Система сбора света с помощью спектросмещающих пластин для внешнего детектора проекта Гипер-Камиоканде

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ИЯИ РАН

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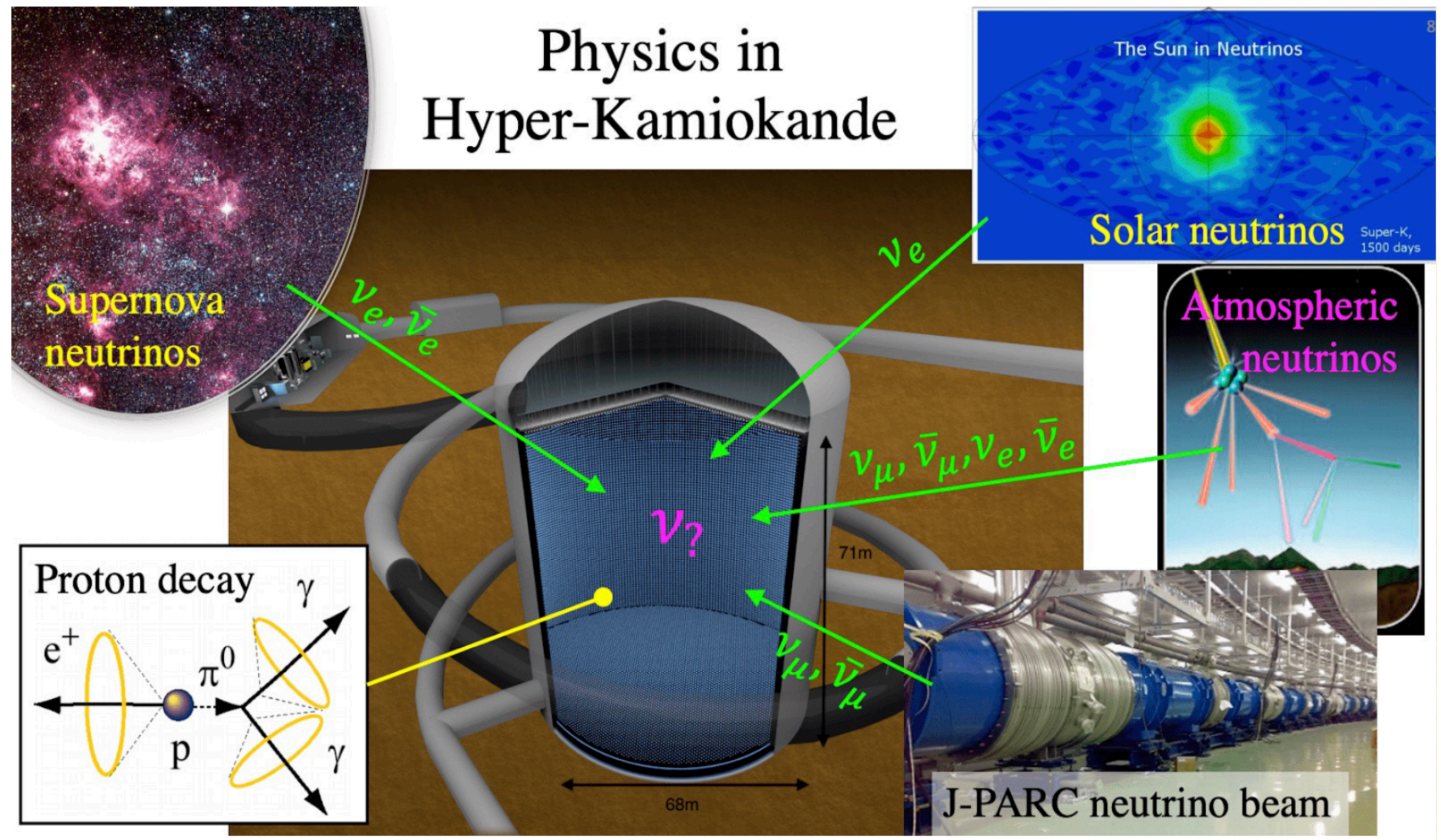
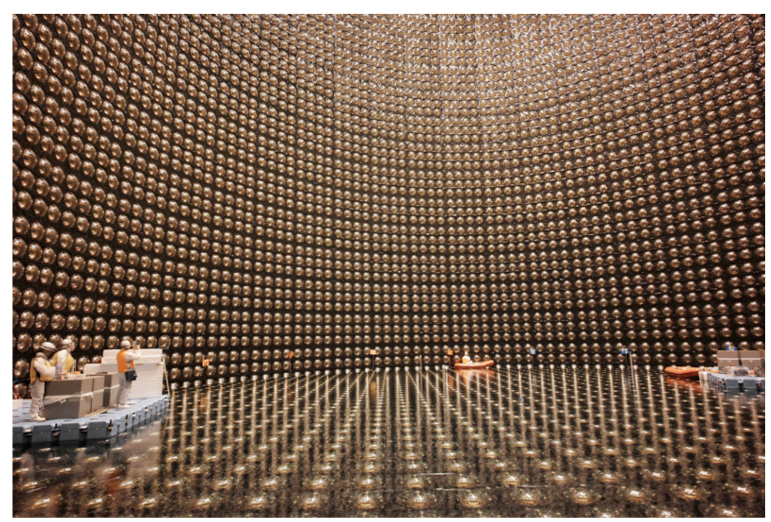
Next Generation Neutrino Projects

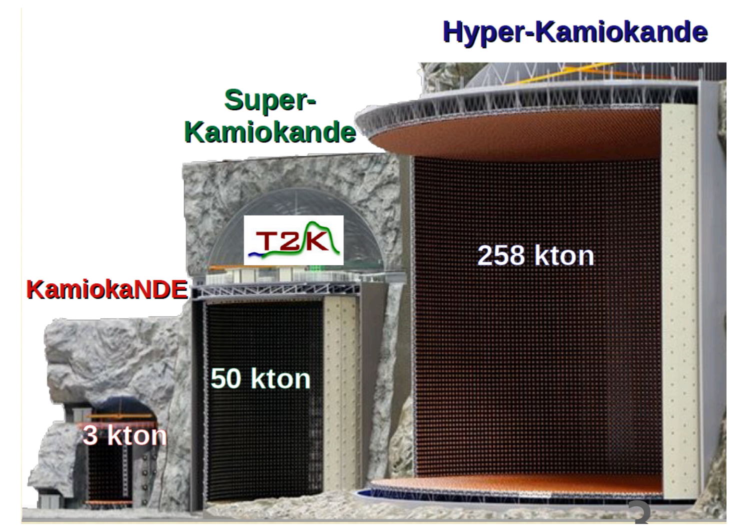
- Despite remarkable success of the current neutrino studies a future-generation of experiments is needed to make definitive discoveries in the field and push forward the frontier of particle physics
    - CP-violation in lepton sector, neutrino mass hierarchy, sterile neutrinos, SN neutrinos, proton decay, BSM physics with neutrino beams
- **Hyper-Kamiokande (Japan)** and DUNE (USA) projects are two flagship accelerator neutrino experiments of the next decade
- Recently intense efforts on preparation of the experiments: physics potential studies, R&D, detector optimisations

Hyper-Kamiokande Project

- Largest ever-built water Cherenkov tank in Kamioka, Japan
  - Data-taking start expected in 2027
- Rich physics program, within 10 years aim for
  - Accelerator neutrinos from J-PARC (T2K beam)
    - 5σ for CPV
    - Atmospheric + beam neutrinos for MO
  - Solar neutrinos
    - >5σ for D/N asymmetry
    - “Upturn” region in vacuum→ MSW
    - hep neutrinos
  - SN neutrinos
    - Discriminate between models
  - Proton decay
    - Reach > 10^{35} years
  - BSM, NSI, steriles

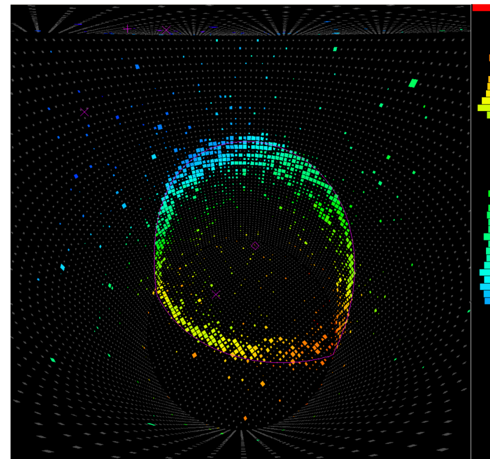


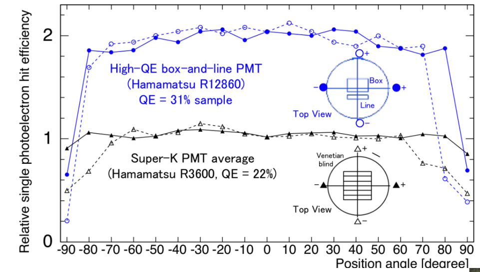


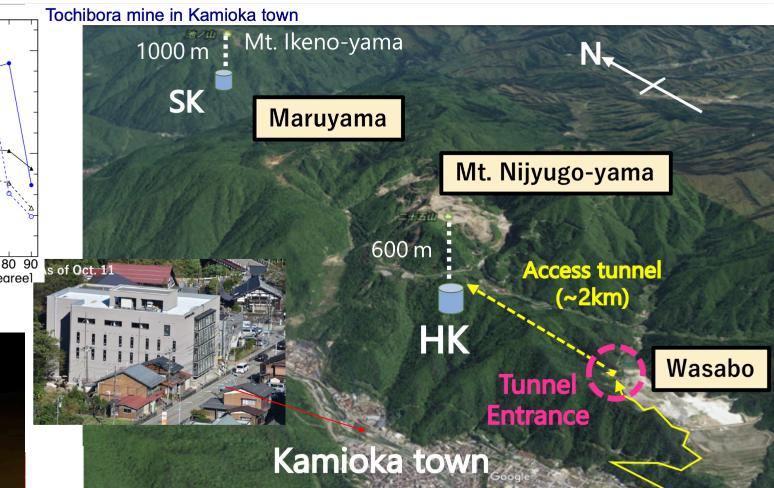


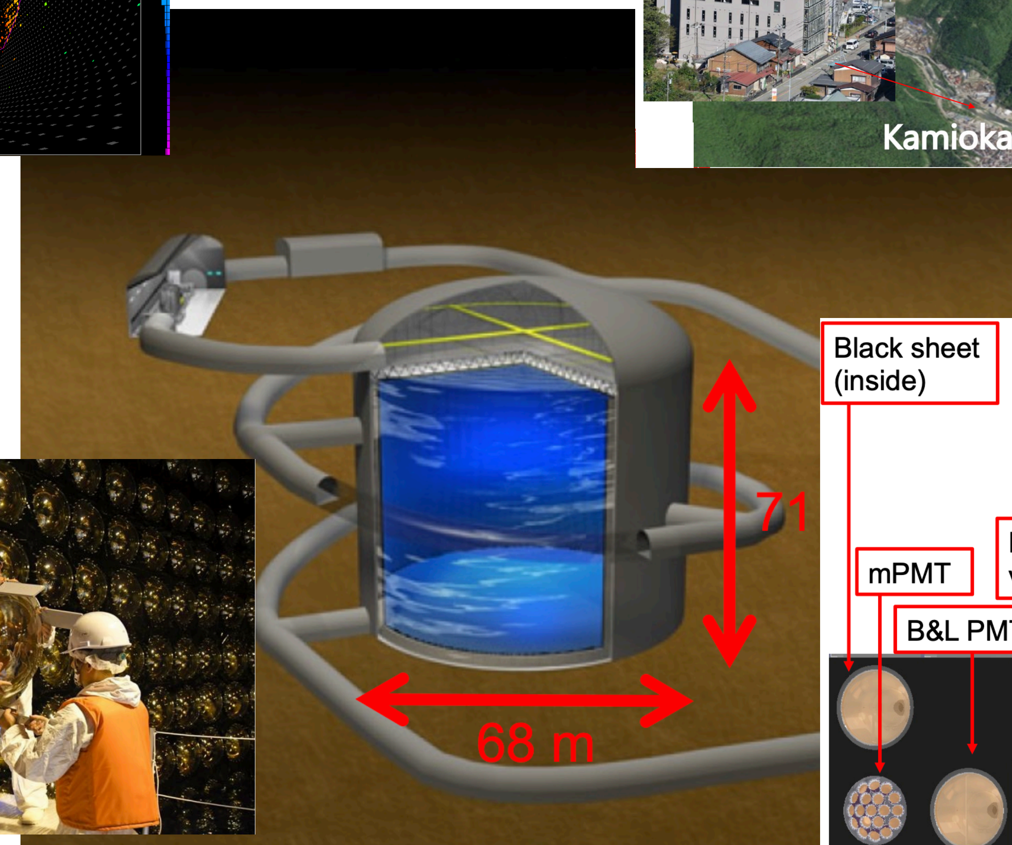
Hyper-Kamiokande Detector Concept

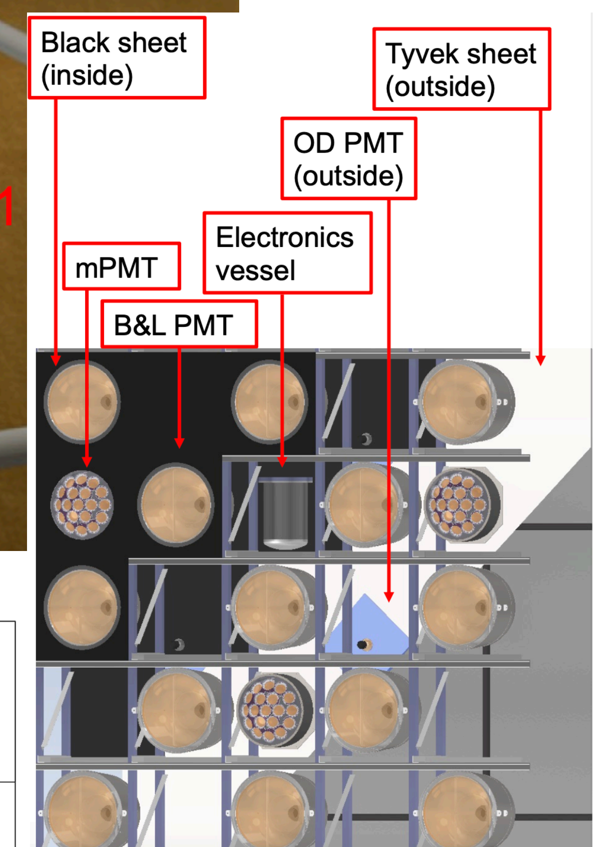
- 258 kton of purified water
  - 217 kton Inner (ID) + veto Outer Detector (OD)
- 188 kton FV → x8.4 Super-K
- 20k 50cm PMTs in ID
  - Photo-cathode coverage 40% (SK)→**20% (HyperK) compensated with**
  - **New generation Hamamatsu** Box&Line R12860 **PMTs** (R3600 in SK)
    - 50% higher quantum efficiency (30%)
    - x2 better charge resolution (30%)
    - x2 better timing resolution (1.5ns)
    - ~Same dark rate (4kHz)
- + Few thousands of multiple mPMTs
- 19 of 8 cm PMTs inside one vessel
  - Directional information

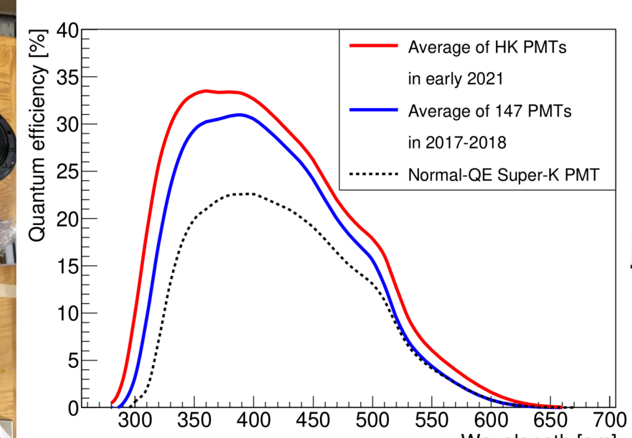






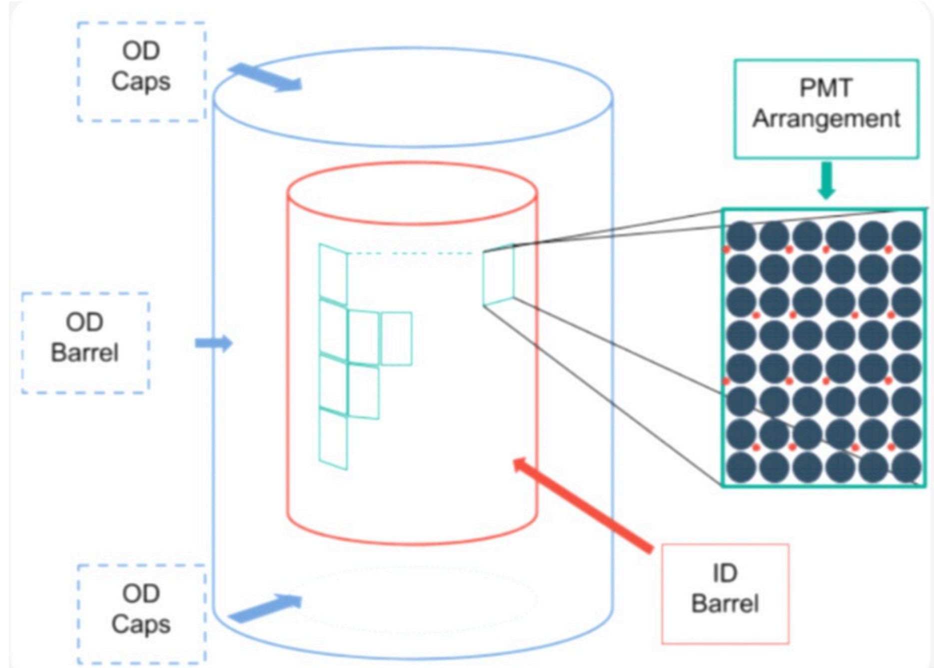


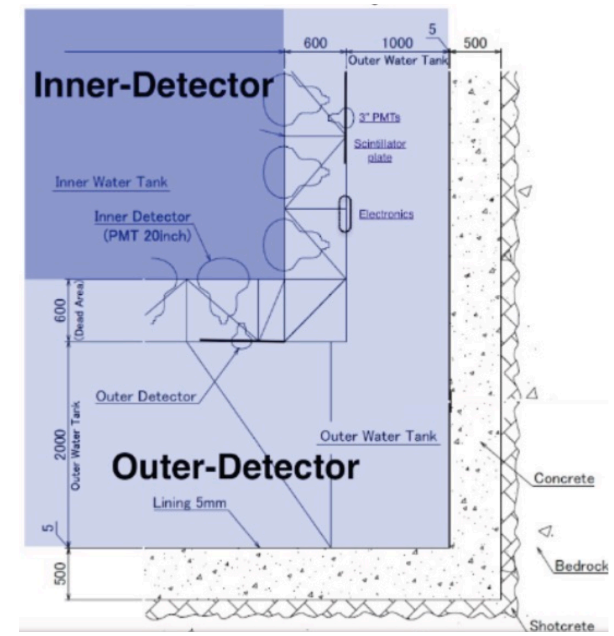


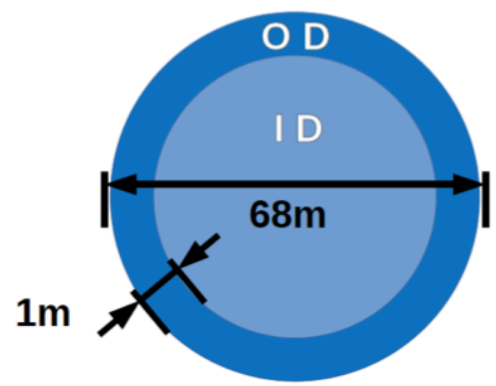


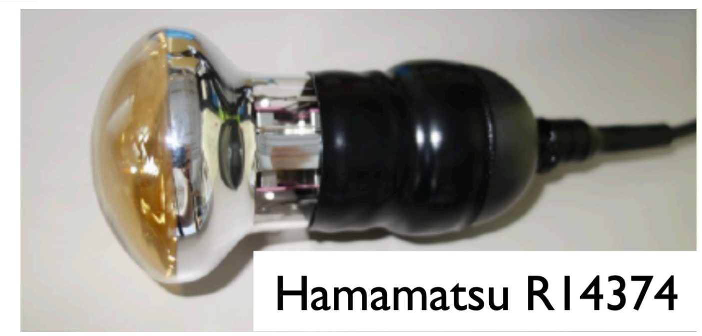
Hyper-Kamiokande Outer Detector

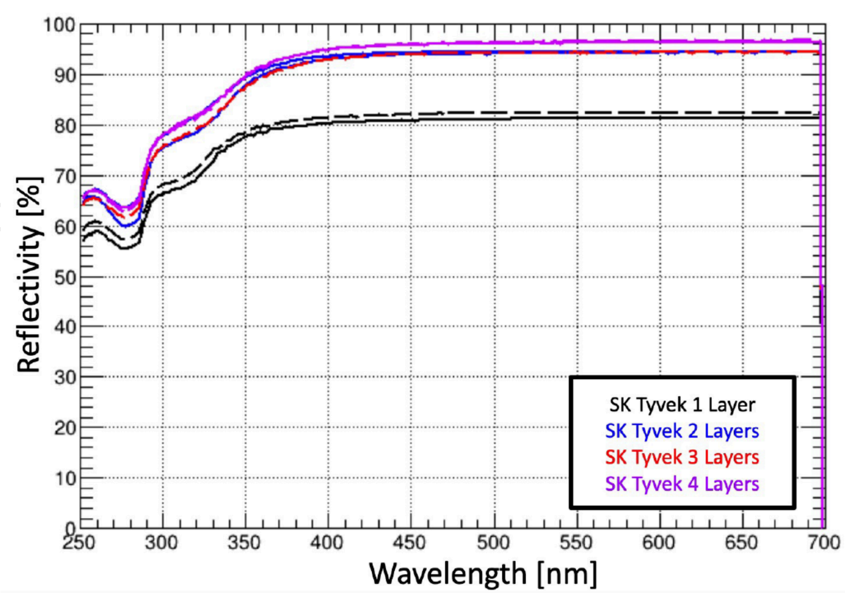
- Optically separated ID and OD
- Challenges (wrt SK)
  - Shallower overburden 1000m → 600m
  - Larger HK volume
    - Cosmic rate **2Hz → 45 Hz**
  - Narrower OD region
    - 2.6/2.7m → 1/2m (caps)
- Performance requirements
  - **Veto inefficiency 10^{-4}**
  - ~4m accuracy of muon exit/ entrance positions
  - Provide passive backgrounds shield
  - Low radioactivity < 10mBq (ID&OD)
  - Thermal power < 1W per channel
  - **Longevity and enough redundancy→** operation for decades + high-cost of draining and intervention
- **Light-collection**
  - **~3.5k 8 cm PMTs***
  - **Tyvek coverage on walls**
  - **WLS plates**







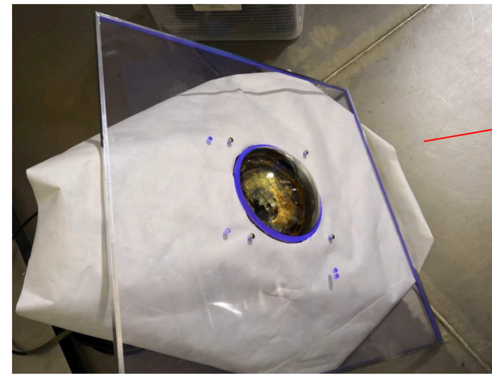


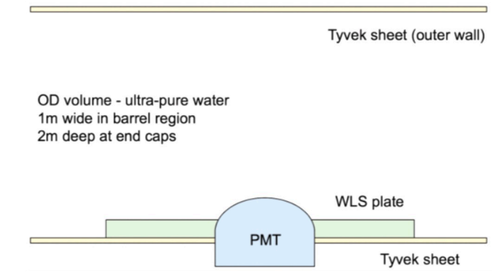


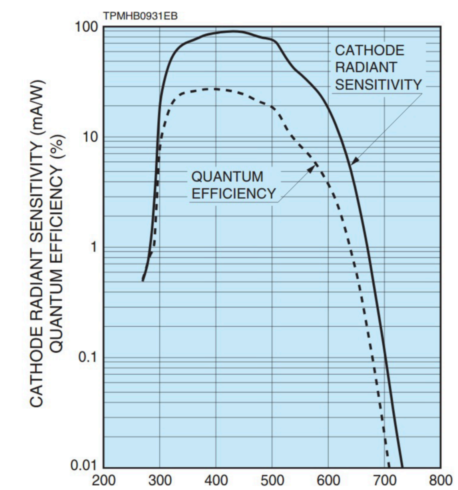
* Hamamatsu R14374 is the primary option, also e.g. NNVT N2031 (China) studied

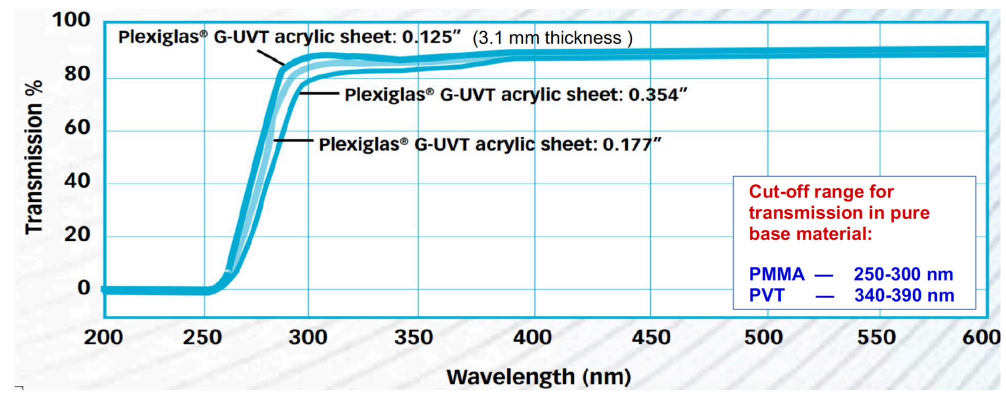
Hyper-K OD: Light Collection With WLS Plates

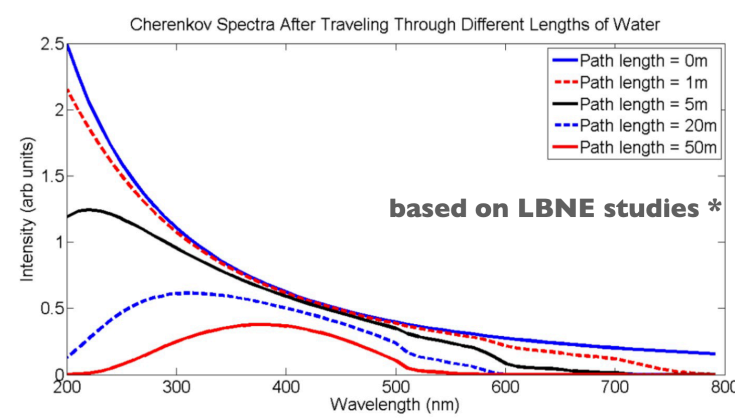
- Light collection can be further **enhanced with WLS plates**
- Plastic plates with WLS dopant(s)
  - Short UV photons collected and re-emitted (uniformly in directions) to longer wavelengths to match PMT QE
  - 250-400 nm region (~300 photons/cm) can be caught and re-emitted by a WLS plate to further concentrate light on PMT
  - x2 N photons in 250-300 nm region wrt 350-400 nm
- Super-K OD uses PMMA + bis-MSB plates
  - ~50% increase in collected light

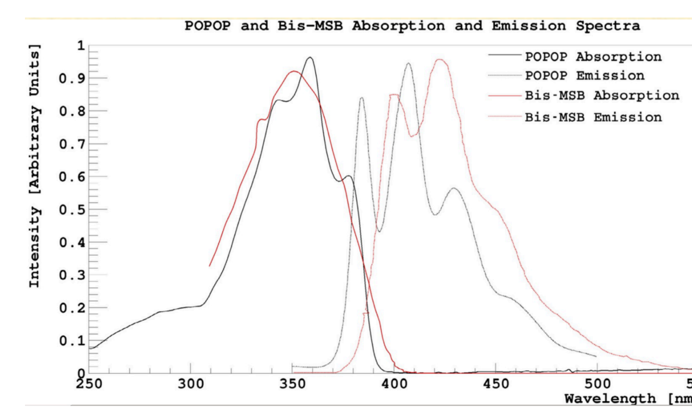












Detector	Number of Channels	PMT Size	WLS Plate Size (cm)	Cladding Reflector	WLS Plate Chemical Composition
Super-K OD	1885	8" (20 cm)	1.3 x 60 x 60	3M polyester film 850 with Al layer	PMMA + 50 mg/l bis-MSB
Hyper-K OD	3500	3" (8 cm)	0.7 x 30 x 30	3M polymeric film DF2000MA	PMMA + 50 mg/l POPOP (+ 3 g/l PP0)

* https://mountainscholar.org/handle/10217/83745 WLS plates studies for LBNE

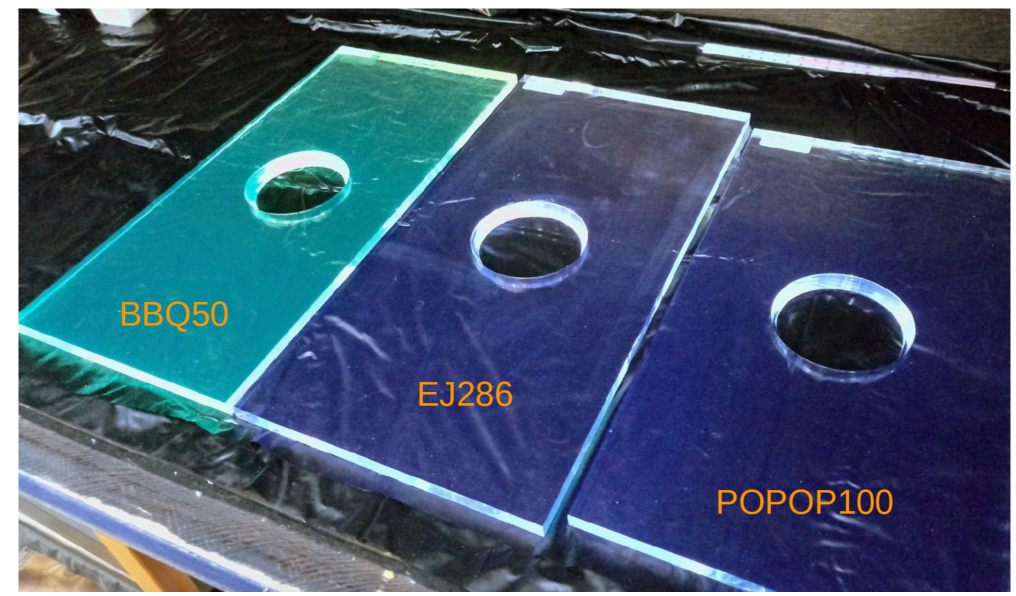
WLS Plates for Hyper-K OD: Chemical Composition

- Intense campaign to find optimal chemical composition for HyperK OD WLS plates
  - INR RAS (Russia), Oxford.U, RAL (UK)
- 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)

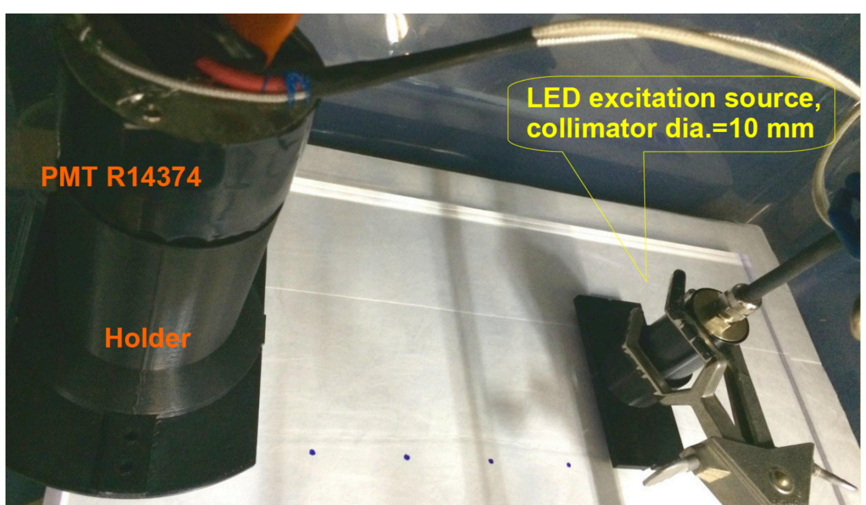
BBQ50, BBQ100, bisMSB50, bisMSB100,
POPOP100, POPOP200, POPOP400,
POPOP50 +PPO3000 (50 mg/l POPOP + 3 g/l PPO — fluor concentrations),
POPOP100+PPO3000 (100 mg/l POPOP + 3 g/l PPO),
POPOP100+PPO10000 (100 mg/l POPOP + 10 g/l PPO),
POPOP200+PPO3000 (200 mg/l POPOP + 3 g/l PPO),
POPOP200+PPO10000 (200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



- Lab tests with LED sources
- Tests in air and water
- Scan plates for L.Y. and attenuation curves

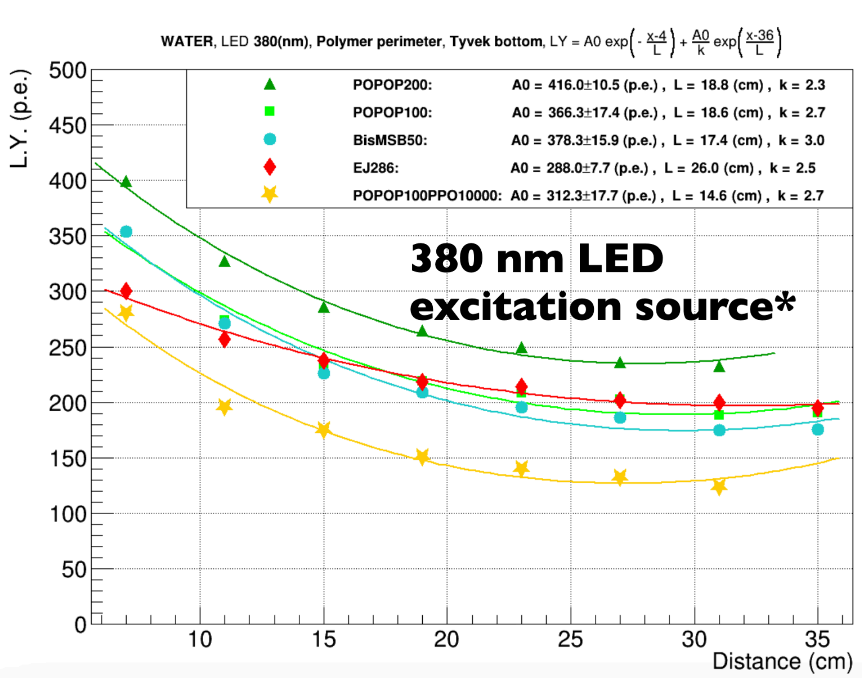


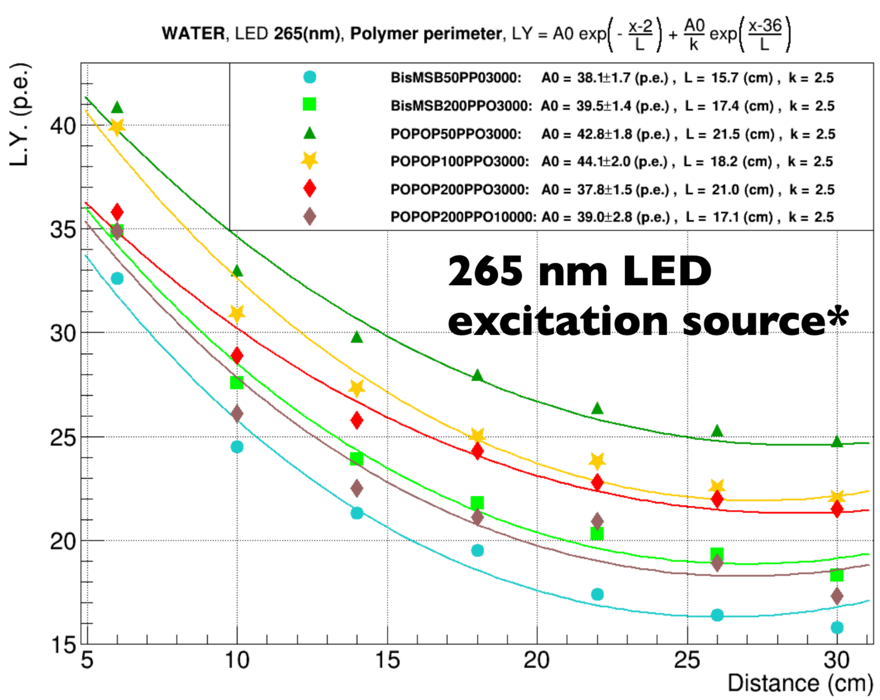
Fast UV LED light sources from PicoQuant
265 nm — spectrum range 260-300 nm
315 nm — spectrum range 300-340 nm
380 nm — spectrum range 365-395 nm
405 nm — spectrum range 380-440 nm

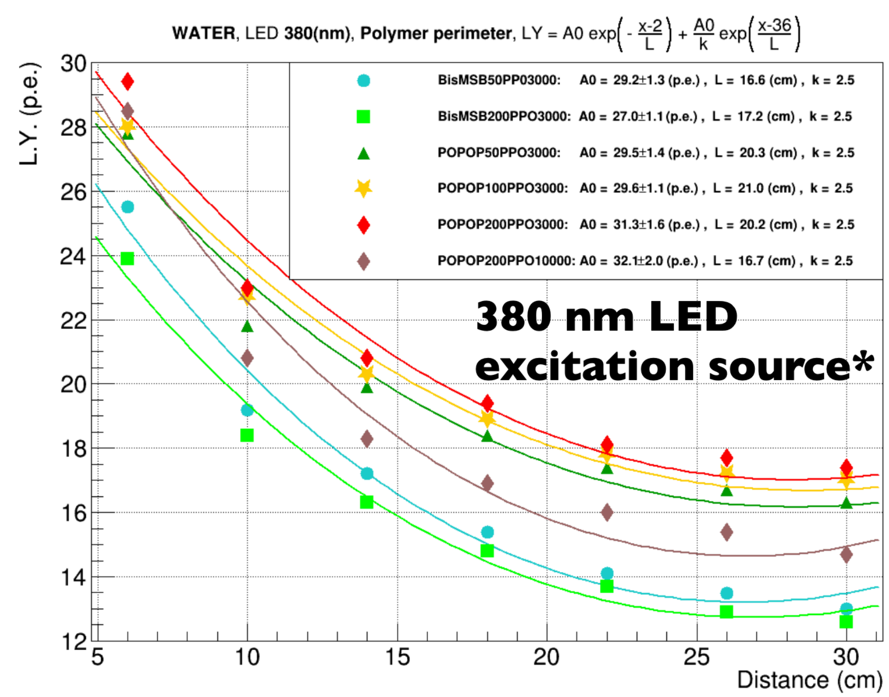
Fluors	Absorption range, nm	Emission range, nm	Notes
BBQ	250-460	420-640 **peak: ~510**	Shifts UV and visible blue light into green spectral area.
bis-MSB	300-400 **peak: 350**	380-530 **peak: 400-460**	Emission spectrum is close to POPOP, cost is higher than POPOP, easier to dissolve in acryl base.
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.

WLS Plates for Hyper-K OD: Chemical Composition

- Double fluor to accept Cherenkov light in wide spectral range 250-400 nm
- Bis-MSB: lower re-emission efficiency than POPOP. Bis-MSB advantage to dissolve in a base material. Manufacturer tests: total polymerization times in PMMA with POPOP and bis-MSB is about the same
- PPO fluor with high concentration 10 g/L shows shorter attenuation length wrt 3 g/L, and lower light signal
  Published data indicate the flat light signal dependence on PPO concentration in range 3-7 g/L
- POPOP concentration of 50 mg/L gives advantage in short UV range 250-320 nm, while with POPOP concentration of 200 mg/L signal gain in long UV range 320-400 nm
- **The optimum dopant composition was found to be: 50 mg/L POPOP + 3 g/L PPO**







WLS plates	BBQ 50	BBQ 100	bis-MSB 50	bis-MSB 100	POPOP 100	POPOP 200	POPOP 400	POPOP 100 PPO 10000	POPOP 800 PPO 5000	EJ286
FOM	2.91	3.34	3.81	3.83	4.38	4.64	3.80	5.89	4.60	3.34

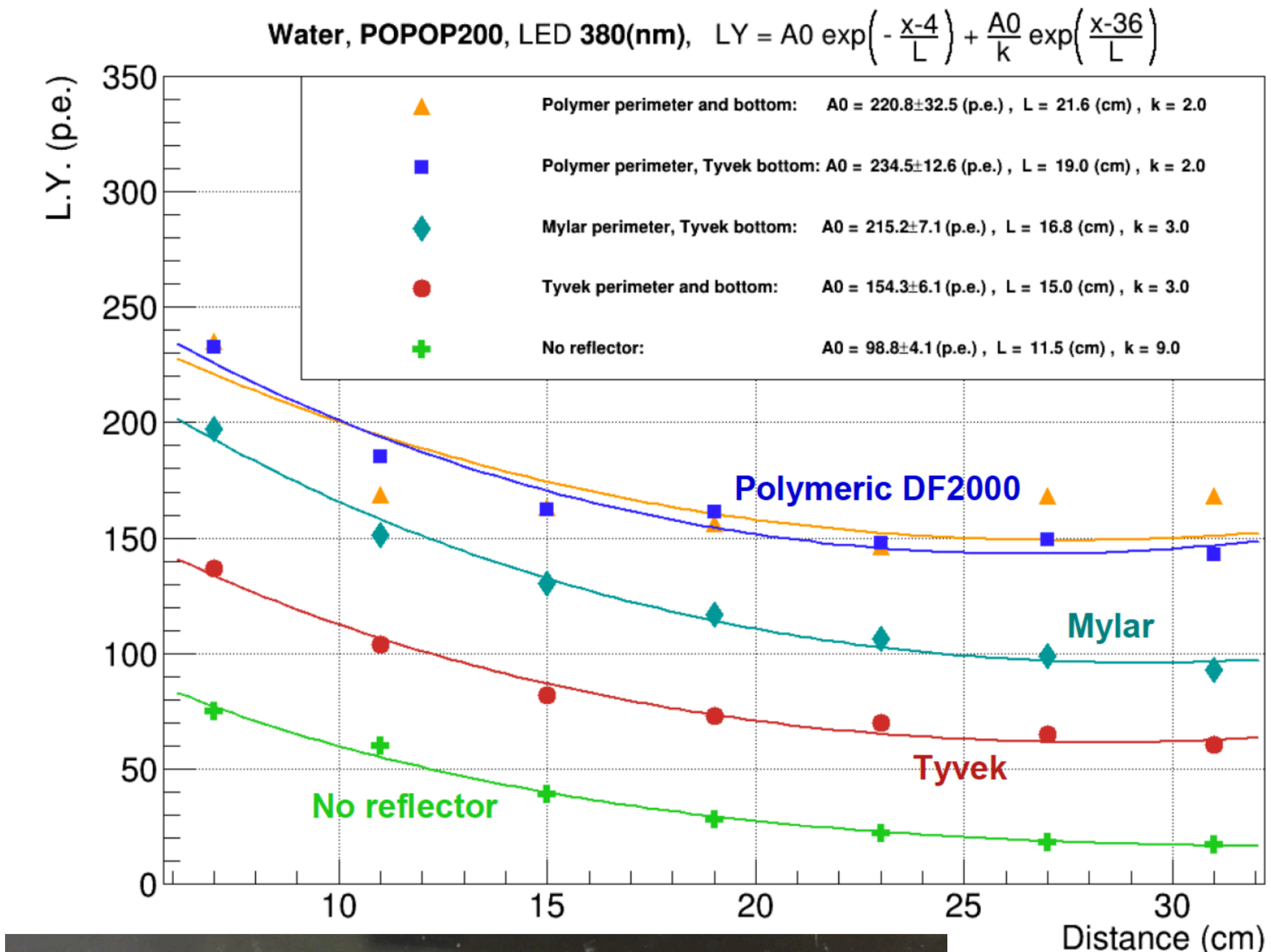
FOM = 0.45*R.L.Y.$_{(250\text{-}300nm)}$ + 0.32*R.L.Y.$_{(300\text{-}350nm)}$ + 0.23*R.L.Y.$_{(350\text{-}400nm)}$

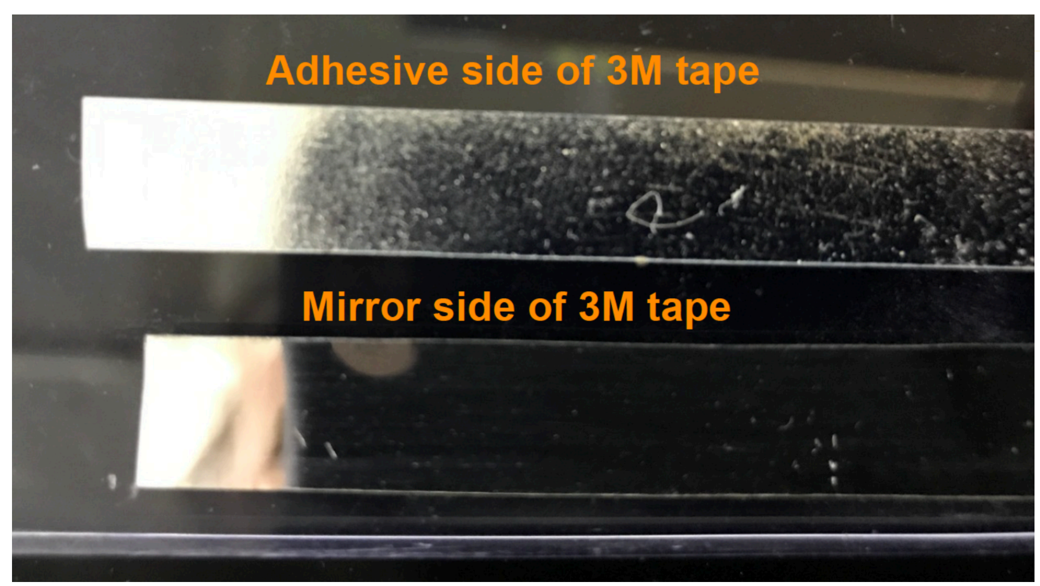
- **0.45, 0.32 and 0.23 — fractions of emitted Cherenkov light spectrum within a range**
- **R.L.Y. — measured relative light yield (fraction of photons converted in photoelectrons) for a range**

* absolute L.Y. is not relevant, relative comparison of different fluor dopants

WLS Plates for Hyper-K OD: Reflector

- Tested 3 material candidates for cladding reflector around plate edges
- Tyvek (diffuse reflector)
- Aluminized Mylar (mirror reflector)
- Polymeric film 3M DF2000MA (mirror reflector) → better performance with adhesive side*
- Mylar increases light signal almost by ~30% comparing with Tyvek
- Polymeric film increases light signal more than x2 comparing with Tyvek
- Tyvek bottom reflector under a WLS plate: gain is limited to <10% although creates the overall reflection environment to collect photons (Cherenkov and re-emitted) with HK OD PMTs



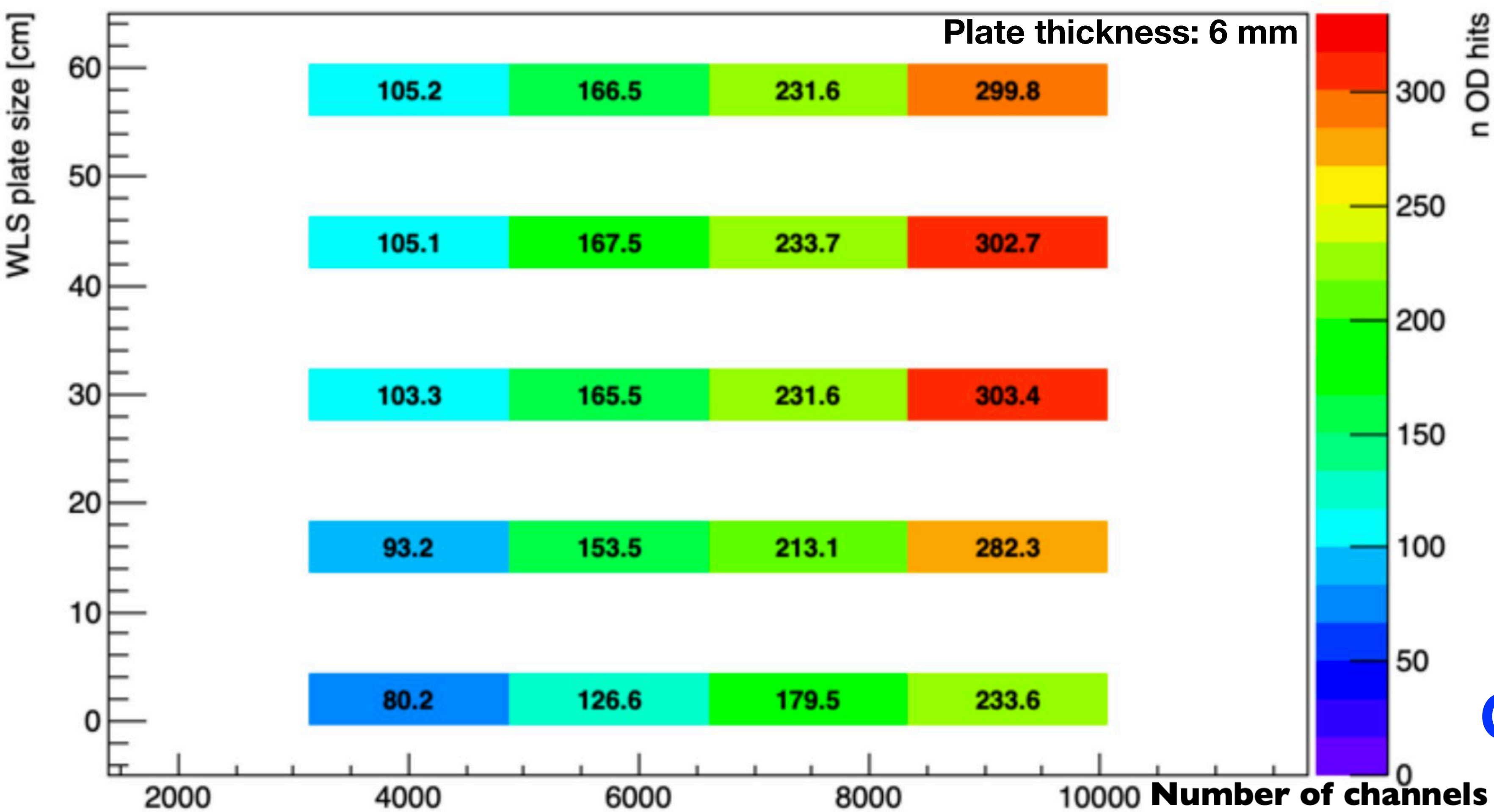


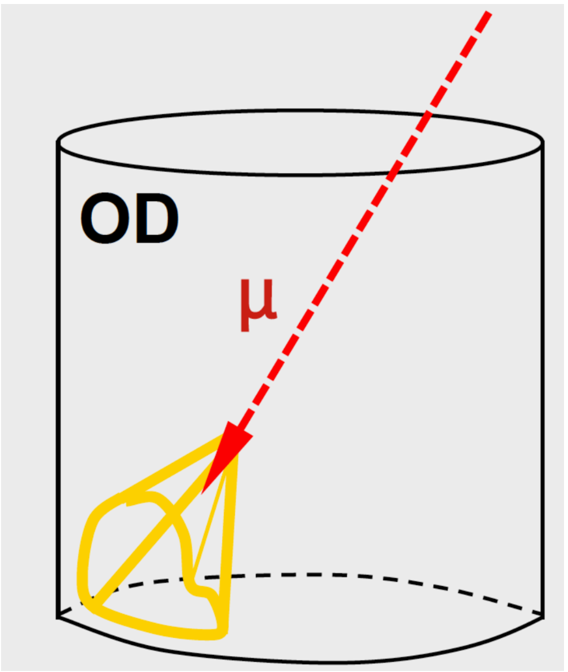
Adhesive side of 3M tape	Mirror side of 3M tape
29.5 p.e	25.4 p.e.

*4 months long test @ 73 °C (~20 years of Hyper-K) → good adhesion to a WLS plate and optical performance

WLS Plates for Hyper-K OD: Optimisation of Plate Size

- WCSim* package → GEANT4 based development and simulation of large water Cherenkov detectors
- Simulate response for cosmic muons with different WLS plate sizes





Check number of OD hits vs WLS plate size + number of PMT+WLS channels instrumented

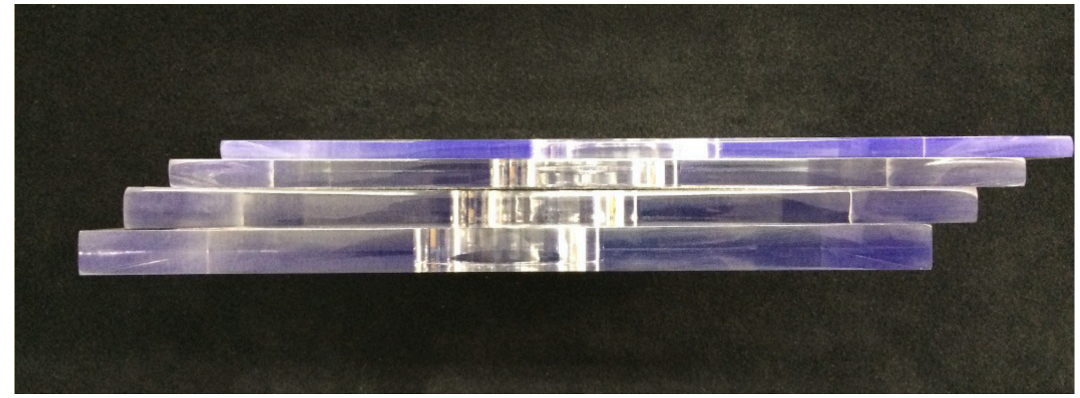
Optimal size: 30 x 30 cm²

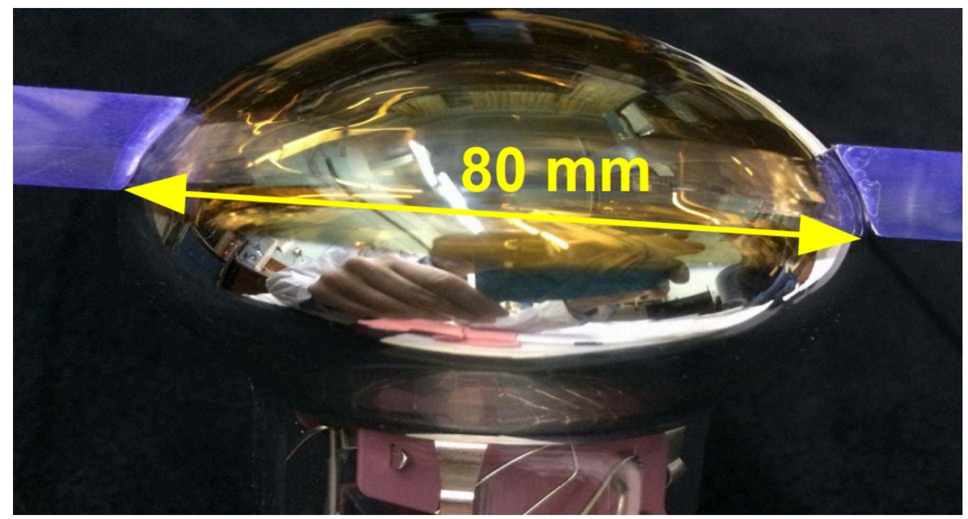
- No gain with WLS plates > 30x30 cm²
  - Path length before hitting the PMT roughly proportional to the plate area, e.g. for the (isotropic) light 40 cm plate gives ~x2 attenuation wrt of a 30 cm plate
- WLS plates can detect UV Cherenkov photons but for the visible light work as an absorber

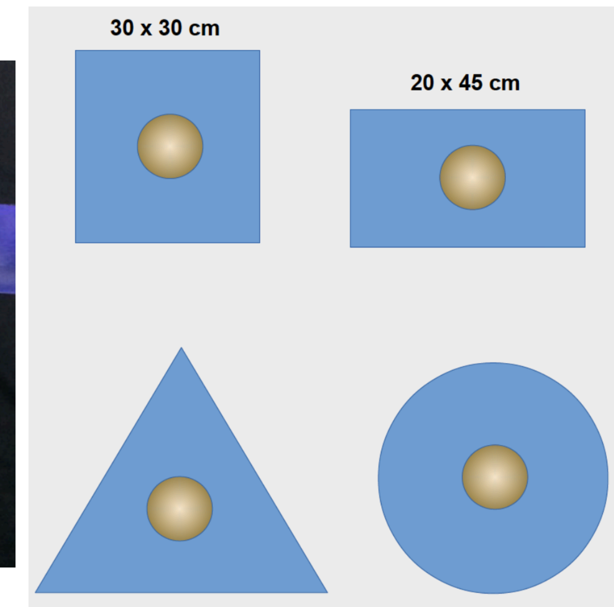
* https://github.com/WCSim/WCSim

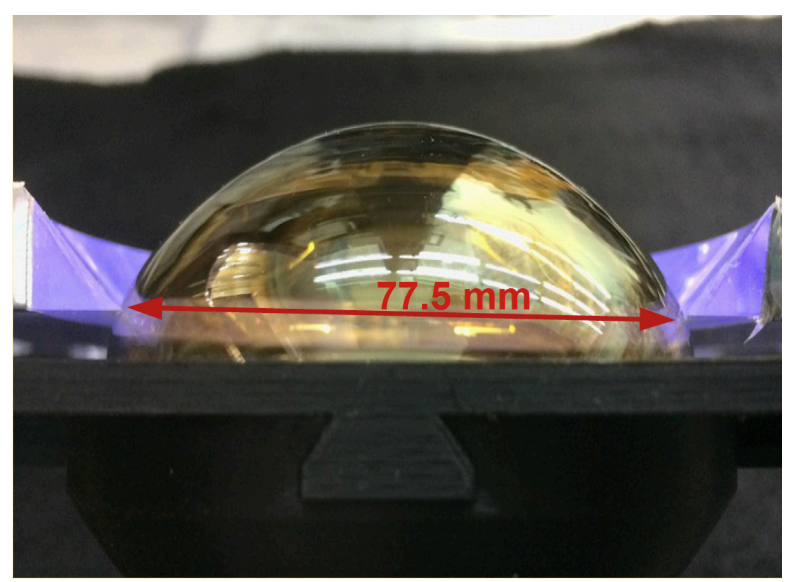
WLS Plates: Shape, Thickness and PMT Coupling*

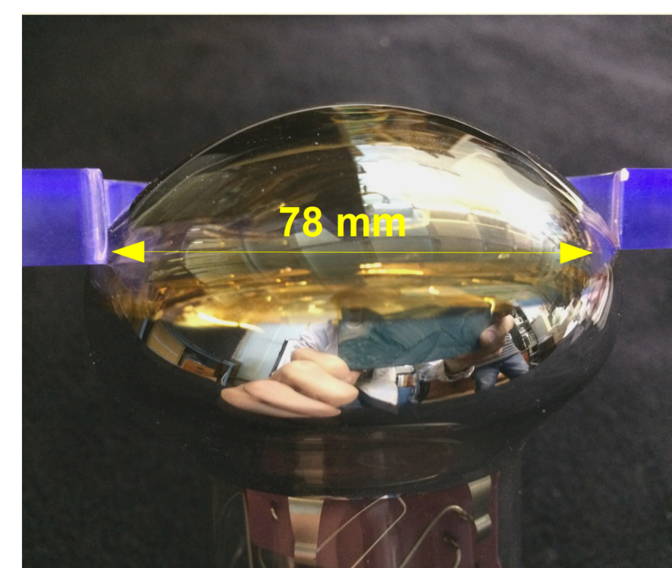
- Optimisation based on simulation results and measurements
  - Absorption of Cherenkov photons, attenuation ← number of reflections, optical coupling, variable photo- cathode sensitivity
- PMT-WLS plate coupling
  - Balance re-emitted photons ←→ direct detection
  - Hemispherical, cylindrical, open-angle
  - Cylindrical opening of 78 mm: match photo-cathode (72mm, eff. drops to ~50% at 78 mm) + performance + ease manufacture
- Plate shape: 30 x 30 cm^2 squares based on simulation and measurements
- Thickness
  - 6-10 mm; for > 10 mm no gain in light ← works as absorber
  - Cost-performance → 7 mm thick plate







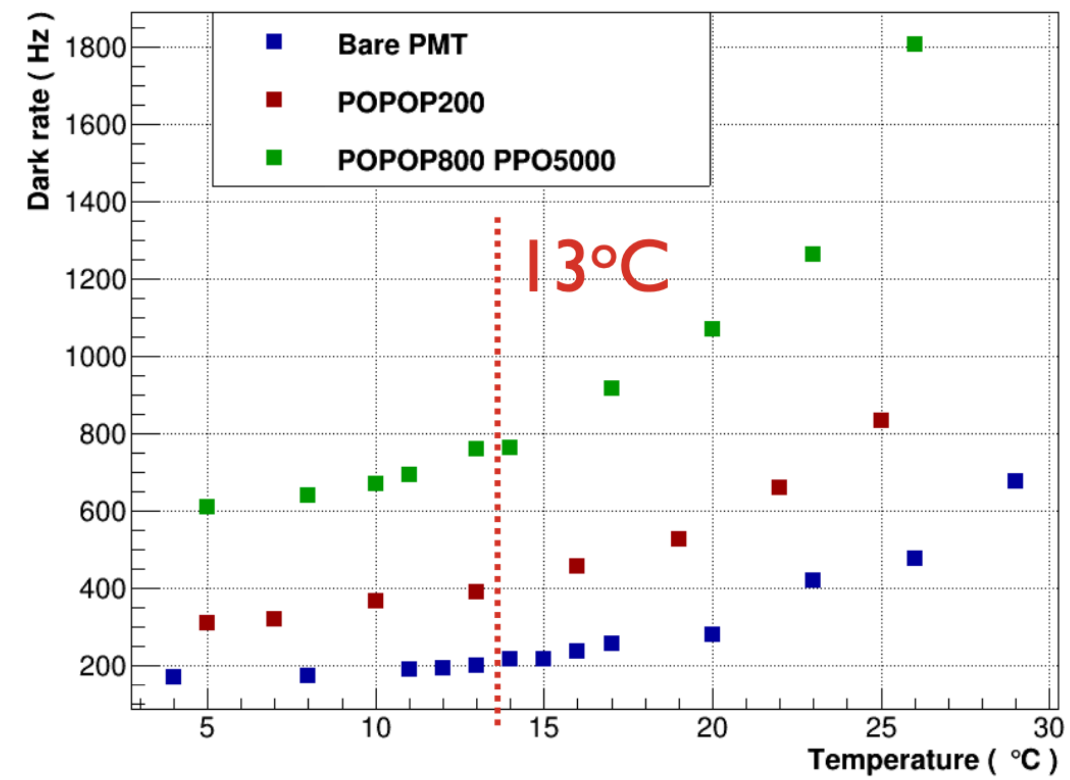




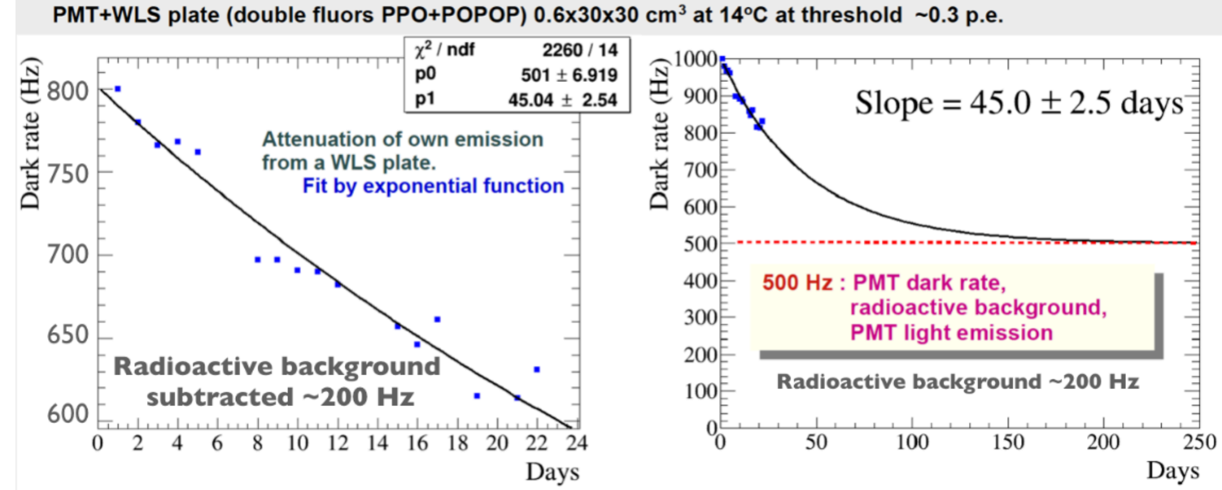
*Details on optimisation work in backup slides

WLS Plates: Dark Rate Measurements

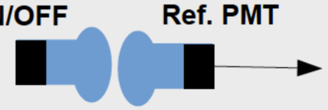
- PMT + WLS plate setup was placed in temperature controlled box
- Dark rate measured @ THR= 0.25 p.e.
- Dark rate at 13°C (Hyper-K expected):
    - Bare PMT ~200 Hz
    - PMT+POPOP200 ~400 Hz
    - PMT+POPOP/PPO ~800 Hz
- Structure of 800 Hz:
    - 200 Hz from PMT
    - ~150 Hz from PMT photon emission → emitted by dynode system, reflected back to photocathode
    - ~200 Hz from radioactive background → studied with Pb box protection (very low rate in real OD)
    - **~250 Hz from WLS plate emission* → PPO fluor**
- WLS plate with double set of fluors can generate
    - ~600 Hz in HK OD → WLS contribution can (?) fade away with time when no light ~months
    - ? - still "PPO" rate present over 3 months of monitoring
    - Dark rate 40 Hz/°C in range 10-20 °C for PMT+WLS plate with double fluor



PMT+WLS plate (double fluors PPO+POPOP) 0.6x30x30 cm³ at 14°C at threshold ~0.3 p.e.



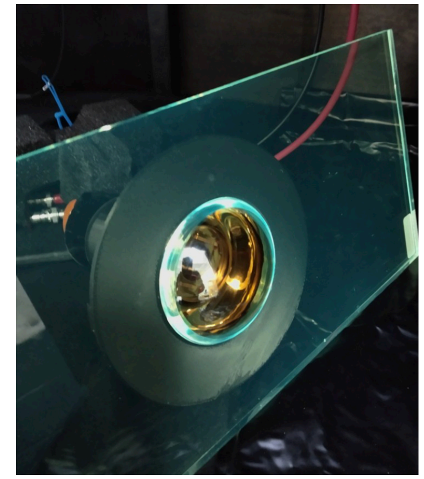
Both PMTs (R14374) are at HV = 1250 V, room temperature

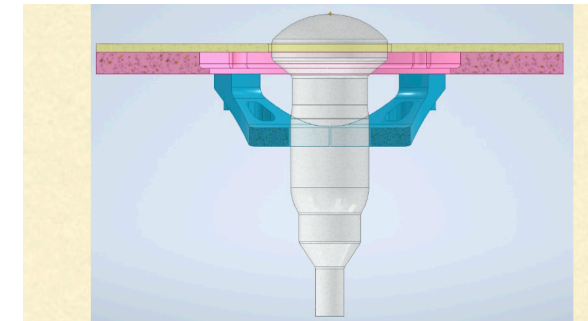
PMT positions	Dark rate at HV OFF	Dark rate at HV ON
HV ON/OFF Ref. PMT 	327 Hz	437 Hz

* induced by optical traps created by accumulated energy from ambient light or thermal movement of molecule

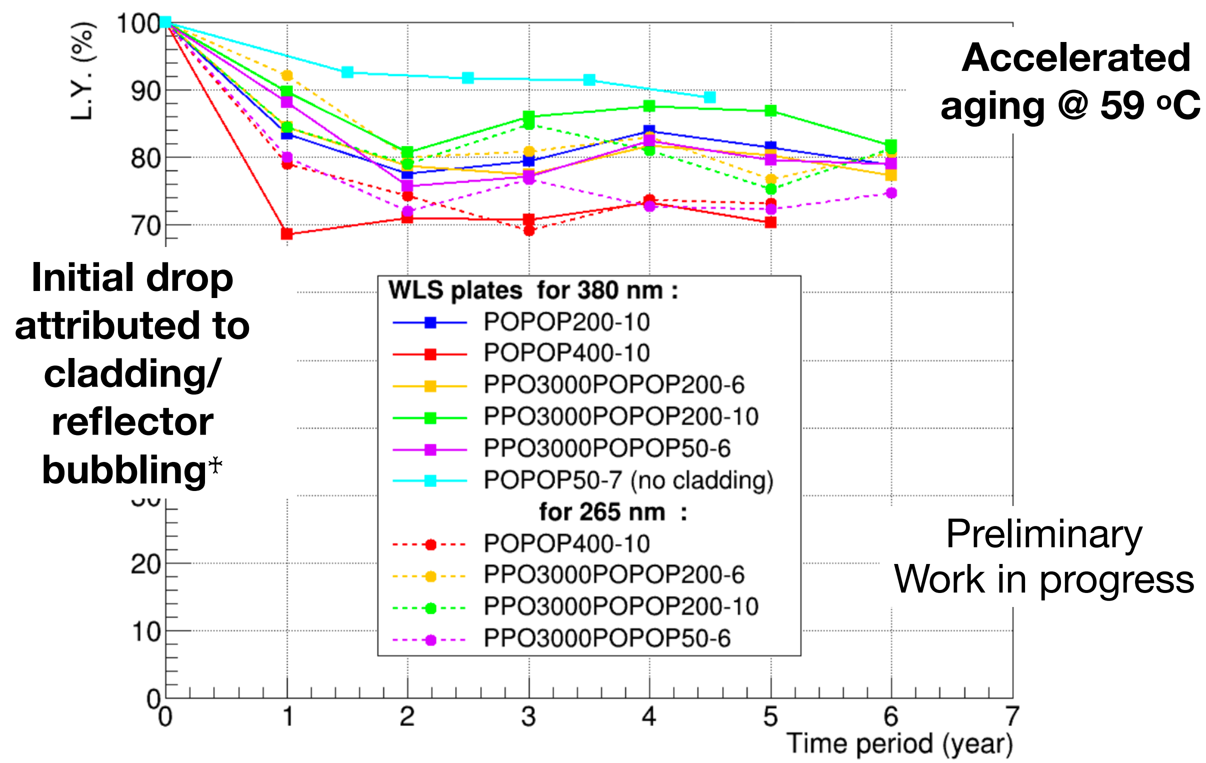
WLS Plates for Hyper-K OD: INR RAS Design Summary

- PMMA based WLS plates
  - Fluor concentration: **POPOP 50 mg/l** + **PPO 3g/l***
  - Manufacturer: **Polymer Chemistry Institute (Dzerzhinsk, Russia)**
  - Plate size: **7x300x300 mm³**
  - Opening for PMTs: cylindrical, 78 mm diameter
    - PMT primary option: **3-inch Hamamatsu R14374**
  - Cutting/polishing: CO_2 laser cutting and polishing machine for edges
  - Reflector: **polymeric film 3M DF2000MA**, adhesive side + **Tyvek** at the back side
  - Dark rate: ~600 Hz* @ 0.3 p.e. and 13 °C expected inside Hyper-K
- **~ x2 increase in light collection**





PMT + WLS plate support structure



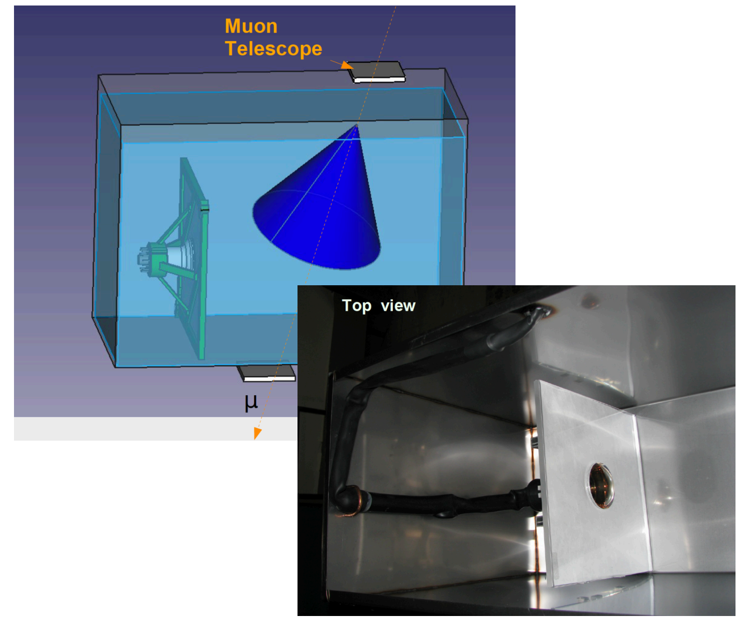
* Double flour option preferable given FOM based on collected light

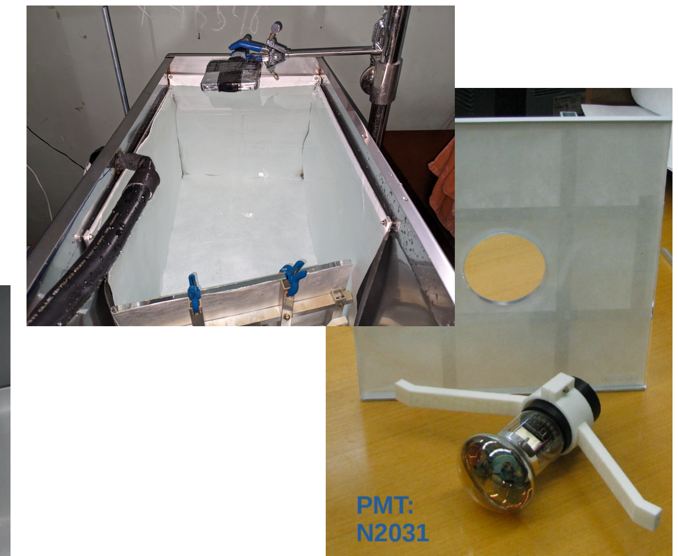
- Although may want to keep dark rate as low as possible ← PPO effect becomes a concern
- Aging measurements on-going† to understand the stability of fluors\` compositions

† detailed on aging studies in backup

WLS Plates: Infant-K Detector @ INR RAS

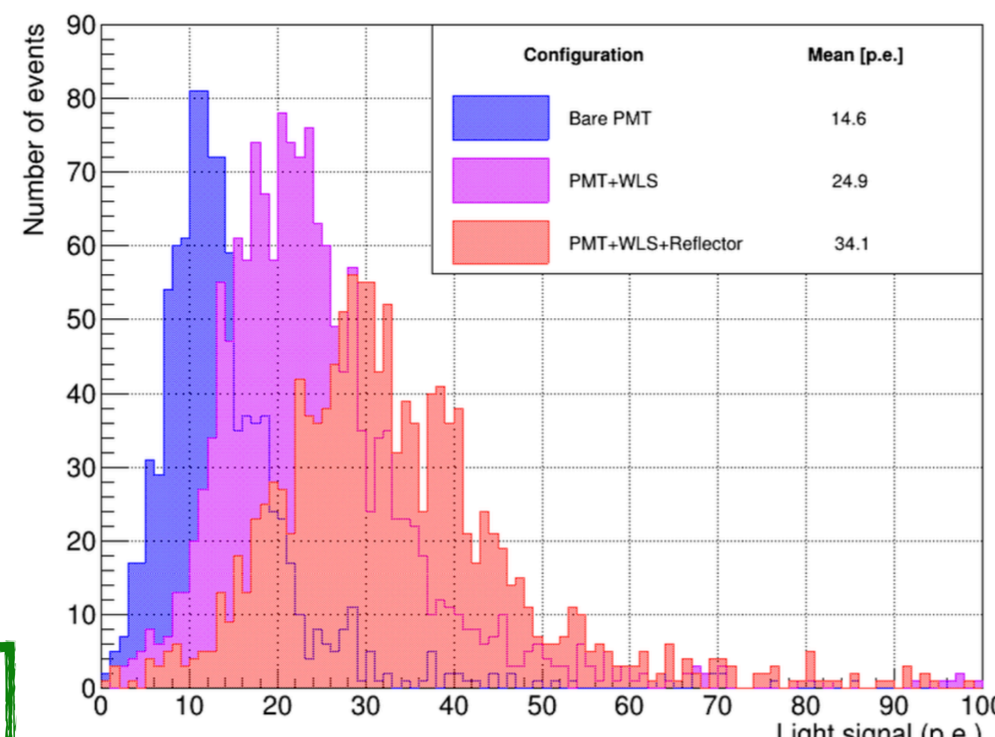
- Measurements with actual Cherenkov light in water ← a combined effect of a few ingredients: reflectors and reflections, spectrum change and attenuation





- St. steel tank, ~110 litres of distilled water
  - Option to put Tyvek on the walls
  - Tests with Hamamatsu 3`` PMTs and NNVT devices (China)
- Muon range in water ~45 cm
  - Adjusting trigger counters` positions study direct and reflected photons
  - Tyvek reflector always placed at the back side of a WLS plate

x2 gain in collected light with full WLS plate + reflectors setup



Tests of PMT+ WLS module*
Reflected photons
300x300x7 mm3 plate
50 mg/L POPOP + 3 g/L PPO

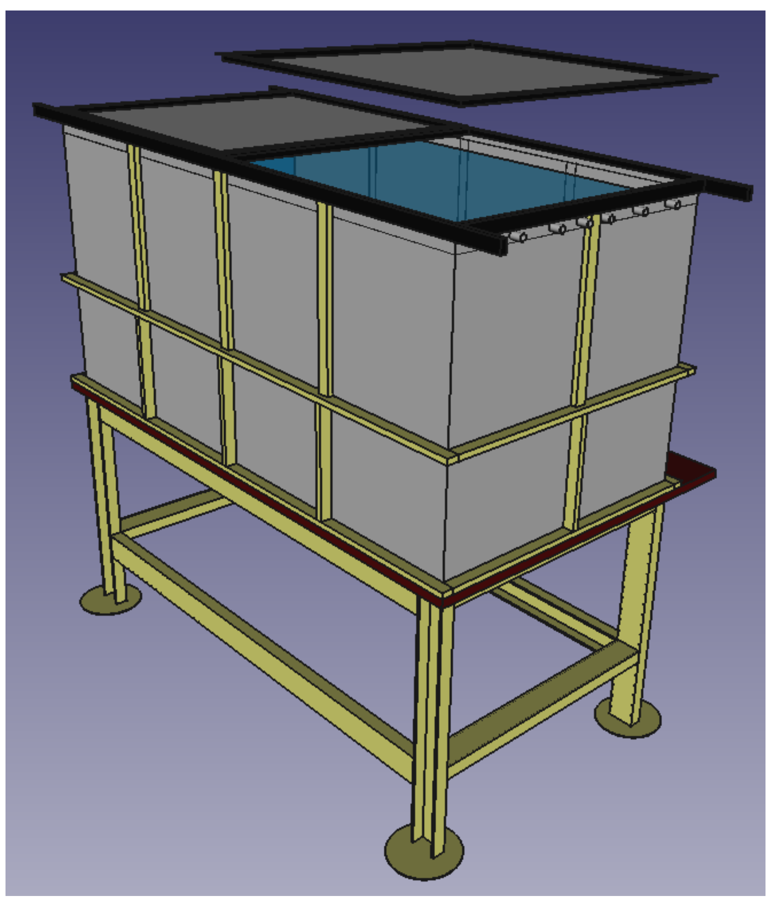
- **Bare PMT + NO WLS plate**
- **PMT + WLS plate + NO edge reflector**
- **PMT + WLS plate + edge reflector**

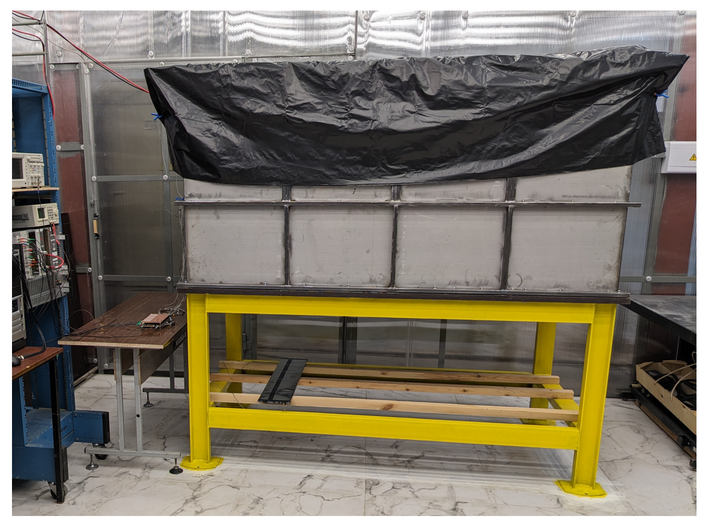
x1.5 light yield gain with 3M DF2000MA edge reflector

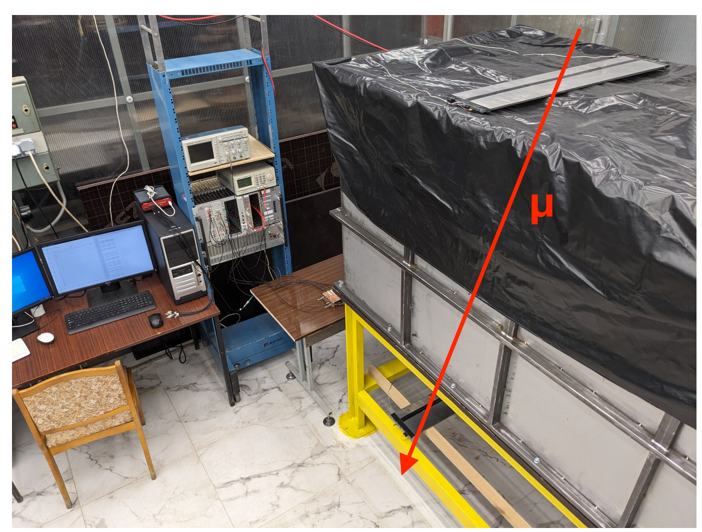
* Measurements with a NNVT N2031 3` (8 cm)` PMT, for NNVT vs Hamamatsu checks see backup

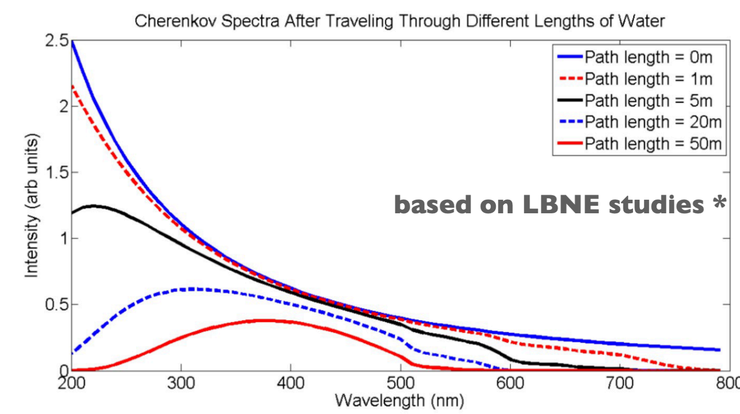
WLS Plates: Toddler-K Detector @ INR RAS

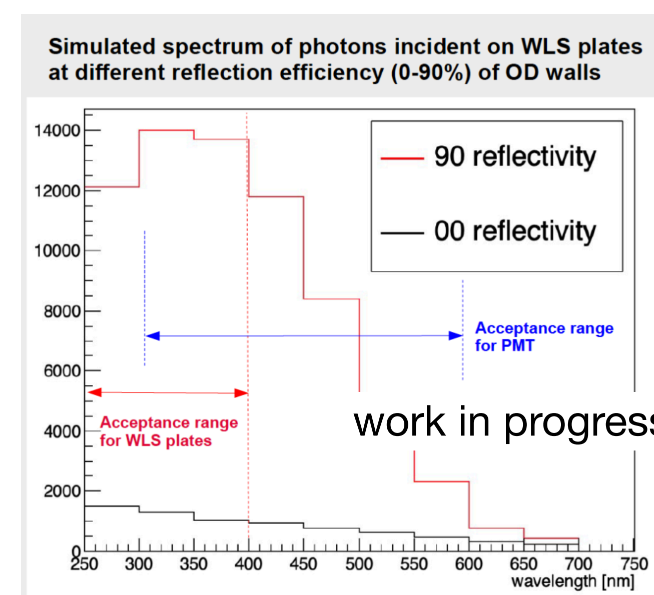
- Measurements with actual Cherenkov light in water ← a combined effect of a few ingredients: reflectors and reflections, spectrum change and attenuation
- Preparing a larger water Cherenkov test detector: **Toddler-K**
  - ~2 tons of purified water
  - Probe longer propagation lengths
  - Simultaneous measurements of several plates
  - Unique reference measurements for further detailed high-precision simulations







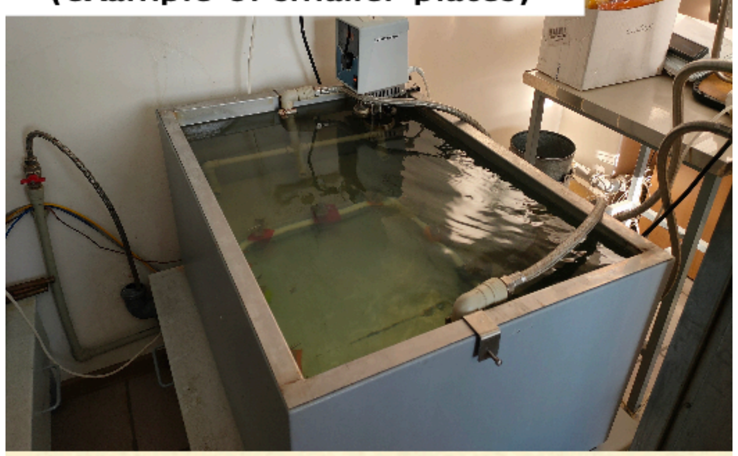




Preparations for Mass Production of WLS Plates

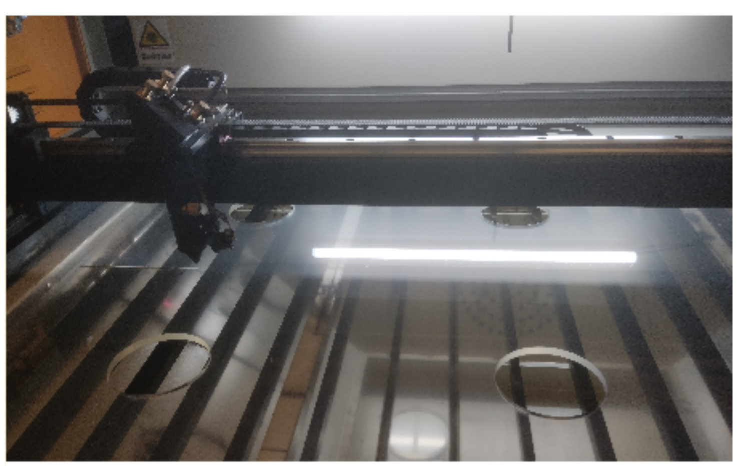
- Fall 2023: test production to probe/tune/adjust various bits of technology, understand process details including bureaucracy needs and retrieve time estimates
  - Larger sized PMMA based WLS plates with POPOP, POPOP+PPO fluors produced @ Dzerzhinsk ← solvent preparation, filtering, polymerisation in water/air
  - Cutting into final sizes, cutting openings, polishing @ INR RAS

Polymerisation in water (example of smaller plates)

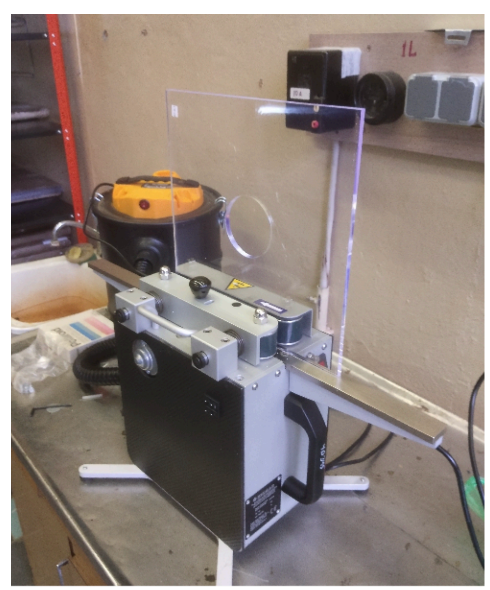


CO_2-laser cutting machine

Final WLS OD plates after laser cutting and polishing



Cutting into smaller plates



Polishing WLS plates` edge surfaces

* https://mountainscholar.org/handle/10217/83745 WLS plates studies for LBNE

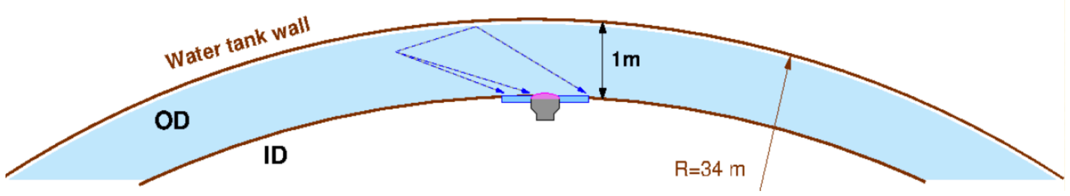
Summary

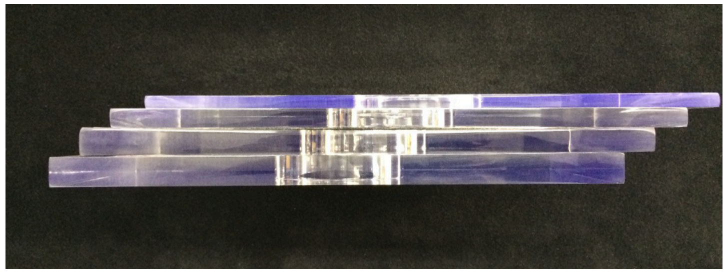
- **Hyper-Kamiokande will open a new era of precision measurements in neutrino physics →** start data taking in 2027
- Intense R&D work to optimise the detector aiming for 20 years of data taking
- **Outer detector crucial for veto purposes → size limitations require efforts to increase light-collection**
    - 3``(8 cm) 3.5k PMTs, inserted into WLS plates, detector walls covered with Tyvek reflector
- **INR RAS option** for WLS plates
    - Design optimised ✓
        - **PMMA based plates with POPOP (+PPO) fluors** provide optimal performance
        - Plates from **V.A. Kargin Polymer Chemistry Institute, Dzerzhinsk, Russia**
    - Test production to develop, establish and check all ingredients ✓→ ready for mass-production
        - Production @ Dzerzhinsk, Russia
        - Final cutting, polishing, adjustments, reflectors + tests @ INR RAS
        - ~4k plates including spares
    - **Rich experimental data on PMMA plates and fluor dopants** + water Cherenkov **test-bench detectors Infant-K and Toddler-K** for PMT+plate+reflector environment checks ✓

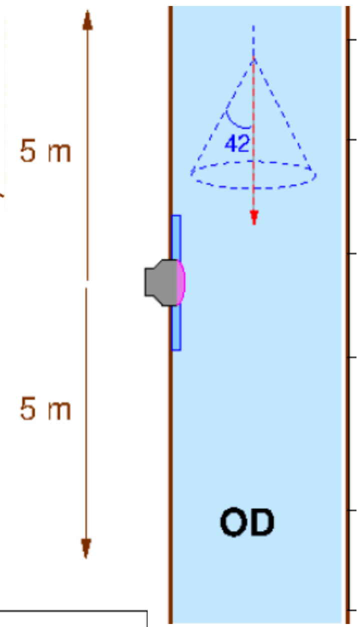
Backup Slides

WLS Plates: Shape and Thickness

- Optimisation based on simulation results and measurements
- Light-collection model in water
- OD walls covered with Tyvek, ~100% reflection
- Reflector around plate edges
- Tyvek at bottom side
- 3“ hemispherical PMT in 78 mm hole
- Attenuation inside bulk PMMA: 1 m, Rayleigh scat. 7 m
- Loss at a water/PMMA reflection: 5% (varied 2-10%) ← measurements` inputs
- Photons in a Cherenkov cone for vertical muons
- Trade-off between cost and light signal leads to
  - 7 x 300 x 300 mm³

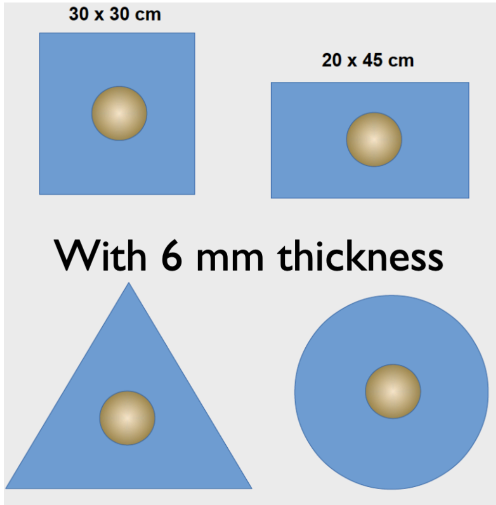






WLS plate thickness	4 mm	6 mm	8 mm	10 mm	13 mm	16 mm
Detection efficiency	2.8%	3.0%	2.8%	2.8%	2.7%	2.3%

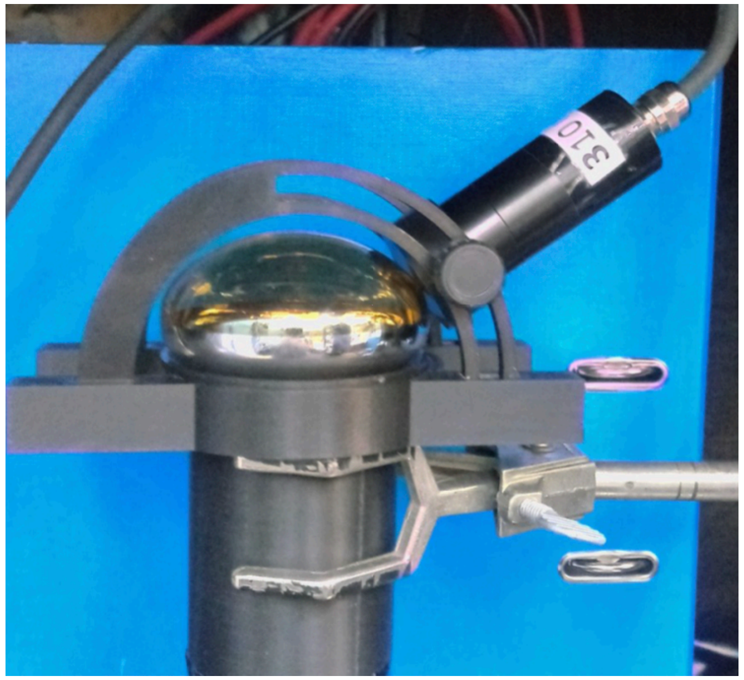
Complexity of factors: absorption of Cherenkov photons, attenuation ← number of reflections, optical plate-PMT coupling, variable photo-cathode sensitivity

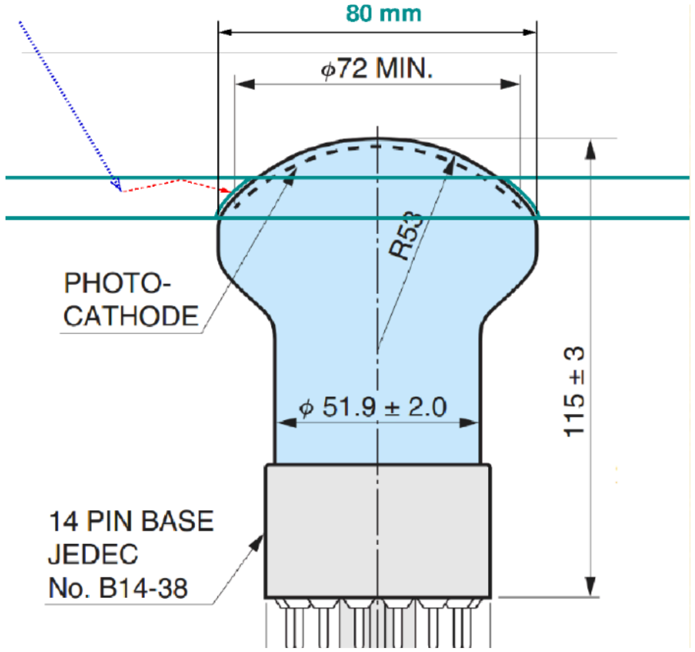


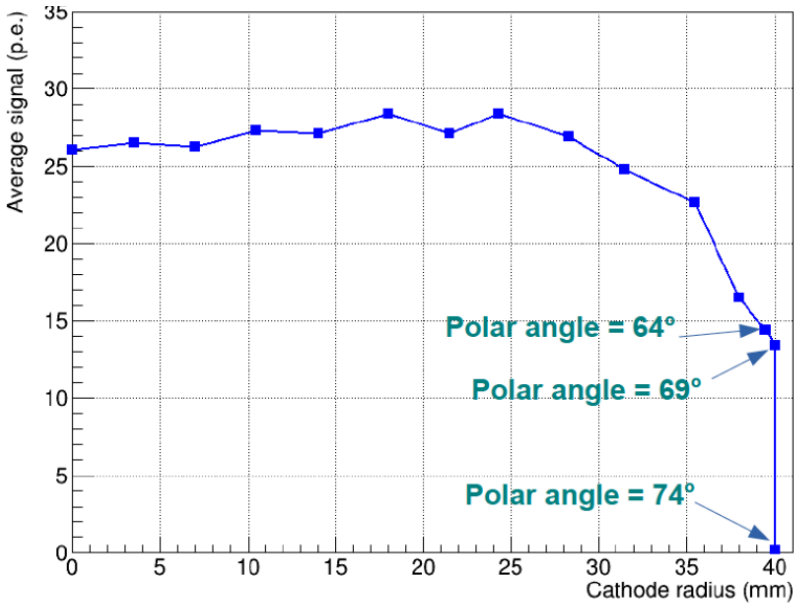
Shapes	Square 30x30 cm	Rectangle 20x45 cm	Rectangle 15x60 cm	Triangle	Circle
Relative light signal	100 %	99 %	97 %	99 %	62 %

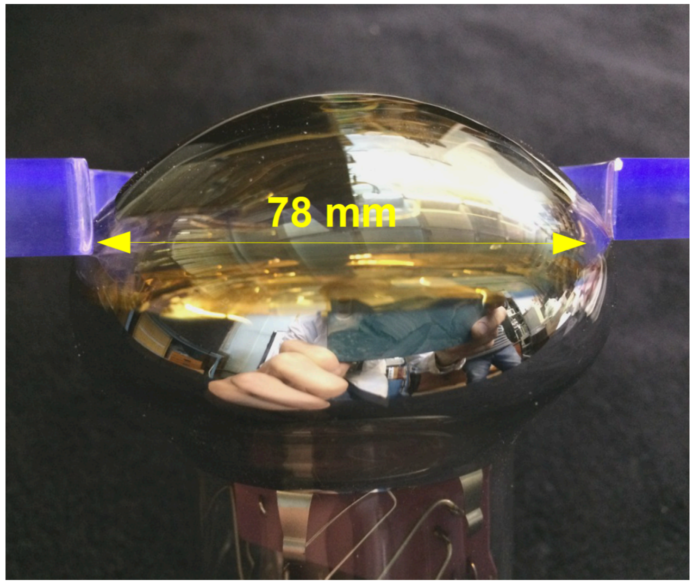
WLS Plates: PMT Coupling

- Scanned Hamamatsu 3` R14374 PMT with 380 mm 1.5 mm collimated LED varying polar angle
  - Probed 0-40 mm radius
  - Confirmed 72 mm cathode specification
  - Cathode sensitivity for simulations
- Aim for PMT-WLS plate optical coupling with D < 78 mm
- Optimise opening for a PMT
  - Balance between collection of re-emitted photons and direct detection



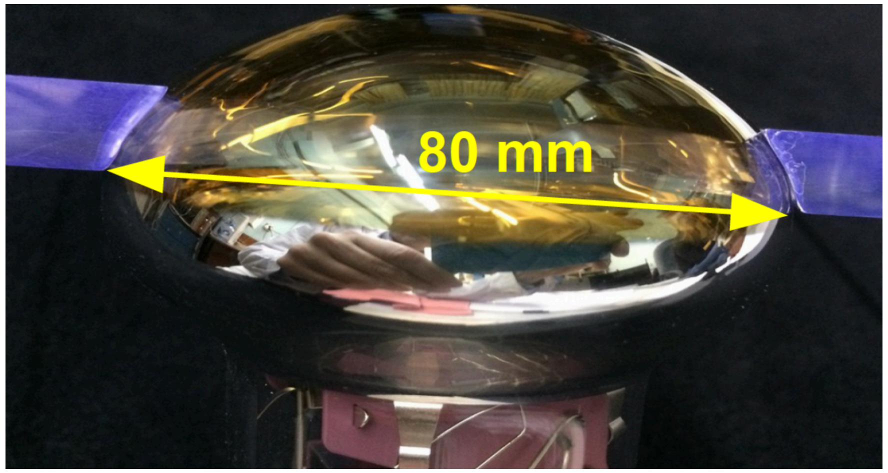


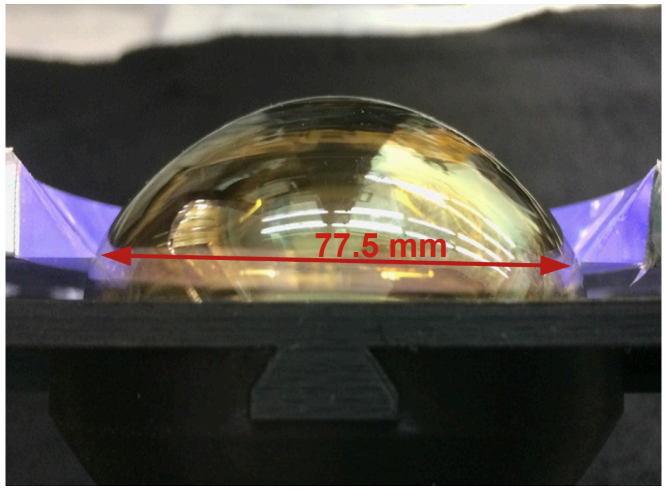




WLS Plates: PMT Coupling

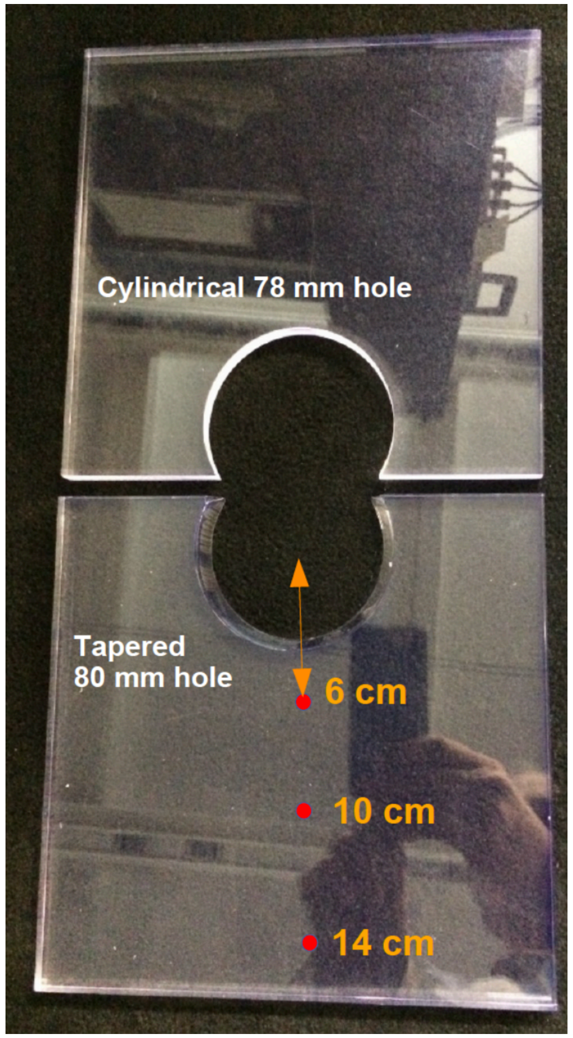
- Different aperture shapes for PMT
- Tests in water with mirror reflector
  - Tapered openings
    - Match PMT hemispherical surface
  - Cylindrical openings of 78 mm
    - Ease manufacturing ↓ cost
    - Photocathode open and Cherenkov photons not blocked
    - Less reflections back for re-emitted photons
  - Open cone
    - Enhance direct photon detection
    - Similar performance to cylindrical shape based on simulation of PMT-WLS plate in a water tank





	Signals in p.e.		
Hole	6 cm	10 cm	14 cm
78 mm, cylindrical	52.2	43.4	41.6
77.5 mm, with 45° cone	40.4	32.1	27.7
Change in signal	- 23 %	- 26 %	- 33 %
Simulation over all surface: change in signal	- 36 %		

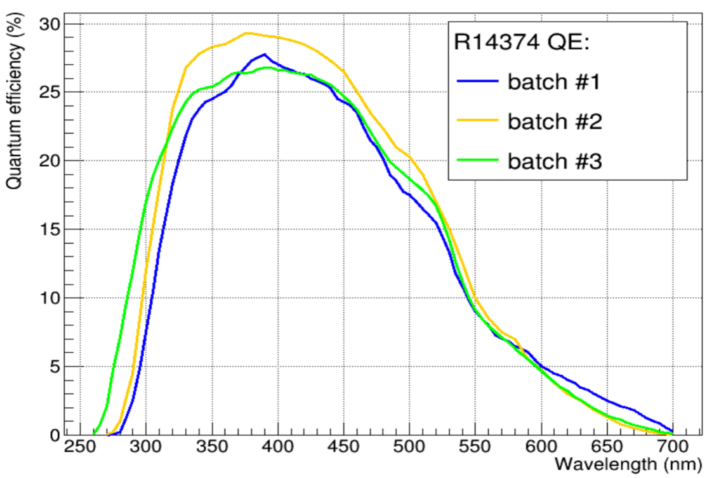
Hole	6 cm	10 cm	14 cm
Old 80 mm	33	28	27
New 78 mm	49	46	46
Change in signal	+ 48 %	+ 64 %	+ 70 %



WLS Plates: Photon Collection Efficiency Measurements

- Plates tested with LED source
  - Size 6 x 300 x 300 mm^3
  - Dopants composition: POPOP 50 + PPO 3000 mg/L
  - Reflector: cladding 3M DF2000MA
  - PMT: Hamamatsu R14374
  - LED sources: 265, 315, 380 nm
- Calibration: LED source intensity measured by direct illumination of the PMT, estimate N incident photons with PMT QE based on specification
- PDE: ~1-3 % (250-380 nm)

Excitation point at 2 cm from the plate edge



PMT QE at 380 nm is 27-29%. We have taken for PDE estimation QE=28% (must be pretty accurate).

Signal at WLS plate, p.e.	5	10	20	30	40	50	60	70
Signal at PMT, p.e.	49	99	197	264	370	464	456	548
PDE	2.9 %	2.8 %	2.8 %	3.2 %	3.0 %	3.0 %	3.7 %	3.6 %

PMT QE at 315 nm is ~ 15 % (very approximate value, estimated range 11-20 %).

Signal at WLS plate, p.e.	7.5	11.5	18.3	30.7
Signal at PMT, p.e.	89	148	225	360
PDE	1.3%	1.2 %	1.2 %	1.3 %

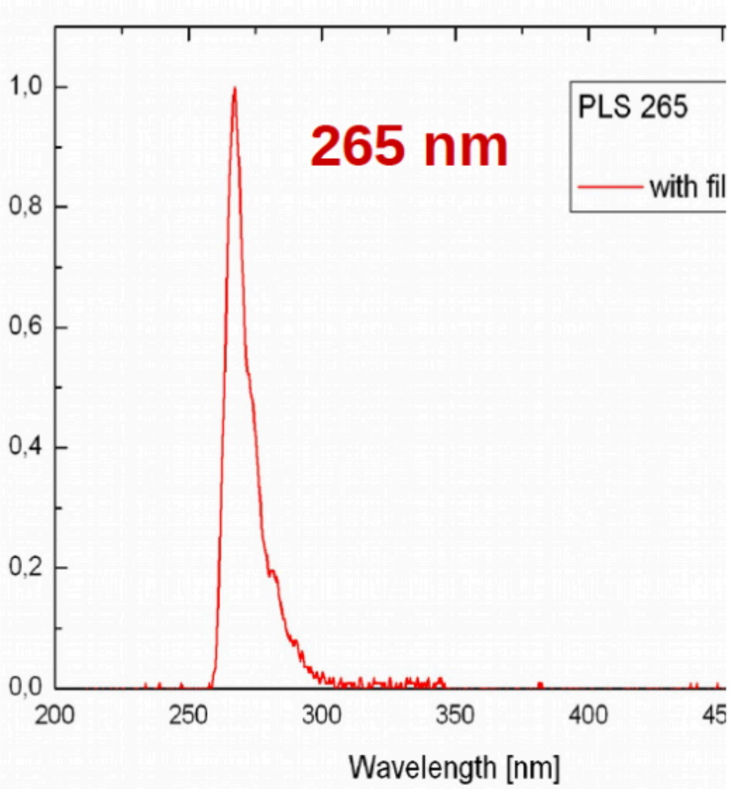
PMT QE at 265 nm is somewere in range ~ 0.03 — 1% (we don`t know QE).

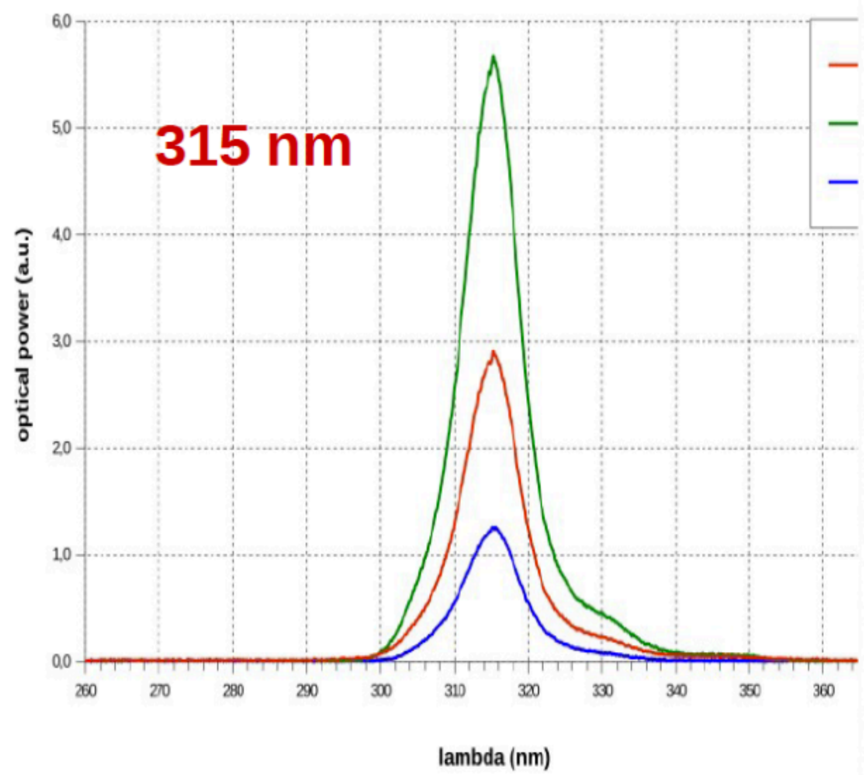
At 265 nm the sensitivities of PMT and WLS plate are almost the same

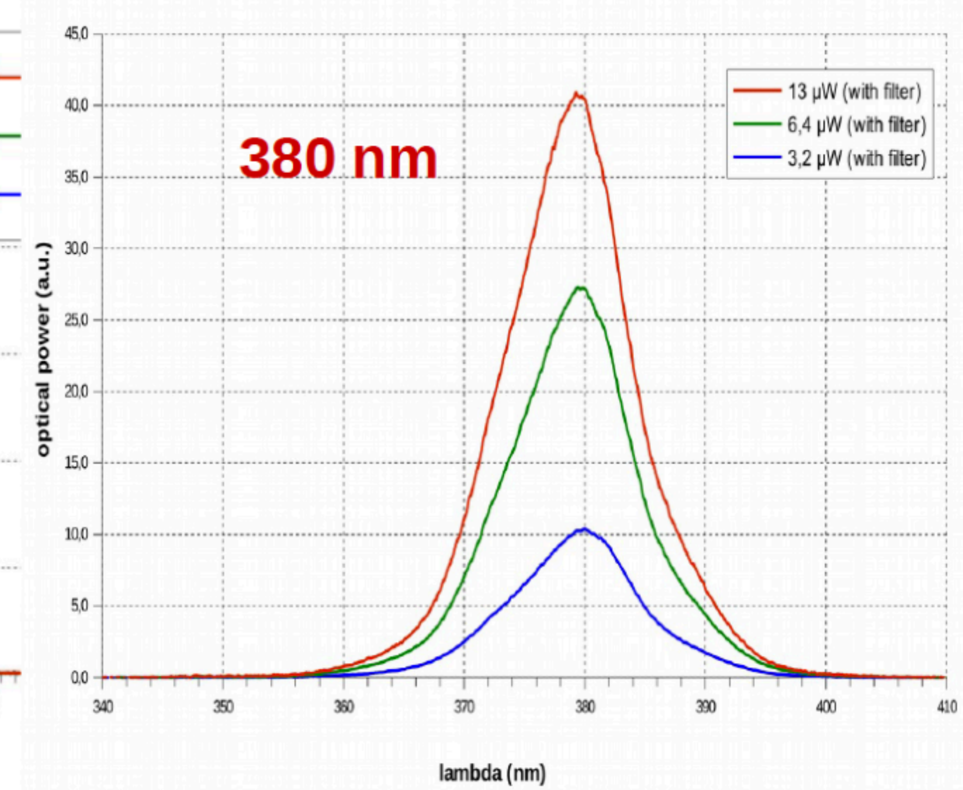
Signal at WLS plate, p.e.	11.4	14.5	24.2	37.9	44.4
Signal at PMT, p.e.	8.1	12.1	17.5	28.8	36.5
PDE	< 1.4 %	< 1.2 %	< 1.4 %	< 1.3 %	< 1.2 %

LED Sources

Fast UV LED light sources from PicoQuant Co.



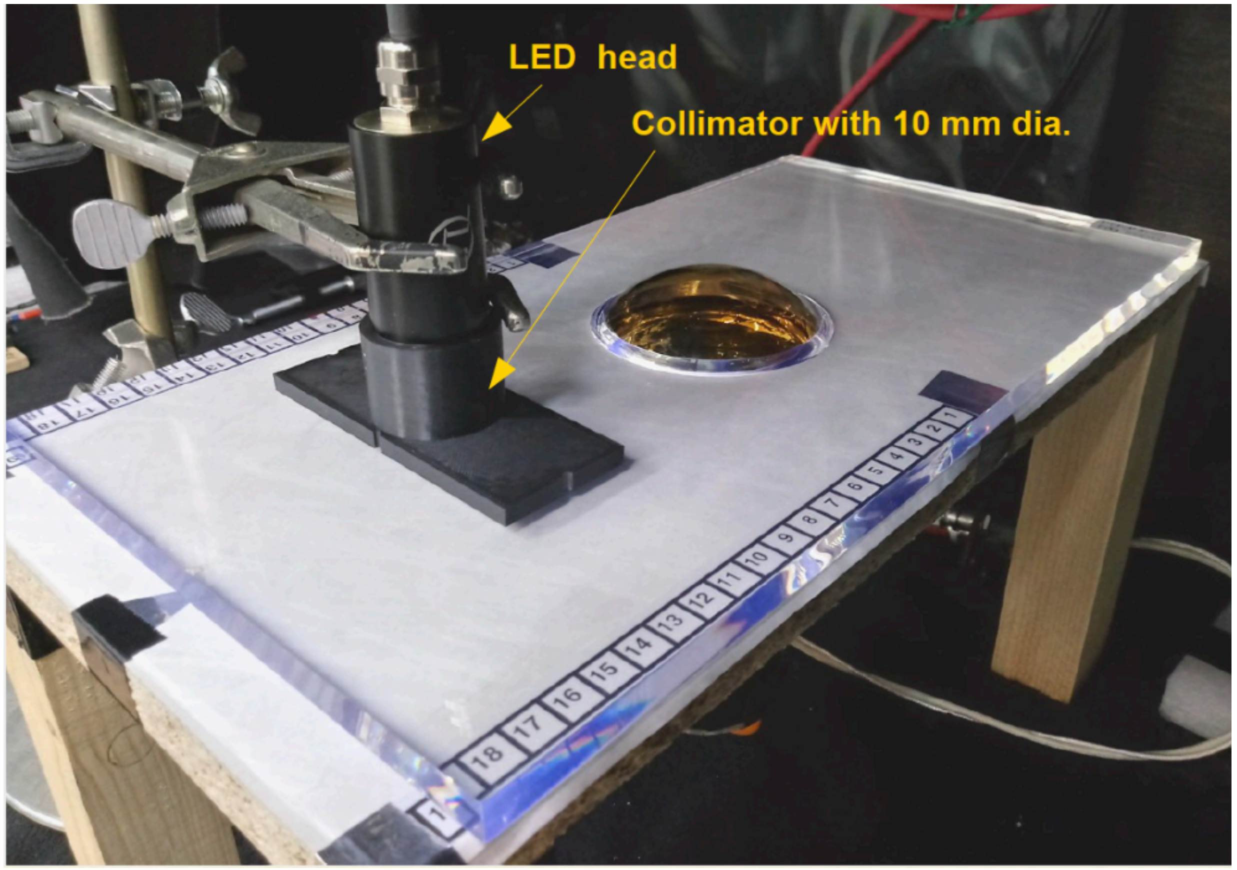


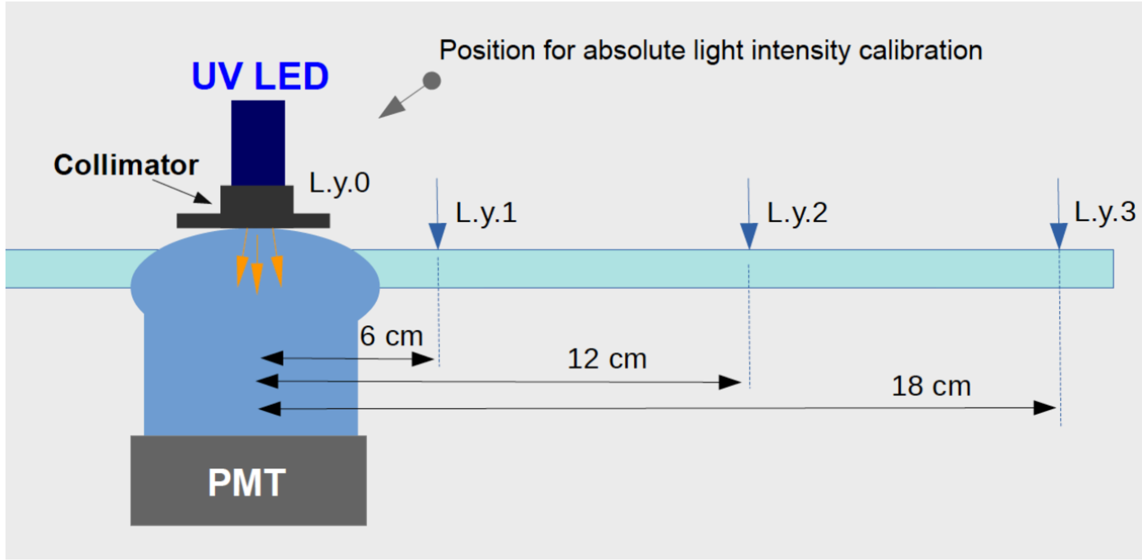


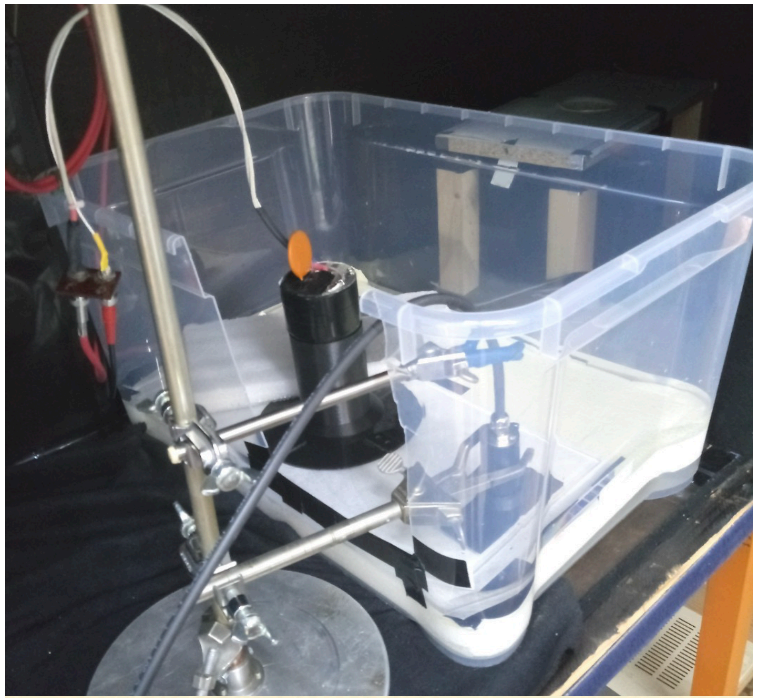
PicoQuant PLS heads are based on sub-nanosecond pulsed UV LEDs.

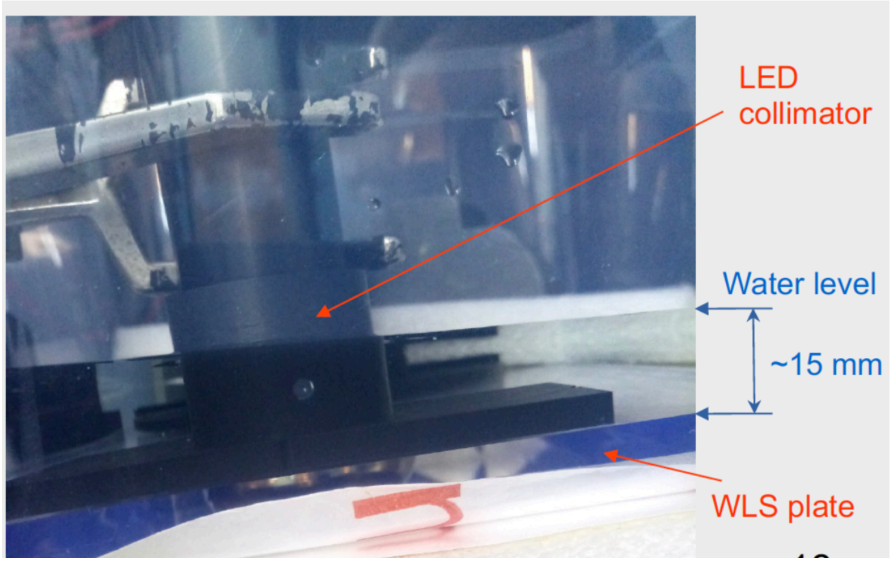
265 nm — spectrum range 260-300 nm
315 nm — spectrum range 300-340 nm
380 nm — spectrum range 365-395 nm
405 nm — spectrum range 380-440 nm

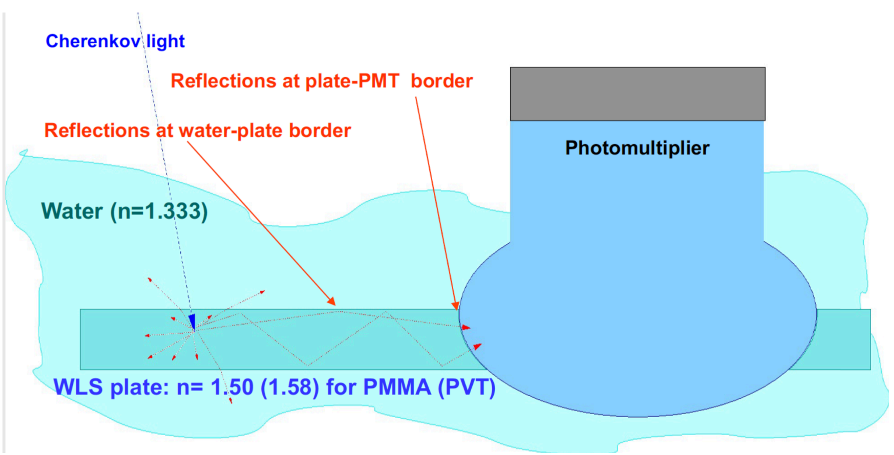
LED Sources


LED head
Collimator with 10 mm dia.

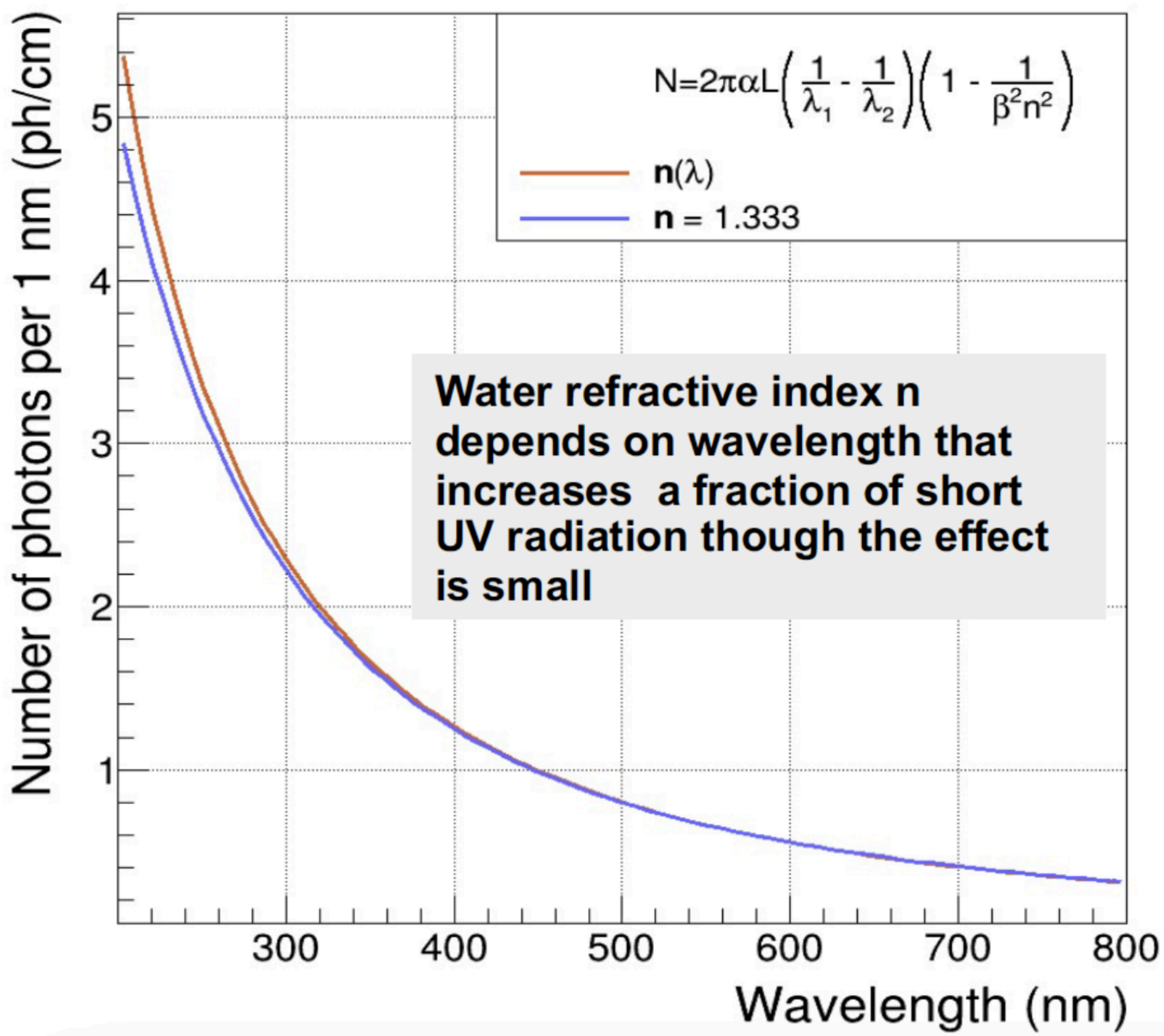

Position for absolute light intensity calibration
UV LED
Collimator
L.y.0
L.y.1
L.y.2
L.y.3
6 cm
12 cm
18 cm
PMT

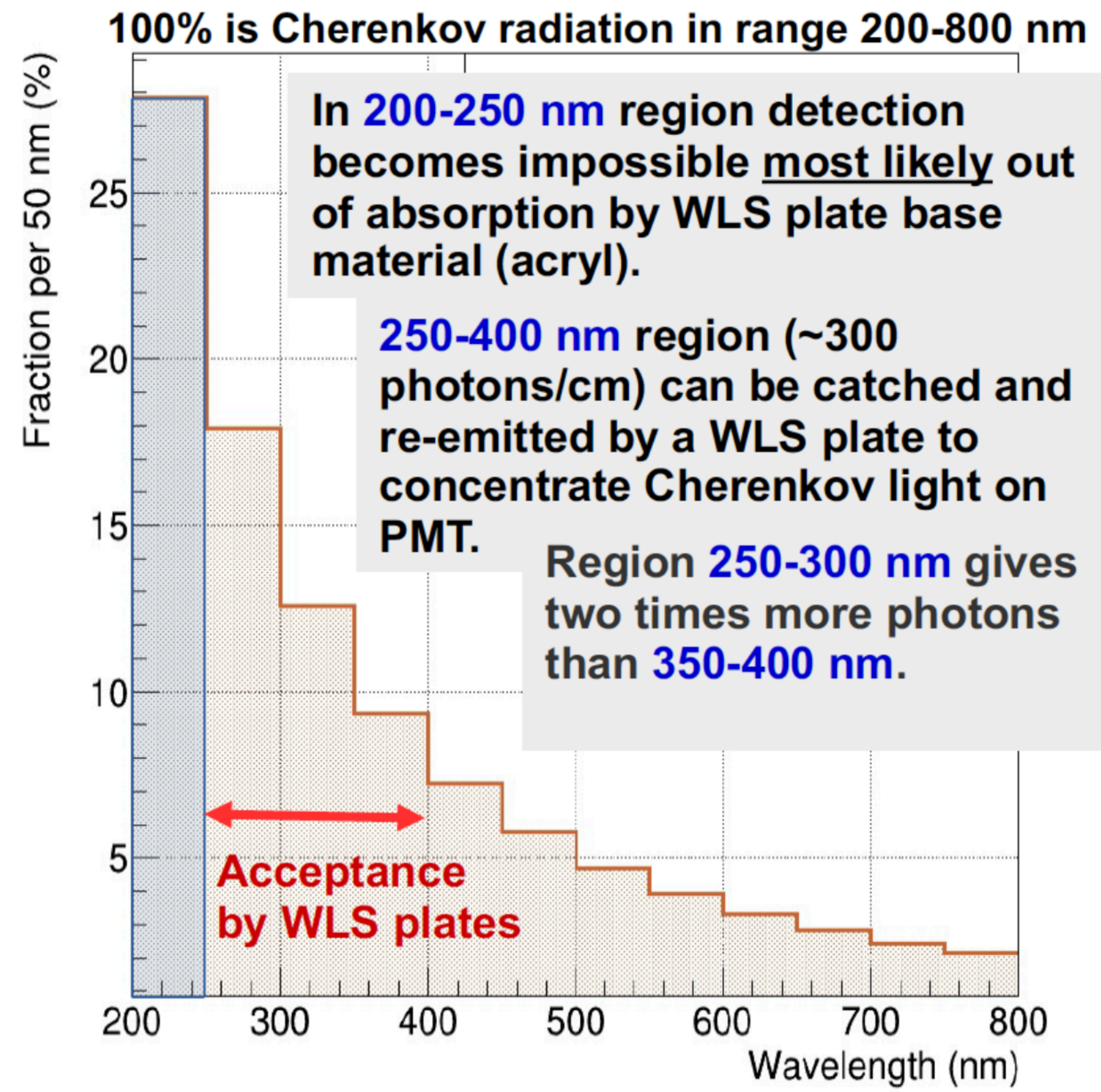



LED collimator
Water level
~15 mm
WLS plate


Cherenkov light
Reflections at plate-PMT border
Reflections at water-plate border
Photomultiplier
Water (n=1.333)
WLS plate: n= 1.50 (1.58) for PMMA (PVT)

Cherenkov Light Spectrum in Water

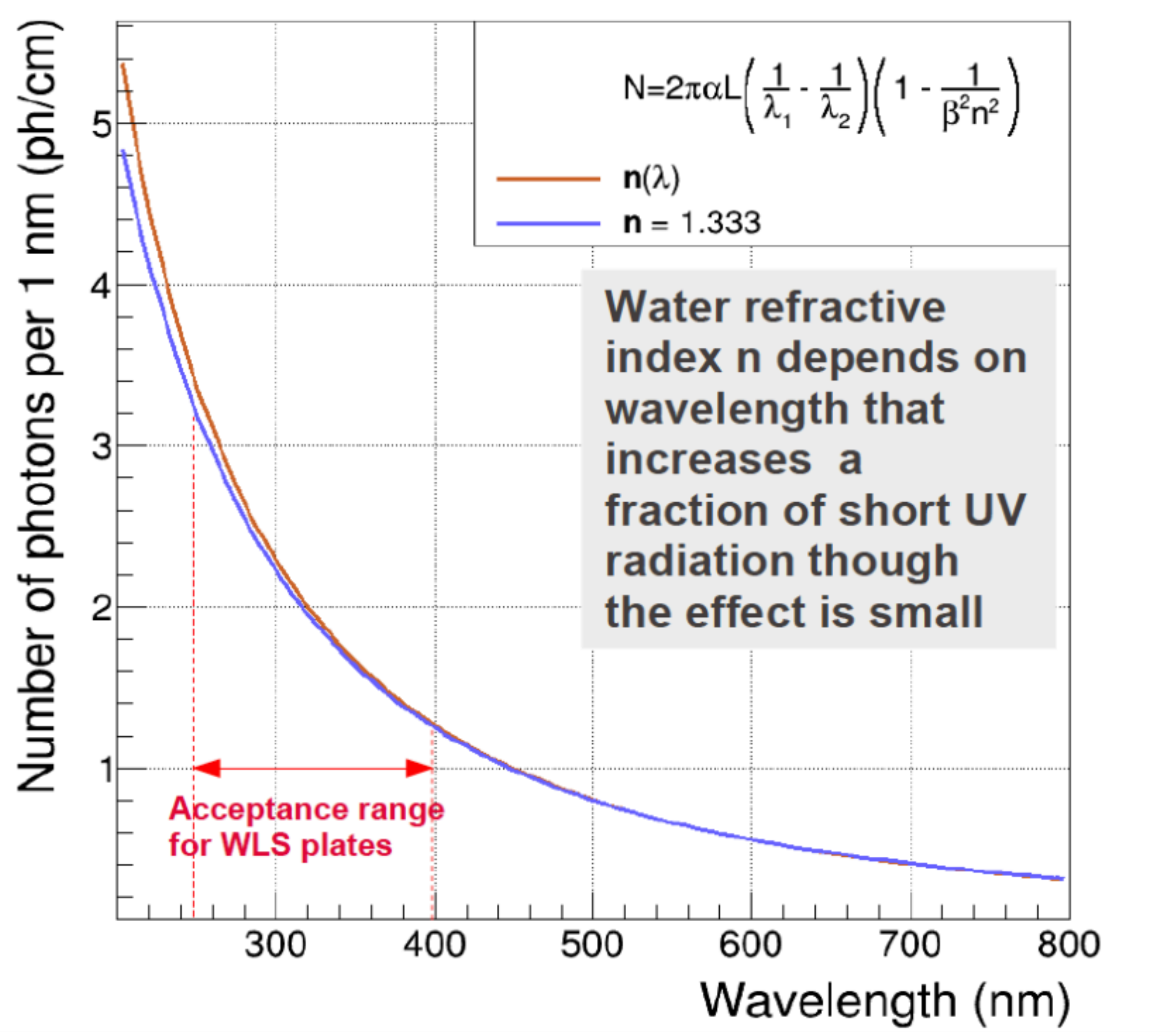




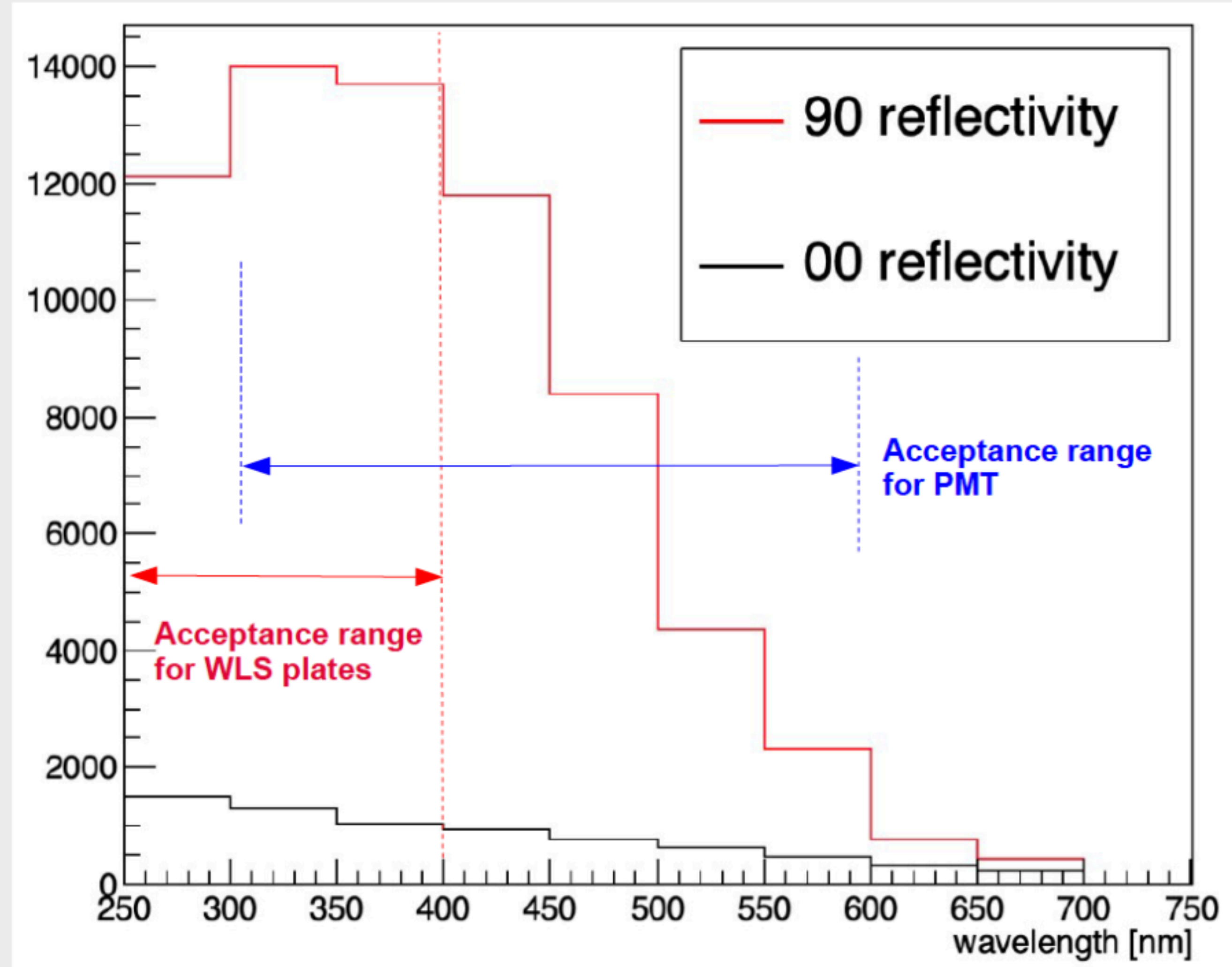
work in progress

Cherenkov Light Spectrum in Water

Emitted Cherenkov spectrum in water



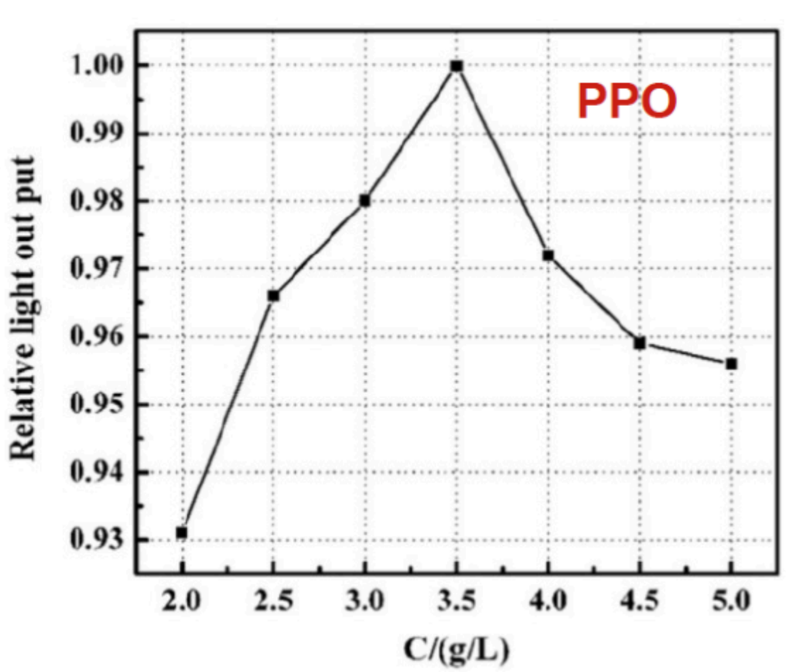
Simulated spectrum of photons incident on WLS plates at different reflection efficiency (0-90%) of OD walls

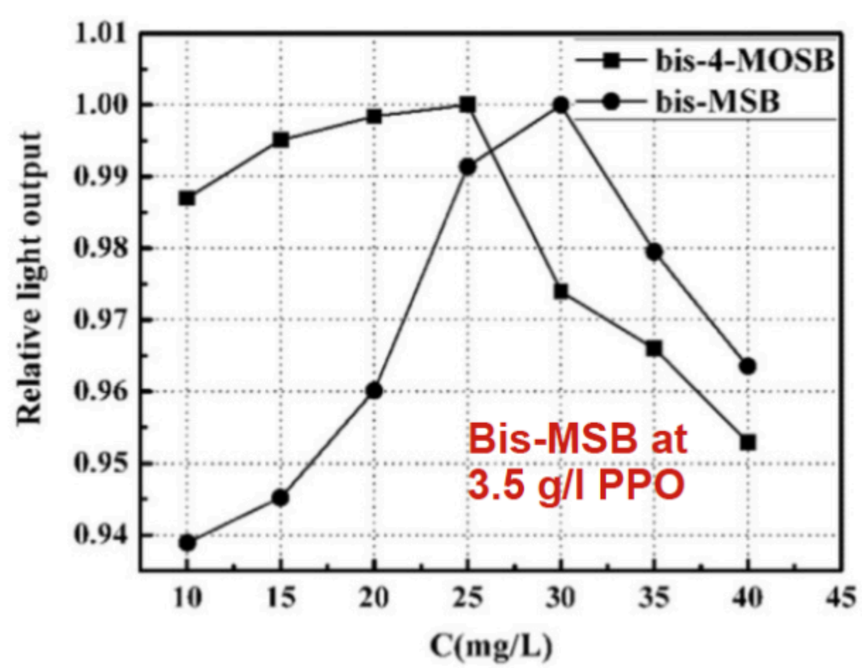


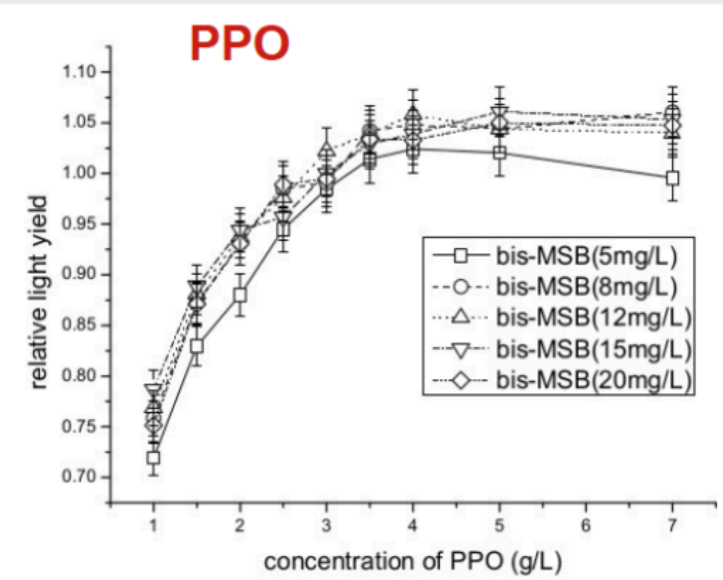
work in progress

Data on Dopant Concentrations

Fluor	Daya Bay liquid scintillator	Double Chooz liquid scintillator	RENO liquid scintillator	SNO+ liquid scintillator	SuperK WLS plate
Bis-MSB mg/L	15	20	30	15	50
PPO g/L	3	7	3	2	--

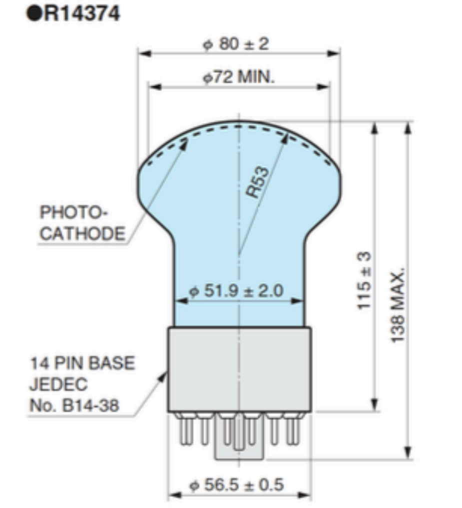


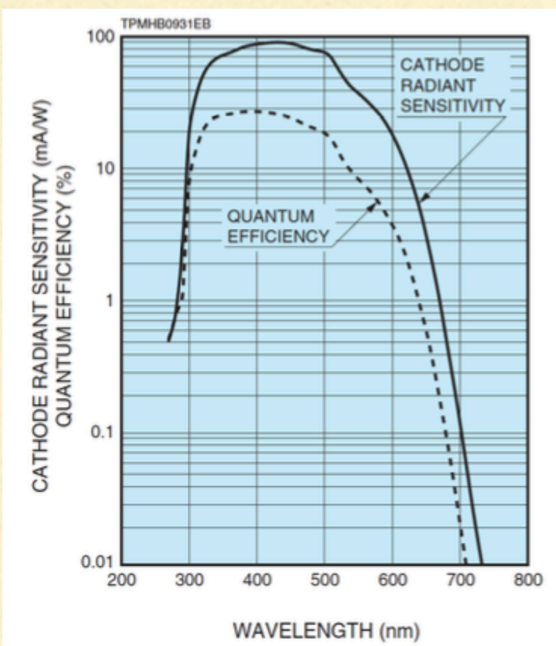


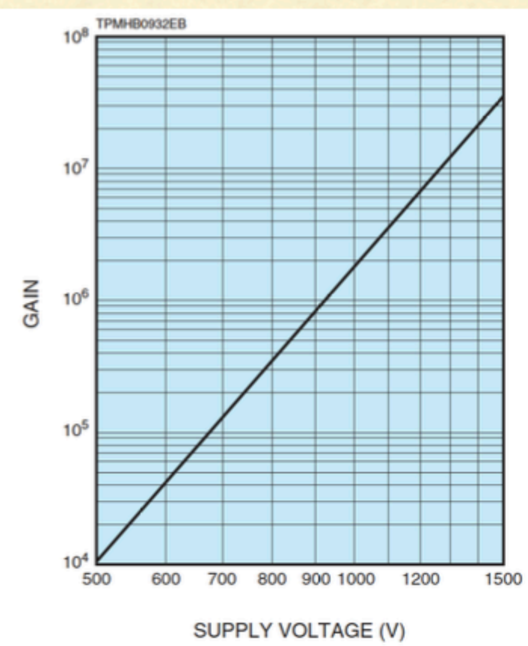


NNVT N2031 Vs Hamamatsu R14374 Specifications

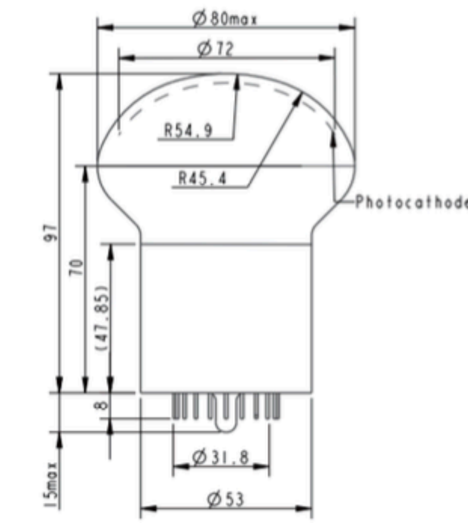
Figure 4: Dimensional outline (Unit: mm)



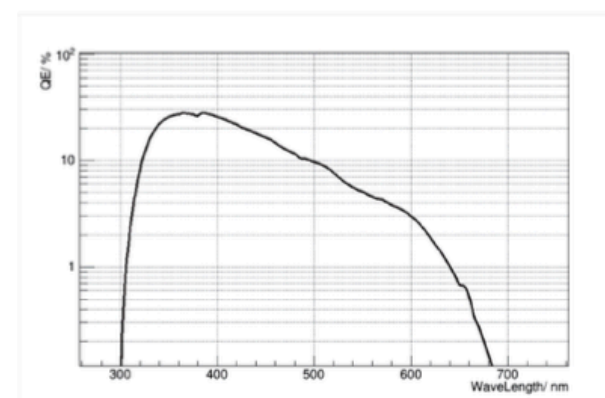




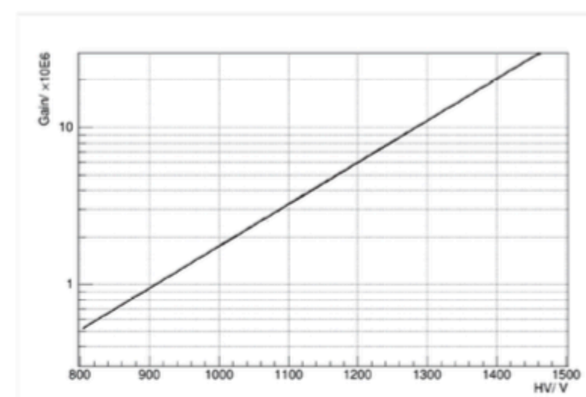
Hamamatsu R14374



N2031光电倍增管结构图
N2031 PMT structure



典型光谱响应曲线
Typical spectral response curve



典型增益曲线
Typical gain curve

NNVT N2031

NNVT N2031 Vs Hamamatsu R14374 Specifications

Hamamatsu R14374

GENERAL

Parameter		R14374	R14689	Unit
Spectral response		300 to 650		nm
Wavelength of maximum response		420		nm
Window material		Borosilicate glass		—
Photocathode	Material	Bialkali		—
	Minimum effective area	ϕ72	ϕ81	mm
Dynode	Structure	Circular and linear-focused		—
	Number of stages	10		—
Base		JEDEC No. B14-38		—
Operating ambient temperature		-30 to +50		°C
Storage temperature		-30 to +50		°C
Suitable socket		E678-14W (Sold separately)		—

MAXIMUM RATINGS (Absolute maximum values)

Parameter		R14374	R14689	Unit
Supply voltage	Between anode and cathode	1500		V
	Between anode and last dynode	300		V
Average anode current		0.1		mA

CHARACTERISTICS (Typ.) (at 25 °C)

Parameter		R14374	R14689	Unit
Cathode sensitivity	Luminous (2856 K)	90		μA/lm
	Radiant at 420 nm	90		mA/W
	Blue sensitivity index (CS 5-58)	11.0		—
	Quantum efficiency at 380 nm	27.5		%
Anode sensitivity	Luminous (2856 K)	900		A/lm
	Radiant at 420 nm	9.0×10^5		A/W
Gain		1.0×10^7		—
Anode dark current (After 30 minute storage in darkness)		50		nA
Time response	Anode pulse rise time	2.9	2.9	ns
	Electron transit time	35	36	ns
	Transit time spread (FWHM)	1.3	1.5	ns

VOLTAGE DISTRIBUTION RATIO AND SUPPLY VOLTAGE

Electrodes	K	Dy1	Dy2	Dy3	Dy4	Dy5	Dy6	Dy7	Dy8	Dy9	Dy10	P
Ratio	3	1	1	1	1	1	1	1	1	1	1	

Supply voltage: 1250 V, K: Cathode, Dy: Dynode, P: Anode

NNVT N2031

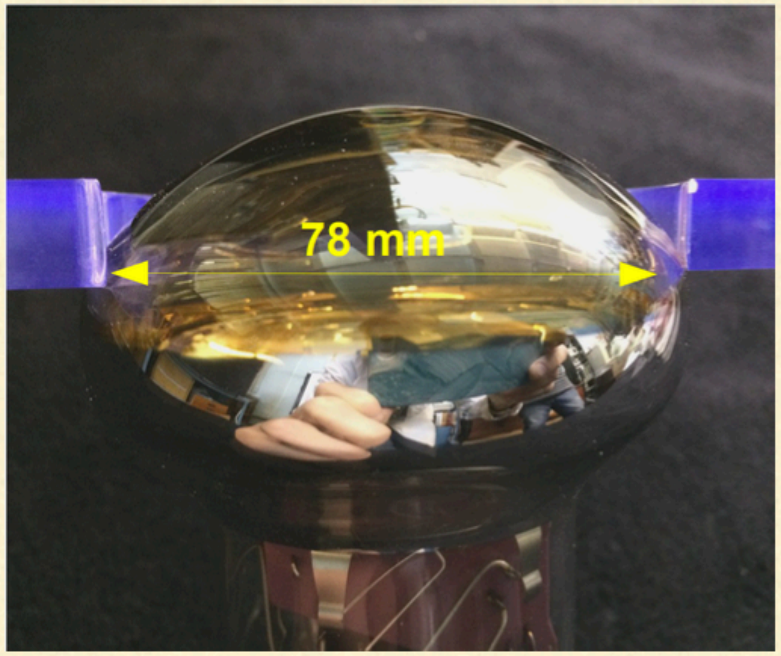
产品型号/ Product Model	N2031			
产品结构/ Product structure	80mm (3") / 10-stage			
玻璃材料/Window material	硼硅酸盐玻璃/ Borosilicate Glass			
光电阴极/Photocathode	双碱/Bialkali			
倍增结构/Dynode structure	盒型和线性聚焦/Box and Linear Focused			
	Min	Typ	Max	Unit
光谱范围/Spectral range	290-650			nm
405 nm下的量子效率 /Quantum Efficiency at 404 nm		26.5		%
增益系数/Gain slope (vs supp. Volt., log/log)	6.5	7.3	8.0	
工作电压/Supply voltage	900	1150	1300	V
增益/Gain		5×10^6		--
暗计数率/Dark count rate		1000	2000	Hz
峰谷比/Peak to Valley ratio		2.5		
上升时间/Anode Pulse Rise Time		1.9		ns
渡越时间离散/Transit time spread (FWHM)		1.8	3	ns

电极	K	Dy1	Dy2	Dy3	Dy4	Dy5	Dy6	Dy7	Dy8	Dy9	Dy10	A
分压比	3	1	1	1	1	1	1	1	1	1	1	

供电电压：1000V, K:阴极，Dy:倍增极，A:阳极

NNVT N2031 Vs Hamamatsu R14374

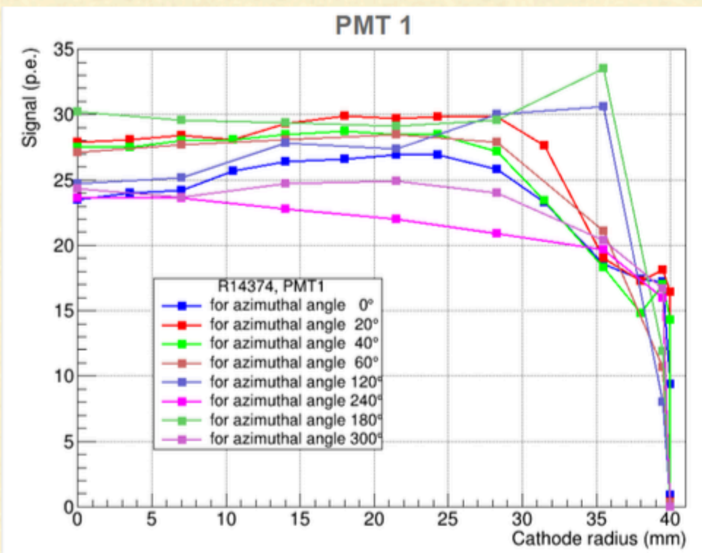
- Compare light signals between NNVT and Hamamatsu PMTs
- Three PMT N2031 checked vs **Hamamatsu reference PMT R14374**
  - Results: average signal in photoelectrons for N2031 **relative to the reference**
    - PMT1 — 68%
    - PMT2 — 70%
    - PMT3 — 69%
  - Similar results obtained with a 265 nm LED

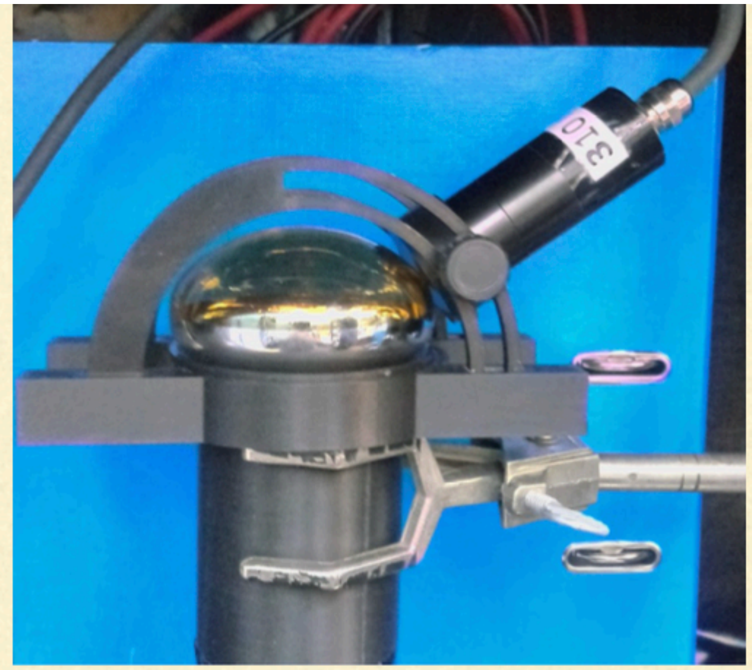


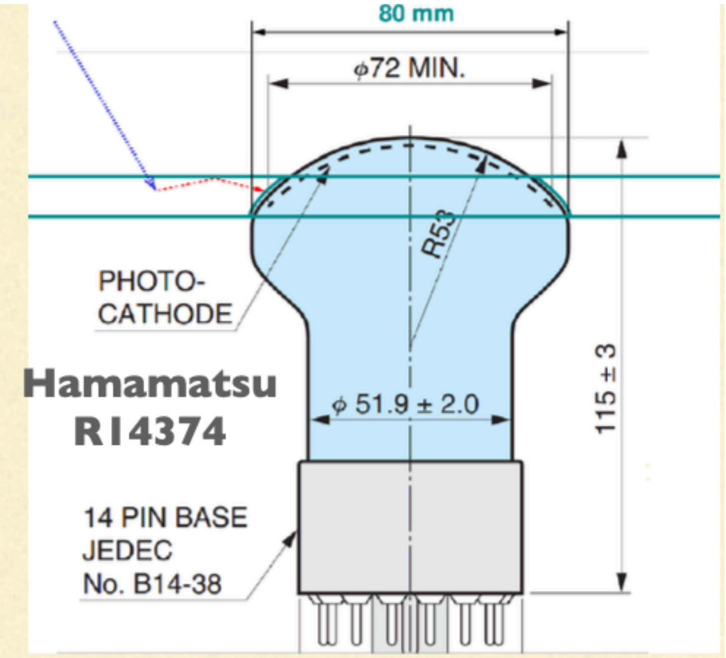
Also NNVT PMTs have shown large non-uniformity for side area of photocathode.
While Hamamatsu PMT signal between corner points varies at 17% offset, N2031 has shown 35% variation.
This variation is caused by the dynode geometry.

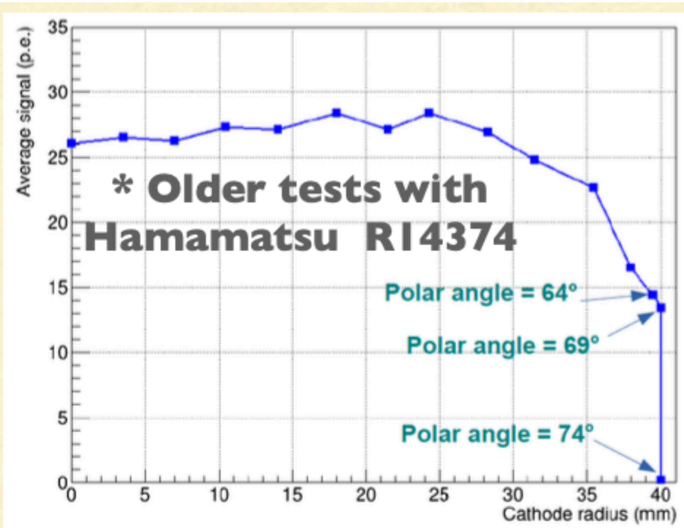
NNVT N2031 Vs Hamamatsu R14374

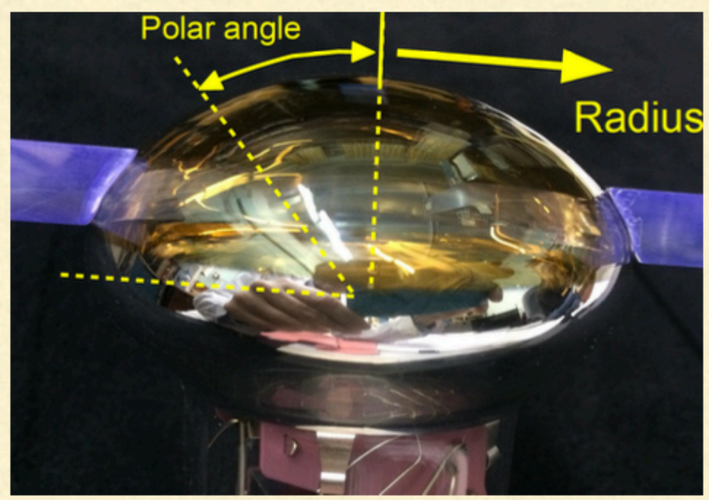
- Scan a PMT with a 380nm Ø1.5 mm collimated LED
- Vary polar and azimuthal angles

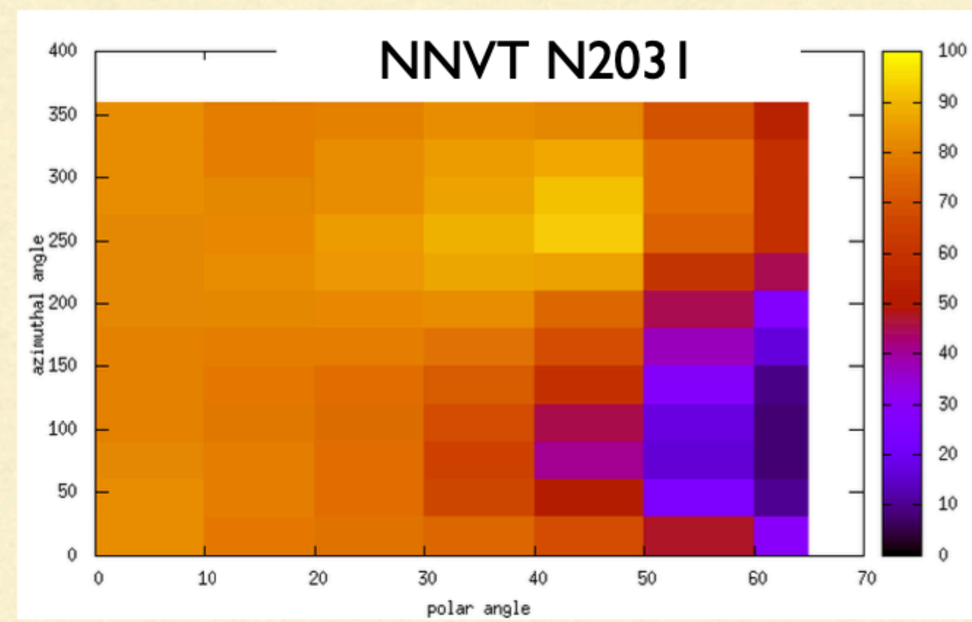










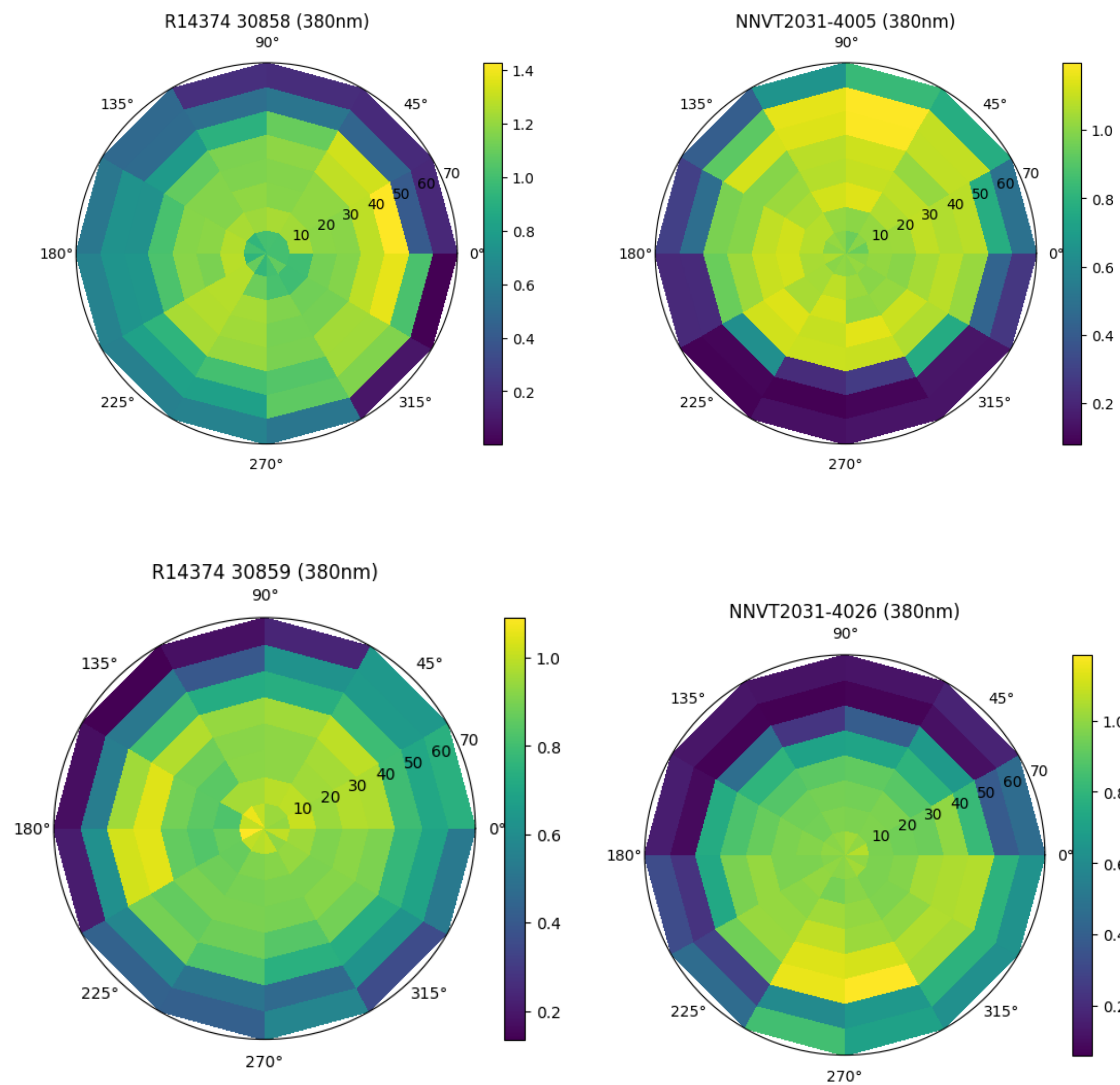


* Preliminary results with NNVT N2031, checks on-going

NNVT N2031 Vs Hamamatsu R14374

- Scan PMTs with a 380 nm 1.5 mm collimated LED varying polar angle
- Larger “blind area” at photo-cathode edges for NNVT devices
- Less optimal for collecting light from a WLS plate where high sensitivity over the full cathode surface is required

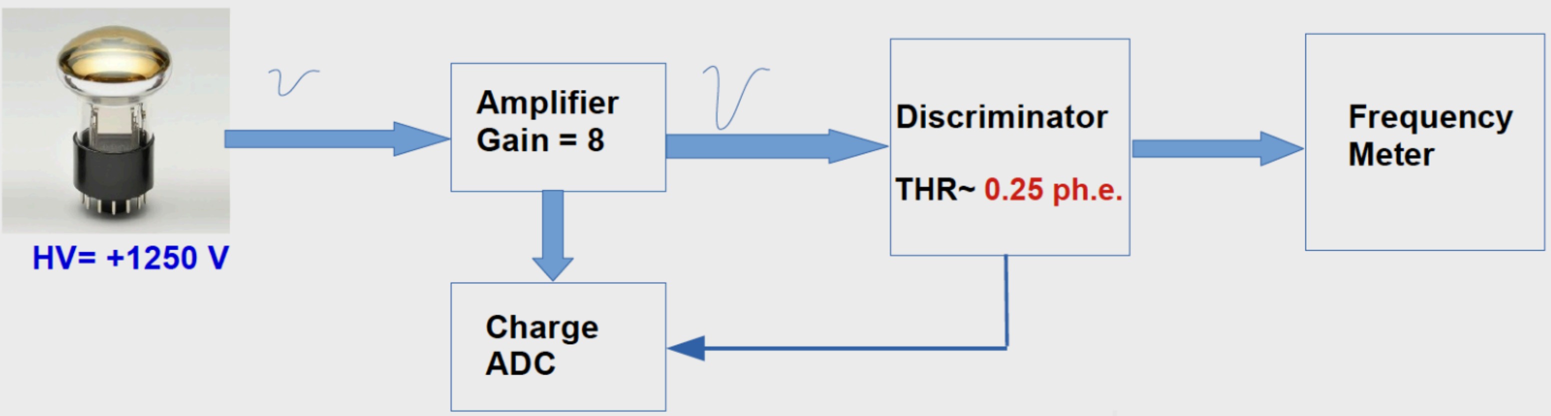
Signal normalised to measurement @ centre



* work in progress

WLS Plates: Dark Rate Measurements @ INR RAS

Dark rate of R14374 Hamamatsu PMT at positive HV



The measurements were made inside a **temperature controlled volume**.

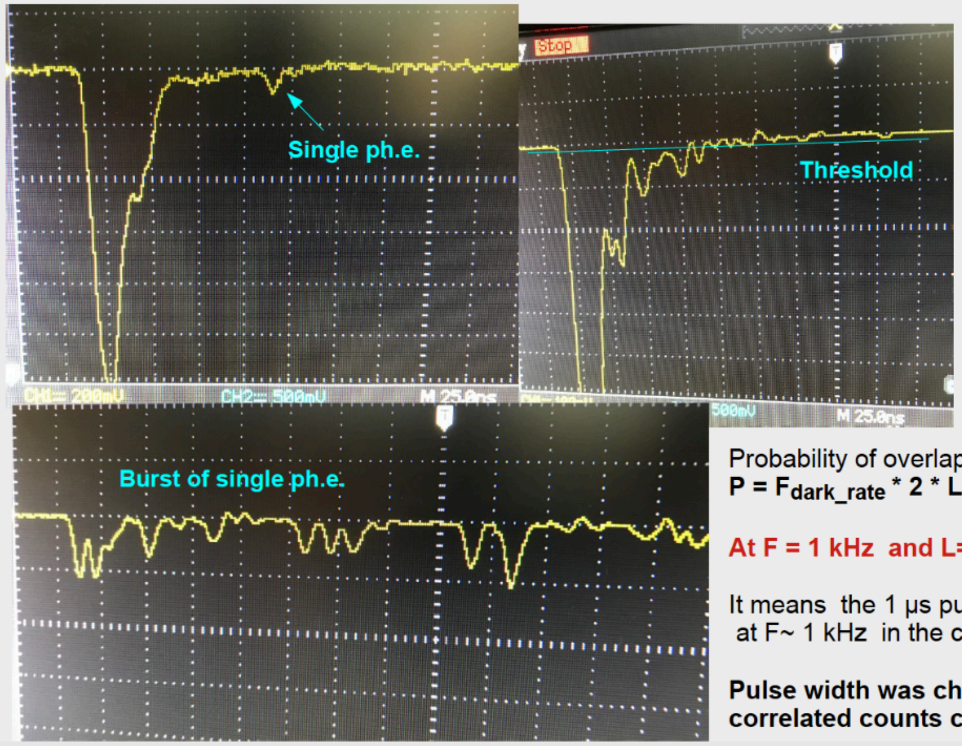
3 tested setups:

1. **Bare PMT**
2. **PMT + WLS plate with a single fluor (POPOP200)**
3. **PMT + WLS plate with double fluor (POPOP800/PPO5000)**

All WLS plates were tested with 3M DF2000MA cladding reflector.

Discriminated pulse width was set to be 1 µs to suppress:
- the generation of multiple transition pulses with low threshold at falling pulse tail;
- multiple correlated pulses at PMT discharges (pulse bursts)

Large pulses and correlated single ph.e. pulses



Large pulses can have long oscillating tail. The discriminator produces many pulses at low threshold for such a tail.

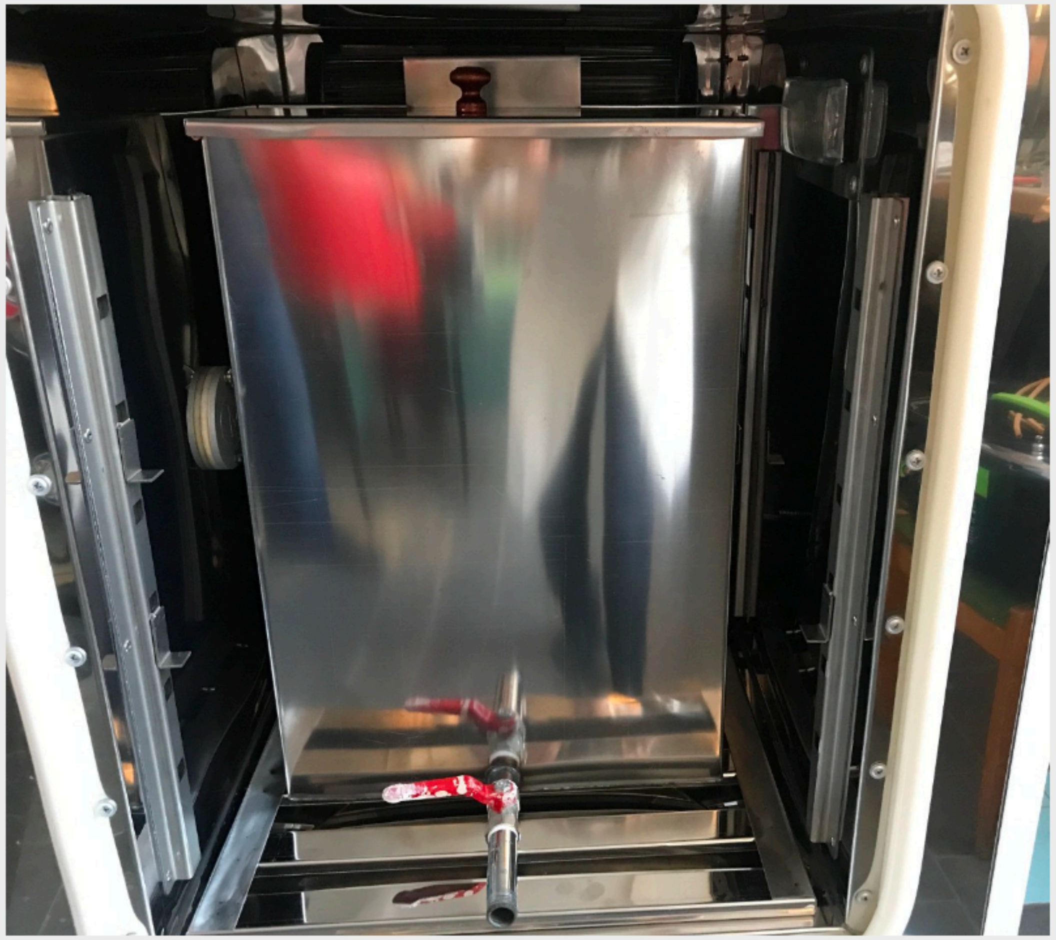
Probability of overlapping between Poisson distributed pulses:
$P = F_{dark\_rate} * 2 * L_{pulse\_width}$

At F = 1 kHz and L= 1000 ns P = 0.2 % (lost counts)

It means the 1 µs pulse width does not change the true dark rate at F~ 1 kHz in the case of accidental distribution of dark pulses.

Pulse width was chosen to be 1000 ns to suppress correlated counts caused by large pulses or PMT dischages.

WLS Plates: Accelerated Aging Studies



Empirical rule for accelerated aging:

All chemical processes go 2 times faster two for each 10°C increment.

SK water temperature +13°C.

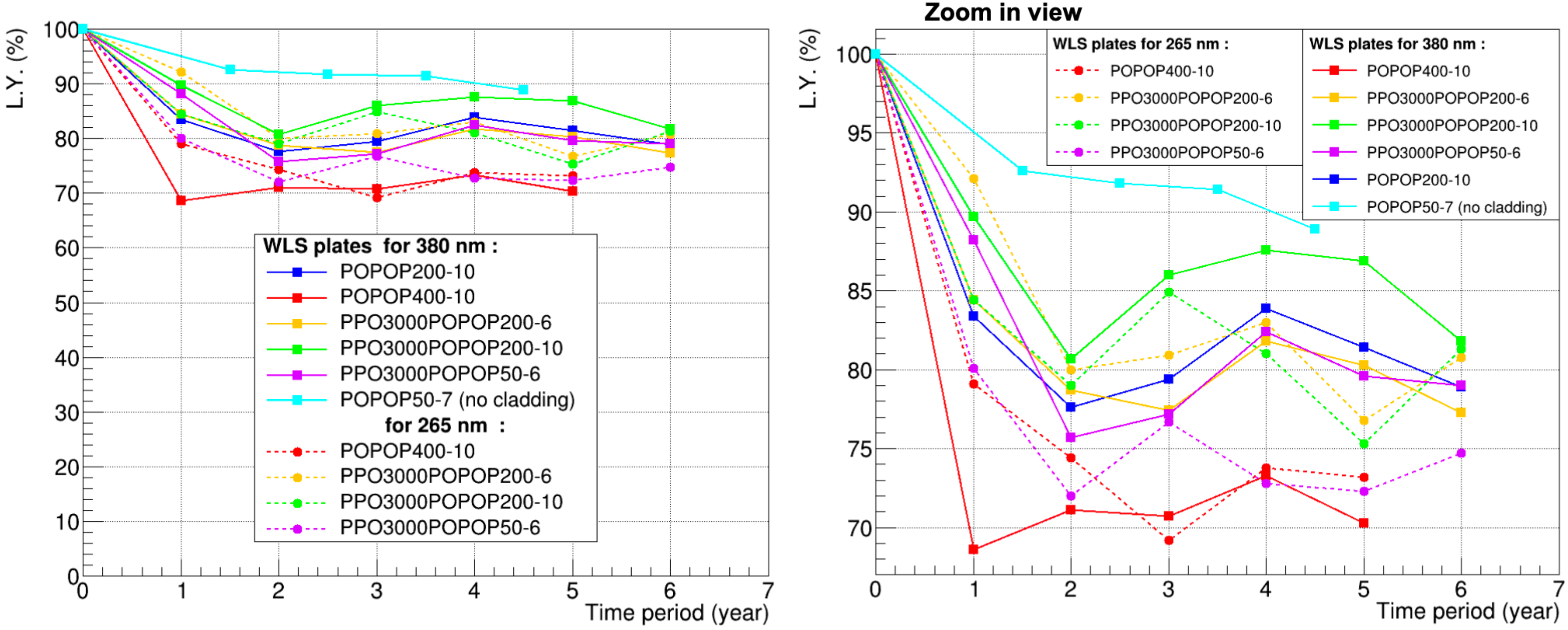
Raising the temperature to +59°C will accelerate aging in 24 times.

2 weeks in hot water correspond to 1 years of HK OD operation.

6 WLS plates were placed in a stainless steel container with distilled water.
They are kept at temperature +59°C .
The plates are measured once in each two weeks in comparison with a reference WLS plate which is kept at room temperature.

WLS Plates: Accelerated Aging Studies

Two LED drivers were used to measure WLS plate responce at 380 and 265 nm. Only the plates POPOP50-7 without cladding reflector and POPOP200-10 (the last number means thickness in mm) were tested at 380 nm because they shows no signal at 265 nm.



The light responces were normalized to have 100% signal at the start point.