

First Results of JUNO-TAO

(Taishan Antineutrino Observatory)

Yichen Li

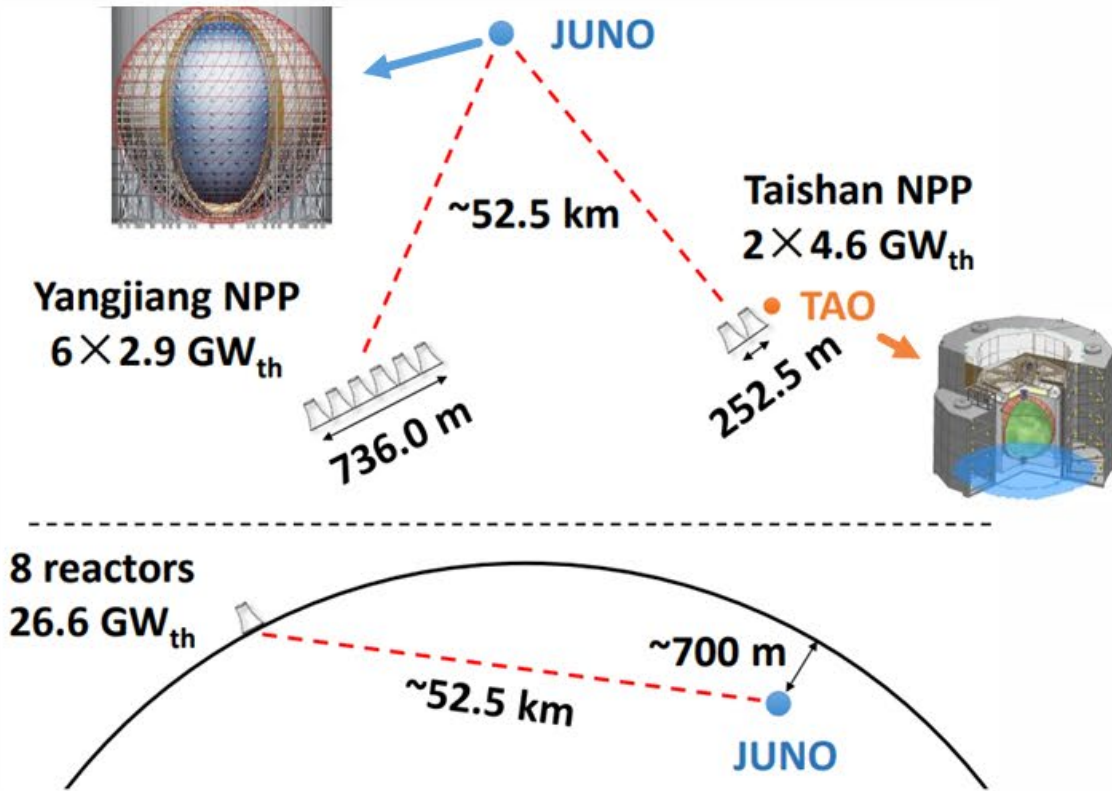
(Institute of High Energy Physics)

on behalf of JUNO Collaboration

NEUTRINO 2026, University of California Irvine



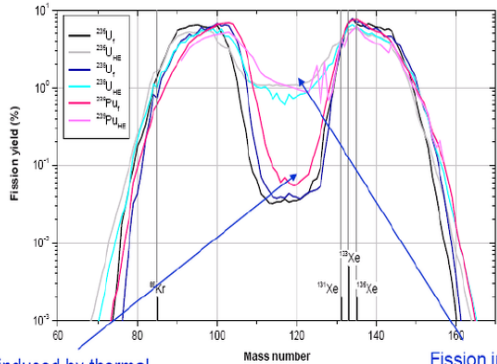
JUNO-TAO: A Short Baseline Reactor Neutrino Experiment



TAO is the satellite experiment of JUNO

TAO is deployed near Unit 1 with a baseline of 43.2 m

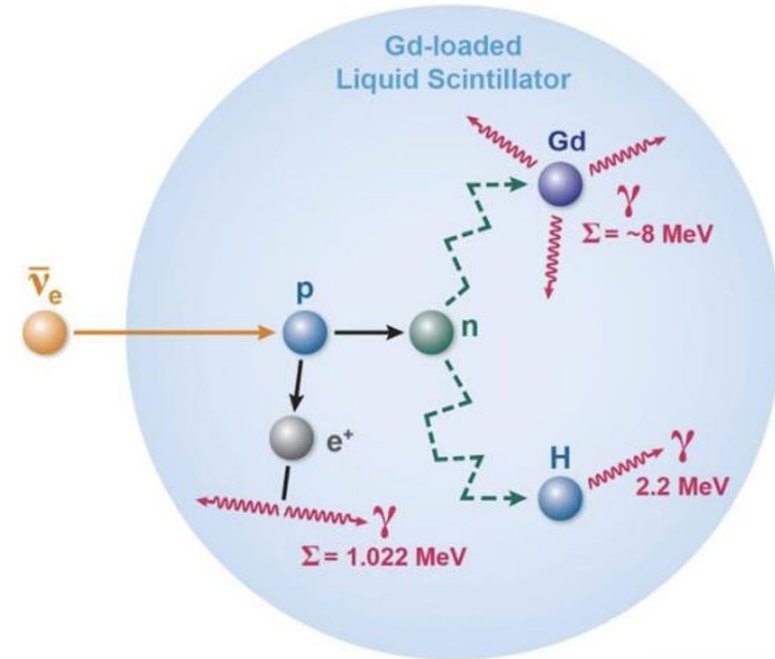
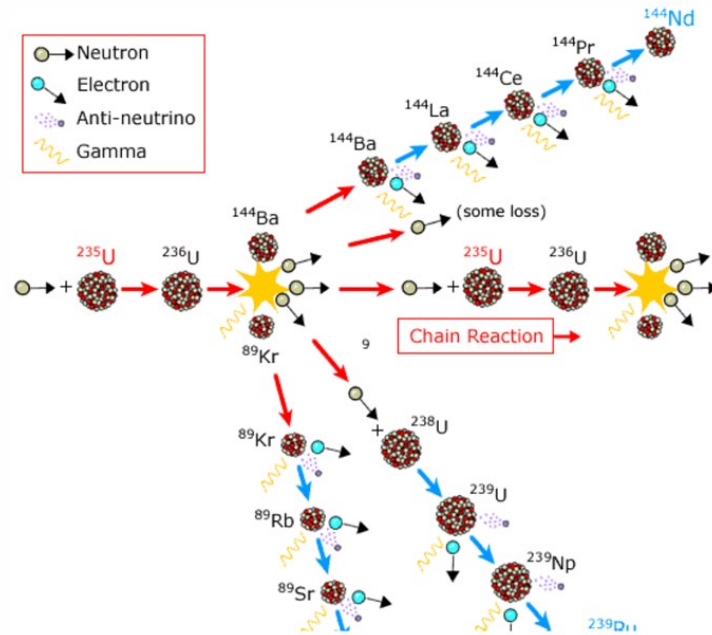
Reactor Neutrino Production and Detection



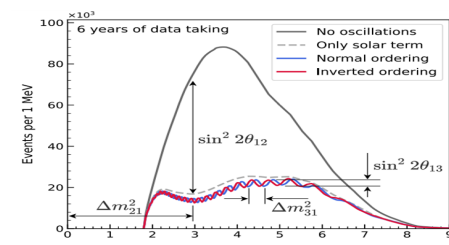
Beta decay chain of fission fragments of U/Pu releases $\sim 6 \bar{\nu}_e$ / fission



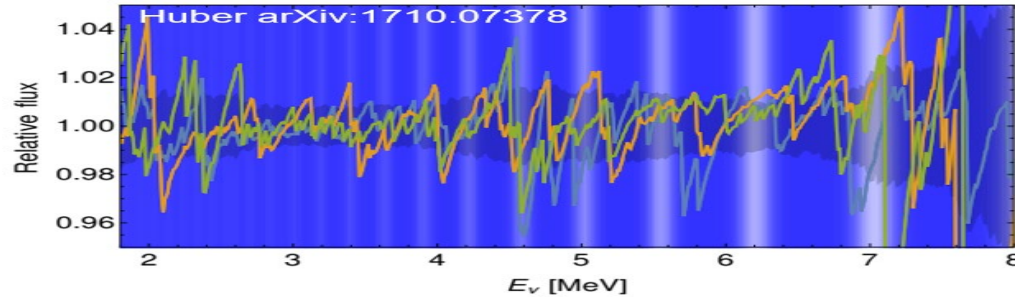
- Inverse Beta Decay
 - $E(\bar{\nu}) \approx E(e^+) + 1.293 \text{ MeV}$
 - Signature
 1. prompt signal (e^+)
 2. delayed signal ($nH / nGd / nCd / \dots$)



Introduction: Motivation

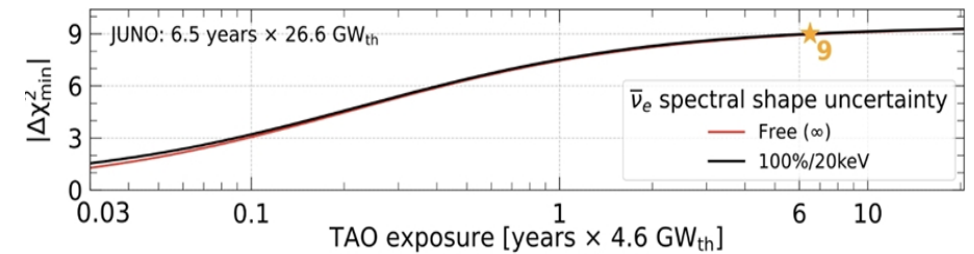
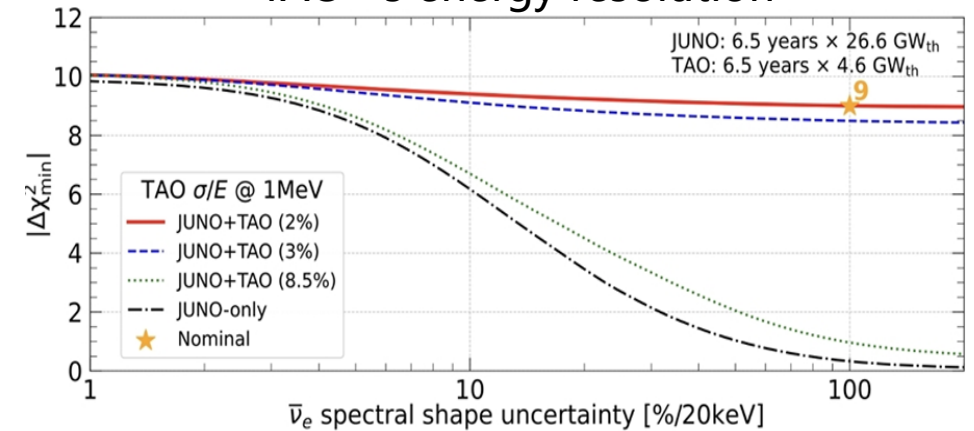


- Unknown intrinsic fine structures could bias JUNO's neutrino mass ordering (NMO) measurement



- No reliable theory/measurement to constrain
 - a **NEW DETECTOR**, with better energy resolution than JUNO (3% @1MeV)
- Taishan Nuclear Power Plant: high power (4.6 GW), ideal space (500 m², baseline 43.2 m, -9.6 m)
 - **Taishan Antineutrino Observatory, TAO** (CDR arXiv 2005.08745)

JUNO NMO sensitivity dependency on TAO's energy resolution

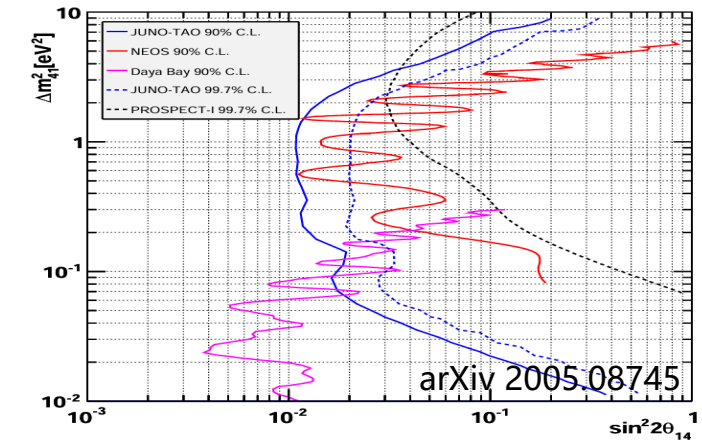


Chinese Physics C, 2025, 49(3)

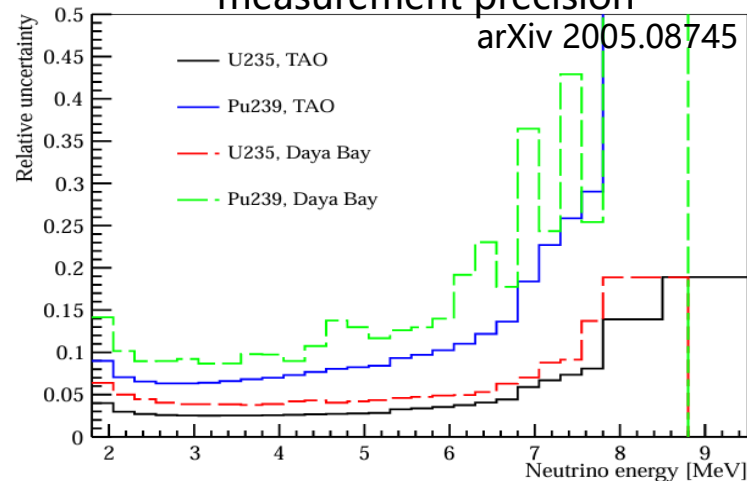
Introduction: Physics Goals

- ❑ Reference data to JUNO and Benchmark data for nuclear database
 - Highest possible energy resolution: 2% @1MeV
- ❑ U/Pu neutrino spectrum measurement with improved precision
- ❑ 5 MeV “Bump” investigation and Fine Structure observation
- ❑ Spent Nuclear Fuel (SNF) neutrino measurement
- ❑ Sterile and other new physics

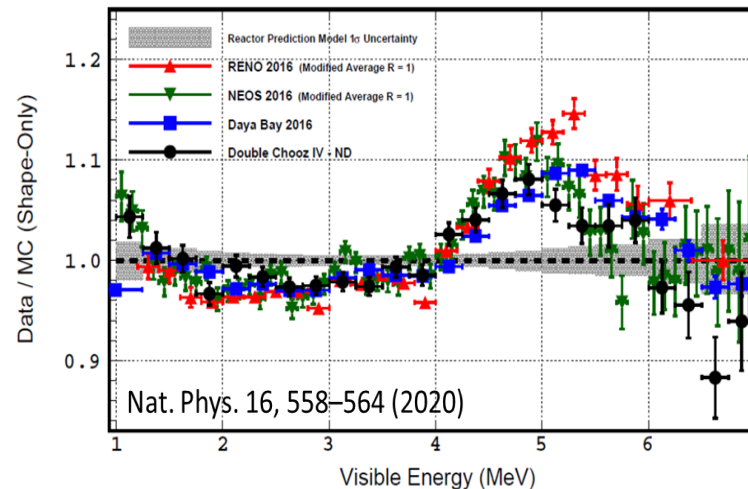
Sensitivity to sterile neutrino



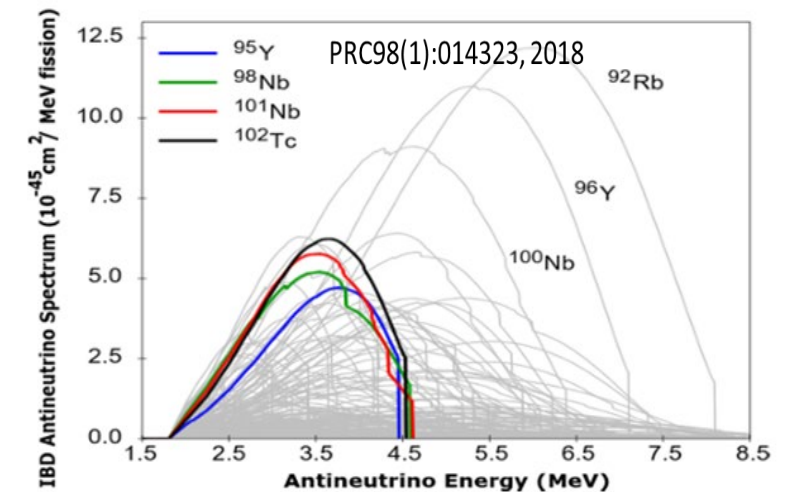
Expected U/Pu neutrino spectrum measurement precision



5MeV “Bump”



Fine Structures



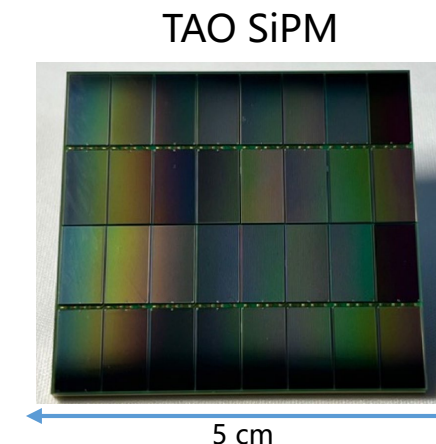
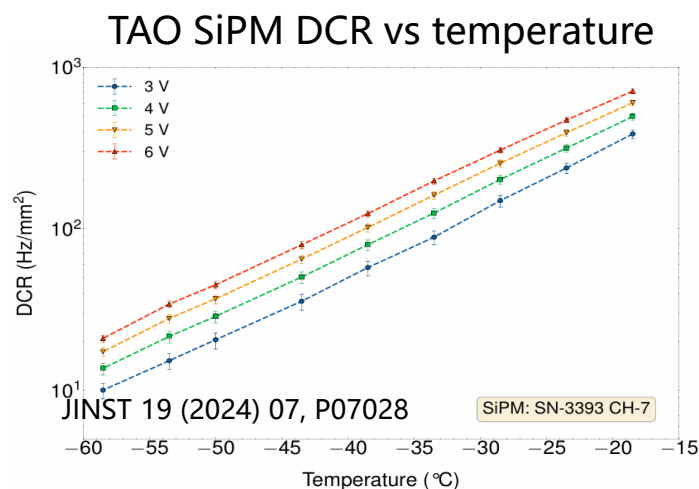
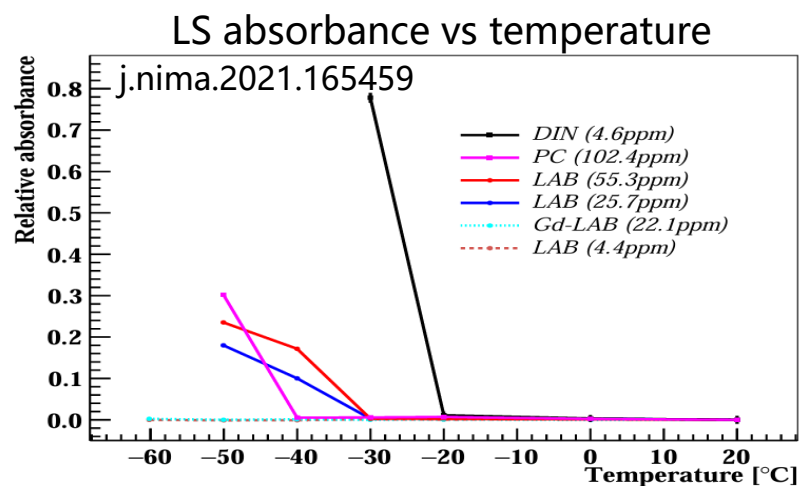
Introduction: Innovation

□ LS+PMT → Low-temperature LS + SiPM

- Photon detection efficiency (PDE): **~50%** (JUNO ~30%)
- **Compact** design: **85%** photo-sensor coverage (JUNO ~78%)
- Small detector → less light attenuation
- LS light yield increase at low temperature: **~10%**
- **Low temperature: -50°C**, dark count rate (DCR) reduced to $< 100 \text{ Hz/mm}^2$ (3 orders of magnitude w.r.t. room temperature)



Photo-electron yield (PE/MeV)
~4500 (JUNO ~1700)
 → statistical component
 suppressed to **1.5% @1MeV**



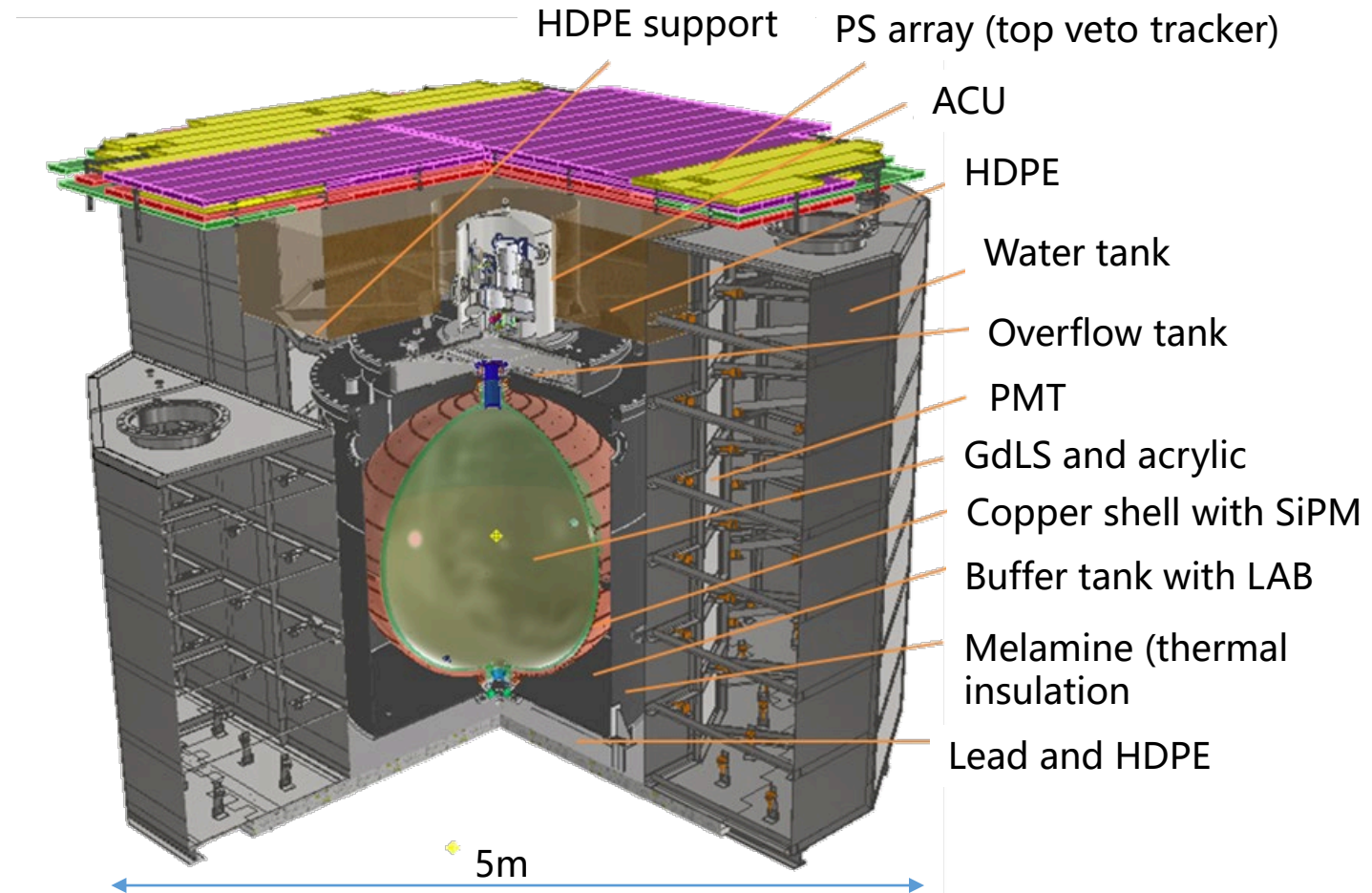
Introduction: Detector Design

□ Central detector (CD)

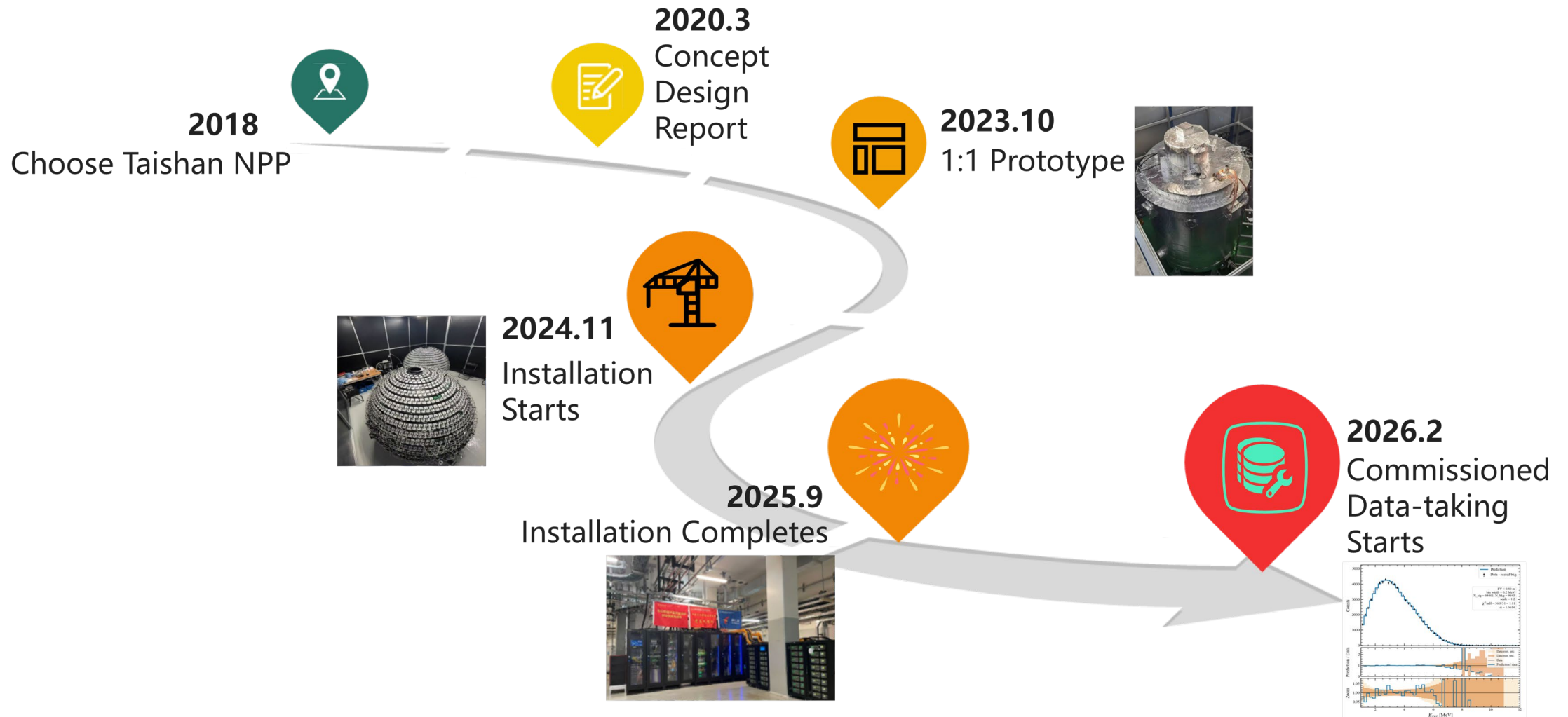
- 2.8 t GdLS in an acrylic vessel ($\varnothing = 1.8\text{m}$)
- 10 m² SiPM on a copper shell
- Tank filled with buffer LAB
- Automated Calibration Unit (ACU) (from Daya Bay) and Cable Loop System (CLS)

□ 2 veto detectors

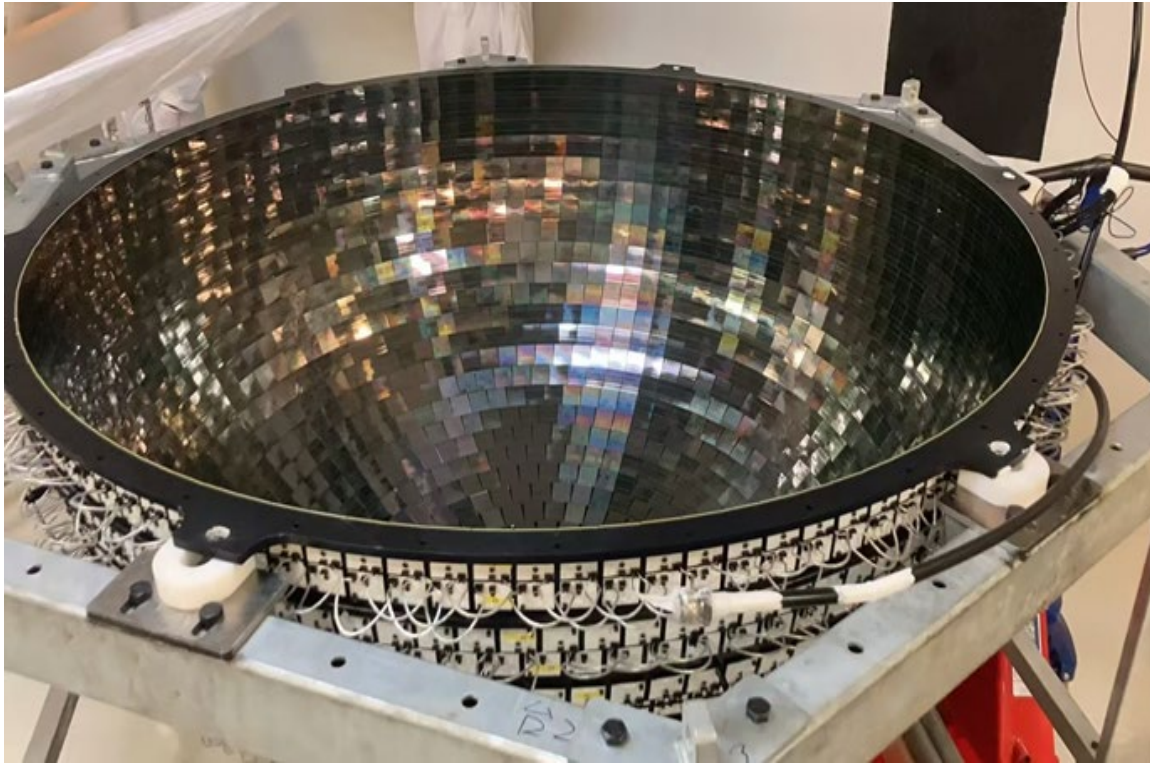
- 3 water Cerenkov detectors
- 4 layers of plastic scintillator (PS) bars



Introduction: Roadmap



Detector Construction: Detector Assembly



South-hemisphere instrumented with SiPMs



Acrylic sphere assembled (2 cm clearance)

Detector Construction: Detector Installation



Fully-cabled sphere loaded into buffer tank



Water tanks positioning around CD tank

Detector Construction: Veto Detectors



Plastic scintillator strips assembly on top of water tanks



PMT assembly in water tank

Detector Performance: Good Channel Map

90% good channel

■ Total channel number: 8048

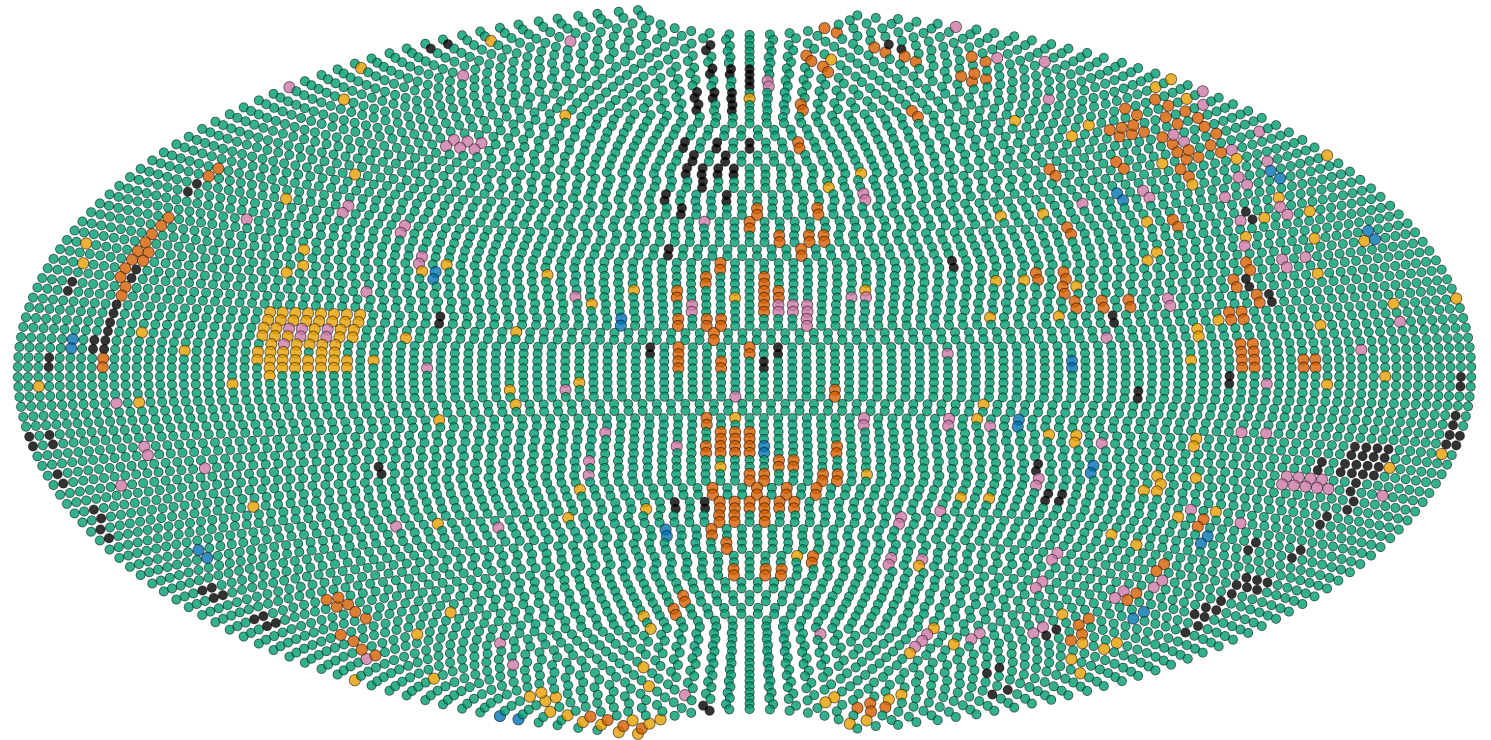
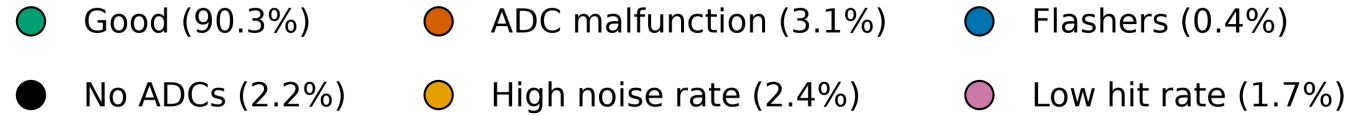
For the rest 10%

■ 5.3% ADC missing/broken
→ will be completed/replaced

■ 2.4 % noisy channels
→ addressing noise issue

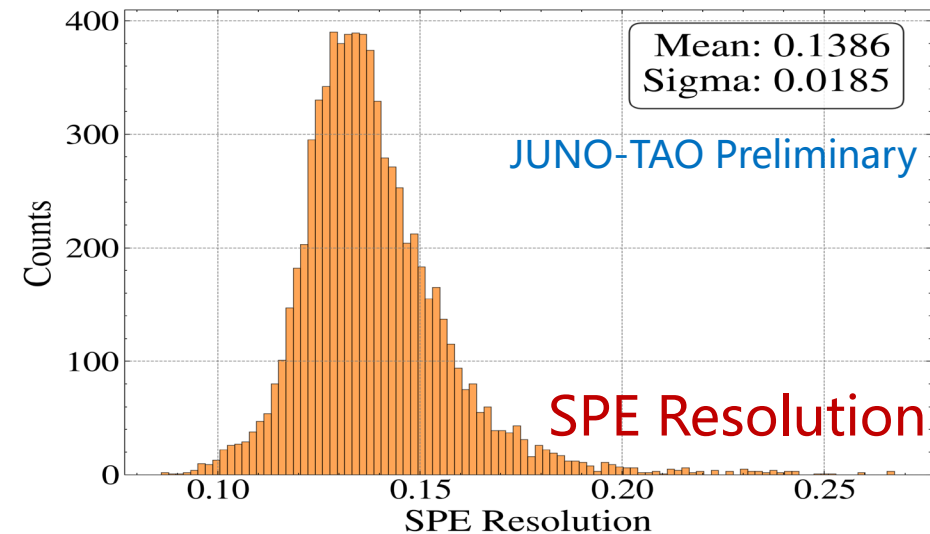
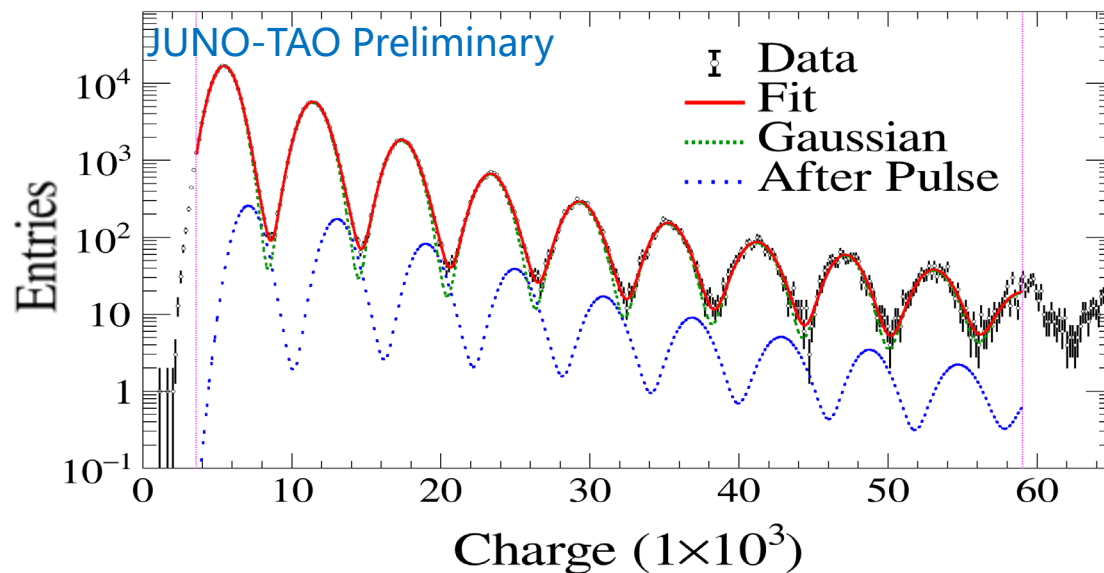
■ Low hit rate: 1.7%

■ Flasher: 0.4%



Detector Performance: SiPM

- ❑ SiPM over voltage V_{ov} : 3.5 V (Ge-68 energy resolution scan)
- ❑ Gain: 6000 ± 130 LSB, **uniformity** $\sim 2\%$, **stability**: $\sim 0.1\%$
- ❑ Single photo-electron (SPE) resolution: $\sim 14\%$ (15% in CDR)
- ❑ DCR: ~ 50 Hz/mm² (100 Hz/mm² in CDR)
- ❑ PDE: $\sim 50\%$ (SiPM QA/QC), **uniformity** $\sim 5\%$
- ❑ **Cross-talk**: $\sim 25\%$ (preliminary)
- ❑ **After-pulse**: $< 5\%$ (SiPM QA/QC)



Detector Performance: Vertex Reconstruction (Charge Center)

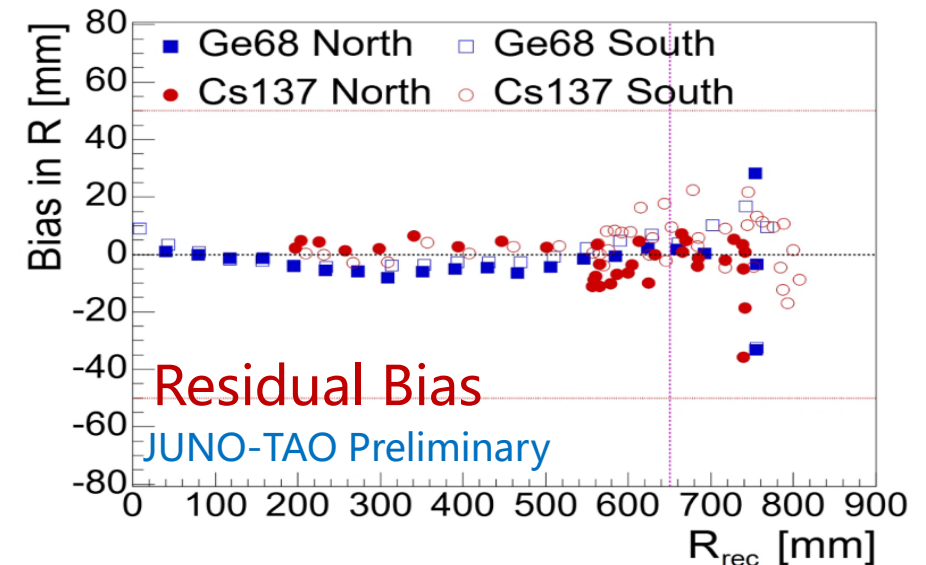
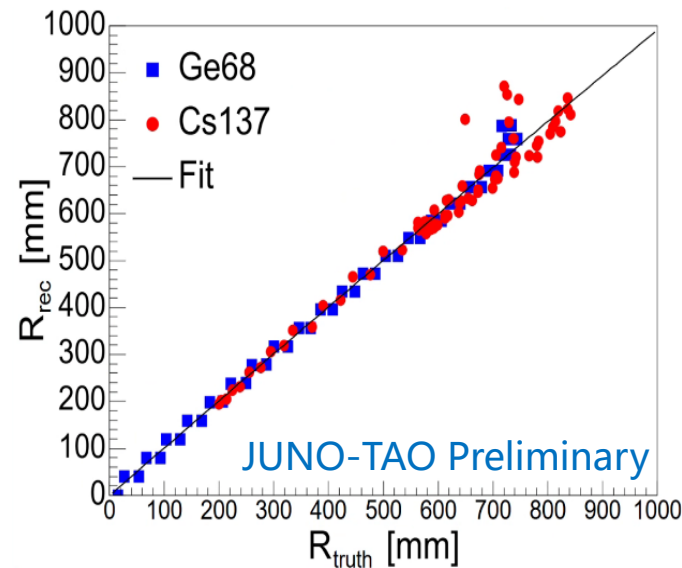
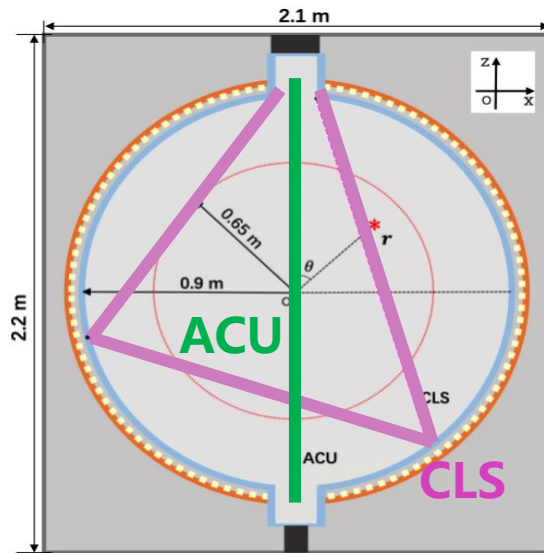
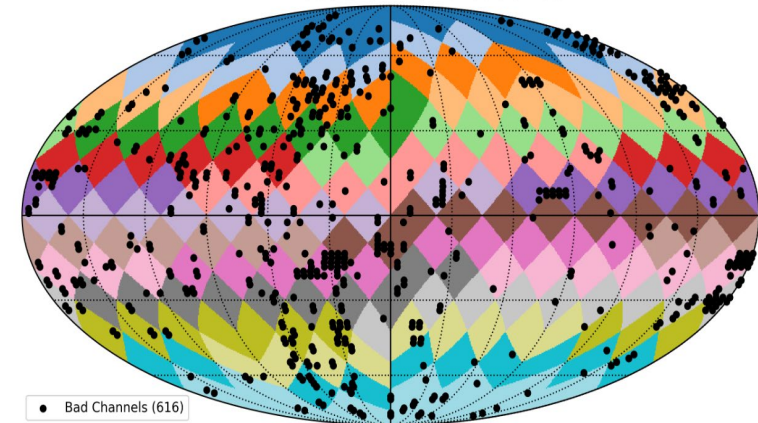


□ Procedure:

- 1) **group channels** to restore spherical symmetry;
- 2) calculate charge center;
- 3) correct R bias (ACU/CLS data in different positions);

□ Performance: **bias 10 (40) mm near R = 650 (800) mm**; resolution \ll γ -source intrinsic smearing

HEALPix Pixels (Npixel=192) and Bad Channels



Detector Performance: Energy Reconstruction (PE Sum)

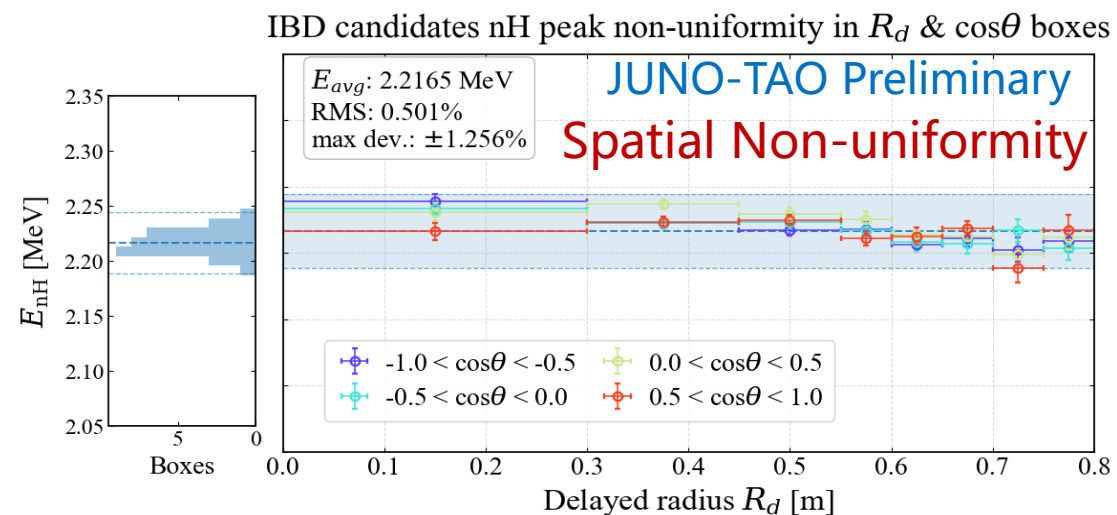
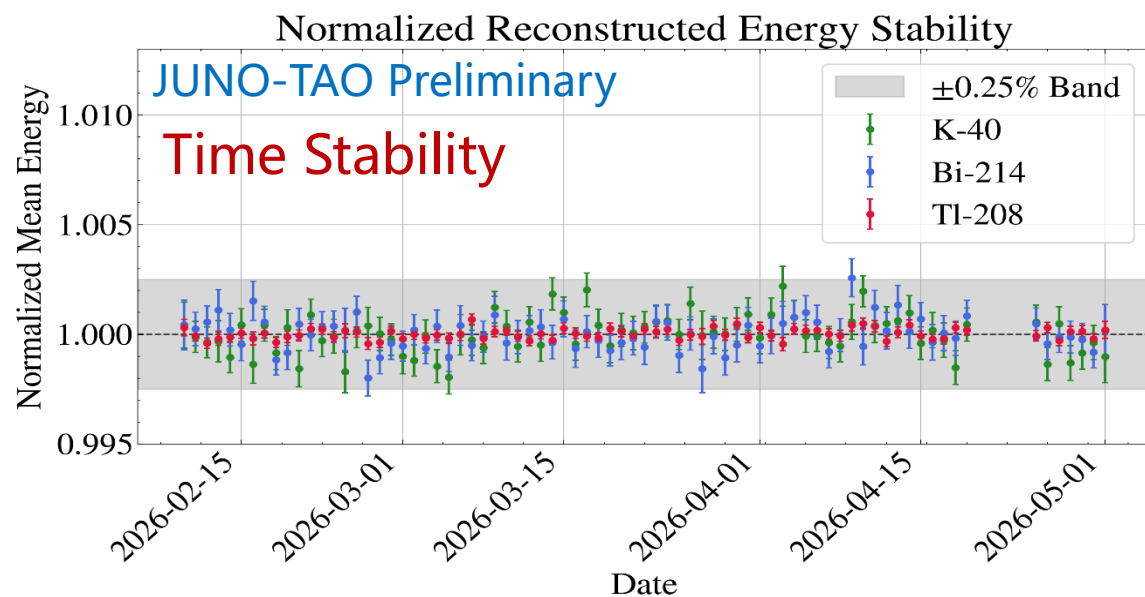
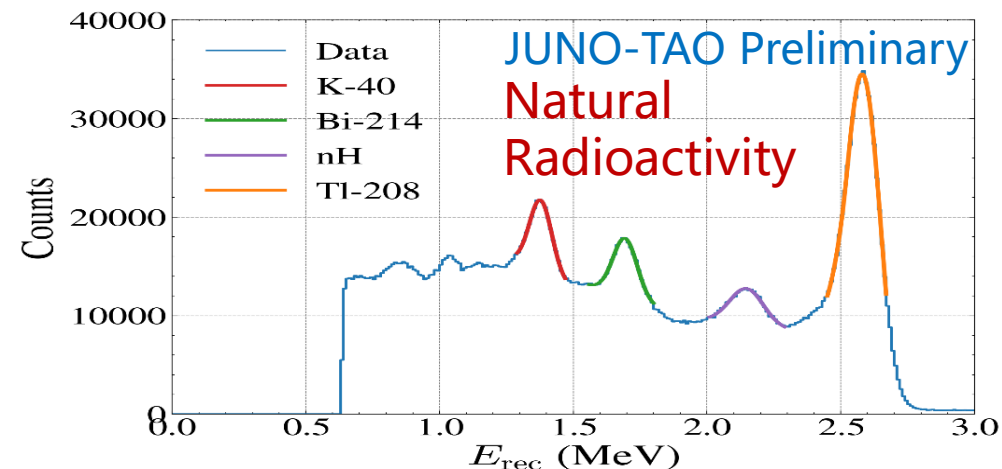


□ Procedure:

- 1) PE counting in channel;
- 2) PE sum in event;
- 3) non-uniformity correction (calibration data and Tl-208);
- 4) time variation correction (Tl-208);
- 5) fix energy scale (nH peak @2.223 MeV)

□ Energy scale performance:

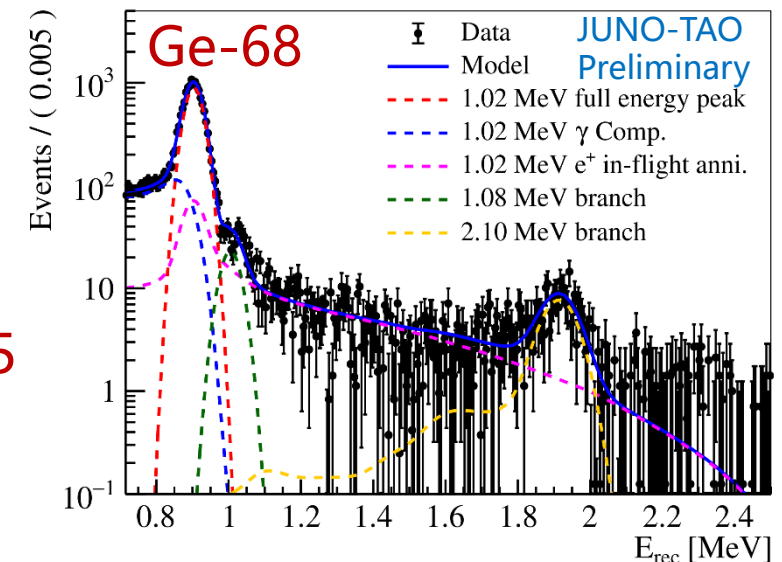
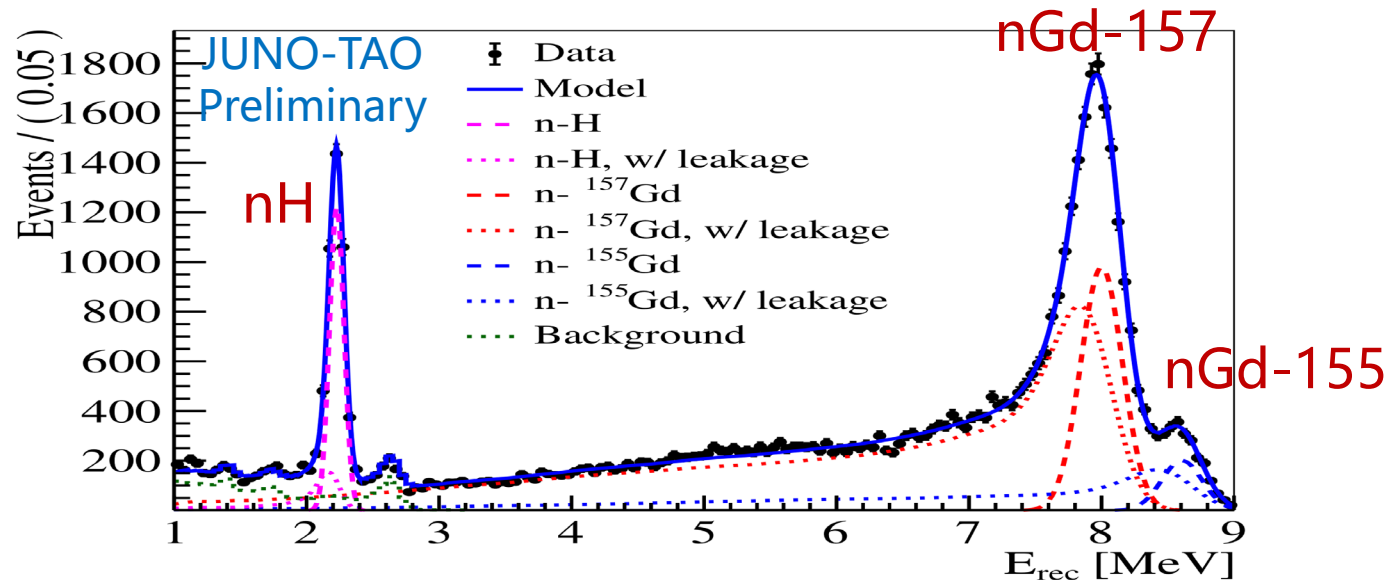
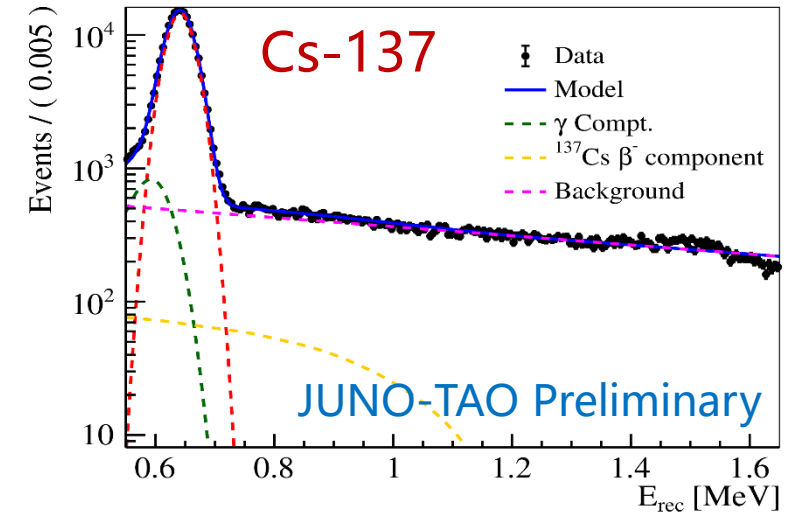
- time stability < 0.25% (natural radioactive events)
- non-uniformity 0.6% (IBD nH events)



Detector Performance: Single Point Energy Resolutions



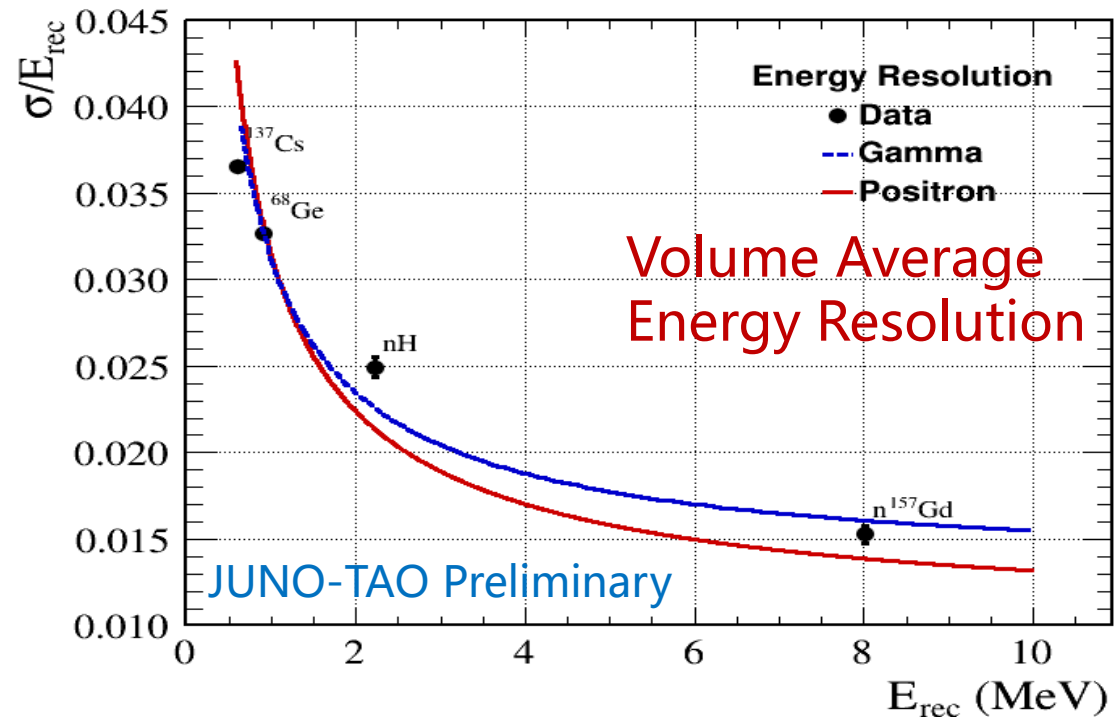
- Cs-137 @R = 200 mm: 3.65%
 - 0.662 MeV peak + beta component + energy leakage
- Ge-68 @R = 0: 2.82% @1MeV
 - 1.022 MeV peak + e+ annihilation in-flight + 1.08 de-excitation + energy leakage
- nH/nGd (R<400mm): 2.24% / 1.91%
 - 2.223 / 7.9 / 8.5 MeV peak + energy leakage tail



Detector Performance: Positron Energy Resolution Curve

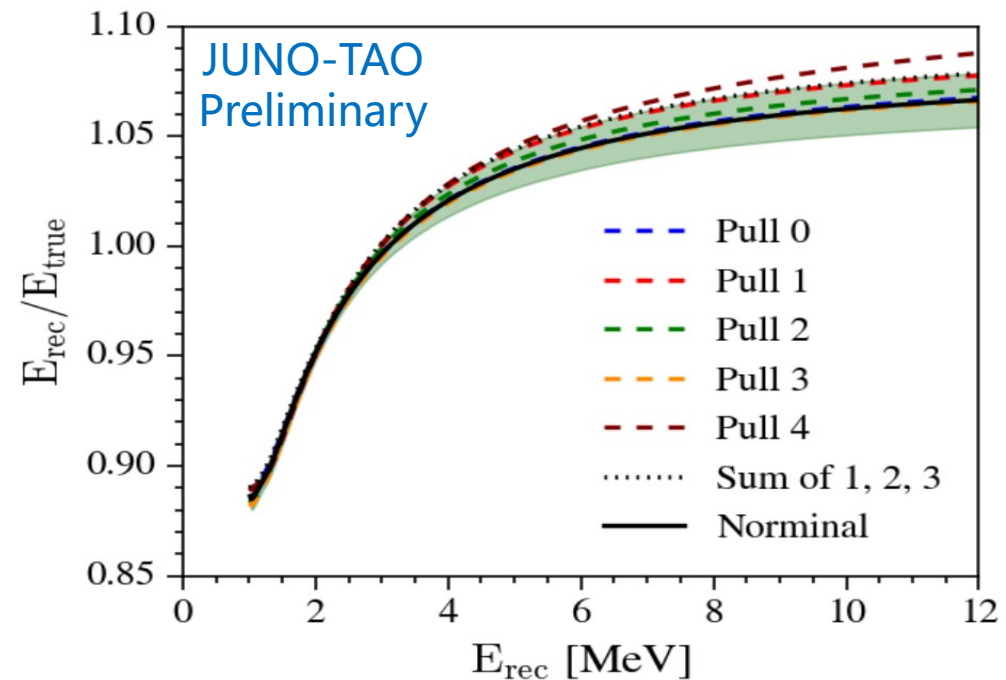
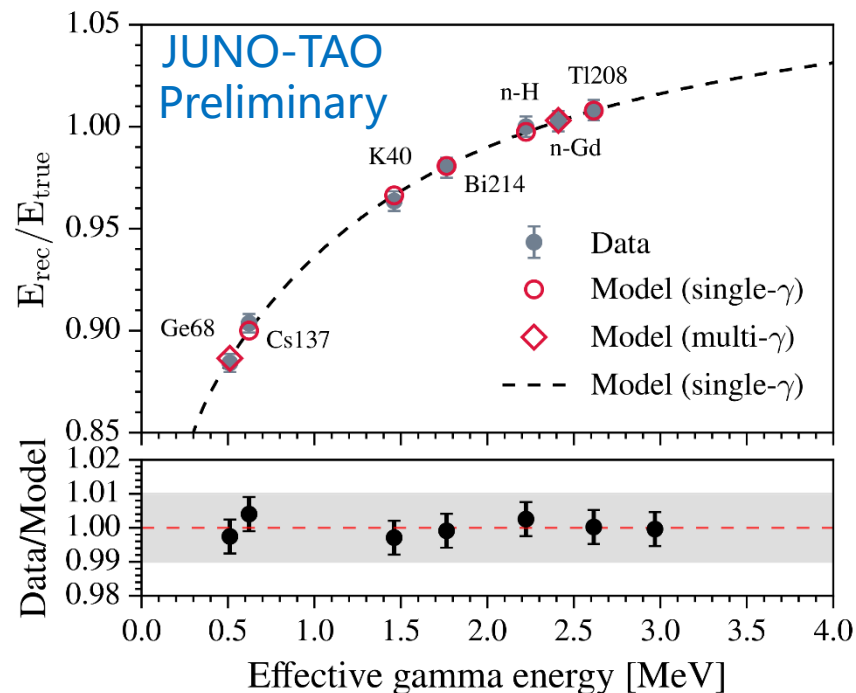


- ❑ 1. Fit single- γ resolution curve: Ge68, Cs137, nH, nGd (multi- γ converted to single- γ by MC)
- ❑ 2. Convert: γ curve $\rightarrow e^+$ curve using MC
- ❑ 3. Correction: spatial non-uniformity, using Ge/nH/nGd resolution variation in space
- ❑ Improvement in near future (to meet our goal of $\sim 2\%$)
 - Reconstruction algorithm (waveform, event)
 - Hardware: more channels, noise reduction
 - Better understanding of the spatial non-uniformity



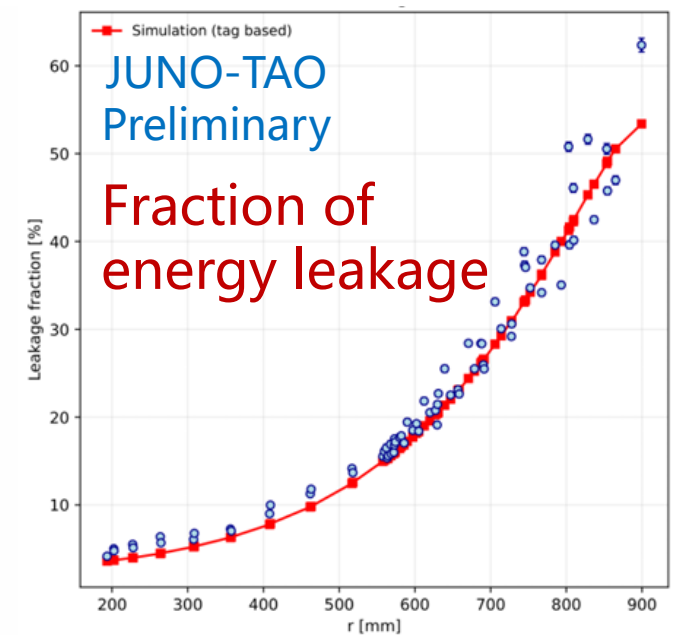
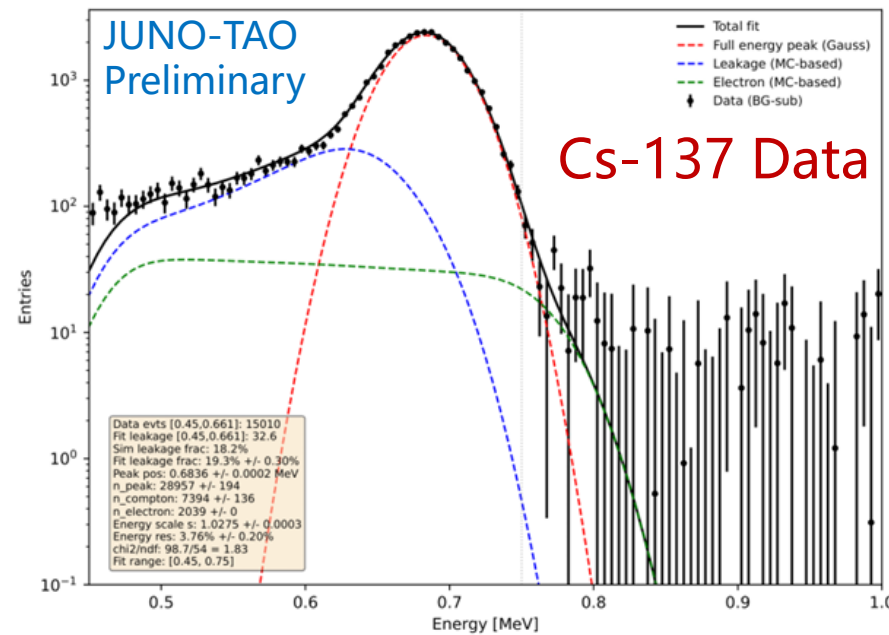
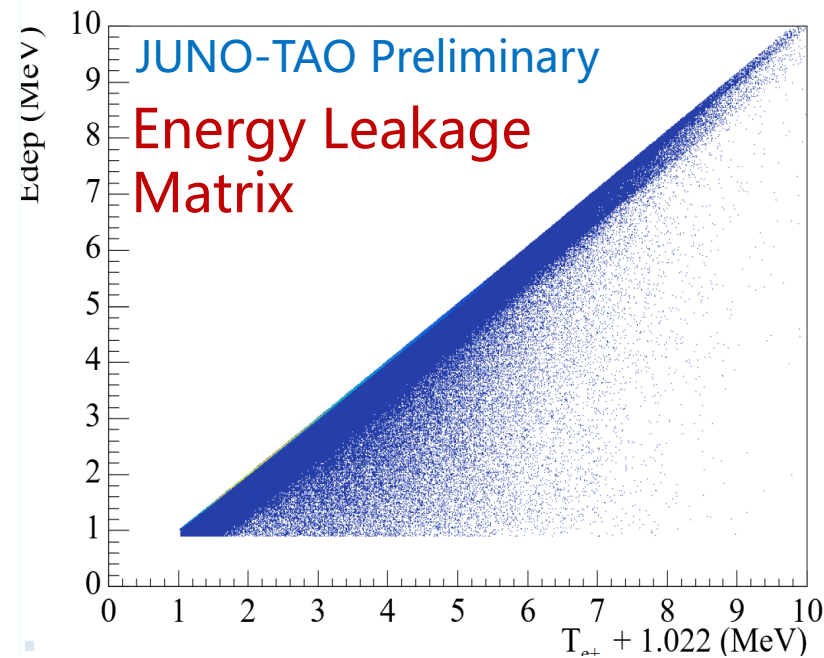
Detector Performance: Energy nonlinearity

- **Method:** fit single- γ nonlinearity (NL) model, convert to positron nonlinearity with MC
- **Results:** similar to JUNO's NL curve, uncertainty 1~2%, dominated by:
 - Uncertainty of input single energy points: each with 0.5% energy scale uncertainty (uncorrelated)
 - Uncertainty in high energy region: 1% assumed to consider electronics NL (under study)



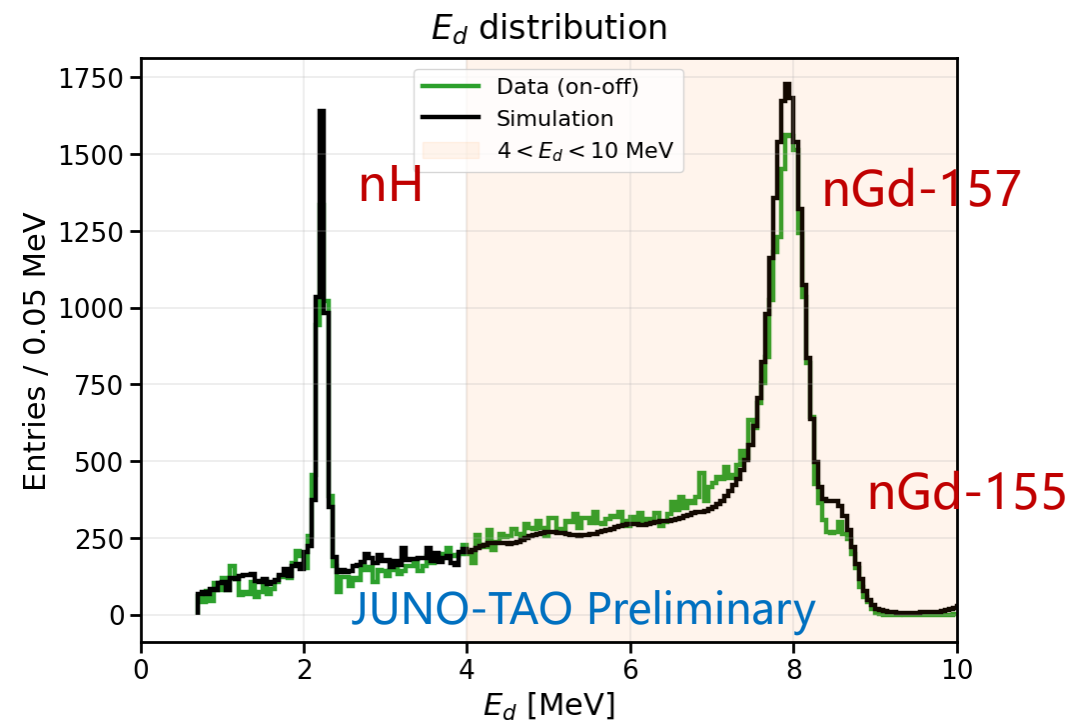
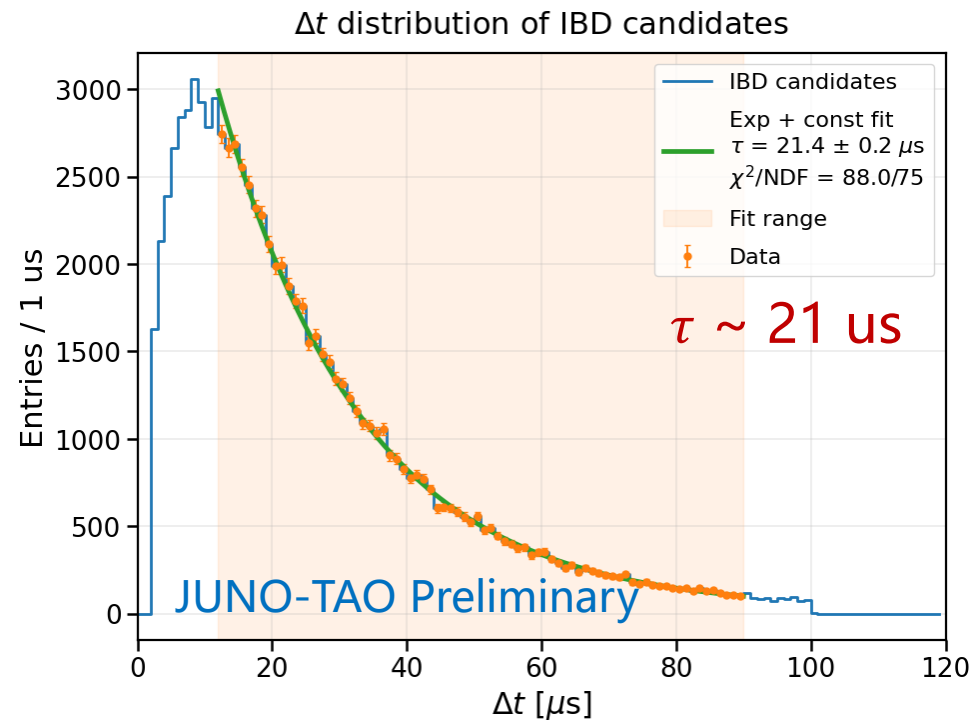
Detector Performance: Energy Leakage

- ❑ **Method:** MC simulation, e^+ energy leakage matrix
- ❑ **Validation:** fraction of Cs-137 Compton plateau in MC/data show good agreement
- ❑ **Shape systematics:** fiducial volume uncertainty + energy leakage \rightarrow IBD prompt spectrum uncertainty



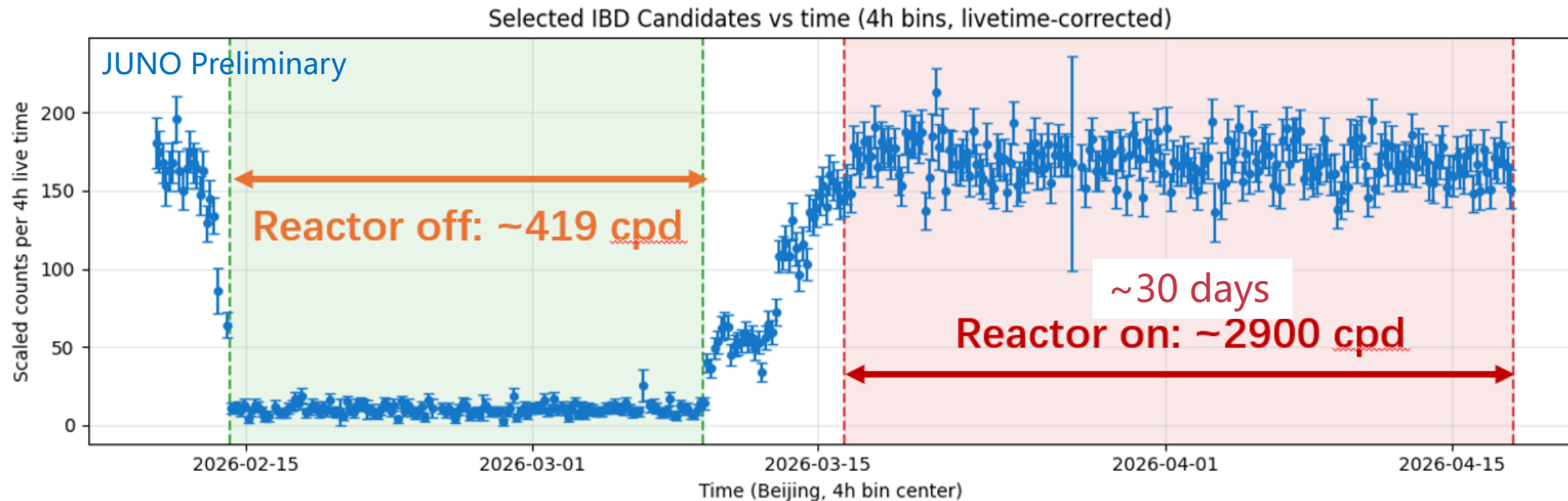
IBD Analysis: Time / Distance / Energy Cut

- ❑ **Time:** $\Delta T(\text{prompt, delayed})$ in (2, 100) μs time window, veto events in (0,100) μs after muon
- ❑ **Space:** $\Delta R(\text{prompt, delayed}) < 500$ mm, $R(\text{prompt}) < 800$ mm (Fiducial Volume Cut)
- ❑ **Energy:** $E(\text{delayed})$ in (4,10) MeV
- ❑ **Total efficiency:** 46.6 ± 5.0 %, **systematics:** FV cut on $R(\text{prompt})$, energy cut on $E(\text{delayed})$



IBD Analysis: Observed IBD Signal Rate

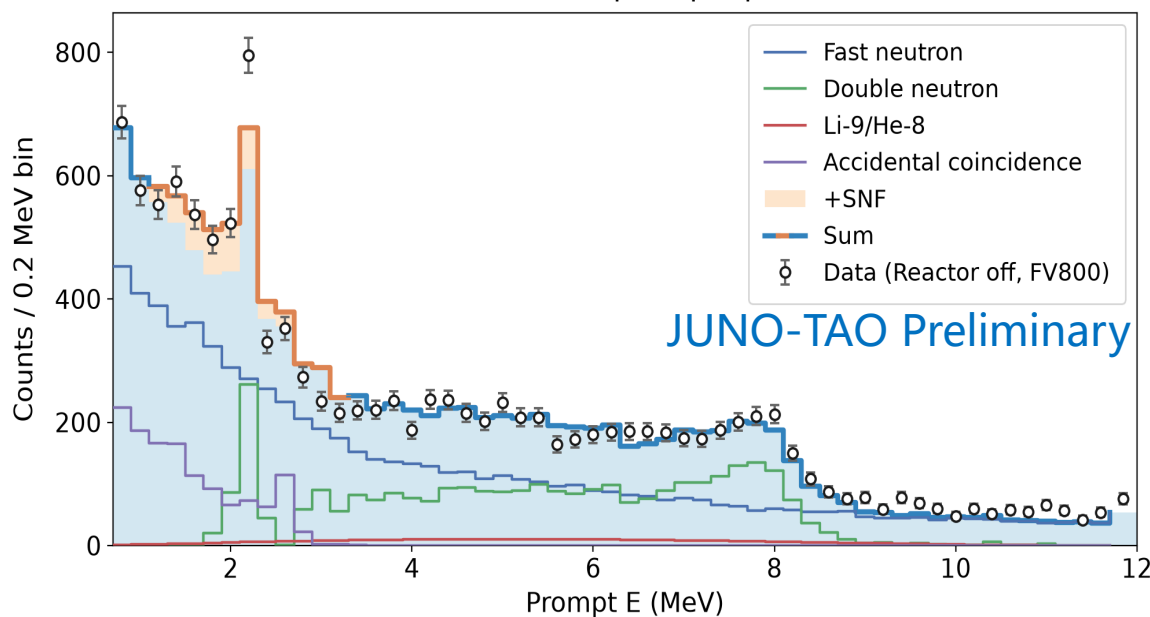
- ❑ Observed IBD signal rate: $\sim 2500/\text{day}$, from reactor-on data minus (scaled) reactor-off data.
- ❑ S:B = 6:1 w/o PSD (pulse shape discrimination),
 - Really good for shallow overburden experiment
 - could be improved in future



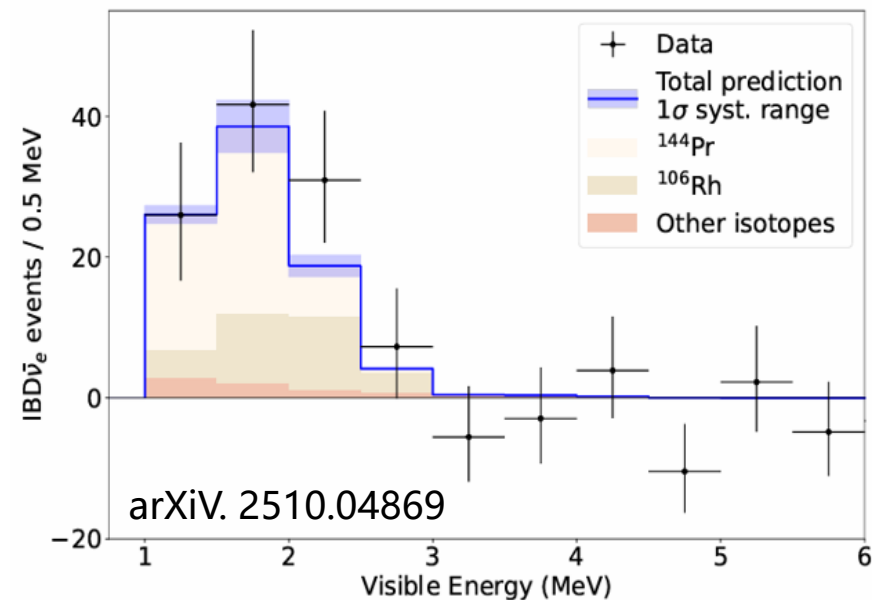
IBD Analysis: Reactor-off & SNF Neutrino

- Direct measurement of background
- Direct measurement of spent nuclear fuel (SNF) neutrino
 - Background: date-driven estimation except for Li-9/He-8, can be further suppressed
 - Remote reactor OFF makes SNF neutrino signal more clear

TAO Reactor-off Data

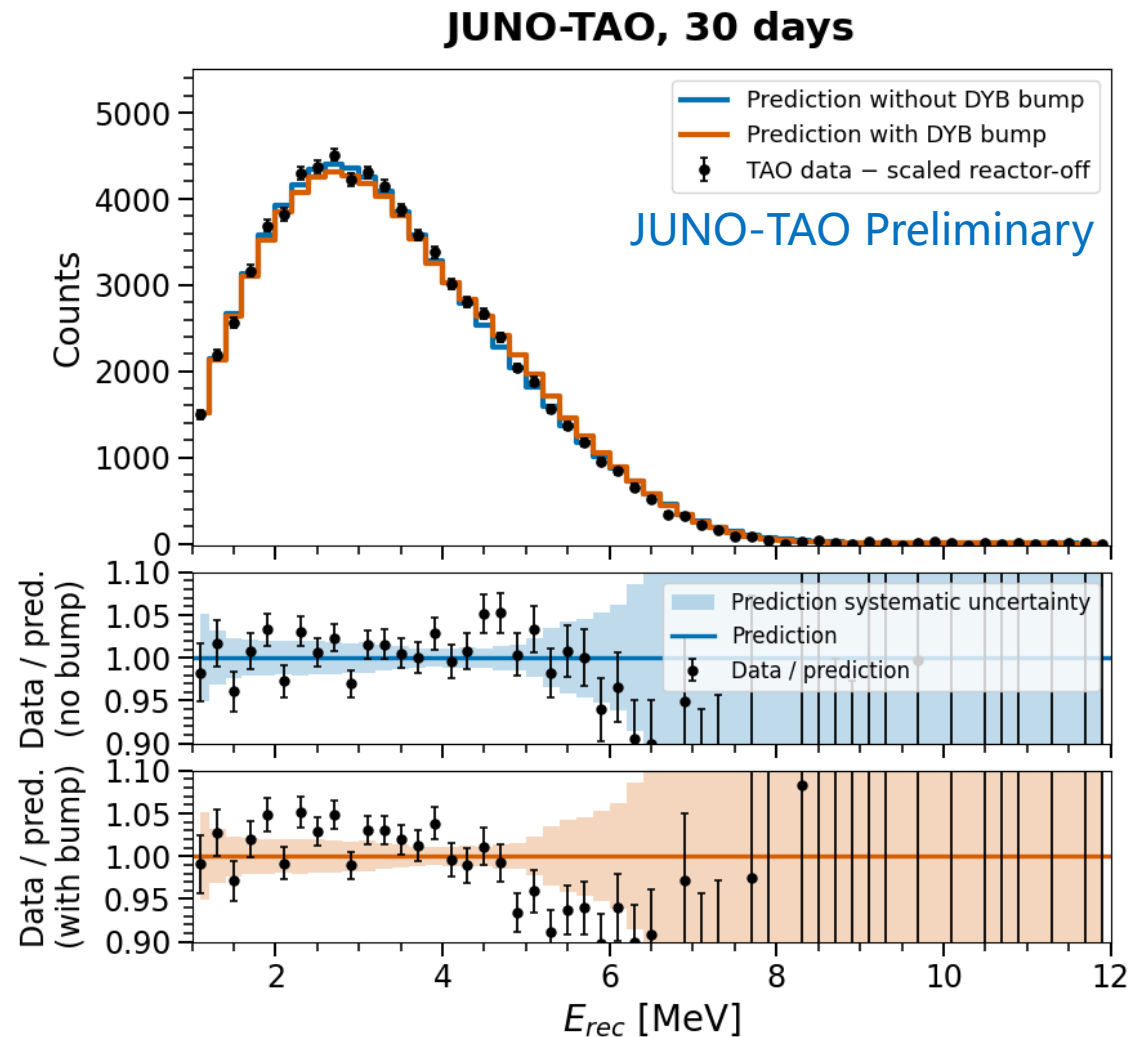
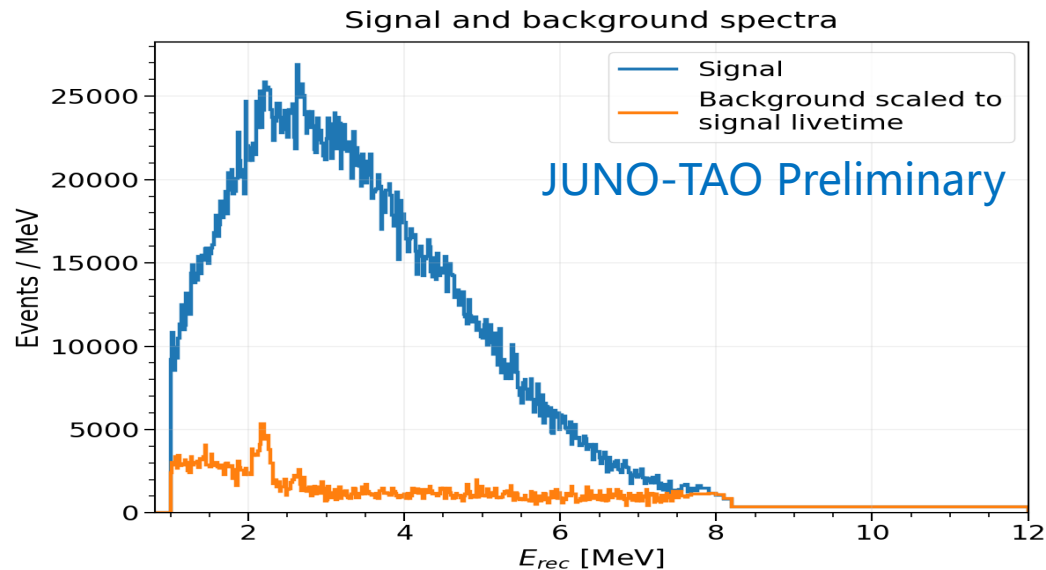


SNF neutrino observed by Double Chooz



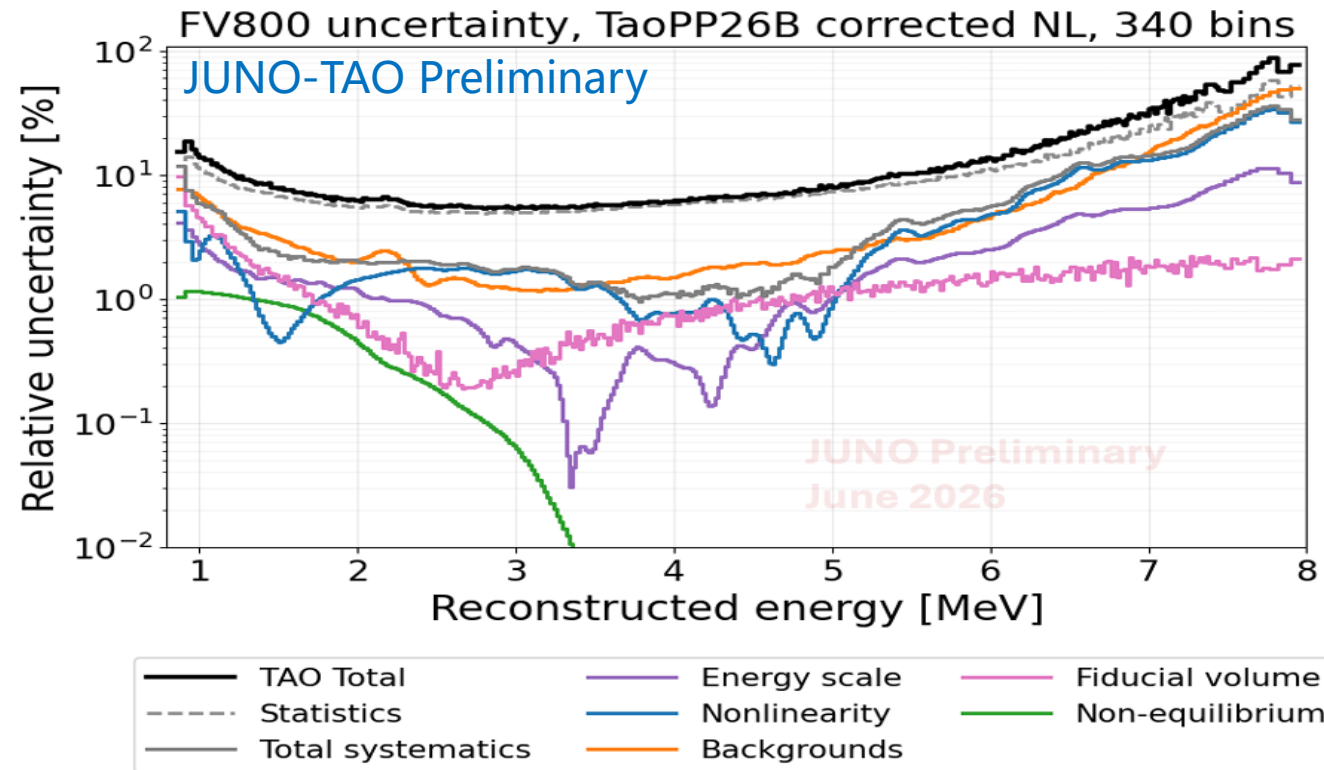
IBD Analysis: Prompt Event Energy Spectrum

- Prediction:** Huber-Mueller model (PRC, 83:054615, 2011, PRC, 84:024617, 2011) + Daya Bay correction (PRL 123(11):111801, 2019) + non-equilibrium correction, convoluted with TAO detector response
- Results:** good data/prediction agreement, sign of 5 MeV bump, small difference in high energy tail



IBD Analysis: Shape Uncertainty

- ❑ **Statistical uncertainty dominates**, with 1 month data and 20 keV bin
- ❑ **Systematics**: energy non-linearity and background (neutron) subtraction (neutron)



Summary

- ❑ TAO detector is constructed and in stable operation since Feb. 10th, 2026
- ❑ **World leading energy resolution 2.8% @Ge-68, further improvements expected**
- ❑ Excellent background control, further background suppression expected
- ❑ Preliminary IBD analysis with 1 month data, good data/prediction agreement
→ spectrum used in JUNO physics analysis (Yifang's Talk)

❑ Posters

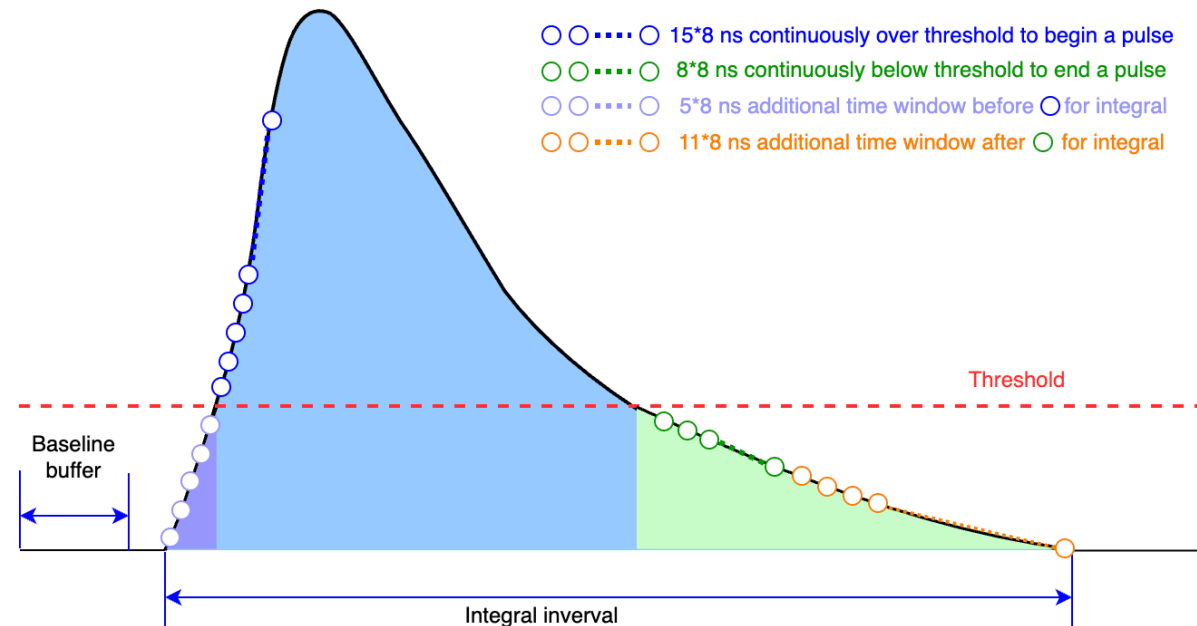
- ID 371, Precision measurement of reactor neutrino spectrum at TAO
- ID 223, Channel-level SiPM calibration at JUNO-TAO
- ID 250, Muon related background at JUNO-TAO
- ID 246, Performance of the Veto System for JUNO-TAO

Backup



Charge/Time Extration

- ❑ Continuous Overthreshold Integration method
- ❑ $Q = \text{Amplitude sum}$
- ❑ $T = \text{1st over-threshold point (ADC sampling rate 125MHz)}$



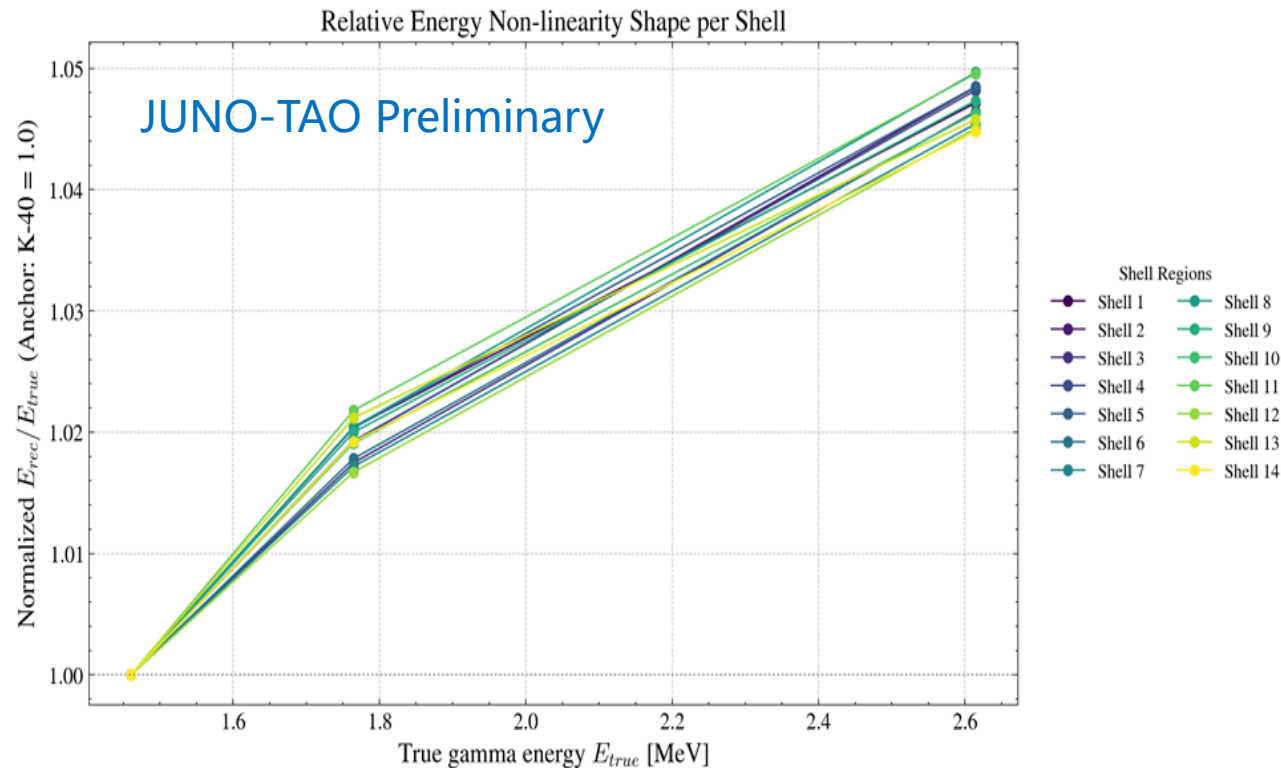
Detector Calibration Overview

- ❑ **SiPM Over-voltage (V_{ov}): 3.5V** (optimized for **Ge-68** peak energy resolution)
- ❑ **Channel trigger threshold: 70 LSB, $\sim 3\sigma$** of noise amplitude

Parameter	Method	Mean	Comment
Noise	Waveform Sampling	26 LSB	13% of single photo-electron (SPE) peak
Gain	Fit Charge Spectrum (finger plot)	6000 LSB	Fine tune V_{ov} to make gain uniform in all channels
SPE Resolution		14%	CDR requires 15%
DCR	Count #hit before signal	50 Hz/mm ²	Cross-talk contamination removed
Time Offset	Fit Time Distribution of Central Events	1 ns	Calibration precision
PDE non-uniformity	Place Ge-68 at center	$\sim 10\%$	Preliminary, not yet used in analysis
Cross-talk probability	Turn on/off cross-talk emitting SiPMs	$\sim 25\%$	

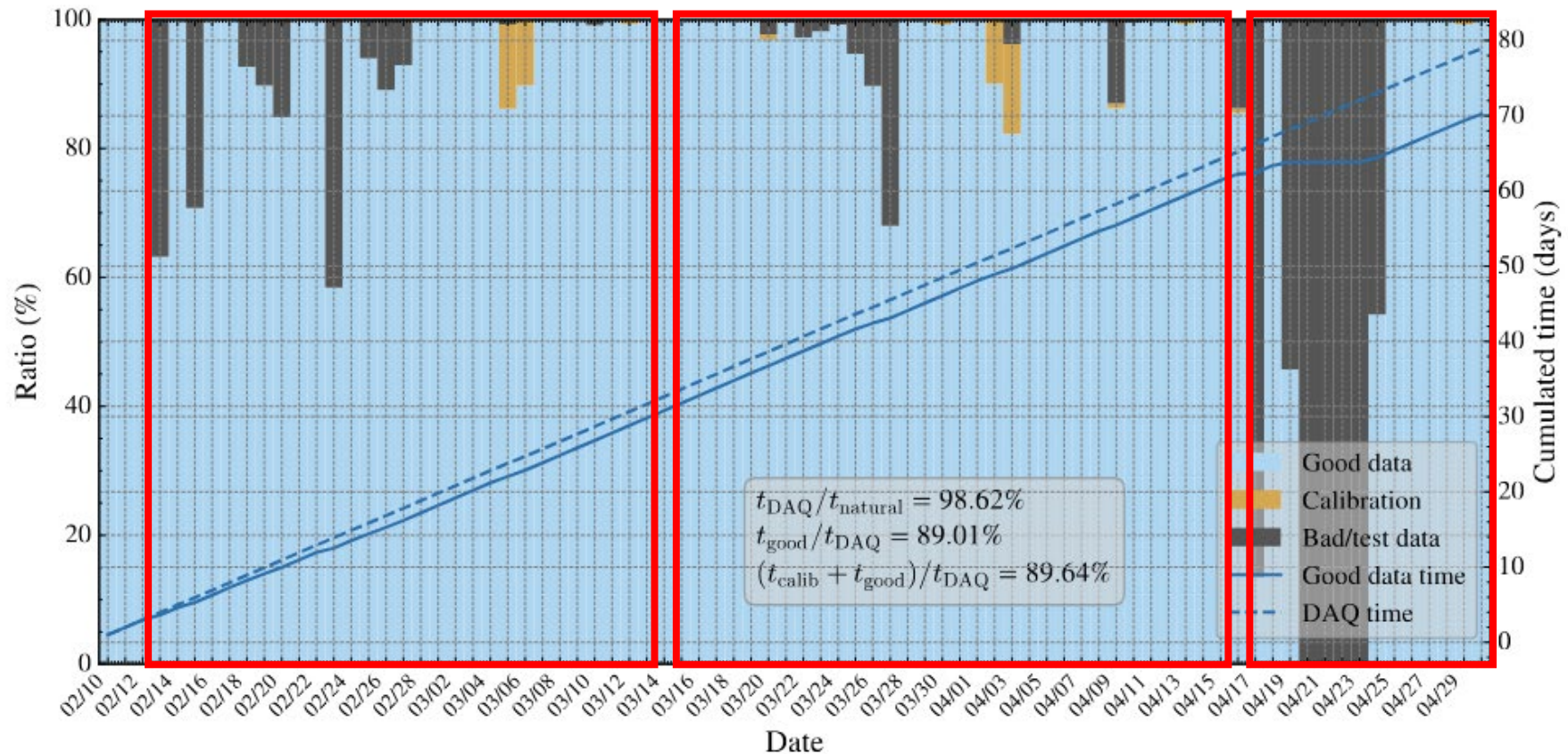
R dependency of Nonlinearity

- R dependency of nonlinearity mainly from residual energy non-uniformity
- Systematics will be assigned to residual non-uniformity -> no systematics considered for nonlinearity to avoid double counting



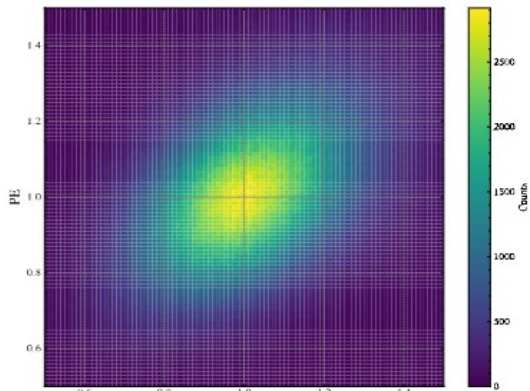
Data-taking

- ❑ Trigger threshold @0.7 MeV, 24h per RUN, 3 Periods (reactor off-on-off)
- ❑ Temperature unstable around April 20th~24th (excluded), cryogenics malfunctioning

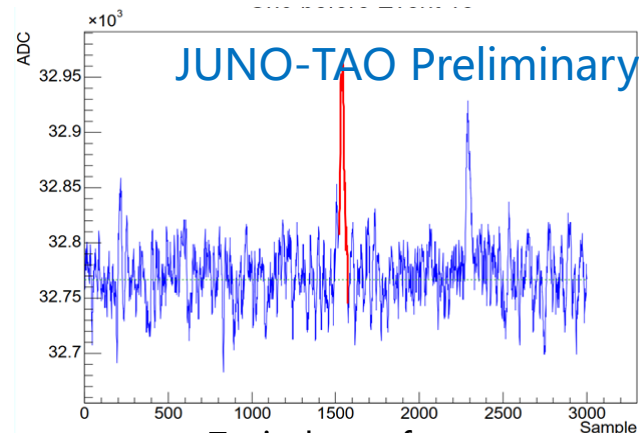


Noise

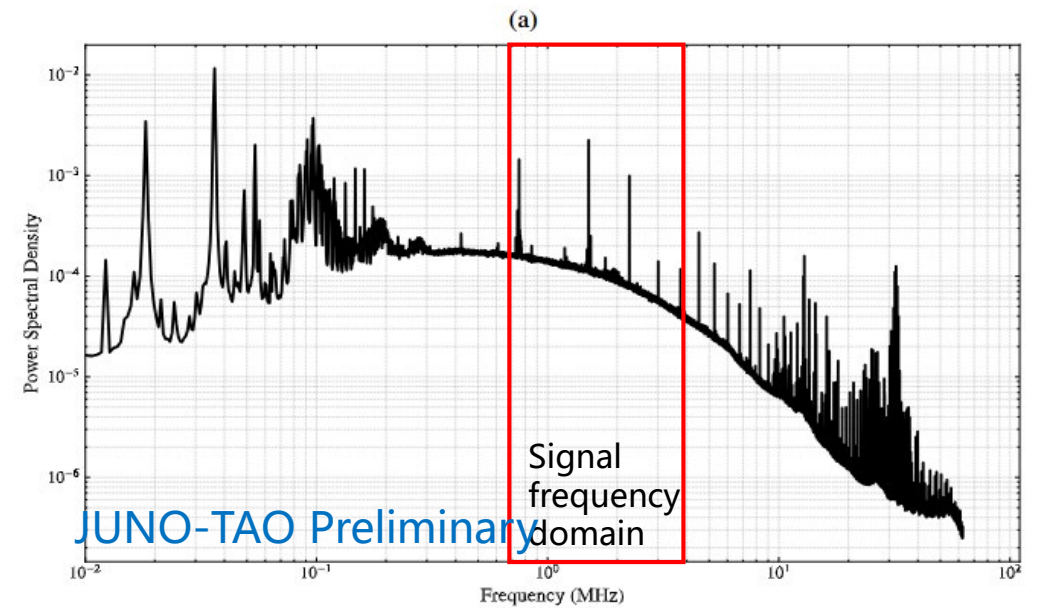
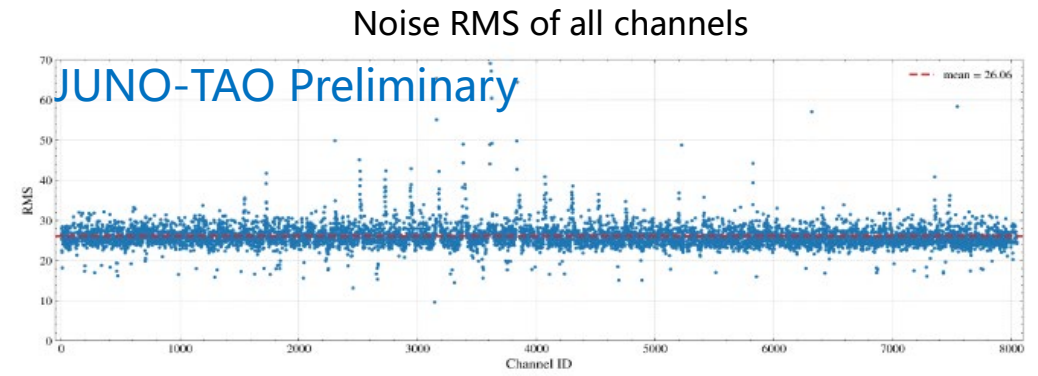
- ❑ **Method:** 1Hz random sampling of waveform
- ❑ **Results:** RMS ~ 26 LSB + a few noisy channels
- ❑ **Issue**
 - **correlation** between the channels in same HV cable (a few cases) \rightarrow **PE counting method**
 - Some noise with similar frequency as signal \rightarrow **fixed baseline** for charge integration



Correlation in HV cable



Typical waveform



Noise power spectral density

IBD Selection Summary

Category	Cut	Condition	Efficiency
Muon Veto	WT muon (≥ 18 PMTs/GCU)	$[-2, 30] \mu\text{s}$	For delayed signal: 95.1% For prompt signal: $97.4 \pm 0.01\%$
	TVT muon (≥ 3 layers fired)	$[-2, 30] \mu\text{s}$	
	CD muon ($E > 20$ MeV)	$[0, 100] \mu\text{s}$	
IBD Selection	Pre-selection	E in $[0.7, 12]$ MeV	$90.0 \pm 1.5\%$
		$R < 875$ mm	$97.8 \pm 0.8\%$
	Pairing and Multiplicity	No other events in $[T_p - 100, T_d + 100]$ us	$96.0 \pm 0.01\%$
	Prompt–delayed time	$[2, 100] \mu\text{s}$	$96.7 \pm 0.08\%$
	Delayed energy	$[4, 10]$ MeV	$74.6 \pm 4.0\%$
	Prompt–delayed distance	$\Delta R < 500$ mm	$96.4 \pm 2.6\%$
	Fiducial volume (prompt)	$R < 800$ mm	$85.6 \pm 7.4\%$
Total	-	-	$46.6 \pm 5.0\%$