The Hyper-Kamiokande Experiment

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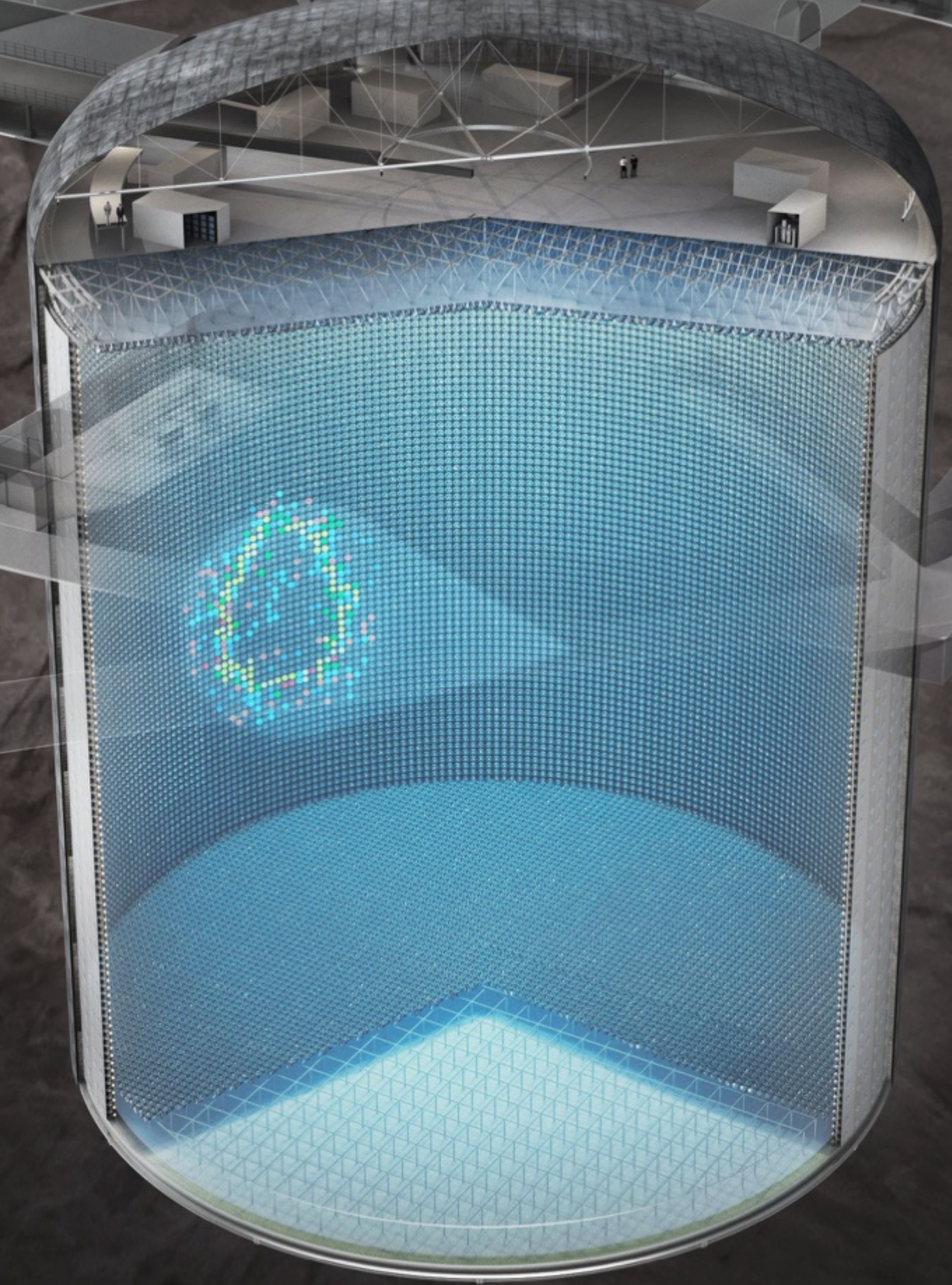
On behalf of the
Hyper-Kamiokande OD
working group*

22 November 2023
CERN
Phose2023 workshop



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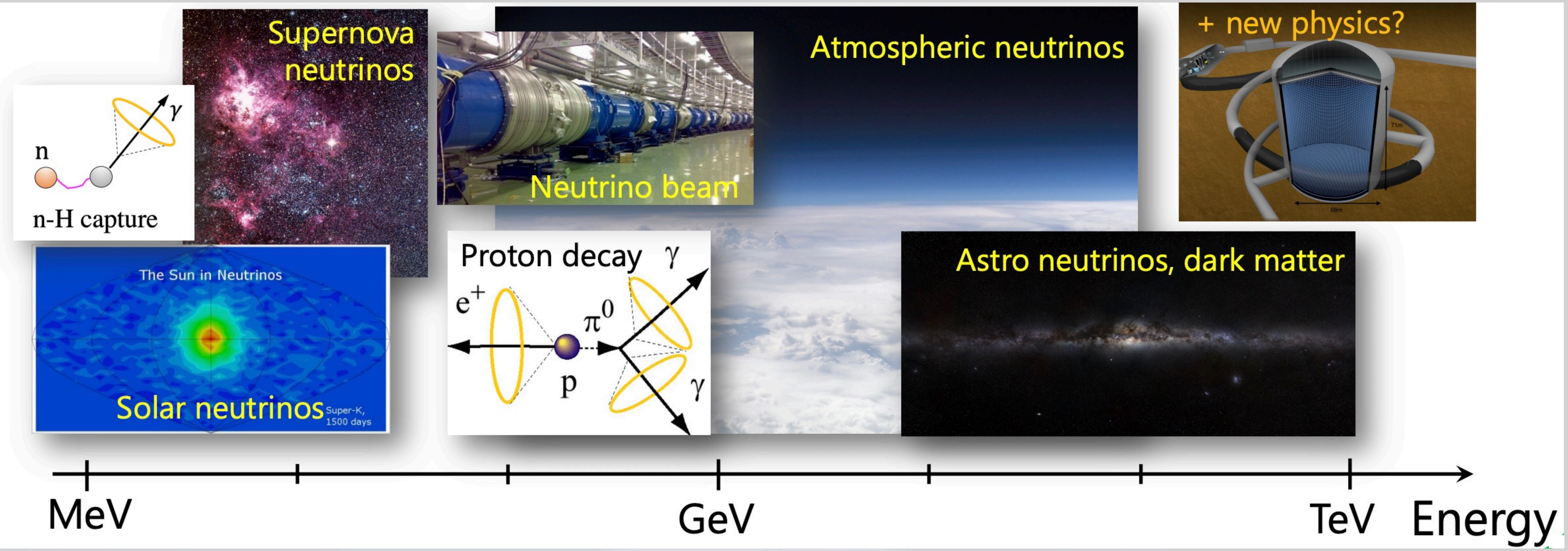
NIKKEN SEKKEI

Hyper-Kamiokande

- Hyper-Kamiokande is a neutrino experiment aiming to address major questions in science:
  - CP-violation in lepton sector, neutrino mass hierarchy, sterile neutrinos, SN neutrinos, proton decay, BSM physics with neutrino beams
- Under construction for start operations in 2027.

Hyper-K Physics Summary

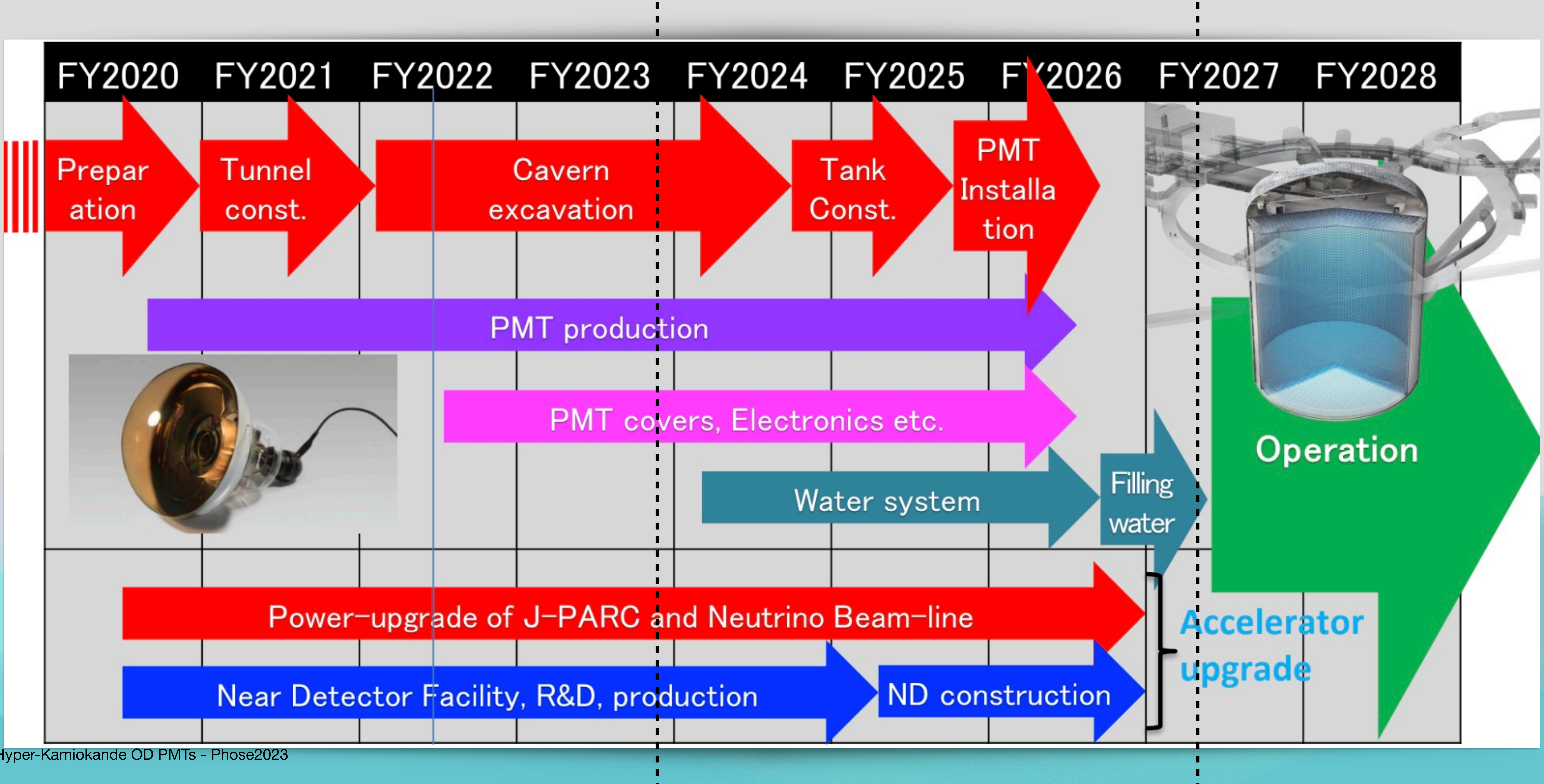
Physics Energy Range



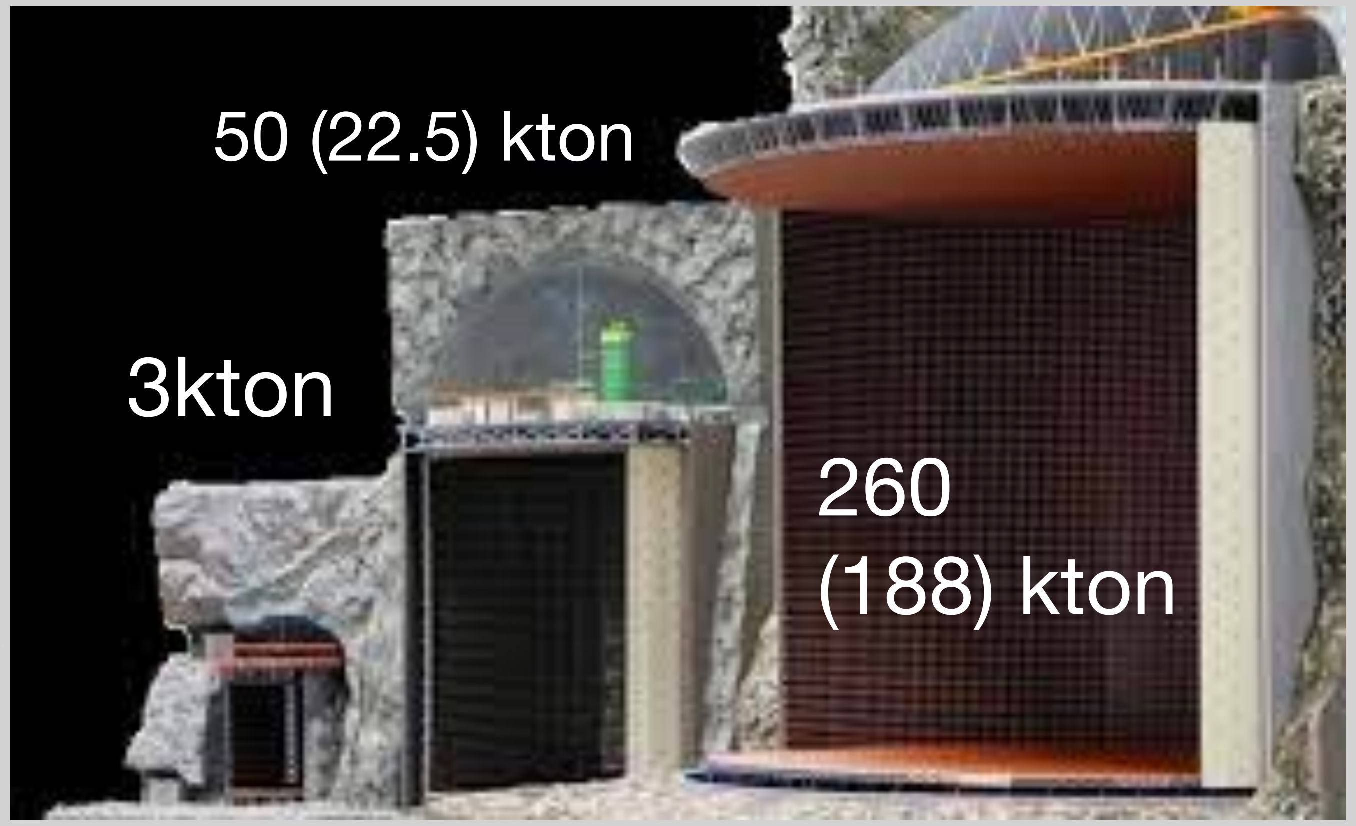
- “Multi-purpose experiment” sensitive to different neutrino physics.
- Wide energy span.
- Astrophysical and human-made sources detected by neutrino experiments.

- Neutrino observation (reactor).
- Oscillation observation (solar, atmospherics).
- Oscillation parameters (accelerator, atmospherics, reactor, solar).
- Supernova observation.
- Extragalactic cosmics observation.

Timeline


FY2020
FY2021
FY2022
FY2023
FY2024
FY2025
FY2026
FY2027
FY2028
Preparation
Tunnel const.
Cavern excavation
Tank Const.
PMT Installation
PMT production
PMT covers, Electronics etc.
Water system
Filling water
Operation
Power-upgrade of J-PARC and Neutrino Beam-line
Near Detector Facility, R&D, production
ND construction
Accelerator upgrade

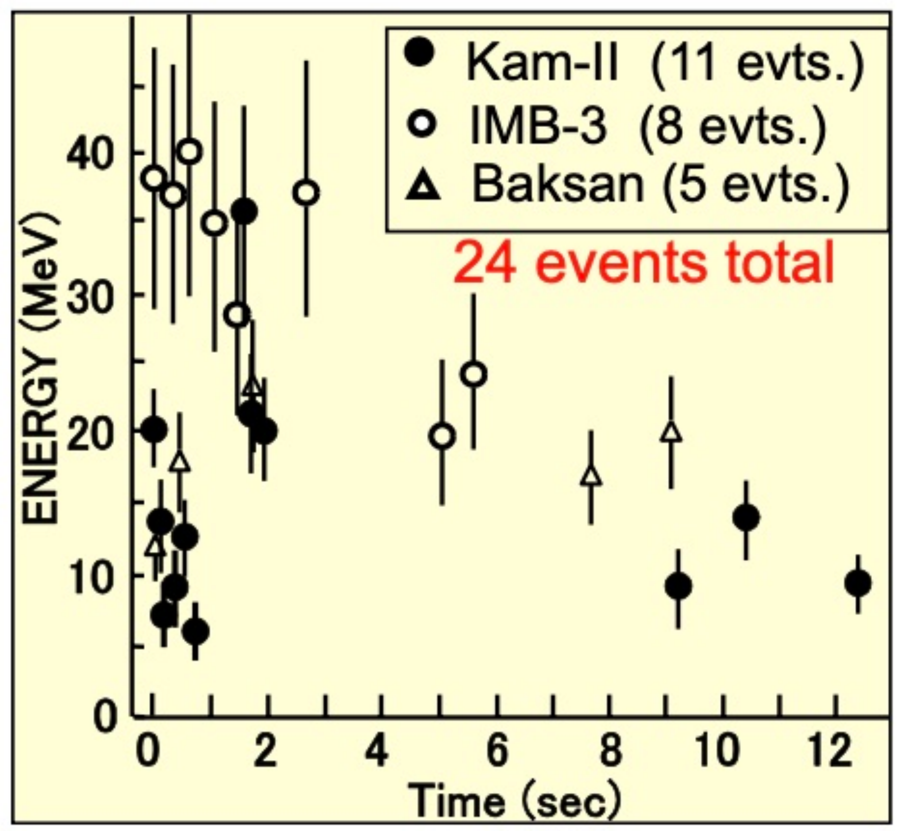
Three generations of Kamiokande



Kamiokande
(1983-1995)

20x

SN1997A



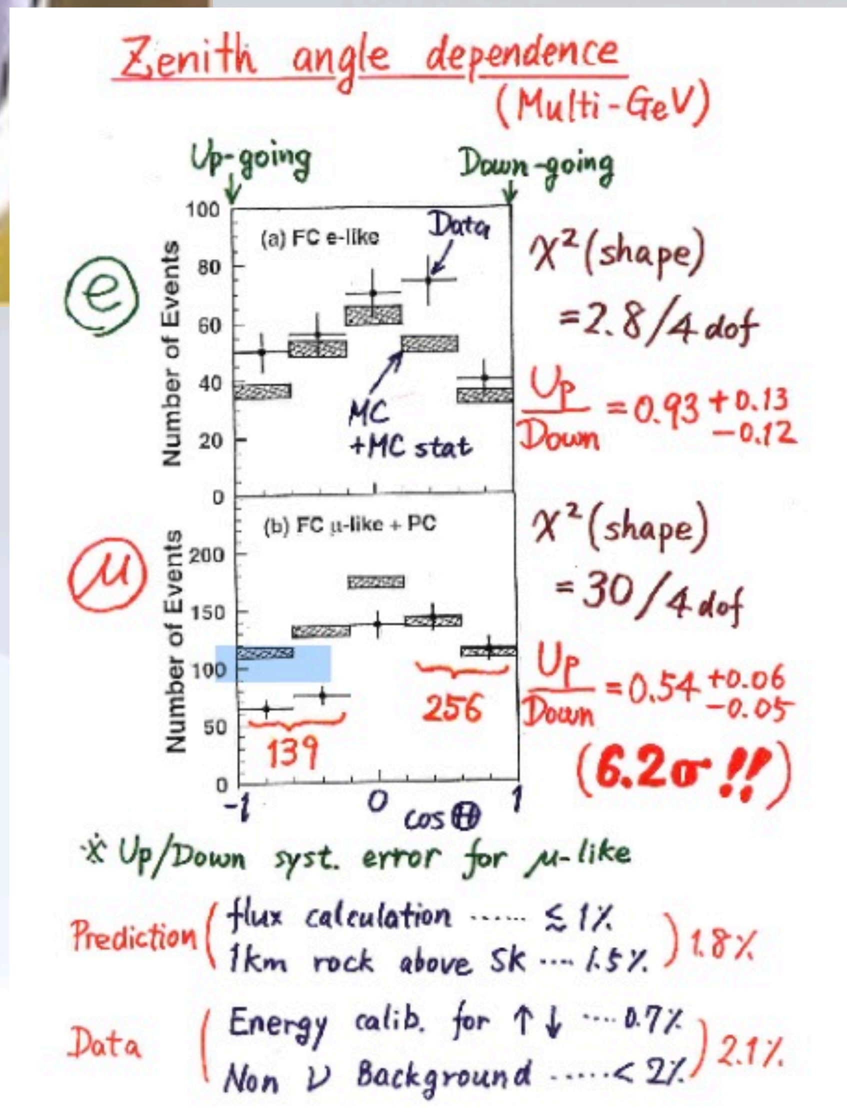
Birth of neutrino astrophysics

Super-Kamiokande
(1996-)

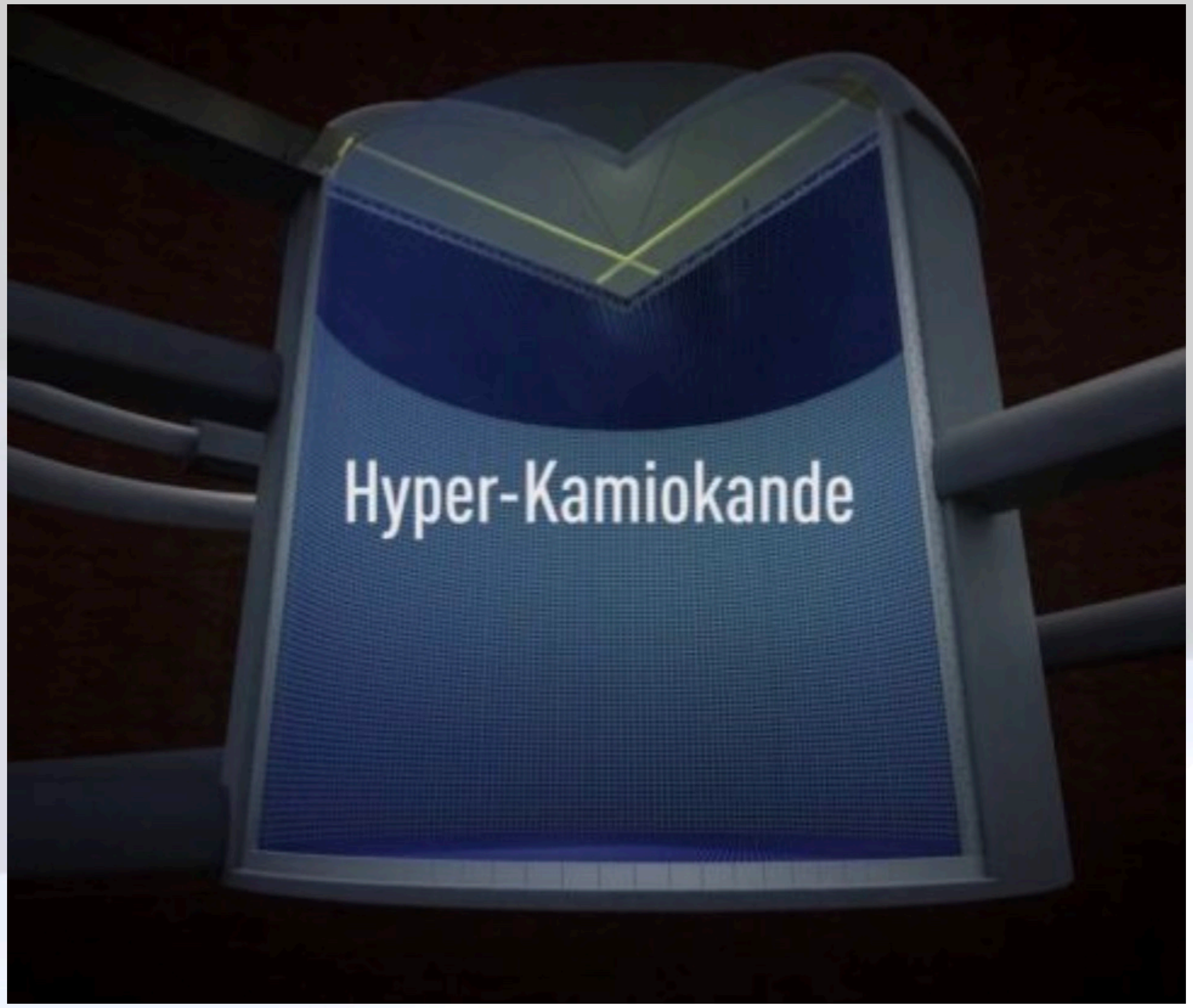
Discovery of neutrino oscillations

8.4x

Takayama (1998)



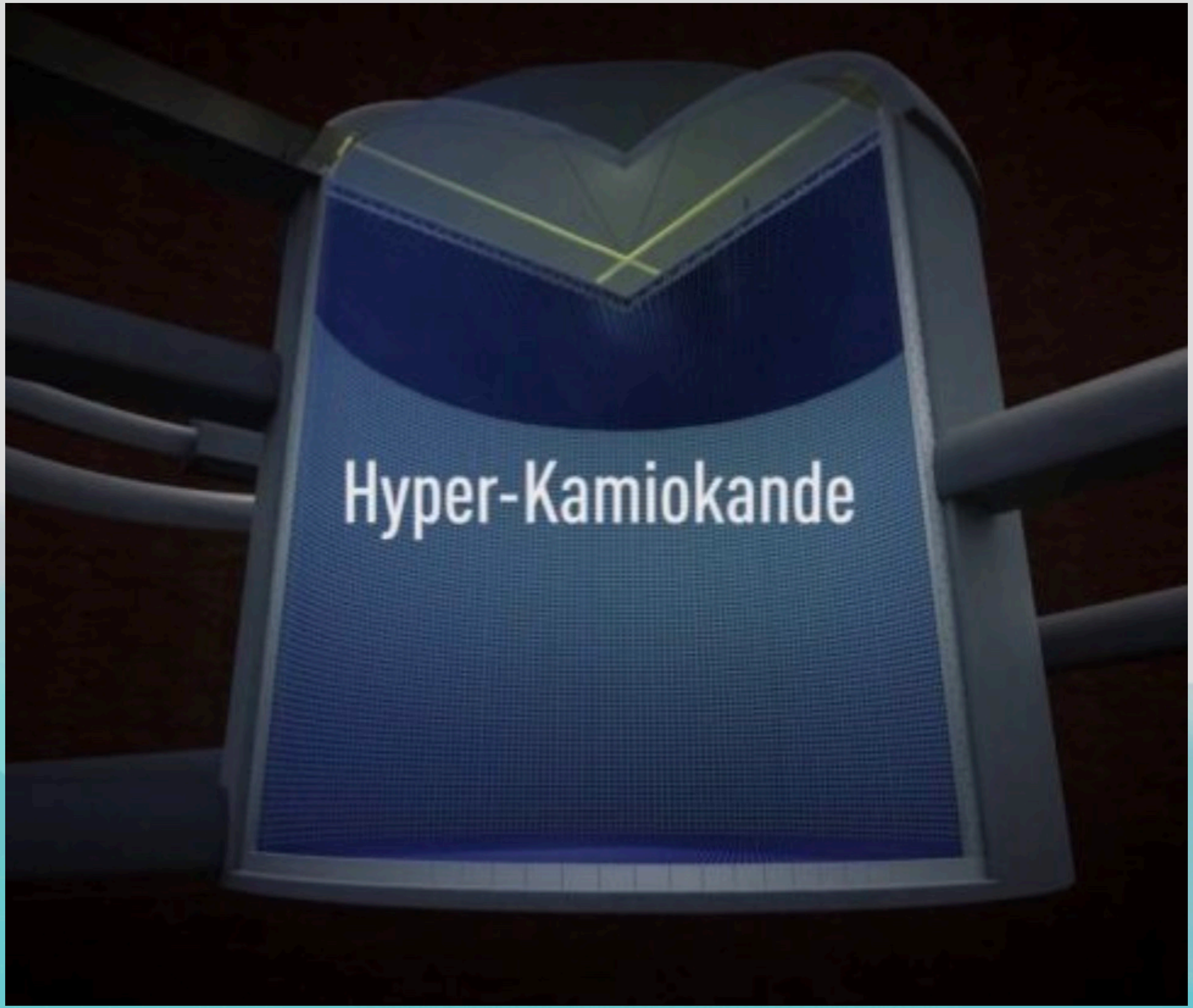
Hyper-Kamiokande
(2027-)



CP, astrophysics, rare decays

Hyper-Kamiokande Detector Concept

- 258 kton of purified water
  - 217 kton Inner Detector (ID) + veto OD
  - 188 kton FV → x8.4 Super-K
- 20k 20” (50cm)PMTs in ID
  - photo-cathode coverage 40%(SK) → 20% (HK) compensated with
  - New generation Hamamatsu Box&Line RI 2860 PMTs (R3600 in SK)
  - 50 % higher quantum efficiency (30%)
  - x 2 better charge resolution (30%)
  - x 2 better timing resolution (1.5 ns)
  - Same dark rate (4 Hz)
- + a few thousands multiple mPMTs
  - 19 x 3” (8cm) PMTs inside one vessel
  - directional information

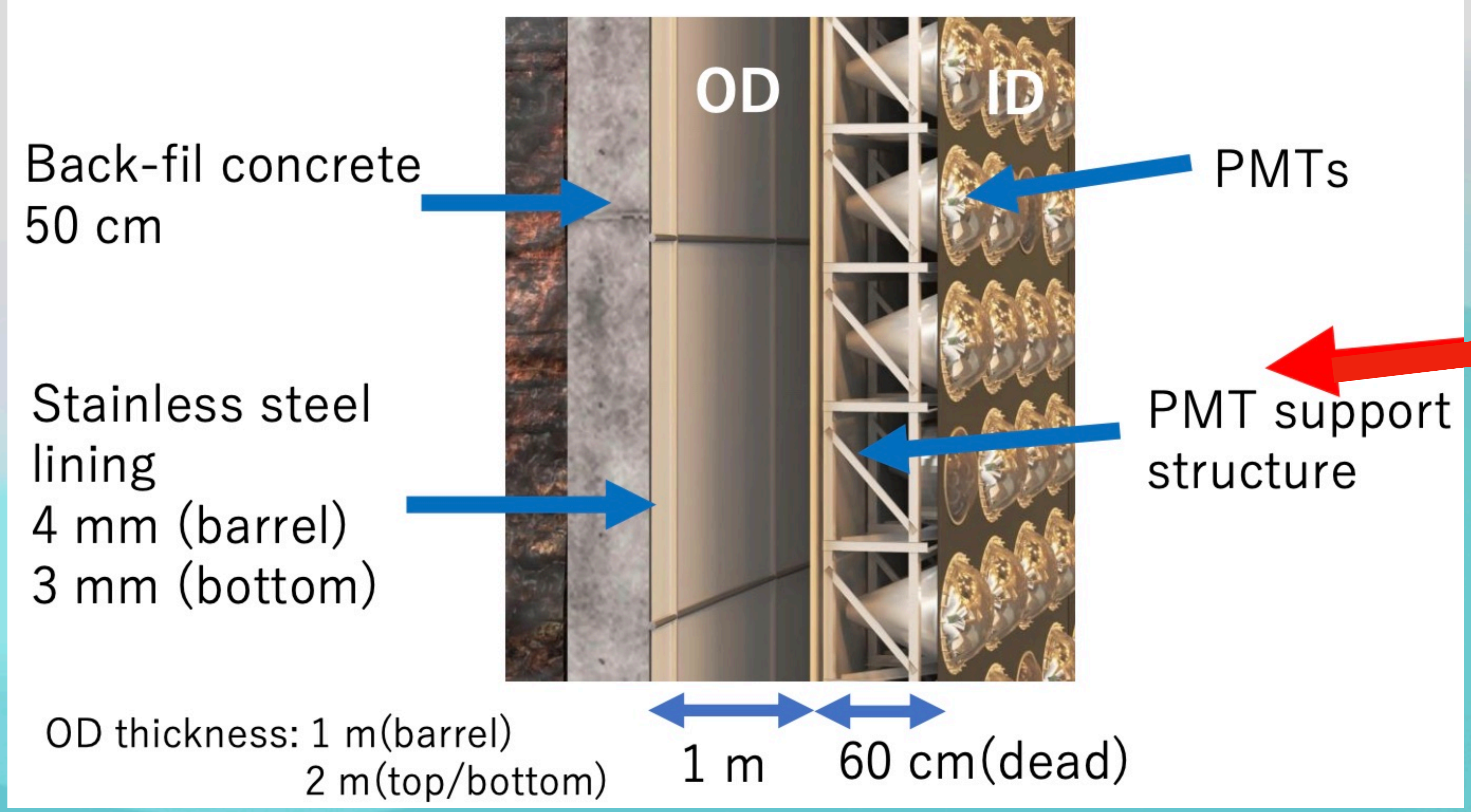


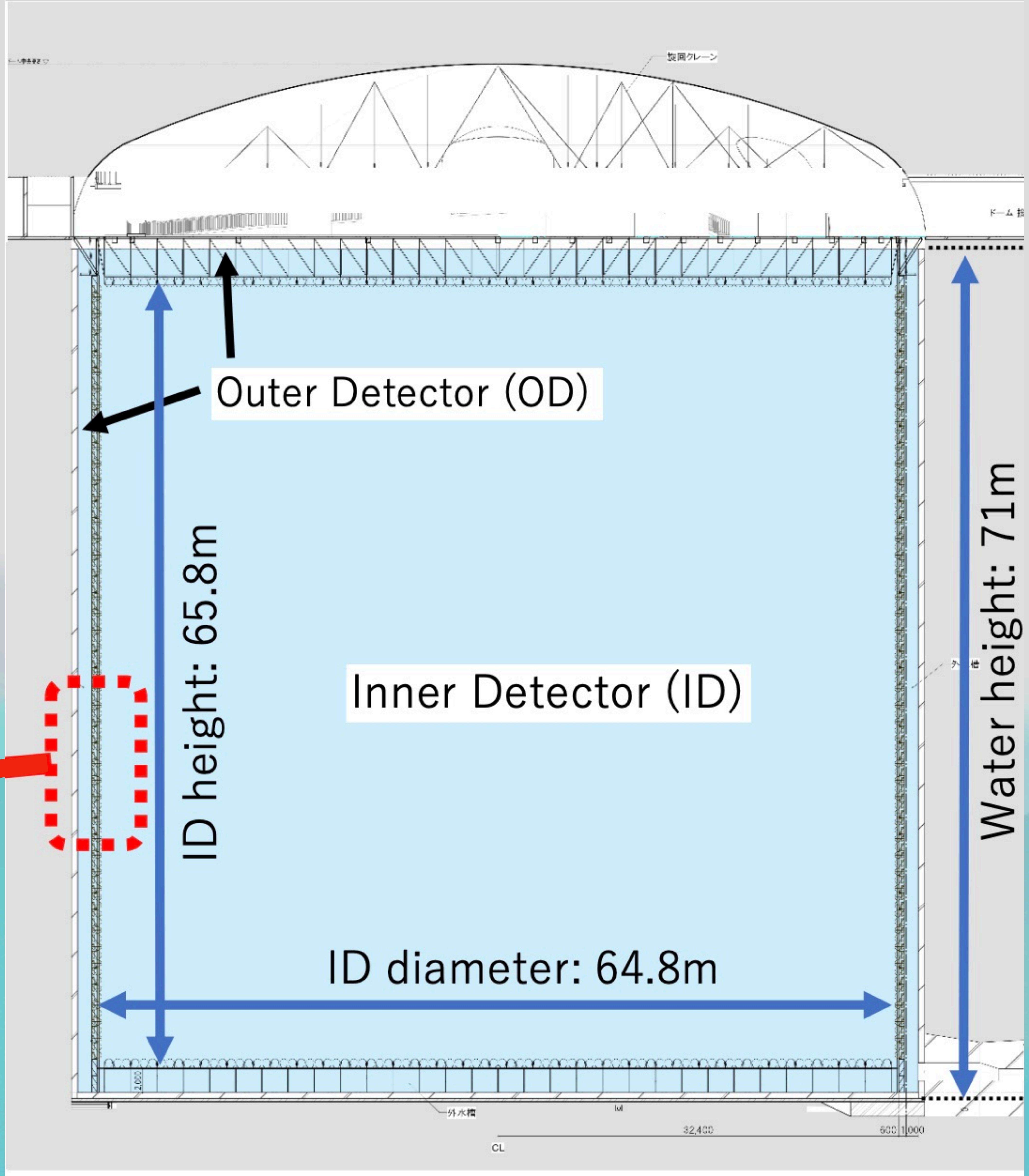
Far Detector

Size of the water tank.

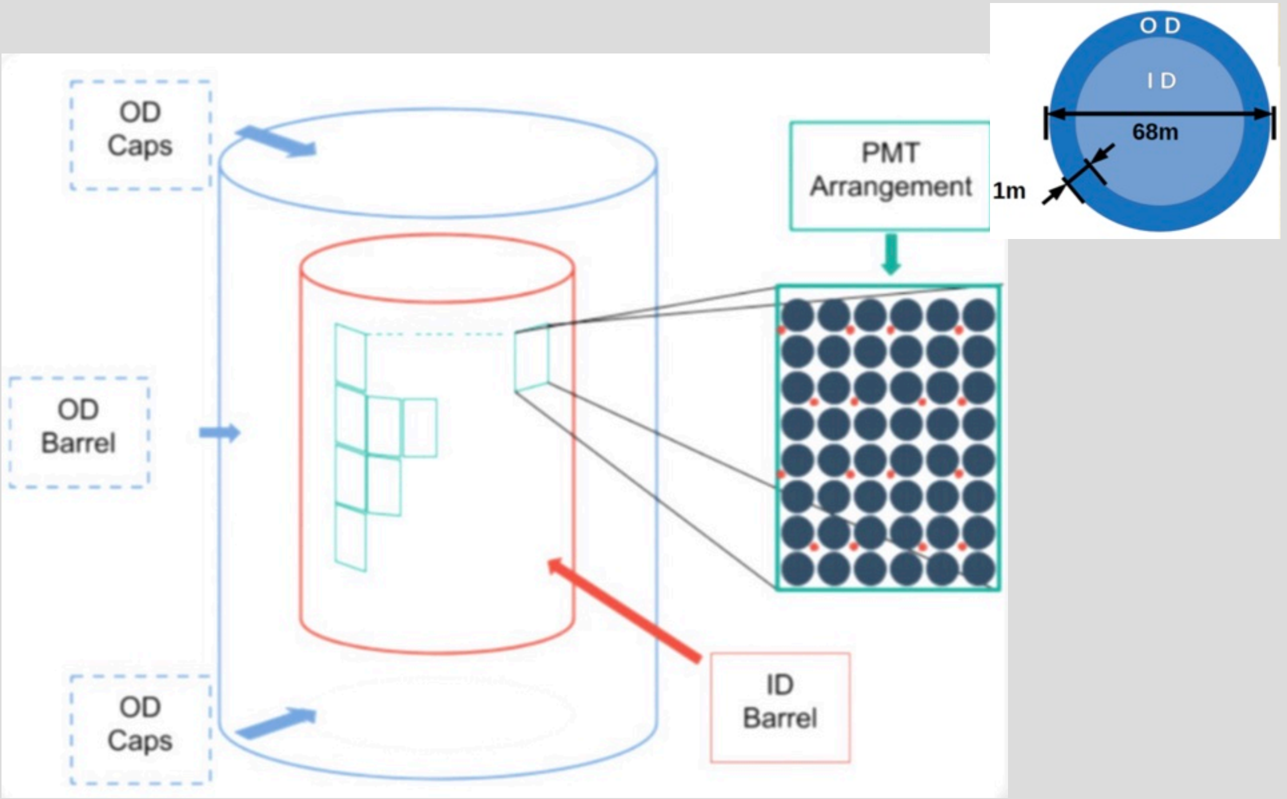
Tank size	Φ68 m × H 72 m
Water height	71 m
ID volume	216.9 kt
Fiducial volume	188.4 kt
ID surface	19991.1 m^2

OD=Outer Detector ID = Inner Detector

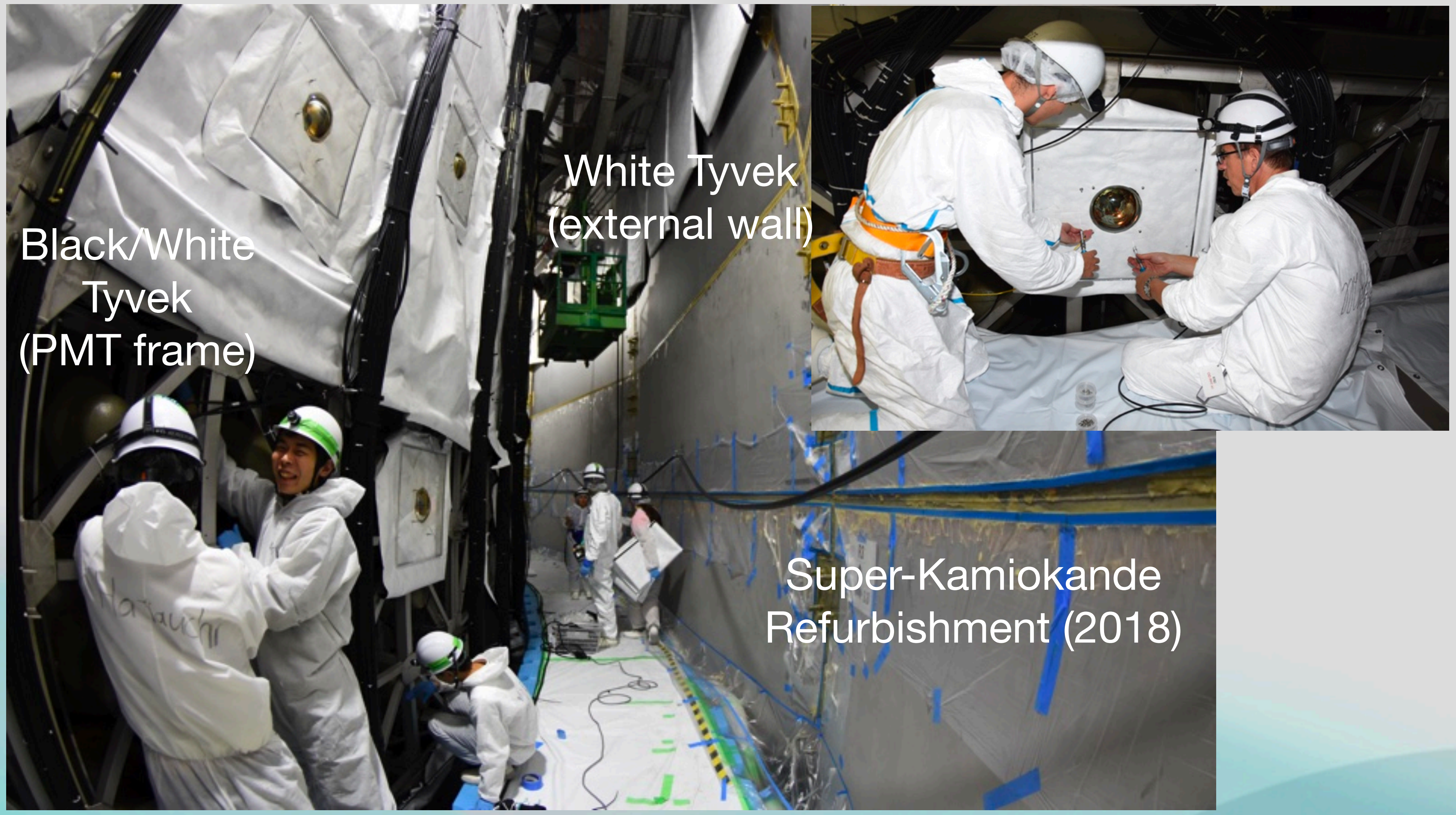


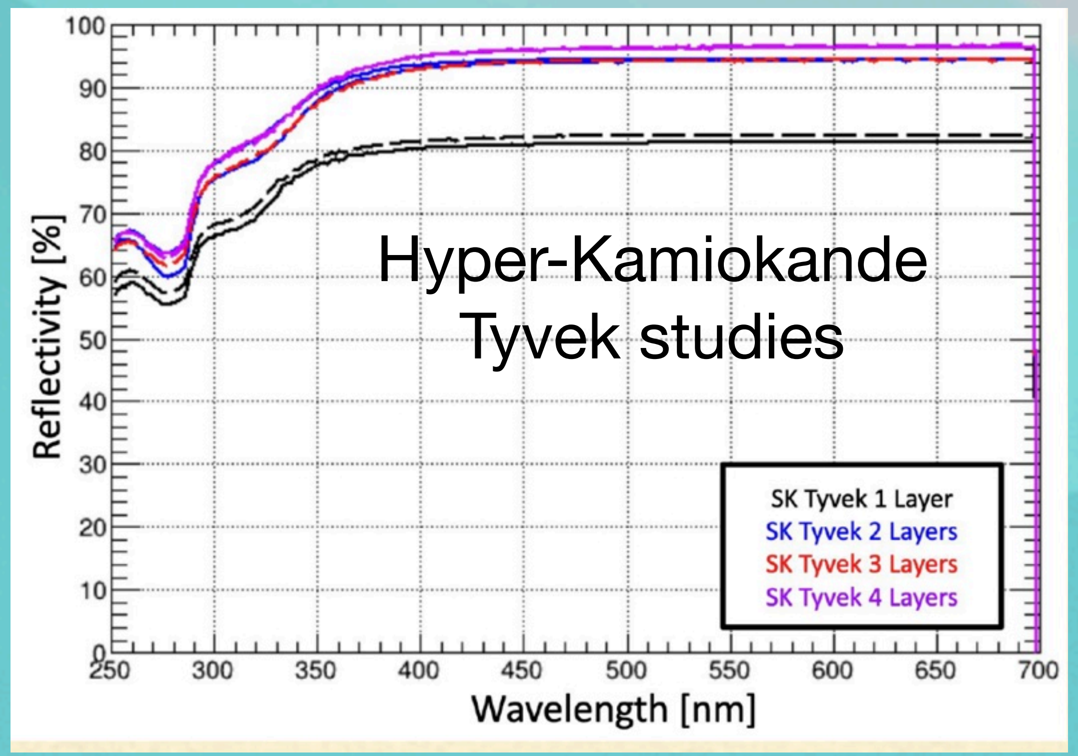


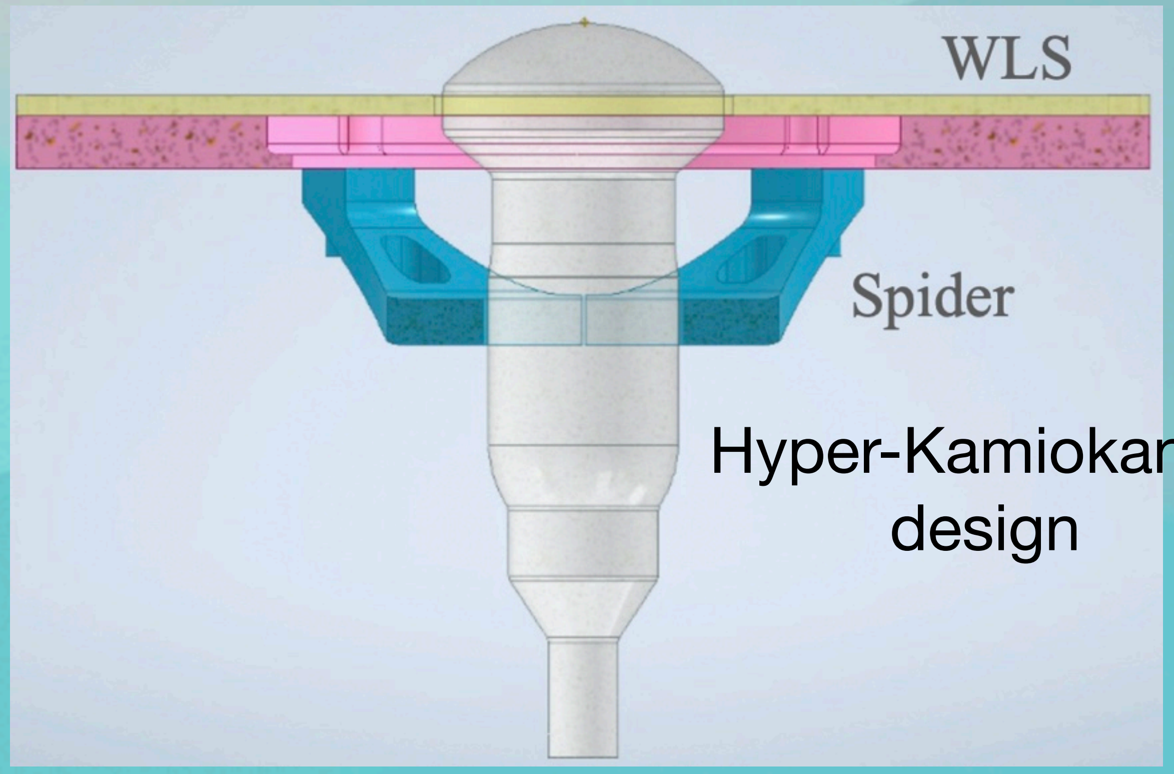
Far Detector Outer Detector



- Optically separated ID and OD
- Challenges (with respect to Super-Kamiokande)
  - Shallower overburden 1000 m → 600 m
  - Larger Hyper-K volume
  - Cosmic rate 2 Hz → 45 Hz
  - Narrower OD region 2.6/2.7 m → 1/2 m (caps)
- Performance requirements
  - Veto inefficiency 10^{-4}
  - ~4m accuracy of muon exit/entrance positions
- Provide passive backgrounds shield
- Low radioactivity < 10 mBq (ID&OD)
- Thermal power < 1 W per channel
- Longevity and enough redundancy → operation for decades + high-cost of draining and intervention
- Light-collection
  - 3,600 3” (8cm) PMTs
  - Tyvek coverage on walls
  - WLS plates







Tank Frame

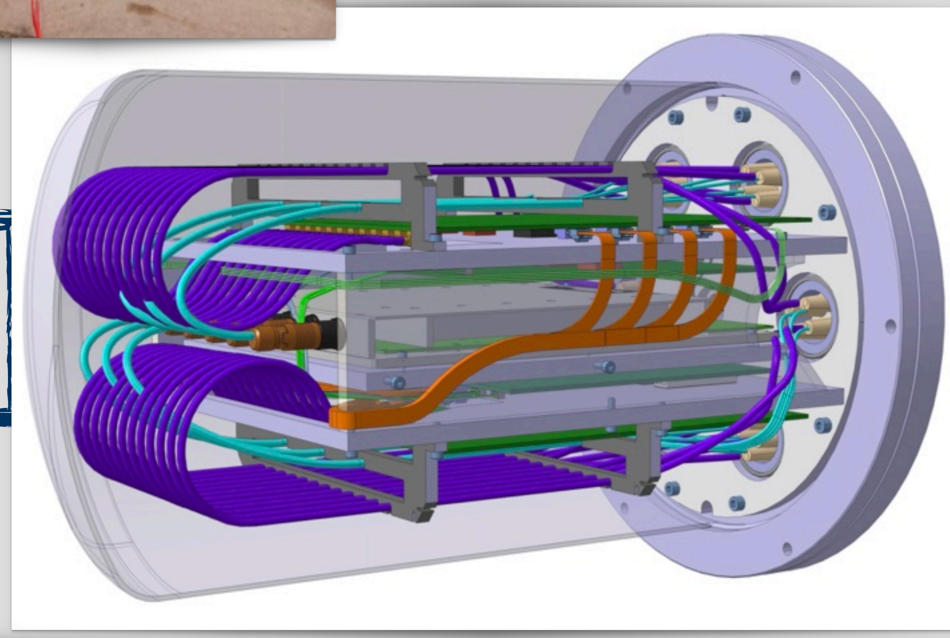
Mockup (Kashiwa,

50cm PMTs

#20,000

ID+OD Electronics

#~1,000

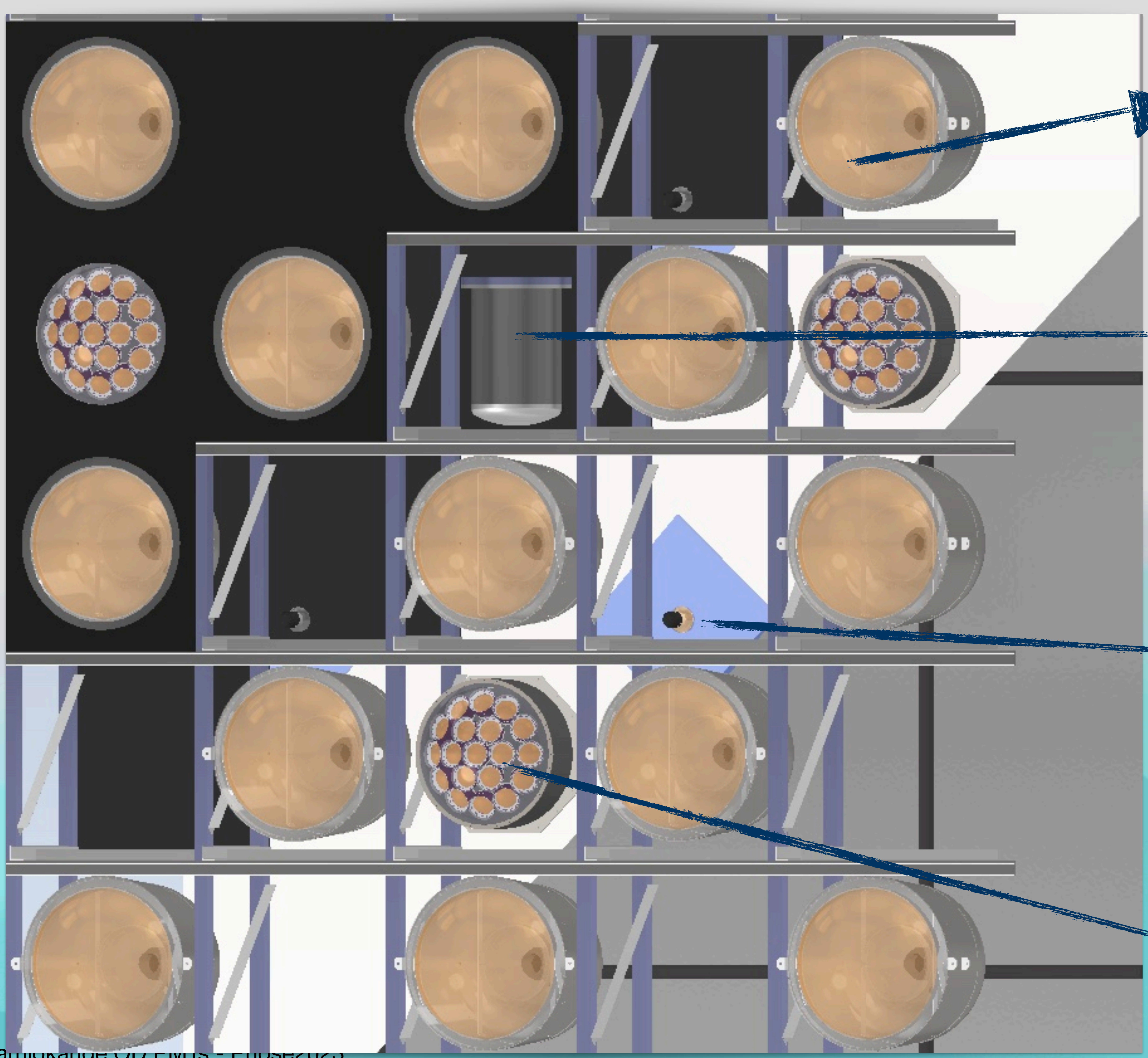


OD

~#3,600

mPMTs

#~1,000



PMT characteristics

Characteristics	
Base:	Waterproof
Voltage:	Anode at $+V_{op}$ (positive high voltage)
Voltage divider:	Non-tapered in later stages
Output cable:	Single output cable to carry both signal and high voltage
Cable type:	50 ohm cable (eg RG-58) (with connector to be specified)

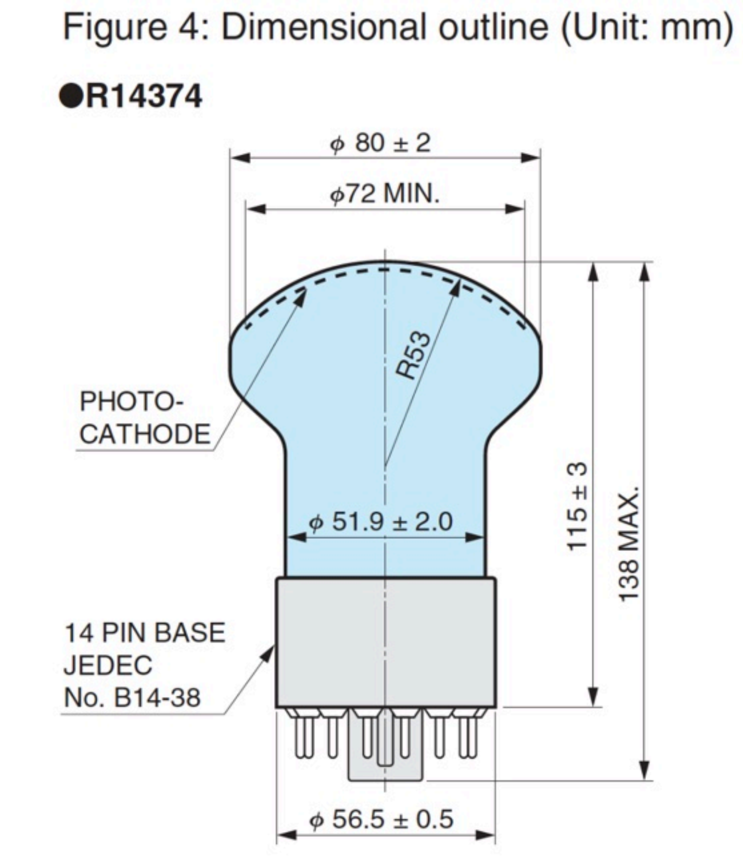
Requirements		
Aging:	> 20 years	
Pressure:	$<$10 bar	Large safety margin - HK bottom is ~7bar
Gain:	$> 3 \times 10^6$ $(900 < V_{op} < 1300\text{V})$	
Timing resolution:	< 10 ns (for 1 p.e. at V_{op})	Loose requirement due to slow WLS collection efficiency
Charge resolution:	50% σ (for 1 p.e. at V_{op})	To be consistent with SK performance
Single-photon peak-to-valley ratio:	> 2 at V_{op}	To allow good noise separation
Dynamic range:	0.2 to 100 p.e. at V_{op}	
Dark rate:	< 1 kHz above a threshold of 0.25 p.e. at $20°$C	It will be lower in HK water (13°C)
Quantum Efficiency:	$> 25\%$ in the 300–500 nm range	To match the wavelength of Cherenkov emission
Magnetic field gain variation:	10% at 100 mG	Magnetic compensation coils reduce Earth's magnetic field to 100 mG
Power consumption:	< 1 W at V_{op}	To limit the heating of the water

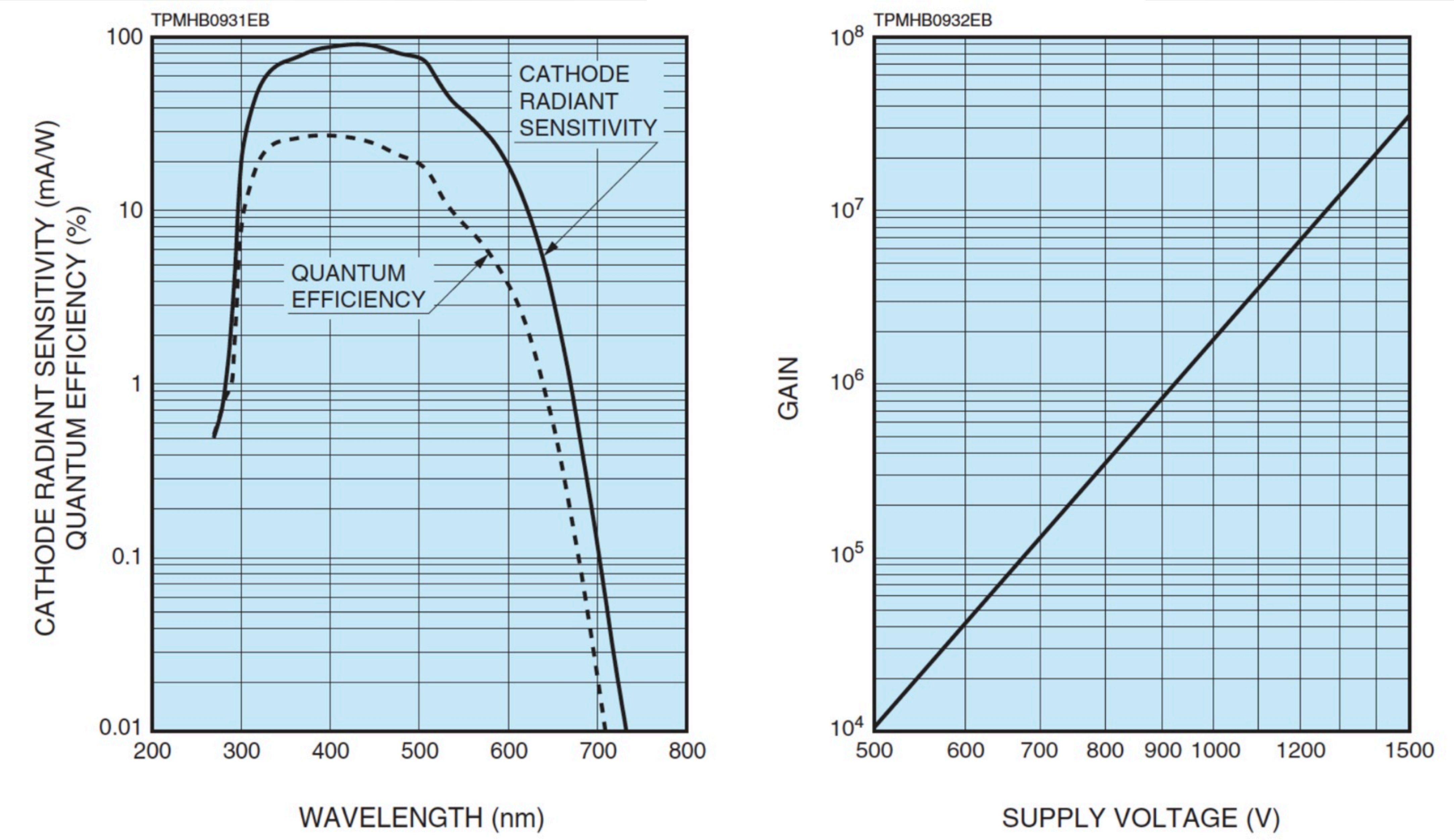
Requirements need to be valid for waterproofed PMTs with ~20m long cable.

PMT candidates

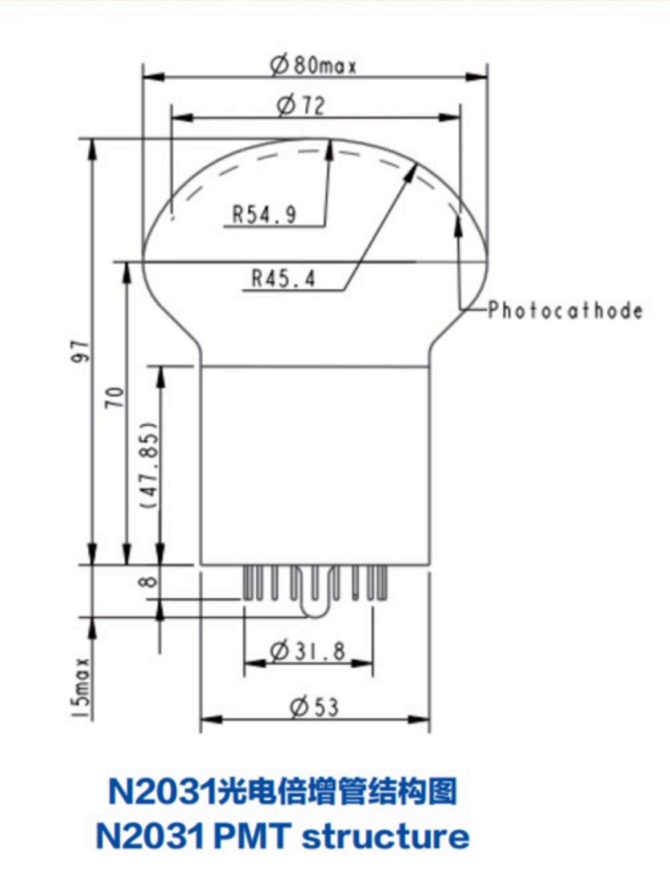
- Two “basic” PMT candidates: Hamamatsu and North Night Vision Technology (NNVT)
  - Hamamatsu: R14734
  - NNVT: N2031

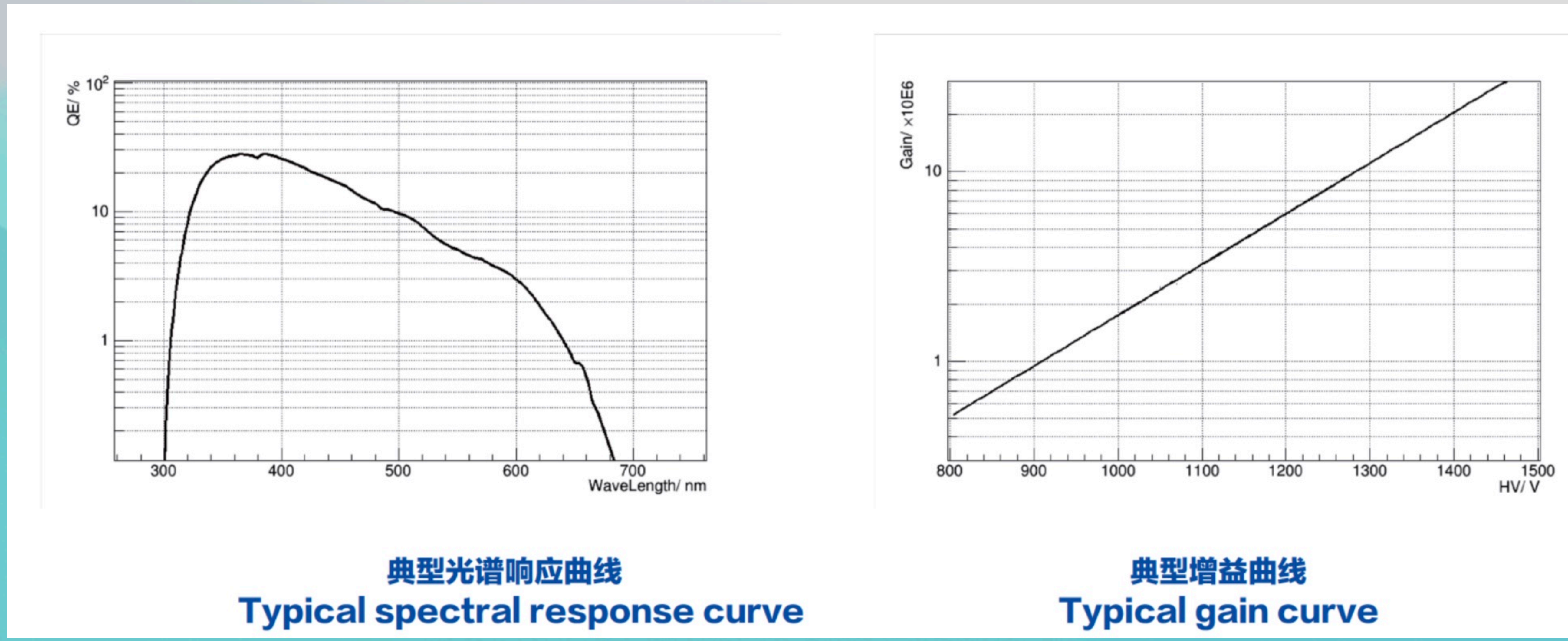
R14734





N2031

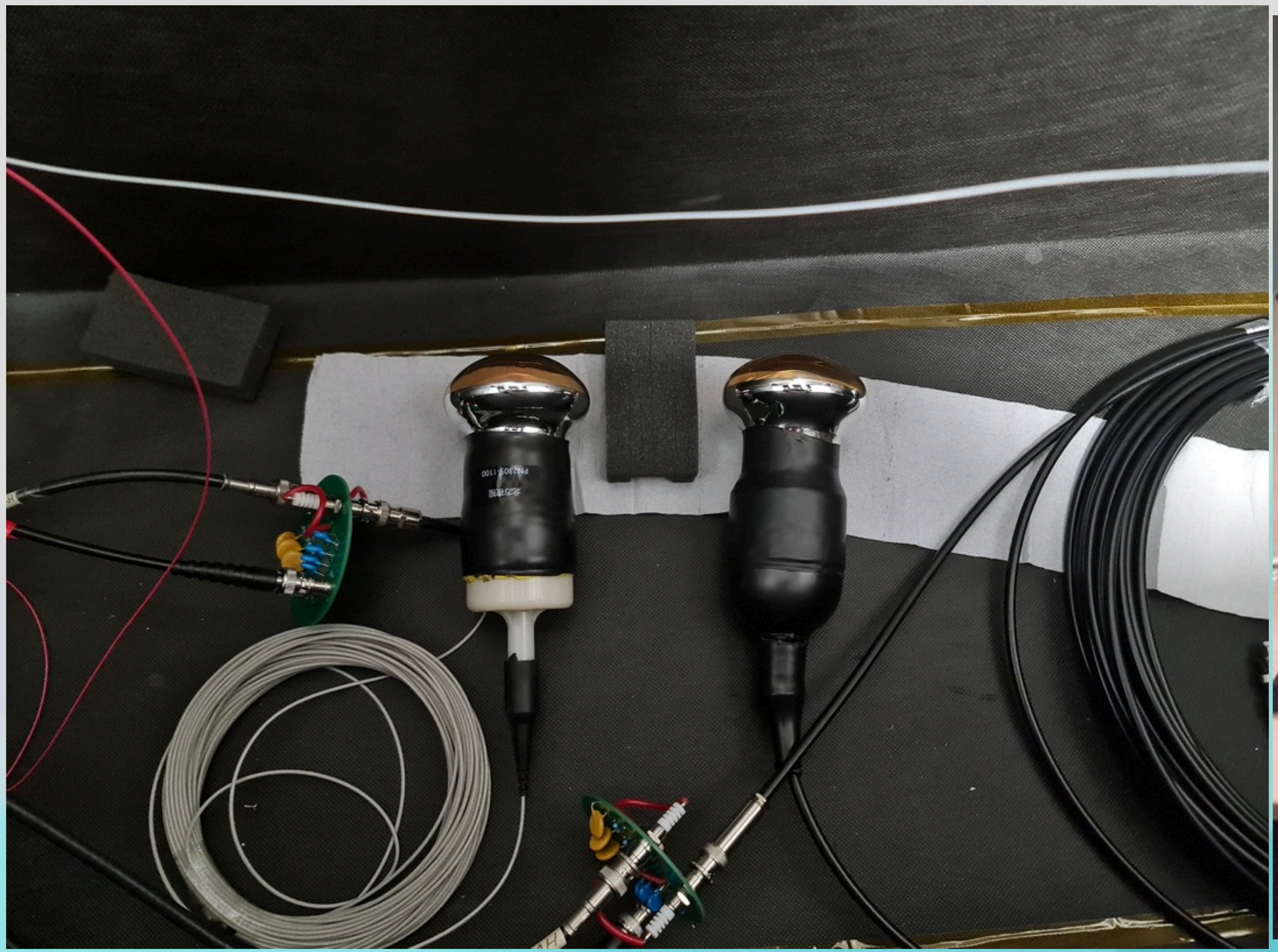




PMT candidates

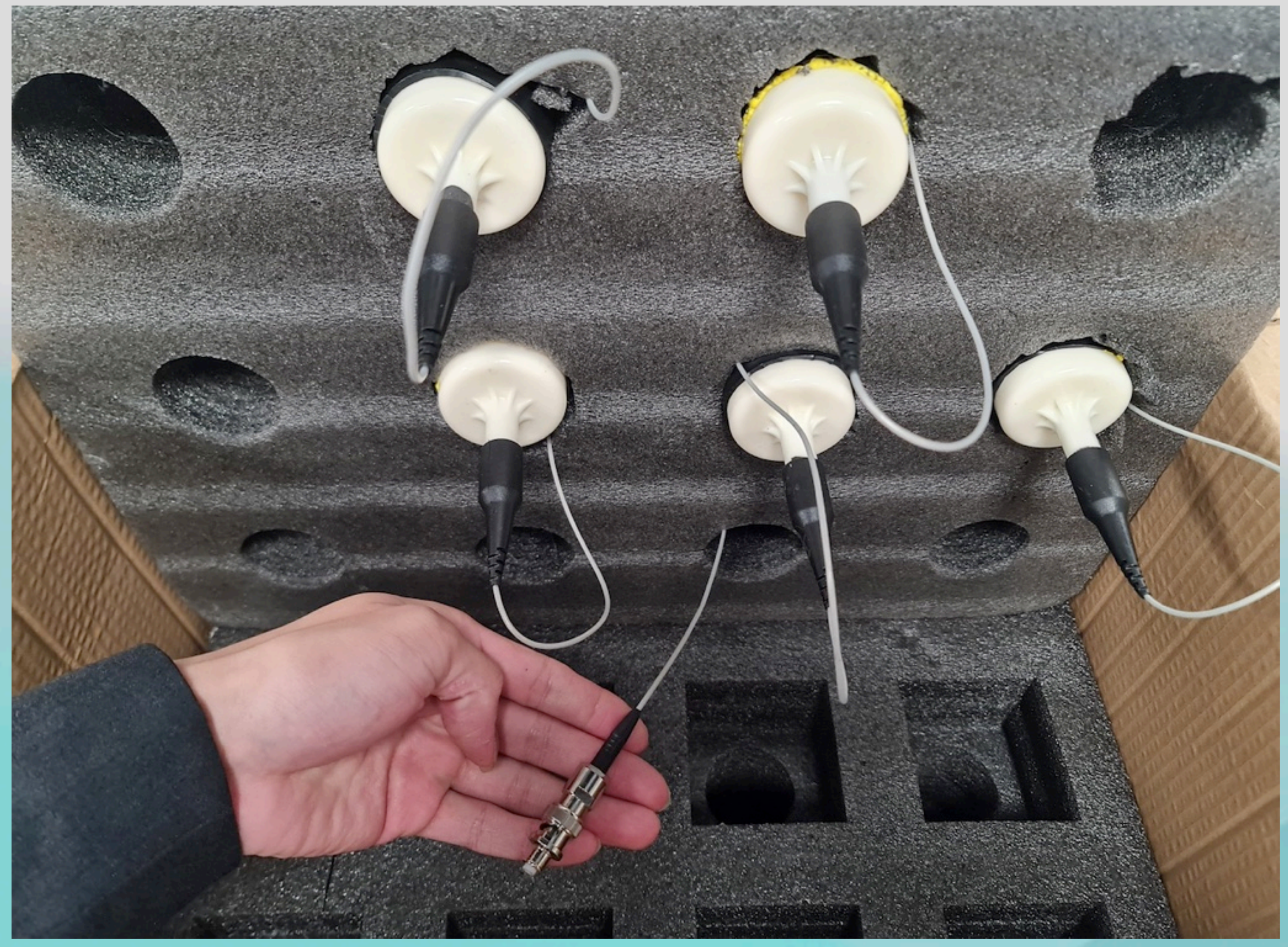
- OD PMTs are waterproofed with a ~20m long cable due to the length needed to reach the electronics board.
- Electronics in water. ~200 vessels for ID and OD hybrid boards.
- Cables reach electronics boards in an efficient way (interleaving).

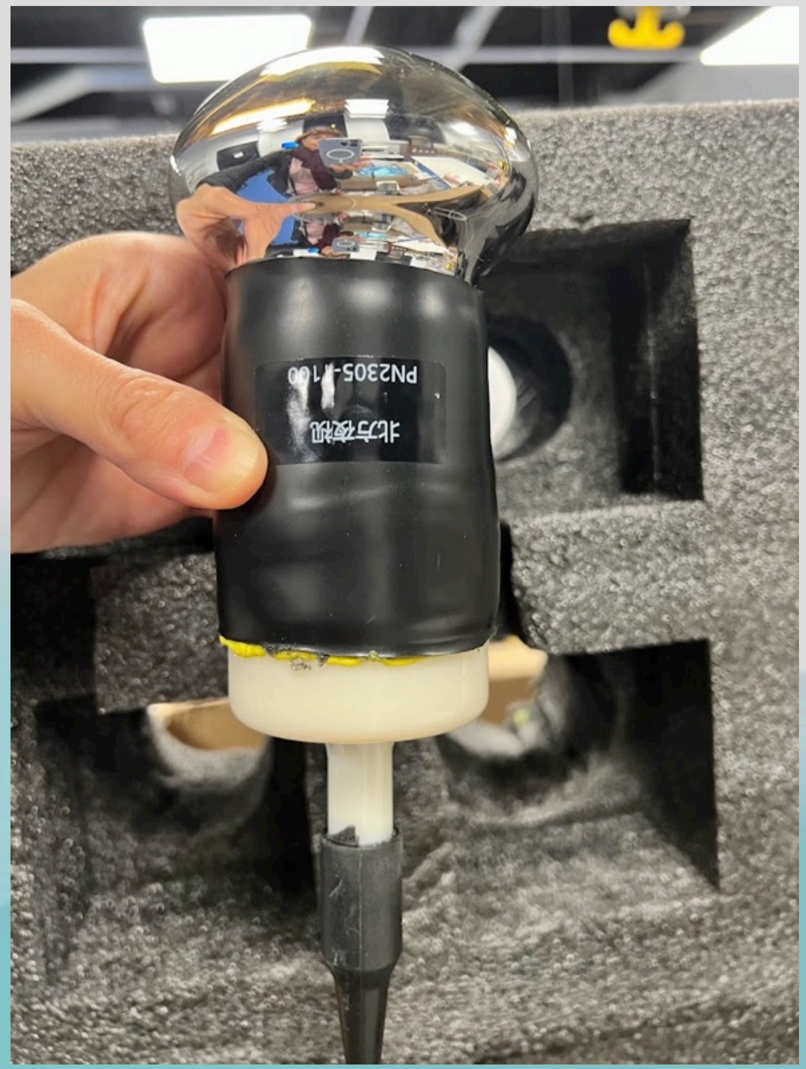
NNVT and Hamamatsu PMTs



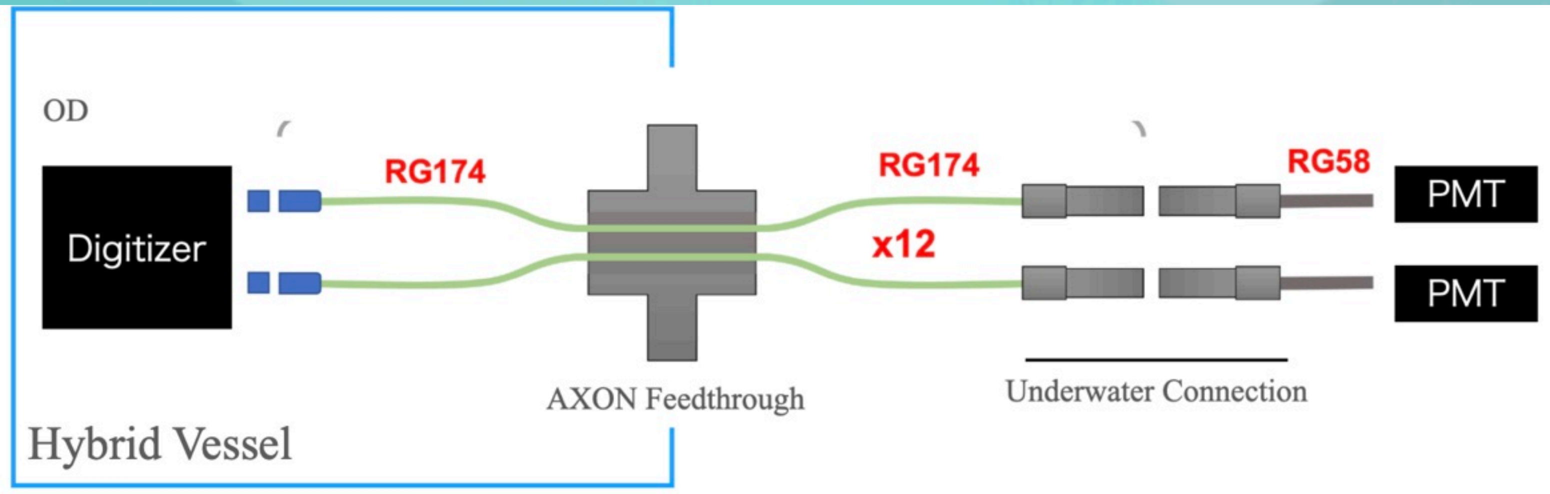
Hamamatsu PMTs

NNVT PMTs

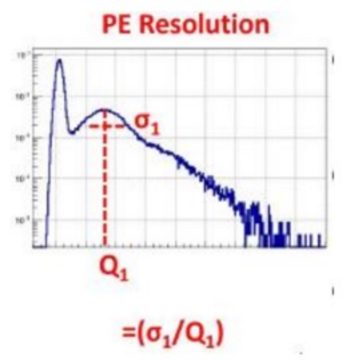


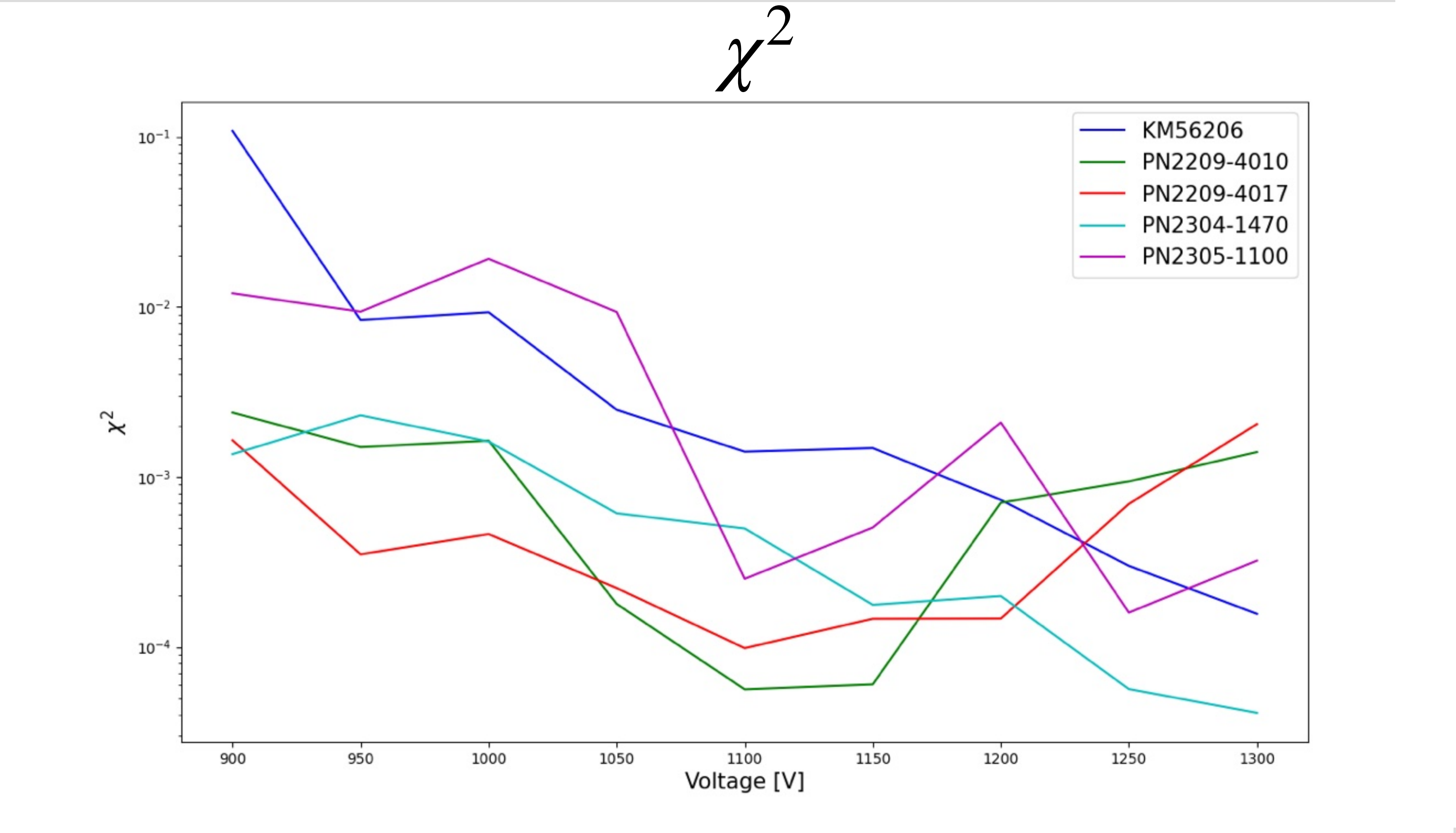


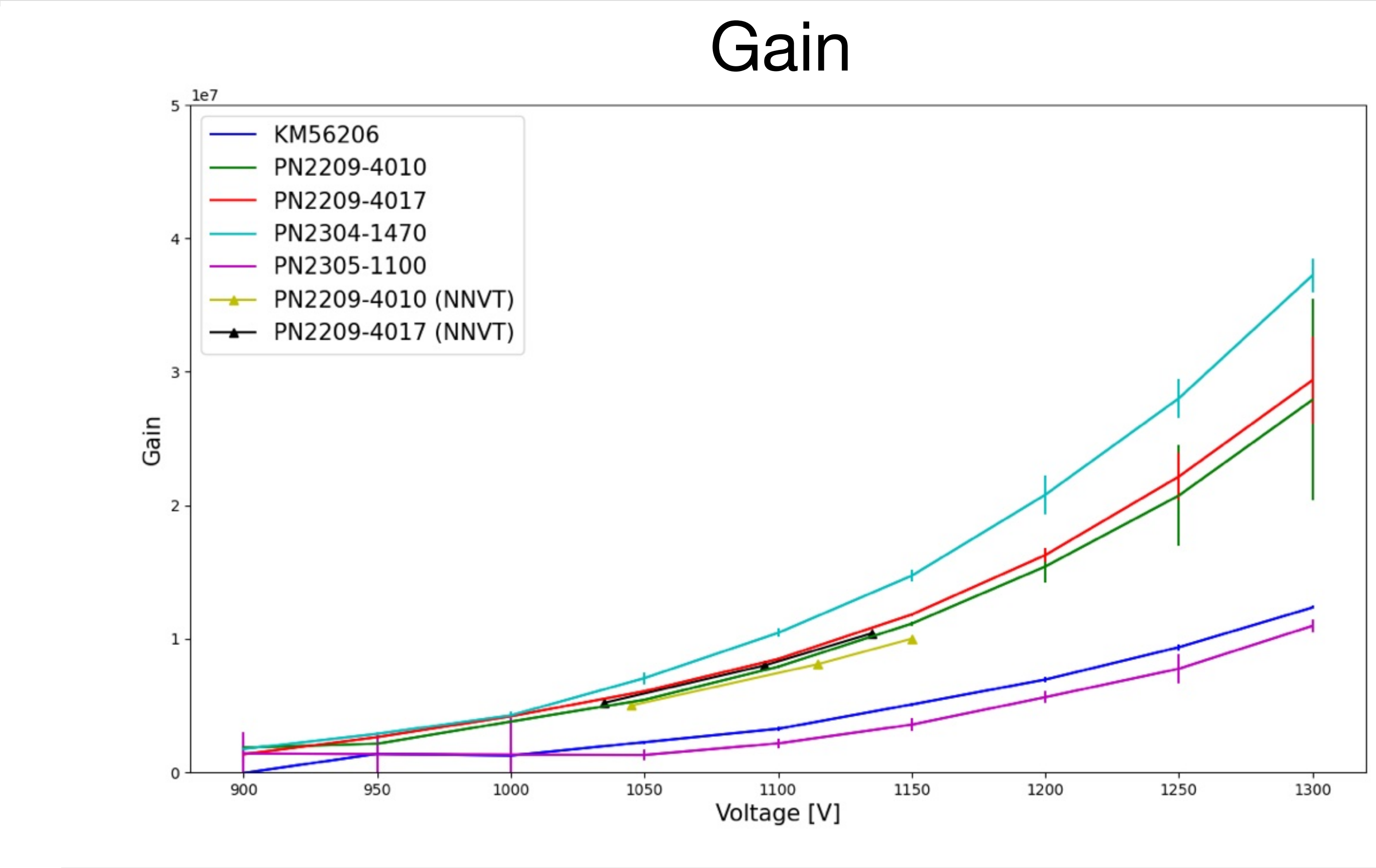
- Current studies are presented in the next slides.

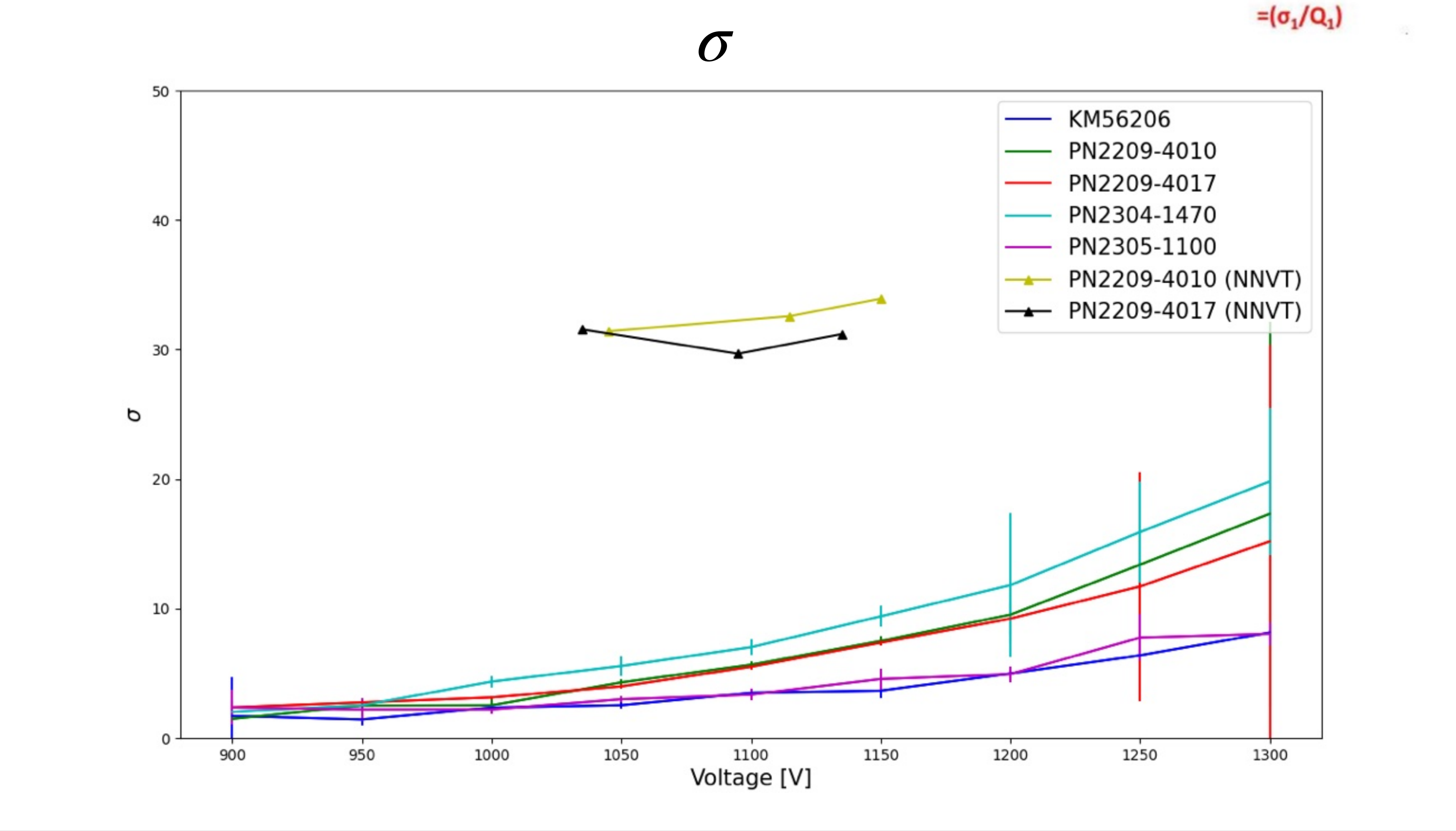


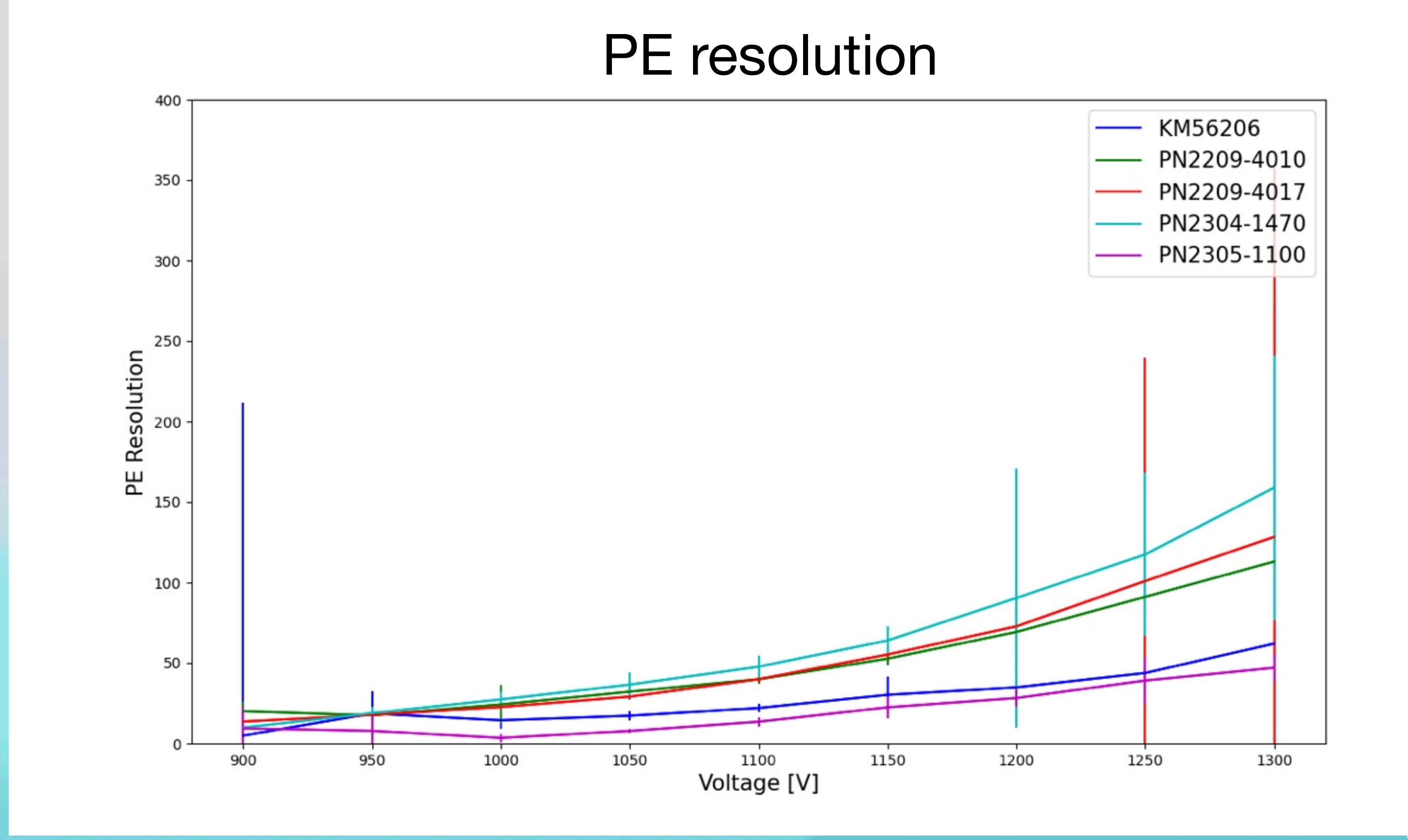
PMT Characteristics

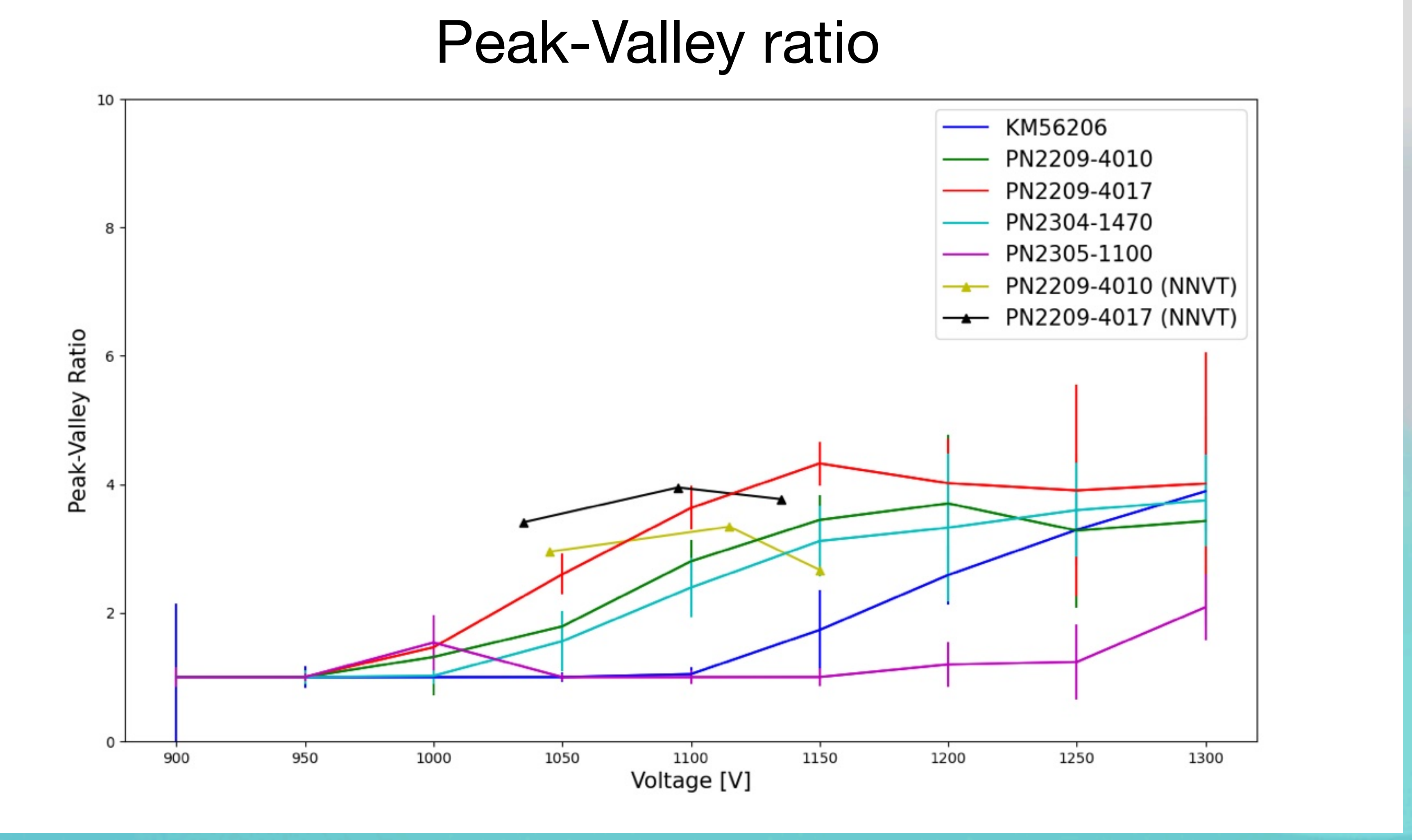




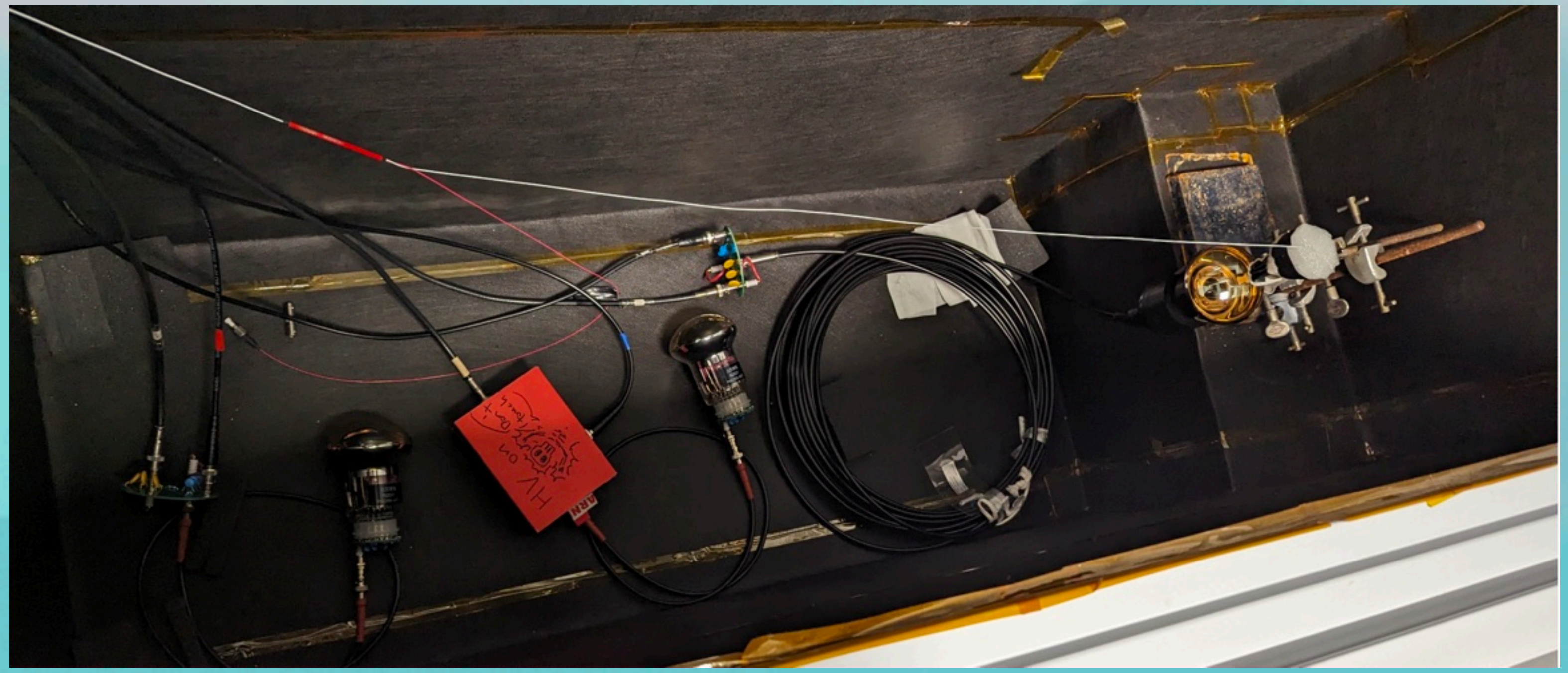








Serial number	Product name	Company	Waterproof	Cable
KM56206	R14374	Hamamatsu	Yes	20 m
PN2209-4017	N2031	NNVT	No	1 m
PN2209-4010	N2031	NNVT	No	1 m
PN2305-1100		NNVT	Yes	20 m
PN2304-1470		NNVT	Yes	20 m

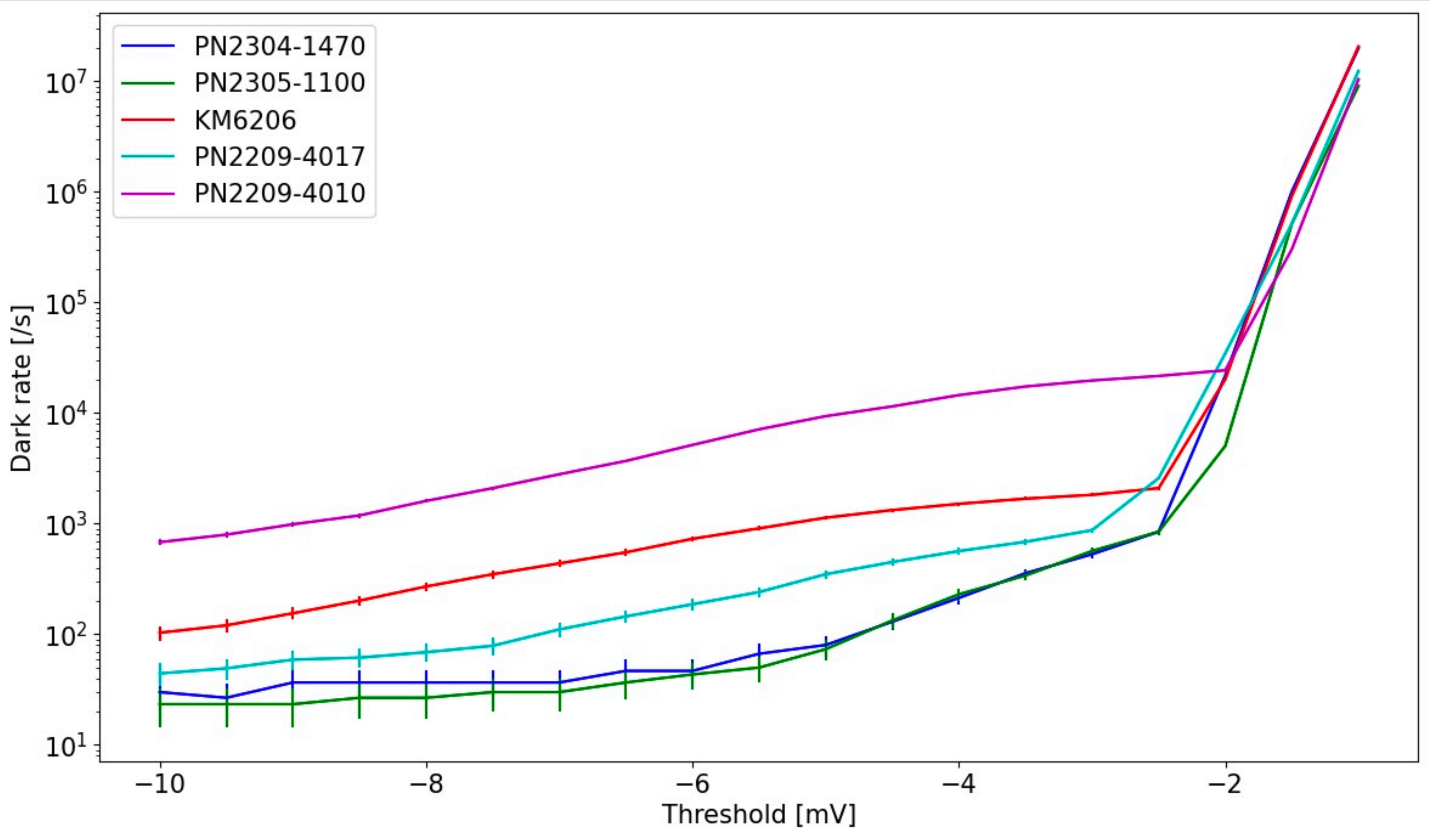


PMT Dark Rate

Serial number	Product name	Company	Waterproof	Cable
KM56206	R14374	Hamamatsu	Yes	20 m
PN2209-4017	N2031	NNVT	No	1 m
PN2209-4010	N2031	NNVT	No	1 m
PN2305-1100		NNVT	Yes	20 m
PN2304-1470		NNVT	Yes	20 m

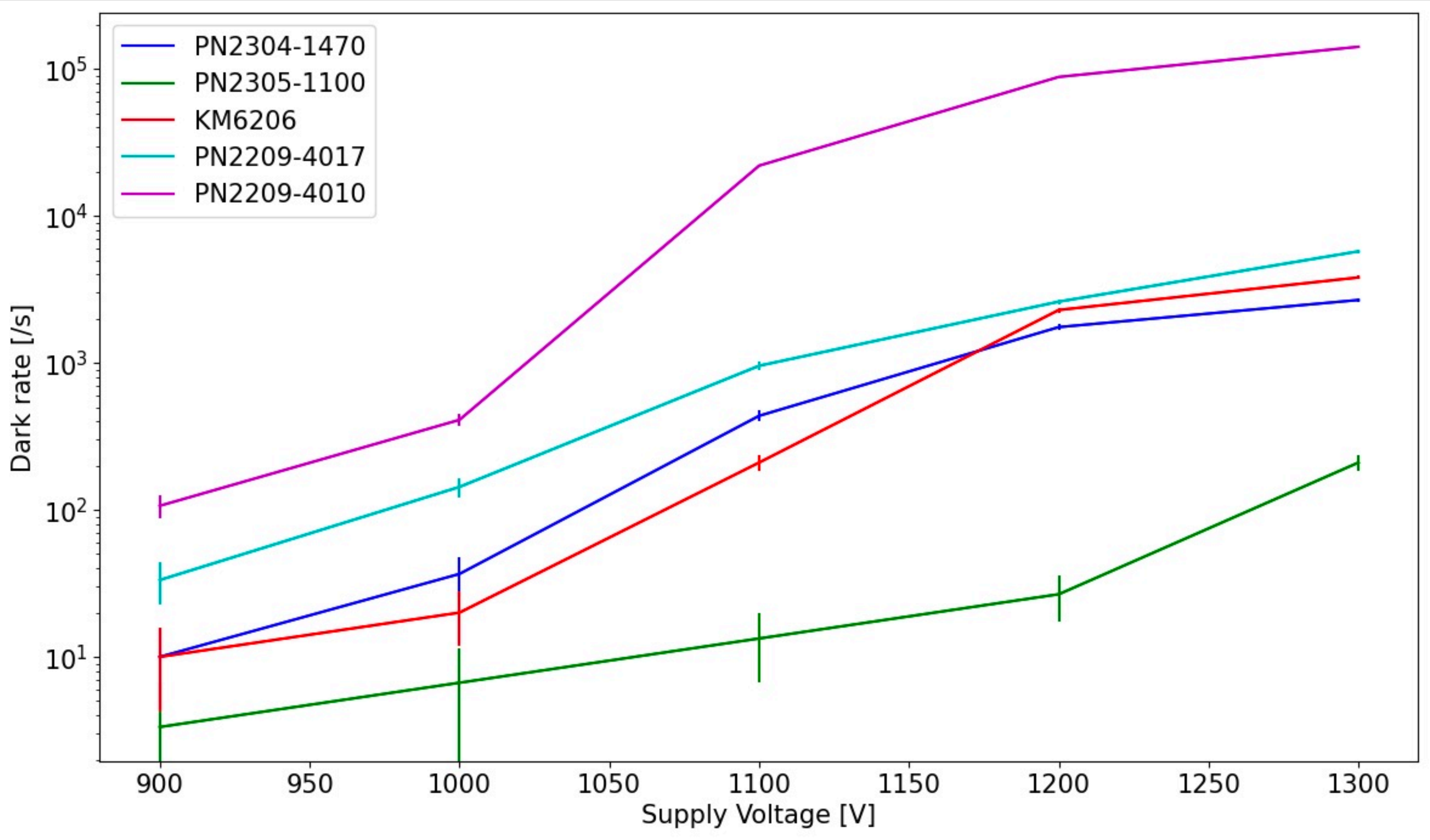
Threshold dependence at Gain=5 × 10^6

- Hamamatsu: 1100 [V]
- NNVT PN2304-1470, non-waterproofed: 1000 [V]
- NNVT PN2305-1100 : 1200 [V]



Voltage dependence

- Threshold = -8.0 [mV]



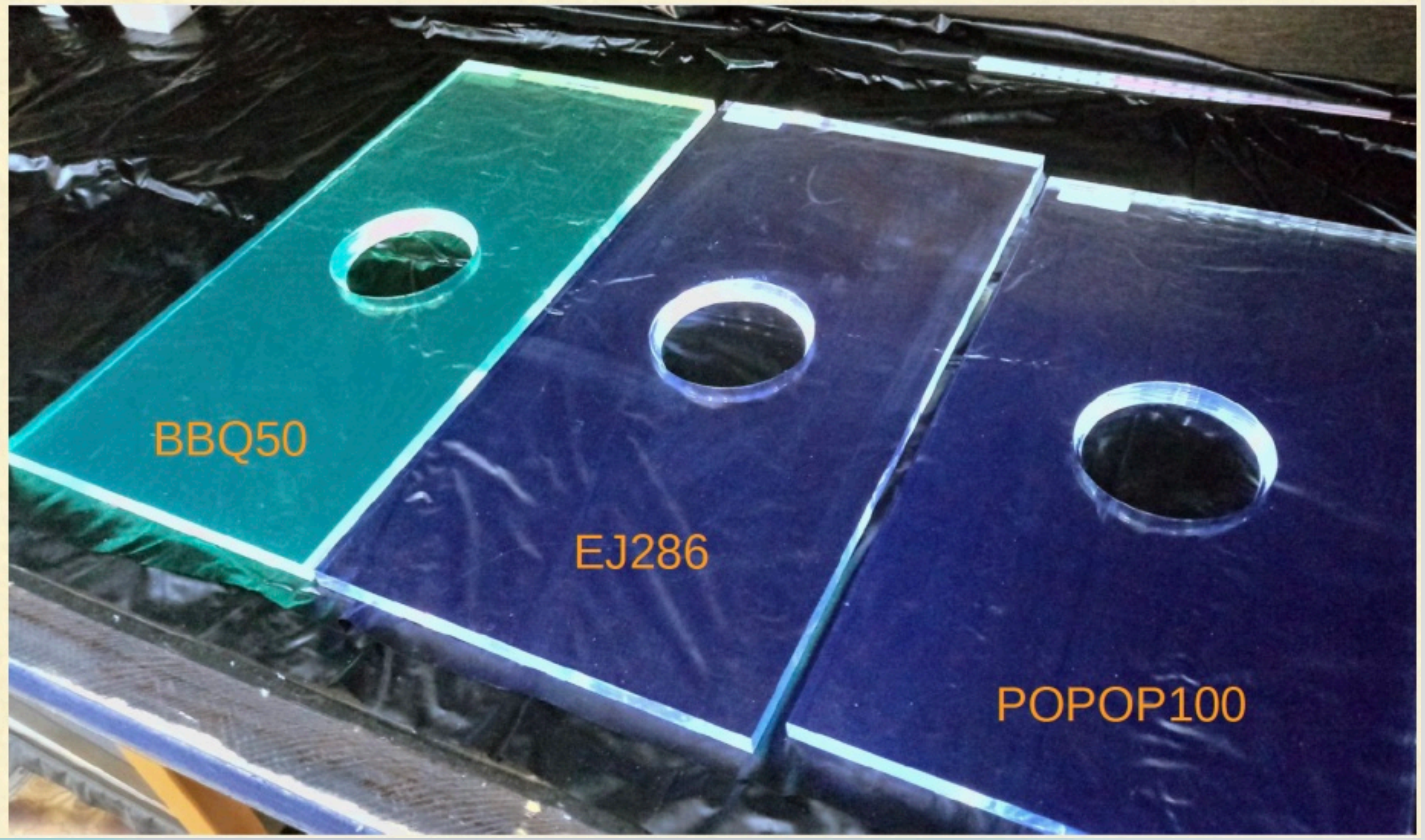
WLS Plates

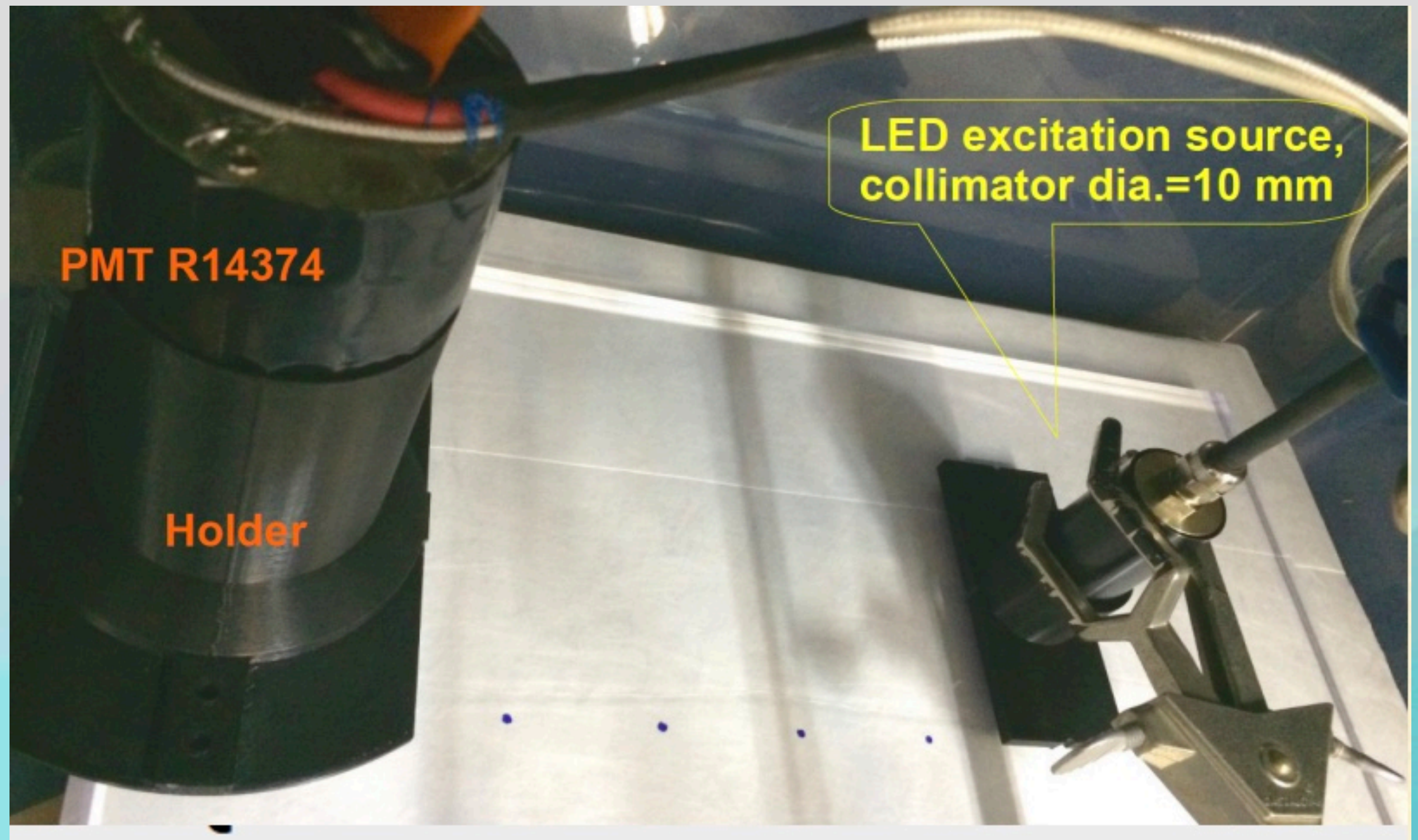
- Intense campaign to find optimal chemical composition for Hyper-K OD WLS plates
- Base material (eg PMMA) + single/double fluor dopants
- Super-K samples
- Eljen (USA) - commercial PVT based type EJ286
- Kuraray (Japan)
- LabLogic (UK)
- V.A. Kargin Polymer Chemistry Institute (Russia)

BBQ50, BBQ100, bisMSB50, bisMSB100,
POPOP100, POPOP200, POPOP400,
POPOP50 +PPO3000 (50 mg/l POPOP + 3 g/l PPO — fluor concentrations),
POPOP100+PPO3000 (100 mg/l POPOP + 3 g/l PPO),
POPOP100+PPO10000 (100 mg/l POPOP + 10 g/l PPO),
POPOP200+PPO3000 (200 mg/l POPOP + 3 g/l PPO),
POPOP200+PPO10000 (200 mg/l POPOP +10 g/l PPO),
POPOP800+PPO5000 (800 mg/l POPOP + 5 g/l PPO),
bisMSB50 + PPO3000 (50 mg/l bisMSB + 3 g/l PPO),
bisMSB200+PPO3000 (200 mg/l bisMSB + 3 g/l PPO),

PMMA base

Double fluor allows to accept short UV part of Cherenkov spectrum





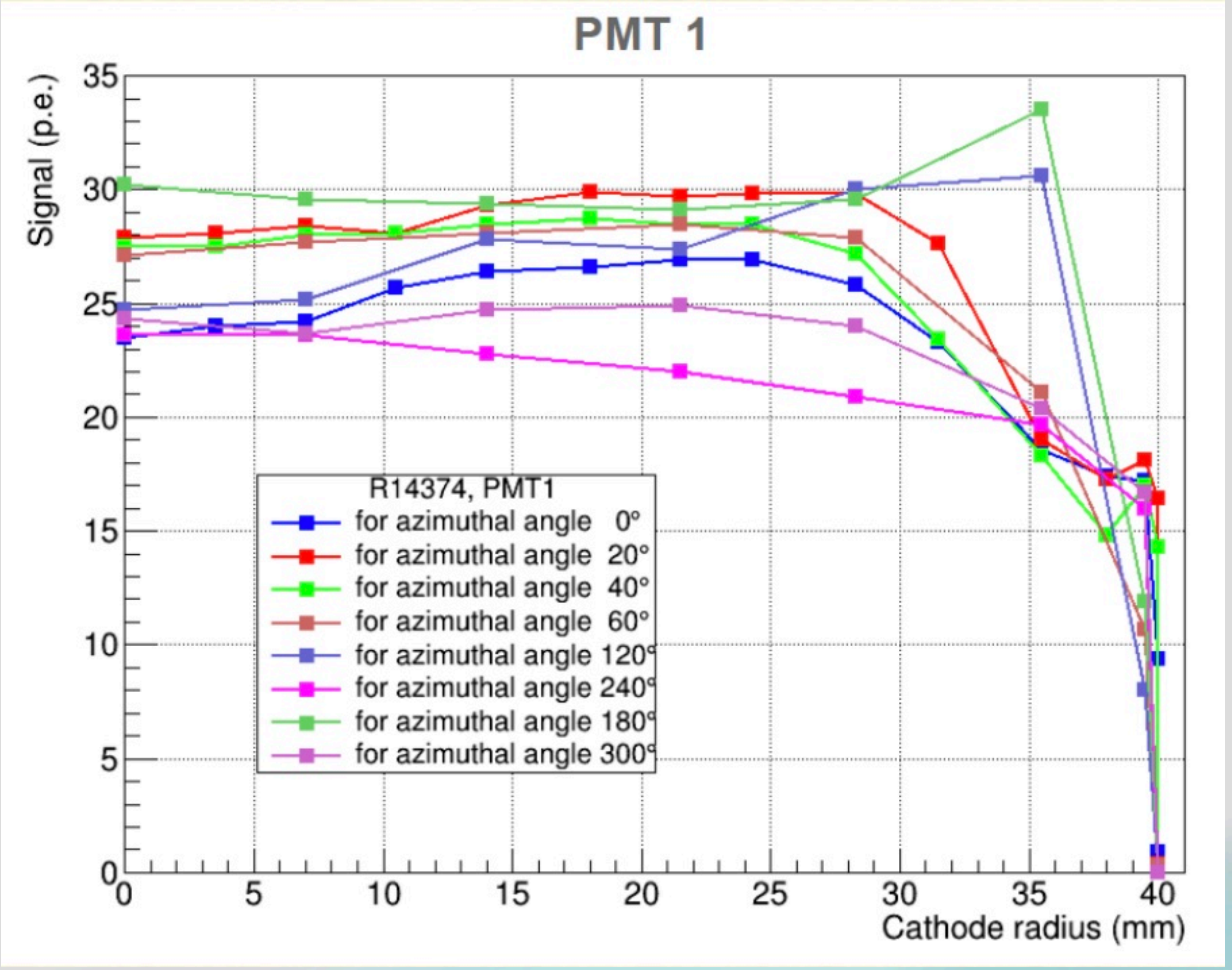
Fast UV LED light sources from PicoQuant
265 nm — spectrum range 260-300 nm
315 nm — spectrum range 300-340 nm
380 nm — spectrum range 365-395 nm
405 nm — spectrum range 380-440 nm

From "Development of wavelength-shifting plate light collector for Outer Detector of Hyper-Kamiokande"

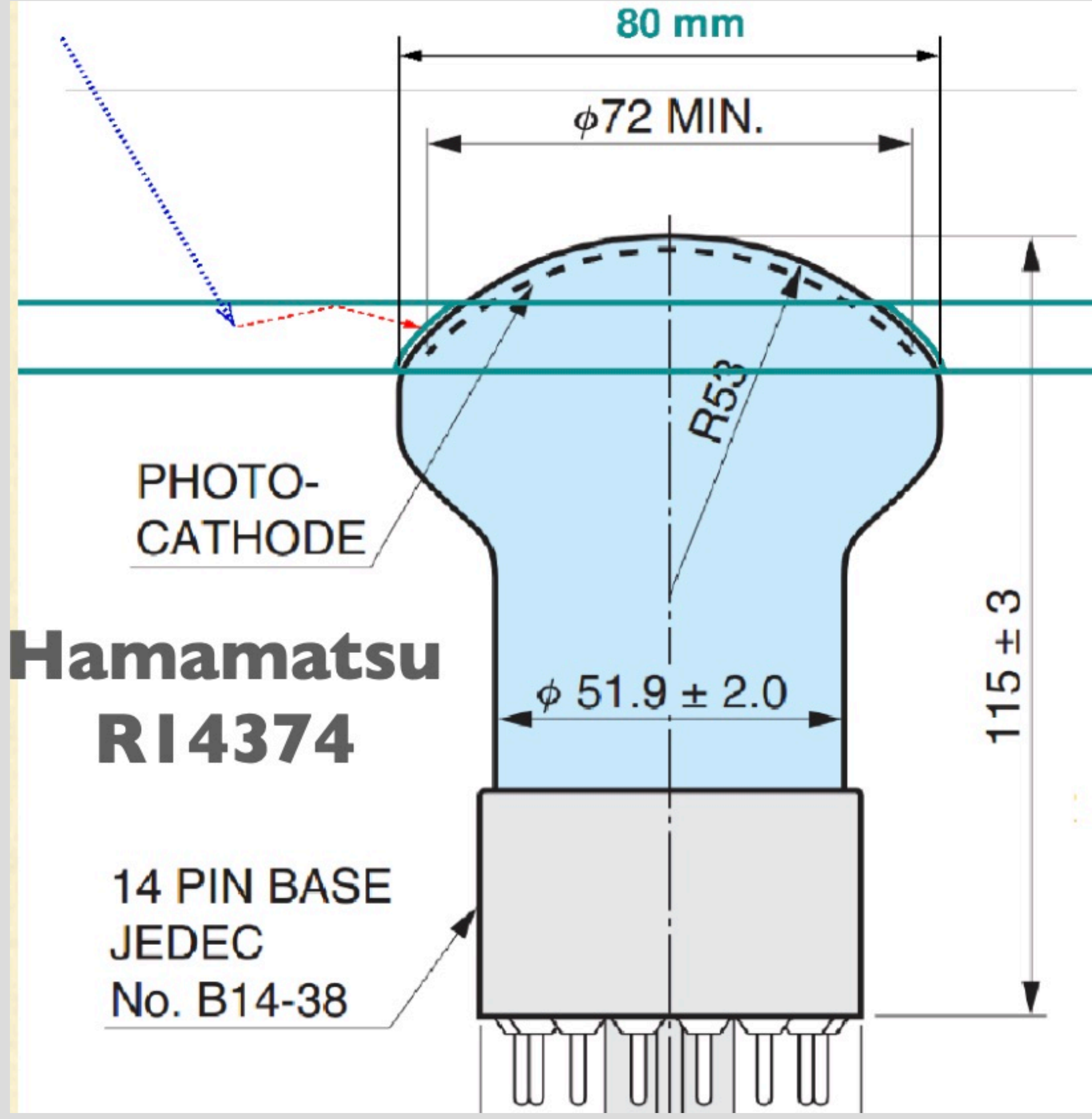
TiPP 2024, Izmaylov

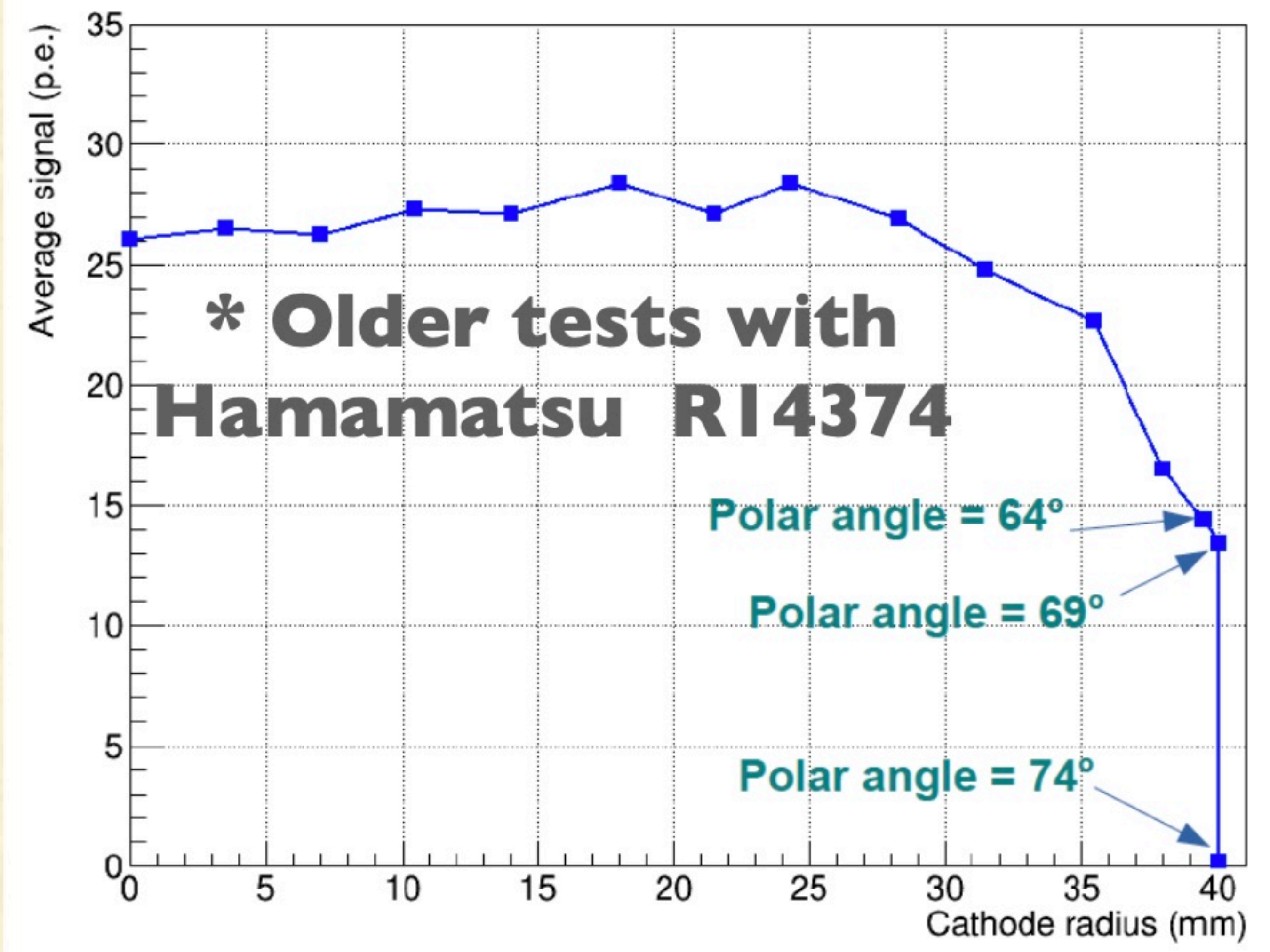
Fluors	Absorption range, nm	Emission range, nm	Notes
BBQ	250-460	420-640 peak: ~510	Shifts UV and visible blue light into green spectral area.
bis-MSB	300-400 peak: 350	380-530 peak: 400-460	Emission spectrum is close to POPOP, cost is higher than POPOP, easier to dissolve in acryl base.
POPOP	250-390 peak: 360	380-510 peak: 390-450	Emission spectrum is close to bis-MSB but harder to dissolve in acrylic base than bis-MSB. Widely used in plastic scintillators with PVT and polystyrene base.
PPO	240-310 peak: 280	320-420 peak: 340-380	Effectively absorbs short UV and re-emits in long UV. Used as a primary WLS in combination with POPOP to shift short UV into visible light.

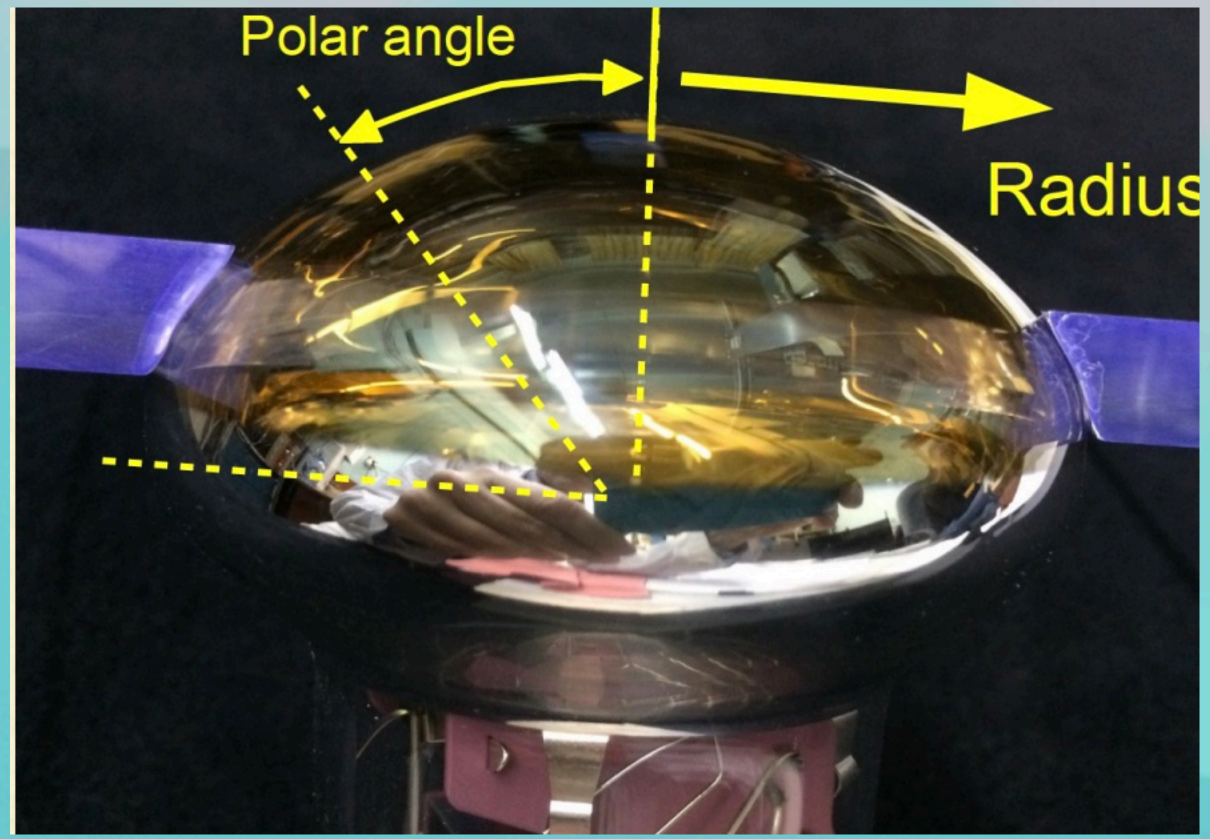
Catode Radius Scan

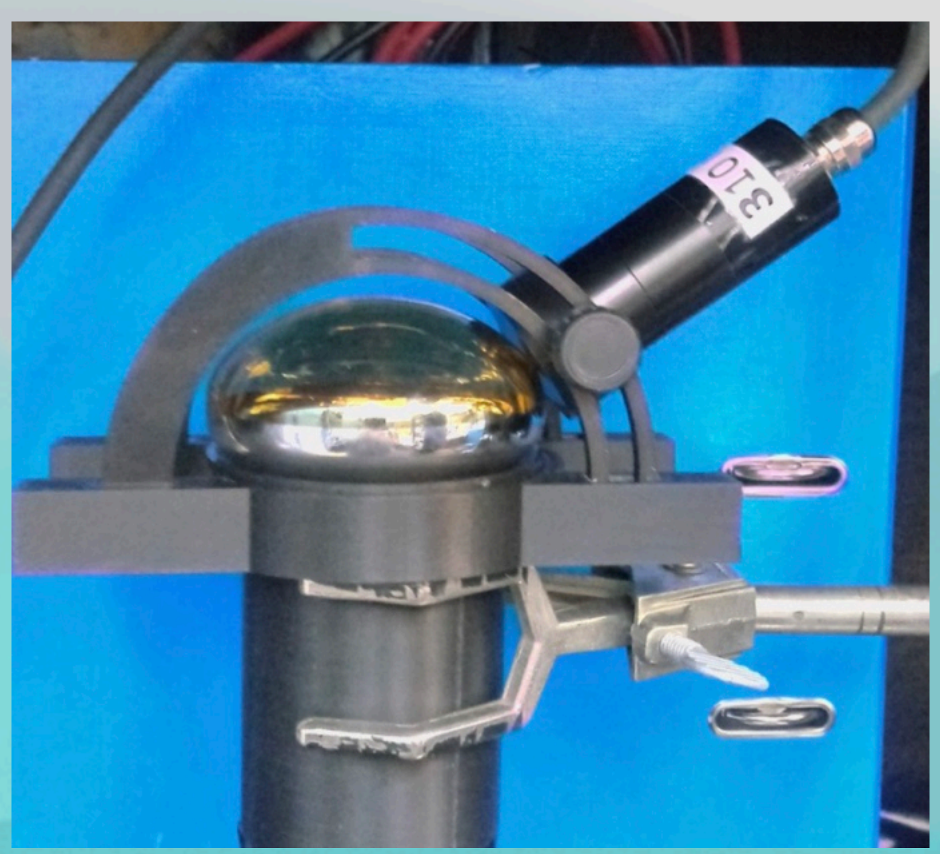


- Scan a PMT with a 380nm Ø1.5 mm collimated LED
- Vary polar and azimuthal angles
- Efficiencies at the sides are important for the use of WLS plates.

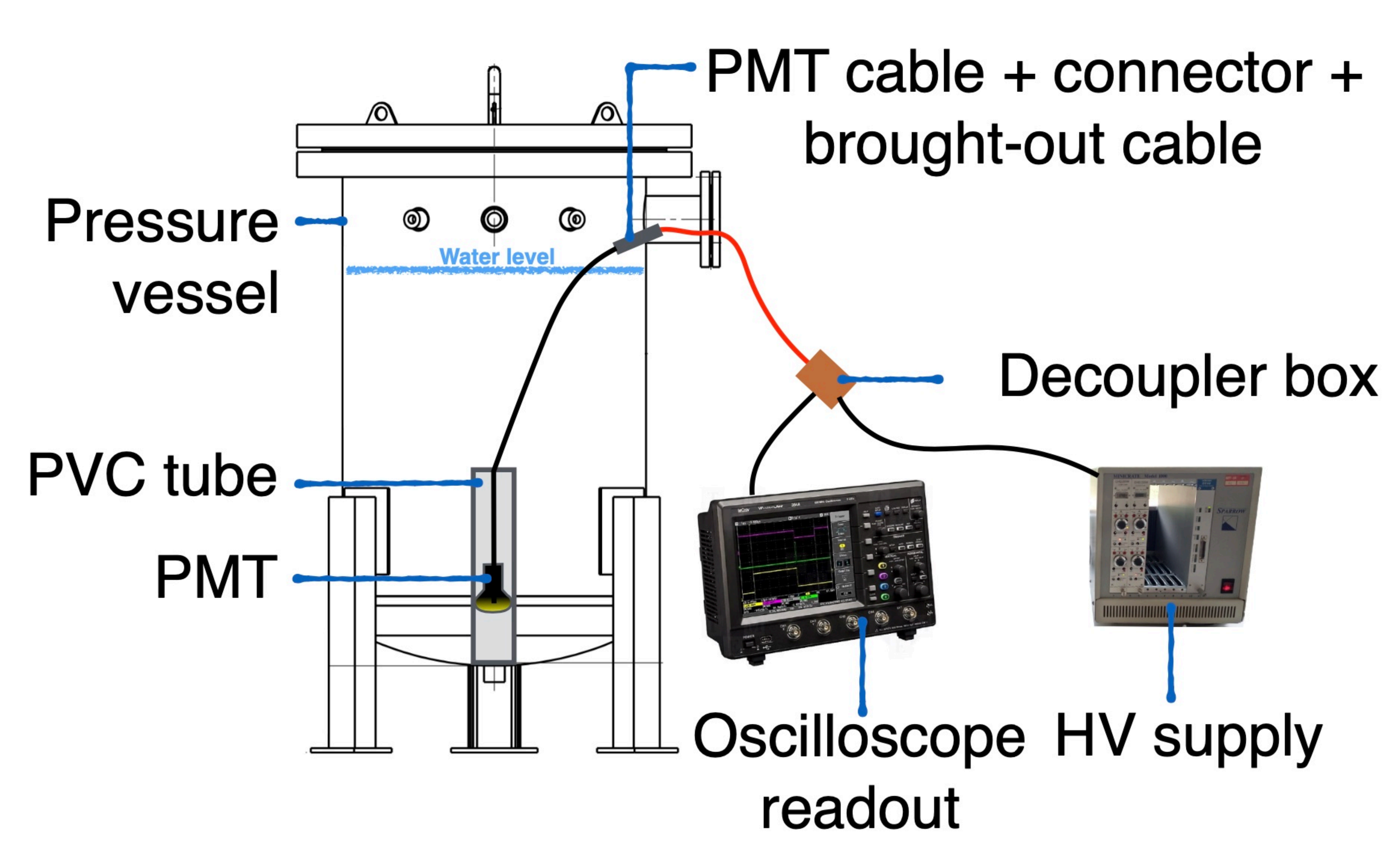








PMT Pressure Tests



- PMTs are tested in water under pressure at 10 bar.
- PMTs, Hamamatsu R14689 (serial number: BC0491) and NNVT 3-inch PMT (serial number: 044012), were tested in the pressure vessel at Charles University (Prague), B. Roskovec, M. Malinský.
- Tests performed in 2021 and 2022. More detailed test in 2022.

- The PMT was put into non-transparent PVC tube and as such placed into the pressure vessel. The PVC tube was used to limit the Cherenkov light muons passing through the vessel.

produced by cosmic-ray muons pas

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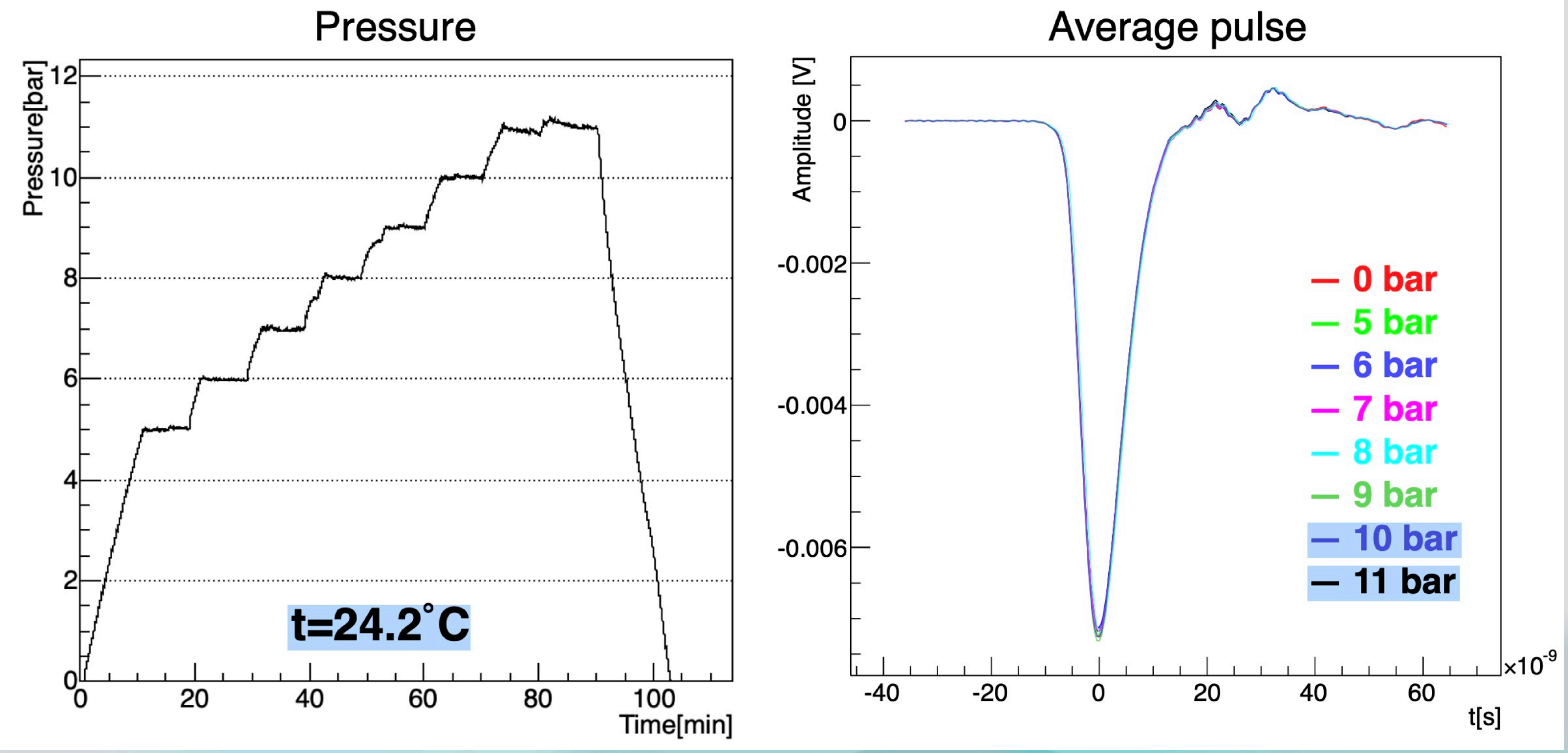
PMT Pressure Tests



- The pressure was initially brought to 5 bar and then increased by 1 bar up to 11 bar
- Each pressure level was maintained for about 8 mins.

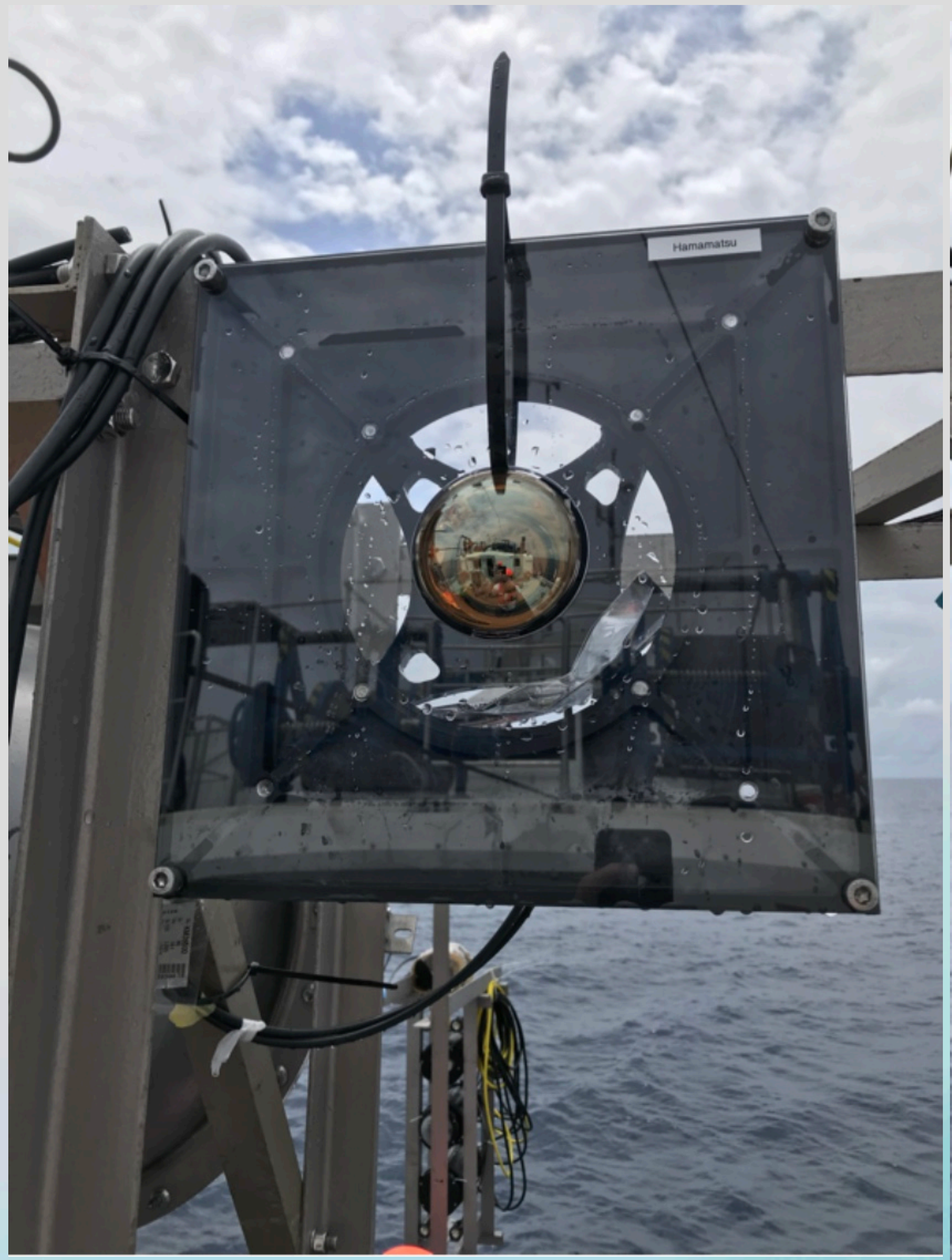
- There was no damage to the PMT and no imminent leakage.
- Similar results were obtained for the NNVT PMTs.

PMT Implosion Tests

- Implosion tests of the OD PMTs if subjected to shock waves of higher peak pressures, or the impact of accidental breakage of an OD PMT.
- Check any risks of implosion and chain reactions that also affect the OD PMTs.
- Implosion tests performed in Hokkaido (Japan) in 2022 and in the Balearic Sea off the coast of Palma, Mallorca (Spain) in 2023.

PMT Implosion Tests

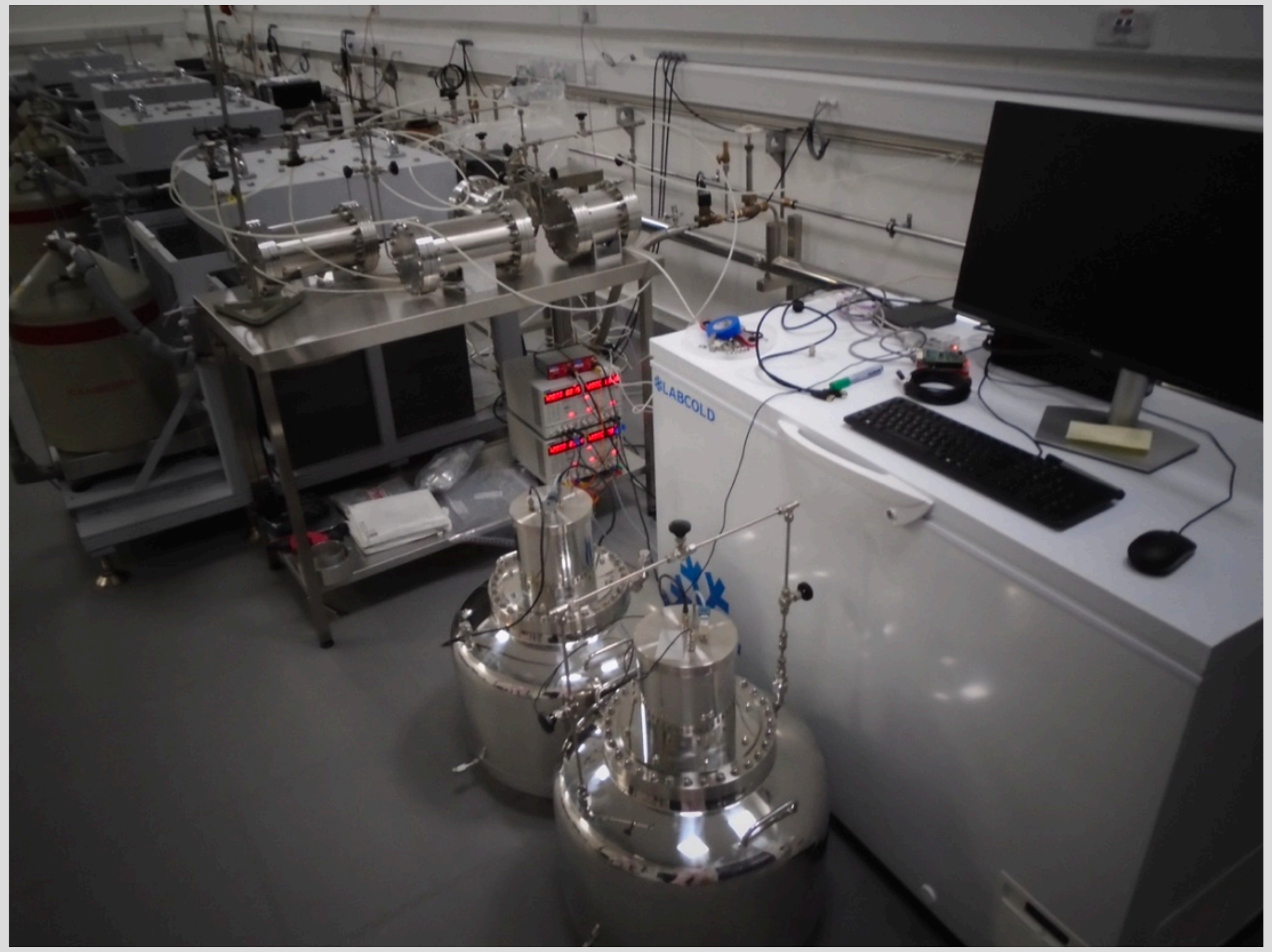
- Before the implosion test in Mallorca.



- After the implosion test in Mallorca.

- Tests successful. No damage was found on the OD PMTs and photo-sensing units.

PMT Material Suitability and Components

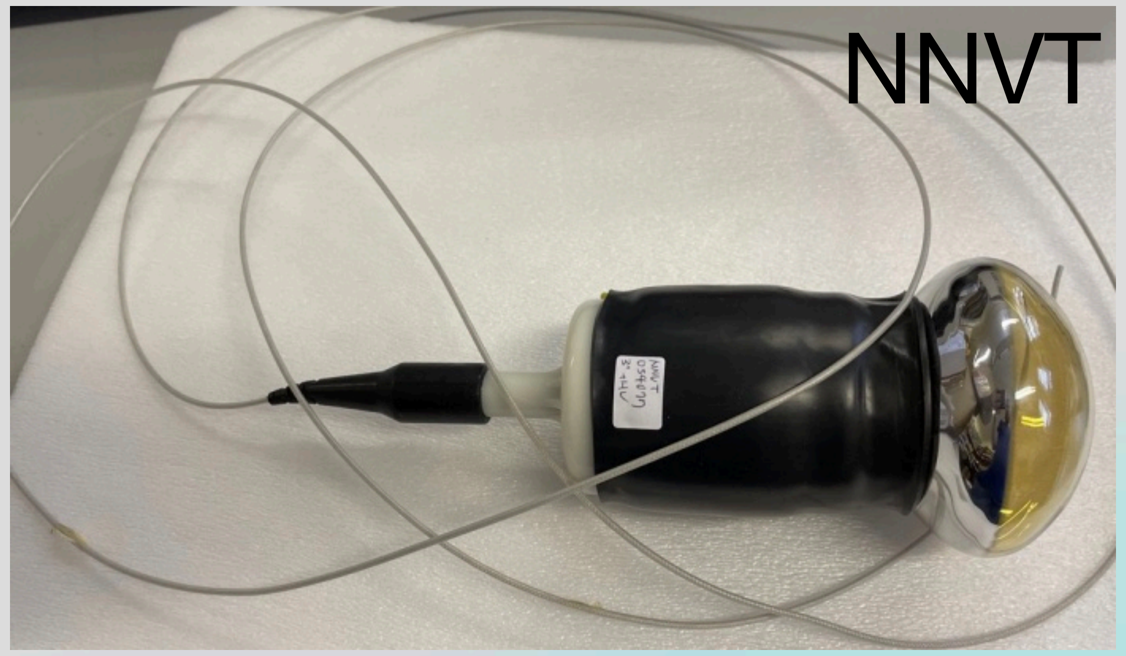


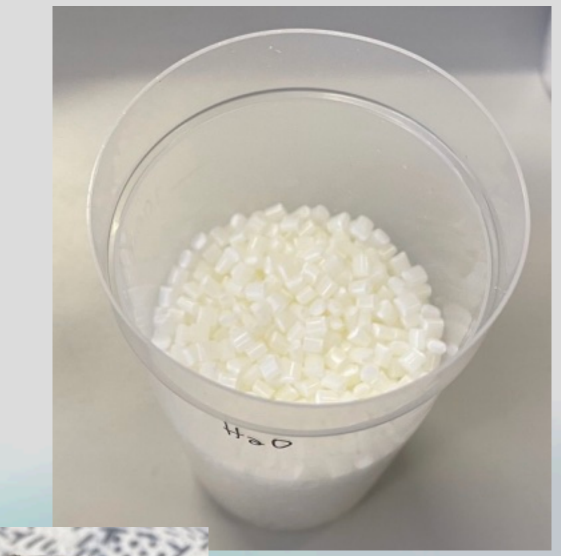
- Soak testing – to check that materials do not contaminate the HK water $(T_{eff} > 100\text{m})$ and to check that materials do not themselves degrade under long-term submergence
- Radon emanation – to check that materials do not emanate large amounts of radon into HK water (<10 mBq/PMT channel)
- Radioactivity – gamma emission from materials may cause isolated "hits" in PMTs, aka "Dark Noise"
- Rn emanation test the Boulby mine, supported by Kamioka emanation test.
- Radon emanation sensitivity of sample emanation chambers around 60 μ Bq at the 95% confidence level.

PMT Material Suitability and Components

Hamamatsu

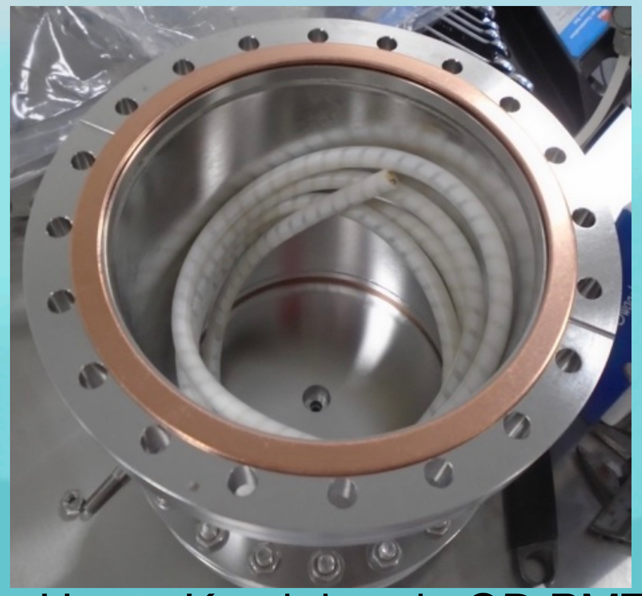
NNVT

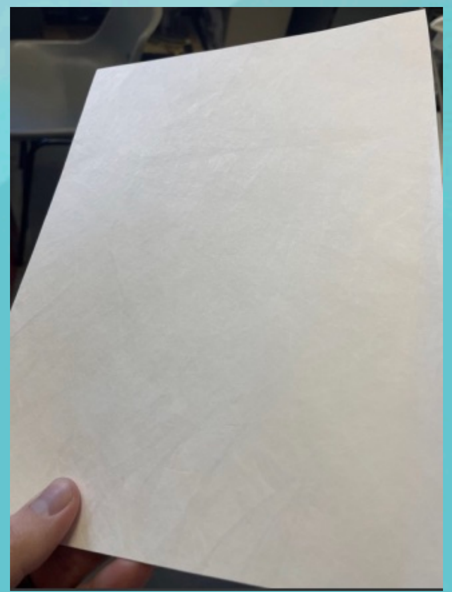


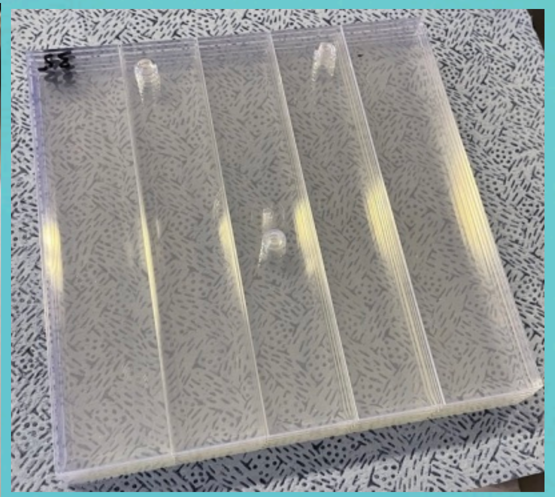


Sample	Lab	^{214}Po Activity (mBq)	Samp. Quan.	PMT Quan.	Scaled ^{214}Po Activity (mBq/PMT)
Hamamatsu:					
R14374 Waterproofed PMT Assy.	K	2.63 ± 0.11	1 ea.	1 ea.	2.63 ± 0.11
Heatshrink Tube w/ mastic	B	5.96 ± 0.15	100g	10g	0.596 ± 0.015
Heatshrink Tube w/o mastic	B	34.6 ± 0.7	47g	??	
Urethane Potting Compound	B	<0.056	200g	190g	<0.053
Case material, PPS Plastic	B	<0.056	106g	??	
Butyl Foam Tape	B	31.6 ± 0.6	25g	0.2g	0.252 ± 0.001
Mastic Tape	B	11.68 ± 0.22	44g	9g	2.39 ± 0.05
Voltage Divider Circuit	–		1ea.	1ea.	
Belden:					
Waterproof PMT Cable RG-58	B	<0.056	2m	30m	<0.84
AXON:					
Waterproof PMT Cable RG-58	B	0.057 ± 0.024	2m	30m	0.86 ± 0.36
NNVT:					
034077 Waterproofed PMT Assy.	K	5.66 ± 0.22	1 ea.	1 ea.	5.66 ± 0.22
Case Material, ABS Beads	–		100g	??	
Cured Resin	K	<0.03	60g	??	
Butyl Mastic Tape	B	7.18 ± 0.13	144g	??	
Heatshrink tube	K	0.10 ± 0.03	120g	??	

Other material





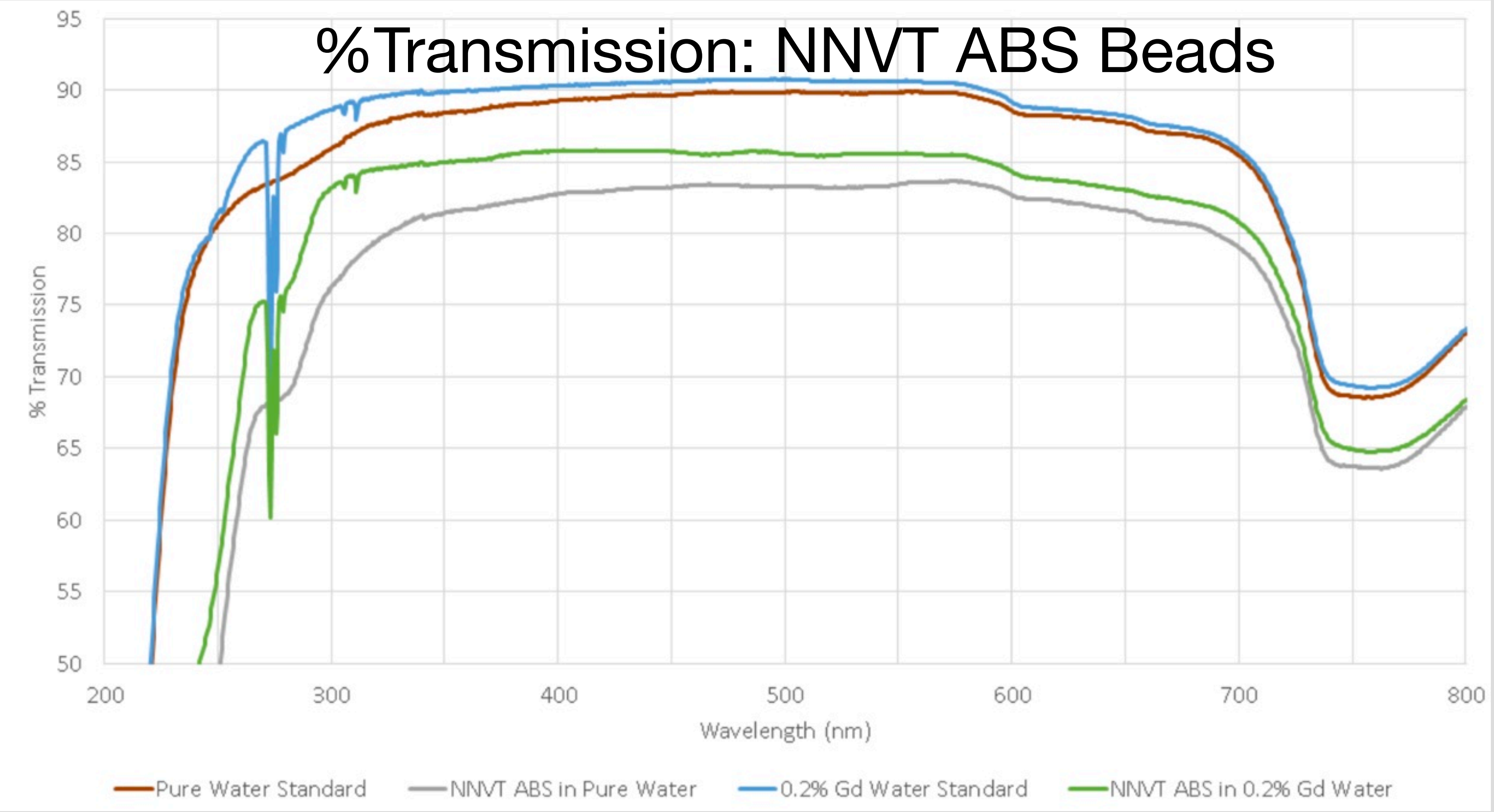


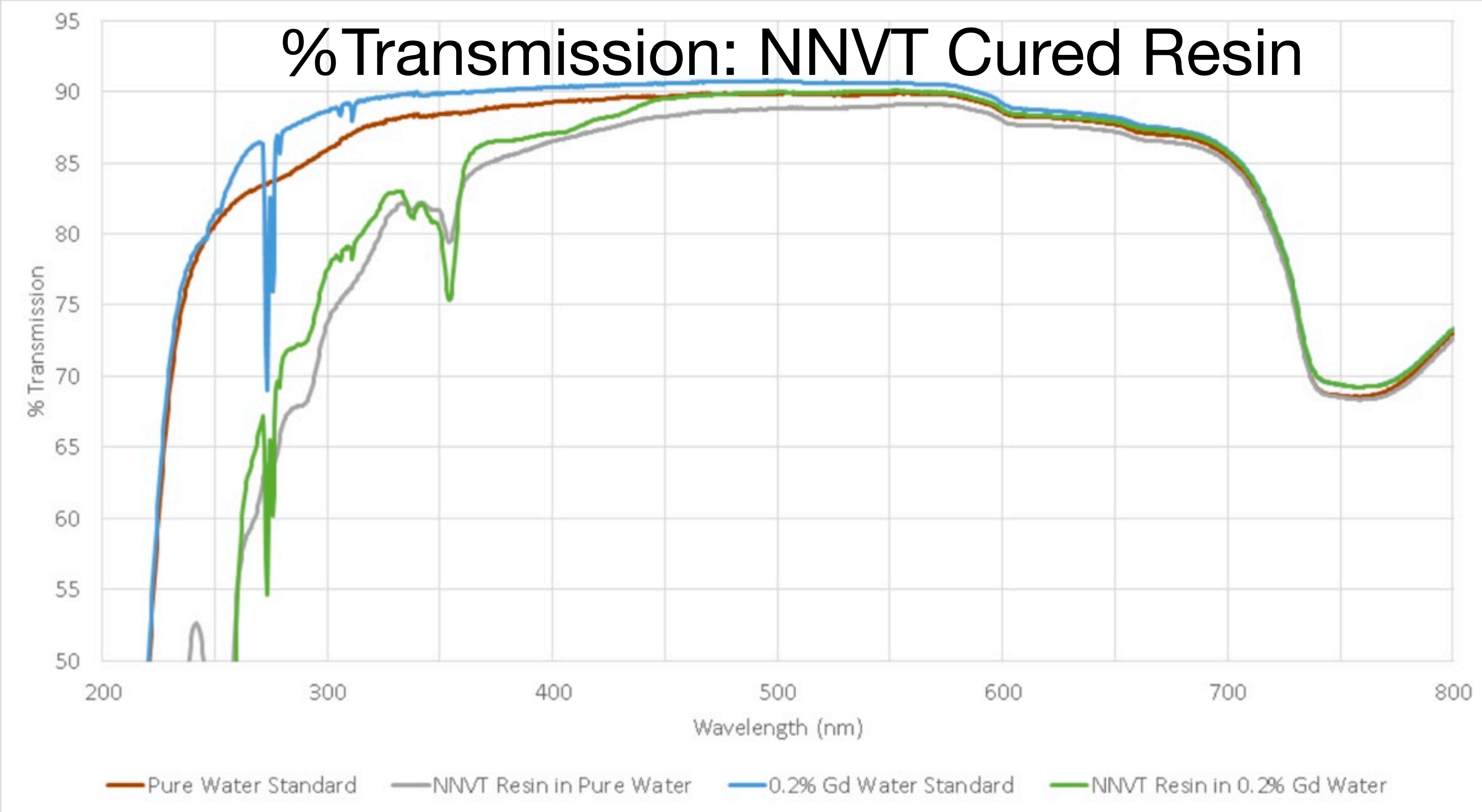
For both Hamamatsu and NNVT PMTs:

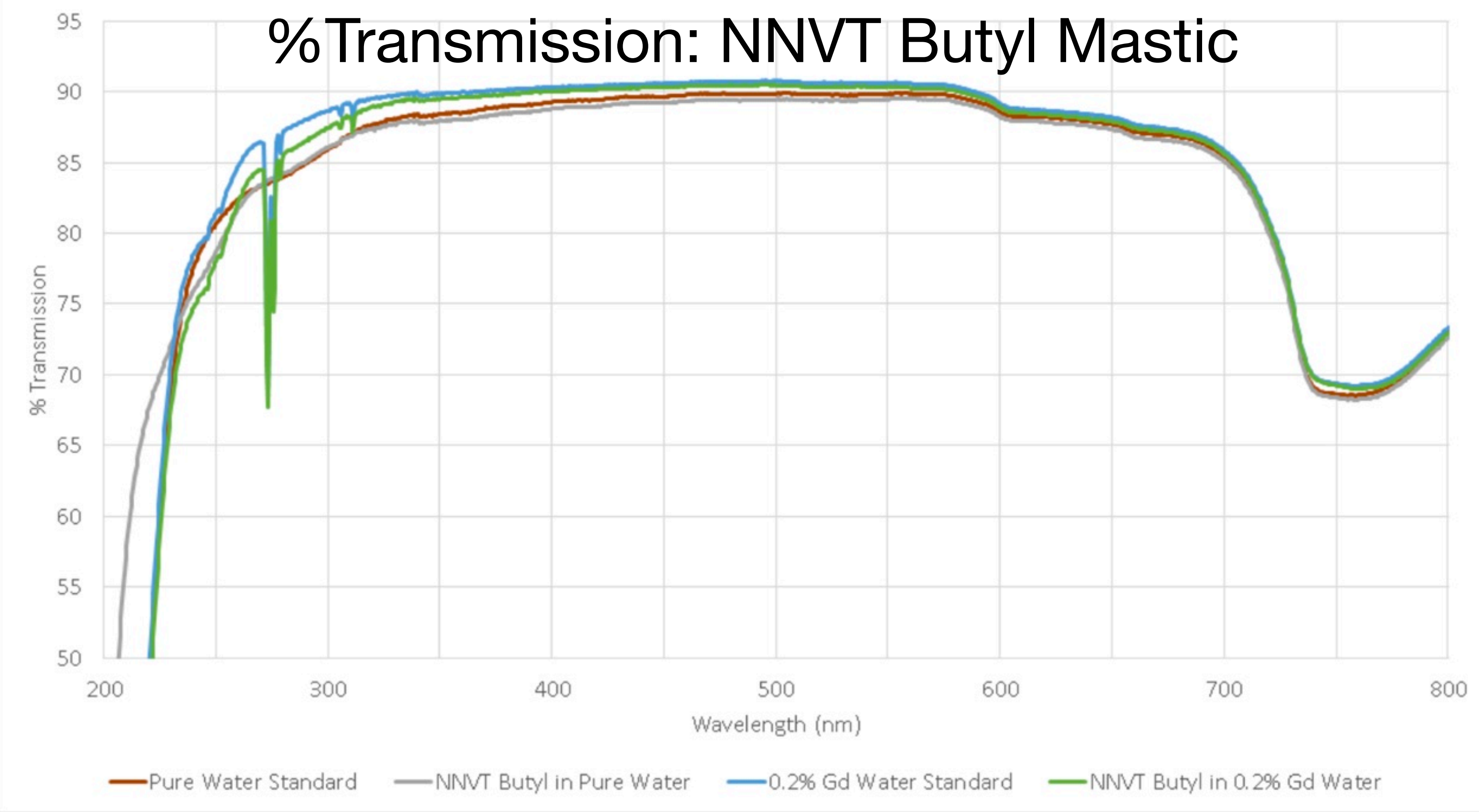
- the Rn emanation is below the required limit of 10 mBq.
- The butyl rubber and mastic adhesives contribute significantly to the total Rn emanation of the waterproofed PMT components

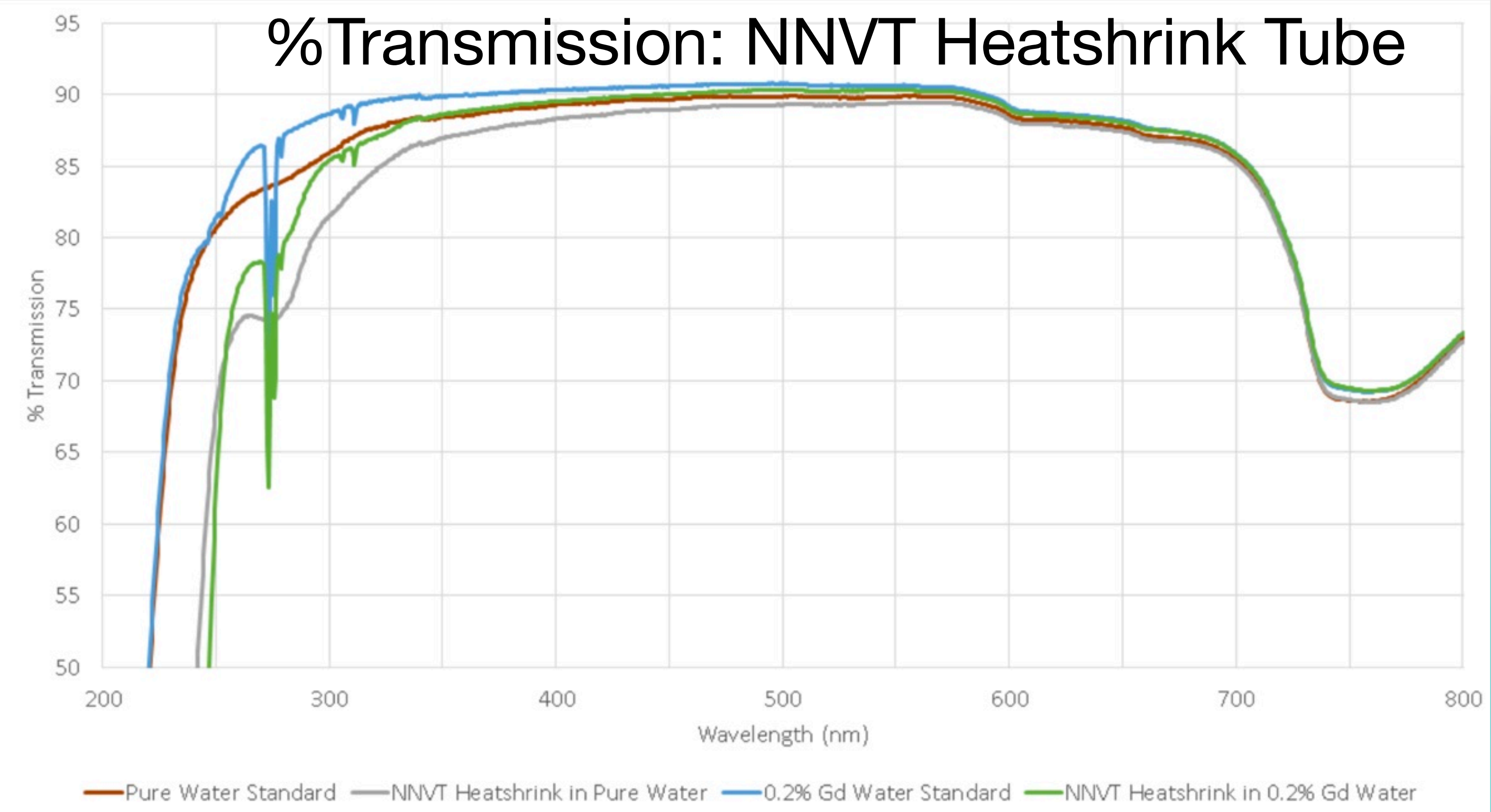
Soak Tests

- The goal for soak testing is to establish the expected change in UV attenuation length of the HK water as a result of long-term dissolution of materials.









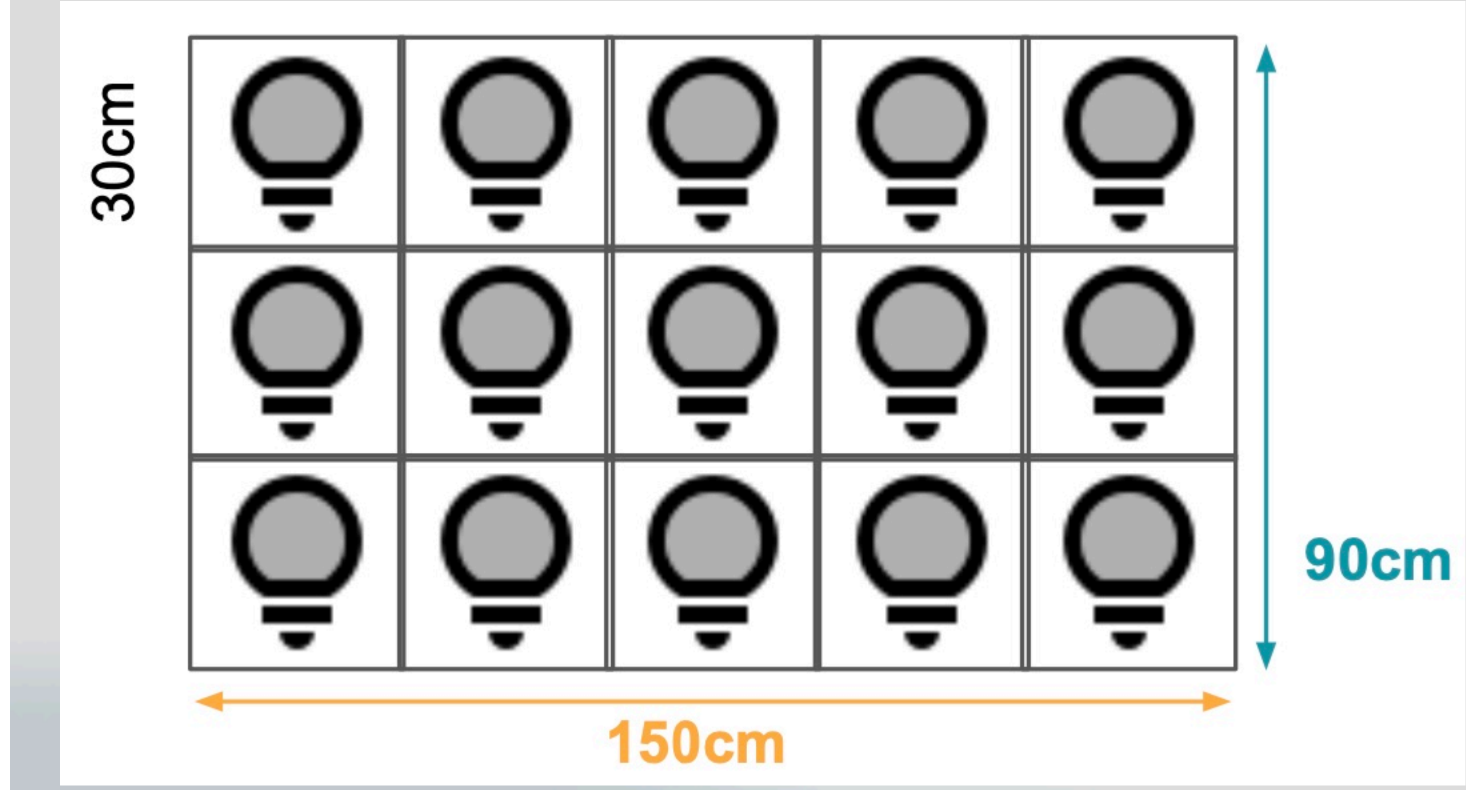
- For all the NNVT PMT waterproofing components measured, the effective attenuation length, L_{HK} (400m), is greater than 1 km.
- We do not expect any of the NNVT PMT waterproofing materials to significantly degrade the HK water.

PMT QA

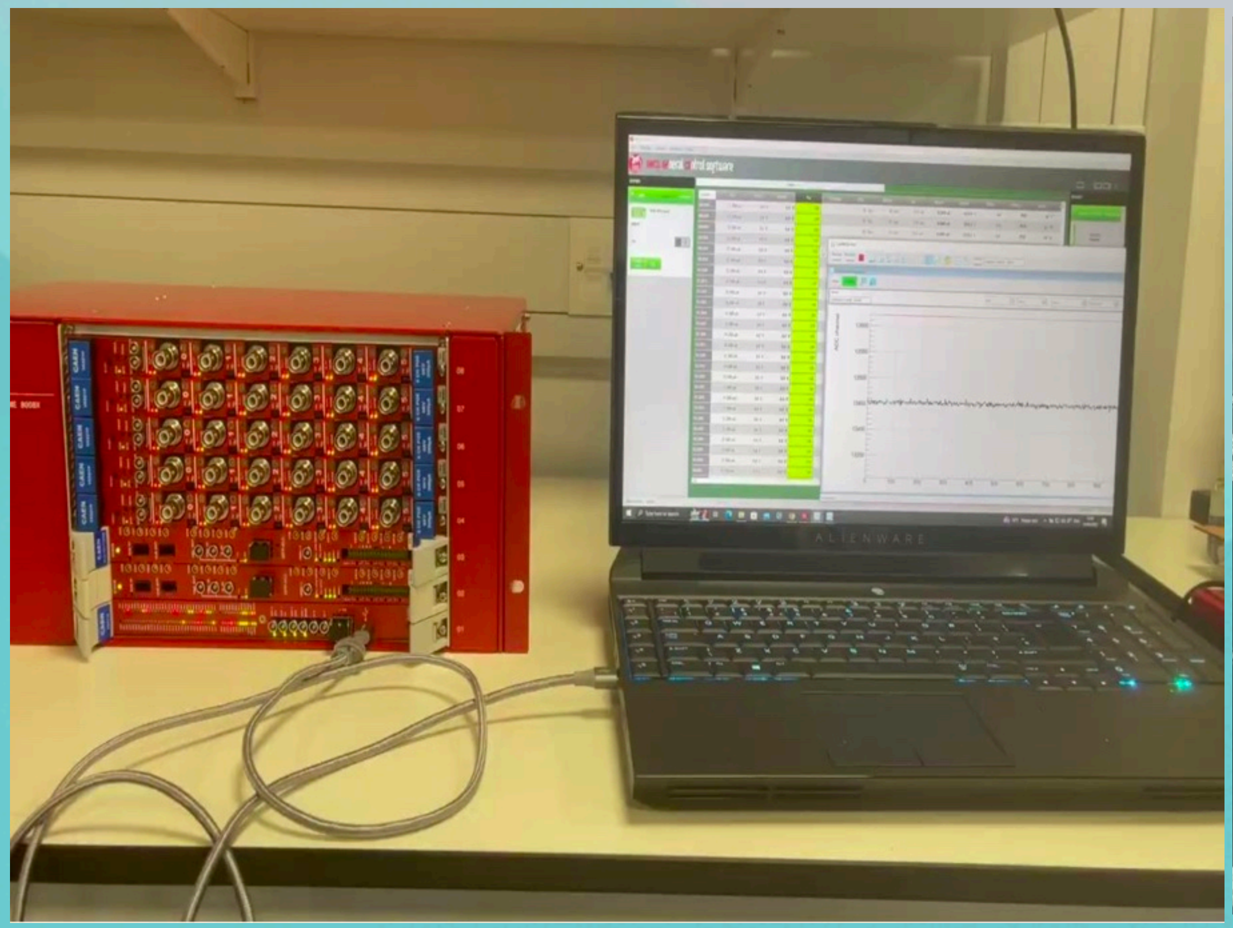
- After visual inspection, a programme of QA will start.

Batch Tests		
Characteristic	**Requirement**	**Comment**
Gain	3×10^6 achieved for $900 < V <$1300 V	Measuring gain variation w.r.t HV between [900, 1300]V
Stability	<10% variation	Gain @ 3×10^6, overnight
Dark rate	$<$ 1kHz	Gain @ 3×10^6, 20°C, overnight
SPE spectrum	peak-to-valley ratio > 2, $\sigma_{PE}/\mu_{PE} = 50\%$	Gain @ 3×10^6.
QE	$> 0.8\times$ reference specification	Gain @ 3×10^6. Relative to common reference per batch

- Top view of dark box.
- Dark box dimension: 100x160x50 cm^3



TEST	REQUIREMENTS	DURATION	💡	💧
Gain	3.10^6 @[900, 1300]V	1h	✅	
Single PE	PE width to Pedestal = 2 @ 3.10^6	few mins	✅	
Relative QE	<20% variation @ 3.10^6	few mins	✅	
Dark rates + stability	<kHz	~10h		



Conclusions

Two PMT models from Hamamatsu and NNVT for 3” PMTs for OD.

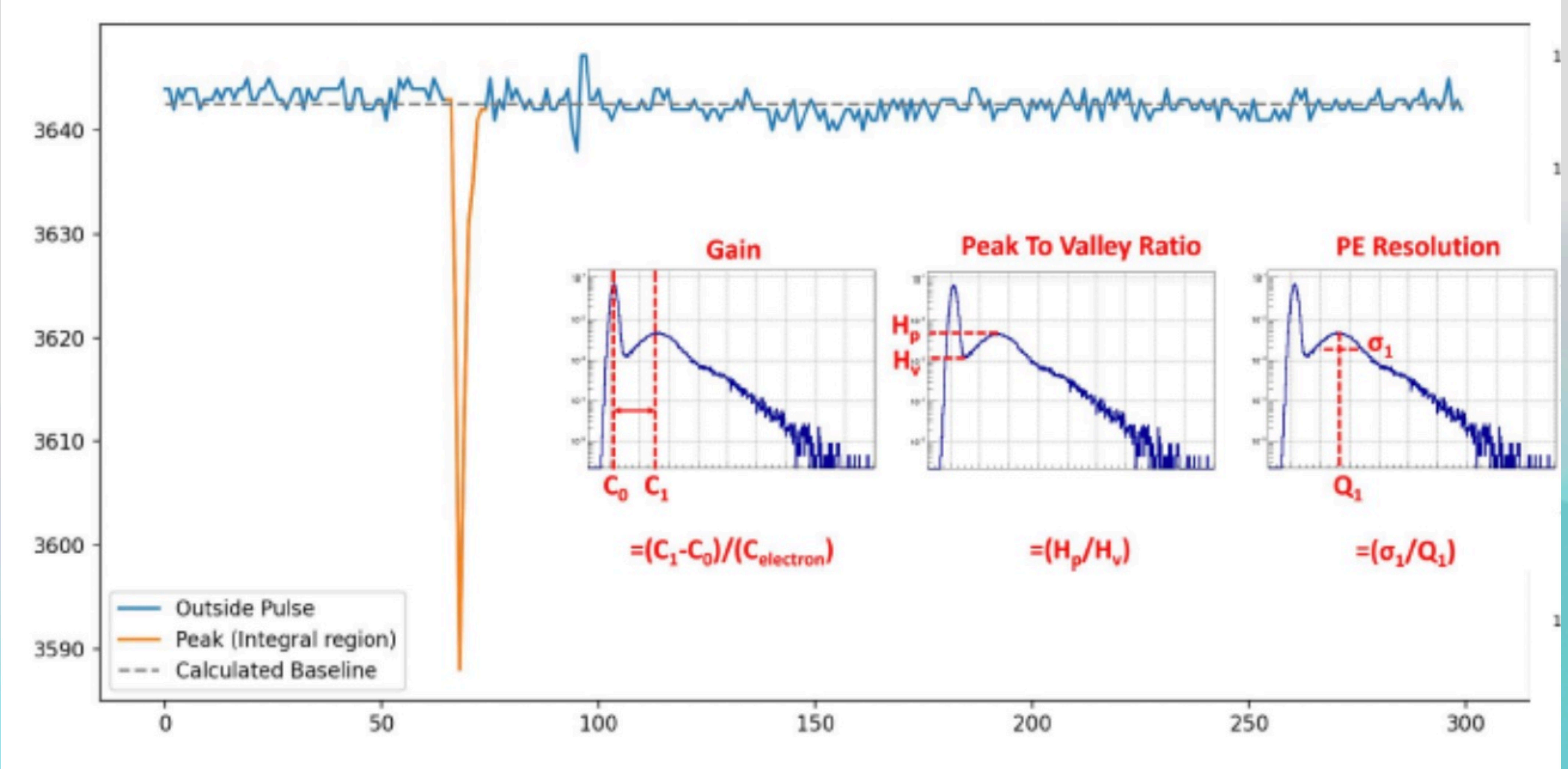
- Waterproof is needed.
- Long cables for reaching electronics board.
- Performing measurements of the PMT properties, and additional tests on pressure/implosion. More planned.
- Material tests being performed on all the material.

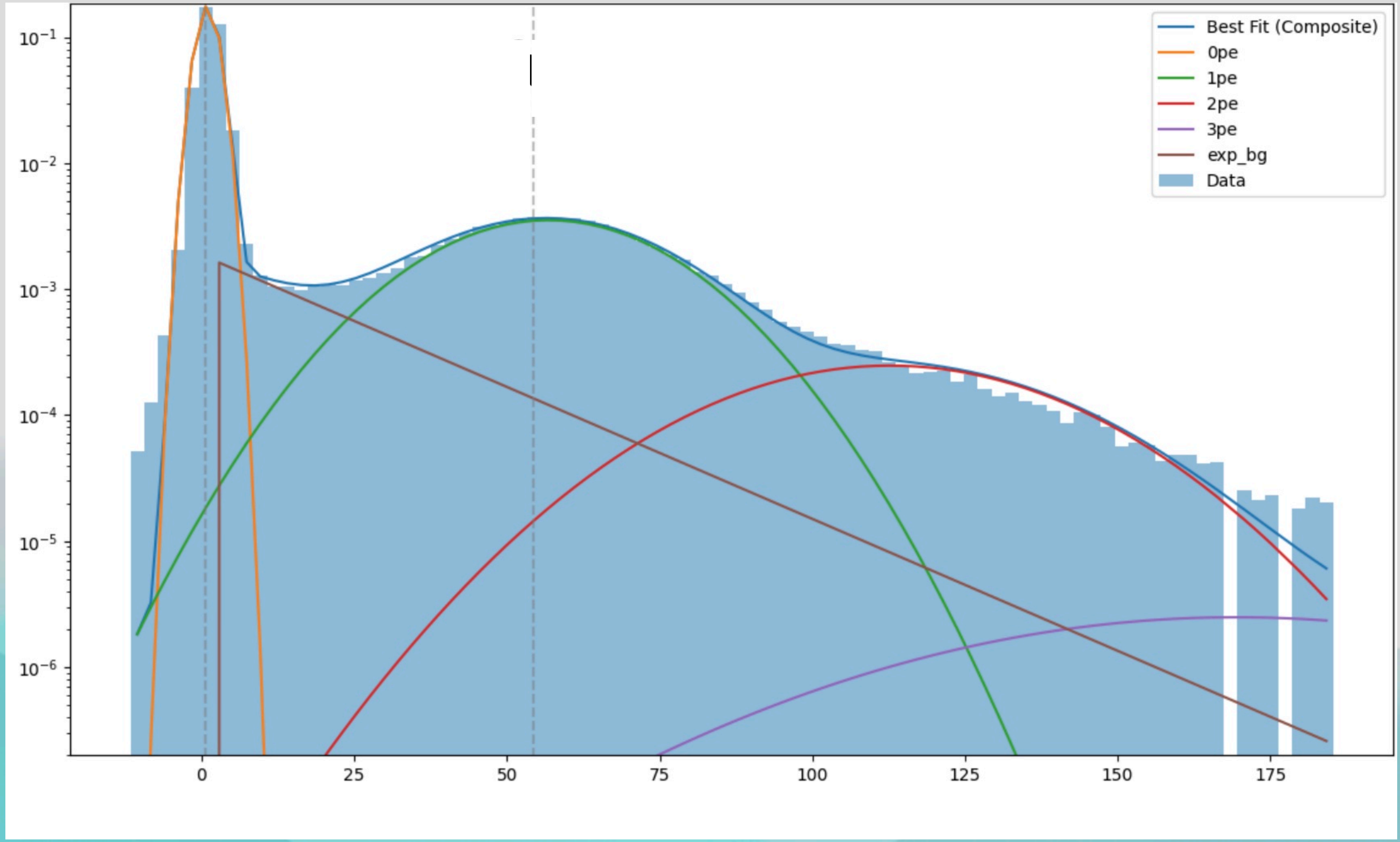
Additional Slides

Waveform measurement

- LED perpendicular to PMT face.
- LED amplitude such that ~10% of triggers provide a pulse.
- Take 500k waveforms, integrate pulse, and set the baseline to truncated mean outside set pulse width region

$$F(x) = G(x; A_0, x_0, \sigma_0) \sum_{n=1}^{2} G(x; A_i, x_0 + n x_1 \sigma \sqrt{n}) + \alpha e^{-\alpha(x-x_0)}$$





Fitting function from

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Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment

Volume 339, Issue 3, 1 February 1994, Pages 468-476