Reactor Antineutrino Flux and Spectrum Measurement at Daya Bay

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On behalf of the Daya Bay Collaboration

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Daya Bay Reactor Neutrino Experiment

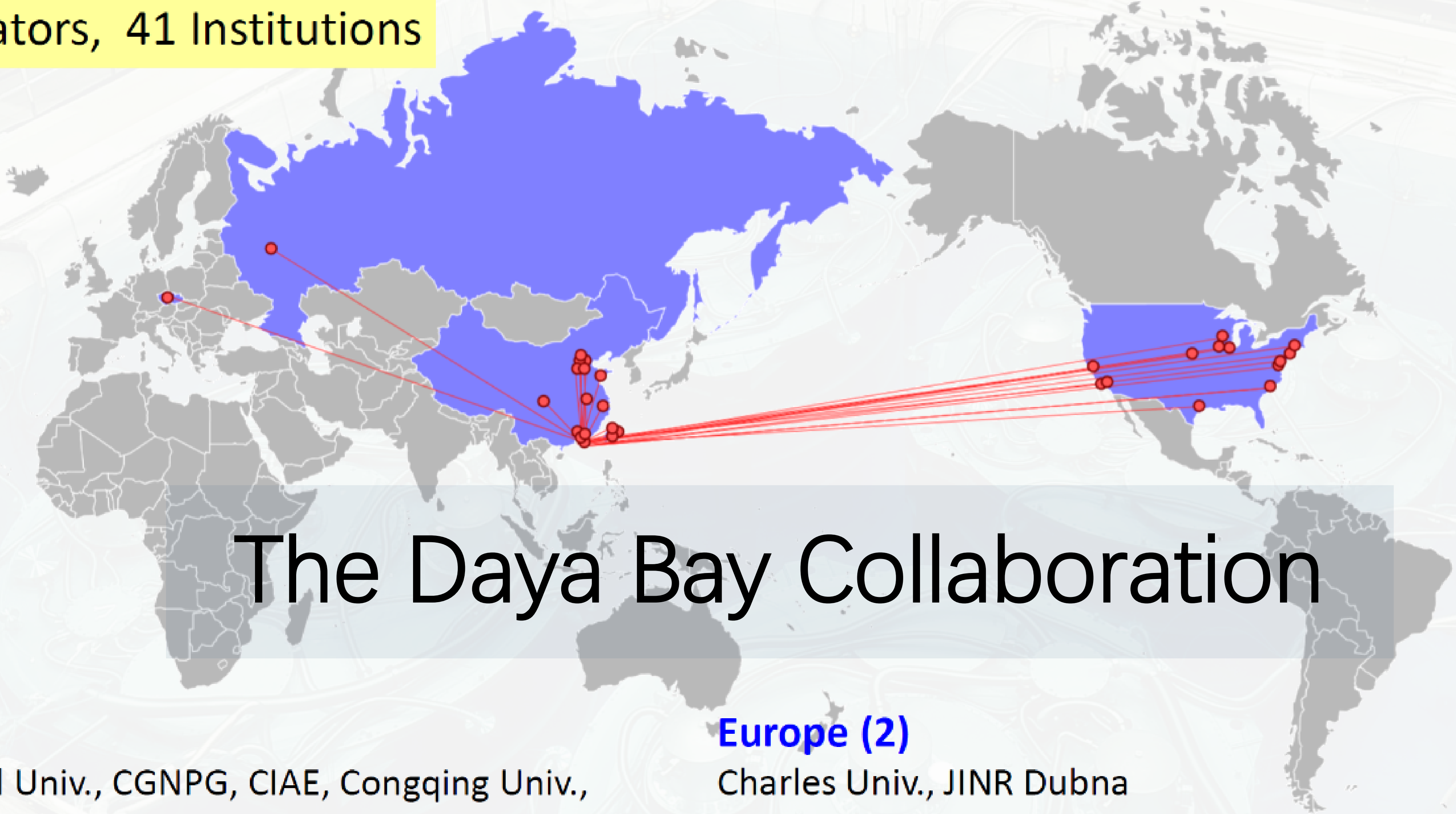
Designed to measure θ_{13}, using antineutrinos produced by reactors.

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.

191 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

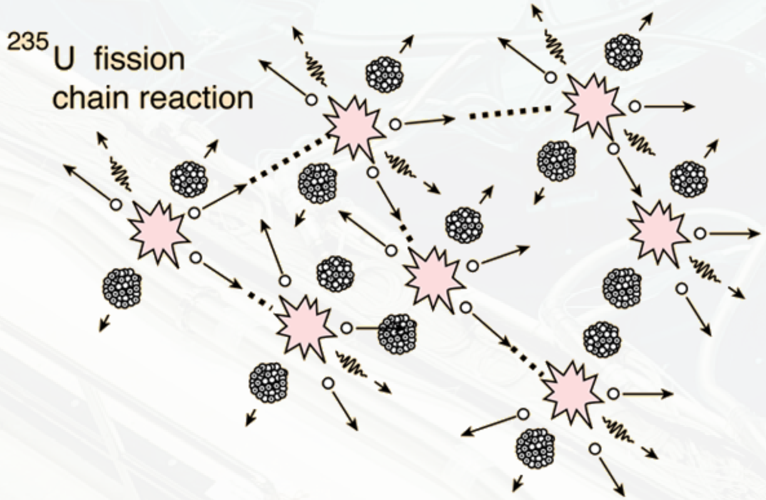
North America (15)

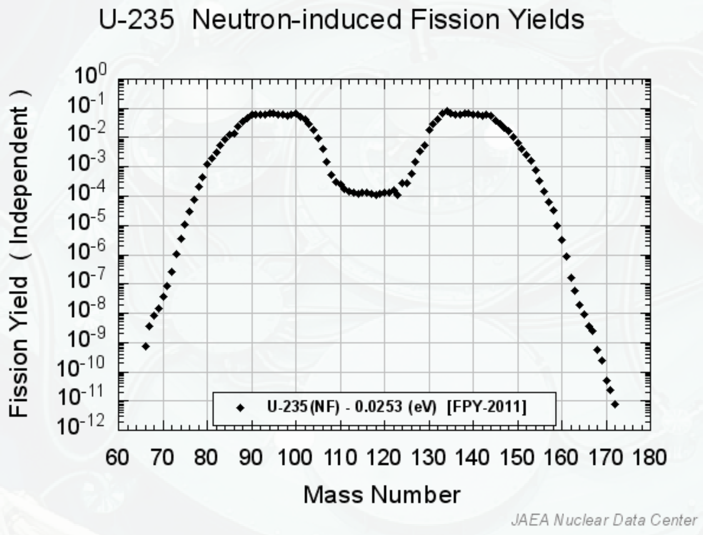
Brookhaven Natl Lab, Illinois Institute of Technology, Iowa State, Lawrence Berkeley Natl Lab, Princeton, Siena College, Temple University, UC Berkeley, Univ. of Cincinnati, Univ. of California Irvine, UIUC, Univ. of Wisconsin, Virginia Tech, William & Mary, Yale

Reactor antineutrinos at Daya Bay

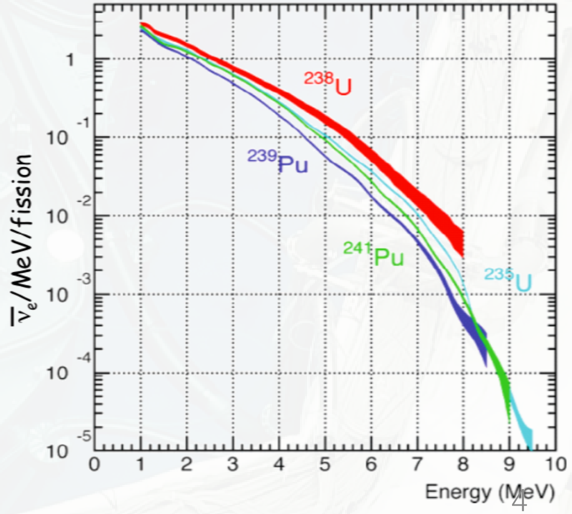
Six reactors with total thermal power of 17.4 GW, producing ~3.5×10^{21} electron antineutrinos per second

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





Huber-Mueller model

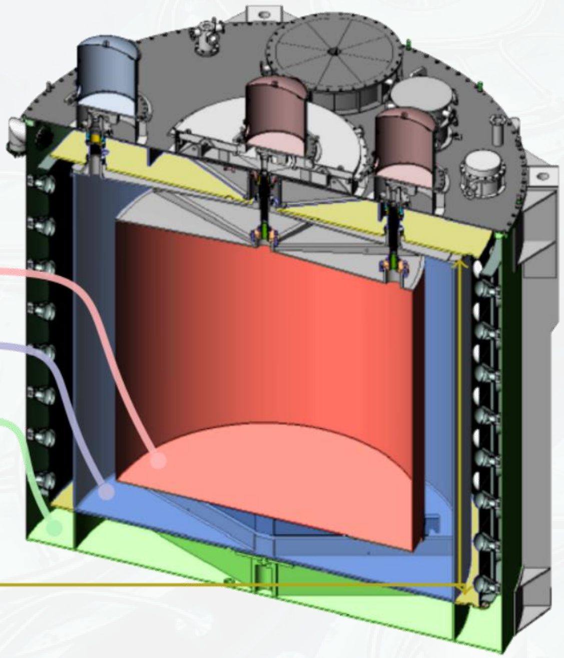


Antineutrino detection at Daya Bay

8 functionally identical detectors reduce systematic uncertainties			
	3 zone cylindrical vessels		
	Liquid	Mass	Function
Inner acrylic	Gd-doped liquid scint.	20 t	Antineutrino target
Outer acrylic	Liquid scintillator	20 t	Gamma catcher
Stainless steel	Mineral oil	40 t	Radiation shielding

192 8 inch PMTs in each detector

Top and bottom reflectors increase light yield and flatten detector response



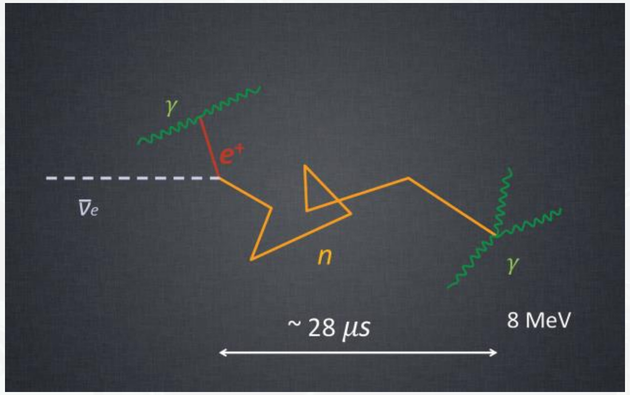
Inverse Beta Decay (IBD)

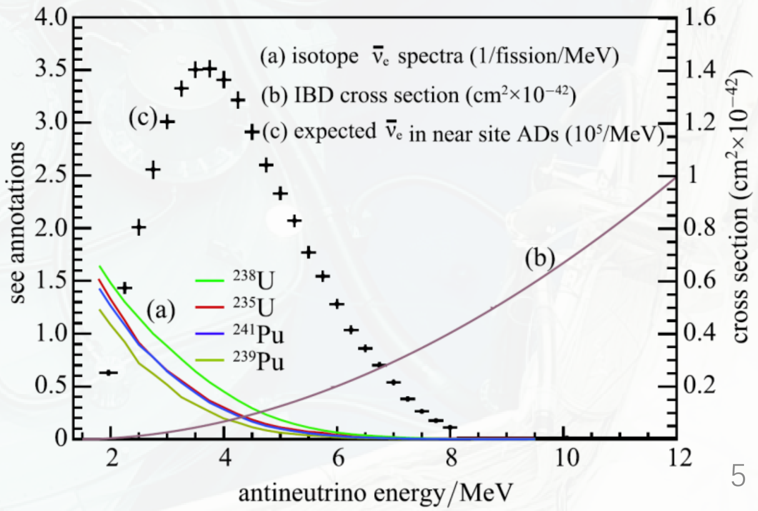
$$\bar{\nu}_e + p \to e^+ + n \quad (prompt)$$

$$\hookrightarrow +p \to D + \gamma \quad (2.2\ MeV delayed)$$

$$\hookrightarrow +Gd \to Gd^*$$

$$\hookrightarrow Gd + \gamma' s\ (8\ MeV delayed)$$





Combined detection efficiency:
80.2%± 1.2%

Energy resolution: $\sigma_E/E \cong 8.5\%/\sqrt{E[MeV]}$

Reactor $\bar{\nu}_e$ flux and spectrum measurements at Daya Bay

paper	reference	data taking time (days)	IBD events (million)	
			Near Sites	Far Site
Measurement of the Reactor Antineutrino **Flux and Spectrum** at Daya Bay	Phys. Rev. Lett. **116**, 061801 (2016)	217	0.30	0.04
Improved measurement of the reactor antineutrino **flux and spectrum** at Daya Bay	Chinese Physics C **41**, 013002 (2017)	621	1.09	0.15
Evolution of the Reactor Antineutrino **Flux and Spectrum** at Daya Bay	Phys. Rev. Lett. **118**, 251801 (2017)	1230	2.24	0.31
Improved Measurement of the Reactor **Antineutrino Flux** at Daya Bay	Phys. Rev. D **100**, 052004 (2019)	1230	2.24	0.31
Extraction of the **^{235}U and ^{239}Pu** Antineutrino **Spectra** at Daya Bay	Phys. Rev. Lett. **123**, 111801 (2019)	1958	3.47	0.38

Recent systematic uncertainty improvements

- Improved energy scale uncertainty to ~0.5% (was 1.0% until 2018)

  Nuclear Inst. and Methods in Physics Research, A **940** (2019) 230–242

  Phys.Rev.Lett. **121** (2018) 24, 241805

- Reduced $^{9}Li/^{8}He$ background uncertainty from 45% to 30%

  Phys.Rev.Lett. **121** (2018) 24, 241805

- Reduced spent nuclear fuel(SNF) uncertainty from 100% to 30%

  Phys.Rev.Lett. **121** (2018) 24, 241805

- Improved neutron detection efficiency uncertainty from 1.69% to 0.74 %

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

  Phys.Rev.Lett. **121** (2018) 24, 241805

- Improved neutron detection efficiency uncertainty from 1.69% to 0.74 %

Comprehensive detector calibration and model study

Calibrations:

- 3 calibration axes (Inside and outside Gd-LS region)
- 2 sources (Am-C and Am-Be)

Total 59 source-calibration points

Models:

- 3 neutron scatter models: free gas, water, and polyethylene
- 4 n-Gd capture gamma models: Geant4 native, Geant4 Phot. Eva., Nuclear Data Sheets, Caltech

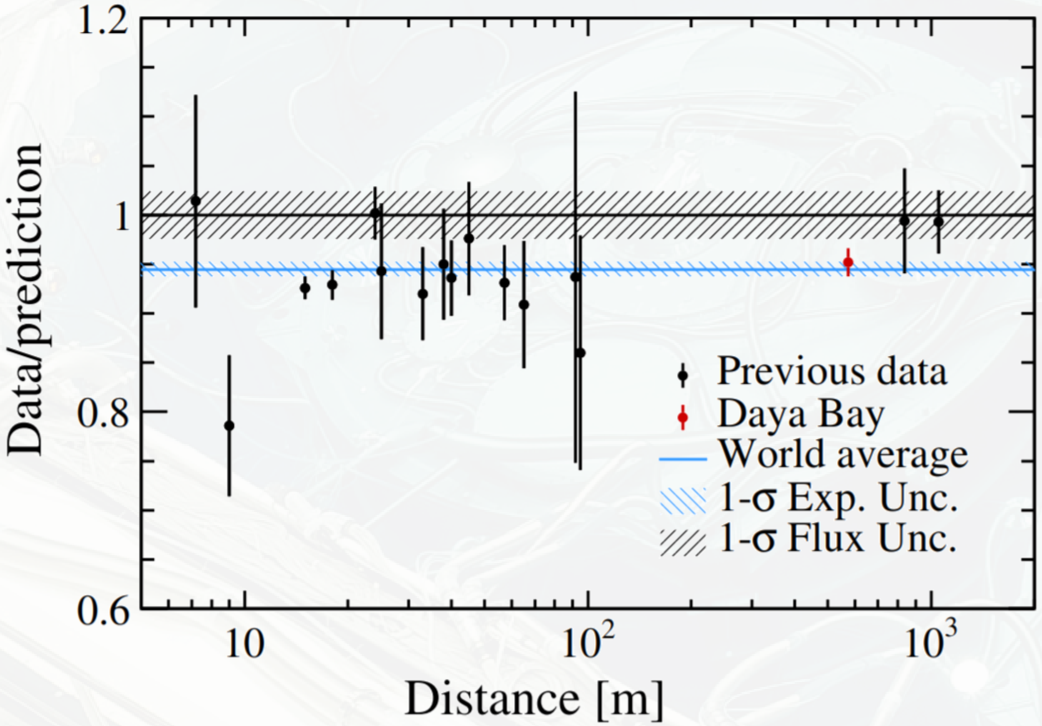
Total 20 simulated model combinations

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

	Previous		This work	
Source	Value	Rel err	Value	Rel err
Statistic	···	0.1%	···	0.1%
Oscillation	···	0.1%	···	0.1%
Target proton	···	0.92%	···	0.92%
Reactor				
Power	···	0.5%	···	0.5%
energy/fission	···	0.2%	···	0.2%
IBD cross section	···	0.12%	···	0.12%
Fission fraction	···	0.6%	···	0.6%
Spent fuel	···	0.3%	···	0.3%
Nonequilibrium	···	0.2%	···	0.2%
$\varepsilon_{\mathrm{IBD}}$				
ε_n	81.83%	1.69%	81.48%	0.74%
$\varepsilon_{\mathrm{other}}$	98.49%	0.16%	98.49%	0.16%
Total	···	2.1%	···	1.5%

Reactor antineutrino flux measurements

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



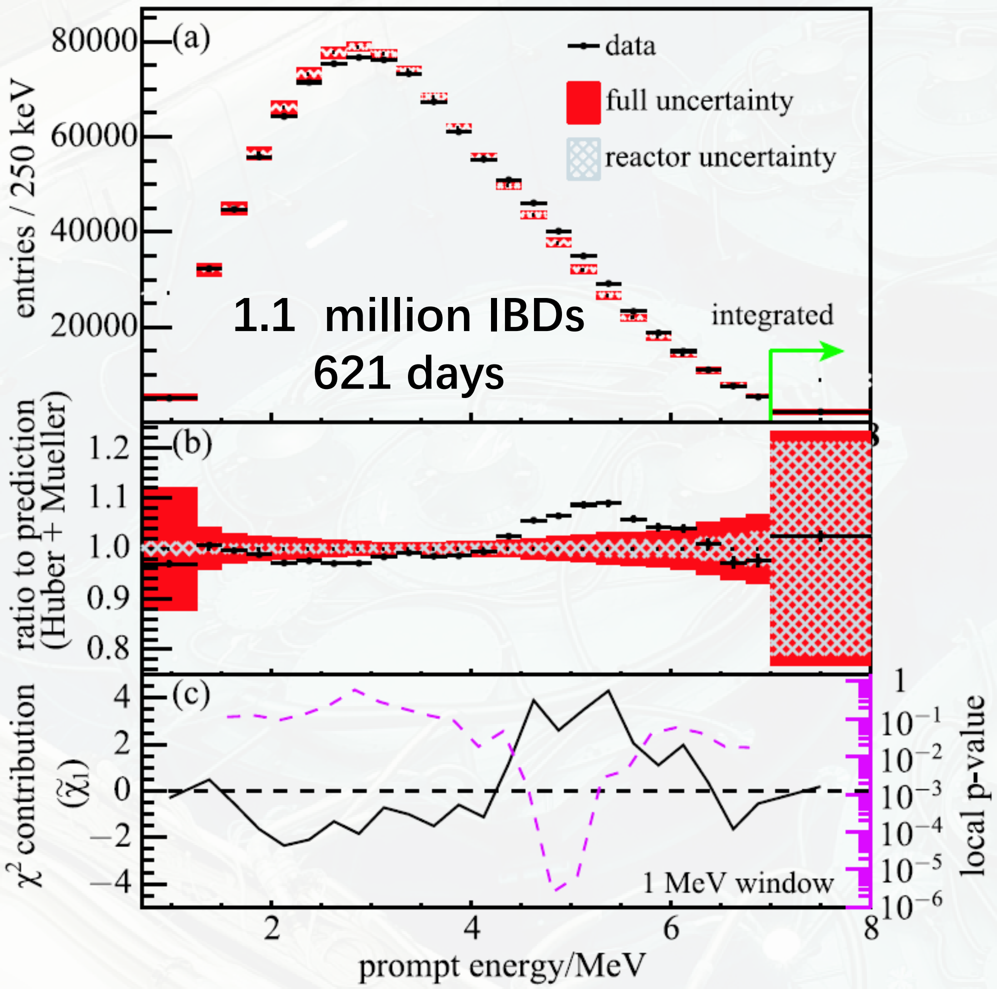
Daya Bay measurement to model (Huber-Mueller)

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

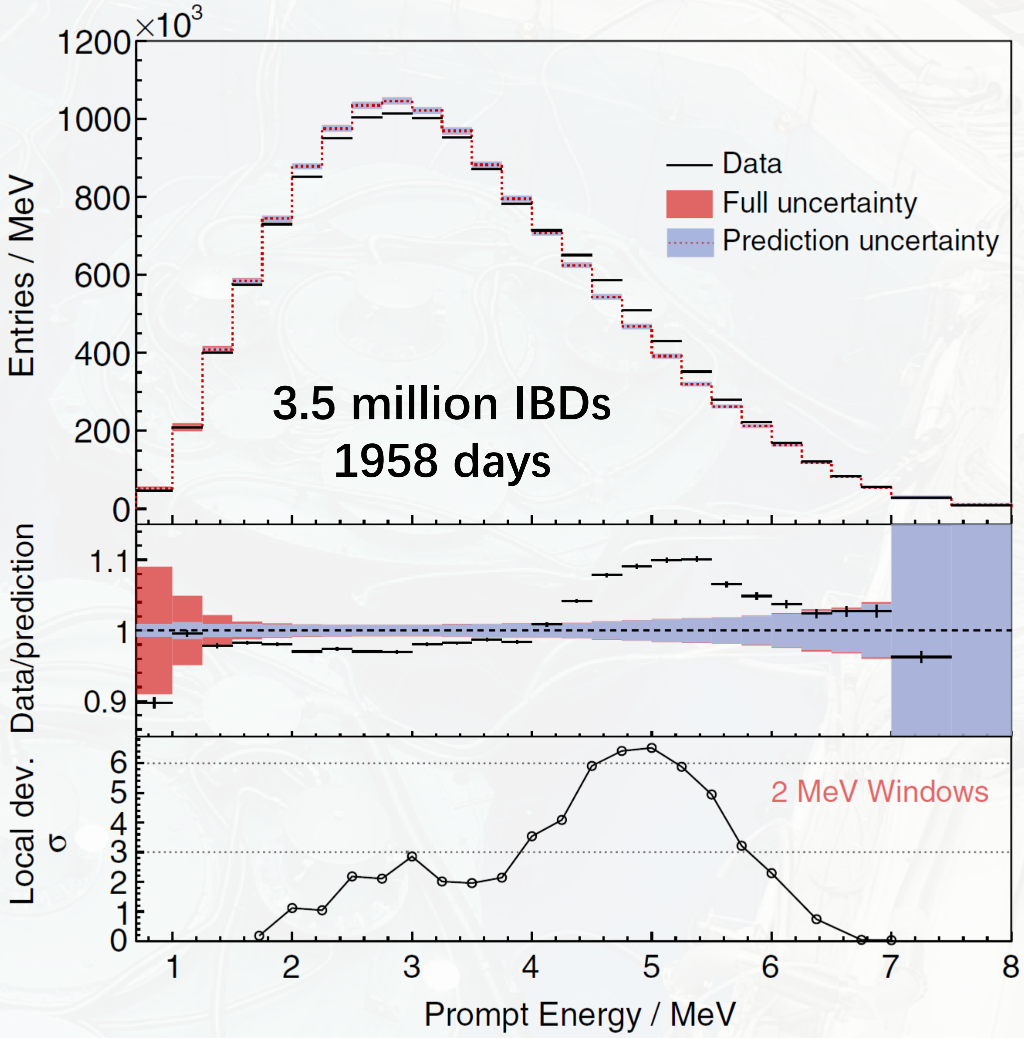
This work: 1230 days analysis :
data/prediction = 0.952±**0.014**(exp.)

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

Reactor antineutrino spectrum measurements



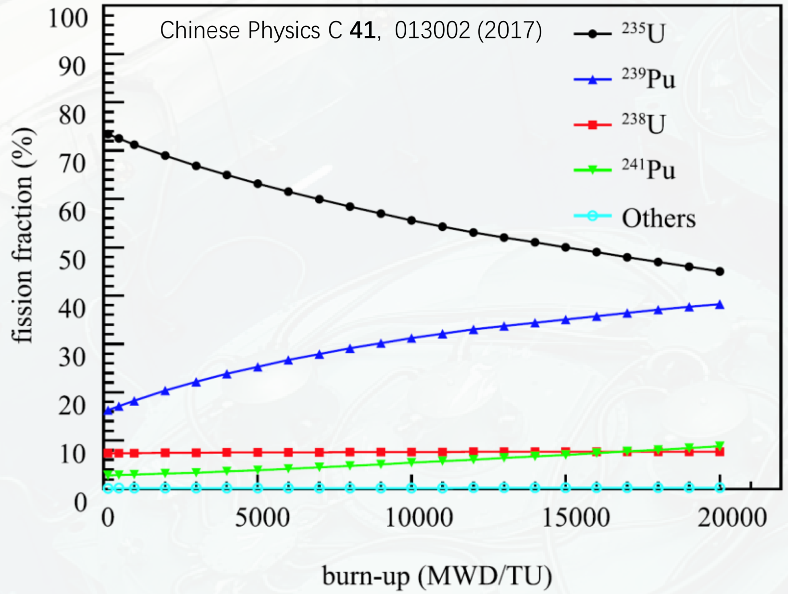
Local deviation ~ 4σ



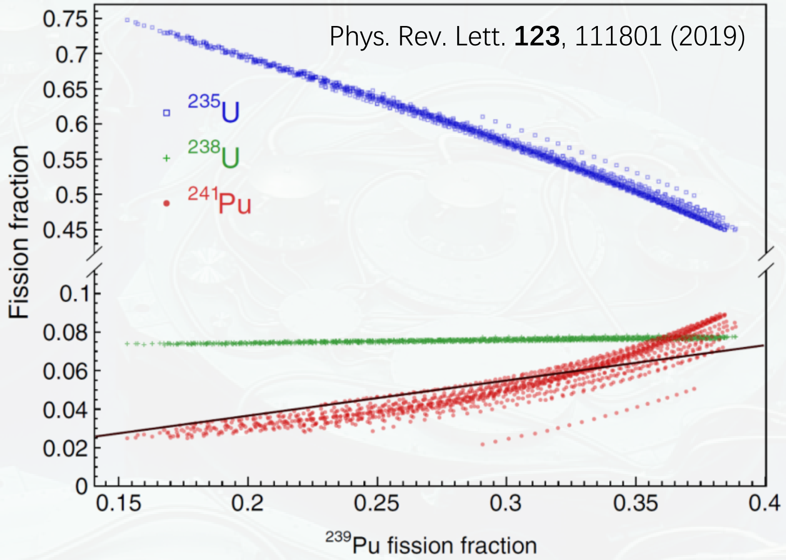
Local deviation ~ 6σ

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

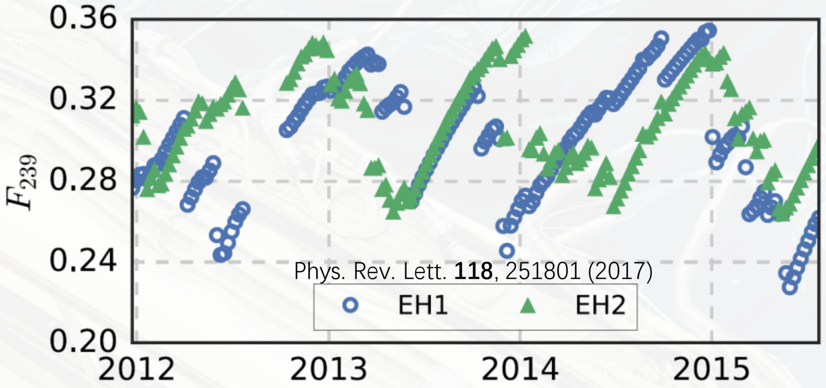
Fission fraction evolution of Daya Bay reactors



Fission fraction in a typical refueling cycle



Stacking all refueling cycles



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

Effective fission fraction:
Fission fraction 'observed' by detectors:

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

Extraction of ^{235}U and ^{239}Pu Spectra

Phys. Rev. Lett. **123**, 111801 (2019), 1958 days

- 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

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

measured spectra of the 20 groups

constraint on nuisance parameters

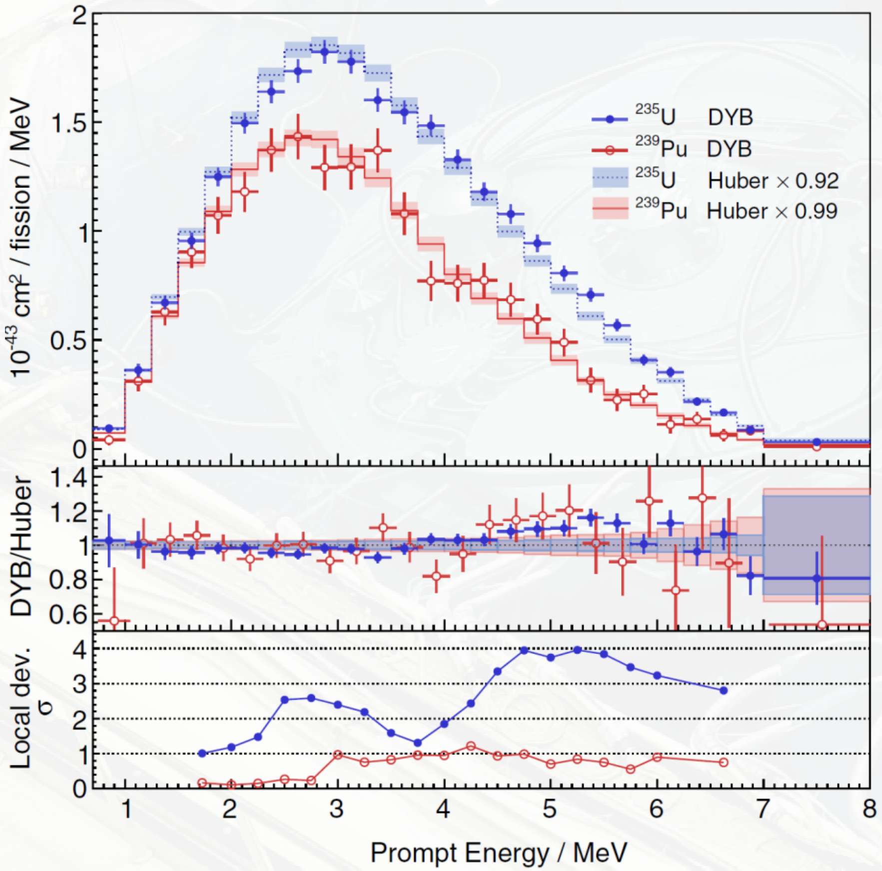
- Not sensitive to the ^{238}U and ^{241}Pu contributions, using the Huber-Mueller model as their priors, but assign >10% uncertainties both in rate and shape

- Time-dependent contributions from non-equilibrium, SNF, nonlinear nuclides, and backgrounds are considered

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

Extracted ^{235}U and ^{239}Pu spectra

Phys. Rev. Lett. **123**, 111801 (2019), 1958 days



- First extraction of the ^{235}U and ^{239}Pu spectra of commercial reactors
- In the 4~6 MeV energy range， the ^{235}U and ^{239}Pu spectra 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"

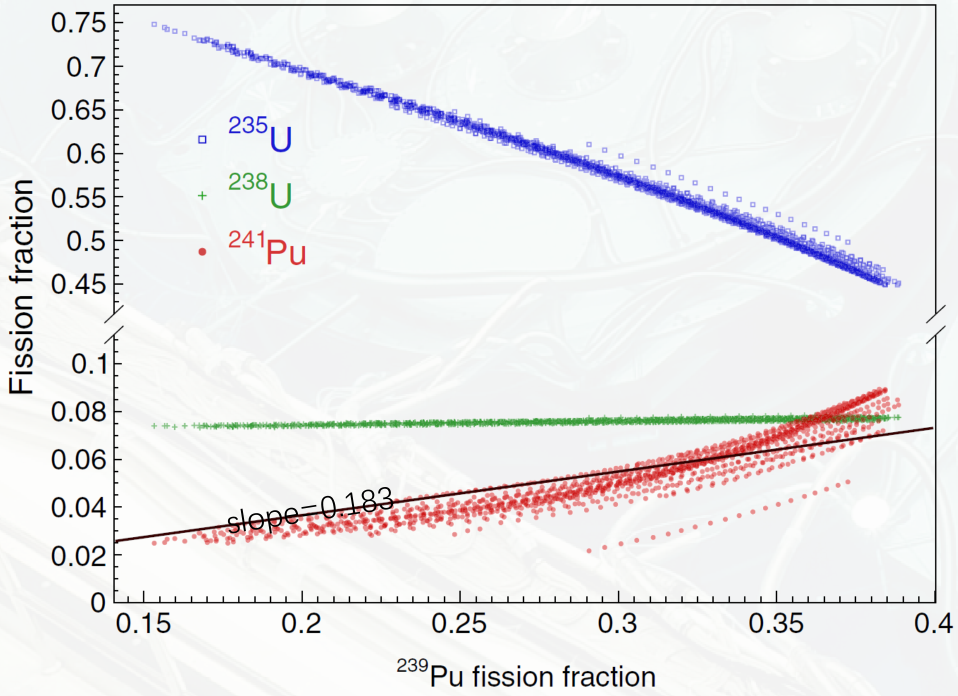
Extracted ^{235}U and Pu-Combo Spectra

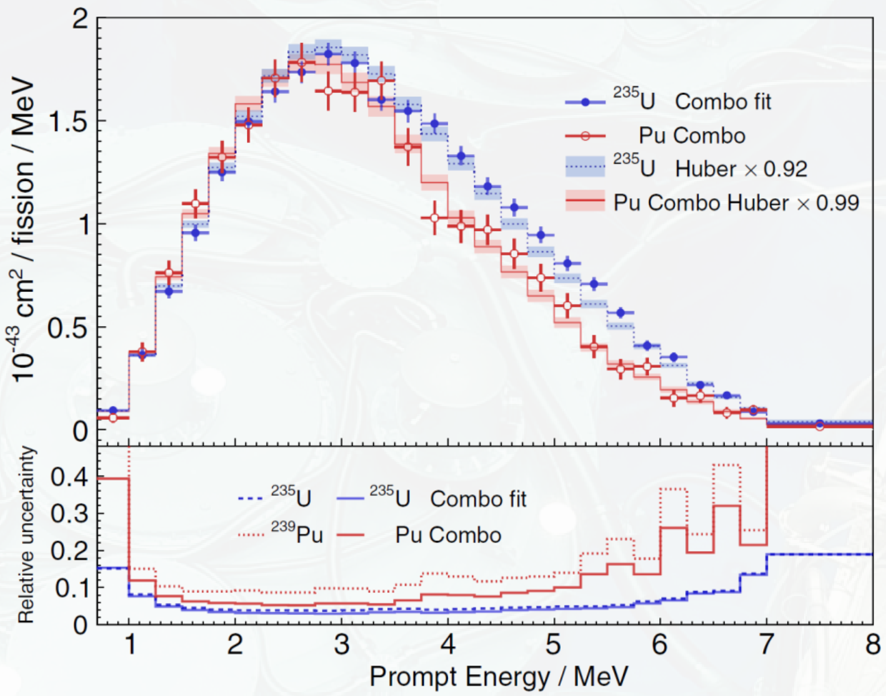
Phys. Rev. Lett. **123**, 111801 (2019), 1958 days

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

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

- 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

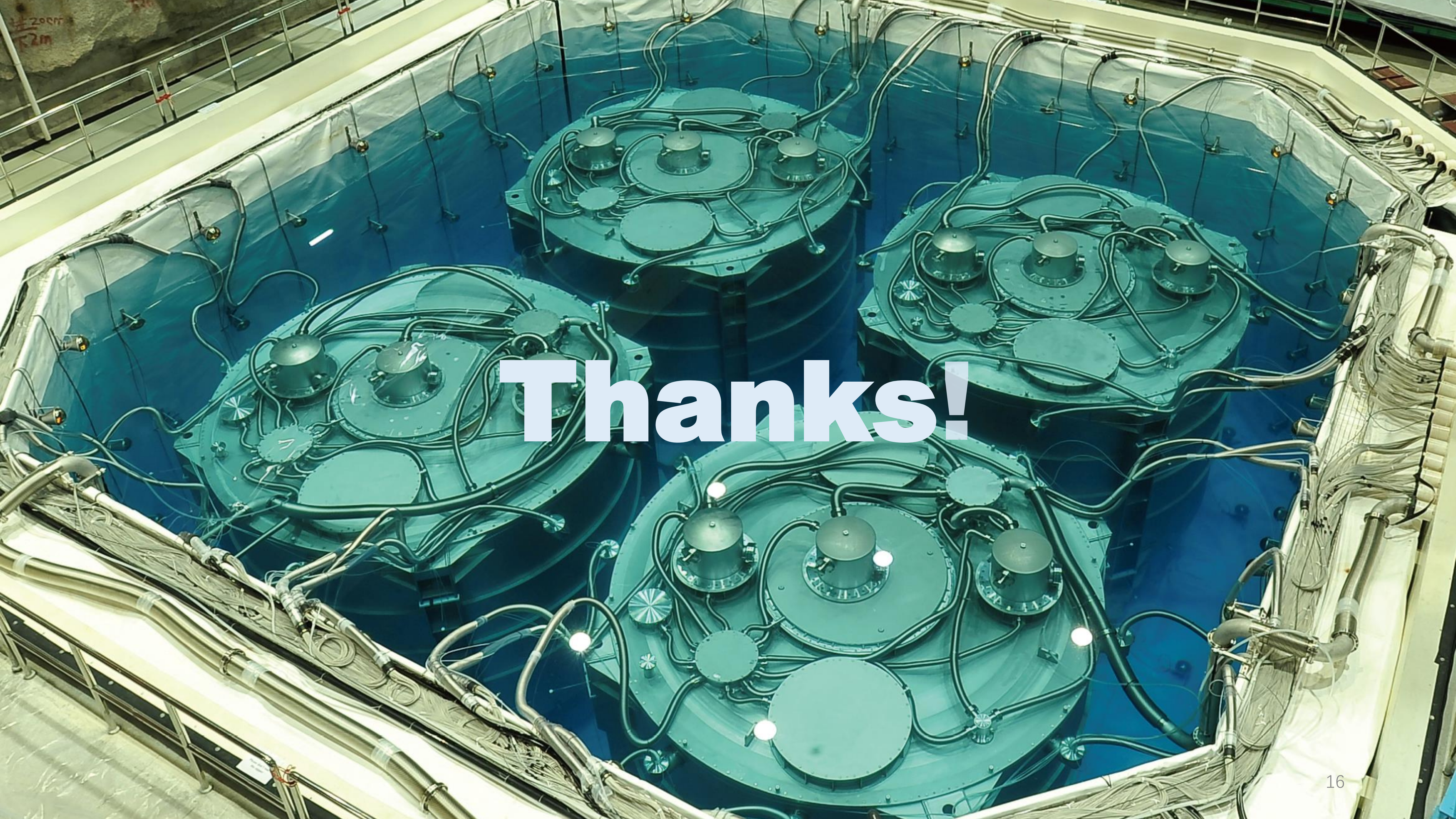
Summary

- Recent developments:
  - Reduced particular systematic uncertainties
  - Acquired>50% more statistics than the previous analysis

- Improved measurement of reactor $\bar{\nu}_e$ flux agrees with other experiments:
  - Data/prediction=0.952±0.014(exp.) ±0.023(model)

- Improved measurement of reactor $\bar{\nu}_e$ spectrum:
  - Spectral shape disagrees with the Huber-Mueller prediction at 5.3σ
  - In the 4~6 MeV energy range the local deviation is ~ 6.3σ

- First extraction of the ^{235}U and ^{239}Pu spectra of commercial reactors
  - Both ^{235}U and ^{239}Pu has similar excess in 4~6 MeV range, with 4σ and 1.2σ deviations
  - ^{235}U is more likely to be responsible for "reactor $\bar{\nu}_e$ anomaly"
  - Extracted spectra can be used as reference spectra for other experiments



Thanks!

backup slides

Reactor Antineutrino Spectrum Prediction

index: ***i*** for isotope, ***r*** for reactor, ***d*** for detector

Reactor spectrum prediction:

thermal power

isotope antineutrino spectrum(Huber-Mueller model)

$$\frac{\phi_r(E_\nu,t)}{dE_\nu dt} = \frac{W_r(t)}{\sum_i f_{ir}(t)\,e_i}\sum_i f_{ir}(t)\,S_i(E_\nu)\boxed{c_i^{ne}(E_\nu,t) + S_{SNF}(E_\nu,t) + S_{NL}(E_\nu,t)}$$

fission fraction

energy release per fission

corrections of non-equilibrium effect, spent nuclear fuel, and nonlinear nuclides

Detector spectrum prediction:

neutrino energy prompt energy

$$S_d(E_\nu,t) = \sum_r \frac{1}{4\pi L_{rd}^2}\frac{\phi_r(E_\nu,t)}{dE_\nu dt}\cdot P_{sur}(L_{rd},E_\nu)\cdot\sigma_{IBD}(E_\nu)\cdot R(E_\nu,E_p)\cdot\epsilon\cdot N_d^p$$

detector efficiency

baseline survival probability IBD cross section detector response proton numbers

Effective fission fraction

index: ***i*** for isotope, ***j*** for group, ***t*** for time, ***r*** for reactor, ***d*** for detector

Define **effective fission number** for isotope ***i*** in group ***j*** :

Thermal power   Fission fraction   Detector efficiency

$$F_{ij} \equiv \sum_{dt\in j} \sum_{r} \frac{1}{4\pi L_{rd}^2} \frac{W_{th}^{rt}}{\sum_i e_i f_{irt}} f_{irt} \cdot N_p^d \epsilon_d$$

Baseline   Energy release per fission   Proton number

Define **effective fission fraction** for isotope ***i*** in group ***j*** :

$$f_{ij}^{eff} \equiv \frac{F_{ij}}{\sum_i F_{ij}}$$