BSM-2023, Nov.6-9
Hurghada
Egypt

1. Wang, Z., Li, M., Wu, D. *et al.* Imaging of CsI(Tl) crystal event and double-slit Young's interference by a single photon sensitive camera. *Eur. Phys. J. Plus* **138**, 591 (2023). https://doi.org/10.1140/epjp/s13360-023-04234-4, arXiv:2206.00876
2. Wang, Z., Li, M., Wu, D. et al. Imaging of CsI(Tl) crystal event and double-slit Young's interference by a single photon sensitive camera. Eur. Phys. J. Plus 138, 591 (2023). https://doi.org/10.1140/epjp/s13360-023-04234-4, arXiv:2301.01969

# Imaging with single photon sensitive camera

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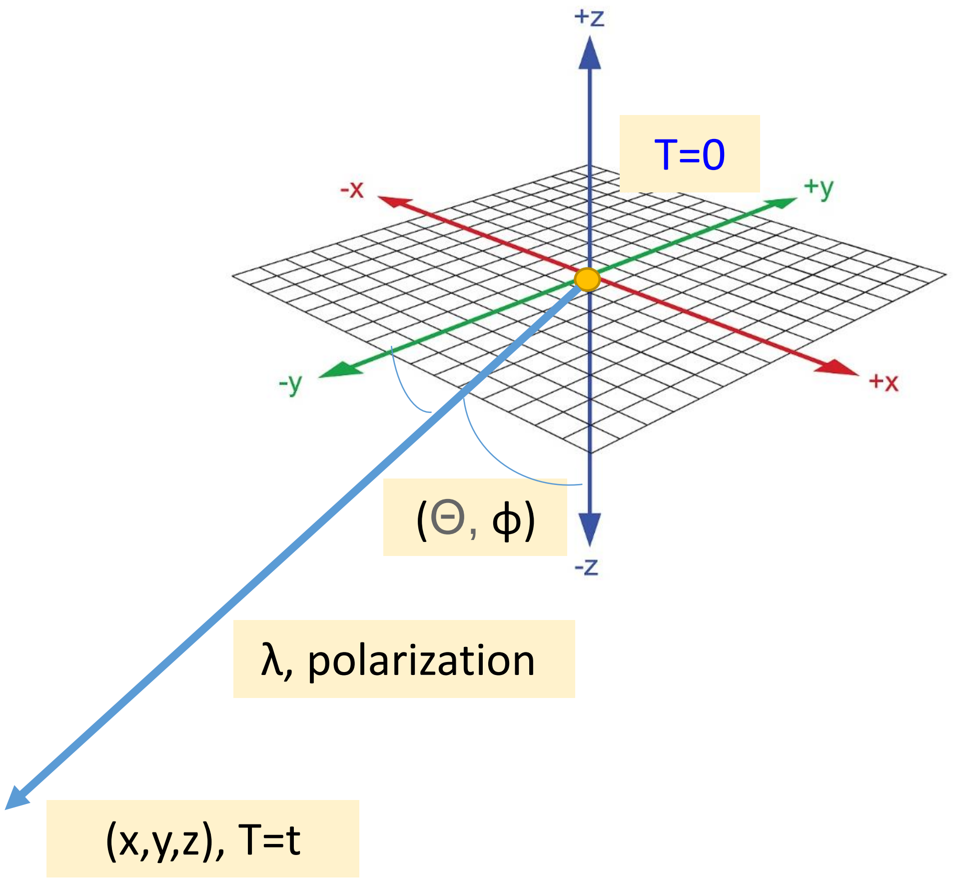
# Outline

- Photon detection & Imaging
- Characteristic of camera
- Double-slit Young's interference
- Particle imaging with CsI(Tl) crystal
- Spatial coincidence of imaging

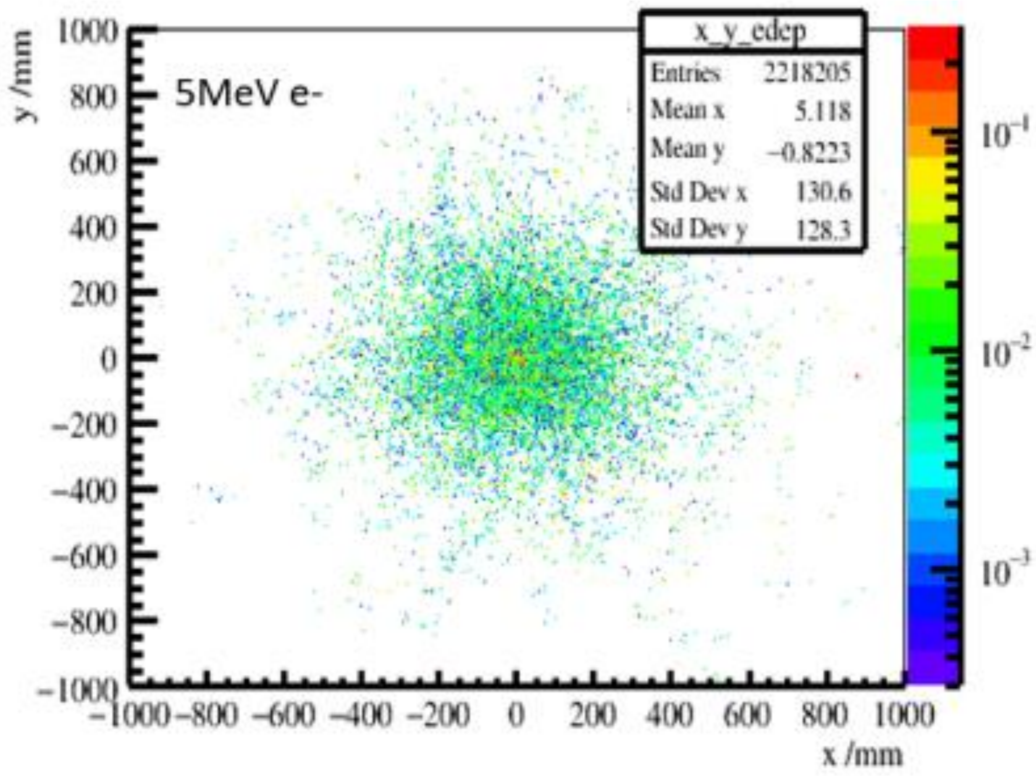
# Parametrization of a single photon

- **Parameters of single photon:**
  - Wavelength: λ
  - Polarization
  - **Direction: (Θ, ϕ)**
  - **Hitting location: (x,y,z)**
  - **Arriving time: t**

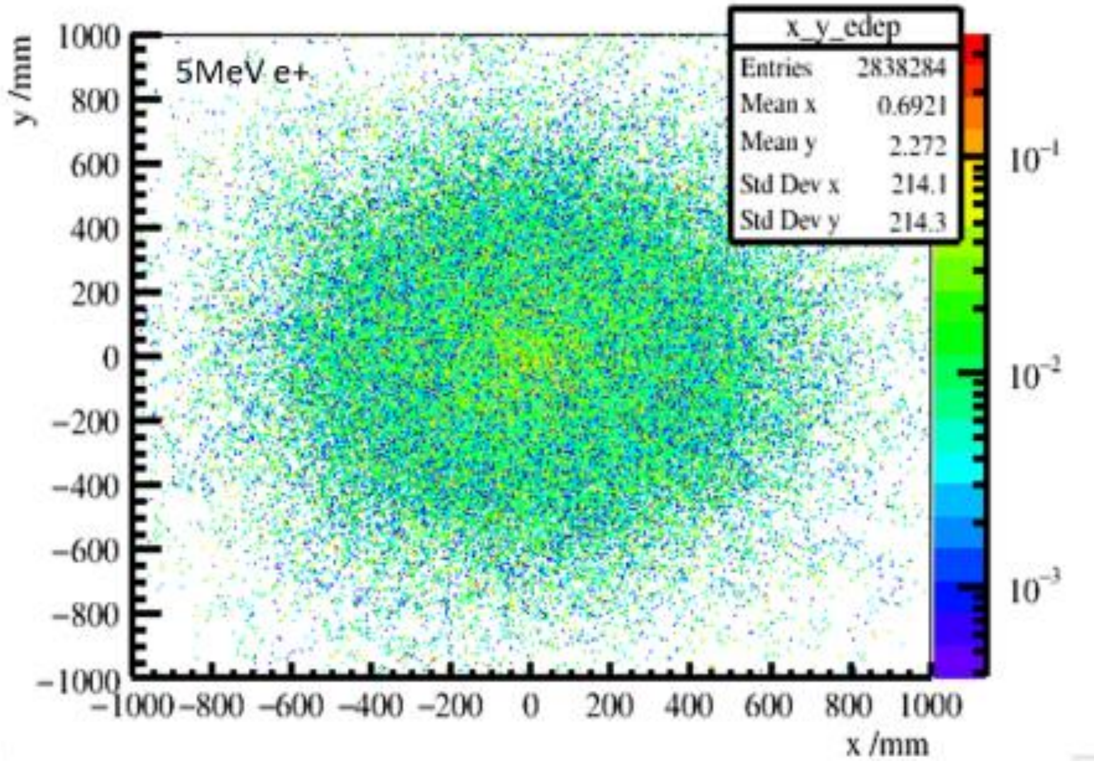
Single photon measurement with possible BSM?
**More measurement dimensions, more possibilities.**



# Simulation of high energy event pattern in LS: electron Spatial features



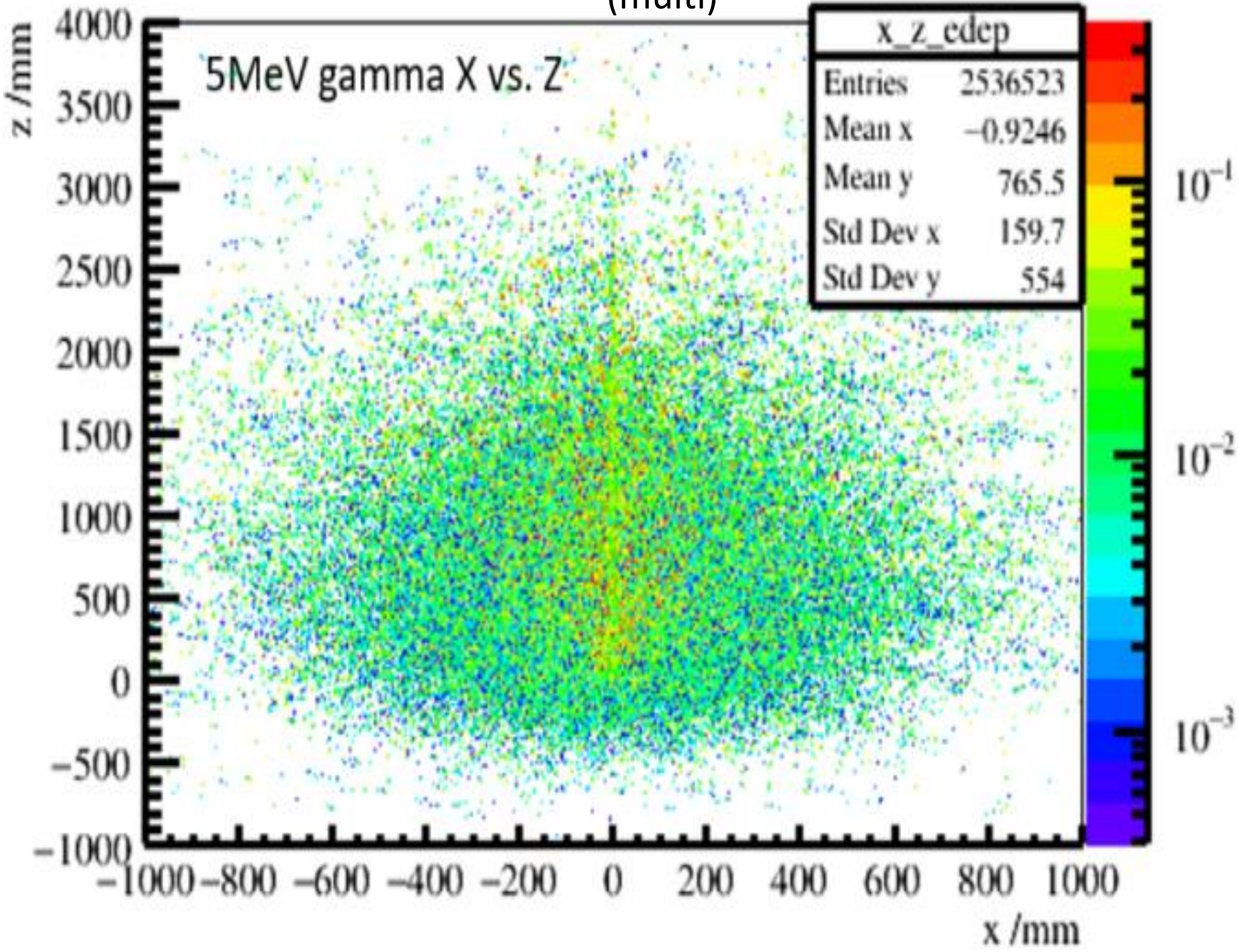

5MeV e-
(multi)



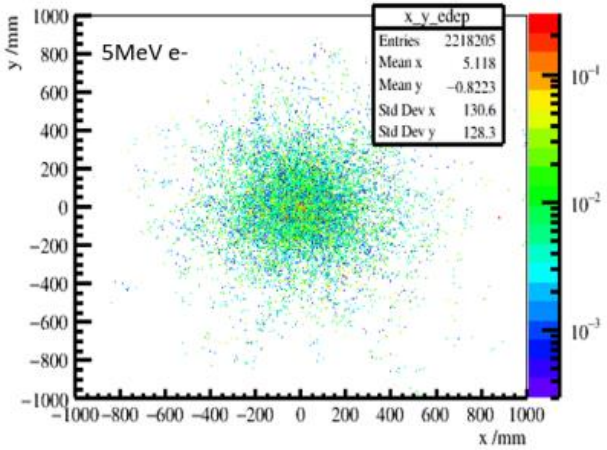

5MeV e+
(multi)

# Preliminary simulation of event pattern in LS

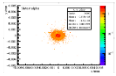
5MeV Gamma
(multi)




5MeV e- (multi)



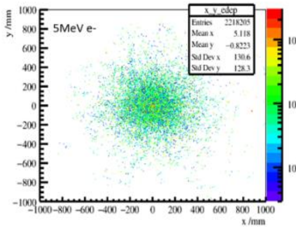

5MeV alpha
(multi)

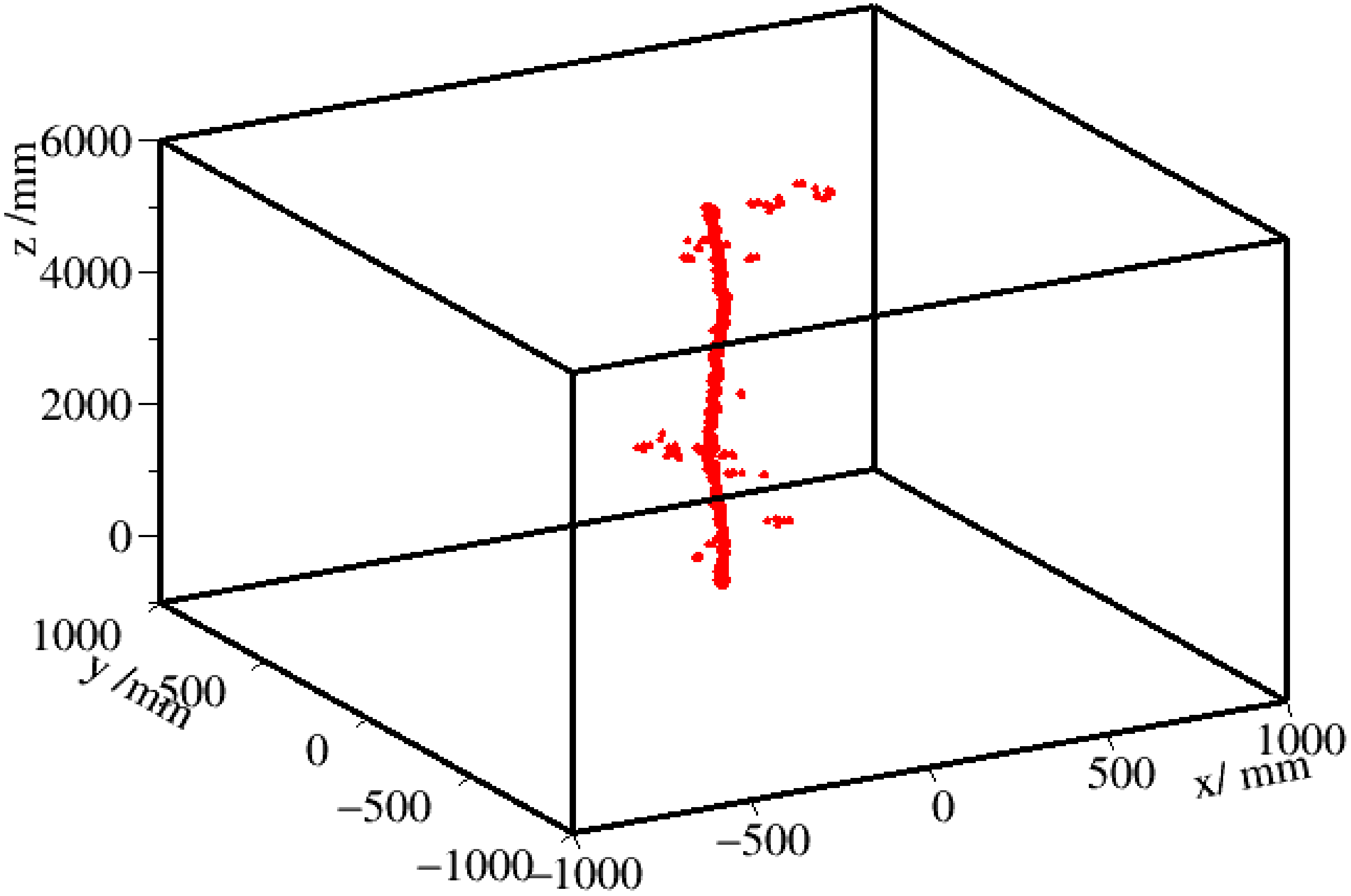


# Preliminary simulation of event pattern in LS: muon

1GeV muon (Single)

5MeV e- (multi)



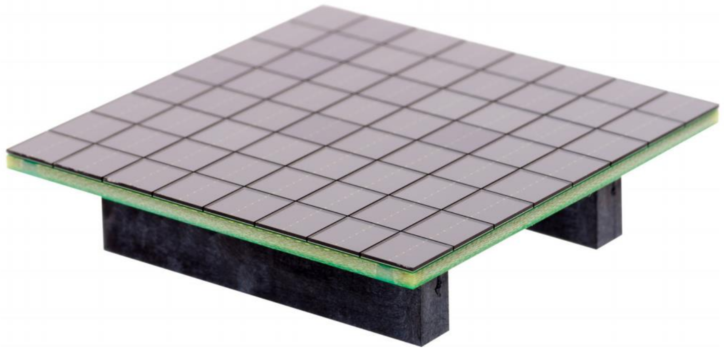



# PMT/SiPM vs. imaging

- PMT/SiPM:
  - Roughly (x,y,z), (cm,mm)
  - T (ns, ps)
- Imaging:
  - (x,y,z) (mm,um)
  - (Θ, ϕ)


https://www.hamamatsu.com/content/dam/hamamatsu-photonics/sites/documents/99_SALES_LIBRARY/etd/PMT_handbook_v3aE.pdf

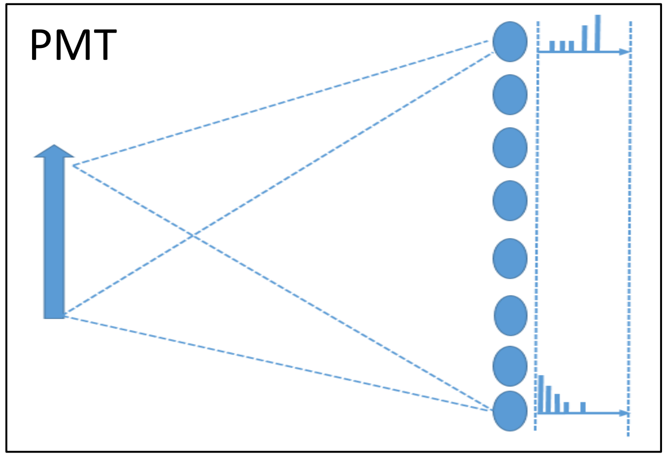
SiPM

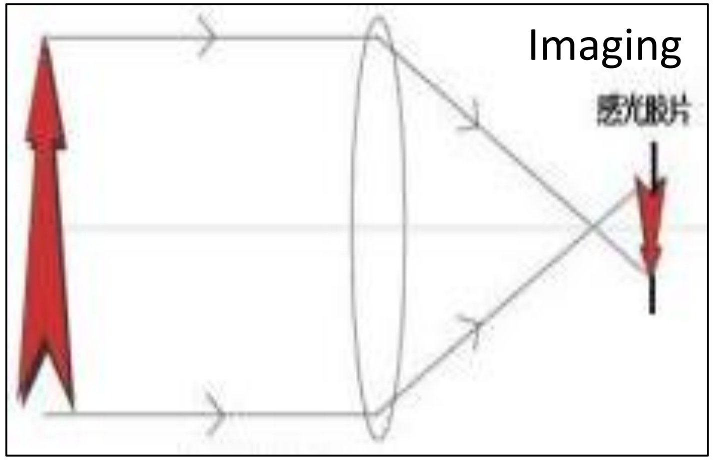


https://www.onsemi.com/pdf/datasheet/arrayj-series-d.pdf

Film

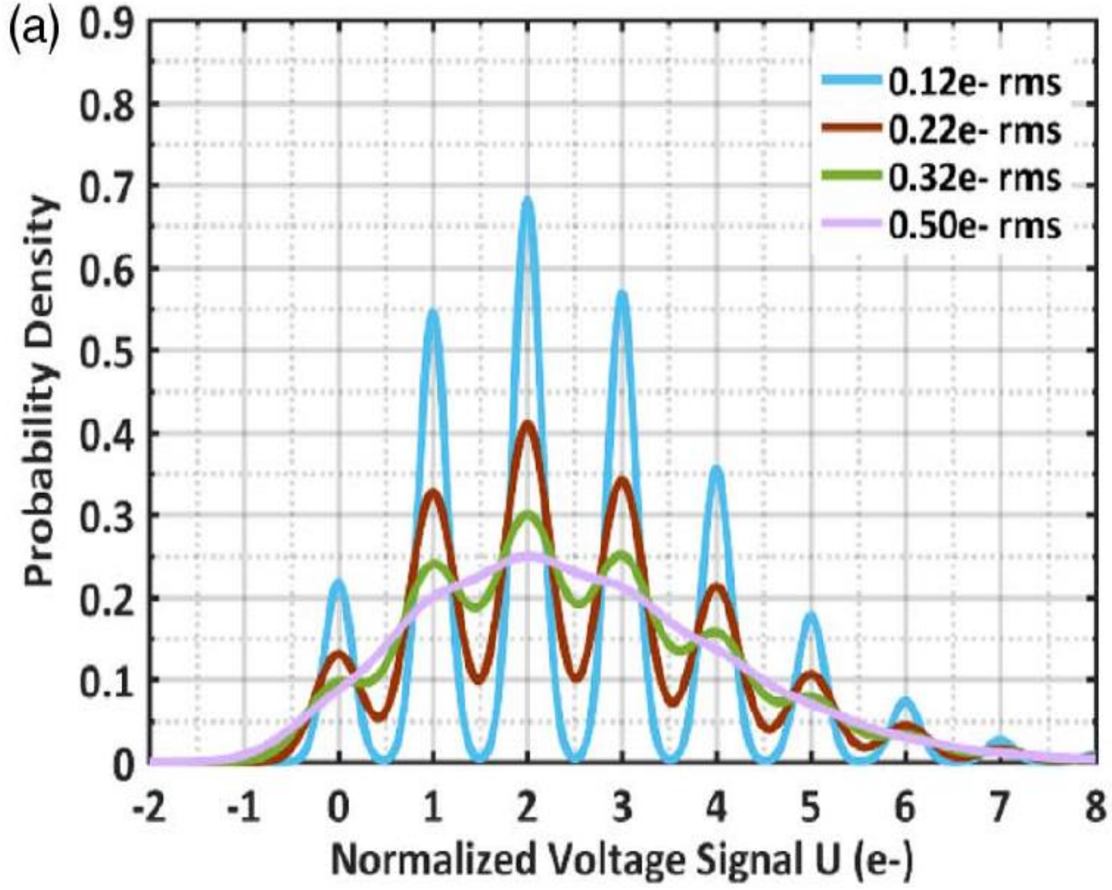
Camera

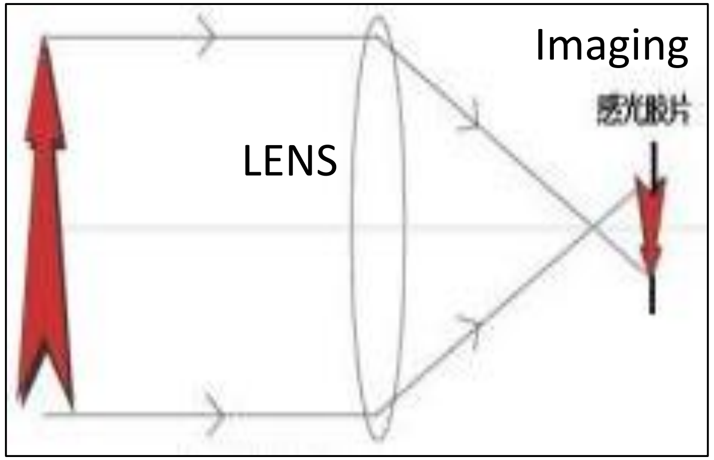



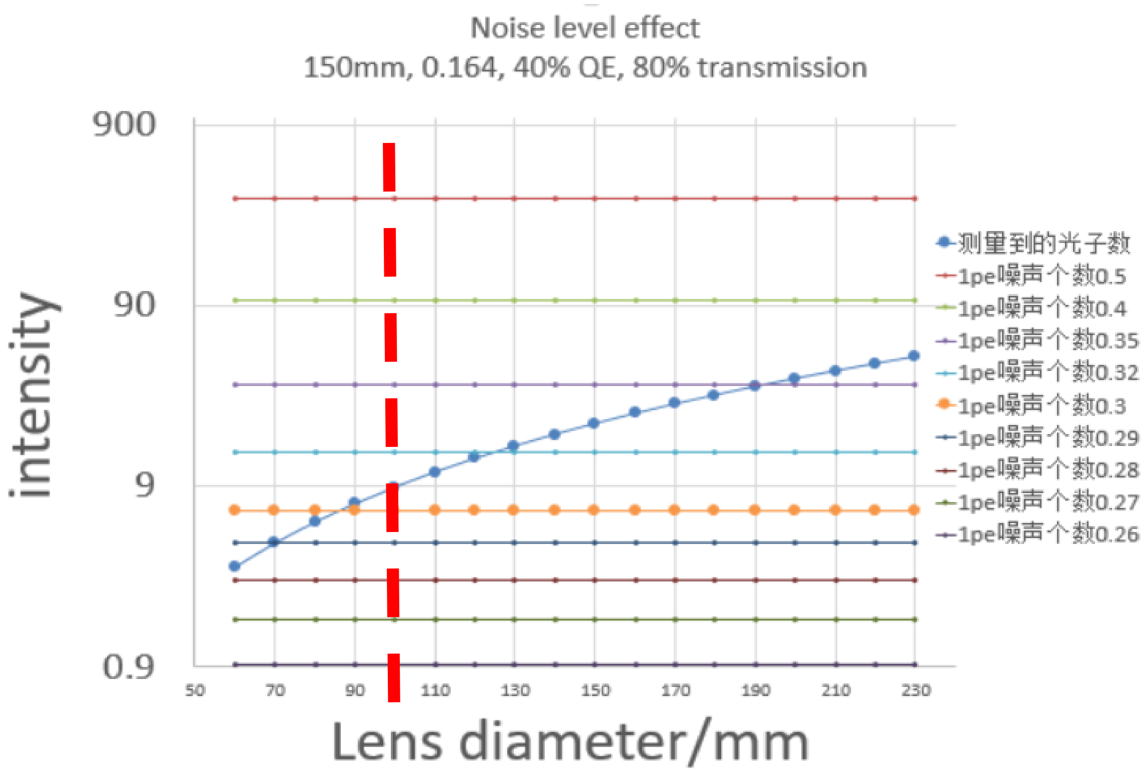

# Noise vs. signal (signal-noise ratio) in single photon level

- Noise level/resolution @single photon level(SPE)
  - PMT: ~30% (0.3e-)
  - SiPM: 10%~20% (0.2e-)
  - Camera: 1~100e-
- Single photon counting
  - <40%@SPE



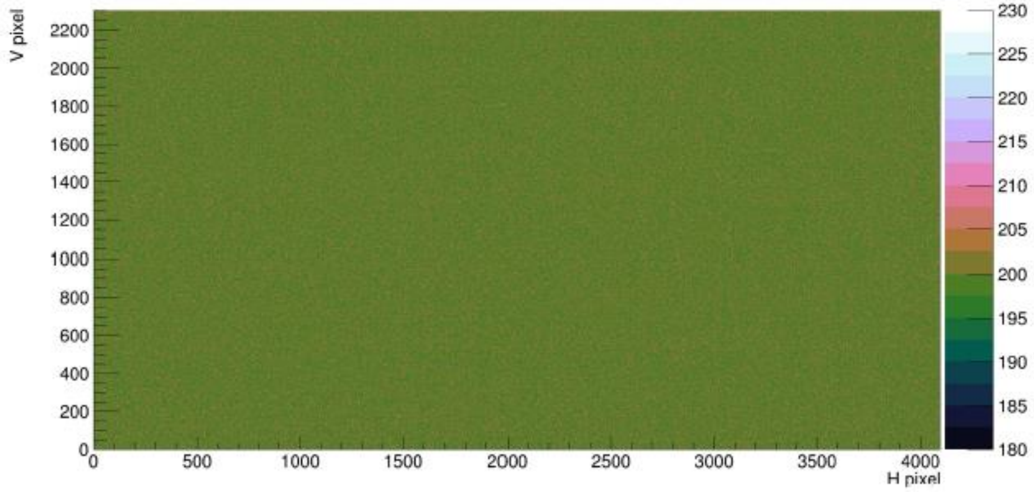
# Noise vs. signal identification @imaging



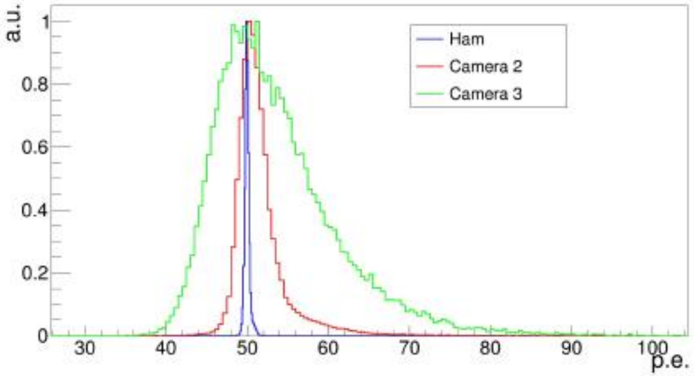

- Possibility to identify a signal from noise
  - Signal intensity
    - Object Distance
  - Solid angle
    - Lens diameter
    - effective aperture
  - Noise level
  - Efficiency

# Single photon sensitive camera

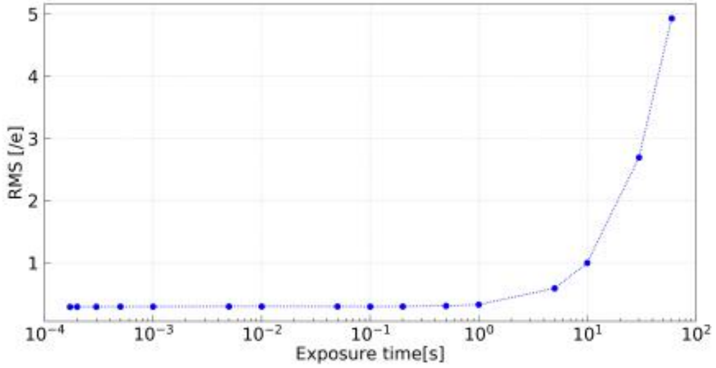



(a) 2-D image of the camera in dark w/ exposure 1 s

Noise level reaching to 0.3e- of a commercial camera




(b) 1-D plot of pixel noise in (a)




(c) Noise vs. exposure time

Dark current
Readout noise

# Joint measurement of PMT & camera

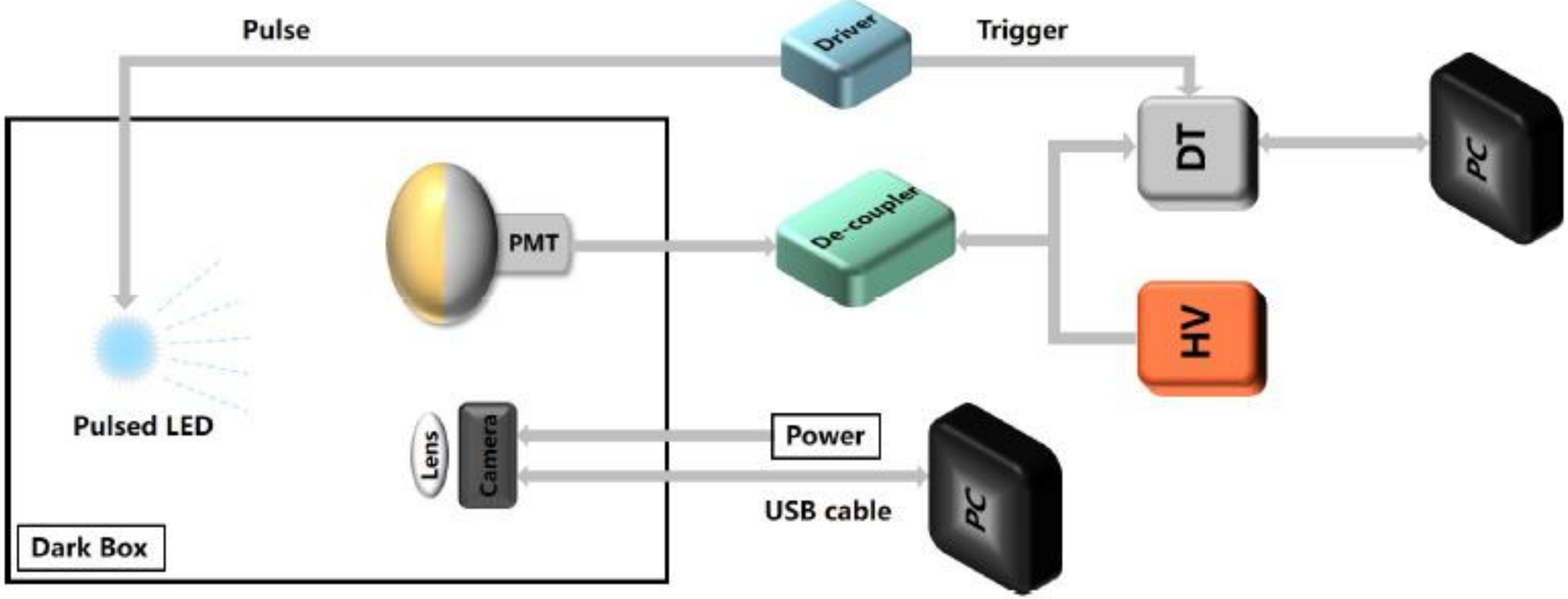
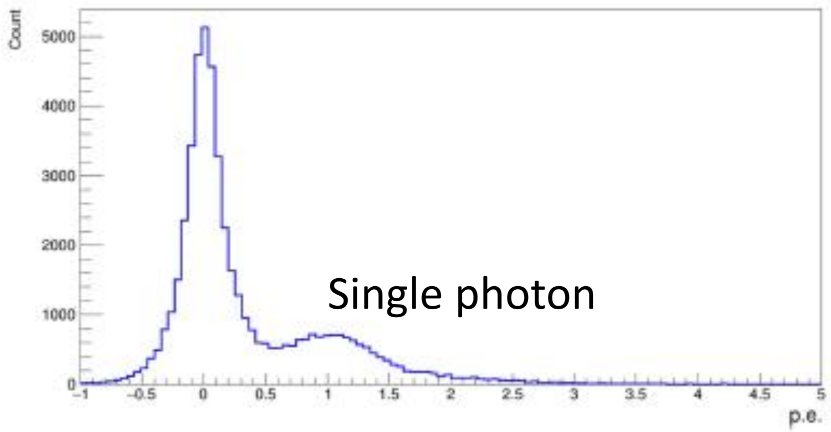


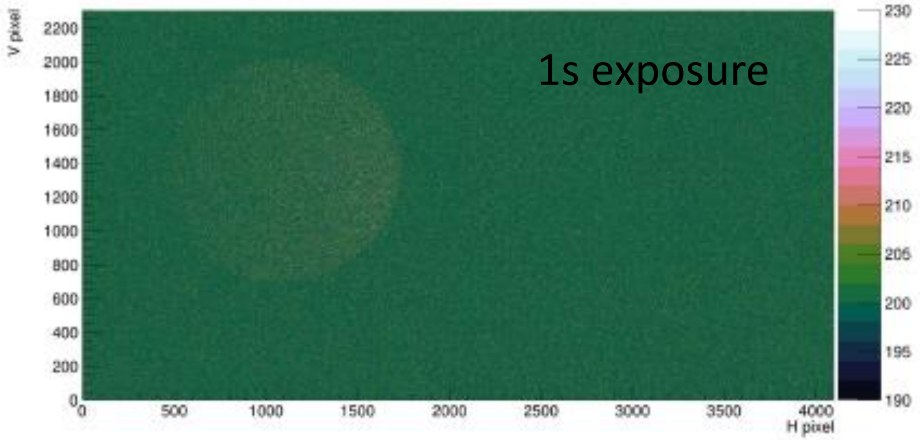

**Fig. 1**: Schema of LED testing system.

# Single photon testing With light source

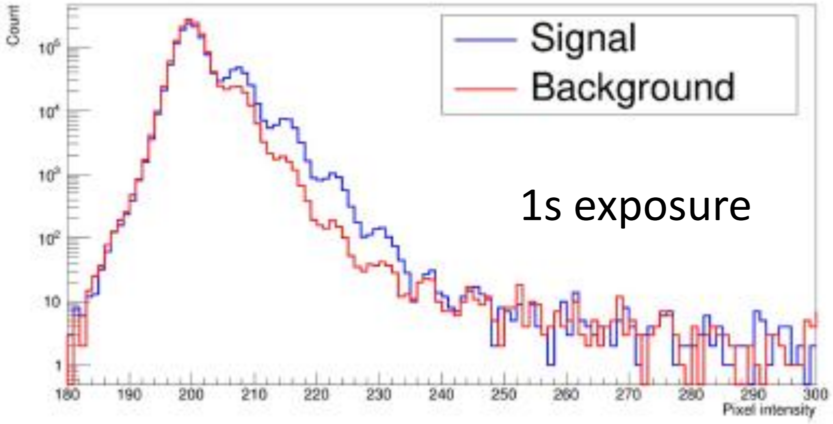
- Pulse light
- Single photon identified
- Light intensity



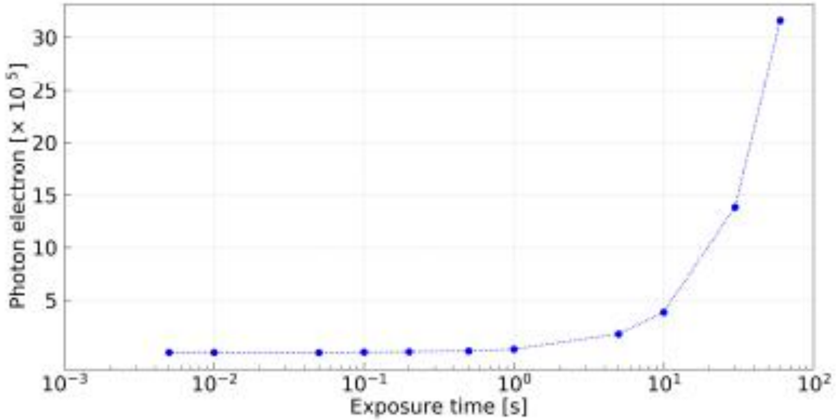

(a) Intensity viewed by PMT.




(b) 2-D image of LED



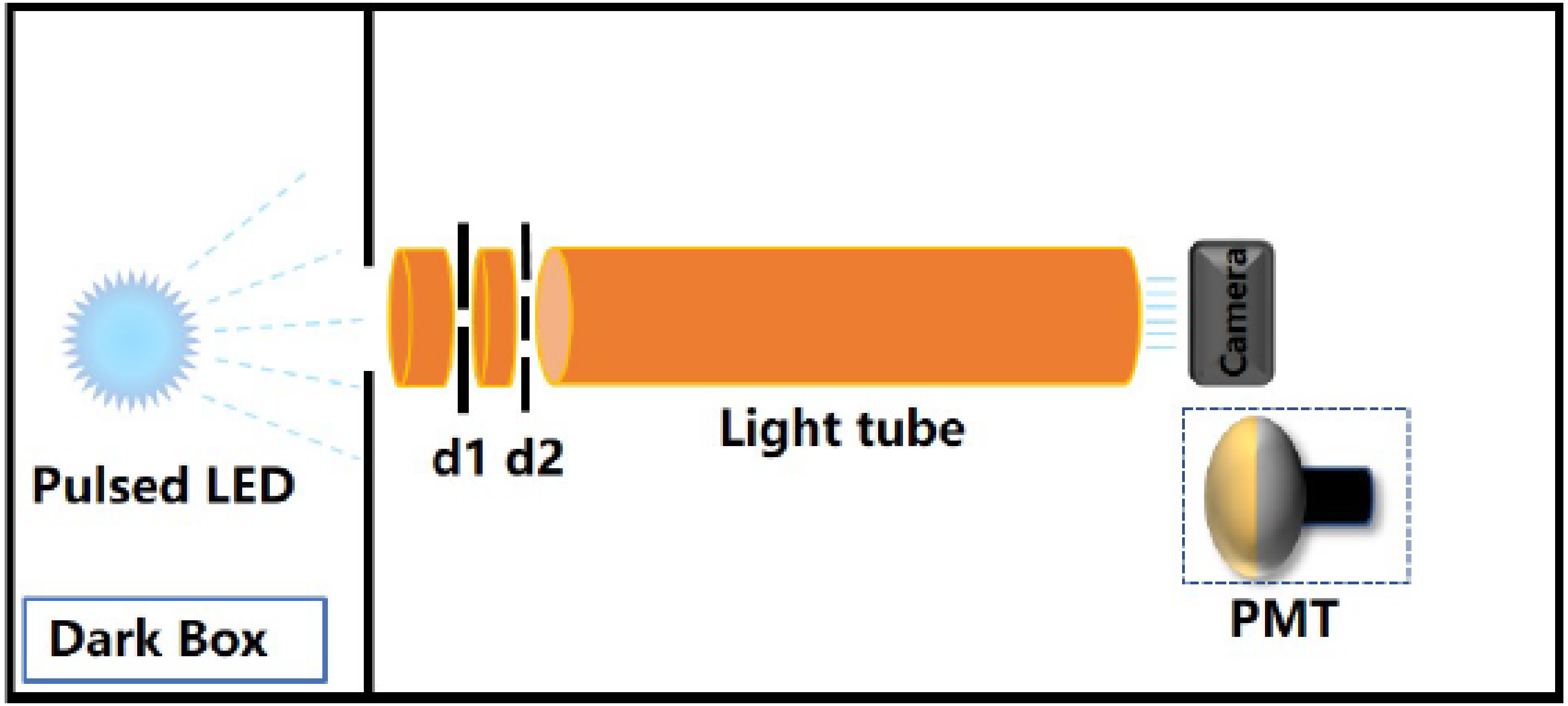

(c) 1-D plot of pixels intensity



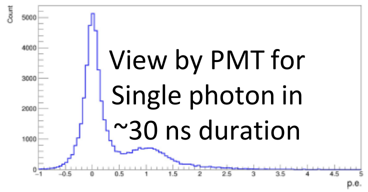

(d) Intensity vs. exposure time.

# Single photon
# Double-slit Young's interference

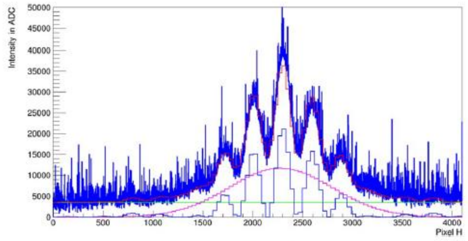
Single photon both in space and time



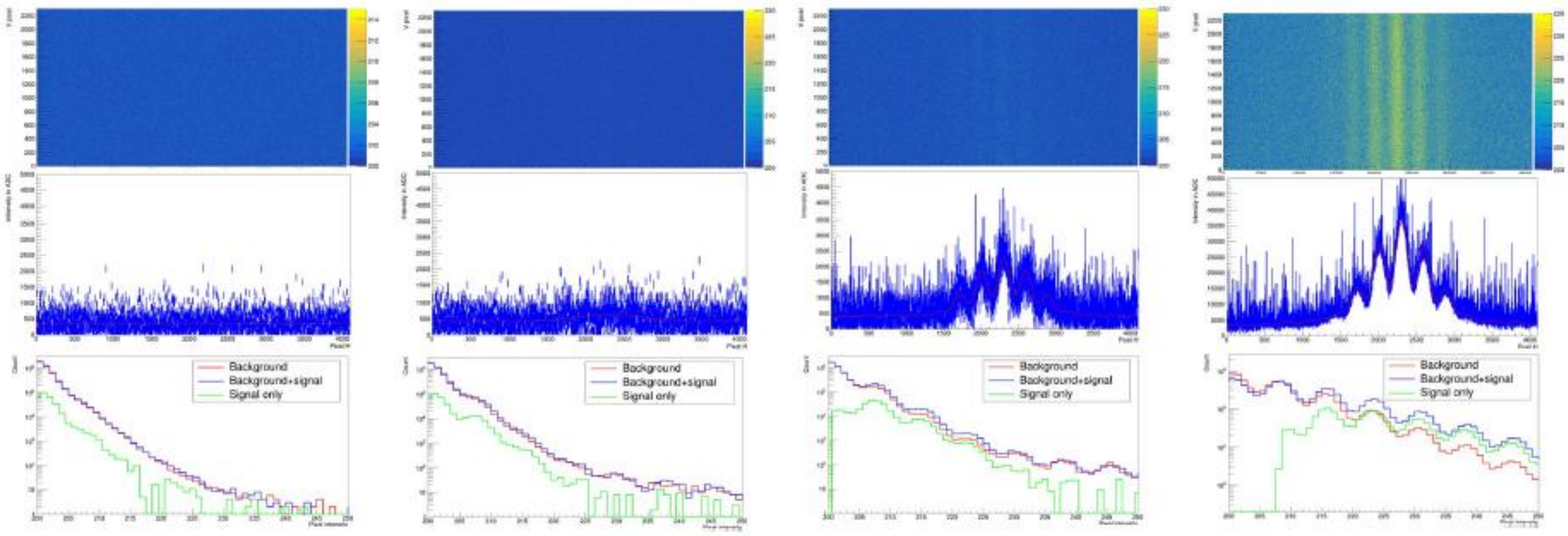

(a) Schema of Young's interference.



# Double-slit Young's interference with single photon

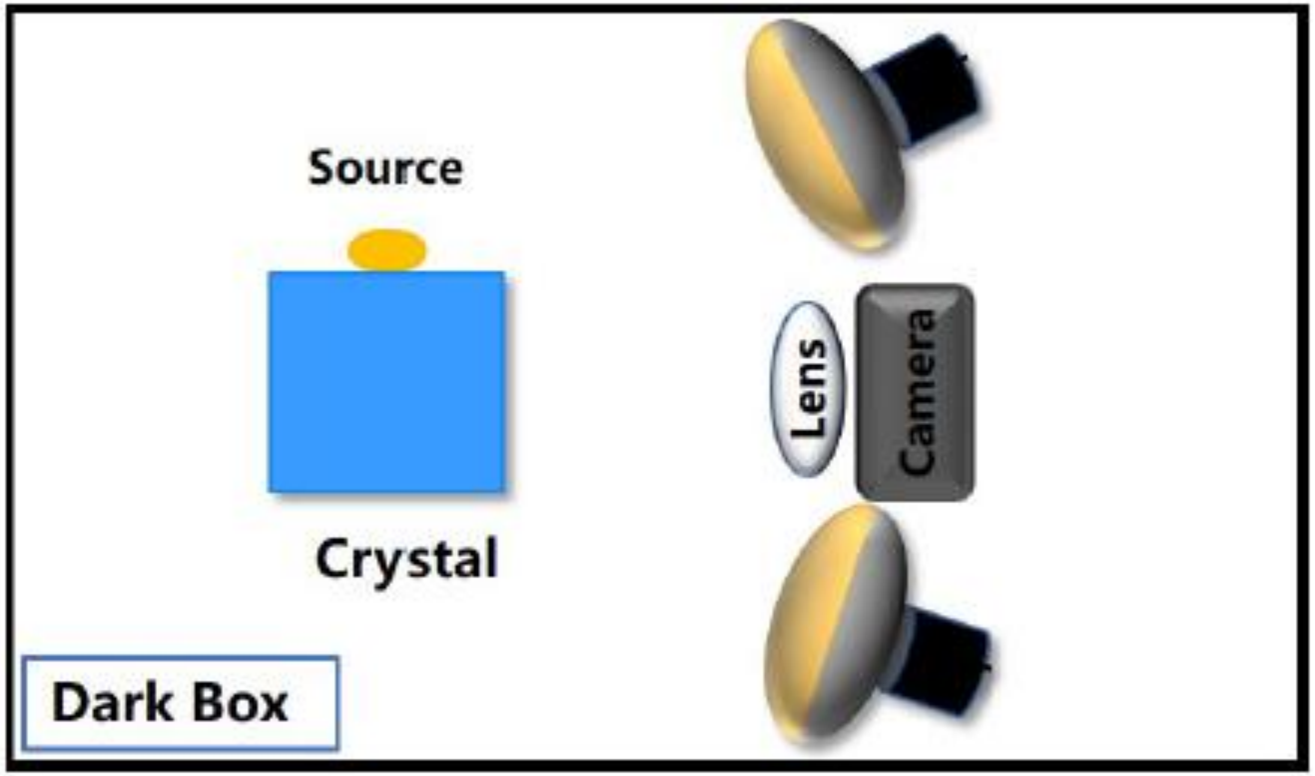


(a) 1-D plot fitting of the interference 60 s



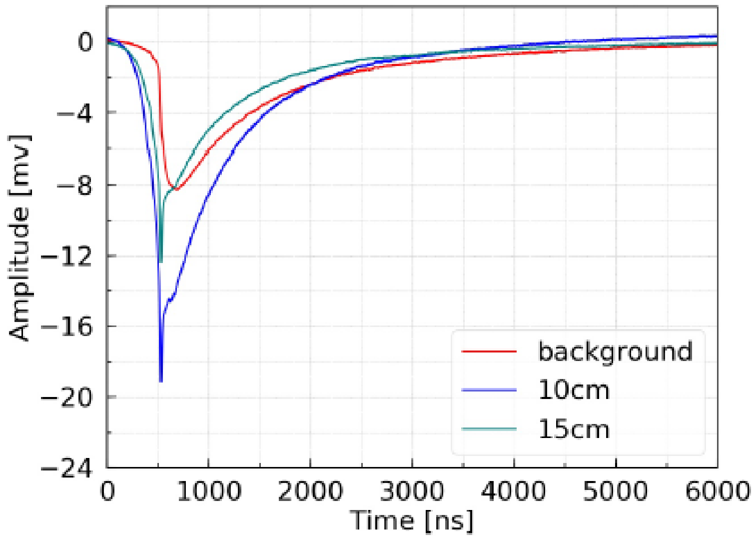

(a) 0.1 s (b) 1 s (c) 5 s (d) 60 s

# Particle imaging with CsI(Tl) crystal & 241Am
(time coincidence of PMTs)

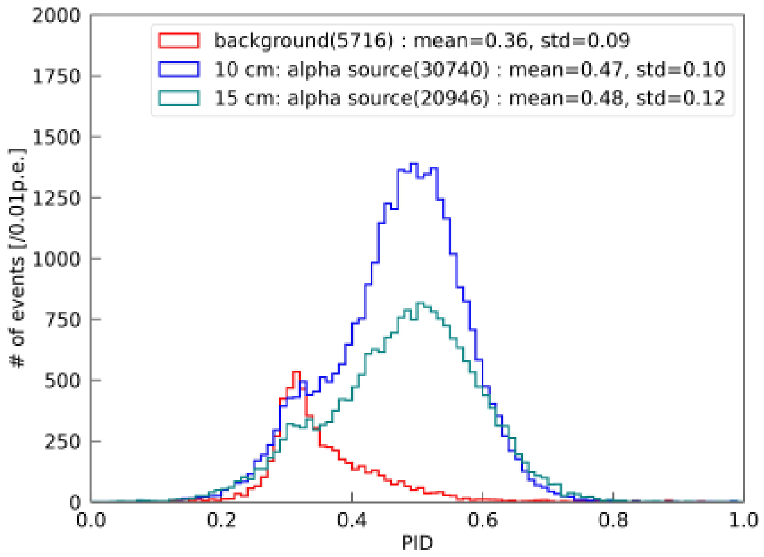



(b) Schema of crystal test.

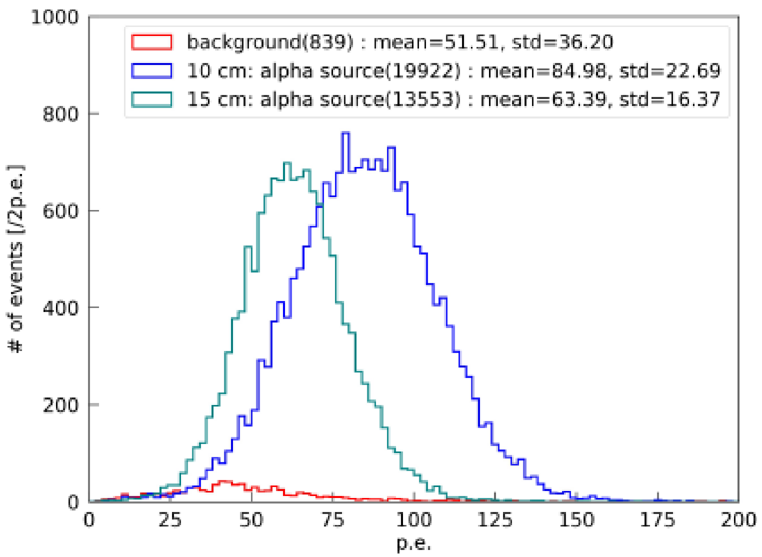
# Selection of Alpha events (by PMT)




(a) Average waveform




(b) PID of crystal

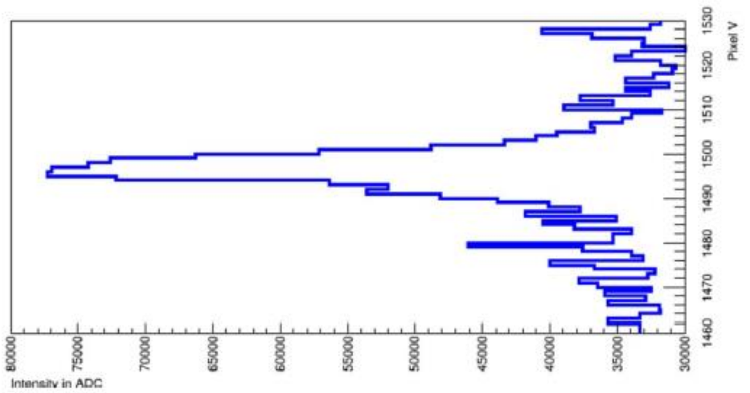



(c) Charge intensity

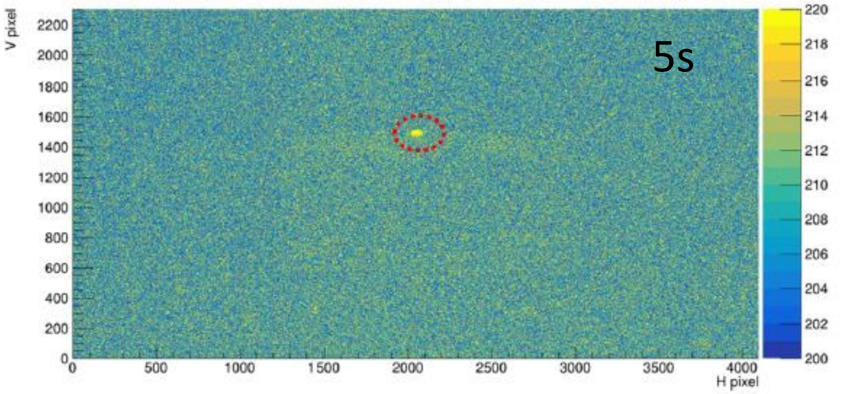
- ~100Hz
- ~80pe/alpha event @ object distance 10cm

# Imaging of 241Am

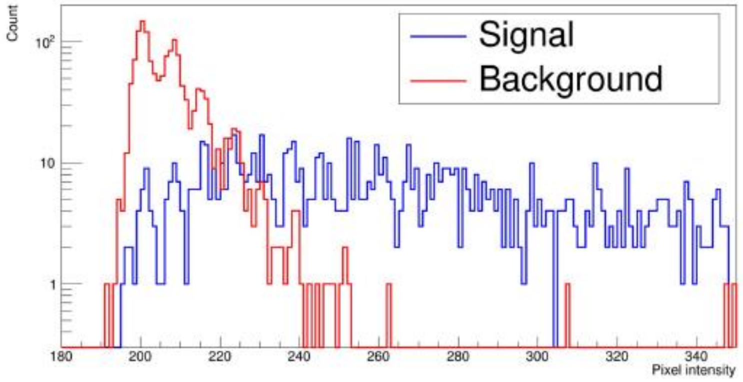
- Source location:
  - ~0.1mm
- Source intensity



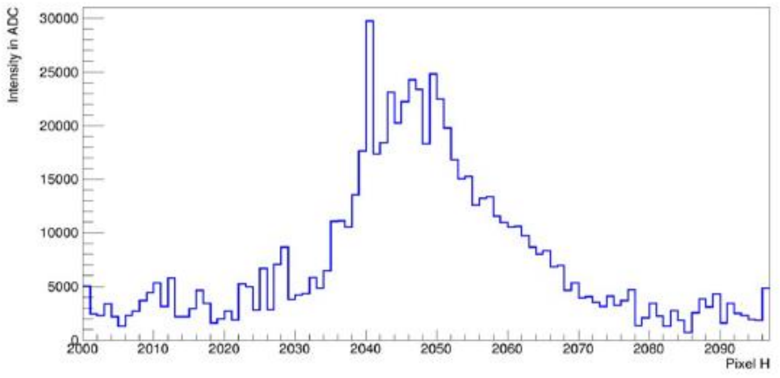

(a) 1-D intensity on vertical




(b) 2-D image of crystal w/ alpha

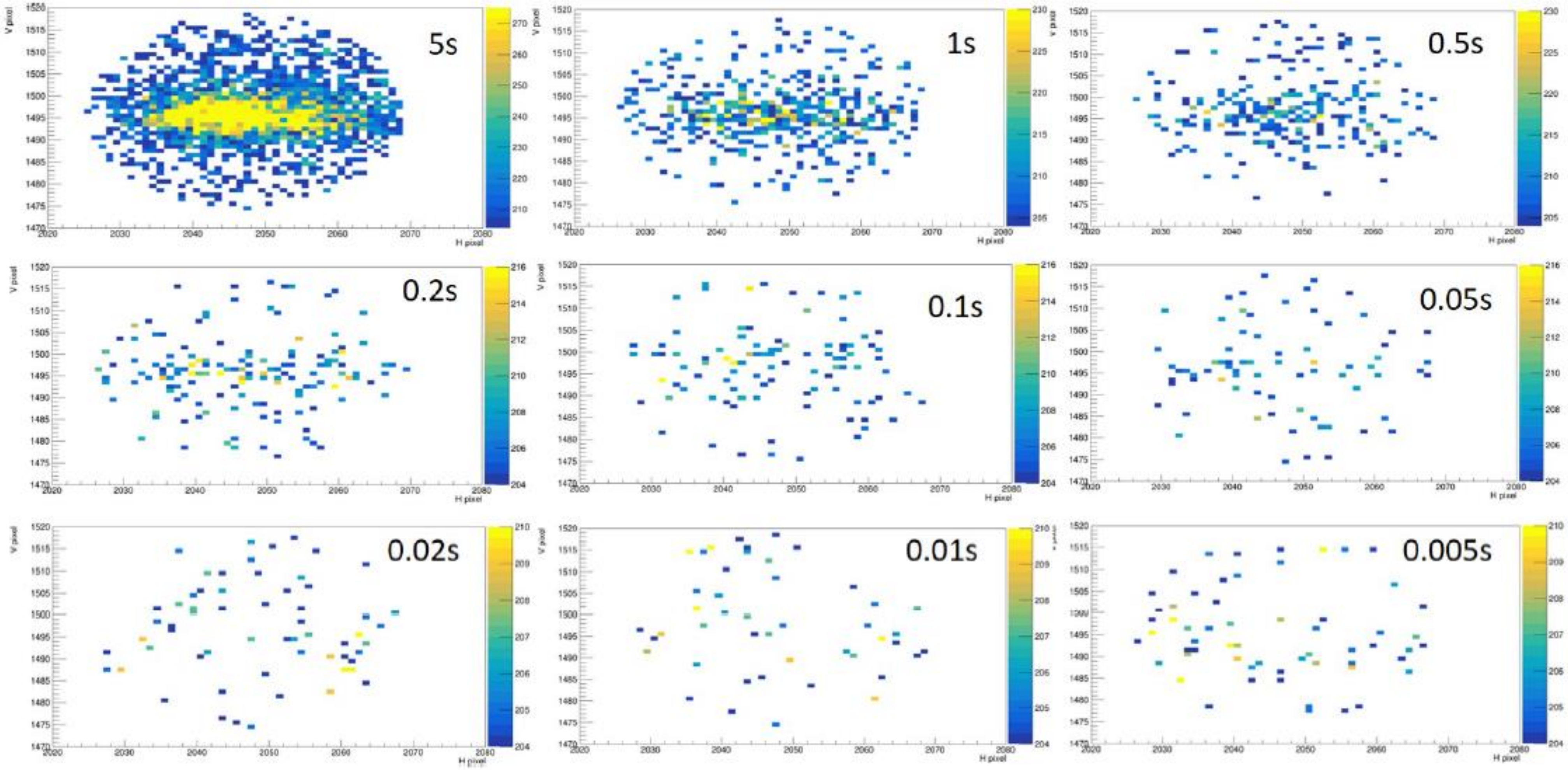



(c) Pixel intensity of source region



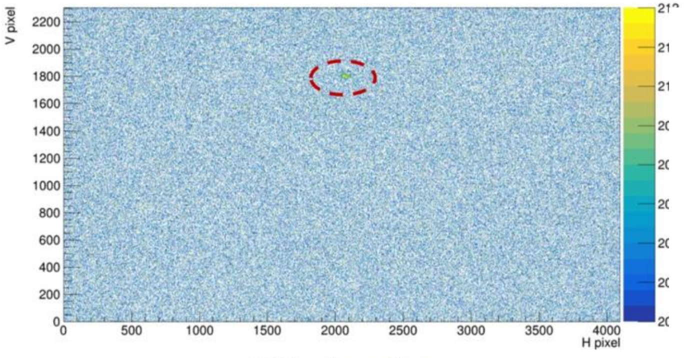

(d) 1-D intensity on horizontal

# Aiming to a single particle: single event~8pe



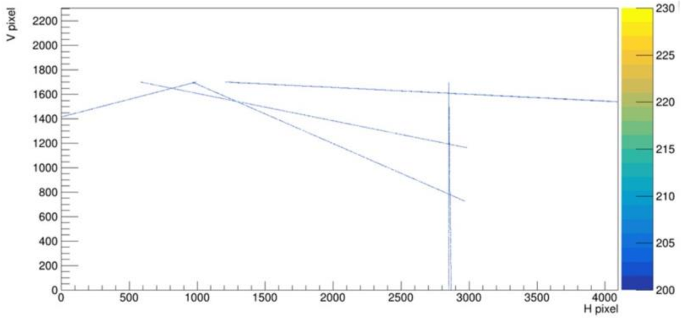
# Muon identification with crystal and camera

1s Image with alpha source aiming for muon in CsI(Tl) crystal

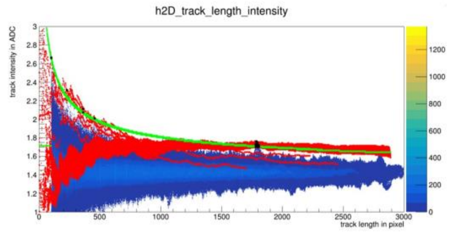



(c) Object distance of 4 cm.

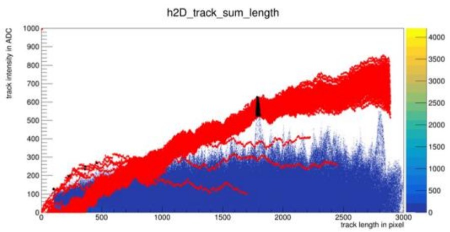
Muon searing in the image




(a) Extended tracks of those reported in figure 12.



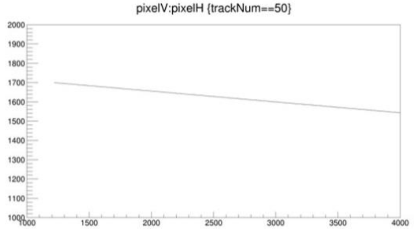

(b) Average of extended surveyed lines of that in figure 11(a): the red lines are selected candidates.



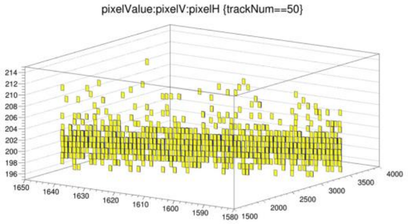

(c) Sum of extended surveyed lines of that in figure 11(b): the red lines are selected candidates.

**Figure 13**. Track candidate checking by extension. For a true muon track in principle, the candidate should have a similar average intensity as the short track, and increasing sum following the track extending. The red lines in (b) and (c) correspond to the extended track candidates. The selected candidate mentioned here is with the cuts discussed in section 3.1.

Identified muon track candidate




(a) Extended track 1D.



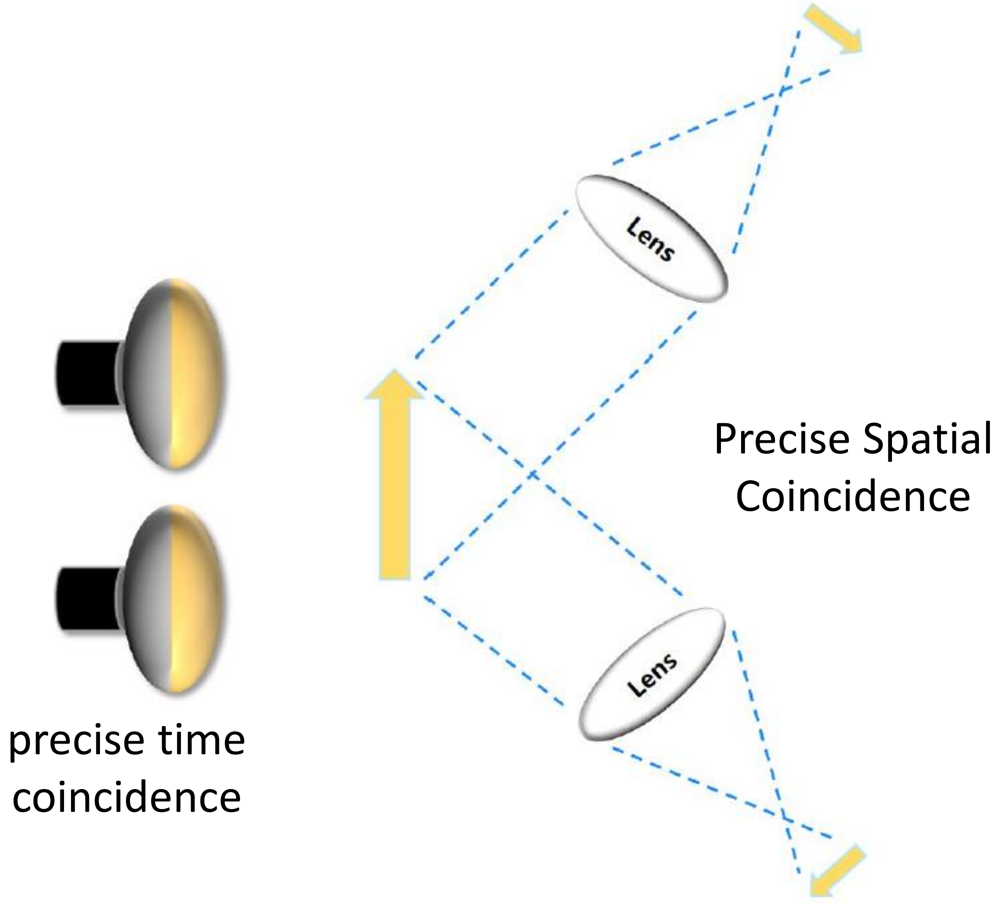

(b) Extended track in 3D.

**Figure 14**. Example of selected track candidate suggested by its averaged pixel intensity. Its raw length is around 1786 pixels (around 2880 pixel after extension), and averaged intensity per pixel is around 1.728 ADC and the summed intensity is around 568 ADC of 1786 pixels (around 73 p.e.). (a) x-axis is the horizontal pixels; y-axis is the vertical pixels. (b) x-axis is the horizontal pixels; y-axis is the vertical pixels; and the z-axis is the pixel intensity expressed in ADC counts.

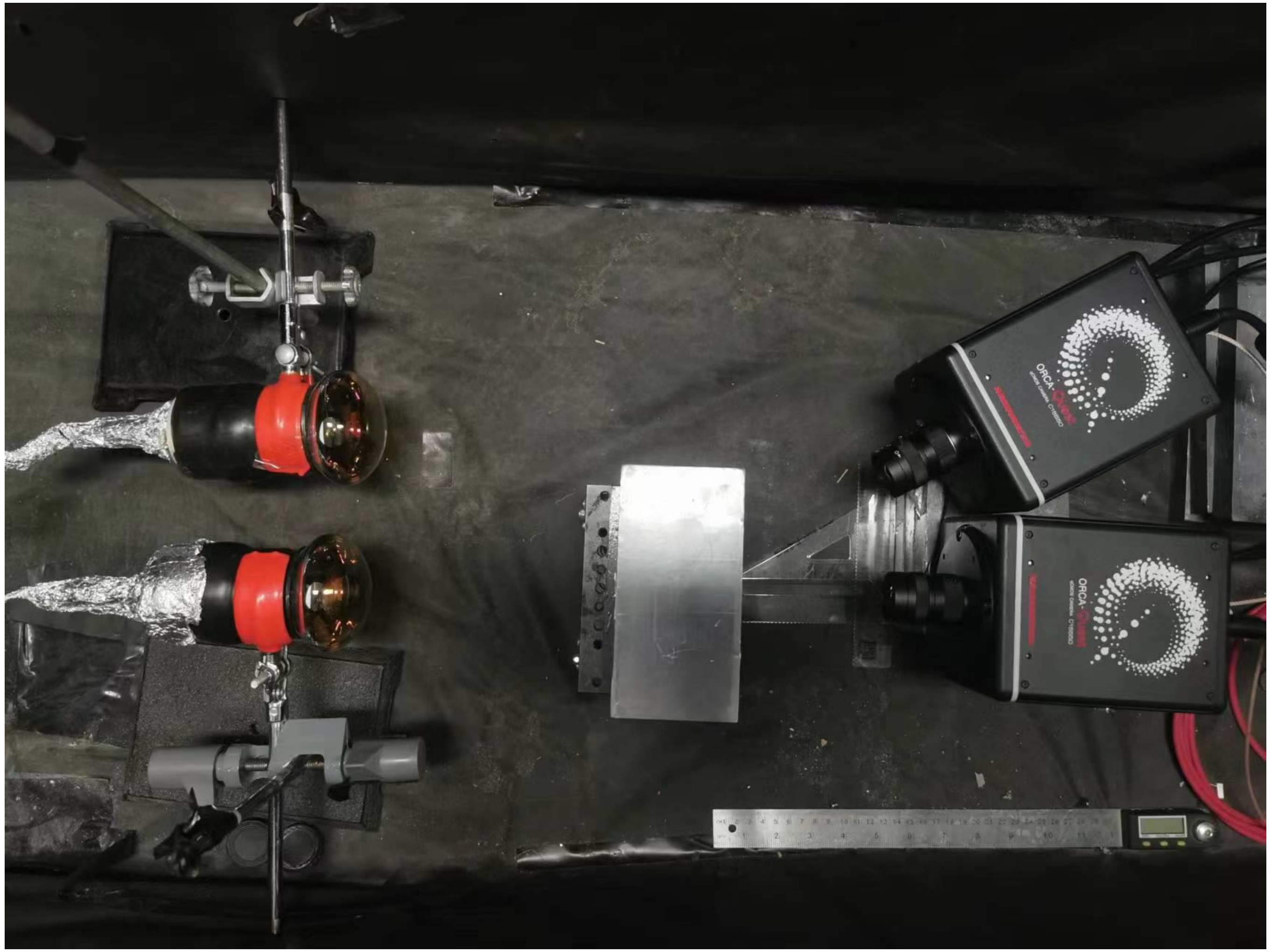
# Proposal for further application

## time & spatial coincidence for precise vertex and track

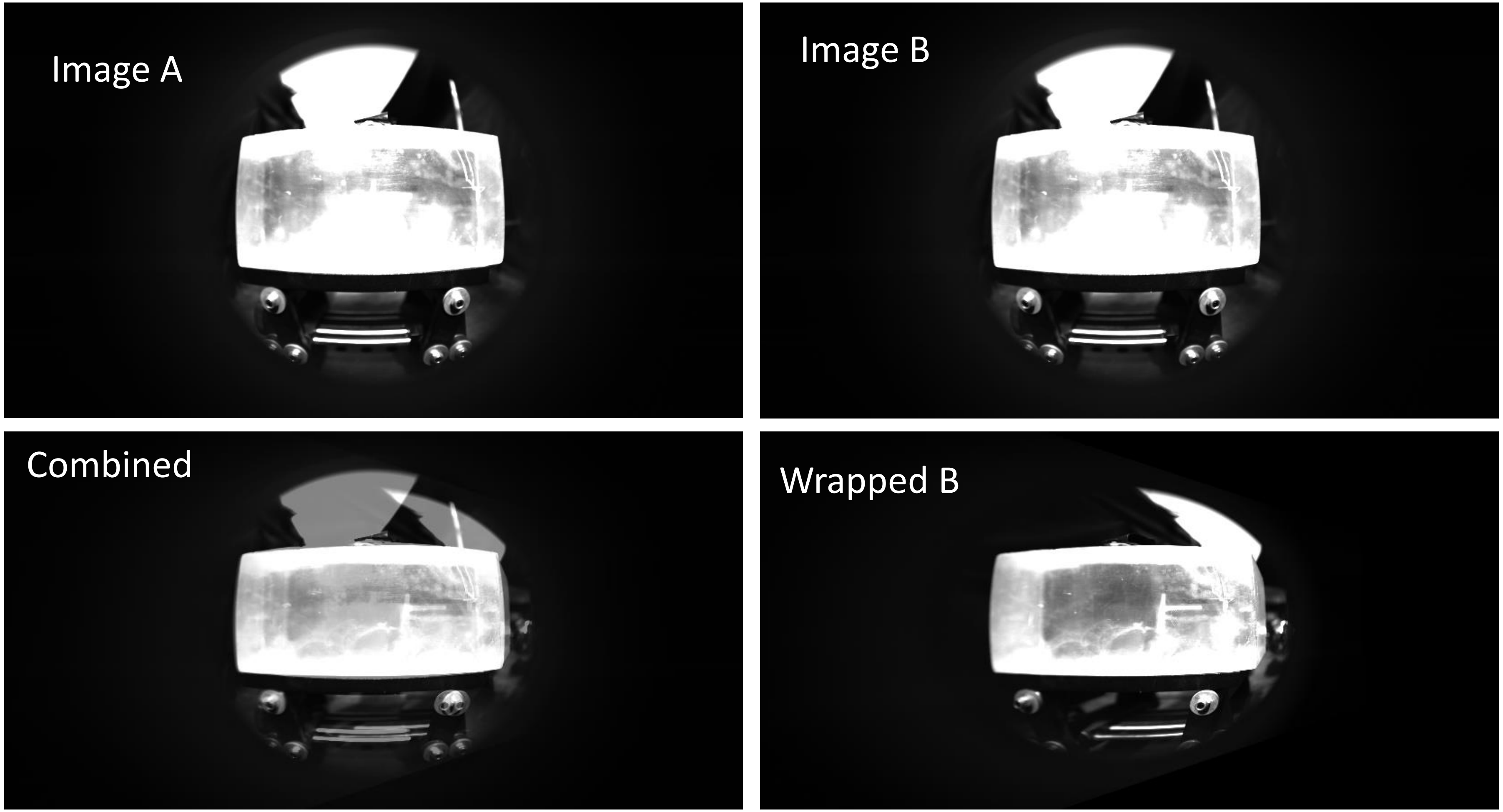
- Spatial Coincidence of Multi cameras
  - 3D vertex (x,y,z)
  - Noise suppression
- Additional to precision time coincidence of PMT/SiPM for
  - Precise vertex
  - Topology of energy deposition



# System setup



# Manually matching photons in lower S/N level



# Summary

- Imaging of single particle in single photon level
  - Possible now!
- Nosie of commercial camera
  - ~0.3e-
- PMT/SiPM+ Multi-cameras in scintillation detector by time and spatial coincidence
  - Noise suppression
  - Vertex, and topology identification
  - Imaging of single particle in crystal, LS
    - Simulation shows a good potential
- Proposal for many future applications
  - Welcome for more discussion

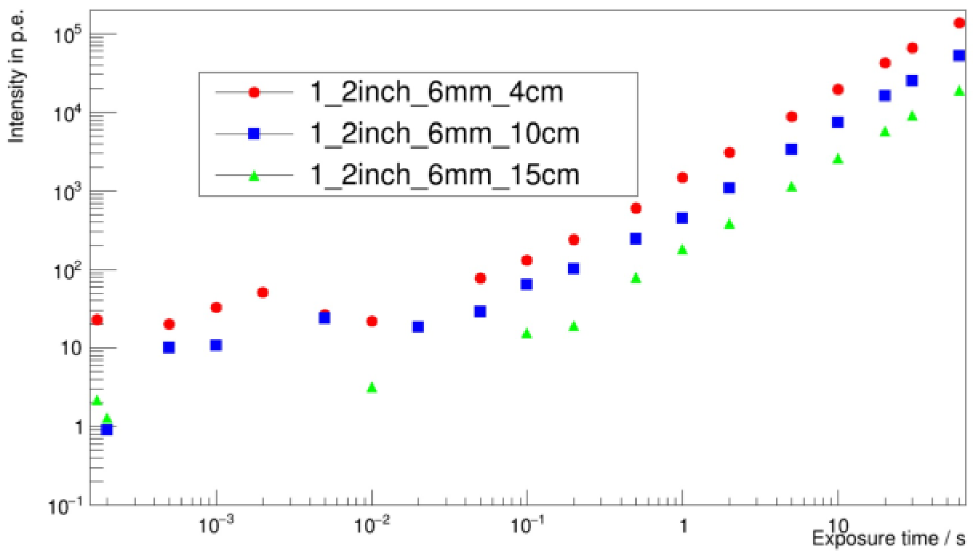
# شكرا جزيلا

# 谢谢

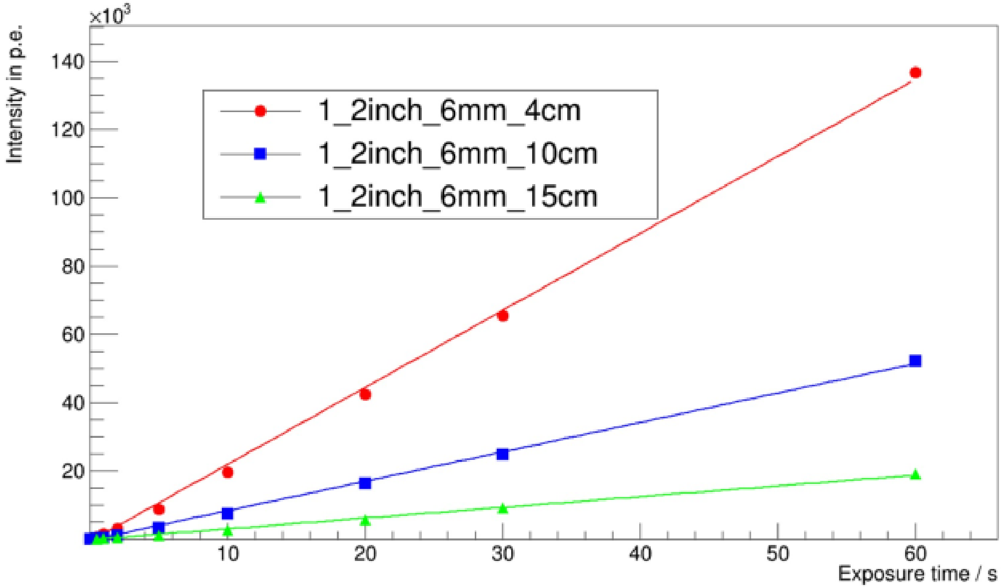
# Thank you



# Expected signal intensity vs. distance or exposure time of single alpha event

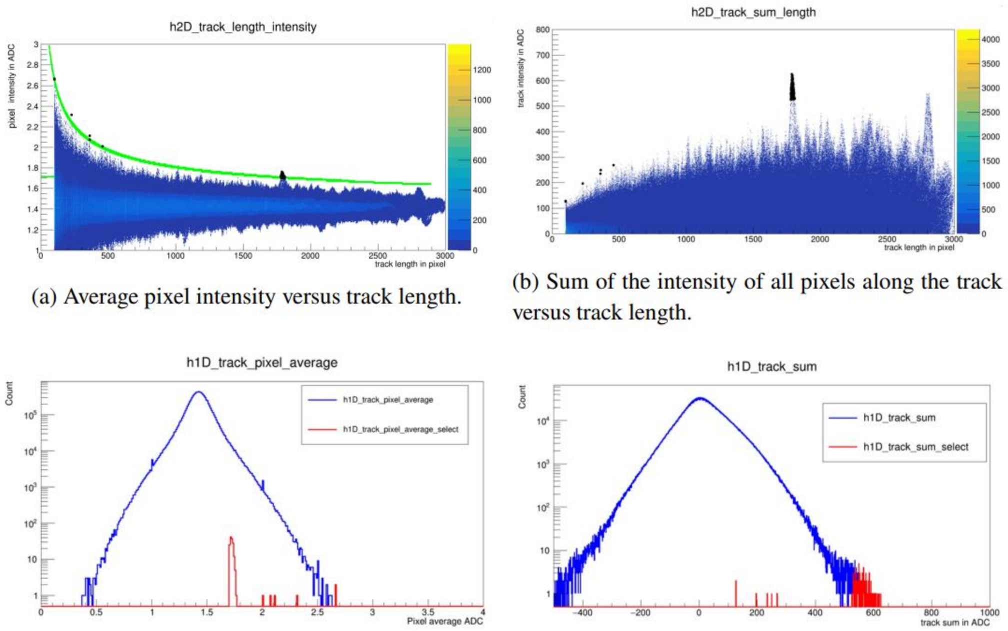



(a) Measured intensity.




(b) Linear fit to data.

# Muon identification




(a) Average pixel intensity versus track length.

(b) Sum of the intensity of all pixels along the track versus track length.

(c) Average pixel intensity.

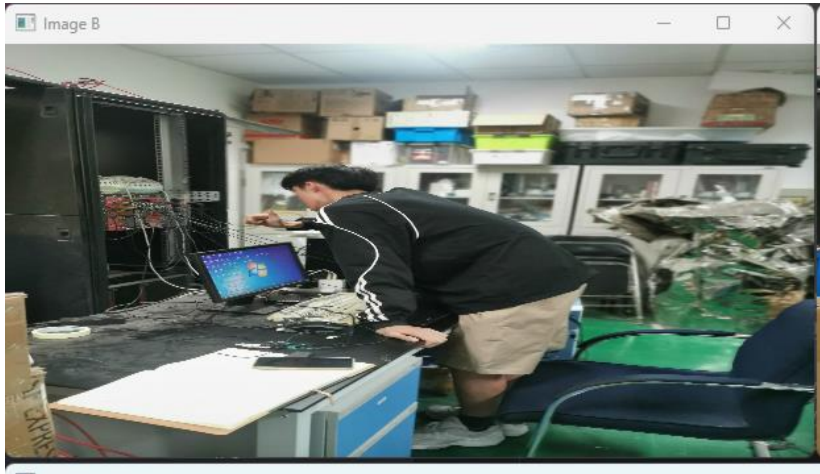
(d) Sum of the intensity of all pixels along the track.

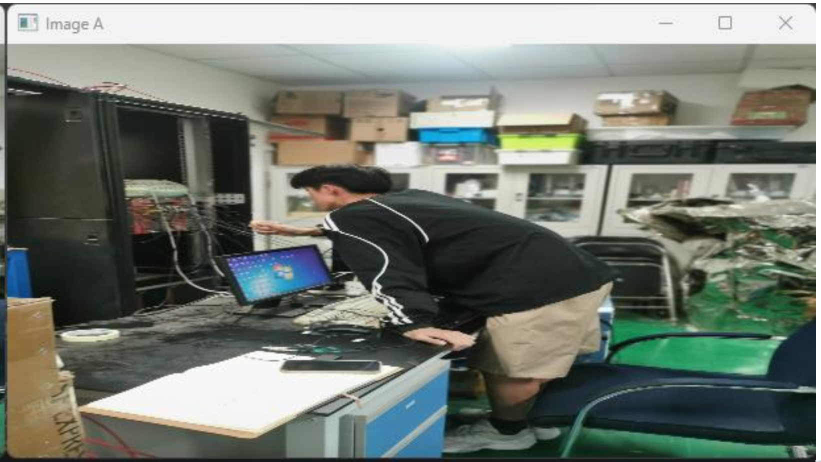
**Figure 11**. Average pixel intensity and the sum of the intensity of all pixels along the track candidates. The z-axis of (a) and (b) reports the number of candidate tracks. The green line in (a) is the applied threshold to identify a selected track candidate, the black dots in (b) are from the selected track candidates. The red lines in (c) and (d) are from the selected track candidates. In (d), the distribution of the total intensity of the selected events is shown in red. It ranges between 100 and 600 ADC (i.e. 12–77 p.e.), which is somewhat lower than the average expectation of 177 p.e. from the calibration and may be due to the muon paths in the crystal.

# Image Matching Test

Photo A

Photo B





Match & combined Photo