Development of New Photo-detectors

Yasuhiro NISHIMURA
Research Center for Cosmic Neutrino,
Institute for Cosmic Ray Research,
The University of Tokyo

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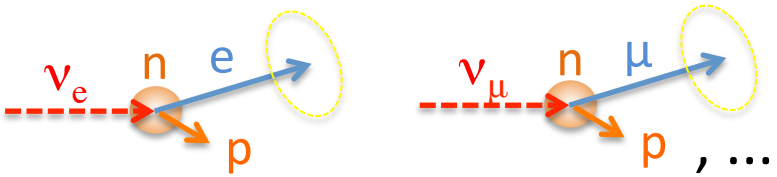
Contents

- Photo-detector development for a large volume detector
- Requirement of photo-detector
- Proof test of hybrid photo-detector and high quantum efficiency
- Development of new 50cm Φ photo-detectors

Physics interest

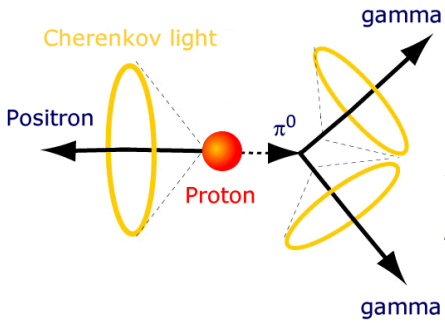
- Physics target in water Cherenkov detector

neutrino with rare detection only by weak interaction



Measure neutrino property such as neutrino oscillation

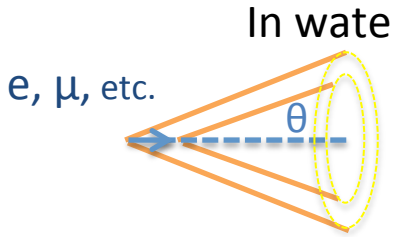
proton decay with rare decay probability in O(10^{-34})



New physics beyond standard model

- Massive detection volume and long operation period are required to detect these rare events.

- Charged particle is observed as Cherenkov ring in water.



Cherenkov radiation cone

← Ring image on detector wall

$$\cos\theta = \frac{1}{n\beta}$$

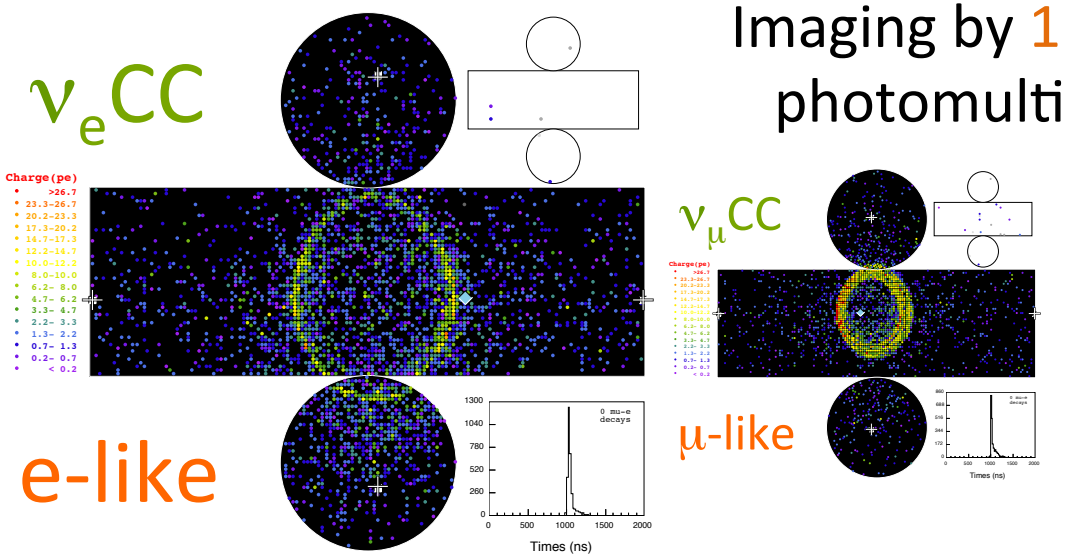
n~1.33, θ~42°

Ring light pattern provides various information such as momentum, particle type and counting, timing, etc.

- Many photo-detectors with large aperture are required.
  - Performance of photo-detectors is critical to physics sensitivity.

Photo-detector in Super-Kamiokande

- Many of photo-detectors detect a water Cherenkov light photons.



Imaging by 11129 50-cm Φ photomultiplier tube (PMT)

Used for 20 years, established but old..

R3600 by Hamamatsu Photonics K.K.

- Time information is used to reconstruct vertex, and to discriminate signal from background or particle decays. → *a few nsec resolution*
- Charge resolution is important for low energy physics, such as solar neutrino and super nova, in several MeV and sensitive to energy resolution and particle identification. → *Good photon counting*
- Event trigger by PMT hit coincidence. → low (a few *kHz) single rate*

New type with high performance is possible now for future experiments.

Photo-detector for Hyper-Kamiokande

Super-Kamiokande (SK) (since 1995)

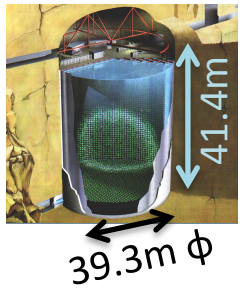
0.0225 (0.05) Mton
Fiducial (Total)

x 25(20)

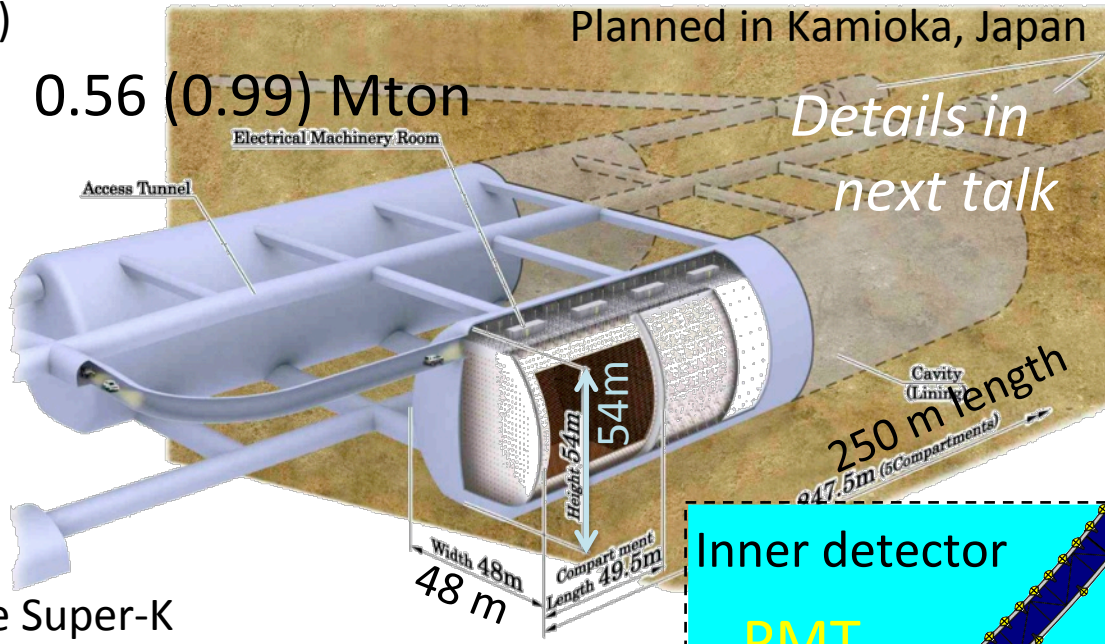
Hyper-Kamiokande (HK) Large water Cherenkov detector
Planned in Kamioka, Japan

0.56 (0.99) Mton

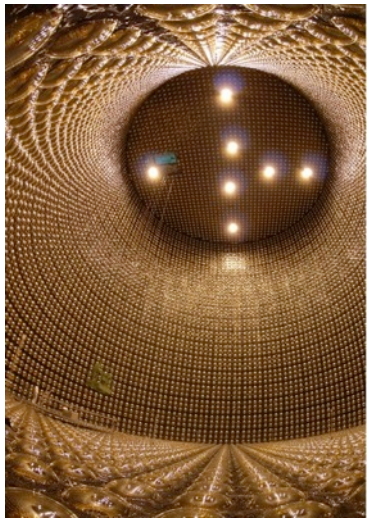
Details in next talk



Based on established technologies
(Large water tank, Electronics, Calibration, etc.)



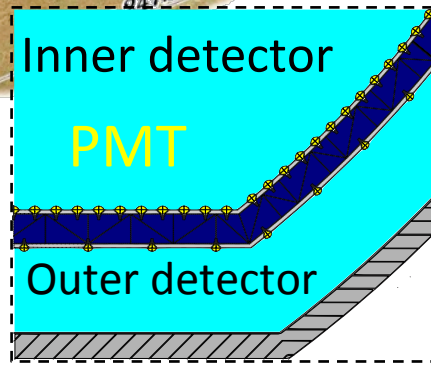
+ Improvement with a new technology such as photosensor (R&D within 3-5 years)



← 20-inch PMTs inside Super-K

	Super-K	Hyper-K
Inner detector (for ν detection)	11,129 (50cmΦ)	**99,000 (50cmΦ)**
Outer detector (for cosmic-ray veto)	1,885 (20cmΦ)	**25,000 (20cmΦ)**
Photo-coverage	40%	20%
QE (quantum efficiency)	22%	**~30%**

= Super-K × 9,
1/4 of total cost



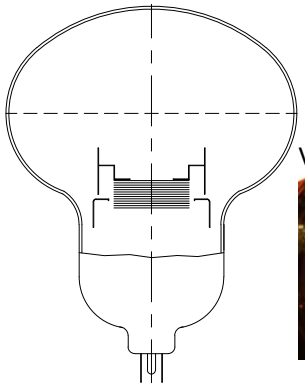
Develop new photo-sensor with low cost and high performance

Photo-detector candidates

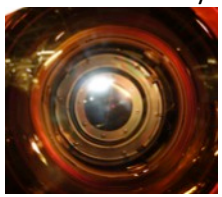
50cmΦ **PMT (Venetian Blind type)** **PMT (Box & Line type)** **Hybrid Photodetector (HPD)**

Safety ⟵ ⟶ *Challenging*

Better performance?

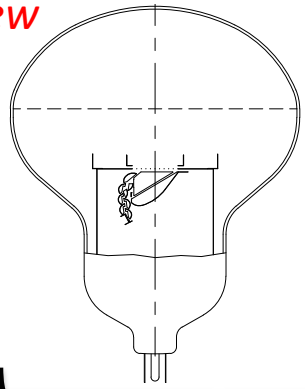


Venetian Blind Dynode



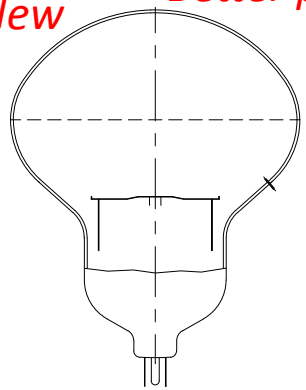
Used in Super-Kamiokande

New



Box&Line Dynode

New



Avalanche diode

and 20cmΦ for 1st R&D

Development → proof test

+ High Quantum Efficiency (QE) option for all candidates

Current status

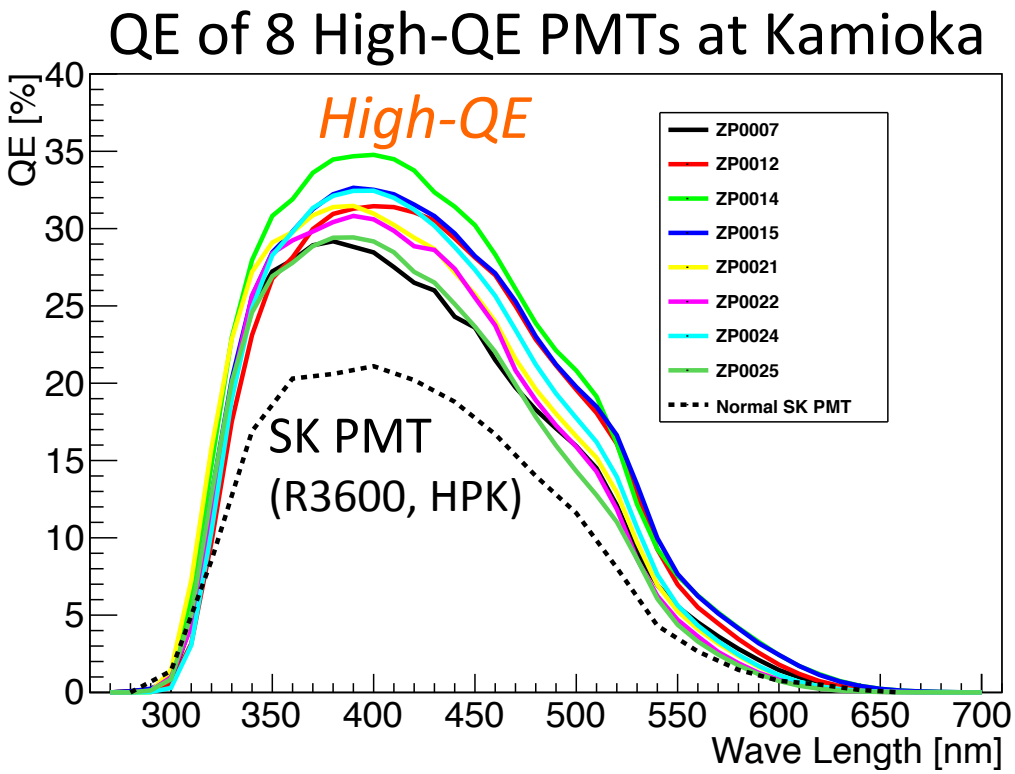
- 2 new photo-detectors were developed.
  - ○ 50cm Φ high-QE PMT
  - ○ 20cm Φ HPD

  } Proof test in a water Cherenkov detector has started
- 50cm Φ high-QE HPD and box&line PMT are under testing.
  - ○ Evaluated performance of 1st prototype → Also tested in water soon

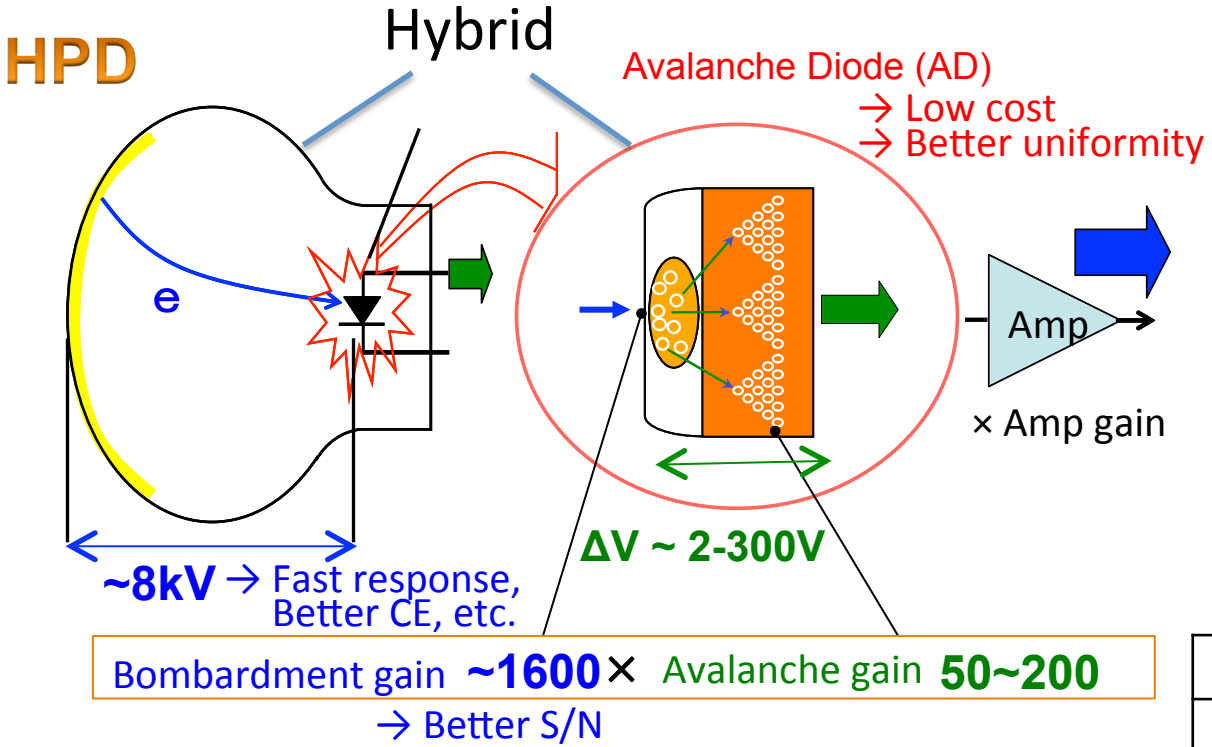
50cmΦ High-QE PMT

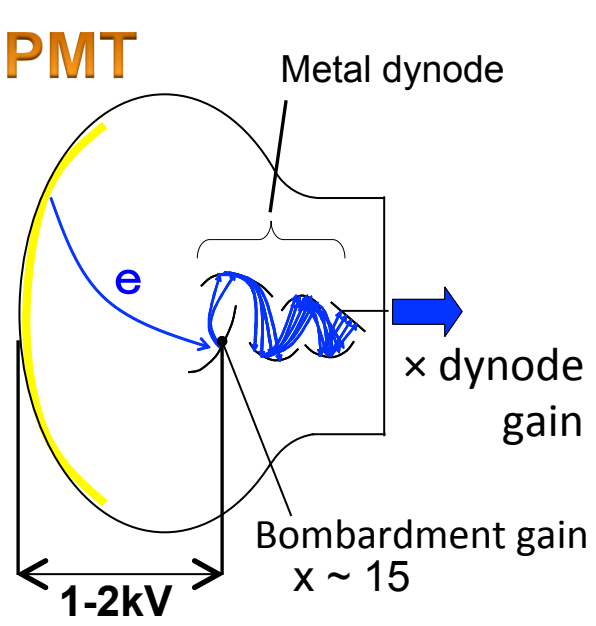
- High Q.E. study starts with PMT, later for HPD.
  - Study (especially for the trigger and stability) is required, because photocathode (related to dark rate) is changed.

- **50cmΦ high-QE PMT**
  - Completely same design and material as SK PMT, except for photocathode.
  - 22% → 30% QE typ.
  - Within 10% uniformity
  - 8 high-QE PMTs are provided and 5 of them are tested in the 1st proof test.



Hybrid PhotoDetector (HPD)





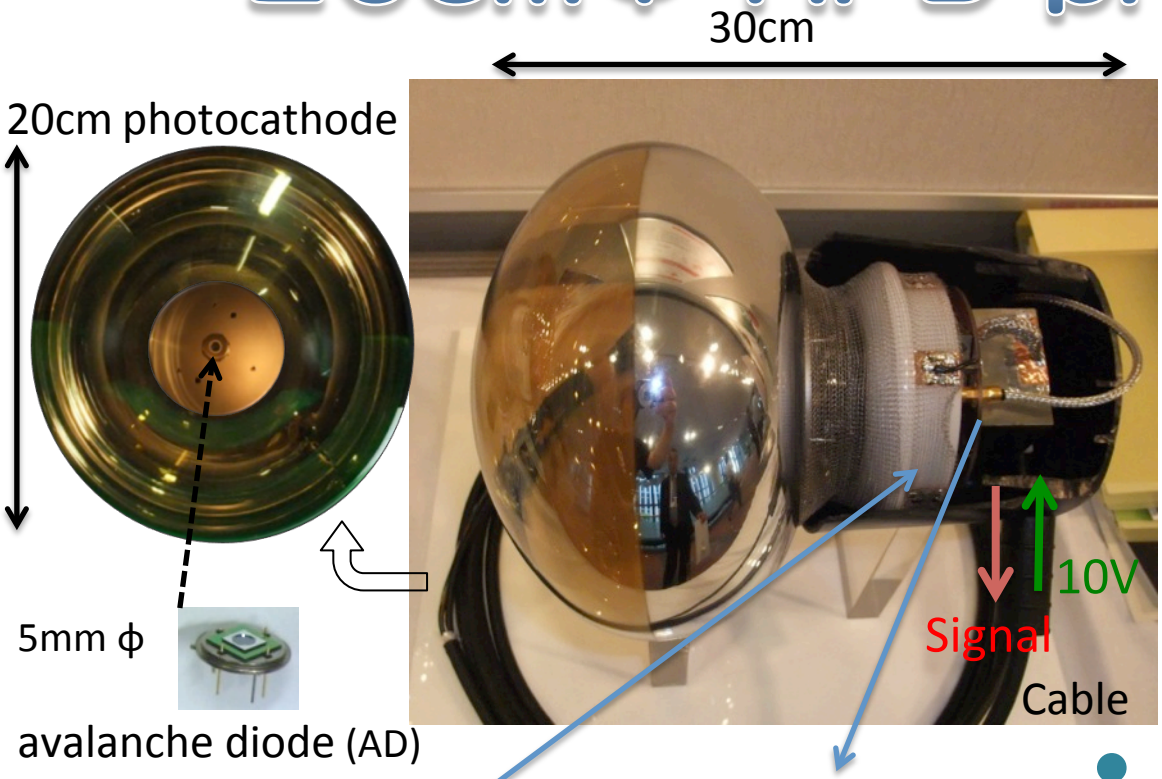
	HPD	PMT
HV	~8kV	1-2kV
Gain	~10^4 - 10^5	~10^7
C.E.	~95%	~80%

High voltage around 8kV is required

- to collect electrons in the small region of AD (5-20mm)
- to increase gain at electron-bombardment

- High performance and low cost
- Factors to be considered for viability in Hyper-Kamiokande:
  - Dark noise from AD + Amp., HV around 8kV, low gain, thermal dependence of AD gain, No prior experience using

20cmΦ HPD prototype



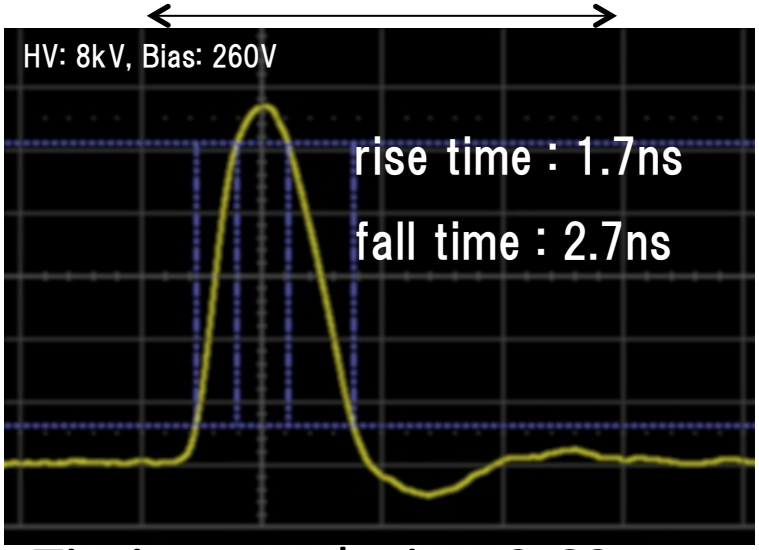
Specification

Spectral response		300 - 650 (420 max.) nm
Photocathode		Bialkali
Window material		Borosilicate glass
Gain		$4 - 9 \times 10^4$
Time	Rise	1.7 ns
	Fall	2.7 ns
	T.T.S.	0.62 ns (σ)
Dynamic range		100 pC (1.5×10^4 p.e.)

- By Hamamatsu Photonics
- HV module and preamplifier are packed and waterproofed.
  - Operated in water without high voltage line.

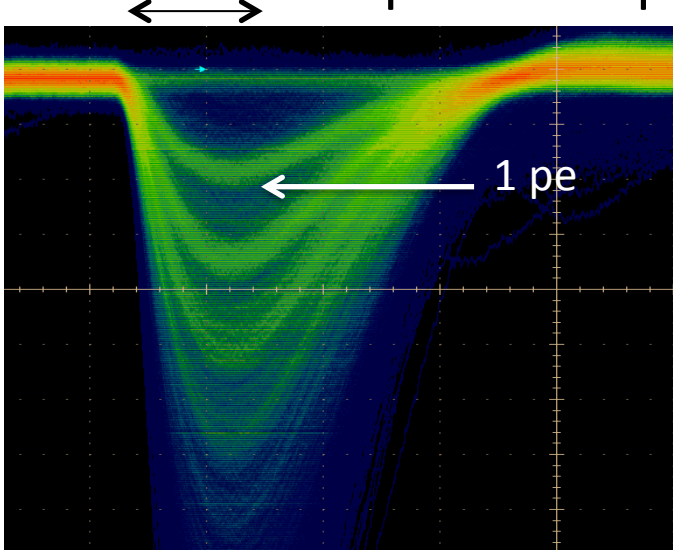
Signal from 20cmΦ HPD

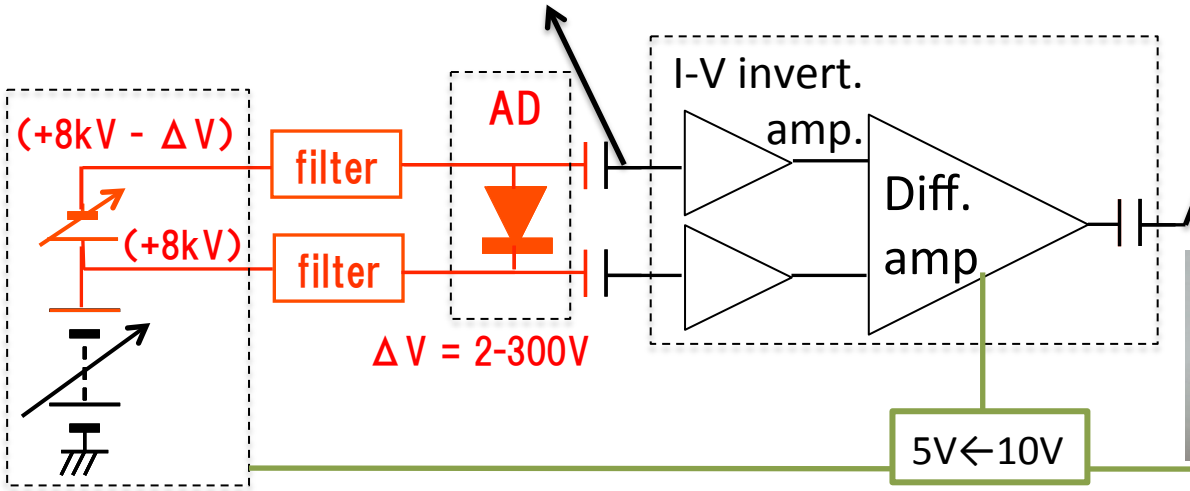
Output of HPD



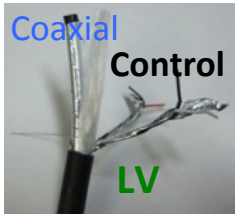
Timing resolution 0.62 ns σ

Output of amplifier





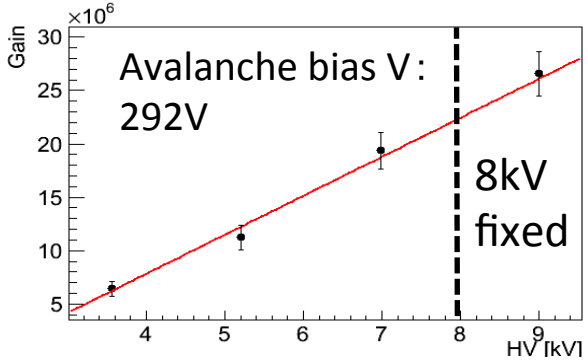
Signal is shaped by amplifier



10ch control Power Supply

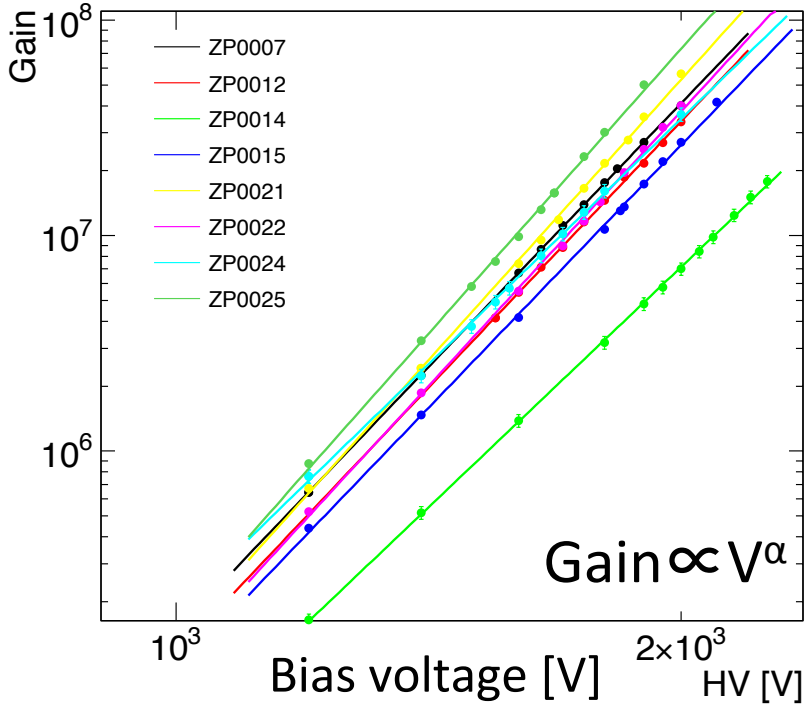
Gain and high voltage

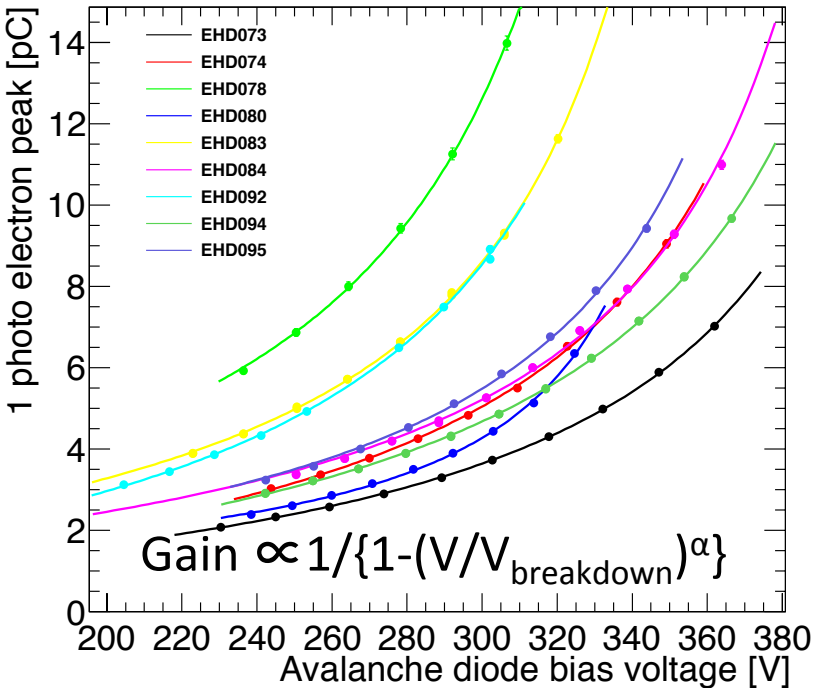
- Gain of all samples was measured.
- Adjust HPD gain by AD bias voltage.



HPD gain = Bombardment gain↑ × ↓Avalanche gain

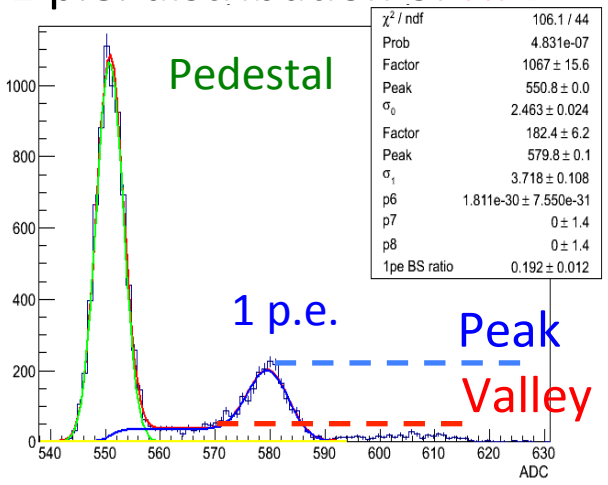
High-QE PMT HV – gain curve

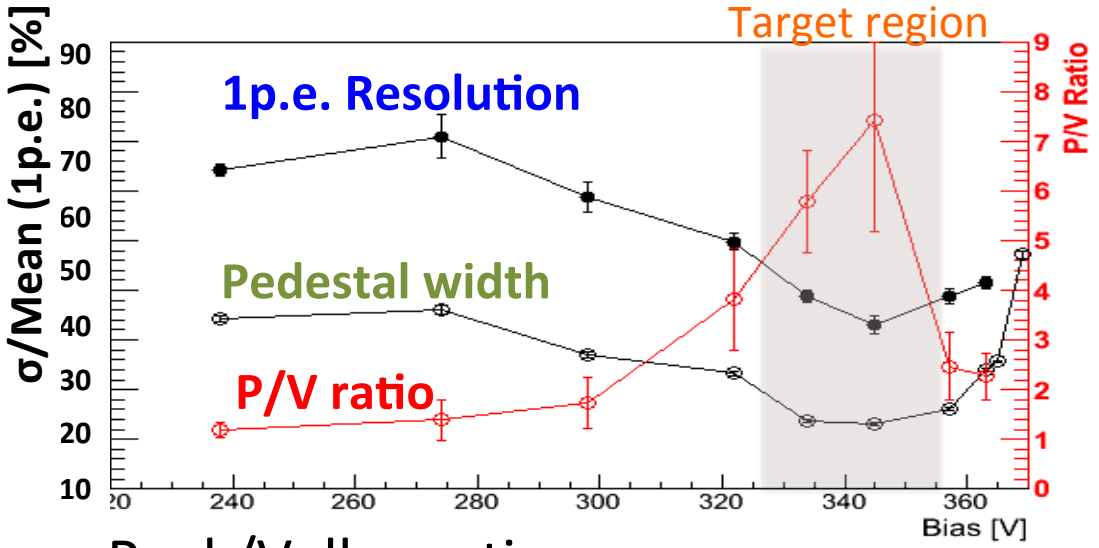




1 photo-electron separation

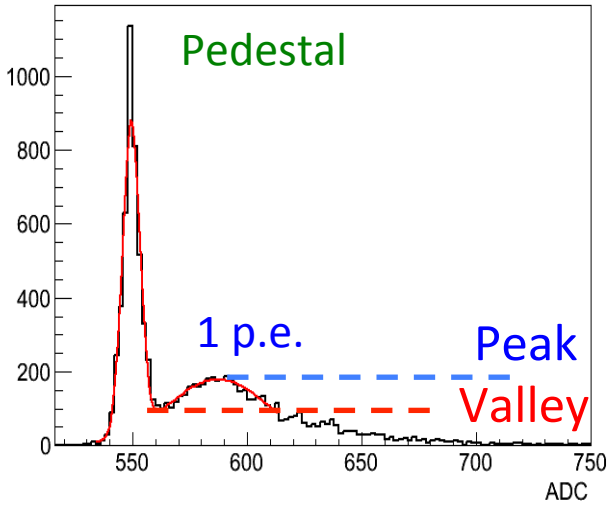
1 p.e. distribution of HPD

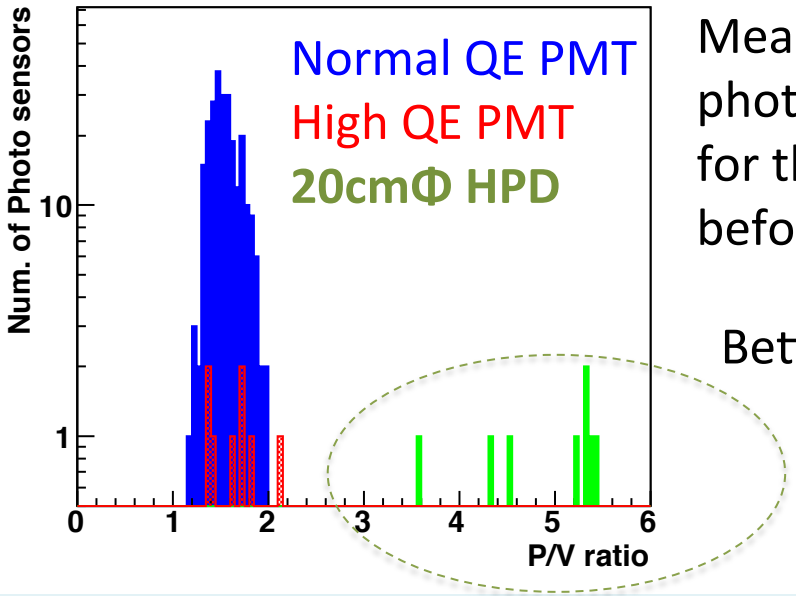




Peak/Valley ratio

High-QE PMT





Measured all photo-detectors for the proof test before installation

Better separation for HPD

Proof-test in 200-ton water tank

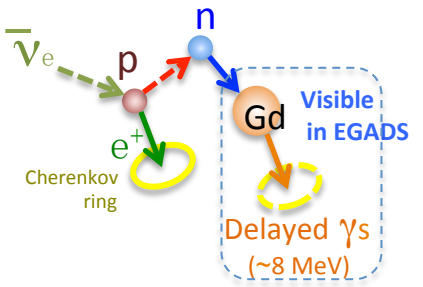
- Test new photodetectors in the 200-ton water tank.

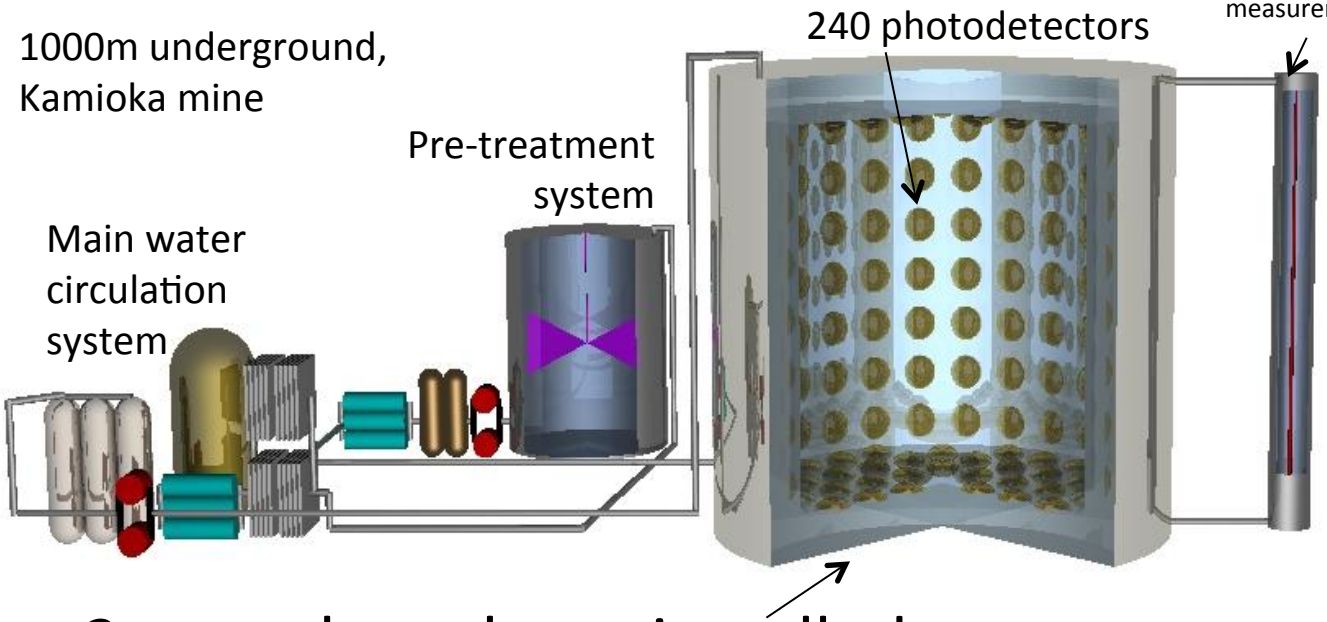
Evaluating Gadolinium's Action on Detector Systems

200-ton test tank to demonstrate the GADZOOKS! Idea.

(**G**adolinium **A**ntineutrino **D**etector **Z**ealously **O**utperforming **O**ld **K**amiokande **S**uper!)

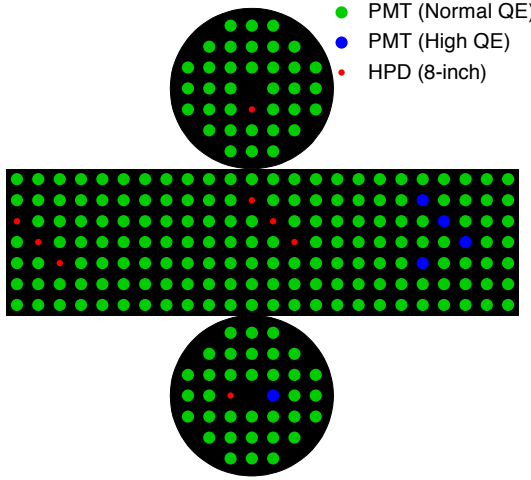
Anti-neutrino tagging by neutron





8 20cm-Φ HPDs

5 50cm-Φ high-QE PMTs



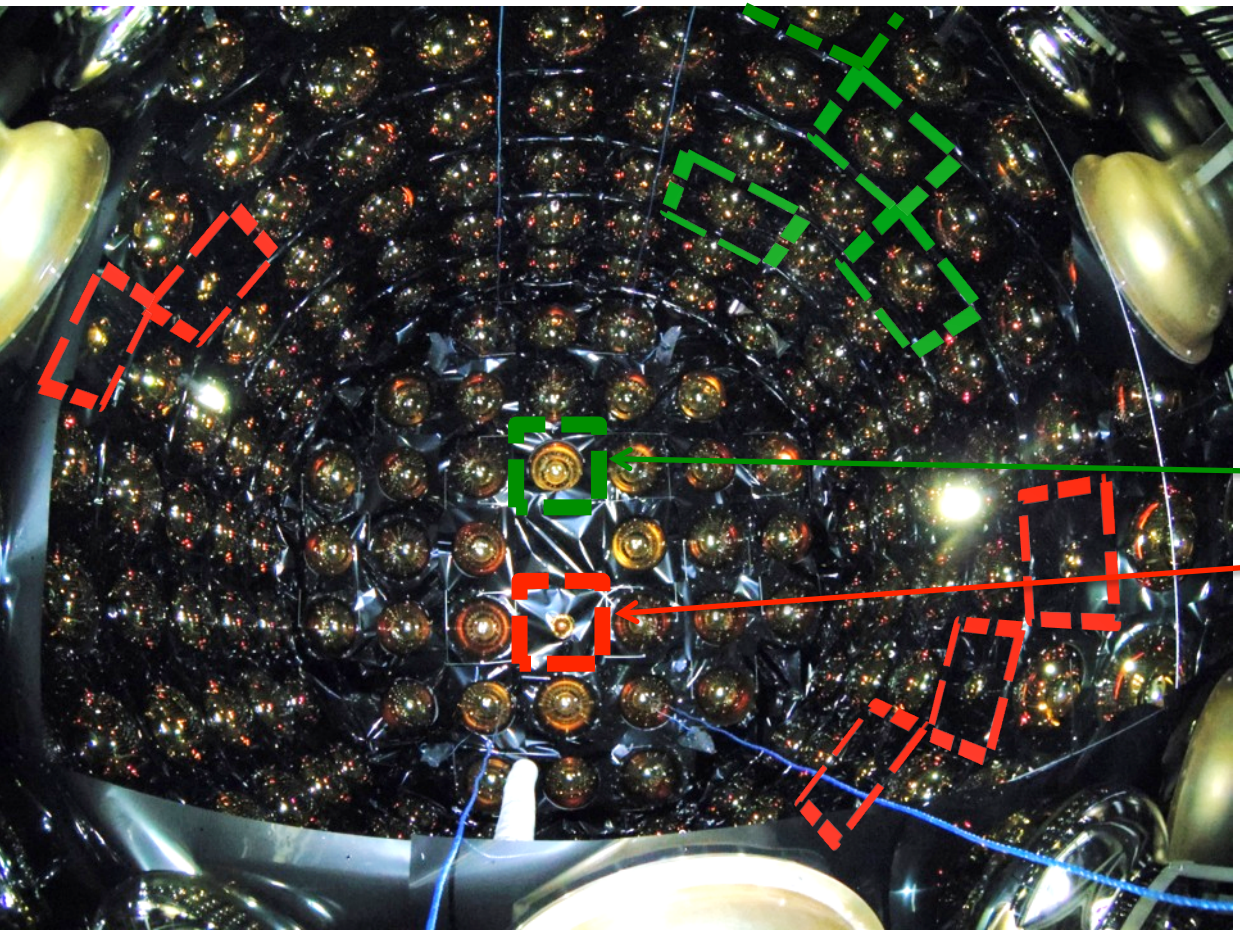
- 2 types have been installed.
- Other new photo-detectors are also tested as soon as it becomes ready.

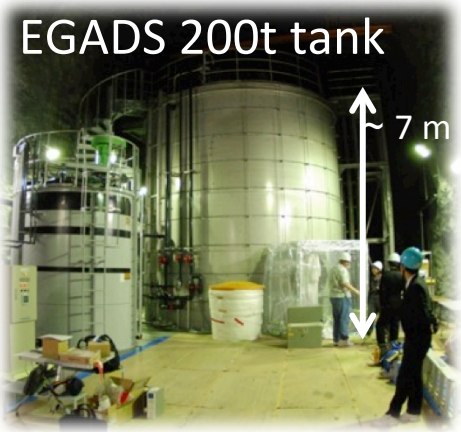
Compared with 227 PMTs used in Super-K

Installation of photodetectors

- All photodetectors were installed in Aug. 2013.

Inside of 200-ton water tank viewed from top





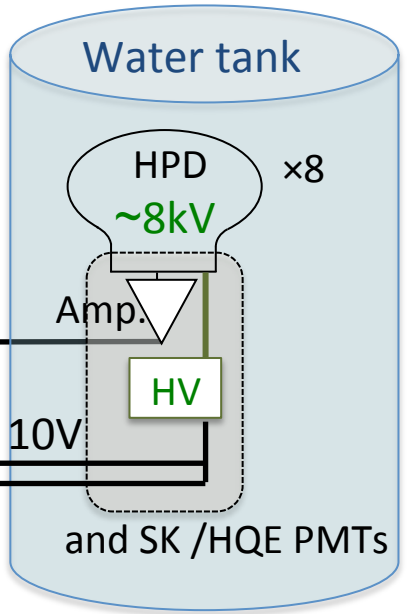
227 Super-K PMT (50cmΦ)
+ 5 High-QE PMT
+ 8 HPD (20cmΦ)

Started a long-term proof test for a few years.

Operation

- Trigger is issued by sum of hits with all photo detectors.
  - 1 hit = 1 HPD (PMT) with 1 p.e. or more signal
- In same DAQ system, electronics of HPD/HQE PMT is separated.
  - 1 p.e. level differs between PMT and HPD.
  - Photons/p.e. differs between normal and high QE.

NOT for Hyper-K case

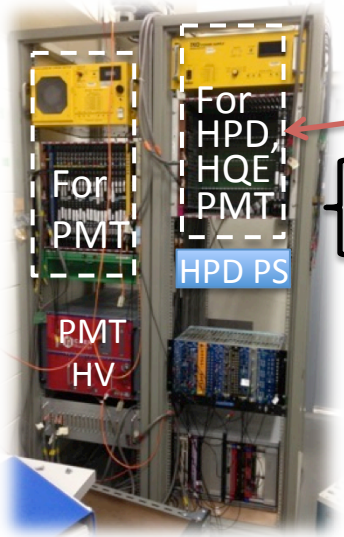


DAQ of charge + time

ATM (Analog Timing Module)

12ch x (2TAC+2QAC)→ADC

used in old SK



1 board for HPD (8/12ch)
1 for HQE PMT (5/12ch)
Trigger threshold is set **by each board (0-12mV)**
Set threshold separately (0.25p.e. in PMT case)
↓
Calibrated HPD/HQE PMT.

*) ATM replaced with QBEE(current SK board) later

70m signal cable

Control Power Supply

10ch x 6 LV cables

2 Power supply lines (10V)
- For HV unit and Pre-amp. (<500mA) + GND

4 HV control lines (<1mA, 5V)
- HV control (0 - 4V out)
- AD bias control (0 - 4V out)
- Latch up monitor (+5V in)
- Enable switch (+5V out)

70m
Low voltage (10V)
+ control cable (5V)

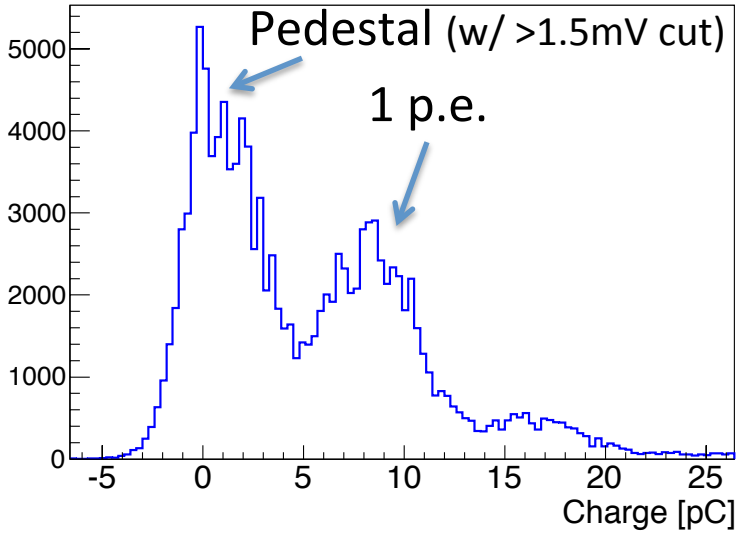
1 photo-electron peak

Check performance in tank

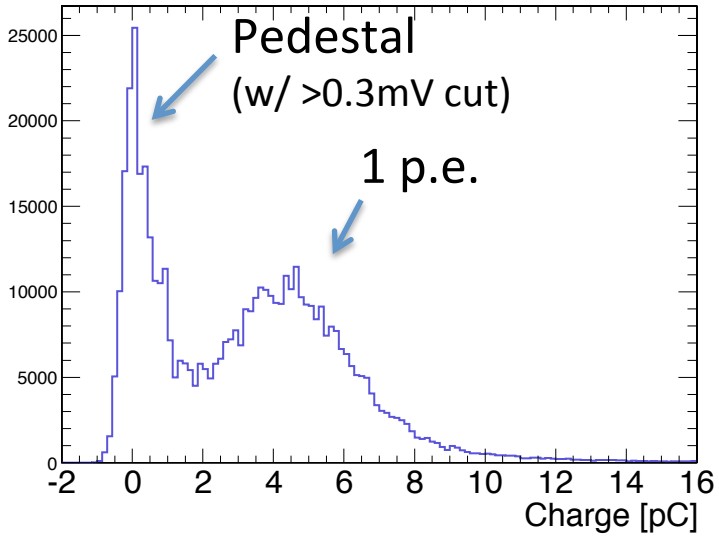
charge integrated in 400ns window

Measured with laser diode (λ = 405nm, 500Hz), 70m cable, 13 °C in water

20cmΦ HPD

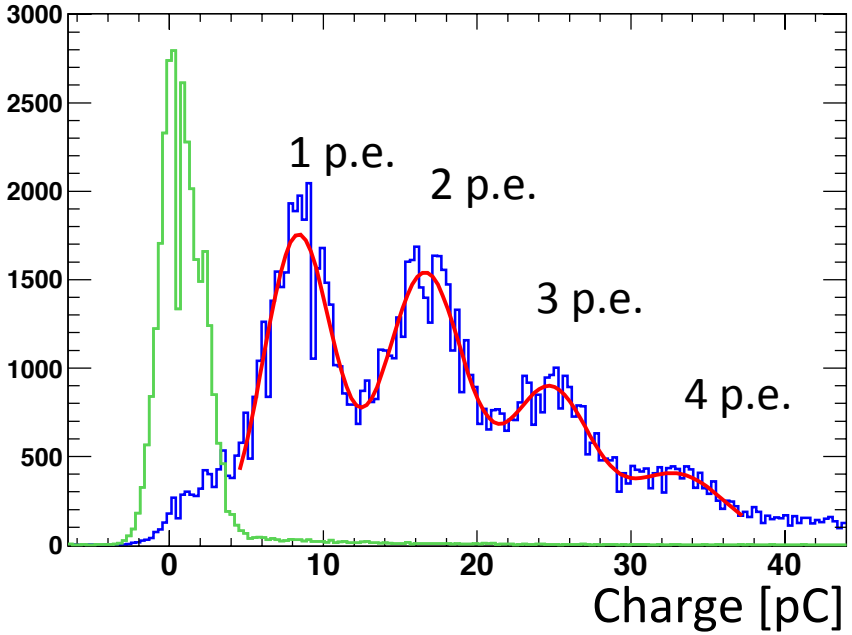


High-QE PMT

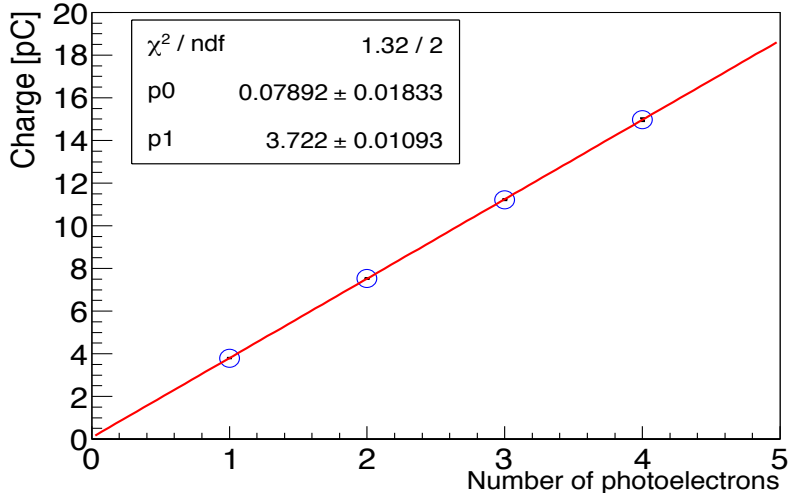


- 1 p.e. peak is recognized in the 200-ton tank.
- Broad pedestal at HPD will be cut out.
  - Threshold is set to cut pedestal out.
- Better p.e. resolution of HPDs.
  - PMT 40-50%, HPD~30%

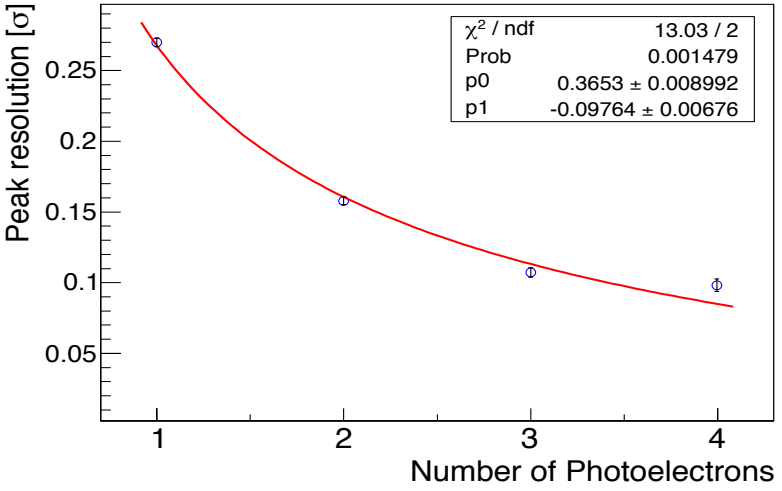
Multi photoelectron peaks by HPD



Output linearity



Peak resolution

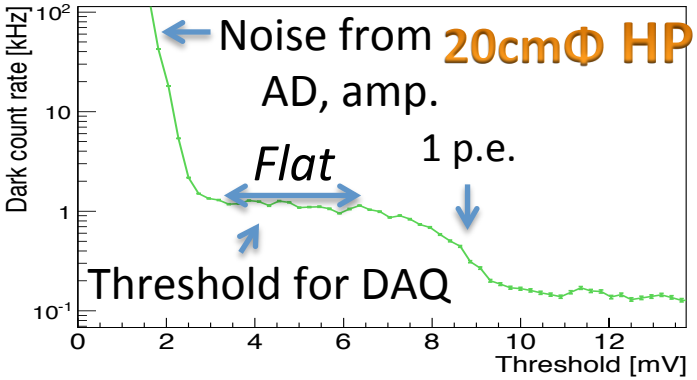


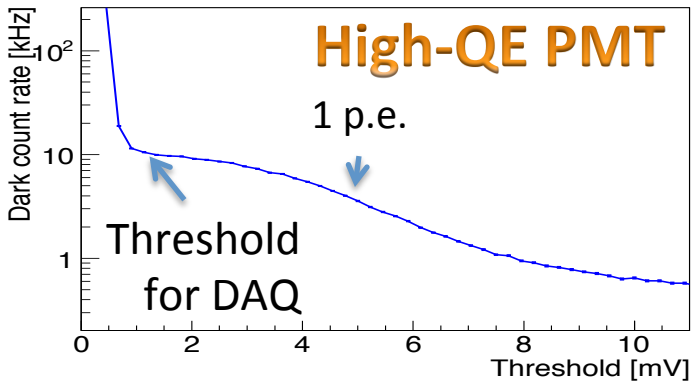
- Multi photoelectron peaks were clearly seen.
- About 30% σ at 1 p.e. peak

Dark count rate

- Event is triggered by hit coincidence. Threshold is set to take 1 p.e.
  - Low dark count rate is essential to take low energy event.

Single noise rate in dark by changing hit threshold

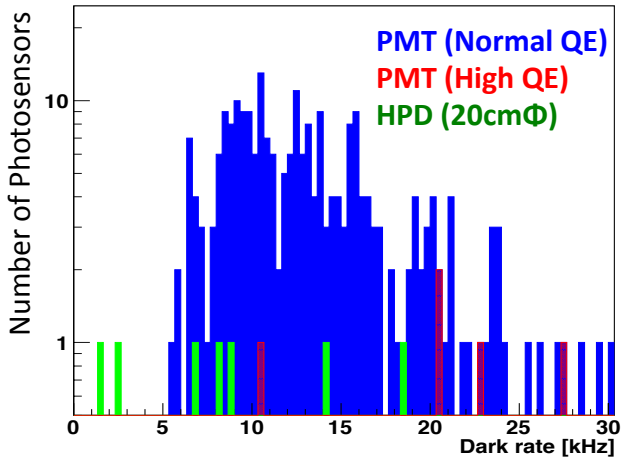




- Dark rate is stabilized gradually in years.

HPD/HighQE PMT is newly manufactured.
Need more time for stabilization?

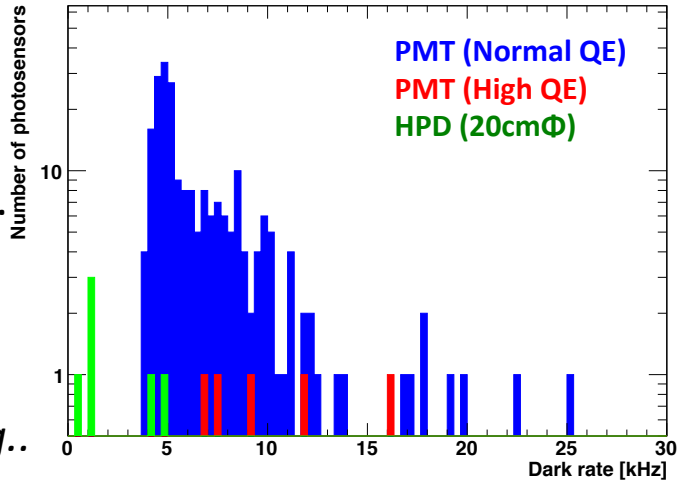
2013 Mar before the installation



Installation in summer 2013
Constant operation started in Feb 2014.

Stabilizing..

2014 Mar in the water tank



Keep monitoring for a year

New 50cm-Φ photodetectors

- Hamamatsu Photonics is developing 2 new 50cmΦ photodetectors of HPD and PMT with box and line dynode type.

Model	R3600 (Used for 2-30 yrs)	R12850 (Under development)	R12860 (Under development)	
C.E.	80%	95%	93%	Calculated value in simulation
T.T.S. (FWHM)	5.5 ns	0.75ns (w/o Preamp.)	2.7 ns	
Bias voltage	2 kV bias	8 kV bias, 20mm ϕ AD	2 kV bias	

- Prototype of the 2 photodetectors was prepared with high QE.
- Basic performance was measured.

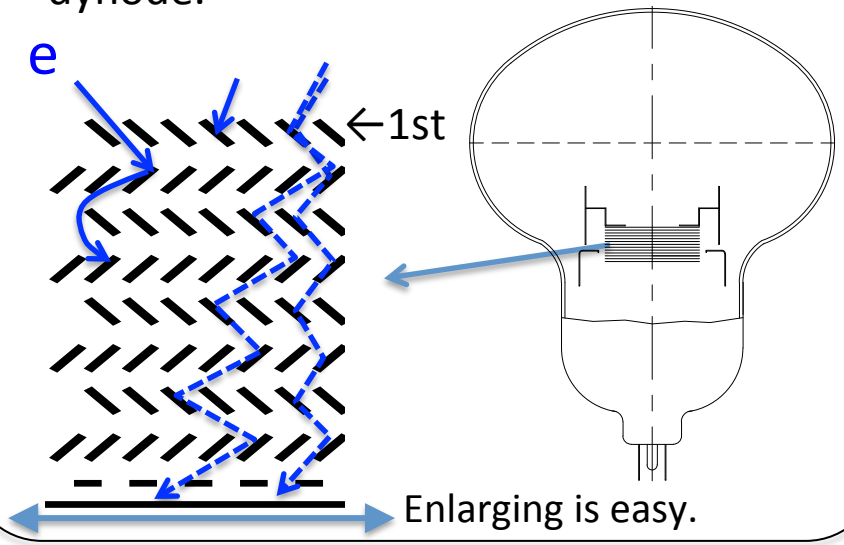
Amplification in dynodes

- Good photon collection by box shape 1st dynode
- Fast time and constant gain by linear-focused dynode

Venetian blind type (Super-K)

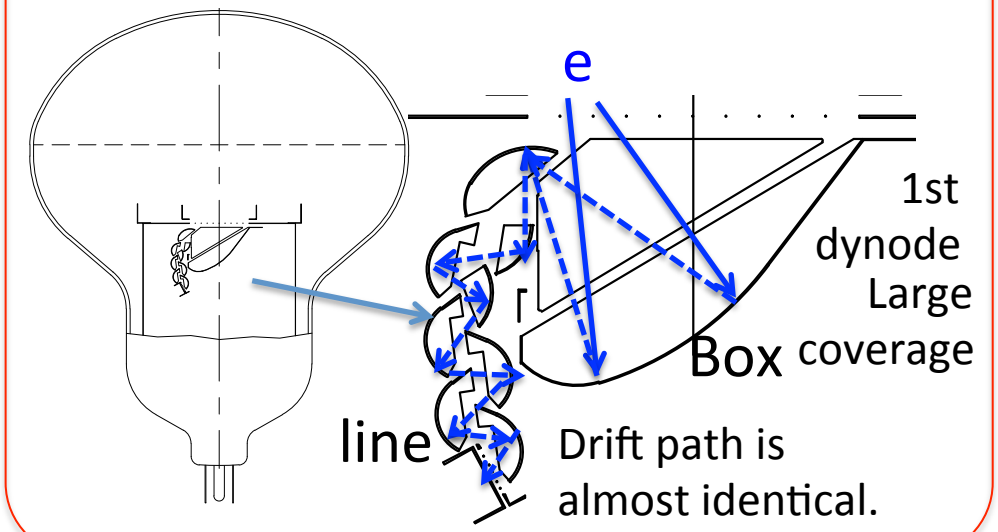
might miss dynode.

Drift path can be varied.



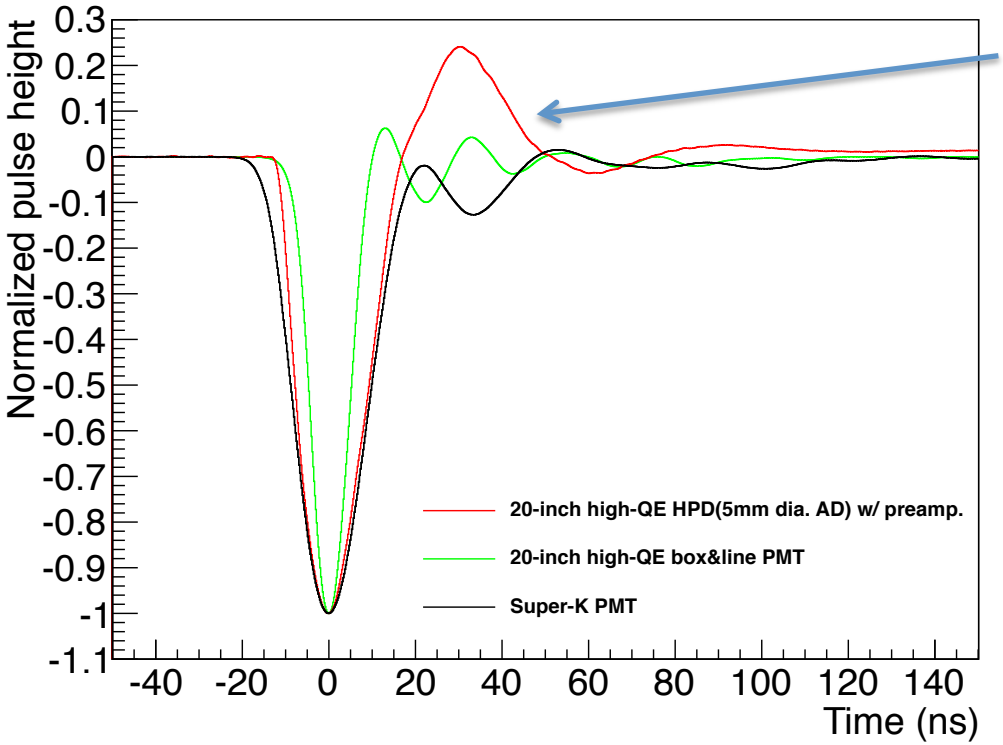
Box and line (B&L) type

+ high QE



- New design of box and line dynode and High QE on it demands well optimizing and manufacturing process.
  - Performance, noise, response uniformity and usability must be confirmed.

Signal Output



- Recovery shape is determined by electronics
  - Bleeder circuit or preamplifier is not final.
- Original waveform of HPD is fast (1.9ns rise time, etc.).
  - Shaped by preamplifier
- Measured HPD prototype with 5mmΦ AD smaller than 20mmΦ in final design

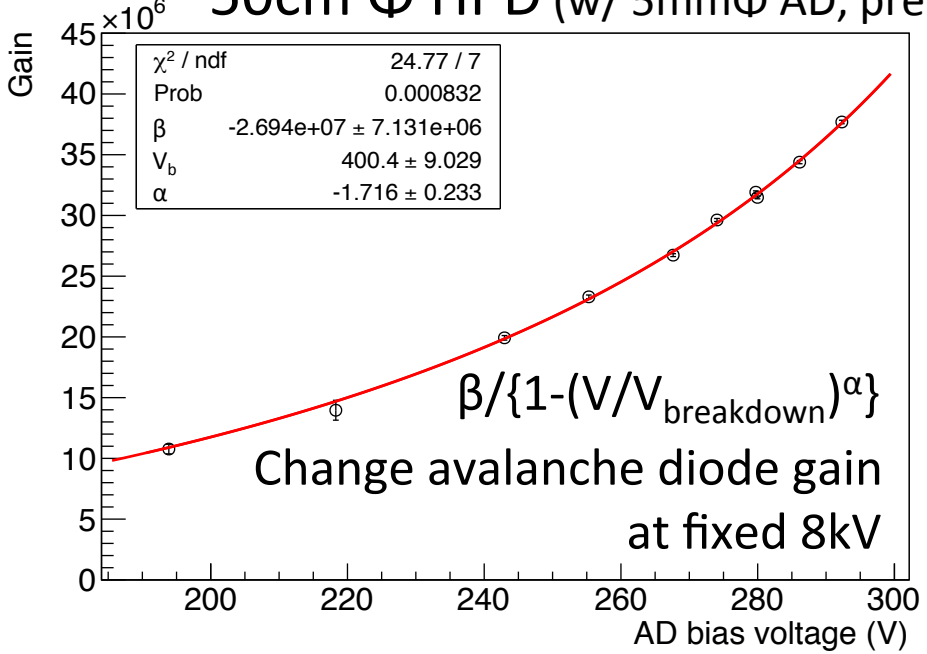
10% - 90%	HPD	B&L PMT	SK PMT
Rise time (ns)	7.4	6.2	10.6
Fall time (ns)	11.5	6.3	13.1
Width (FWHM, ns)	25.5	16.7	31.4

Both new photodetectors show faster response.

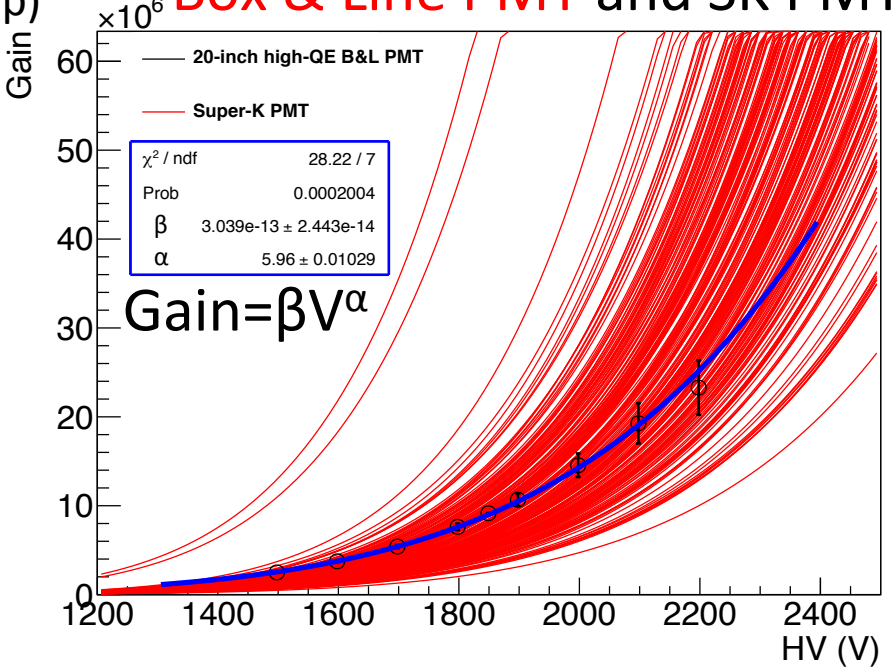
Gain by applied HV

- Started R&D and measurement with a few photo-detector prototypes.
  - Electronics, all design is still under development.

50cm Φ HPD (w/ 5mmΦ AD, preamp)



Box & Line PMT and SK PMT



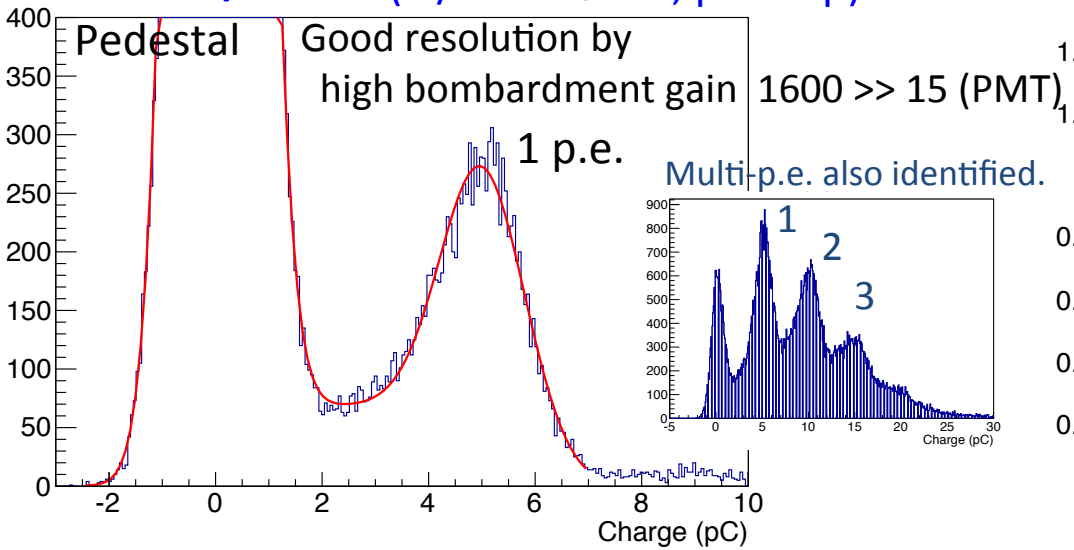
- Confirmed all photo-detector prototypes working with proper gain level.

→ Evaluate detection performance

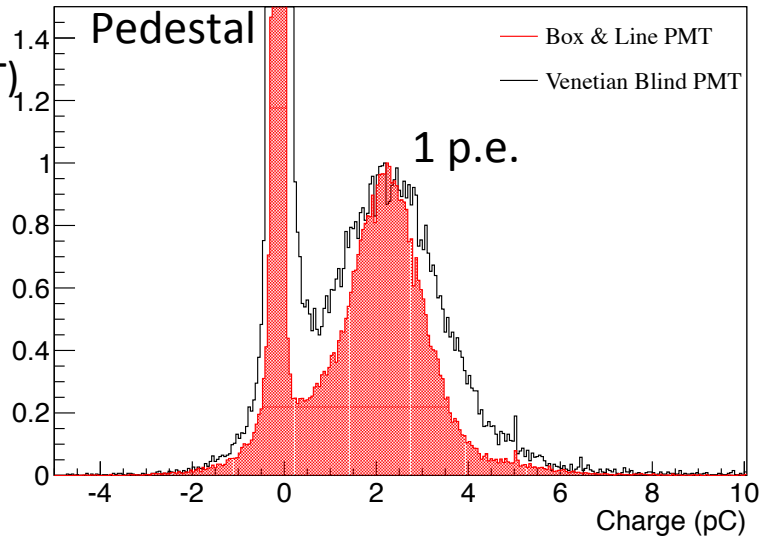
1 p.e. charge resolution

- Better p.e. resolution is obtained in new photo-detectors.

50cm Φ HPD (w/ 5mmΦ AD, preamp)



Box & Line PMT and SK PMT

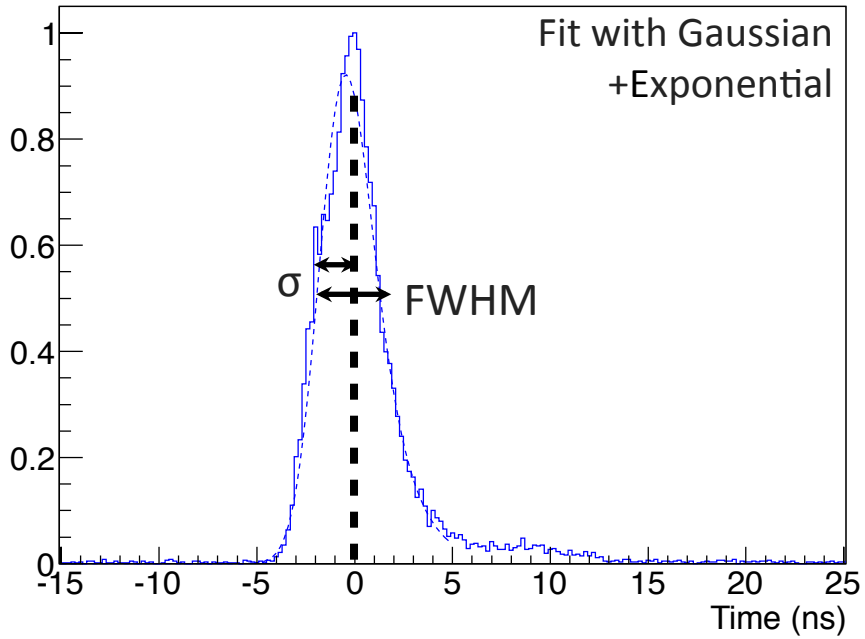


1 photoelectron peak	HPD (50cm Φ)	HPD (20cm Φ)	B&L PMT (50cm Φ)	SK PMT (50cm Φ)
Resolution (σ/mean)	16%	12%	35%	53%
Peak / Valley ratio	3.9	5.2	4.3	2.2

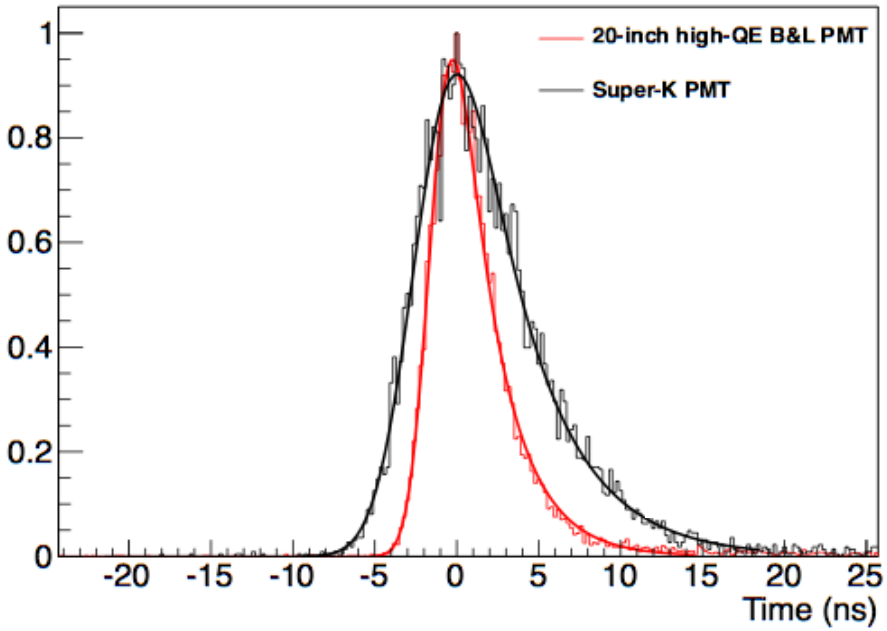
- HPD performance is limited by current amplifier design.
  - Amplifier, readout and avalanche diode R&D are going on.

1 p.e. time resolution

HPD (w/ 5mmΦ AD, preamp.)



Box & Line PMT and SK PMT



	HPD (50cm Φ)	HPD (20cm Φ)	B&L PMT (50cm Φ)	SK PMT (50cm Φ)
Resolution in σ [ns]	1.4 ns	1.1 ns	1.1 ns	2.1 ns
FWHM [ns]	3.4 ns	3.3 ns	4.1 ns	7.3 ns
(Calculation)	(0.75 ns)	(0.62 ns)	(2.7 ns)	(5.5 ns)

- Better time resolution is obtained in new photo-detectors.

Plan of R&D

Hyper-K time scale

Goal of R&D

2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
				Tunnels →				Wall construction →				Water filling ▶	
								Cavity excavation →					
		Preparation →										Operation →	
								Photodetector production →					
Photodetector R&D →						Pre-test - - →							
								Photodetector supporter, installation →					

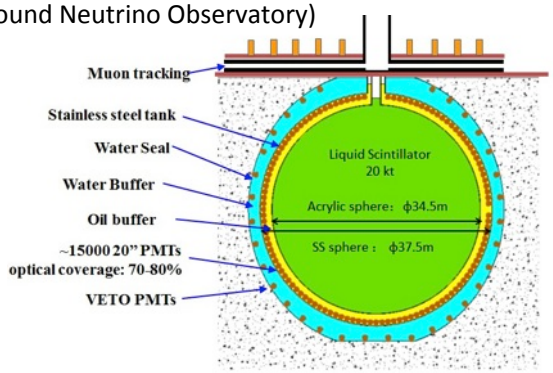
- Our R&D purpose and goal match other neutrino experiments.

JUNO (Jiangmen Underground Neutrino Observatory)

in China

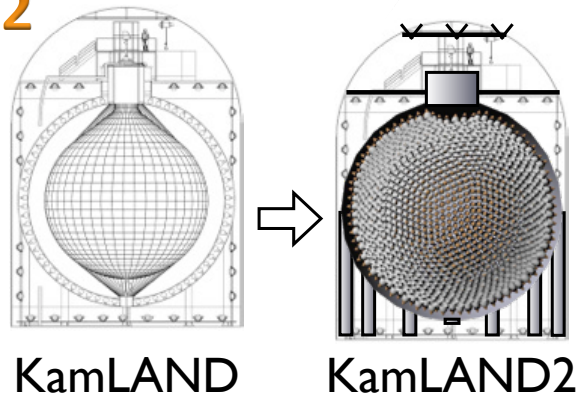
after DayaBay experiment

15000 PMTs



KamLAND2

in Japan



KamLAND KamLAND2

Other ν experiments plan to use many 50cm Φ photodetectors.

Summary

- Development of new photo-detectors is going on.
  - HPD and new PMT with high quantum efficiency.
- Proof test started with 20cm-Φ HPD and 50cm-Φ high-QE PMT in the 200-ton water tank.
- Prototypes of 50cm-Φ high-QE HPD and PMT with box and line dynode show better resolution in both charge and time than Super-K PMT.
  - Studying on noise, dark hit, after pulse and response uniformity
  - Development of electronics is in progress.
- All R&D and test will finish in 2016.
  - Select the best photo-detector for Hyper-K