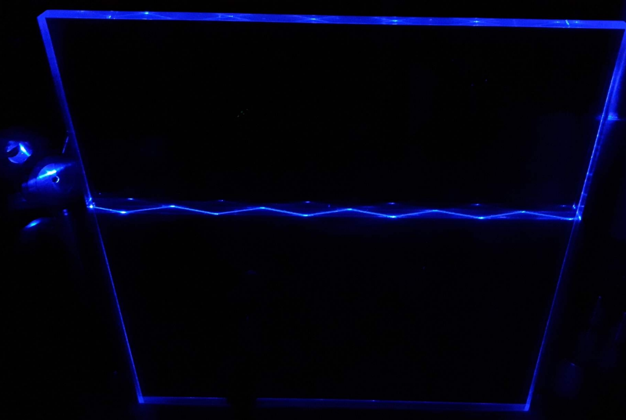
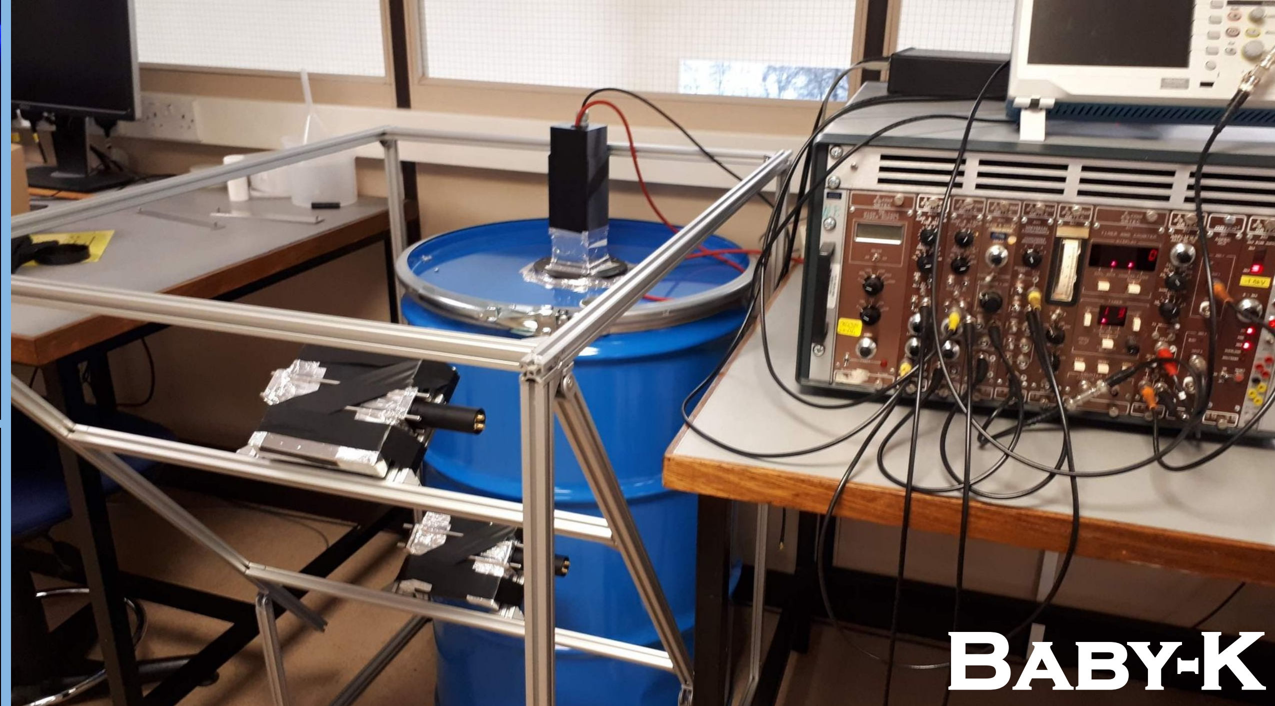




Precision Measurements of Photosensor Components for the Hyper-K Outer Detector

Soniya Samani, on behalf of the Hyper-K Collaboration

ICHEP 2022 Detectors for Future Facilities, R&D, Novel Techniques

July 9, 2022

UNIVERSITY OF OXFORD

Hyper-K

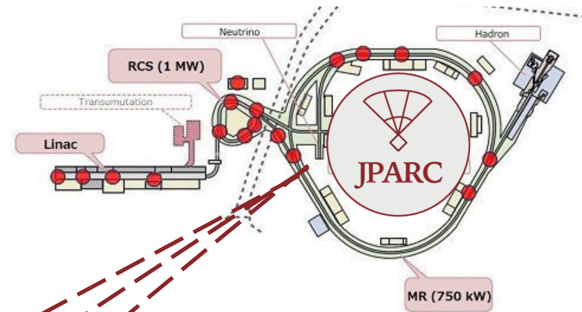
The Hyper-Kamiokande Detector

Physics Program:

- Neutrino oscillation parameters.
- Astrophysical neutrinos
- CP Violation in the leptonic sector
- Proton decay

?

Tokai -> Kamioka (295 km)



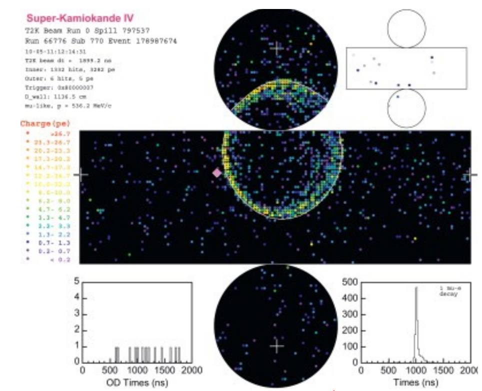
Construction:

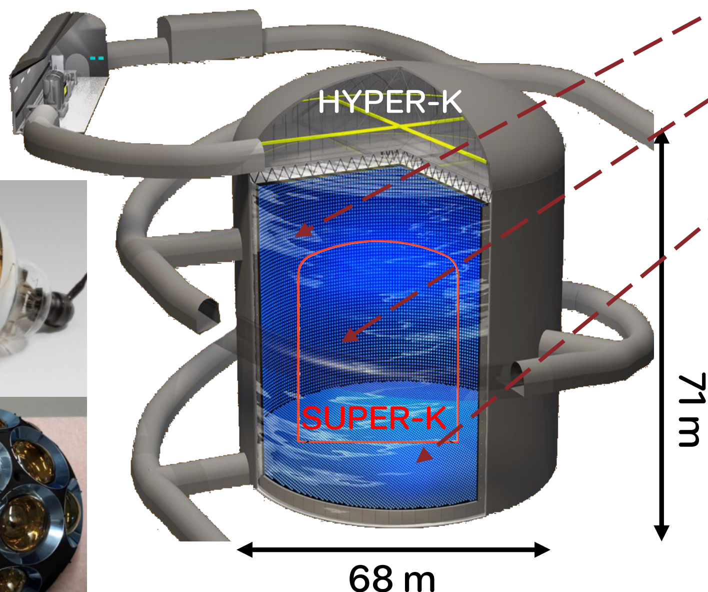
- **71 m x 68 m**
- **188 ktons** fiducial volume (8x Super-K)
- **650 m** rock overburden.

ν_μ

ν_μ

ν_μ





Hybrid Inner Detector Design:

- Ring-imaging Cherenkov light.
- Box&Line 20″ PMTs
  - 2x quantum efficiency
  - 1/2 TTS (1 ns)

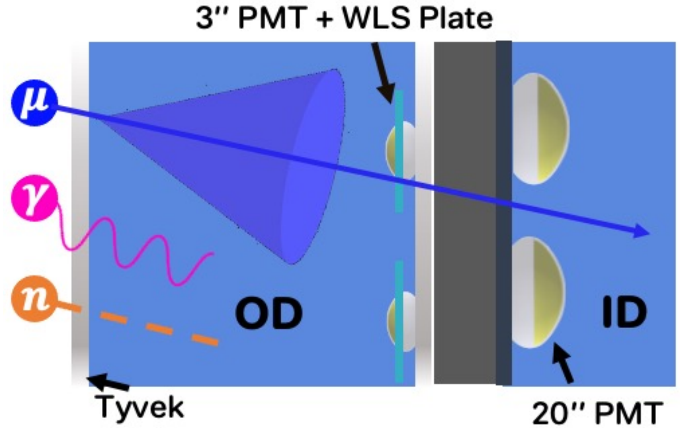
  Compared to Super-K PMTs
- mPMT's housing 19 3″ PMTs.
- **20% photocathode coverage.**

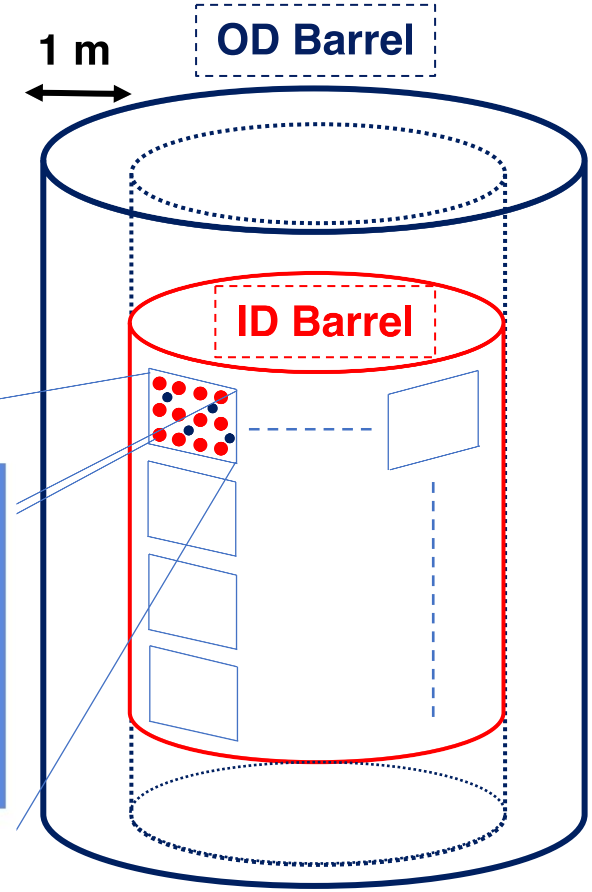
Outer Detector Veto System

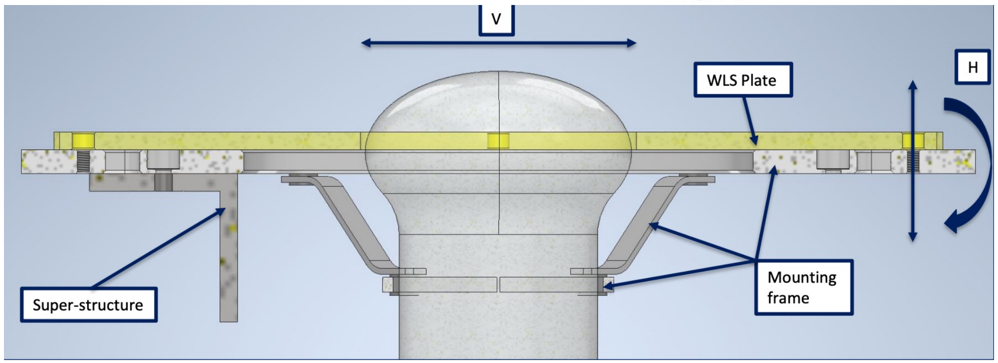
OD Design:

- PMT support structure separates ID and OD.
- **2 m** endcaps/ **1 m** barrel water thickness.
- **7.2 – 8.6 k 3-inch PMTs**
- **30 x 30 cm** Wavelength Shifting Plates.
- Lining with **90% reflective Tyvek.**

Trigger on PMT hit clusters above a threshold defined by PMT dark rate.







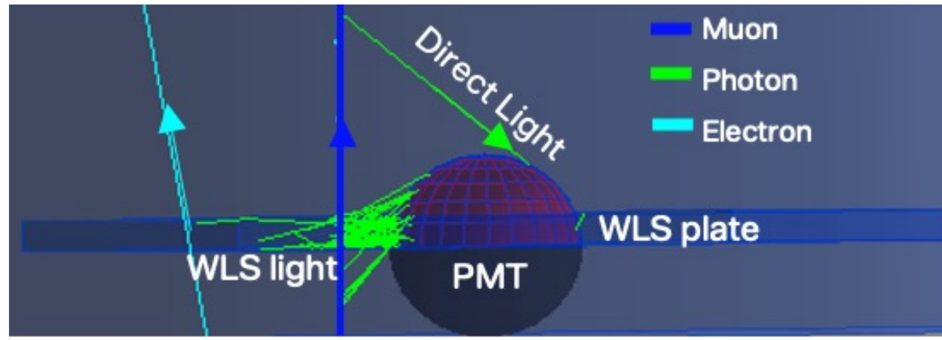
Performance Requirements:

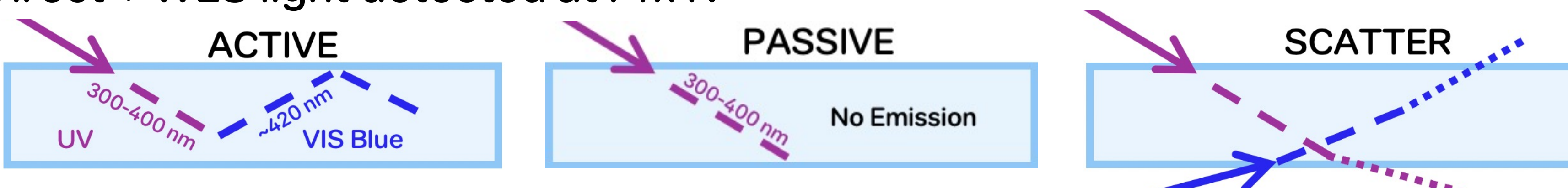
- 45 Hz cosmic ray muon flux – miss fewer than 1 in 10^6 muons.
- Passive shielding
- Event selection

Wavelength Shifting Plates

Evaluate candidate WLS plates to design OD photosensor with an economical cost per detected photon.

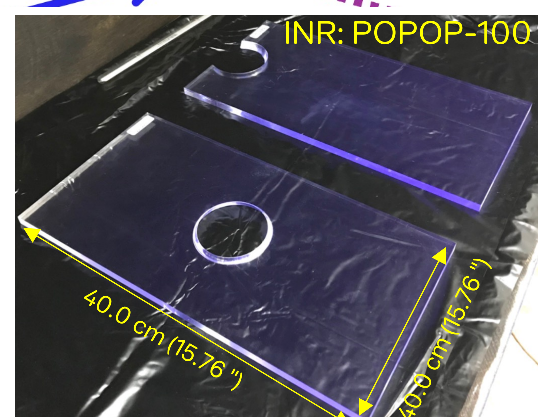
- Polymer base (PVT or PMMA).
- n = 1.49 – 1.57
- Doped with **fluorescent** compound.
- **Absorbs UV** light maximally.
- **Re-emission** at In VIS blue.
- Trapped via **Total Internal Reflection.**
- **Direct + WLS light detected at PMT.**





WLS Candidates:

- **Eljen** EJ286
- **Kuraray** UVOK WLS, WLSA, WLSB, B2
- **LabLogic**
- **V.A Kagrin POPOP** mixed concentrations

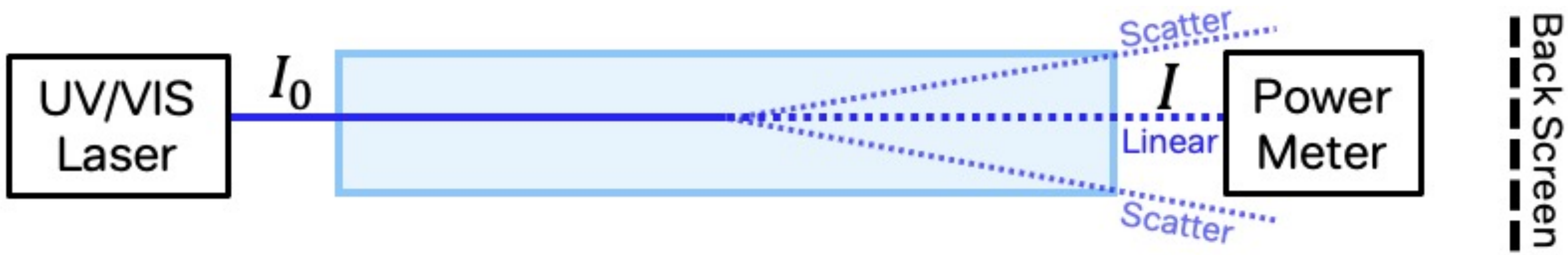


Optical Measurements

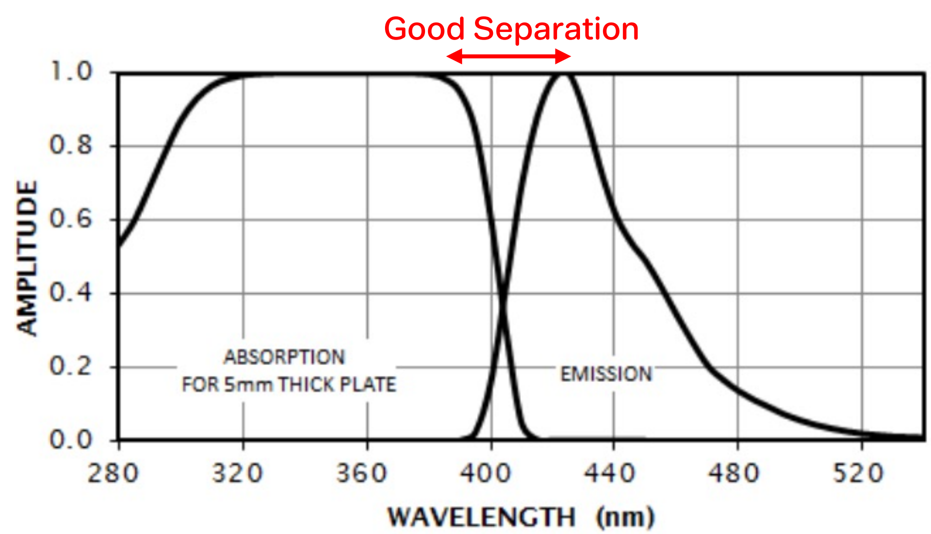
WLS Requirements:

- Maximal absorption 300 – 400 nm.
- Peak emission spectra above 400 nm.
- Bulk material uniformity and optical clarity.
- High light collection efficiency.

UV-VIS Spectrophotometry to measure optical properties in-air

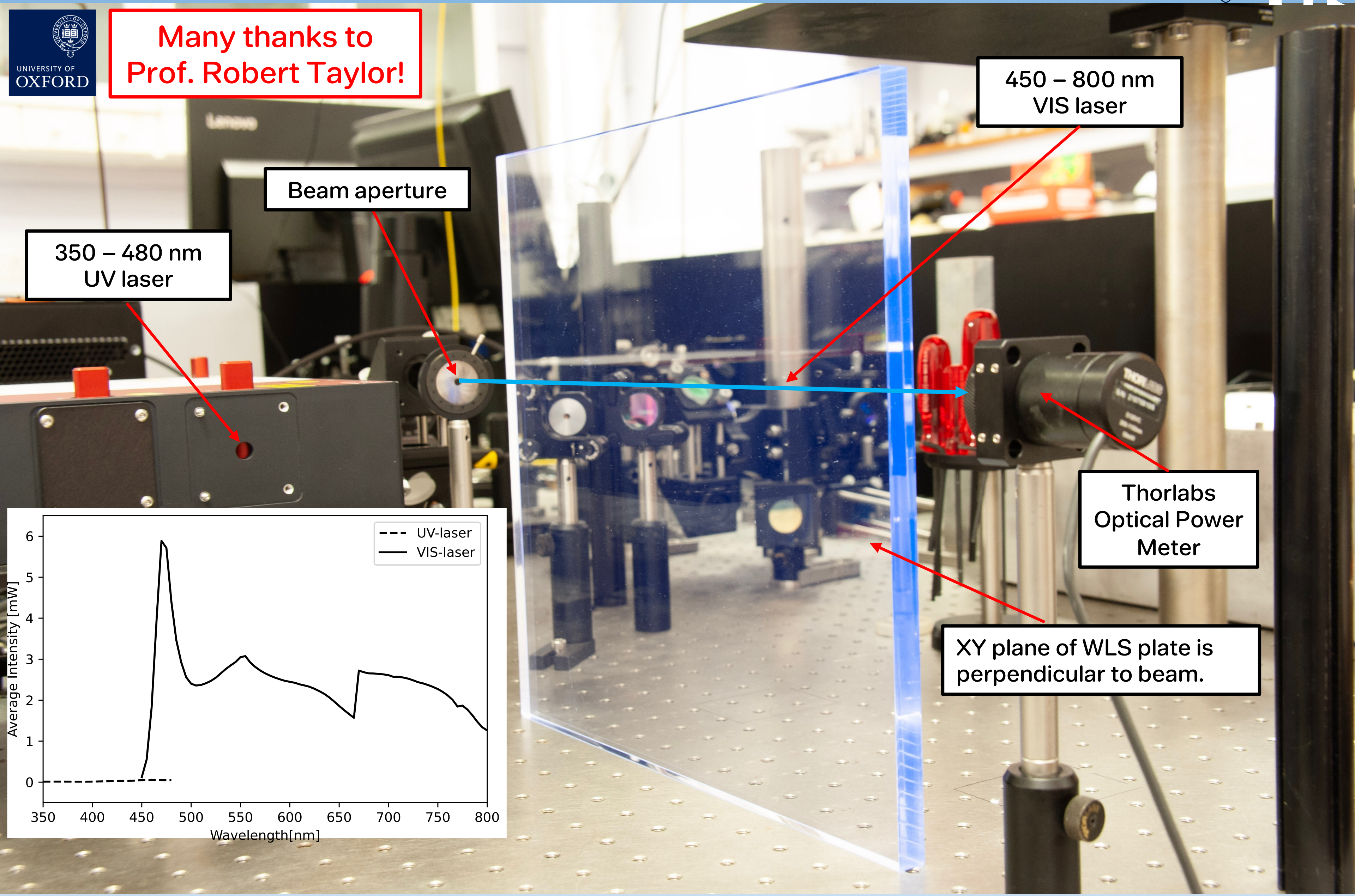


- Transmittance: $\mathbf{T} = \frac{\mathbf{I}}{\mathbf{I_0}}$
- Absorbance: $\mathbf{A} = -\ln(\mathbf{T})$
- Attenuation length: $\lambda_{\mathbf{eff}} = \frac{-\mathbf{d}}{\ln(\mathbf{T}(\lambda))}$
- Beer-Lambert Law: $P(\lambda) = e^{-\frac{d}{\lambda_{\mathrm{eff}}}}$

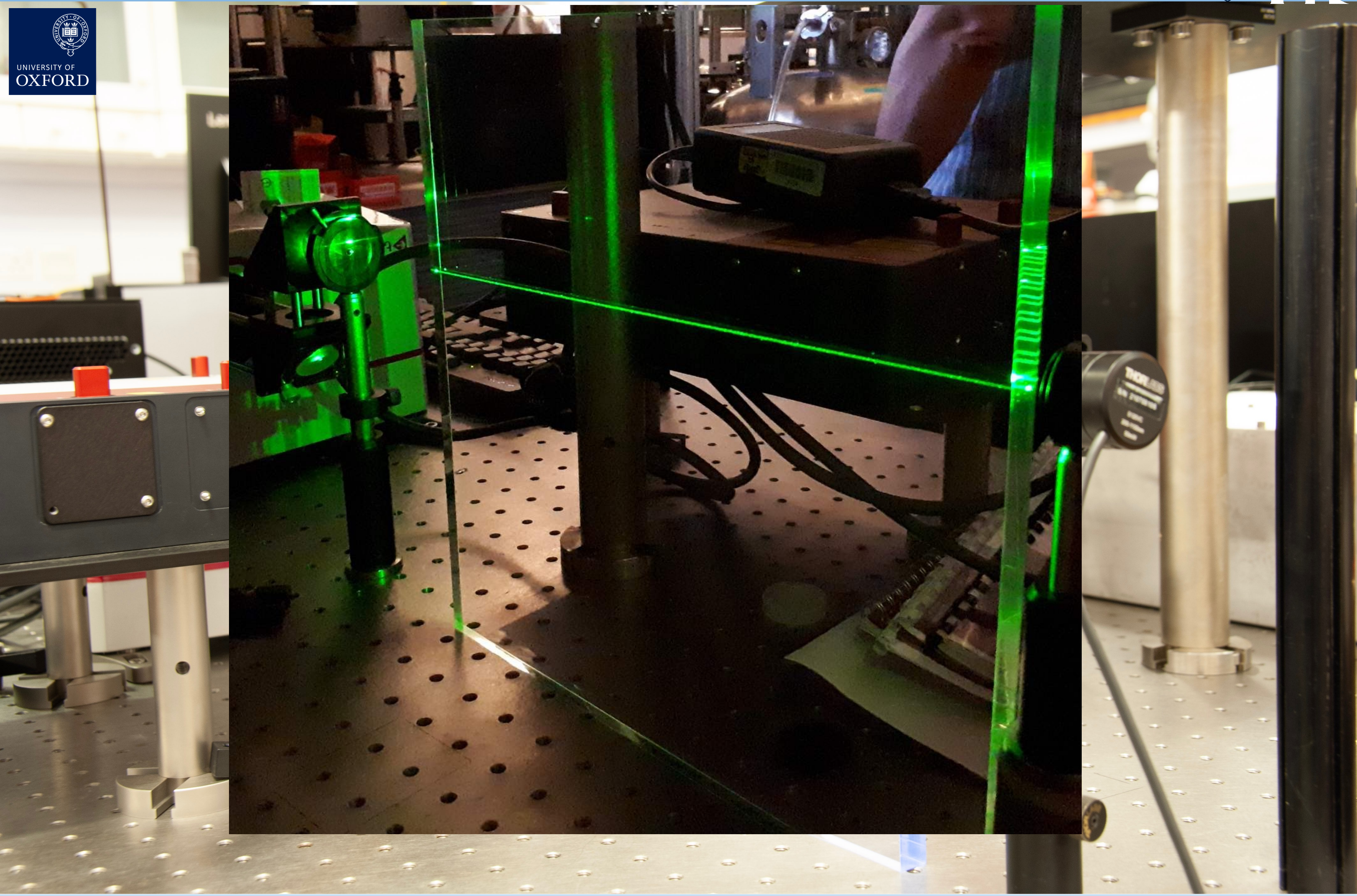


Precision Optical Laser Setup

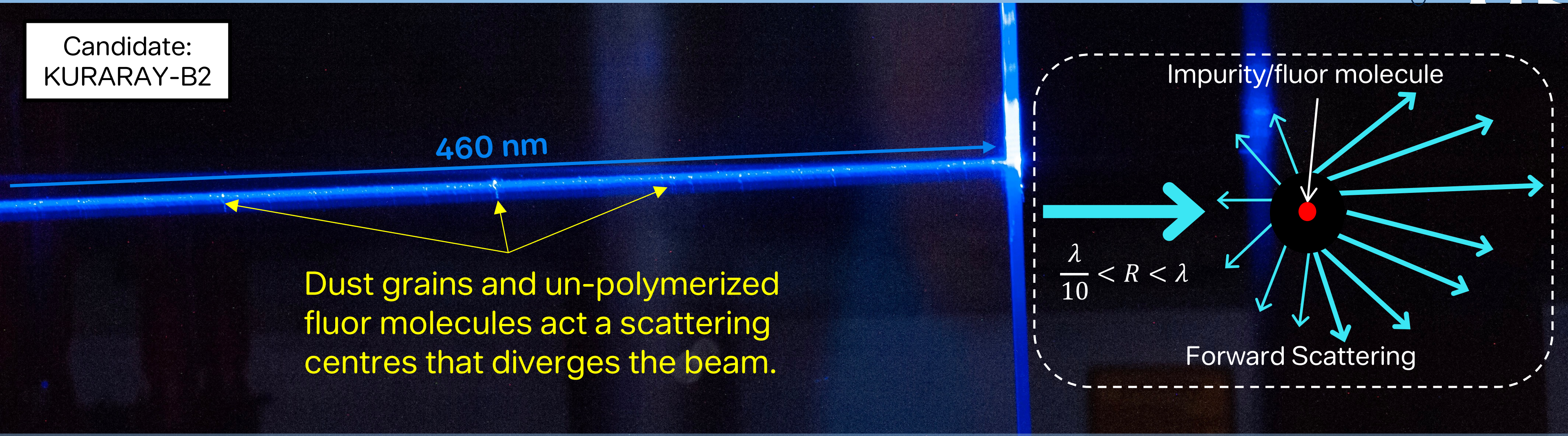
Many thanks to Prof. Robert Taylor!

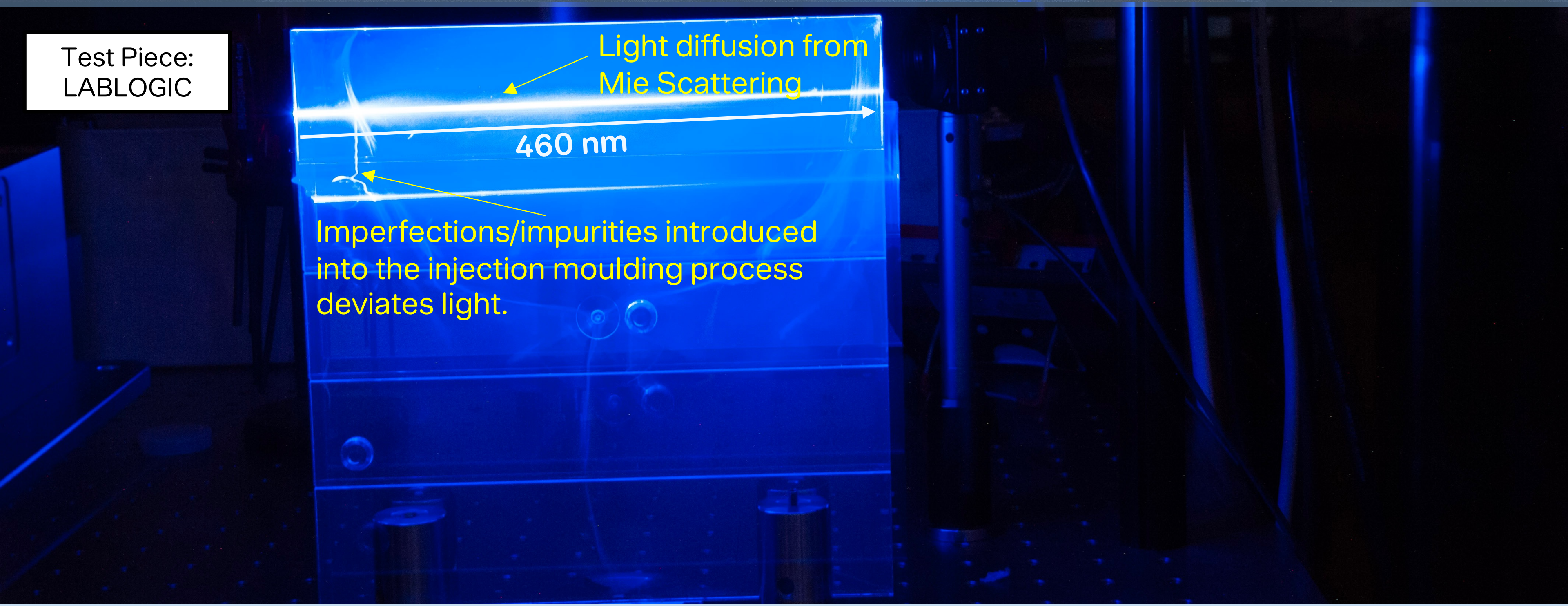


Precision Optical Laser Setup

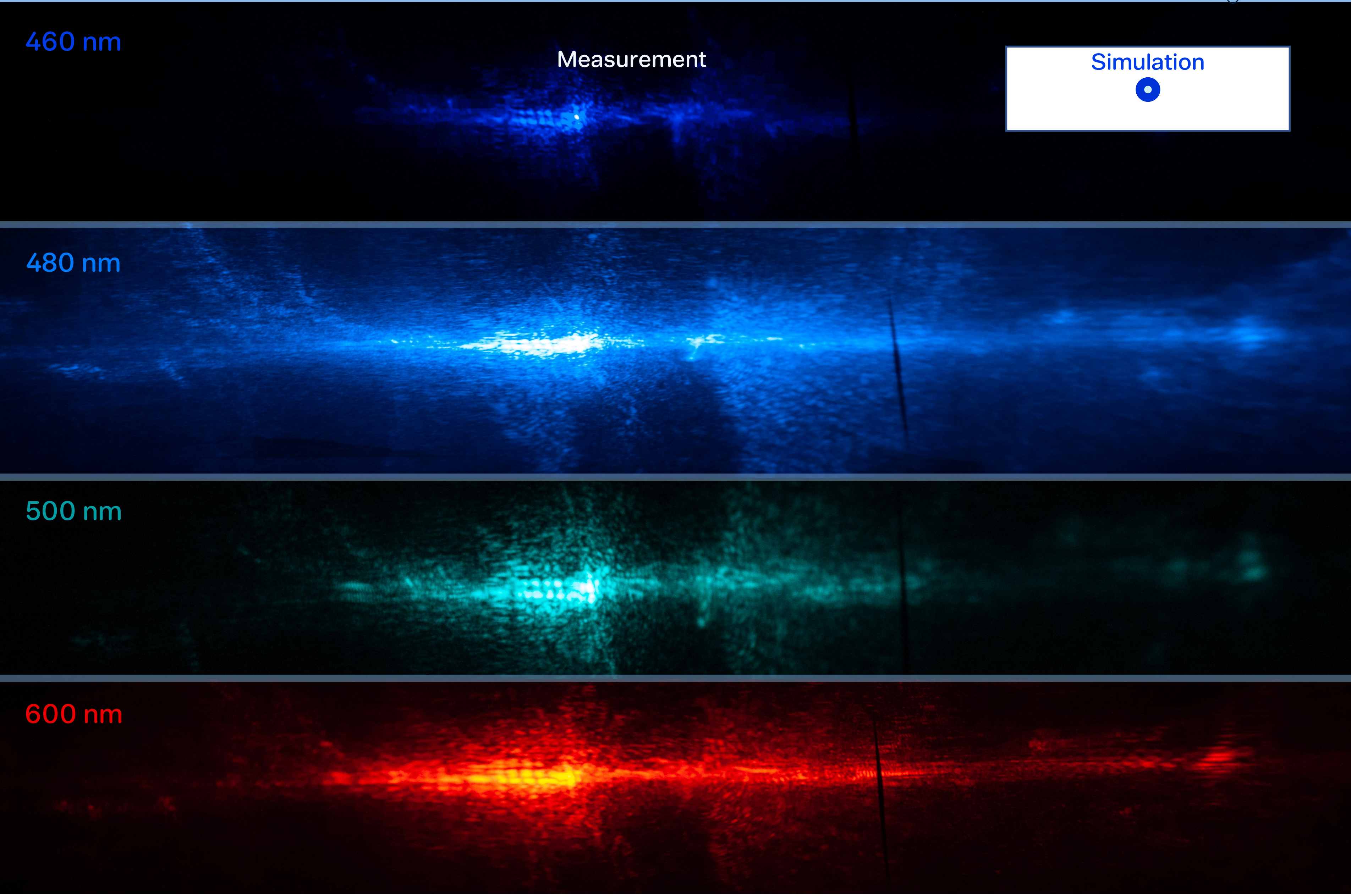


Mie Scattering Effect

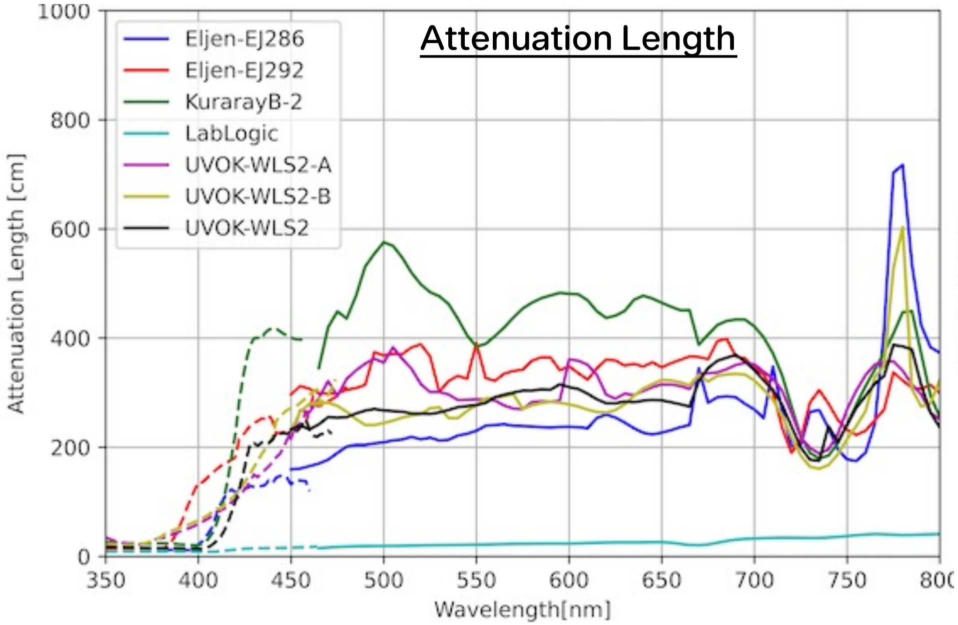


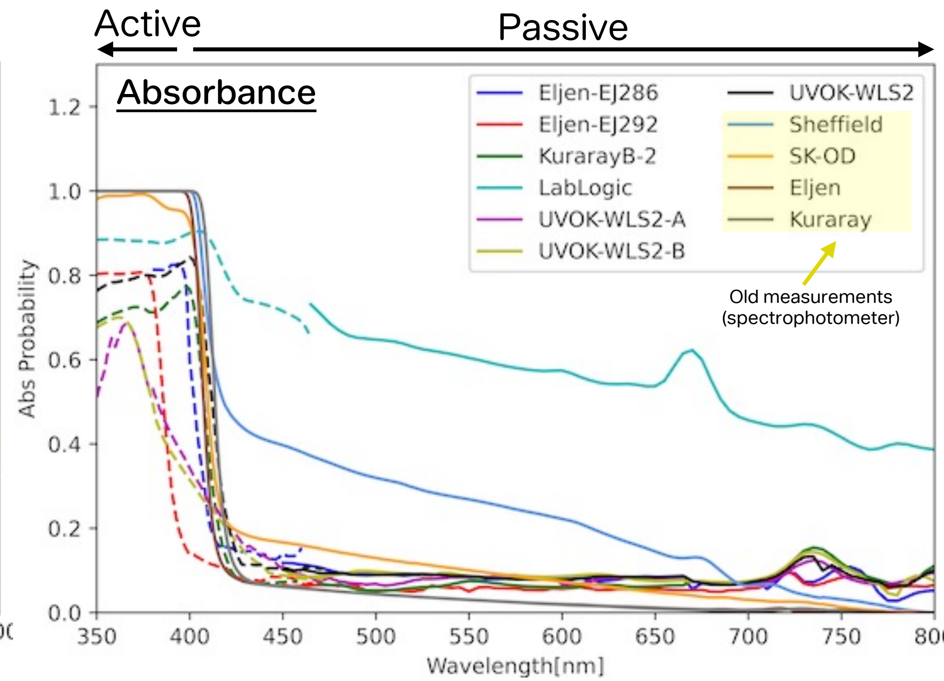


Scattering Projections on the Back Screen



Measurements of WLS Candidates

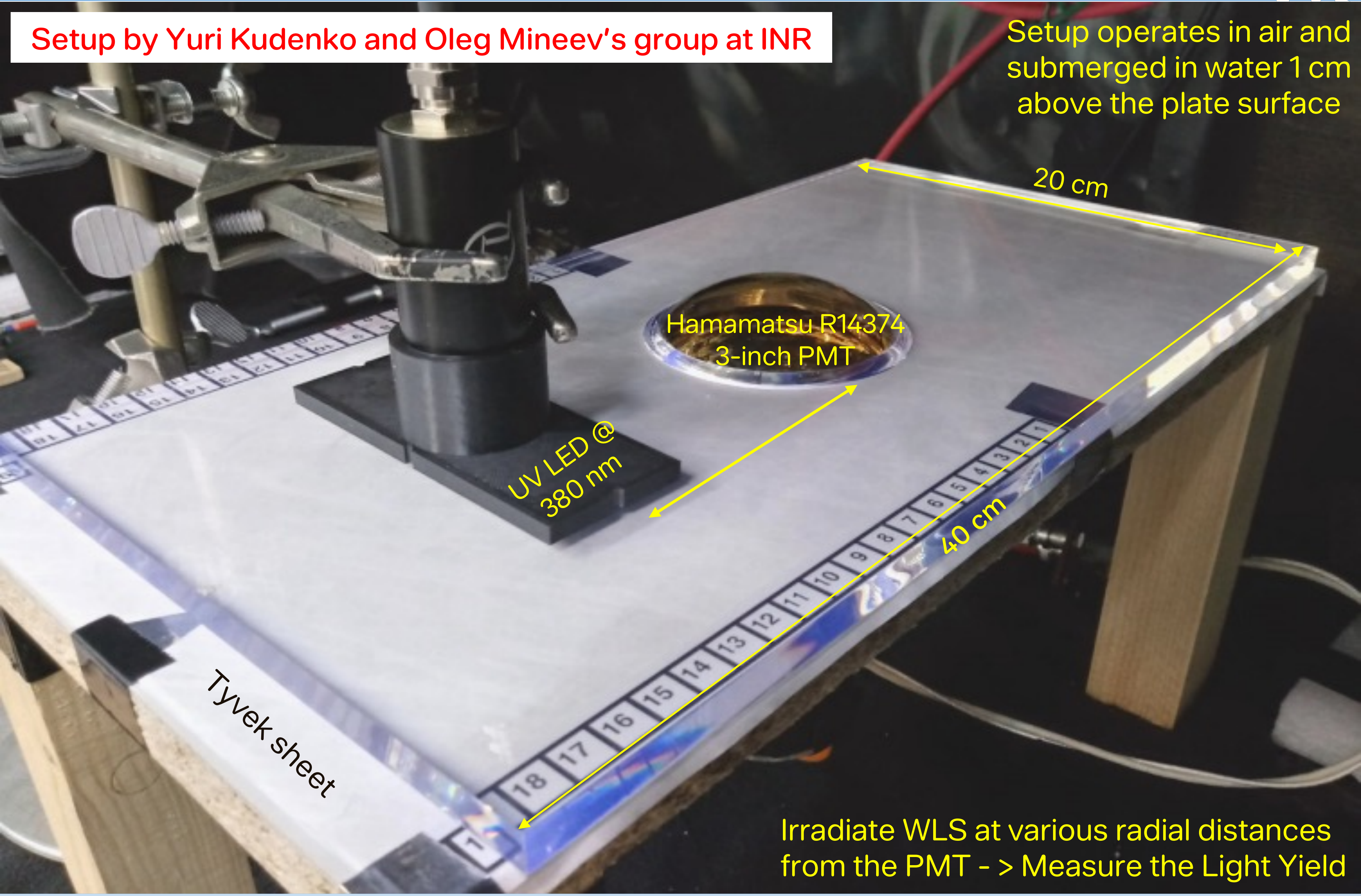




- The net effect of **Active, Passive and Mie Scattering.**
- Active absorption **350 – 400 nm.**
- ***O*(2 m)** above 400 nm at the peak emission wavelength.
- Scattering is highly dependent on plate microstructures, and cannot be modelled precisely in MC.
- Further **WLS qualification -> precise water-based measurements.**

WLS Performance Setup in Air and Water

Setup by Yuri Kudenko and Oleg Mineev's group at INR



Attenuation Length in Air and Water

Measurement by Yuri Kudenko and Oleg Mineev's group at INR

$$Y = \underbrace{A_0 e^{\left(-\frac{x-4}{L}\right)}}_{\text{Direct re-emitted light at PMT}} + \frac{A_0}{k}\underbrace{e^{\left(-\frac{x-36}{L}\right)}}_{\text{Reflected re-emitted light}}$$

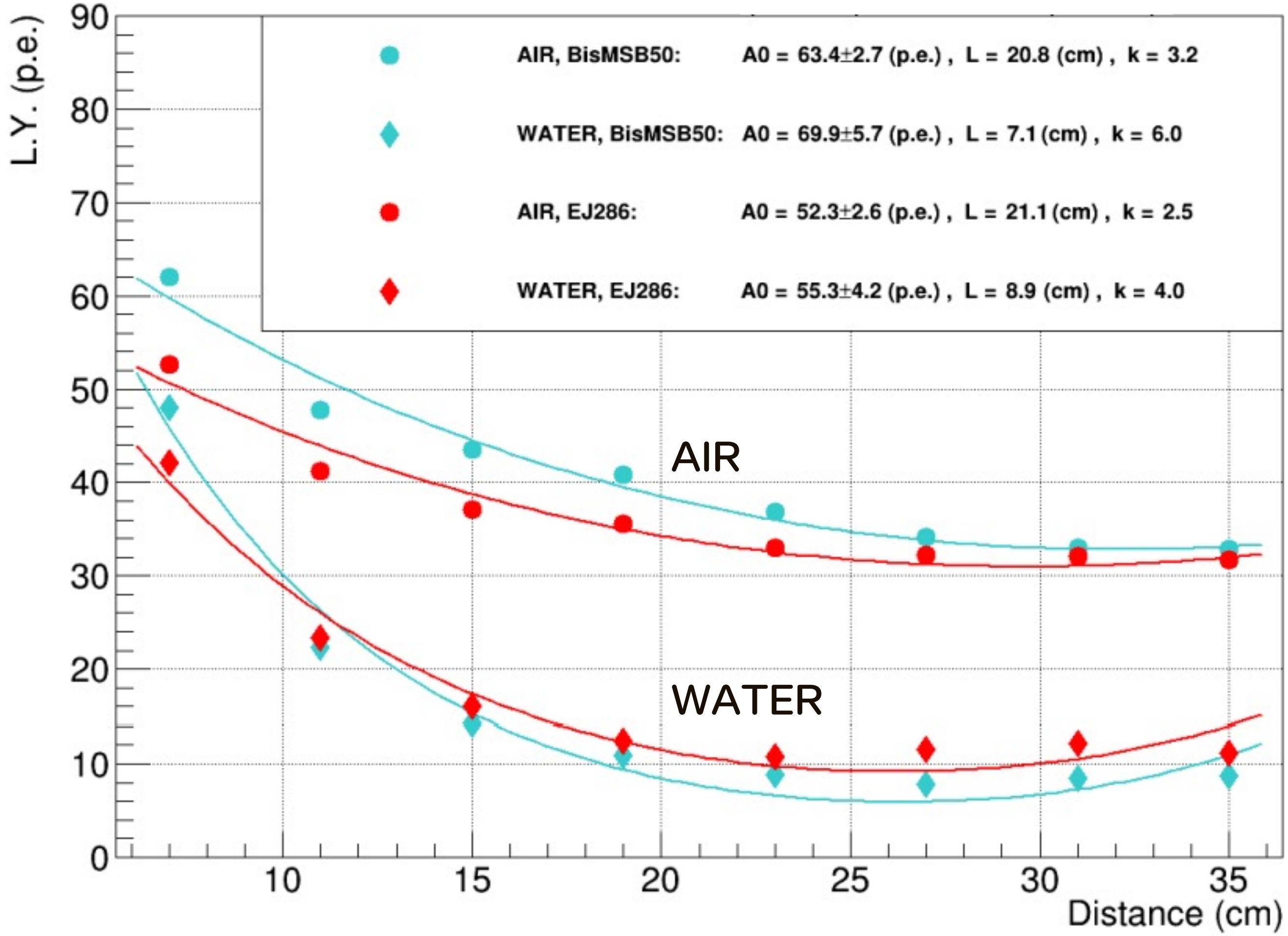
$\mathbf{A_0}$: Initial light amplitude
$\mathbf{k}$: Fraction of re-mitted light reflected from plate edge

Light Attenuation at 380 nm:

$L_{AIR} = 21\ cm$

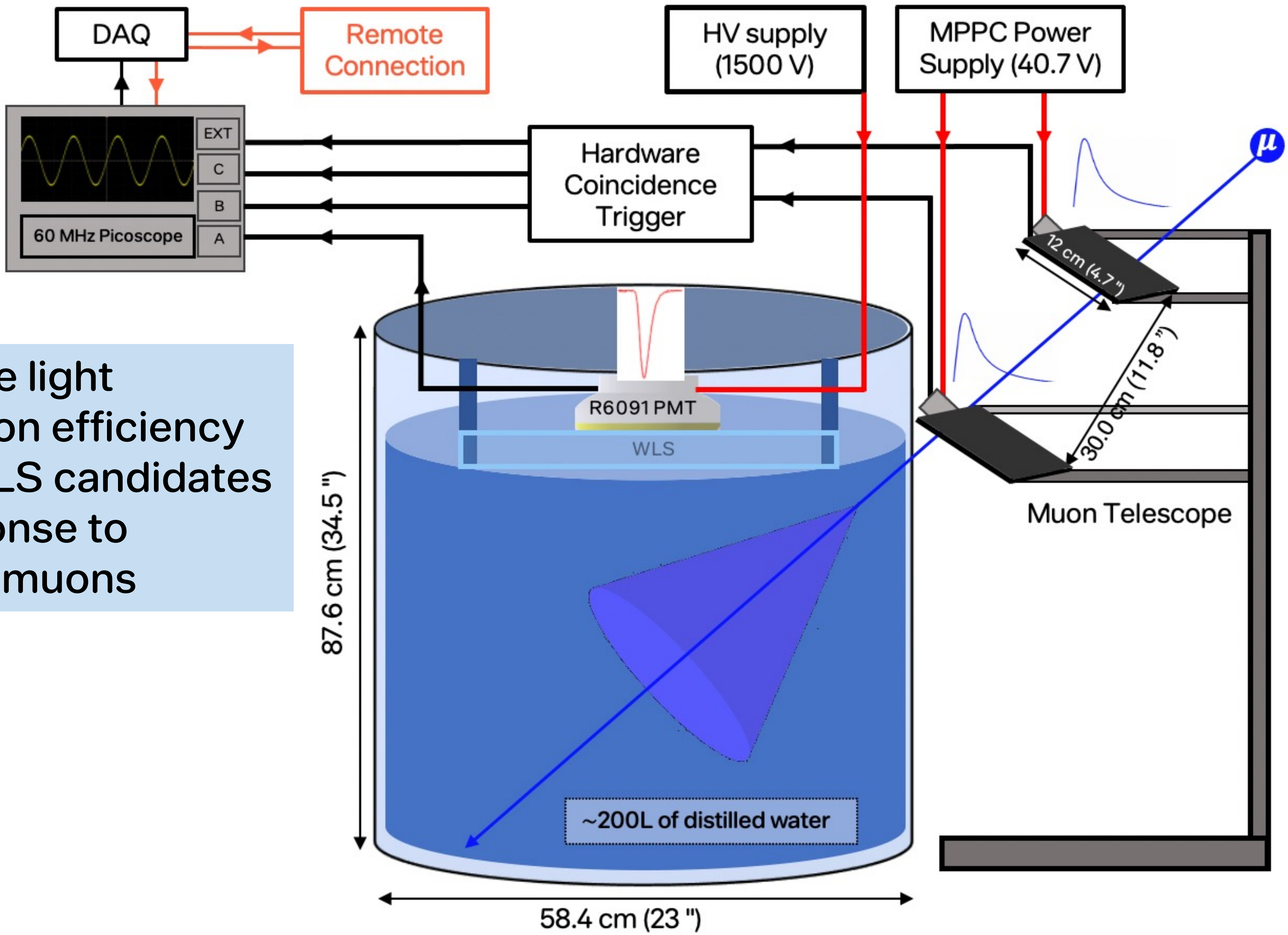
$L_{WATER} = 7\ - 9\ cm$

Need water-based measurements over entire Cherenkov spectrum

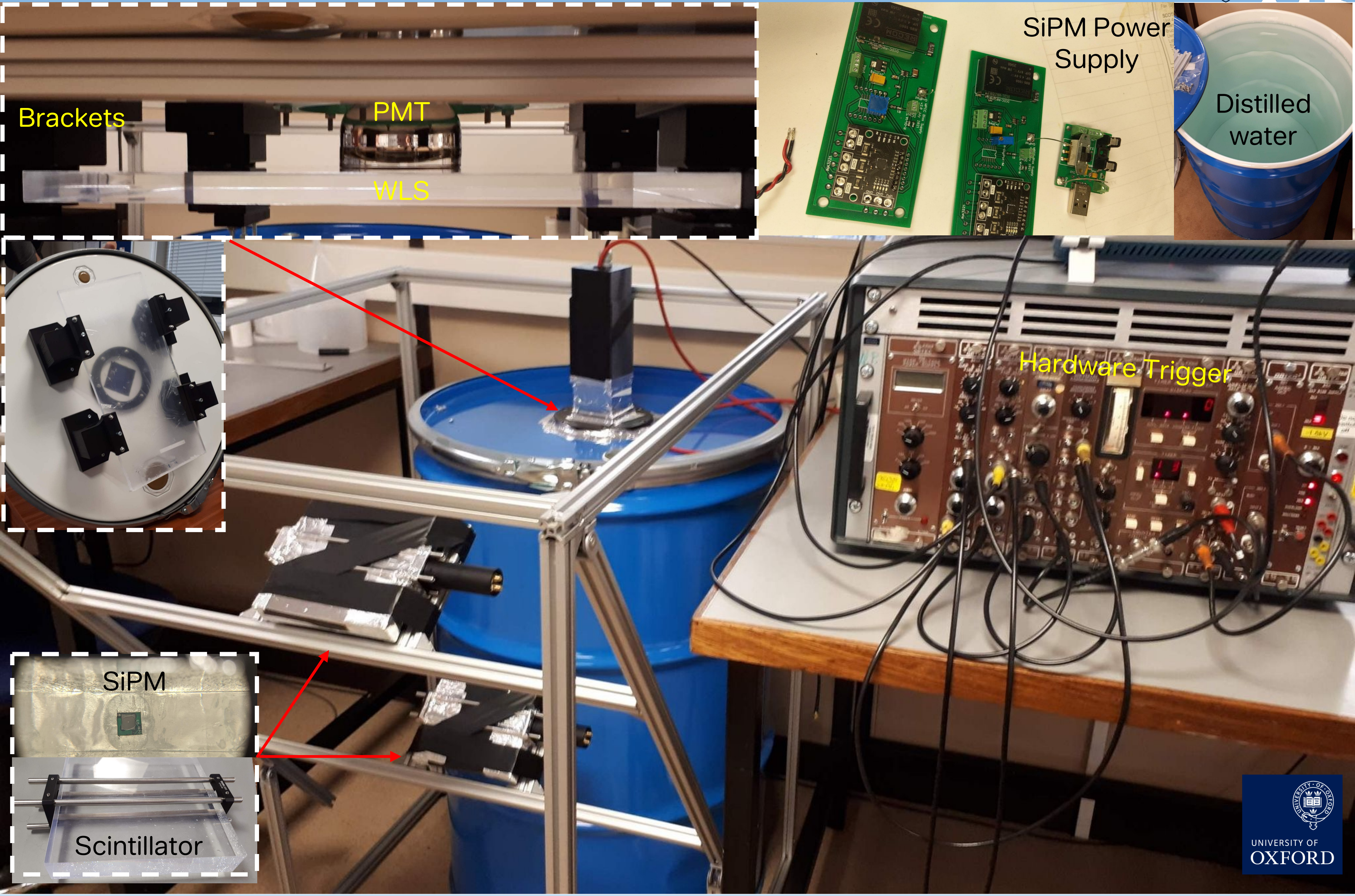


Baby-K: Water Based WLS Test Facility

Evaluate light collection efficiency of all WLS candidates in response to cosmic muons

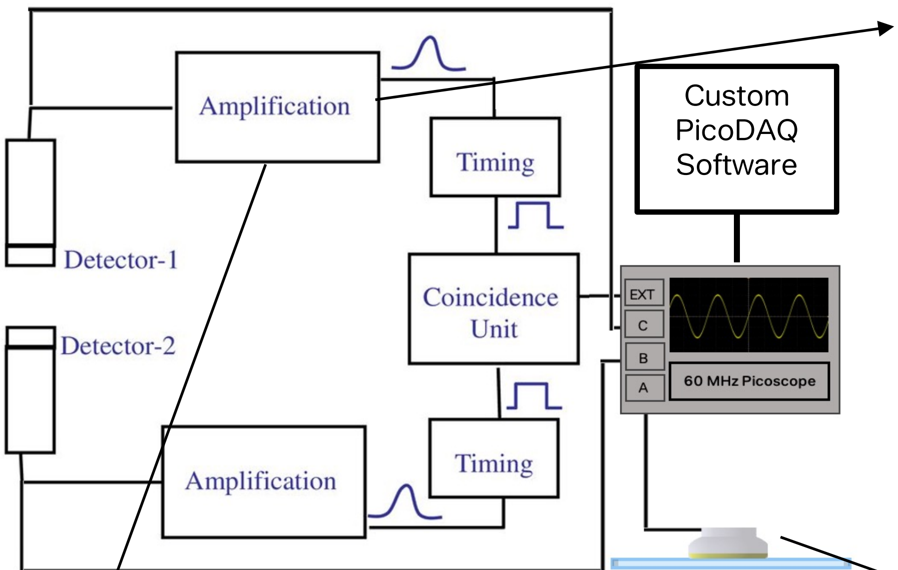


Baby-K: R&D Program

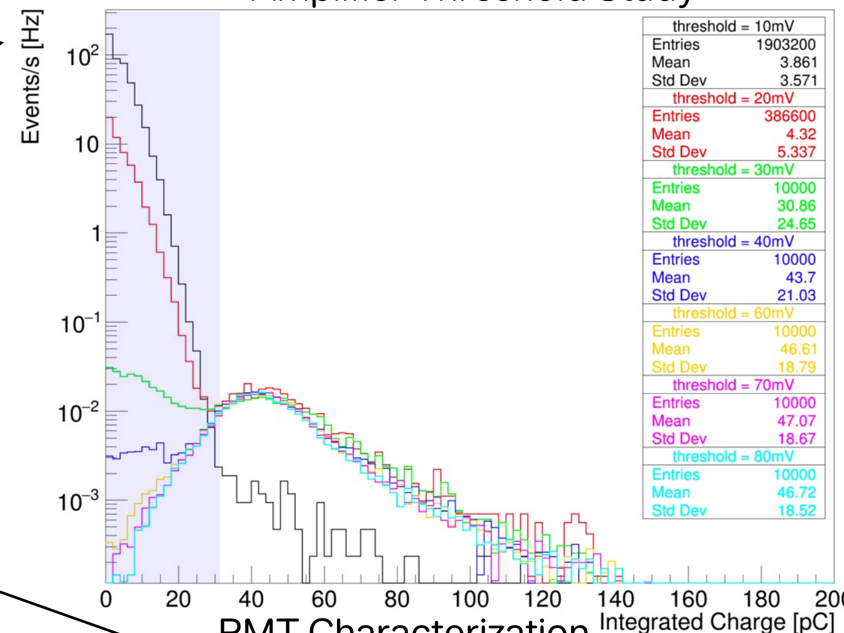


Baby-K: Calibration

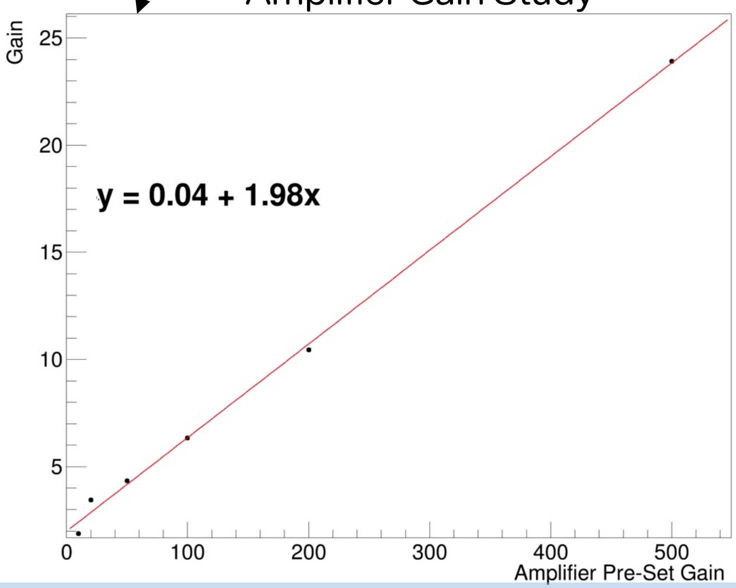
Hardware Trigger System



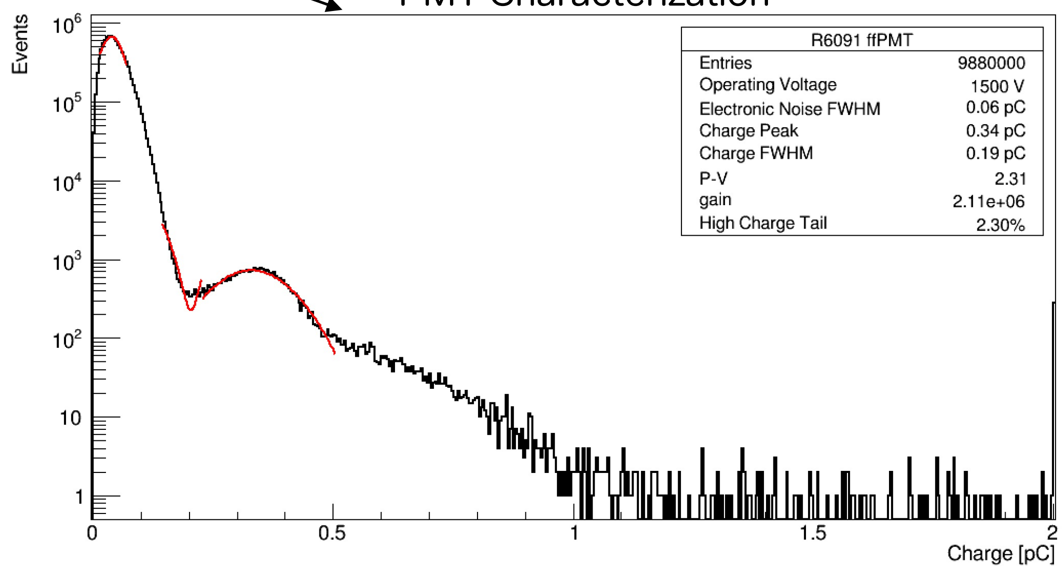
Amplifier Threshold Study



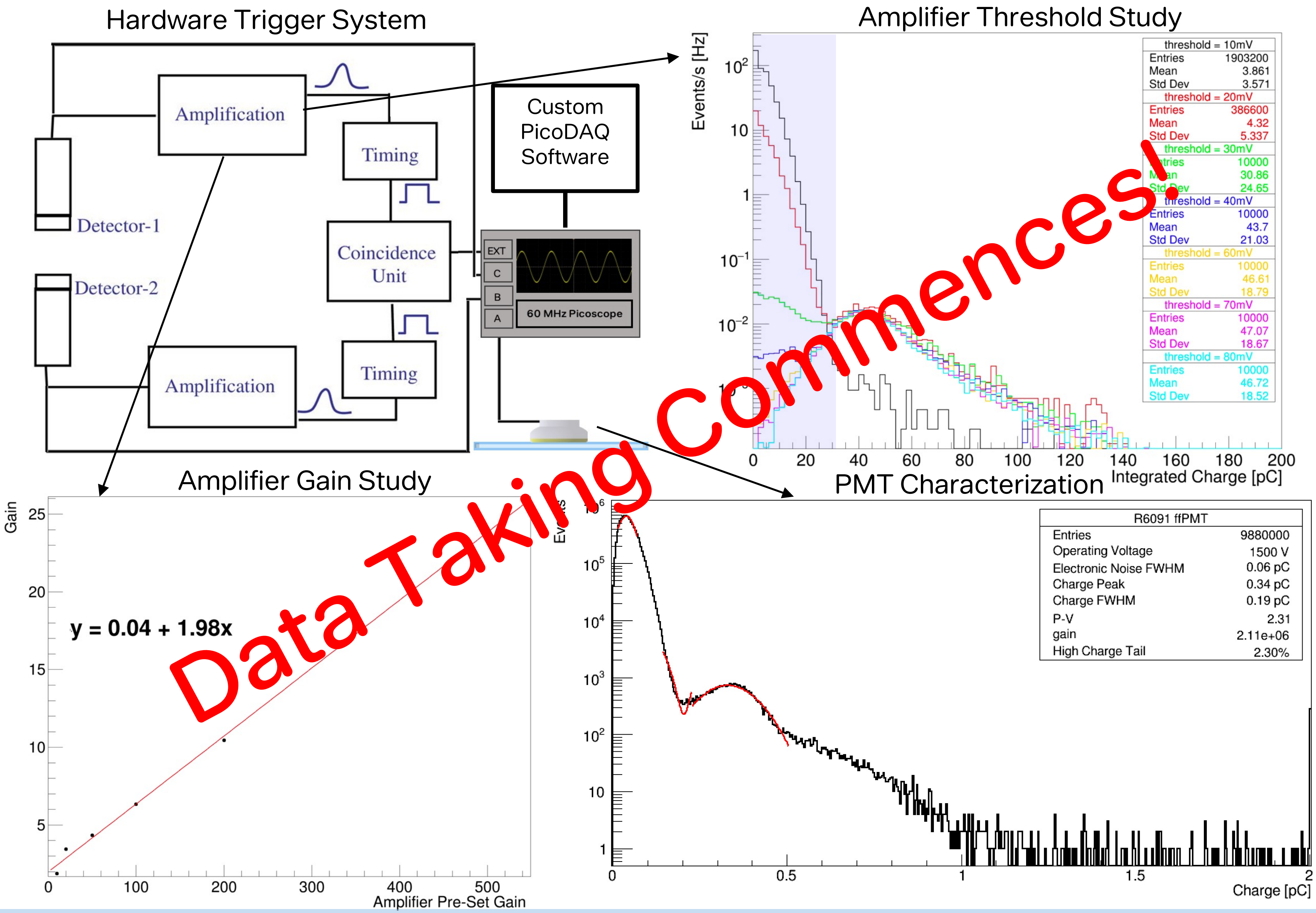
Amplifier Gain Study



PMT Characterization



Baby-K: Calibration



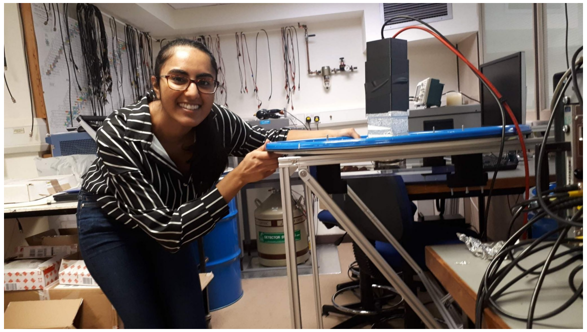
Conclusion

Evaluate candidate WLS plates to design OD photosensor with an economical cost per detected photon.

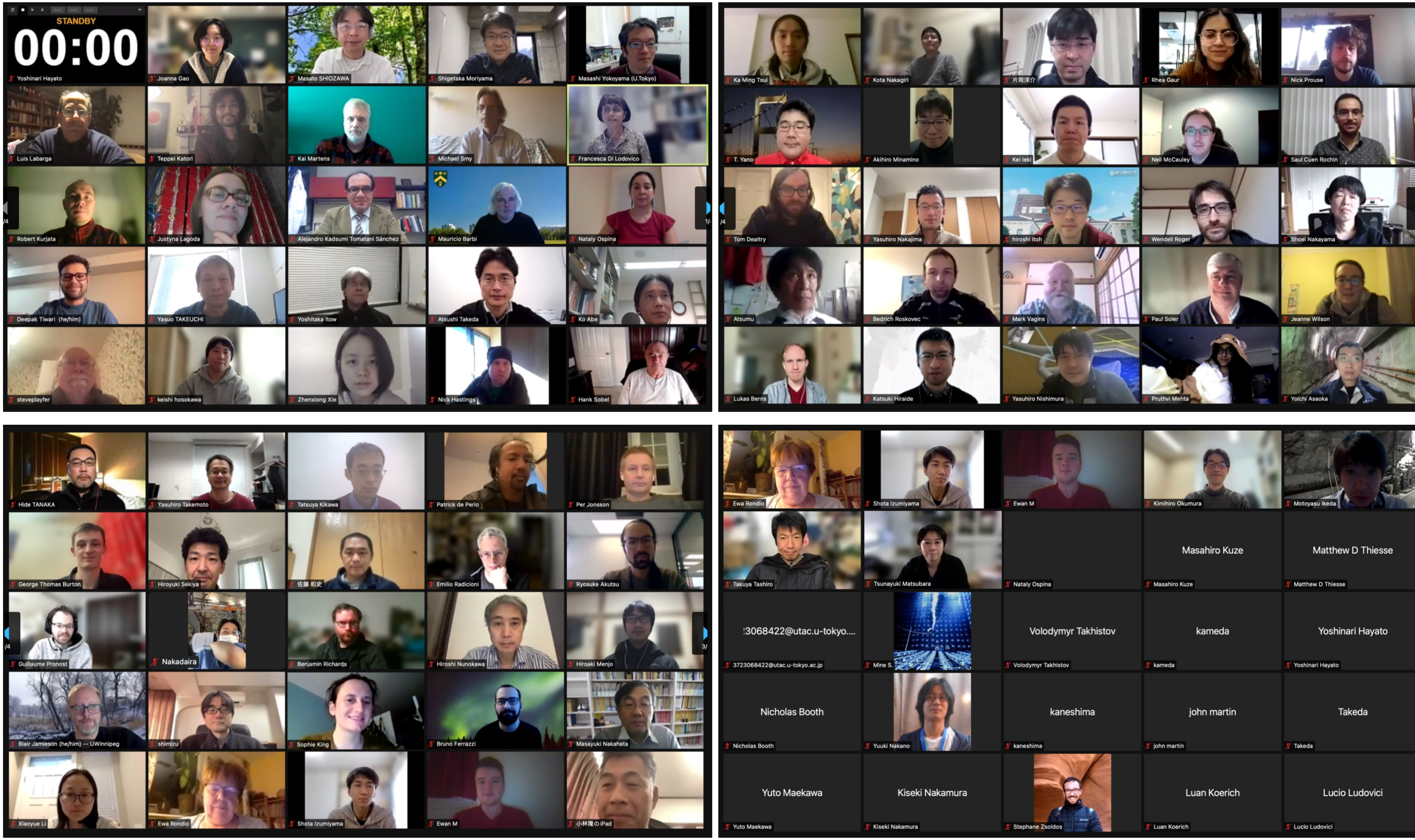
- Optical Setup:
  - Absorbance and Attenuation Length evaluated in air.
  - Prominent Mie Effect.
  - Cannot rely on MC simulations to guide WLS selection.

- INR:
  - $L_{AIR} = 21\text{ cm}, L_{WATER} = 7 - 9\text{ cm}$
  - Ongoing studies on optimisation of mechanical assembly, plate thickness (backup).

- Baby-K:
  - Water Cherenkov detector to evaluate WLS candidates using muons. Measurements coming soon!



Thank you!


STANDBY
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Masahiro Kuze
Matthew D Thiesse
Volodymyr Takhistov
kameda
Yoshinari Hayato
Nicholas Booth
kaneshima
john martin
Takeda
Yuto Maekawa
Kiseki Nakamura
Luan Koerich
Lucio Ludovici

BACKUP SLIDES

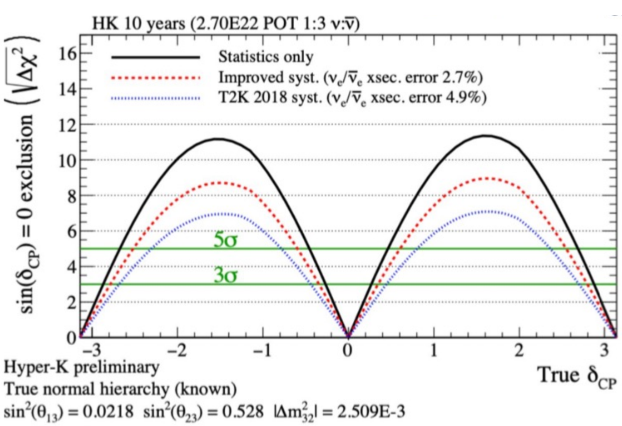
Hyper-Kamiokande Physics

CP Violation

High statistics over 10 years increases sensitivity to δ_{CP}.

Potential 5σ discovery for $\sin(\delta_{CP}) \neq 0$.

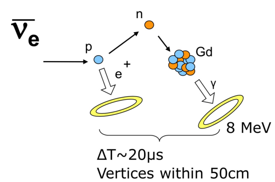
Up to 8σ exclusion at δ_{CP} = - 90°

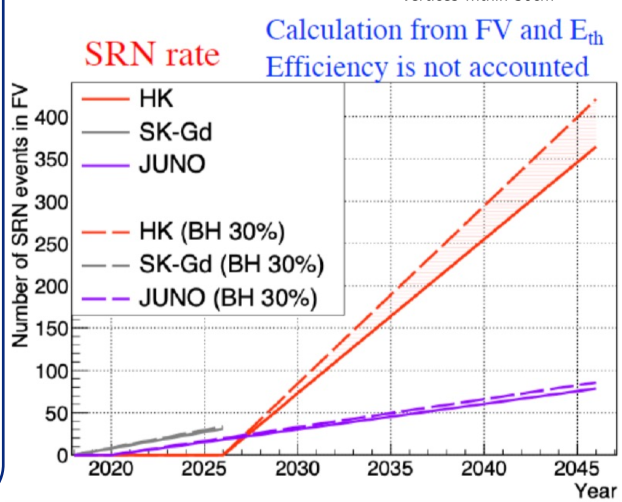


DSNB

Large FV improves statistics.

Enhanced neutron tagging capability - > Gd doped.



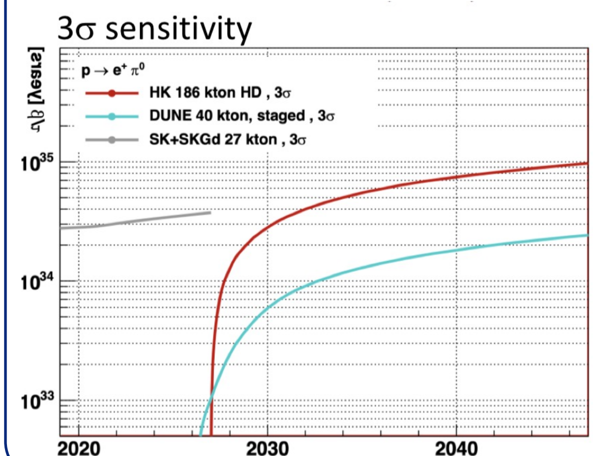


Proton Decay

Sensitivity to 10^{35} years for $p \rightarrow e^{+}\pi^{0}$ mode.

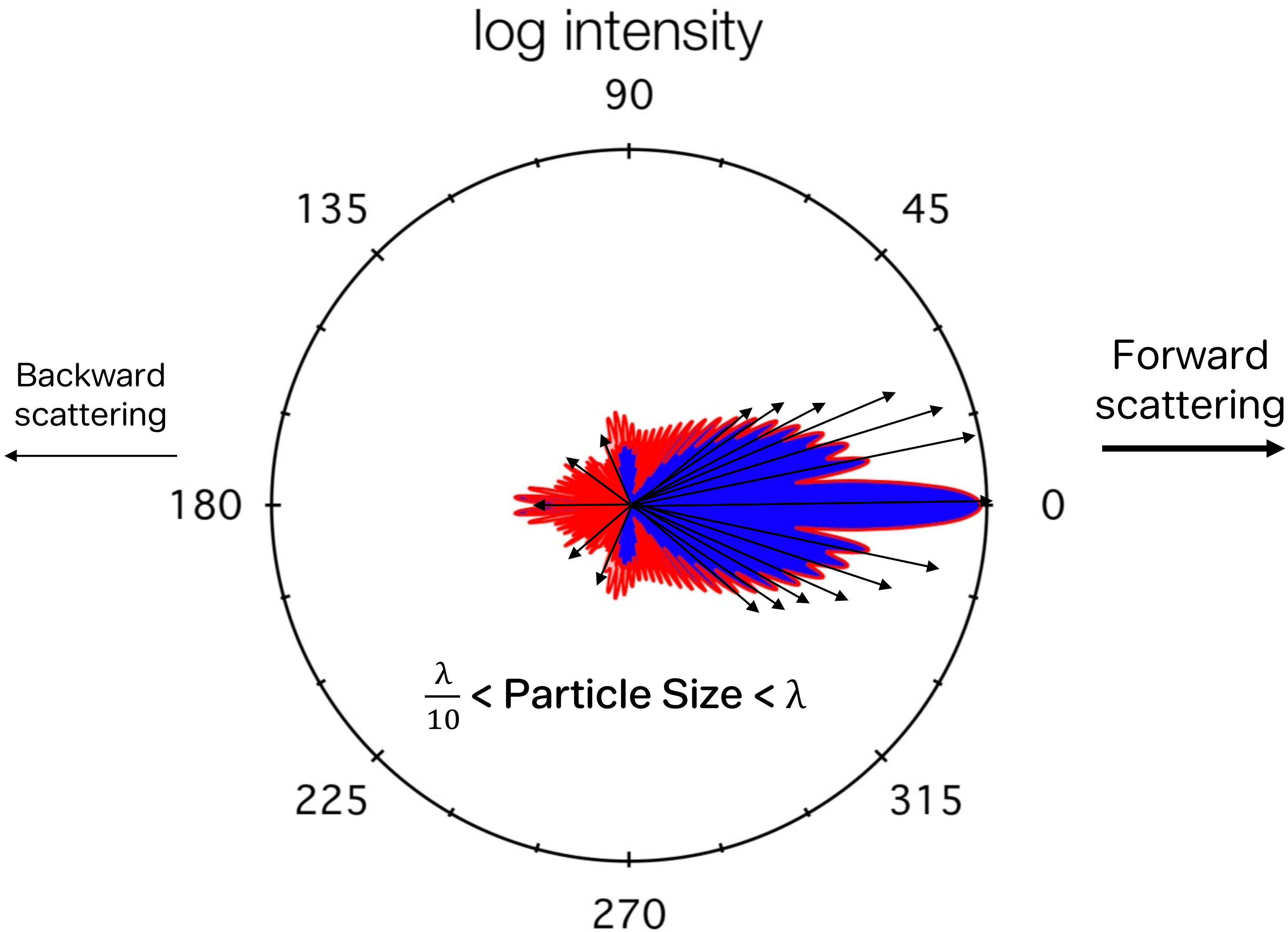
Excludes many GUT theories and parameter space.

Competitive sensitivity with DUNE.

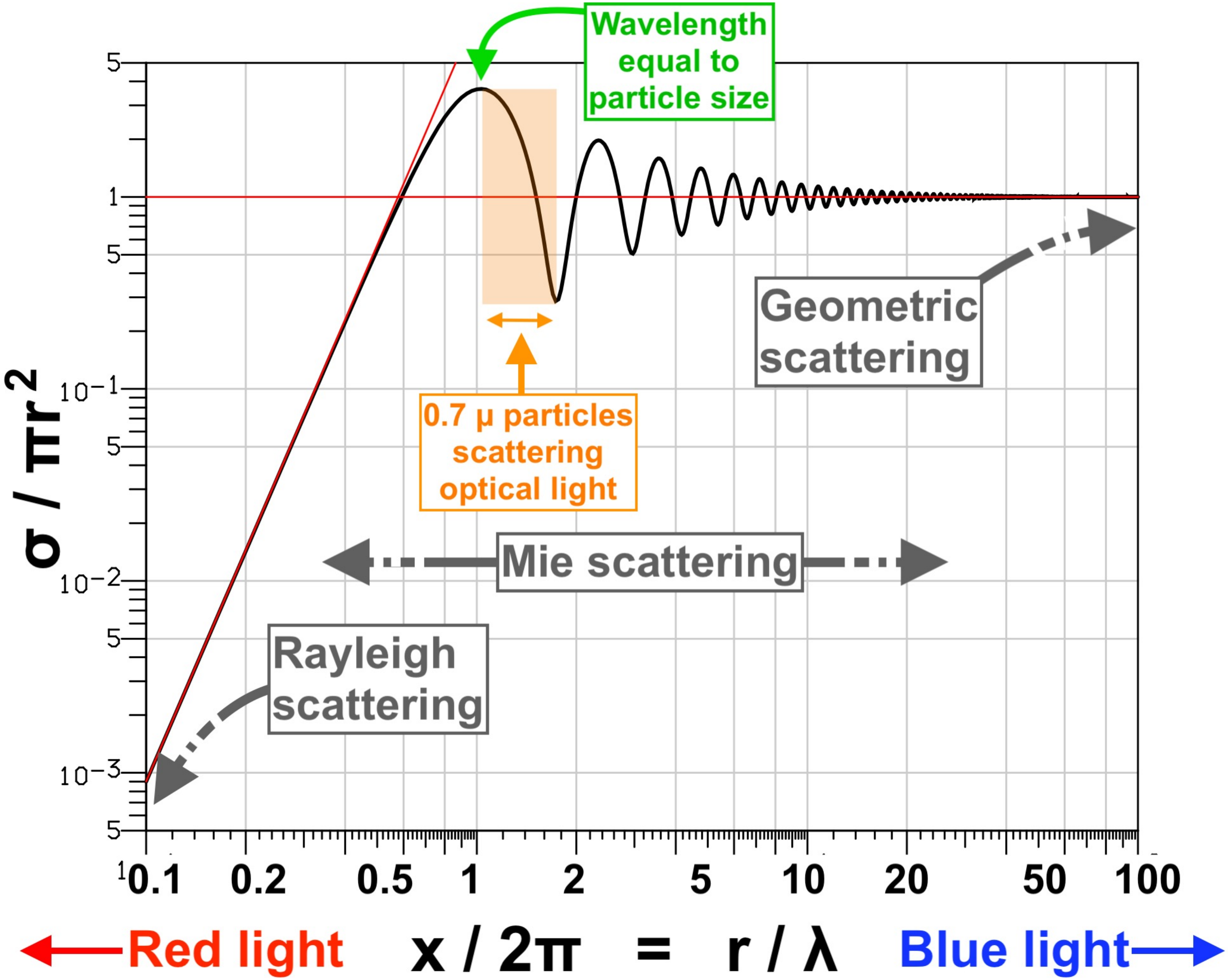


Mie Effect MC Studies

Mie Scattering Geometry



Scattering Spectrum



Henyey-Greenstein Approximation

- Full Mie Theory: Computationally expensive and time-consuming.
- HG Approximation mimics the angular dependence of light scattering from small particles:

$$\mathbf{p}(\boldsymbol{\theta}) = \frac{1}{4\pi}\frac{1-g^2}{[1+g^2-2g\cos(\theta)]^{\frac{3}{2}}}$$

- As a function of $\mu = \cos\theta$:

$$\mathbf{p}(\boldsymbol{\mu}) = \frac{1}{2}\frac{1-g^2}{[1+g^2-2g\mu]^{\frac{3}{2}}}$$

g > 0: forward scatter dominant
g < 0: backward scatter dominant

- Asymmetry parameter g controls distribution of scattered light.
- Vary in MC: Scattering attenuation length, Forward propagation, Backward propagation and Forward-backward angle ratio.

Mie Theory

- Gustav Mie developed analytical solution of the scattering problem.

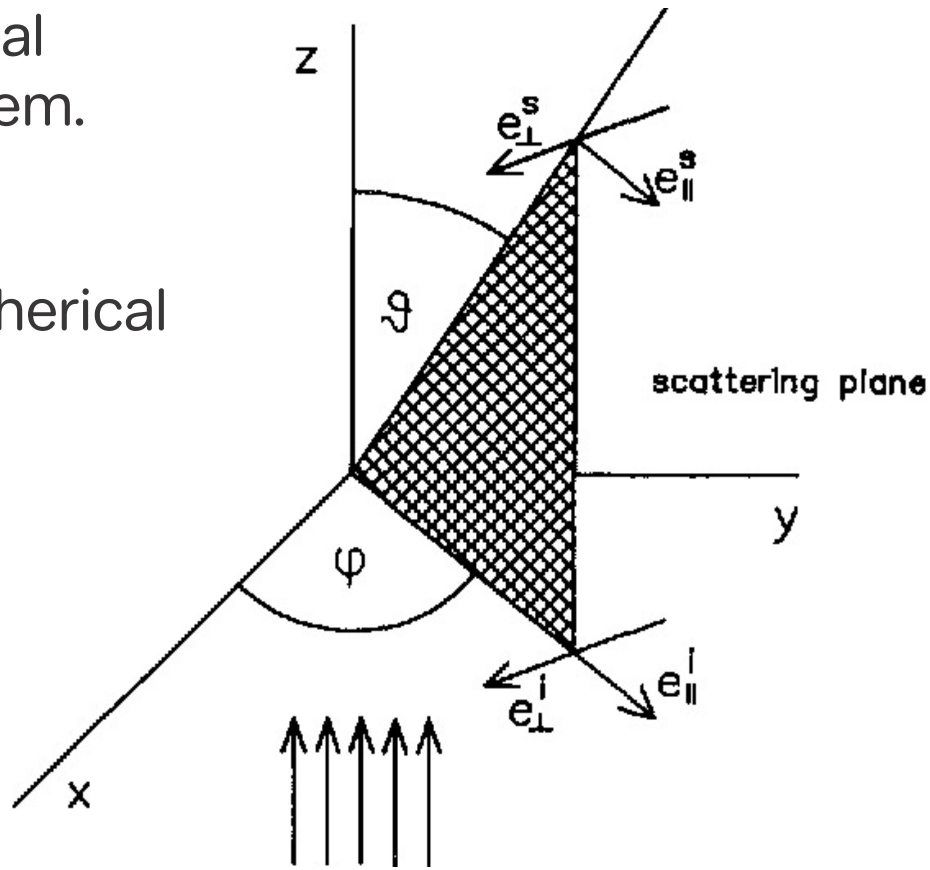
- Solutions are based on series expansion of plane waves in spherical coordinates.

$$E_i = (E_{||i}\boldsymbol{e}_{||i} + E_{\perp i}\boldsymbol{e}_{\perp i})e^{ikz - i\omega t}$$

$$E_{||i} = \cos\varphi E_{ix} + \sin\varphi E_{iy}$$

$$E_{\perp i} = \sin\varphi E_{ix} - \cos\varphi E_{iy}$$

$$\begin{pmatrix} E_{||s} \\ E_{\perp s} \end{pmatrix} = \frac{e^{ik(r-z)}}{-ikr}\begin{pmatrix} S_2 & S_3 \\ S_4 & S_1 \end{pmatrix}\begin{pmatrix} E_{||i} \\ E_{\perp i} \end{pmatrix}$$

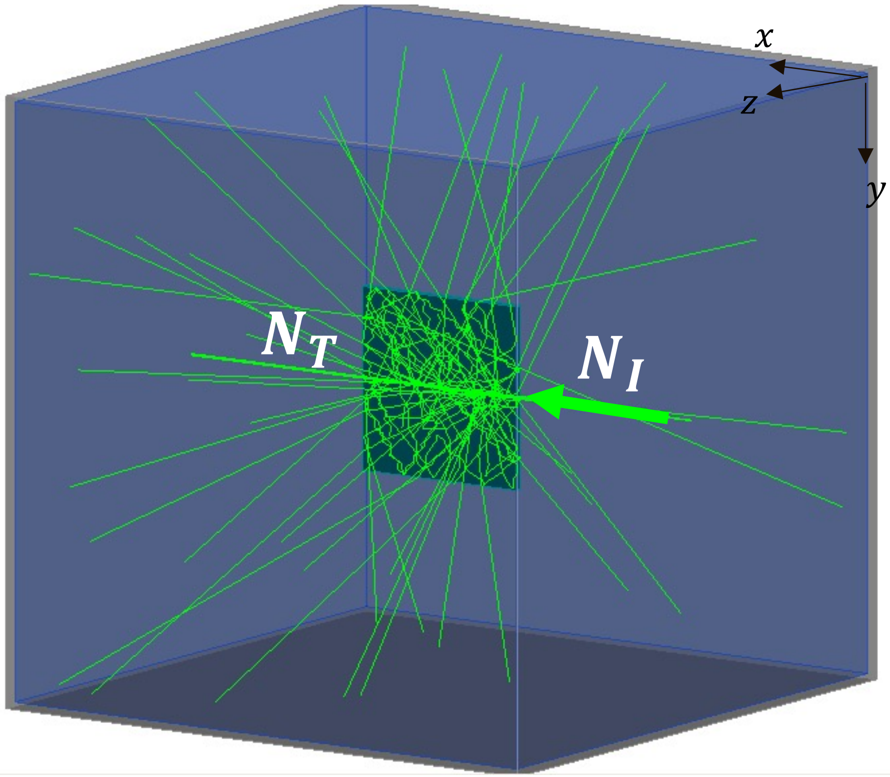


$$E_i = (E_{ix}, E_{iy}, 0)$$

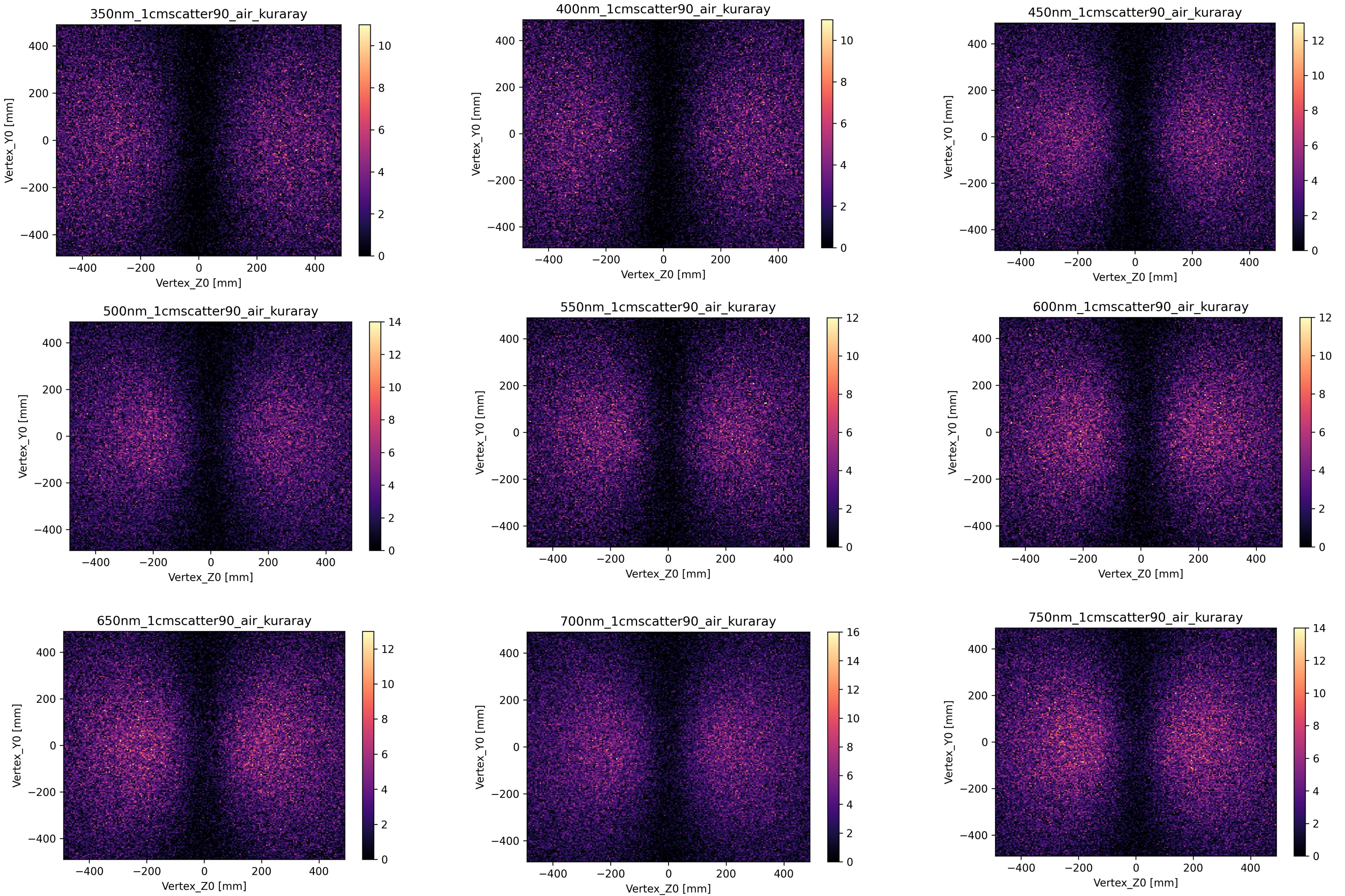
- For a sphere $S_3 = S_4 = 0$

Mie Scatter MC Study

- Optical photons over 3 x 3 mm plane along x-axis
- 350 – 800 nm
- Kuraray WLS plate
- Record hits on the back wall.
- Mie Scattering lengths: 1 cm, 10 cm, 100 cm
- Mie Forward Propagation: 0.5, 0.7, 0.9

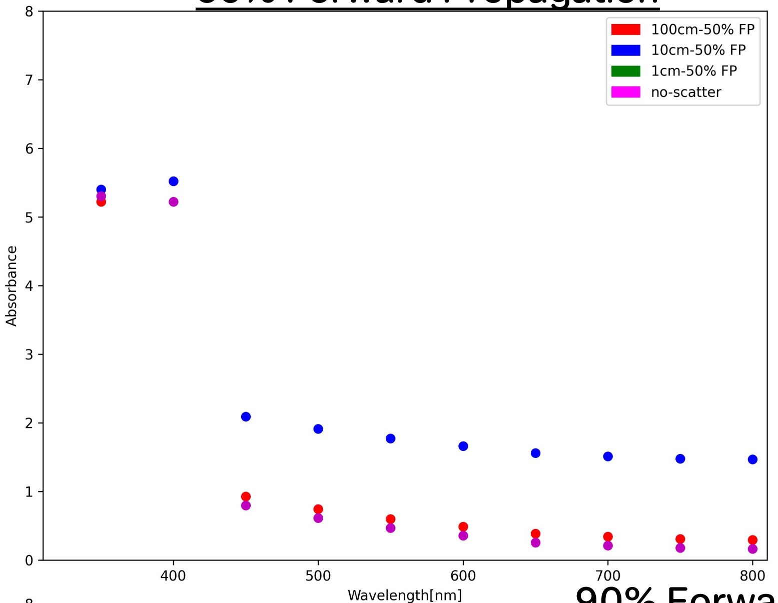


2D Projection: Mie Scatter 1cm, 0.9FP

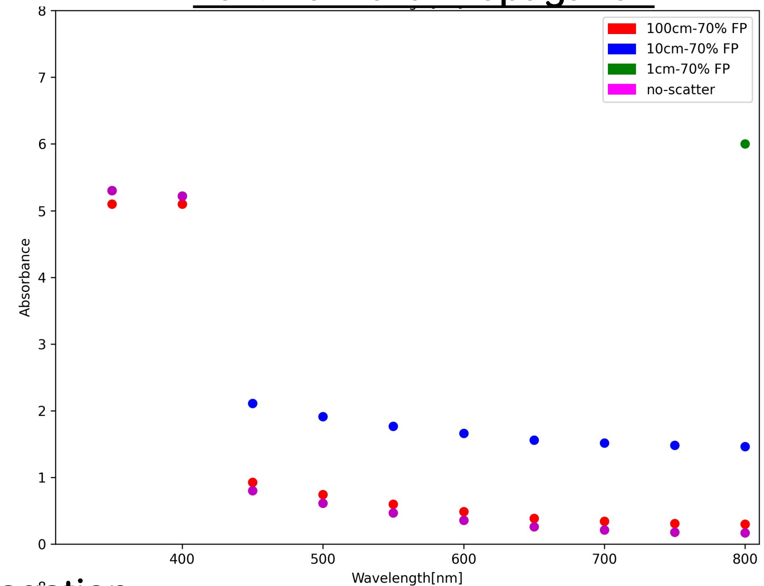


Absorbance with Mie Scattering

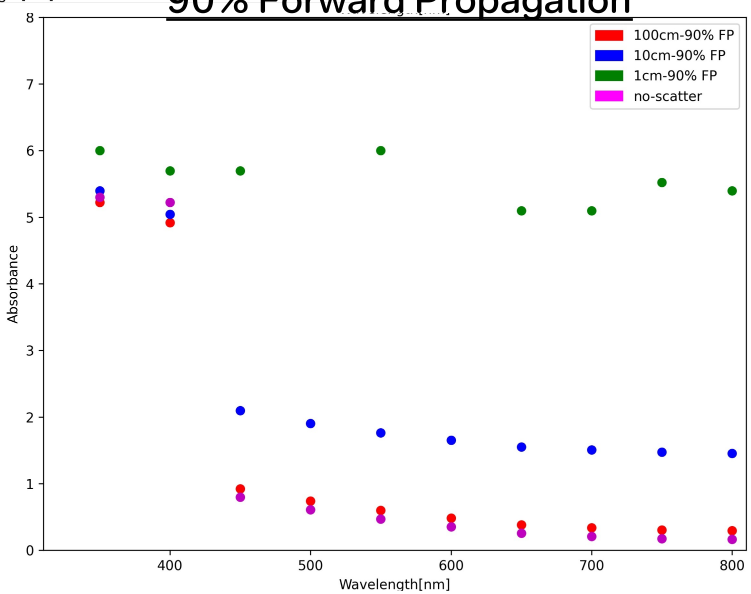
50% Forward Propagation



70% Forward Propagation



90% Forward Propagation



$$A = -\ln\left(\frac{N_T}{N_I}\right)$$

Mechanical Assembly MC Studies

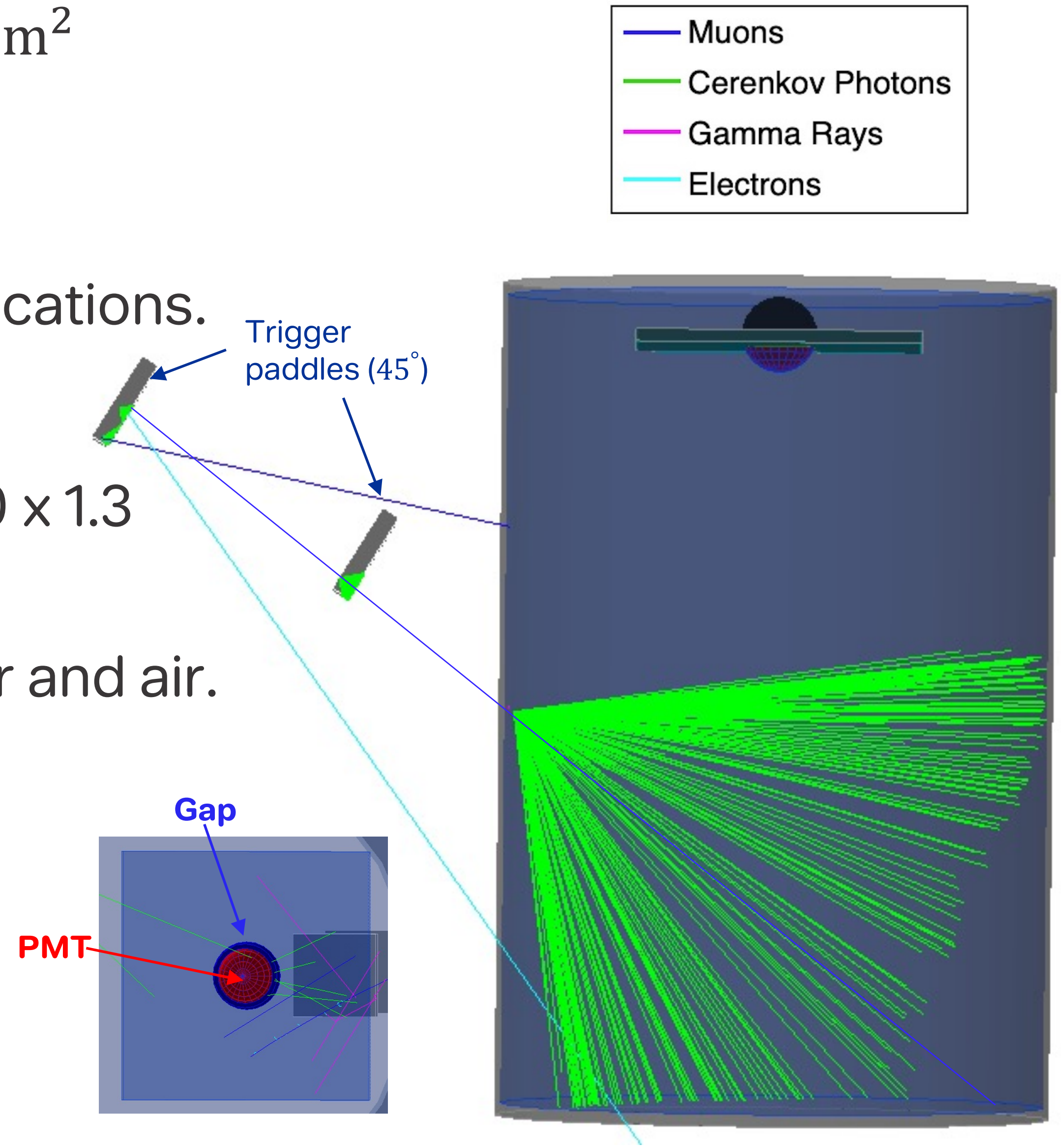
Photosensor Mechanical Tolerance MC

- CRY Muon Generator: $10\ \text{cm}^2$ trigger paddles.
- 100,000 muons per run.
- HZC photocathode specifications.
- 7 cm dia. Hemispherical.
- WLS: Kuraray-B-2 (30 x 30 x 1.3 cm).
- Tolerance/Gap: 1mm water and air.

$$\mu_{det}\colon\ N_\gamma \geq 2$$

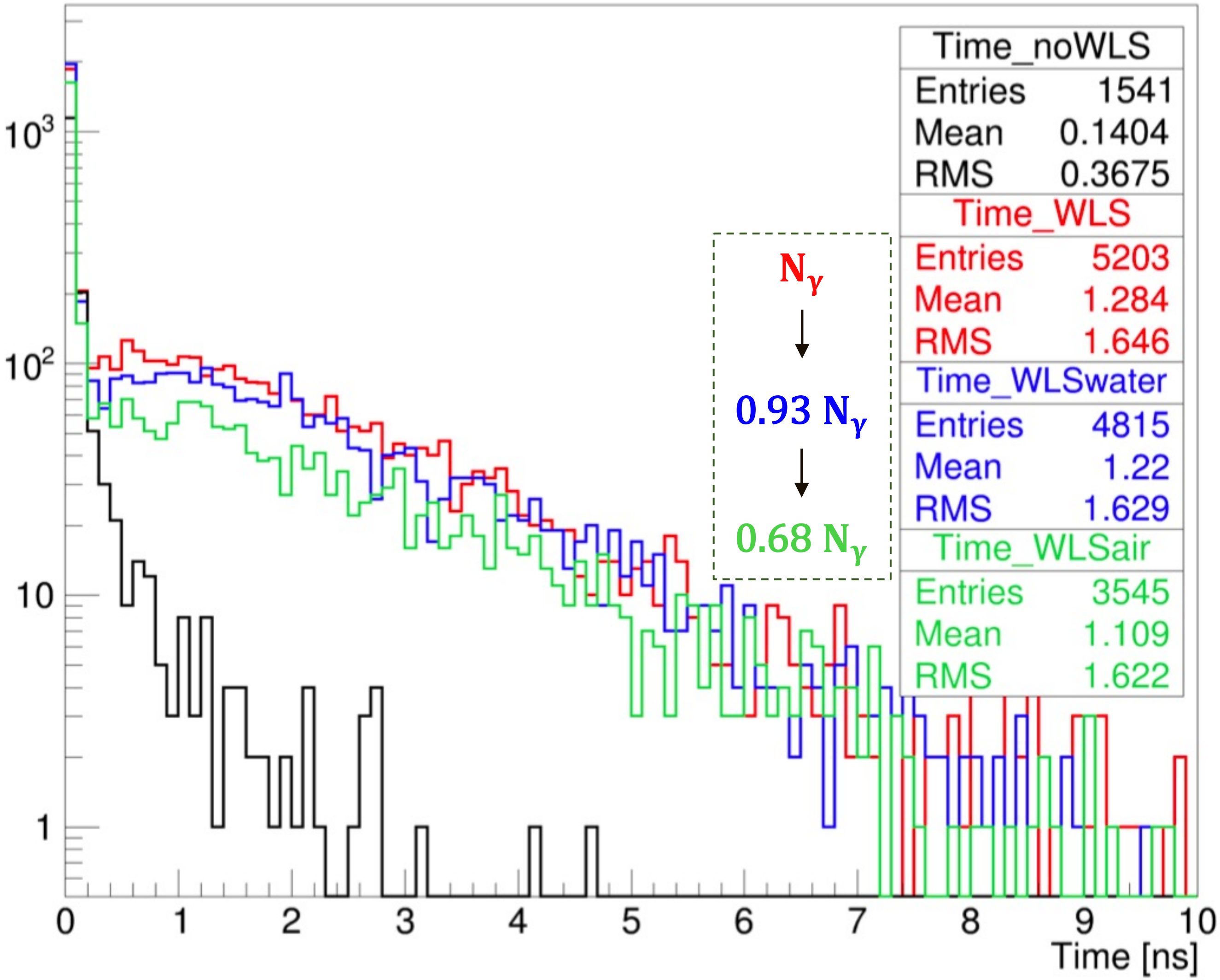
↓

Time Distribution



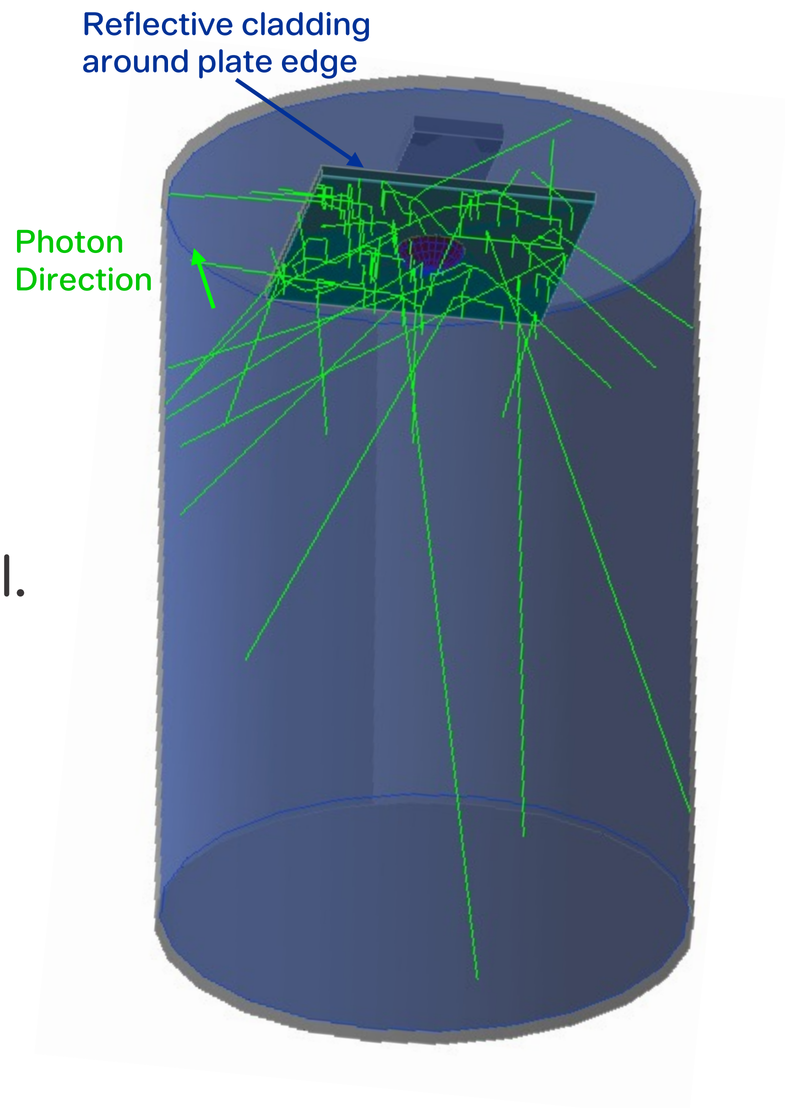
Time Distribution

Hemispherical PMT + Kuraray WLS + Water Gap + Air Gap



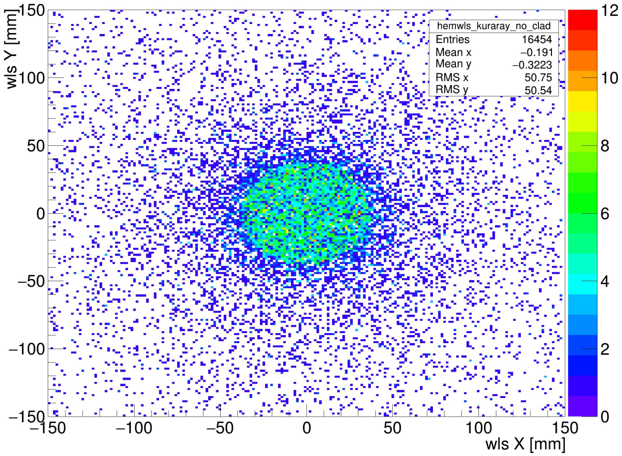
Photosensor Mechanical Tolerance MC

- **Optical Photons:** 30cm square plane, below WLS plate.
- **3.34 – 3.36 eV,** random polarisation (Mahdi's LED spectrum).
- 1 million photons per run.
- HZC photocathode specifications.
- 7cm dia. Flat faced and Hemispherical.
- **WLS: Eljen-286, Kuraray, LabLogic(Feb2020), LabLogic(Eljen Absorption), SKOD.**
- Tolerance: **1mm only water.**
- **Cladding CR: none - 100%**

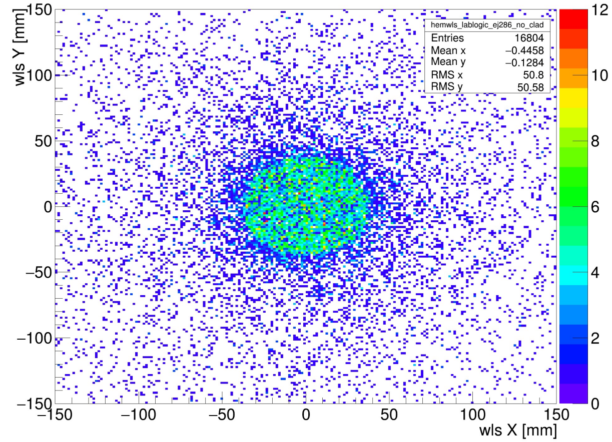


2D Photon Distributions: No Cladding

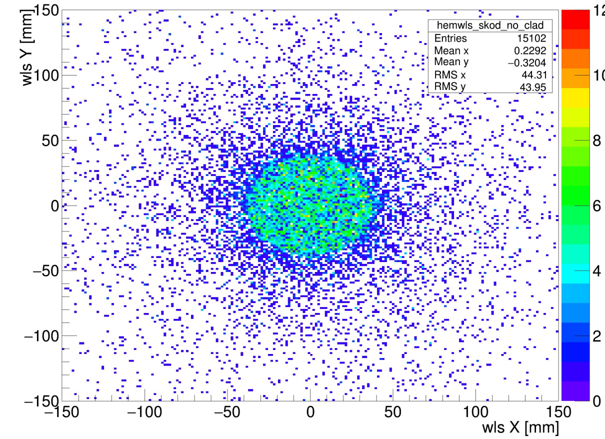
KURARAY



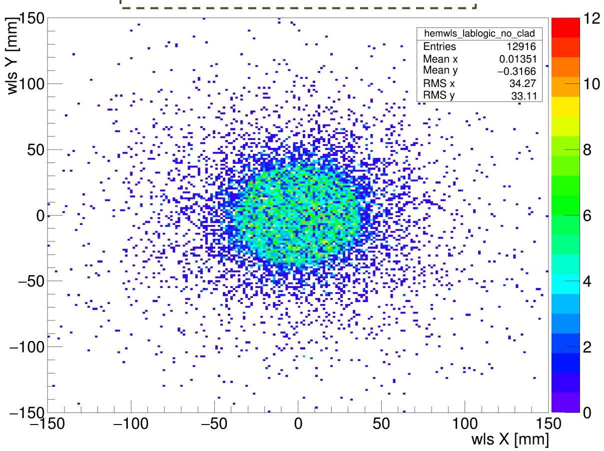
ELJEN-EJ286



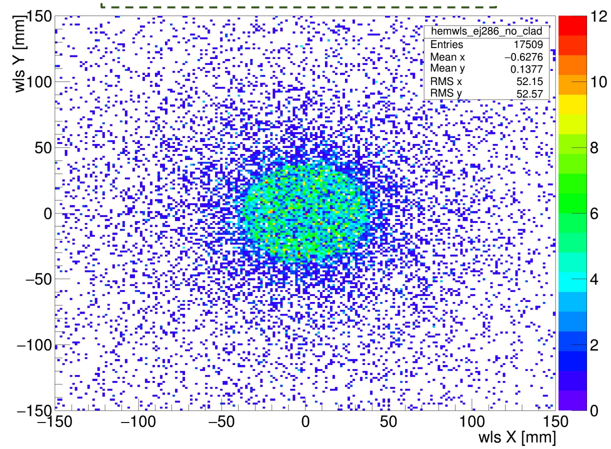
SKOD



LABLOGIC (Feb2020)



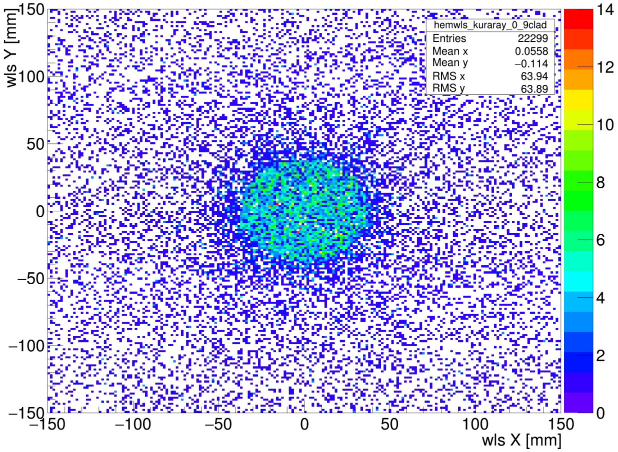
LABLOGIC (EJ286-ABS)



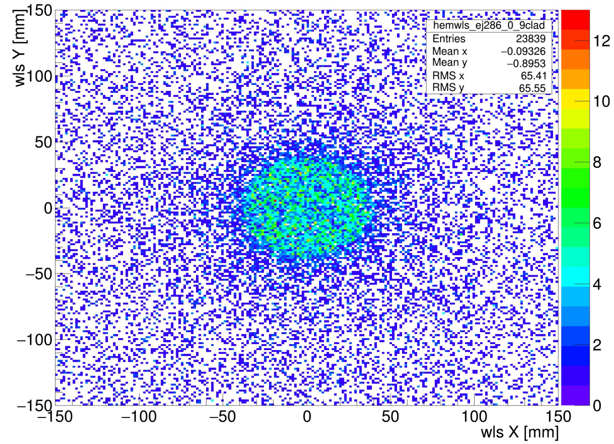
- Bare WLS Plates – No Reflective Cladding (CR = 0%).
- Hemispherical PMT + WLS Plate in perfect optical contact.

2D Photon Distributions: With Cladding

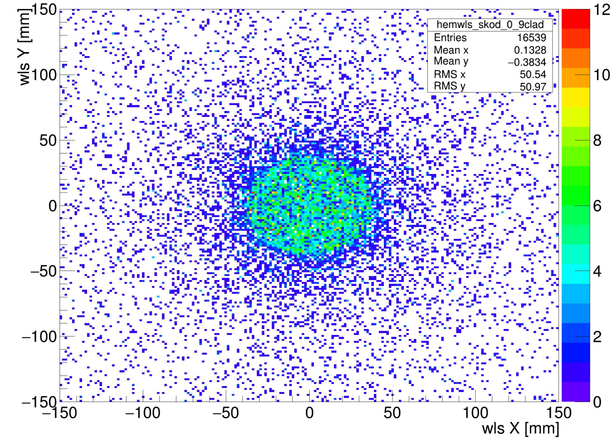
KURARAY



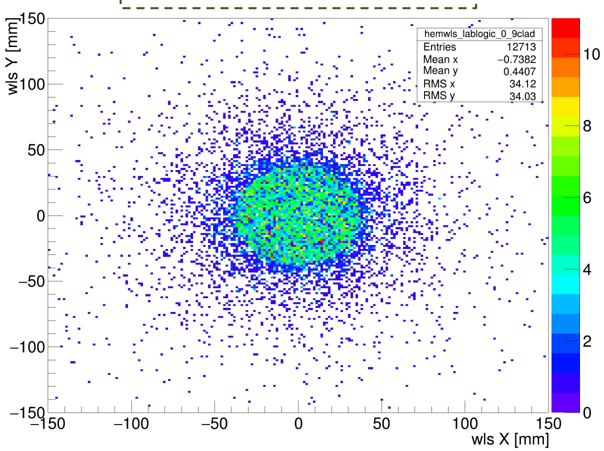
ELJEN-EJ286



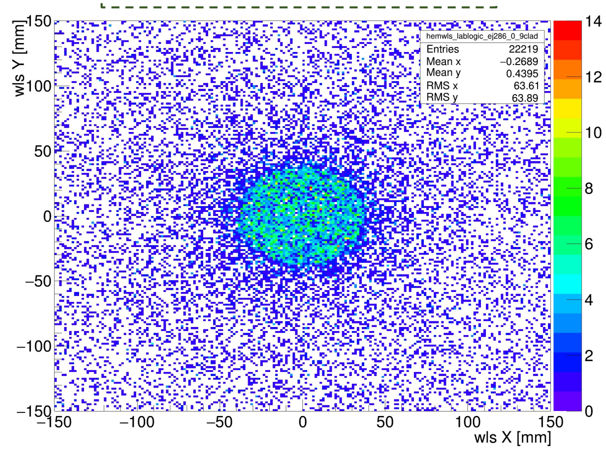
SKOD



LABLOGIC (Feb2020)

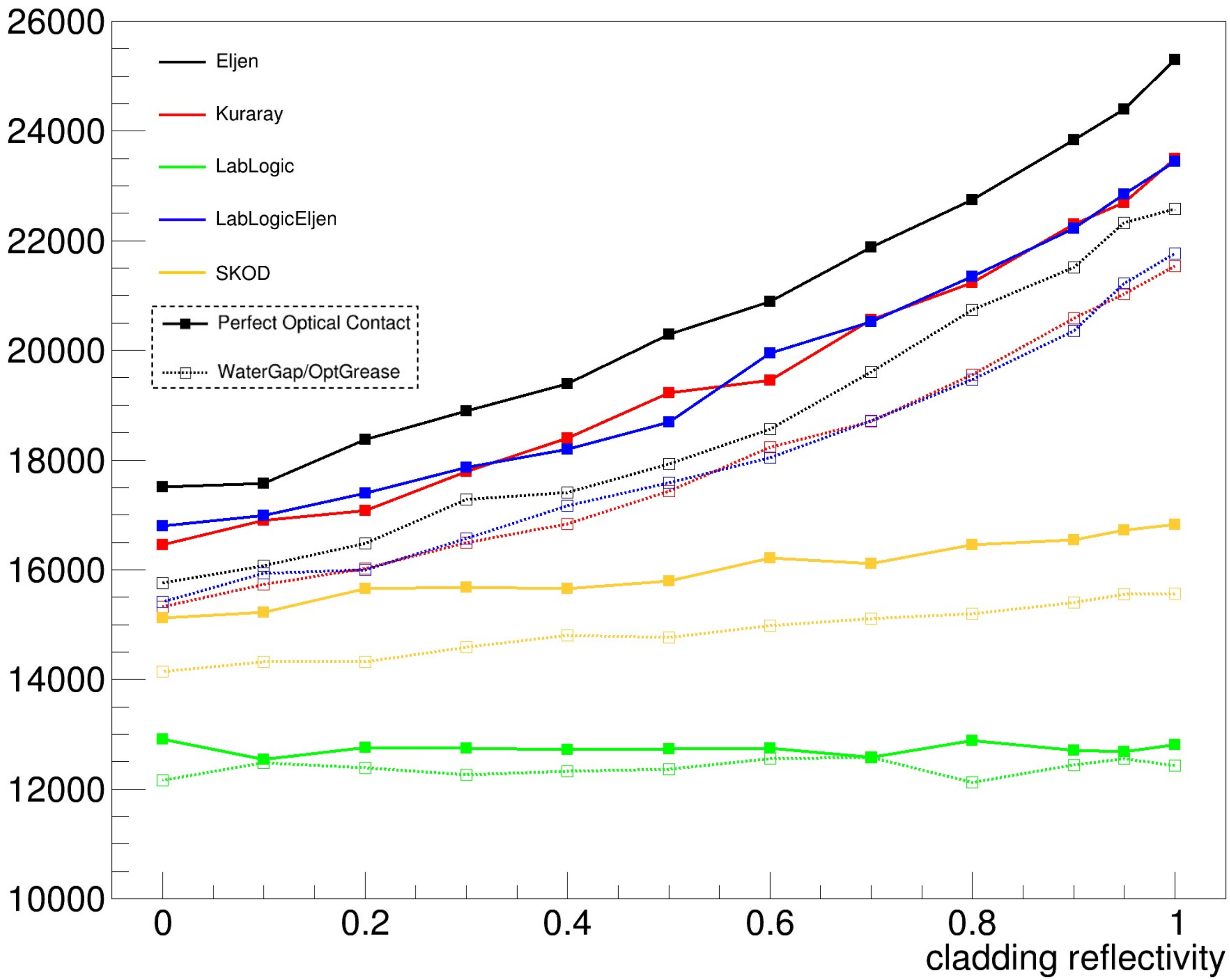


LABLOGIC (EJ286-ABS)



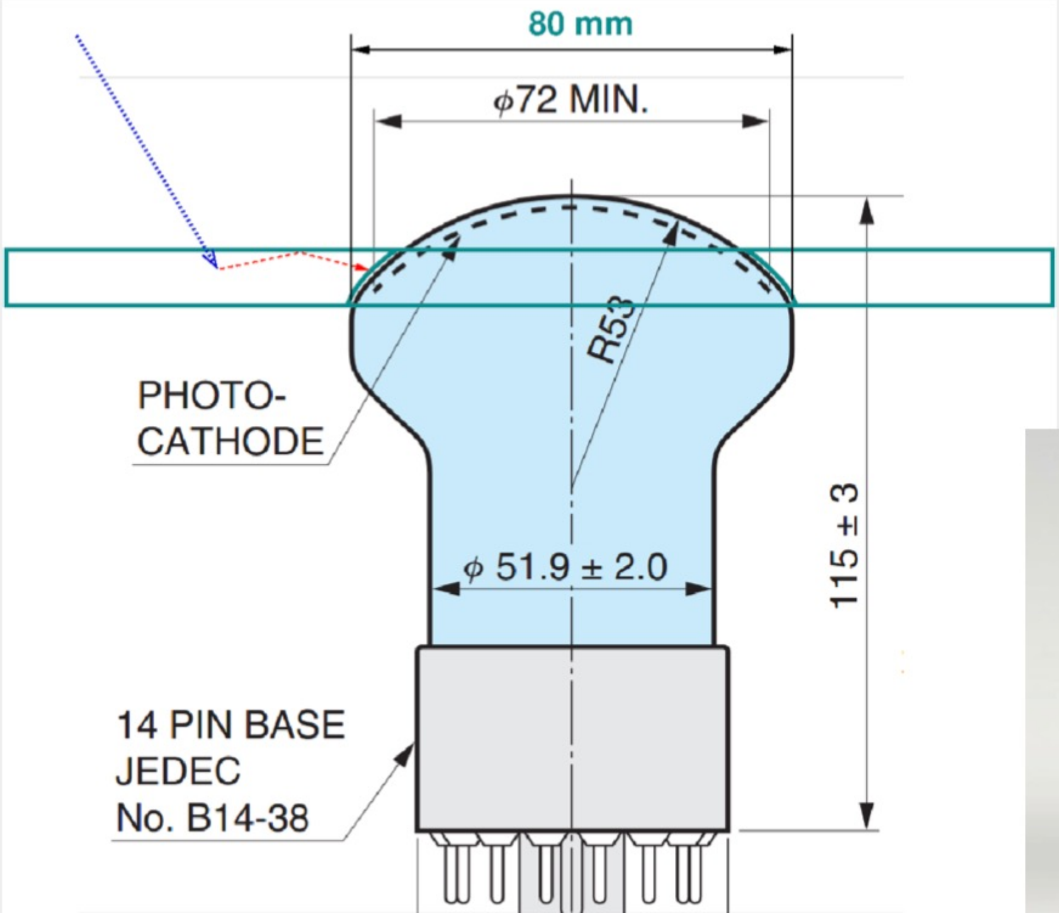
- WLS Plates – With Reflective Cladding (CR = 90%).
- Hemispherical PMT + WLS Plate in perfect optical contact.

Photon Detection Efficiency



INR: Mechanical Assembly Optimisation

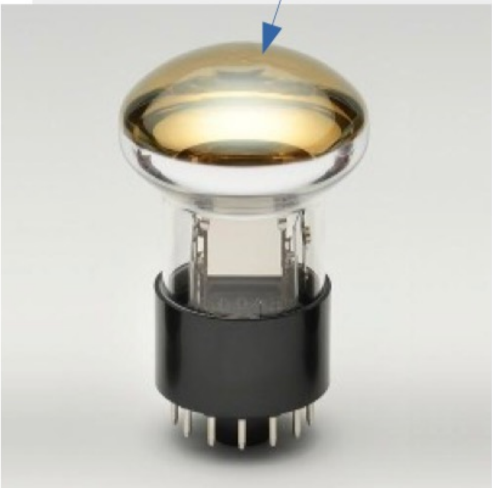
Coupling of the PMT Hamamatsu R14374 to a WLS plate



The WLS plate hole cross-section was matched to the hemispherical shape of a PMT head.

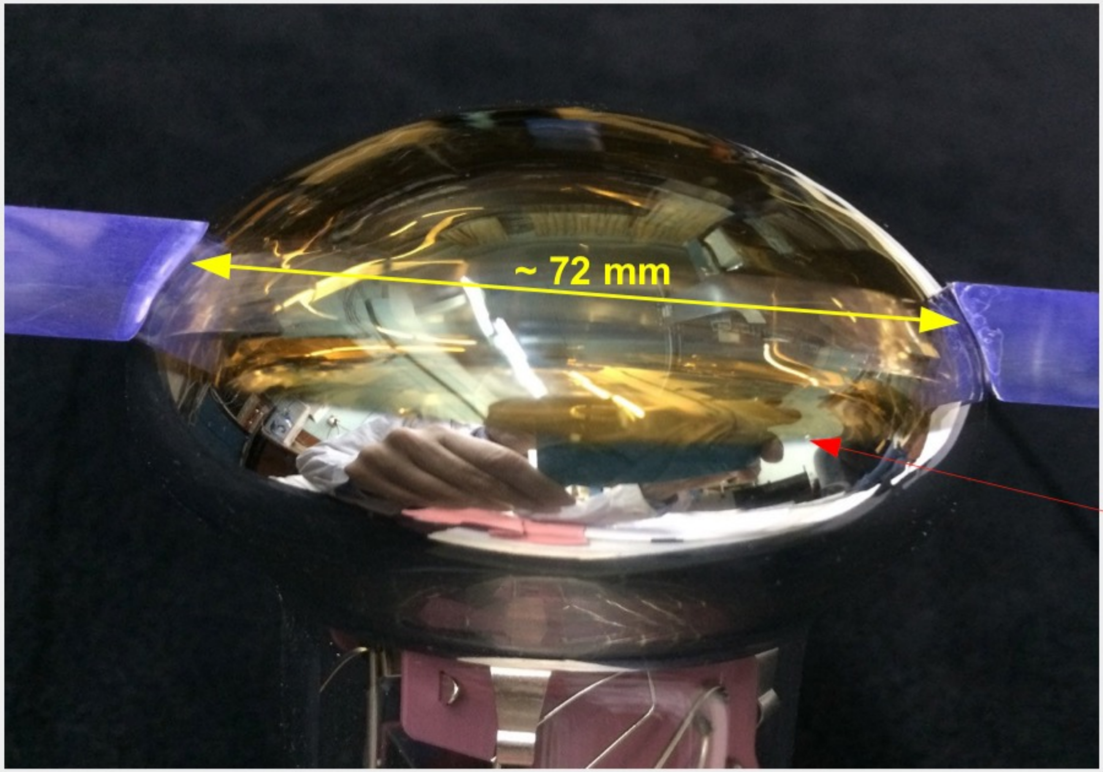
Hamamatsu R14374 specification tells that minimum diameter of the photocathode is 72 mm while PMT outer diameter is 80 mm.

We have supposed that we can see photocathode by eyes as semi-transparent layer of light brown color.



2

Matching of the tapered hole and PMT Hamamatsu R14374



The matching between PMT photocathode and the hole looks fine by eyes. Lower edge of the hole is about **2 mm above** the visible border of the photocathode.

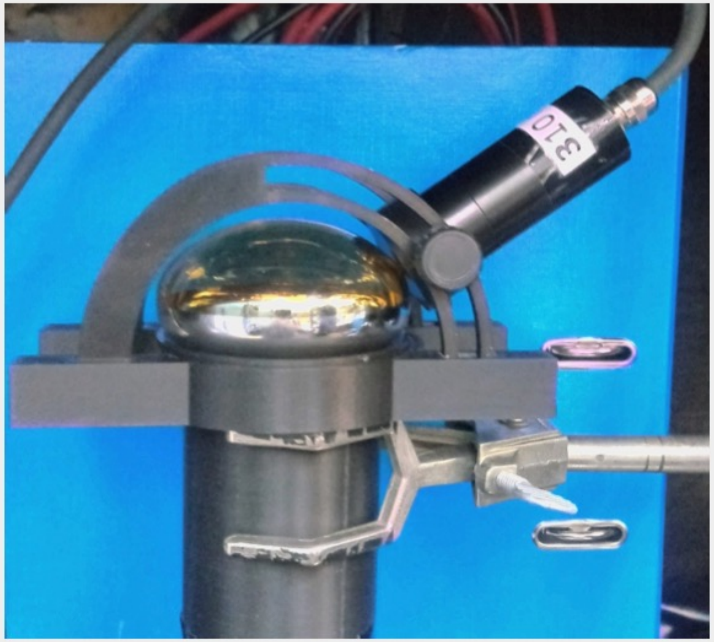
However the outer diameter of the glass bulb is **80 mm** though the spec tells the minimum diameter of the photocathode is **72 mm**.

We have to find out the outer diameter for the sensitive part of the PMT.

Visible border between the upper photocathode layer and lower mirror layer.

3

The gadget to measure relative sensitivity of the photocathode



The PMT head was irradiated by 380 nm and 310 nm LED through 1.5 mm collimator. The gadget provides the constant incident angle over all PMT head surface, and so the constant light intensity on the photocathode.

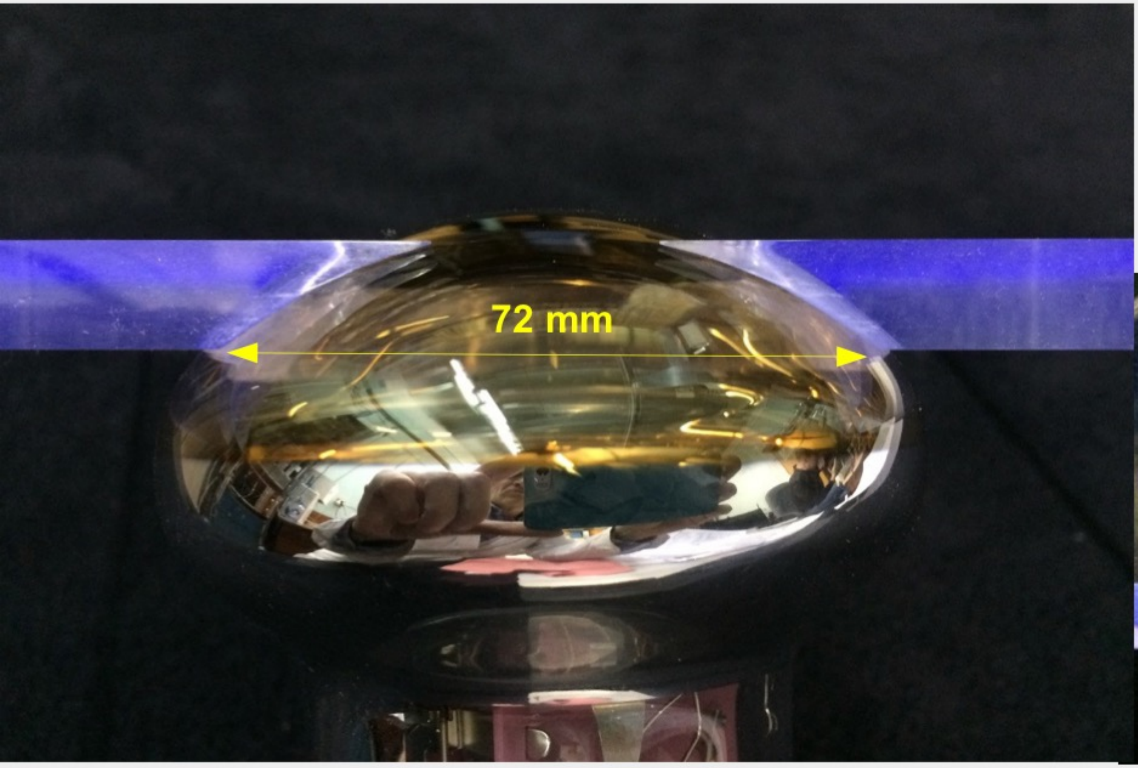
It was found that sharp drop of PMT signal starts at the outer diameter of **77 ± 0.5 mm**.

The test confirms good optical matching of the hole with PMT as a whole although still there is edge area where we are not sure in good optical contact.

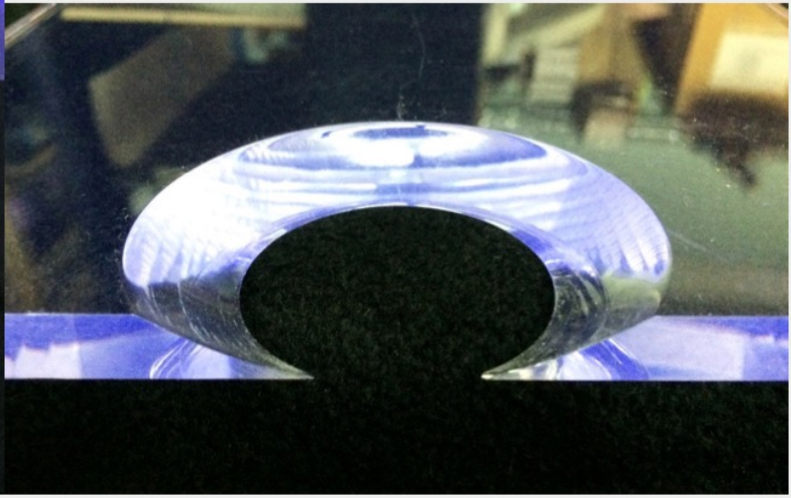
We decided to make a new hole where all light going out of a WLS plate strikes the photocathode, at least geometrically.

4

The new hole with maximum diameter of 72 mm

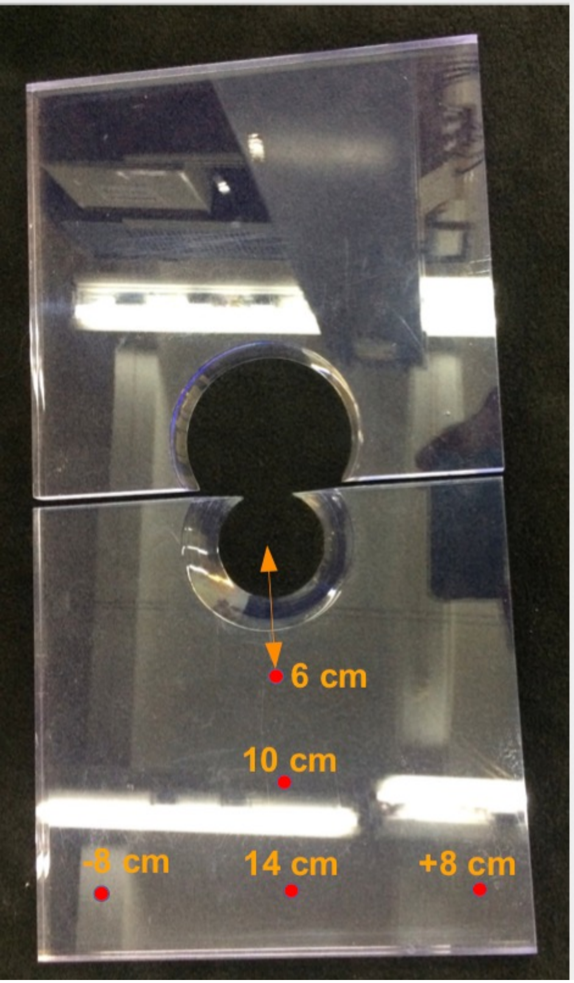


The new hole ensures all light goes into photocathode. The associated problem appears that the plate blocks large part of Cherenkov photons from direct detection by a PMT.
Before investigating this disadvantage we wanted to check how much re-emitted light can be collected with the new hole shape.



5

Tests of new 72 mm hole vs old 80 mm hole



To test new 72 mm hole we have used a POPOP100 WLS plate, which was measured before with 80 mm hole cut near the edge.
The plate was cut in two halves and a new 72 mm hole was made near the edge of one of halves.
We´ve got two identical WLS plates of 20x20 cm^2 size with different holes.

380 nm LED had irradiated WLS plates in 5 positions: 6, 10 and 14 cm from the center of the PMT.
Tyvek reflector was under the plates, no other reflector. **All measurements in water.**

Light signals in p.e. :

Hole	6 cm	10 cm	14 cm	-8 cm	+8 cm
Old 80 mm	42	25	17	15	16
New 72 mm	48	26	17	14	15

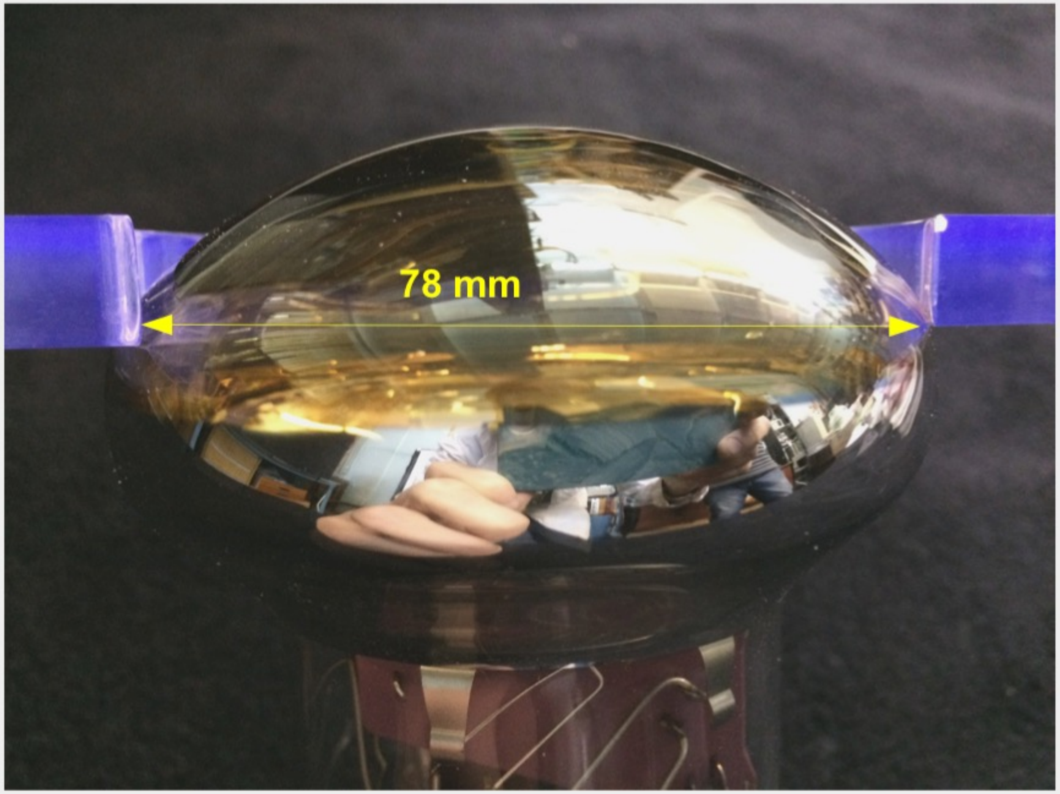
The measurements in water have shown no difference in light responce for old and new holes except in a position near the PMT. The new hole has more complicated shape to made, and has a disadvantage of blocking Cherenkov UV photons from direct detection by a PMT.

So we should reject the option with 72 mm hole.

But we´ve got another idea about the hole!

6

Cylindrical 78 mm hole



Motivation to cut the hole with simple cylindrical shape:

1. From coommon sense we expect that cylindrical shape provide less reflections back for re-emitted photons. More light can escape a WLS plate and go towards PMT head.

2. The hole of cylindrical shape leaves the photocathode open and does not block Cherenkov photons.

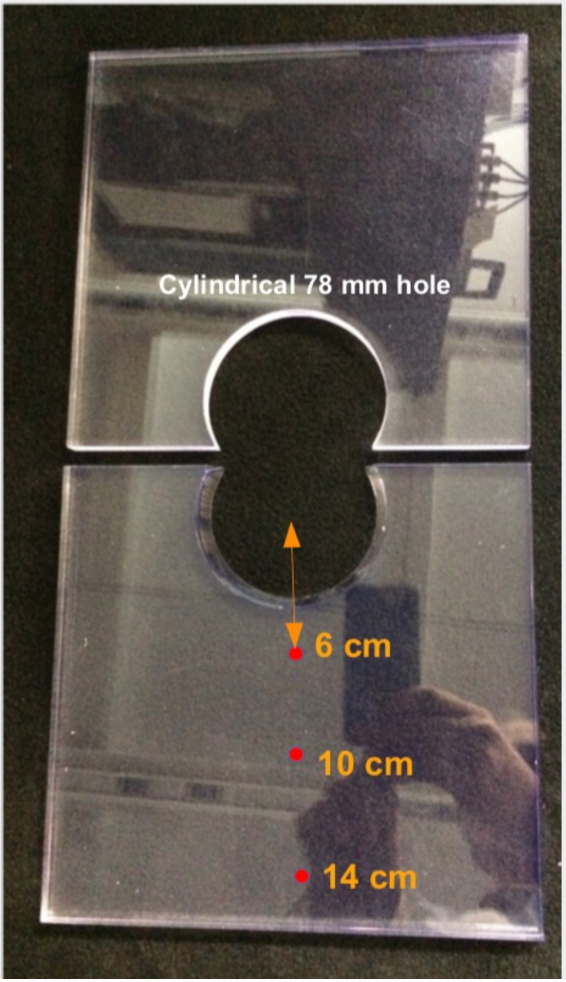
3. Cylindrical shape gives a very easy way to cut holes, for example by laser cutting machine. This will reduce the cost significantly.

4. Preliminary simulations of our WLS plate optical model have shown increase in light signal with cylindrical hole. The model is under development still.

The cylindrical hole of 78 mm diameter was cut instead of 72 mm hole, so we can test and compare two identical plates with different holes.

7

Cylindrical 78 mm hole vs old 80 mm hole (no reflector)



Test in water without reflector, only Tyvek under the WLS plates.

380 nm LED as a light source, collimator is 1 cm.

Light signals in p.e. :

Hole	6 cm	10 cm	14 cm
Old 80 mm	45	26	17
New 78 mm	56	34	23
Change in signal	+ 24 %	+ 31 %	+ 35 %
Simulation: change in signal	+ 10 %	+ 12 %	- 1 %

Distance from PMT center affects the angular distribution of re-emitted photons and probability for them to escape outside through the hole.

Simulation model employs pure geometrical optics with attenuation in bulk material. Photons are emiited isotropically in a given point, then either reach PMT (glass wall) or escape the WLS plate or disappear according attenuation length. Some parameters of the model are being adjusted now.

8

Cylindrical 78 mm hole vs old 80 mm hole (with reflector)

Test in air and water with <u>mirror reflector</u> around WLS plate sides.

Air. Light signals in p.e. :

Hole	6 cm	10 cm	14 cm
Old 80 mm	46	41	42
New 78 mm	57	53	52
Change in signal	+ 24 %	+ 29 %	+ 24 %

Water. Light signals in p.e. :

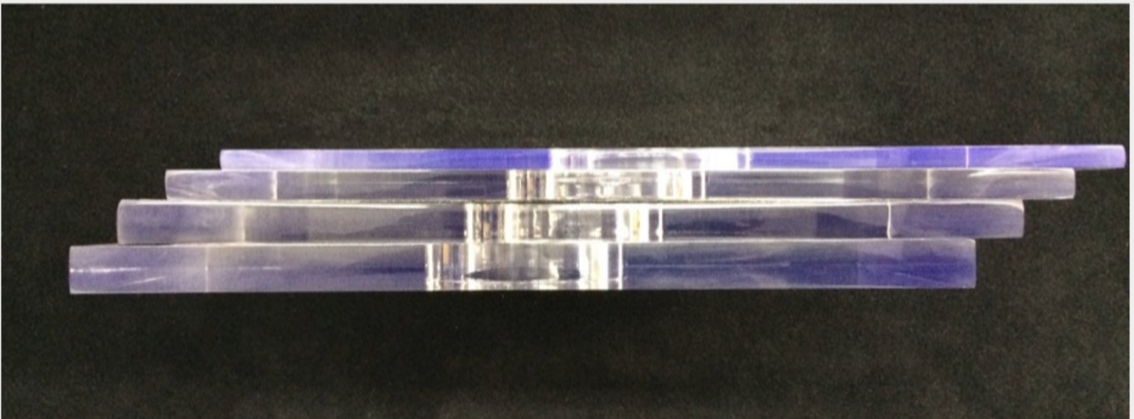
Hole	6 cm	10 cm	14 cm
Old 80 mm	33	28	27
New 78 mm	49	46	46
Change in signal	+ 48 %	+ 64 %	+ 70 %

We have some considerations to explain the difference in light signal for different shapes of a hole though the large gain in light signal looks unexpected. The additional tests will be done to get the more reasonable arguments.

9

INR: Plate Thickness Optimisation

WLS plates with different thickness



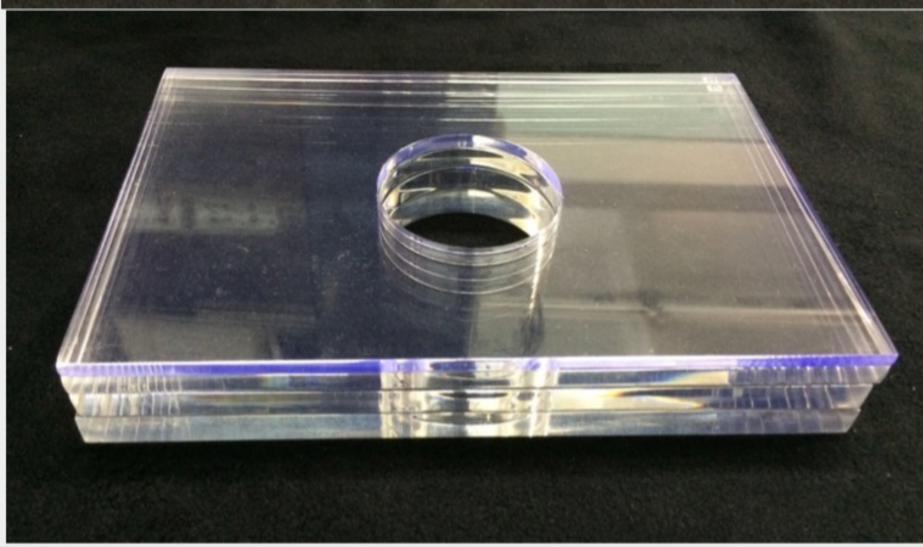
WLS plate size: 20 x 30 cm^2

Thickness: 6, 10, 13, 16 mm

PMT hole: cylindrical, 78 mm diameter

Reflector: cladding polymeric film DF2000MA

Fluor composition: POPOP 50 + PPO 3000

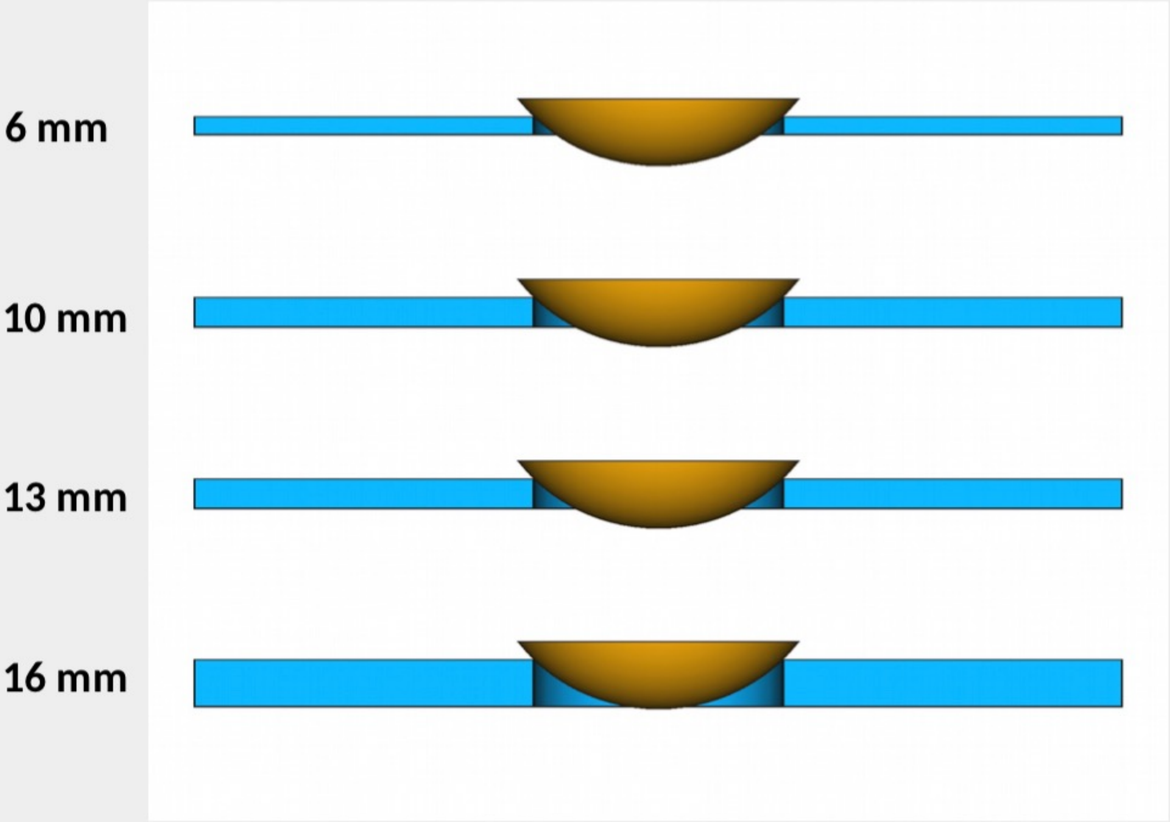


Measurements were done in 8 points around perimeter, ~ 12 cm from a PMT center. The average value was taken as a light yield for the plate.

Excitation LED wavelengths: 265, 315, 380, 405 nm
The wavelength value affects the absorption and re-emission depth, and the depth can affect the light collection on a PMT at different thicknesses.

2

Coupling of a 3-inch PMT to WLS plates



Factors involved in light collection in the WLS plates of different thickness:

1. Wavelength-dependent absorption of Cherenkov photons. UV photons must be absorbed in first 3 mm of the material except in relatively narrow spectral band around 400 nm.

2. Attenuation of re-emitted photons. The attenuation in bulk material is the same for all plates, but the number of reflections is different. Light loss at a single reflection affects the whole light attenuation in the plates with different thicknesses.

3. Optical matching between escaped re-emitted photons and a photocathode. Here are two factors: variable photocathode sensitivity and geometrical overlapping.

3

Measurement results

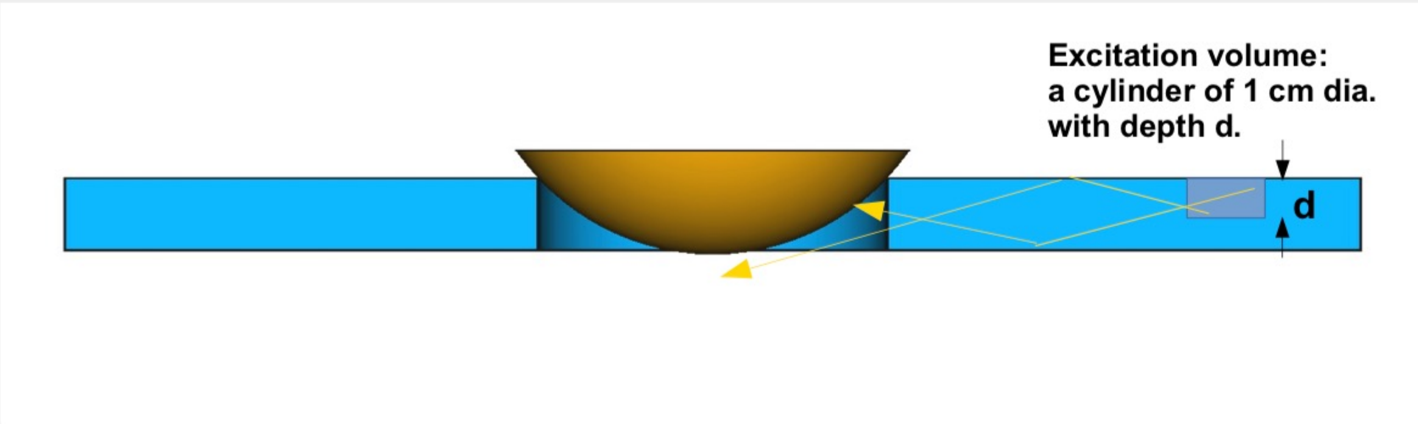
Light yield was measured in 8 points around WLS plate perimeter. The average value is used to compare the plates with normalization of 100% for 6 mm thick plate.

Excitation wavelength	6 mm plate	10 mm plate	13 mm plate	16 mm plate
265 nm	100 %	125 %	112 %	122 %
315 nm	100 %	135 %	123 %	125%
380 nm	100 %	117 %	110 %	111 %
405 nm	100 %	109 %	105 %	112 %

Looks like the thickness effect on light signal is different for spectral bands of 265-315 nm and 380-405 nm. The first one involves the double re-emission of short UV photons, the second band deals with a single re-emission of long UV.

4

Simulation for the tested WLS plates. No loss at a reflection.



WLS plate simulation model:

1. Water
2. Cladding mirror reflector + Tyvek under a plate
3. Absorption length in bulk PMMA is 1 m + Rayleigh scattering length of 7 m.
4. Fresnel reflections
5. Variable photocathode sensitivity according to the measurements.

No loss at a single reflection, photons are escaped the plate or absorbed in a material

Excitation volume depth d	6 mm plate	10 mm plate	13 mm plate	16 mm plate
1 mm	100 %	97 %	84 %	79 %
6 mm	100 %	96 %	90 %	86 %

Table shows the light signals relative to 6 mm thick plate.

5

Simulation results for the tested WLS plates. Loss at a reflection.

The re-emitted photons reflected from the cladding reflector form a core group of the photons which reach the photocathode. The reflection event includes a bounce of a photon at the mirror reflector plus double pass through optical border. It is hard to estimate the probability of a reflection.
Soniya had measured the effect of light attenuation vs the number of reflections from PMMA-air boundary. The result indicates that the loss at a single total internal reflection must be **smaller than 3%**.

Excitation volume depth is 2 mm. Loss at a single reflection is a variable parameter: 2%, 5% and 10%.

Reflection probability	6 mm plate	10 mm plate	13 mm plate	16 mm plate	Comments
0.90	100 %	116 %	114 %	117 %	Consistent with measurements at 380 nm
0.95	100 %	109 %	105%	104%	Consistent with measurements at 405 nm
0.98	100 %	101 %	95%	92%	The reflection probability is overestimated
Average number of reflections	16	11	9	8	For simulated photons which hit a photocathode
Average photon path to a photocathode	39 cm	40 cm	40 cm	40 cm	Distance from a simulated point to the PMT head : **~7- 9 cm**

6