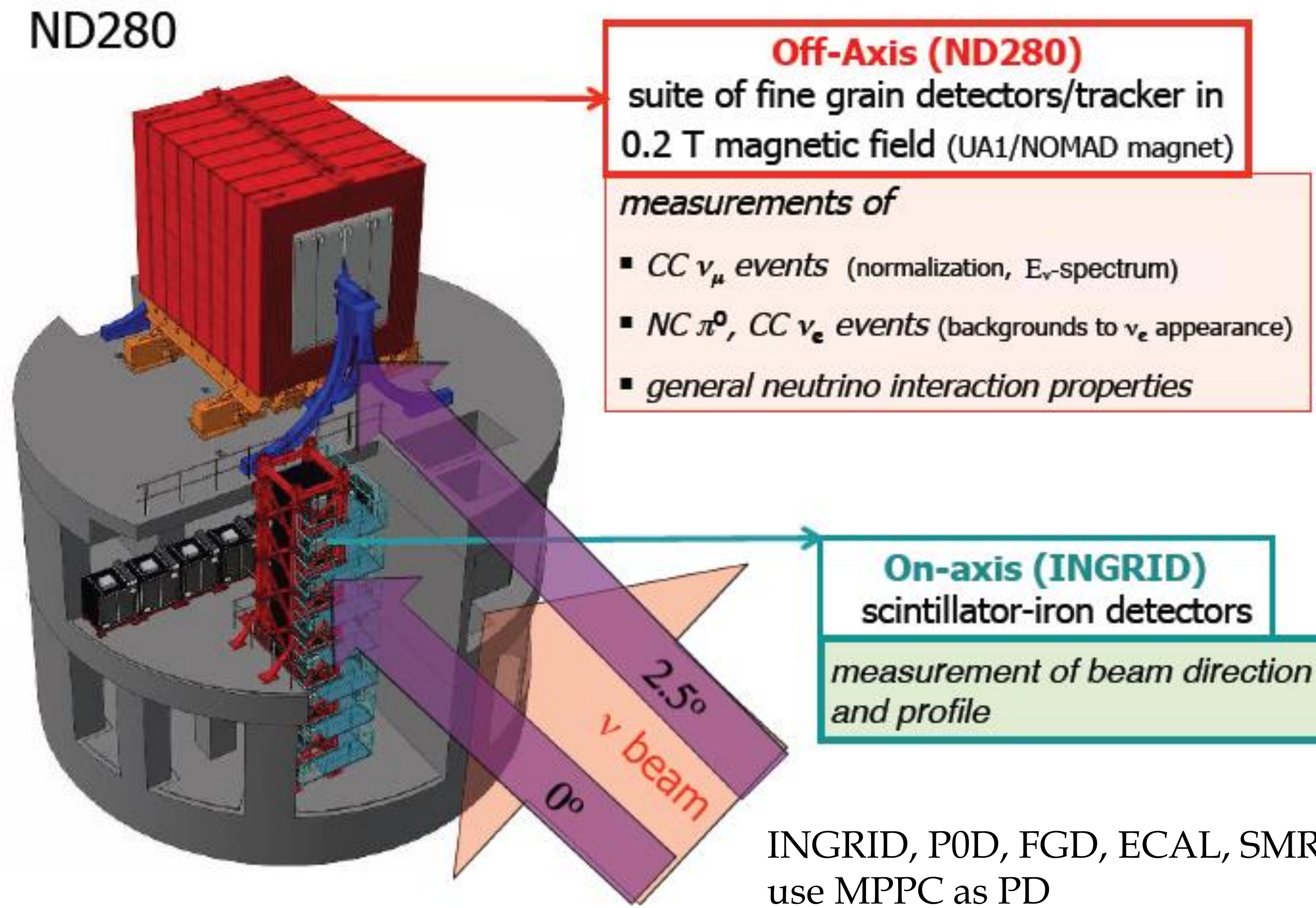
PD R&D for HyperK detector

Gianfranca De Rosa
Univ. Federico II & INFN, Naples, Italy

JENNIFER Consortium General Meeting
Rome, 10-12 June 2015

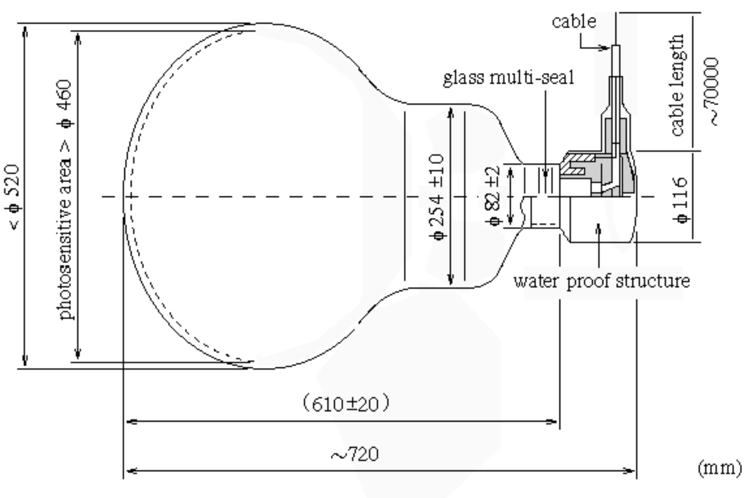
T2K Near detectors



INGRID, P0D, FGD, ECAL, SMRD use MPPC as PD

T2K Far detector

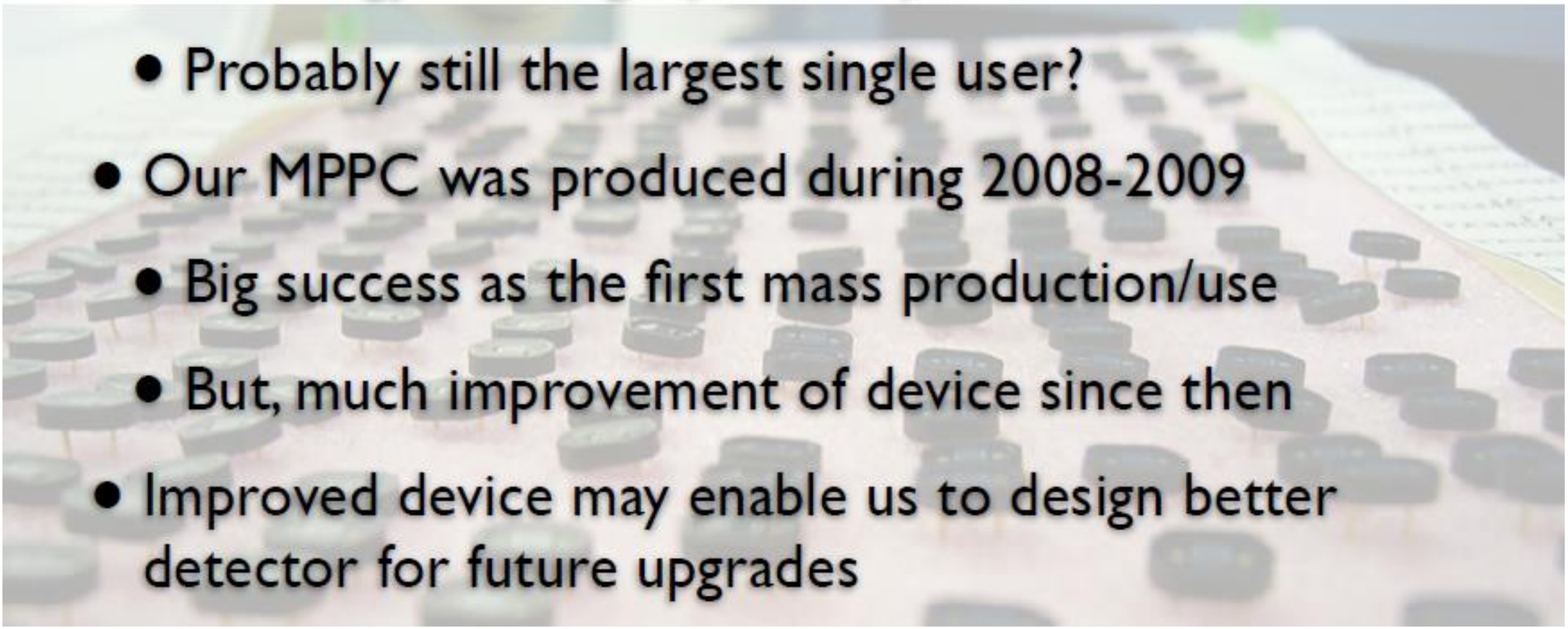
SuperKamiokande



SK PMT developed with Hamamatsu photonics.
The diameter of the photosensitive area is 20 inch (about 50cm) and is the largest in the world.

MPPC in T2K

- T2K is the first experiment that adopted MPPC/SiPM technology in a large (>10,000) scale.



  - Probably still the largest single user?
- Our MPPC was produced during 2008-2009
  - Big success as the first mass production/use
  - But, much improvement of device since then
- Improved device may enable us to design better detector for future upgrades

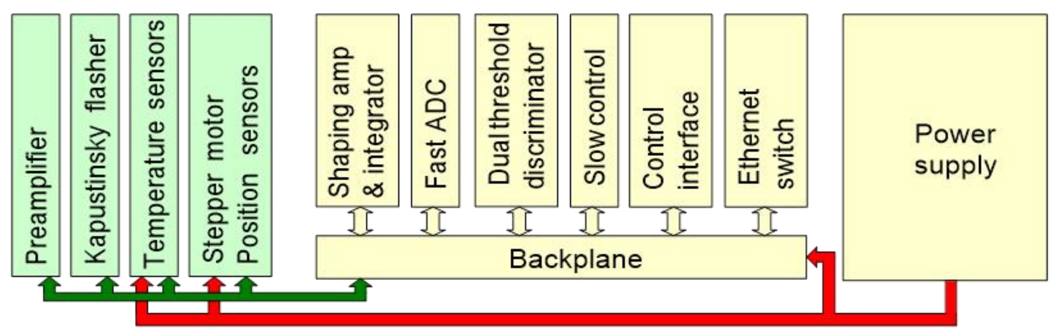
M. Yokoyama
Department of Physics, University of Tokyo, 3 Feb. 2015

T2K-MPPC Activities @Warsaw University of Technology

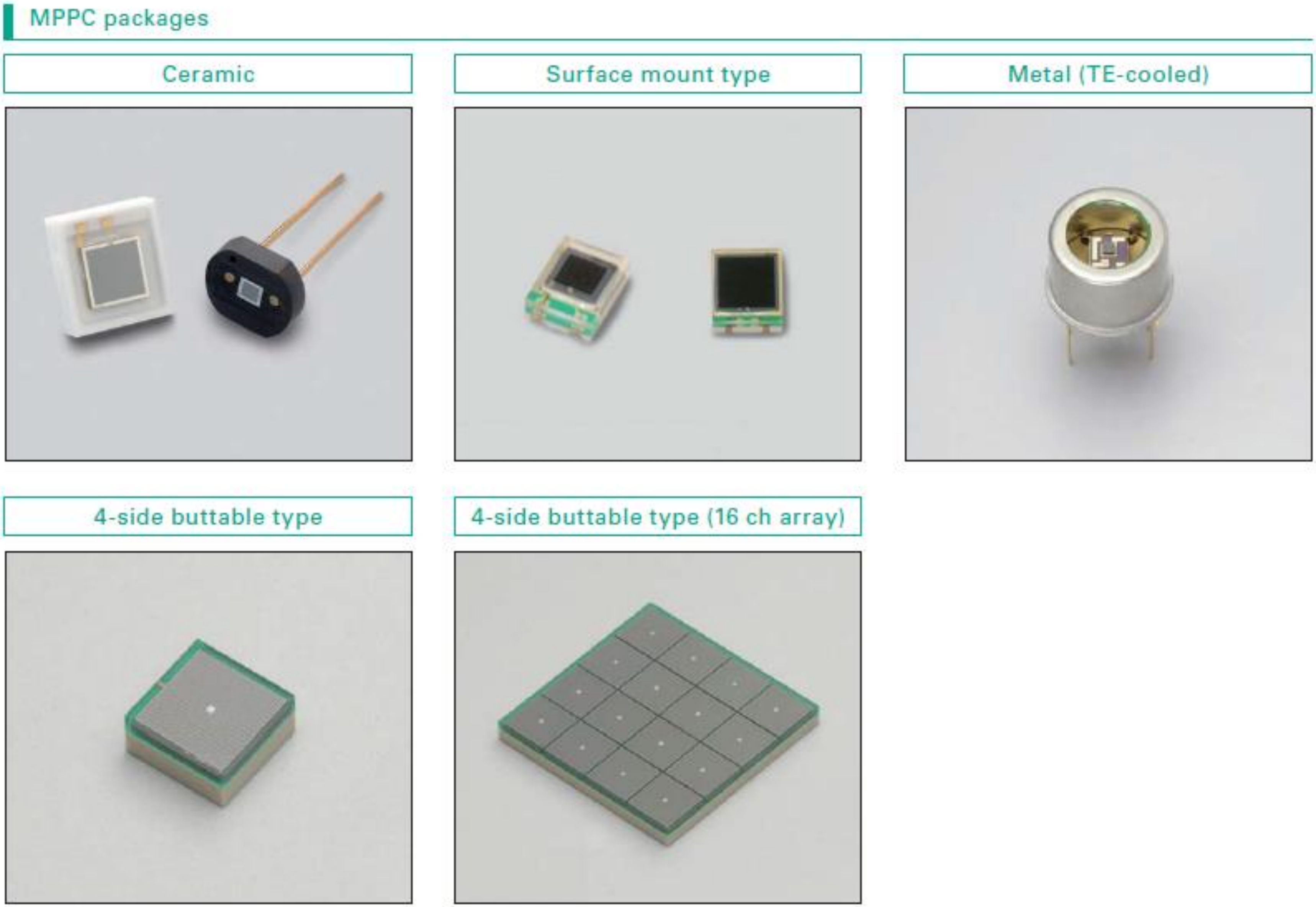
- Involvement in construction of SMRD detector
- Quality Assurance of MPPCs (approx. 1200 sensors tested)
  - Designed and built fully automated measurement device
  - Development of mechanics, electronics and software for measurement control and data processing

- Detailed characterization of T2K MPPCs
  - Co-authored T2K MPPC paper
- Involvement in neutrino ToF project
  - Built some hardware for traveler box with Cs clock

MPPC Feeder Electronics Software



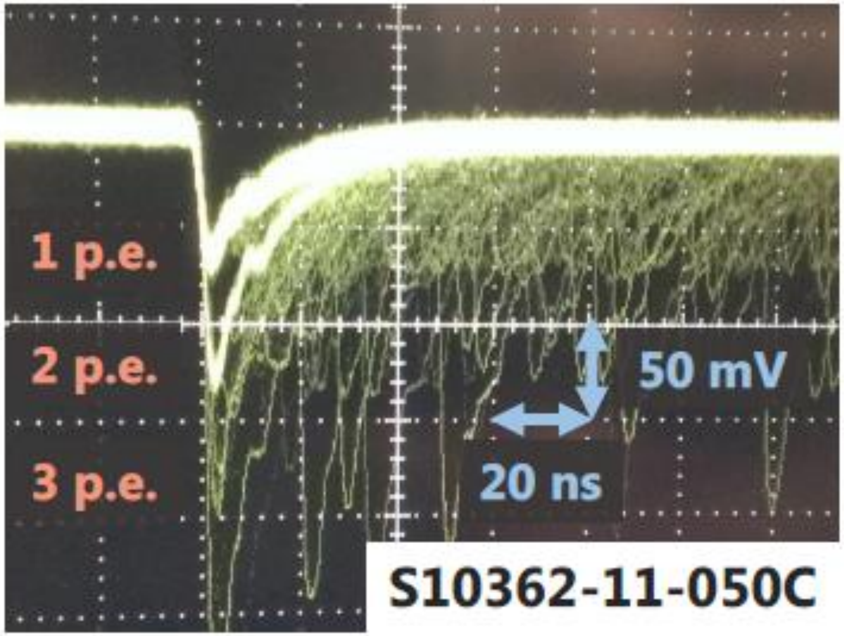
M. Ziembicki, Warsaw University of Technology

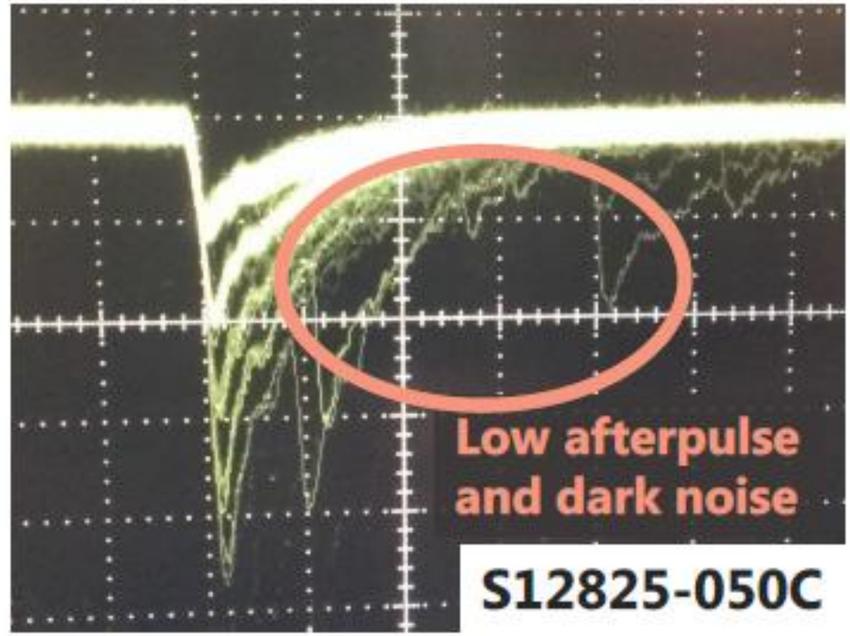


from Hamamatsu document

Recent developments

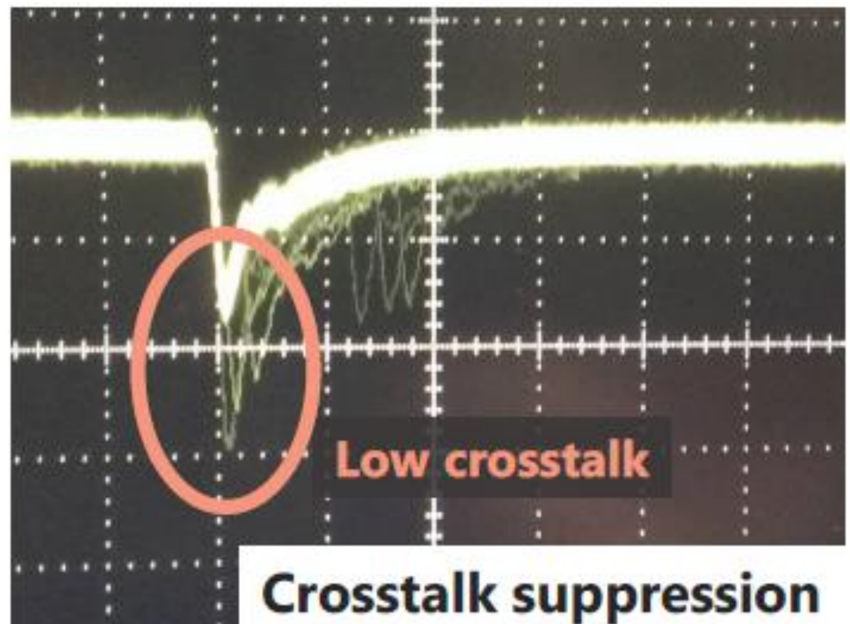
- Metal quenching resistor
  - Improve fill factor (esp. small pixel devices)
  - Less temp dependence of resistance (low temp usage)
- Noise and after pulse suppression
  - Improvement of wafer quality and processing
  - Implementation of some structure (buried layer) in bulk (?)
- Cross-talk suppression
  - Trench structure to optically separate pixels
  - Reduction of active area
  - More gettering effect? (trapping impurities by defect/distortion)





Waveforms of MPPC

Oscilloscope images
Showing dark noise
Amplified by 100
Over voltage=2.0 V



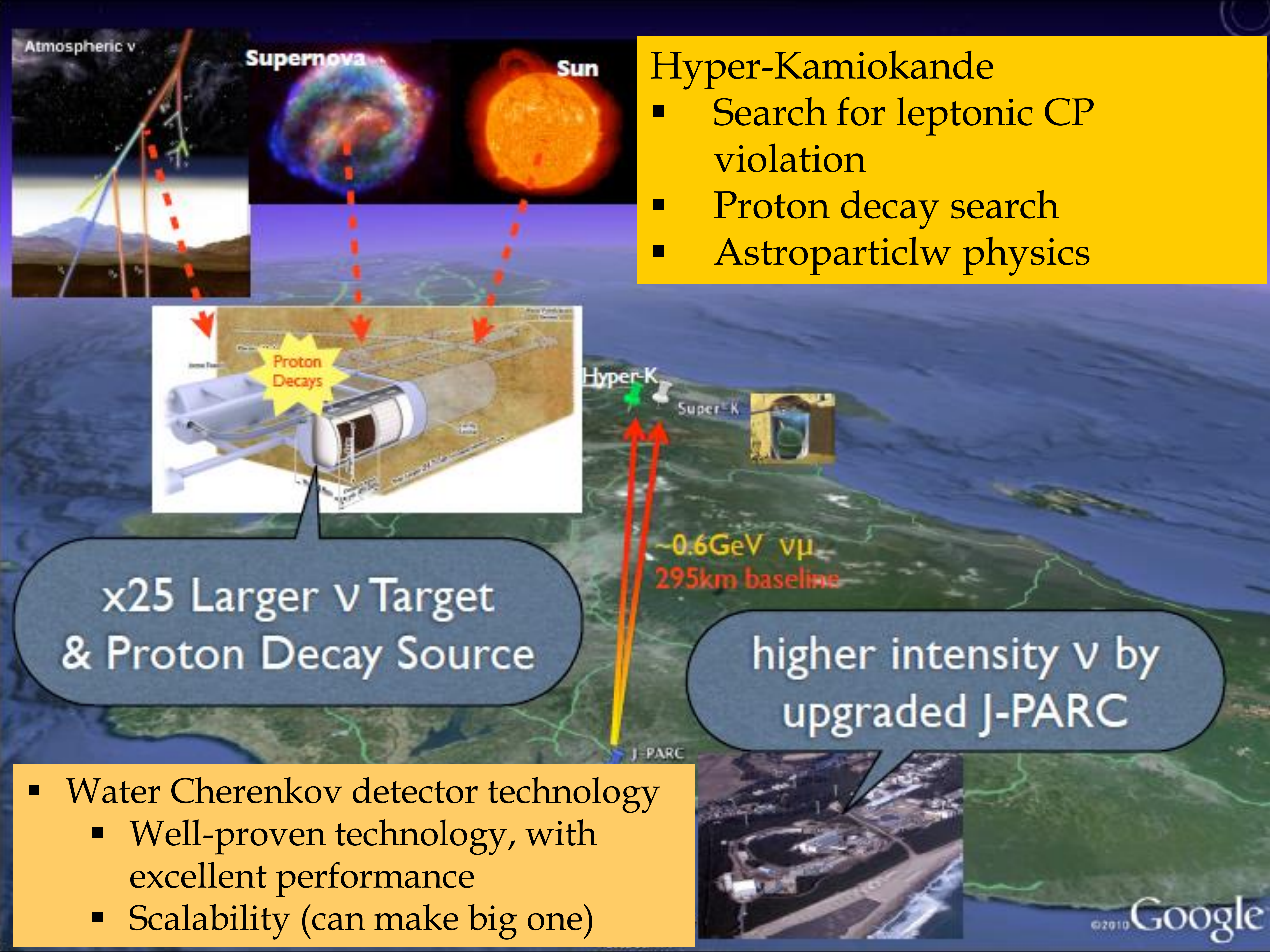
F.Hosomi(Tokyo) @ T2K meeting, Oct. 2014

Hyper-K

PhotoDetector R&D

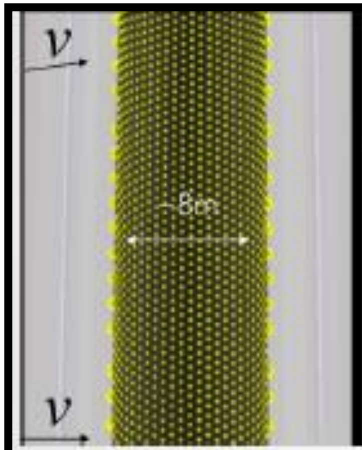
Hyper-Kamiokande

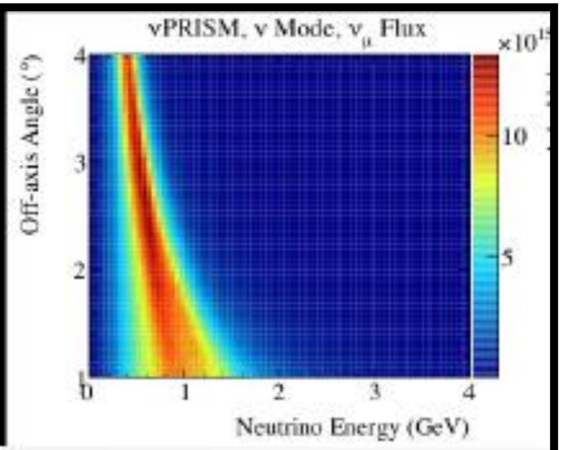
- Search for leptonic CP violation
- Proton decay search
- Astroparticlw physics



- Water Cherenkov detector technology
  - Well-proven technology, with excellent performance
  - Scalability (can make big one)

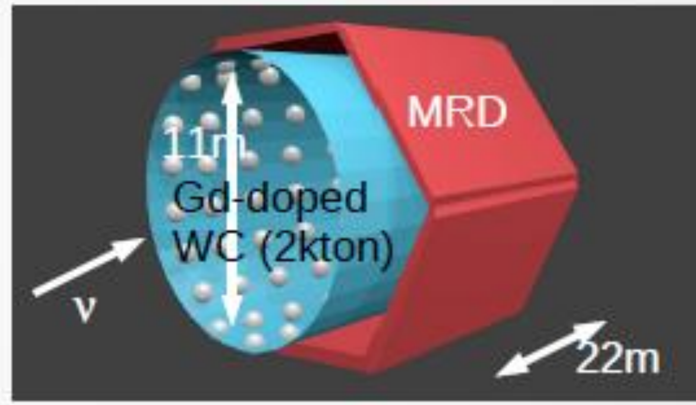
Additional Near Detectors



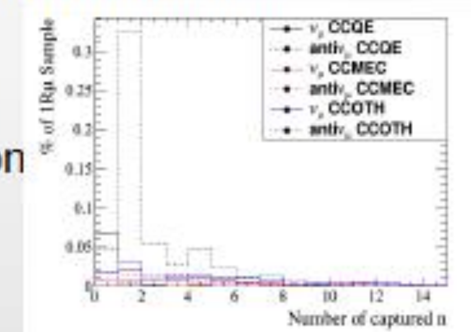


"ν-PRISM" (~1km)
- tall (~50 m) WC detector spanning wide range of off-axis angles
- effectively isolate response in narrow band of energy by comparing interactions at different off-axis angles

"TITUS" (~2 km)
- 2 kt Gadolinium-doped WC detector with HPDs and LAPPDs



- Use G_d for neutrino interaction separation
- In particular, G_d for $\overline{\nu}/\nu$ separation



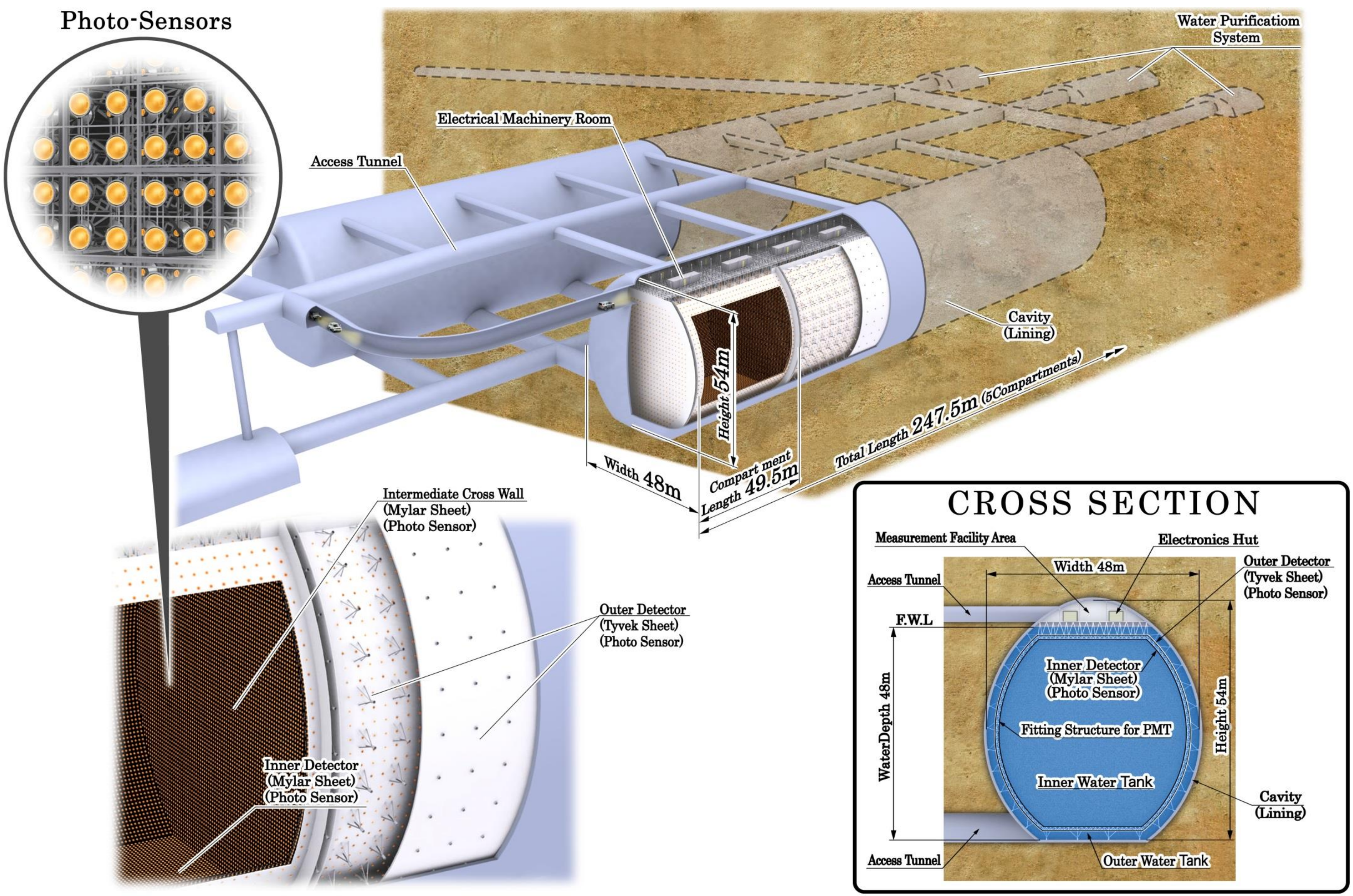
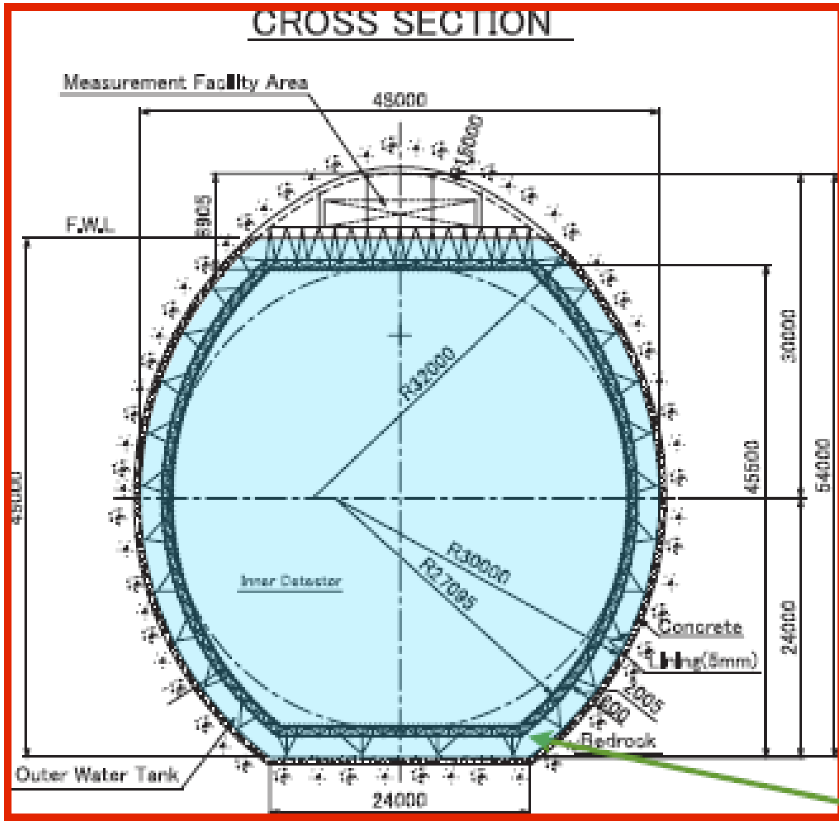
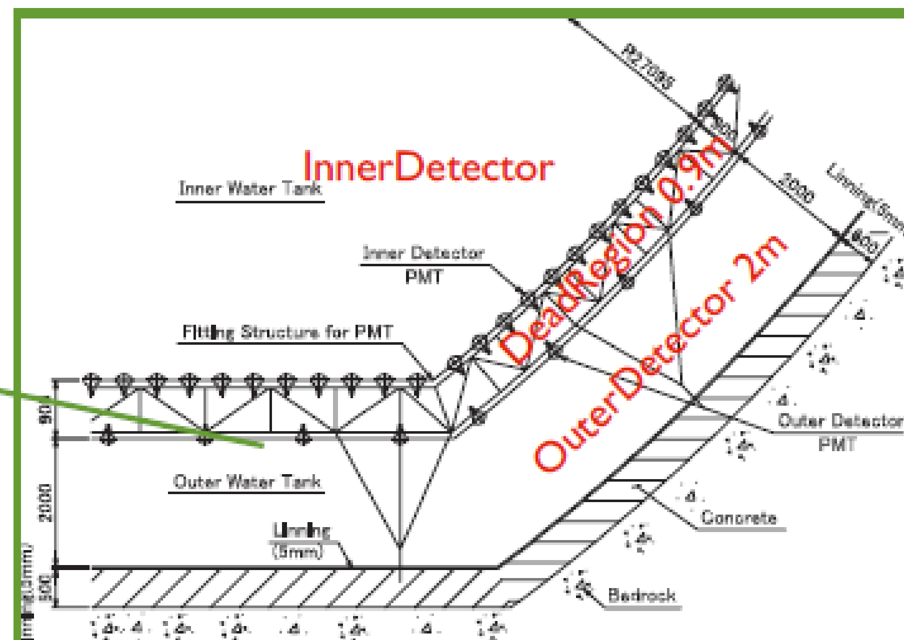


Photo-Sensors
Water Purificatiom System
Electrical Machinery Room
Access Tunnel
Cavity (Lining)
Height 54m
Total Length 247.5m (5Compartments)
Width 48m
Compart ment Length 49.5m
Intermediate Cross Wall (Mylar Sheet) (Photo Sensor)
Outer Detector (Tyvek Sheet) (Photo Sensor)
Inner Detector (Mylar Sheet) (Photo Sensor)
CROSS SECTION
Measurement Facility Area
Electronics Hut
Width 48m
Outer Detector (Tyvek Sheet) (Photo Sensor)
Access Tunnel
F.W.L
Inner Detector (Mylar Sheet) (Photo Sensor)
WaterDepth 48m
Fitting Structure for PMT
Height 54m
Inner Water Tank
Cavity (Lining)
Access Tunnel
Outer Water Tank

Hyper-K Cross section view



- The cavern with egg-shape optimized for stability
  - avoiding sharp edges



Numbers

- Depth of tank water 48m
- Cavern size 48m(W) x 54m(H) x 250m(L) x 2 caverns
- optically separated compartments 5x2 = 10
- Water Volume
  - Total: 0.496x2=0.992 Megaton
  - ID volume: 0.74 Mton
  - Fiducial Volume: 0.056x10 = 0.56 Mton (25 x Super-K)
- PMT
  - ID: 99,000 20" PMTs (20% photo-coverage)
  - OD: 25,000 8" PMTs (same coverage as SK)

Photodetectors are the key component of a WC detector.
The fraction of the photodetector cost is significant (~1/3 of the total construction cost in the current estimation).

Hyper-K photodetectors in the baseline design (LoI)

Volume	0.99 Mton (Super-K: 50 kton)
Number of PD (Inner detector)	~99000 (Super-K: 11146)
Number of PD (Outer VETO)	~25000 (Super-K: 1885)
Photo coverage	20 % (Super-K: 40%)

- Hamamatsu R3600 PMTs (used in SK)
  - Known to satisfy basic requirements
  - Operated for more than 15 years in SK. Long-term stability are well understood.
- Acrylic and FRP protective cases.

- QE : 22% @λ=390nm
- Gain : 10^7
- Dark rate : 4.5kHz @0.25p.e. threshold
- Transit time spread : 2.2nsec (1σ) for 1p.e. signals
- Pressure tolerance : 6kg/cm^2

Many options….

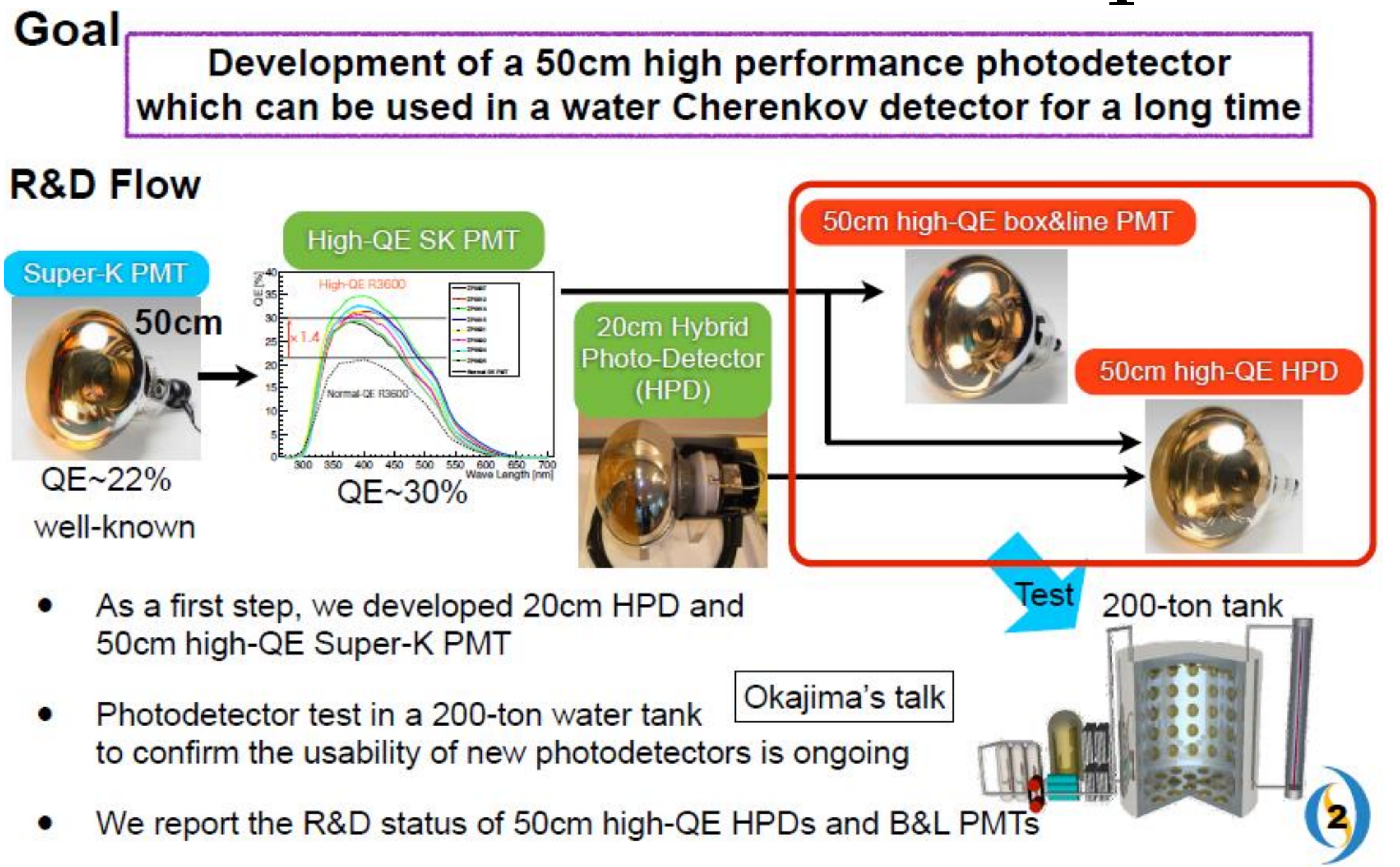
- Sensors
  - HPD, PMT w/ box-line dynodes, PMT w/ venetian blind dynodes, …
  - High QE, Normal QE
  - 20-inch, 12-inch, 8-inch, …
- Light collection
  - No light collectors, WLS plates, Winston cones, …
- Protective cases
  - All acrylic, Acrylic+Stainless, …
  - w/ passive magnetic shielding (such as mu-metal wire cages) ?

Should be chosen primarily by physics requirements.

Cost, quality control in mass production, and production/assembly period are also important for the choice.

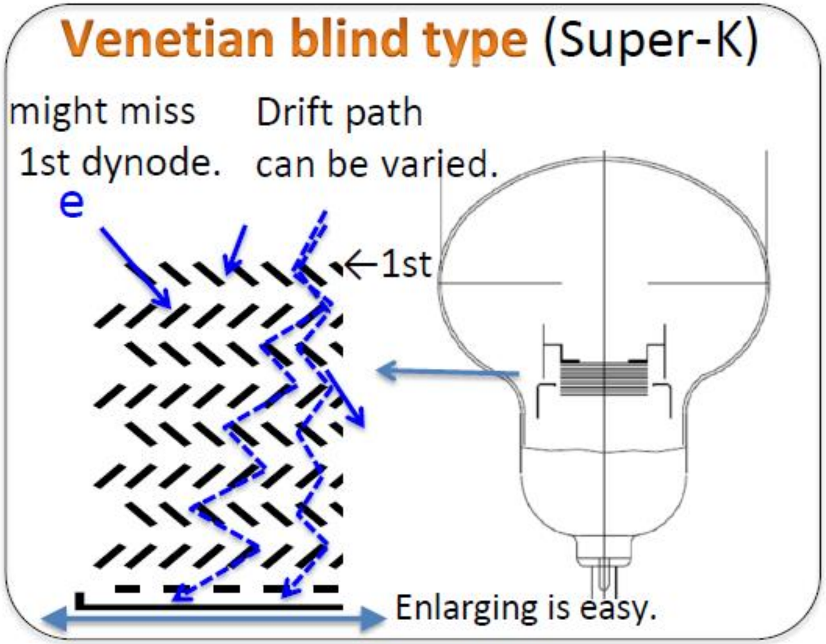
R&D of 50cm PDs in Japan

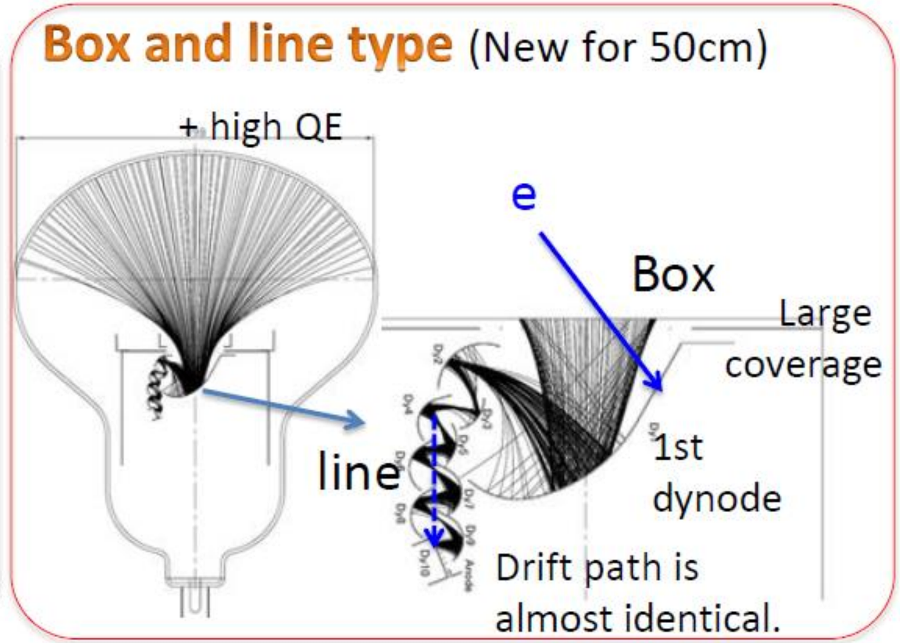
R&D of 50cm PDs in Japan



Yusuke Suda (UTokyo), *5th Open Meeting for the Hyper-Kamiokande Project*

Box&Line PMT





Effective area:
43cm

50cm KamLAND
B&L PMT

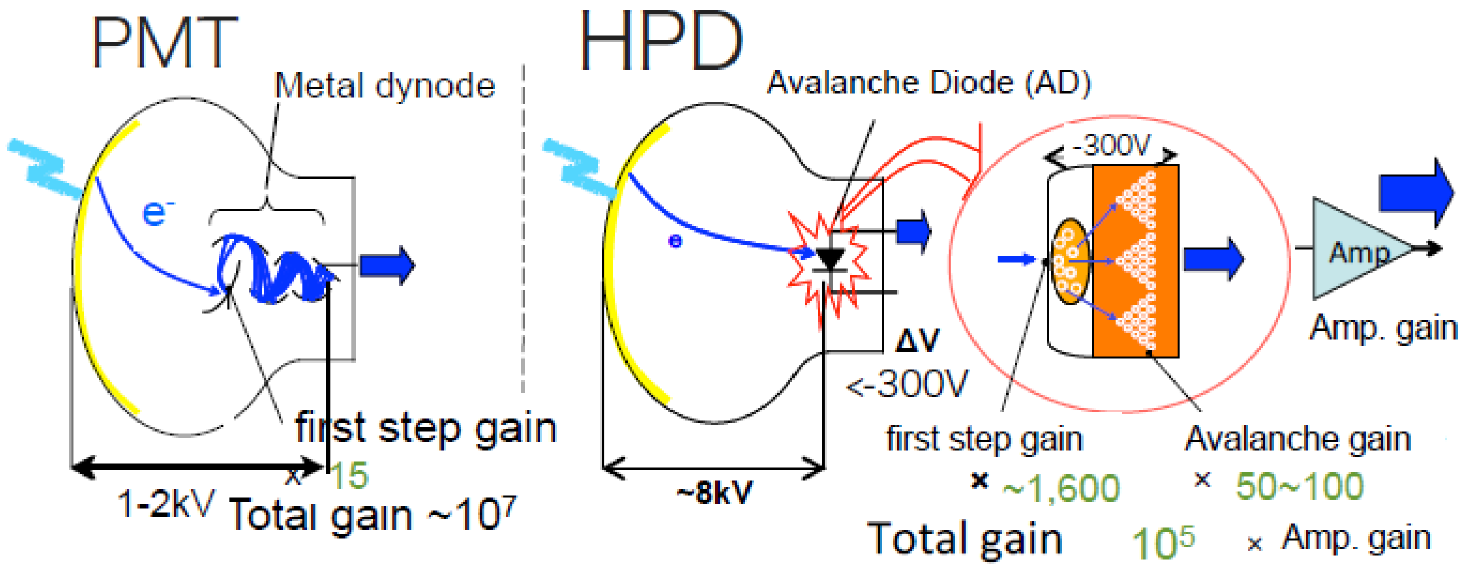
50 cm photomultiplier tube with box-and-line dynode

Good photon collection by box shape 1st dynode

Fast time response by line shape dynode

Box & Line
Better timing and 1PE resolution

Hybrid Photo-Detector



HPD

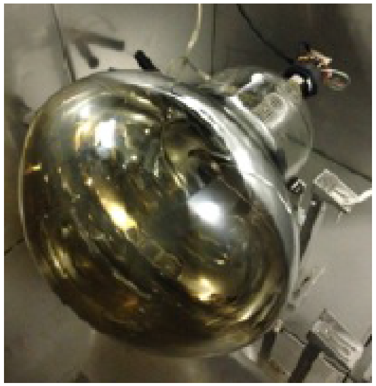
Advantage

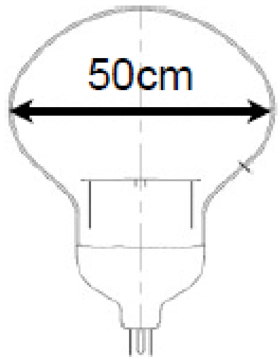
- Simple structure → Low cost production possibility
- Short drift length → Fast timing response
- High first step gain → High single photoelectron resolution

Challenge

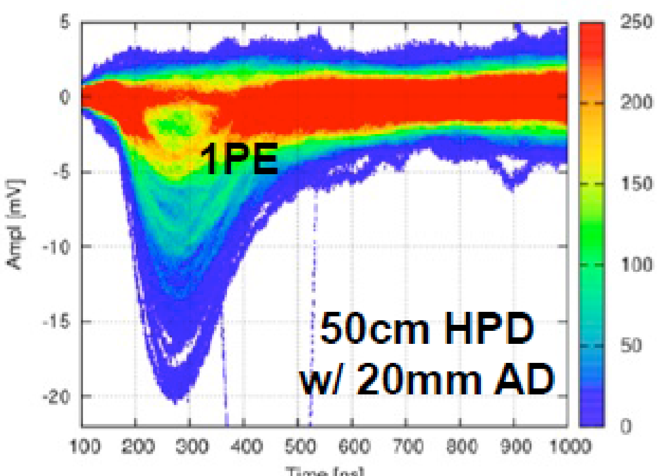
- Difficulty in handling 8kV
- No experience to use in a water Cherenkov detector

50 cm HPD ptototype





50cm high-QE HPD w/ 5mm AD

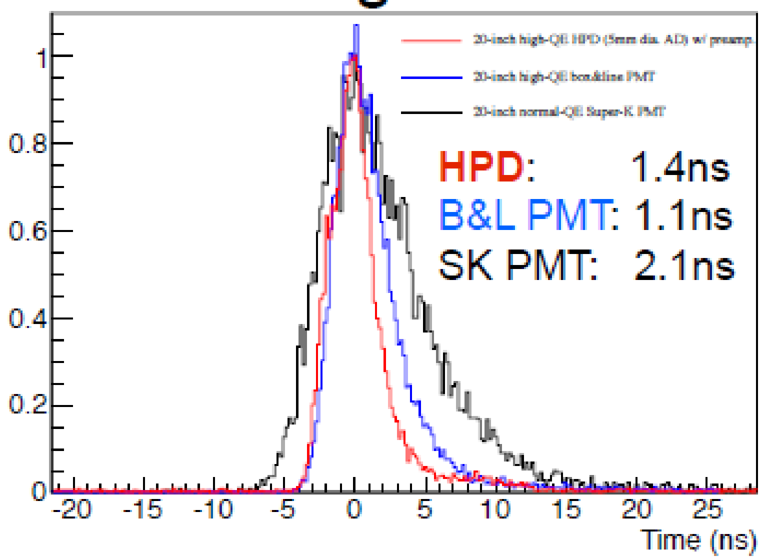


Prototype preamp. for 20mm AD

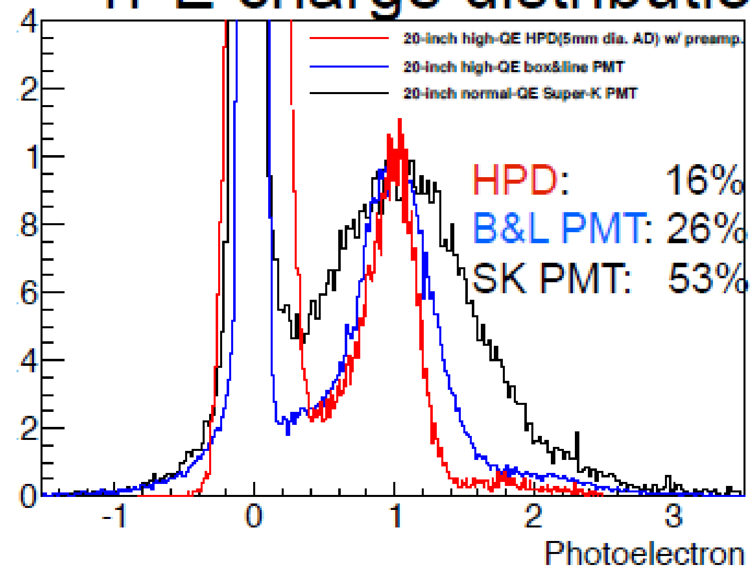
- To keep high-CE (~95%), the size of AD should be 20mm diameter
- Since 20mm AD has a large capacitance, we have been developing a low noise preamplifier
  - We have 2 types of preamp. and can see 1PE peak in both type
    - But not enough S/N and response speed
- For this test, we measured the prototype of HPD with 5mm AD (same AD size as 20cm HPD)

Timing & Charge

1PE timing distribution



1PE charge distribution



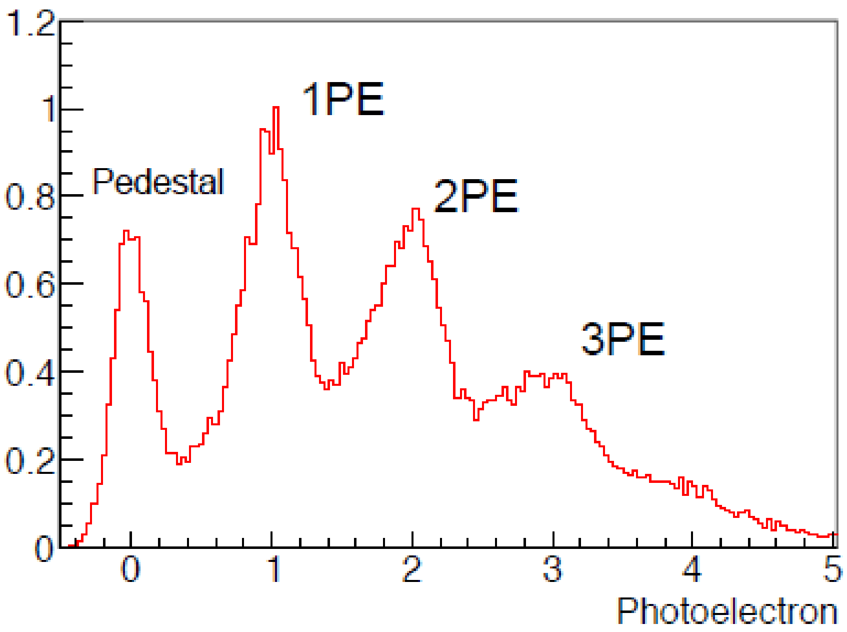
	HPD (20cm HPD)	**B&L PMT**	**SK PMT**
Timing resolution σ (ns)	1.4 (1.1)	1.1	2.1
FWHM (ns)	3.4 (3.3)	4.1	7.3
1PE resolution σ/μ	16% (12%)	26%	53%
Peak to Valley ratio	4.0 (5.2)	4.5	2.2

HPD calculated timing resolution FWHM: 0.75ns (20mmφ AD w/o preamp)

- Both box&line PMT and HPD show better timing and charge resolution than Super-K PMT

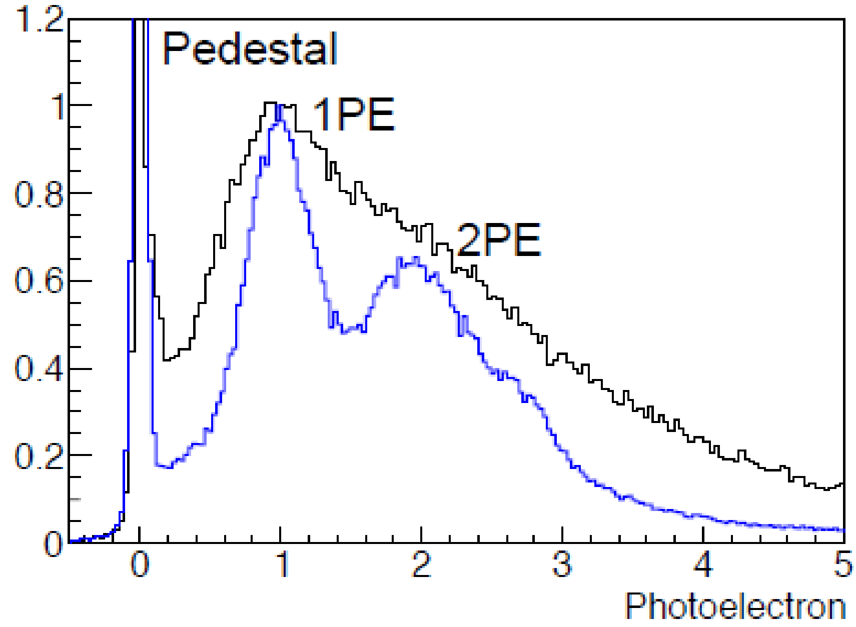
Multi-PE distribution

50cm high-QE HPD



50cm high-QE Box&line PMT

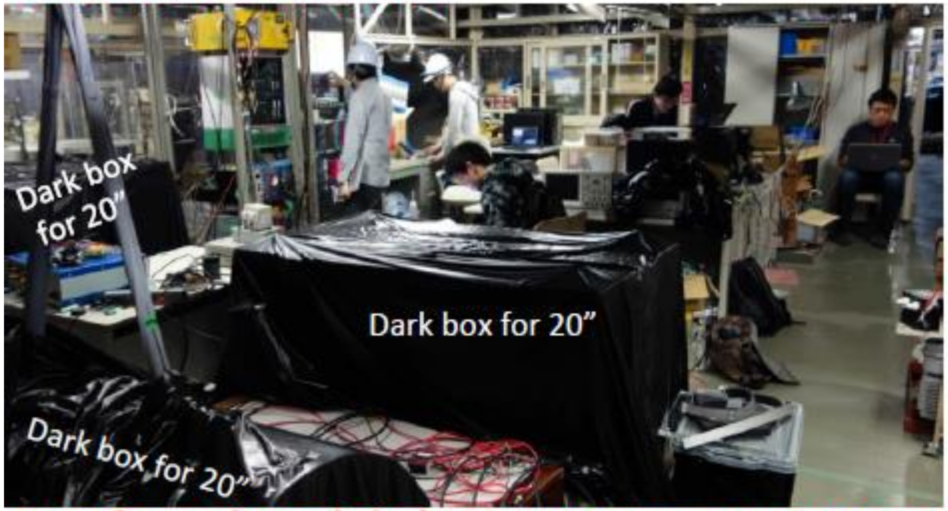
High-QE SK PMT



Multi-PE peaks are clearly seen in both HPD and B&L PMT

Current activities

Evaluation t Kamioka



50cm photosensor (HAMAMATSU)

HPD electronics
(KEK, ERI, U.Ttokyo, ...)

New 8" HPD study (UK, ..)

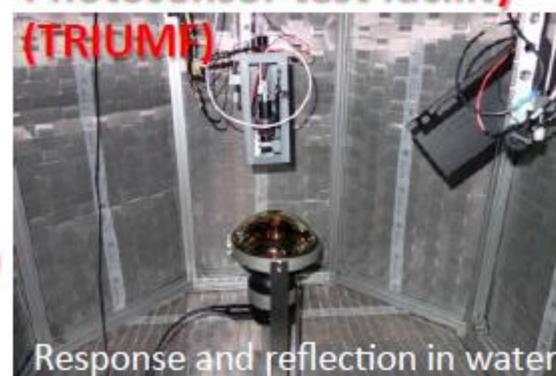
28cm PMT (ETEL/ADIT, US)

Proof test (Kamioka)

8" HPD thermal effect (Kyoto-U)

Stability (Kashiwa ICRR)

Photosensor test facility (TRIUMF)



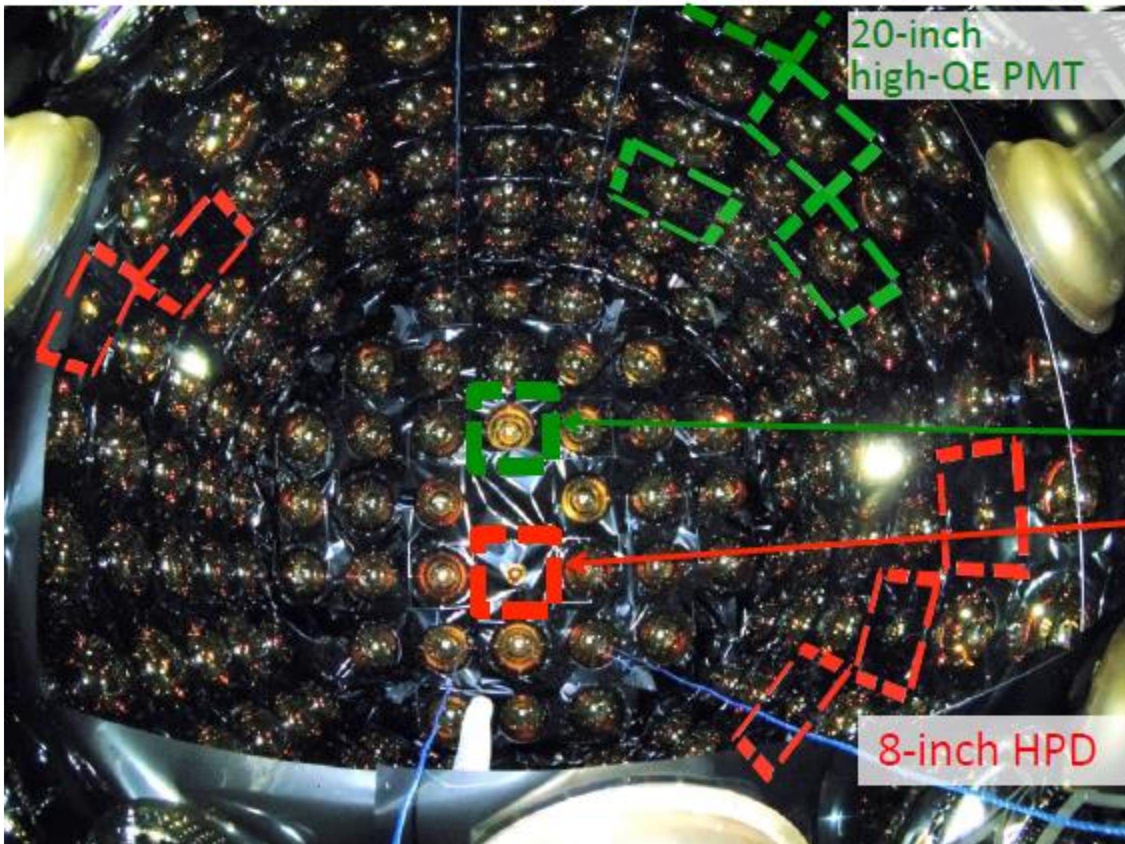
- There are many activities, but still not sufficient to cover all necessary developments.

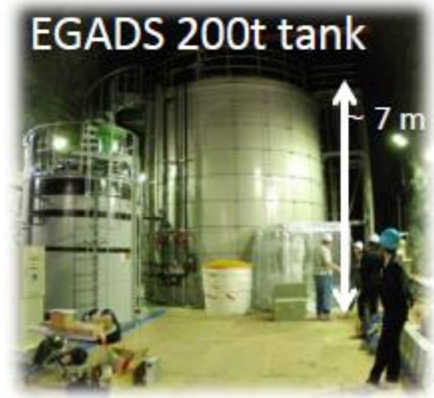
Photodetectors for the 1st proof test

- All photodetectors were installed in Jul-Aug 2013.

Inside of 200-ton water tank viewed from top

[Many pics in http://www.icrr.u-tokyo.ac.jp/~ynisi/pic/EGADS/index.php]

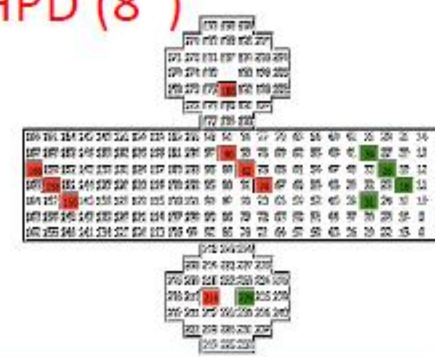




227 Super-K PMT (20")

+ 5 High-QE PMT (20")

+ 8 HPD (8")



Small photosensors for Hyper-K

Photon detector System

Km3Net experience:
Multi-PMT system with small PMTs (DOM)

Use small PMTs
- Almost uniform coverage
- Photon counting
- Several manifacturer of small PMTs
- Directional sensitivity

Photodetectors and electronics arranged inside a pressure resistent vessel

Km3Net DOM

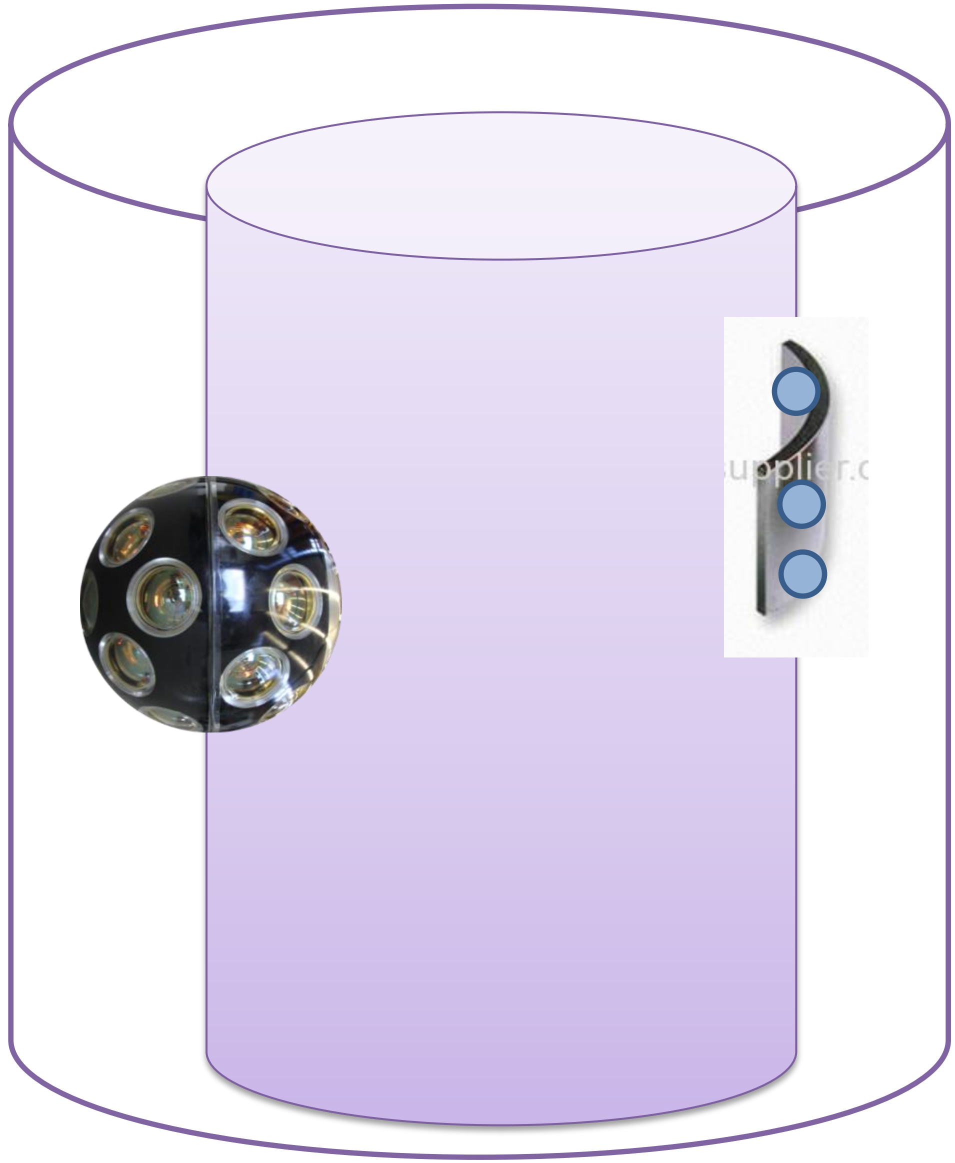
INFN Naples, TRIUNF and UBC Canada

MultiPMT in HyperK

semiDOM (spherical geometry)

DOM structure as in Km3Net:

ID/OD DOM → part of DOM looking at inner detector, part looking at outer detector



Small Photodetectors Options

As in Km3Net: 3-inch PMTs

Key features:

– timing	≤ 4.5 ns (FWHM)
– QE	≥ 25-30%
– collection efficiency	≥ 90%
– photon counting purity	100% (by hits, up to 7)
– price/cm^2	≤ 10” PMT

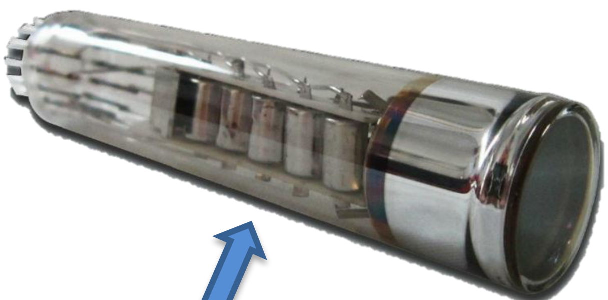
ETEL D792

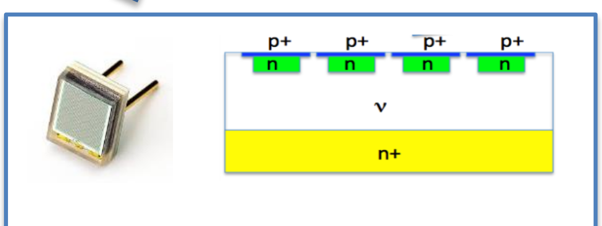
Hamamatsu R12199

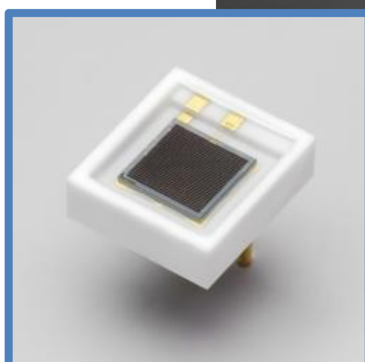
HZC XP53B20

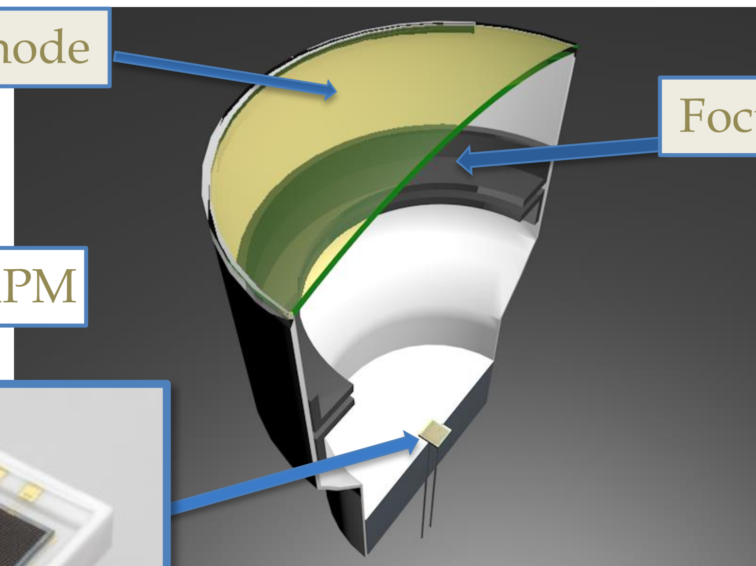
Vacuum Silicon PhotoMultiplier Tube
VSiPMT

An innovative design for a modern hybrid photodetector based on the combination of a Silicon PhotoMultiplier (SiPM) with a Vacuum PMT standard envelope







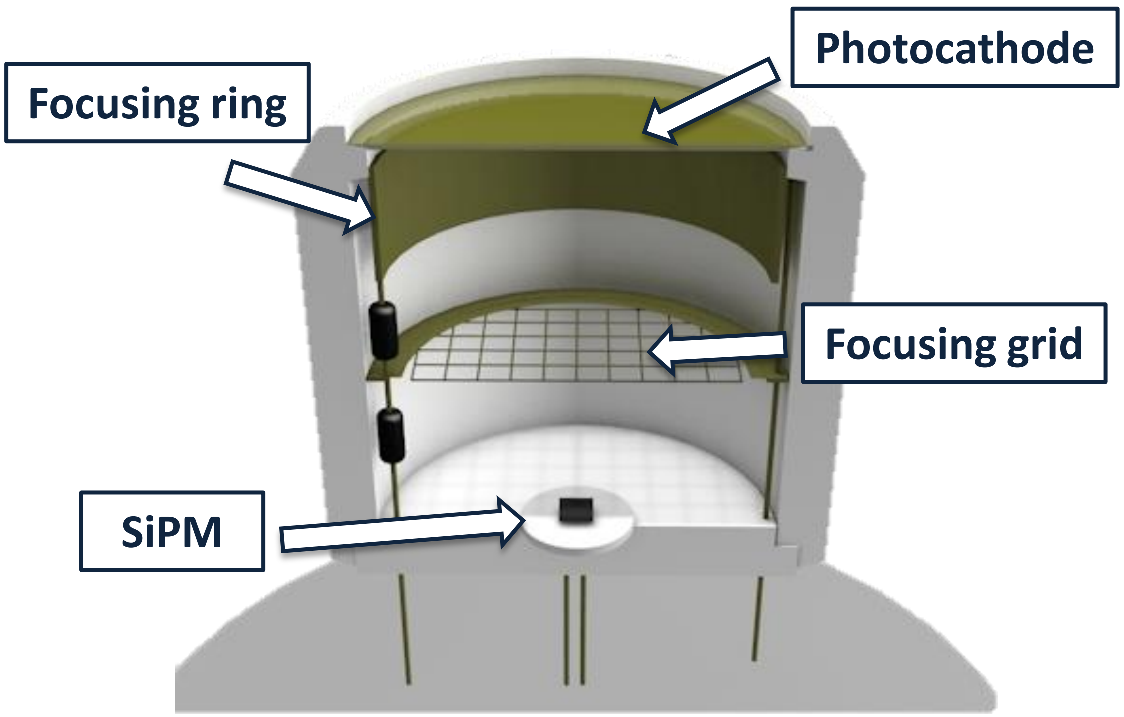


increase the SiPM surface with SiPM performnces

The classical dynode chain of a PMT is replaced with a SiPM, acting as an electron multiplying detector.

GC . Barbarino et al
INFN - Napoli

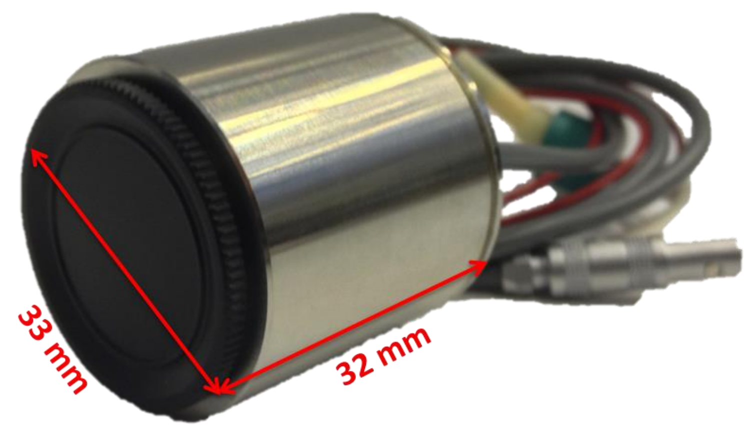
VSiPM: The industrial prototypes



In 2013 Hamamatsu realized for us two industrial prototype, by arranging a no-windowed SiPM inside a commercial Hamamatsu HPD.

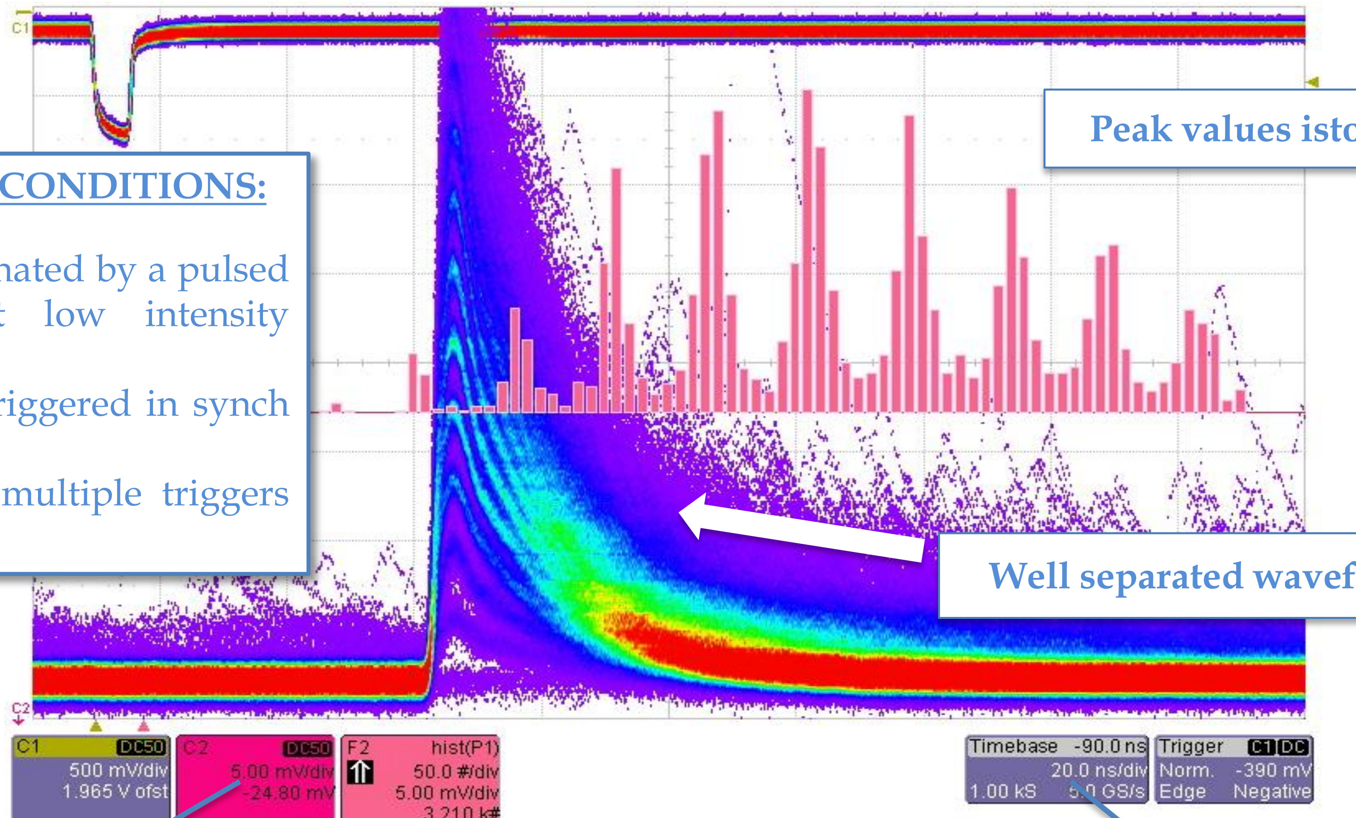
- **7x7 mm^2 Borosilicate glass entrance window**
- **3 mm Ø GaAsP photocathode**
- **p$^+$nνn$^+$ configuration**
- **special non-windowed MPPC series**

Prototype	ZJ5025	ZJ4991
SiPM Area (mm^2)	1×1	1×1
Cell size (μm)	50	100
Total number of cells	400	100
Fill Factor	61%	78%



VSiPM: The prototypes characterization

Waveforms and spectra



MEASUREMENT CONDITIONS:

- VSiPMT illuminated by a pulsed laser light at low intensity (407nm)
- Oscilloscope triggered in synch with the laser
- Responses for multiple triggers are overlaid

Peak values istogram

Well separated waveforms

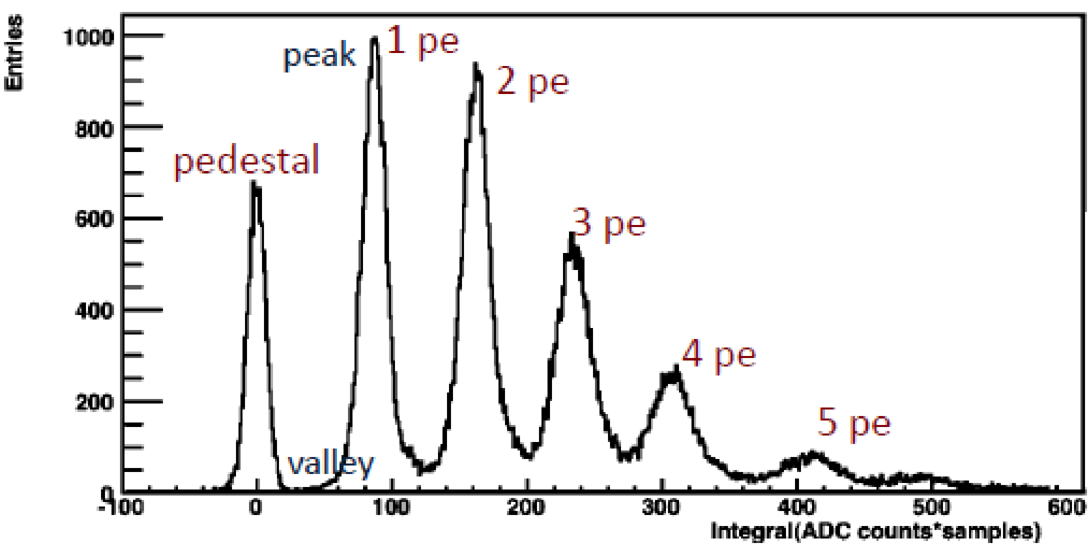
5 mV/div

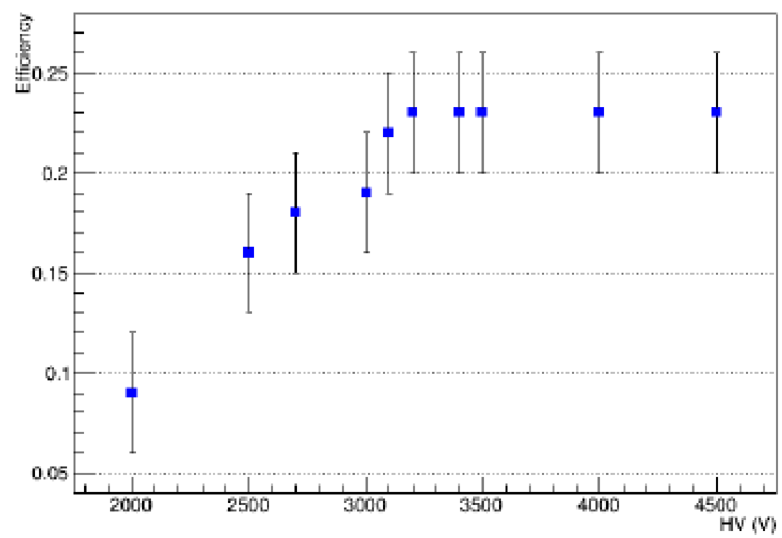
20 ns/div

Excellent photon counting capability

VSiPMT features

- Excellent **photon counting** capabilities
- Photon Detection Efficiency: ≈23% @ 407nm
- High gain: $10^5 \div 10^6$, HV-stable
- Good timing performances: TTS < 0.5ns
- Low power consumption: 5mW (amplifier stage)
- SPE resolution 17.8%
- Peak-to-valley ratio ≈65





A new project for the Realization of a 3-inches VSiPM

VSiPMT prototypes characterization provided the unequivocal proof of feasibility of the device.

Engineering and design phase

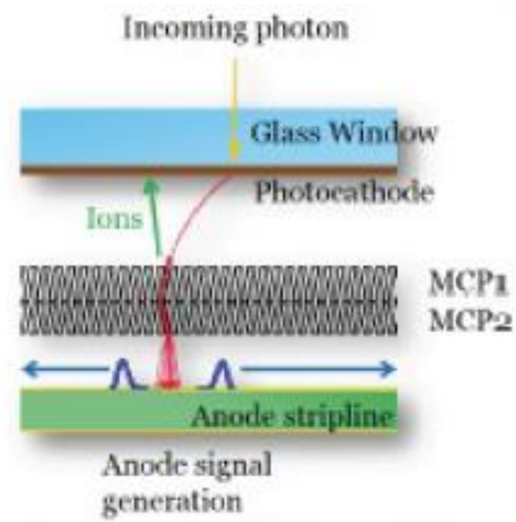
- development of VSiPMT 3 inches photocathode area prototype
- focusing system for linearity and TTS optimization;

Contacts with companies for new prototypes

Photosensor plans for the UK for Hyper-Kamiokande

LAPPDs (Large Area Picosecond Photo-Detector)

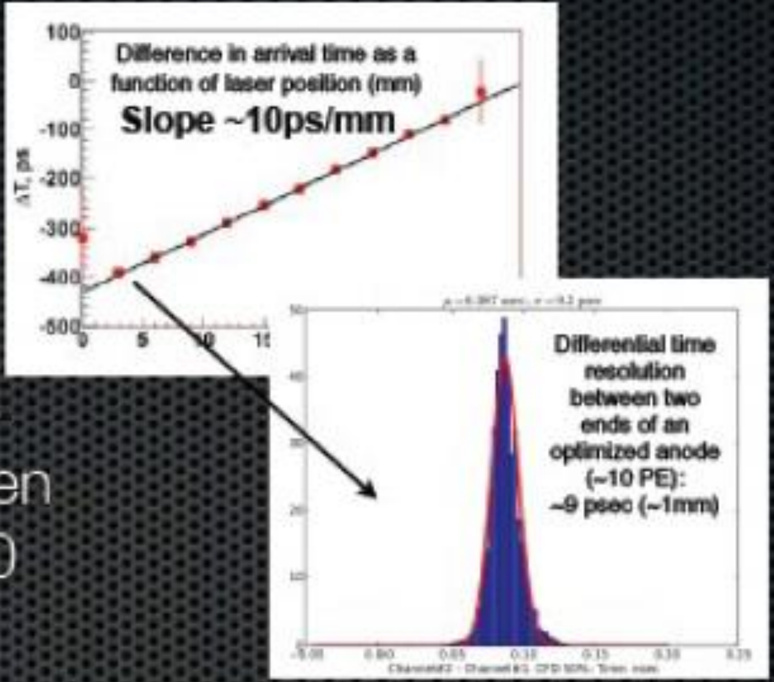
- Base on Existing Technology: Micro Channel Plate (MCP) photo-multiplier
  - Picosecond-level time resolution
  - Micron-level spatial resolution
  - Excellent photon-counting capabilities
  - Expensive
- New Aspect: Fully Integrated Approach
  - Exploit advances in material science and electronics to produce large-area MCP-PMTs:
    - Preserve time and space resolutions of conventional micro-channel plate detectors
    - At low enough cost per unit area

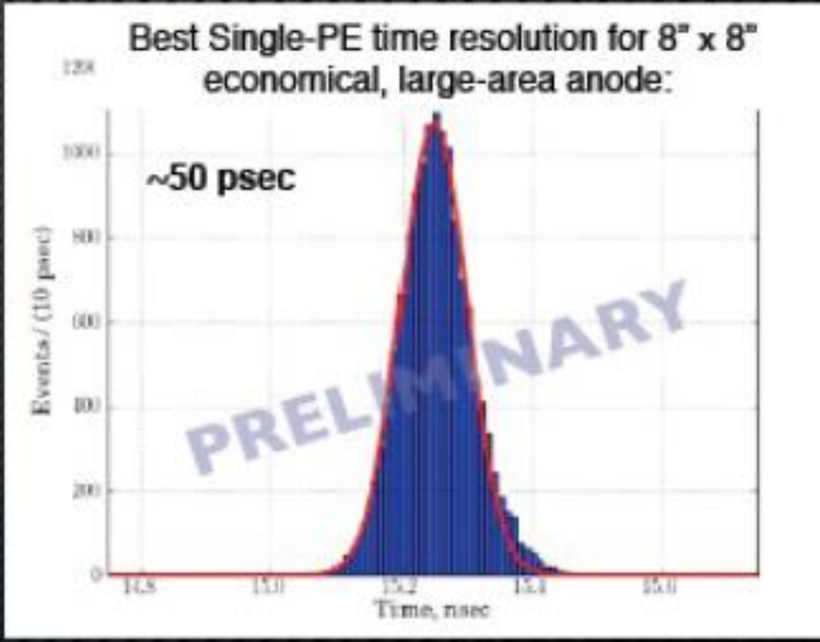


F. Di Lodovico et al., 18 June 2014 , 2th EU Hyper-Kamiokande Open Meeting, CERN,

LAPPD Status

- Testing 8" x 8" (Argonne-made) MCPs:
  - Pulse height peaked at **10^7 gain**.
  - Differential time resolution between two ends of delay-line anode <10 psec.
  - **2 mm spatial resolution** parallel to the strip direction, <1 mm in transverse.
  - **Time resolution of ~50 psec** using economical anode design.
- Commercialization progress: **$3 M awarded** in SBIR funding to US company to commercially develop LAPPDs.





M. Wetstein/A. Elagin (UChicago/ANL)

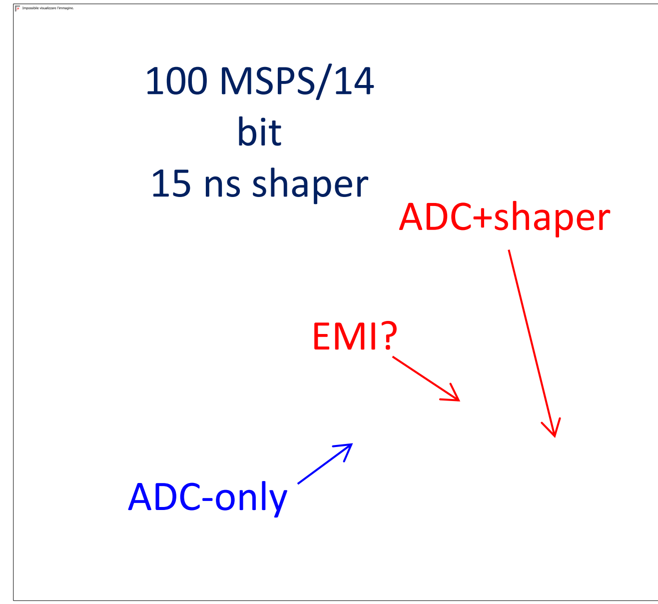
Activities in Hyper-K/nuPRISM

R&D on Flash-ADC based DAQ

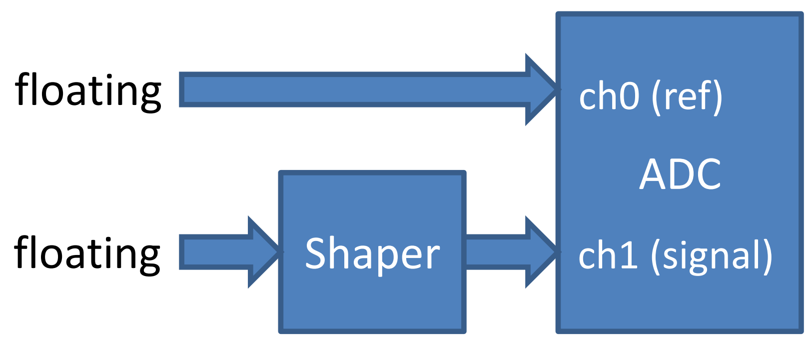
- Study with the aim of system optimization (cost/performance ratio):
  - ADC parameters
  - Signal conditioning & shaping
  - Signal processing (optimal FIR filters)
  - Impact of noise and EMI pickup on system performance
- Development of Monte-Carlo models of electronics chain.
- Already have some nice data
- Joint effort with TRIUMF

M. Ziembicki, Warsaw University of Technology

Example measured noise spectrum



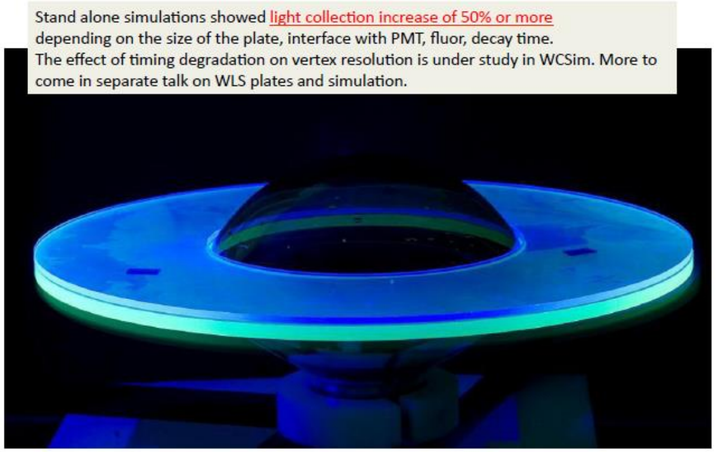
Measurement setup



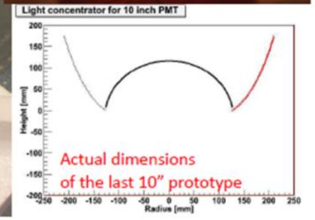
Activities in US

- Evaluation of Hamamatsu 10 and 12 inch High Quantum Efficiency (HQE) PMTs and ETL 8′′ 9354KB
- Development and evaluation of three concepts for external light collectors

Various light collection options are being studied
Wavelength shifter+dichroic mirror
Acrylic Fresnel lens



- Three different light concentrator option are subject to R&D
  - Wavelength shifting film: coat thin layer of wavelength shifting material on the PMT glass surface - ~10-15% light collection improvement
  - Wavelength shifting plates: flat panels put around PMT above the equator doped with WLS: large light collection improvement, will discuss in simulation talk
  - Winston cones: elliptically shaped, reflective, non imaging cones – interface with PMT close to equator: large light collection improvement, will discuss in simulation talk



Conclusions

Many, many activities on PD R&D

Many Jennifer groups involved in this development

Jennifer funds will help in keeping the activities linked with the Japanese group.

Thanks!

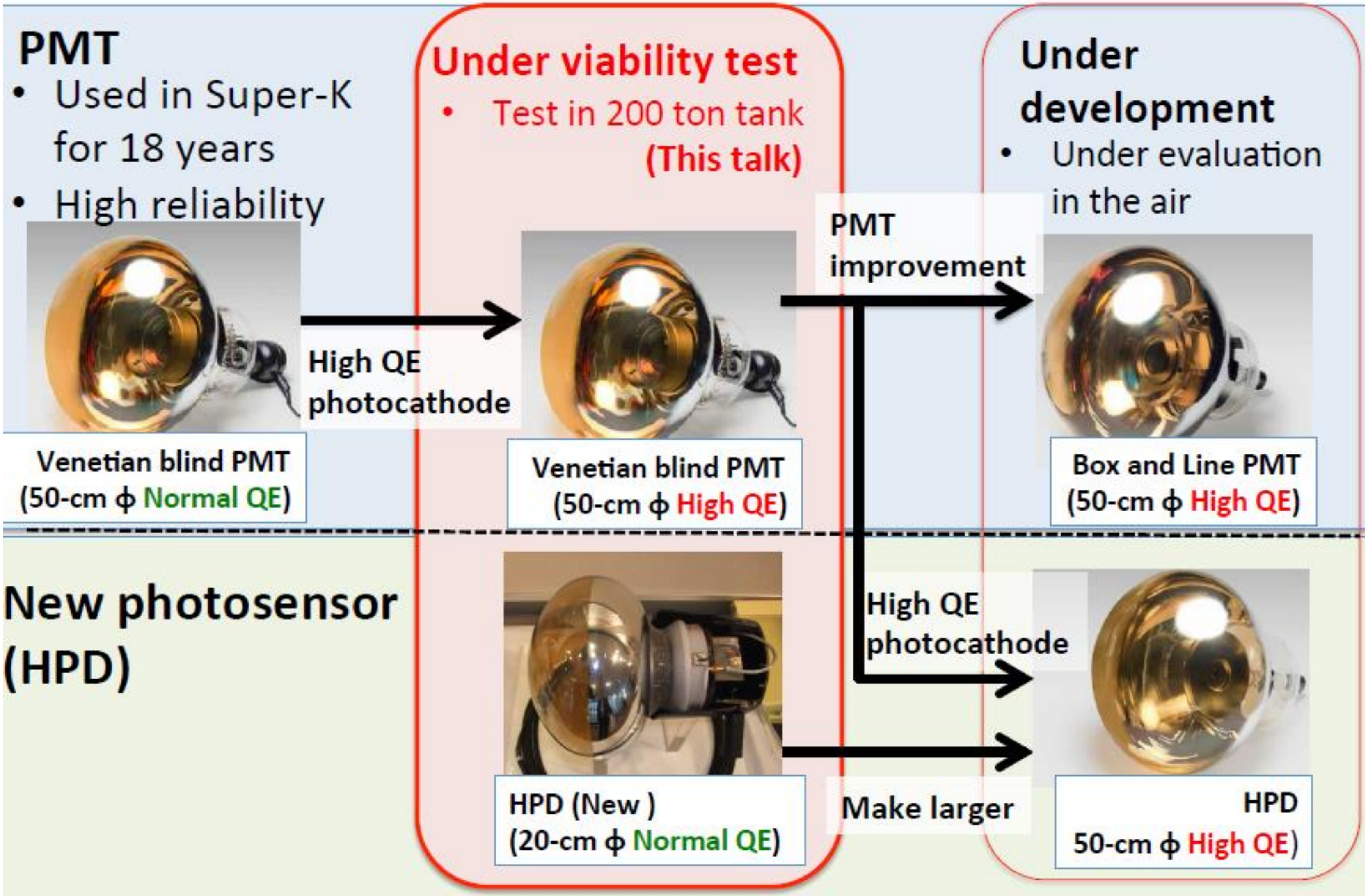
Backup

Requirements on PDs from physics

A practical way may be to check physics sensitivities by HK simulaLons with measured/assumed PD performances for each option

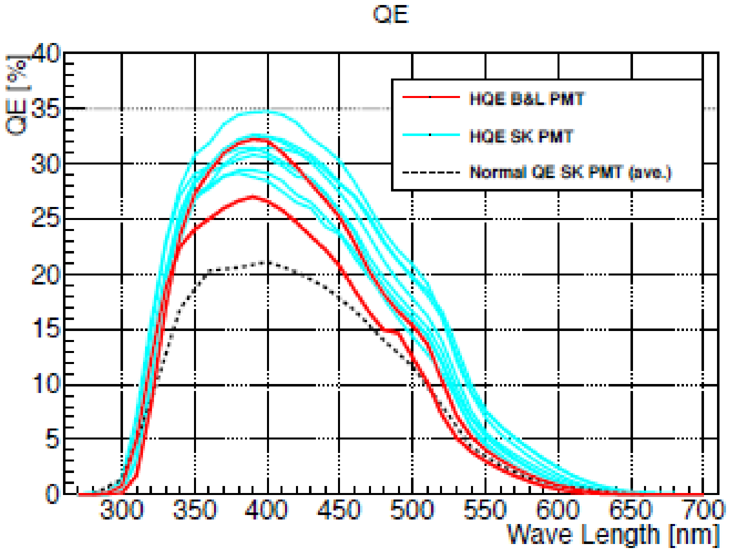
Collaborative work with software WG, physics WG, and calibration WG

R&D of 50cm PDs in Japan

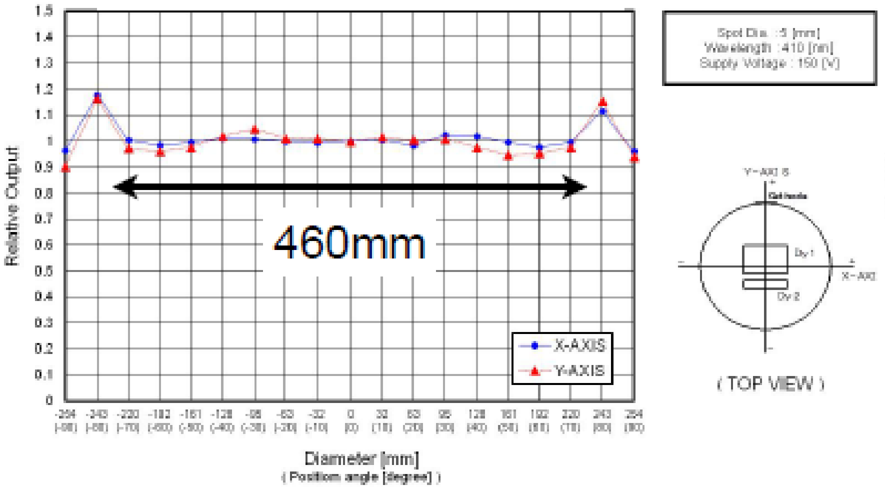


B&L PMT~QE, CE~

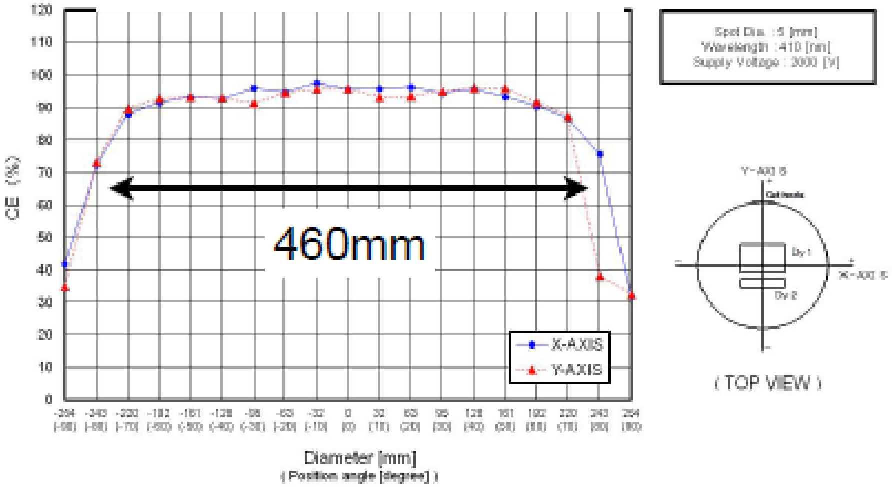
- High-QE photocathode
  - B&L PMT: 32% at 400nm (SK PMT: 22%)
- QE and CE are uniform over 46cm area of the photocathode



QE

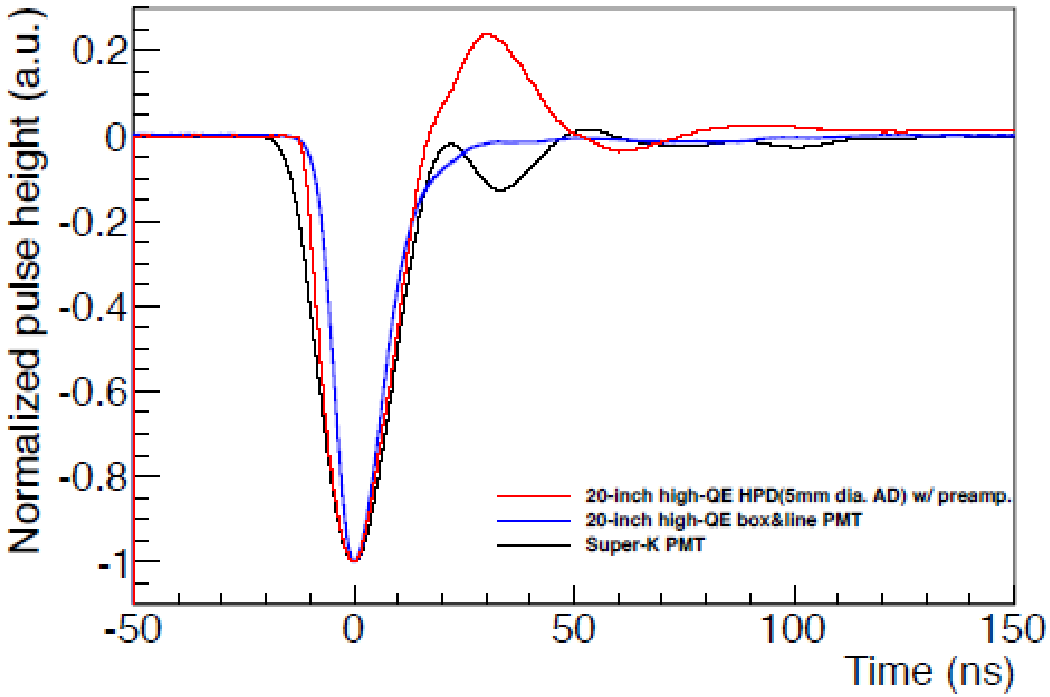


CE

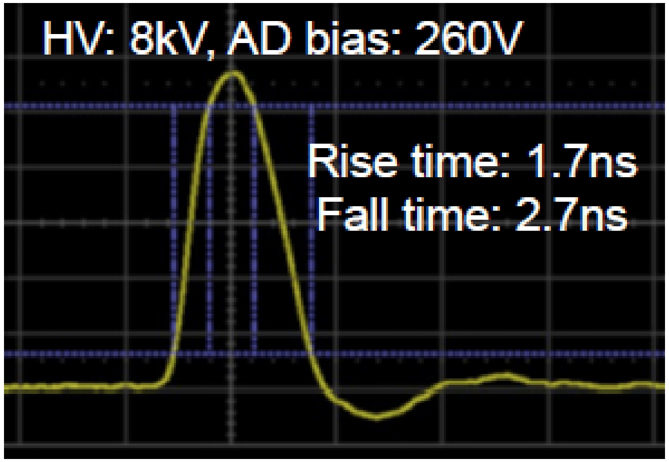


Waveforms

- HPD and B&L PMT are faster than SK PMT



8" HPD w/o preamp.

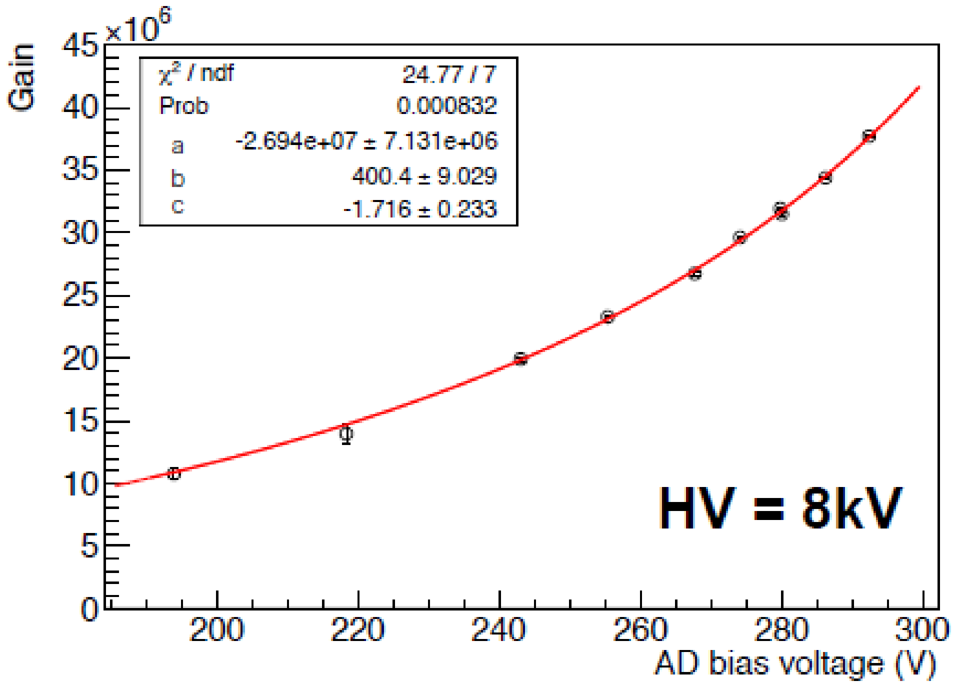


HPD itself has very fast response.

	HPD (20cm HPD w/o amp.)	B&L PMT	SK PMT
Rise time (ns)	7.4 (1.7)	6.7	10.6
Fall time (ns)	11.5 (2.7)	15.2	13.1
Pulse width in FWHM (ns)	17.1	13.0	18.5

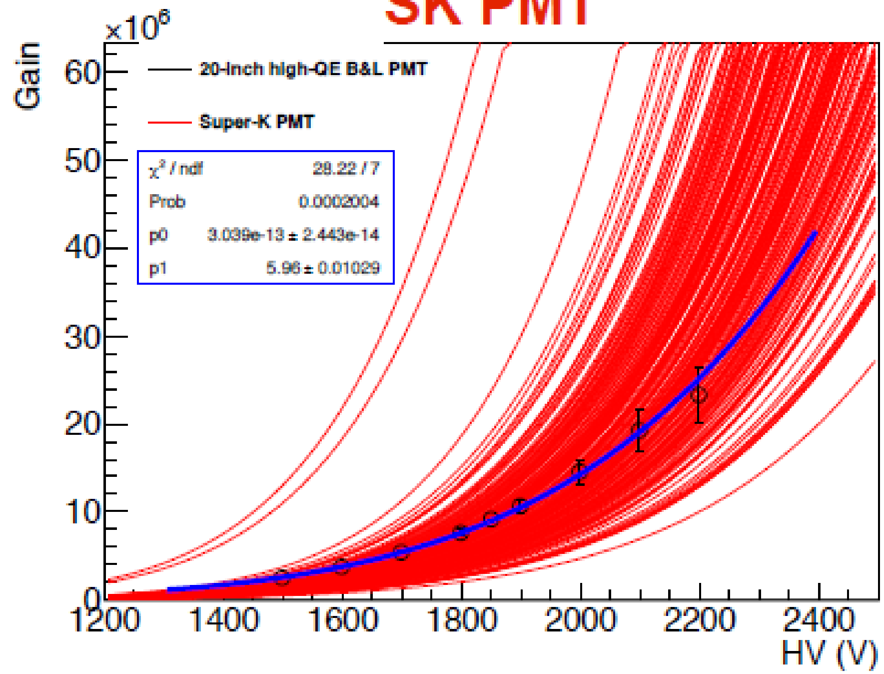
Gain curve

50cm high-QE HPD w/ preamp.



50cm high-QE B&L PMT

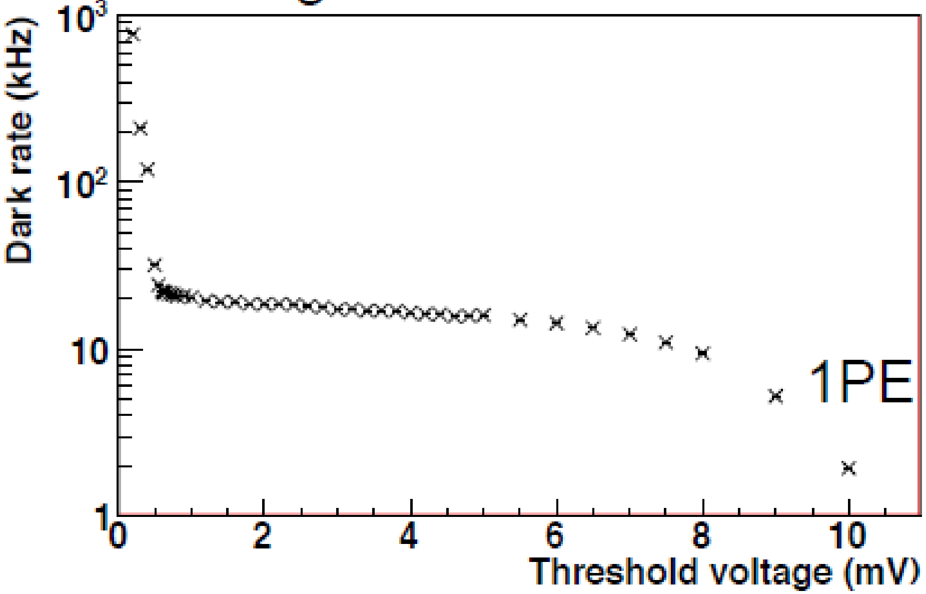
SK PMT



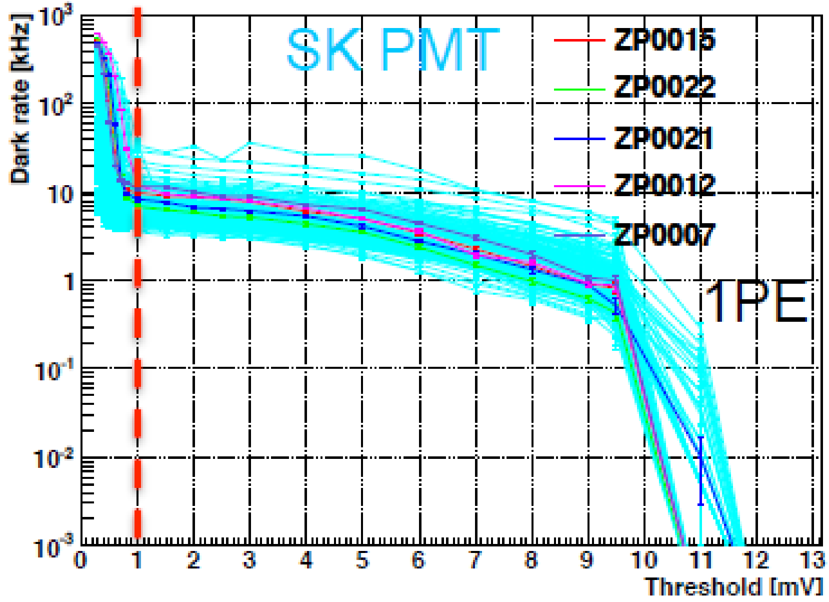
- The shape of gain curve of B&L PMT is almost same as that of SK PMT
- Both HPD and B&L PMT has the gain of 10^7

Dark rate

High-QE B&L PMT



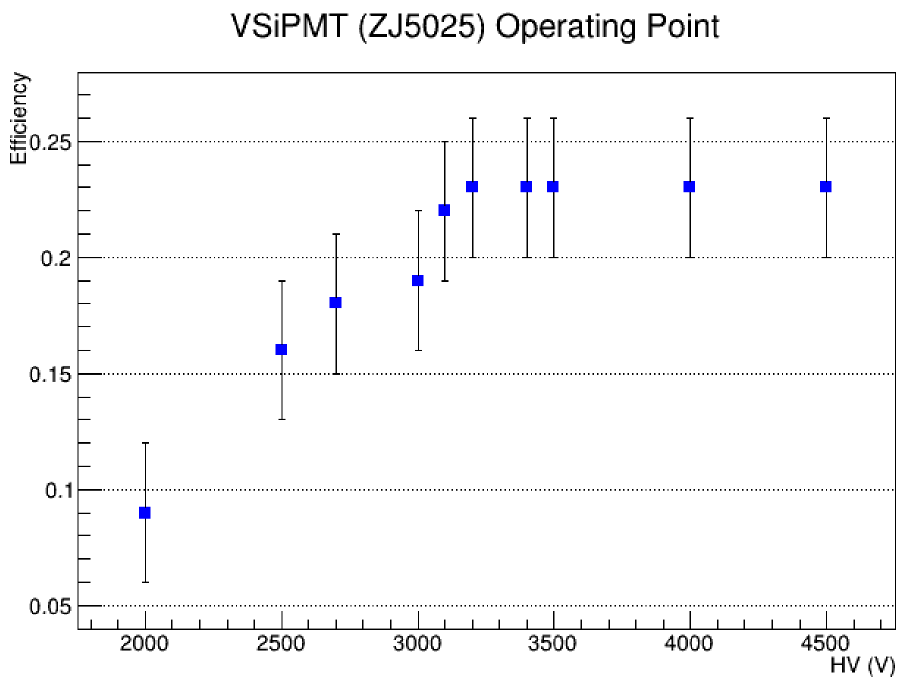
High-QE SK PMT

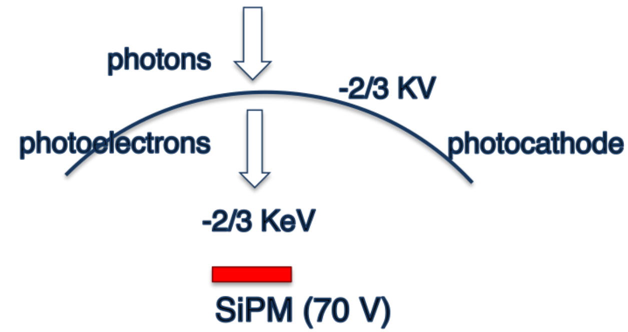


- Dark rate of high-QE B&L PMT is same level as that of high-QE SK PMT

VSiPM: The prototypes characterization

Work function





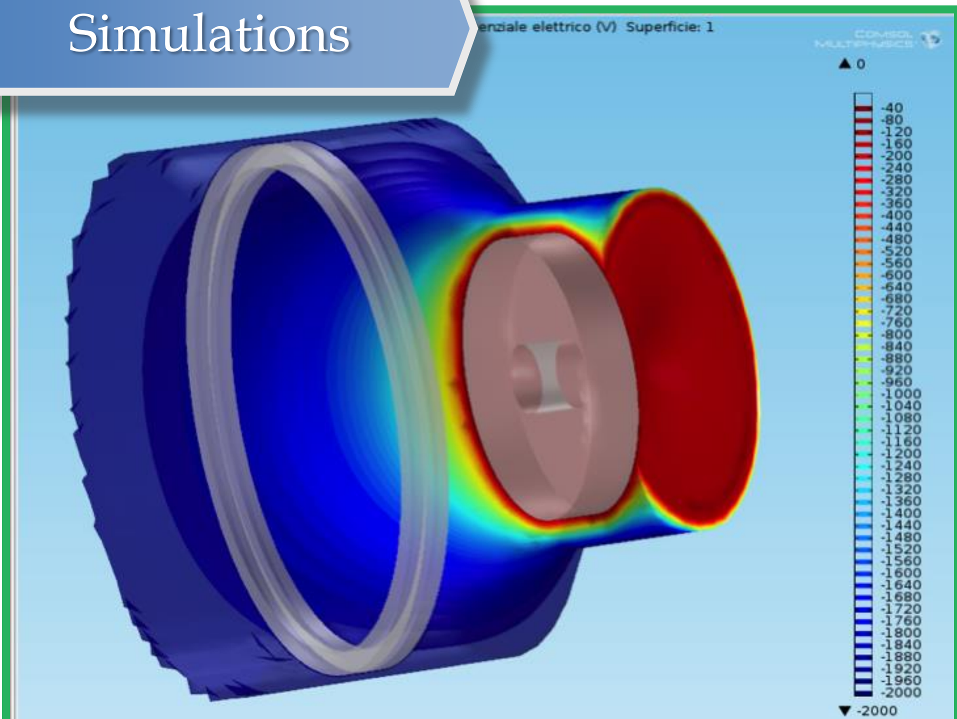
Efficiency is highly stable over 3200 V. No need for high voltage stabilization.

- HV: photoelectron transfer → **NO power consumption (NULL current)** unlike PMTs.
- LV-based gain → **EASY STABILIZATION**
- Reducing the SiO_2 coating layer it will be possible to reach the plateau region at **even lower voltages**.

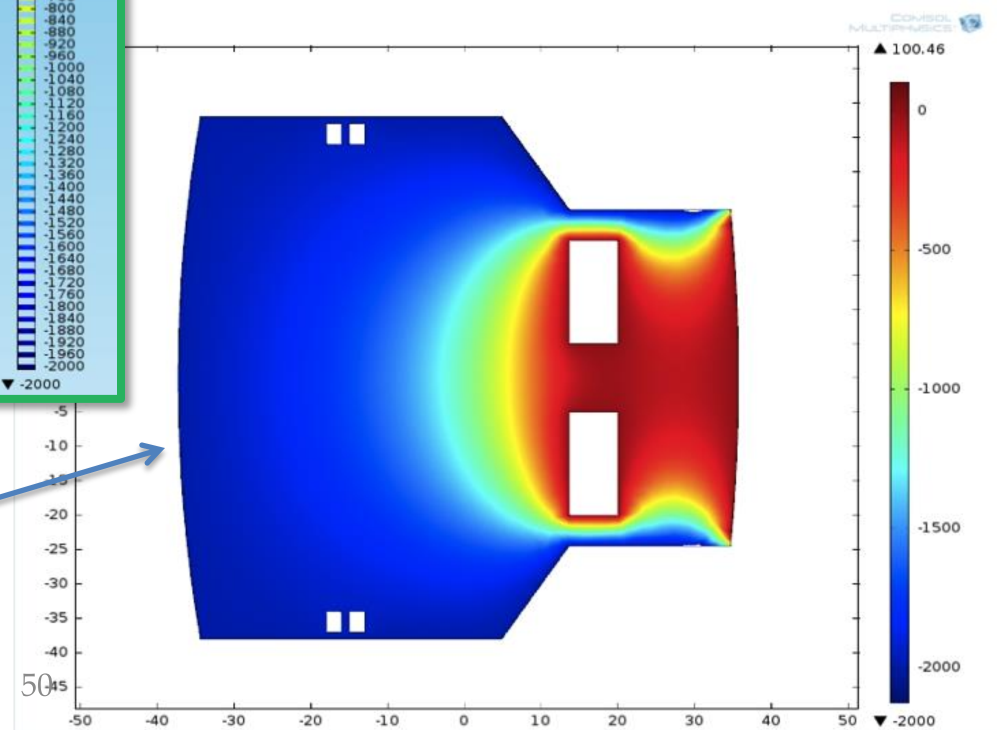
A new project for the
Realization of a 3-inches VSiPMT

Simulations

Focusing optimization



Equipotential surfaces inside the VSiPMT.



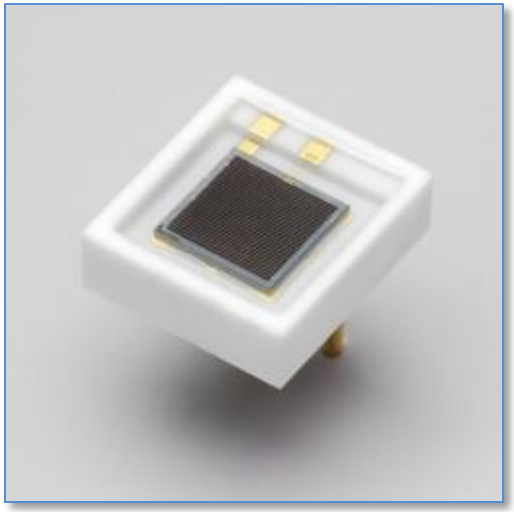
Electroctatic potential distribution inside the VSiPMT.

A new project for the
Realization of a 3-inches VSiPMT

The prototypes by Hamamatsu showed a linearity range much lower than expected

We selected a special non-windowed SiPM with a high pixel-number and a reasonable noise in order to achieve a wide dynamic range

SiPM selection and characterization



SiPM	MPPC Hamamatsu S10943-3360 (X) n.1
V_{bias}	67.15V
Gain	1.25×10^6
Dark Count Rate	≈ 400 kcps
Size	3x3 mm^2
Pixel Size	50 μm
Number of pixels	3600

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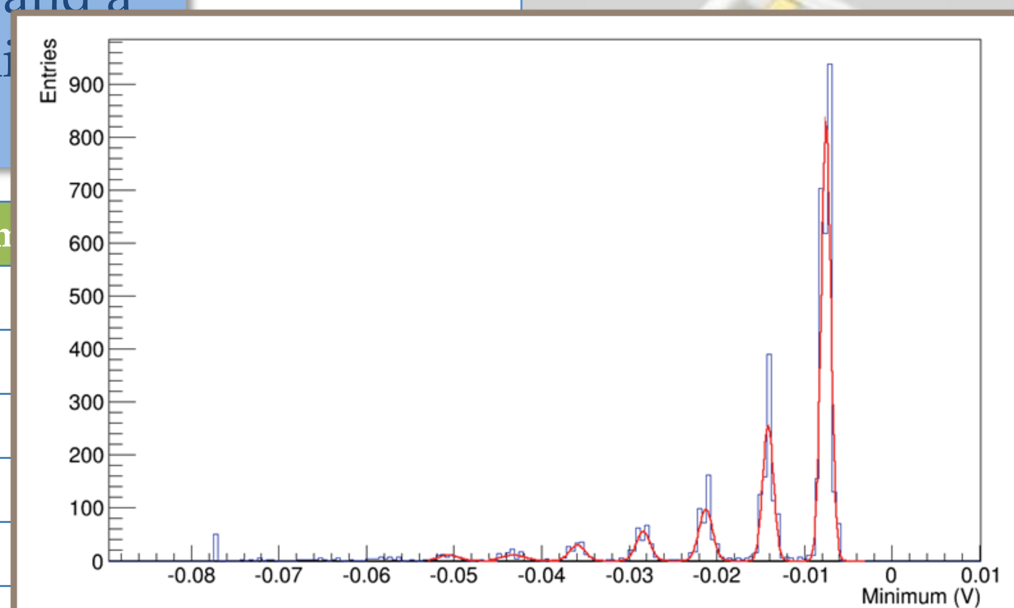
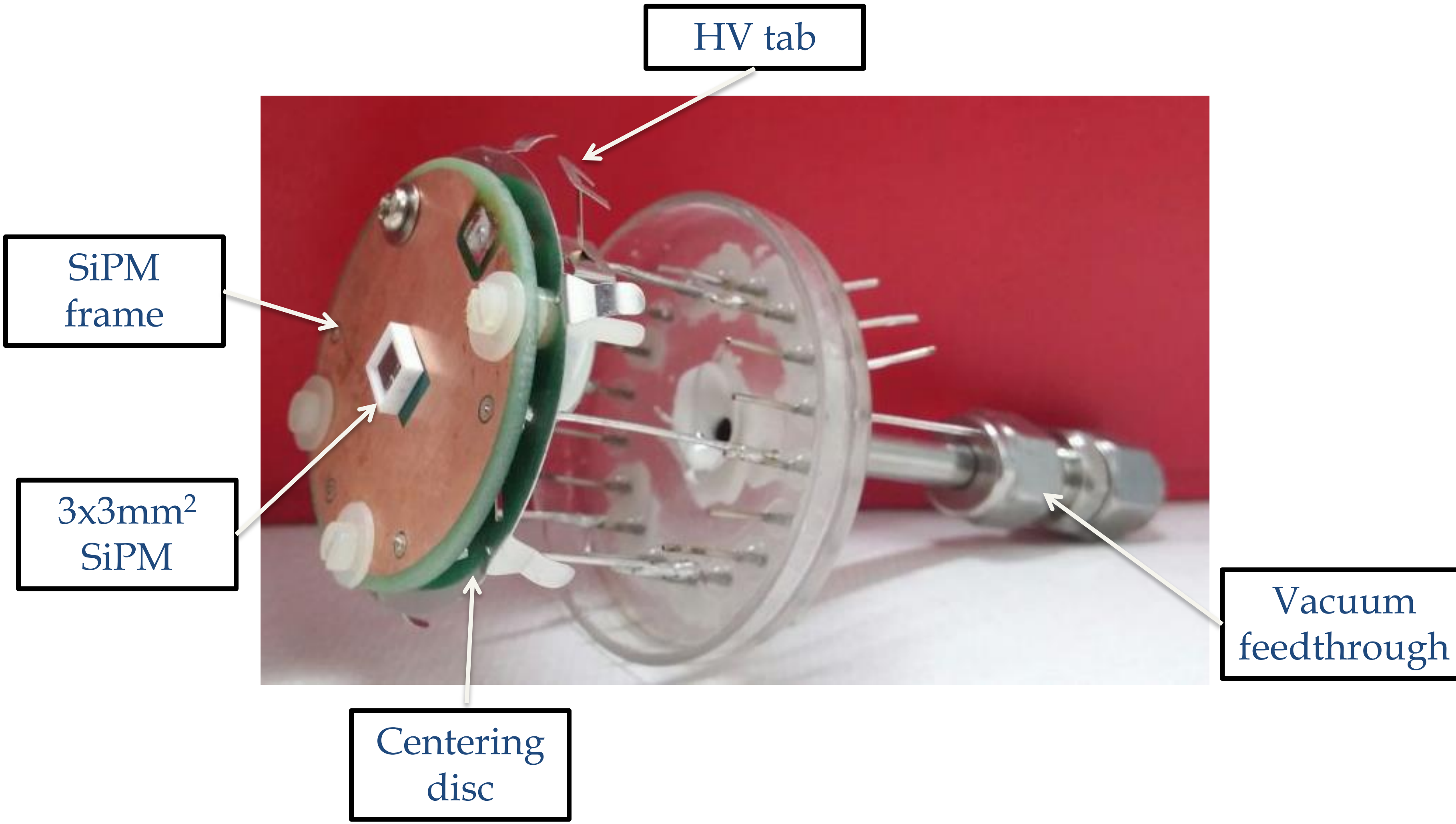
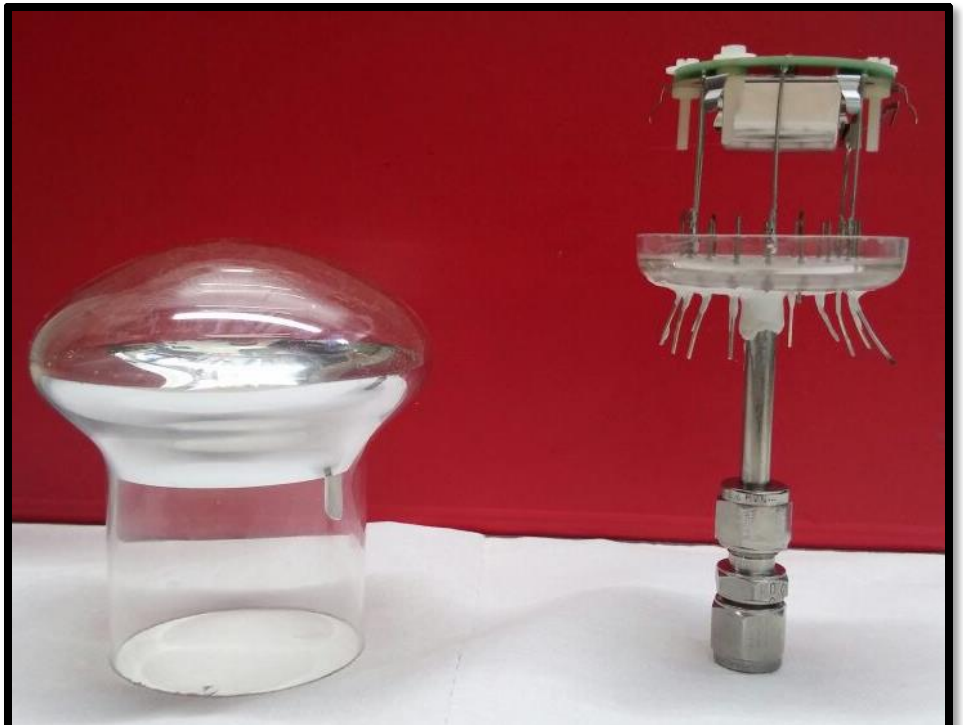


SiPM	MPPC Haman
V_{bias}	
Gain	
Dark Count Rate	
Size	
Pixel Size	
Number of pixels	[illegible]

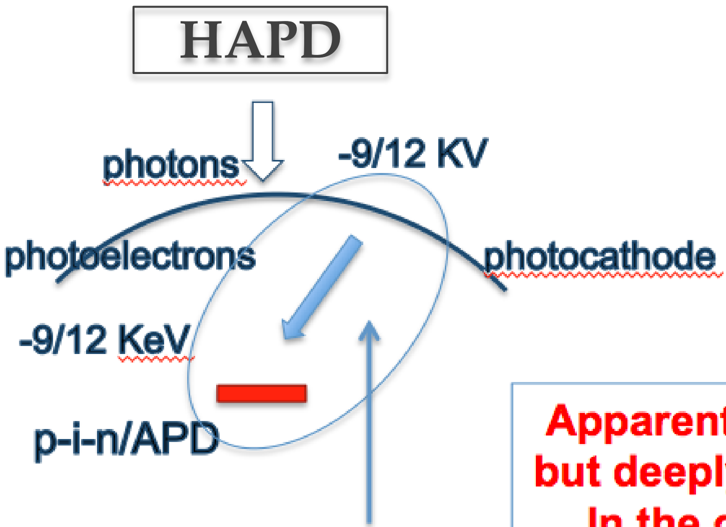
A new project for the
Realization of a 3-inches VSiPMT

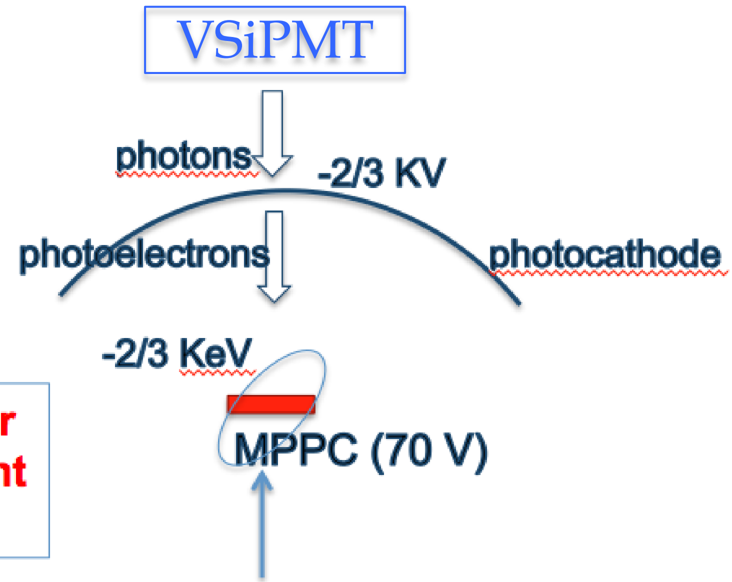


A new project for the
Realization of a 3-inches VSiPMT



VSiPMT vs HAPD





Apparently similar but deeply different In the concept

Need of HV to obtain a high gain

High gain obtained with low voltage in the SiPM

Drawbacks of the APD solution

- $G = E_{phe}/E_{e,h} \approx 10^4\text{-}10^5$
- too **low Gain. HV gain required**
- G **depending** on HV
- Need a strong HV critical **stabilization.**
- Difficult **and expensive insulation**

Advantages in the VSiPMT solution

- **G > 10^6** : a factor 10 higher.
- **Low HV, no need for bombardment gain** only energy for photoelectron transfer
- **Low voltage Gain: easy to stabilize**
- **Normal insulation**

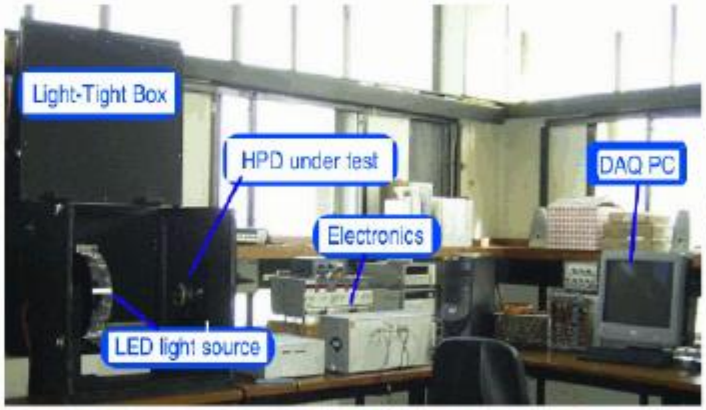
VSiPMT vs PMT

Features	PMT	VSiPMT	Comparison
Efficiency	$QE_{photocathode}$x $\varepsilon_{1dynode(0.8)}$	$QE_{photocathode}$x $FillFactor_{(twd\ 1)}$	≈equivalent
Gain	10^6 - 10^7	10^5 - 10^6	PMT
Timing	ns	Fraction of ns (no dynode spread)	VSiPMT
Linearity	Depending on gain	Depending on #cells	≈equivalent
Power Consumption	Divider Dissipation	VSiPMT: No dissipation Amp. (G=10-20): <5mW	VSiPMT
Power Supply Stability	HV Stabilization	LV easy stabilization	VSiPMT
Dark counts rate (new)	≈ kHz @ 0.5pe	≈ few kHz @0.5pe	≈equivalent (today)
Photon Counting	Difficult	Excellent	VSiPMT
Afterpulse (new)	≈10% @0.5pe	<0,3% @0.5pe	VSiPMT (today)
Peak-to-valley ratio	≈3	>60	VSiPMT

Contributions from the UK

In contact with Hamamatsu UK. Ordered

HPD Testing in Scotland:



Test station at Edinburgh, showing dark box and electronics

J.McCarron University of Edinburgh 6

Recent photo

Photo-sensor HPD R12112 (A-type): General Specification

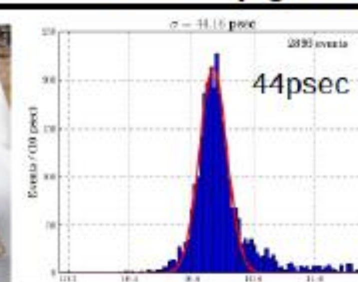
Parameter		Description/Value	Unit
Spectral Response		300 — 650	nm
Typical Maximum Photocathode Sensitivity (Quantum Efficiency)@390nm		20	%
Photocathode Material		Bialkali	-
Minimum Effective Photocathode Area		180	mm dia.
Window Material		Borosilicate glass	-
Electron Multiplication Method		Semiconductor Electron Bombardment Multiplying System	-
Target Semiconductor		Stamp Backside Illumination Avalanche Diode	-
Absolute Maximum Ratings	Photocathode – Target Semiconductor	10	kV
	Target Bias Voltage	350	V

Planning to do quality checks, make tests in magnetic field and work on new preamp.

Experience in LHCb by Edinburgh:

- Responsible for HPD testing during construction and now operations
- Testing performance of multianode photomultipliers MaPMTs for LHCb upgrade

- Investigating the option of using the LAPPDs (Large Area Picosecond Photo-Detectors) at QMUL both sw and hw when available. Relevant for ND.



A new design of large area MCP-PMT for the next generation neutrino experiments

Yuekun Heng

IHEP, Beijing

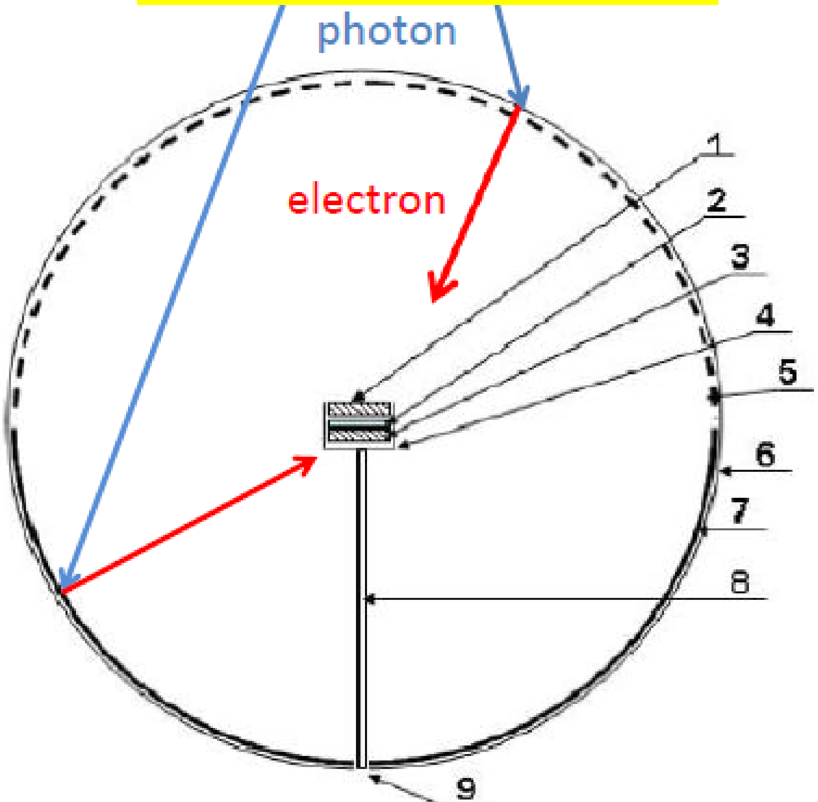
Representing the collaboration

The new design of a large area PMT

1) Using two sets of Microchannel plates (MCPs) to replace the dynode chain

2) Using **transmission photocathode (front hemisphere)**
reflective photocathode (back hemisphere) } ~ 4π viewing angle!!

60% absorbed, 40% passed



1. up MCP
2. anode
3. down MCP
4. insulated trest
5. transmission
6. glass shell
7. reflection pho
8. bracket of the
9. glass joint

- Quantum Efficiency:
  - Transmission photocathode: 20%
  - Reflection photocathode: 40%
- MCP Collection Efficiency: 80%

Photon detection efficiency:

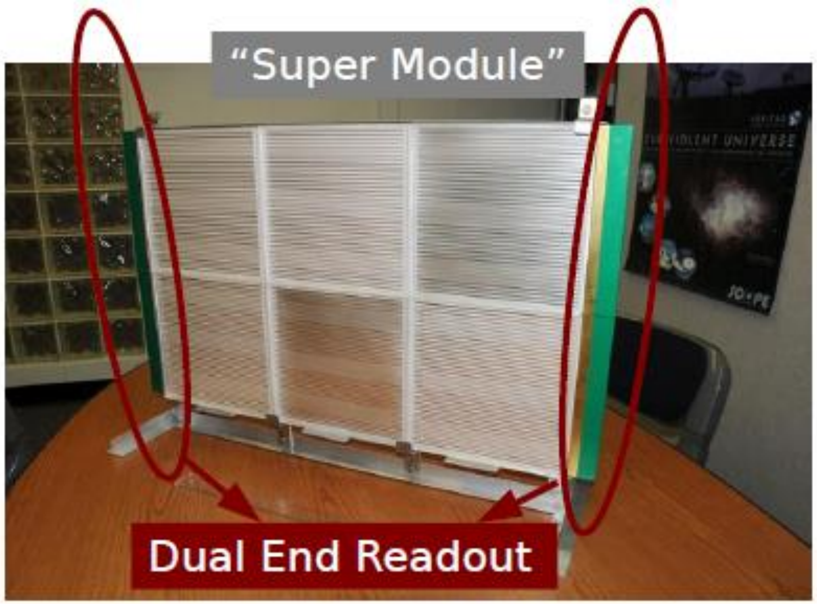
→20% * 80% = 16%

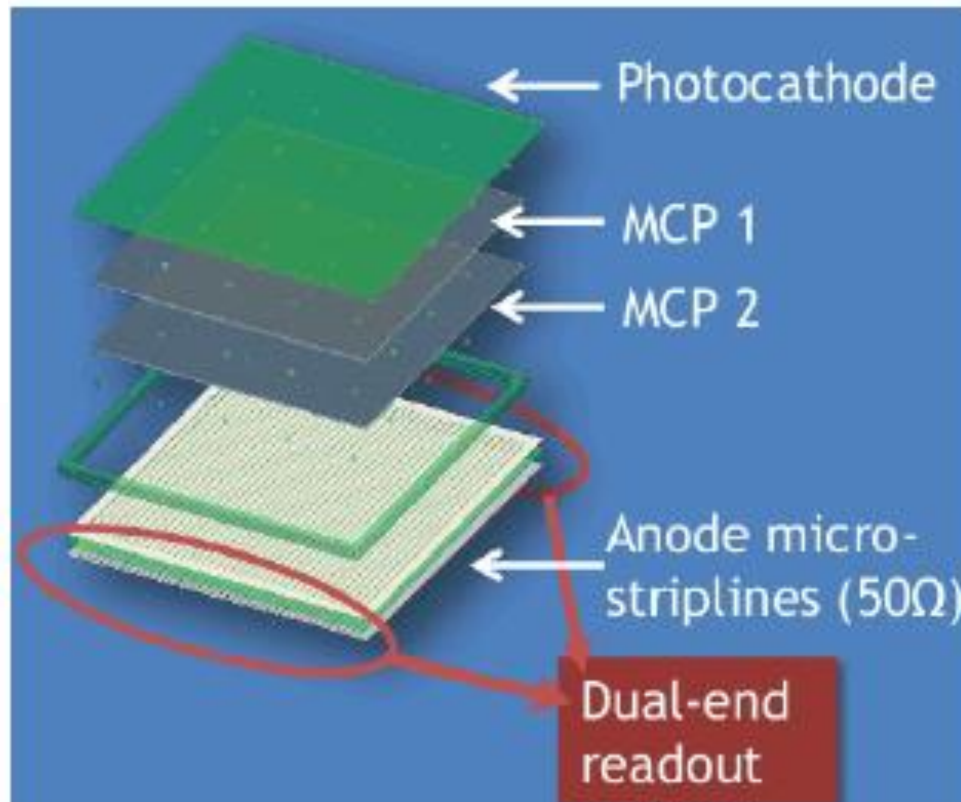
→40% * 40% * 80% = 13%

➤ Total Photon Detection Efficiency: ~30%

Photon Detection Efficiency: 16% → 30% ; ×~2 at least !

LAPPDs


"Super Module"
Dual End Readout


Photocathode
MCP 1
MCP 2
Anode micro-
striplines (50Ω)
Dual-end
readout

Basic requirements for HK photodetectors

- High efficiency single photon detection
- Good T resolution (a few ns σ for 1 PE)
- Good Q resolution and linearity in a wide dynamic range (1-1000 PEs for a 50cmϕ PD)
- Low dark rate (< several kHz for a 50cmϕ PD)

- Long-term stability (> 20 years)
- High pressure tolerance (depending on detector designs)