The Multi-messenger Trigger System for JUNO Experiment

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Introduction

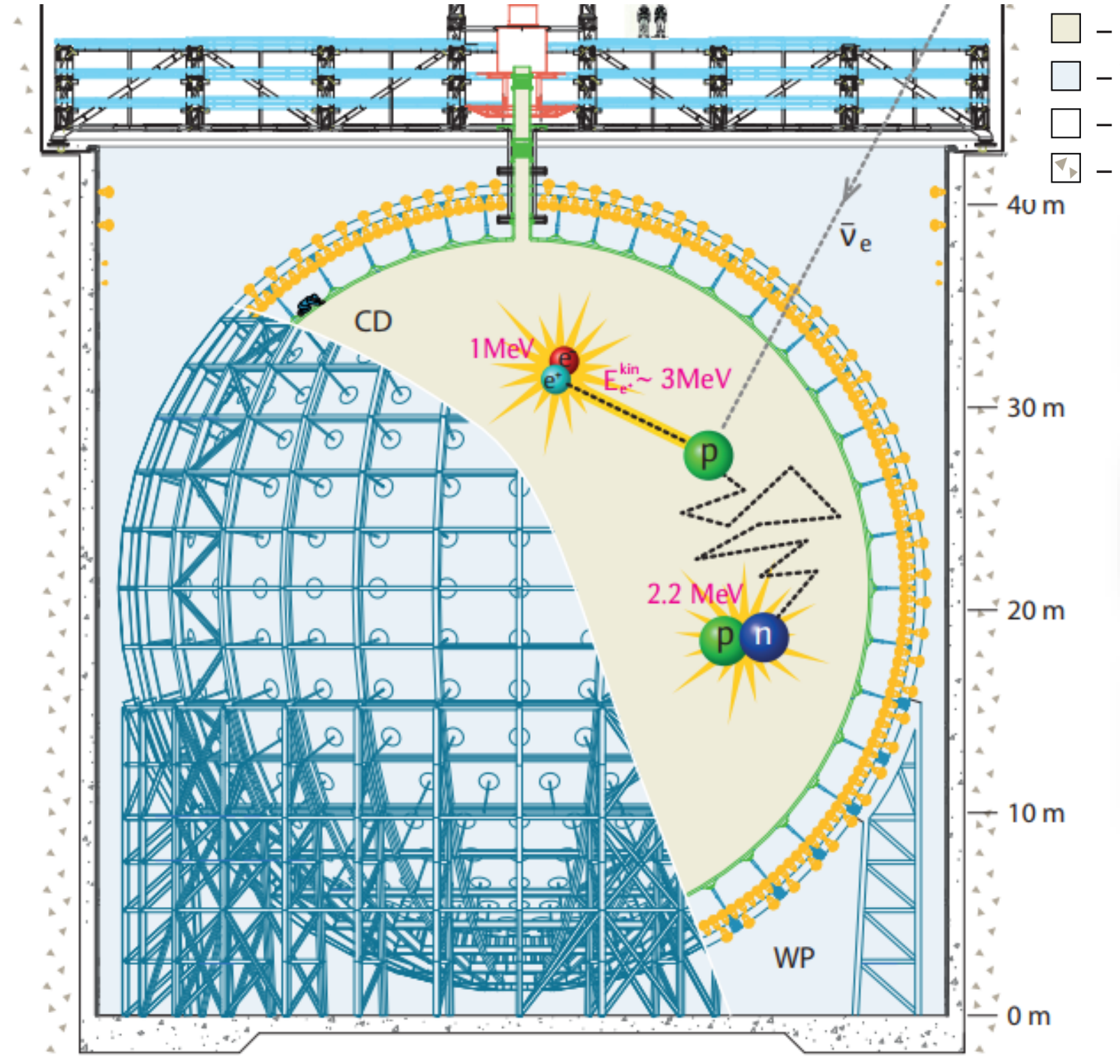
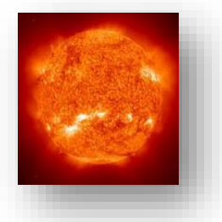


Figure 1: JUNO Schematic [1]

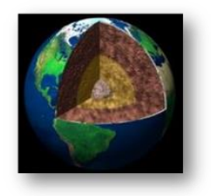
Reactor ν

Atmospheric ν



Solar ν

Supernova ν



Geo- ν

JUNO Detector

- 20 kiloton liquid scintillator
- 35 kiloton ultrapure water
- 17,596 20”+ 25,587 3” PMTs
- **World-leading solar parameter** precision in first 59 days of data[1]!

Started physics data taking on **26 August 2025**!

Trigger System

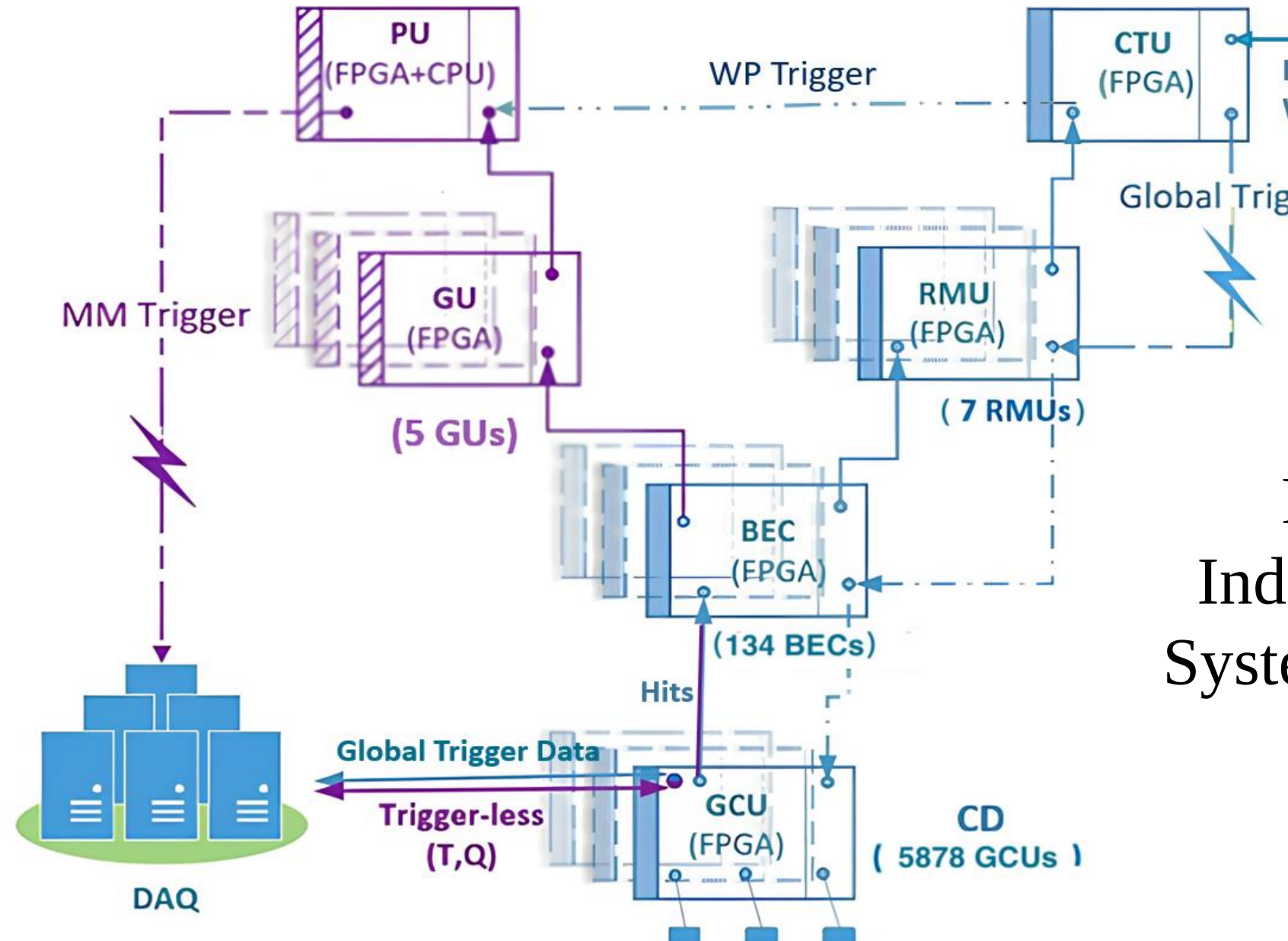


Figure 2: Two Independent Trigger Systems Schematic for JUNO

	Global trigger	Multi-messenger (MM) trigger
Algorithm	Multiplicity	Likelihood-based
Function	Reactor ν & General physics	Transient bursts & Sub-MeV
Threshold	~ 200 keV	~ 110 keV
Trigger Rate	~ 400 Hz	~ 7 kHz

Table 1: Comparison between Global Trigger and MM Trigger

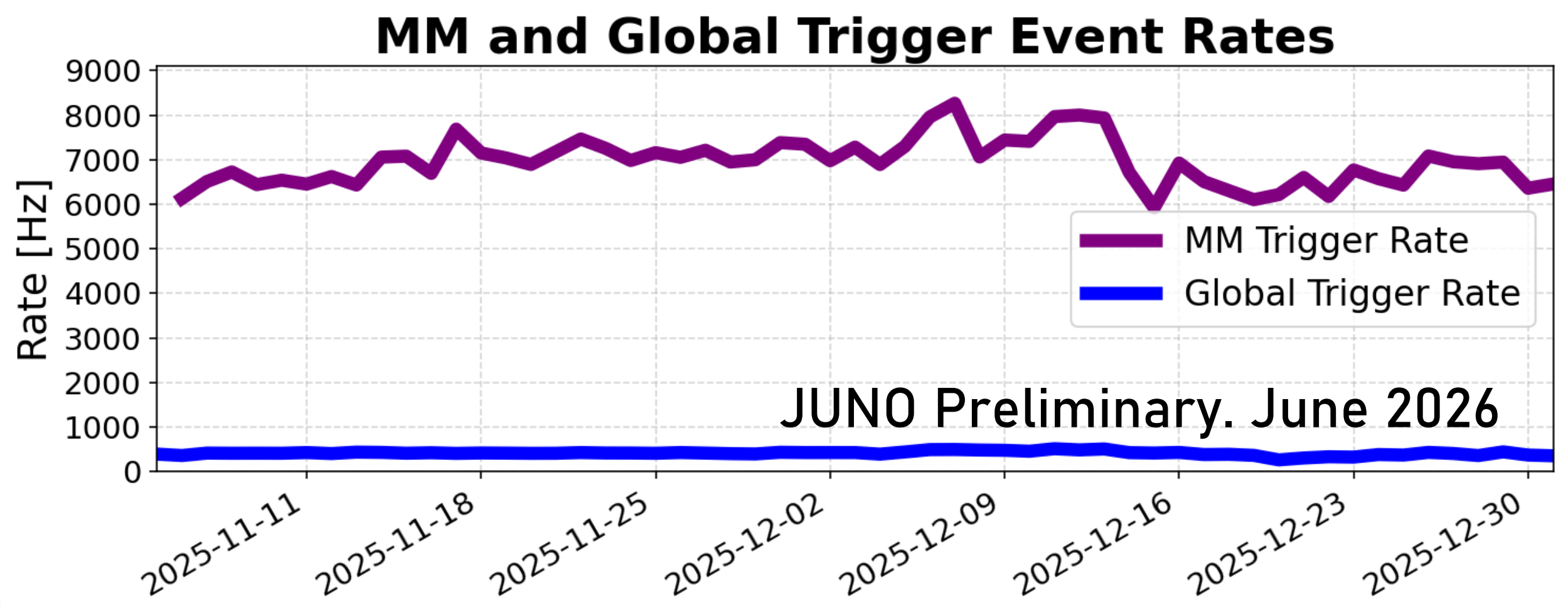


Figure 3: JUNO Global Trigger and MM Trigger Rate

MM Trigger Algorithm

1. Core Concept

☐ Goal: Separate clustered physical events from PMT dark noise, expected to be uniform in space.

☐ Method: Likelihood-based trigger algorithm.

2. Space-Time Binning

☐ Time Window: 192 ns, divided into 4 time bins ($B_t = 4$).

☐ Spatial Grid: 17,596 PMTs divided into 16 spatial blocks ($B_\theta \times B_\varphi = 4 \times 4$).

☐ Total: 64 space-time bins.

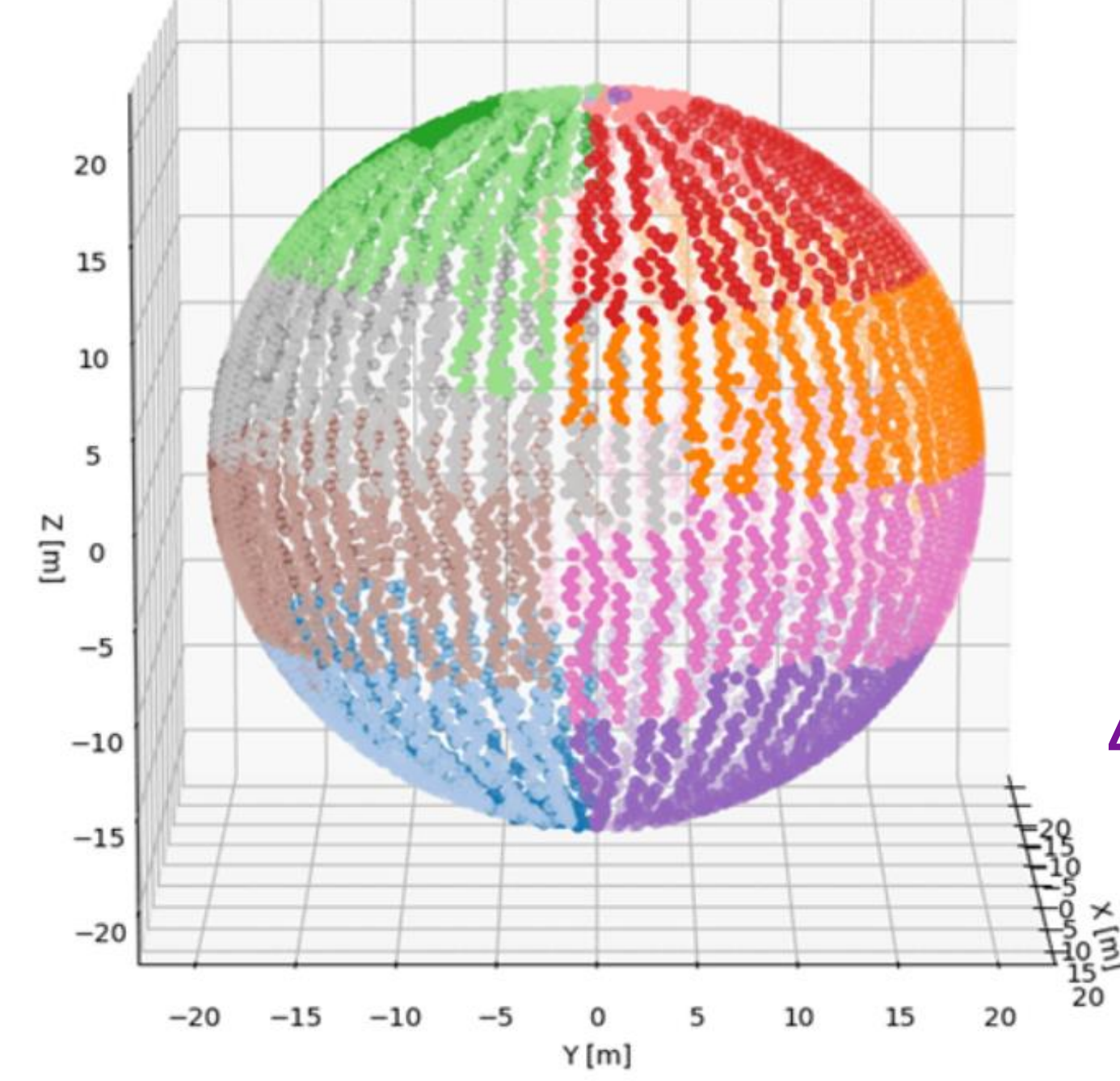


Figure 4: Spatial Grid

3. Likelihood Equation

$$\mathcal{L} = \prod_{i=1}^{4}\prod_{j=1}^{4}\prod_{k=1}^{4} \frac{\lambda^{N_{ijk}}}{(N_{ijk})!} e^{-\lambda}$$

☐ N_{ijk} : Number of hits in bin (i, j, k) .

☐ $\lambda = 1.58$: Expected dark noise hits per bin.

4. FPGA Implementation

☐ Trigger condition: $-\ln\mathcal{L}$ > Threshold.

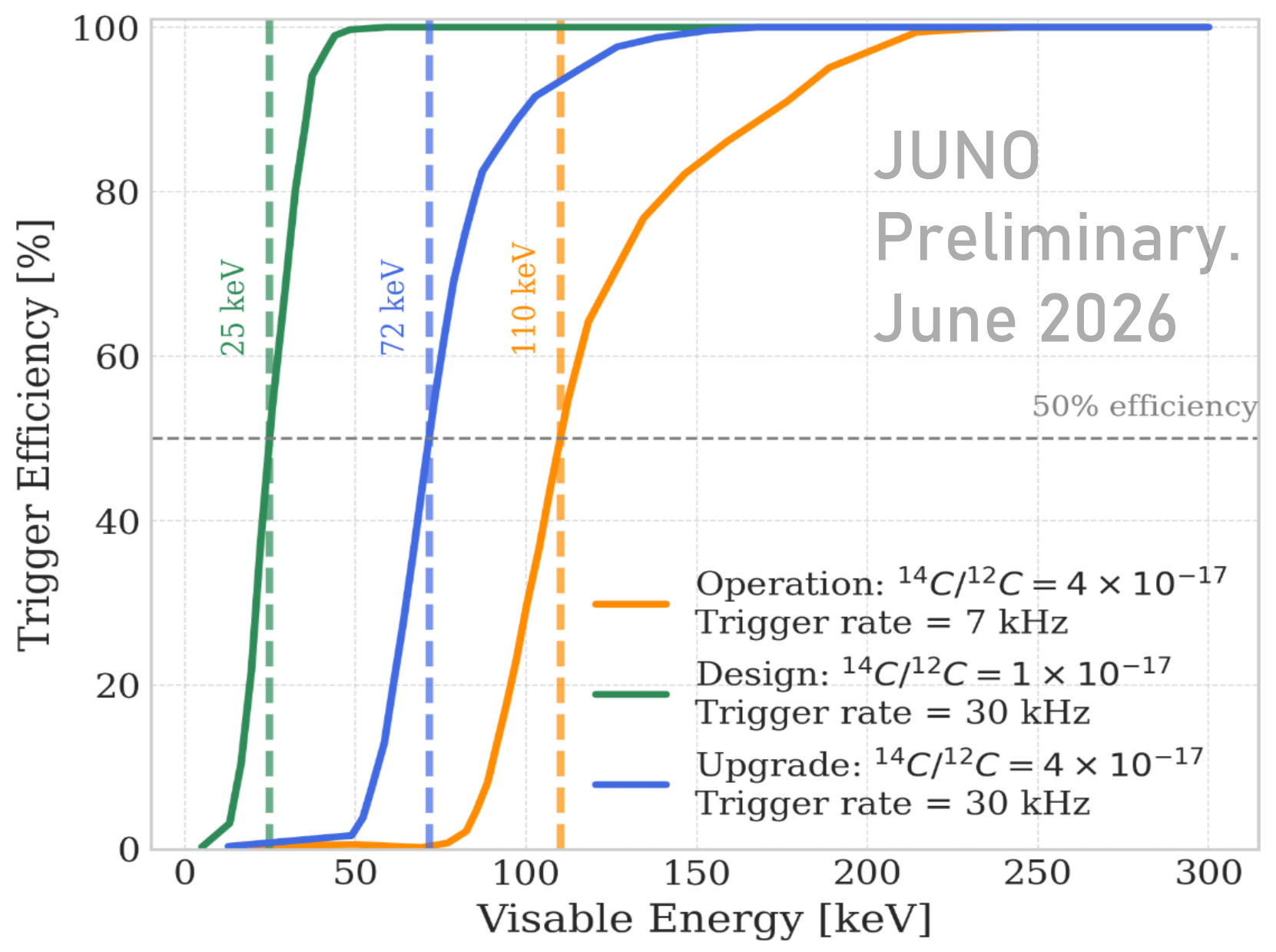


Figure 5: MM Trigger Efficiency

5. Minimum Energy Threshold

Initial Design:

☐ Threshold: ~25 keV.

☐ Assumes ^{14}C / ^{12}C ratio (1×10^{-17}) and 30 kHz rate.

Current Operation:

☐ Threshold: ~110 keV.

☐ Trigger Rate: ~7 kHz.

☐ Measure ^{14}C / ^{12}C ratio (4×10^{-17}, Poster #323)

Future Upgrade

☐ Threshold: ~72 keV.

☐ Requirement: bandwidth upgrade to support a 30 kHz total trigger rate.

Hardware

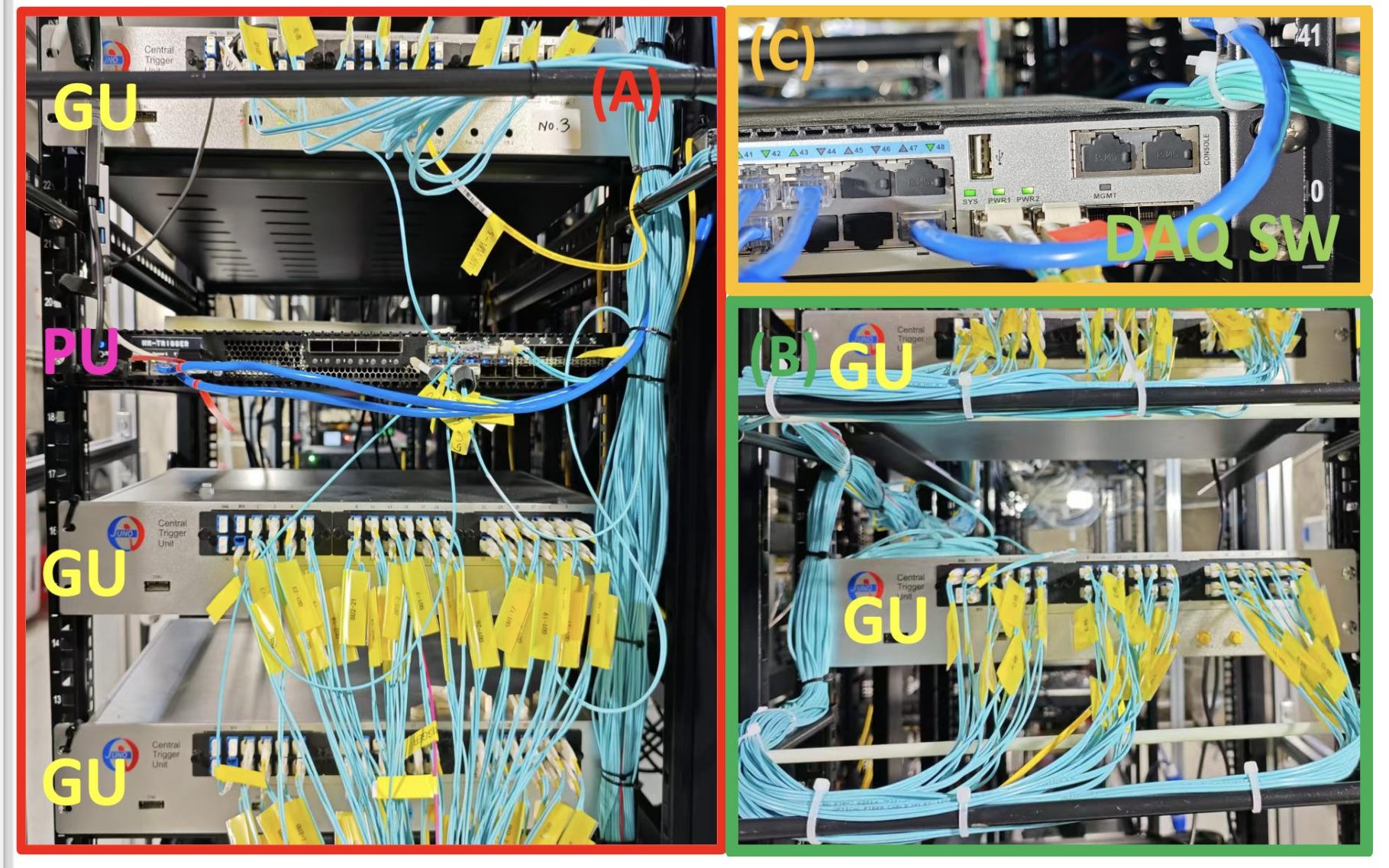


Figure 6: MM Trigger Hardware

GU (Gather Unit):

☐ White Rabbit (WR) system for accurate timestamp.

PU (Processing Unit):

☐ A TeraBox-1100L FPGA server. Trigger in FPGA and Monitor in CPU.

Transient Neutrino Burst Monitor

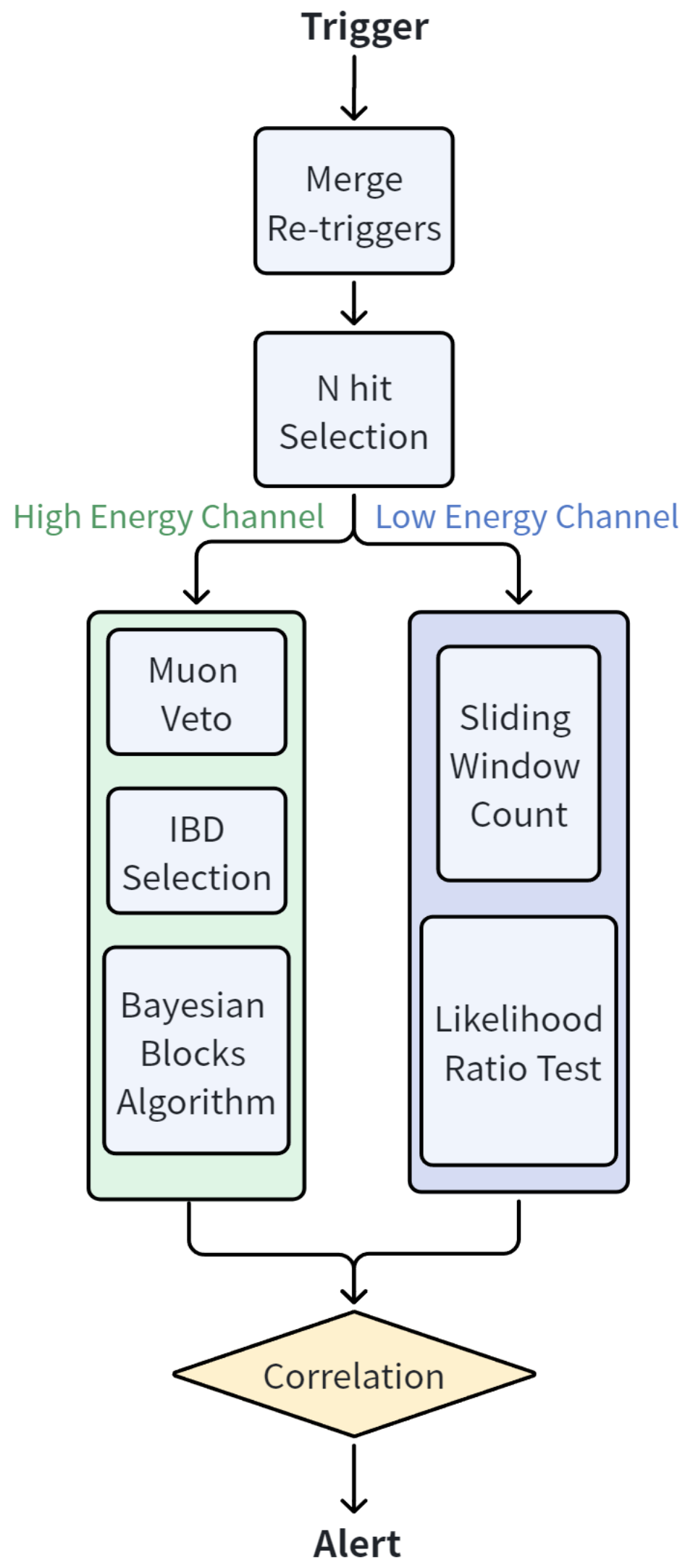


Figure 7: Workflow

Introduction:

☐ Goal: Fast, low-latency alert generation without full reconstruction and the number of PMTs hit (Nhit) used to measure energy.

☐ **High Energy Channel**: Focuses on IBD events (~5-40 MeV). Uses Bayesian Blocks Algorithm[2] (BBA) for model-independent burst detection.

☐ **Low Energy Channel**: Focuses on νpES and νeES (~0.1-5 MeV). Uses a sliding window counting method.

Background Suppression (high energy channel)

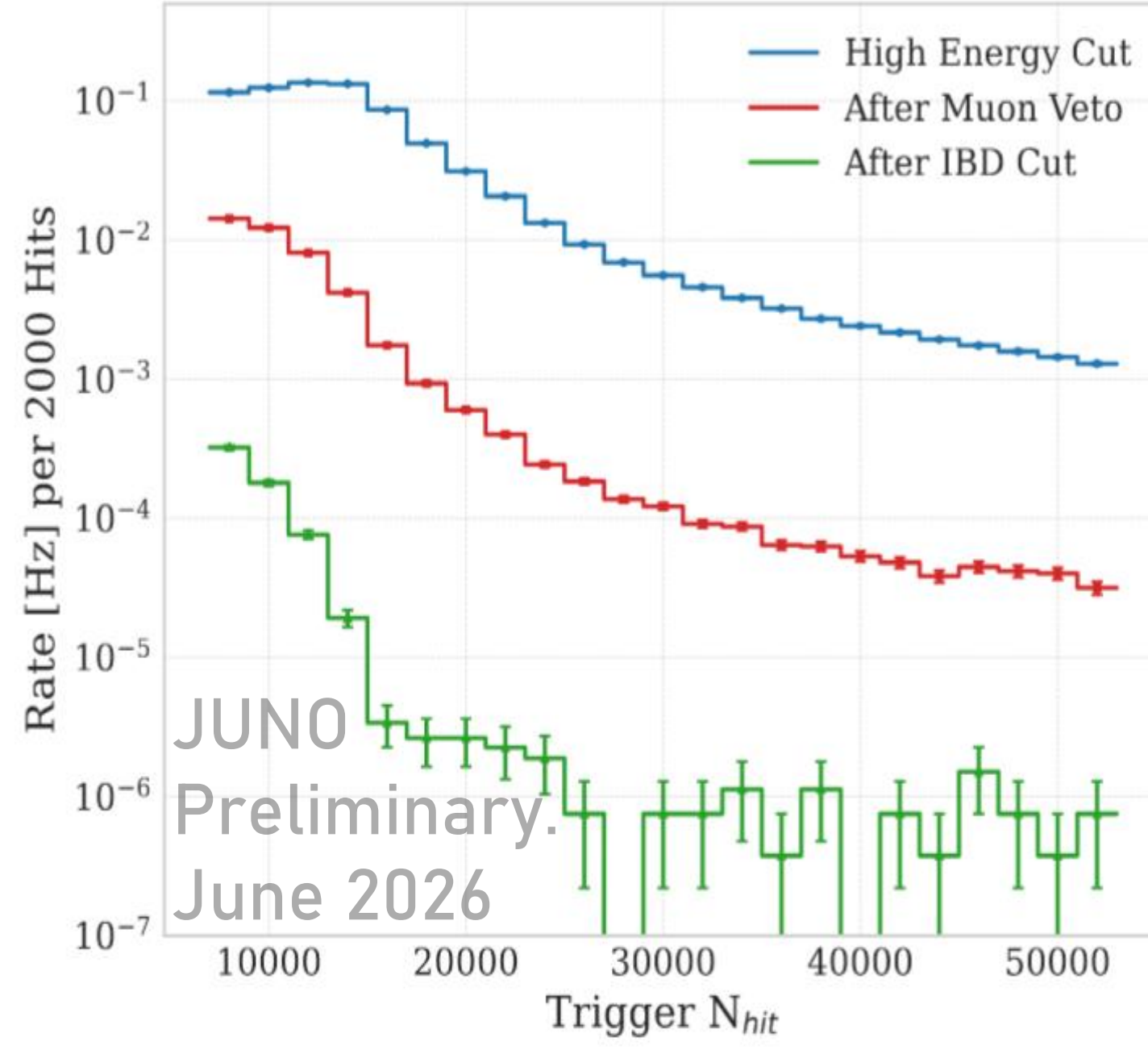


Figure 8: High Energy Channel Background

☐ Muon Veto: ~97% efficiency using water pool PMTs.

☐ Inverse Beta Decay: Simple prompt-delayed coincidence cuts reduces background from 2500 events/day to ~ 64 events/day.

Test Statistic

$$\mathrm{TS}_{\mathrm{high}} = \begin{cases} -2\ln\left(\frac{L_0}{L_1}\right), & \text{if } L_1 > L_0 \\ 0, & \text{otherwise} \end{cases} \qquad \mathrm{TS}_{\mathrm{low}} = \begin{cases} 2\left[n\ln\left(\frac{n}{b}\right) - (n-b)\right], & \text{if } n > b \\ 0, & \text{if } n \le b \end{cases}$$

High energy channel

☐ L_0 : Likelihood of single-block hypothesis.

☐ L_1 : Likelihood of multi-block hypothesis.

Low energy channel

☐ n : Number triggers in 5 ms window.

☐ b : Expected baseline.

False Alert Rate(FAR)

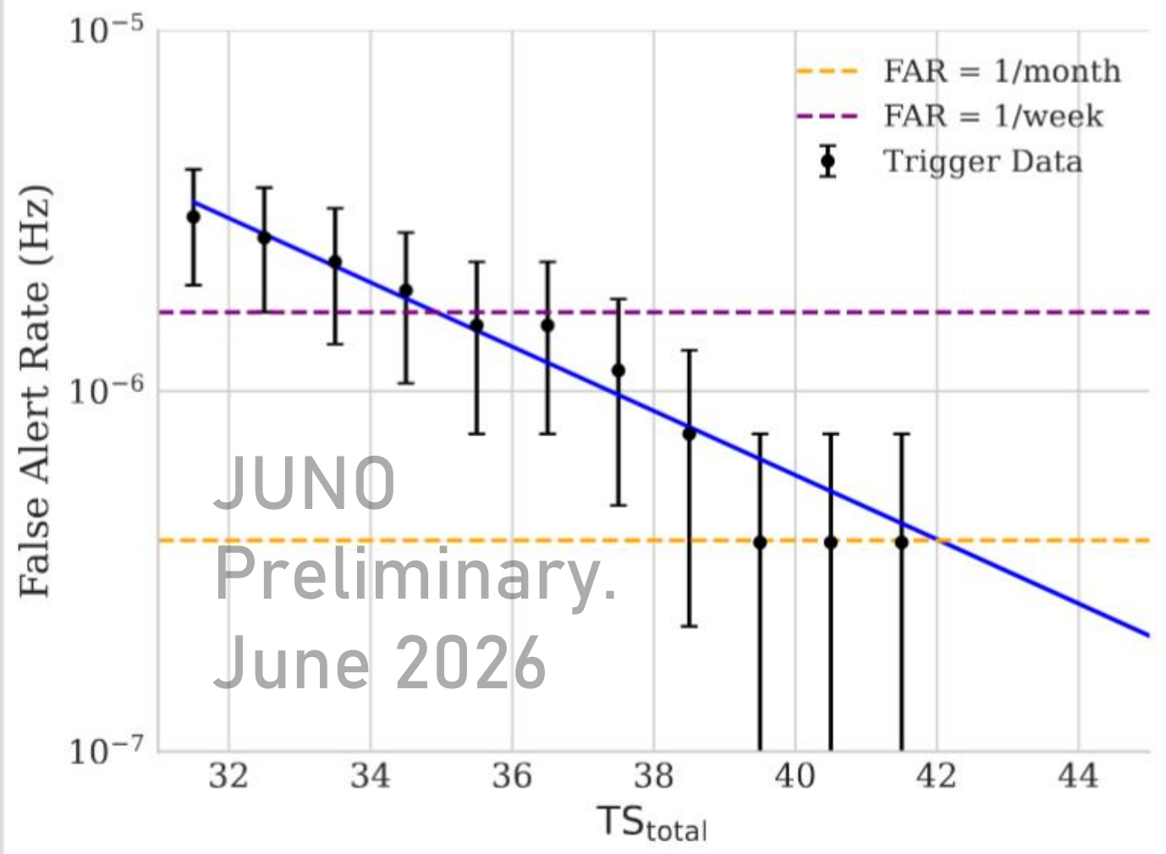


Figure 9: FAR versus $\mathrm{TS}_{\mathrm{total}}$

☐ Condition: BBA Block rate is increasing.

☐ Combination:

$$\mathrm{TS}_{\mathrm{total}} = \mathrm{TS}_{\mathrm{low}} + \mathrm{TS}_{\mathrm{high}}$$

☐ Threshold: $\mathrm{TS}_{\mathrm{total}} \geq 42$ corresponds to FAR = 1/month (evaluated with 1-month background data).

A False Alert Example (by shower muon)

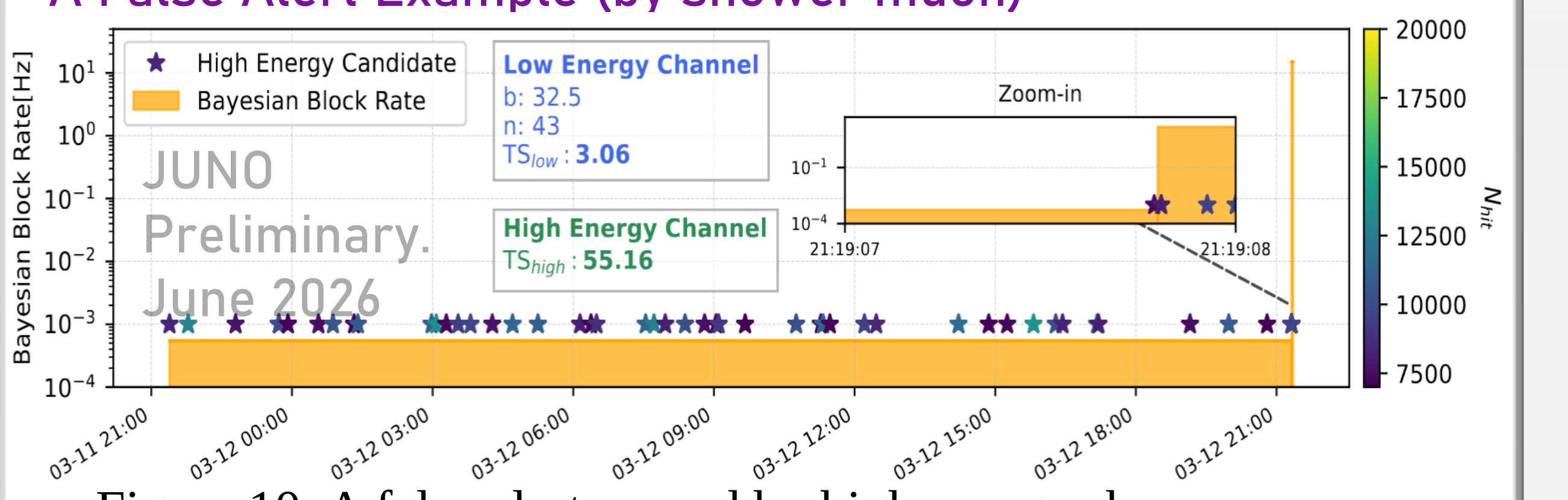
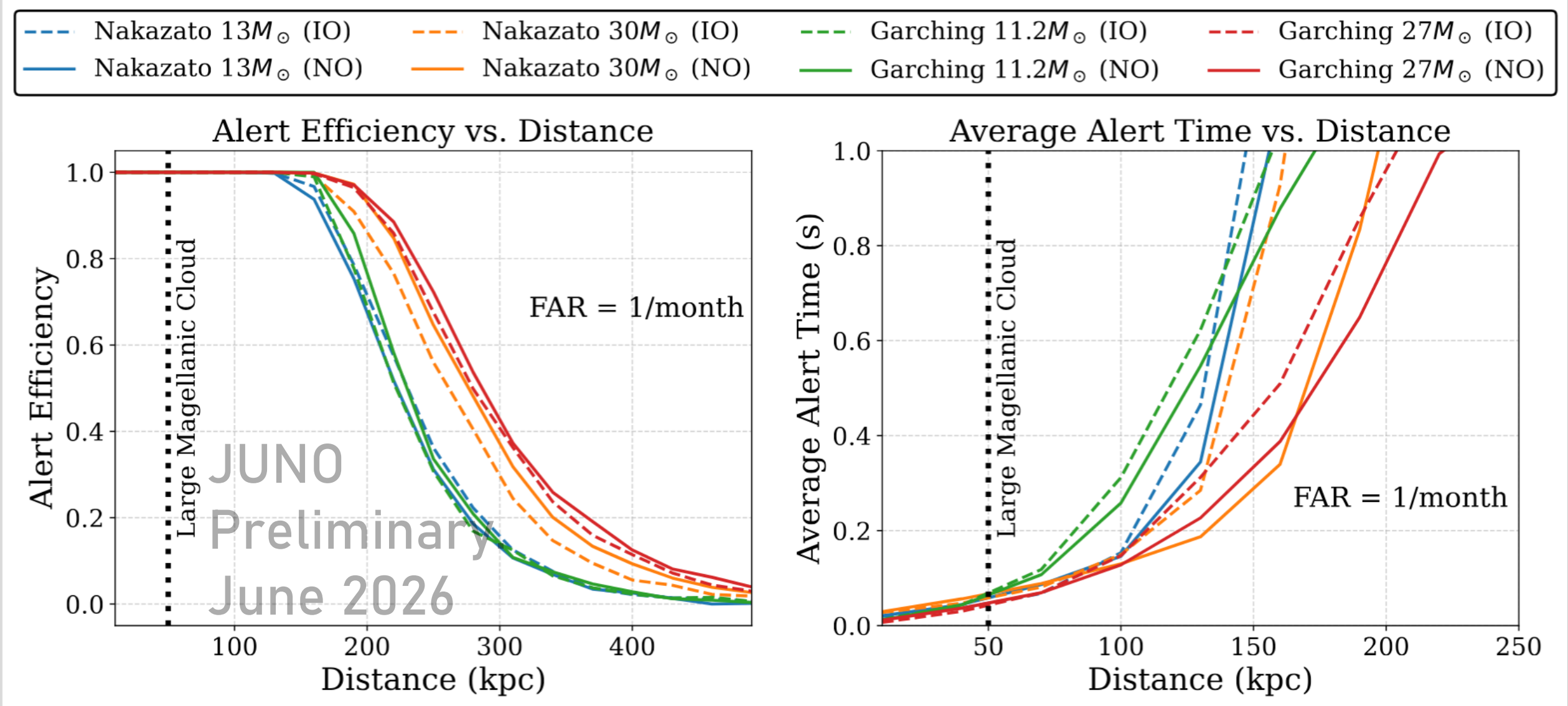


Figure 10: A false alert caused by high energy shower muon

Monitor Performance

Current Monitor Performance



☐ Test Models: Evaluated with 4 CCSN models (Nakazato[3] & Garching[4]) at FAR = 1/month(: $\mathrm{TS}_{\mathrm{total}} \geq 42$).

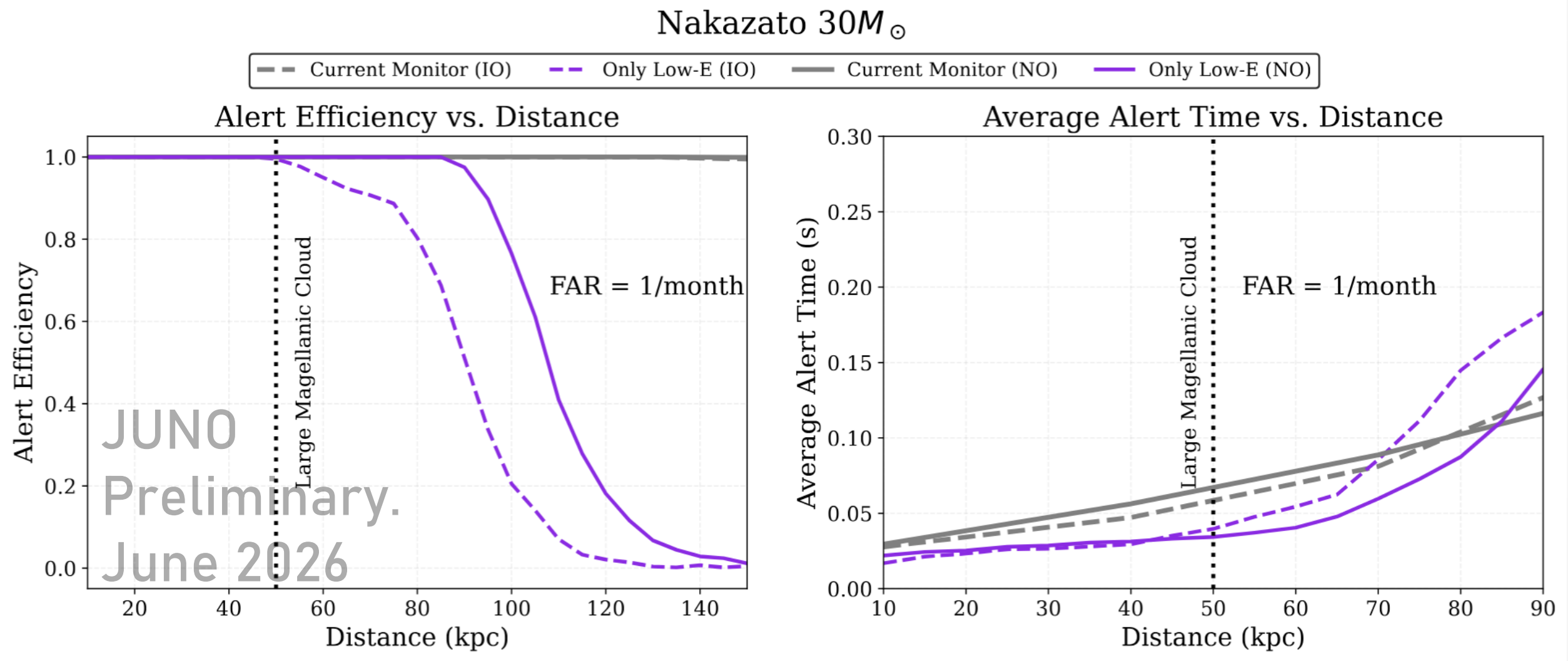
☐ Coverage: 100% alert efficiency for the Milky Way and Magellanic Clouds (< 100 kpc).

☐ Sensitivity: 50% alert efficiency reaches 220-280 kpc.

☐ Alert Time: < 0.1 s after core bounce for the Large Magellanic Cloud (LMC).

☐ SNEWS 2.0[5]: Connected since Nov 28, 2025

Potential of Low-Energy Channel



☐ Independent Alert: The Low-E channel alone can provide 100% efficiency for the LMC.

☐ Faster Response: Issues alerts ~10 ms earlier at close distances by detecting the early ν_e burst via νpES and νeES .

Reference

[1] JUNO Collaboration, Nature 654 (2026) 343–348
[2] J. D. Scargle, Astrophys. J. 504 (1998) 405
[3] K. Nakazato et al., Astrophys. J. Suppl. 205 (2013) 2
[4] F. S. Kitaura et al., Astron. Astrophys. 450 (2006) 345
[5] S. Al Kharusi et al., New J. Phys. 23 (2021) 031201

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