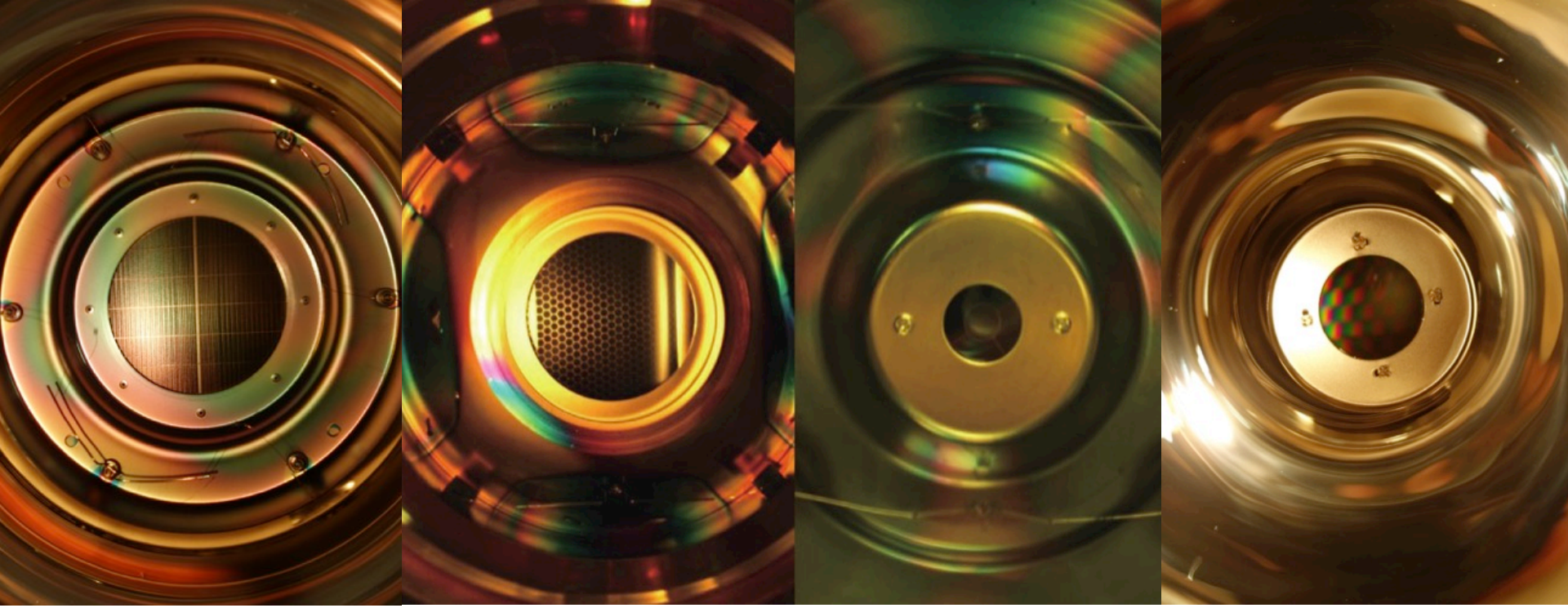

Photosensor Development for Neutrino Experiments

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Keio University

NUFACT 2019
29/Aug/2019

Photosensors for Neutrinos

Large aperture photomultiplier

Active progress by several manufacturers

HAMAMATSU

NIGHT VISION GROUP CO., LTD NVT

PHOTONIS HZC PHOTONICS

ET Enterprises electron tubes ADIT INCOM BRIGHT IDEAS

The largest 20-inch (50 cm) aperture developed with single photon counting and sub-nanosecond resolution for neutrino experiments

Semiconductor detector

Near side to neutrino source, fast time response and multi channel readout, high magnetic field tolerance, for various application

Hybrid detector

To get a large aperture with a small sensor

- Focusing on the photodetector with large aperture today.

Pioneers

- Large aperture photodetectors, developed for proton decay discovery, are now key technologies for neutrinos.

Irvine–Michigan–Brookhaven (IMB) 1982-1991

8 kton water
(17 × 18 × 23m^3)
2048 PMTs

5″ PMT (EMI 9834B/9870B)

→ R1408 8″ PMT (Hamamatsu)

→ Reused in Super-K Outer Detector

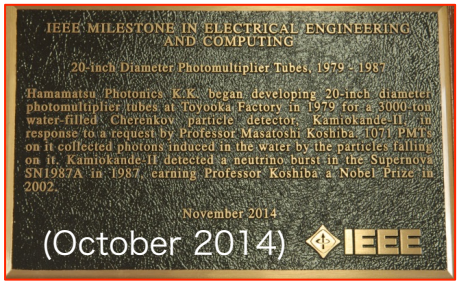
Kamiokande 1983-1995

3 kton water
(16 mH × 16 mϕ)
948 PMTs

R1449 20″ PMT (Hamamatsu)

→ Reused in KamLAND

Certified as an IEEE milestone



Led to success in supernova ν detections

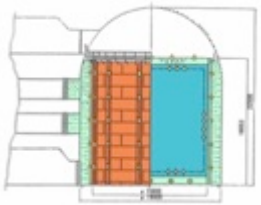
History of Largest Aperture PMT

Development of large aperture photo-detectors is a key to explore neutrino physics.

First 20-inch (50 cm) Photomultiplier Tube (PMT)

Hamamatsu R1449 (Venetian blind dynode)

For Kamiokande

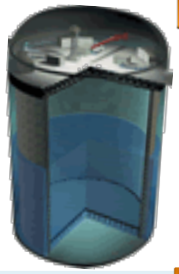


(1983-1996)

1k PMTs
/ 3 kton water

Supernova ν observation!

R3600 (Venetian blind dynode, improved)



For Super-Kamiokande (Super-K, SK)

(1996-)

11k PMTs
/ 50 kton water

ν oscillation discovery!

42 cm (17") Box&Line PMT

R7250
(Box&Line dynode)
with 50 cm bulb
of R3600

For KamLAND

50 cm MCP PMT
(Micro-Channel Plate)

GDB-6201 by NNVT

For JUNO

Recently developed in **China**

For Hyper-Kamiokande (Hyper-K, HK)

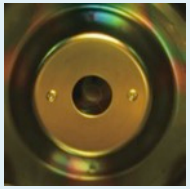
50 cm Box&Line PMT

R12860-HQE (Box&Line dynode)

Installed in Super-K, For JUNO and Hyper-K

50 cm Hybrid Photo-Detector (HPD)

R12850-HQE (Avalanche diode)



→ Possible further improvement

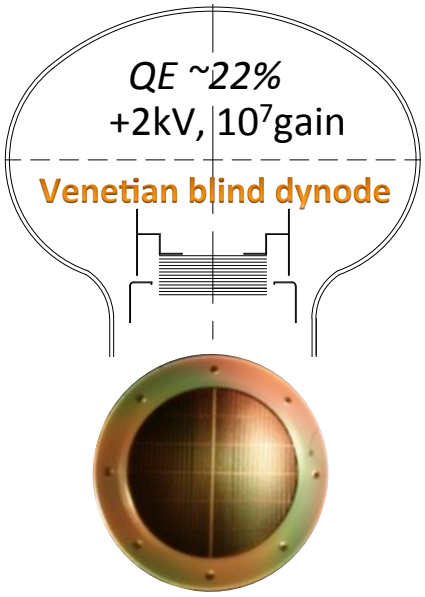
50 cm MCP PMT

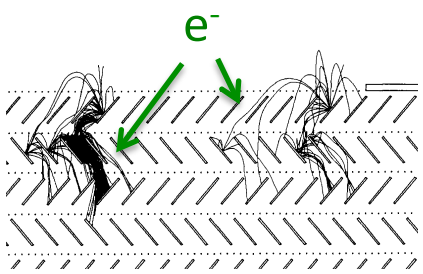
w/ TTS improved

New 20-inch Photodetectors

- High performance by photocathode and amplification

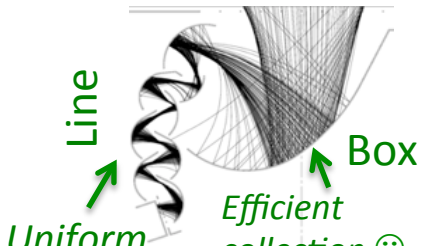
Super-K PMT
Hamamatsu R3600



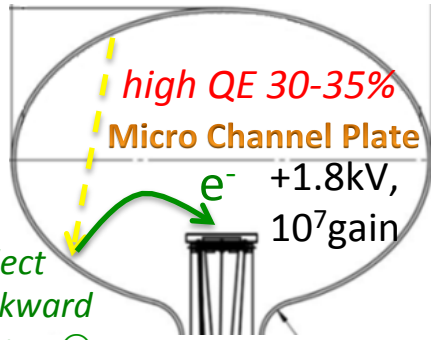


Varied path ☹

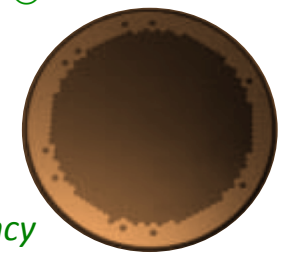
Box&Line PMT
Hamamatsu R12860



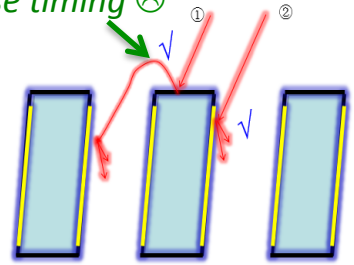
MCP PMT
NNVT GDB-6201



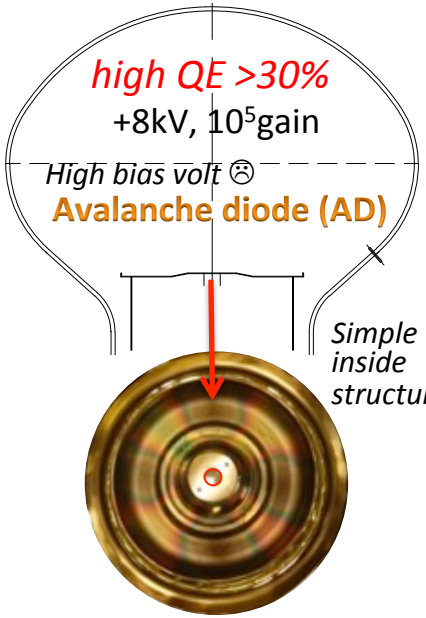
Collect backward photon ☺



Efficiency recovered ☺
Worse timing ☹

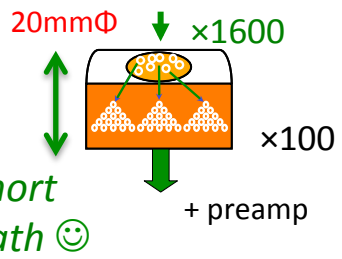


HPD (Hybrid PhotoDetector)
Hamamatsu R12850



Simple inside structure ☺

High bombardment gain ☺



Short path ☺

20-inch Box-and-Line PMT

×2 high pressure bearing for Hyper-K water height

×2 high detection efficiency

and half time&charge resolutions

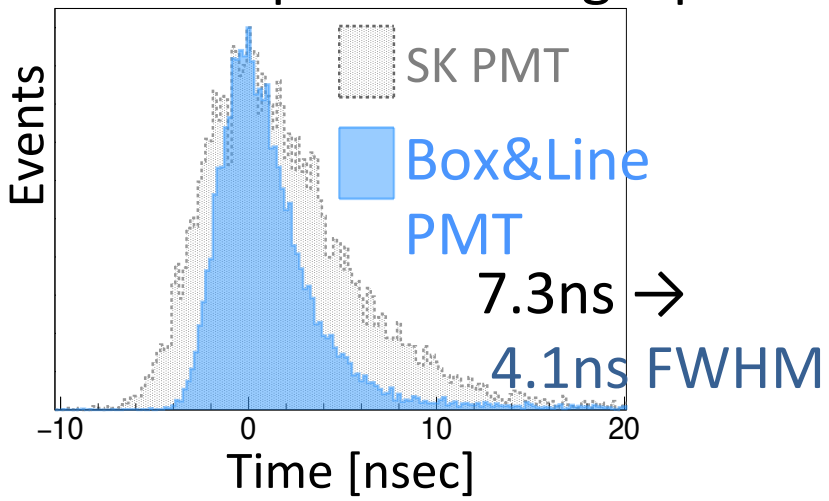
improved from Super-K PMTs

40k PMTs for Hyper-K

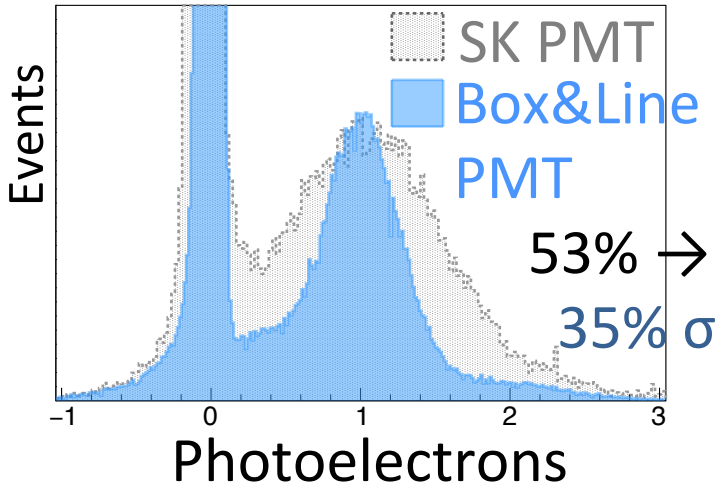
5k PMTs for JUNO

- High resolutions were achieved smoothly as it was designed.

Transit Time Spread at Single p.e.

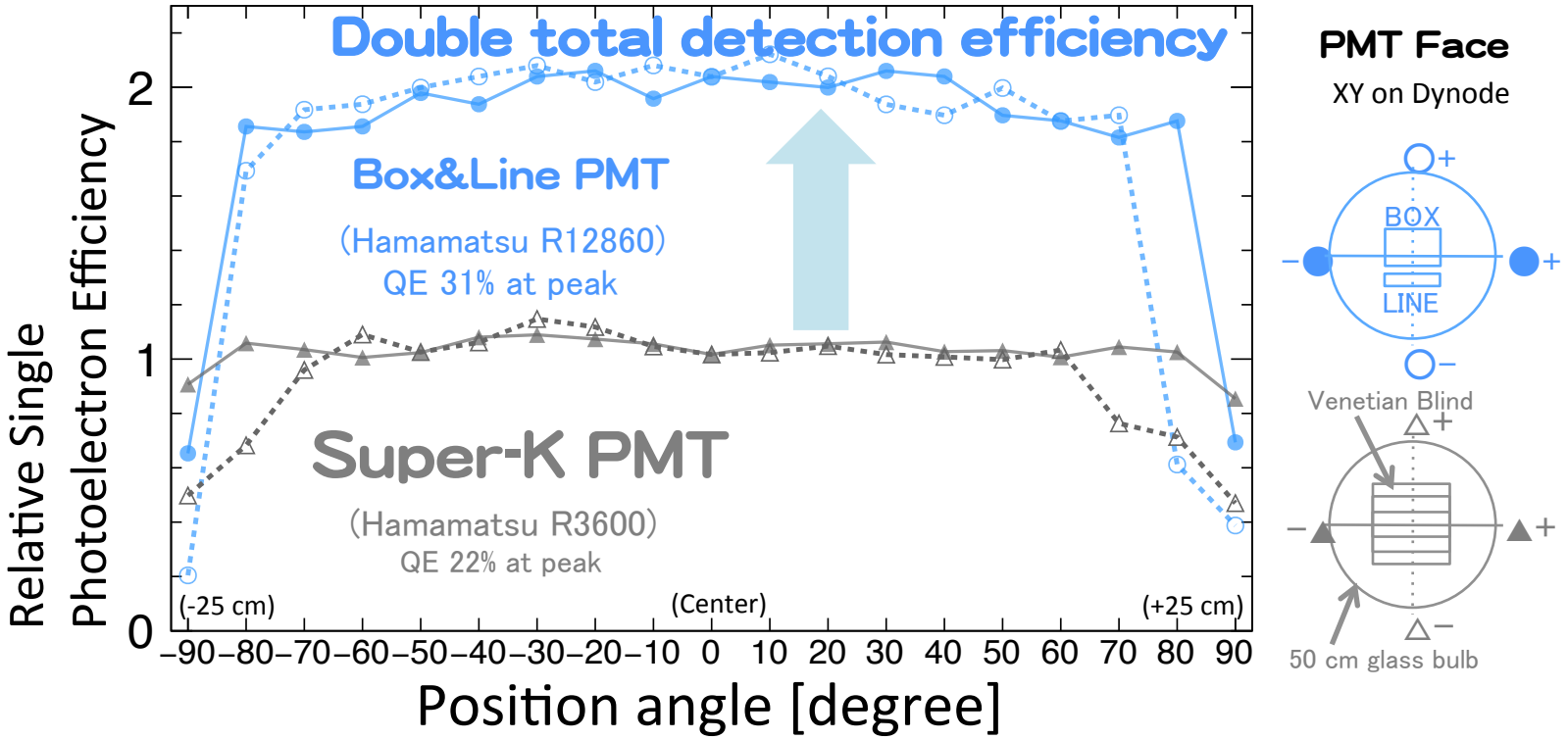


Single p.e. charge



20-inch Box-and-Line PMT

- Double detection efficiency was achieved.
  - Quantum efficiency : 22% peak in SK → 30%
  - Collection efficiency (in 46 cm ϕ) : 73% → 95%



What was improved by R&D?

High resolutions were quickly achieved in the initial prototype.

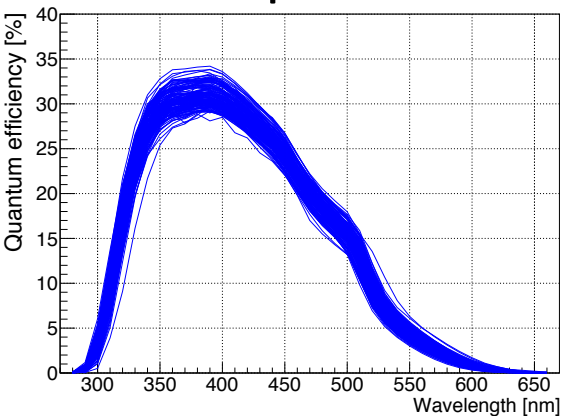
- Uniform response
  - Improve overall uniformity by injection positions for detection efficiency and transit time within 100 mG magnetic field
- PMT base optimization
  - Pulse shape optimization
  - Dynamic range
- Noise reduction
  - After pulse rate reduced from 30% to a few %
  - Dark rate reduced from 20 kHz to 6 kHz (still trying toward 4 kHz)
- Mechanical strength
  - Improved from ~0.8 MPa to over 1.25 MPa water pressure resistance
  - Waterproof housing was improved with the hard material
- Confirming long operation
  - 3 PMTs installed in 200-ton water tank and operated for 5 years since 2014
  - Over hundred PMTs were installed in Super-K in 2018

Quality of the Production

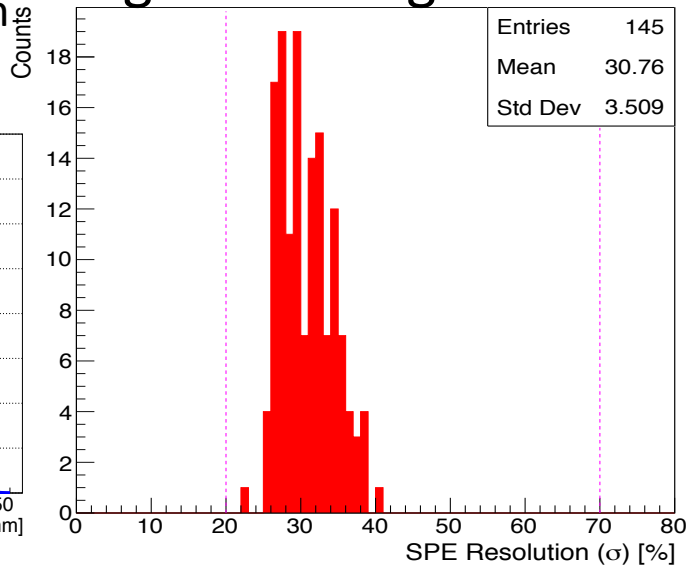
- About 140 PMTs were measured in Kamioka.

1931±118 V at 1.4e7 gain

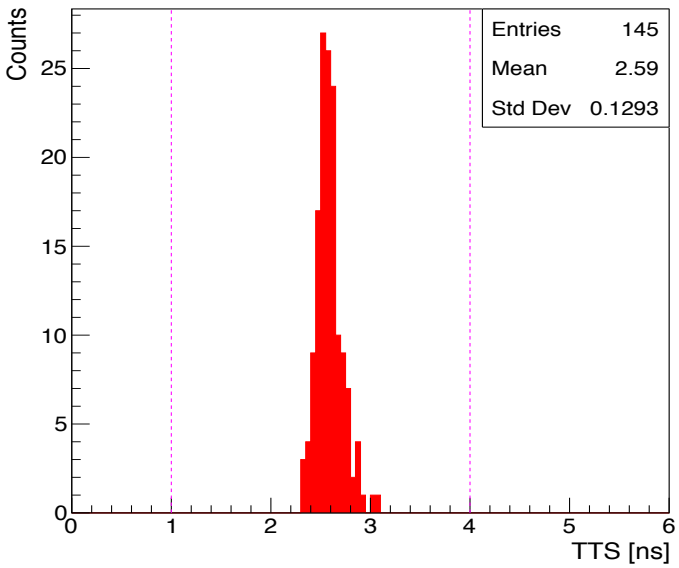
QE Spectra



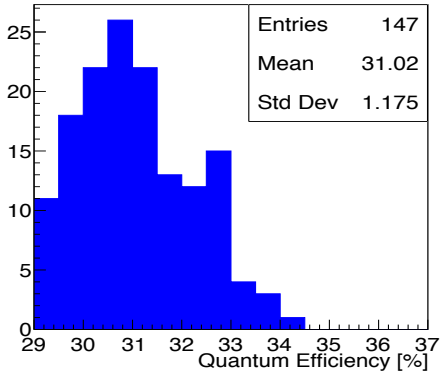
Single PE charge resolution



Transit Time Spread



Peak QE 31±1.2% (22% in SK PMT)



30.8 ± 3.5 % σ
(60.1% in SK PMT)

2.59 ± 0.13 ns FWHM
(6.73 ns in SK PMT)

Individual difference ~ 10% or less
All PMTs were tested up to 0.95 MPa water,
and no damage was found.

20-inch MCP PMT

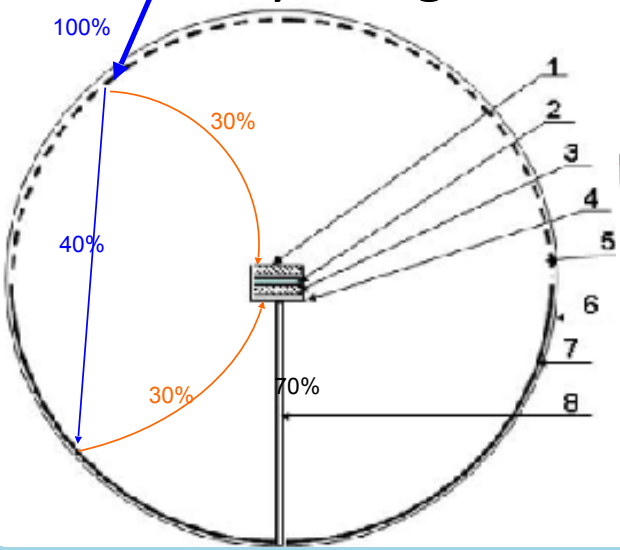
S.Qian (ICHEP2018, etc.)

Waterproofing by IHEP

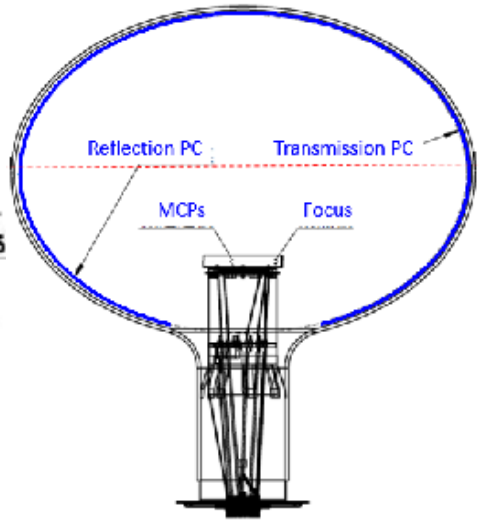
MCP PMT

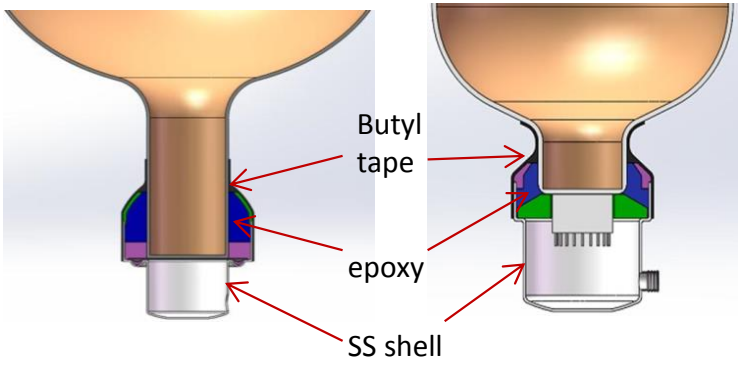
Hamamatsu PMT

Primary design



Design for JUNO



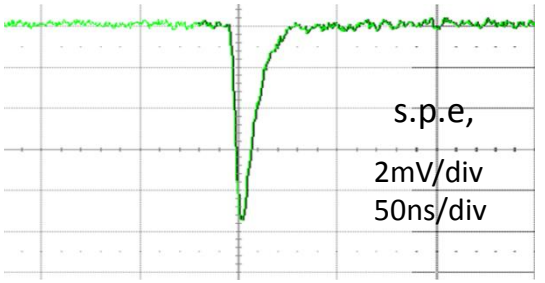


NNVT GDB6201

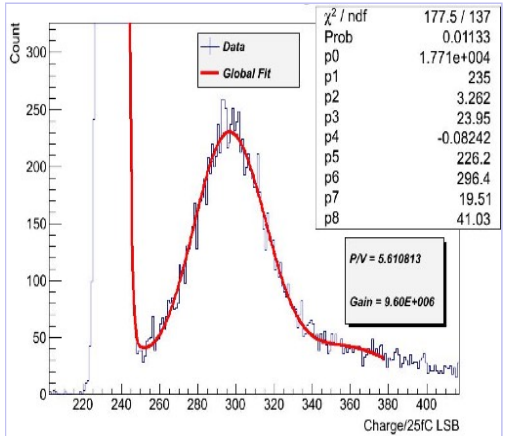
Hamamatsu R12860

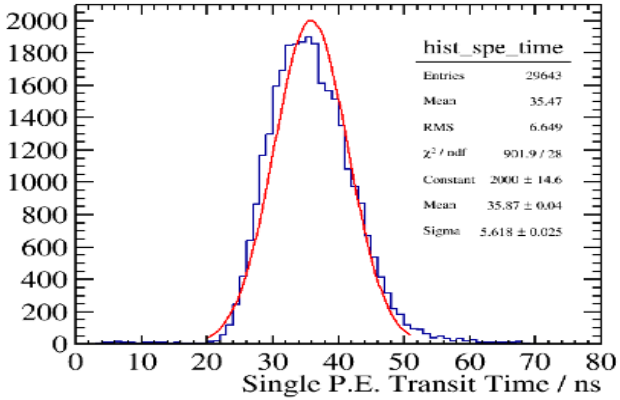
MCP PMT Performance

Type	20″ GDB-6201		
	Min.	Typ.	Max.
Spectral Range(nm)		300-650	
Maximum sensitivity at (nm)		380	
Sensitivity			
Luminous(μA/lm)		80	
QE at 405 nm(%)		30	
Supply Voltage(V)	1500	1750	2000
Gain		1×10^7	
Anode Dark Current(nA)		150	1000
Background Noise@22℃(cps)		30 k	100 k
Single Electron Spectrum			
Energy Resolution(%)		35	
Peak to Valley Ratio	3	7	10
Anode Pulse			
Rise Time(ns)		1.4	
TTS (FWHM) (ns)		15	
Linearity @10% (P.E.)	800	1000	1400
After pulse ratio(%)		1	
Background radioactive			
^{238}U (Bq/kg)		2.5	
^{232}Th (Bq/kg)		0.5	
^{40}K (Bq/kg)		0.3	

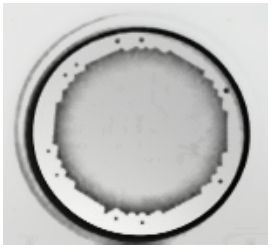


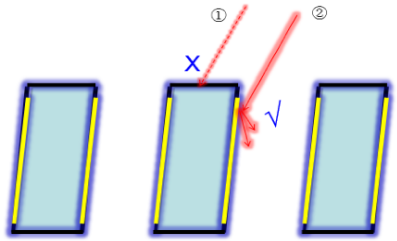
MCP PMT signal





Improvement on Detection Efficiency



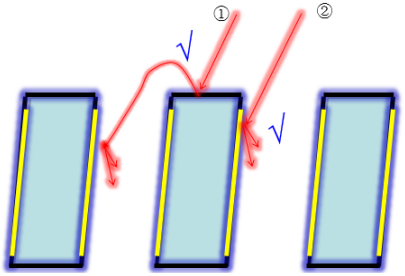


CE = 70%

The p.e. into the channel directly ~70%

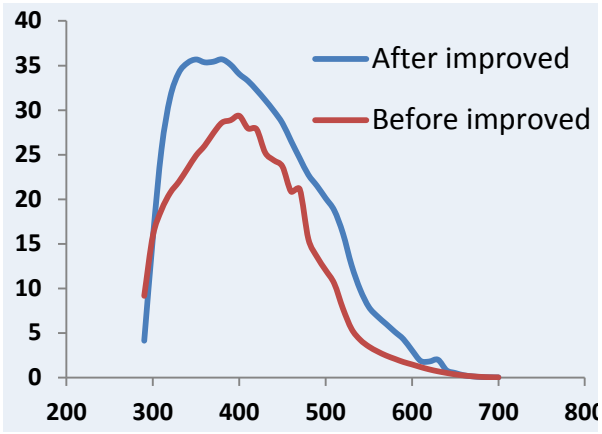
change

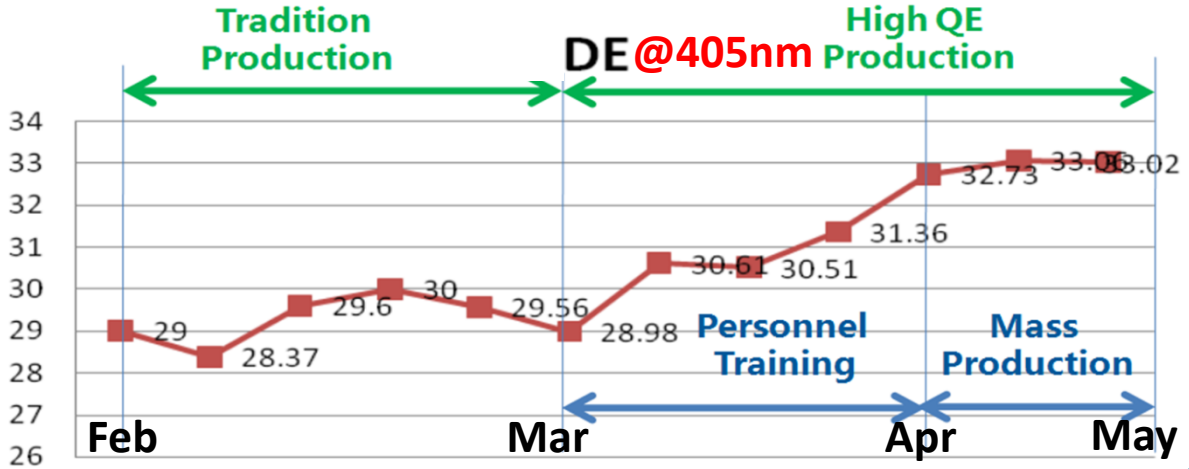
The Diameter of the MCP: **33mm; 50mm;**
The Diameter of the Hole: **6um; 8um; 10um; 12um**;
The Inclined Angle: **0°**; **8°**; **12°**;
The Open Area Ratio: **60%**; **77%**;
The Depth of output electrode:……



CE = 100%

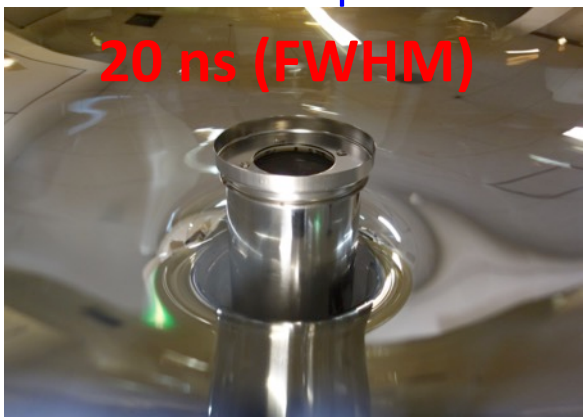
The p.e. into the channel directly ~70%
The p.e. from the electrod indirectly ~ 30%



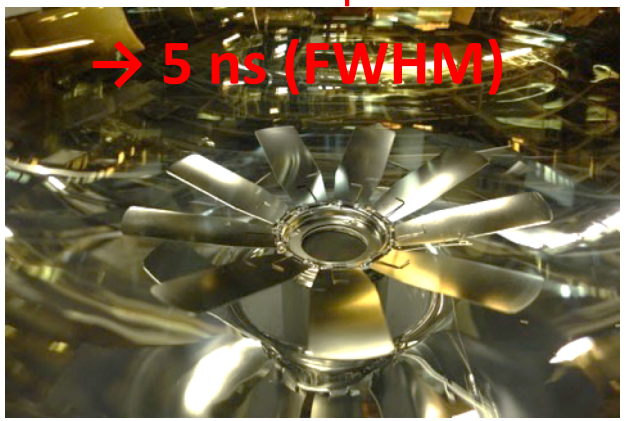


20-inch MCP PMT for Hyper-K

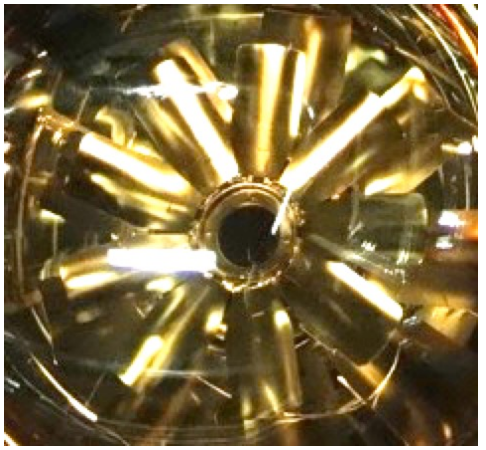
Before improved



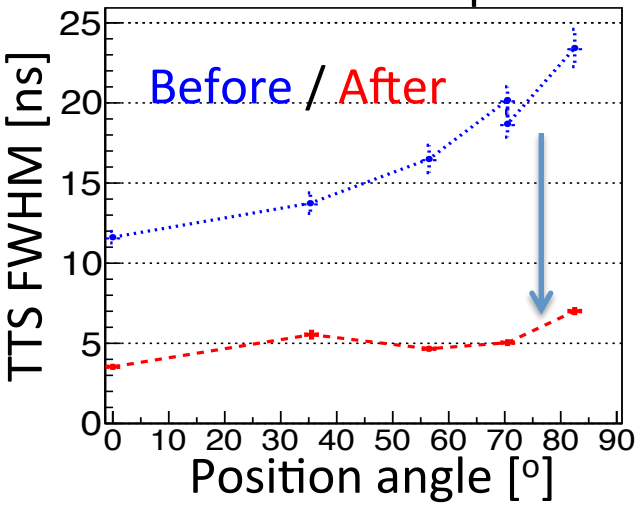
After improved



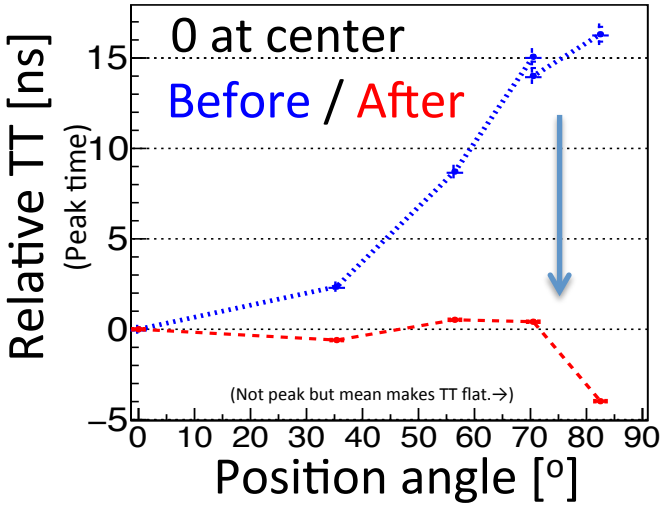
Latest

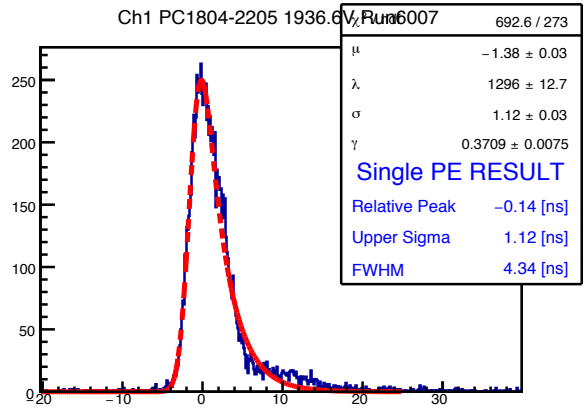


Transit Time Spread



Relative Transit Time





Latest: **4.3ns** FWHM

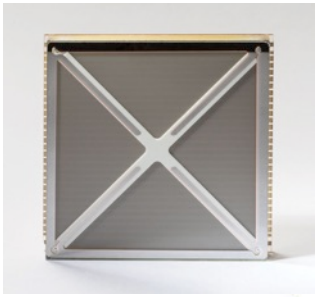
Detection efficiency ~100% → 85%

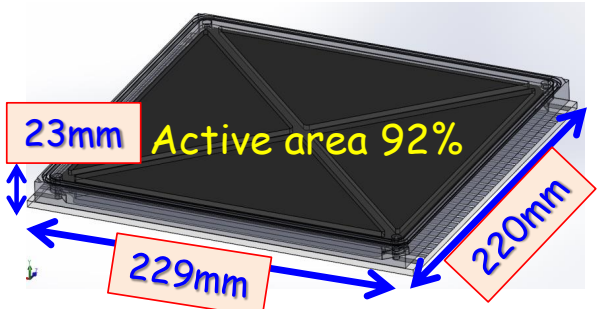
TTS was dramatically improved by adding electrodes.

Flat MCP PMT

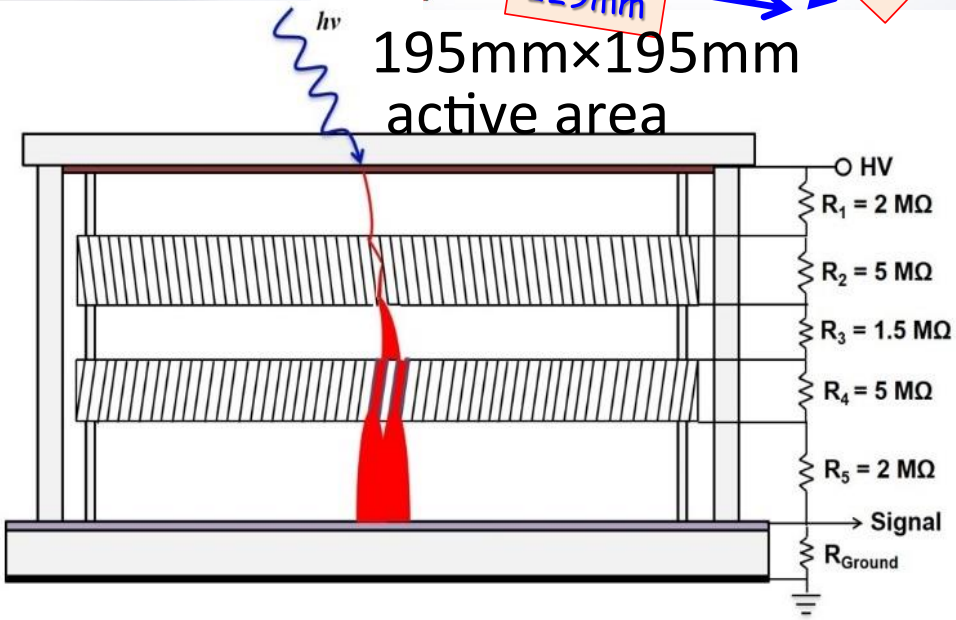
NIM A 936 (2019) 527-531
https://incomusa.com/lappd/

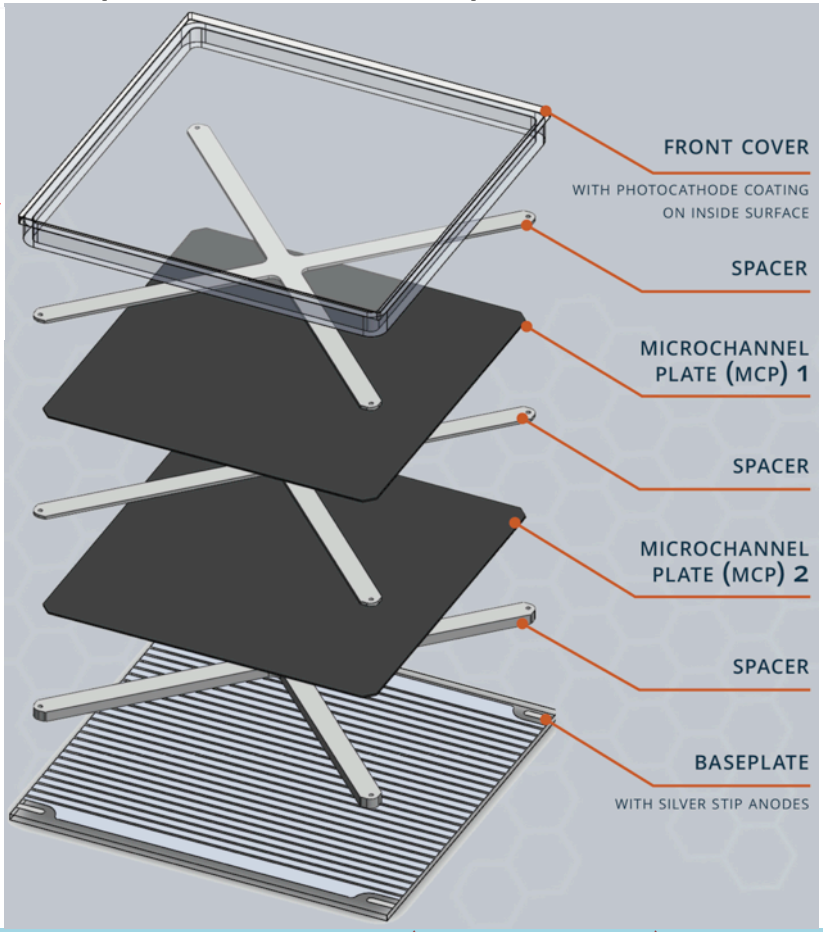
- LAPPD™ - Large Area Picosecond Photodetector
  - By Incom, Argonne National Labs, and the University of Chicago
  - Extremely high resolutions of ~mm spatial and ~50ps





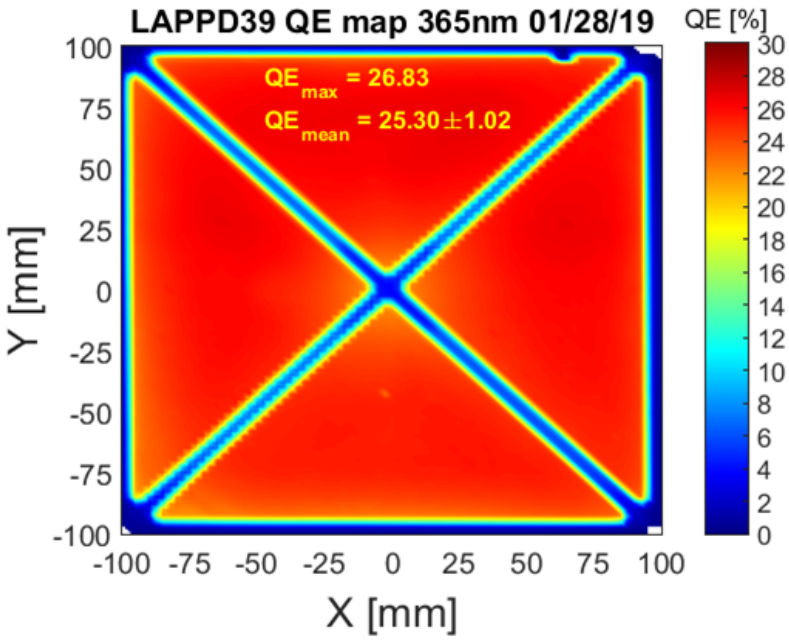
195mm×195mm
active area

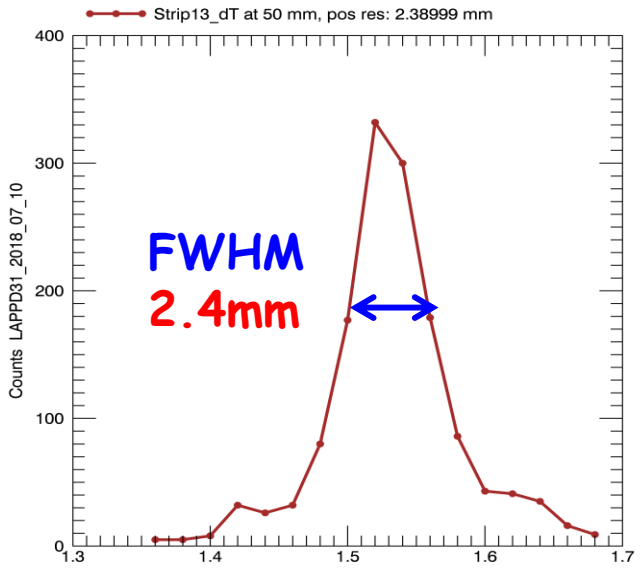


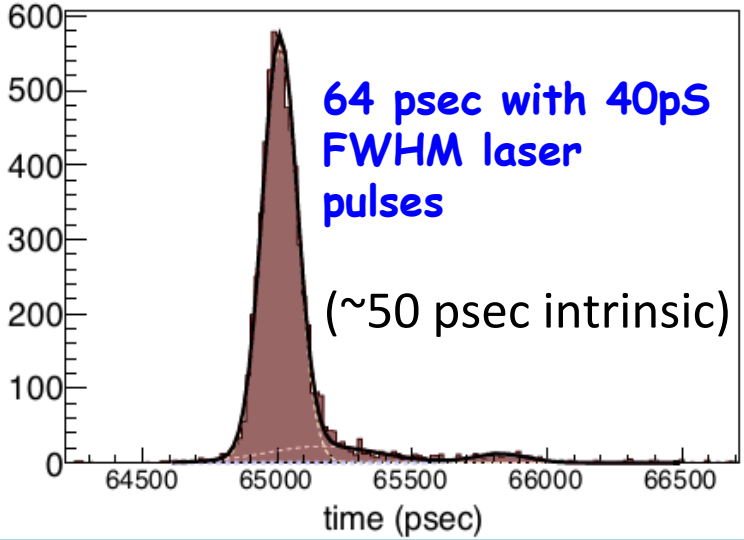


LAPPD Prototype Performance

PD18, VCI2019







high gain of 10^7,

high photocathode QE of up to 25% ,

low noise of 100Hz/cm^2 at a gain of $6 \cdot 10^6$,

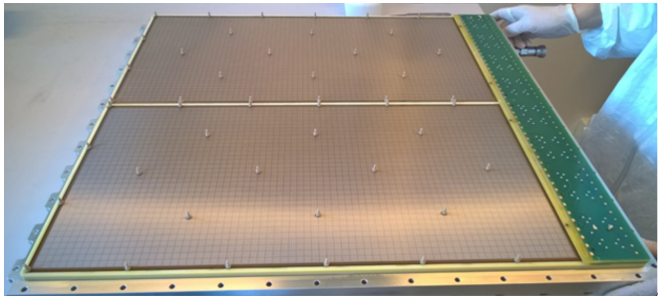
mm scale position resolution (electronics limited),

timing resolution of 50pS (electronics limited).

Gaseous PMT

- GEM(Gas Electron Multiplier) with photocathode for photon detection
  - micromegas (Micro-MEsh Gaseous Structure), RPC (Resistive Plate Chamber), etc.
- Stability and selection of the photocathode are essential.
  - For long operation
  - Sensitive wavelength
- Many small prototypes

COMPASS RICH-1 PDs (600 × 600 mm²)



+ CsI photocathode

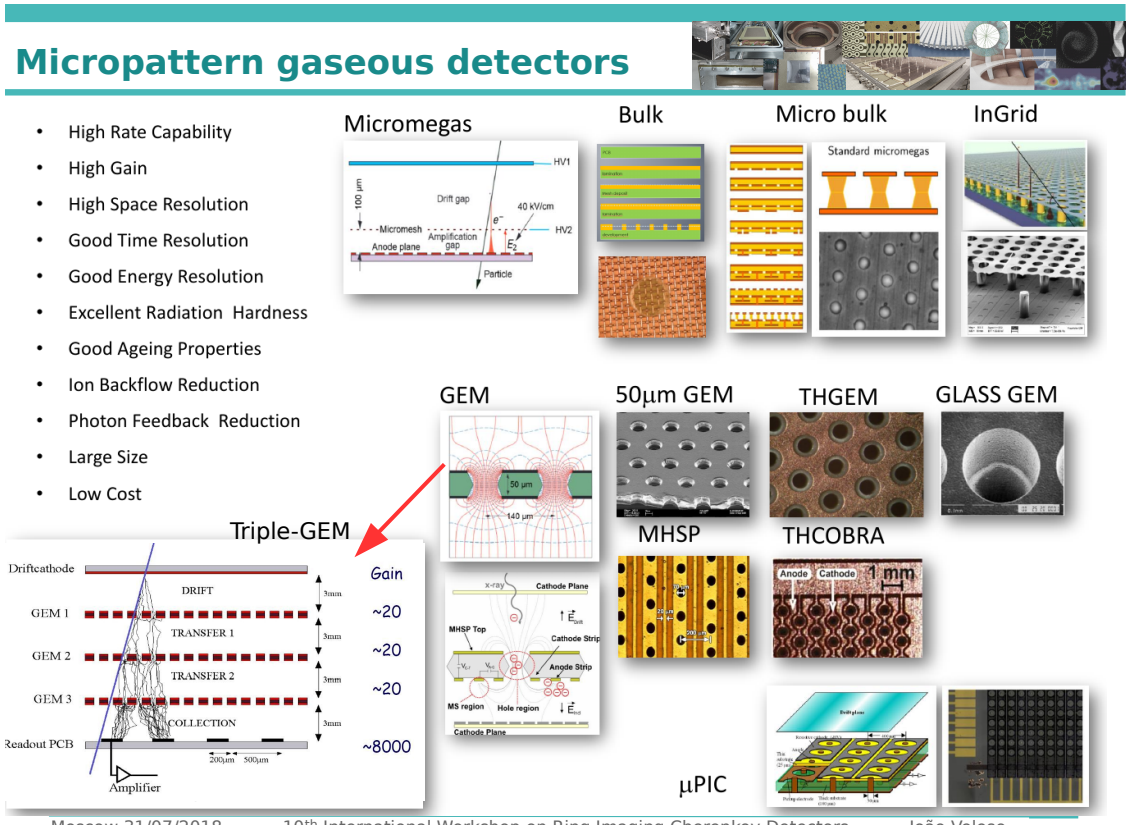
https://doi.org/10.1016/j.nima.2019.01.058

Status and perspectives of gaseous photon detectors

João Veloso

10th International Workshop on Ring Imaging Cherenkov Detectors

https://rich2018.org/indico/event/1/contributions/77/attachments/34/54/GPM-20.pdf



Moscow 31/07/2018 - 10th International Workshop on Ring Imaging Cherenkov Detectors - João Veloso

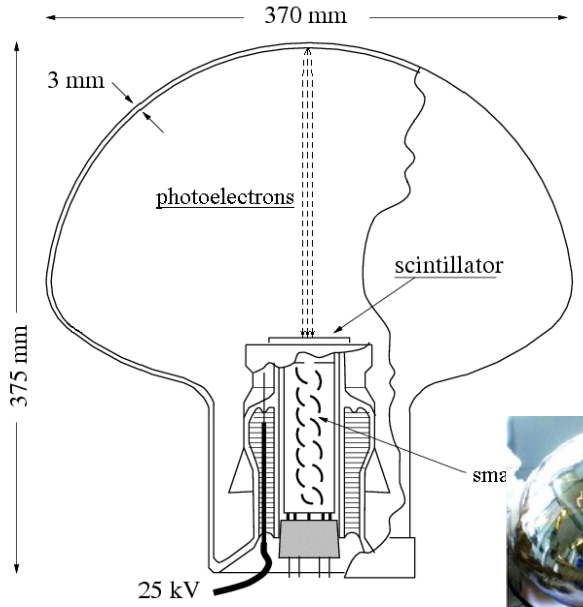
Hybrid Photodetector

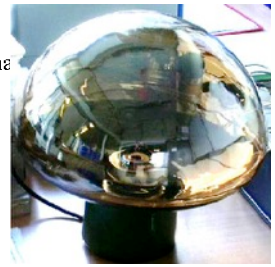
- Hybrid Phototube with phosphor
- Hybrid SiPD (VSiPM, ..)
- Hybrid Avalanche diode photodetector (HAPD or HPD)

Pioneers

Bikal

15-inch Quasar-370 +UGON

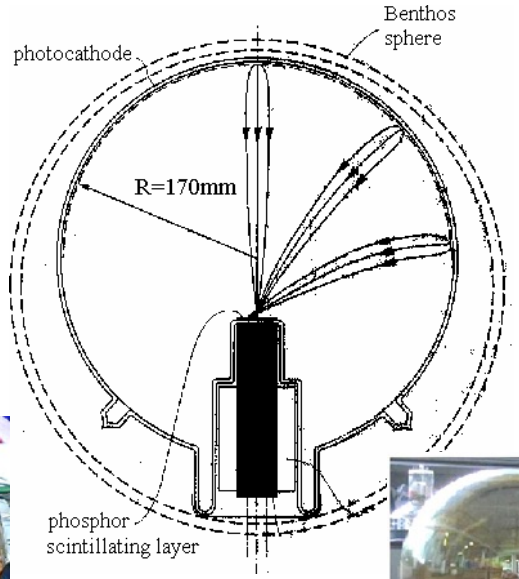




NIM A610, 68 (2009), etc.

Dumand

15-inch XP2600



X-HPD

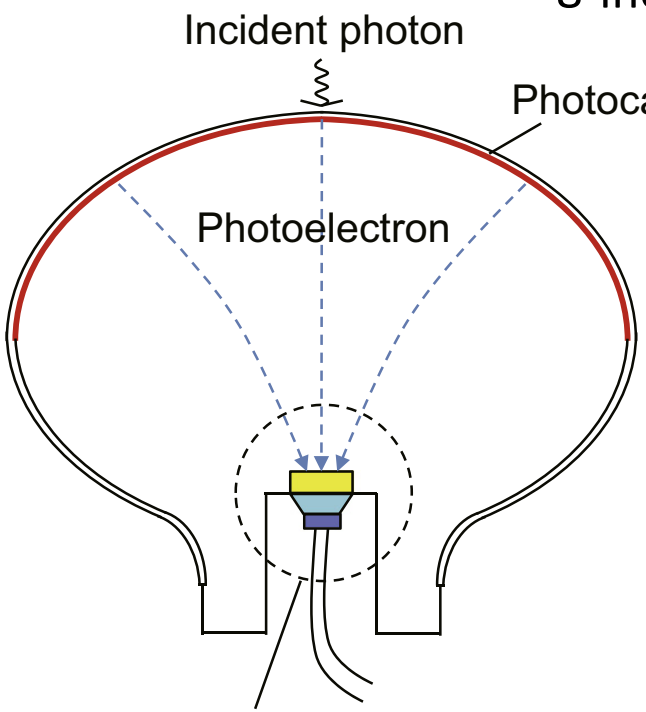
8-inch XP3102

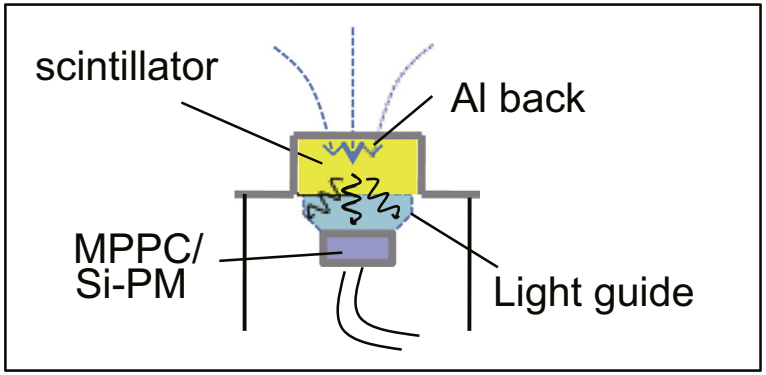
NIM A610 (2009) 61

8-inch phototube with phospher

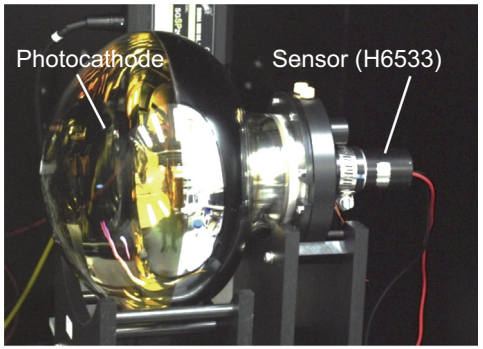
8-inch by Hamamatsu

NIM A 766 (2014) 173-175





(a)



(b)

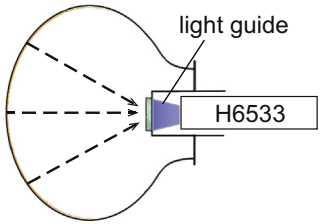


Fig. 2. 8-in. prototype photodetector with a J9758 phosphor.

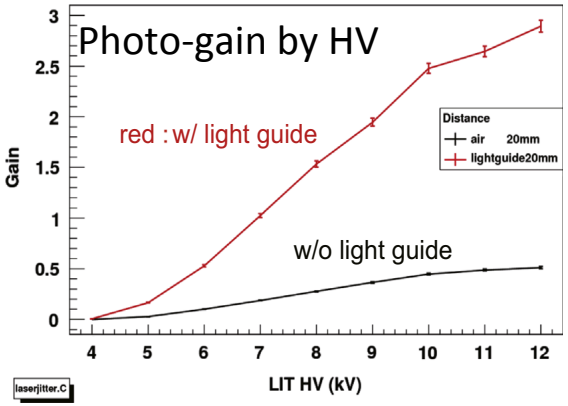
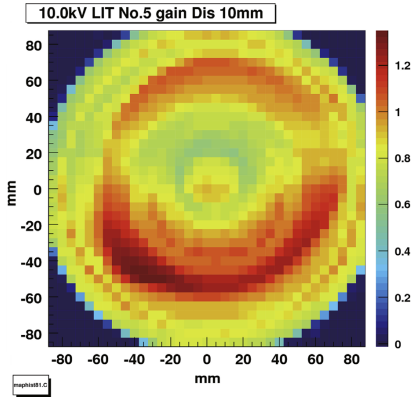
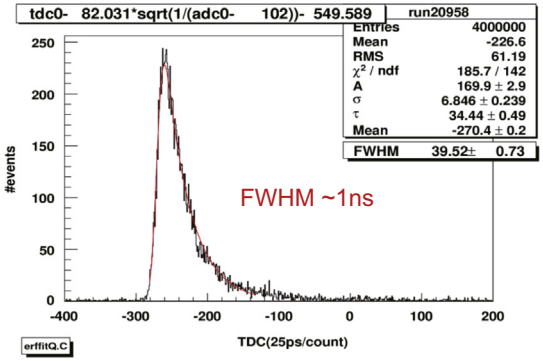


Photo-gain



Transit time spread at single PE

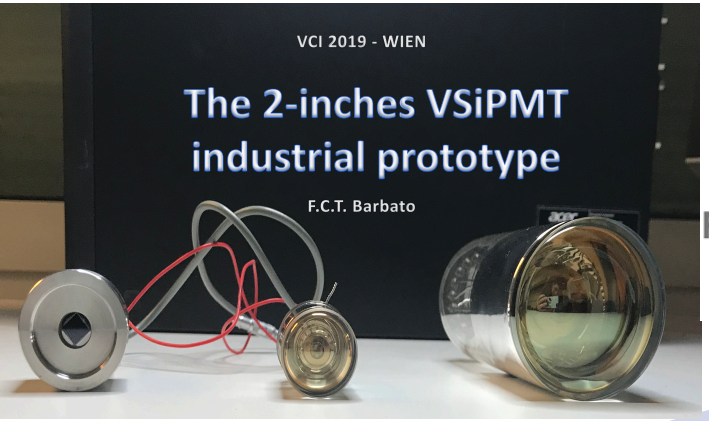


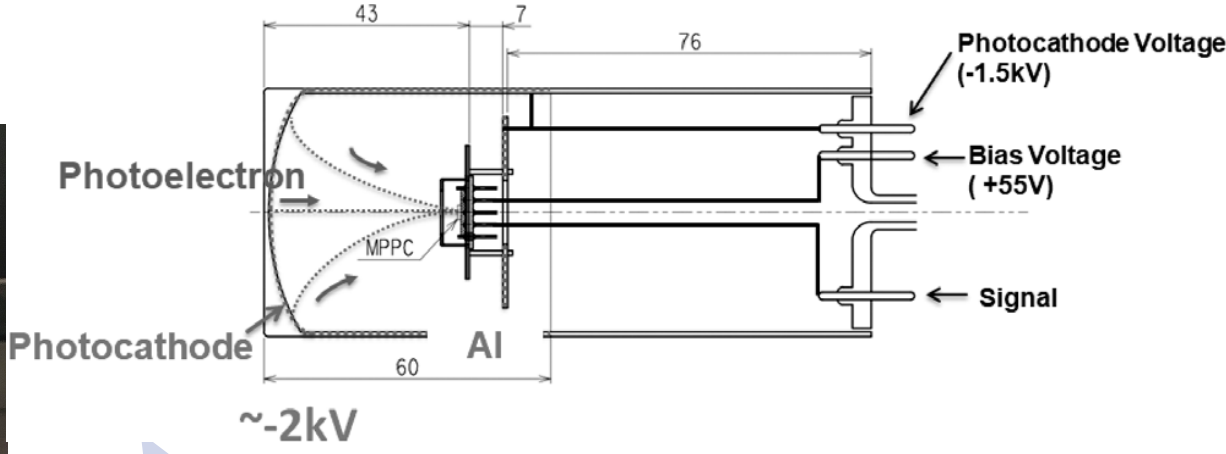
2-inch VSiPMT

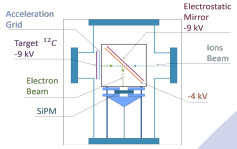
- Vacuum Silicon PhotoMultiplier Tube (or H-MPPC)
  - Hybrid with SiPM(→SiEM) without resin window

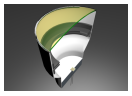
[NIM A 912 (2018) 290-293]

[Report at VCI2019]









2008
Idea

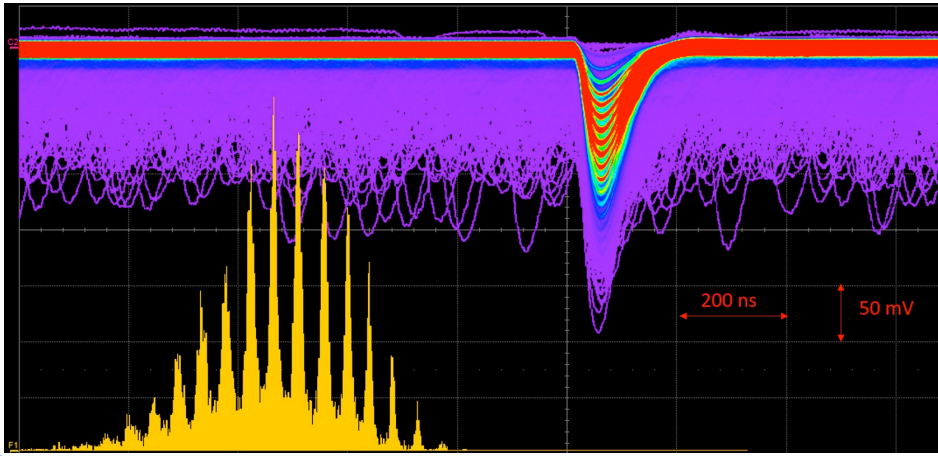
2012
Proof of feasibility

2013
First industrial prototype by Hamamatsu

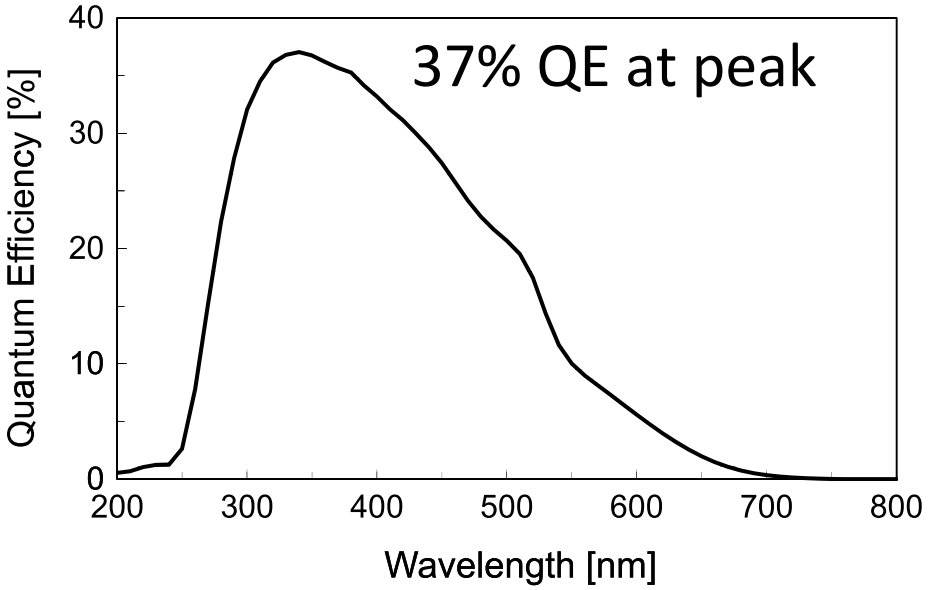
2014
LEGO prototype

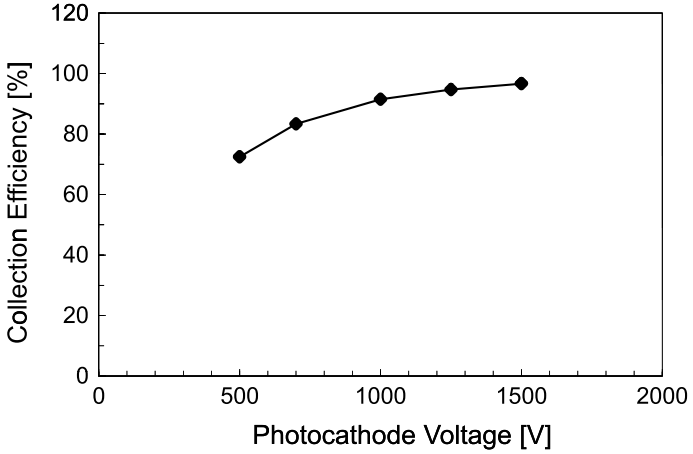
2016
1" prototype

2018
2" prototype

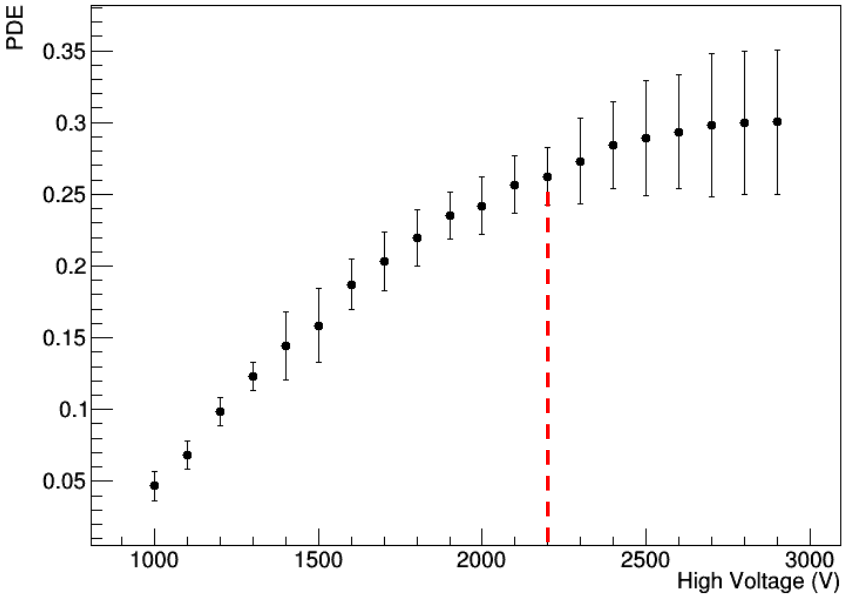


2-inch VSiPMT Photon Detection Efficiency





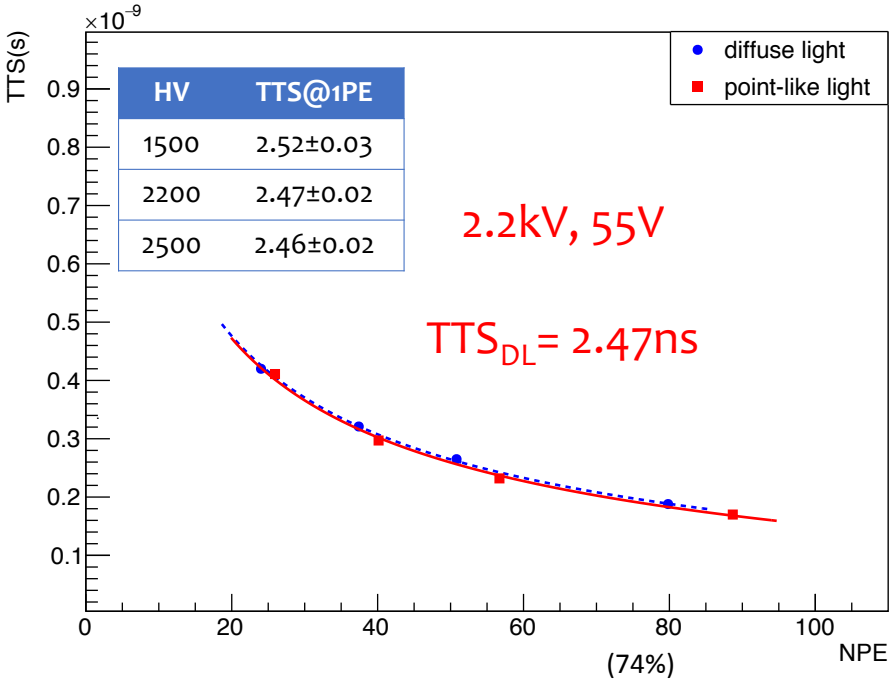
PDE ZJ9498

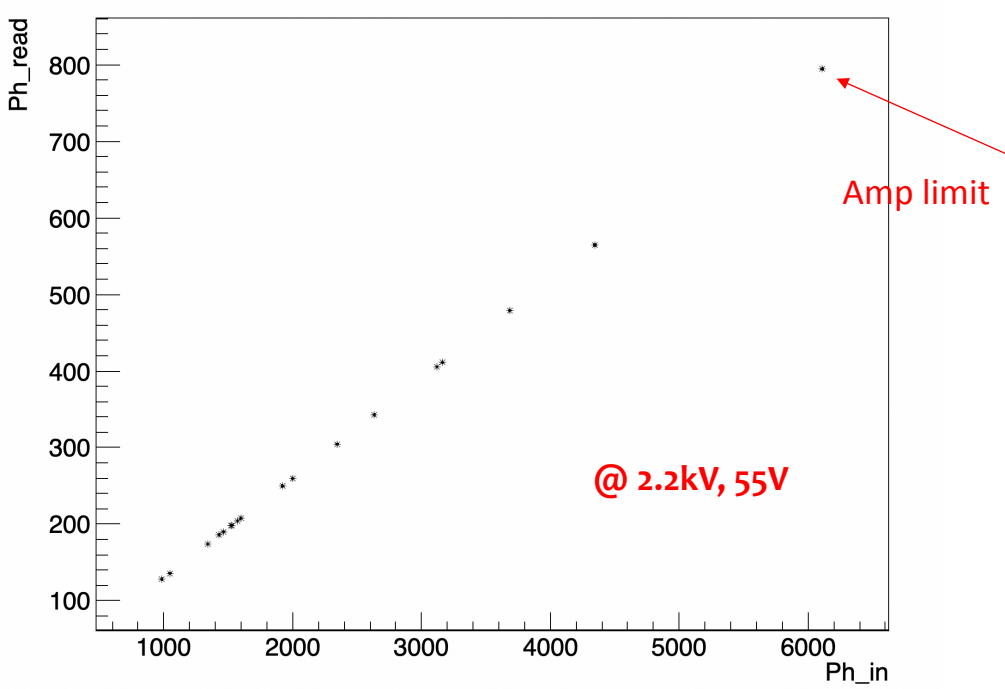


2 SiPM	ZJ9496	ZJ9498
Photocathode dia.	46 mm	46 mm
SiEM size	3×3 mm^2	3×3 mm^2
Pixel size	25×25 μm^2	50×50 μm^2
Fill factor	47	74

$$PDE = QE \cdot FF = 27\%$$
(74%)

2-inch VSiPMT Performance

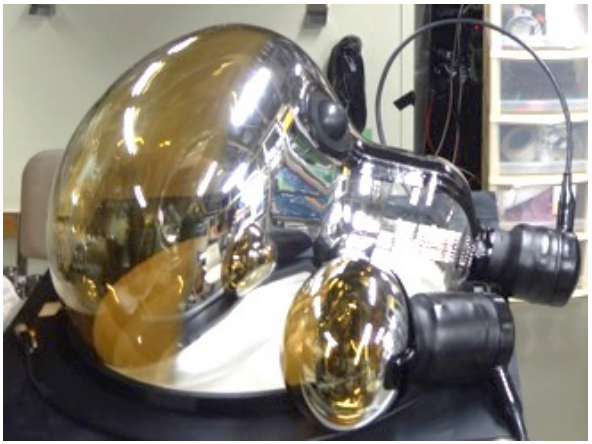


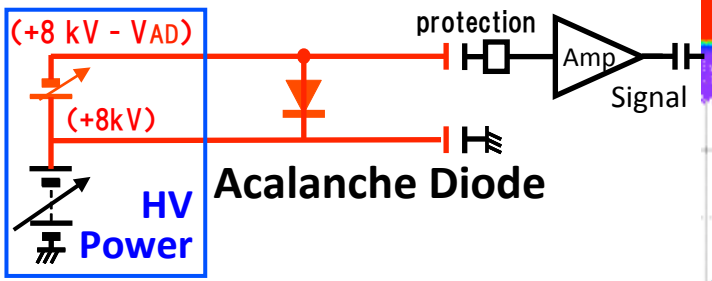


Prospect

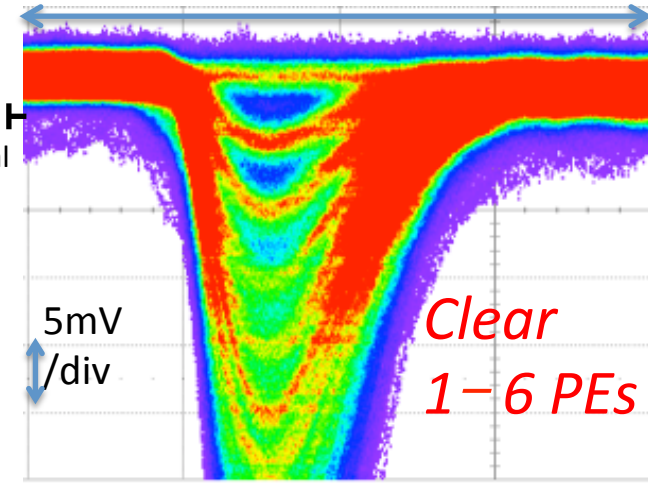
- High dark rate in SiPM matters at SPE, which is different from HAPD.
- Linearity and dynamic range might be limited.
  - Slow response in high light yield might be useful to avoid saturation by amplifier.
- General concern using SiPM inside
  - SiPM can emit photons, though it can be shaded on the surface.
- Larger dimension of SiPM for larger photocathode might be difficult.

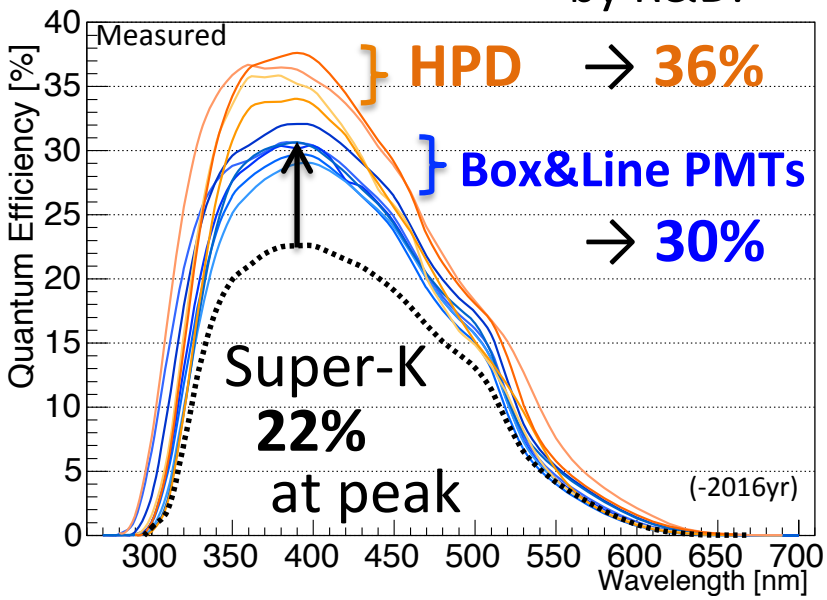
20-inch HPD

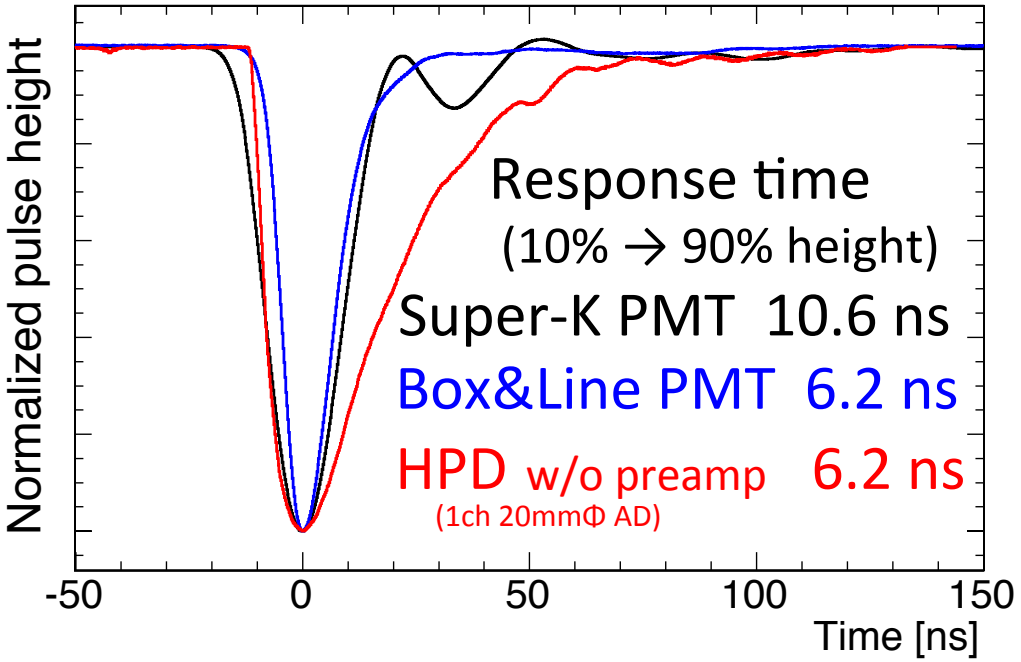




Large junction capacitance reduced from 800pF to 400pF by R&D.

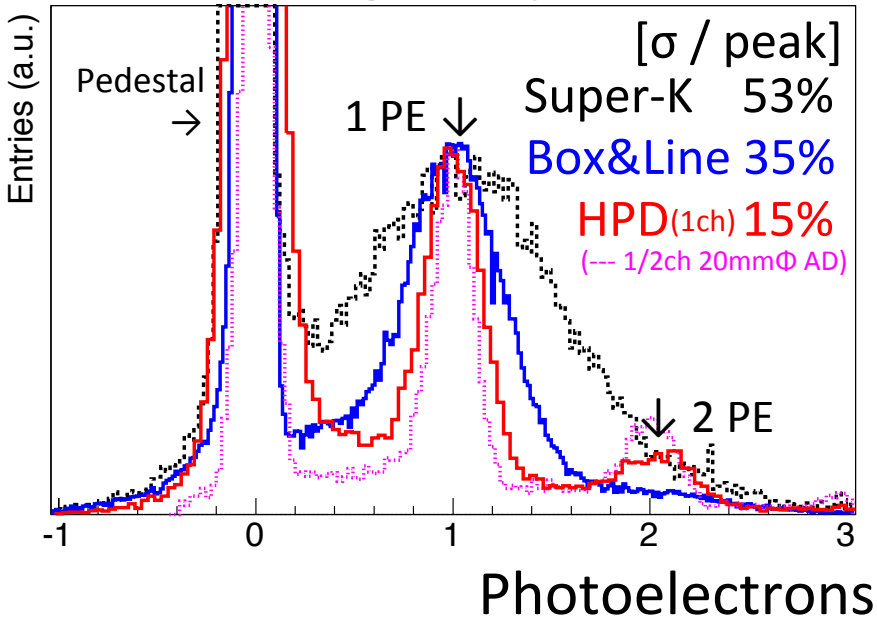




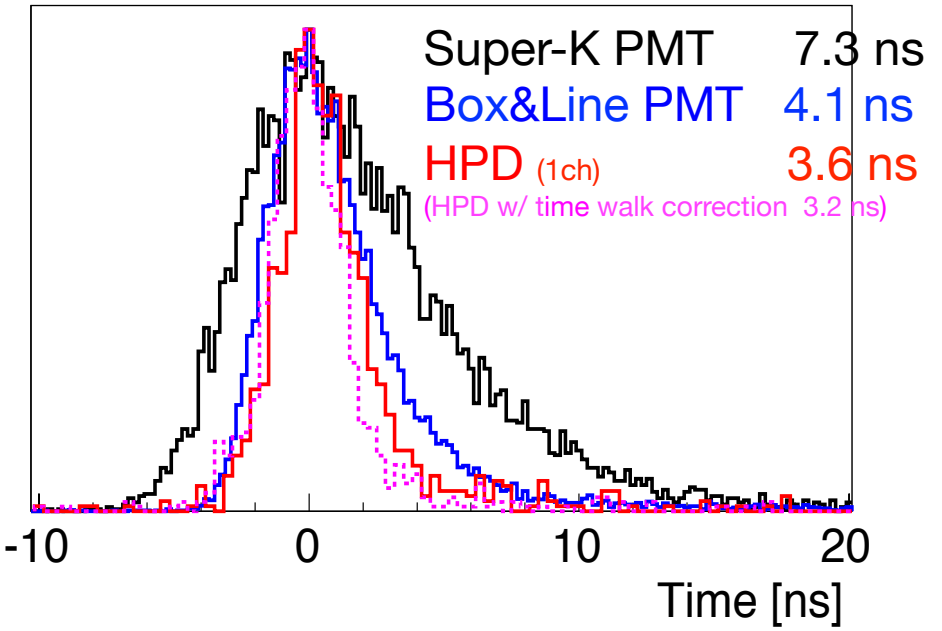


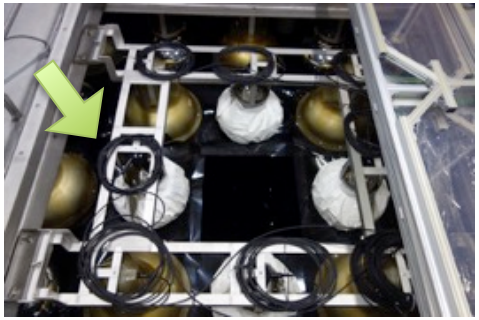
HPD performance and test

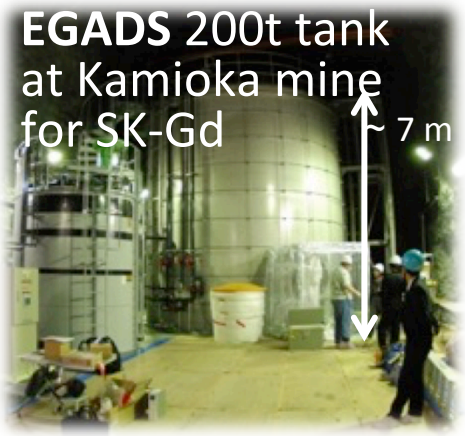
Single PE peak



Single PE transit time spread FWHM





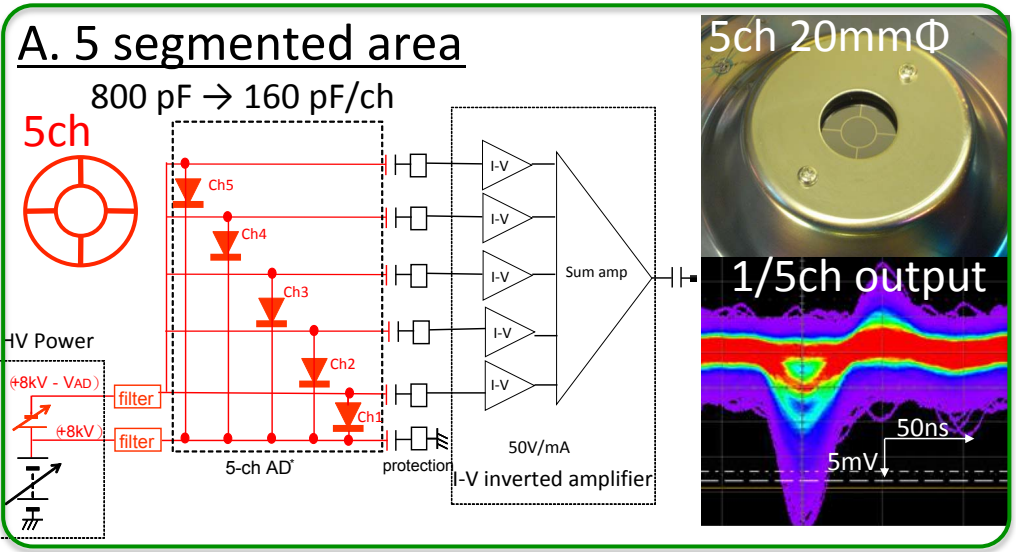


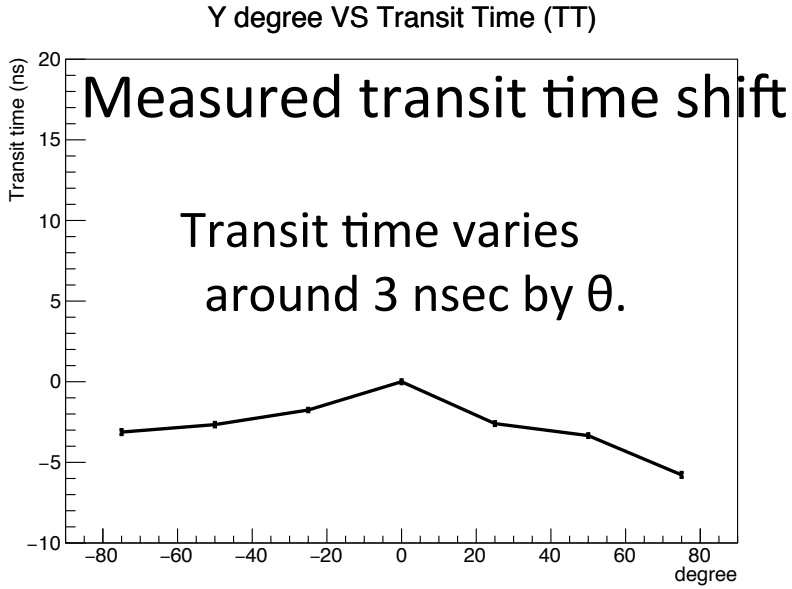
Installed the 20-inch HPD in late 2017.
(8 8-inch HPDs were already installed in 2013.)

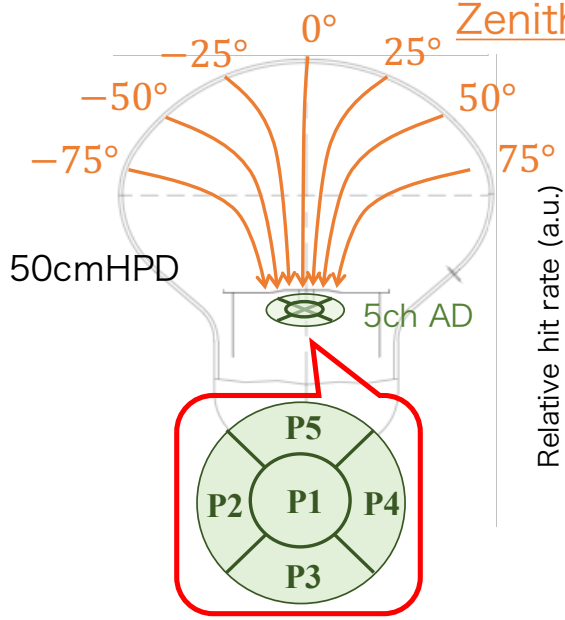
5 multi-ch readout in single 20" HPD

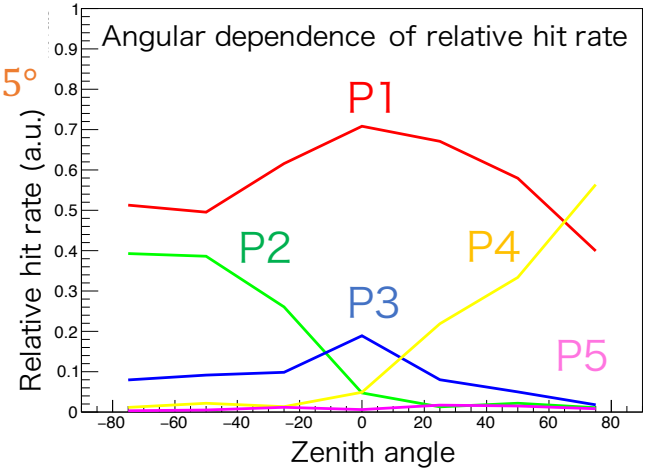
A. 5 segmented area

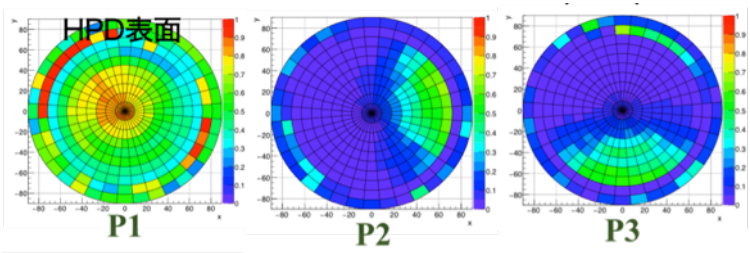
800 pF → 160 pF/ch









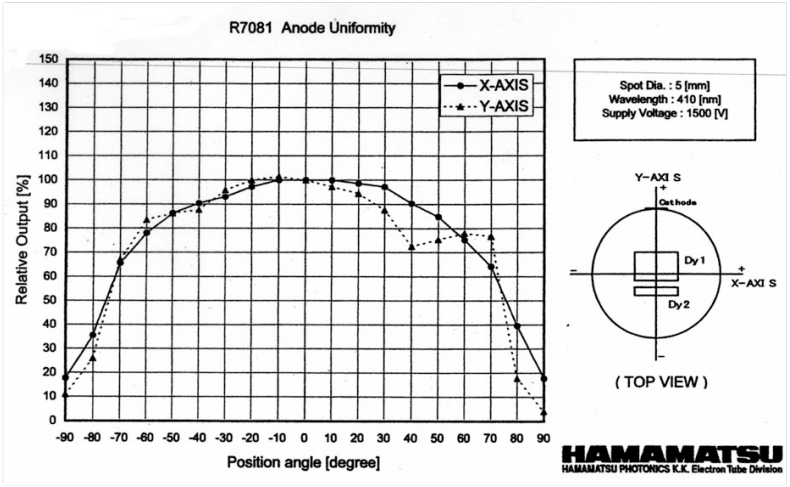


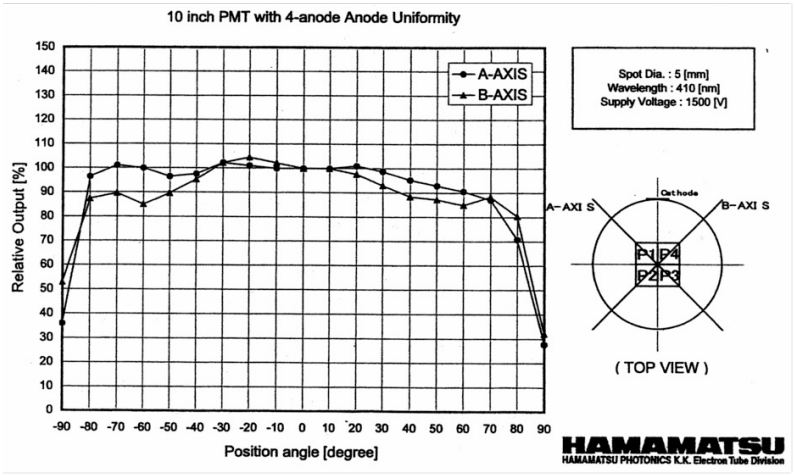
Possible improvement of position reconstruction using timing shift and multi-channel readout

4 multi-ch readout in single 10" PMT

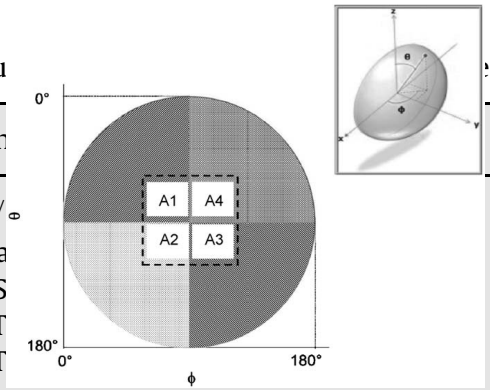
NIM A 605 (2009) 293-300

10-inch Hamamatsu R7081 with 4 separate dynode with common HV.

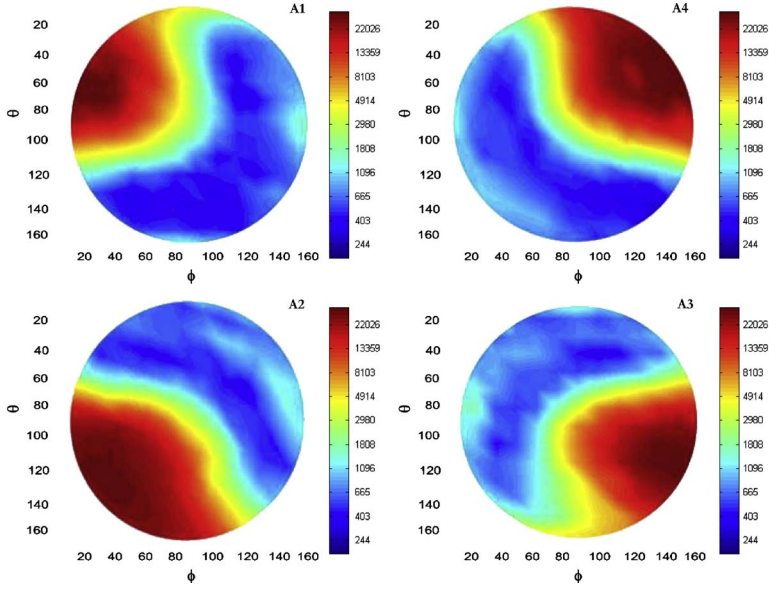




Su …er properties at a HV of 1550 V.



An	A2	A3	A4
P/	3.09	2.95	2.75
Ga	5.4	5.0	3.9
RS	30.6	37.3	35.2
TT	106	106	105
TT	4.0	3.5	4.2



Possible position/direction sensitive detection in a single sensor

Multi-PMT Module

- Many digital optical modules were developed for deep sea / south pole experiments.
- Combination of small sensors works as a large aperture photodetector unit.

NEVOD

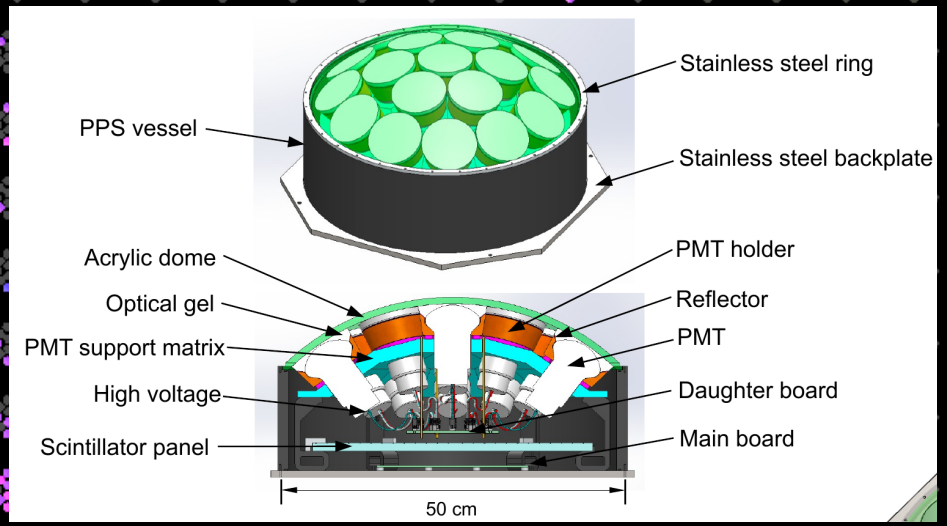
Russian PMTs FEU-49,
FEU-125 (now, FEU-200)

IceCube-Gen2 (24ch)

KM3NeT (31ch)

Multi-PMT for Hyper-K and IWCD

Intermediate Water Cherenkov Detector



Summary and Prospect

- Various large aperture photodetectors are being considered and being ready for coming neutrino experiments.
- Other possible ways to enhance photons
  - Mirror
  - Wavelength shifter
  - Photon trapping
- Key for next generation beyond current running projects
  - Low cost and easy mass production
  - High pressure tolerance and long-term stability
  - There is a room to improve photo-detection more.