大阪公立大学
Osaka Metropolitan University

Development of the Fiber Optic Module (FOM) to improve veto capability in IceCube-Gen2

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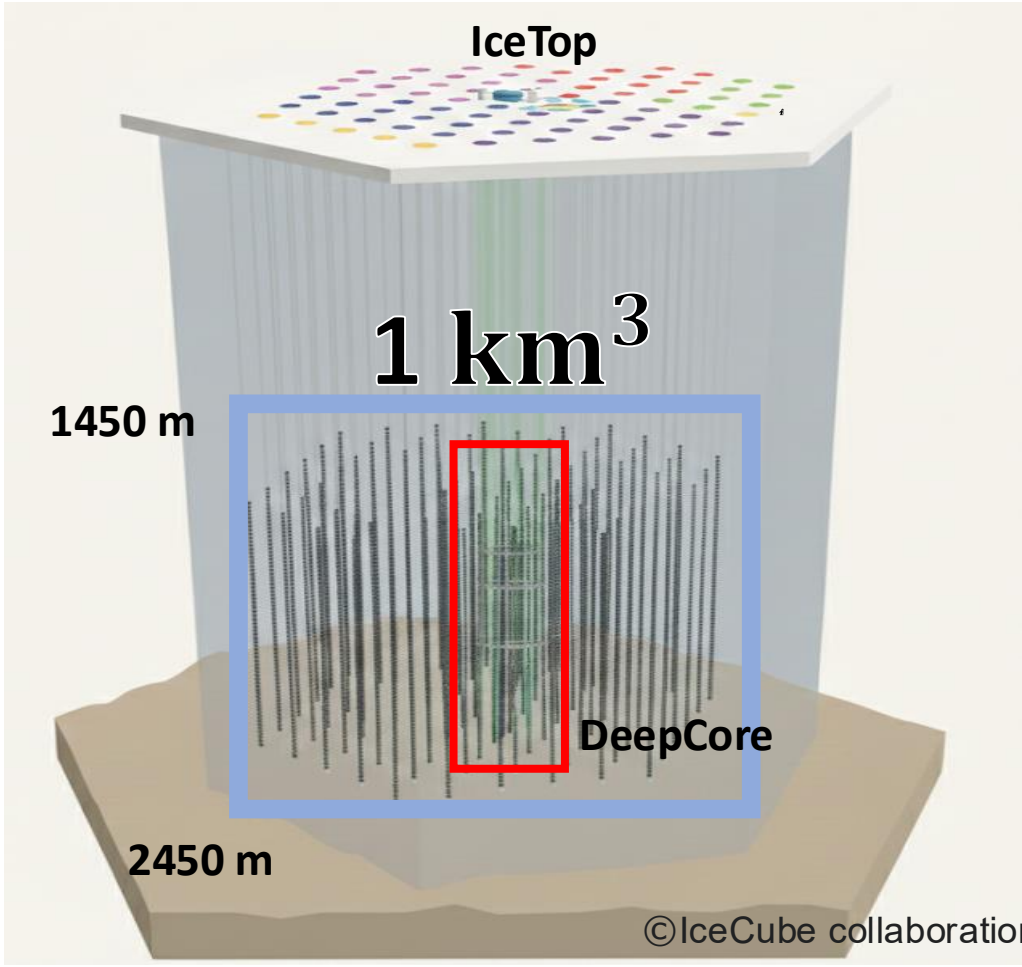
For the IceCube-Gen2 Collaboration

IceCube

◆ IceCube Neutrino Observatory
- 1 km³ detector in Antarctic ice
- Multi-purpose design:
  IceTop (surface) & DeepCore (dense)

◆ Scientific Objectives
- Astrophysical neutrinos:
  High-energy phenomena
  (Supernovae, GRBs, Black holes)
- Fundamental physics:
  Dark matter, Neutrino properties



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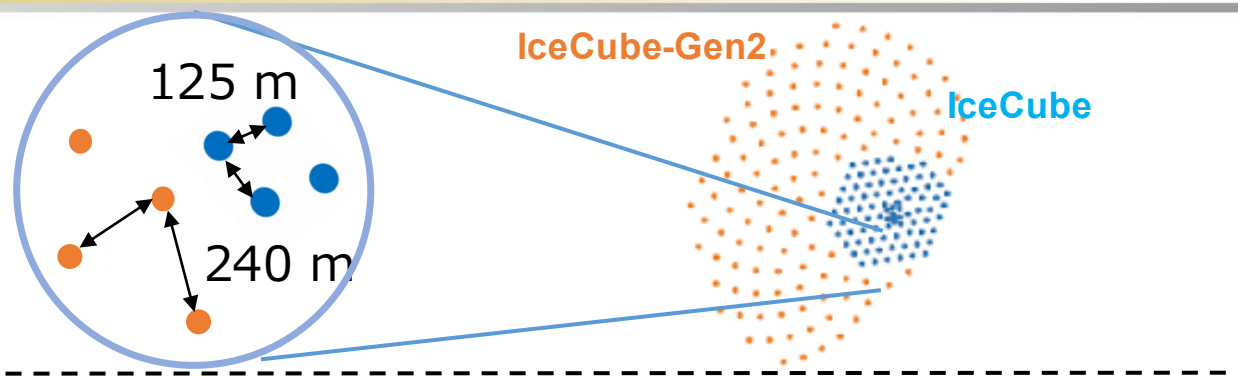
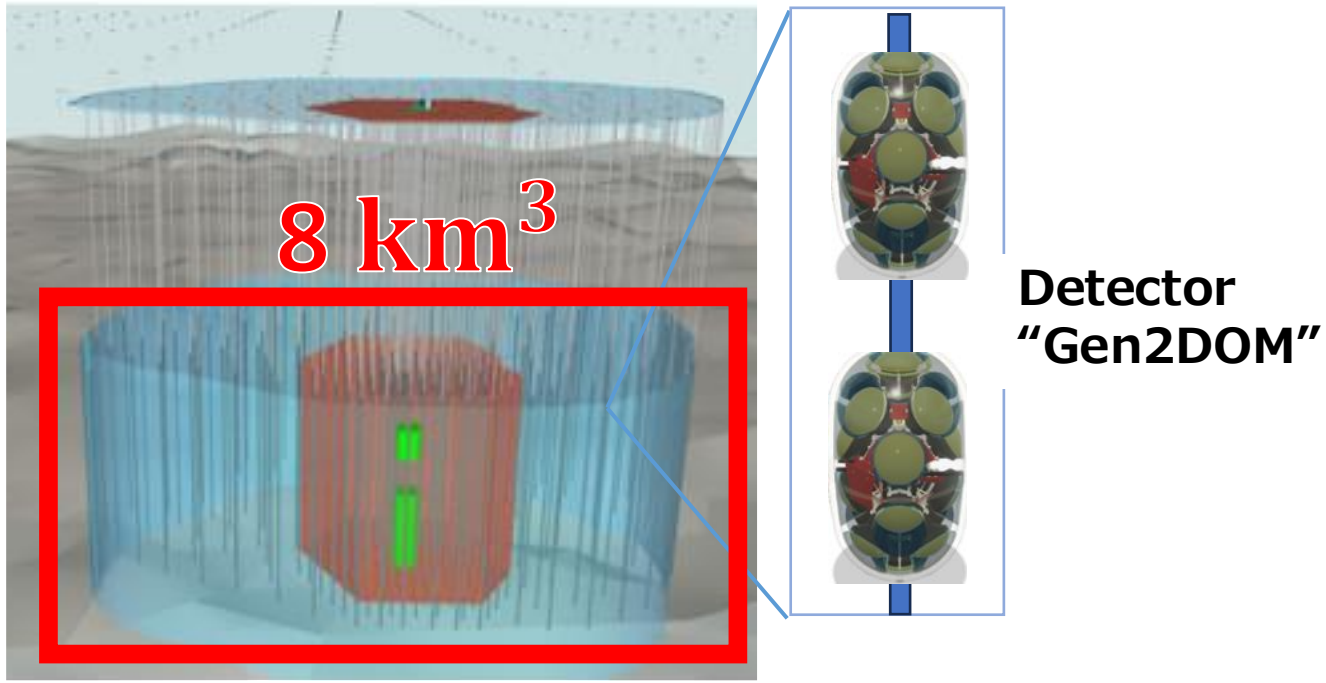
IceCube-Gen2

◆ IceCube major upgrade
- **8 × IceCube volume**
- Doubled string spacing

◆ IceCube-Gen2
- Wider spacing
  →Lower low energy muon rejection
- Solution: Enhanced light collection





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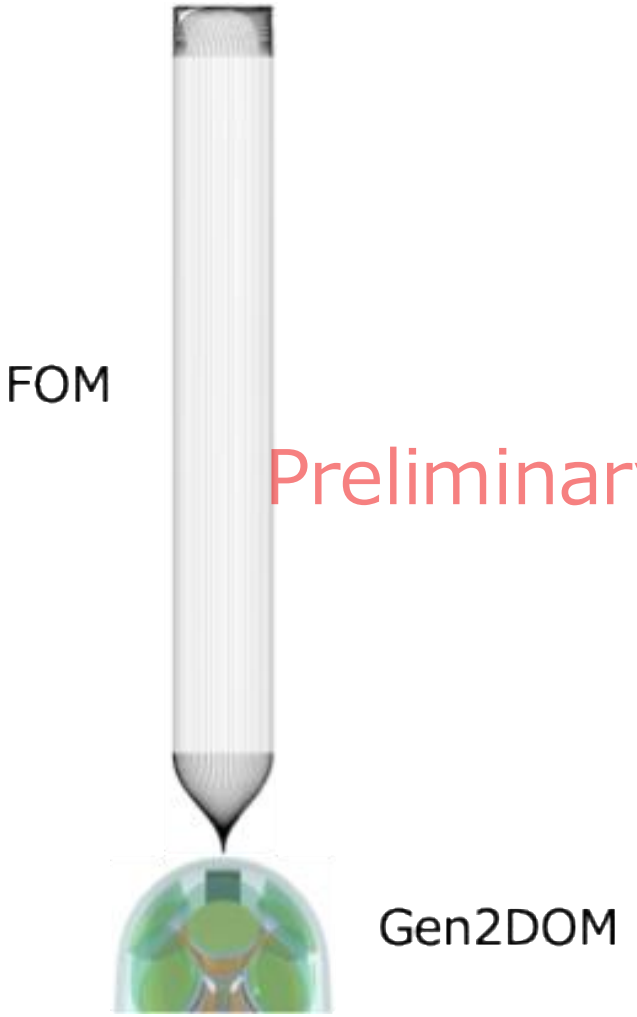
To enhance light-collecting power

◆ **F**iber **O**ptic **M**odule （FOM）
Attachment for Gen2DOM

- Structure
  Cylindrical wavelength shifting (WLS) fiber bundle

◆ Objective of this study
Characterization of the optical performance of FOM



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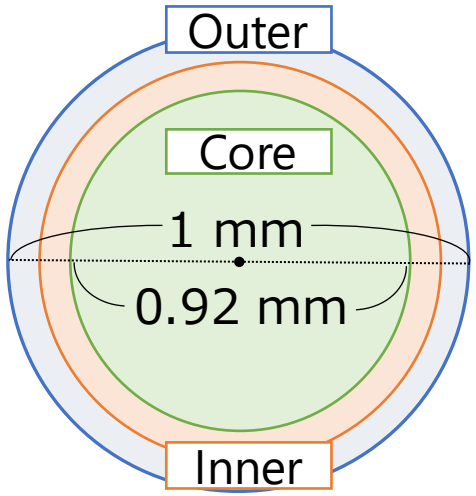
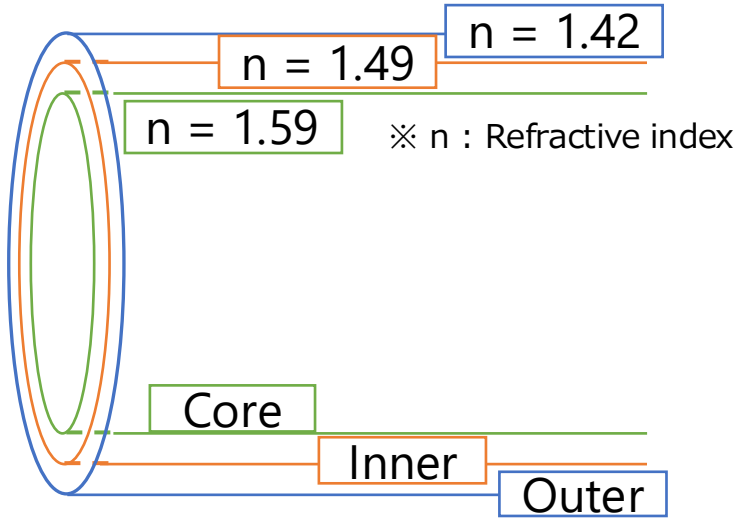
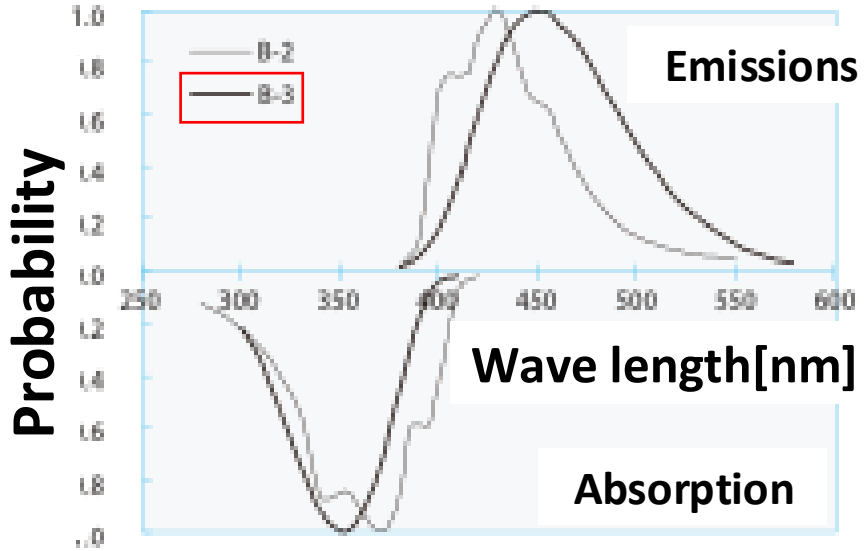
Wavelength shifting fiber currently used

◆WLS Fiber Specifications: Kuraray B-3(200)M

- Diameter: 1 mm
- Inner / Outer clad: 0.02 mm each
- Dye concentration: 200 ppm
- Attenuation length> 4.0 m







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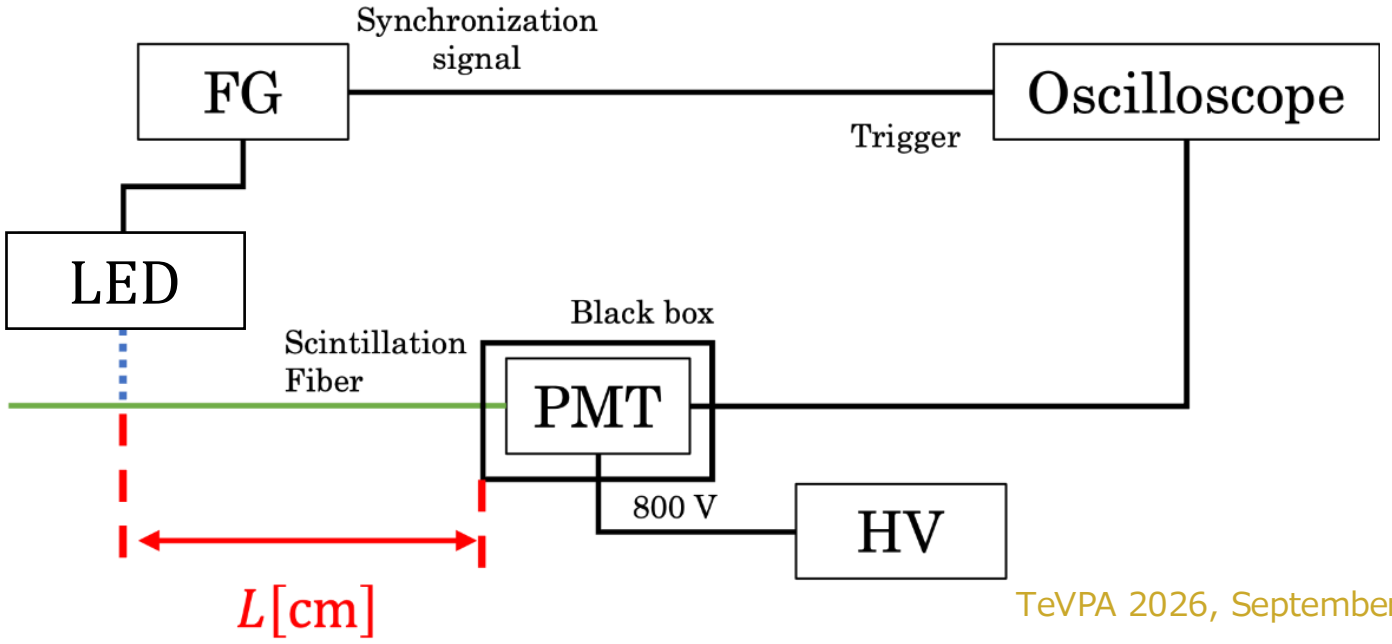
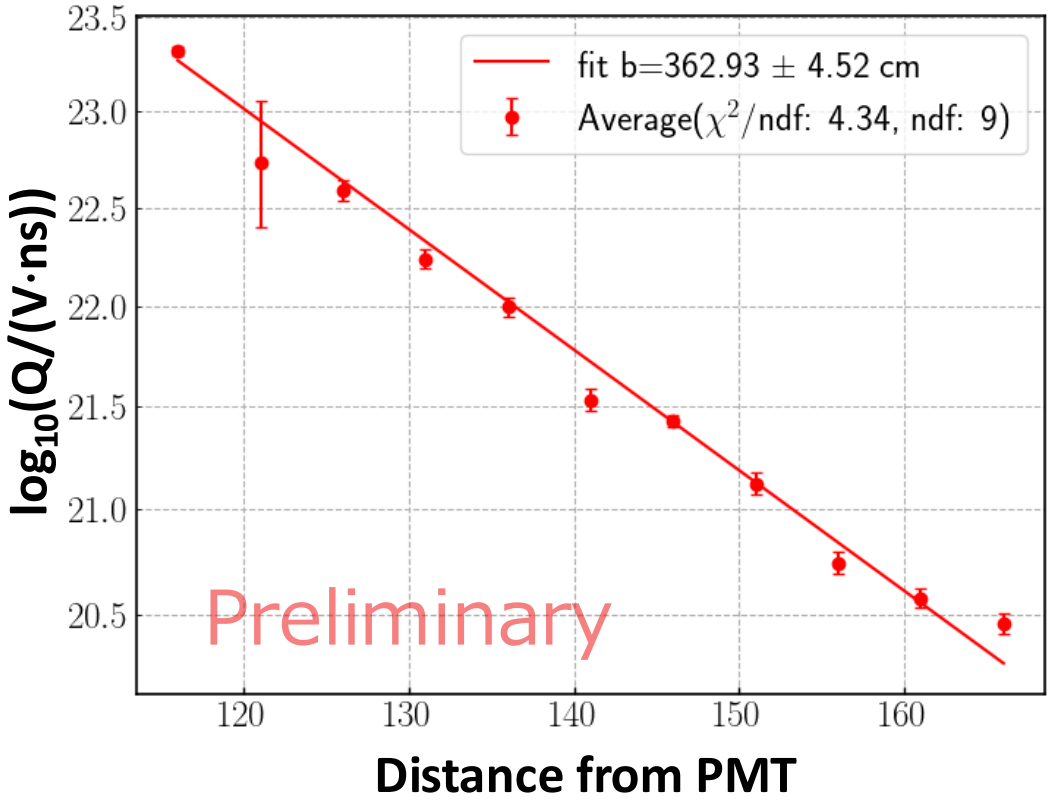
Measurement of the attenuation length

◆ Setup
- Pulsed LED, 365nm, 20mW
- L =116 – 166 cm

◆ Results
Attenuation length = **363 ± 5 cm**





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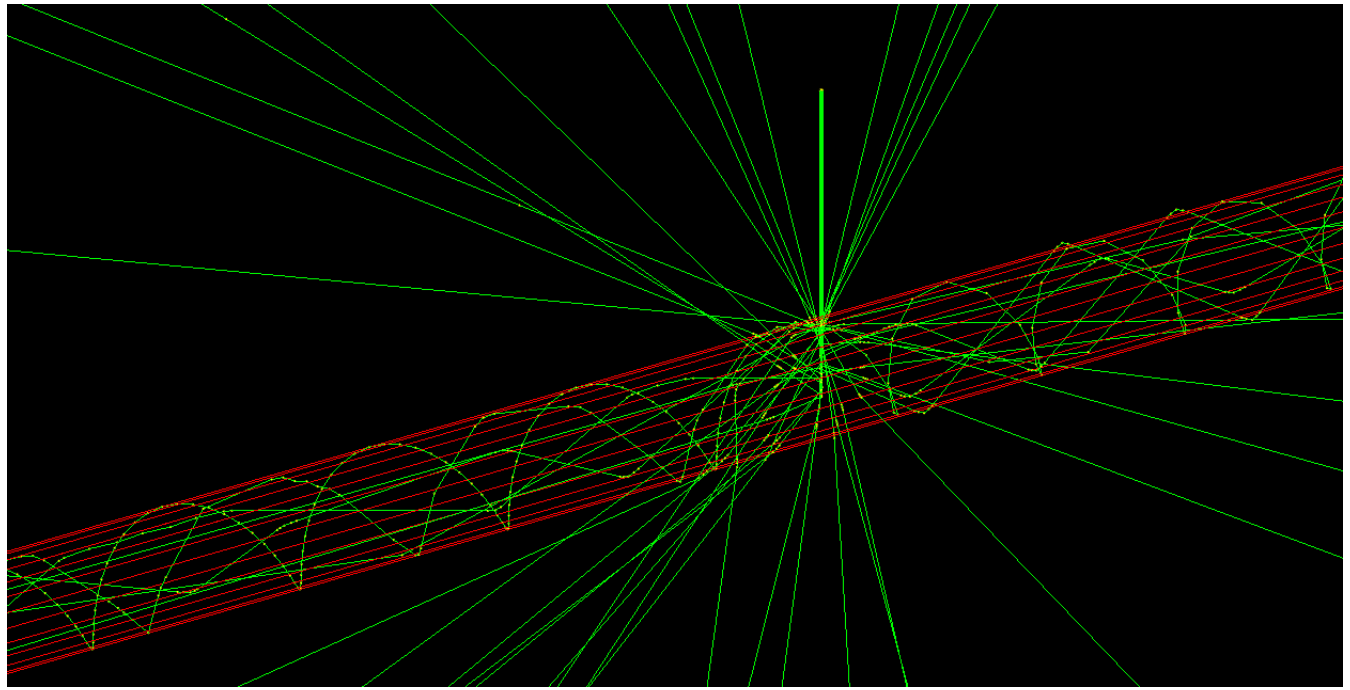
Performance evaluation by Geant4

◆ Particle-matter interaction simulation toolkit

◆ Simulation Details

- WLS fibers modeled using Kuraray's nominal values
- Performance evaluation:
  ① Single fiber
  ② FOM with 100–300 fibers



Conceptual rendering

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Effective area of a single fiber

◆ Definition of Effective Area

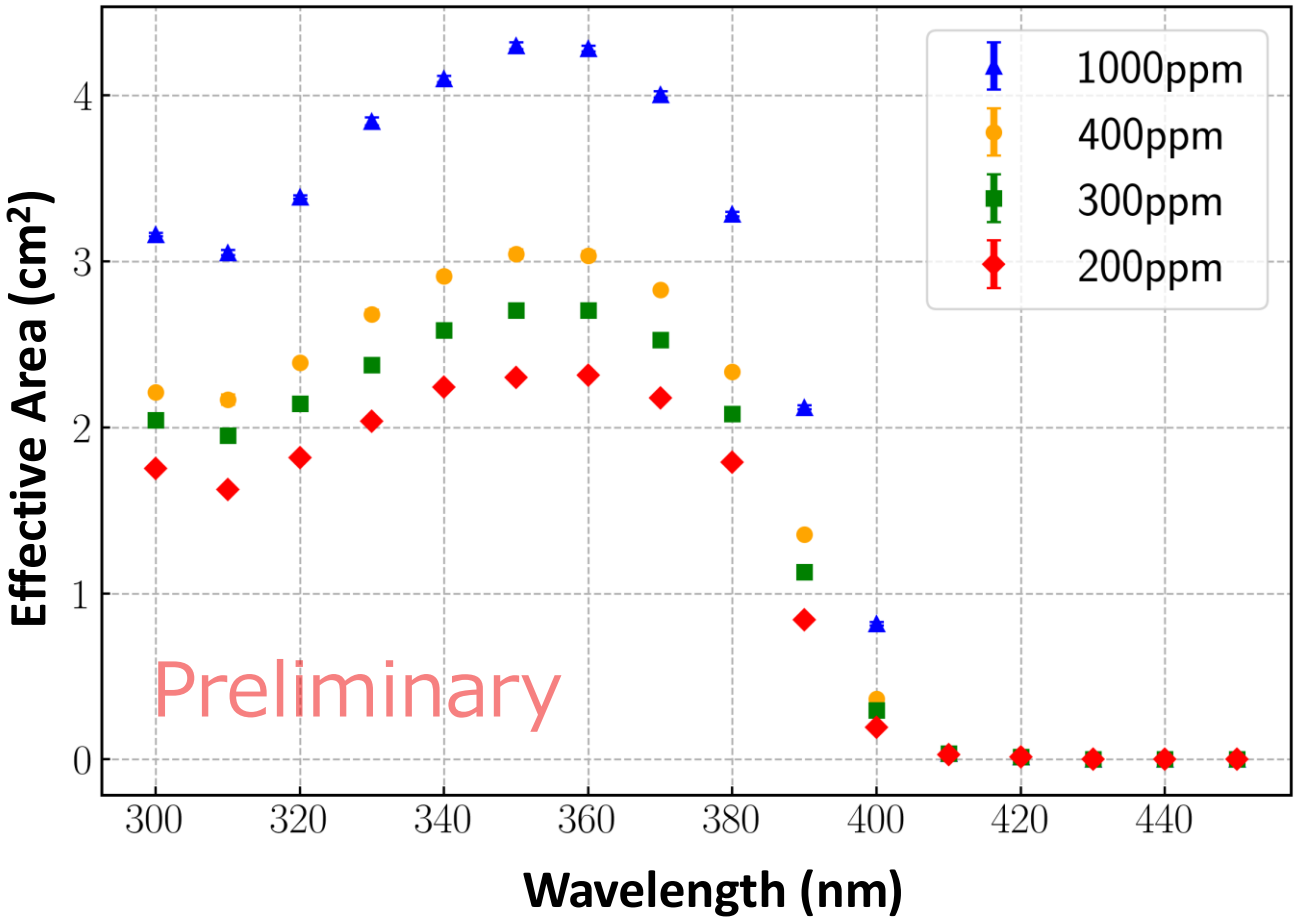
$$A_{\mathrm{eff\_fiber}} = \frac{N_{\mathrm{detect}}}{N_{\mathrm{gen}}} \times A_{\mathrm{gen}}$$

N_{detect} : Number of detected photons

N_{gen} : Number of generated photons

A_{gen} : Generate area

→**Dye concentration 1000 ppm gives the maximum A_{eff}**



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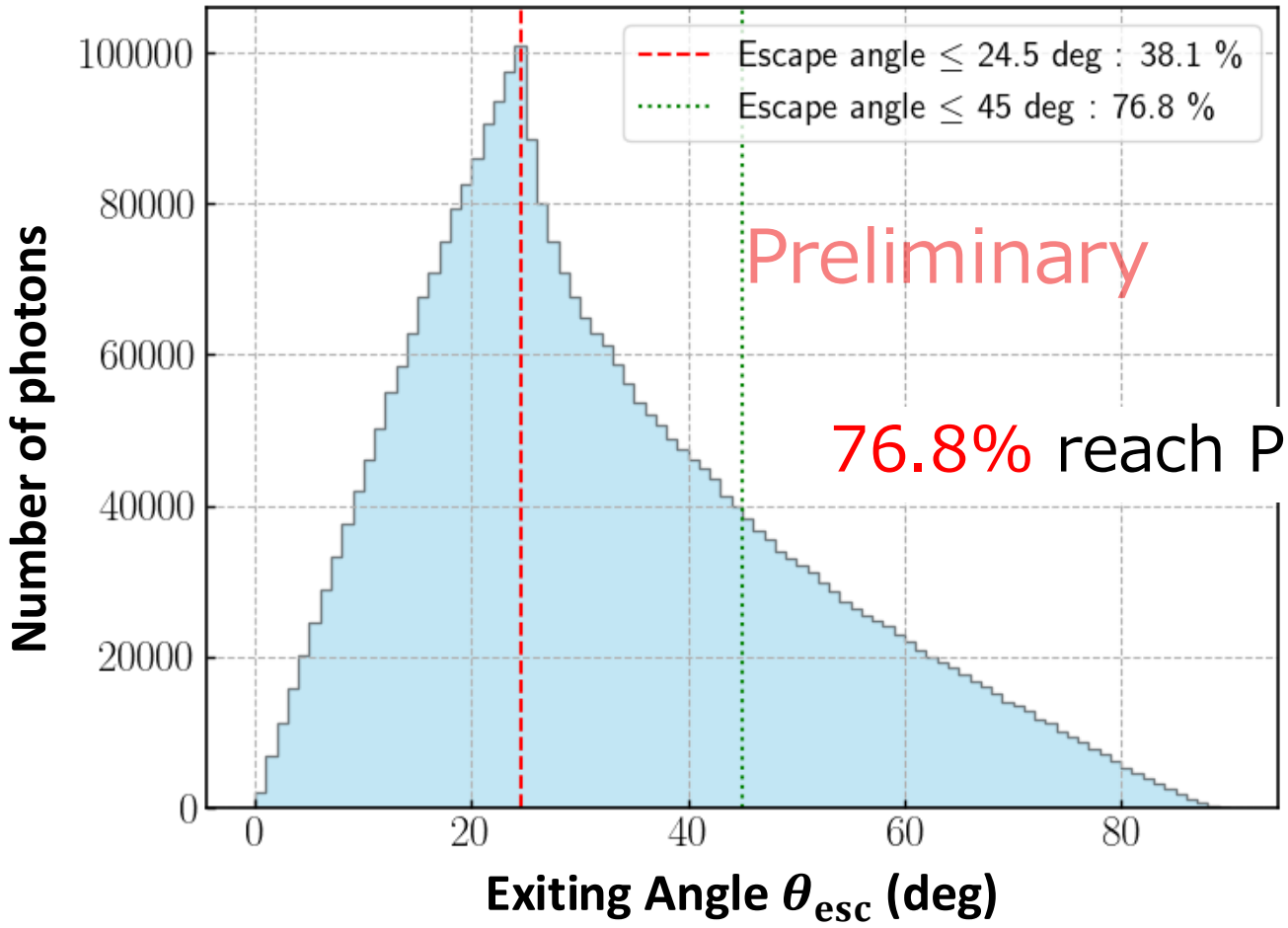
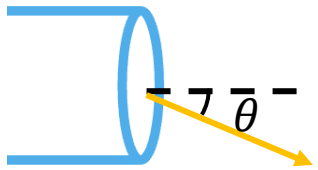
Photon exiting angles at the fiber end

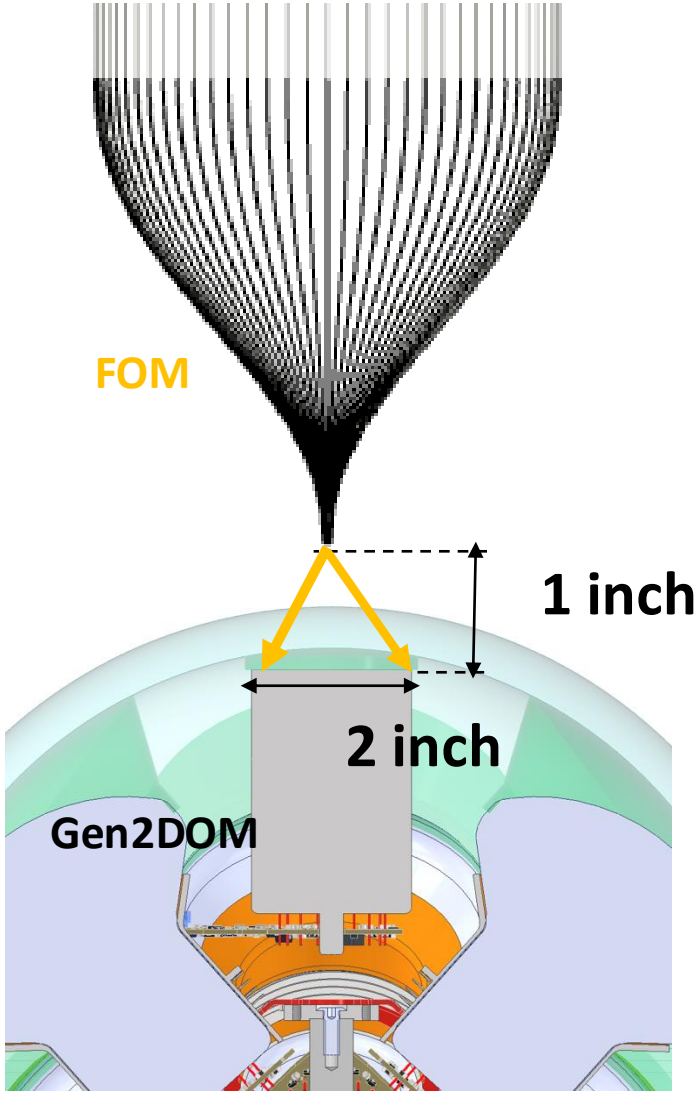
◆Light collection by a 2-inch PMT
⇨Detection condition: Exiting angle ≤ 45°



76.8% reach PMT



Exiting angle θ



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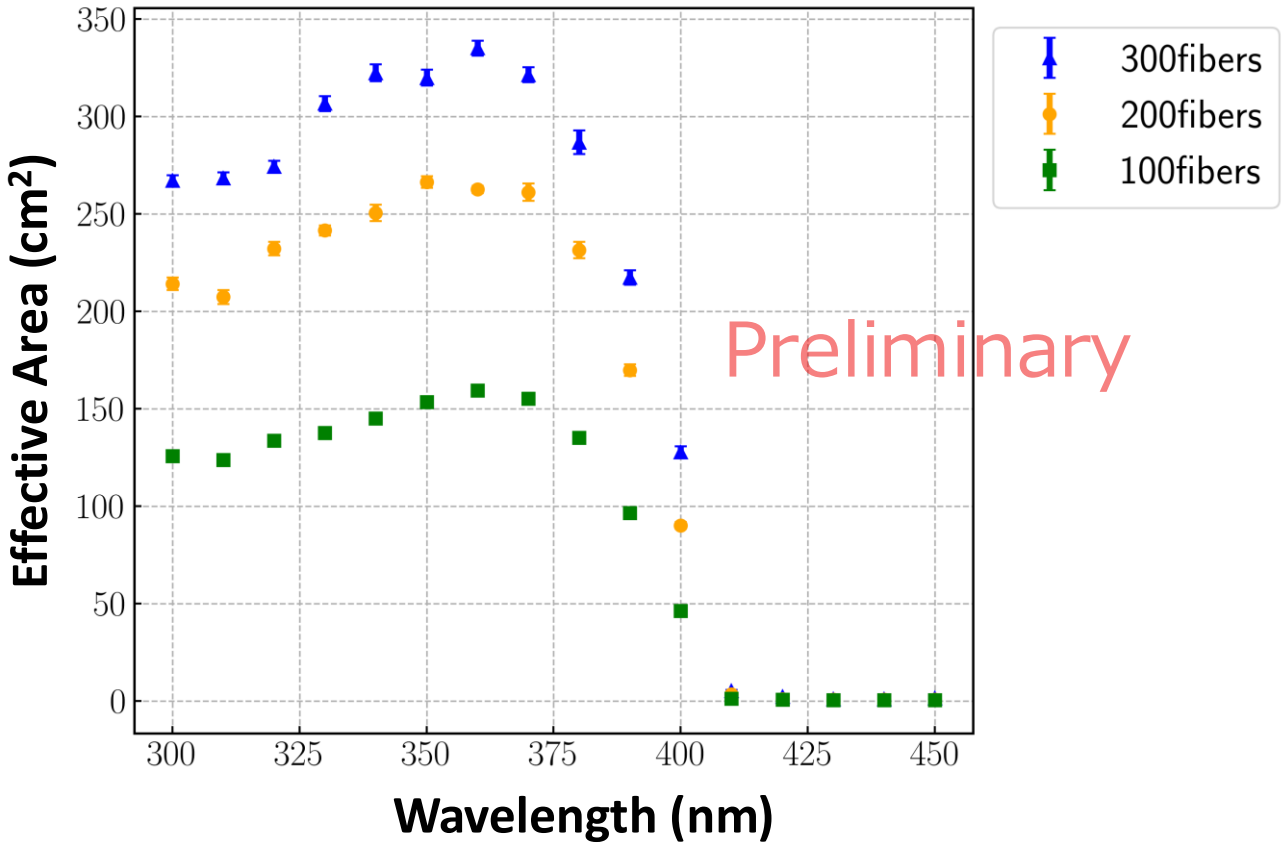
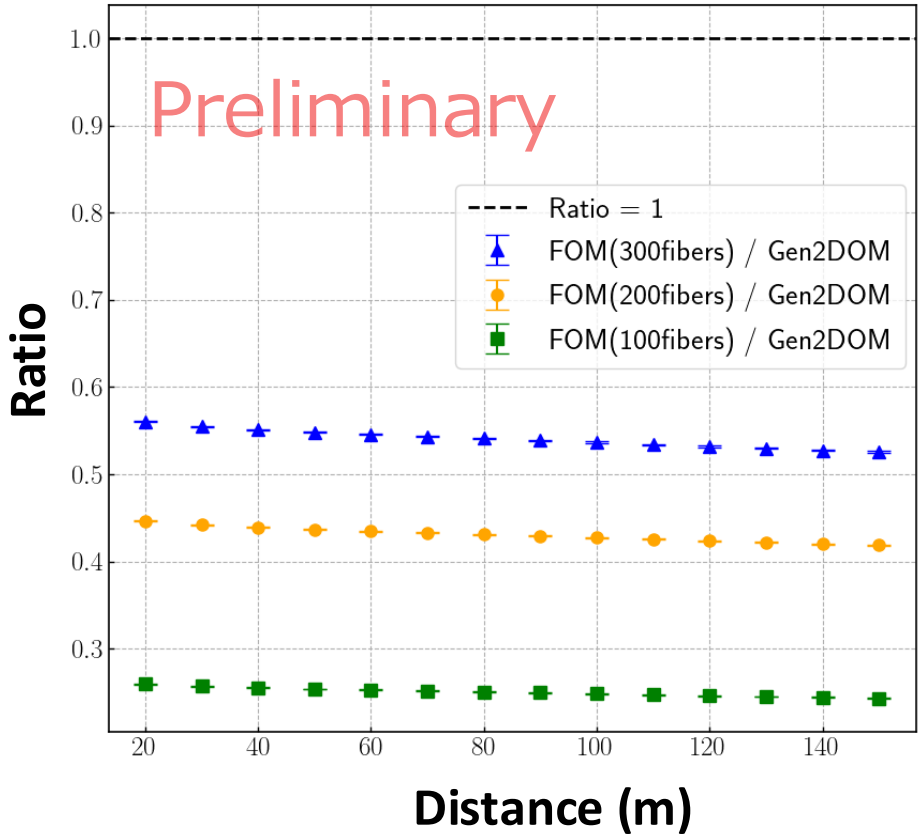
Effective area of FOM with 100-300 fibers

◆ Shadowing effect included



◆ Comparison with Gen2DOM

- Maximum A_{eff} limit: 0.5 × Gen2DOM



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Summary & Future Work

◆ Summary

- Wider string spacing
  → Lower low energy muon rejection in IceCube-Gen2
- **Solution:** Enhanced light collection using WLS fiber bundles (**FOM**)
- **Results:**
  - Measured attenuation length: 3.6 m (< nominal value)
  - Maximum A_{eff}: **0.5 × Gen2DOM**

◆ Future Work

- Validation of attenuation length (multiple samples) & bending loss
- Integrated A_{eff} evaluation (FOM + Gen2DOM)
  → Veto capability assessment
- Performance validation using a physical prototype

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Back Up

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PMT Details

R14095-01 by HAMAMATSU

Parameter	Description / Value	Unit
Spectral Response	**300 to 650**	**nm**
Wavelength of Maximum Response	**420**	**nm**
Photocathode - Material	Bialkali	-
Photocathode - Minimum Effective Area	ϕ 46	mm
Window Material	Borosilicate glass	-
Dynode - Structure	Box and Line	-
Dynode - Number of Stages	10	-
Weight	approx. 84	g
Operating Ambient Temperature	-30 to +50	degree C
Storage Temperature	-80 to +50	degree C

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Calculation of effective area

◆ Definition of the effective area of a fiber

$$A_{\mathrm{eff\_fiber}} = \frac{N_{\mathrm{detect}}}{N_{\mathrm{gen}}} \times A_{\mathrm{gen}}$$

N_{detect} : Number of detected photons
N_{gen} : Number of generated photons
A_{gen} : Generate area

◆ Calculation of the effective area of FOM

$$A_{\mathrm{eff\_FOM}}(D) = \int_{\lambda_{\mathrm{min}}}^{\lambda_{\mathrm{max}}} A_{\mathrm{eff\_fiber}}(\lambda) \cdot \varepsilon_{\mathrm{exit}} \cdot \frac{\mathrm{d}N}{\mathrm{d}\lambda}(\lambda, D) \cdot \mathrm{QE}(\lambda)\, \mathrm{d}\lambda$$

ε_exit : Losses due to escape angle ~ 0.768
$\mathrm{d}N/\mathrm{d}\lambda\ (\lambda, D)$: The Cherenkov Light Spectrum Reaching FOM
QE(λ) : Quantum efficiency of PMT

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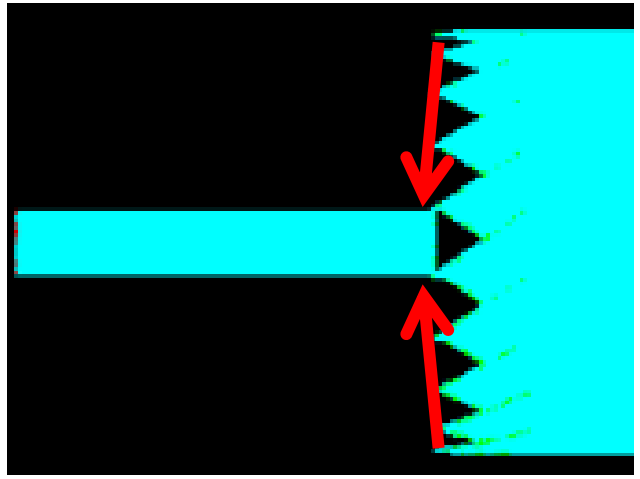
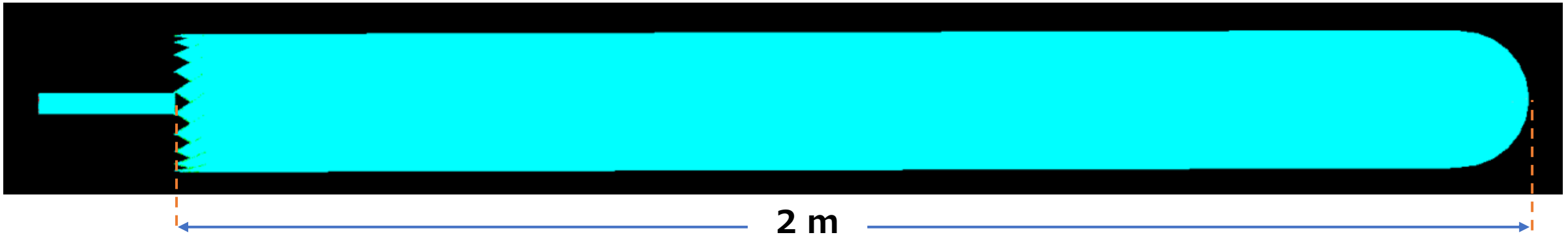
Effective area of FOM

◆ Creating FOM with Geant4
- Non-overlapping U-shaped fibers
- Gen2DOM interface: Photon warping





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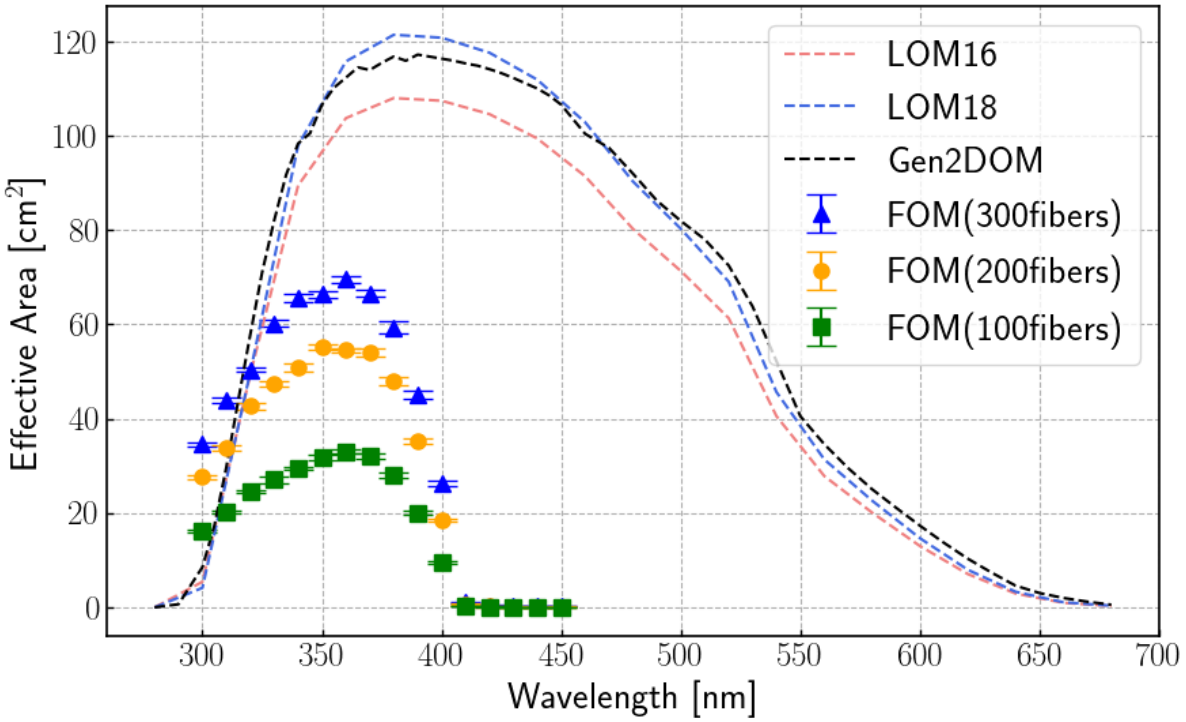
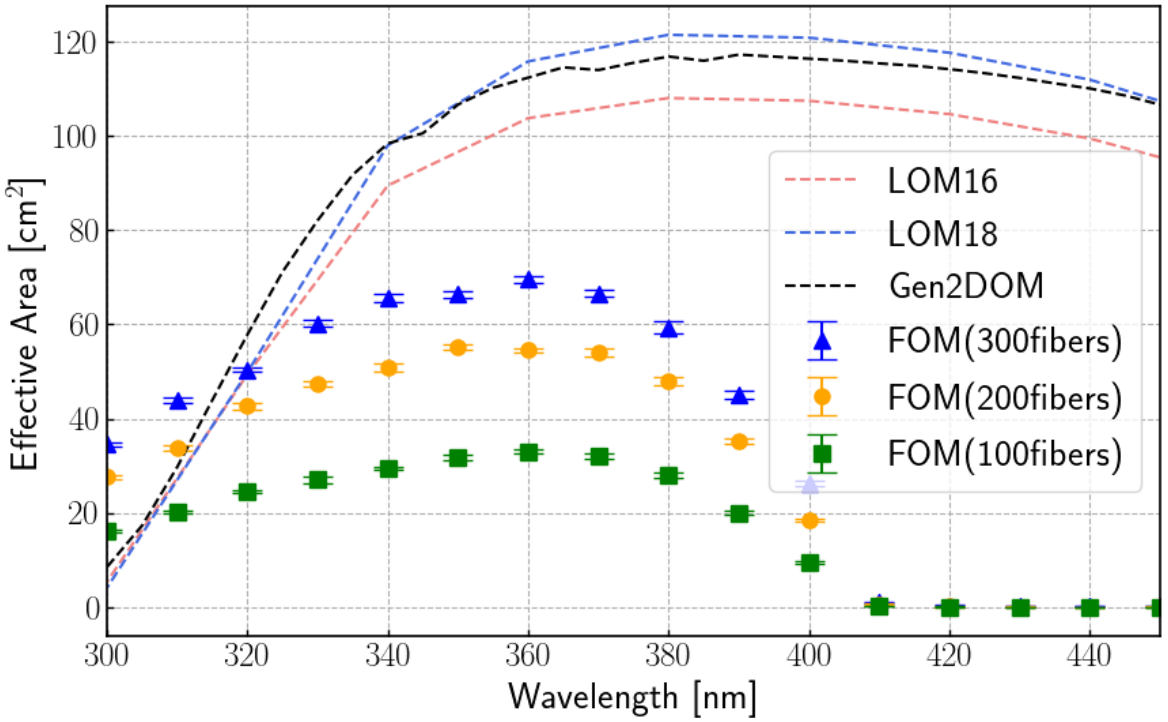
Effective Area of FOM and Gen2DOM

◆ Comparison of effective area by wavelength
Reinforcement of the shrinking short-wavelength range





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