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SUN YAT-SEN UNIVERSITY SCHOOL OF PHYSICS



Reactor Antineutrino Flux and Spectrum Uncertainty

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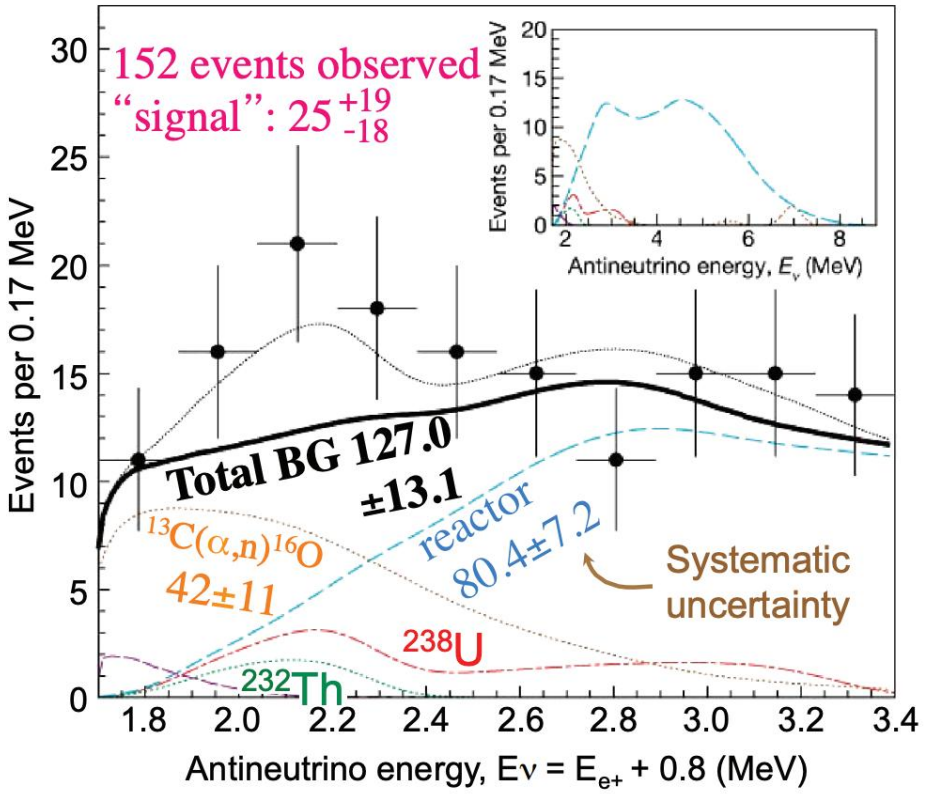
Neutrino Geoscience Workshop 2026 Zhuhai

Background in Geoneutrino Detection

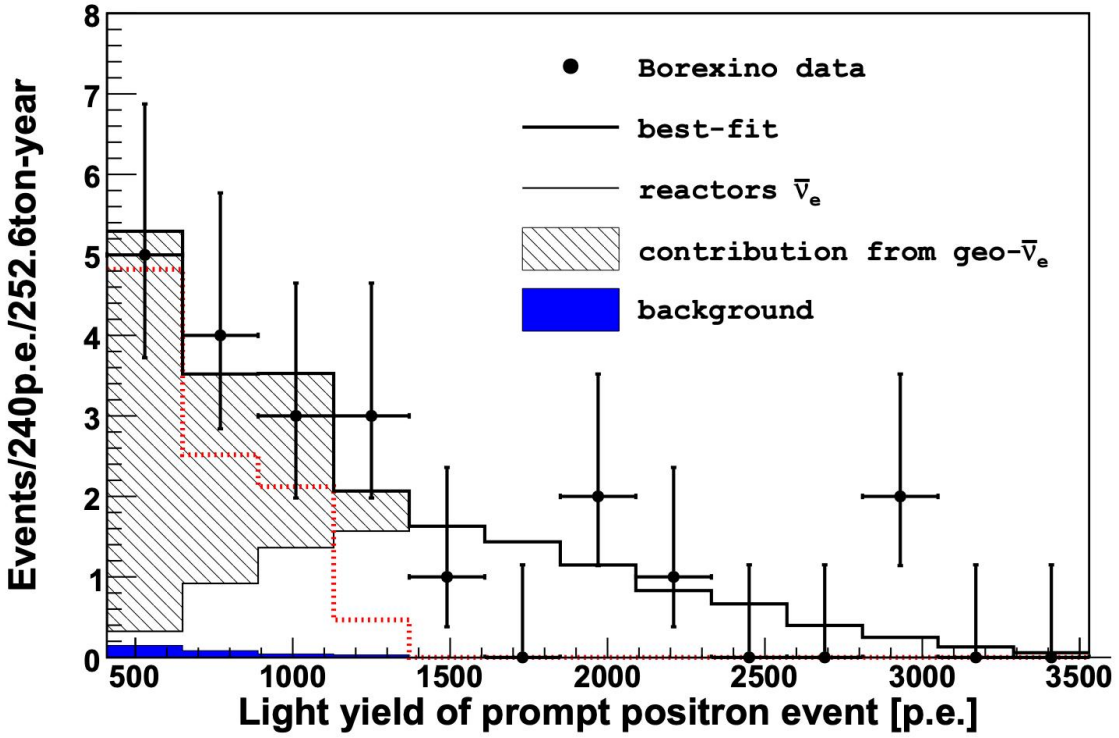
- Reactor antineutrinos are an important background for Geoneutrino analysis.
- From the first experimental research in KamLAND to the high-statistics evidence in Borexino.

KamLAND



Nature 436 499 (2005)

Borexino

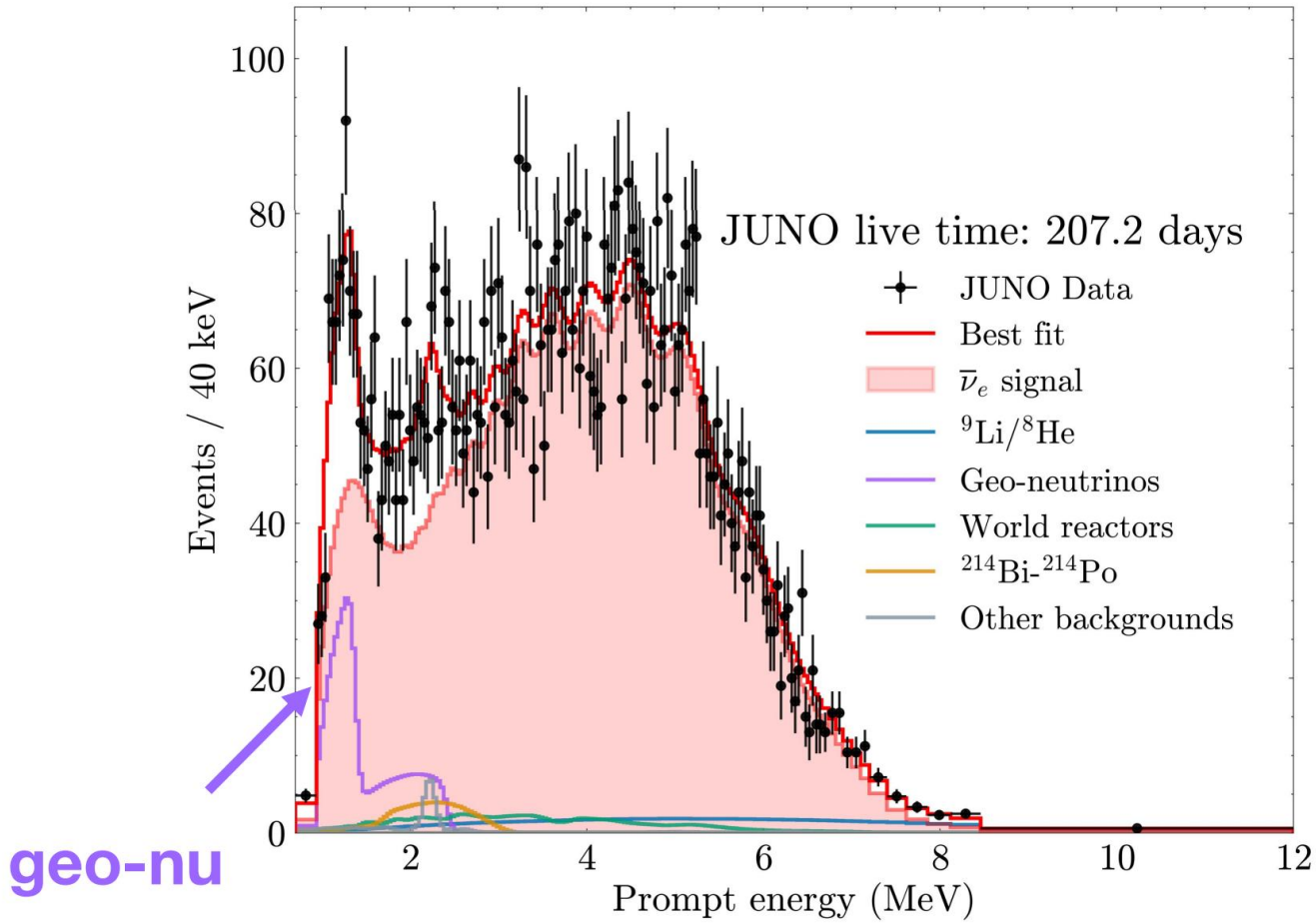


Phys.Lett.B 687 (2010) 299-304

Background in Geoneutrino Detection

- Recently, JUNO has masured geoneutrino signal of 73 ± 11 TNU.
- Expect to a world-leading flux precision of about 8% over ten years (arXiv: 2511.07227).
- Precise constraint from reactor antineutrino spectrum → improved precision of Geoneutrino measurement!

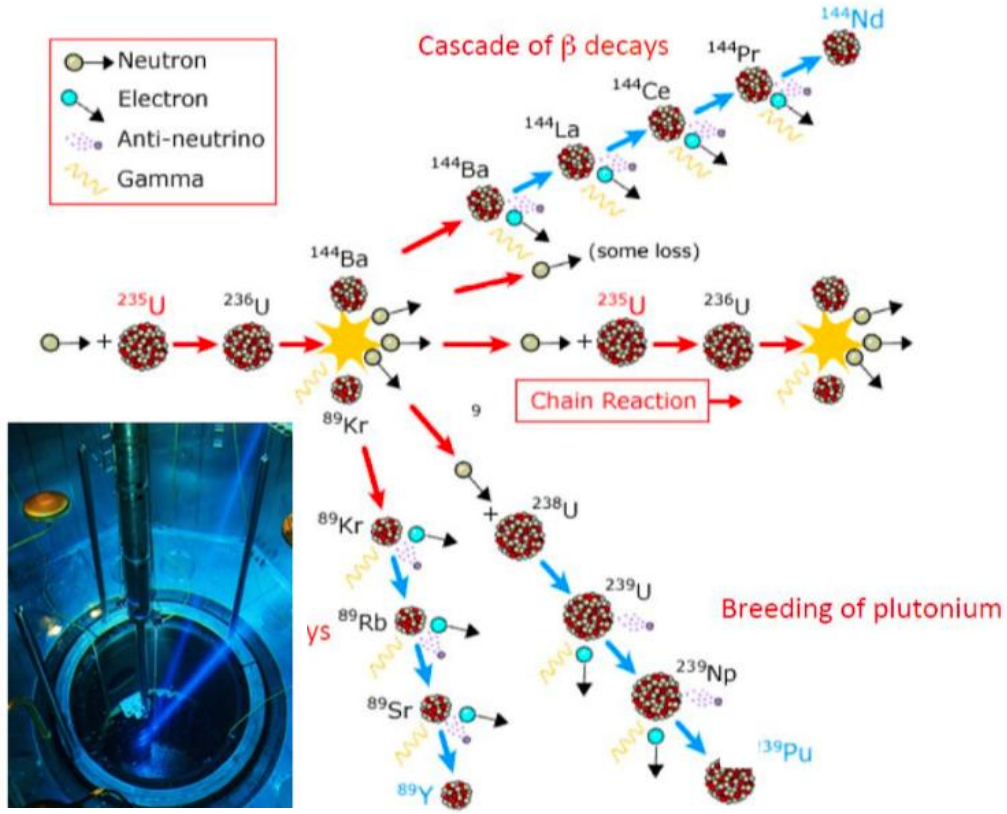
(Qishan's talk)

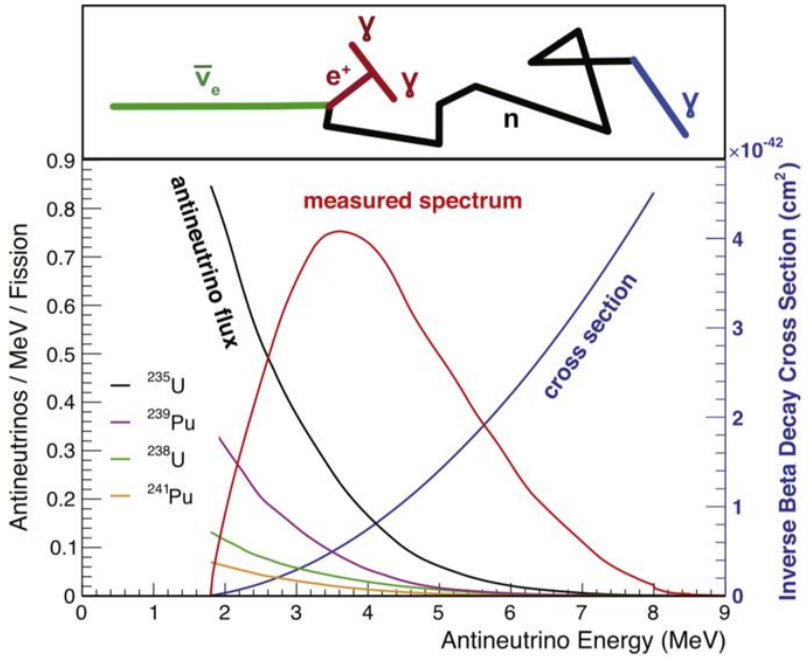


arXiv: 2609.37895

Reactor Antineutrino*

- Electron antineutrinos produced in commercial nuclear reactor cores.
- Mainly from fission fragments of the fissile isotopes ^{235}U, ^{238}U, ^{239}Pu, and ^{241}Pu.



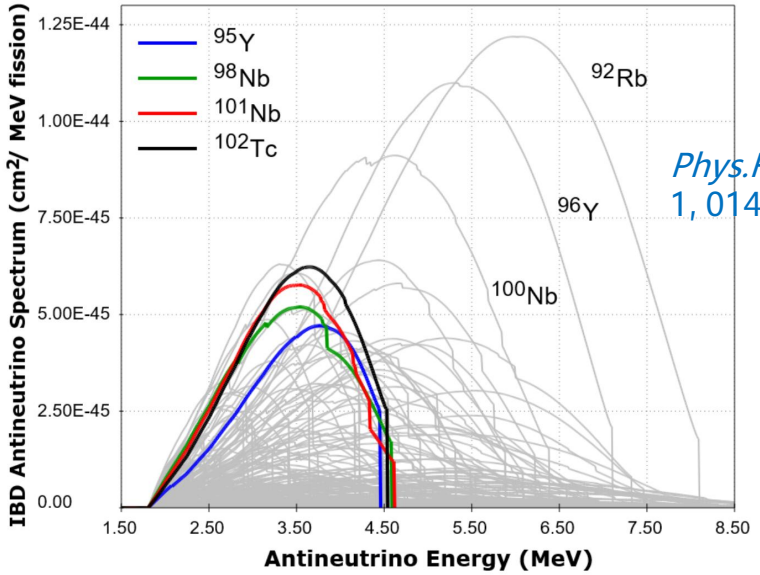


Inverse β decay (IBD)*:

- Prompt: $E_{\text{prompt}} \approx E_{\nu} - 0.8$ MeV
- Delayed: nGd (~8 MeV)
  nH (~2.2 MeV)

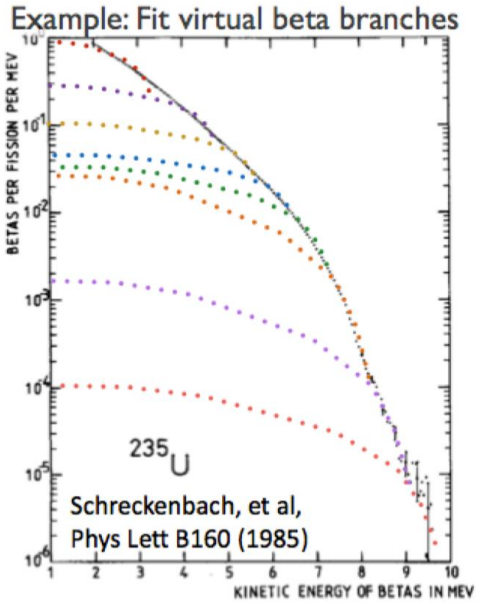
Reactor Antineutrino Models

- Summation (ab initio) method
  - > 6000 decay branches
  - Missing data in the nuclear database
  - ~30% forbidden decays
  - ~ 10% uncertainty
  - Recent Updates: SM2018, SM2023, et al.



Phys.Rev.C 98 (2018) 1, 014323

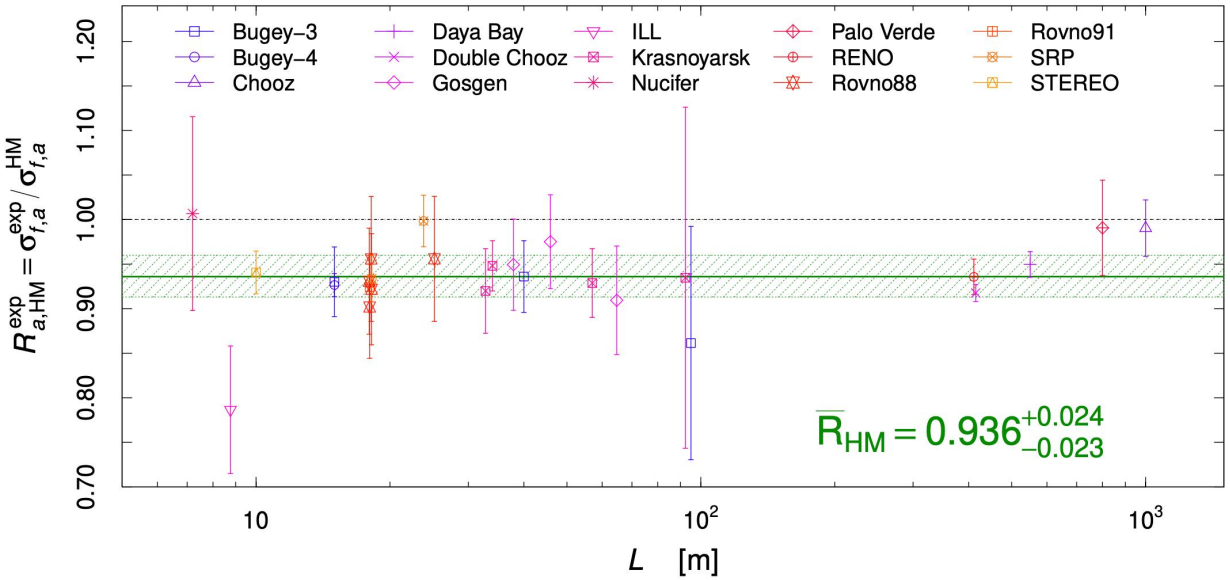
- Conversion method
  - Convert ILL measured ^{235}U, ^{239}Pu and ^{241}Pu β spectra to $\bar{\upsilon}_e$ with >30 virtual β-decay branches
  - Commonly use Huber + Mueller (^{238}U) model (2011)
  - ~ 2.4% uncertainty
  - Kurchatov Institute (KI) found an overestimation of the ^{235}U contribution in the ILL measurements.



Reactor Antineutrino Anomaly

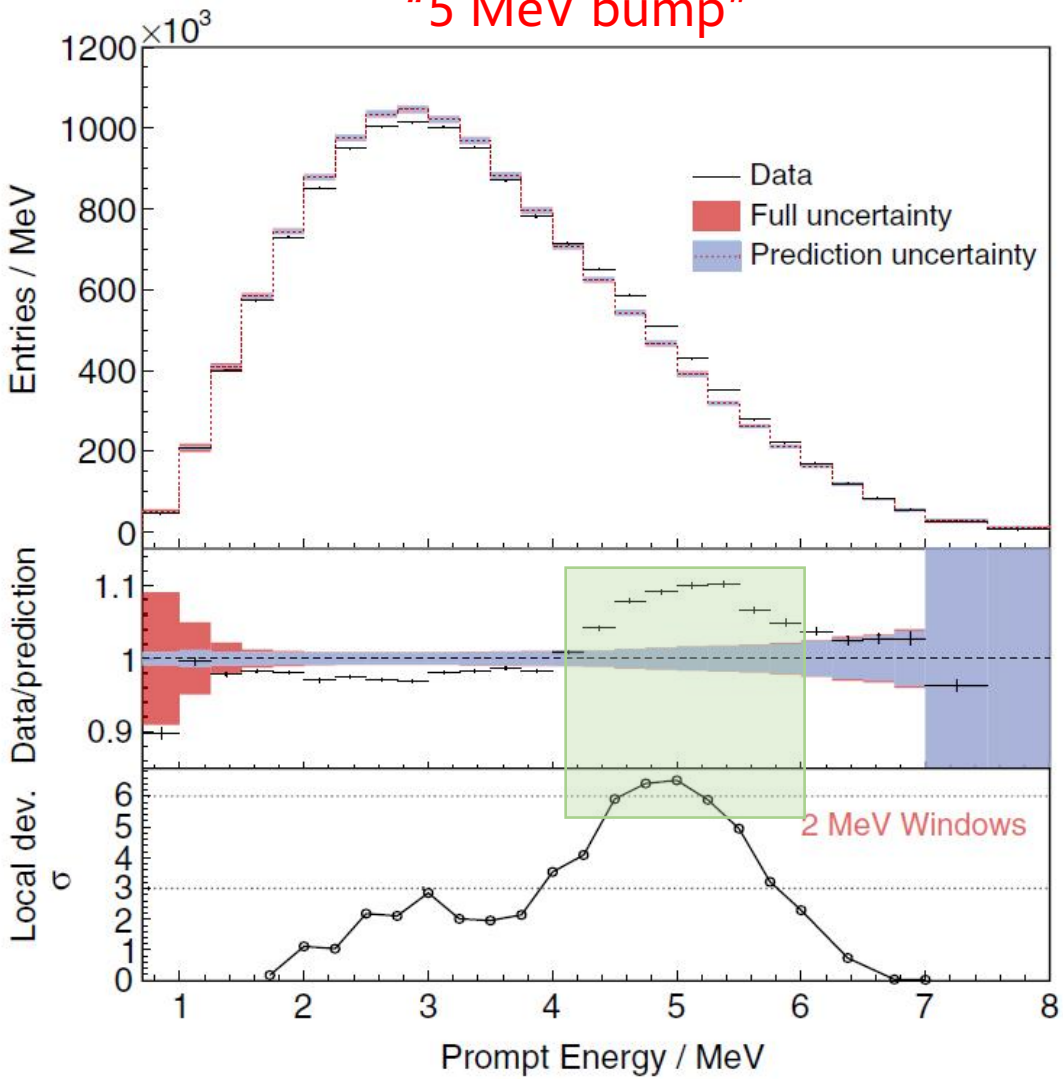
- Flux deficit: measured rate is 6% lower than prediction from HM model.
- “5 MeV bump”: Data/prediction spectrum shows an overall >5σ deviation, local deviation >6σ in maximum.

Flux deficit



Phys. Lett. B 829 (2022) 137054

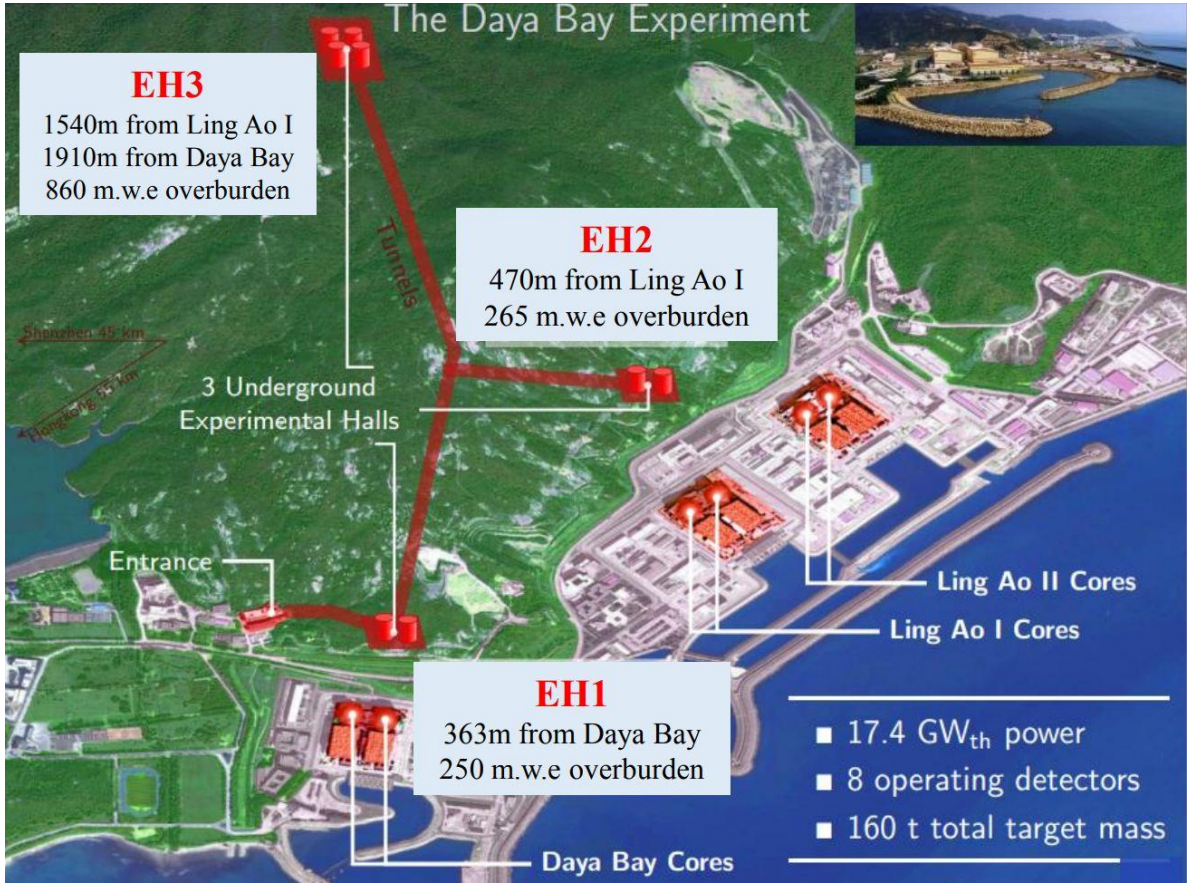
“5 MeV bump”

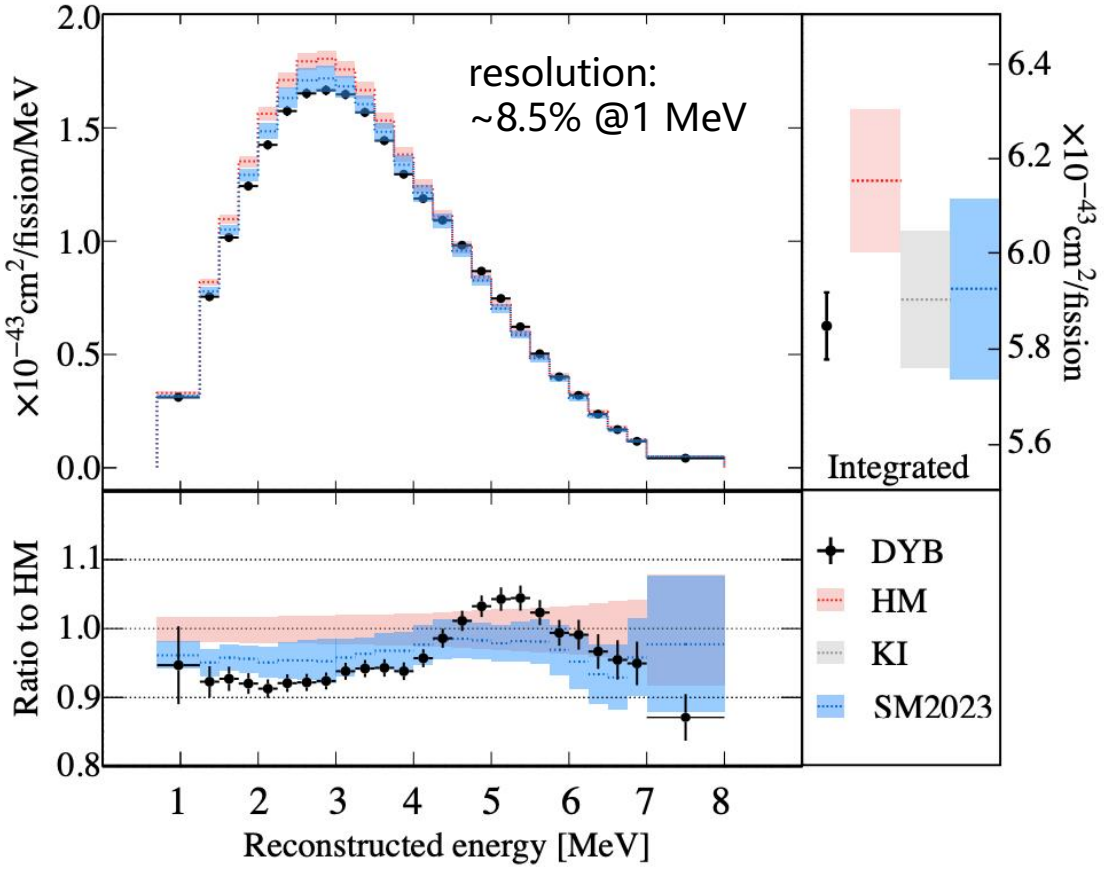


Phys. Rev. Lett. 123, 111801 (2019)

Daya Bay

- Near detectors at Daya Bay Experiment measures reactor antineutrinos with baseline of ~400 m, with 4.7 million IBD candidates in total (3158 days).
- Spectrum uncertainty: ~1.3% around 3 MeV (Rate uncertainty: 1.2%), systematic uncertainty dominated.

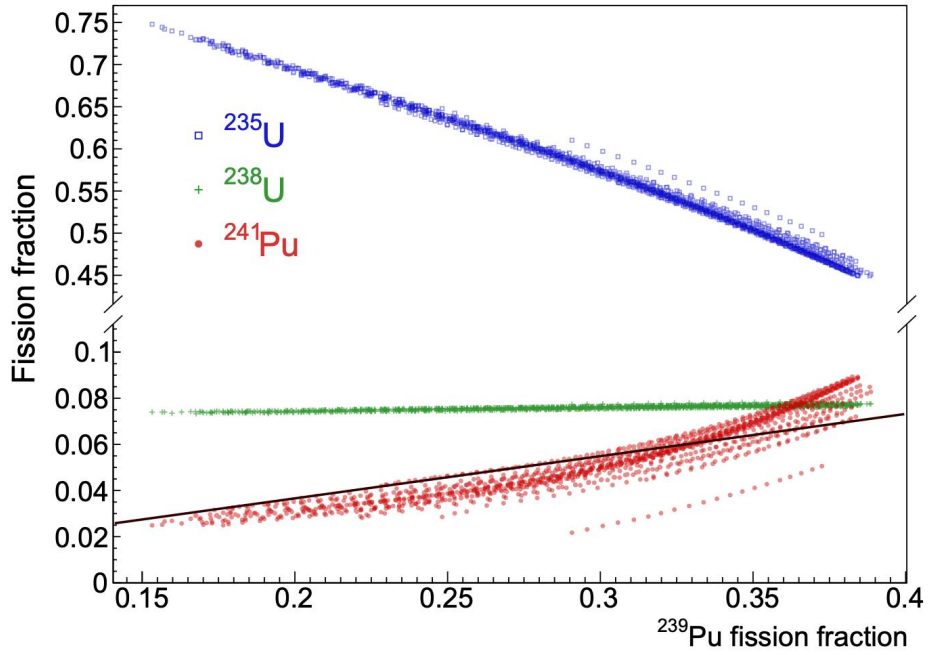




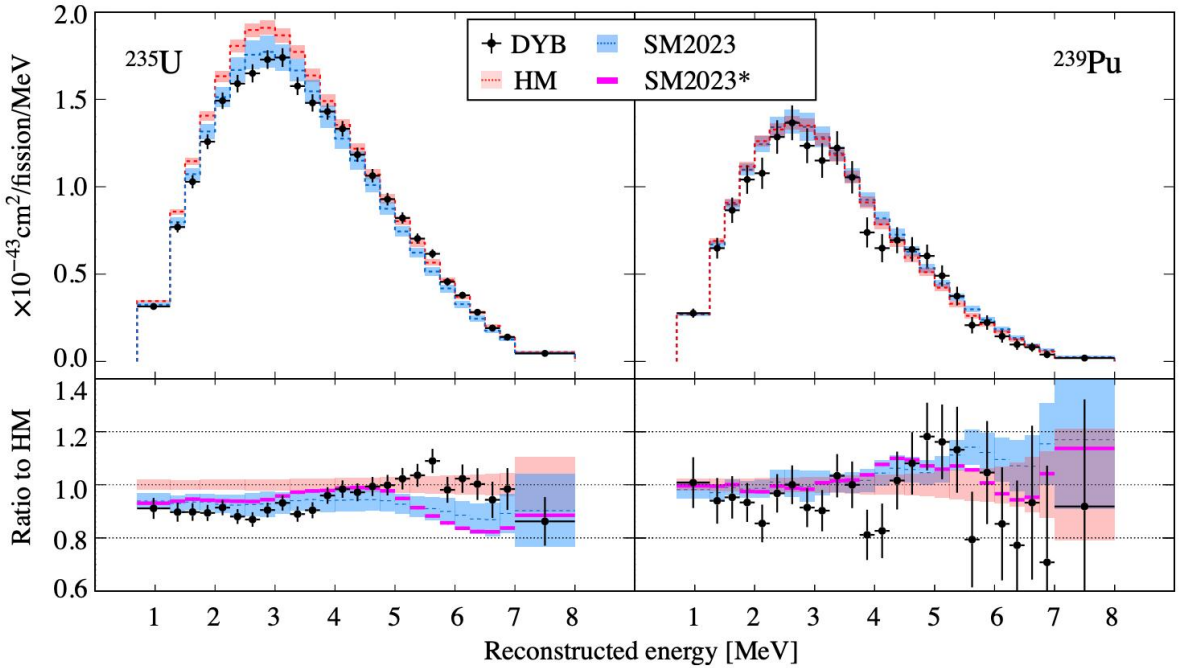
Phys.Rev.Lett. 134 (2025) 20, 201802

Fuel Evolution at Daya Bay

- As the fuel burns in the reactors, the fission fractions and the antineutrino flux evolve.
- 4 isotopes have different spectrum → total spectrum changes as fuel evolves.
- Extract the ^{235}U and ^{239}Pu spectrum by constraining the others with enlarged errors.
  - The significances w.r.t. the HM model are 4σ ($<2\sigma$) for ^{235}U (^{239}Pu) from 4 to 6 MeV.



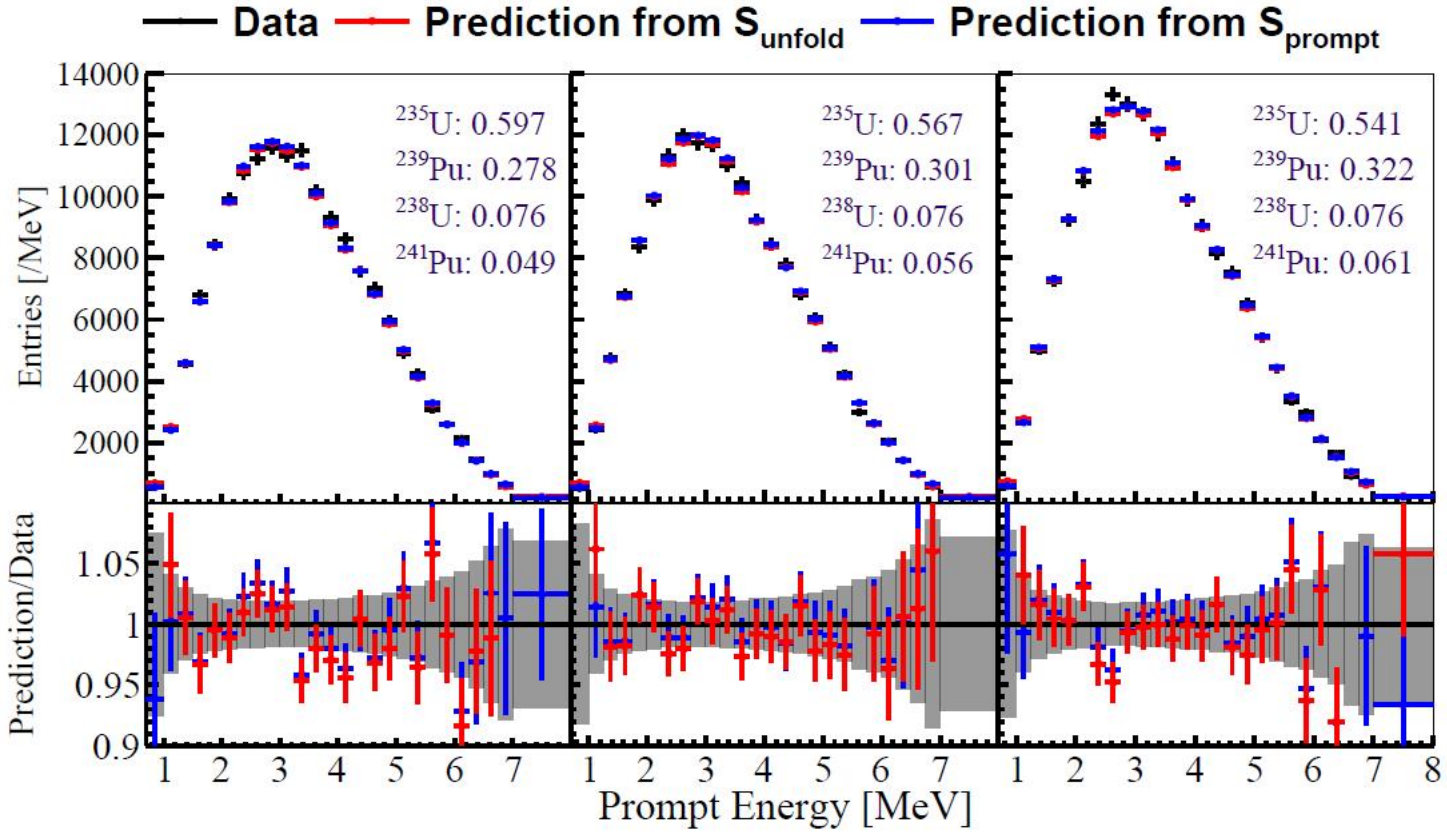
Phys. Rev. Lett. 123 (2019) 111801



Phys.Rev.Lett. 134 (2025) 20, 201802

Data-driven Prediction for Other Experiments

- Not all experiments have similar fission fractions.
- Provide a data-based prediction for other reactor antineutrino experiments.
  - With known reactor fission fractions, the technique can predict the energy spectrum to a 2% precision.

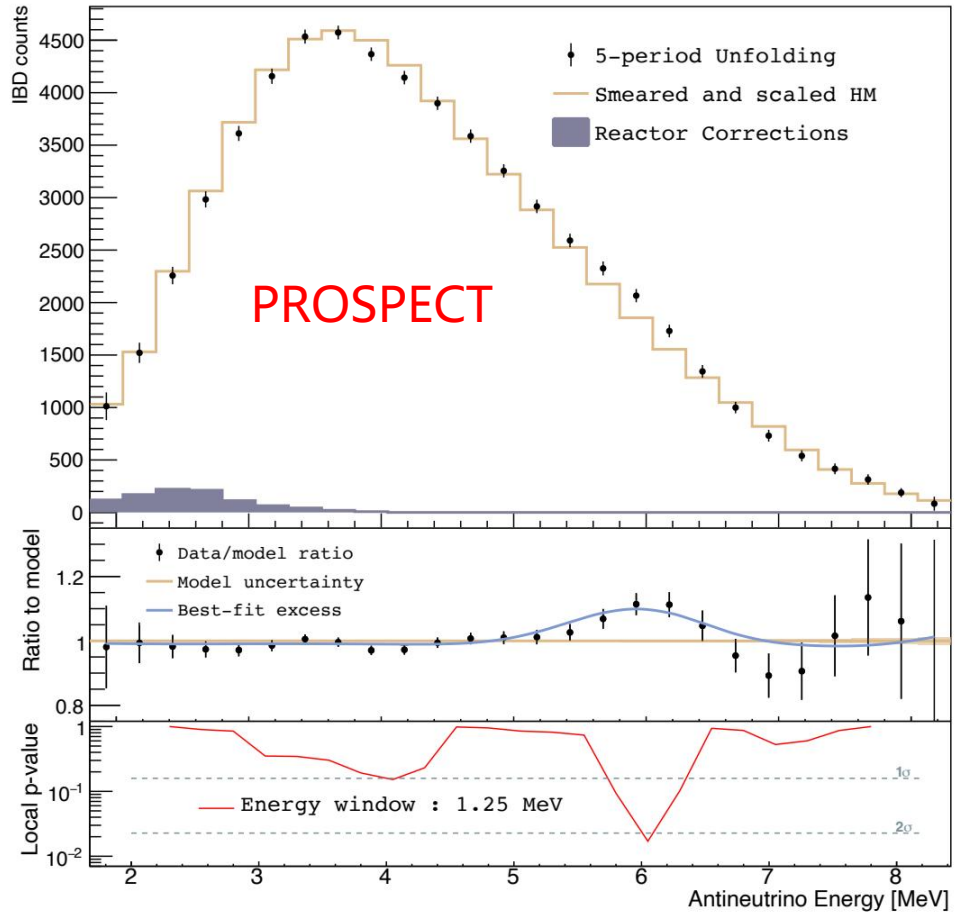


- Total and isotopic antineutrino energy spectra is unfolded.

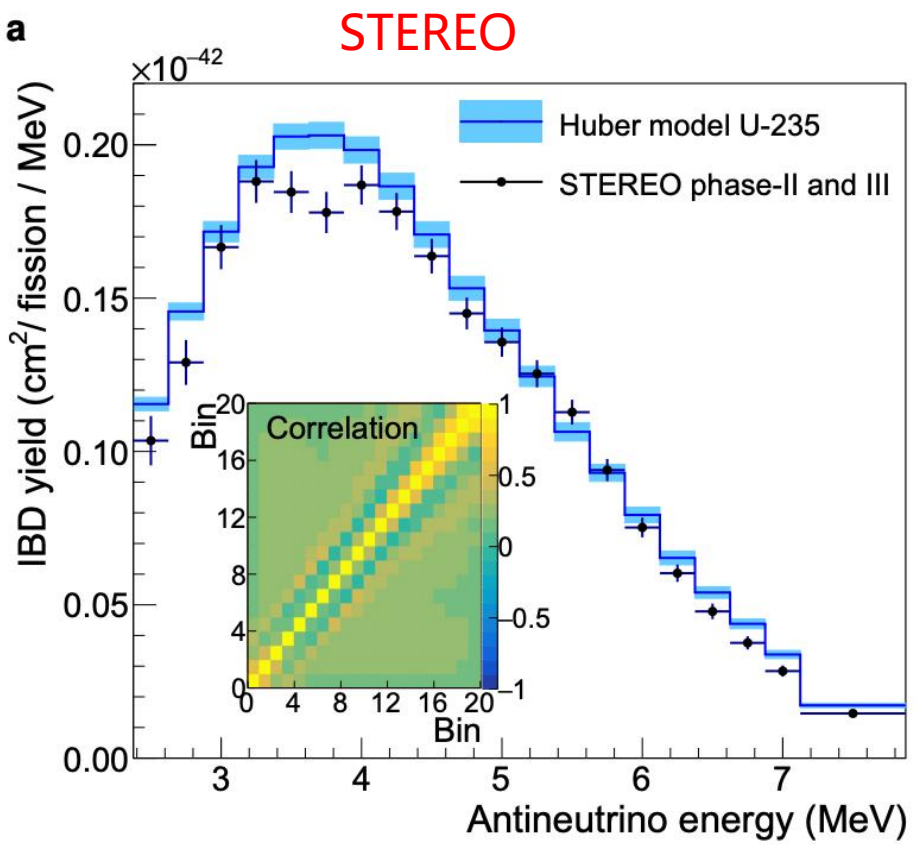
[Chinese Phys. C 45 073001 (2021)] Supplemental materials provided in arXiv:2102.04614.

Pure ^{235}U Spectrum

- Pure ^{235}U Spectrum can be measured by high-flux research reactor (enriched ^{235}U fuel).
- Spectrum uncertainty is at 3% level around 3 MeV (stat. uncer. still dominates).



Phys.Rev.Lett. 131 (2023) 2, 021802

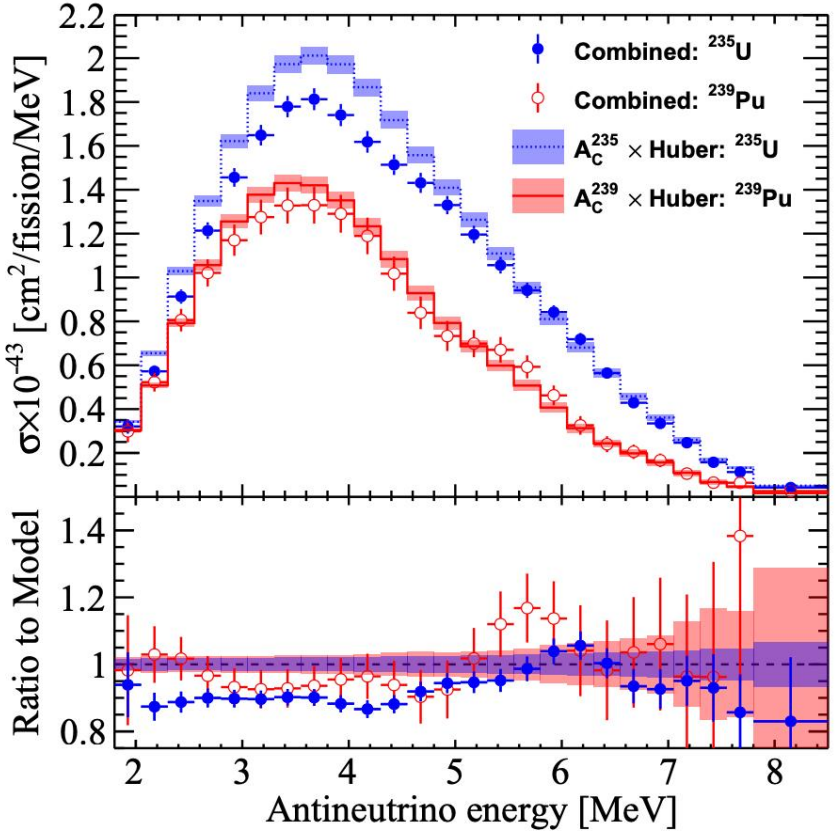


Nature 613 (2023) 7943, 257-261

Joint Analyses

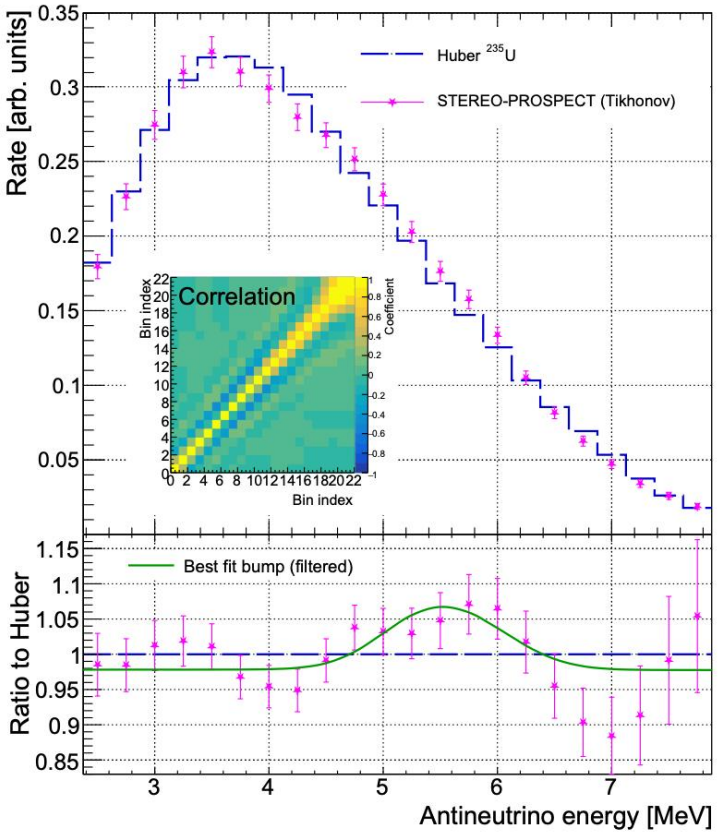
- Joint analyses among experiments are done to check the robustness of either analysis and reduce the uncertainty.
- Take DYB+PROSPECT as an example: ^{235}U spectral shape err: 3.5% (DYB) → 3%
  - Reduce the degeneracy between ^{235}U and ^{239}Pu (by 20%).

Daya Bay + PROSPECT:



Phys.Rev.Lett. 128 (2022) 8, 081801

PROSPECT + STEREO:

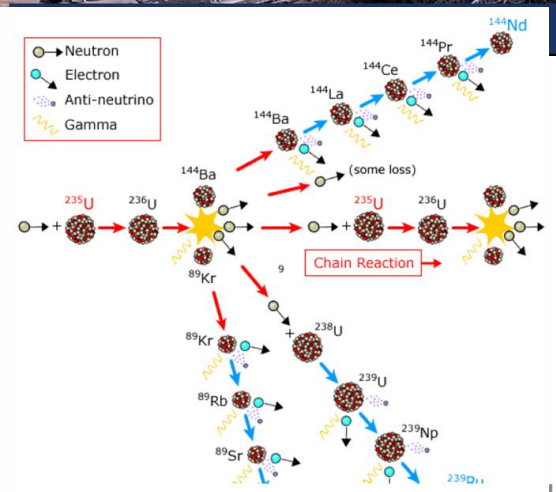


Phys.Rev.Lett. 128 (2022) 8, 081802

JUNO-TAO (Taishan Antineutrino Observatory)







- TAO is the satellite experiment of JUNO
- TAO is deployed near Unit 1 with a baseline of 43.2 m
- In reactors, beta decay chain of fission fragments of U/Pu releases ~6 $\overline{\nu}_e$/ fission

Introduction: Roadmap

2018 Choose Taishan NPP

2020.3 Concept Design Report

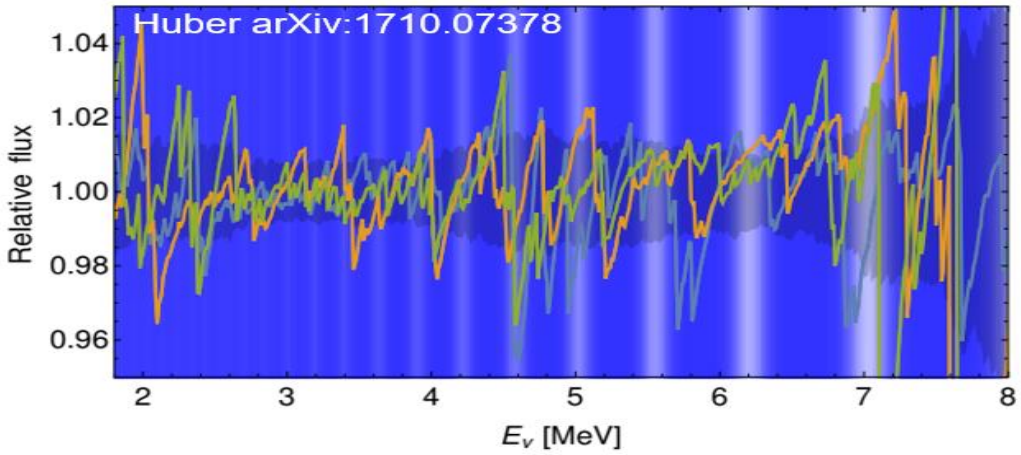
2023.10 1:1 Prototype

2024.11 Installation Starts

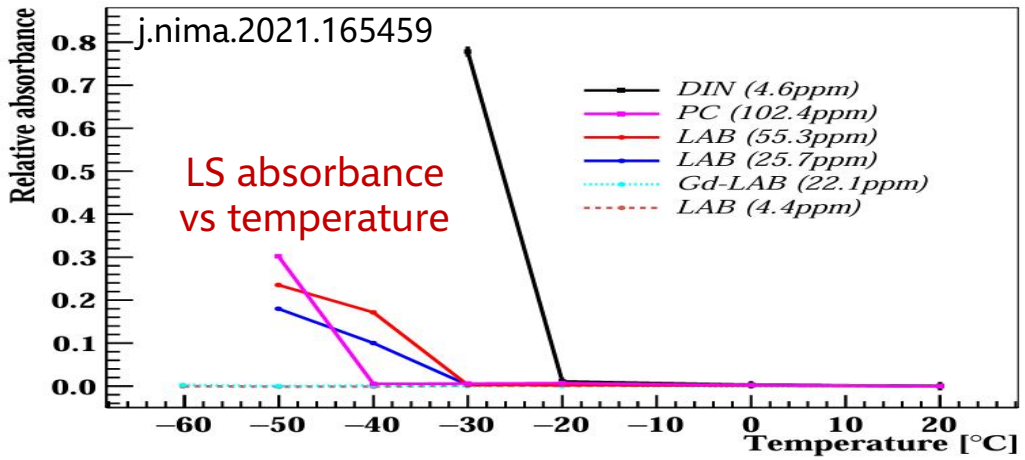
2025.9 Installation Completes

2026.2 Commissioned Data-taking Starts

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

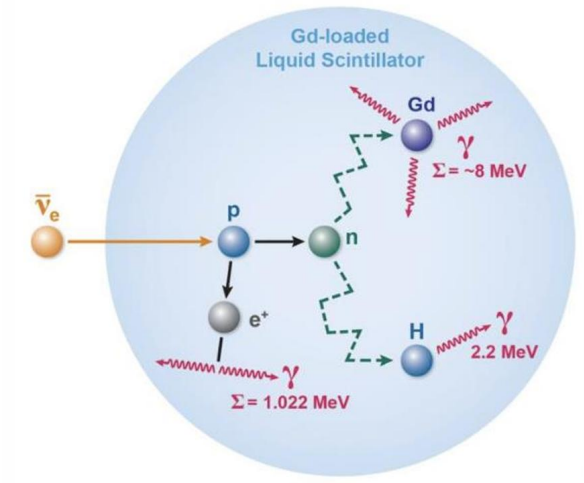


- LS+PMT (JUNO) → Low-temperature LS + SiPM (TAO)
  - Photo-electron yield (PE/MeV) ~4500 (JUNO ~1700)
  - Low temperature: -50℃, dark count rate: < 100 Hz/mm^2

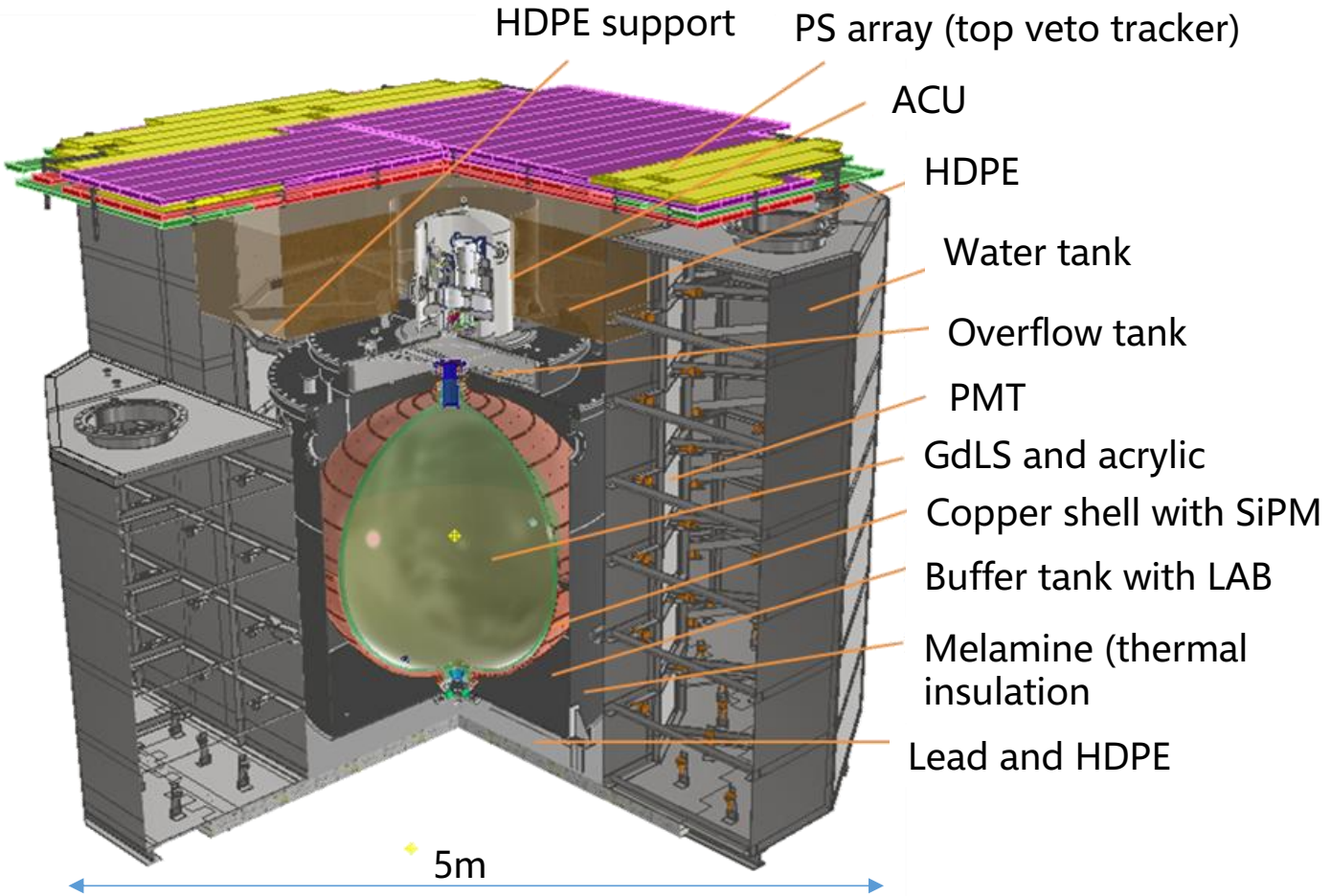


Introduction: Detector Design

- Central detector (CD)
  - 2.8 t GdLS in an acrylic vessel ($\emptyset$ = 1.8m)
  - 10 m^2 SiPM on a copper shell
  - Tank filled with buffer LAB
  - Automated Calibration Unit (from Daya Bay) and Cable Loop System
- 2 veto detectors
  - 3 water Cerenkov detectors
  - 4 layers of plastic scintillator bars



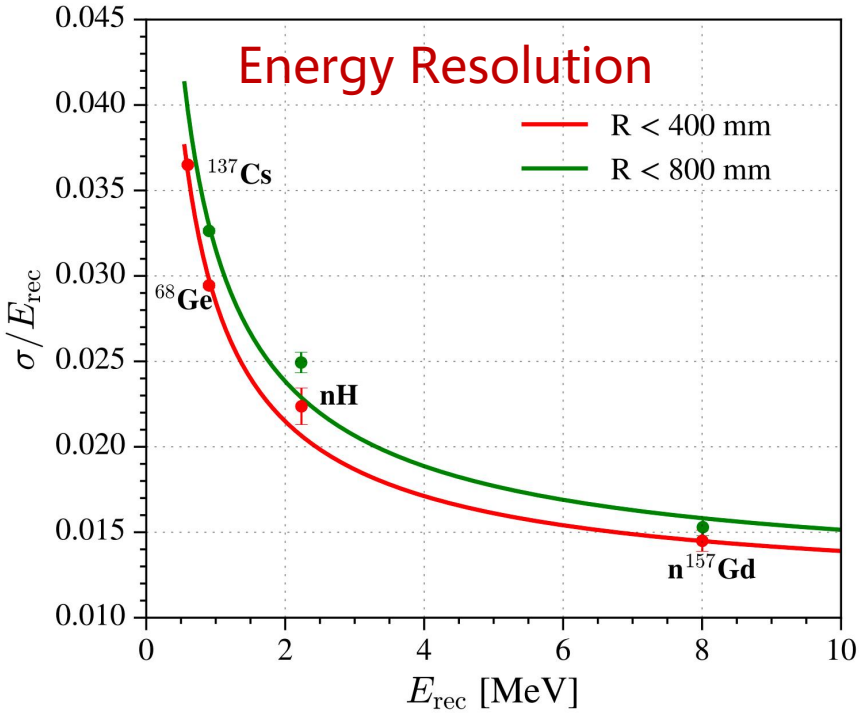
- IBD to detect reactor $\overline{\nu}_e$
- neutron captured by Gd

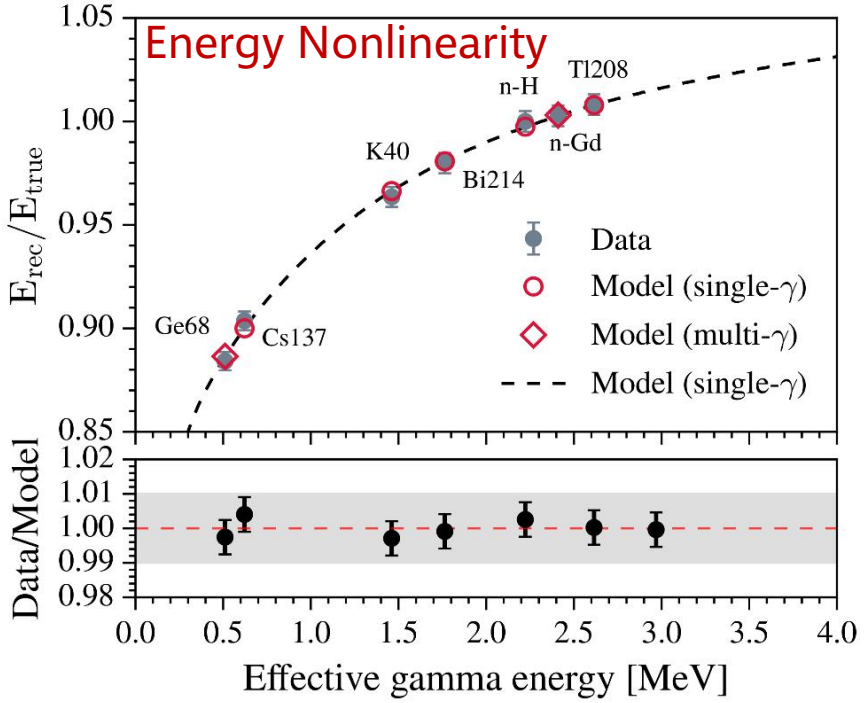


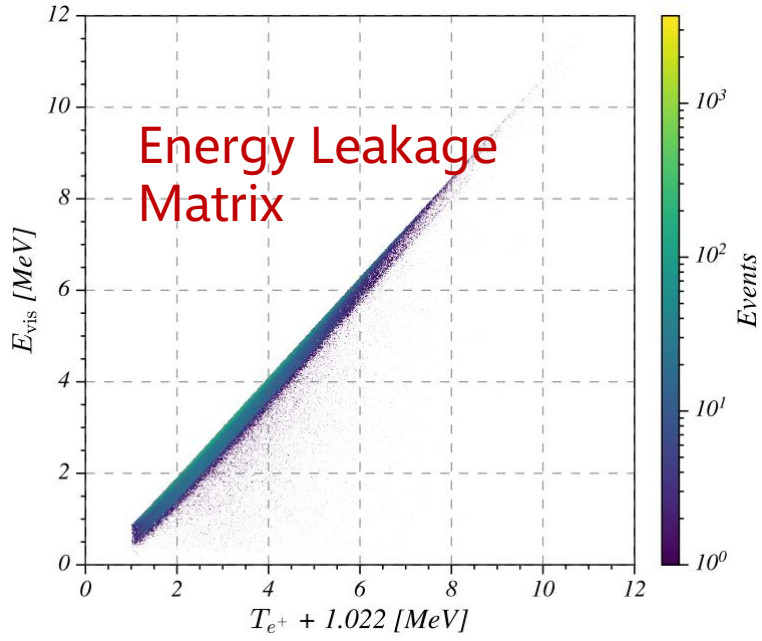
From Yichen's talk in Neutrino2026

TAO Detector Performance: Energy Response

- **Energy resolution**： 1. **Ge-68 @R = 0**: 2.82% @1MeV; 2. γ curve → e^+ curve using MC
- **Energy nonlinearity**: 1. fit single-γ nonlinearity (NL) model, convert to positron nonlinearity with MC; 2. uncertainty 1~2%
- **Energy leakage**: 1. Generated by MC, validation with CLS Cs-137 MC/data; 2. Shape systematics: fiducial volume uncertainty + energy leakage → IBD prompt spectrum uncertainty



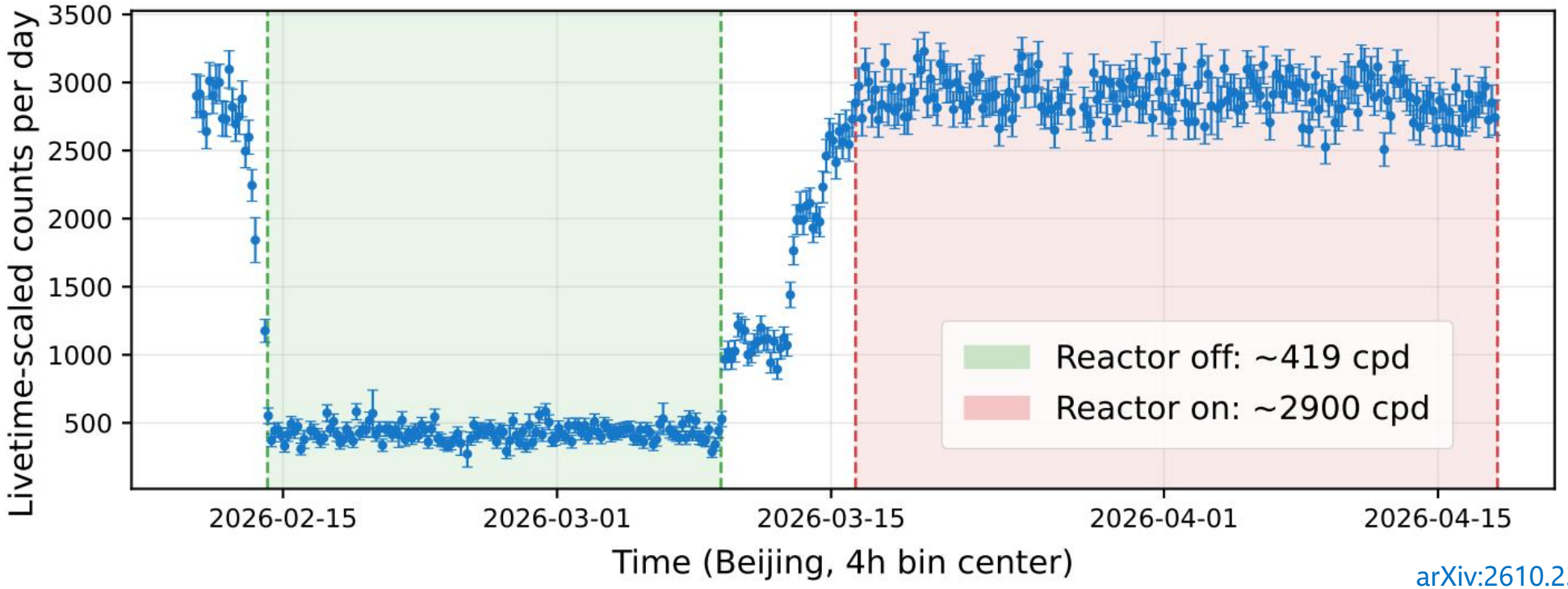




arXiv:2610.23331

TAO IBD Analysis: Observed IBD Signal Rate

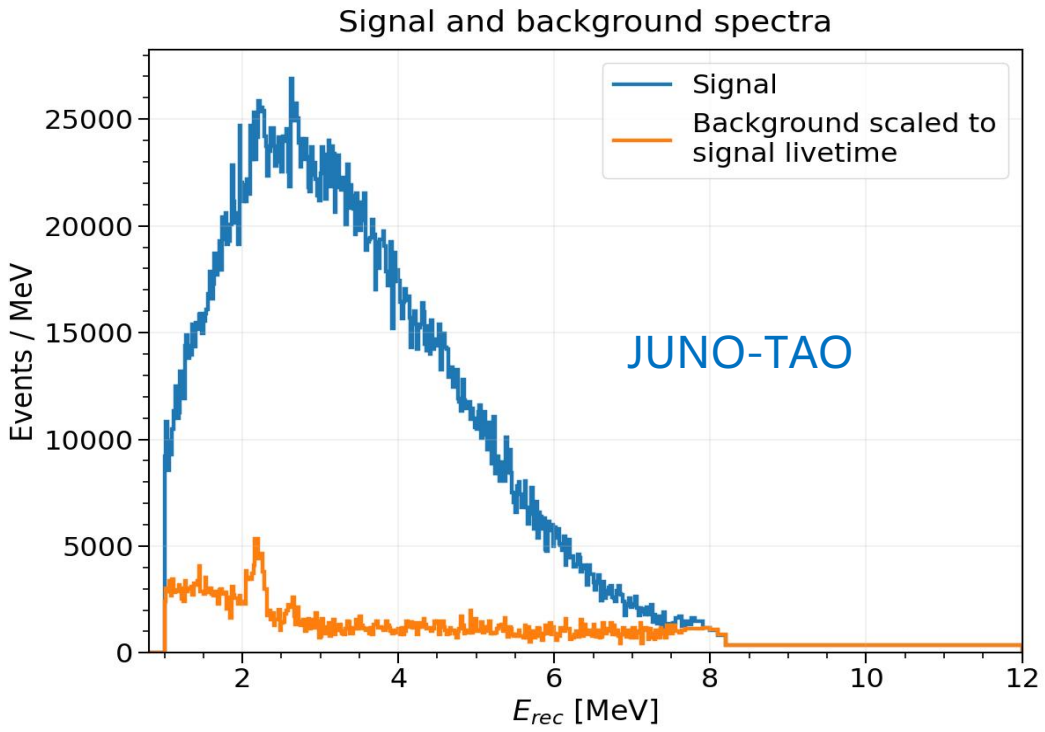
- **Observed IBD signal rate**: ~2500/day, from reactor-on data minus (scaled) reactor-off data.
- **S:B = 6:1 w/o PSD (pulse shape discrimination)**,
  - Really good for shallow overburden experiment
  - could be improved in future

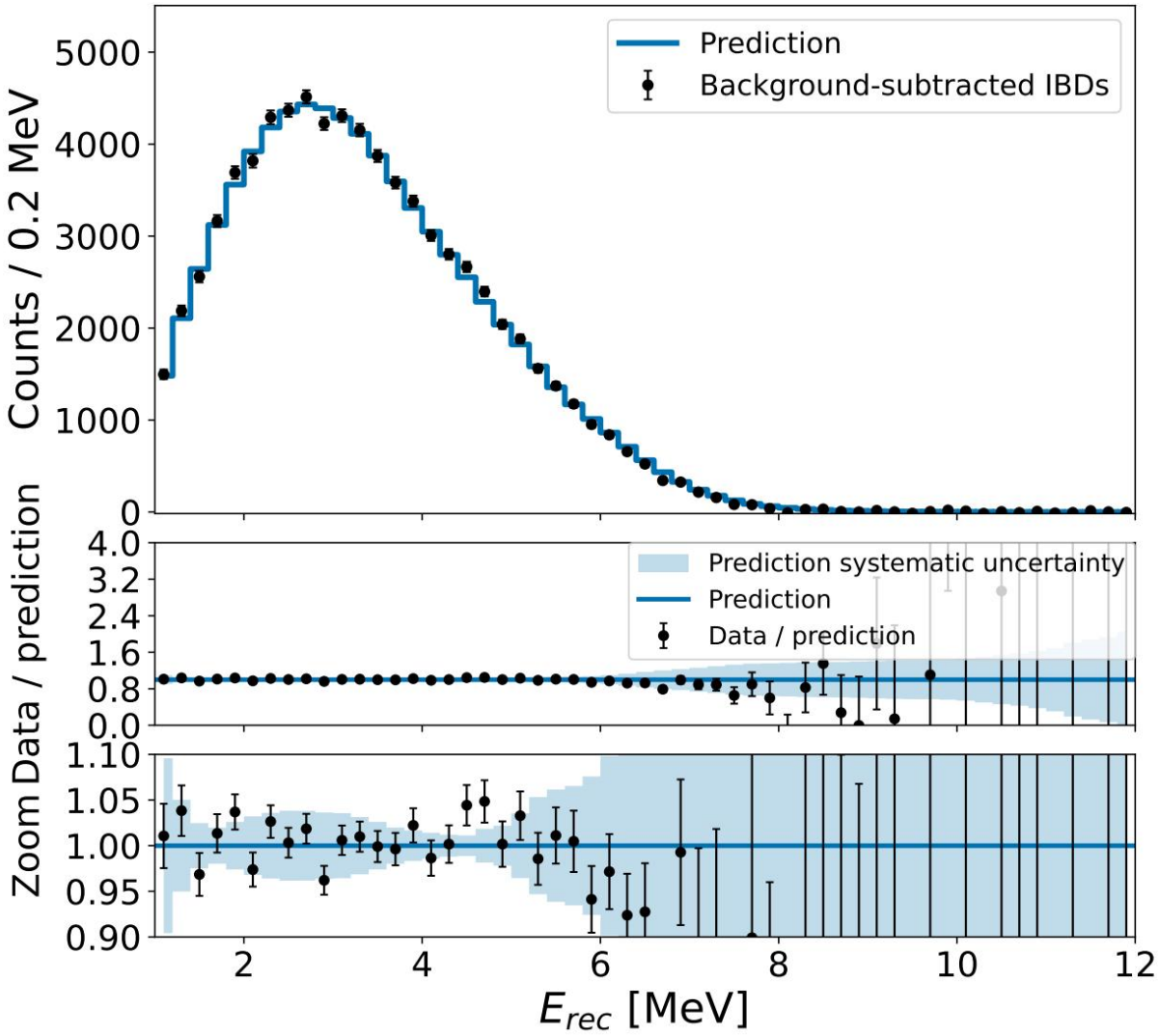


arXiv:2610.23331

TAO IBD Analysis: Prompt Event Energy Spectrum

- **Prediction**: Huber-Mueller model, convoluted with TAO detector response
- **Results**: sign of 5 MeV bump, small difference in high energy tail

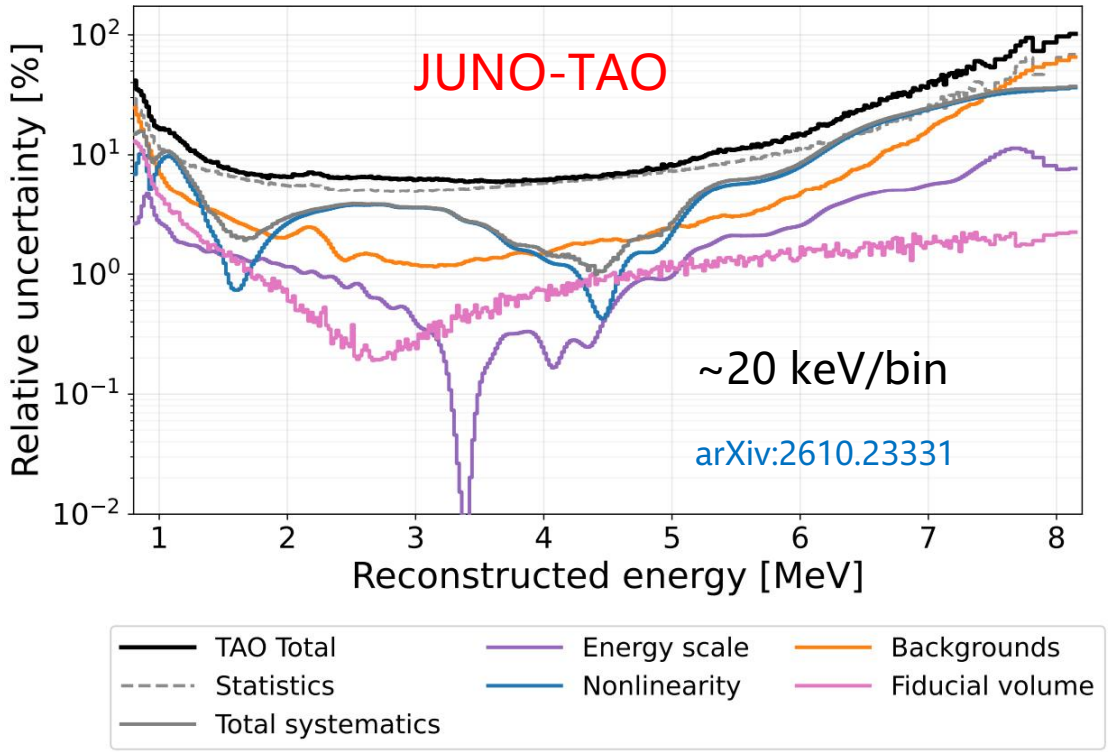


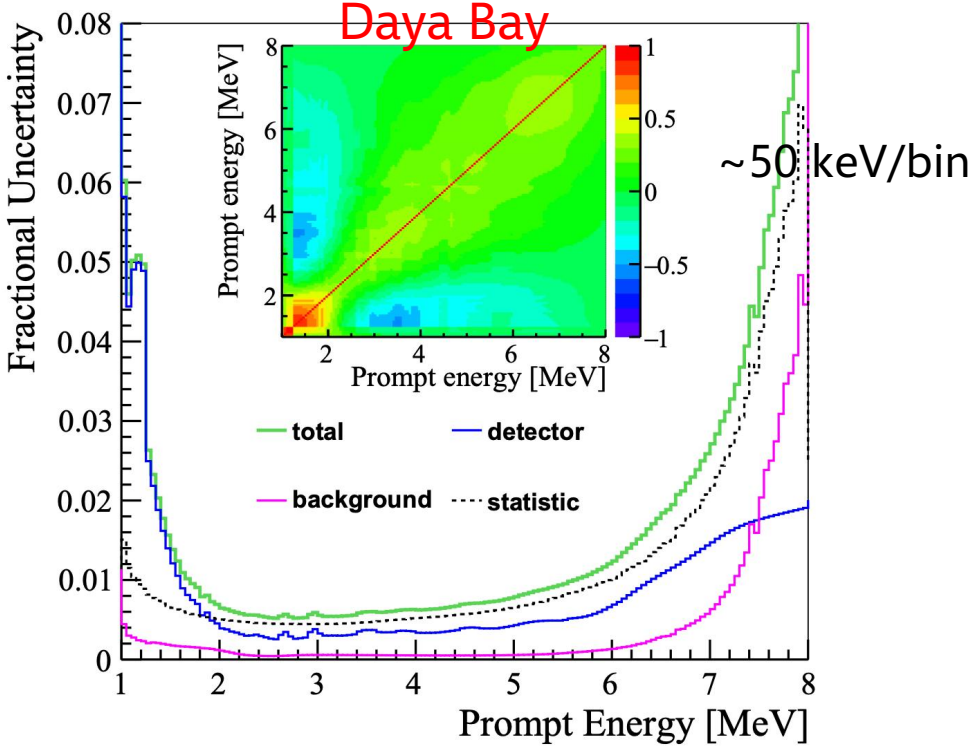


arXiv:2610.23331

For Geoneutrino Measurement

- Current measurement have relatively big uncertainty at low energy region (< 2.5 MeV).
- With reactor-on and off subctration, method like PSD is needed to reduce the statistical uncertainty of background.
- Energy non-linearity and energy leakage effects are dominated systematic uncertainties → need better understanding on response to help the geoneutrino study.

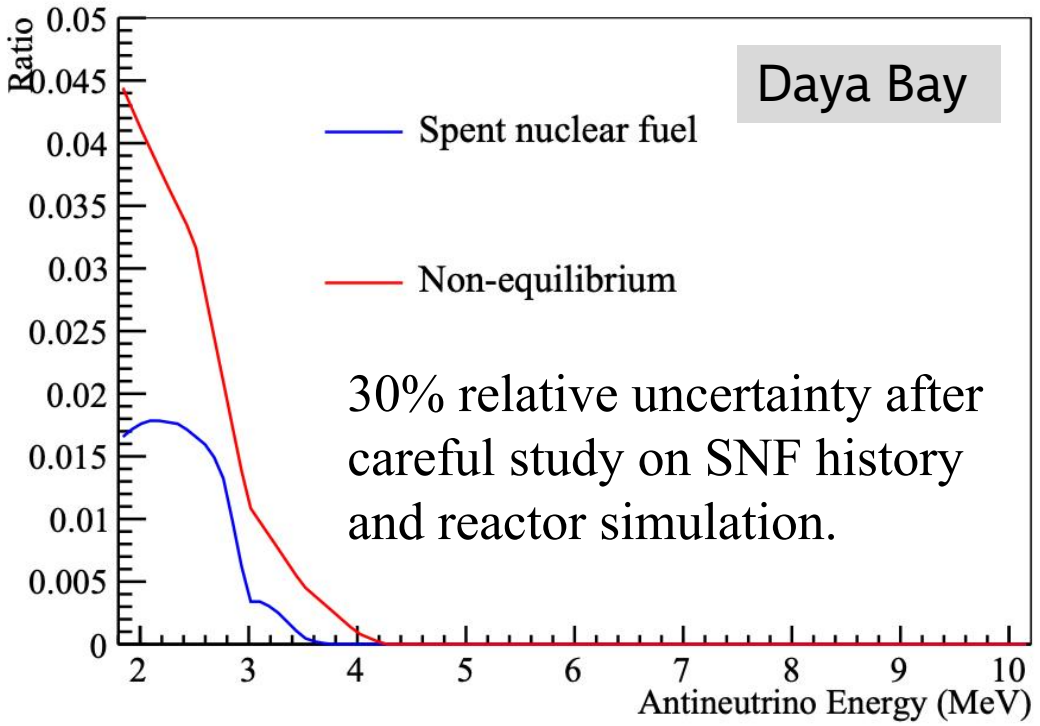




Chin. Phys. C 45 (2021) 073001

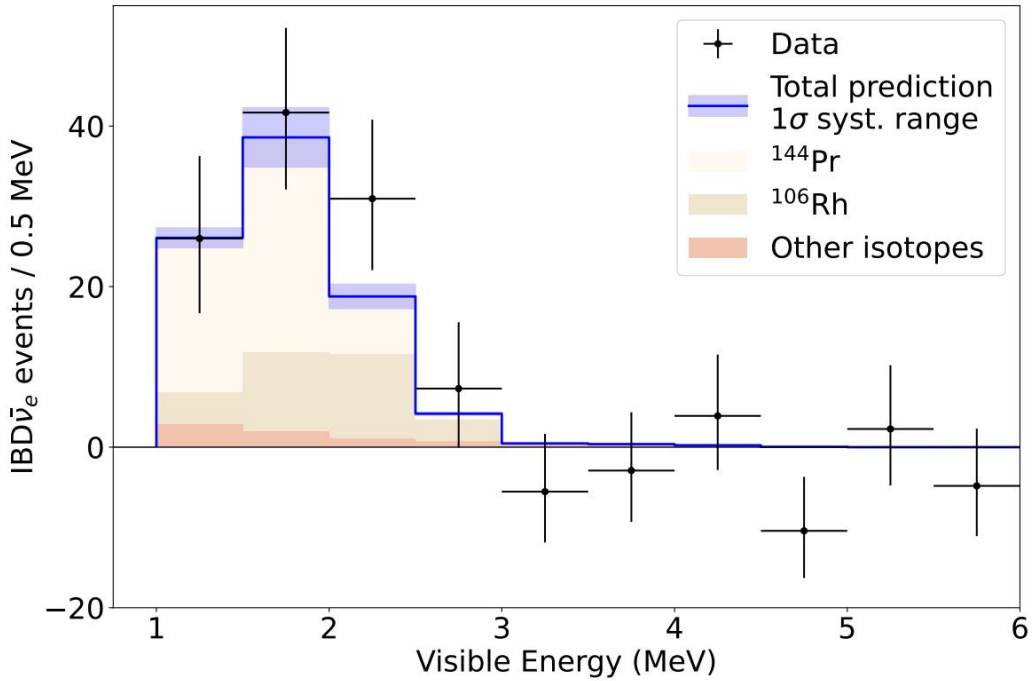
For Geoneutrino Measurement

- Reactor antineutrinos from non-equilibrium contribution and SNF (spent nuclear fuel) relies heavily on the burning history and the location of SNF.
- Previous study at Daya Bay assign 30% relative uncertainty for both effects.
- Non-neglible contribution to spectrum uncertainty especially at low energy region → first direct observation (5.9σ) at Double Chooz.



Chinese Physics C, 2017, 41(1): 13002-013002

SNF neutrino observed by Double Chooz



Phys.Rev.Lett. 137 (2026) 6, 061803

Summary

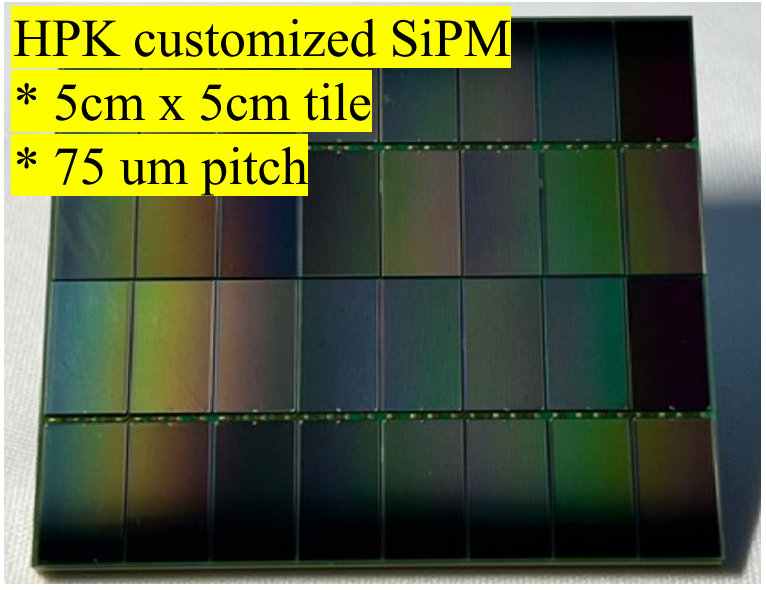
- Reactor antineutrinos are important background for Geoneutrino studies.
- Experiments (like Daya Bay, PROSPECT, STEREO) provides precise antineutrino measurements of total spectrum and isotopic spectra.
  - Data-driven prediction method is provided.
- TAO detector is constructed and in stable operation since Feb. 10th, 2026.
  - World leading energy resolution 2.8% @Ge-68, further improvements expected.
  - Preliminary IBD analysis with 1 month data, sign of 5 MeV bump.
- Further efforts are needed to reduce uncertainties in the low energy part of the spectrum.
- Below IBD threshold: 1.8 MeV?

Backup

SiPM Assembly and Cabling at TAO



Full-cover SiPM



HPK customized SiPM
* 5cm x 5cm tile
* 75 um pitch



4024 SiPM tiles
* 1 signal, 1 HV, ¼ LV cables / tile

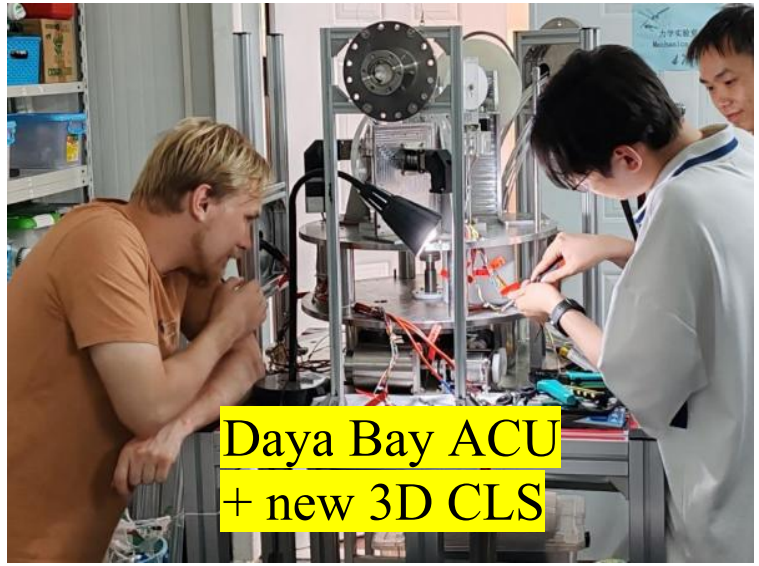


SiPM-Acrylic clearance: < 2cm



Good control of cleanness

Calibration and Veto Systems at TAO


Daya Bay ACU
+ new 3D CLS


PS module
before packaging


PS array
Installation

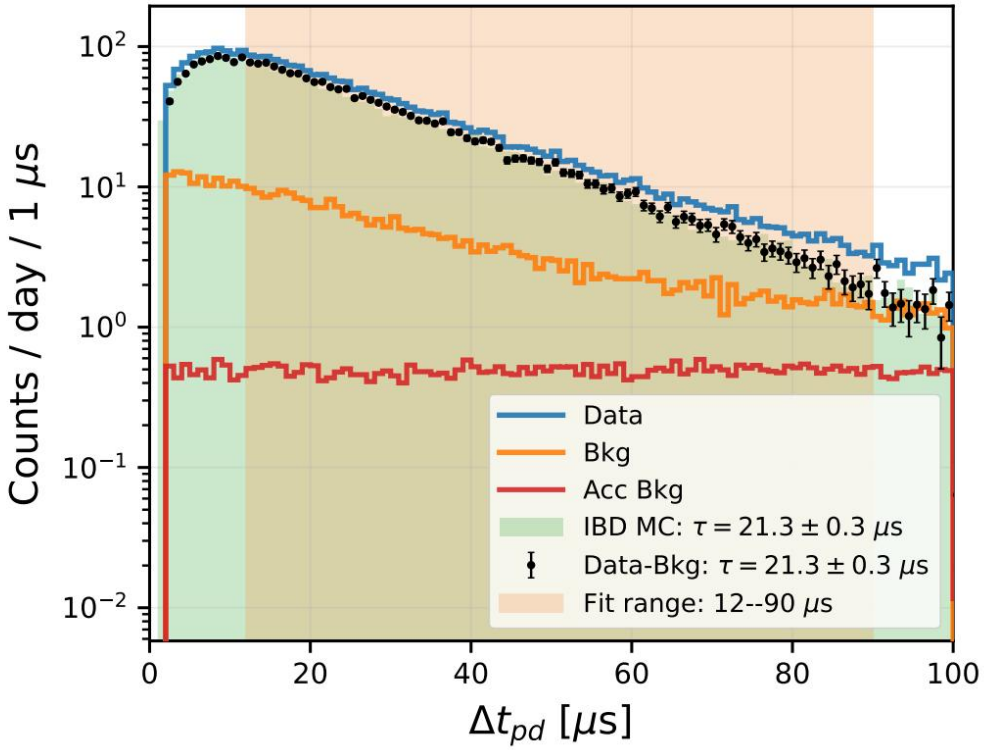

Adapted JUNO
sPMT elec. box

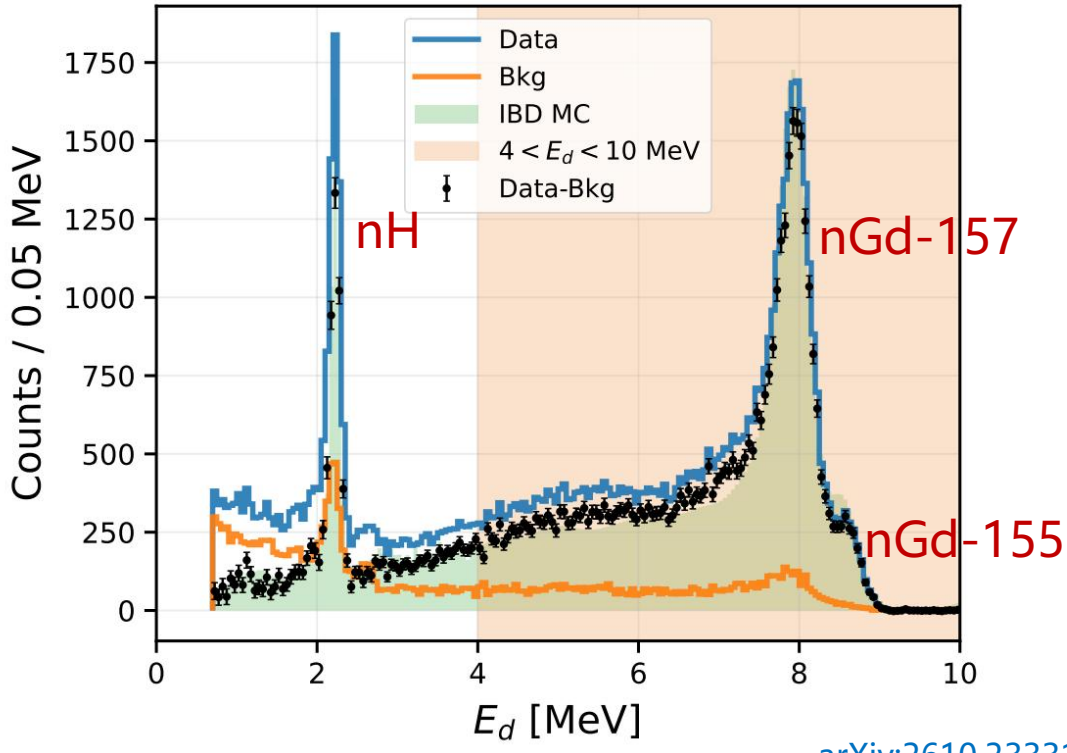

Water tank positioning


sPMT Installation

TAO IBD Analysis: Time / Distance / Energy Cut

- **Time**: ΔT(prompt, delayed) in (2, 100) us time window, veto events in (0,100) us after muon
- **Space**: ΔR(prompt, delayed) < 500 mm, R(prompt) < 800 mm (Fiducial Volume Cut)
- **Energy**: E(delayed) in (4,10) MeV
- **Total efficiency**: 46.6 ± 5.0 %, **systematics**: FV cut on R(prompt), energy cut on E(delayed)

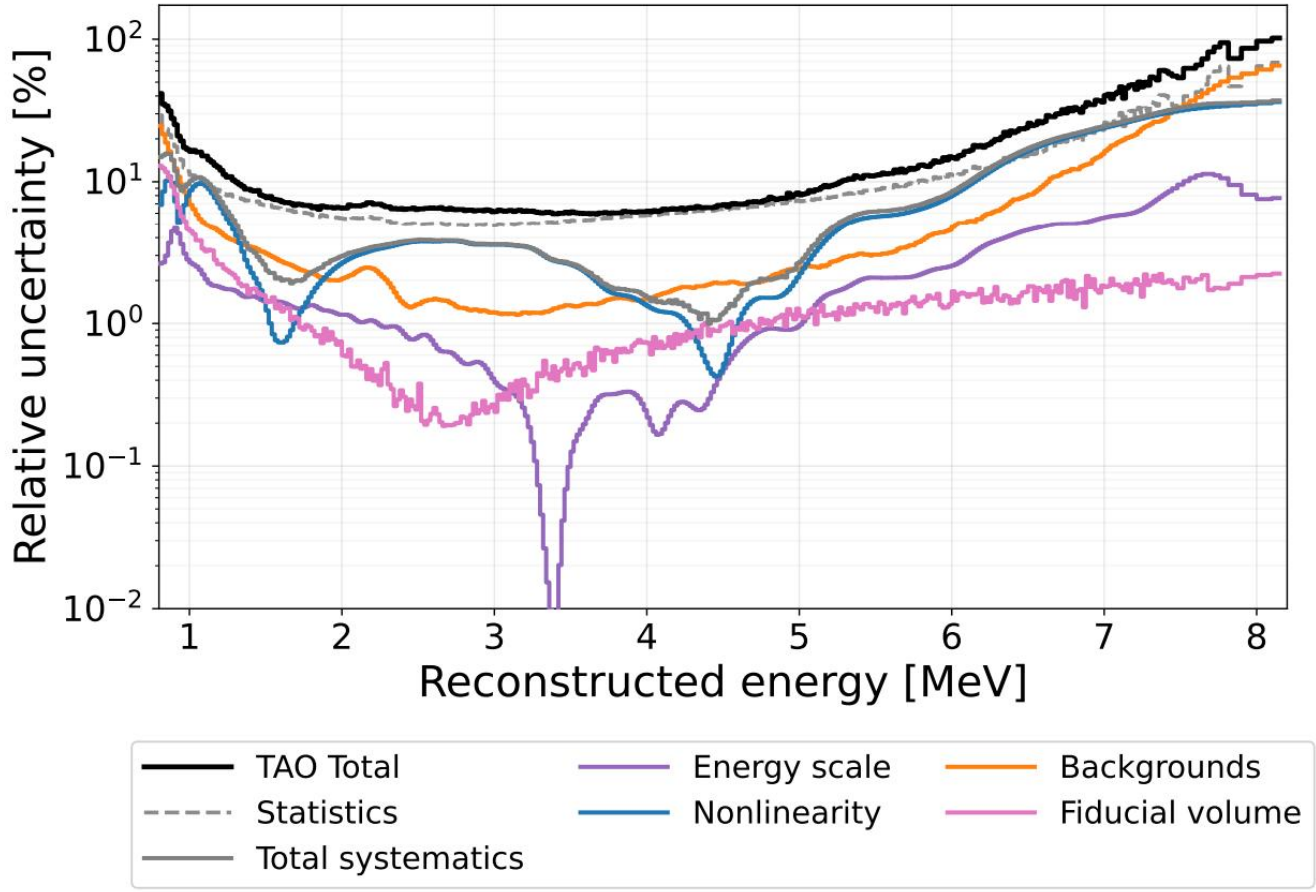




arXiv:2610.23331

TAO IBD Analysis: Shape Uncertainty

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

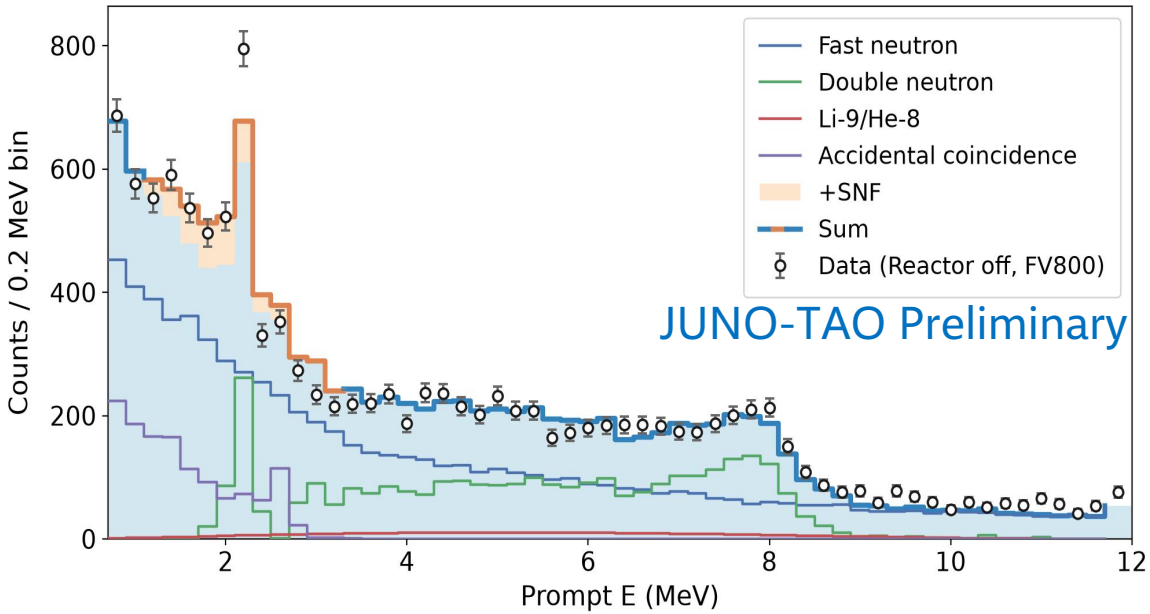


arXiv:2610.23331

TAO 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

