反应堆中微子能谱：
大亚湾实验最新结果与JUNO-TAO实验

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全国粒子物理学术会议
2024.8.13~18　　青岛

大亚湾实验
反应堆中微子能谱测量
最新结果

Reactor antineutrinos

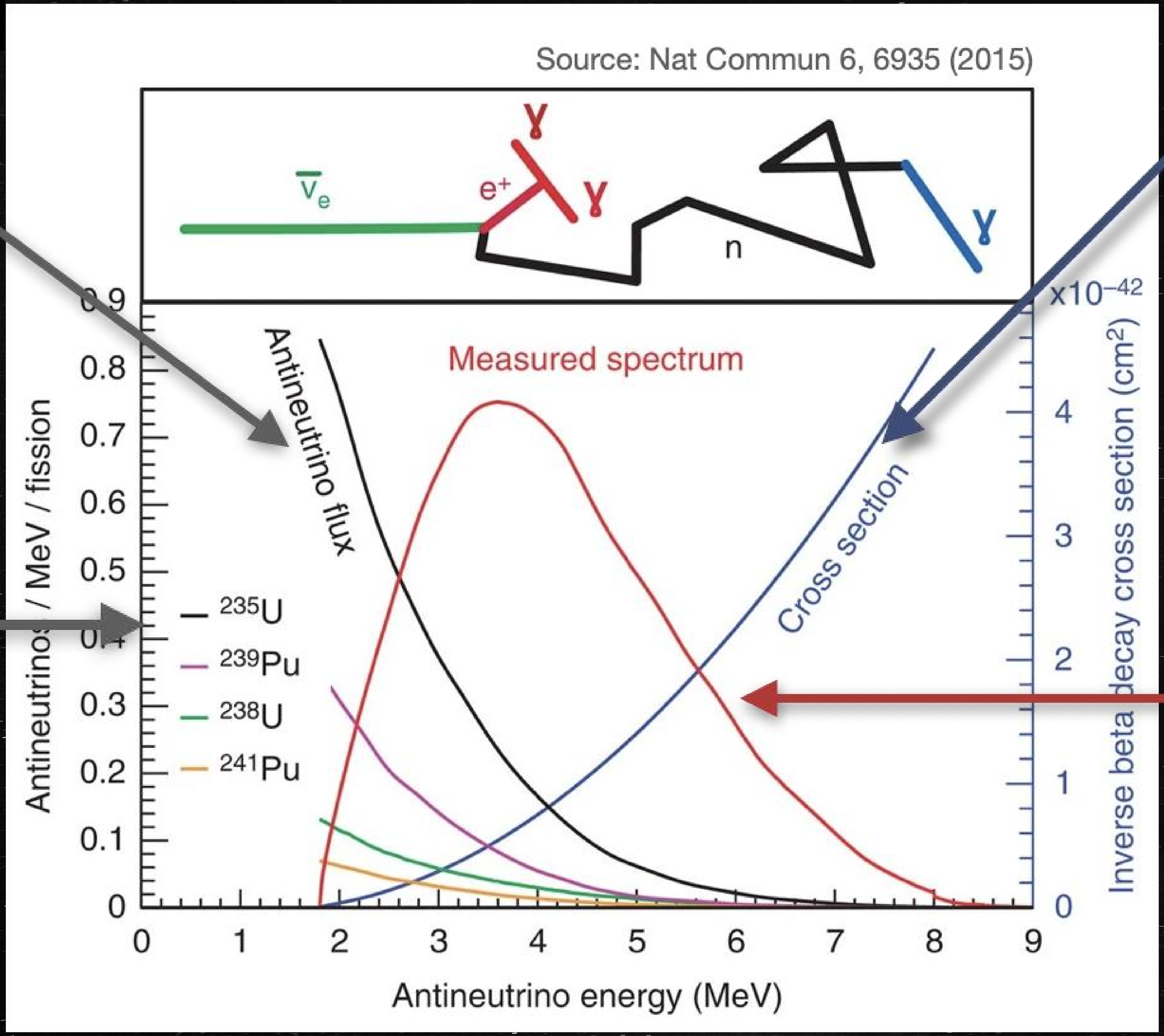
- **Nuclear reactor: powerful & pure $\bar{\nu}_e$ source**

- **Production via beta decay:**

$$n \rightarrow p + e^- + \bar{\nu}_e$$

- **^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu contribute >99% $\bar{\nu}_e$**
  (commercial reactors)

- **Model predictions:**
  Conversion method
  Summation method



- **Measurement via inverse beta decay:**

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

Prompt   Delayed

- **"Direct" measurement:**
  (commercial reactors)
  Overall IBD yield

$$\sigma_f = \frac{N_{IBD}}{\beta}$$

IBD number
Effective fission number

- Combination of isotopic yields
- Evolution along fuel burning

Daya Bay (DYB) experiment

- **Detect $\bar{\nu}_e$:**

  from 2 nuclear power plants (6 cores);

  with 8 identical antineutrino detectors (ADs);

  in 3 experimental halls (EHs);

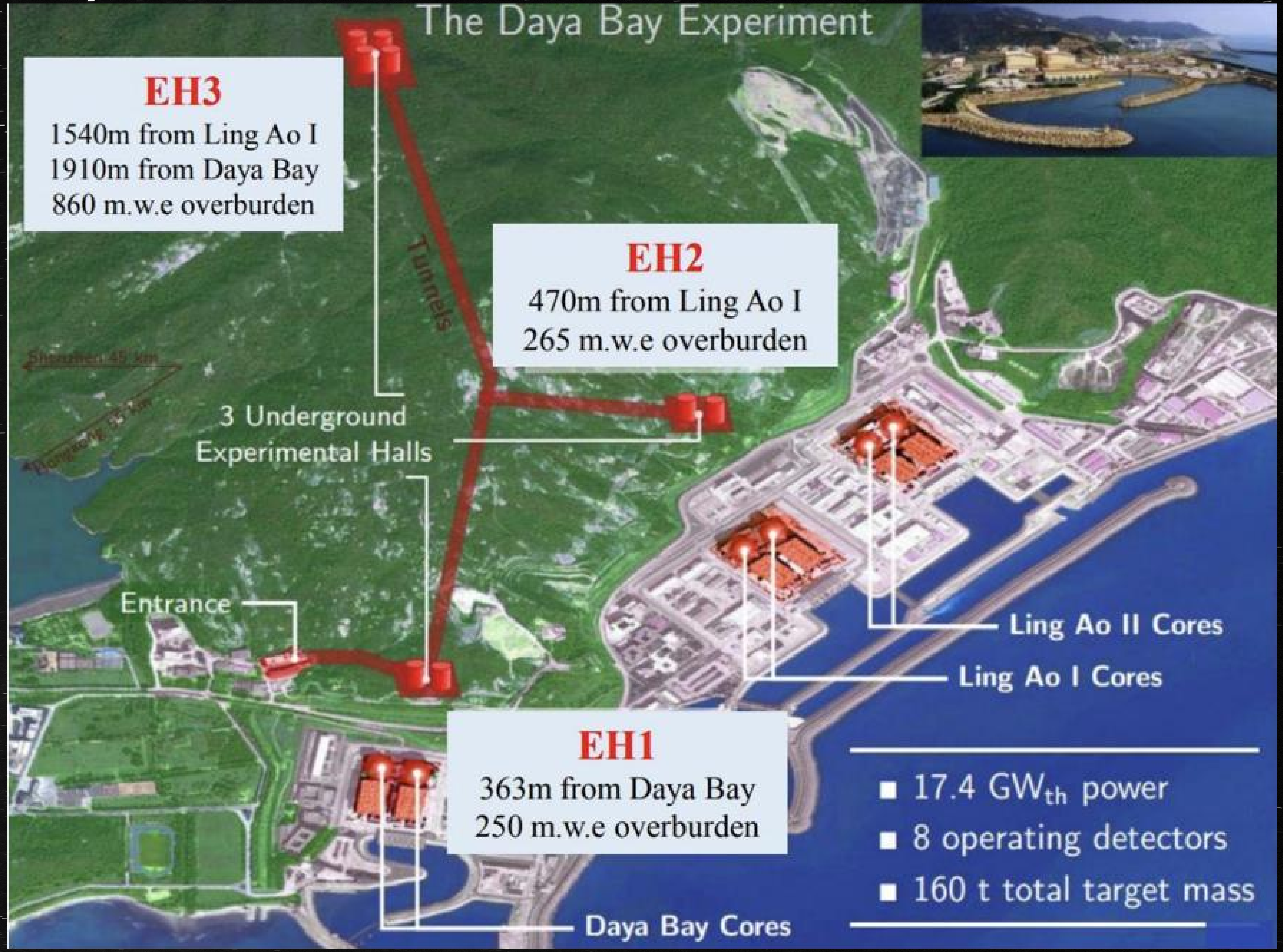
- **Leading θ_{13} experiment.**

  $$sin^2 2\theta_{13} = 0.0851 \pm 0.0024$$

  PRL 130 (2023) 16, 161802

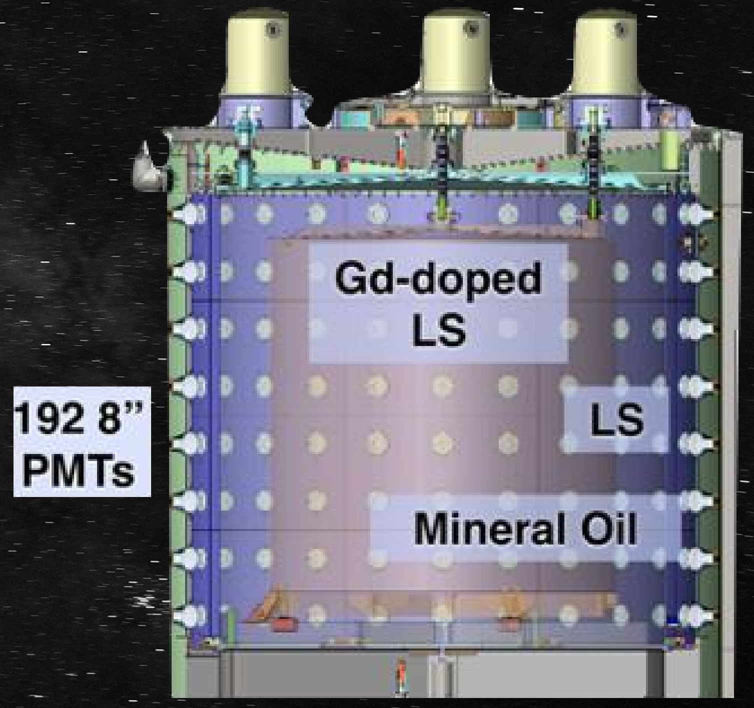
  (Relative near/far measurment for θ_{13})

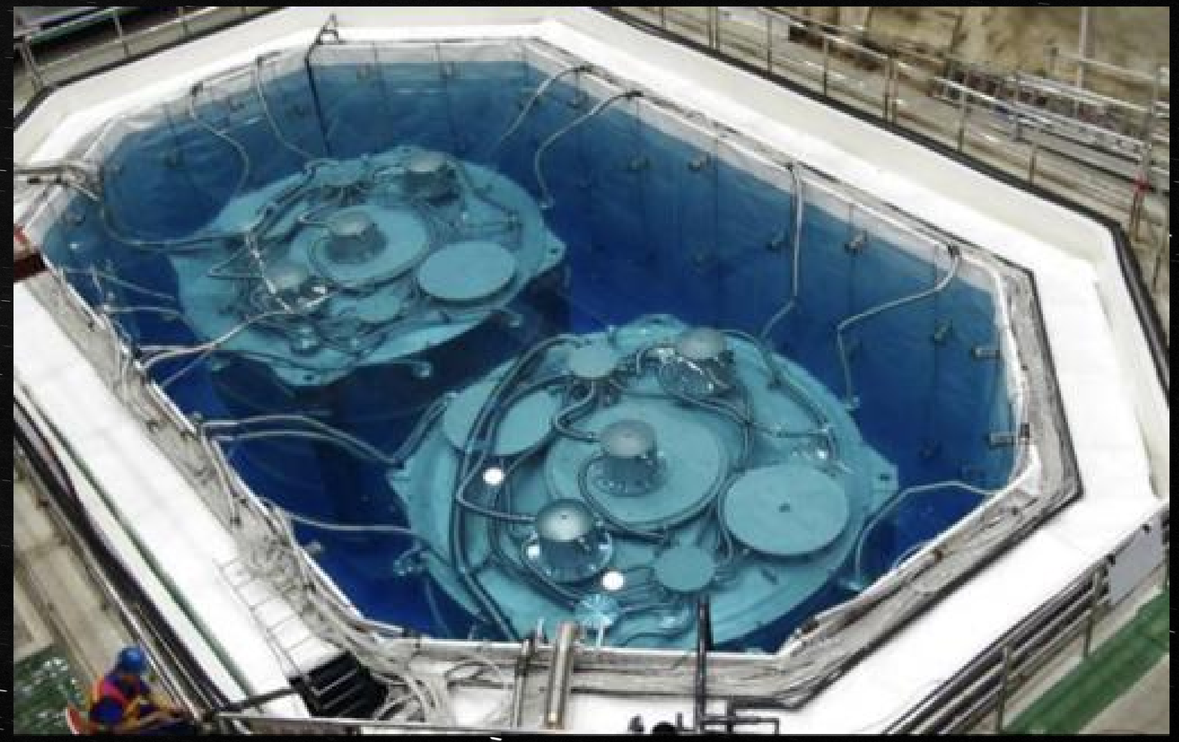
Running from 2011 to 2020.



This talk:

Full data set: ~4.7 million IBD (n-Gd) sample at DYB near ADs.
Precision measurement of reactor $\bar{\nu}_e$ flux and spectrum.
(absolute measurement)





Overall spectrum and flux

- **Spectrum:**

  ~1.4% precision in 2~5MeV

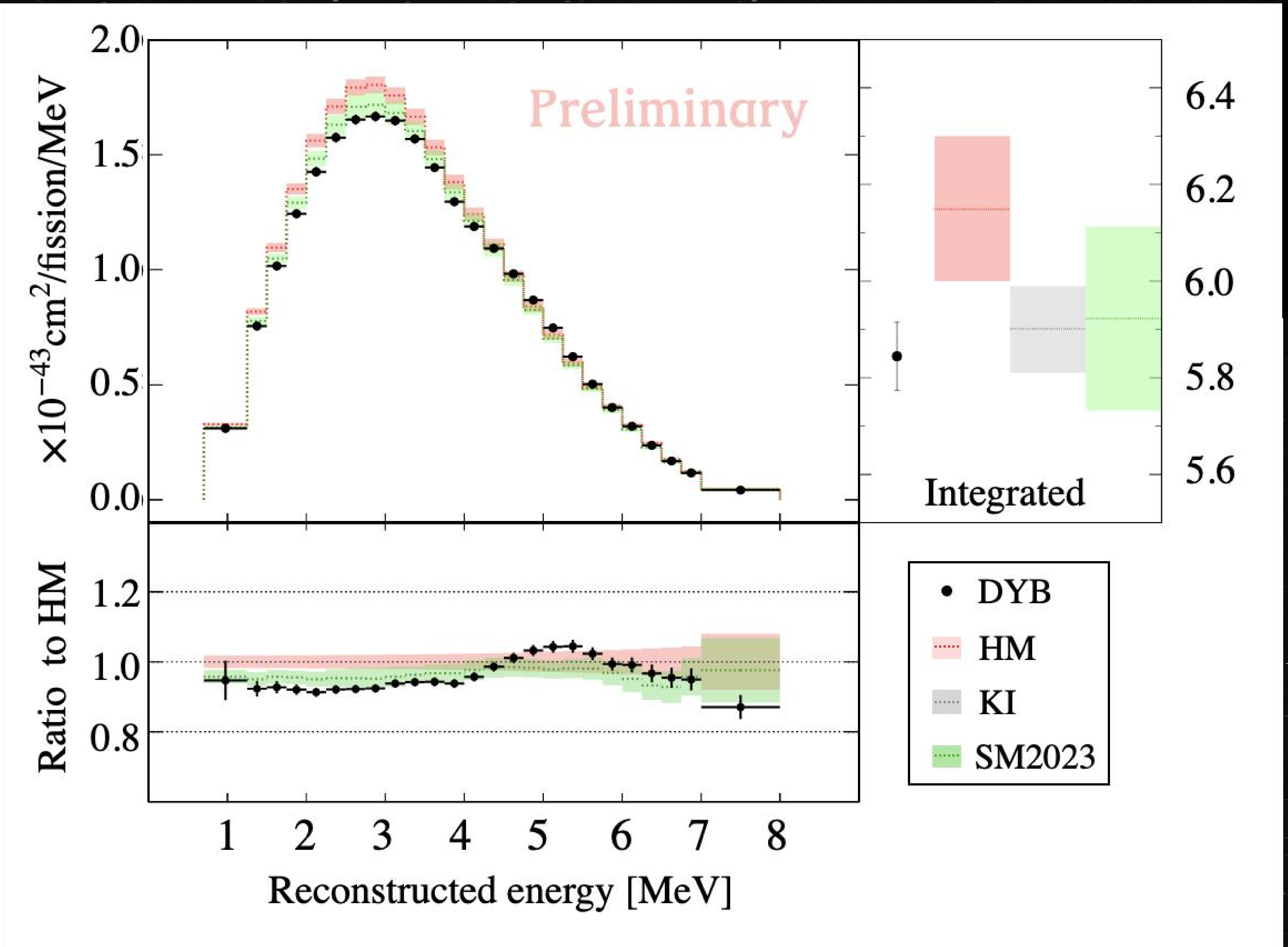
  Comparison with models

- **shape + rate:**

  DYB differs from **HM** (more significant) and **SM2023**;
  "constant" deficit below 4MeV
  "slight" excess around 5MeV

- **shape-only:**

  DYB differs from **HM** and **SM2023** by feasuring a "**5MeV bump**"



- **Flux:**

  $[5.84 \pm 0.07] \times 10^{-43} cm^2/fission$

  1.2% precision

  Comparison with models

- **rate-only:**

  DYB differs from **HM**, **agrees** better with **SM2023** and **KI**

Conversion models:

Huber-Mueller (HM)
PRC 83, 054615 (2011)
PRC 84, 024617 (2011)
KI (updated ^{235}U)
PRD 104, L071301 (2021)

Summation models:

SM2023 (latest)
PRC 108, 055501 (2023)
PRL 130, 021801 (2023)

Fuel Evolution

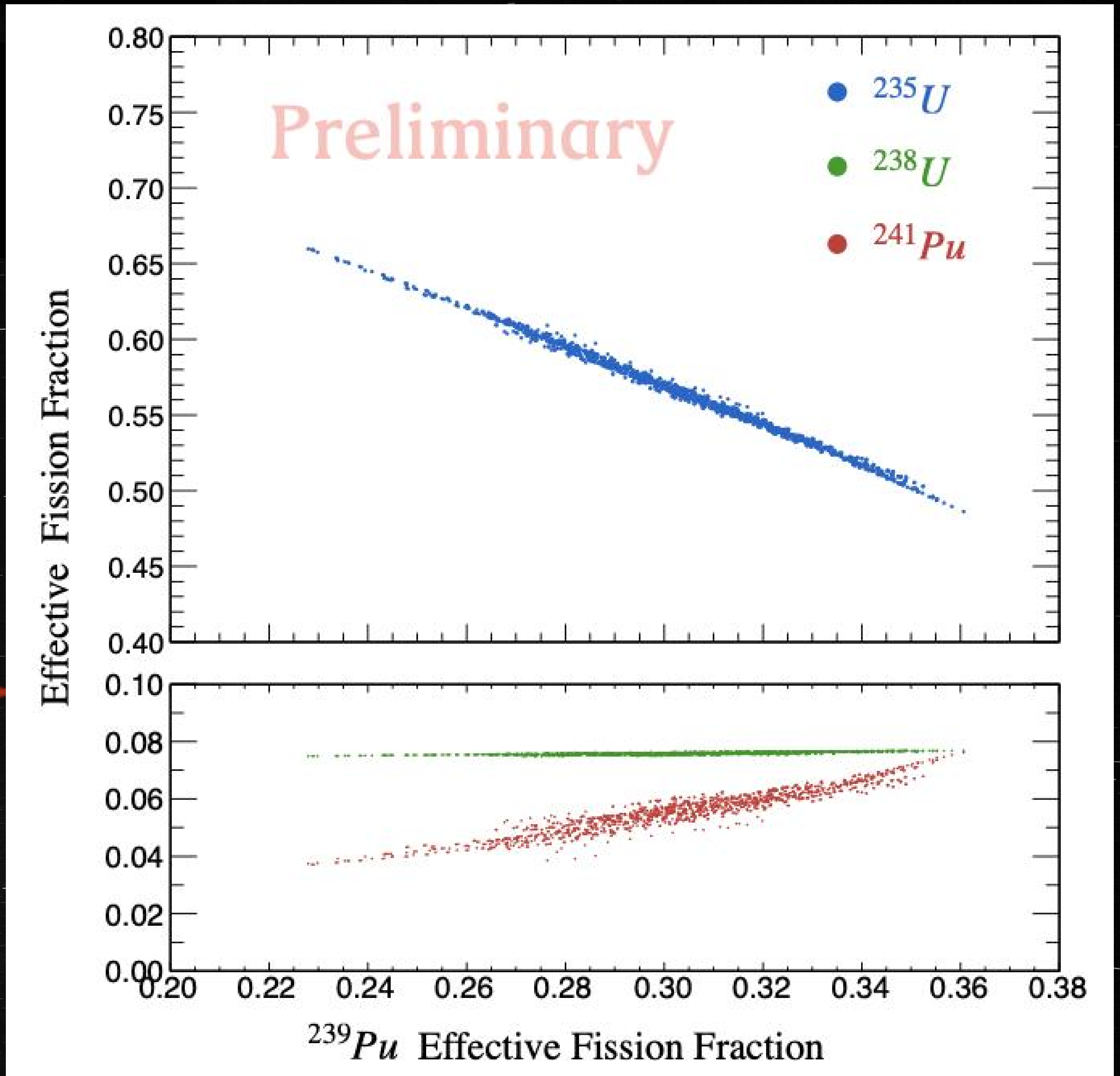
- **Fraction of fission isotopes** changes with fuel burning, in one period:

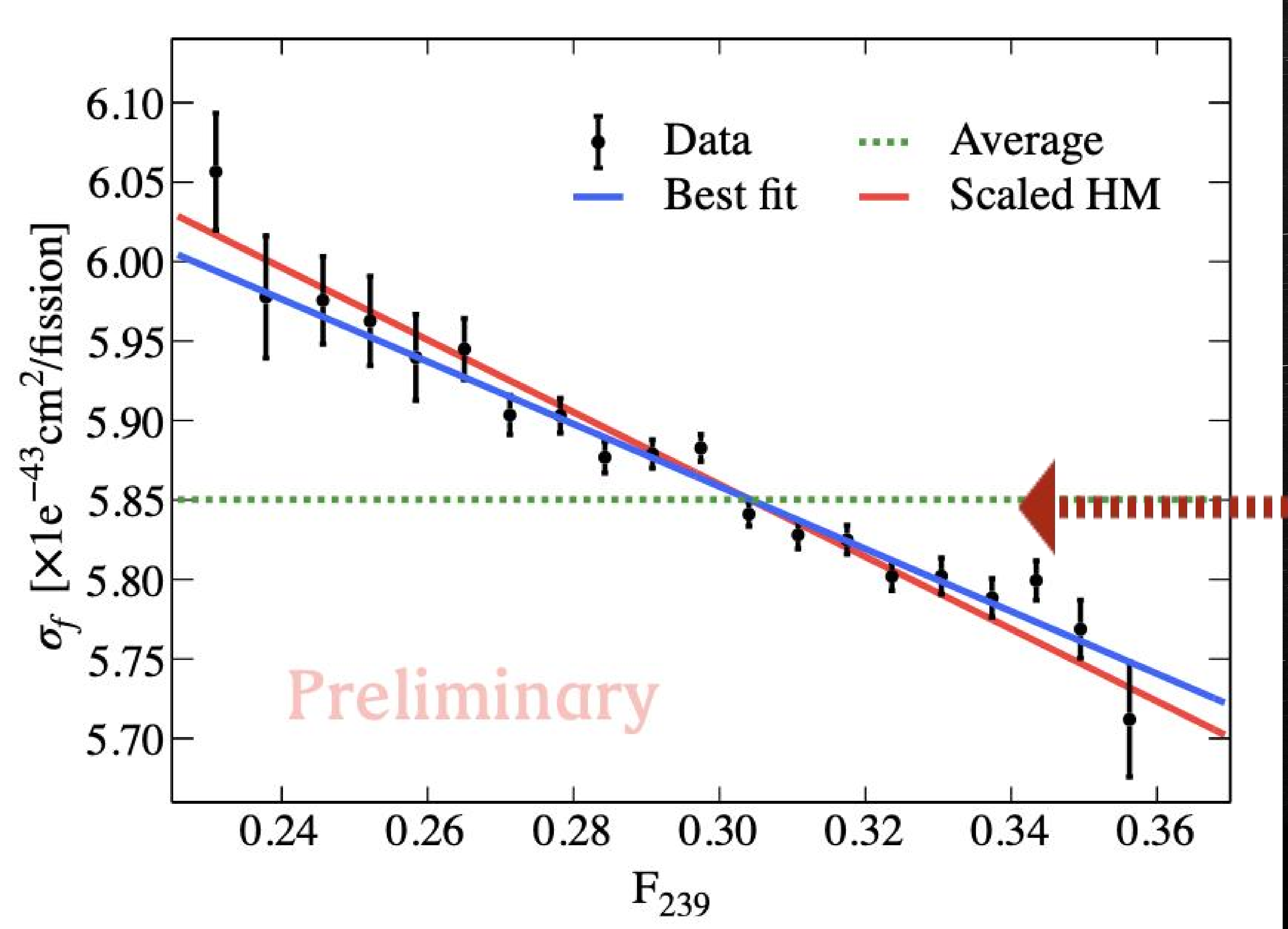
$^{235}U \downarrow \quad ^{238}U \rightarrow \; ^{239}Pu \uparrow \quad ^{241}Pu \uparrow$

- **Effective fission fraction**: frac. of fiss. isotopes viewd by detectors

$$F_i = \sum_{r=1}^{6} \frac{W_{th,r}(t) f_{i,r}(t)}{L_r^2 \overline{E}_r(t)} / \sum_{r=1}^{6} \frac{W_{th,r}(t)}{L_r^2 \overline{E}_r(t)}$$

- **Fuel evolution** in terms of F_{239}





- **Overall IBD yield evolution**: (σ_f) change w.r.t. F_{239}

$$\frac{d\sigma_f}{dF_{239}} = [-1.96 \pm 0.13] \times 10^{-43} cm^2/fission$$

- Enable **extraction** of istopic spectrum and flux

Isotopic spectrum

- **Extract isotopic spectra of ^{235}U and ^{239}Pu through fuel evolution analysis:**

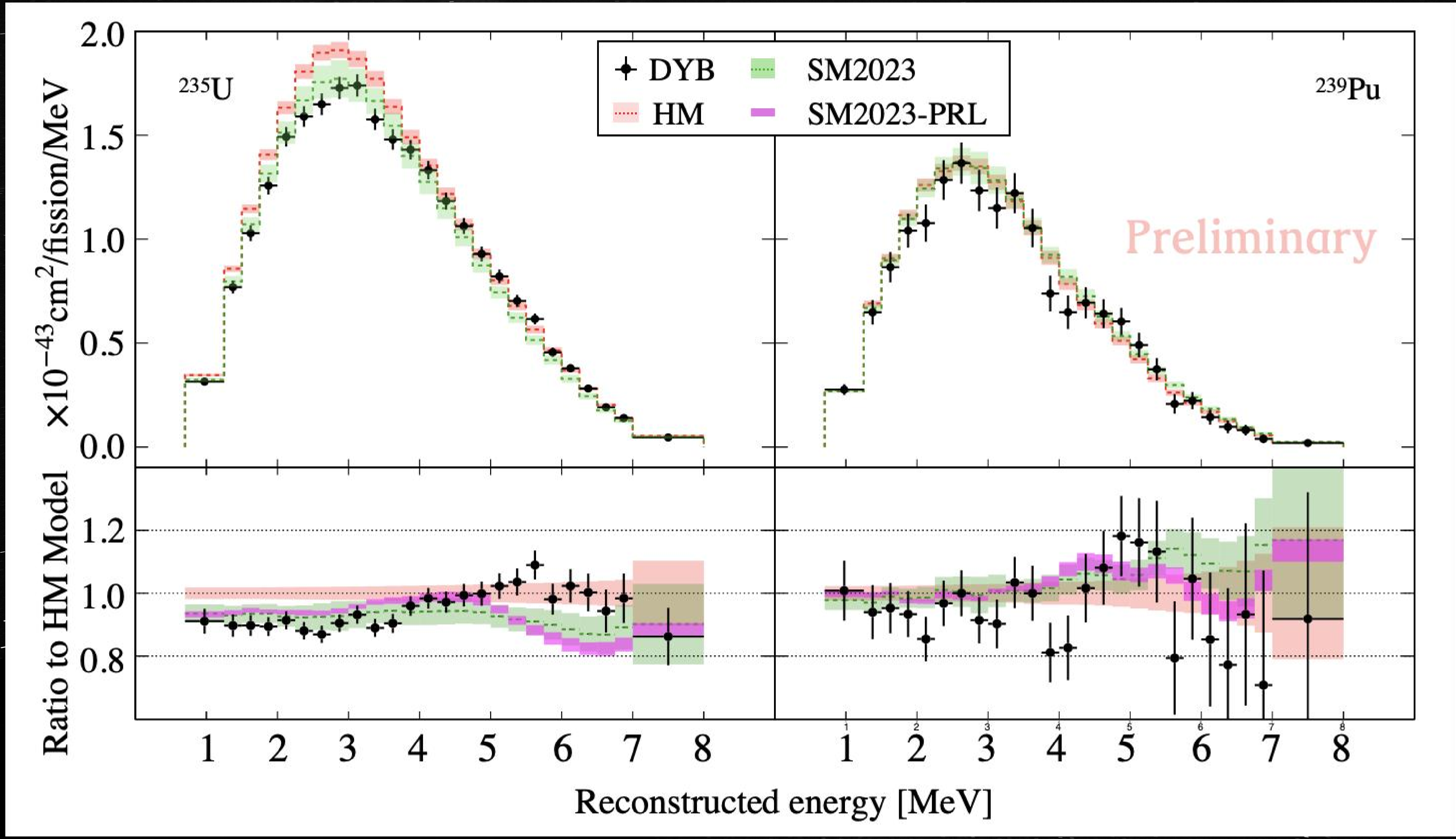
$$\chi^2 = \chi^2(s_f, F, s_i, \epsilon) + \chi^2(s_{238}, s_{241})$$

- s_f, F → Overall spectrum evolution data
- s_i → Isotopic spectrum
- ϵ → Systematics
- s_{238}, s_{241} → Constrain ^{238}U, and ^{241}Pu with HM (conservative setting with enlarged HM errors)

^{235}U spectrum:
~3% precision in 2~5 MeV

- **Rate+shape:**
  DYB vs **HM**: >3σ deficit below 4MeV
  DYB vs **SM2013**: >3σ bump above 4MeV
- **Shape-only:**
  DYB vs **Models**: >3σ bump above 4MeV

PS: Stereo (Nature 613, 257–261) agrees with SM2023-PRL (new summation model)



^{239}Pu spectrum:
~7% precision in 2~5 MeV

- **DYB** with larger errors, consistency with **Models**: at ~**2**σ level

Isotopic flux

- **Extract ^{235}U and ^{239}Pu fluxes with fuel evolution data**

$$\sigma_{235} = [6.16 \pm 0.12] \times 10^{-43} cm^2/fission$$

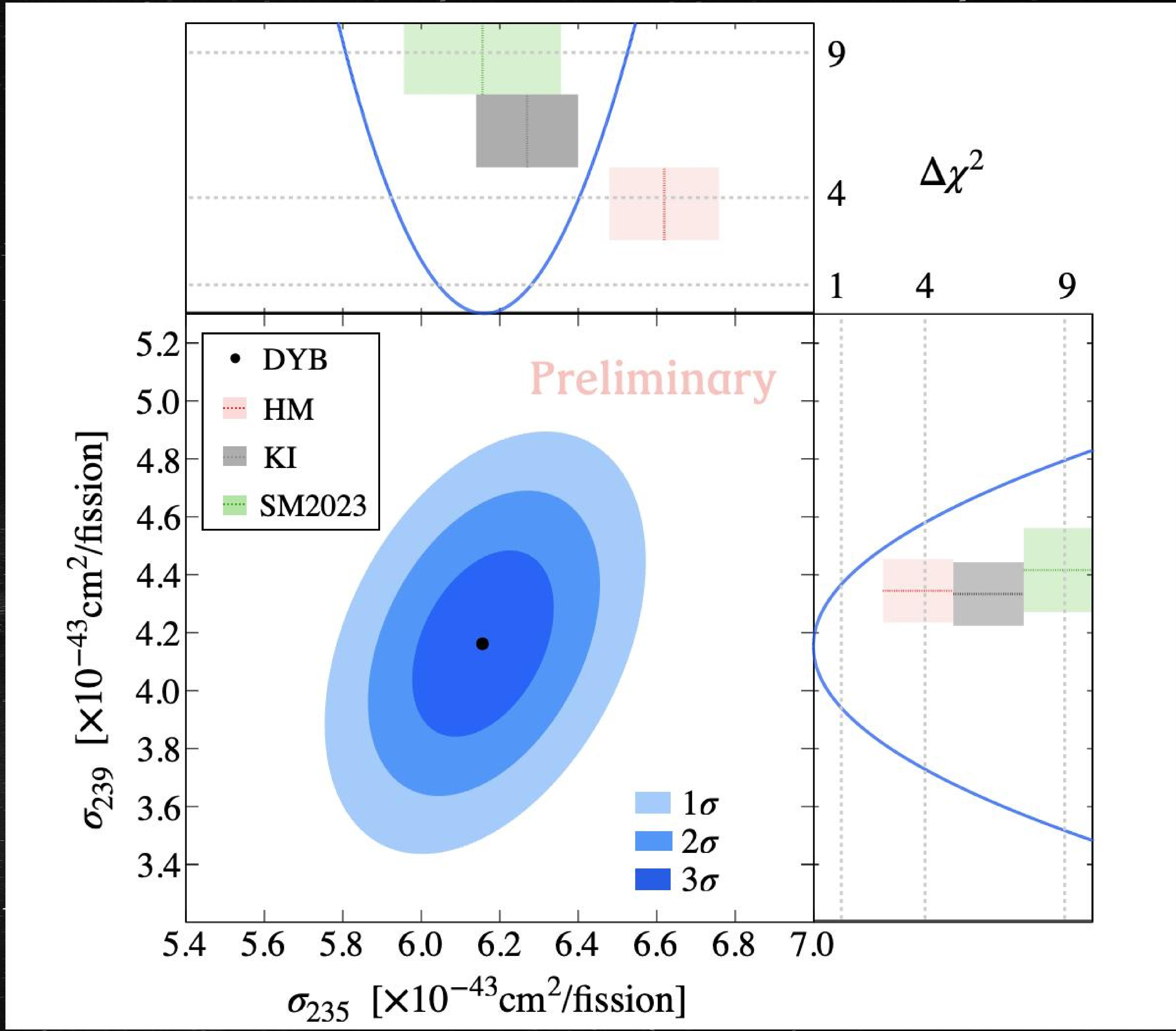
$$\sigma_{239} = [4.16 \pm 0.21] \times 10^{-43} cm^2/fission$$

^{235}U flux:

DYB differs from **HM** (>2σ), agrees better with **KI** and **SM2023**

^{239}Pu flux:

- **DYB** with larger errors, consistency with **Models** at ~**1**σ level



Spectrum unfolding

"Direct" measurement of rec. energy spectrum of IBD prompt signal

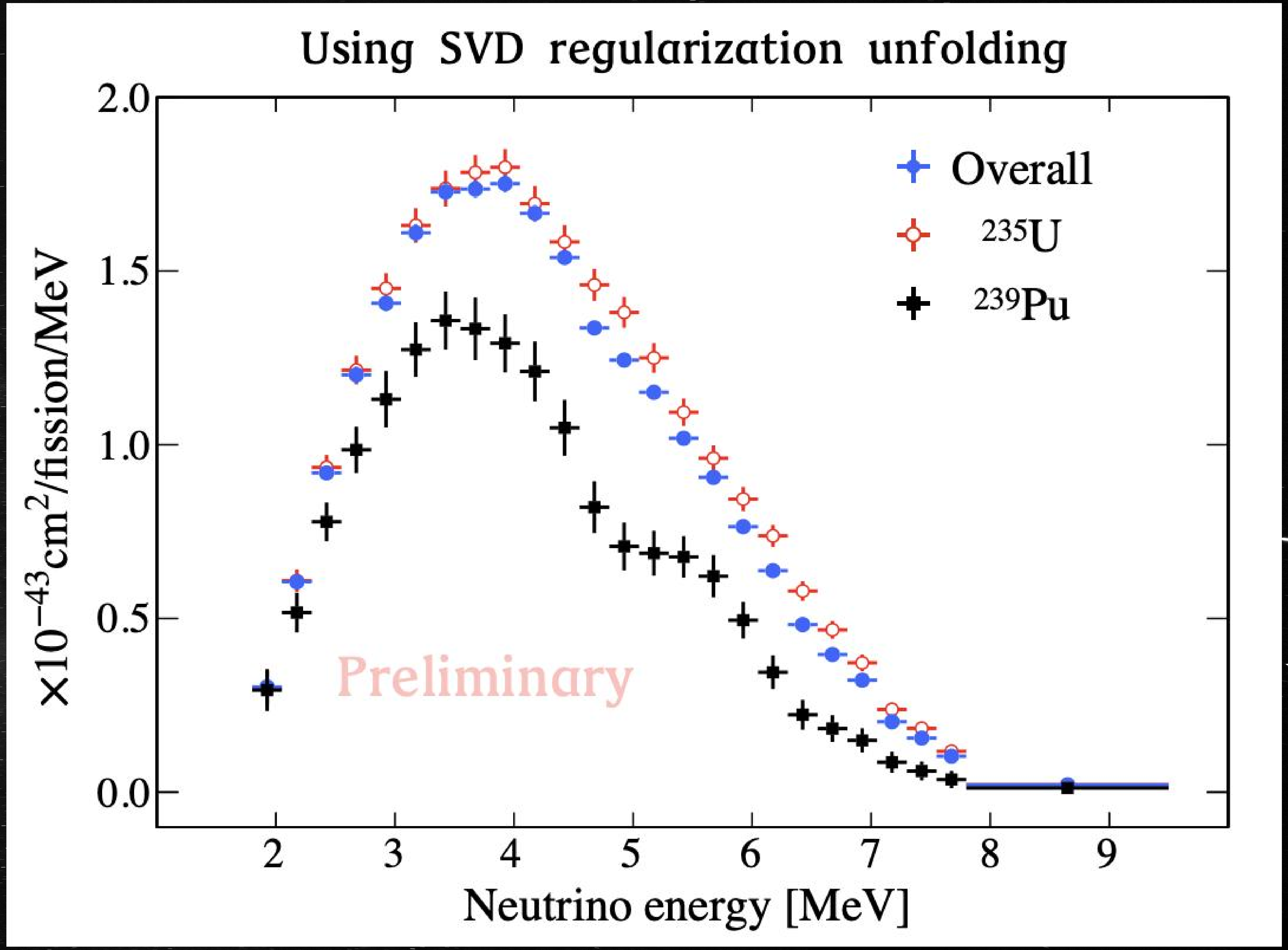
Unfolding → "Remove" detector response

Neutrino energy spectrum of reactor antineutrino signal:

- **Motivation & Possible usage of unfolded spectra:**
  - **Direct comparison with models**
  - **Input for other experiments, e.g. JUNO**

- **At DYB: ^{235}U and ^{239}Pu spectra obtained simultaneously from decomposition, so correclation exists between spectra.**

- **Unfolding multiple spectra together, by considering their correlations. (for the first time)**



To summarize:

- Raector antineutrino spectrum and flux measurement with **DYB full data set** (n-Gd, 4 ADs)
  - Overall, ^{235}U and ^{239}Pu spectra and fluxes at few percent precision — world-leading
  - Unfolded neutrino spectra, "free" from detector response

- Still open questions
  - Reactor antineutrino rate anomaly: anomaly w.r.t. HM; seems to vanish with KI, not firmly sloved !
  - Reactor antineutrino shape anomaly w.r.t. all models !
  - Fine structure (see talk of TAO)
  - ……

- More efforts needed from both experimental and theoretical sides

- TAO will help to address some of these open questions…

台山中微子实验
(JUNO-TAO或TAO)

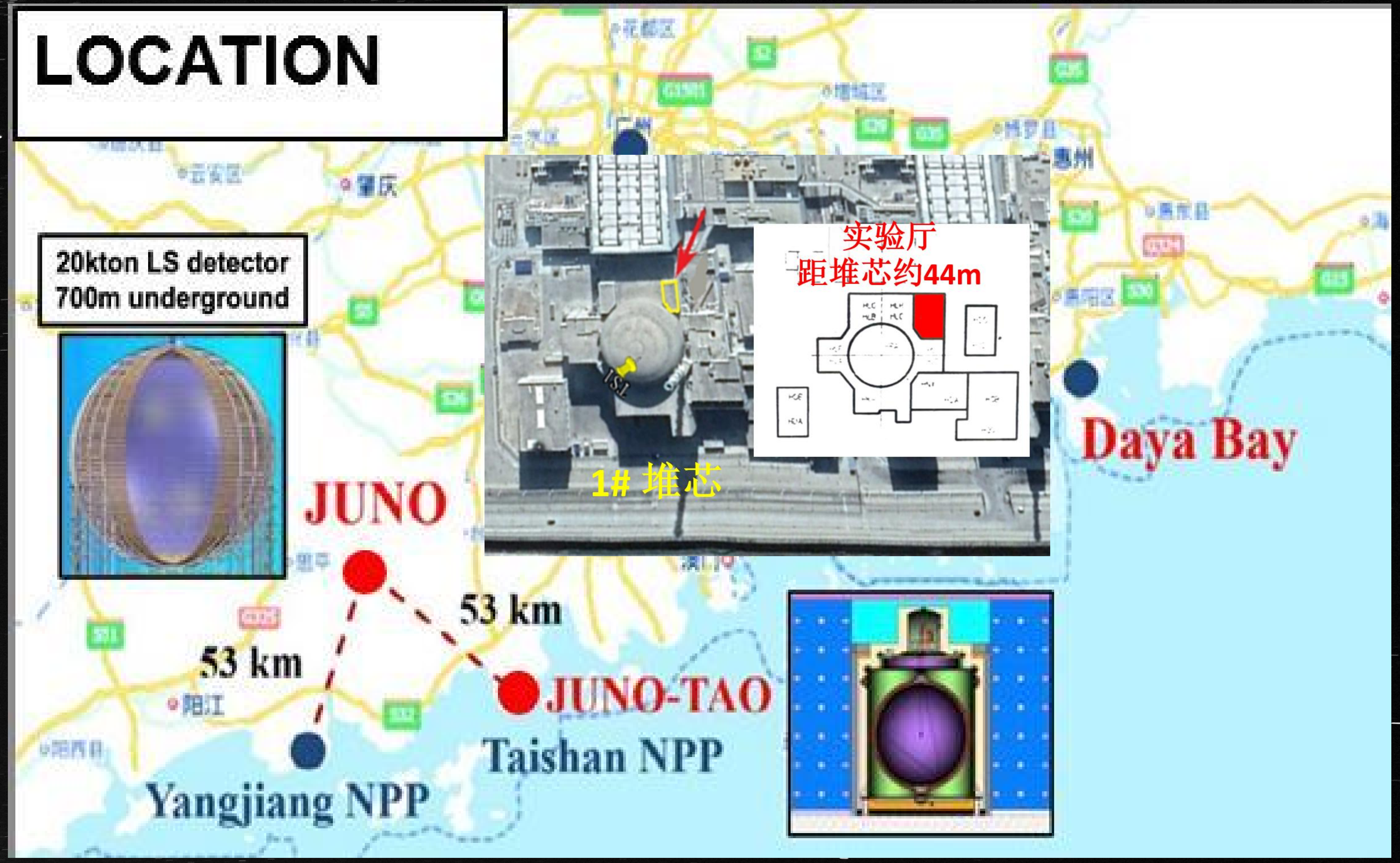
The Taishan Antineutrino Observatory(JUNO-TAO or TAO)

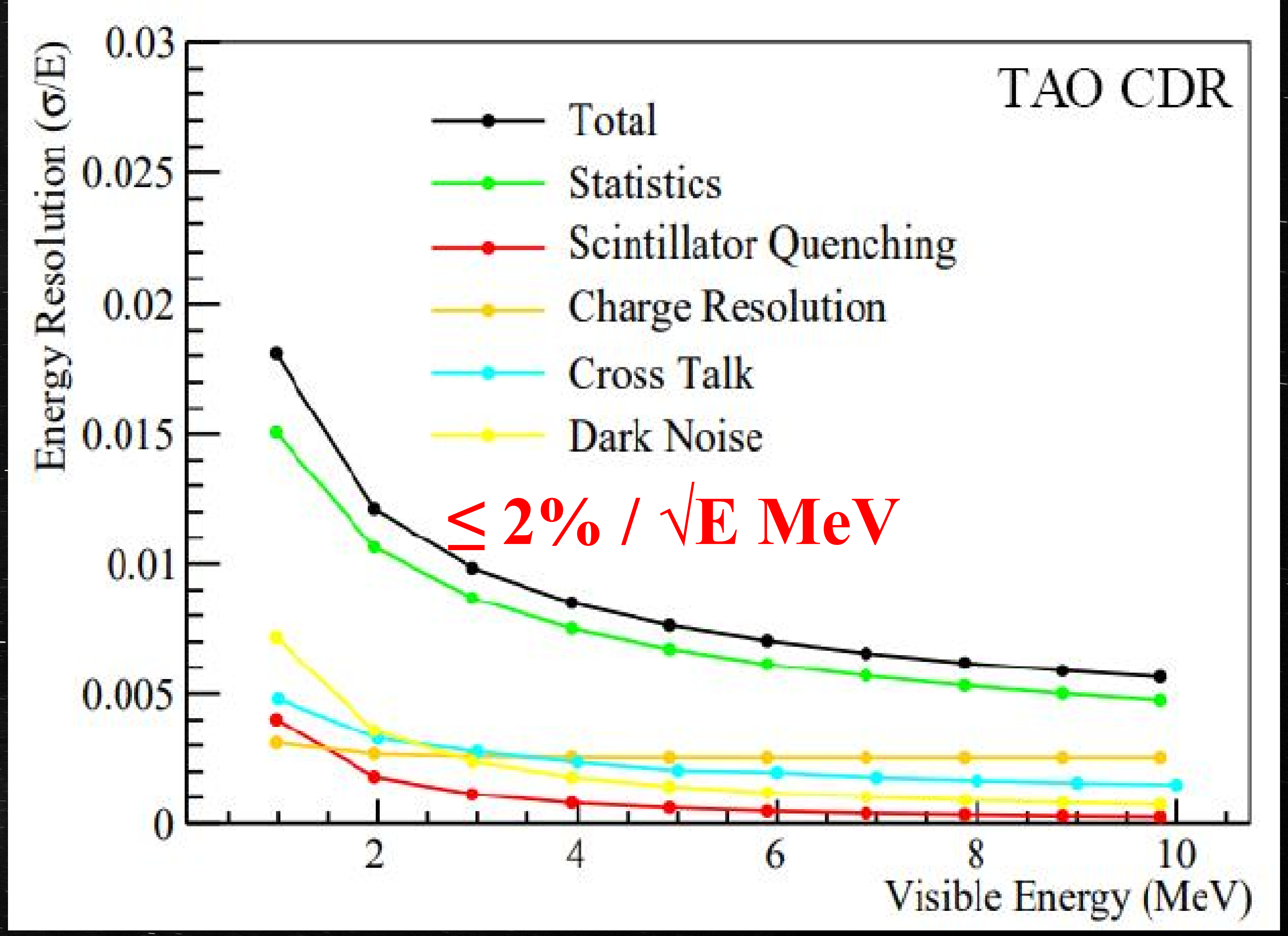
✱ TAO is a satellite experiment of the JUNO

✱ A ton-level Gadolinium-doped Liquid Scintillator detector at 44 m from a reactor core of the Taishan NPP

✱ 10 m² SiPM coverage(94%), operate at -50°C, 4500 p.e./MeV, the energy resolution better than 2%/√E MeV

✱ 1 million IBD events@3years, installation start in the fall of 2024, operation in early 2025





TAO Physics Goals

1.Fine structure measurement

2.Provide a benchmark spectrum for nuclear database

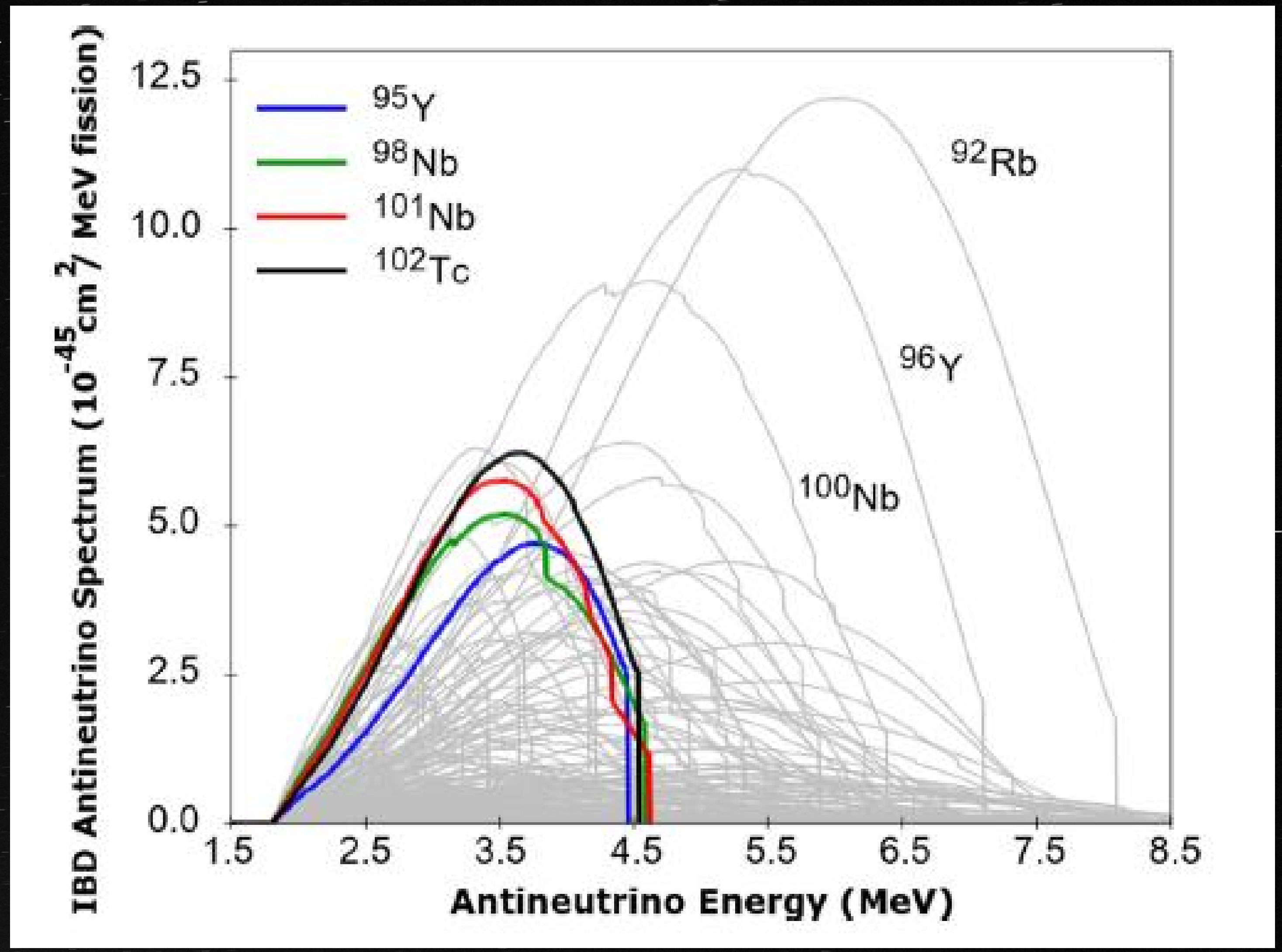
3.Provide reference spectrum for JUNO

Provide reference spectrum to remove effect of fine structure and spectral shape dependence

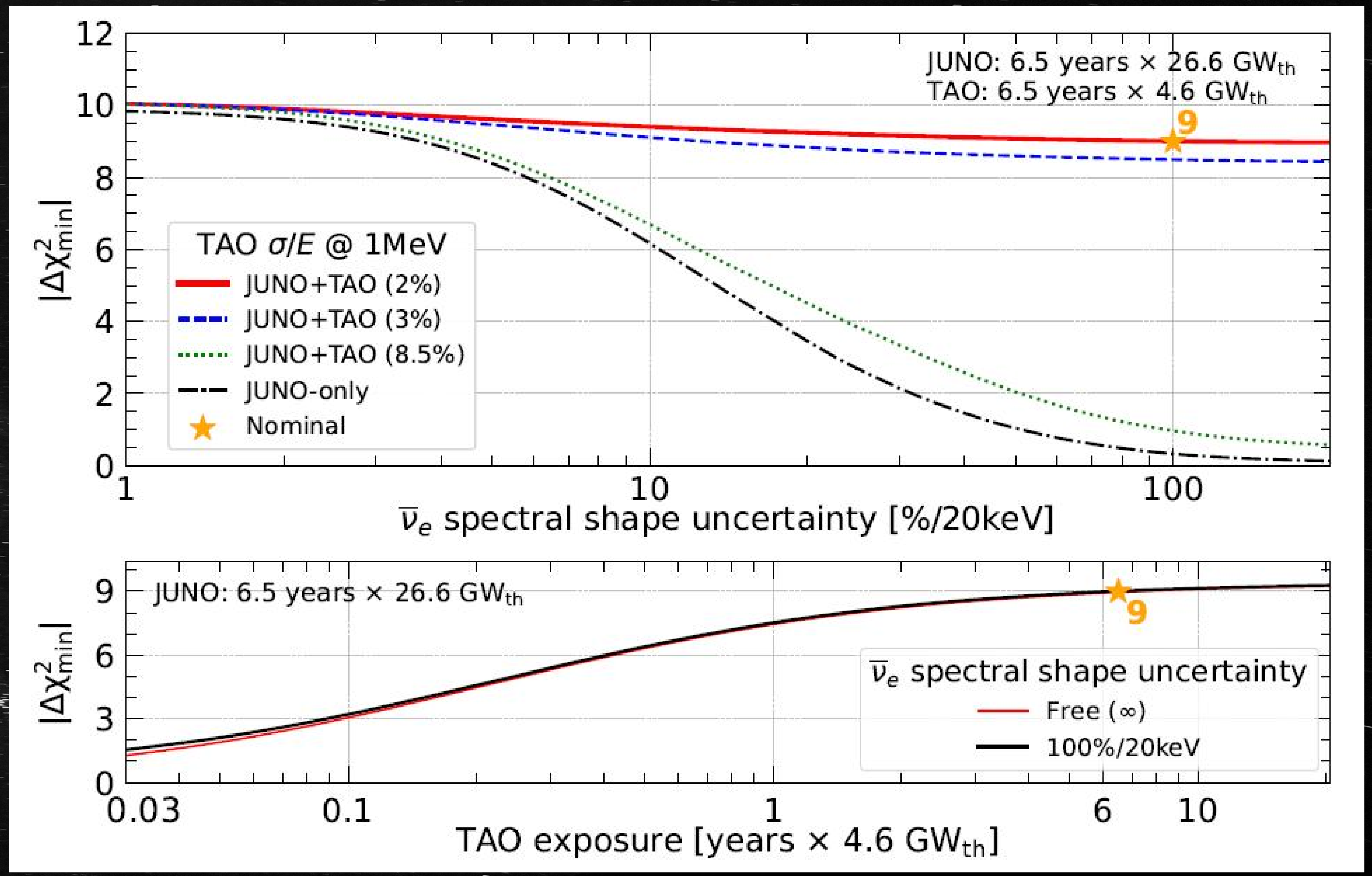
4.Search for sterile neutrino

5.Reactor monitoring

arXiv:2005.08745



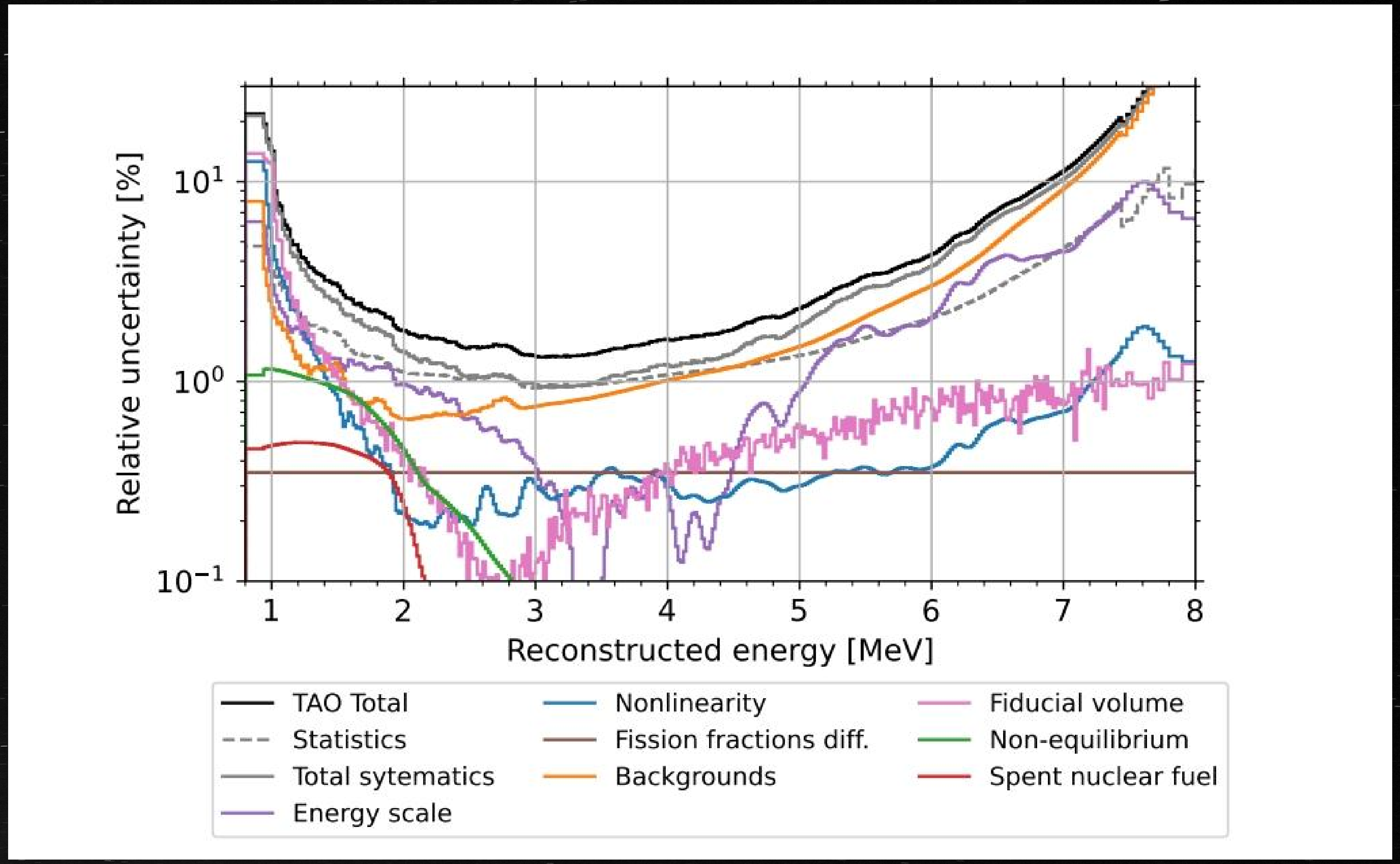
arXiv:2405.18008



TAO Spectrum

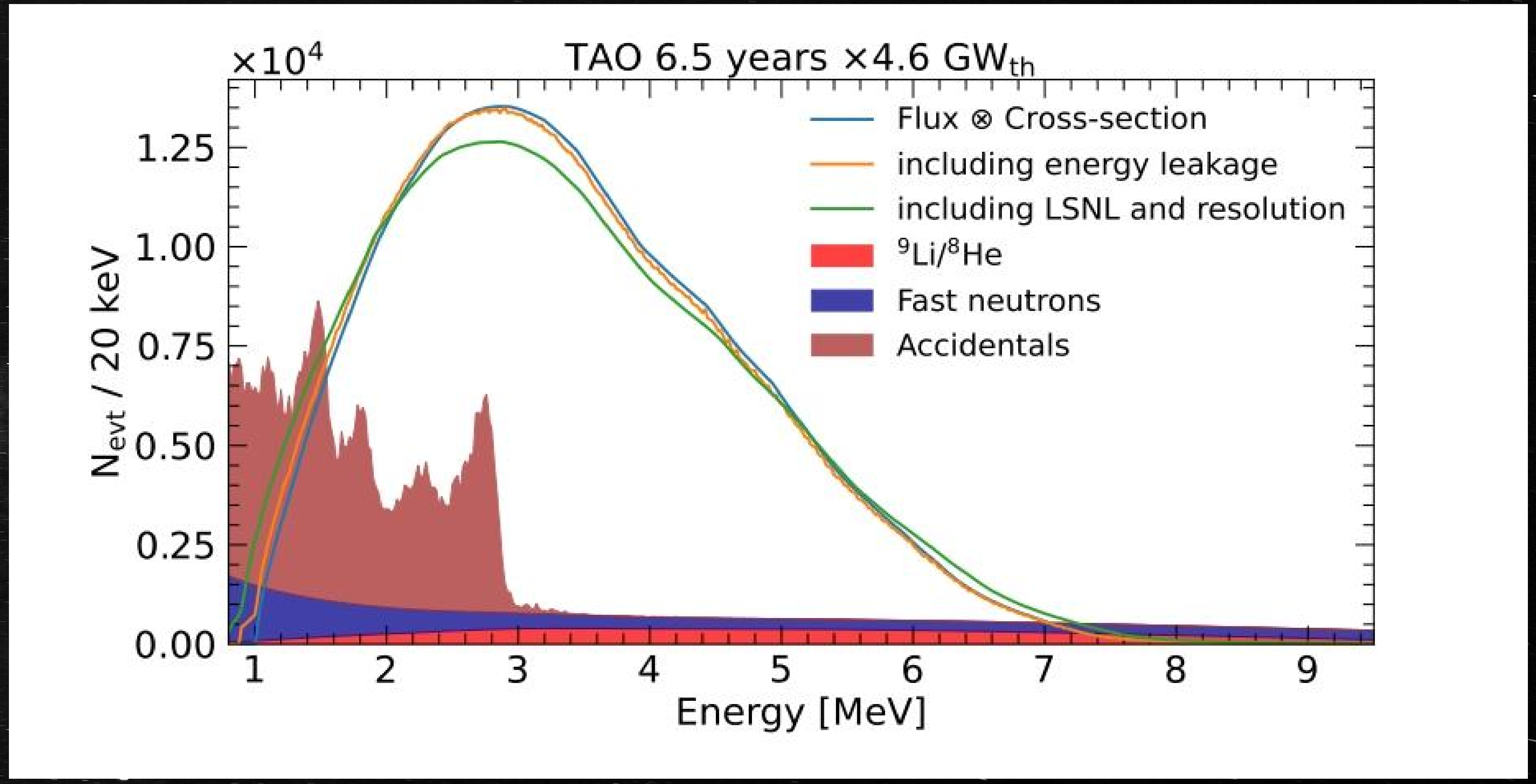
arXiv:2405.18008

<2% shape uncertainty@3years
in NMO sensitive energy range



~1% shape uncertainty from statistics@3years

~0.8% shape uncertainty from backgrouds@3years
Fast Neutron, flux ratio ~9%
^{9}Li/^{8}He， flux ratio ~5%
Accidental， flux ratio ~20%



~0.3% shape uncertainty from detector response@3years
Include: Energy Leakage, Liquid Scintillator Nonlinearity

TAO Detector

✱ Central Detector

2.8 ton dewatering (<10 ppm) low-temperature GdLS

10 m² SiPM coverage(94%), High PDE(~50%, 4500 p.e./MeV)

Operate at -50°C, SiPM DCR: <100 Hz/mm² @-50°C

Temperature uniformity:±0.5°C

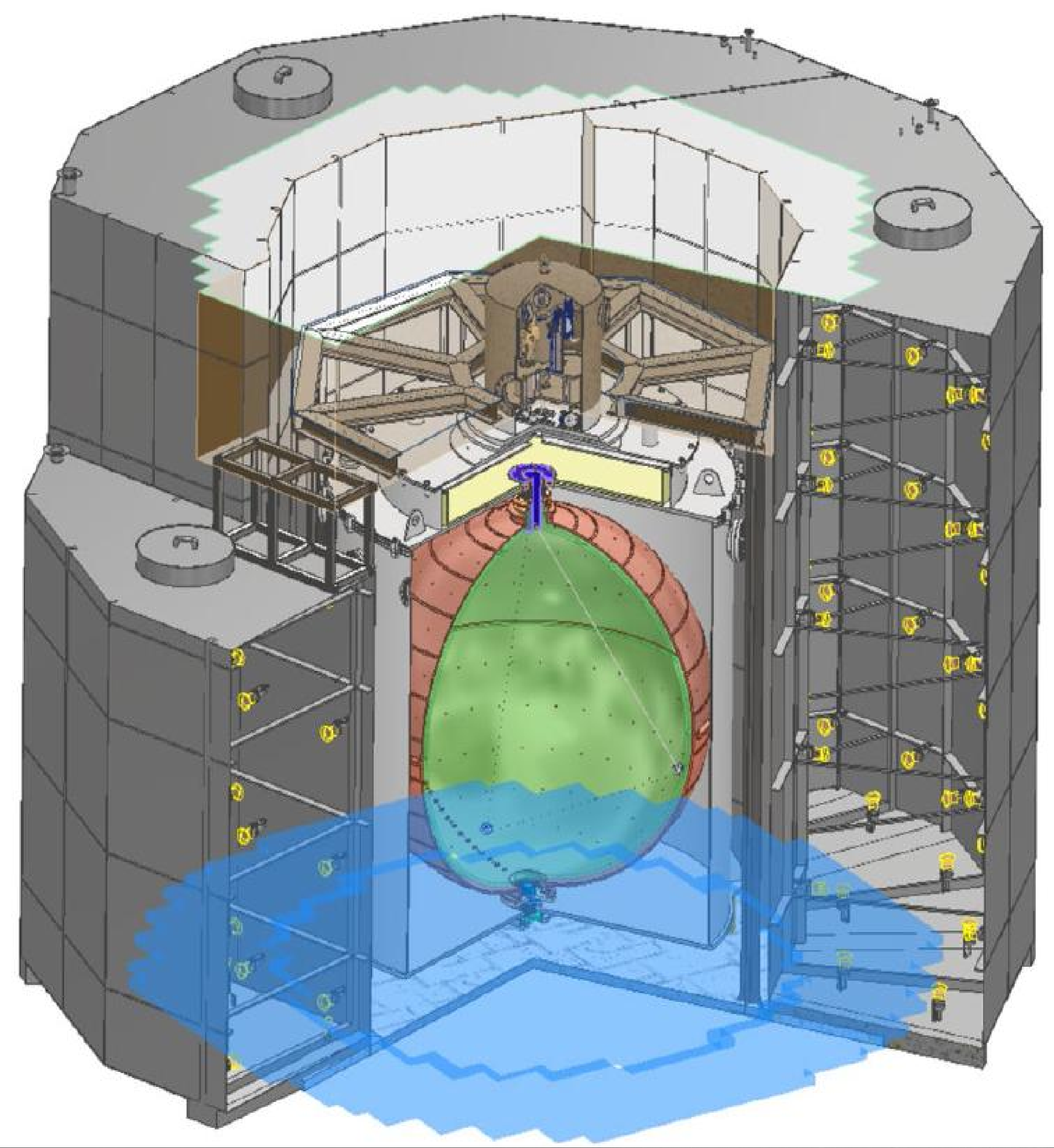
✱ Calibration System

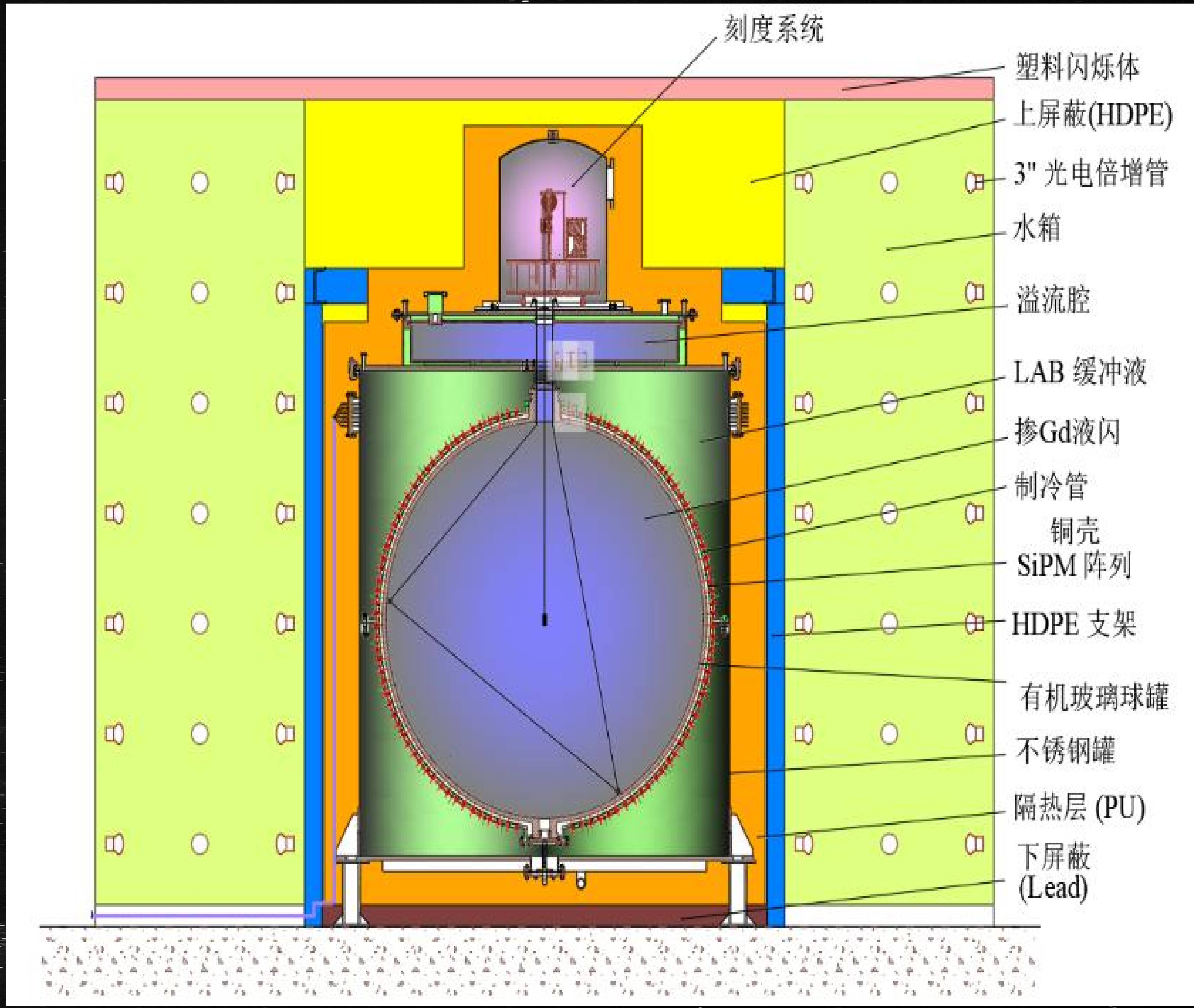
ACU+CLS

✱ Muon Veto System

Top Veto Tracker (Top)
4-Layer PS + SiPM

Water Tank(Around)
3 irregular water tanks
300 3 inch PMTs





GdLS

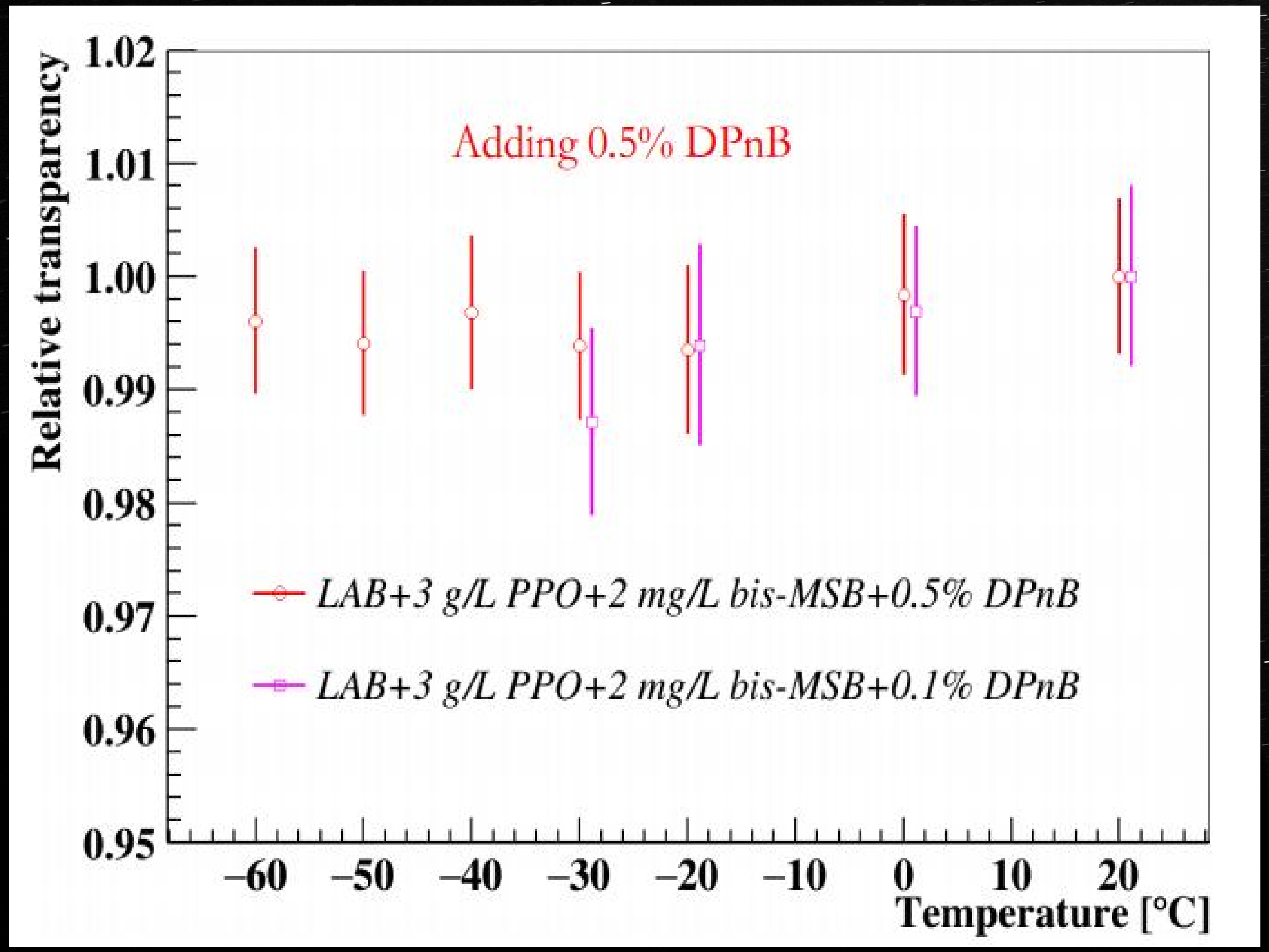
DOI 10.1016/j.nima.2021.165459

GdLS recipe: LAB + 3 g/L PPO + 2 mg/L bis-MSB + 0.1%Gd + 0.5%DPnB

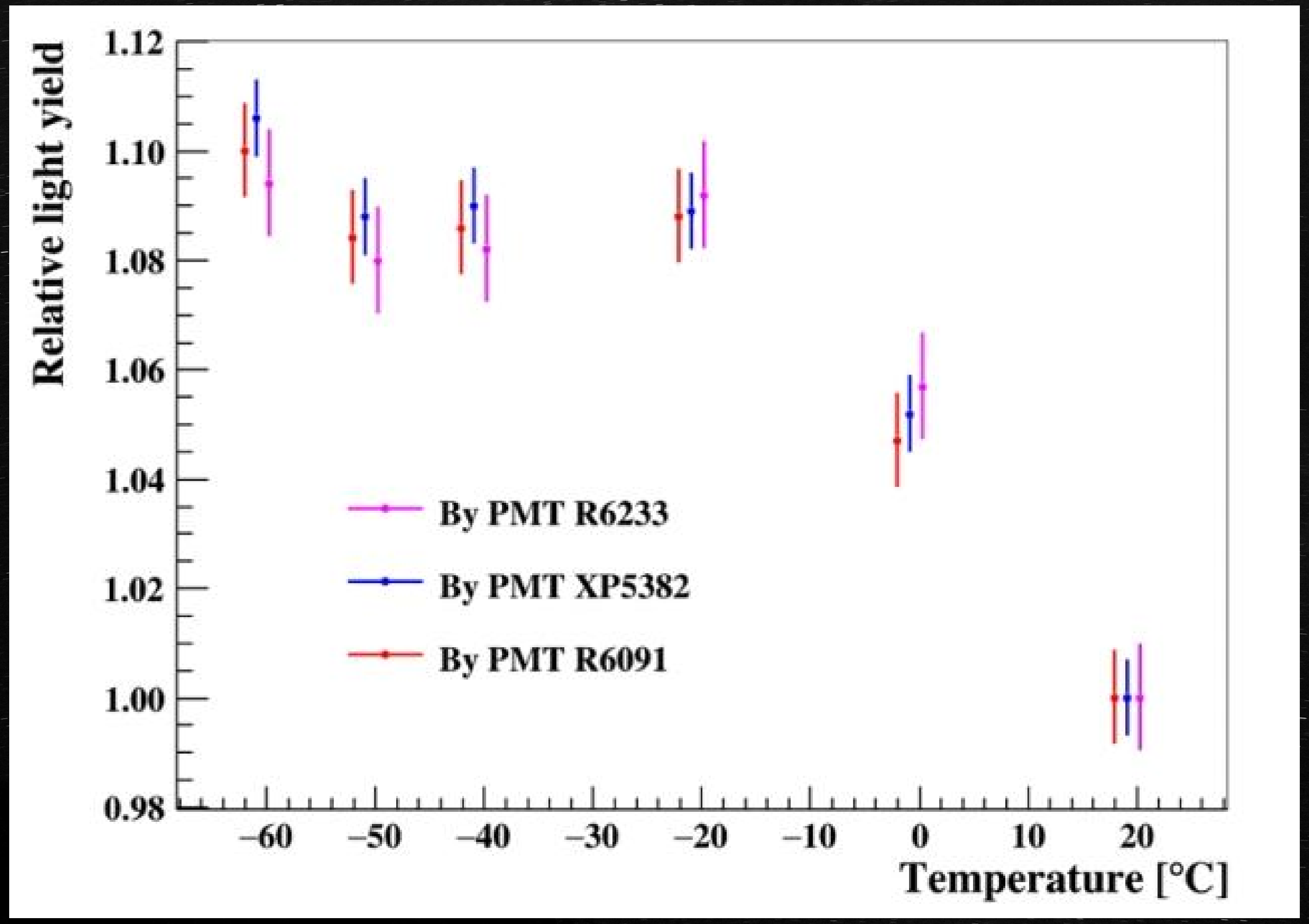
GdLS index: High light yield(~15000/MeV), High transparency (~93%), High flash point (>100°C)
No precipitation@-50°C(Add DPnB), Stable property@-50°C, Low water content(<10ppm)

3.5t LAB and 3.3t GdLS have been prepared, ready to be shipped

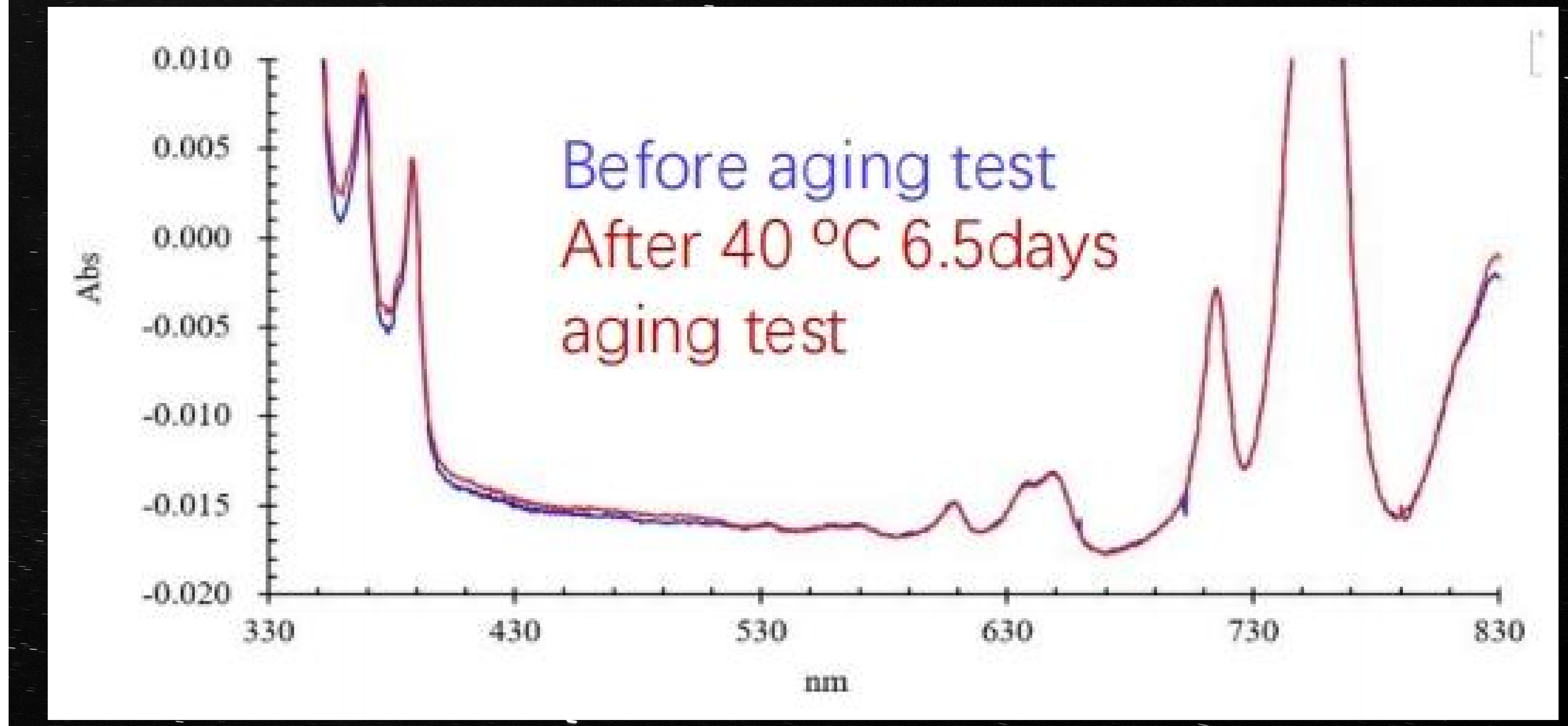
Relative Transparency



Relative Light Yield



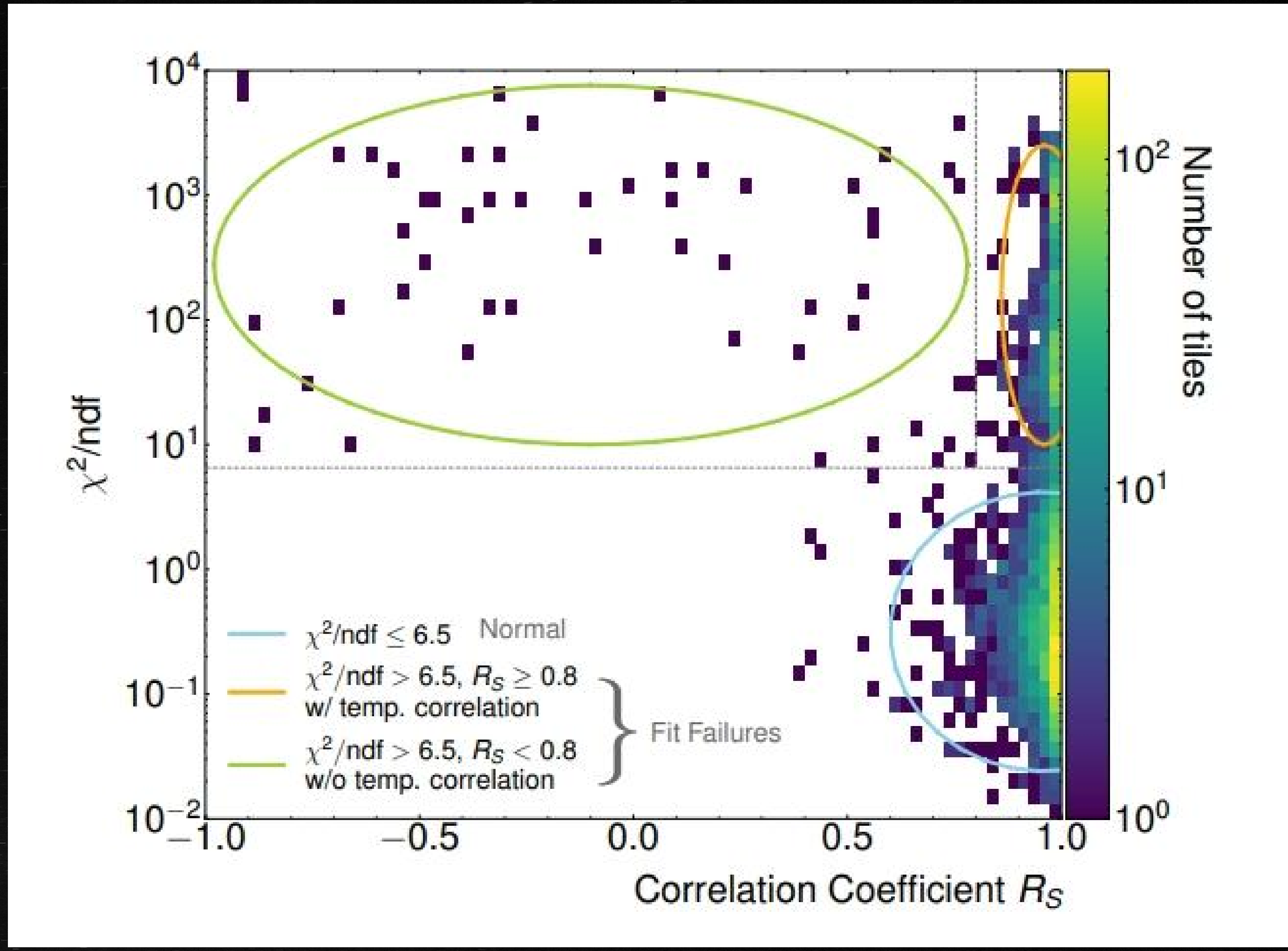
GdLS Aging Test Result



SiPM Quality Control

Burn-in Test Result

DOI 10.1088/1748-0221/19/07/P07028



Visual test → Burn-in test → Characterization test

All SiPMs have been tested

298 SiPM tiles disqualified

Average PDE: ~48.8%@-50°C, 3.2V(~50%); Average DCR:~45Hz/mm²@-50°C, 3.2V(<100Hz/mm²)

Characterization Test Result

Parameters	Value	Measured*	Unit
Photon Detection Efficiency	Min: 0.44, Typical: 0.47	0.488	-
Dark Count Rate	Max: 41.7, Typical: 13.9	45.06	Hz / mm^2
Crosstalk Probability	Max: 0.15, Typical: 0.12	0.121	-
After-pulsing Probability	Max: 0.08, Typical: 0.04	< 0.001 (360ns)	-
Pixel Gain	Min: 1×10^6, Typical: 4×10^6	> 1×10^6	-
Dark Current Deviance	Max: 95, Typical: 40	-	%
Operating Voltage Range	Min: 6, Typical: 6.5	> 6.5	Volt

SiPM Electronic System

DOI 10.1088/1748-0221/19/07/C07008

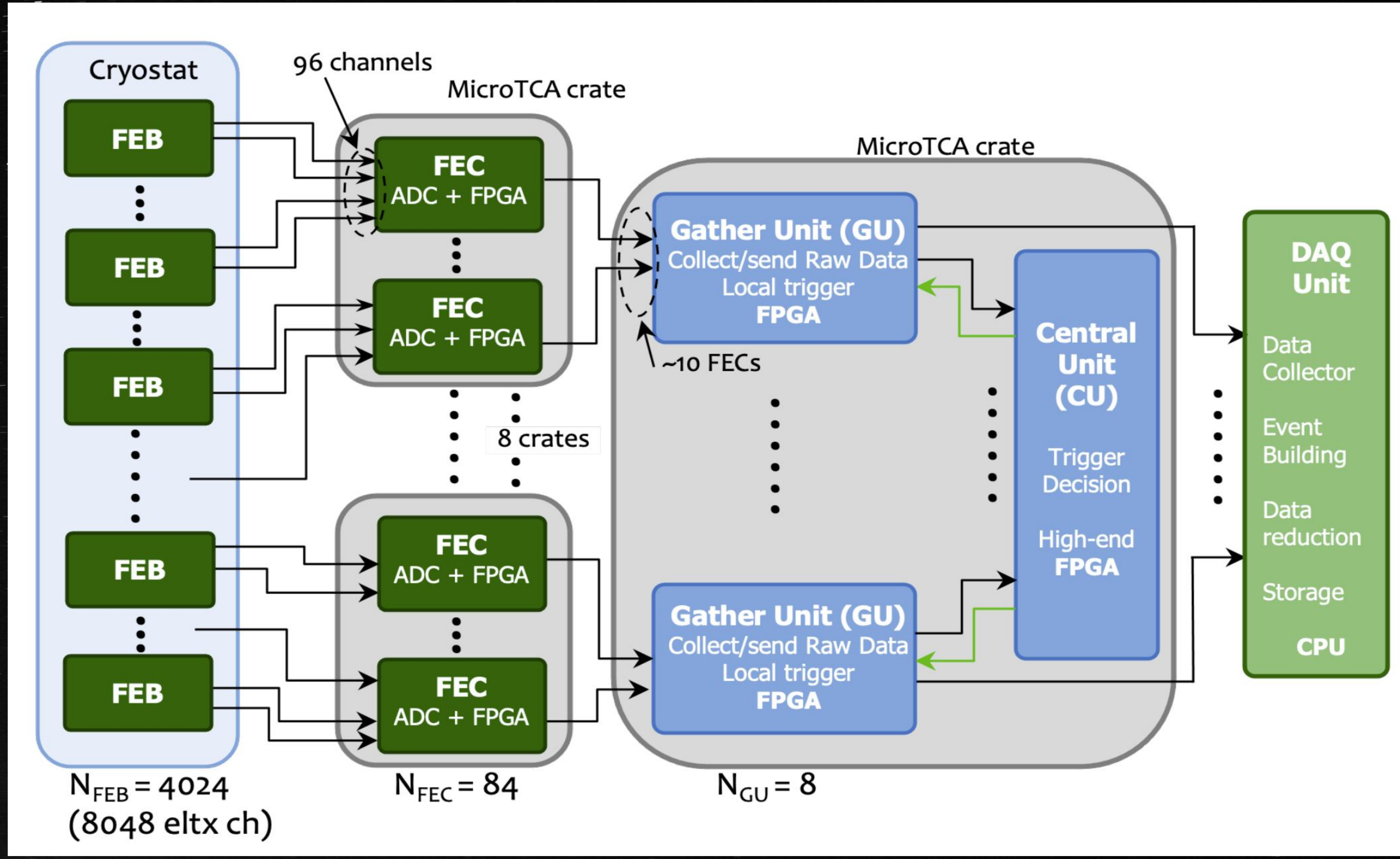
Final System: SiPM+FEB+FEC+GCU+DAQ

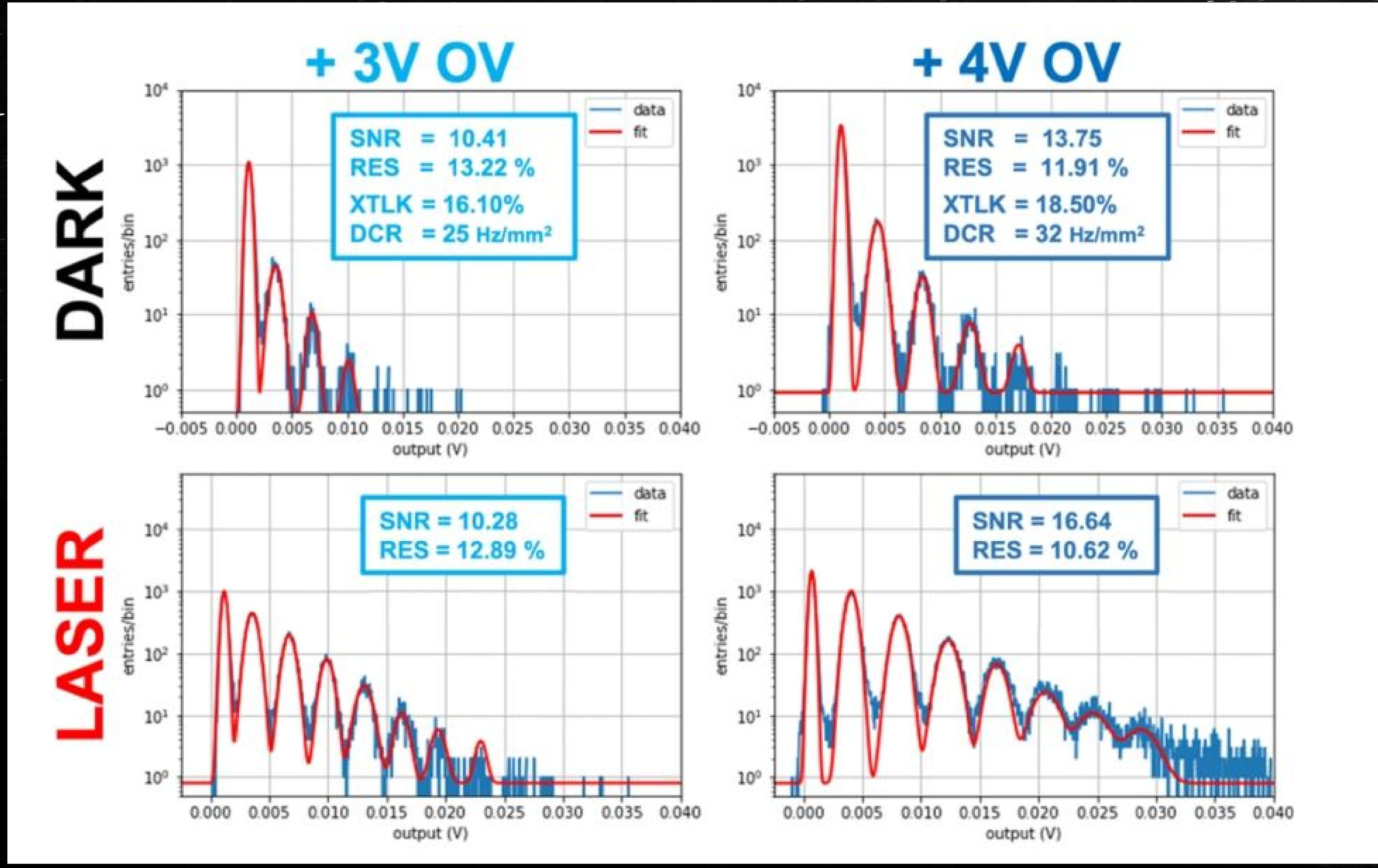
System Design: 8048 chs, 1SiPM-1FEB-2chs， 96chs-1FEC

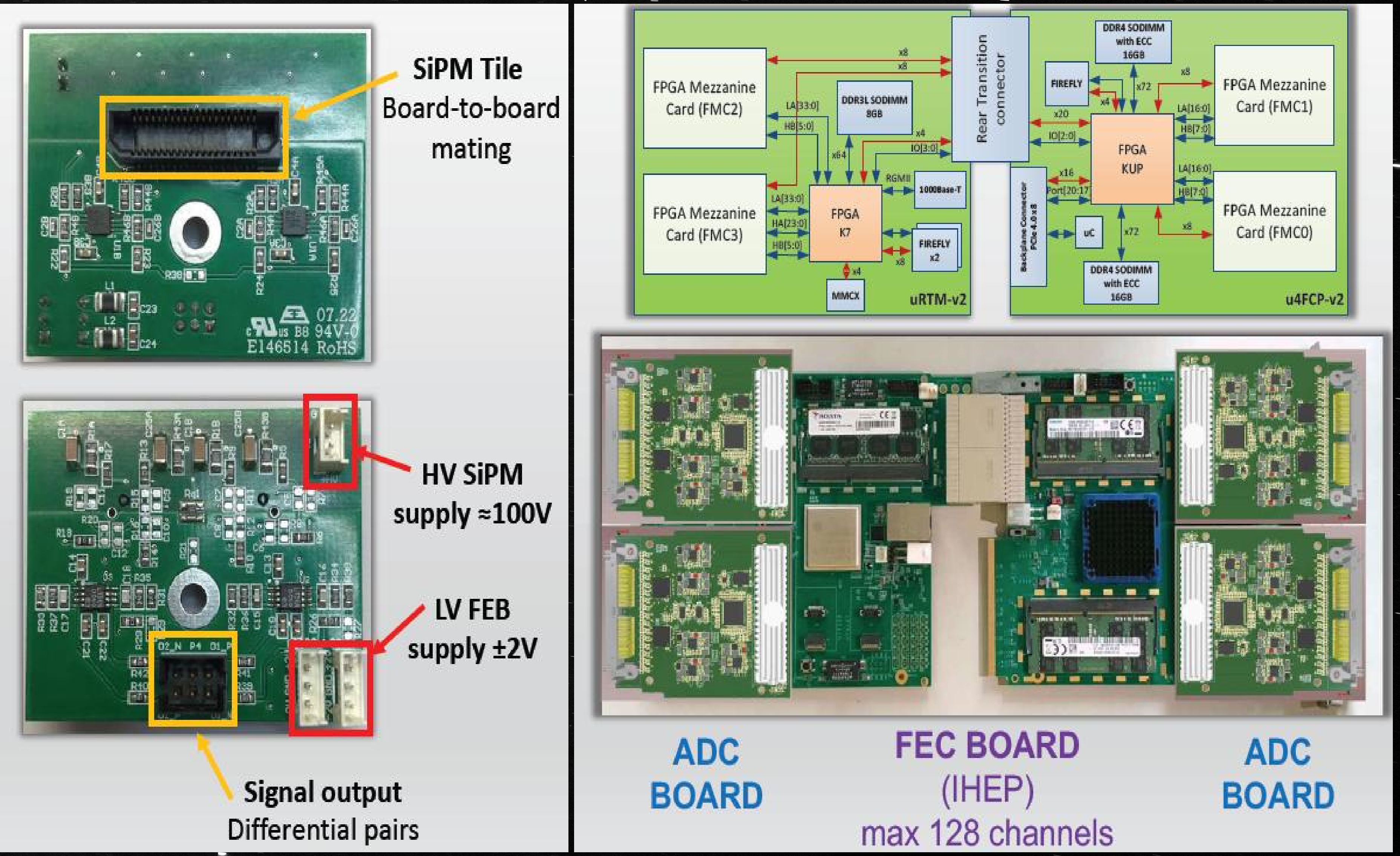
System Index: Charge RES<15%， SNR>10， Time RES<1ns

ADC: 250MHz/12bit or 125MHz/16bit, Dynamic Range:1-180 p.e./ch

Data Rate: FEC TDAQ: ~70 Gbps, TDAQ Disk: ~100 Mbps







Calibration System

DOI 10.1140/epjc/s10052-022-11069-3

✱ **Automatic Calibration Unit** (ACU, from Daya Bay)

^{68}Ge source, Combined γ source（^{137}Cs + ^{54}Mn + ^{40}K + ^{60}Co ）

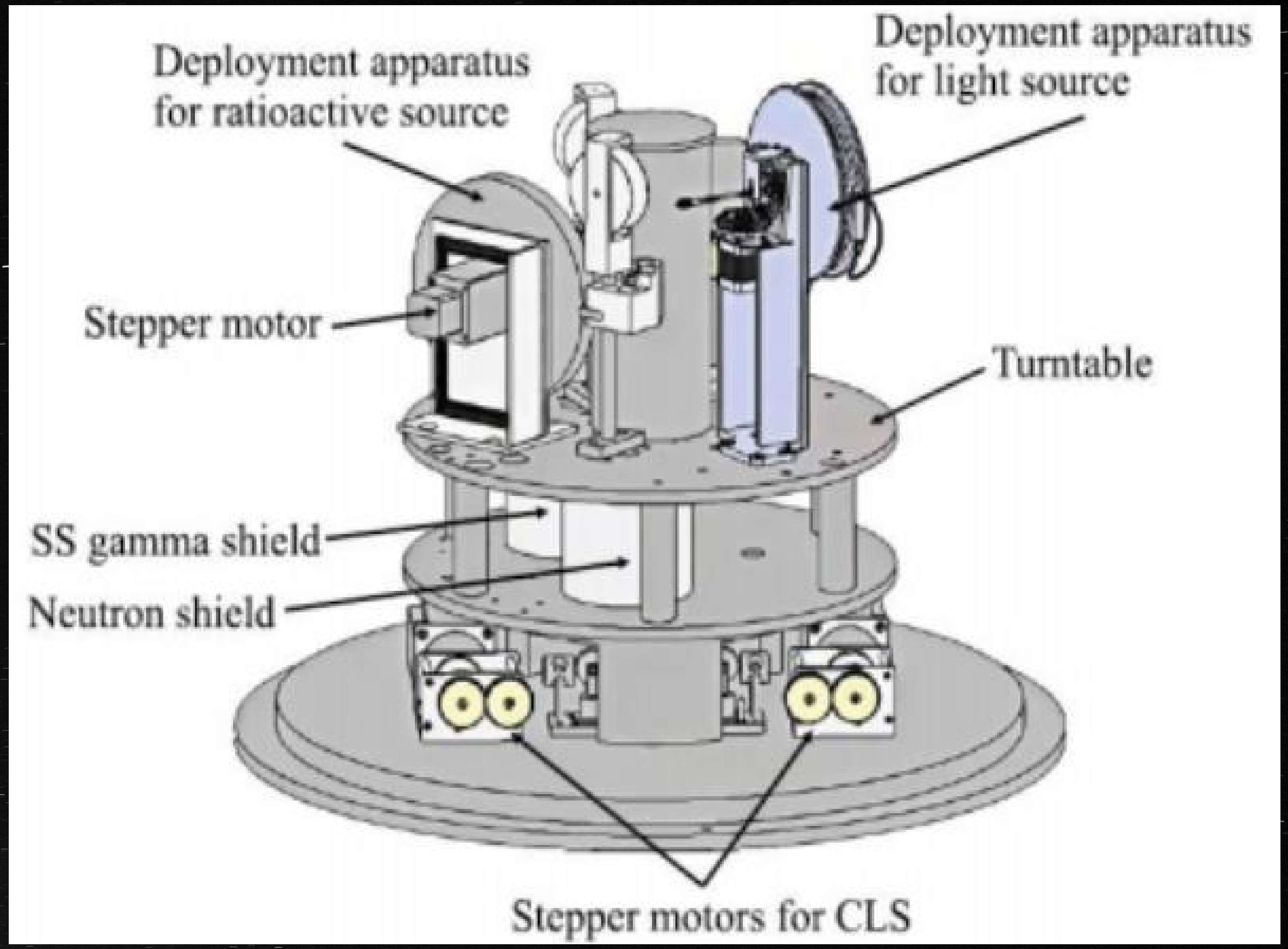
LED system（Wave length, Trigger rate, Intensity can be changed）

Non-linearity(uncertainty<1%), SiPM characterization calibration

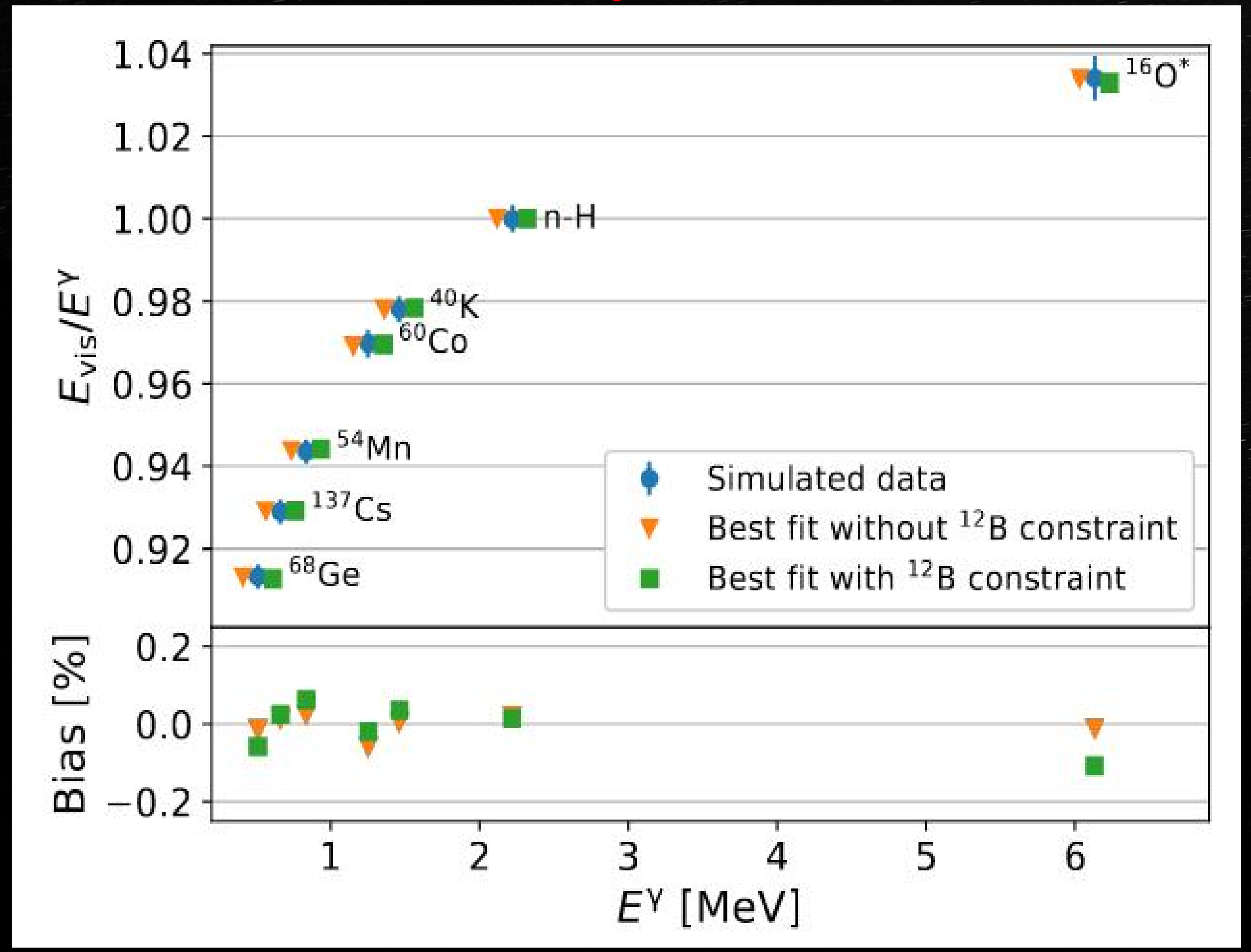
✱ **Cable Loop System** (CLS)

^{137}Cs source, 110 points

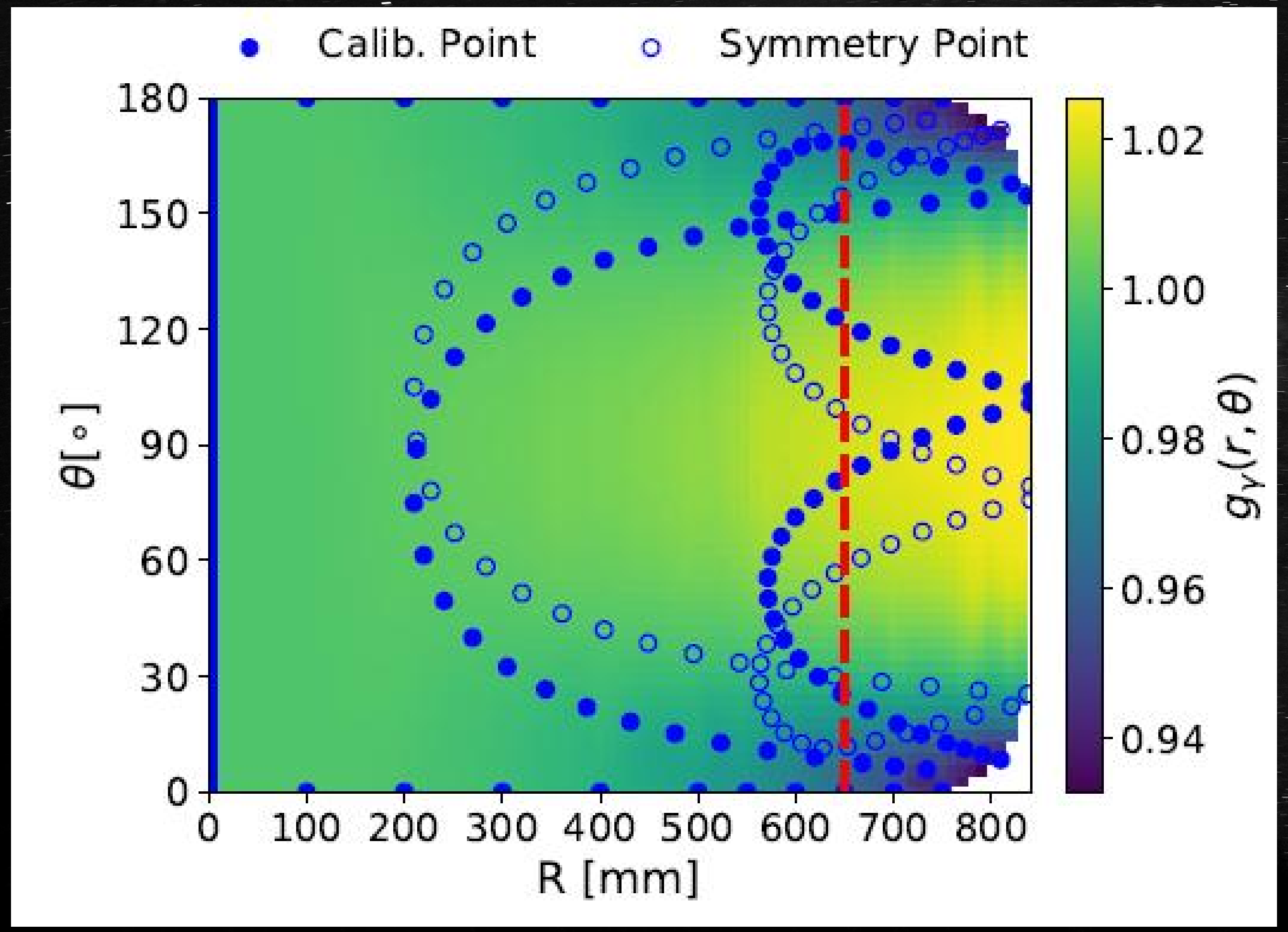
Non-uniformity calibration(uncertainty<0.5%)



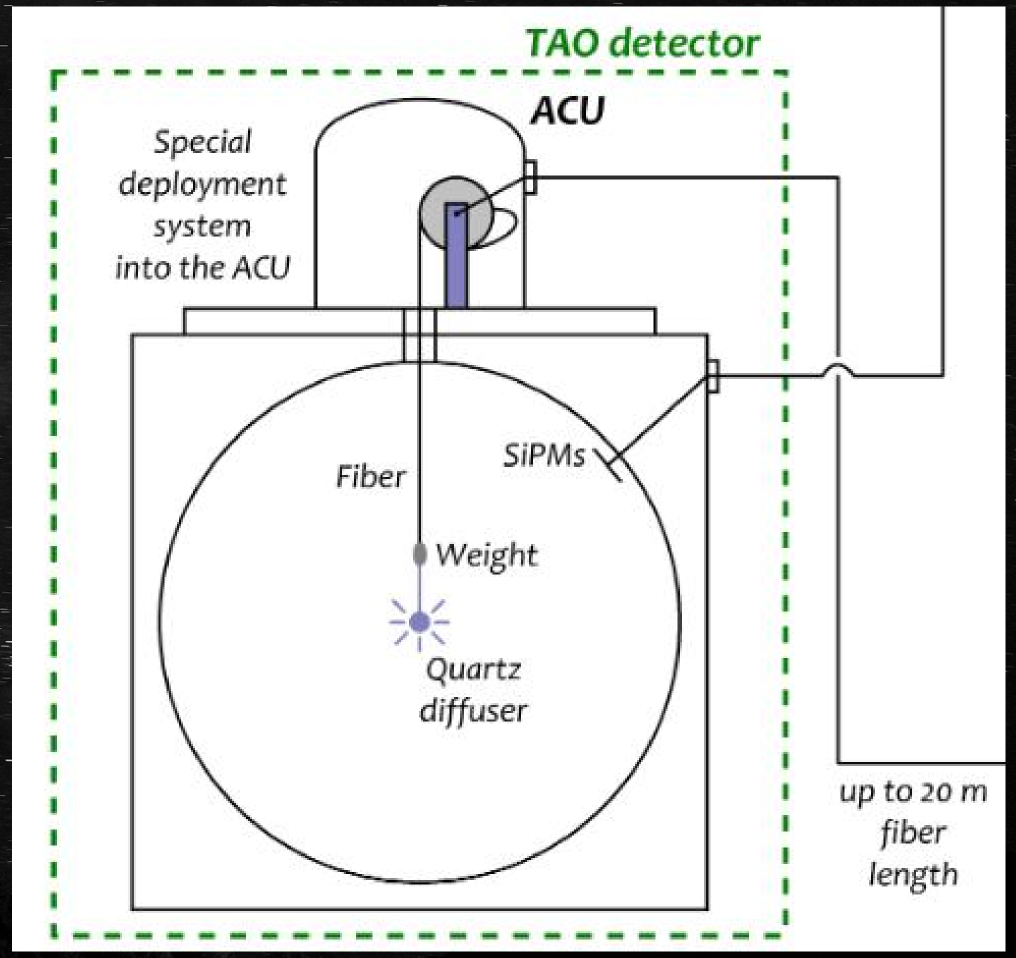
Non-linearity Calibration



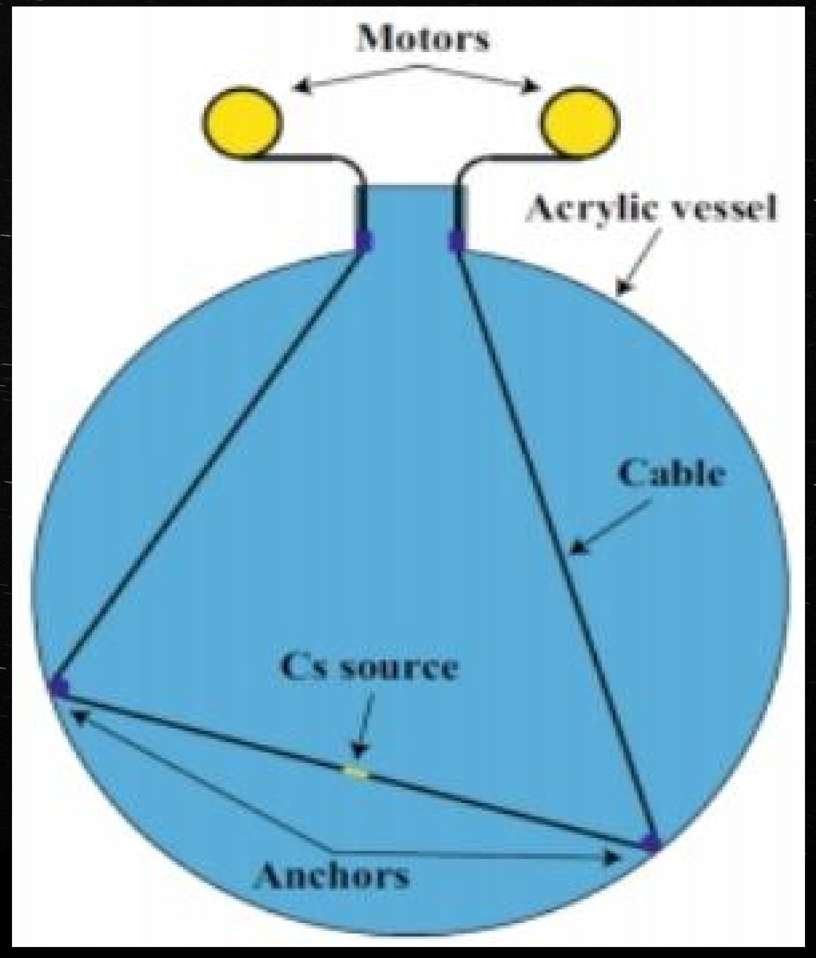
Non-uniformity Calibration



ACU System



CLS System



Muon Veto System

arXiv:2406.15973

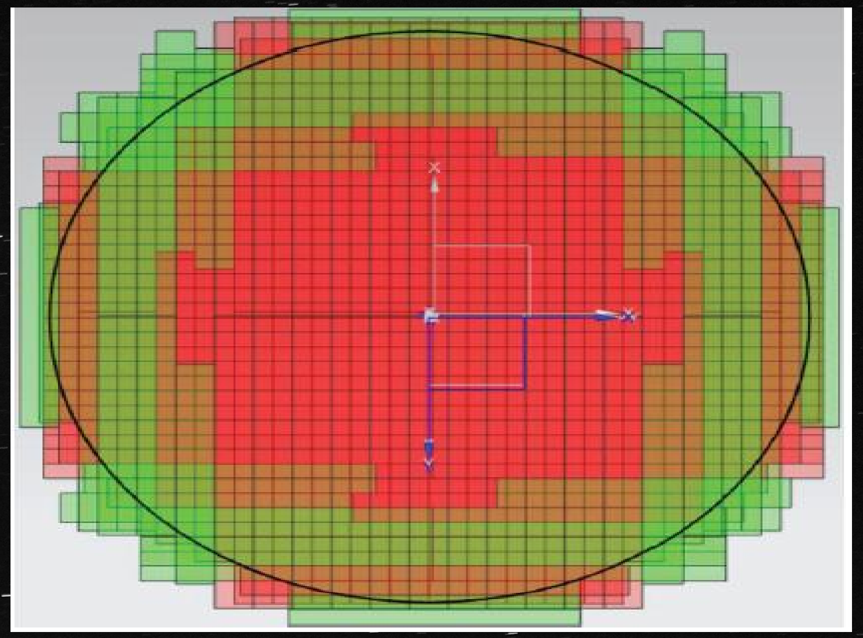
✱ Top Veto Tracker (TVT)

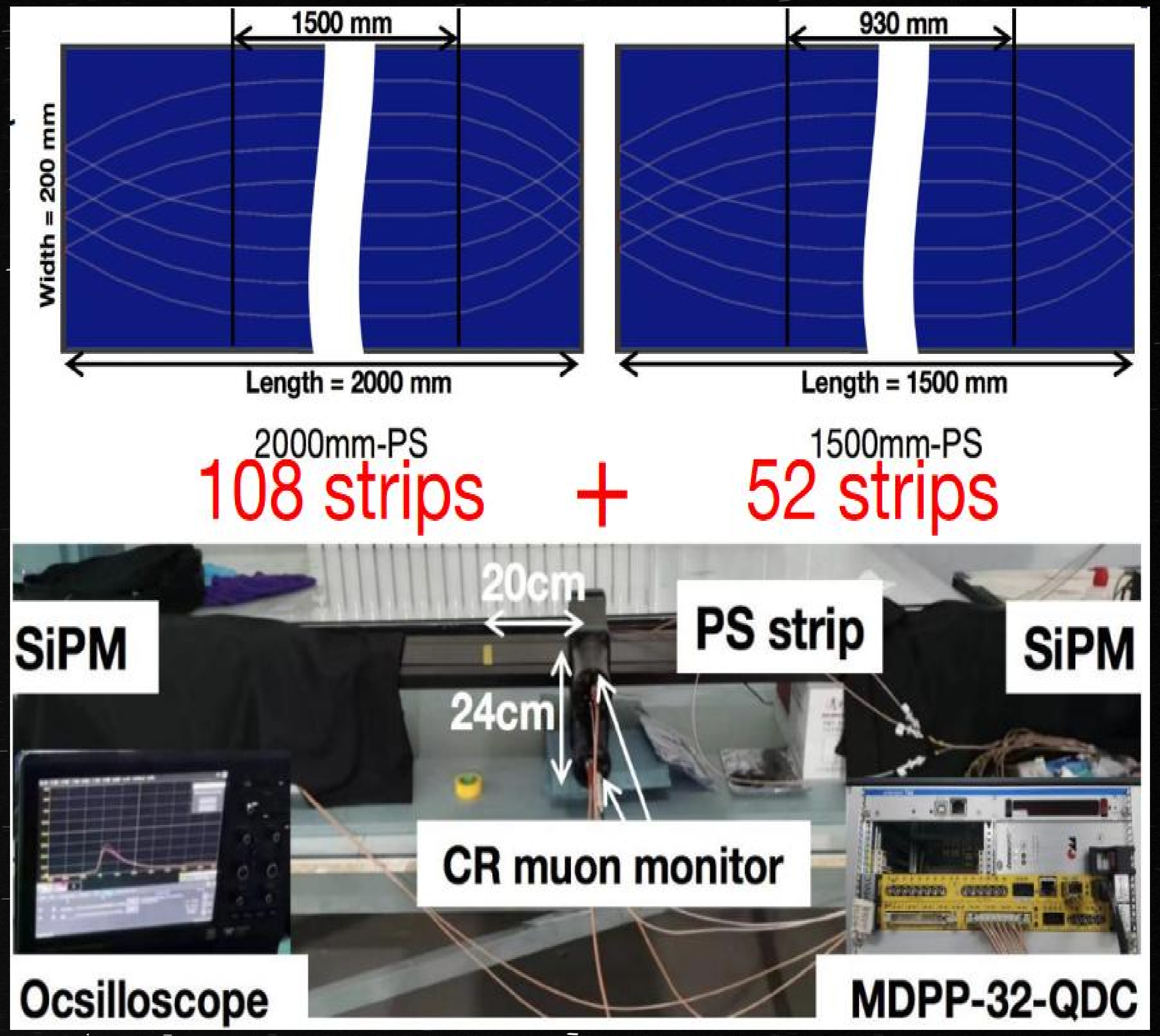
PS+ Wave-Shifting Fiber + SiPM

4 Layers, 160 strips, 2 m×20 cm×2 cm/strip

Muon veto efficiency>99%

Production and QA finished





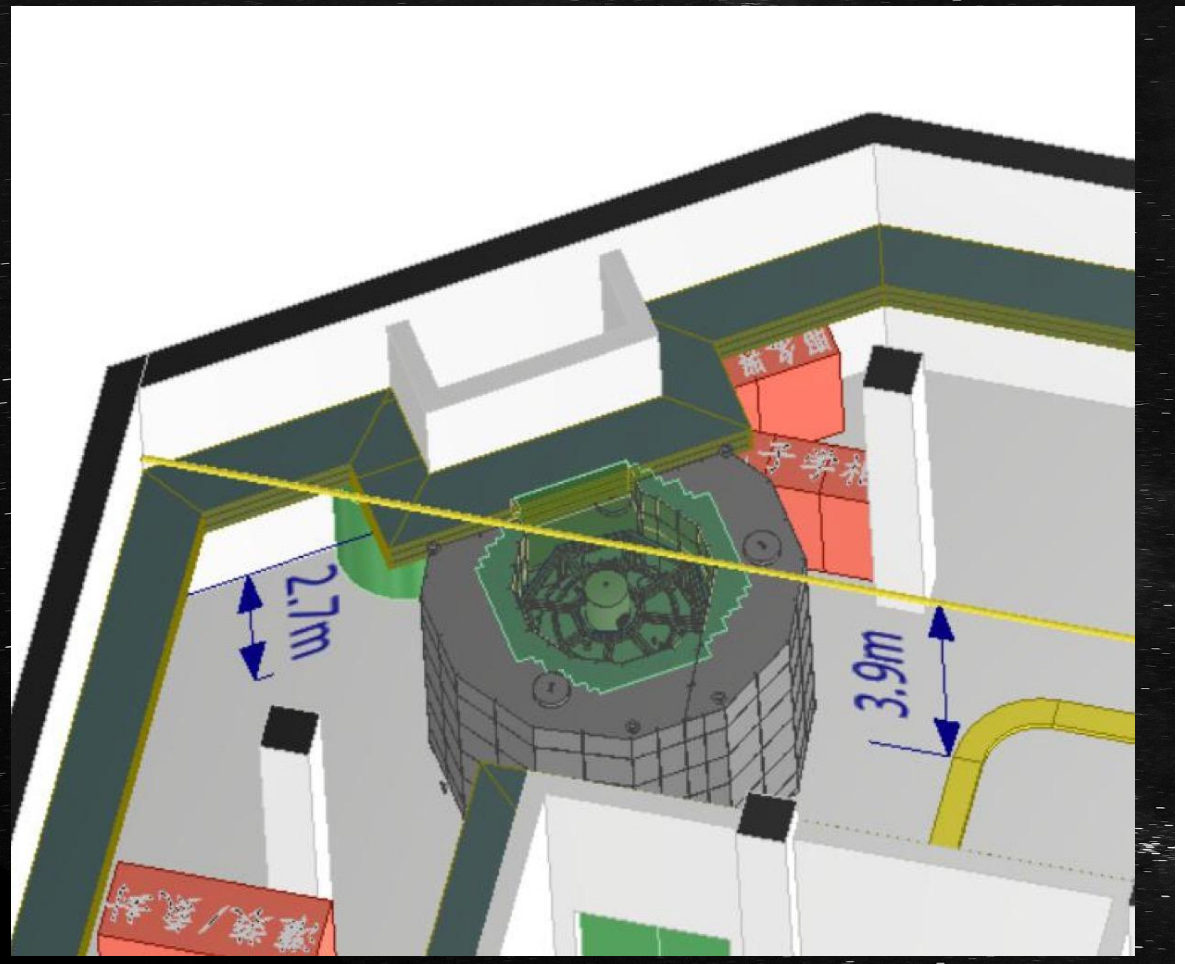
✱ Water Tank (WT)

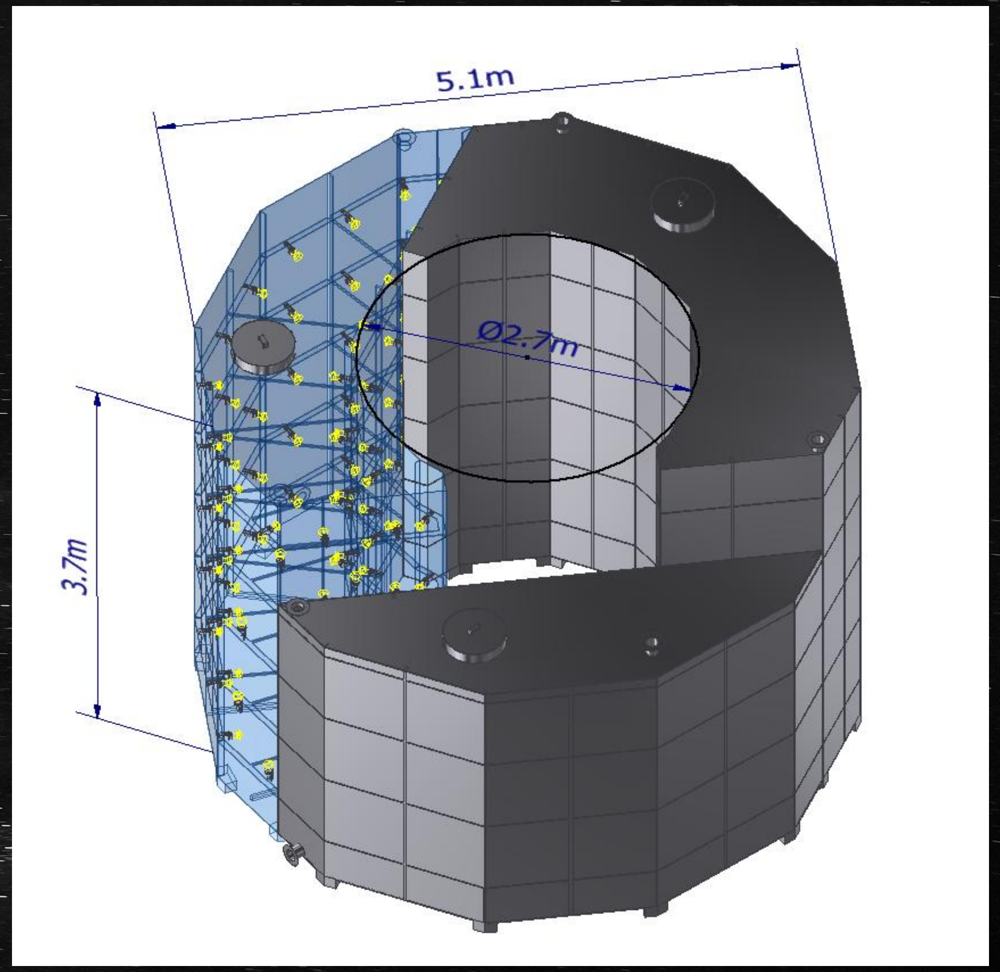
3 standalone water tank

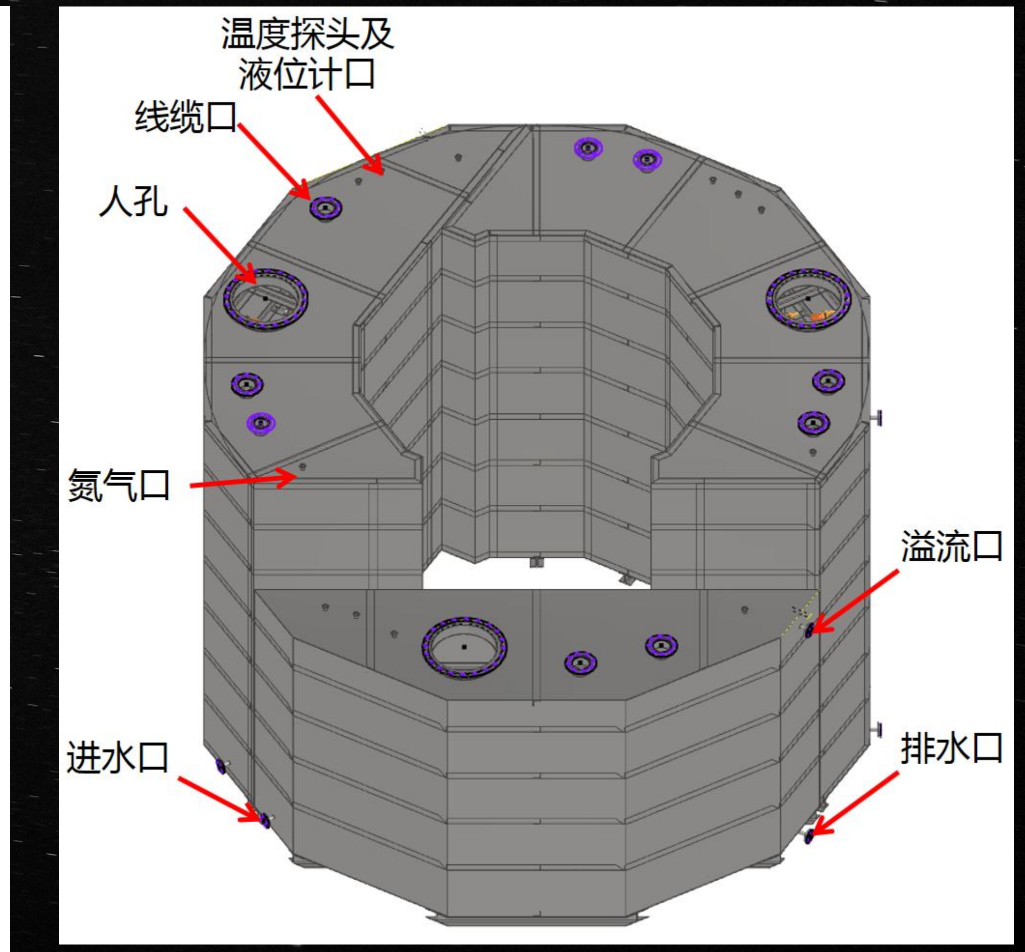
300 3 inch PMT, 50 ton pure water

Muon veto efficiency>99%

Detailed design finished, to be produced







1:1 Prototype

Motivation: Assemble and test each system

CD 1:1 Prototype Assembling:
Verified and improved assembly produce, finished in Dec. 2023 in IHEP

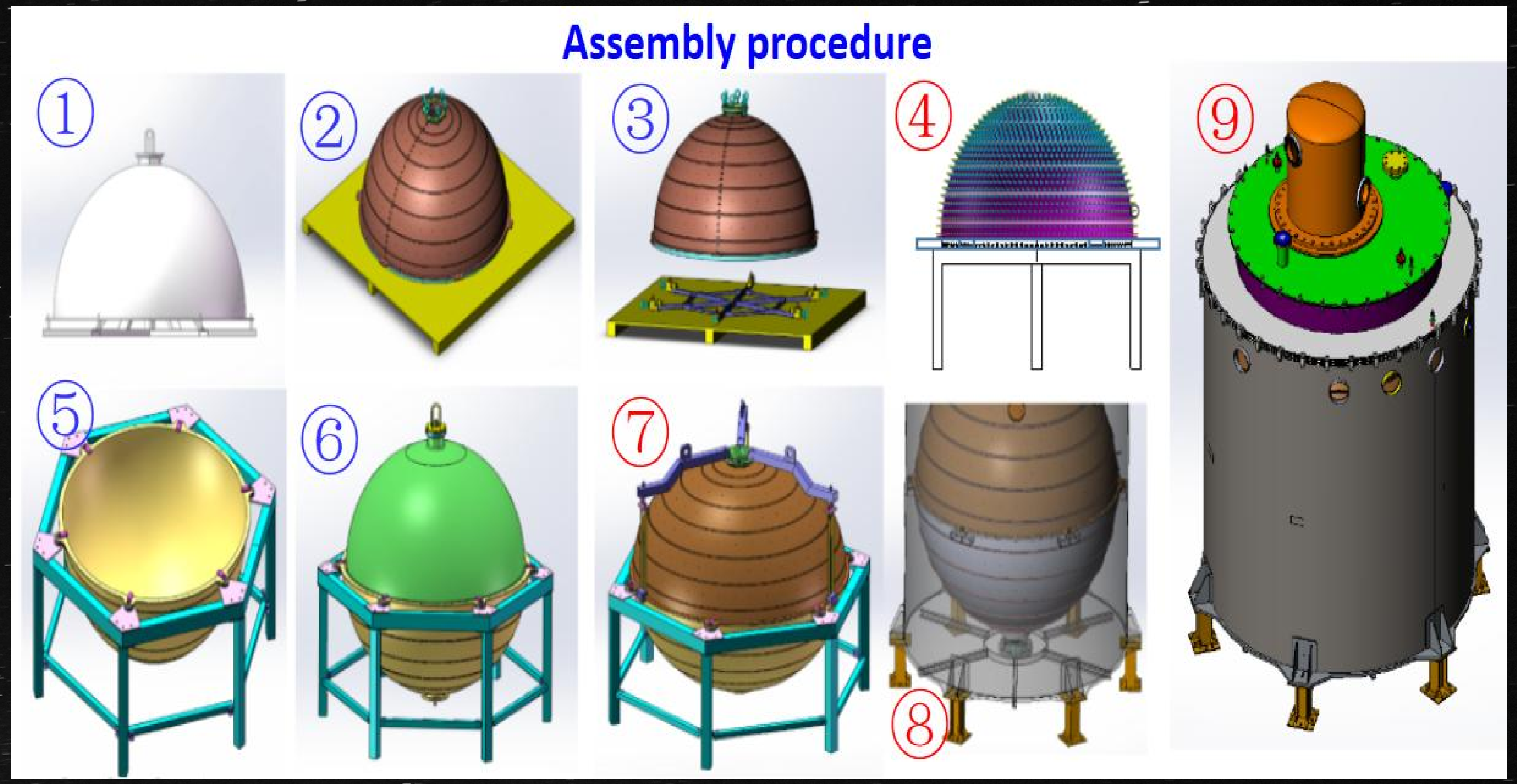
Cooling System Testing:
Temperature non-uniformity < 1°C,
System temperature stability: 0.1 °C

Calibration System Testing:
ACU, CLS, and LED system can operate normally

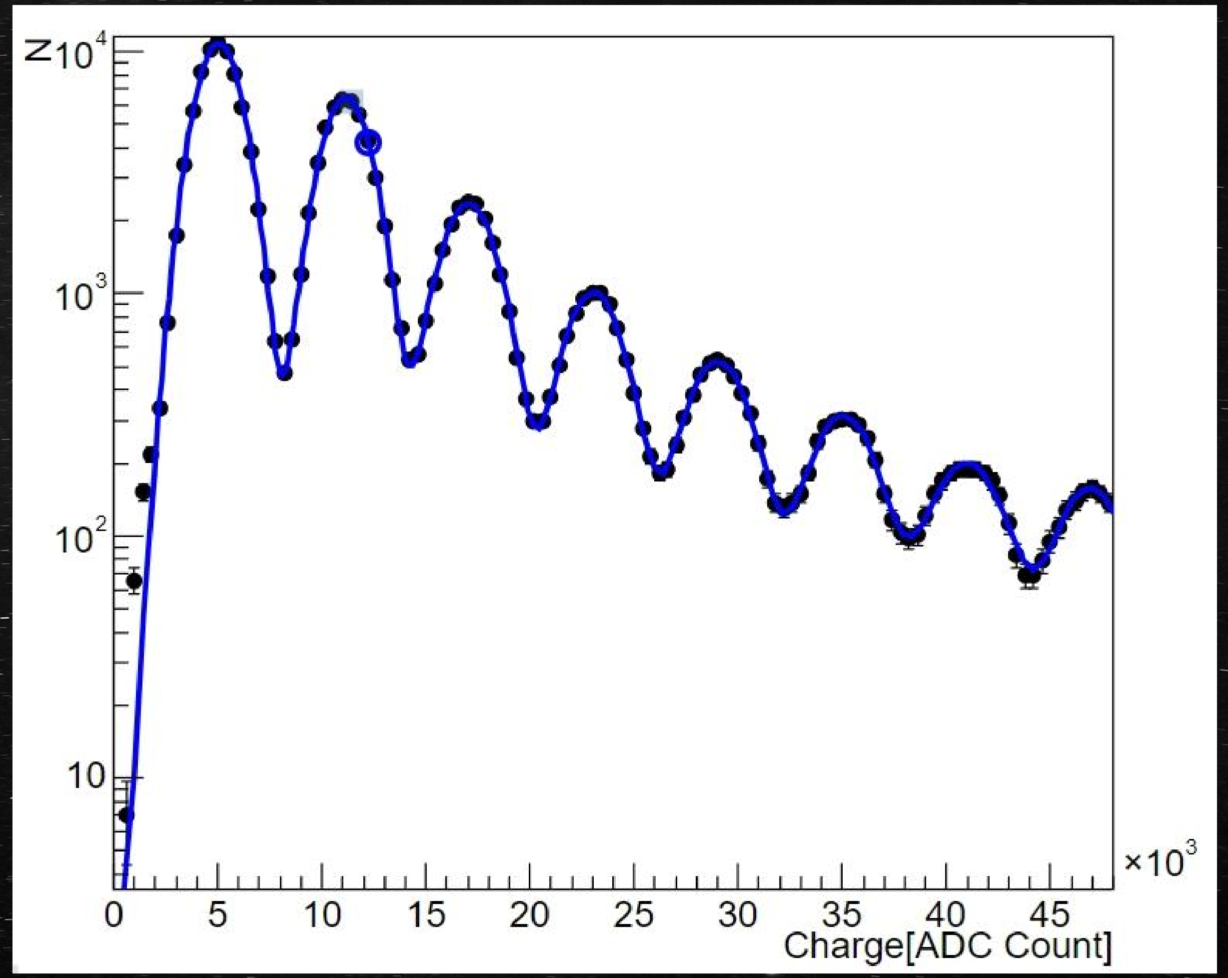
Electronic System Testing:
Data can be triggered and readout

SiPM Testing: Usage LED source to calibrate SiPM DCR and PDE, consistent with SiPM quality test result

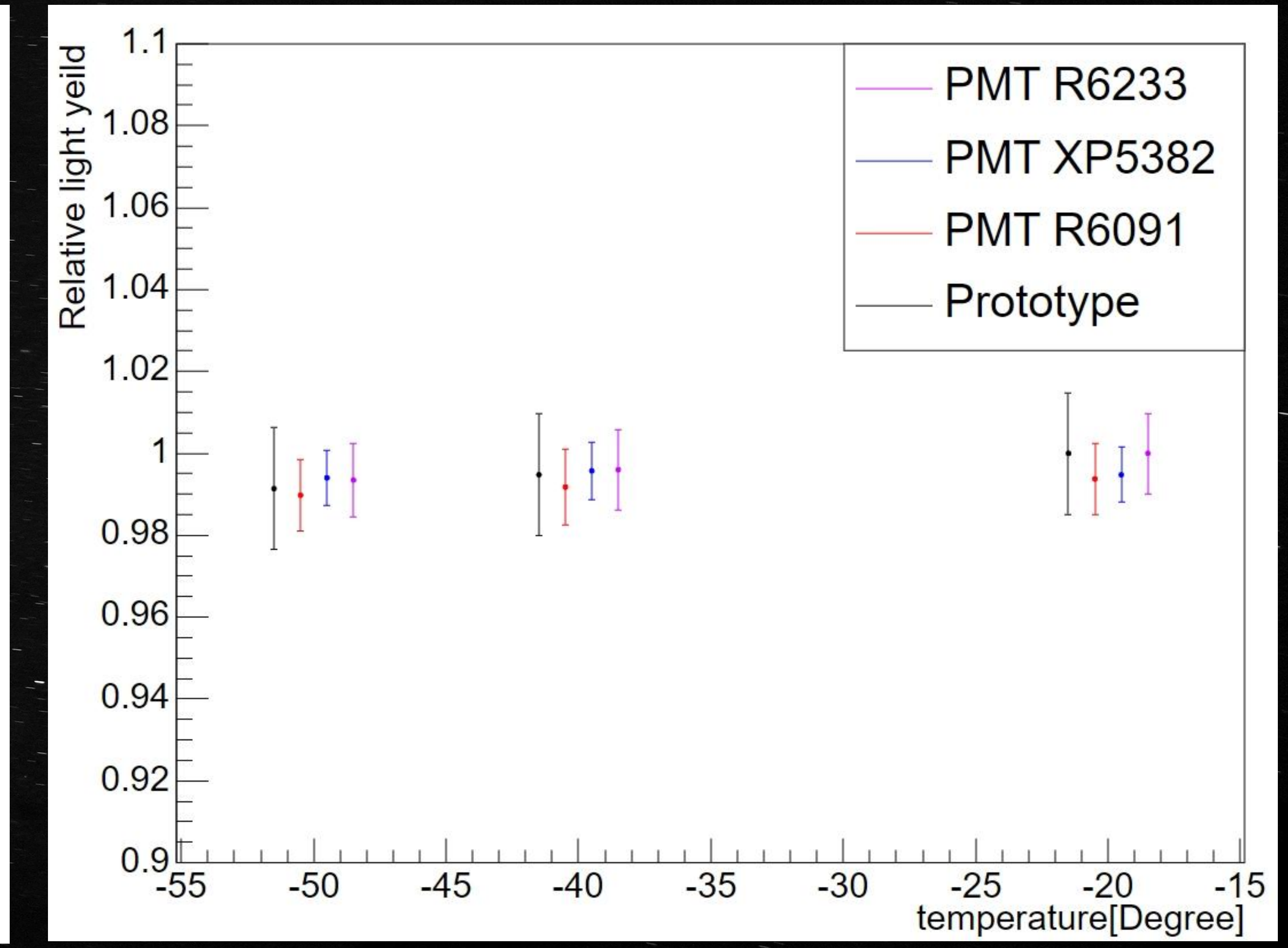
GdLS Testing: Usage cosmic ray muon, get relative light yield from different temperature, consistent with external test result



Charge Distribution by Electronics Readout



Relative Light Yield



Summary of TAO

✱ TAO will measure reactor antineutrino spectrum with sub-percent energy resolution (<2%/ $\sqrt{E}$), and provide a precision reference antineutrino spectrum for JUNO

✱ Feasibility of each system have been verified through quality test and prototype

✱ Will start assembling in Taishan NPP in 2024, and start data taking in early 2025