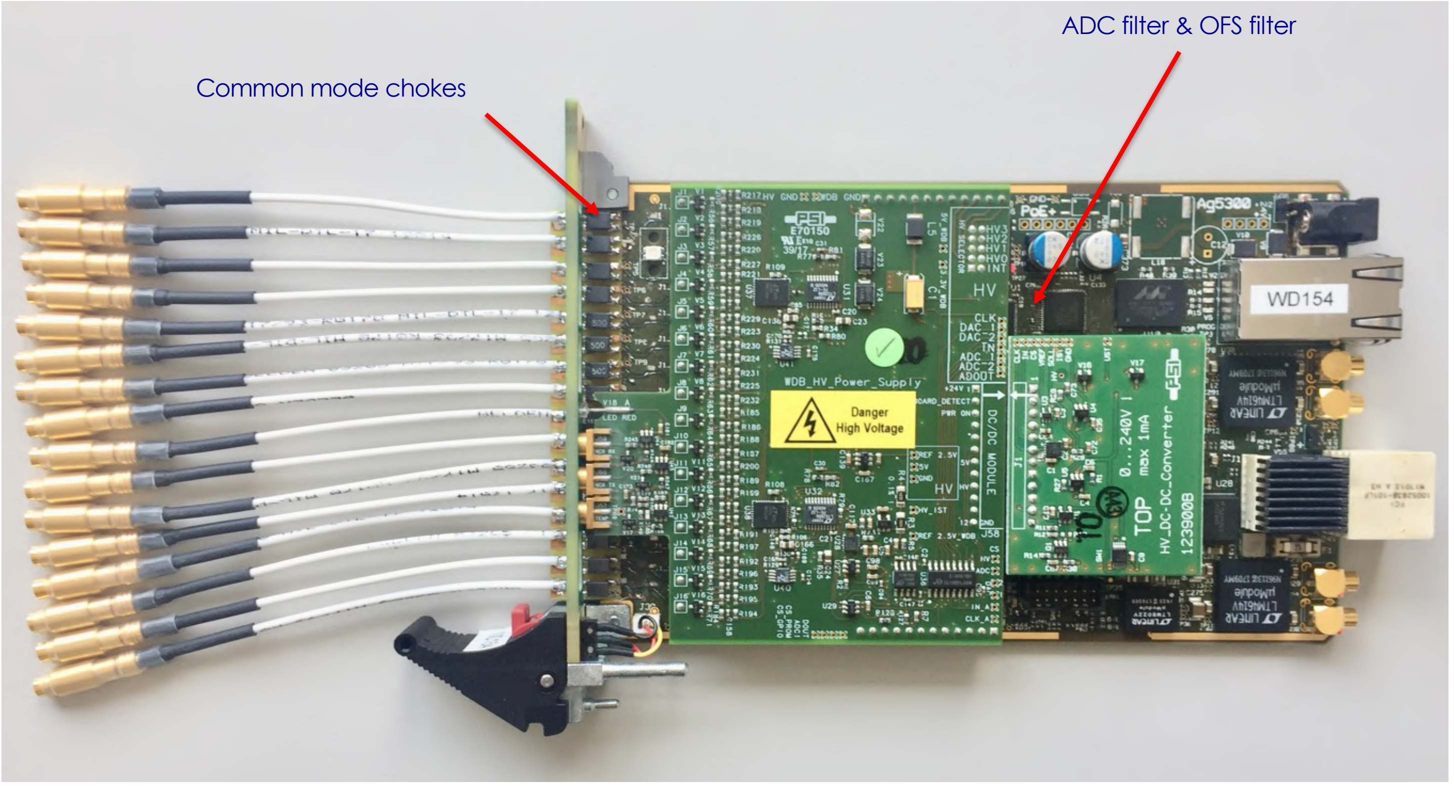
Noise

- **Currently, the most crucial issue is "noise"**
  - Current noise level is larger than expected from lab. measurement
  - Low frequency noise (~O(MHz)), which is coherent over the readout channels (for both MPPC and PMT)
  - Coherent noise will directly influence the detector performance
  - Need to reduce by a factor of 2-4 to reach ~1% level energy resolution
- **Work in progress to reduce noise**
  - Hunting for noise source
    - It seems that significant part of the noise comes from new readout electronics
  - Noise filtering for both hardware and software

Coherent low-freq. noise in sum waveform for MPPC



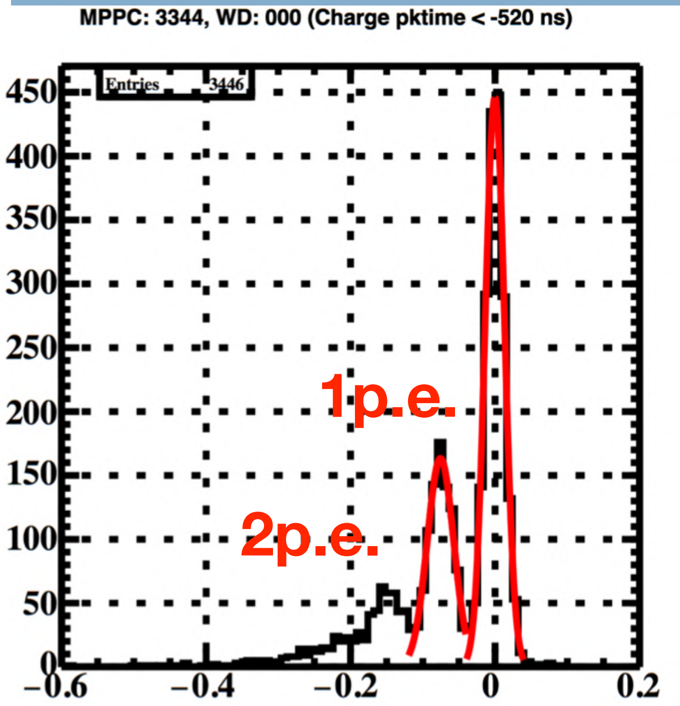
Modified waveDREAM board with noise filters



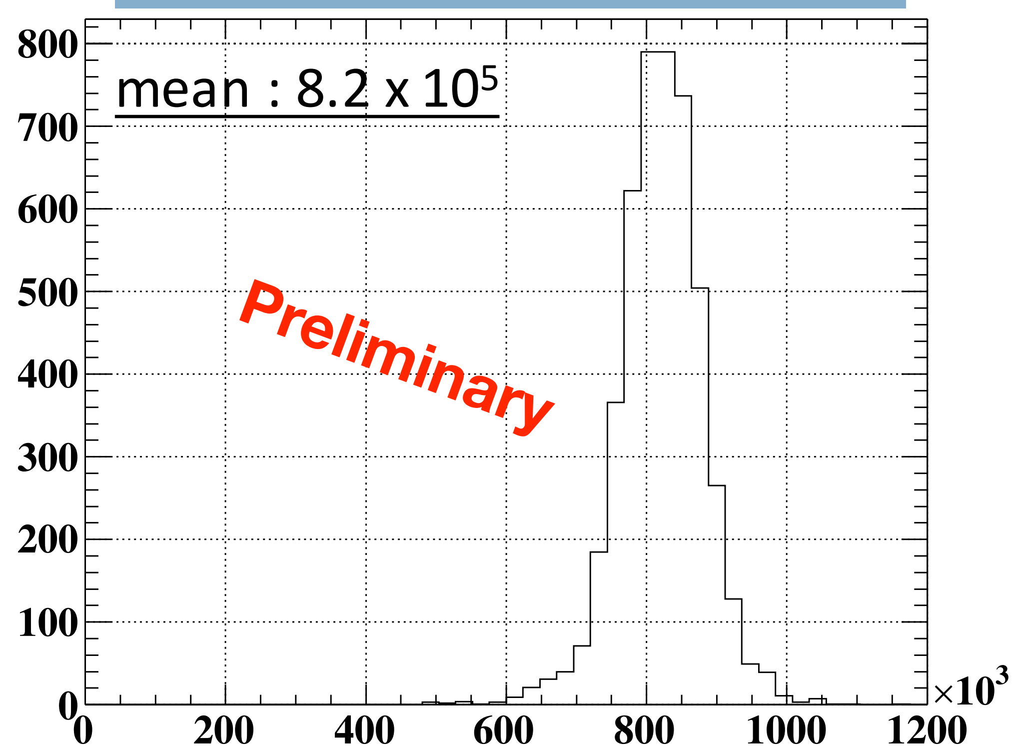
Gain

- **Gain calibration using LED**
  - Single photoelectron charge for low-level LED light
  - Average gain: 8×10^5 at over-voltage of 7V
  - Sensor-by-sensor variation at same over-voltage: 5%
- **Long term stability**
  - Observed slight variation, which is consistent with variation of LXe temperature

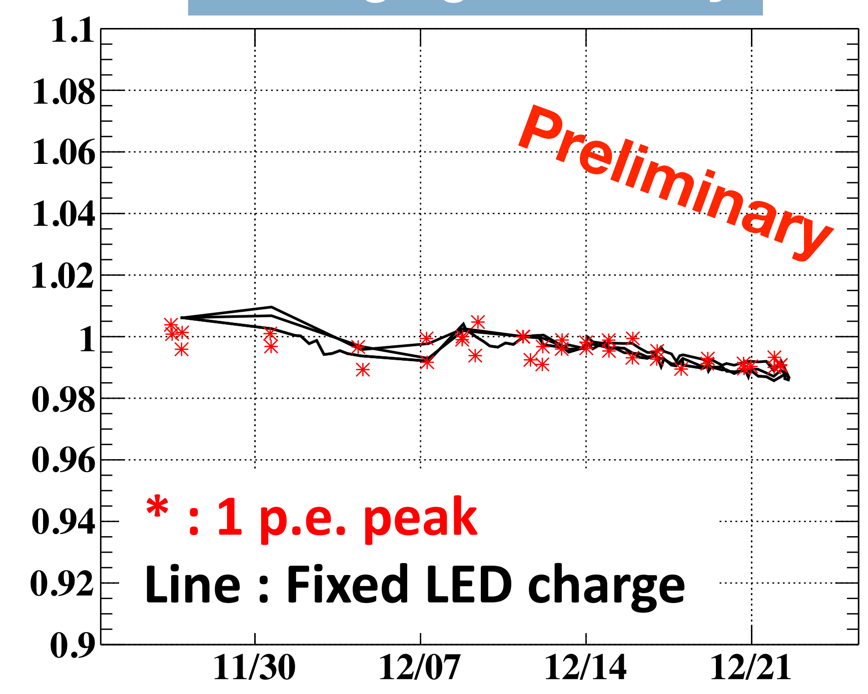
MPPC charge distribution for LED light



Gain distribution at V_{bias} = 54V



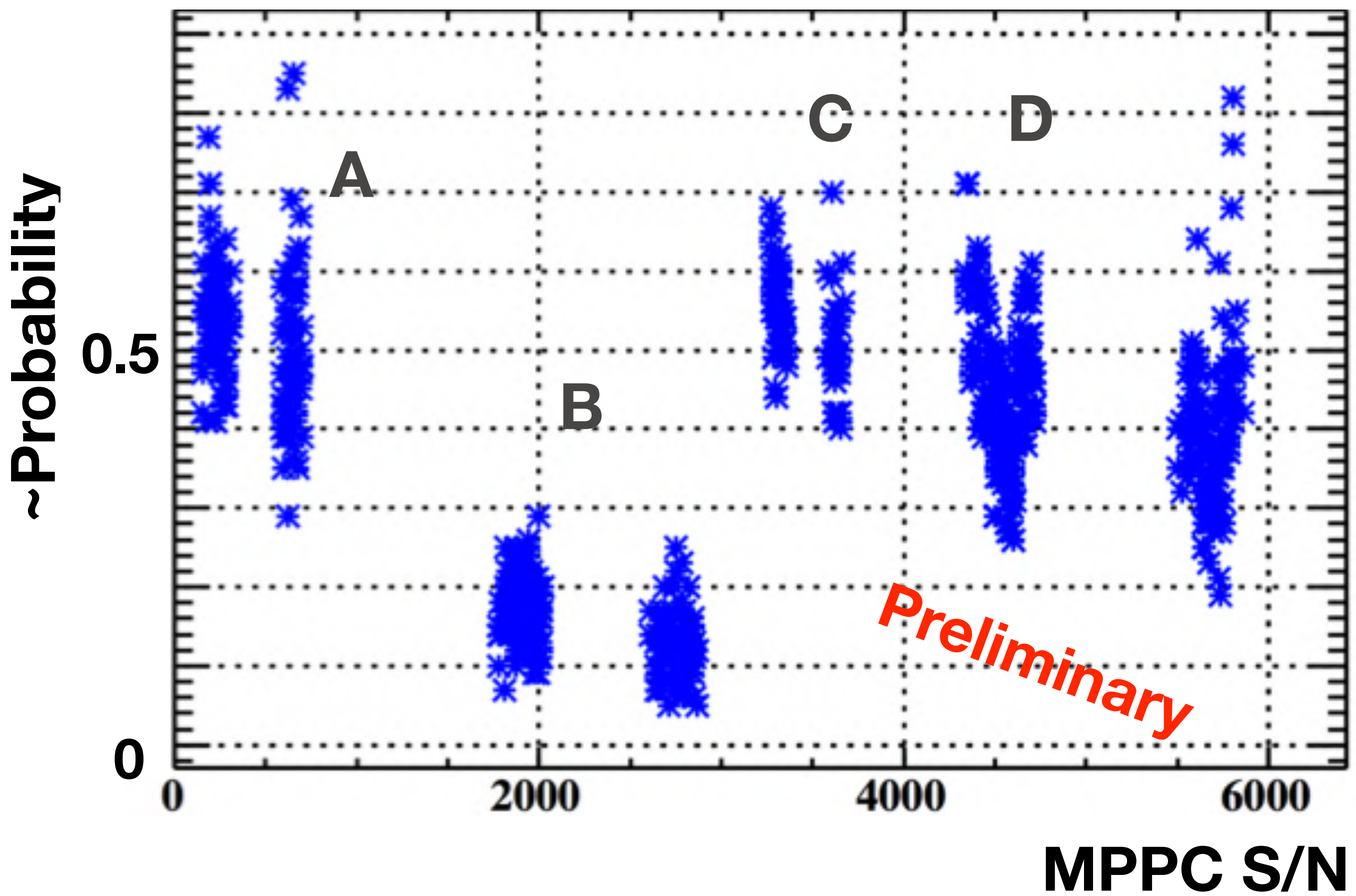
Average gain history



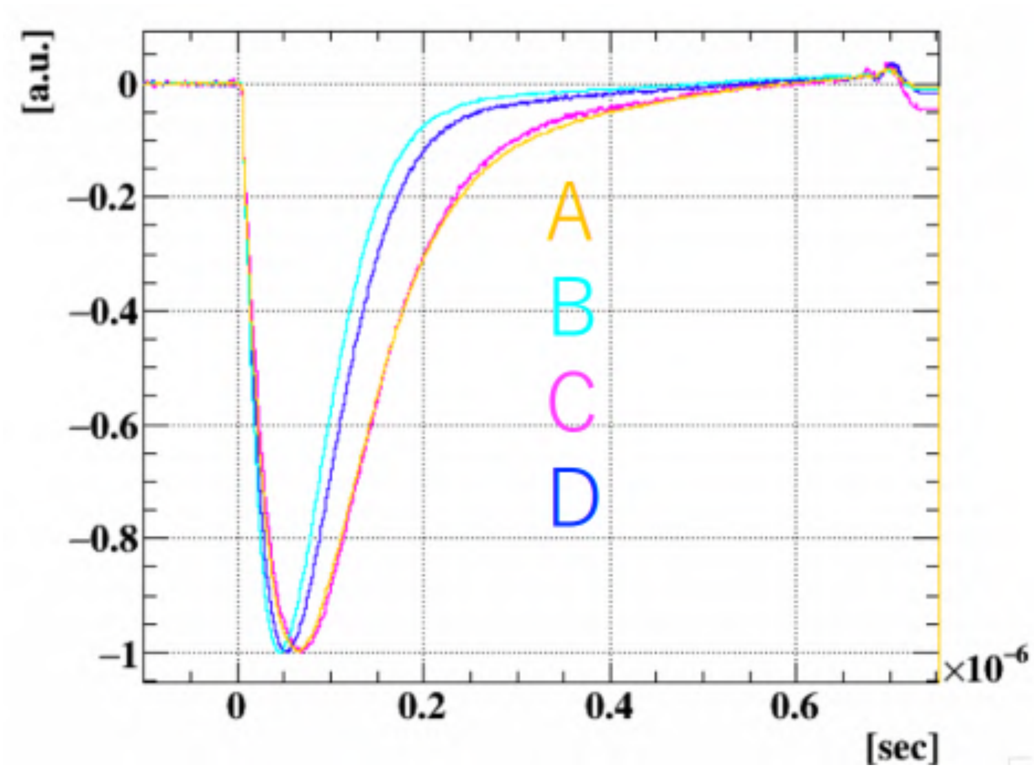
Correlated Noise

- **Correlated noise measured from spectrum with low intensity LED light**
  - Production lot dependence observed
  - Need careful calibration/correction

Cross-talk and after-pulsing at over-voltage of 7V



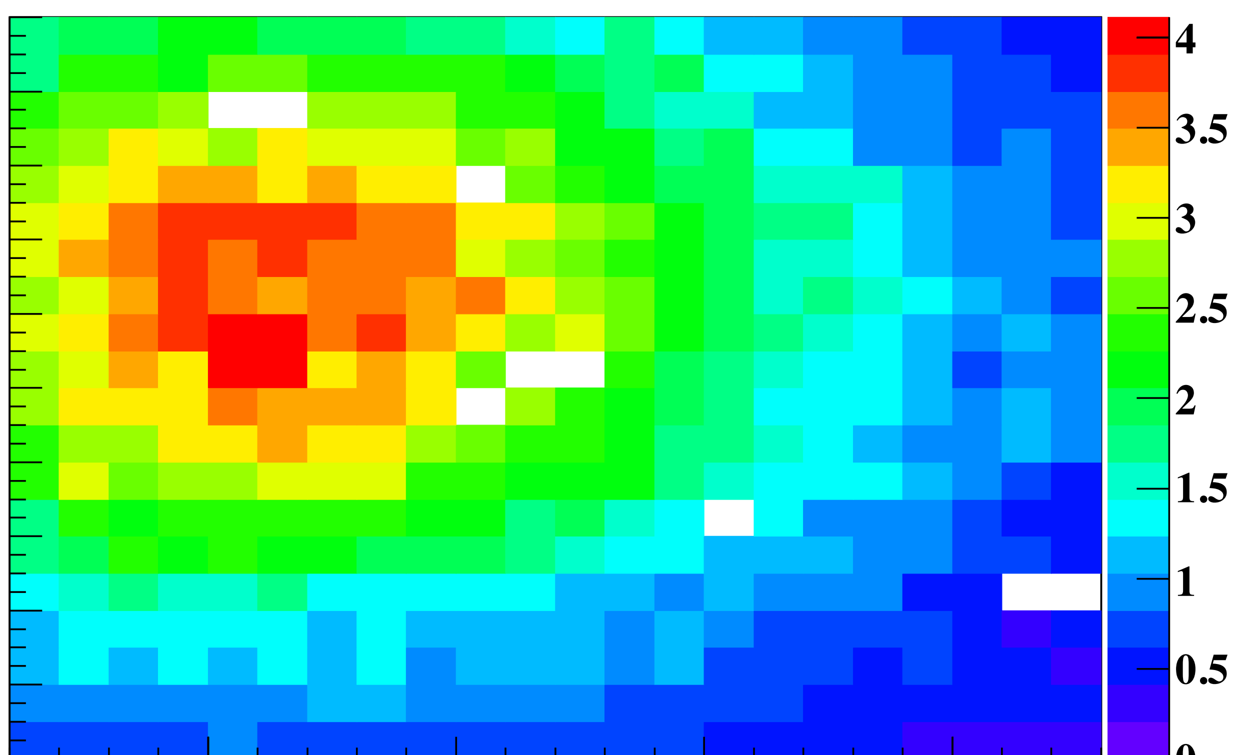
Lot dependence of pulse shape



Photon Detection Efficiency (PDE)

- **MPPC PDE measured using α-spot source (Am-241)**
  - PDE = (measured # of photoelectrons)/(expected # of photons)
  - **Average PDE of 18%** at over-voltage of 7V (preliminary, incl. CT and AP)
    - Lower than lab. measurement, probably due to non-optimal light yield and/or analysis parameters

Average # of p.e. for MPPCs near alpha source

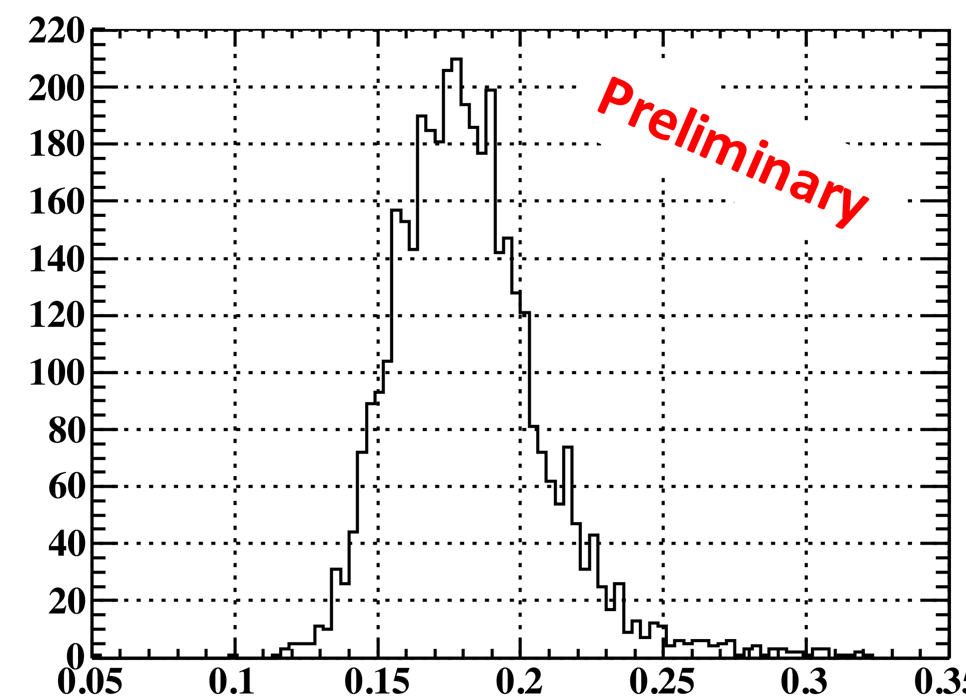


20 MPPCs

22 MPPCs

※ one bin = one MPPC

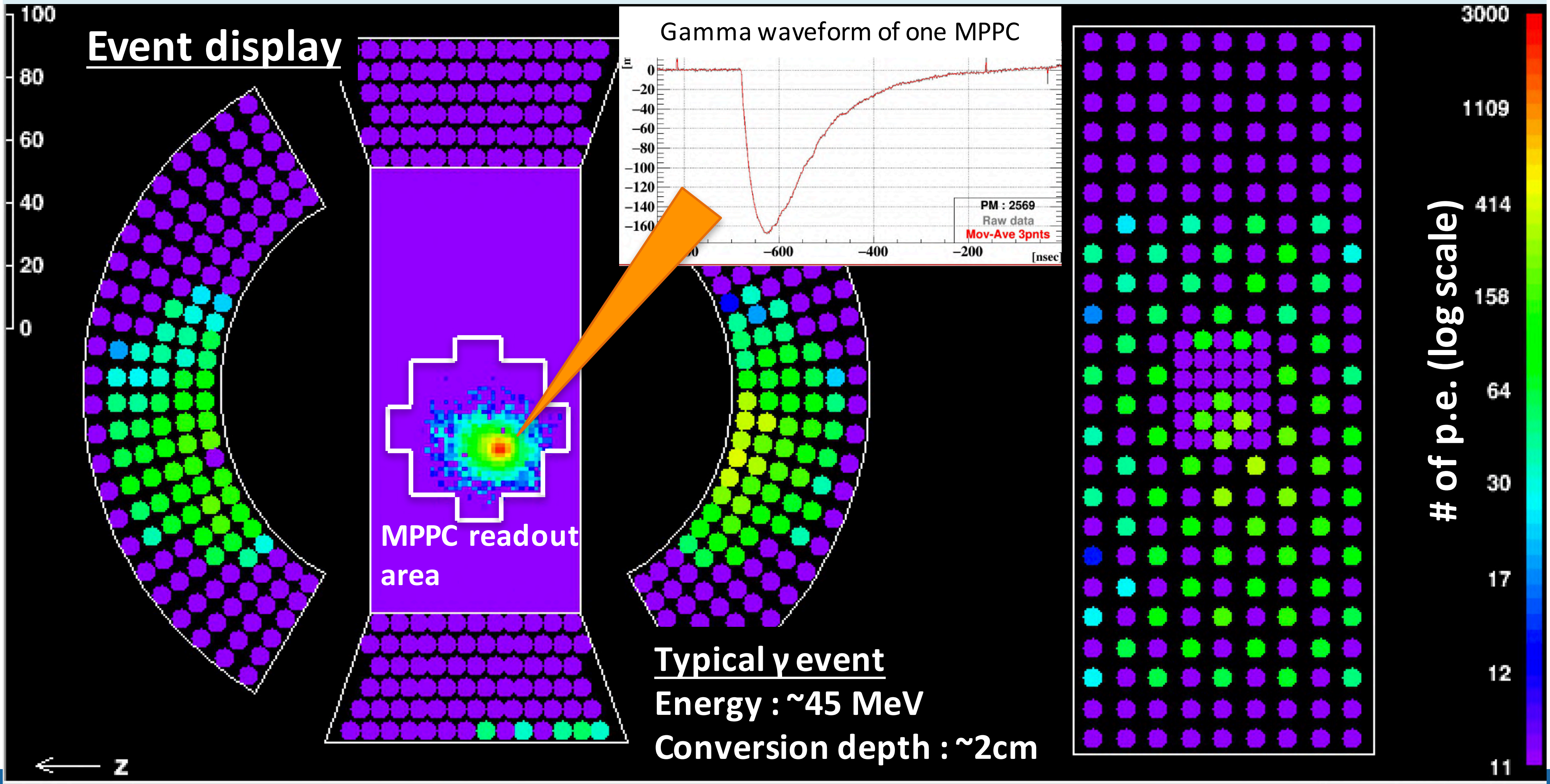
PDE measured for all MPPCs



(@ over-voltage of 7V, incl. cross-talk and after-pulsing)

First Observation of ~50MeV Photons

- **Background photons near signal energy (~50MeV) from radiative muon decays successfully observed**
  - Not ready for serious reconstruction due to the limited number of readout electronics channels (~25%) and unexpectedly larger noise
  - Significant improvement of imaging performance is obvious just from event displays



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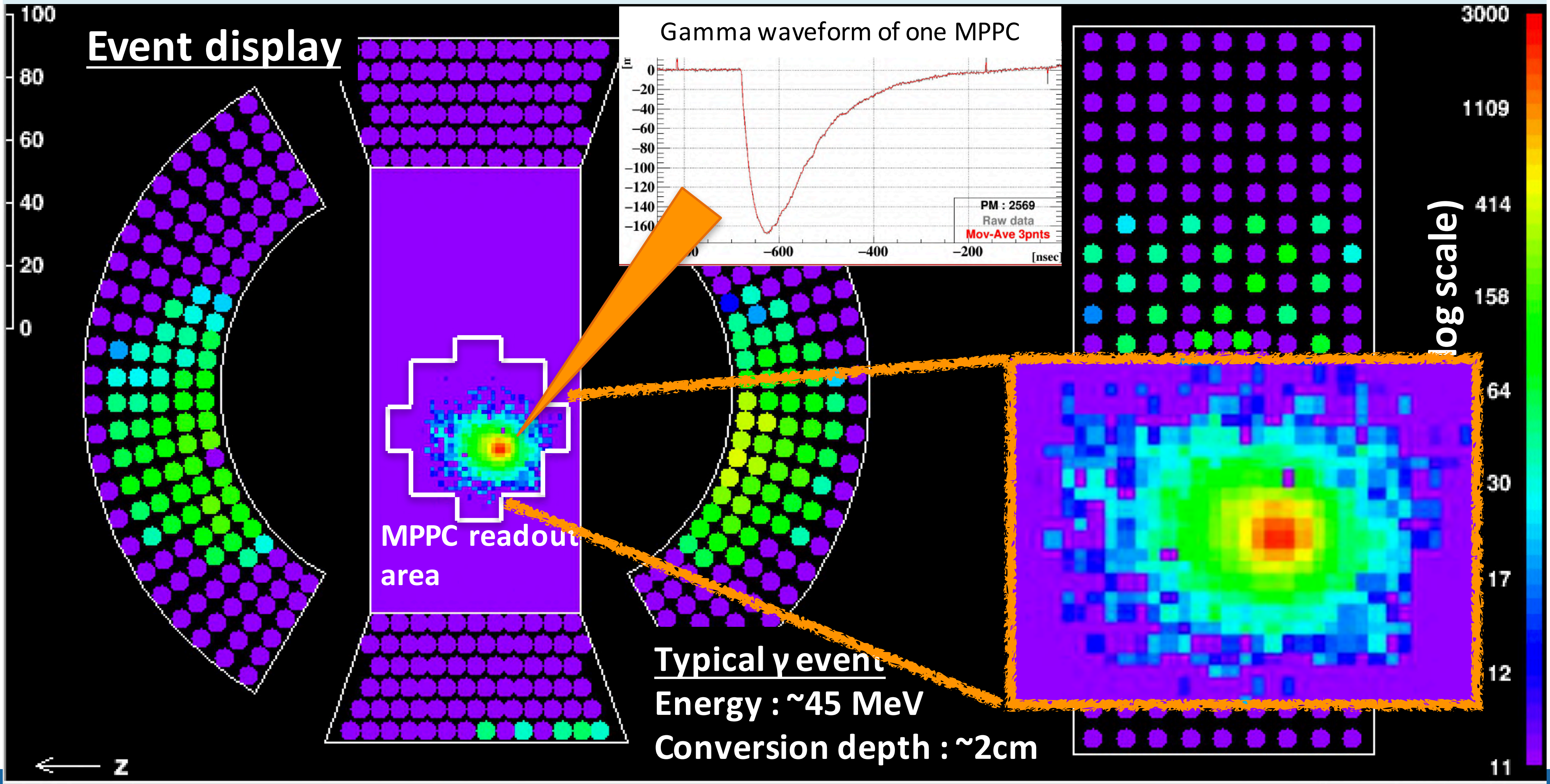
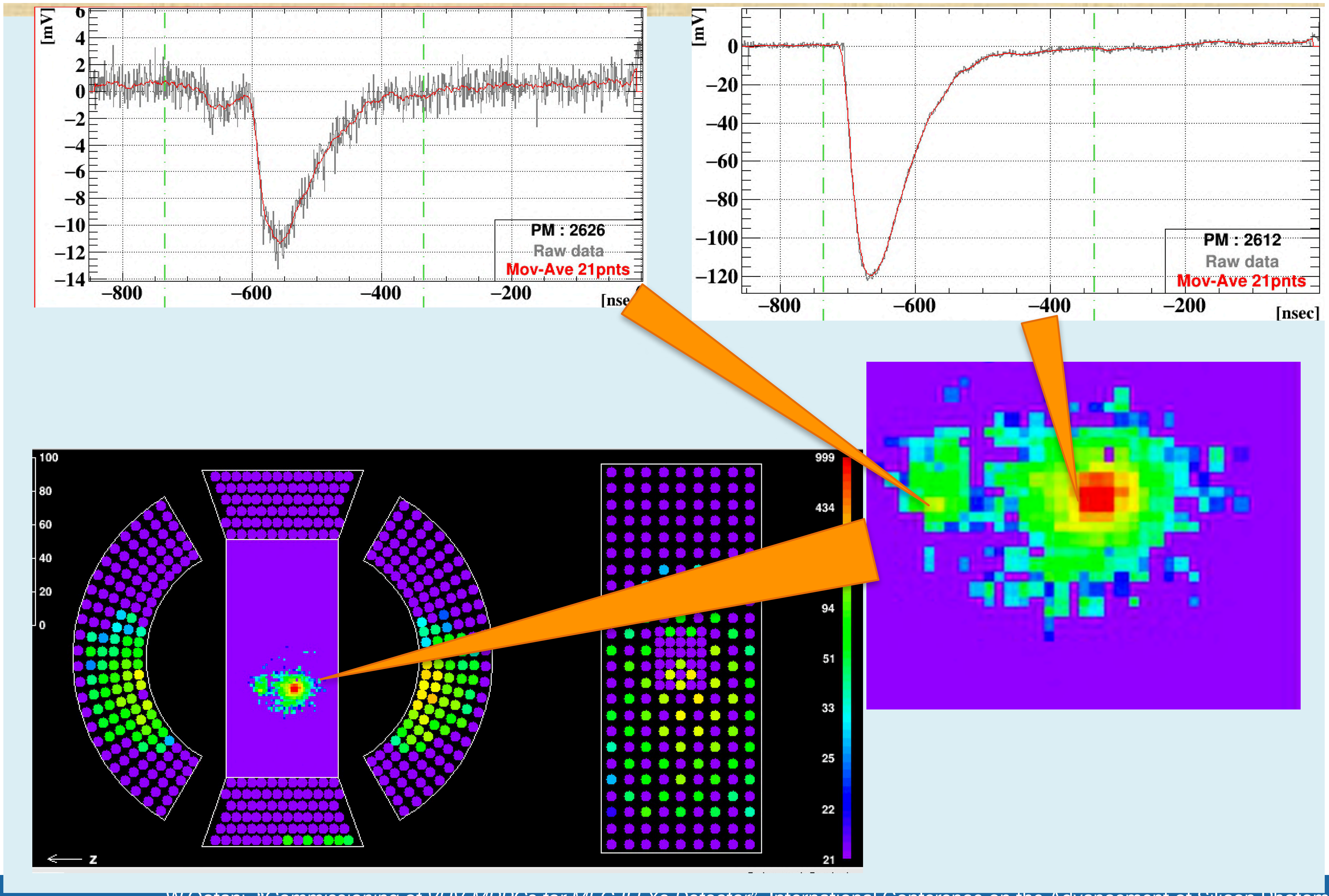


Pileup Photon

- **Pileup photon can also be clearly resolved thanks to higher granularity**



Summary and Perspectives

- **Significantly improved performance of MEG LXe photon detector with high-granularity scintillation readout by VUV-MPPCs**
- **Detector construction completed and commissioning is in progress.**
  - Calibration of VUV-MPPCs
    - Gain, PDE, correlated noise, alignment,…
  - Larger noise than expected. Under investigation.
  - First observation of photon around signal energy (~50MeV) at in-beam test at full μ-beam intensity
- **The detector has just been filled with LXe again after PSI accelerator shutdown**
  - First thermal cycle. VUV-MPPCs can survive?
- **Detector calibration with monochromatic photon around signal energies planned this year, but full detector calibration will be done in 2019 after delivery of full readout electronics**
- **Production of MEG II physics data will start in 2019**

International Conference on New Photo-detectors (PD18)

Nov 27th-29th, 2018, University of Tokyo, Tokyo, Japan

- The 5th in a series of PD conference
  - PD07@Kobe, Japan; PD09@Matsumoto, Japan; PhotoDet12@Orsay, France, PhotoDet15@Moscow, Russia
- Scope
  - Recent progress and new ideas on photo-detectors (SiPM, APD, PMT,…)
  - Readout techniques
  - Applications

First bulletin will come soon. Please mark it on your calendar!

Thank you for your attention!