PMT at JUNO

Jun Cao
Institute of High Energy Physics

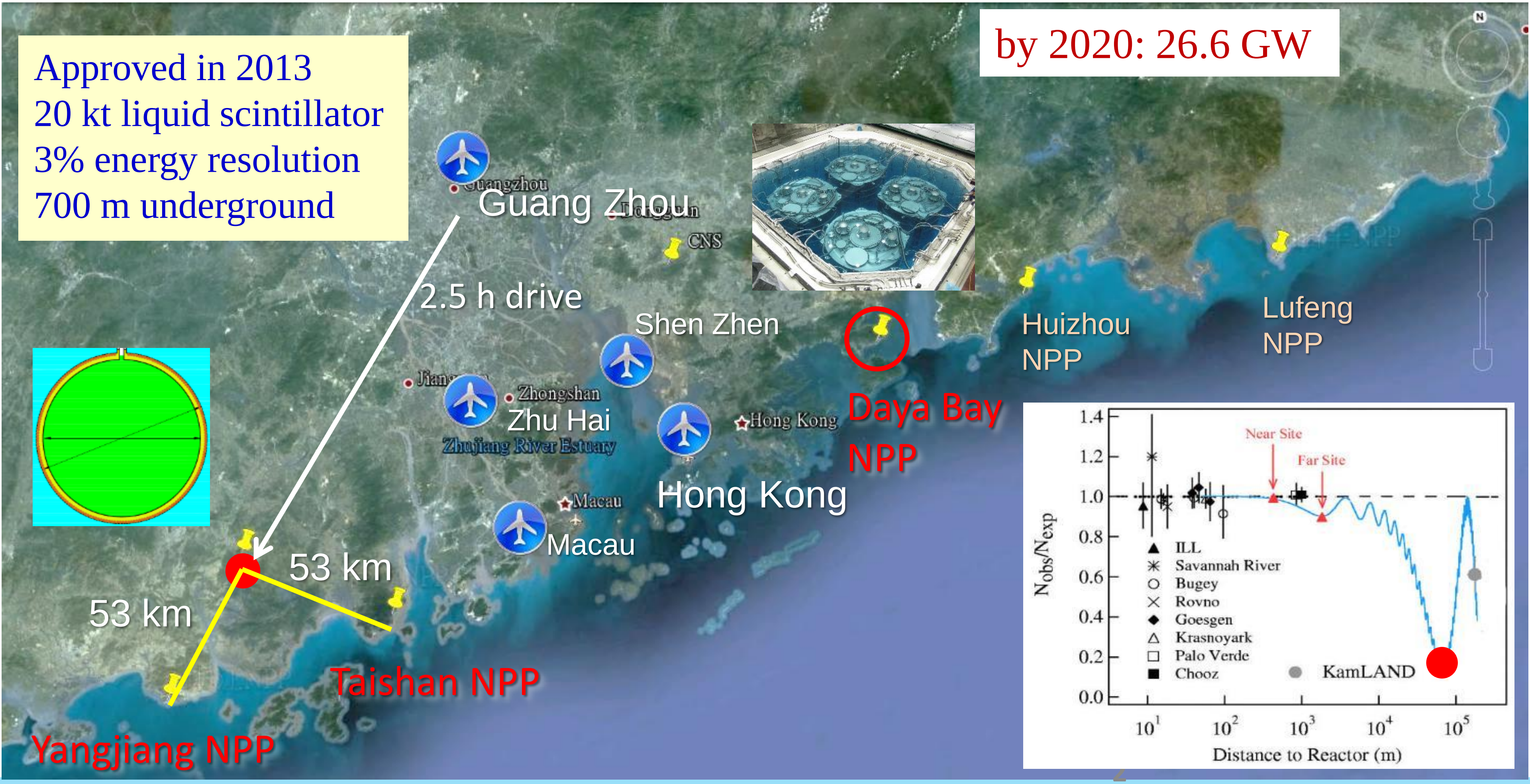
Hyper-K open meeting, Queen Mary University of London, 10-11 July 2016

JUNO Experiment

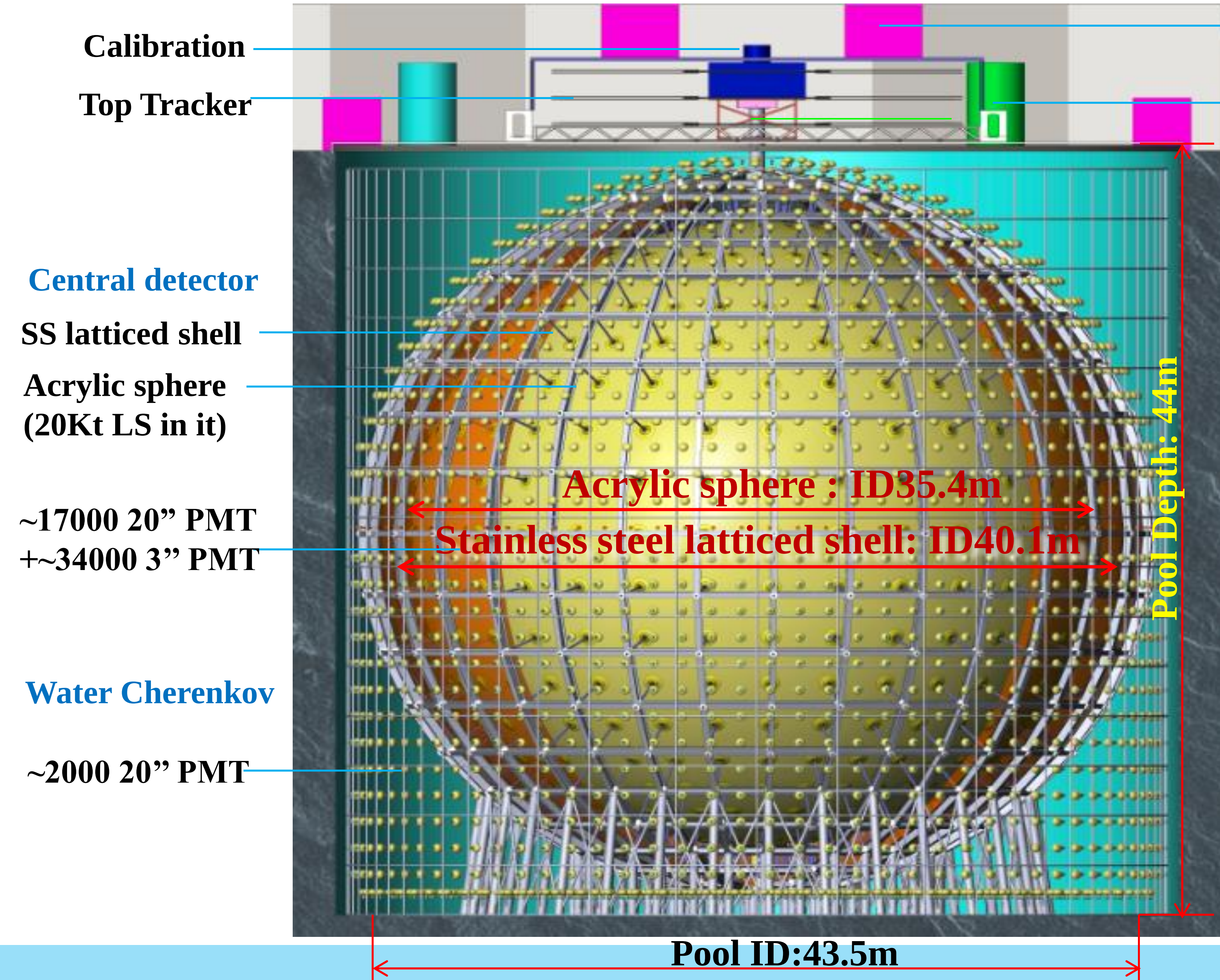
NPP	Daya Bay	Huizhou	Lufeng	Yangjiang	Taishan
Status	Operational	Planned	Planned	Under construction	Under construction
Power	17.4 GW	17.4 GW	17.4 GW	17.4 GW	18.4 GW

Approved in 2013
20 kt liquid scintillator
3% energy resolution
700 m underground

by 2020: 26.6 GW



JUNO Detector

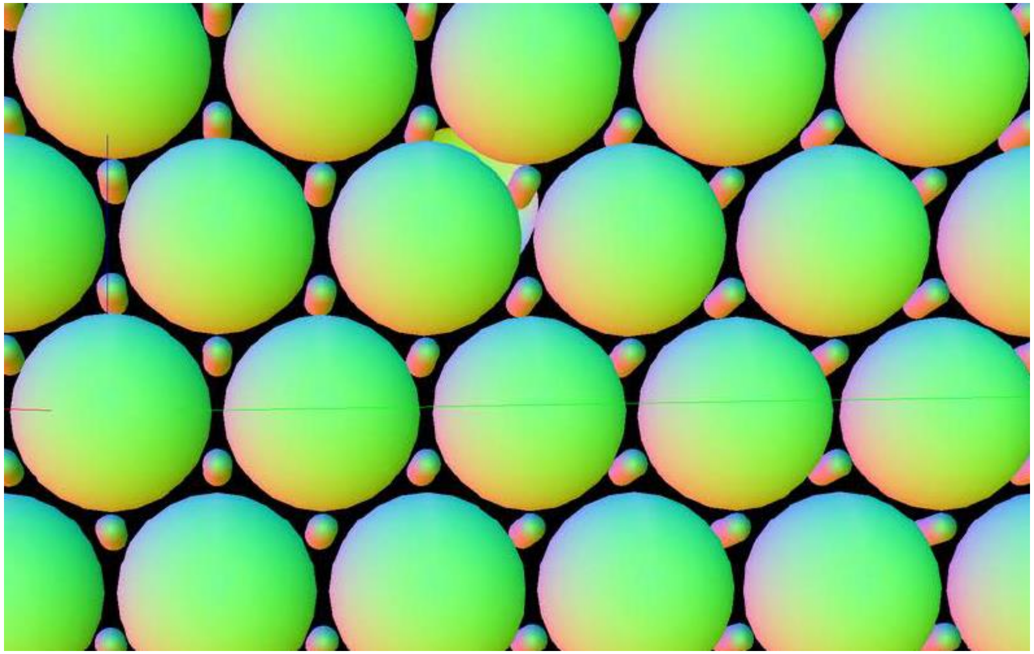


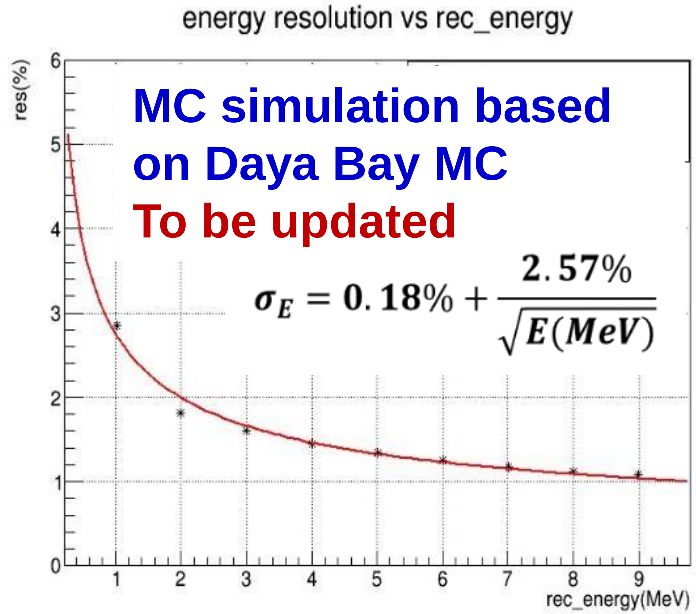
Acrylic Sphere:
ID: 35.4m
Thickness:120mm

SSLS:
ID: 40.1m
OD: 41.1m

Water pool
ID: 43.5m
Height: 44m
Water Depth:
43.5m

Major Challenge: Photoelectron Yield



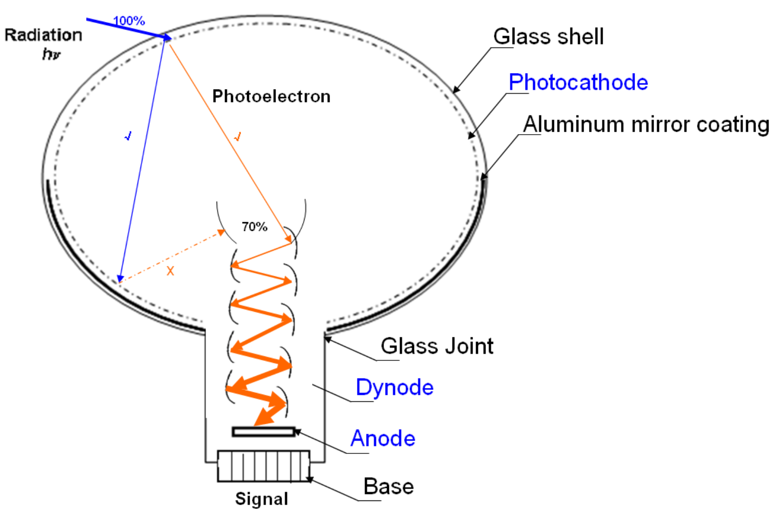


- Maximum photocathode coverage
- 36 000 3-inch PMTs for double-calorimeter

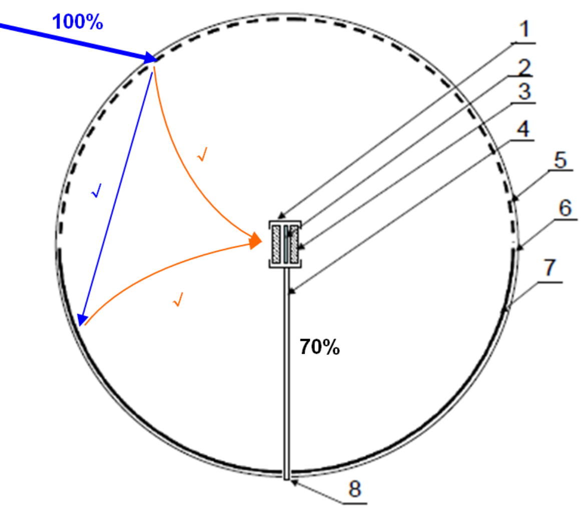
- 77% photocathode coverage
- PMT peak QE: 35%
- Attenuation length of 20 m
  ➔ abs. 60 m + Rayl. scatt. 30m

	KamLAND	BOREXINO	JUNO
LS mass	1 kt	0.5 kt	20 kt
Energy Resolution	$6\%/\sqrt{E}$	$5\%/\sqrt{E}$	$3\%/\sqrt{E}$
Light yield	250 p.e./MeV	511 p.e./MeV	1200 p.e./MeV

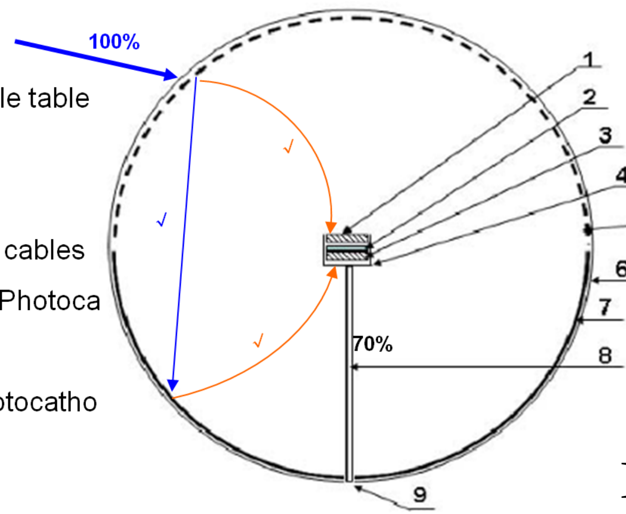
Motivation of the MCP-PMT



- **Started PMT R&D in 2008, chose MCP-PMT in 2009**
- **Optimize for p.e., with large effective area and large detection efficiency**
- **Detection Efficiency (DE) = QE @410nm × Collection Efficiency (CE)**
  - ⇨ **Small light blocking enable reflection photocathode**
- **Simpler structure, "free" MCP, etc.**



1.Insulated trestle table
2.Anode
3.MCP dodule
4.Bracket of the cables
5.Transmission Photoca
6.Glass shell
7.Reflection Photocatho
8.Glass joint

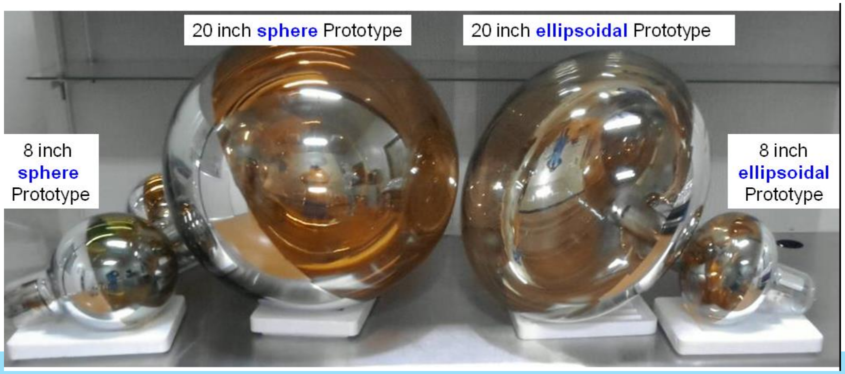


Patent by
Y.F.Wang, S.Qian,
T.C.Zhao, J.Cao
in China (2009), US,
Russia, Japan,
(EU under review)

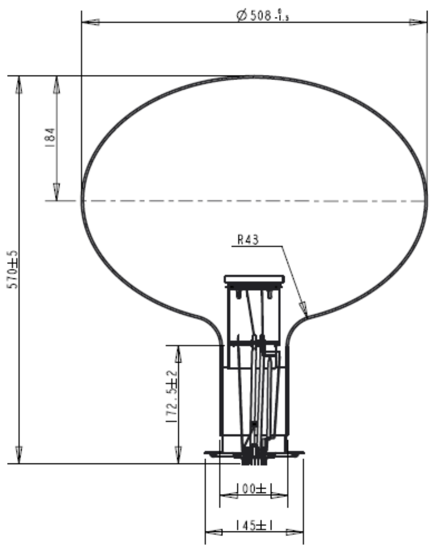
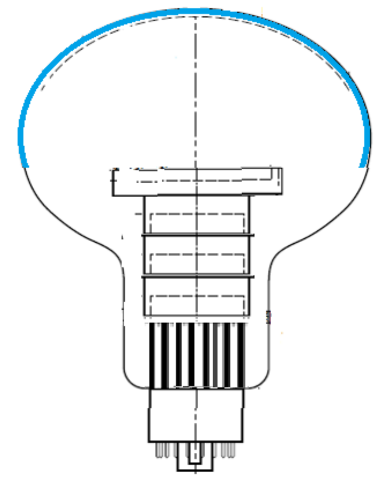
Design evolved later

Roadmap of the MCP-PMT R&D

- 2009: the design of the MCP-PMT
- 2010~2011: 5” MCP-PMT prototype without SPE
- 2012: 8” MCP-PMT prototype without SPE
- 2013: 8” prototypes with normal performance
- 2014: 1st 20” prototype, with normal performance
  - QE ~ 25%@410nm; CE ~ 60%; P/V of SPE > 2
- 2015: 20” prototypes with normal performance
  - QE ~ 26%@410nm; CE ~ 100%; P/V of SPE > 3
- **2016: High QE R&D, Production Line (1000 PMT prod.)**
- **2017~2019: Mass Production for JUNO**



Characterization of Several 20-in MCP-PMTs

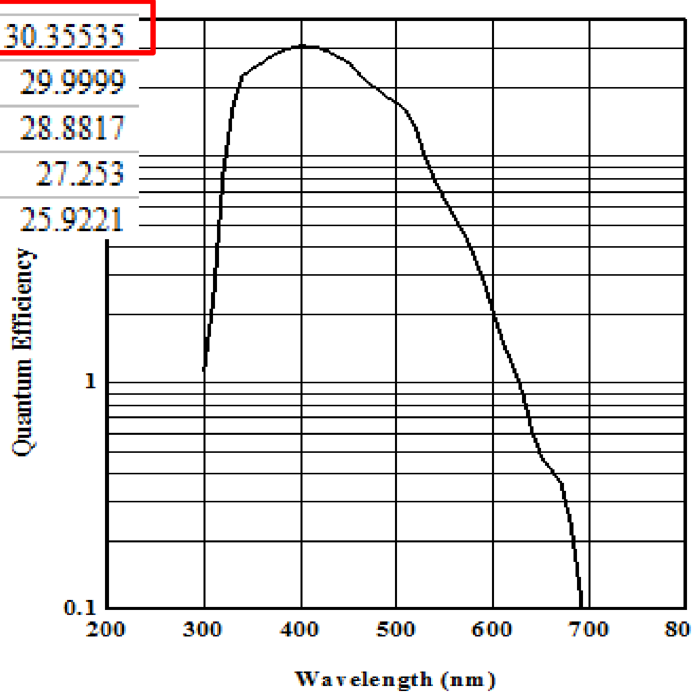
20-inch MCP-PMT Horizontal MCPs, refl. Photocathode, Ellipsoidal	20-inch Hamamatus PMT Dynode
 	 

QE of the Photocathode

20 inch Prototype	R12860	MCP-PMT
QE@410nm	~30%	~26% (transmission)

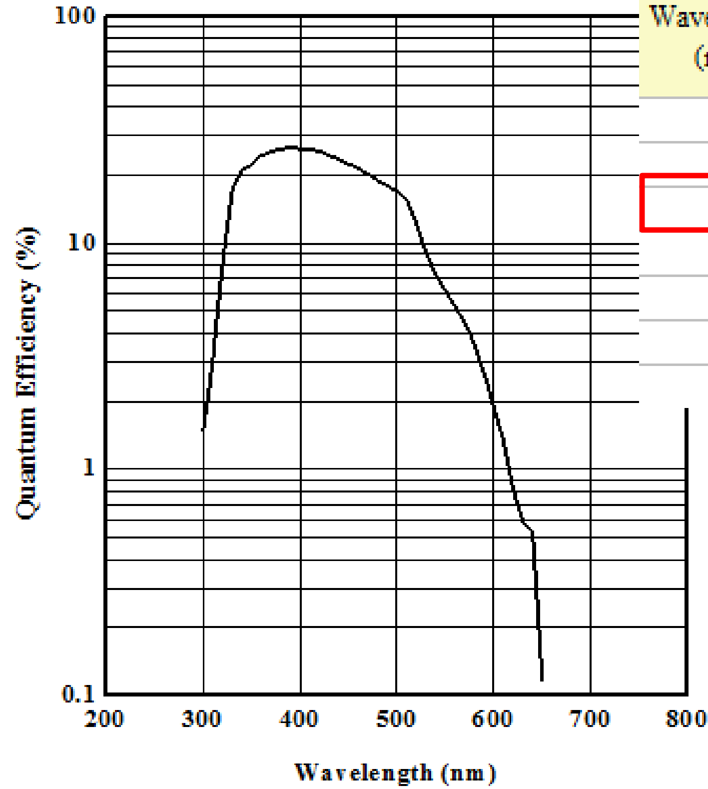
~30% (trans. + refl.)

Wavelength (nm)	QE
390	29.9283
400	30.7108
410	30.35535
420	29.9999
430	28.8817
440	27.253
450	25.9221



Hamamatsu R12860

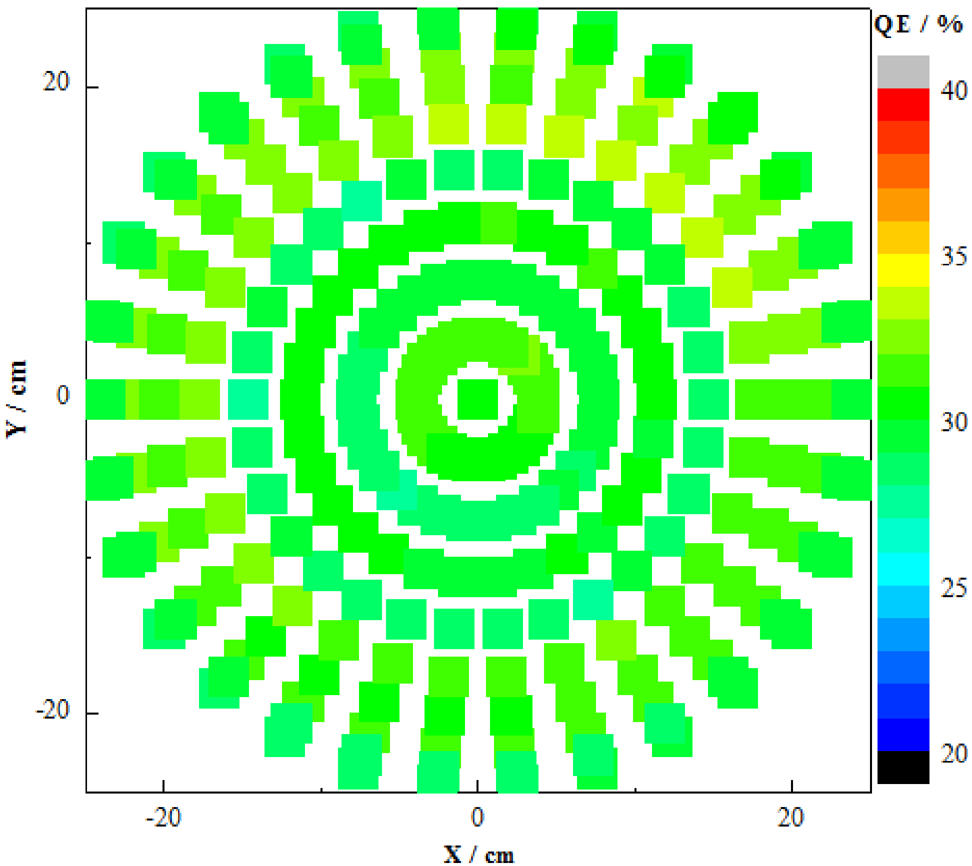
Wavelength (nm)	79#
390	26.32155
400	26.18978
410	26.058
420	25.4807
430	24.47675
440	23.4516
450	22.37645



MCP-PMT

Photocathode QE Uniformity

Hamamatsu R12860

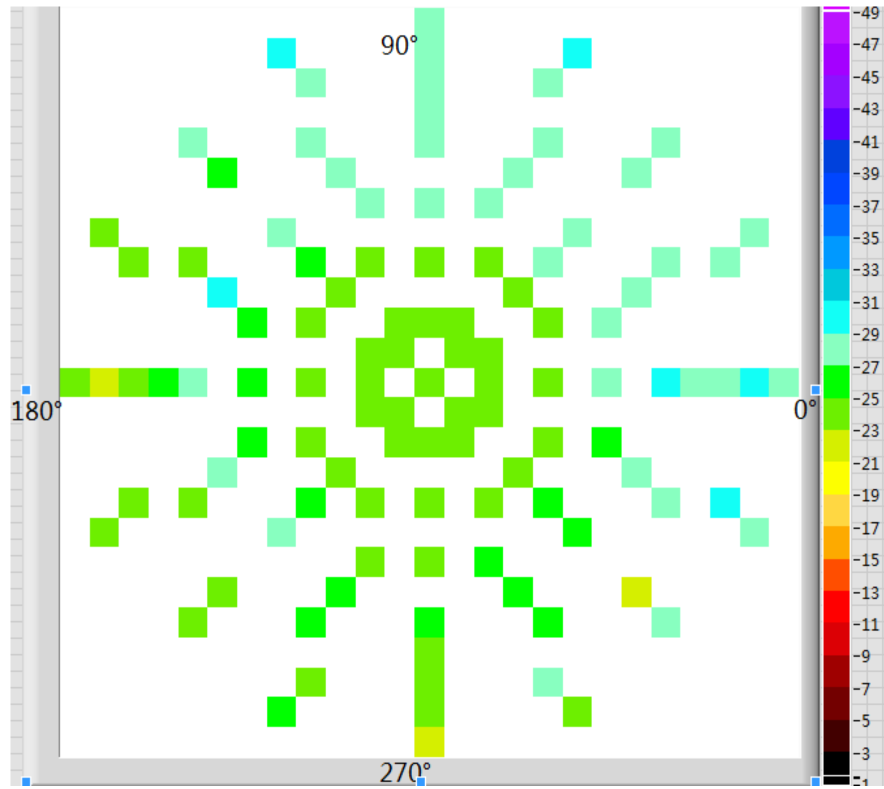


Min:27.5%

Max:33.6%

Average:30.5%

MCP-PMT

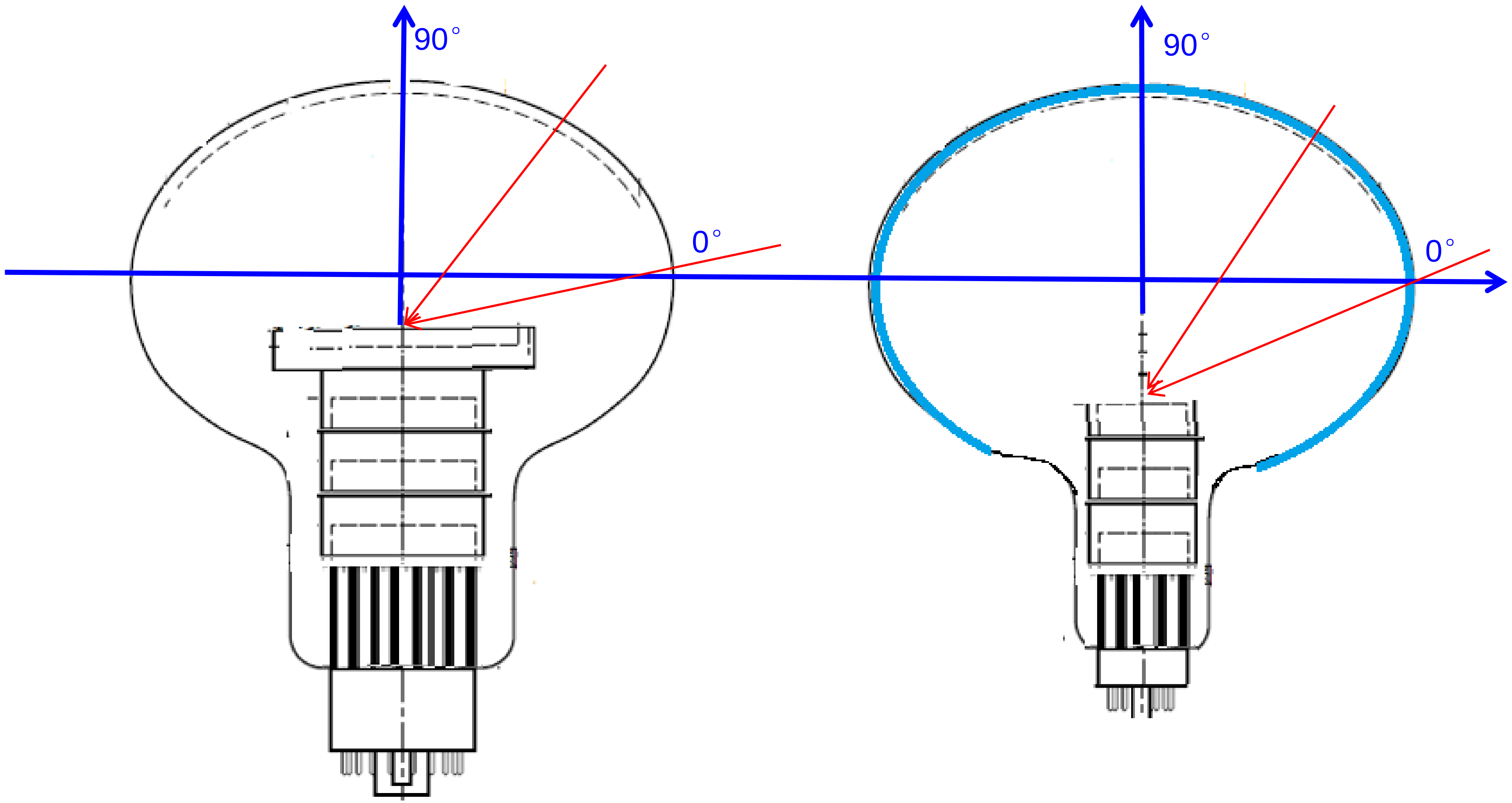


Min:24.5%

Max:29%

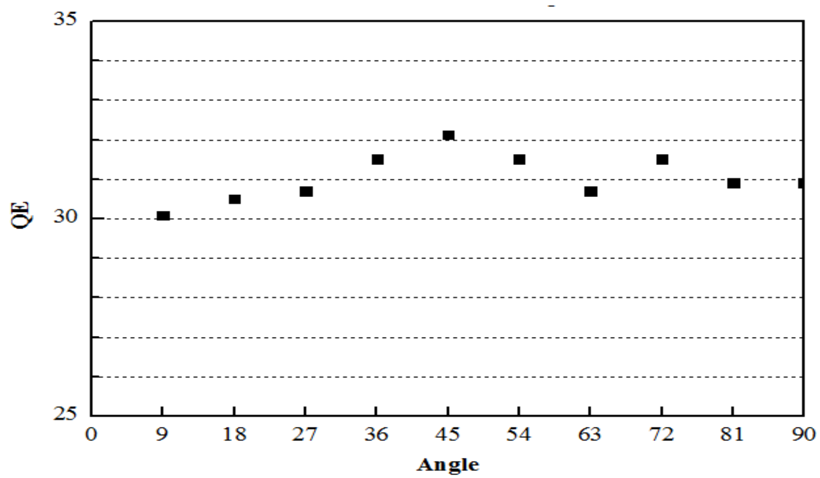
Average:26.5%

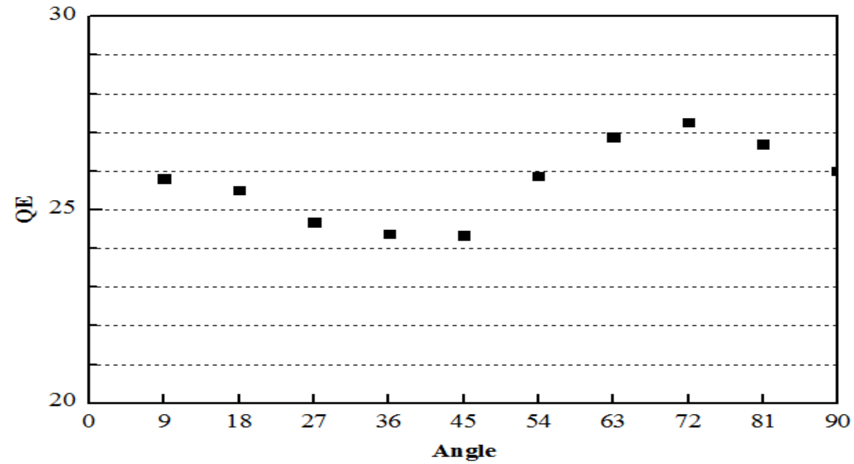
Detection Efficiency Uniformity

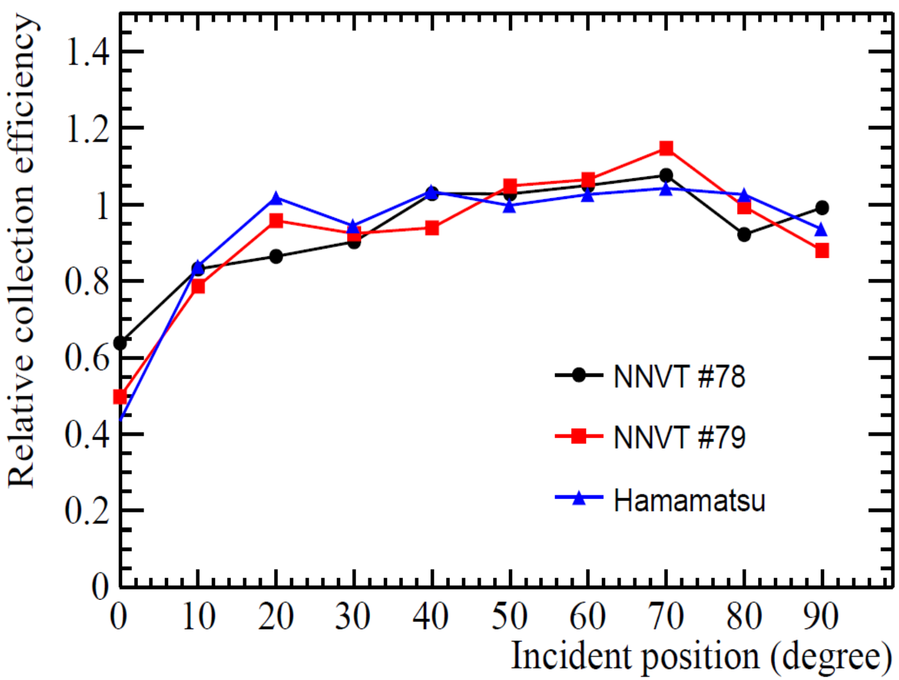


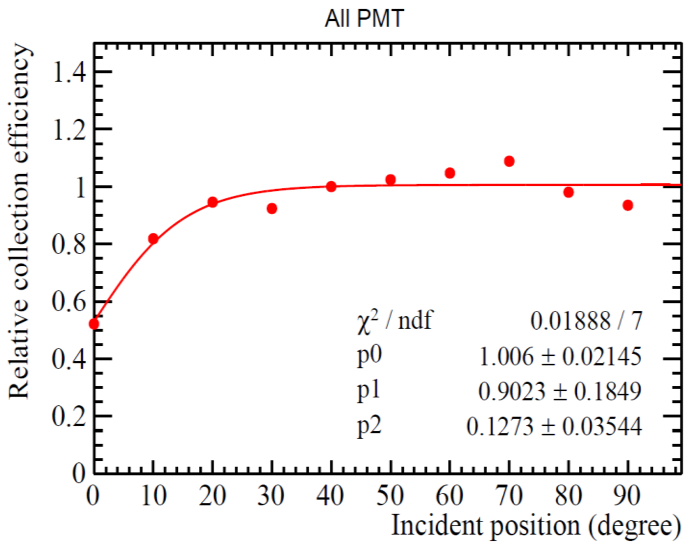
Hamamatsu R12860

MCP-PMT





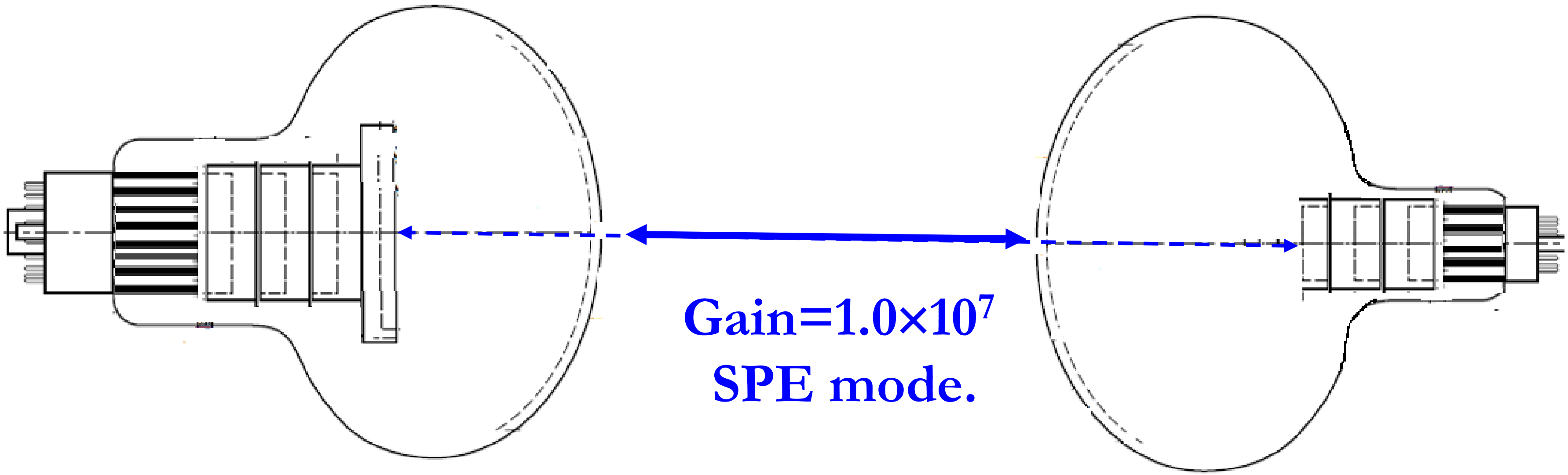




Average of 3 MCP-PMTs

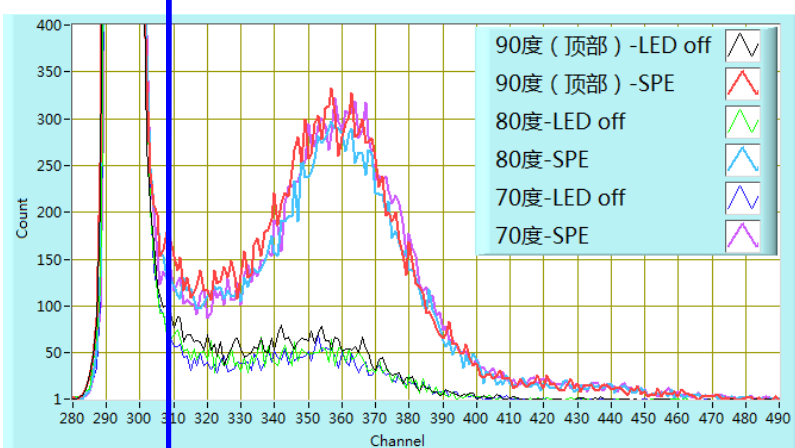
Relative detection efficiency of most area higher than 80% for both the two tubes

Relative Detection Efficiency

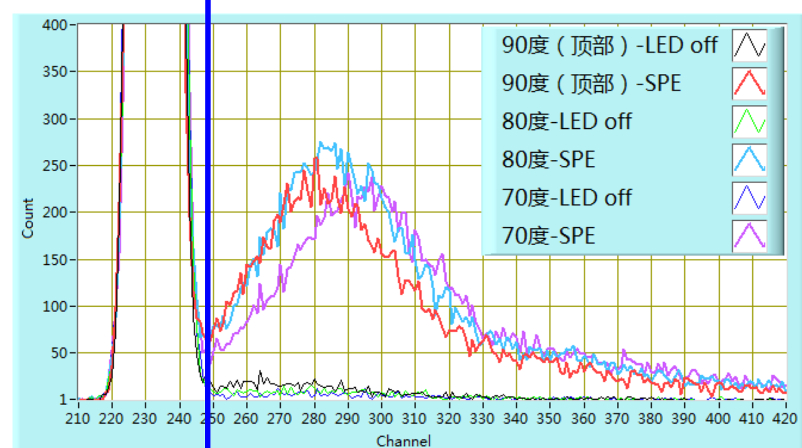


Hamamatsu R12860

MCP-PMT

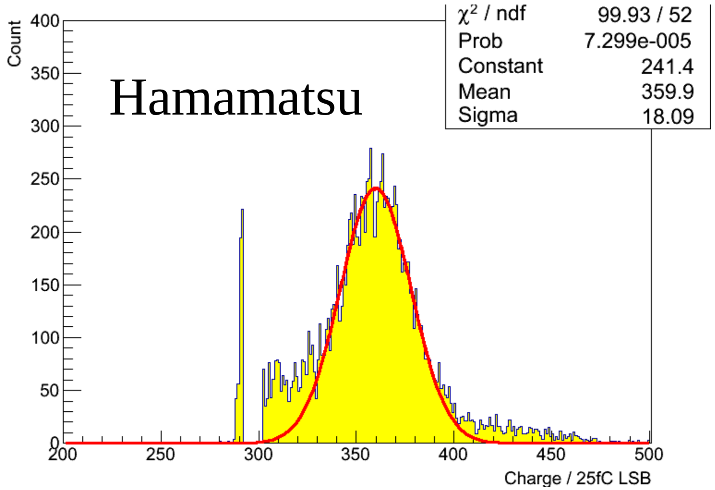


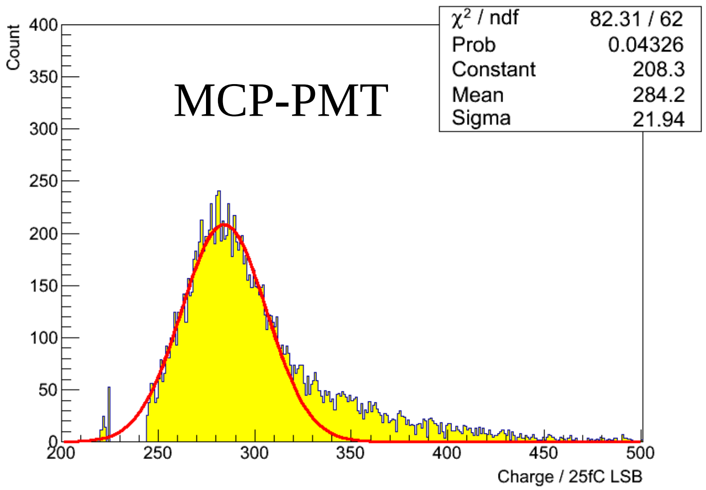
cut@310



cut@248

Relative Detection Efficiency



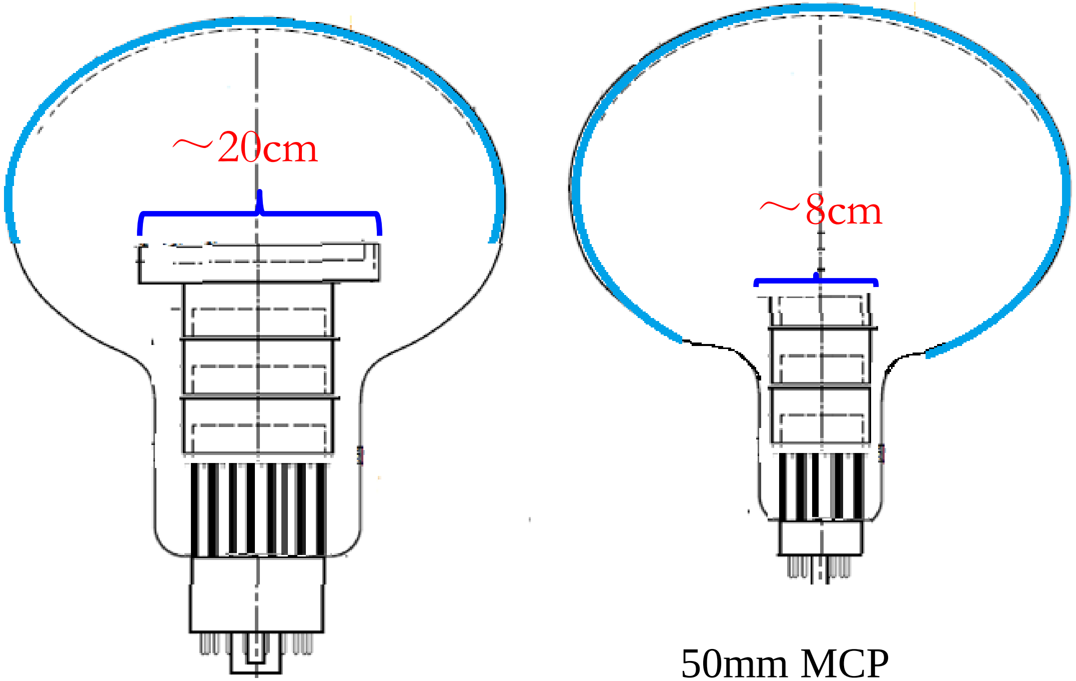


	SPE count	Total count	SPE ratio
90°	10795	108878	0.099
80°	10222	110038	0.093
70°	11479	110546	0.104

	SPE count	Total count	SPE ratio
90°	10888	109384	0.099
80°	13145	110872	0.119
70°	12406	111351	0.111

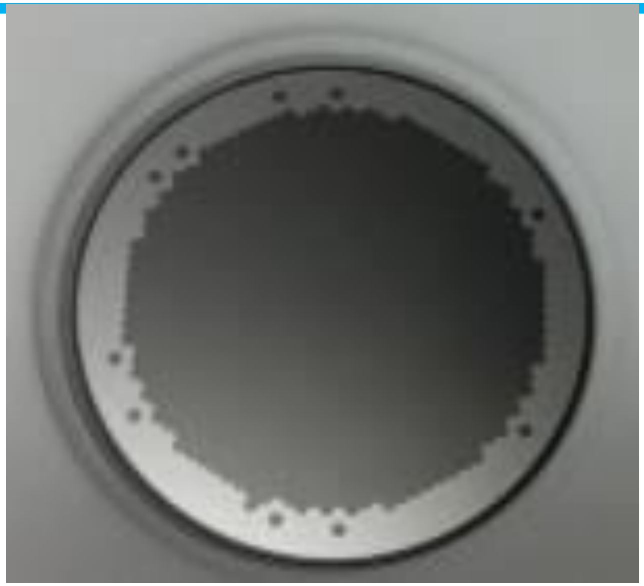
angle	MCP/**R12860** Ratio	**Average**
90	1.004	
80	1.276	
70	1.073	**1.117**

MCP: Large area PC (Rrf. + Tran.)



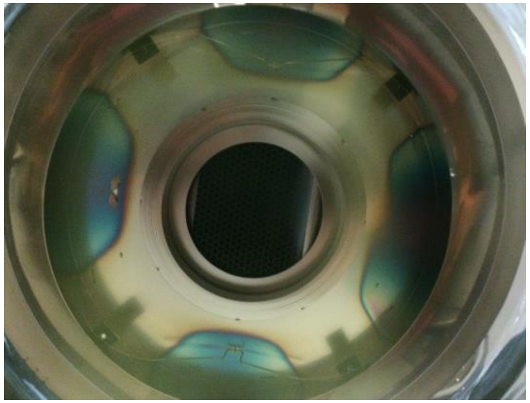
50mm MCP

MCP: Special MCP for CE~100%



	Relativity DE	QE
Dynode-PMT	100%	30%
MCP-PMT	110%	26%

Dynode: A mesh covering the dynode

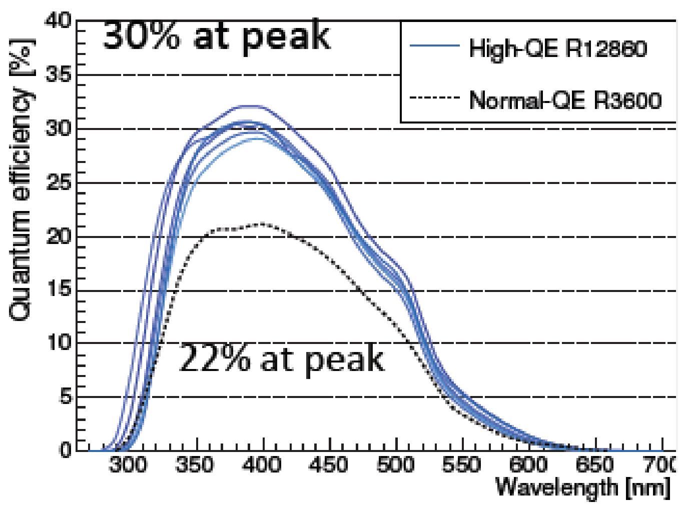


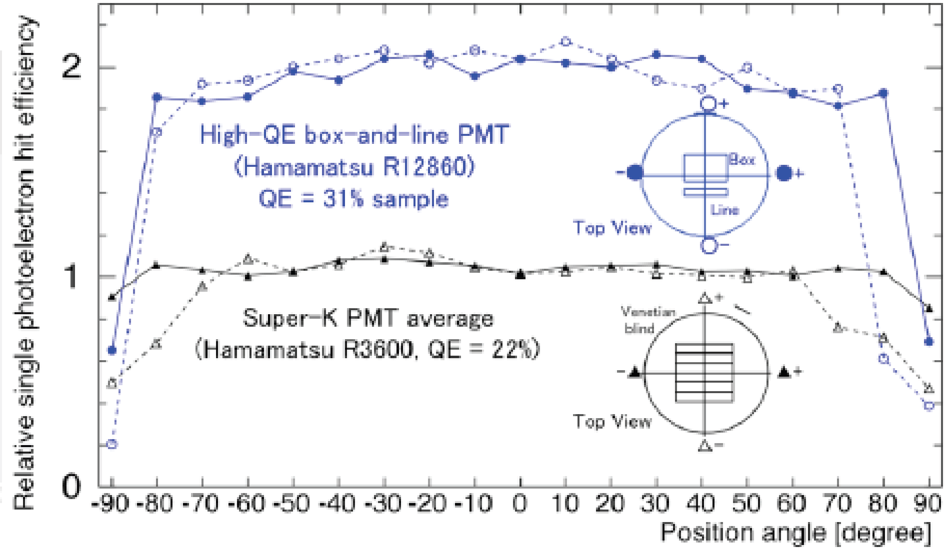
- **Reflection contribution**
- **Higher collection efficiency**

Hamamatsu 20-in, old vs new

High QE of Box&Line PMT

Total detection efficiency
QE x CE measured by hit counting efficiency

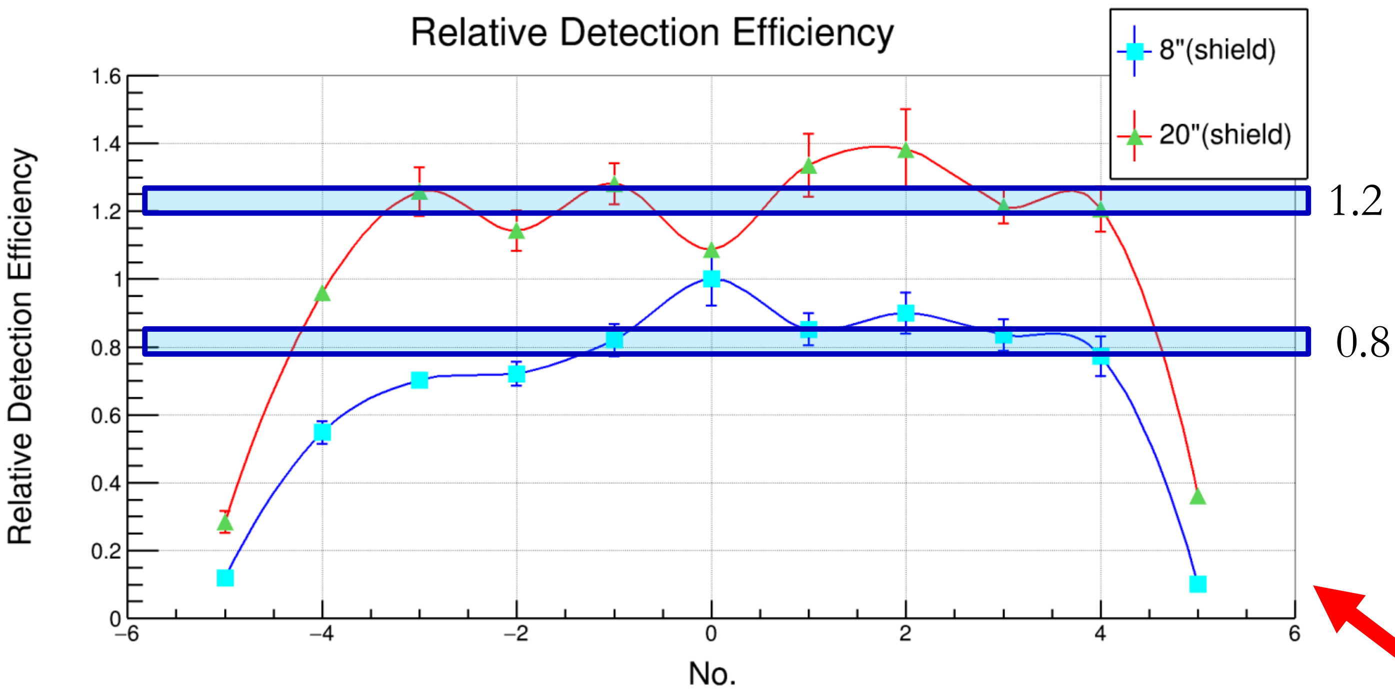


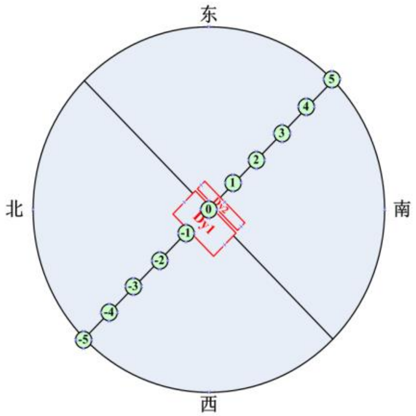


- High QE and CE were confirmed in measurements.
  - QE 22% → 30%
  - CE 67% → 95% (Calculated in Φ46cm)

Hamamatsu data	Tube	QE	CE	DE(100%)
	20-in (old)	22%	67%	14.7%
	20-in (new)	30%	95%	28.5%

Daya Bay 8-in (R5912) vs 20-in R12860

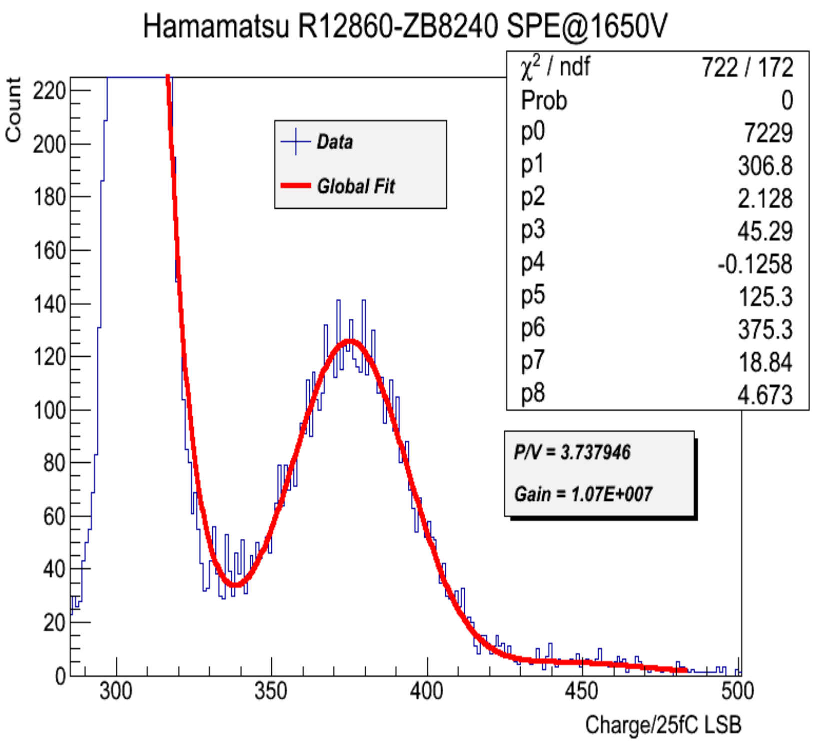




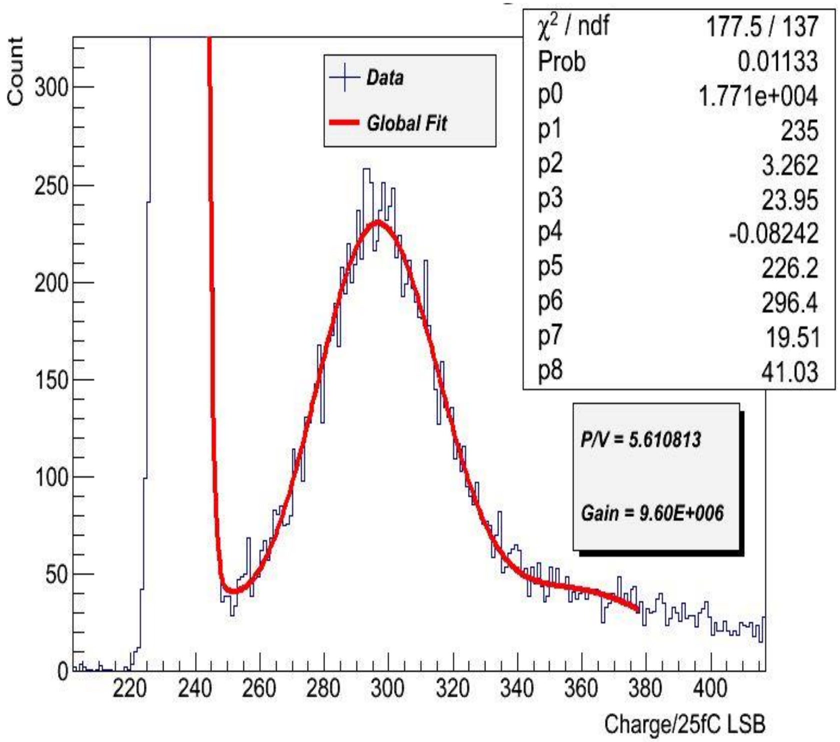
Tube	QE	CE	DE（100%）	Projected relative DE	Measured relative DE
R5912	25%	70%	17.5%	1	1
R12860	30%	90%	27%	1.54	1.5

SPE of the Prototype

	HV	Gain	P/V
R12860	1650V	~1.1E7	~3.7
MCP-PMT	1930V	~9.6E6	~5.6



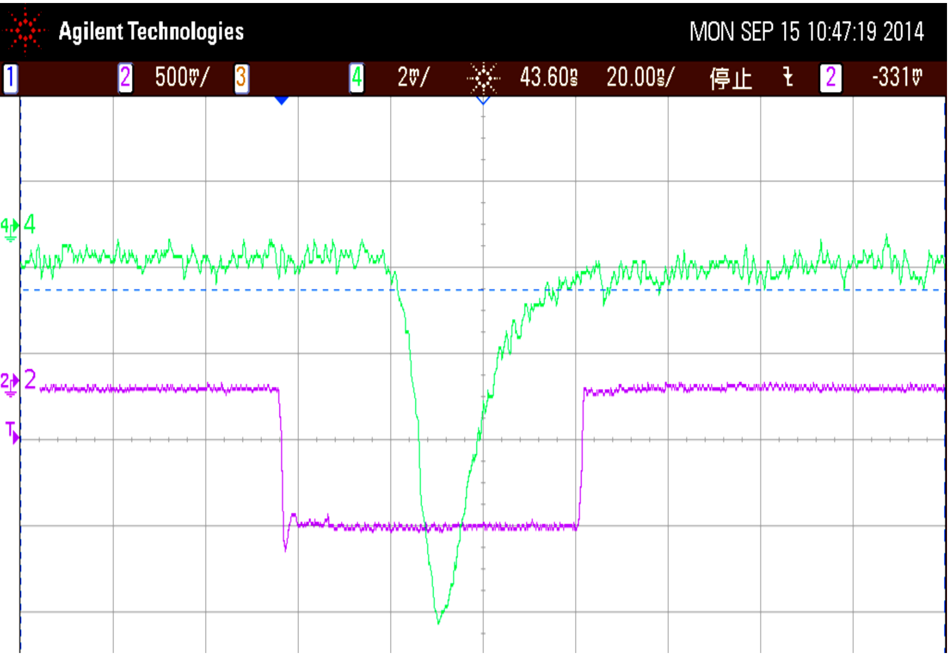
Hamamatsu R12860



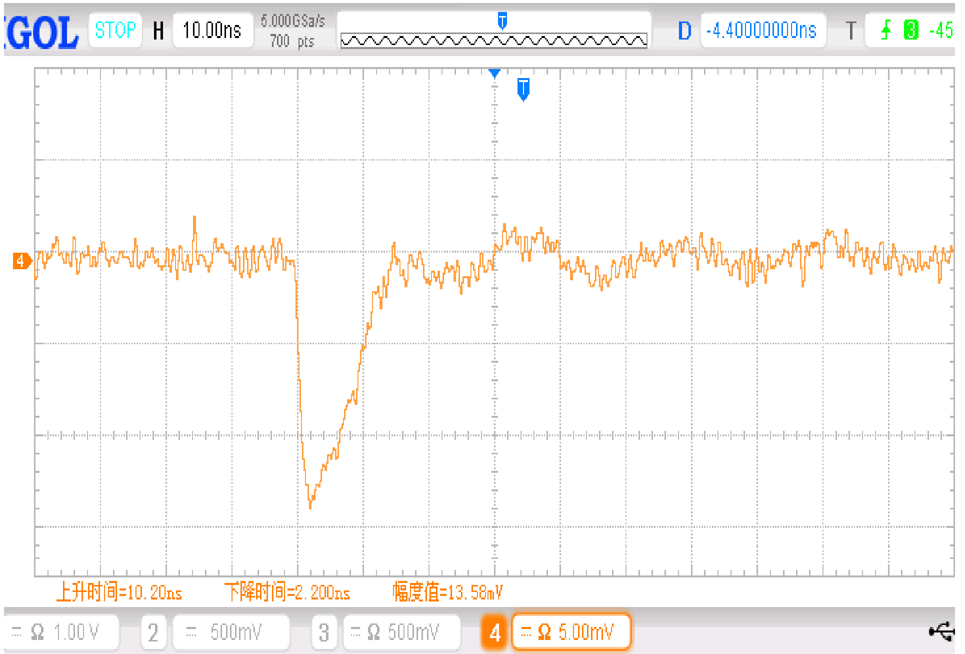
MCP-PMT

Waveform of the Prototype

	Rise Time	Fall Time
R12860	~6.7 ns	~17.7 ns
MCP-PMT	~2.2 ns	~10.2 ns



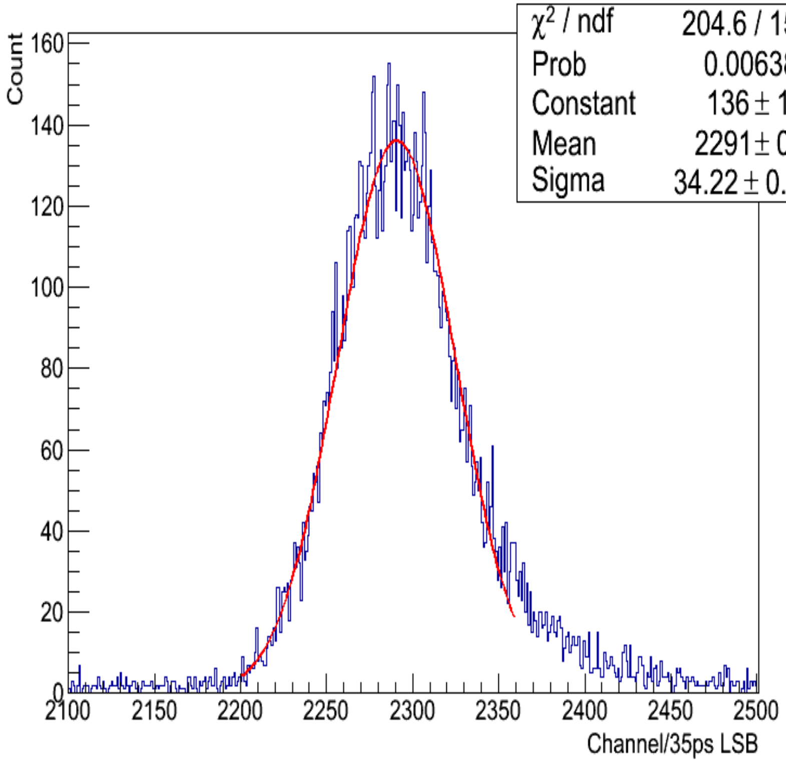
Hamamatsu R12860



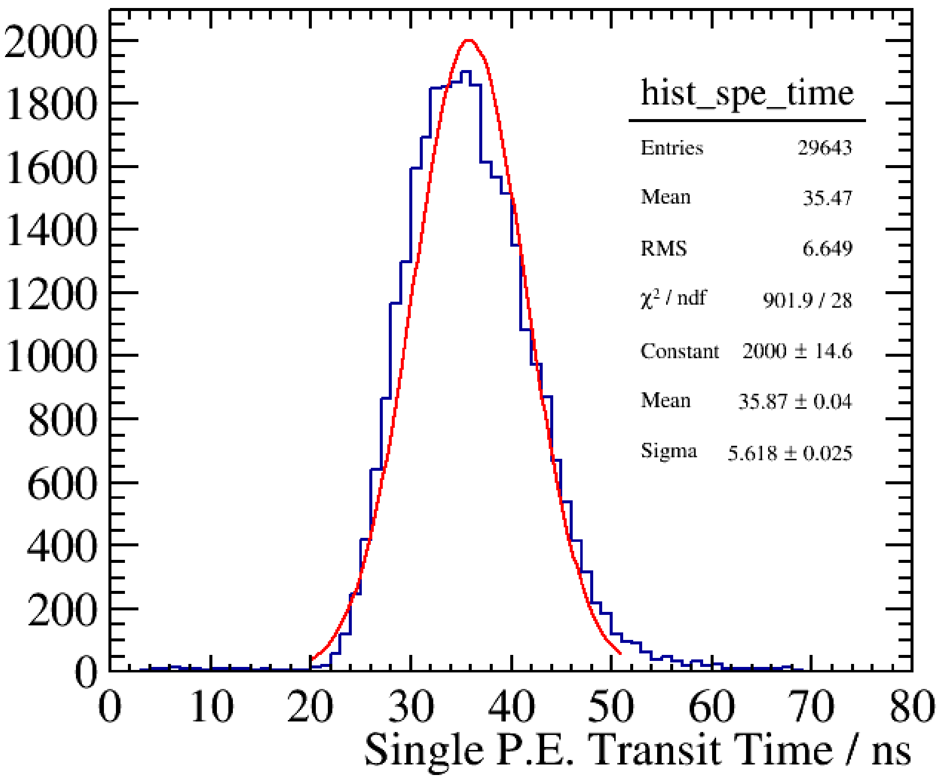
MCP-PMT

TTS of the Prototype

	HV	Gain	TTS @ top center
R12860	1650V	~1.1E7	~2.8 ns
MCP-PMT	1930V	~9.6E6	~12 ns



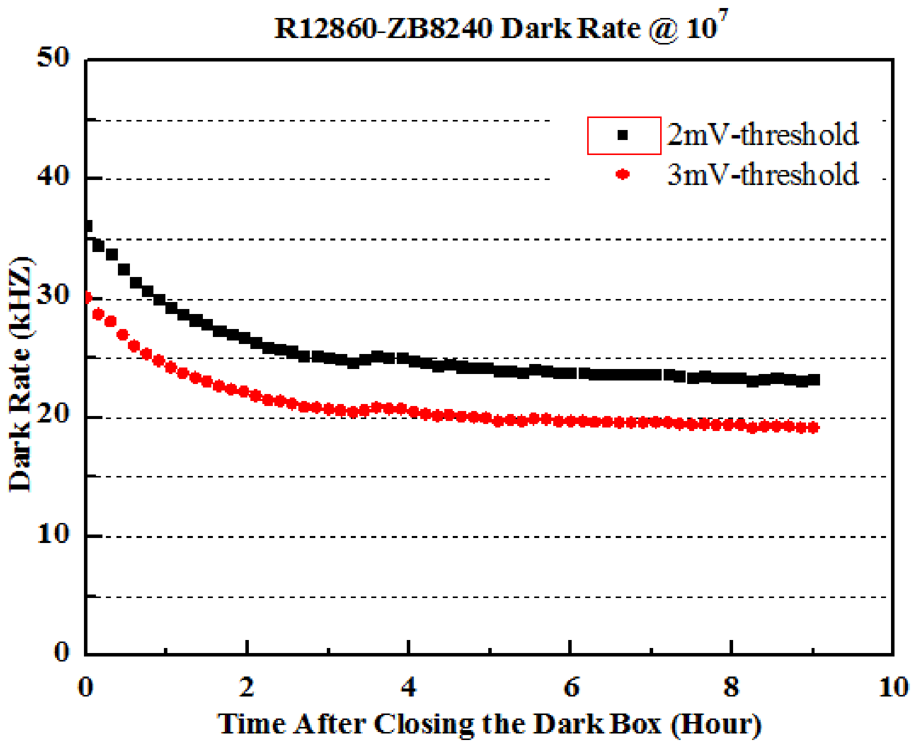
Hamamatsu R12860



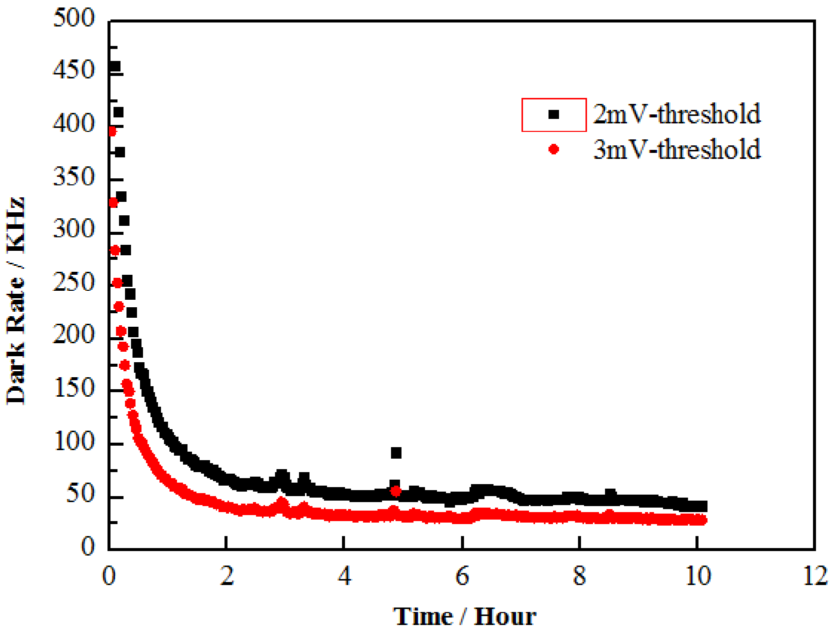
MCP-PMT

Dark count of the Prototype

	HV	Gain	Dark rate @ 0.25PE
R12860	1650V	~1.1E7	~25 kHz
MCP-PMT	1930V	~9.6E6	~30 kHz



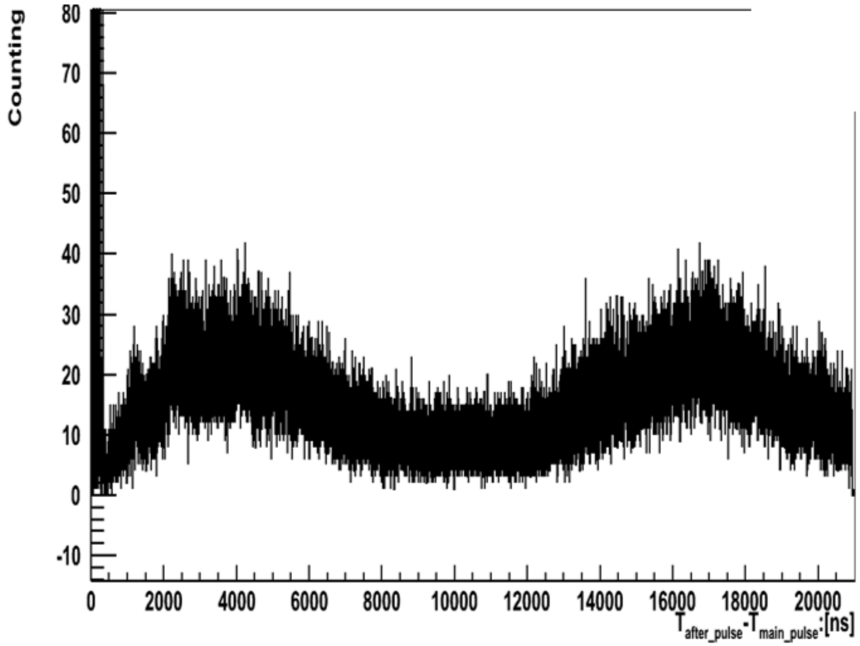
Hamamatsu R12860



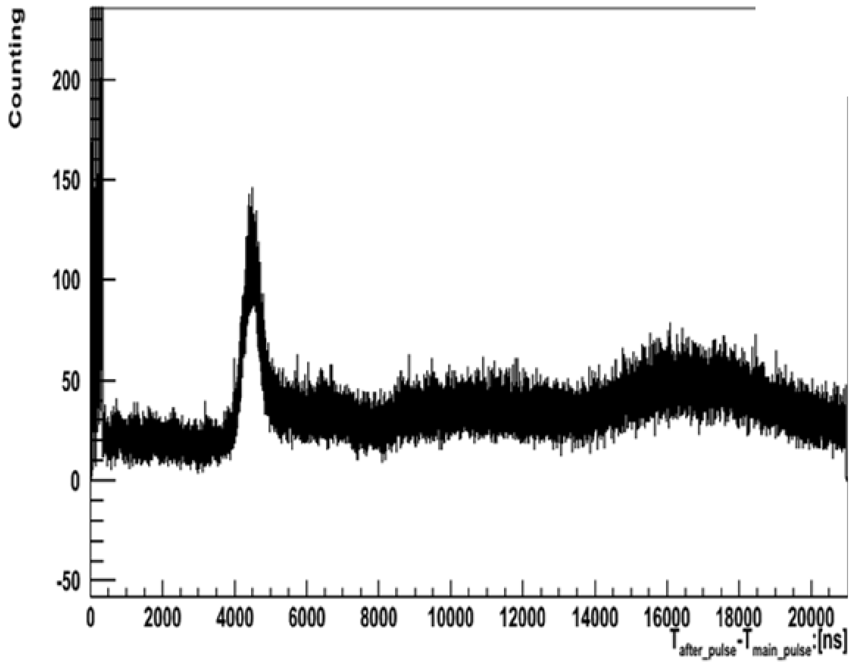
MCP-PMT

After Pulse Rate of the Prototype

	Time distribution	After Pulse Rate
R12860	4 μs, 17 μs	10%
MCP-PMT	4.5 μs	2.5%



Hamamatsu R12860



MCP-PMT

Performance of the 20-inch PMTs

Characteristics	unit	MCP-PMT	R12860 (Hamamatsu)
Electron Multiplier	--	**MCP**	Dynode
Photocathode mode	--	**Refl. + trans.**	transmission
Quantum Efficiency（400nm）	%	**26 (T), 30 (T+R)**	**30 (T)**
Relativity Detection Efficiency	%	**~ 110%**	**100%**
P/V of SPE		**＞3**	**＞3**
TTS on the top point	ns	**~12**	**~3**
Rise time/ Fall time	ns	**R~2, F~10**	**R~7, F~17**
Anode Dark Count	Hz	**~30K**	**~30K**
After Pulse Time distribution	µs	**4.5**	4, 17
After Pulse Rate	%	**3**	10
Glass	--	**Low-Potassium Glass**	HARIO-32

Specification in the Contracts

- Evaluate both the PMT characteristics' impacts on MH hierarchy and the cost.
- Finished 20" PMT bidding at end of 2015:

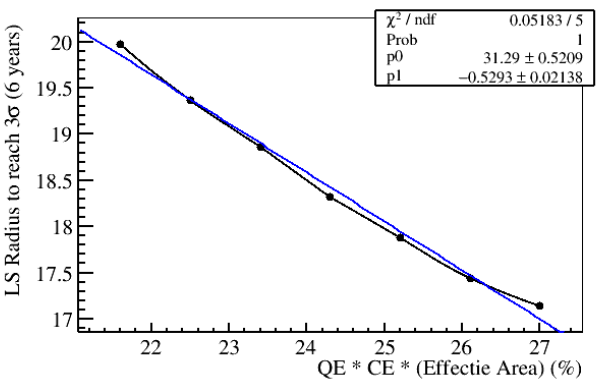
  -- 15000 MCP-PMT (NNVT)

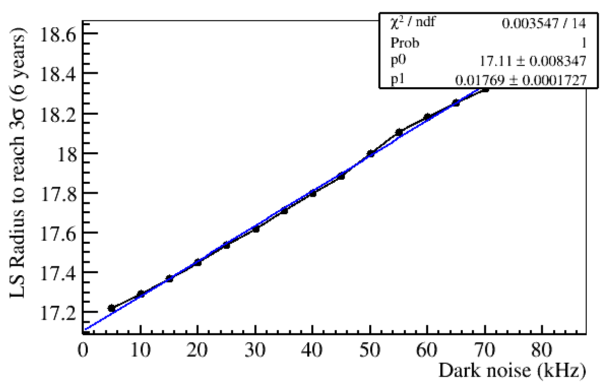
  -- 5000 Dynode-PMT (Hamamatsu)

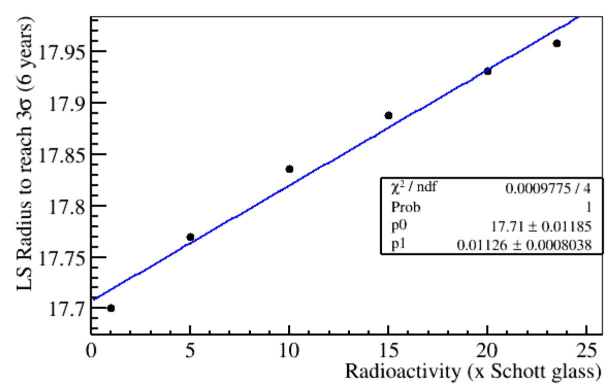
Characteristics	unit	MCP-PMT（NNVC）	R12860（Hamamatsu）
Detection Eff.(QE*CE*area)	%	27%, > 24%	27%, > 24%
P/V of SPE		3.5, > 2.8	3, > 2.5
TTS on the top point	ns	~12, < 15	2.7, < 3.5
Rise time/ Fall time	ns	R~2 , F~12	R~5, <7; F~9, <12
Anode Dark Count	Hz	20K, < 30K	10K, < 50K
After Pulse Rate	%	1, <2	10, < 15
Radioactivity of glass	ppb	238U:50 232Th:50 40K: 20	238U:400 232Th:400 40K: 40

Bidding Strategy

- **Risk + Cost**
- **Risk → multiple vendors (Hamamatsu, NNVT, HZC)**
- **Cost → fix the goal: 3σ MH determination in 6 years → compensating the PMT performance with fiducial volume → convert all specifications to cost (figure of merit)**
- **Radioactivity, dark noise, TTS, ……**







Different type of PMTs

- **Dynode-PMT- 20” from Hamamastu**
- **MCP-PMT- 20” from NNVT**

MCP-PMT- 8”

Dynode-PMT- 9” from HZC

Dynode-PMT- 8”

Summary

- Bidding started on Oct. 23, 2015, completed on Nov. 17, 2015
- No constraint on PMT type or size. E.g. 20k 20-inch PMT, or 8/9-in PMT or 3-inch PMT with equal photocathode coverage.
- 15k MCP-PMT contract signed with NNVT on Dec.16, 2015
- 5k dynode-PMT contract signed with Hamamatsu in May, 2016
- MCP-PMT: building production line, improve QE. Will start to receive PMTs from the end of 2016.
- Improvements of both the dynode-PMT (1.5x DYB) and MCP-PMT (1.6x DYB) make the 3% E resolution feasible.
- Cost is significantly reduced with multiple vendors.

Chikan town in Kaiping, near the JUNO site