Outer Detector of Hyper-Kamiokande

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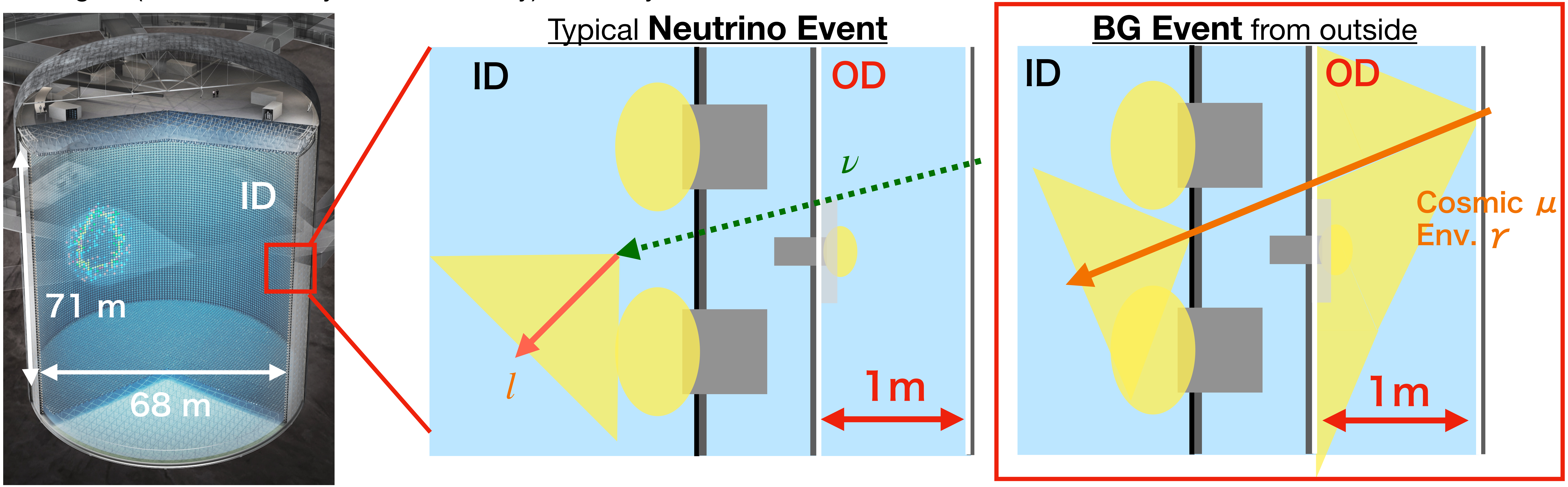
Hyper-Kamiokande & the Role of Outer Detector

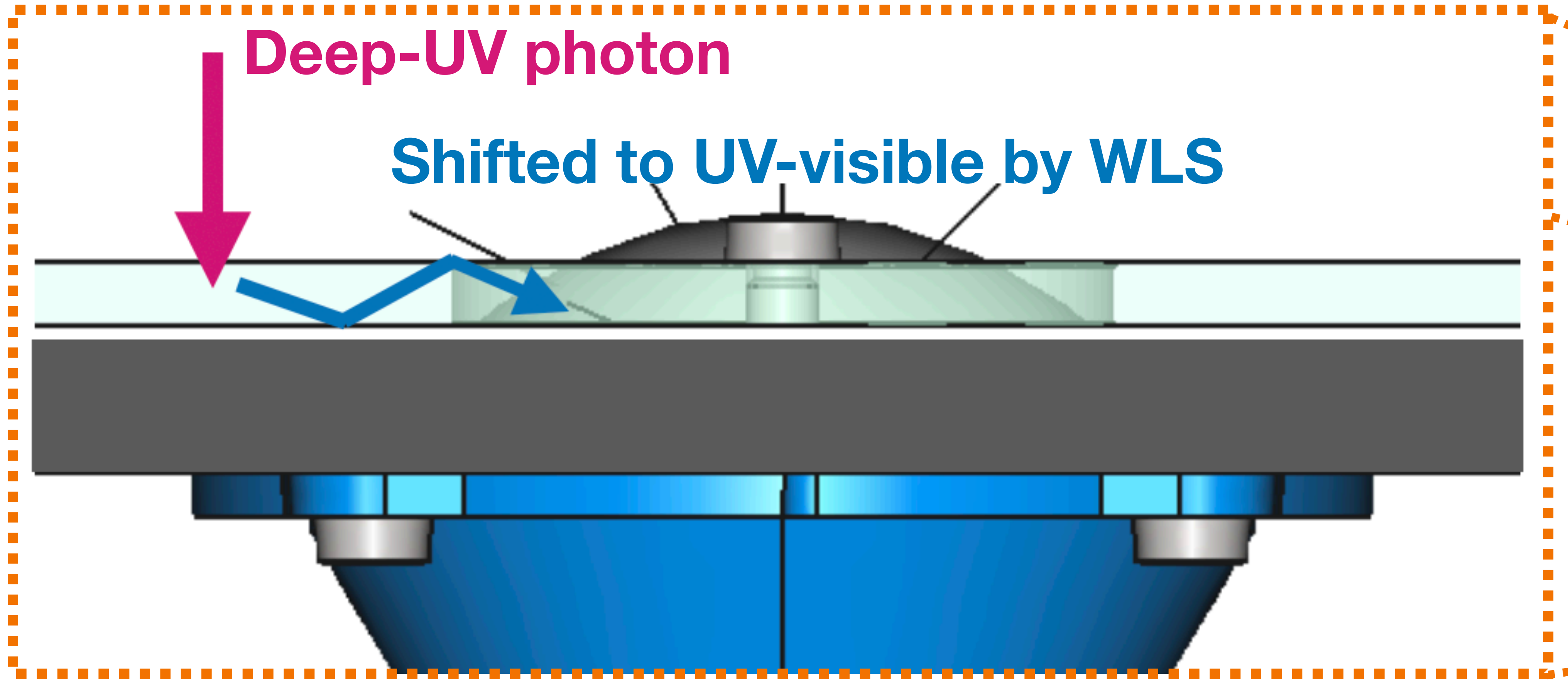
- World's largest water Cherenkov ring-imaging detector (As referred in previous Ben's talk)
  - Nucleon decay searches, ν mass hierarchy, precise δ_{CP} measurement etc.
- Two layer detector structure
  - Inner Detector (ID): 190 kton fiducial volume
  - **Outer Detector (OD): 1-2 m layer surrounds ID on all sides, optically separated from ID**
- **OD rejects background events** entering from outside
  - Cosmic-ray μ BG: ~50 Hz → PMT hits in both ID and OD
  - Signal (atm. ν: ~80/day, nucleon decay): hits only in ID

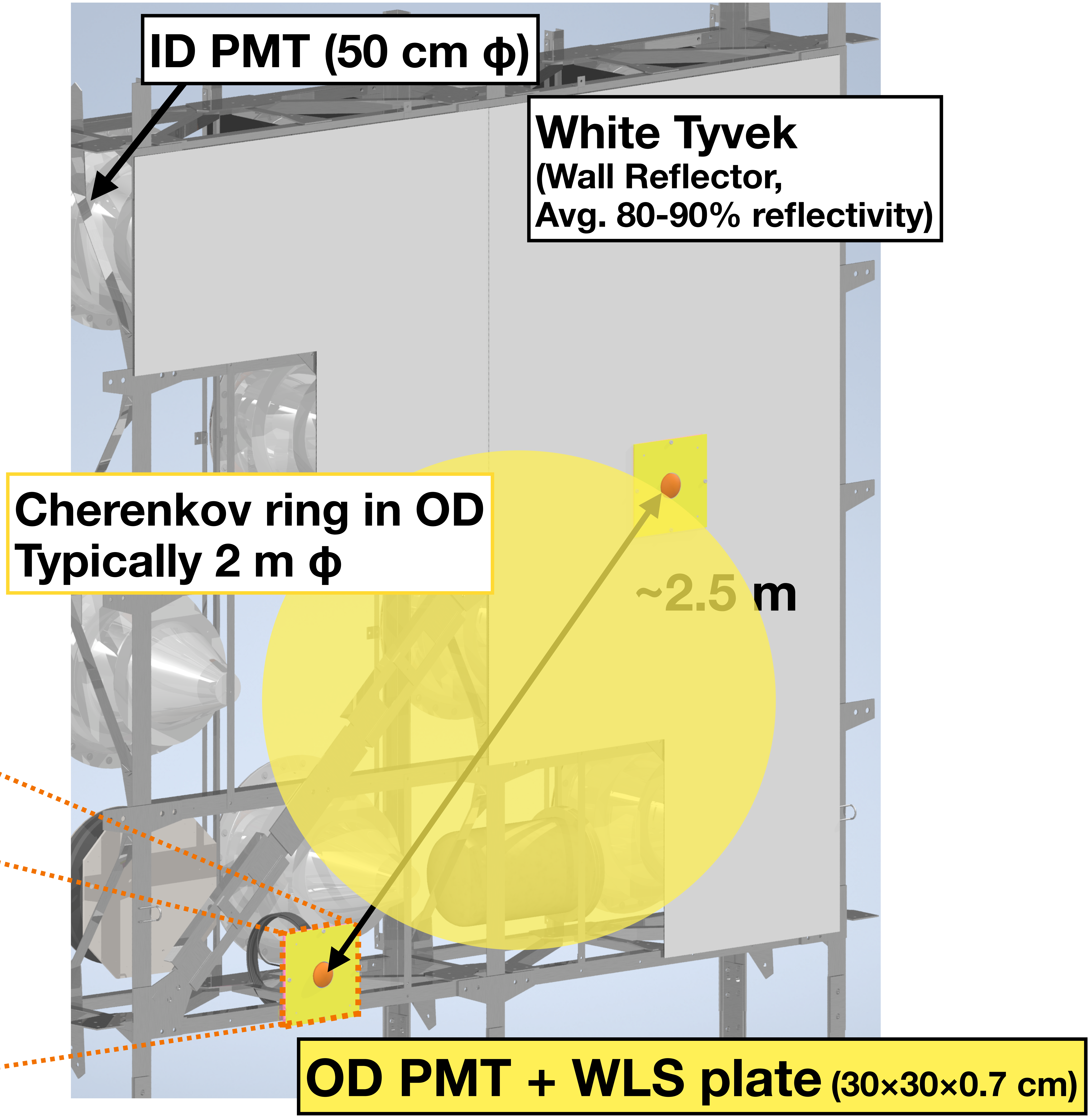
Detect by OD



Specifications of Outer Detector

- **8 cm diameter PMTs**
  - ~3600 pcs.
- **Wavelength-shifting (WLS) plates** covering PMT edges
  - To improve photo-coverage effectively
- **Tyvek sheets** (wall reflector)
- Design optimized to **detect as many photons from background events** as possible within budget constraints



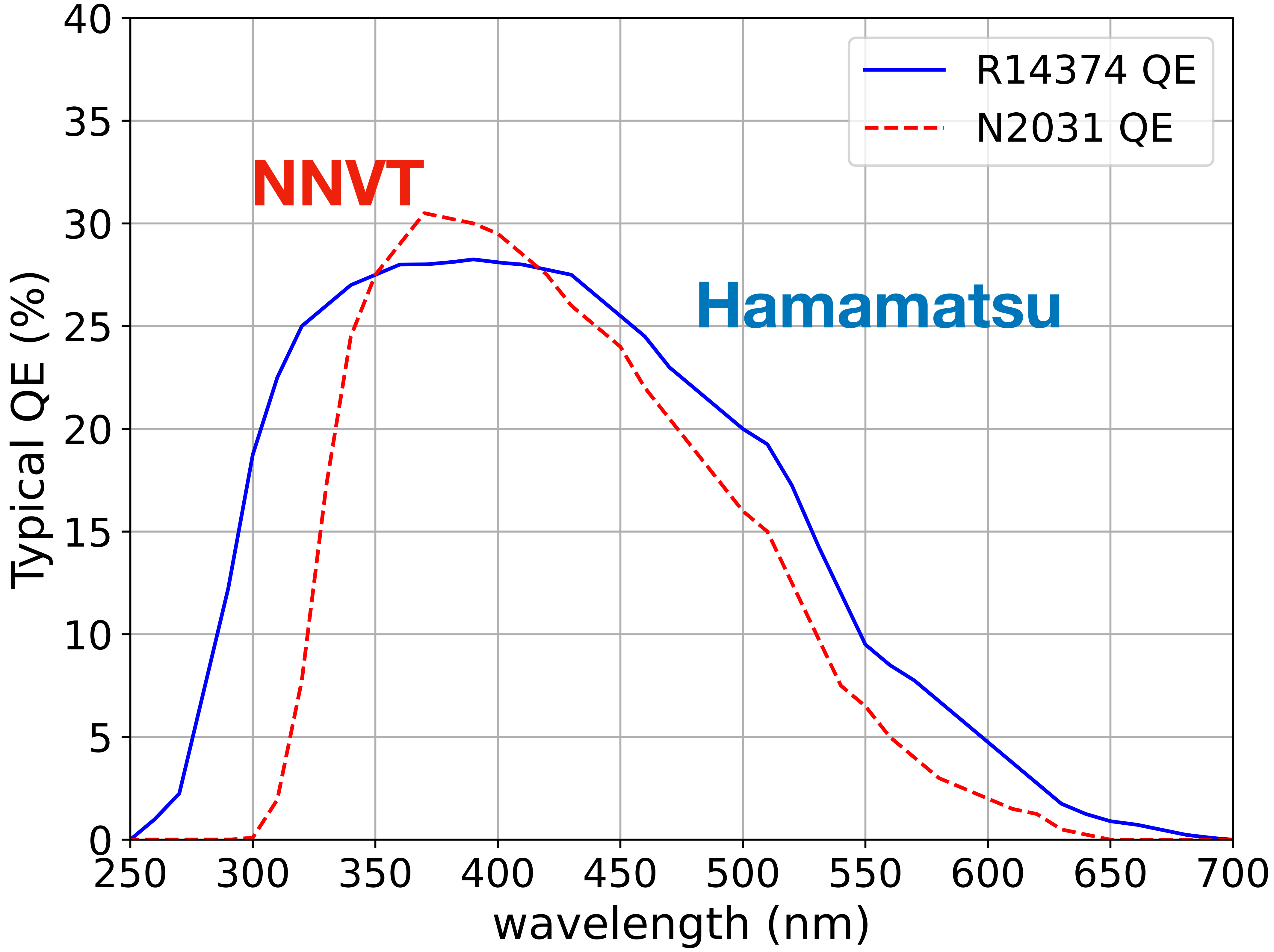


Optimization of Outer Detector

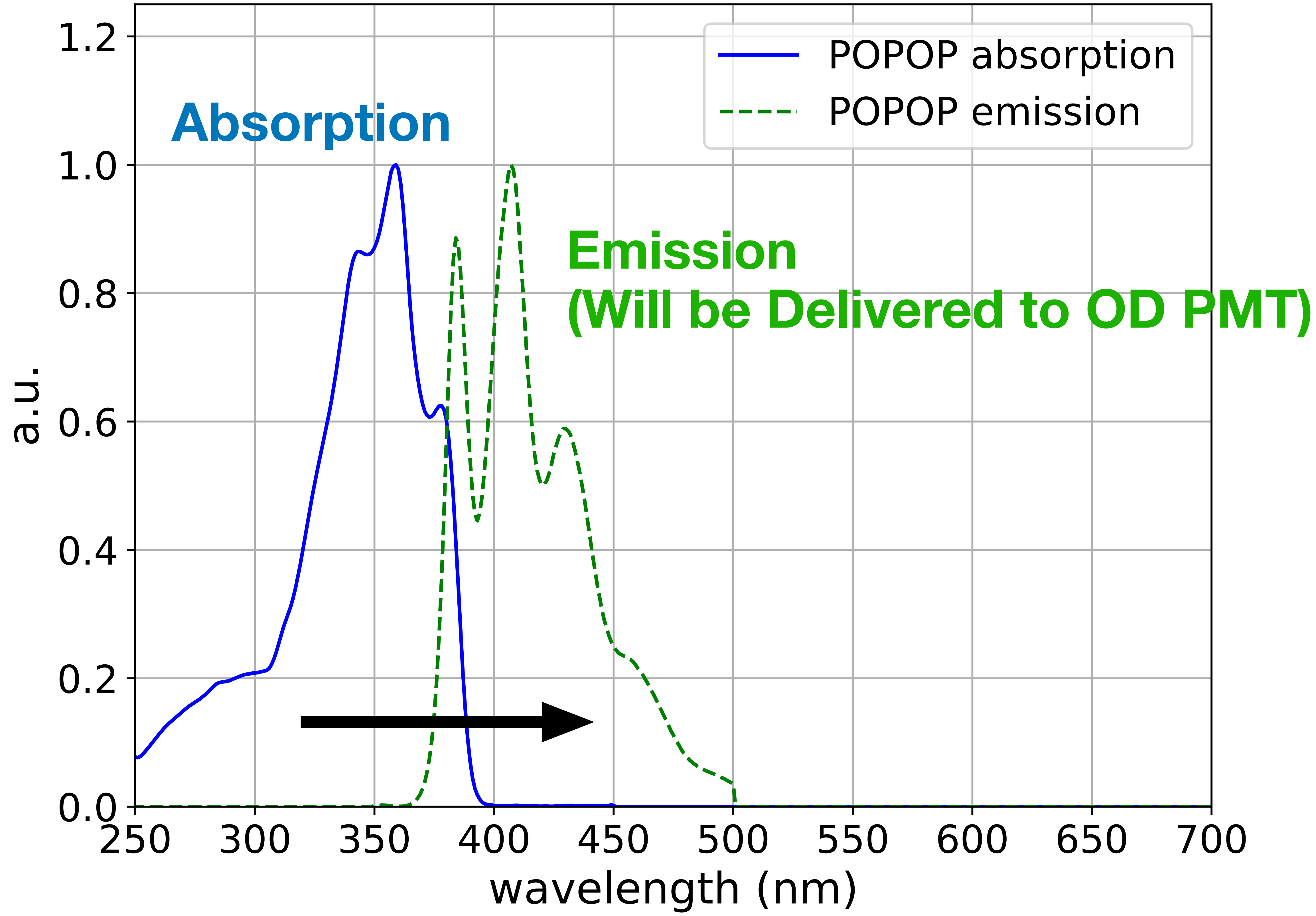
- Hamamatsu R14374 and NNVT (North Night Vision Technology, China) N2031 were OD PMT candidates, **required the selection**
- **Detection efficiency and long-term stability are critical performances for OD PMT**
  - QE value from vendors were provided
  - Detection efficiency through WLS plate is also important

} We measured these

Typical OD PMT QE values from vendors



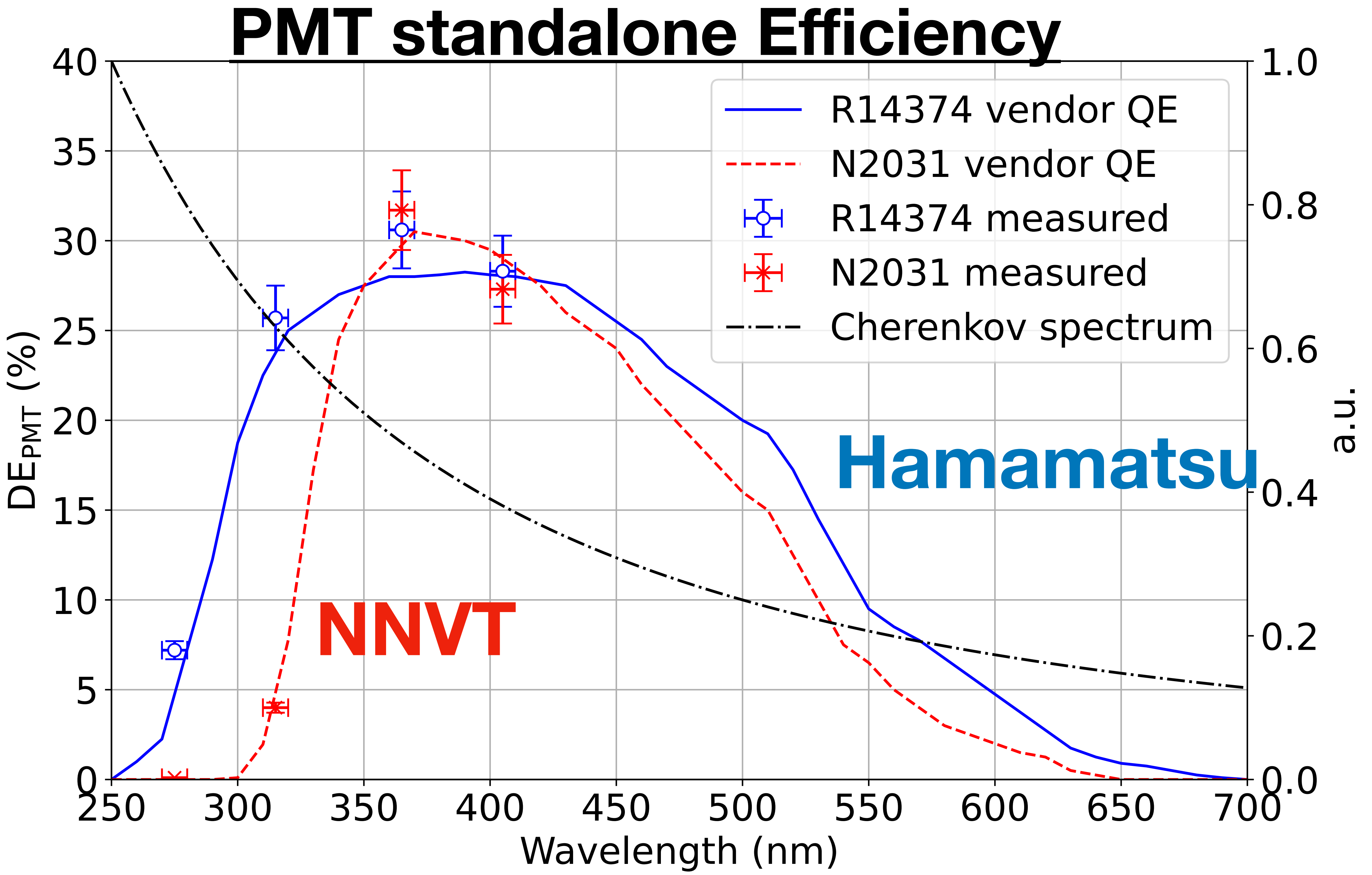
WLS plate fluorescent (POPOP) specta (reference)

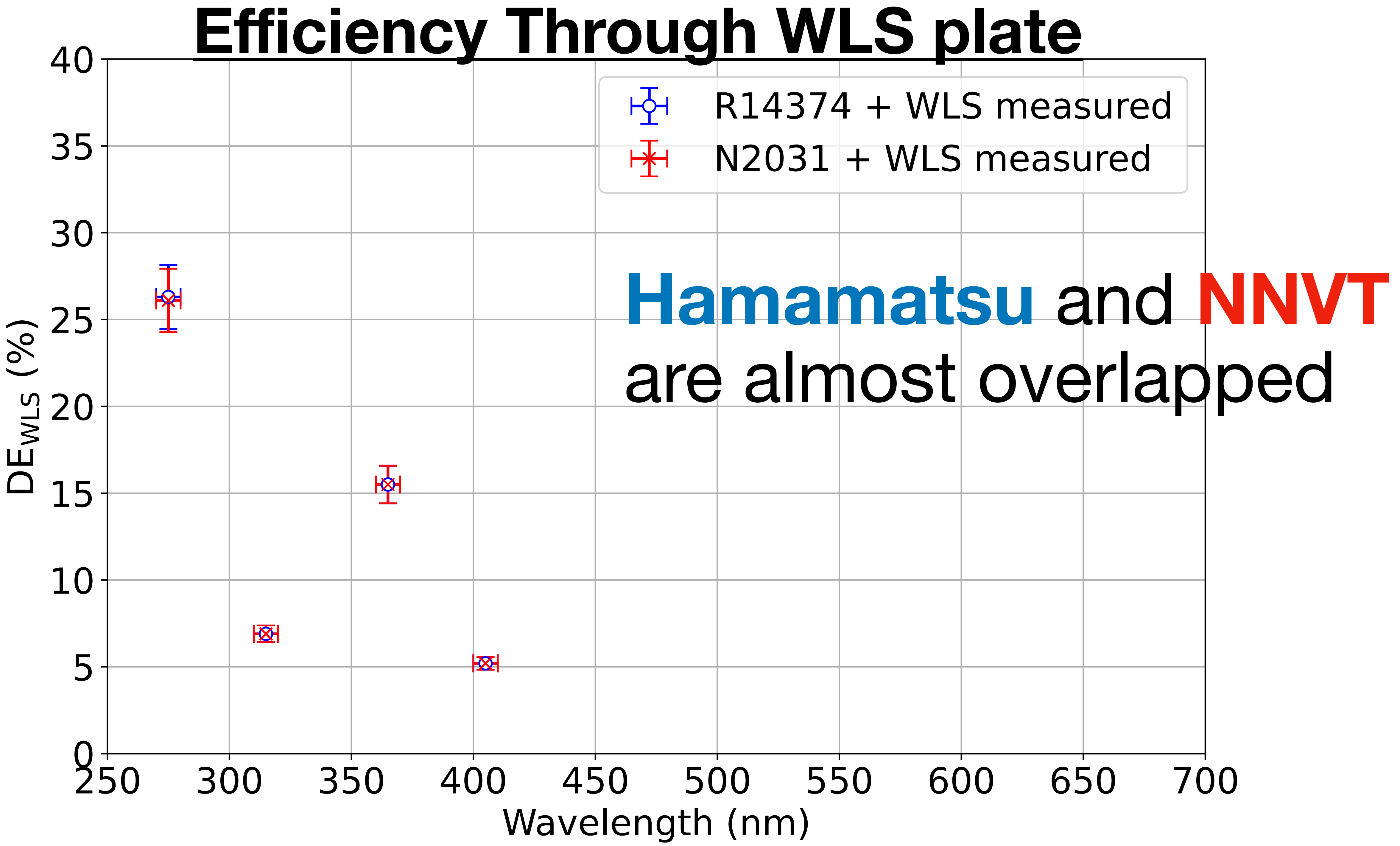


Detection Efficiency Measurement

- Detection efficiency was measured in combination with the identical WLS plate in water
  - Measured at four wavelengths (405, 365, 315, 275 nm)

1. **<u>Result of PMT standalone</u>**
   - **Hamamatsu PMTs showed superior detection efficiency in deep-UV**
     - This is consistent within ±10% (relative) with vendor-provided QE values at each wavelength
2. **<u>Result of through WLS plate</u>**
   - No significant difference at any measured wavelength
     - Understood as POPOP re-emits light near 400 nm where the QE difference between the two is minimal





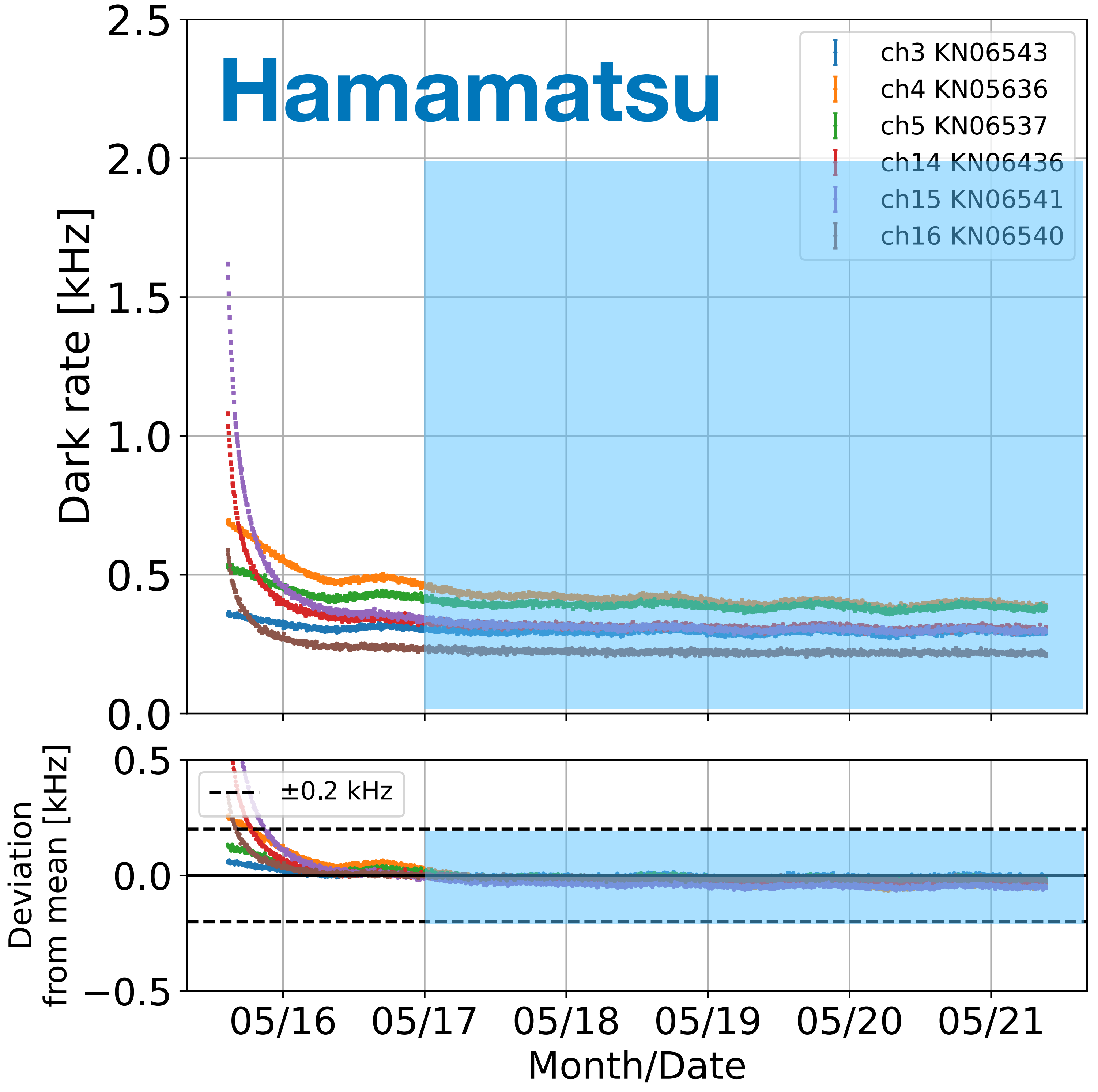
Basic PMT Characteristics Measurement

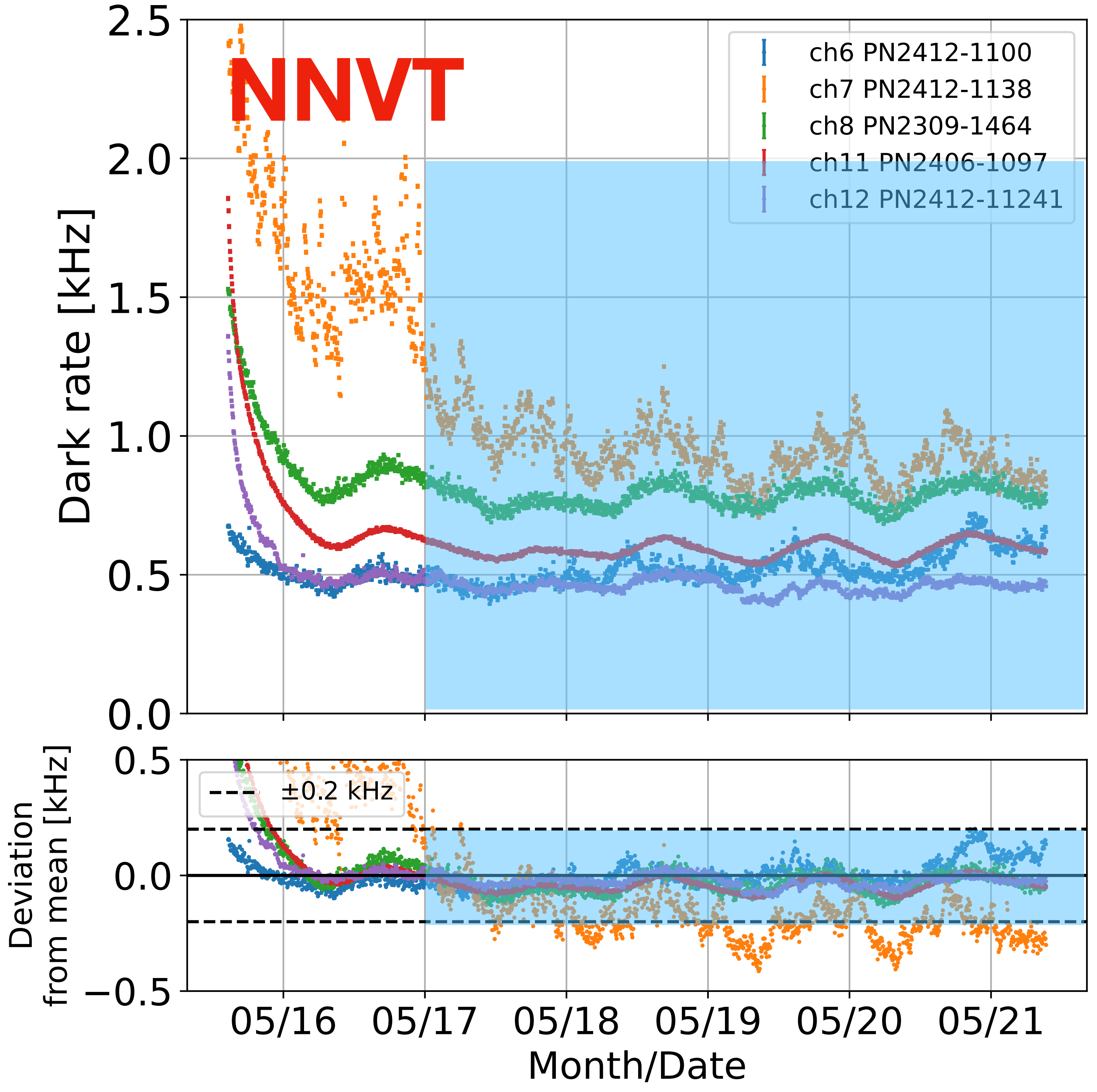
- PMT standalone performances and their stability were measured in air
  - Operating voltage, dark rate*, gain*, timing resolution*, charge resolution* (*stability also evaluated)

1. **Result**
   - **Hamamatsu satisfies all basic specification requirements and more stable**

- **Hamamatsu PMTs were adopted for the HK OD**

Example: Stability of Dark Rate in a week





Dark rate (top)

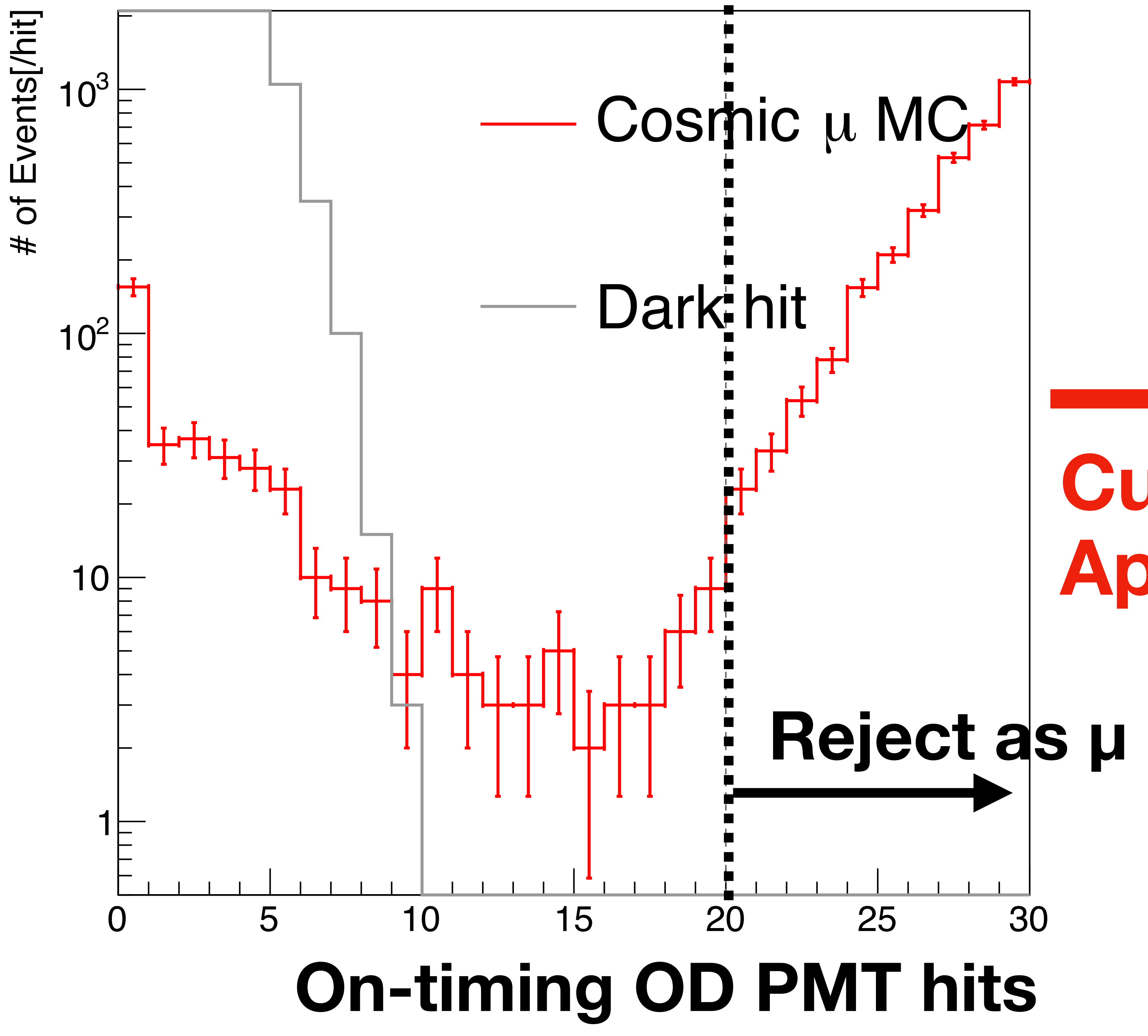
Deviation from mean (bottom)

Requirement shown in blue

Performance Evaluation of Outer Detector

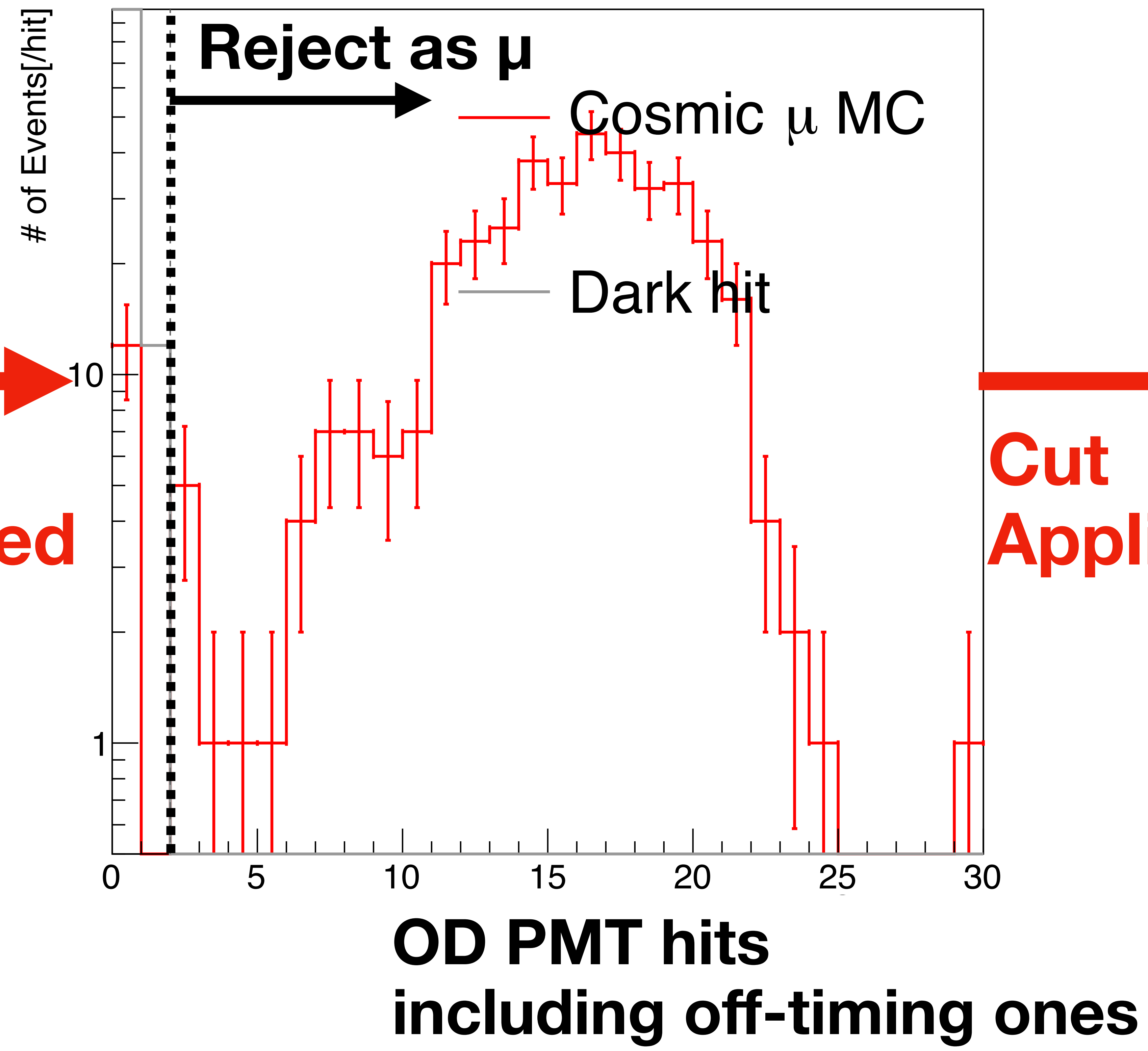
- Evaluated cosmic-ray μ BG reduction efficiency for atmospheric ν analysis
  - Using HK **detector sim. based on measurements** of cosmic-ray μ with Hamamatsu PMTs
- Applied three-stage cuts to MC-generated 10^7 equivalent events
  - Reduce Cosmic-ray μ using temporal and spatial info. of PMT hits

1. Typical Muon Reduction



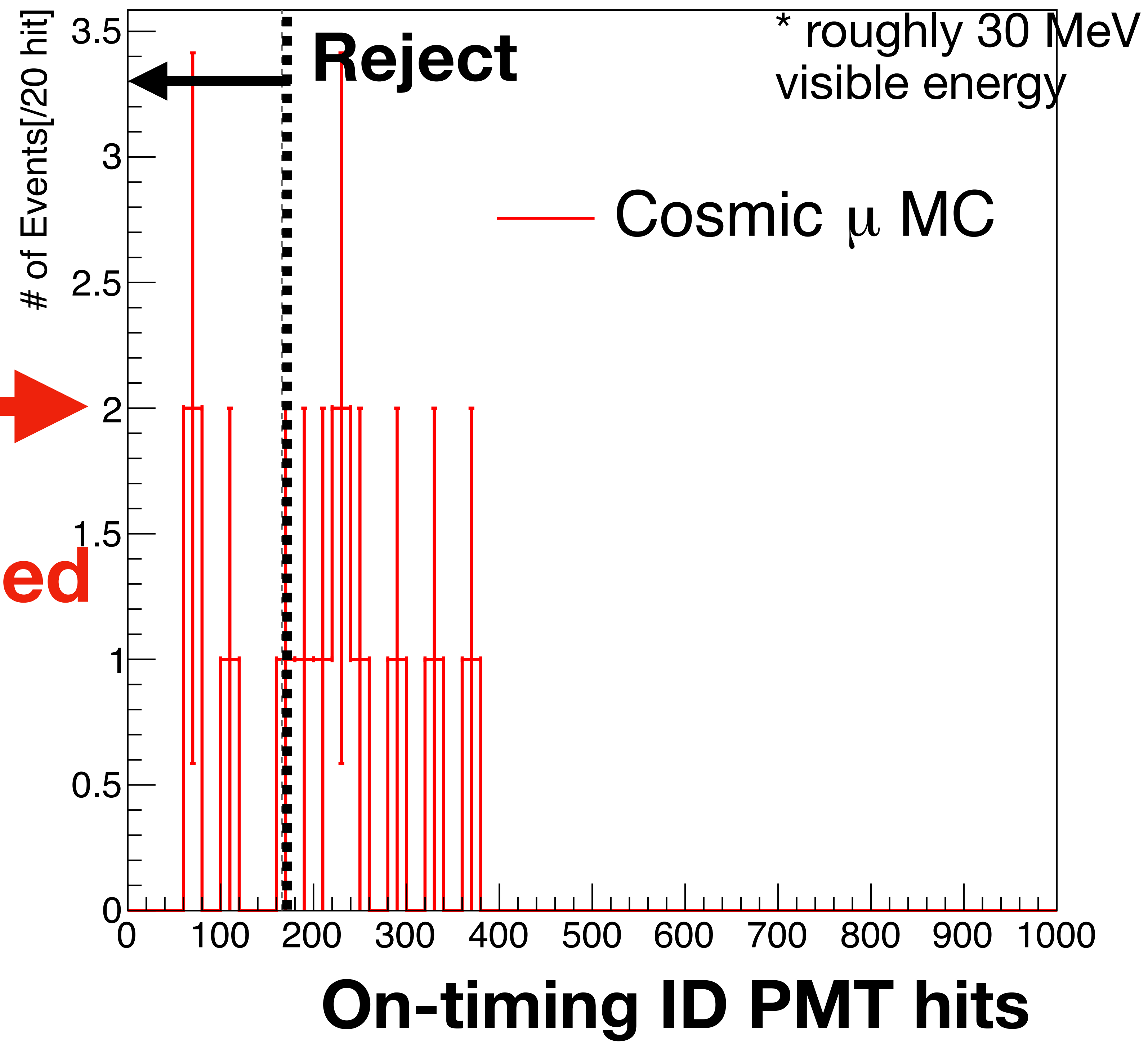
Cut Applied

2. Michel Electron Event Reduction



Cut Applied

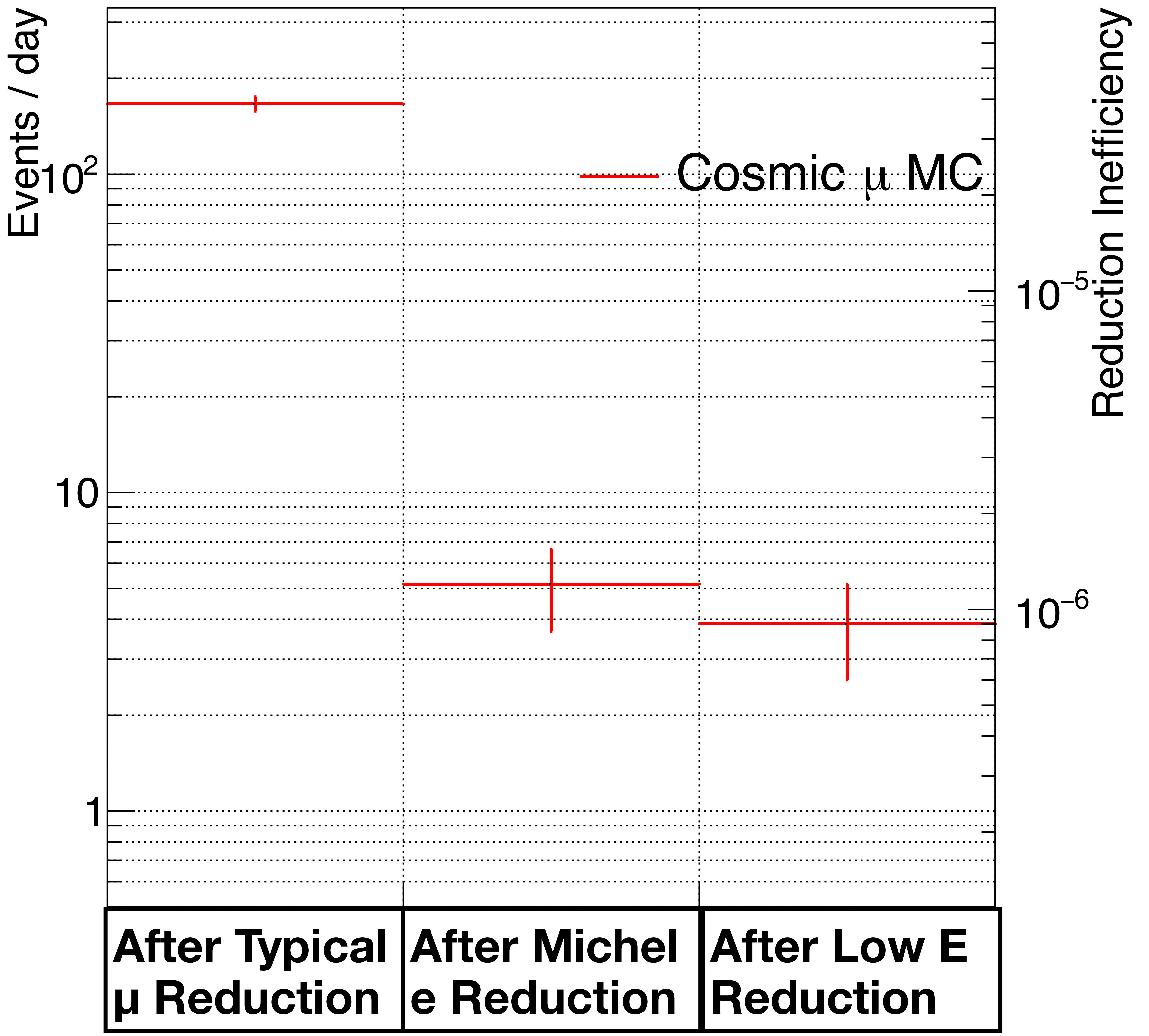
3. Low Energy* Event Reduction



Stat. err. only

Performance of Outer Detector

- Reduction inefficiency can reach O(10^{-6})
  - 80 atm. ν signal events/day, S/B is 80/3.8 ~ 20
- **In future, expecting to achieve O(10^{-9}) inefficiency**
  - **By fiducial volume cut on reconstructed vertex**
    - Cosmic-ray μ has true vertex at the ID wall
    - Fiducial volume (≥1 m inside ID wall) corresponds to >3σ given ~30 cm vertex reconstruction resolution near the wall
- Reduction efficiency is **sufficient for analyses**
  - Evaluation of long-term (>10 years) performance is the next task



Stat. err. only

Summary

- **Background and challenges:**
  - **Selection of 8 cm diameter PMTs** for Hyper-K OD was required
    - Candidates: Hamamatsu R14374 and NNVT N2031
  - Verification was needed that **cosmic-ray μ BG reduction efficiency with OD is sufficient** for physics analyses
- **Results achieved:**
  - **Hamamatsu PMTs were adopted for the HK OD**
    - As they satisfies all basic requirements and has relatively superior detection efficiency and stability
  - **Cosmic-ray μ BG can be reduced to O(10^{-9}) level**
    - Evaluated by HK detector sim. based on measurements of cosmic-ray μ with Hamamatsu PMTs
    - Reduction inefficiency is a sufficiently negligible for nucleon decay and atmospheric ν analyses
  - **The OD design was confirmed to achieve the required performance**
- **Prospects:**
  - Long-term (>10 years) detector performance evaluation
    - Malfunction of electronics and PMT, degradation of wall-reflector due to aging

Back Up

Summary of PMT Performance Evaluation

- **Hamamatsu PMTs adopted:** they satisfy all requirements and have superior detection efficiency

*Items not meeting requirements

Measured item	Requirement	Hamamatsu (satisfied/tested)	NNVT (satisfied/tested)
HV for 5×10^6 gain per PMT	900 - 1450 V	7/7	3/5*
Mean HV for 5×10^6 gain	1100 - 1300 V	1162V	1383V*
Gain Stability	±10%/day	7/7	5/5
Dark Rate	< 2 kHz (0.3pe room tmp.)	7/7	5/5
Dark Rate Stability	±0.2 kHz	7/7	3/5*
Time Resolution	< 3 ns FWHM	7/7	5/5
Charge Resolution	< 70% σ	7/7	5/5
Photon DE (405 nm)	None	1.0±0.1	1 (Normalized)
Photon DE (365 nm)	None	1.0±0.1	1 (Normalized)
Photon DE (315 nm)	None	3.0±0.3	1 (Normalized)
Photon DE (275 nm)	None	1.3±0.1	1 (Normalized)
Cherenkov light DE (estimated)	None	1.3±0.1	1 (Normalized)

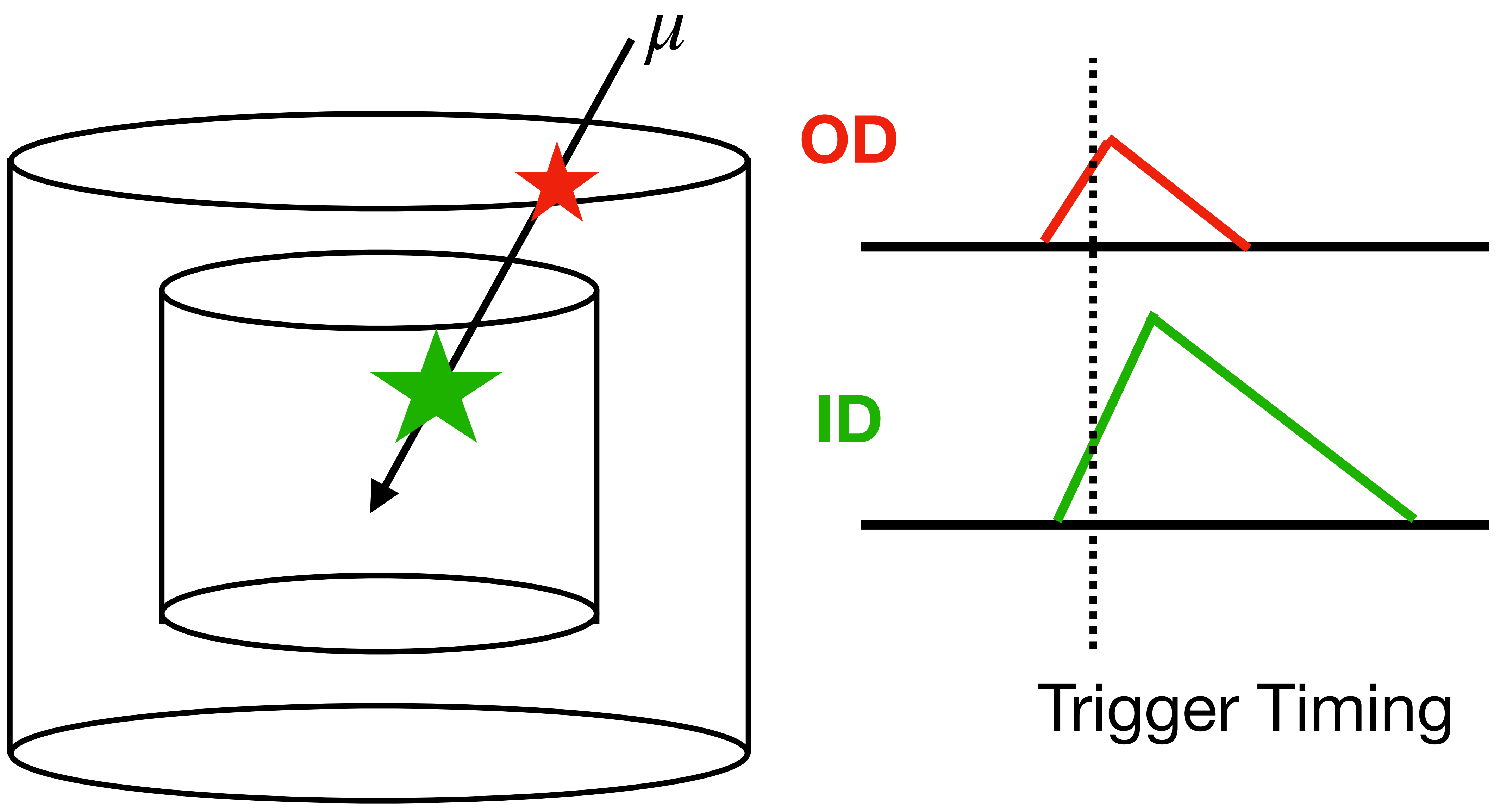
Setting Cosmic-Ray μ Reduction Criteria

- Preliminary three-stage cuts applied to MC-generated events:
  1. **General muon event reduction (NHITAC < 20)**

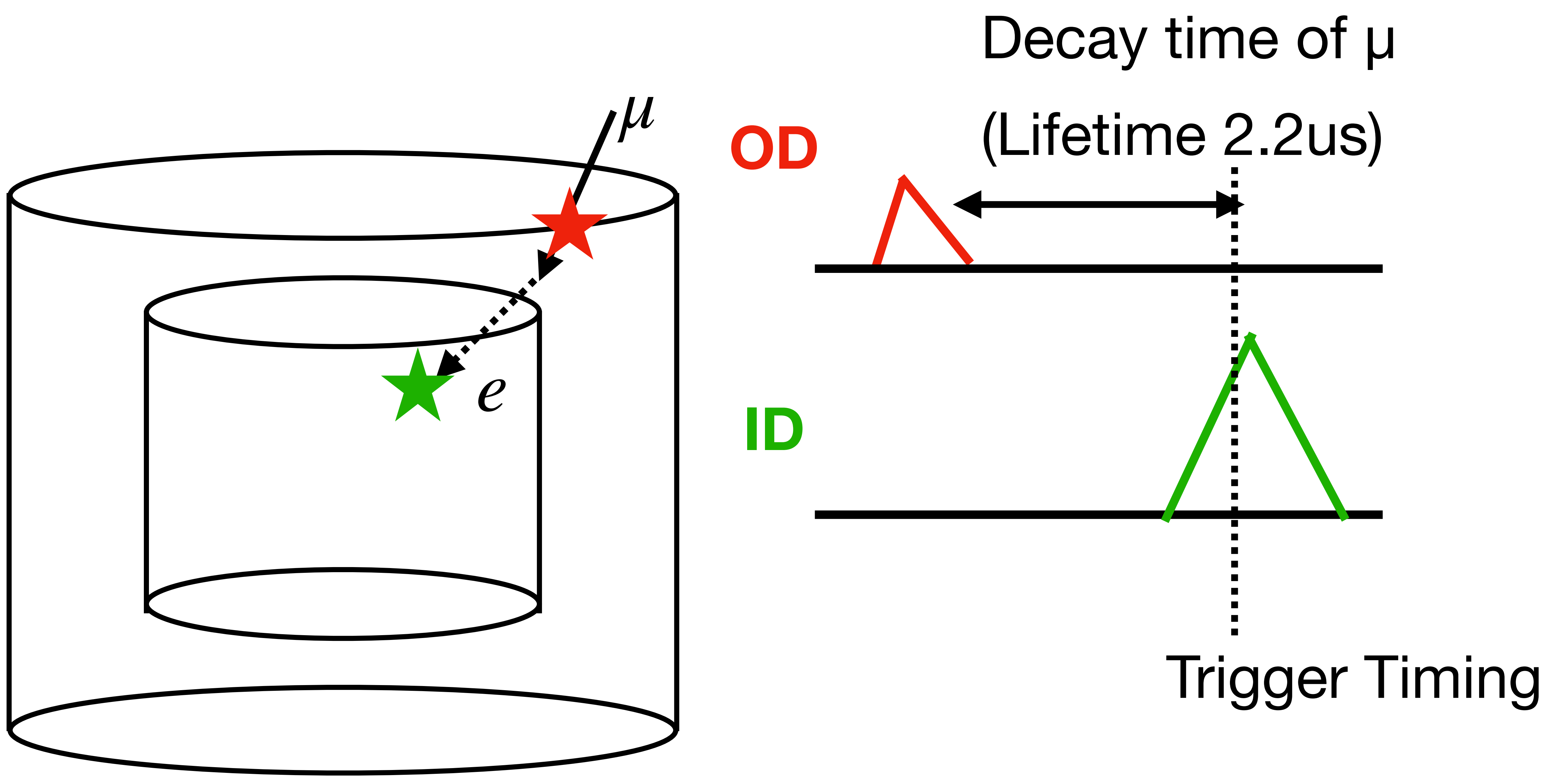
     Reject events with ≥ 20 OD PMT hits (Number of HIT Anti-Counter) within on-timing (trigger time ±1 μs)
  2. **Michel electron triggered events reduction ($NHITAC_{1000ns}$ < 2)**

     Compute OD PMT hits in a 1 μs sliding window up to trigger time −50 μs
     Reject events with maximum value; $NHITAC_{1000ns}$ ≥ 2 hits; use only PMTs within 10 m of the muon's true ID entry point
  3. **Low-energy events reduction (NHIT > 166)**

     Exclude events with visible energy ≤ 30 MeV equivalent using on-timing ID PMT hits (NHIT)



Typical Muon



Triggered by Michel Electron