Reactor Antineutrino Flux and Spectrum Measurement at Daya Bay

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On behalf of the Daya Bay Collaboration

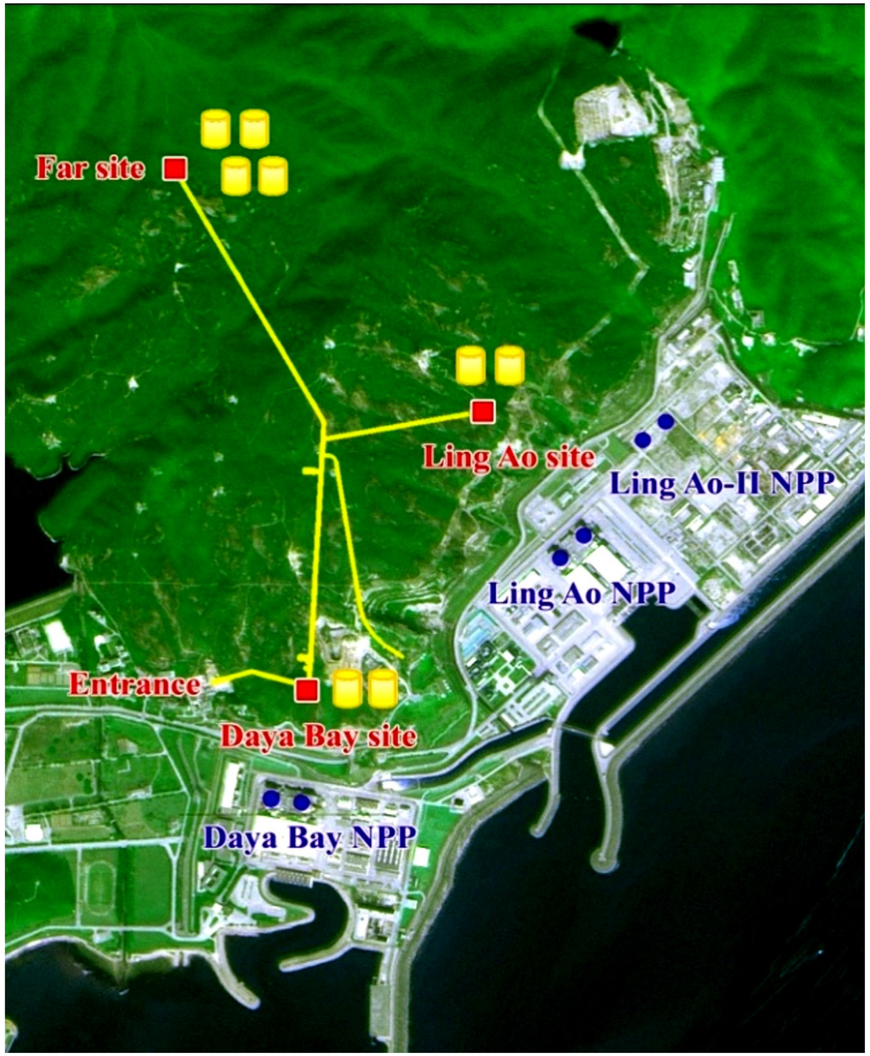
16th Jan, 2023

Outline

- Daya Bay Reactor Neutrino Experiment
- Reactor antineutrino flux evolution of Daya Bay experiment
- Extraction of isotope antineutrino spectra at Daya Bay
- Joint analysis of Daya Bay experiment and PROSPECT experiment

Daya Bay Reactor Neutrino Experiment

Designed to measure θ_{13}, using antineutrinos produced by reactors.



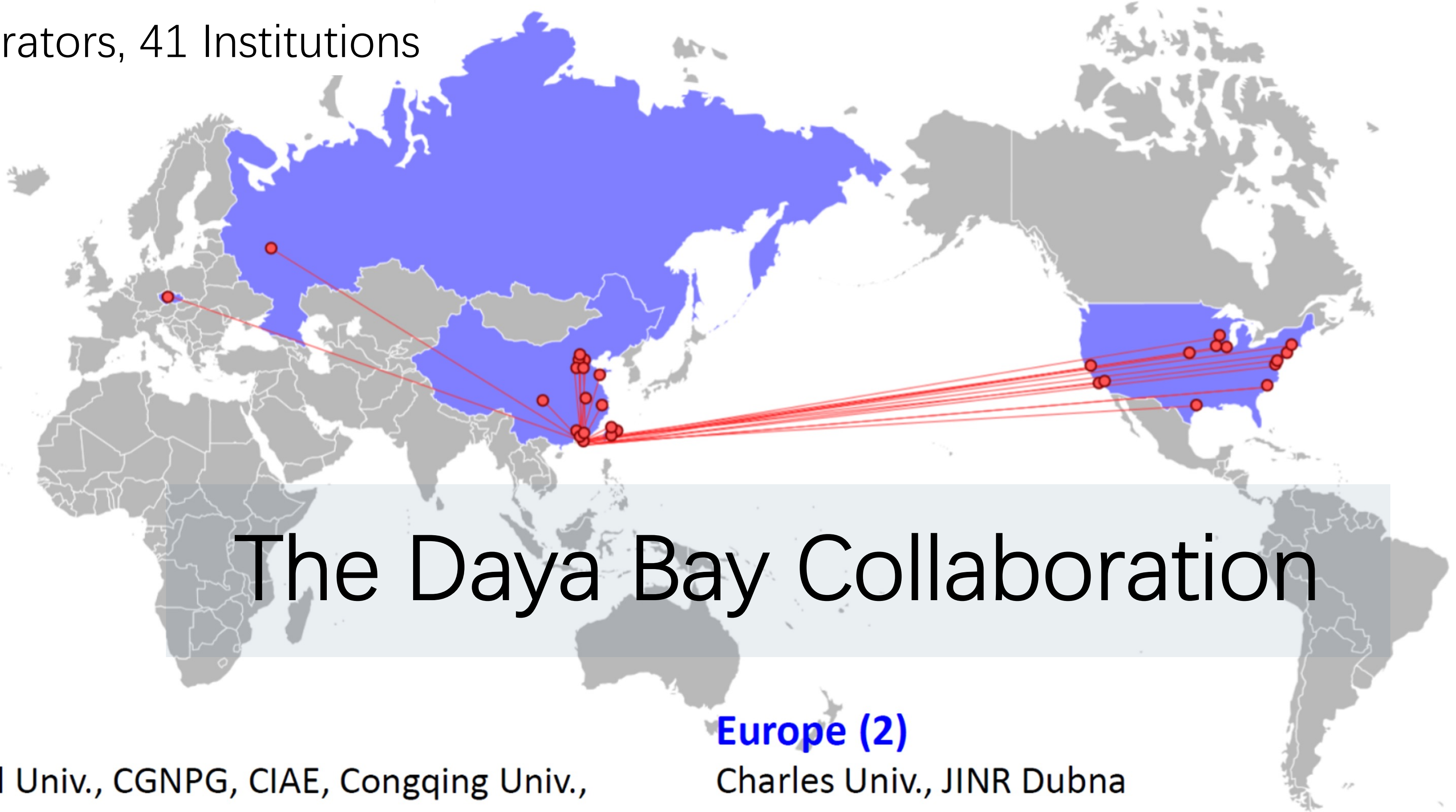
6 commercial pressurized-water reactors, each with 2.9 GW thermal power.

8 identically designed Antineutrino Detectors (ADs), in 3 Experimental Halls (EHs).

Starting from Dec 24, 2011, discovered the non-zero θ_{13} mixing angle in 2012.

Finished data taking on Dec 12, 2020

~200 Collaborators, 41 Institutions



The Daya Bay Collaboration

Asia (24)

Beijing Normal Univ., CGNPG, CIAE, Congqing Univ., Dongguan Univ. Tech., ECUST, GXU, IHEP, Nanjing Univ., Nankai Univ., NCEPU, NUDT, Shandong Univ., Shanghai Jiao Tong Univ., Shenzhen Univ., Tsinghua Univ., USTC, Xian Jiaotong Univ., Zhongshan (Sun Yat-sen) Univ., Chinese Univ. of Hong Kong, Univ. of Hong Kong, National Chiao Tung Univ., National Taiwan Univ., National United Univ.

Europe (2)

Charles Univ., JINR Dubna

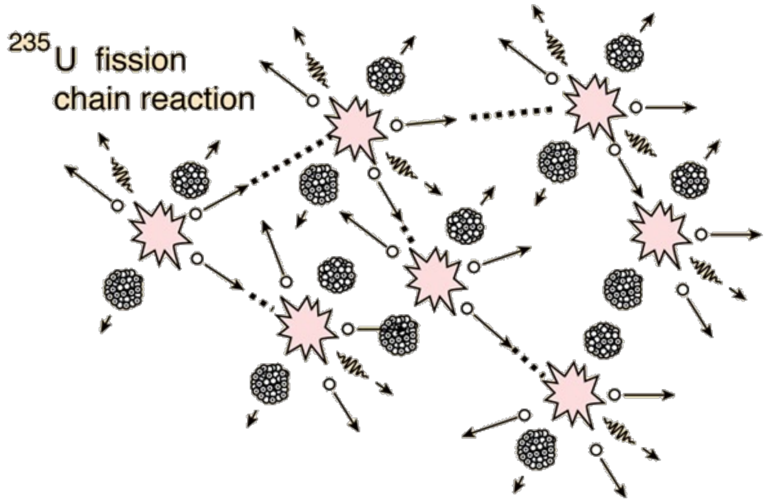
North America (15)

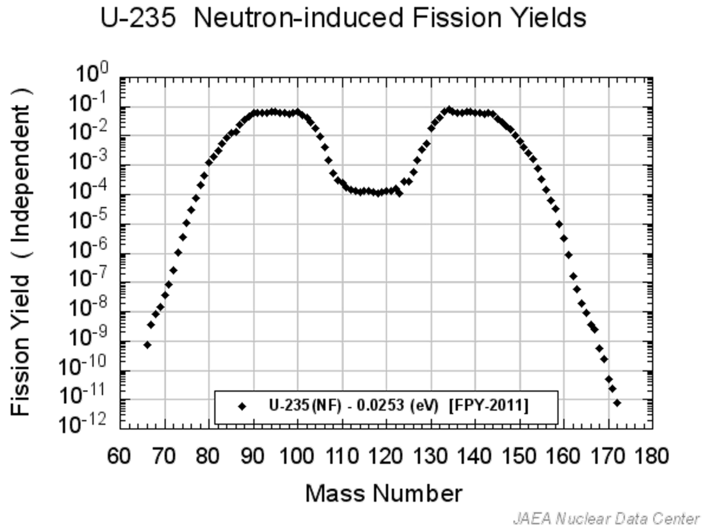
Brookhaven Natl Lab, Illinois Institute of Technology, Iowa State, Lawrence Berkeley Natl Lab, Princeton, Siena College, Temple University, UC Berkeley, Univ. of Cincinnati, Univ. of California Irvine, UIUC, Univ. of Wisconsin, Virginia Tech, William & Mary, Yale

Reactor antineutrinos at Daya Bay

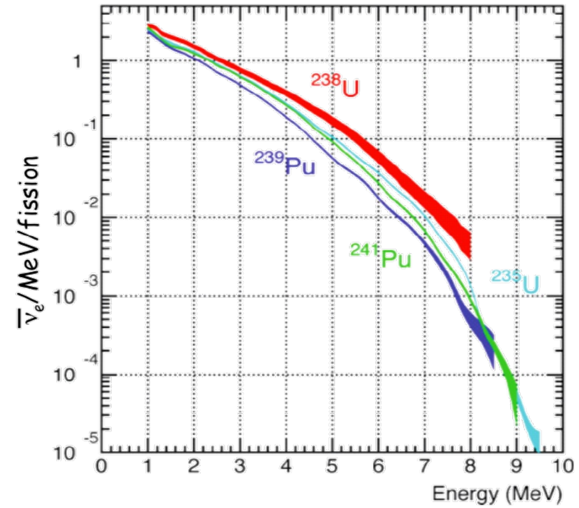
Six reactors with total thermal power of 17.4 GW, producing ~3.5×10^{21} electron antineutrinos per second

Antineutrinos are mainly produced by the beta decay of fission products of ^{235}U, ^{238}U, ^{239}Pu and ^{241}Pu .





Huber-Mueller model*



*Phys. Rev. C **83**, 054615 (2011), Phys. Rev. C **84**, 024617 (2011)

Antineutrino detection at Daya Bay

- Detect inverse β-decay reaction (IBD):

prompt delayed

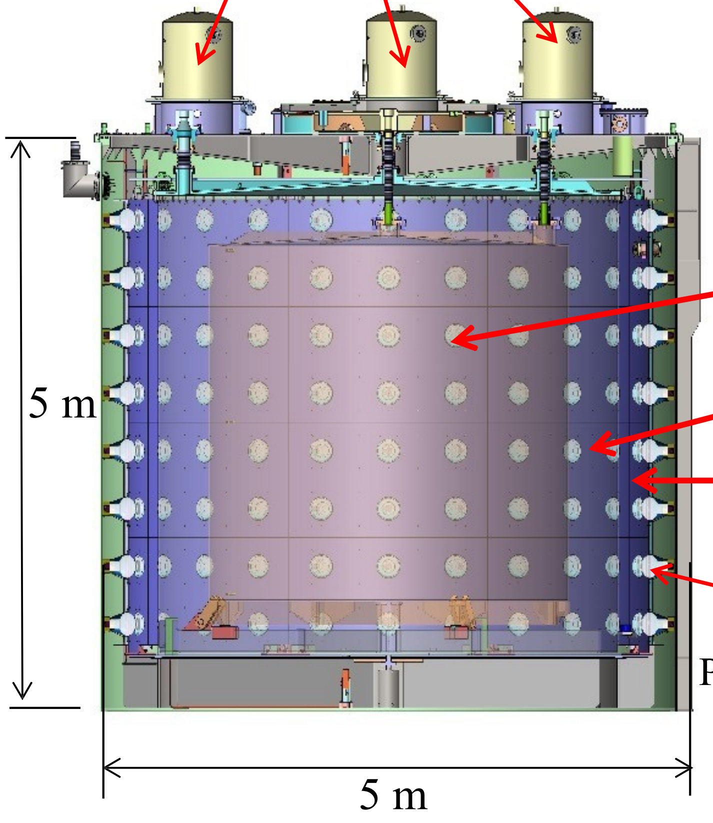
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

~180 μs $\rightarrow + p \rightarrow d + \gamma$ (2.2 MeV)

$\rightarrow + Gd \rightarrow Gd^*$

~30 μs for 0.1% Gd $\rightarrow Gd + \gamma$'s (~8 MeV)

Automated Calibration units (LED, ^{68}Ge, AmC-Co)



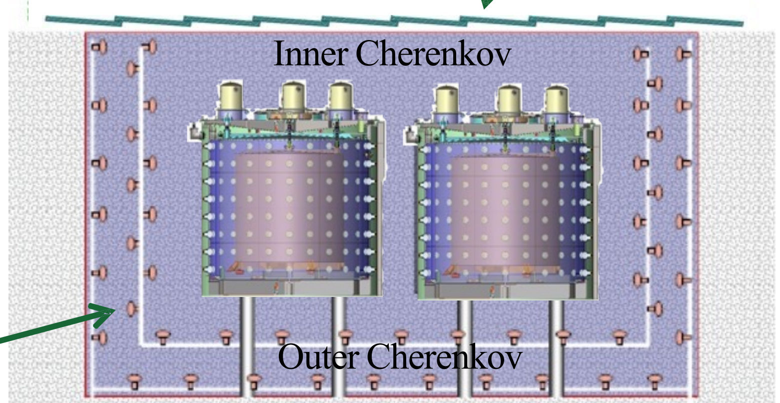
20-t 0.1% Gd-loaded liquid scintillator (target)

22-t LS (gamma catcher)
(LS = LAB + 3 g/l PPO + 15 mg/l Bis-MSB)

40-t mineral oil shield

192 Photomultiplier tubes (PMTs)

Four layers of RPC's to tag muons

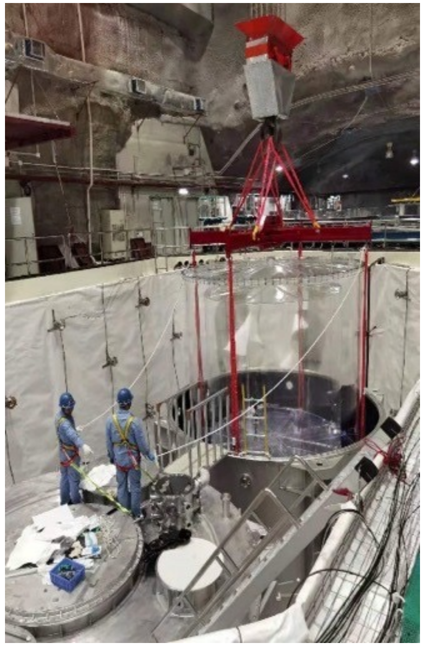


2.5-m water:
- Attenuates gamma rays & neutrons
- Forms two optically decoupled Cherenkov counters

NIM A**773** (2015) 8
NIM A**811** (2016) 133

Brief History of Onsite Operation

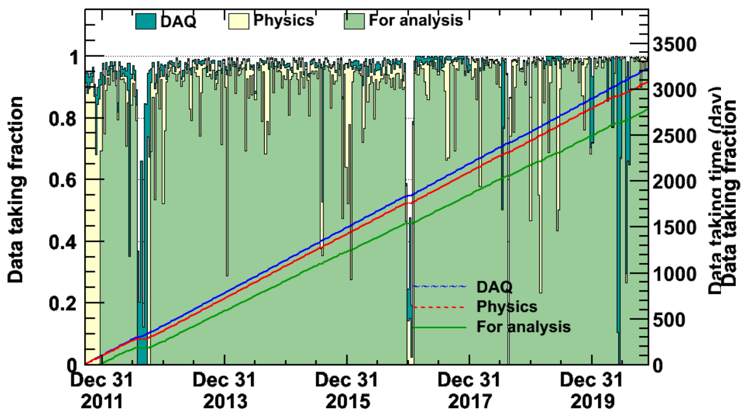
- Detector commissioning on 15 August 2011
- Collection of physics data began on 24 Dec 2011
- Collection of physics data ended on 12 Dec 2020
- Decommissioning: 12 Dec 2020 – 31 Aug 2021



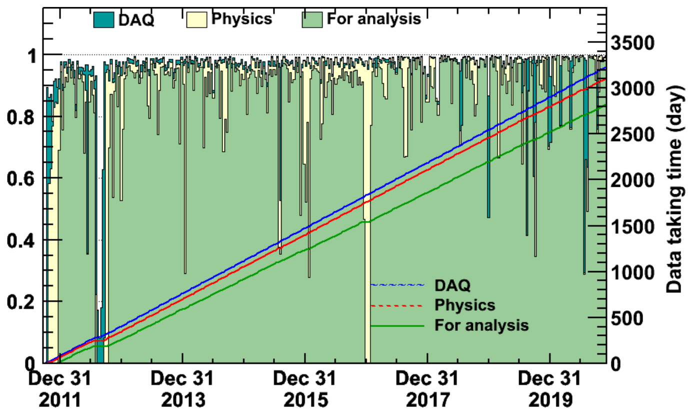
Data Acquisition

- Operational statistics:

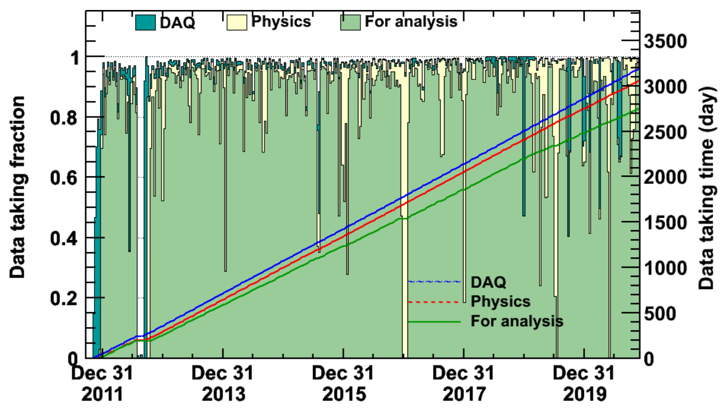
EH1



EH2



EH3



- Three physics runs:

Configuration	EH1	EH2	EH3	Start date – End date	Duration (Days)
6-AD	2	1	3	24 Dec 2011 – 28 July 2012	217
8-AD	2	2	4	19 Oct 2012 – 20 Dec 2016	1524
7-AD	1	2	4	26 Jan 2017 – 12 Dec 2020	1417
Total					**3158**

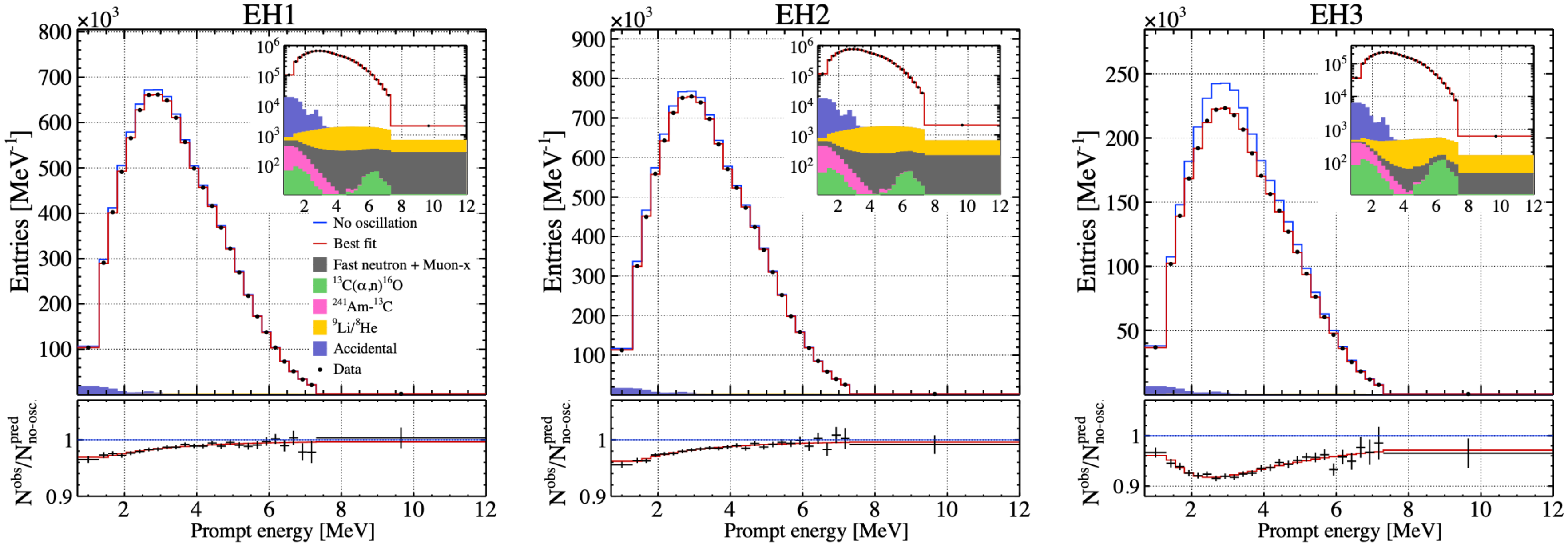
- Data available for analyses: ~2700 days

Improvements

- Statistics of nGd data:

Year	Calendar days	EH1	EH2	EH3	Total IBD’s
2018 (PRL **121**, 241805)	1958	1,794,417	1,673,907	495,421	3,963,745
2022 (arXiv:2211.14988)	3158	2,236,810	2,544,894	764,414	5,546,118

- Improved energy calibration as well as background determination and mitigation

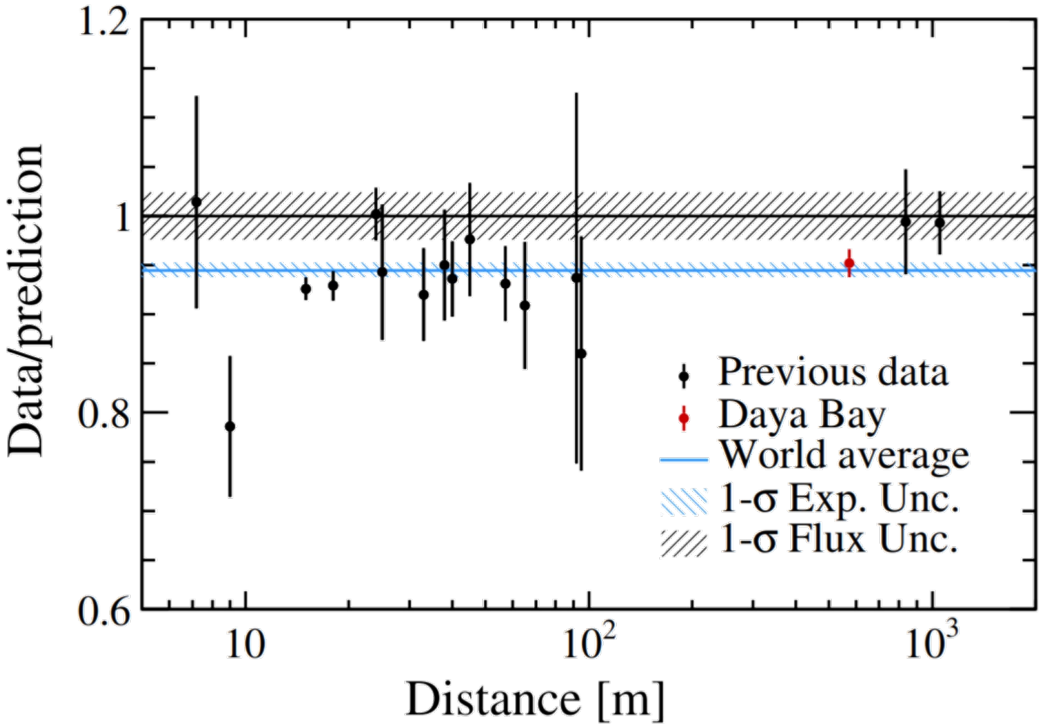


fantastic signal-to-background

excellent agreement between the best-fit prompt-energy distribution and the observed spectra

arXiv:2211.14988 [hep-ex]

Reactor antineutrino flux measurements



Daya Bay measurement to model (Huber-Mueller)

- 621 days analysis :
  data/prediction = 0.946±**0.020**(exp.)

- 1230 days analysis :
  data/prediction = 0.952±**0.014**(exp.)

Agrees with other experiments:
Global deficit = 0.945±0.007(exp.)±0.023(model)

IBD yield: $\sigma_i = \int S_i(E_\nu)\sigma(E_\nu)dE_\nu \quad \sigma_f = \sum_{i=1}^{4} F_i\sigma_i$

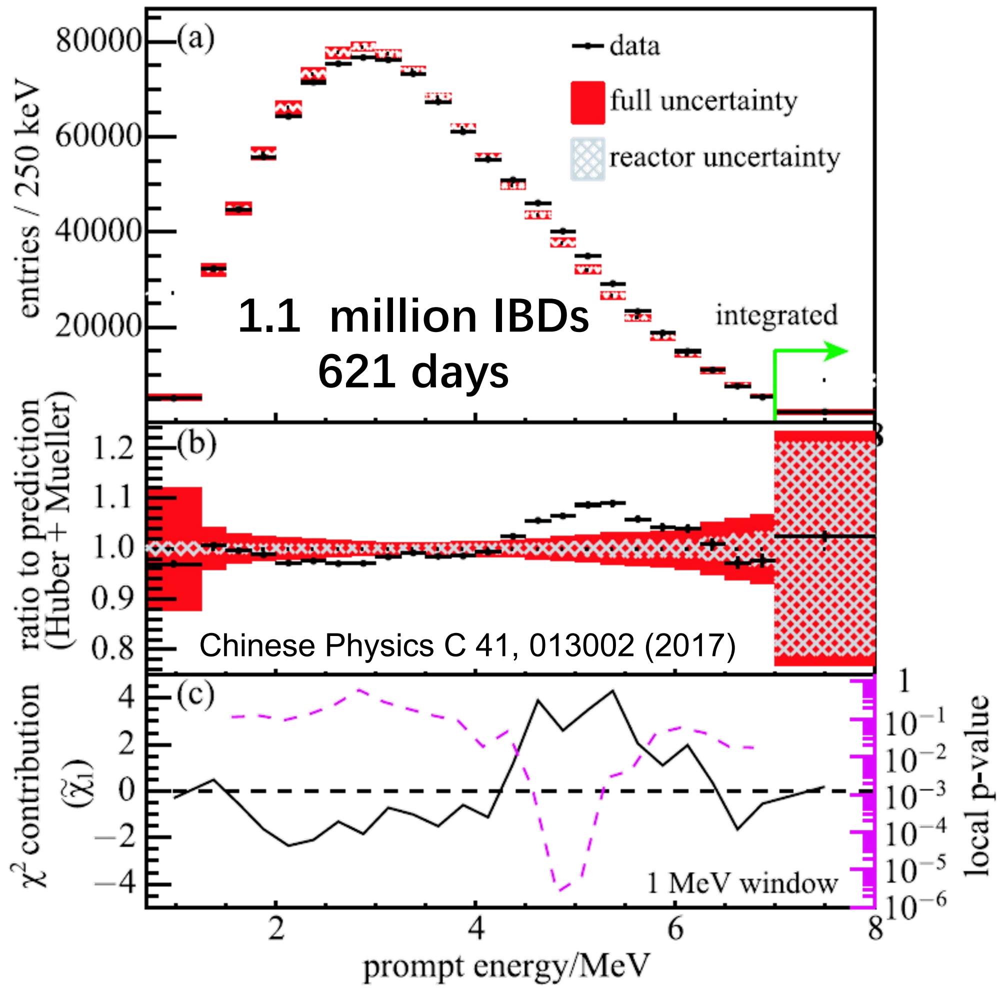
$$\sigma_f = (5.91 \pm 0.09) \times 10^{-43} cm^2/fission$$

$^{235}U : {}^{238}U : {}^{239}Pu : {}^{241}Pu$ = 0.564 : 0.076 : 0.304 : 0.056

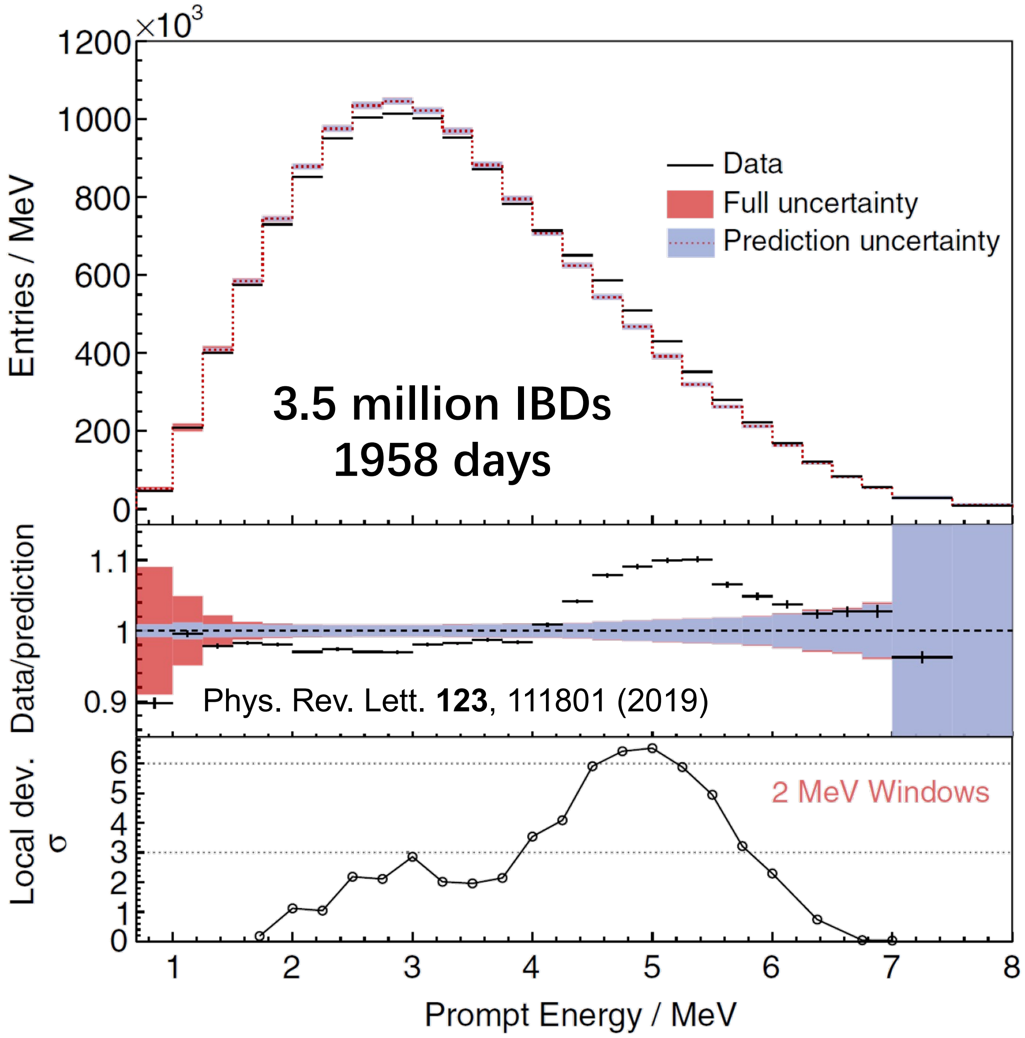
Reactor Antineutrino Anomaly(RAA):
deviation of data/prediction from unity

Phys. Rev. D **100**, 052004(2019), 1230 days

Reactor antineutrino spectrum measurements



Local deviation ~ 4σ



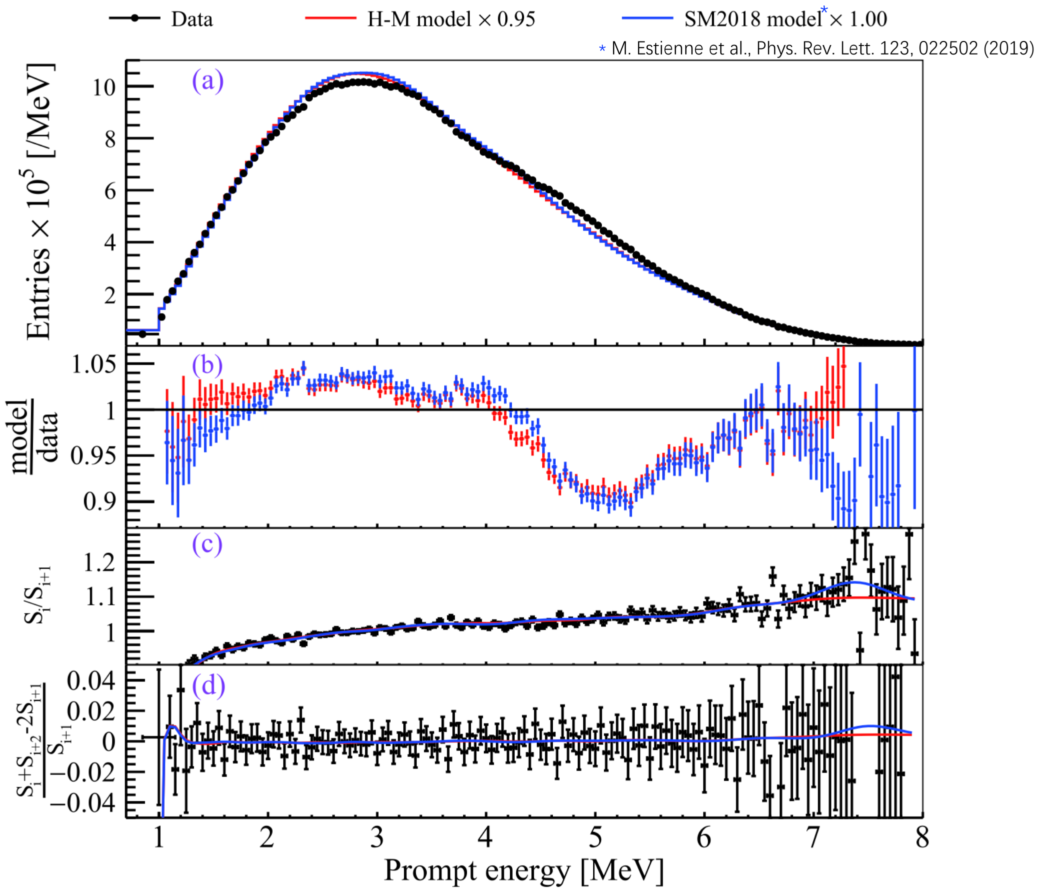
Local deviation ~ 6σ

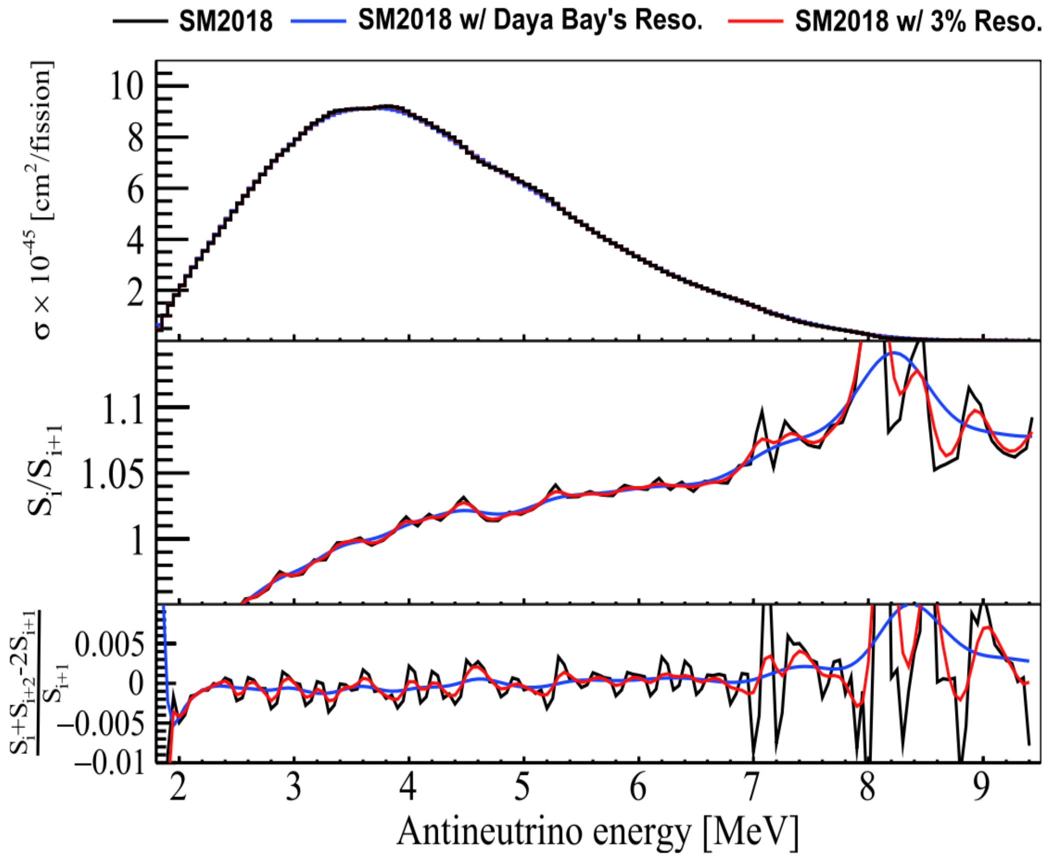
The spectral shape disagrees with the Huber-Mueller model at 5.3σ
an excess in 4~6 MeV range is observed with a 6.2σ discrepancy

Finely binned antineutrino spectrum measurement at Daya Bay

Motivation
- Fine structures may be important for experiments with high resolution
- Fine structures are interesting research topic for nuclear physics

1958 days

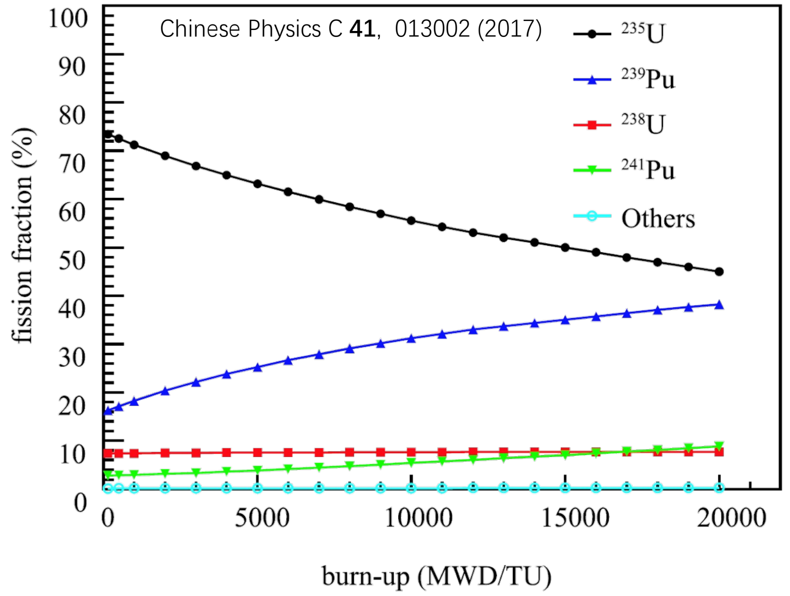




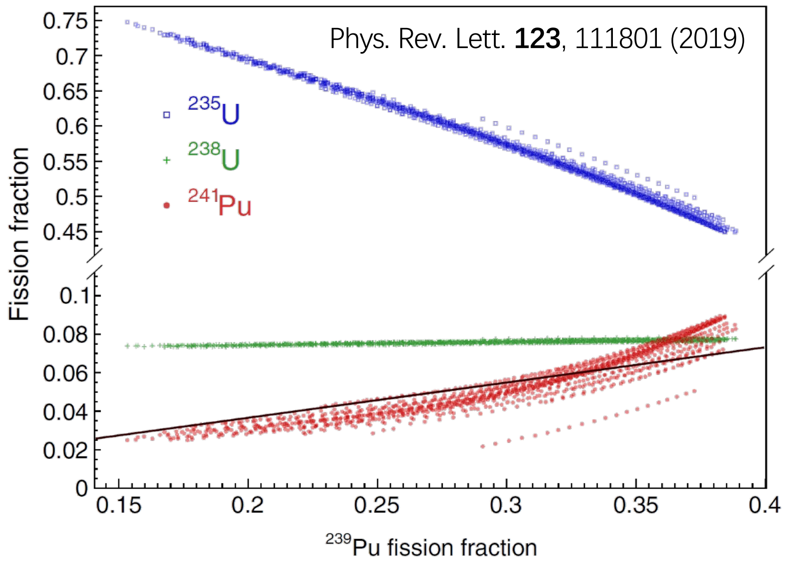
- The Daya Bay measurement is not sensitive to fine structures calculated from current nuclear databases because of the finite energy resolution.
- No evidence of fine structures in reactor antineutrino spectrum with Daya Bay measurement is found.

Chinese Phys. C **45** 073001 (2021)

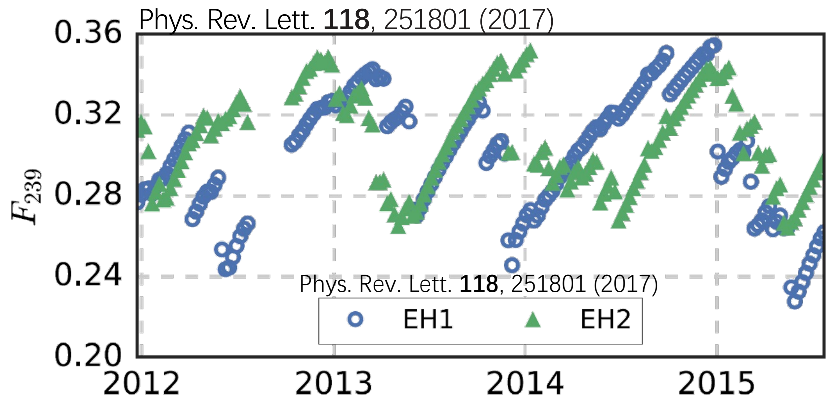
Fission fraction evolution of Daya Bay reactors



Fission fraction in a typical refueling cycle



Stacking all refueling cycles



Effective fission fraction of ^{239}Pu of near sites

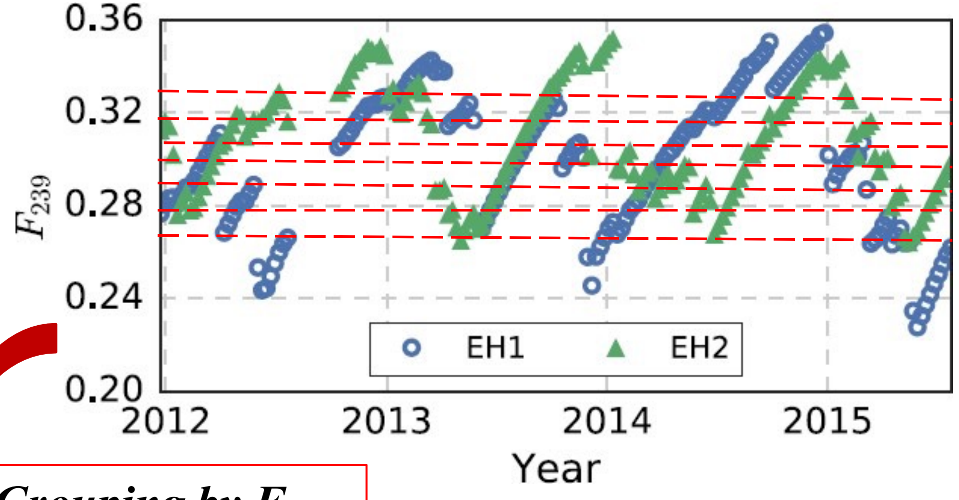
Effective fission fraction (EFF):
detector "observed" fission fraction

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

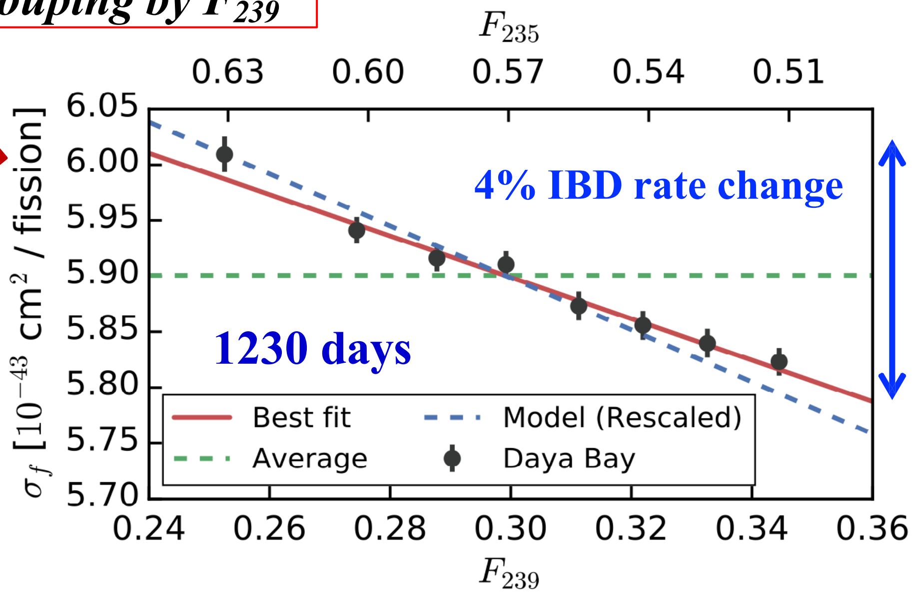
^{235}U: 50% ~ 65%
^{239}Pu: 24% ~ 35%

Reactor antineutrino flux evolution:1230 days

As the fission fraction evolves, the antineutrino flux also evolves

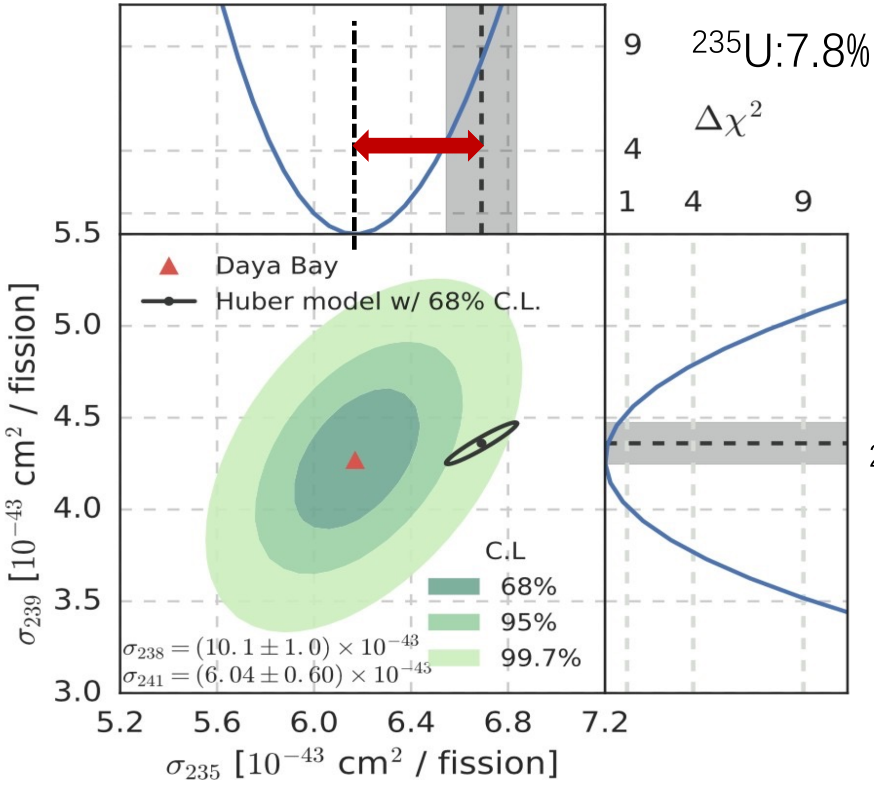


Grouping by F_{239}



Phys. Rev. Lett. **118**, 251801 (2017)

Combined fit of two major isotopes ^{235}U and ^{239} Pu by constraining ^{238}U and ^{241}Pu

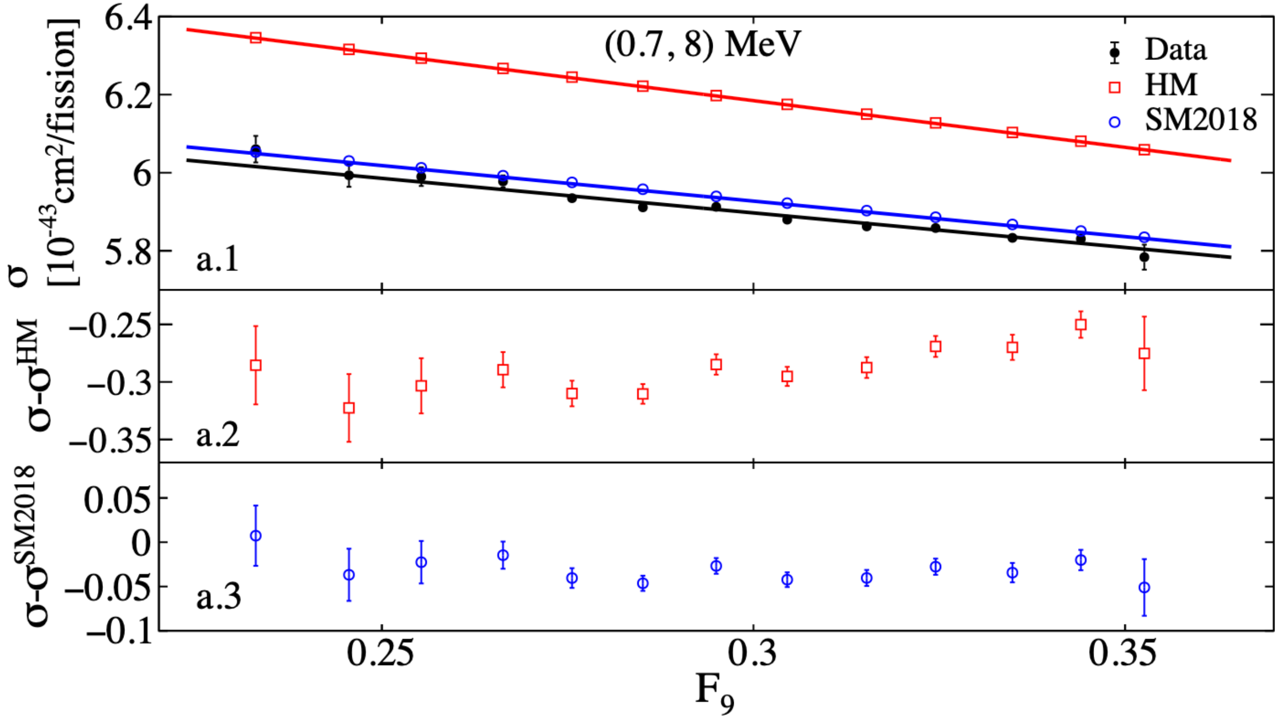


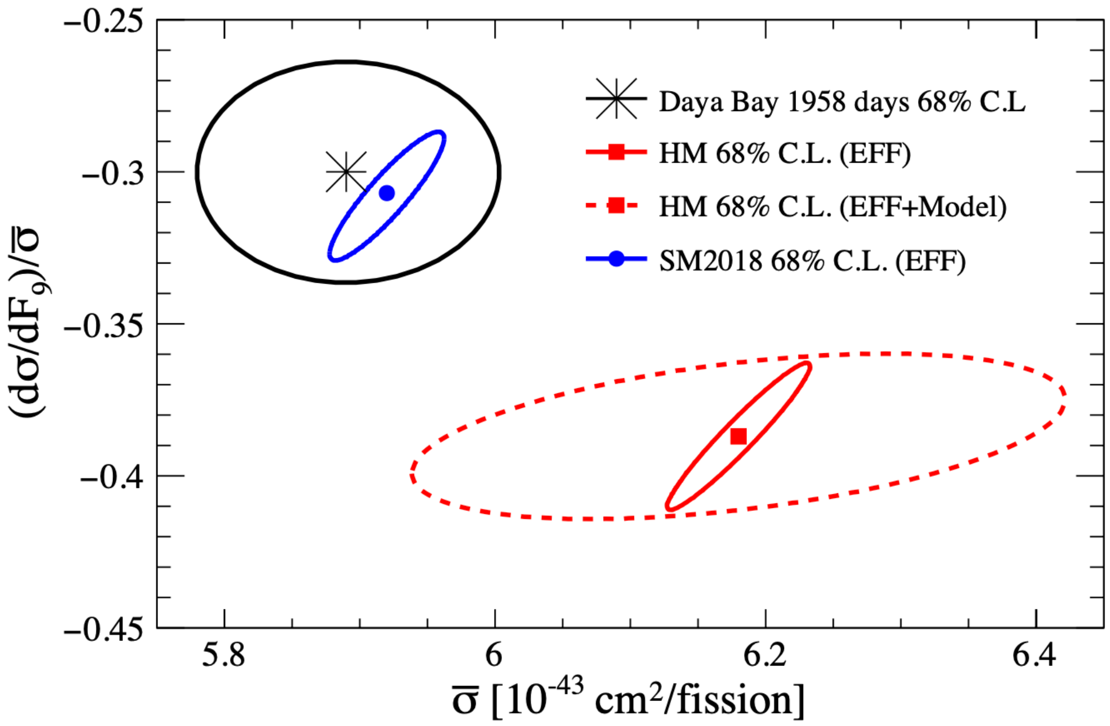
^{235}U:7.8% deficit

^{239}Pu:consistent

- The data prefer ^{235}U to be mainly responsible for the RAA
- Disfavor all isotopes with equal deficit (2.8σ) or ^{239}Pu only hypothesis (3.2σ)

Reactor antineutrino flux evolution: 1958 days





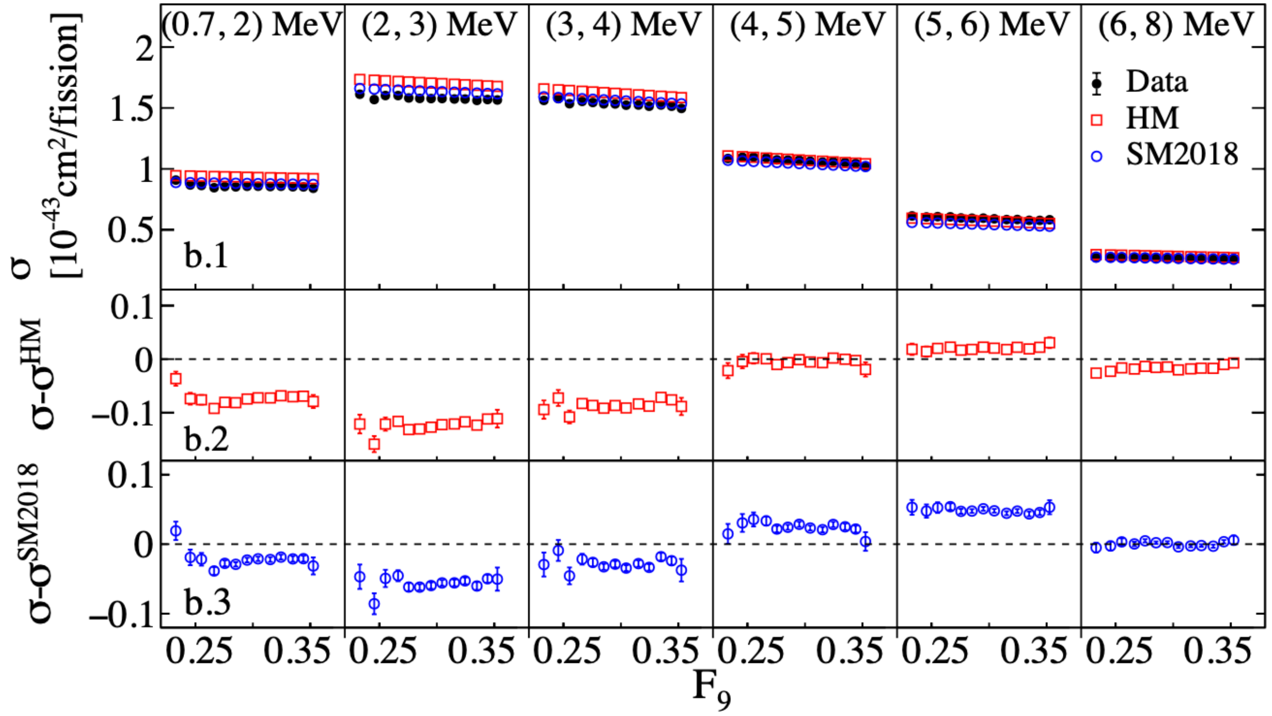
- The measured average flux and their evolution with the ^{239}Pu isotopic fraction, are inconsistent with the the Huber-Mueller model prediction.

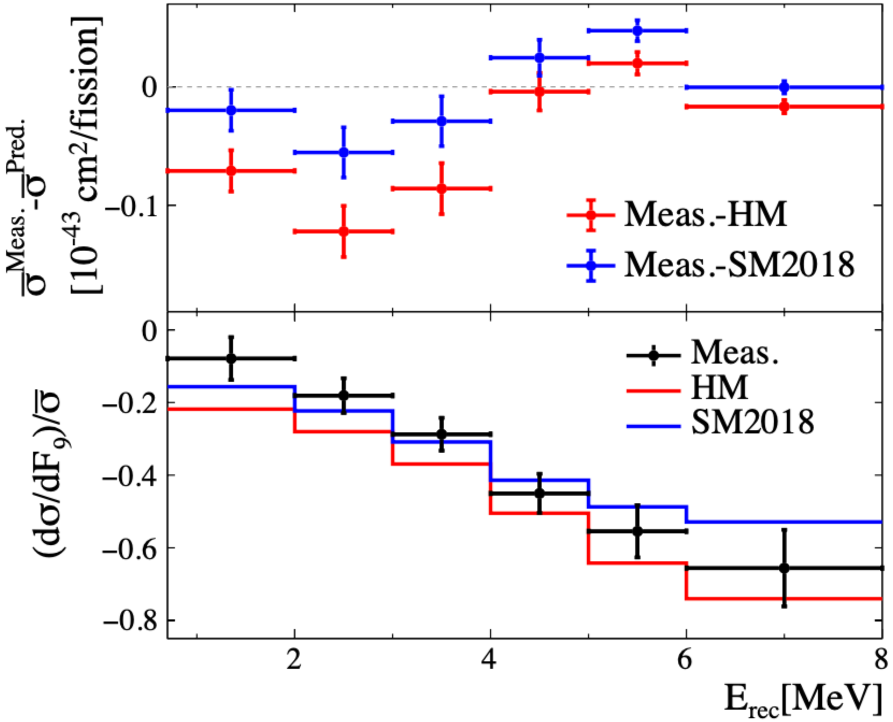
- The SM2018* model agrees with the average flux and its evolution

* M. Estienne *et al.*, Phys. Rev. Lett. 123, 022502 (2019)

arXiv:2210.01068 [hep-ex]

Reactor antineutrino flux evolution: 1958 days





Model	$\bar{\sigma}^e$	$[(d\sigma/dF_9)/\bar{\sigma}]^e$
HM	675/6 (25)	11/6 (1.8)
SM2018	748/6 (27)	5.5/6 (0.7)

Both the HM model and the SM2018 fails to describe the energy spectrum evolution.

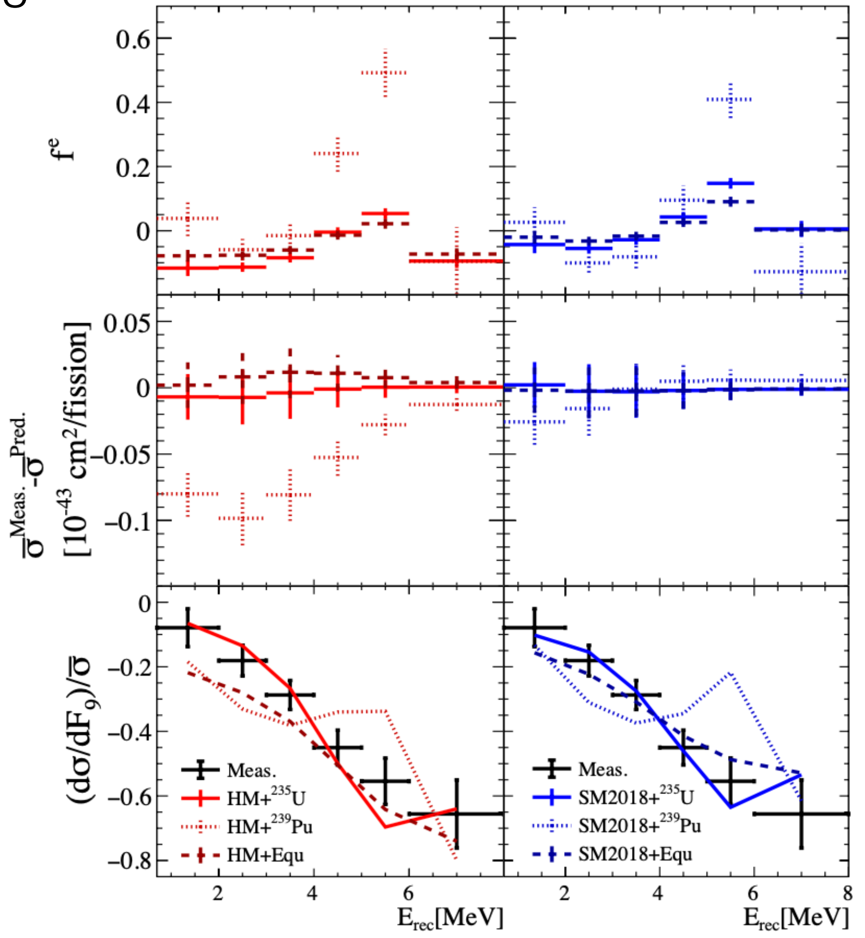
arXiv:2210.01068 [hep-ex]

Reactor antineutrino flux evolution: 1958 days

Three types of modified models with new free parameters + HM/SM2018 are introduced to investigate the data and model difference

the best-fit χ^2/NDF when fitting to data

Modified model	Model	χ^2/NDF	η
$\sigma^{\text{model},eg} = \eta[F_5^g\sigma_5^e(1+f_5^e) + F_8^g\sigma_8^e + F_9^g\sigma_9^e + F_1^g\sigma_1^e]$ Alter U-235 spectrum	HM+^{235}U	83/71 (1.4)	0.985±0.021
		83/72 (1.4)	1 (fixed)
	SM2018+^{235}U	80/71 (1.2)	0.997±0.021
		80/72 (1.2)	1 (fixed)
$\sigma^{\text{model},eg} = \eta[F_5^g\sigma_5^e + F_8^g\sigma_8^e + F_9^g\sigma_9^e(1+f_9^e) + F_1^g\sigma_1^e]$ Alter Pu-239 spectrum	HM+^{239}Pu	116/71 (3.4)	0.935±0.014
		136/72 (4.5)	1 (fixed)
	SM2018+^{239}Pu	126/71 (4.0)	0.995±0.014
		127/72 (4.0)	1 (fixed)
$\sigma^{\text{model},eg} = (1+f_E^e)[F_5^g\sigma_5^e + F_8^g\sigma_8^e + F_9^g\sigma_9^e + F_1^g\sigma_1^e]$ Equal change	HM+Equ	89/72 (1.7)	NA
	SM2018+Equ	82/72 (1.3)	NA



- Altering the ^{239}Pu spectrum only does not improve the agreement with data for either model.
- Altering the ^{235}U spectrum or changing all isotope's spectra equally, can bring better agreement with data

arXiv:2210.01068 [hep-ex]

Extraction of ^{235}U and ^{239}Pu isotope antineutrino spectra

The isotope antineutrino spectrum can be extracted from fuel evolution

- The 3.5M antineutrinos detected in near sites are divided into 20 groups ordered by the ^{239}Pu effective fission fraction
- Fit the ^{235}U and ^{239}Pu spectra , as two unknown arrays (26 energy bins for each isotope)

predicted spectra of the 20 groups

$$\chi^2(\boldsymbol{\eta}^5, \boldsymbol{\eta}^9) = 2\sum_{djk}\left(S_{djk} - M_{djk} + M_{djk}\ln\frac{M_{djk}}{S_{djk}}\right) + f(\boldsymbol{\epsilon}, \boldsymbol{\Sigma})$$

measured spectra of the 20 groups

constraint on nuisance parameters

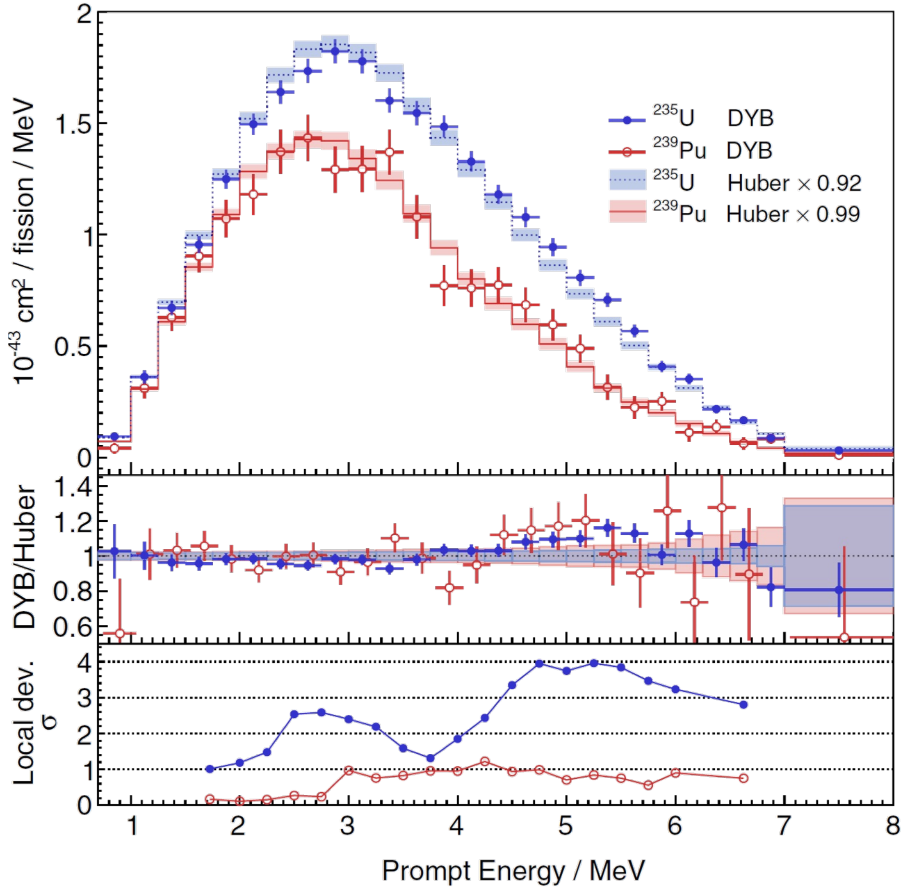
- Not sensitive to the ^{238}U and ^{241}Pu contributions, using the Huber-Mueller model as their priors, but assign >10% uncertainties both in rate and shape

- Time-dependent contributions from non-equilibrium, spent nuclear fuel, nonlinear nuclides, and backgrounds are considered

- An independent analysis using Markov Chain Monte Carlo based on Bayesian inference obtains consistent results

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

Extracted ^{235}U and ^{239}Pu spectra: 1958 days



- First extraction of the ^{235}U spectrum of commercial reactors
- First measurement of the ^{239}Pu spectrum

- In the 4~6 MeV energy range, the ^{235}U and ^{239}Pu spectra might have similar bump structure like the total spectrum.

- Local deviation(bump)： ^{235}U ~4σ, ^{239}Pu ~1.2σ

IBD yield ratio：

- ^{235}U: data/prediction = 0.92 ±0.023(exp.)±0.021(model)
- ^{239}Pu: data/prediction = 0.99 ±0.057(exp.) ±0.025(model)

^{235}U is more likely to be responsible for "reactor $\bar{\nu}_e$ anomaly"

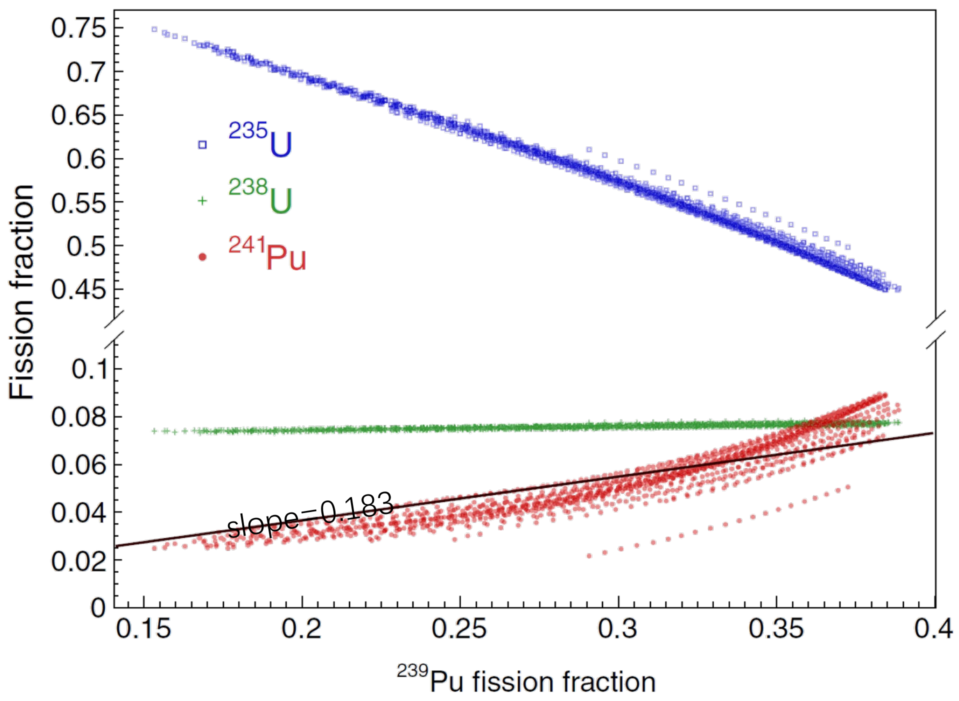
Phys. Rev. Lett. **123**, 111801 (2019)

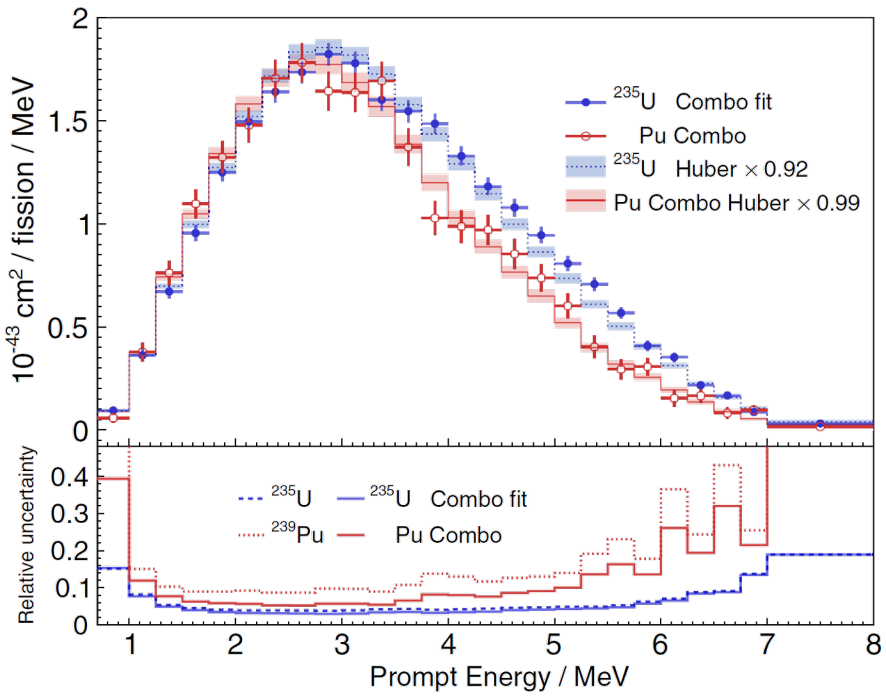
Extracted ^{235}U and Pu-Combo Spectra

- Combine ^{239}Pu and ^{241}Pu as one term to reduce the Pu uncertainty

$$s_{\text{combo}} = s_{239} + 0.183 \times s_{241}$$

- Dependence on the input of ^{241}Pu is largely removed
- The extracted Pu-combo spectrum uncertainty: 6% (9% for ^{239}Pu-only)





^{235}U : ^{239}Pu : ^{238}U : ^{241}Pu

0.564 : 0.304 : 0.076 : 0.056

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

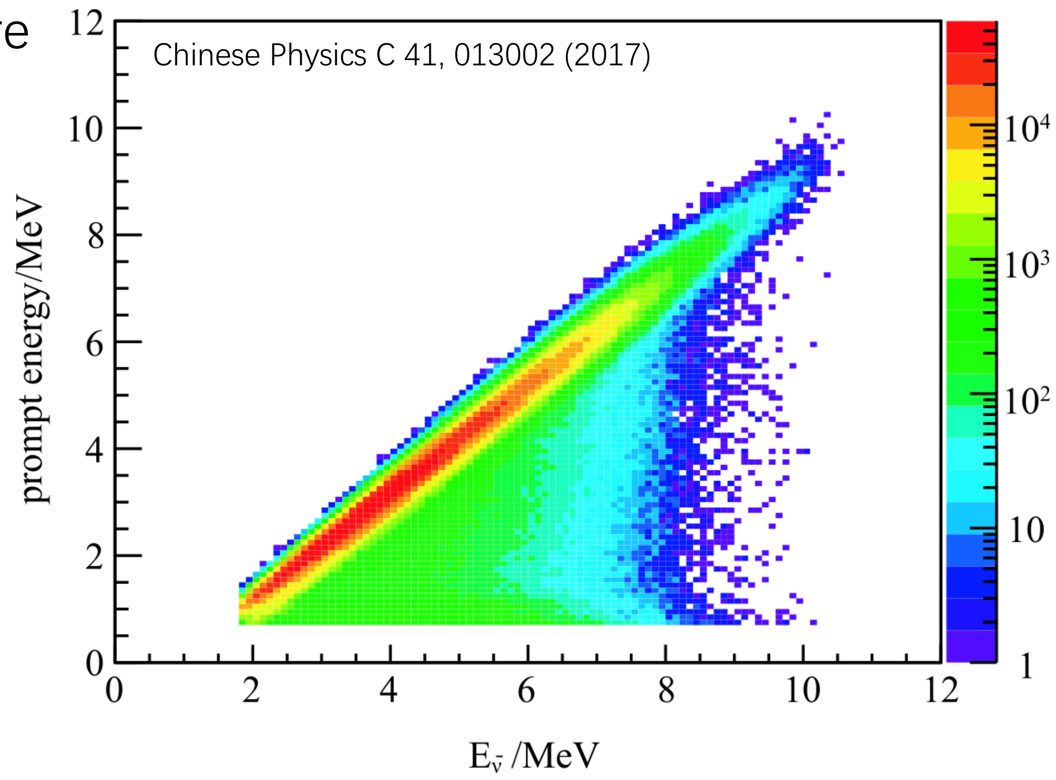
Antineutrino energy spectrum unfolding

Physics goal: provide a precise data-based prediction for other reactor antineutrino experiments

- The extracted isotope spectra of ^{235}U, ^{239}Pu or Pu-combo are prompt spectra which contains the DYB detector response

- Detector response includes:
  - IBD neutron recoiling: energy shift
  - IAV effect: energy loss in inner acrylic vessel
  - Nonlinearity (scintillation quenching, electronics response)
  - Energy Resolution: ~8.5% at 1 MeV

- An operation called **unfolding** is performed to remove the detector response, transforming the prompt spectra into antineutrino energy spectra.



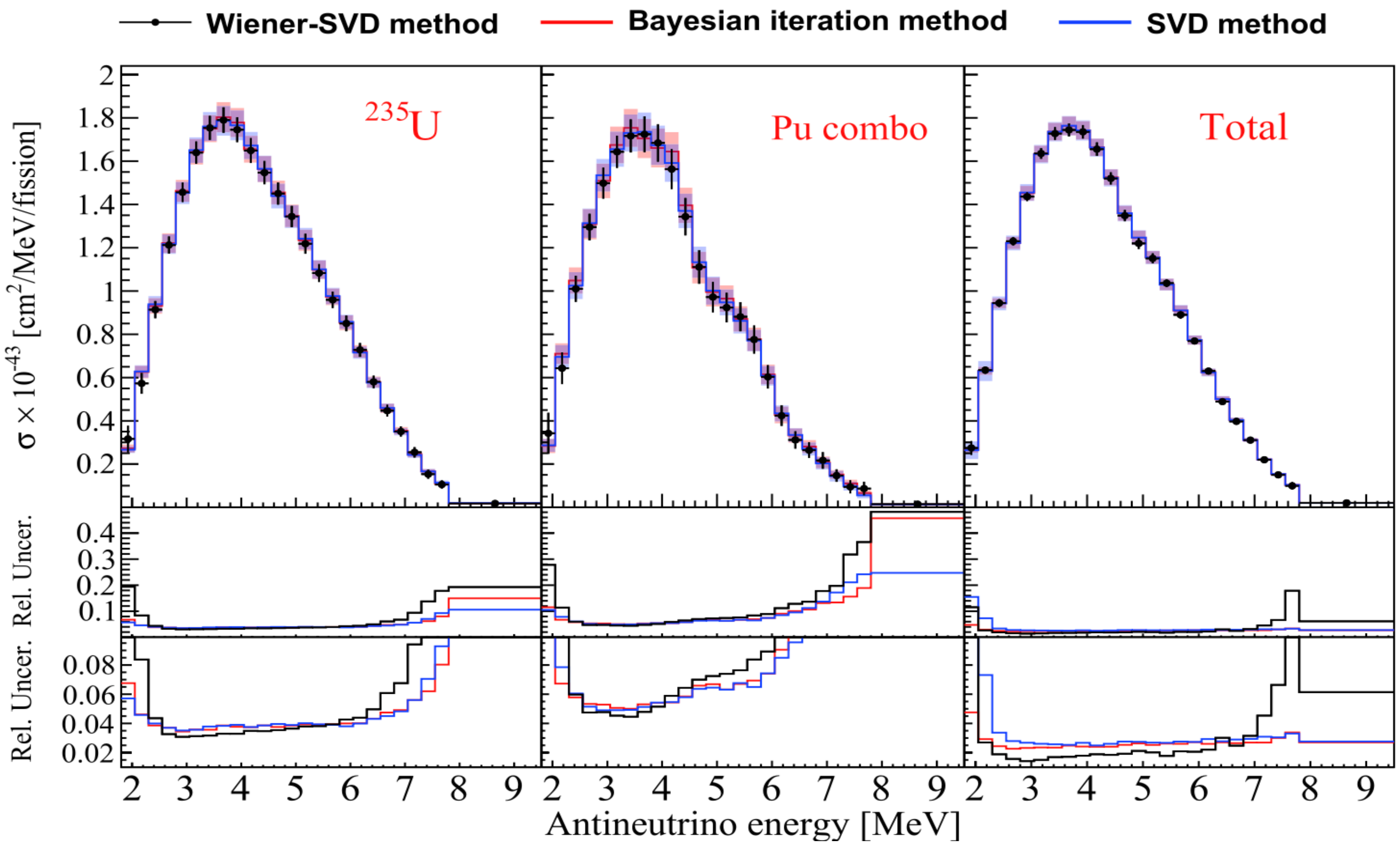
The Daya Bay detector response matrix

- Inputs of unfolding: the IBD prompt spectrum and its covariance matrix, and the response matrix
- Ouputs of unfolding: the antineutrino spectrum and the corresponding covariance matrix

Isotope antineutrino unfolding at Daya Bay

Total and isotope antineutrino energy spectra is unfolded by Wiener-SVD method*.

*JINST **12**, P10002 (2017)



Three unfolding methods were used:

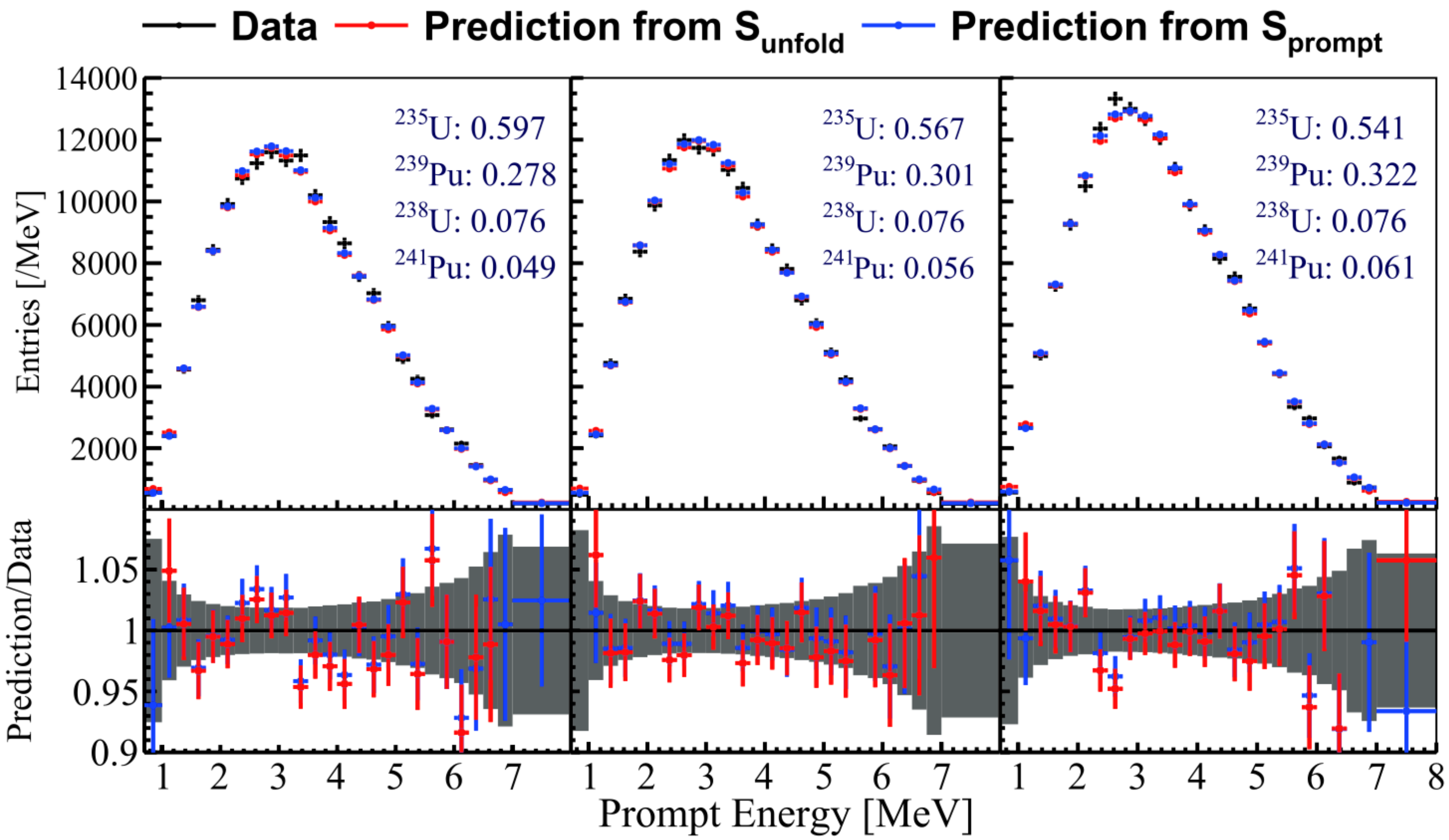
- Wiener-SVD method
- Bayesian iteration method
- SVD method

An ***Ac*** smearing matrix obtained through Wiener-SVD procedure encodes effect from unfolding regularization into any model

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

Isotope antineutrino unfolding at Daya Bay

- An example of reactor IBD prediction using the Daya Bay unfolded spectra



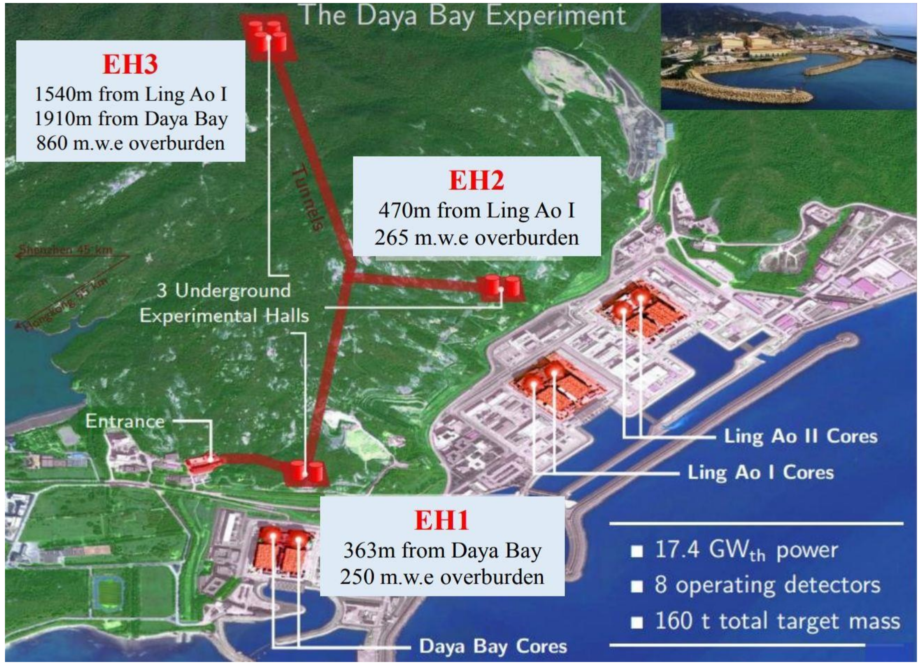
Prediction for 3 different fission fraction stages for EH1 AD1 at Daya Bay

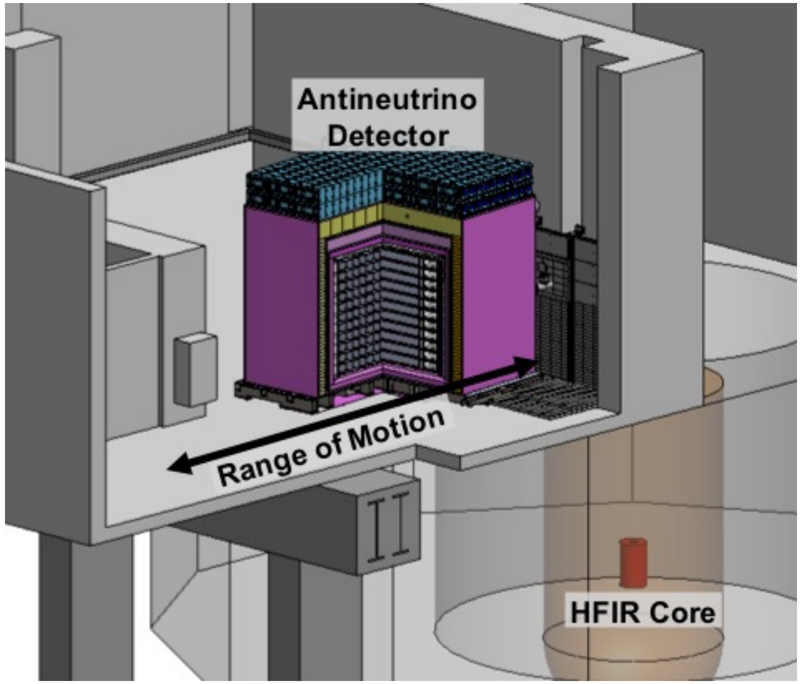
- The difference between the prediction and the data are consistent within statistical uncertainty in the 1 to 7 MeV energy region.

- With known reactor fission fractions, the technique can predict the energy spectrum to a 2% precision (statistics, unfolding, systematics included).

Chinese Phys. C **45** 073001 (2021)

Joint Determination of Reactor Antineutrino Spectra from ^{235}U and ^{239}Pu Fission by Daya Bay and PROSPECT

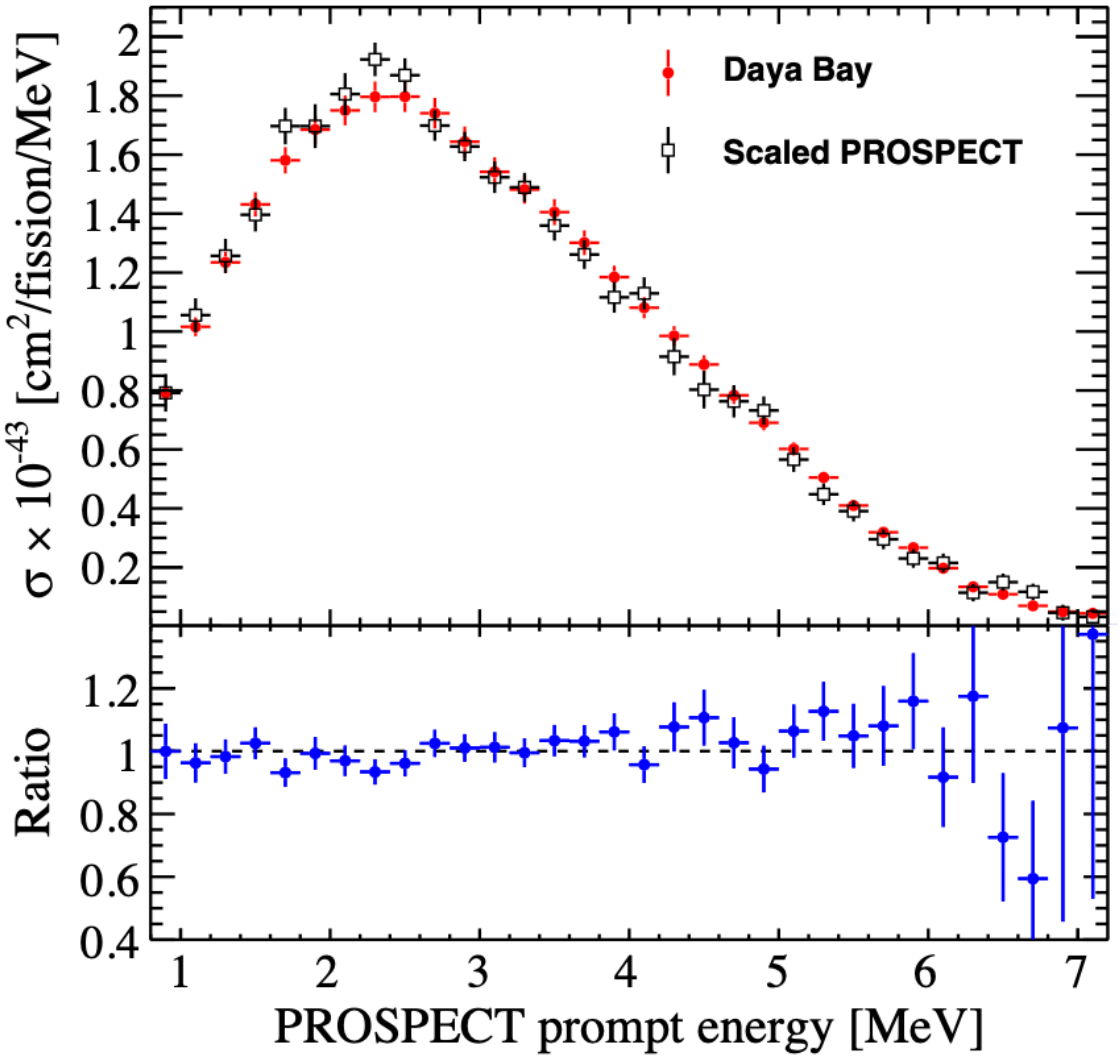




Daya Bay
- The most precise measurement of θ_{13}
- Baseline to near detectors ~600 m
- Low-enriched uranium (LEU) commercial reactors
- Four main fissile isotopes evolves with time

PROSPECT
- In search for active-to-sterile neutrino oscillations
- Baseline: 7.9 m
- High Flux Isotope Reactor
- Pure ^{235}U fuel

Prompt IBD Spectrum Shape Compatibility between Daya Bay and PROSPECT



Map the DYB spectrum from DYB energy space into the PRO energy space through detector response functions:

$$\boldsymbol{S}_{\rm map}^{\rm DYB} = \boldsymbol{R}^{\rm map}\boldsymbol{S}_{\rm p}^{\rm DYB} = \boldsymbol{R}^{\rm PRO}(\boldsymbol{R}^{\rm DYB})^{-1}\boldsymbol{S}_{\rm p}^{\rm DYB}$$

PROSPECT Response Matrix

Daya Bay Response Matrix

Daya Bay Measured Prompt Spectrum

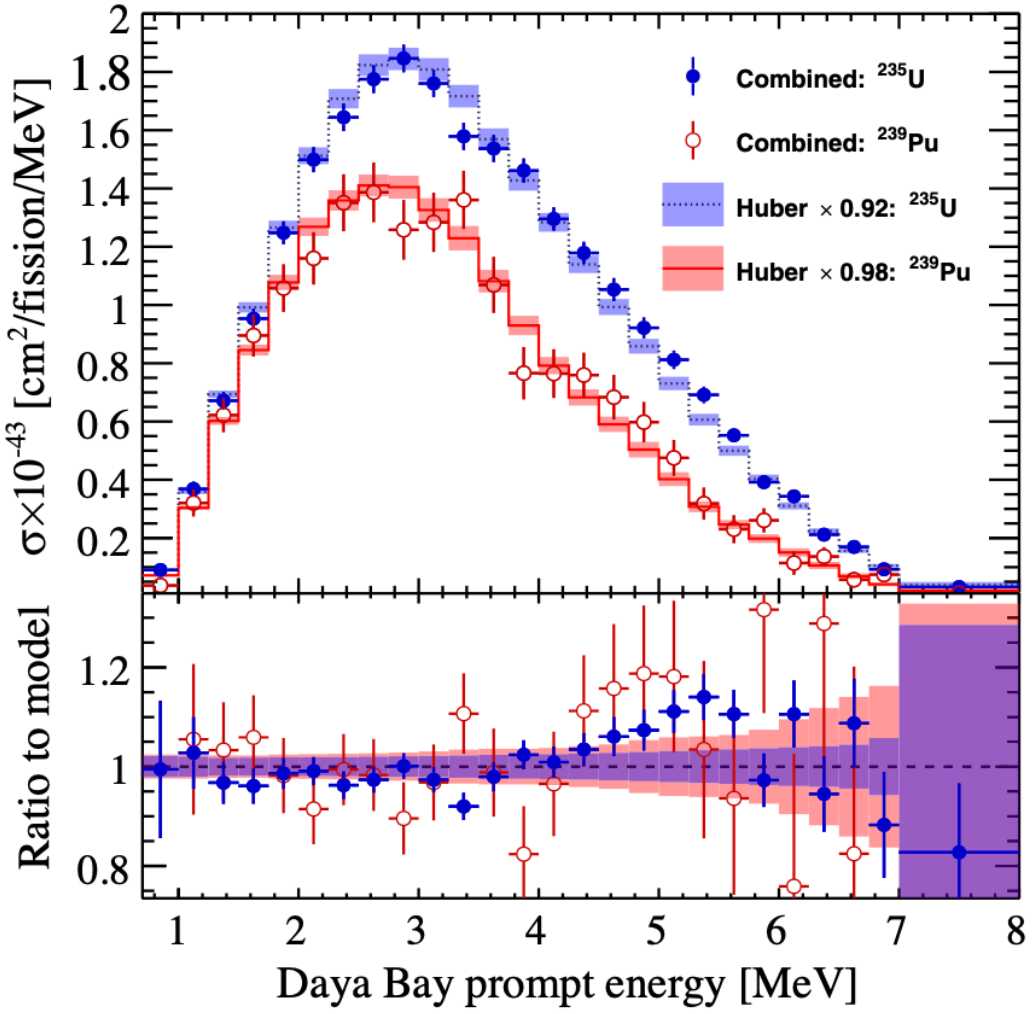
Comparison between S_{map}^{DYB} and PROSPECT spectrum:

- χ^2/NDF = 25.4/31
- p-value = 0.75
- Further validated with a frequentist approach
- Consistent

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

Joint analysis of Daya Bay and PROSPECT

Use PROSPECT measured prompt spectrum as a constraint term in the fitter of Daya Bay spectrum extraction analysis



Fitter to extract ^{235}U and ^{239}Pu spectrum from Daya Bay

$$\chi^2 = \chi^2_{\mathrm{DYB}} + \left(\boldsymbol{R}^{\mathrm{map}} \boldsymbol{S}^{\mathrm{fit}} \eta^{\mathrm{rate}} - \boldsymbol{S}_{\mathrm{p}}^{\mathrm{PRO}}\right)^T \left(\mathbf{Cov}^{\mathrm{PRO}}\right)^{-1} \left(\boldsymbol{R}^{\mathrm{map}} \boldsymbol{S}^{\mathrm{fit}} \eta^{\mathrm{rate}} - \boldsymbol{S}_{\mathrm{p}}^{\mathrm{PRO}}\right)$$

Constraint on ^{235}U spectrum from PROSPECT

$\boldsymbol{S}^{\mathrm{fit}}$: prediction for ^{235}U spectrum
η^{rate}: rate free parameter

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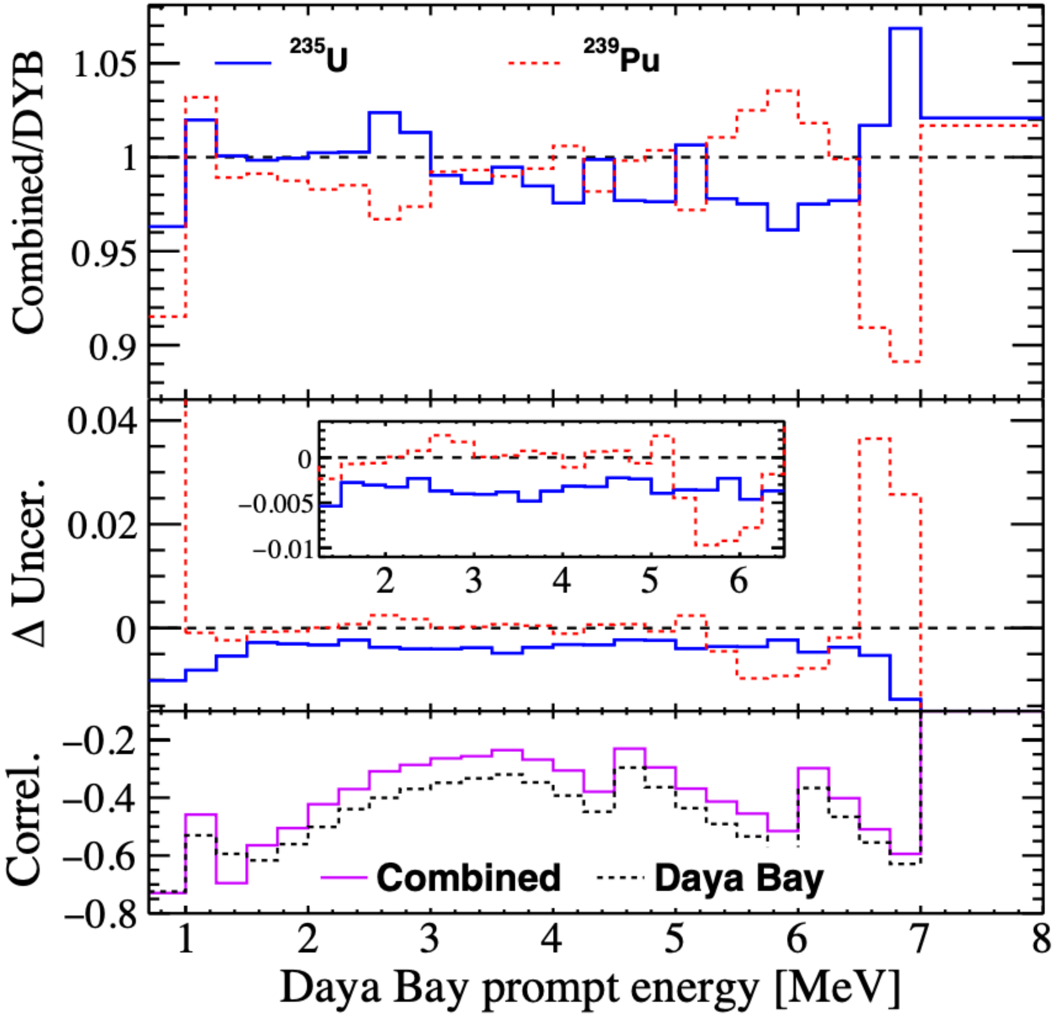
Comparison with Daya Bay only results:



- Extracted ^{235}U and ^{239}Pu spectra change at 2% level (well within uncertainties)
- Relative shape uncertainty of ^{235}U: 3.5% -> 3% around 3 MeV
- Degeneracy between ^{235}U and ^{239}Pu decreases by ~20%

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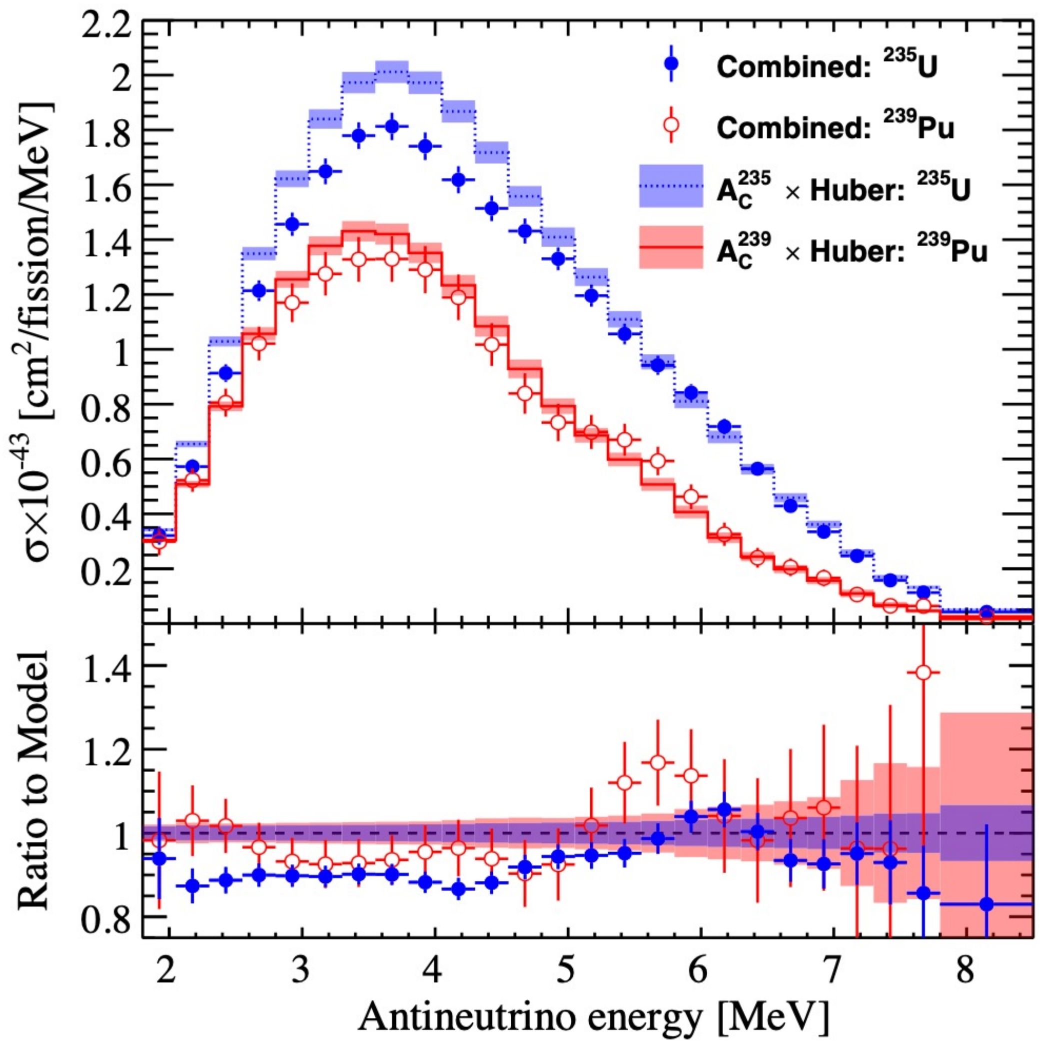
Jointly Unfolded ^{235}U and ^{239}Pu Spectrum



A joint unfolding was done via Wiener-SVD method, combing the spectra, response functions and covariance matrices from both experiments

Provides a more precise antineutrino energy spectrum for other reactor neutrinos measurements and applicaitons

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Summary

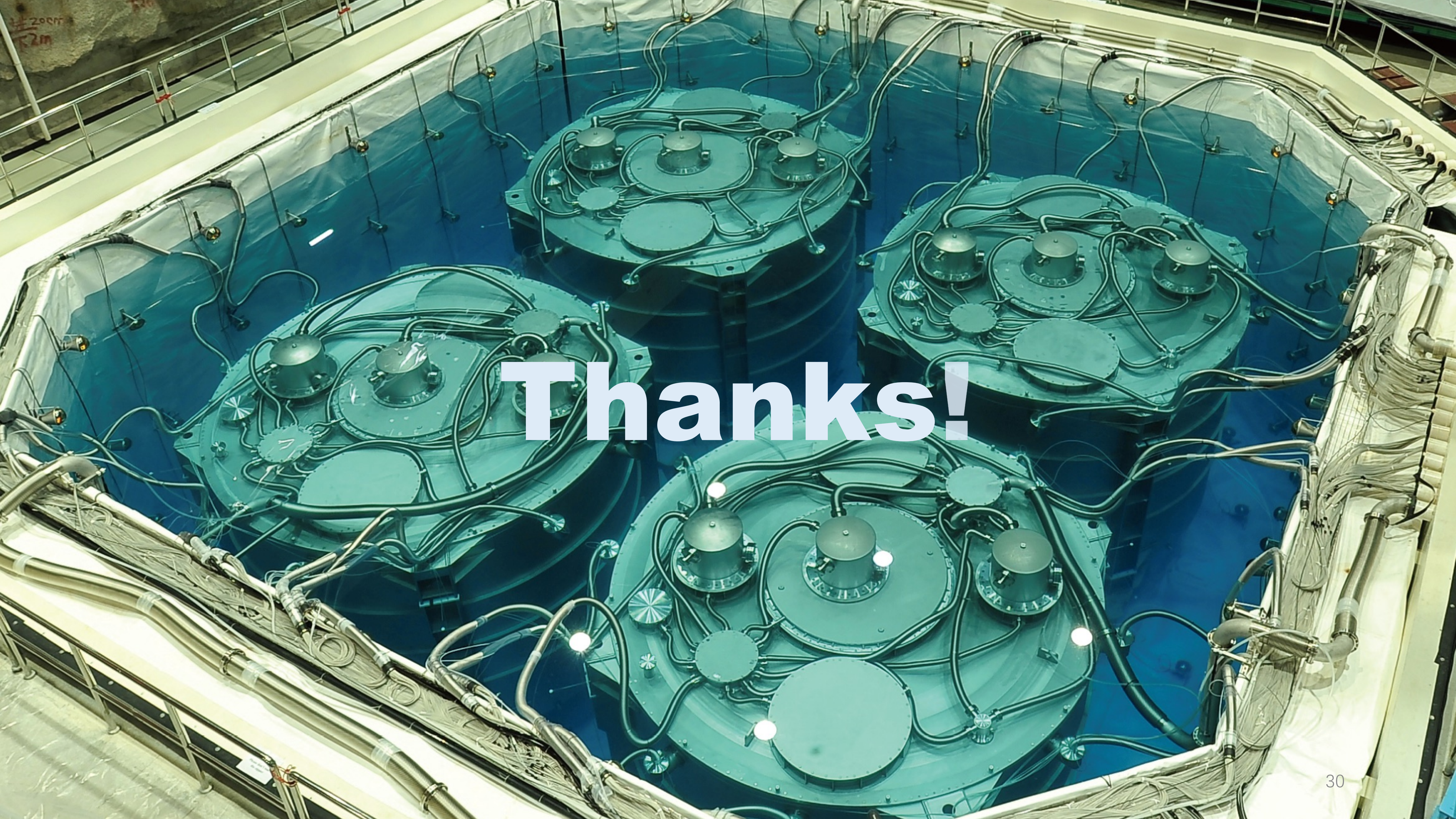
- The Daya Bay Experiment finished data taking and acquired the largest sample of reactor antineutrino to date:
  - 5.5 million events with neutron captured on Gd.

- The updated evolution study shows:
  - The measured average flux , as well as their evolution, are inconsistent with the predictions of the Huber-Mueller model.
  - The SM2018 model agrees with the average flux and its evolution but fails to describe the energy spectrum.

- First extraction of the ^{235}U spectrum from commercial reactors and first measurement of ^{239}Pu spectrum.
  - Both ^{235}U and ^{239}Pu has similar excess in 4~6 MeV range, with 4σ and 1.2σ deviations, respectively.
  - ^{235}U is more likely to be responsible for "reactor antineutrino anomaly" .

- First combination between Daya Bay (LEU) and PROSPECT (HEU) to reduce the ^{235}U spectrum uncertainty.

- The unfolded isotope antineutrino spectra provide a data-based prediction for reactor antineutrino experiments.



Thanks!

Backup slides

Improvements

- Statistics of nGd data:

Year	Calendar days	EH1	EH2	EH3	Total IBD's
2018 (PRL **121**, 241805)	1958	1,794,417	1,673,907	495,421	3,963,745
2022 (arXiv:2211.14988)	3158	2,236,810	2,544,894	764,414	5,546,118

- Analysis:
  - Energy calibration
    - Electronics non-linearity calibrated at the channel-by-channel level
    - Improved non-uniformity correction
  - New correlated background after 2017
    - Remove additional very rare PMT flashers
    - Suppress and identify untagged muon events
  - Correlated background
    - New approach for determining the $^{9}Li/^{8}He$ background