Reactor Antineutrino Flux and Spectrum Measurement at Daya Bay

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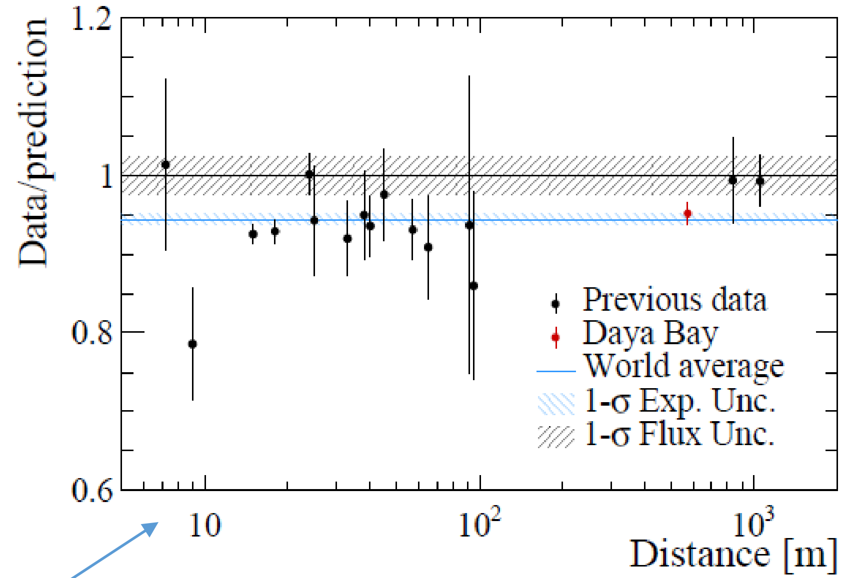
(On behalf of the Daya Bay Collaboration)

Aug. 6, 2019 at Lepton Photon 2019, Toronto

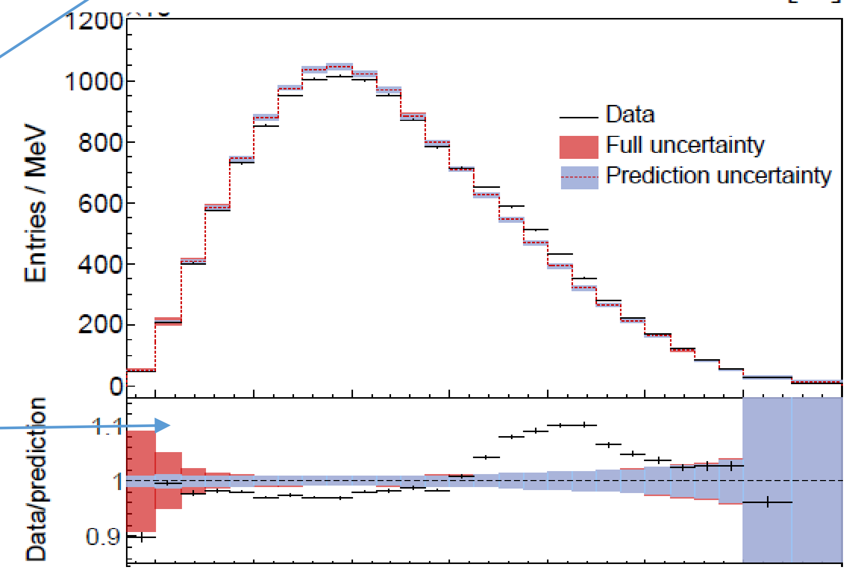
Recent Reactor Neutrino Research at Daya Bay

- Daya Bay observed θ_{13} with the best precision, and measured the effective-mass splitting Δm_{ee}^2 in $\bar{\nu}_e$ disappearance (See poster 283)



- Reactor anomaly: Detected neutrino flux is 5-6% lower than the recent Huber-Mueller prediction

- Observed $\bar{\nu}_e$ is significantly different than the H-M and other predictions



Is there any new physics? Or just complicated nuclear physics issue?

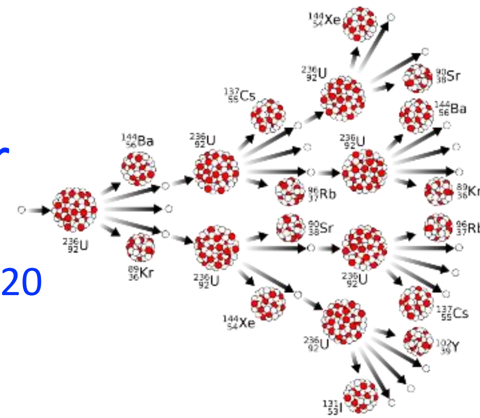
Reactor Antineutrino Flux and Spectra Measurement Roadmap in Daya Bay

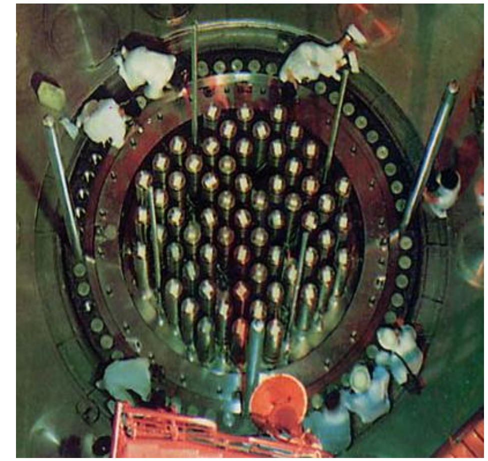
- Flux and Spectrum Measurement Using 217-day Data
  PRL 116, 061801 (2016)
- Improved Flux and Spectrum Measurement Using 621-day Data
  Chinese Physics C 41, (2017) 013002
- Flux and Spectrum Evolution Study Using 1230-day Data
  PRL 118, 251801 (2017)
- Systematic-Improved Flux Measurement Using 1230-day Data
  arXiv:1808.10836 (2018), accepted by PRD
- Measurement of Antineutrino Spectra from ^{235}U and ^{239}Pu Using 1958-day Data
  arXiv:1904.07812 (2019)

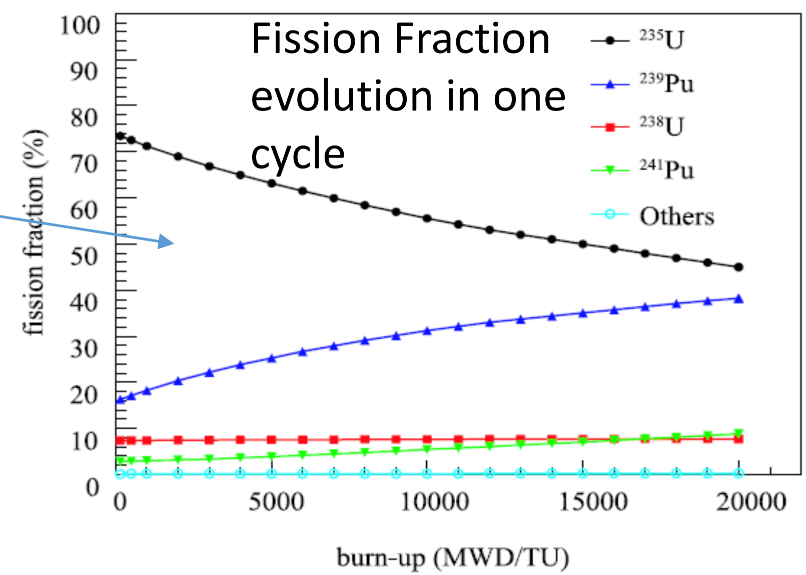
This Talk

Daya Bay Reactor Complex

- Six commercial reactors
  - Pressurized Water Reactor
  - 3.7 m height, 3 m diameter
  - Thermal power of each reactor: 6x2.9 GW_{th} (~2×10^{20} $\bar{\nu}_e$/s/GW)
  - Replace 1/3 (1/4) fuel every 18 (12) months
  - Four major fission isotopes: ^{235}U, ^{239}Pu, ^{238}U, ^{241}Pu (^{235}U, ^{239}Pu dominant)
  - Spent nuclear fuel storage
  - Status update given by power plant (Reactor simulation: APPOLO2 or DRAGON)



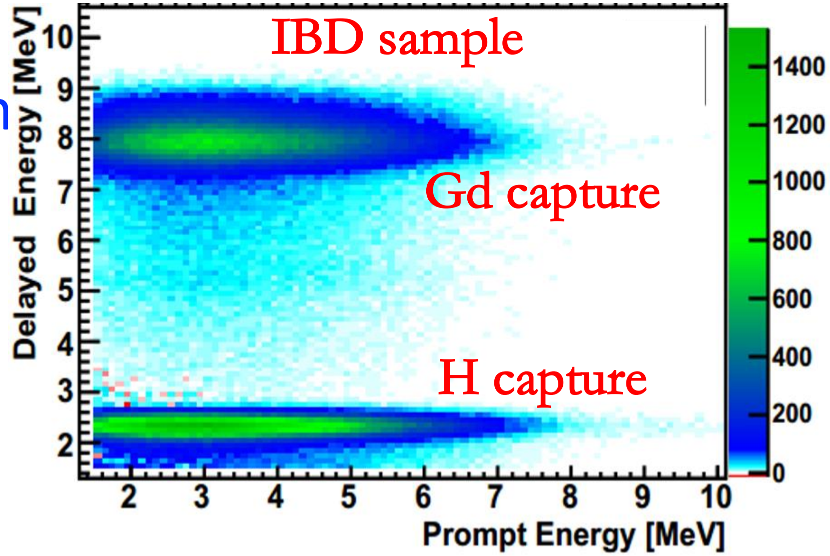




Daya Bay Electron-antineutrino Detector

- Four near detectors (AD)
  Reactor-detector distance 300 – 500 m
- Each AD contains
  20 ton Gd-LS and 22 ton LS
- Inverse Beta Decay (IBD) on free proton (hydrogen)

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



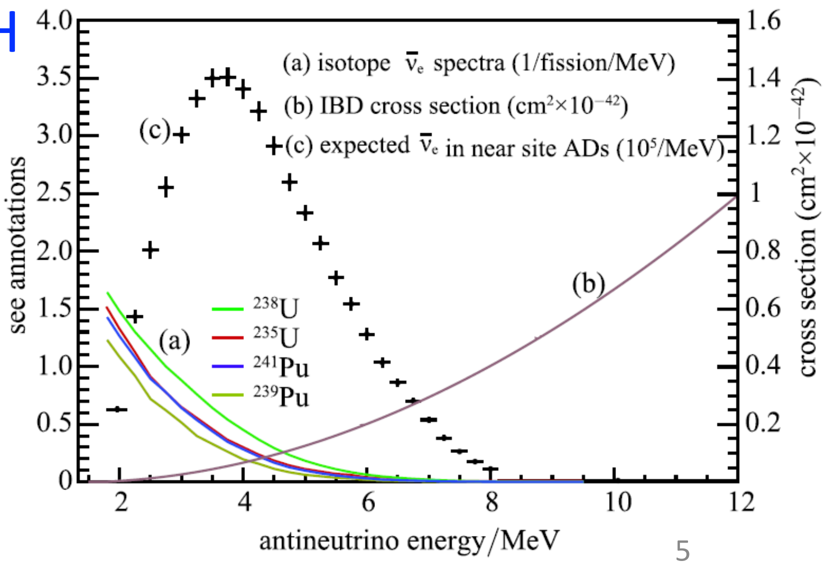
Threshold 1.8 MeV, n-capture on Gd or H

- Neutrino energy reconstruction

$$E_{\text{prompt}} = E_{e+} + E_{\gamma's}$$

$$E_{\bar{\nu}_e} = E_{\text{prompt}} + \bar{E}_n + 0.78\ \text{MeV}$$

- Non-linear energy response corrected



Reactor Antineutrino Flux Measurement and Prediction

Yield: σ_f, Number of neutrinos per fission × IBD crossseciton

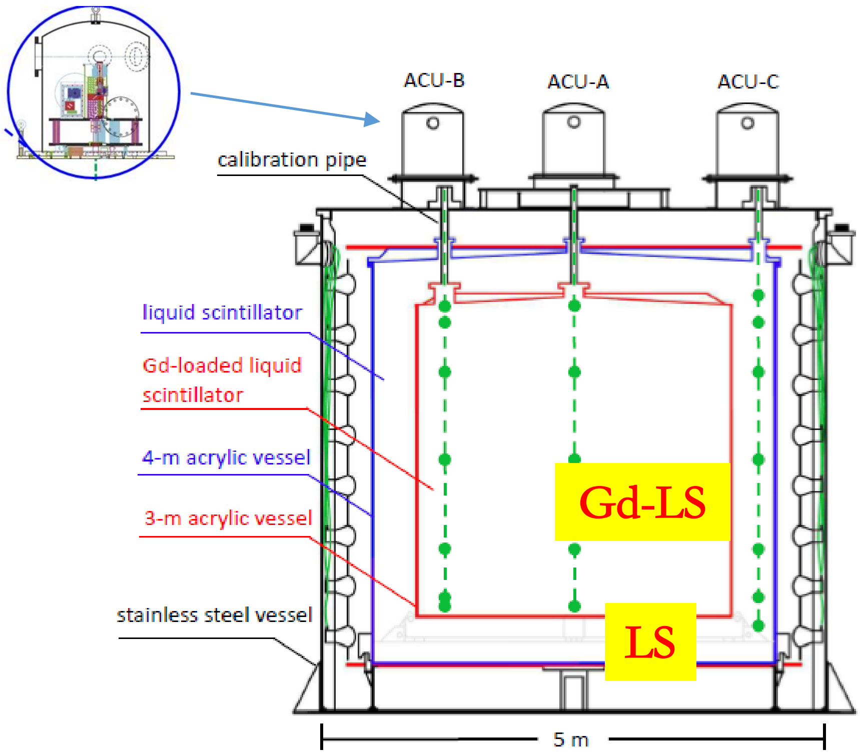
Measurement:
$$N_{\mathrm{IBD}}(1 - c^{\mathrm{SNF}}) = \sigma_f \sum_{d=1}^{4} \sum_{r=1}^{6} \frac{N_d^P \varepsilon_{\mathrm{IBD}} P_{sur}^{rd} N_r^f}{4\pi L_{rd}^2}$$

- N_{IBD}, # of detected IBDs
- c^{SNF}, spent nuclear fuel correction
- N_d^P, # of protons at detector d
- ϵ_{IBD}, IBD detection efficiency
- P_{sur}^{rd}, neutrino survival probability
- N_r^f, # of fissions of reactor r
- L_{rd}, reactor-detector distance

Prediction:
$$\sigma_f = \sum_{iso=1}^{4} f_{iso} \int (S_{iso}(E_\nu) + k_{iso}^{\mathrm{NE}}(E_\nu))\sigma_{\mathrm{IBD}}(E_\nu)\mathrm{d}E_\nu$$

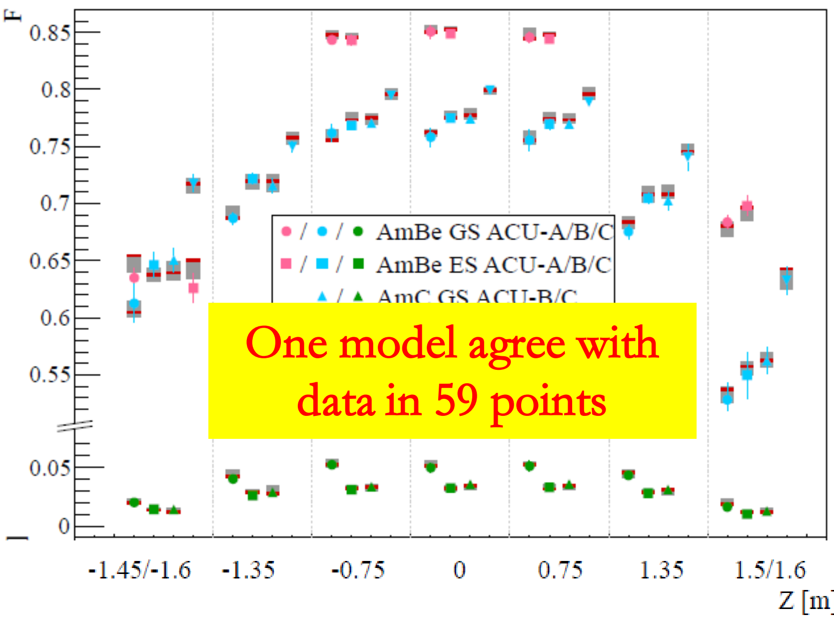
- f_{iso}, Fission fractions
- S_{iso}, Fission spectra (H-M)
- k_{iso}^{NE}, Non-equilibrium correction
- σ_{IBD}, IBD crosssection

Recent Development: Comprehensive Detector-Calibration and Model Study, Sub-percent Agreement



Proxy variables for MC-Data comparison

$$F = \frac{N([6, 12]\ \mathrm{MeV})}{N([1.5, 12]\ \mathrm{MeV})}$$



- Three calibration axes (Inside and outside Gd-LS region)
- Two sources (AmC and AmBe)
- Two kinetic energy ranges of neutrons (thermal and fast)

Total 59 source-calibration points

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

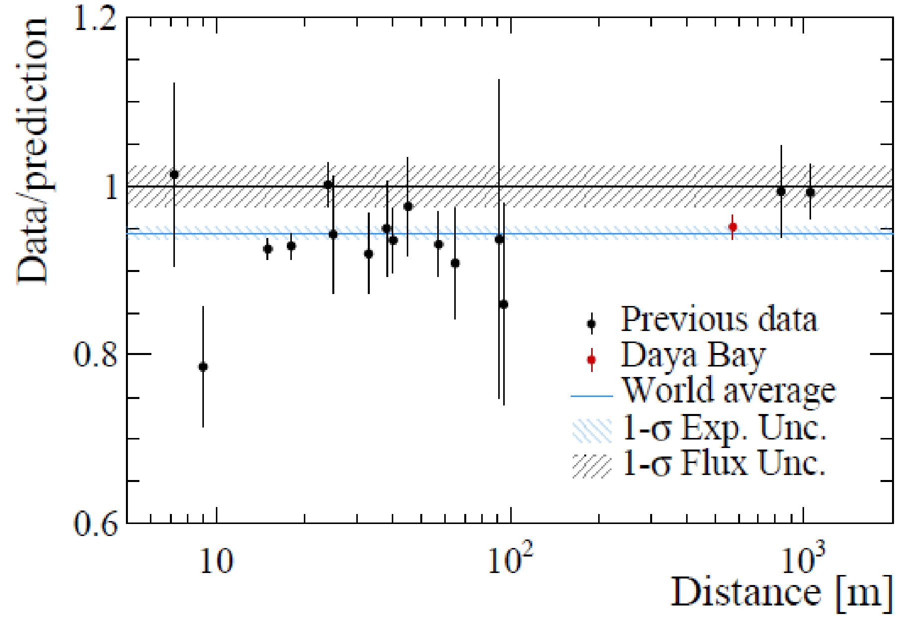
Total 20 simulated model combinations

Uncertainty Summary and Comparison to Model

source	rel. err.
statistic	0.1%
oscillation	0.1%
target proton	0.92%
reactor	
power	0.5%
energy/fission	0.2%
IBD cross section	0.12%
fission fraction	0.6%
spent fuel	0.3%
non-equilibrium	0.2%
$\varepsilon_{\rm IBD}$	
ε_n	1.69% → 0.74%
$\varepsilon_{\rm other}$	0.16%
total	2.1% → 1.5%

2.2×10^6 IBDs at near ADs

Recent improvement



Ratio to model (Huber-Mueller)

$0.946 \pm 0.020(exp)$

$0.952 \pm 0.014(exp)$ **New**

Average with other exp results

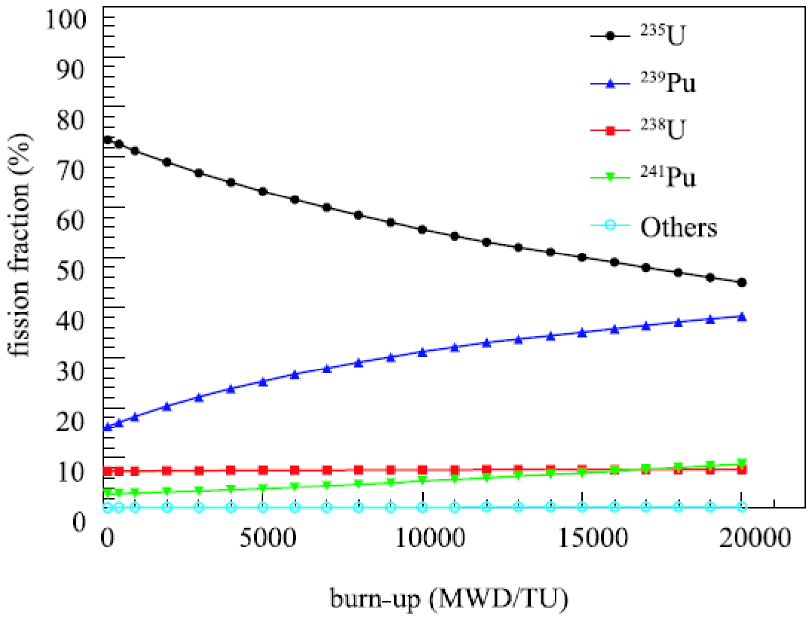
$0.945 \pm 0.007(exp) \pm 0.023(model)$

Latest yield measurement result:

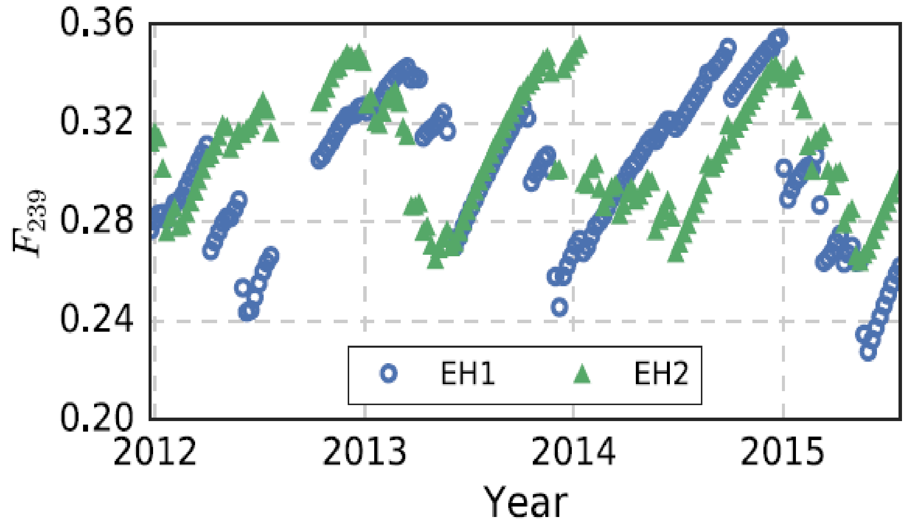
$$\sigma_f = (5.91 \pm 0.09) \times 10^{-43}\ \mathrm{cm}^2/\mathrm{fission}$$

Reactor Evolution Analysis

Fission Fraction
evolution in one cycle



Multi-asynchronous cores



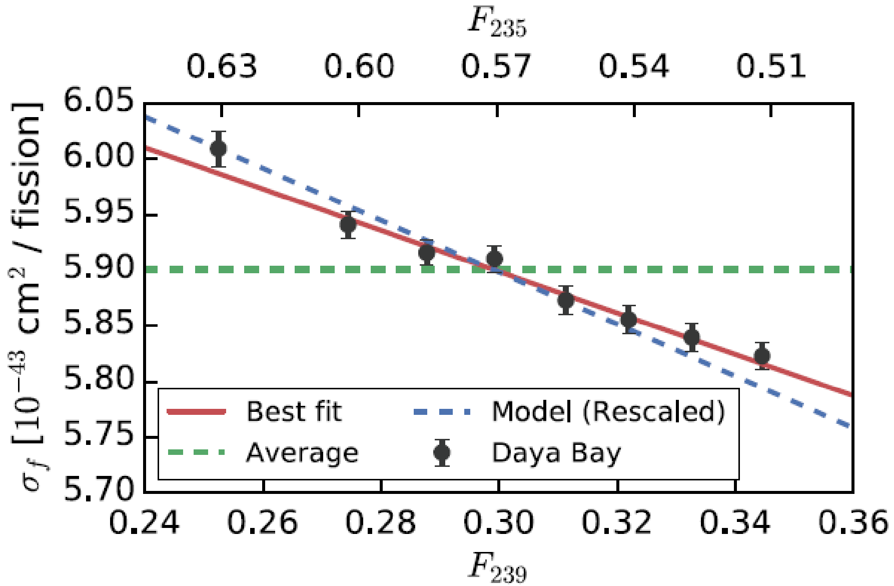
^{239}Pu fission fraction seen by EH1 and EH2 detectors

- Reactor flux and spectrum changes along with reactor burn-up
- We can study yield deficit and spectrum structure as a function of fission fraction
- The data is grouped into eight fission-fraction groups

Neutrino yield vs ^{239}Pu fission fraction

1. Yield follows reactor running
2. The prediction is scaled according to an integral deficit
3. Measure yield changing rate

$$\sigma_f(F_{239}) = \bar{\sigma}_f + \frac{d\sigma_f}{dF_{239}}(F_{239} - \bar{F}_{239})$$



4. A 3.1 σ difference in $\frac{d\sigma_f}{dF_{239}}$ is found vs model

Next:

- We have eight total yield measurements at eight fission fraction points
- The total yield is the different combinations of four fission isotopes
- Solve it after ^{238}U and ^{241}Pu constrained

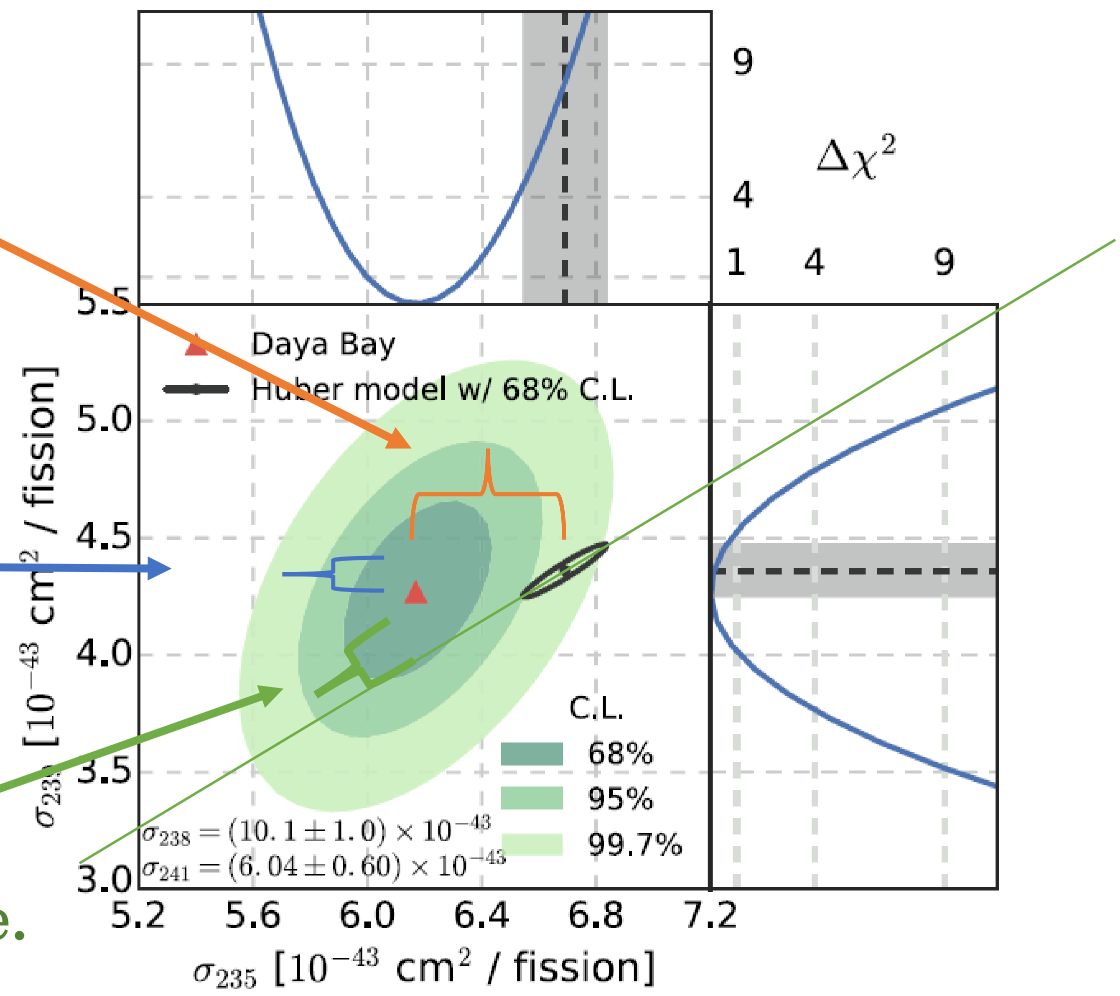
$$\sigma_f(t) = \sum_{\substack{i=235,238,\\239,241}} F_i(t)\sigma_i$$

Measured neutrino yield for ^{235}U and ^{239}Pu

Test the yield deficit is solely from ^{235}U prediction, Prob=0.68

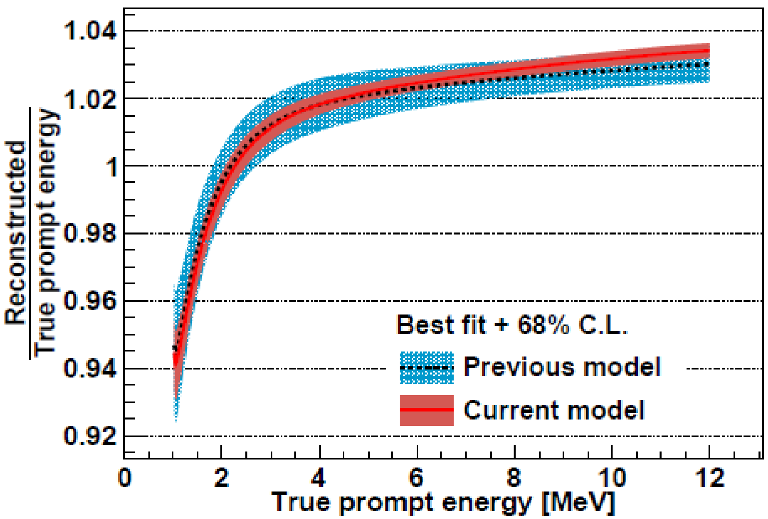
Test the deficit is solely from ^{239}Pu, Prob=0.00016

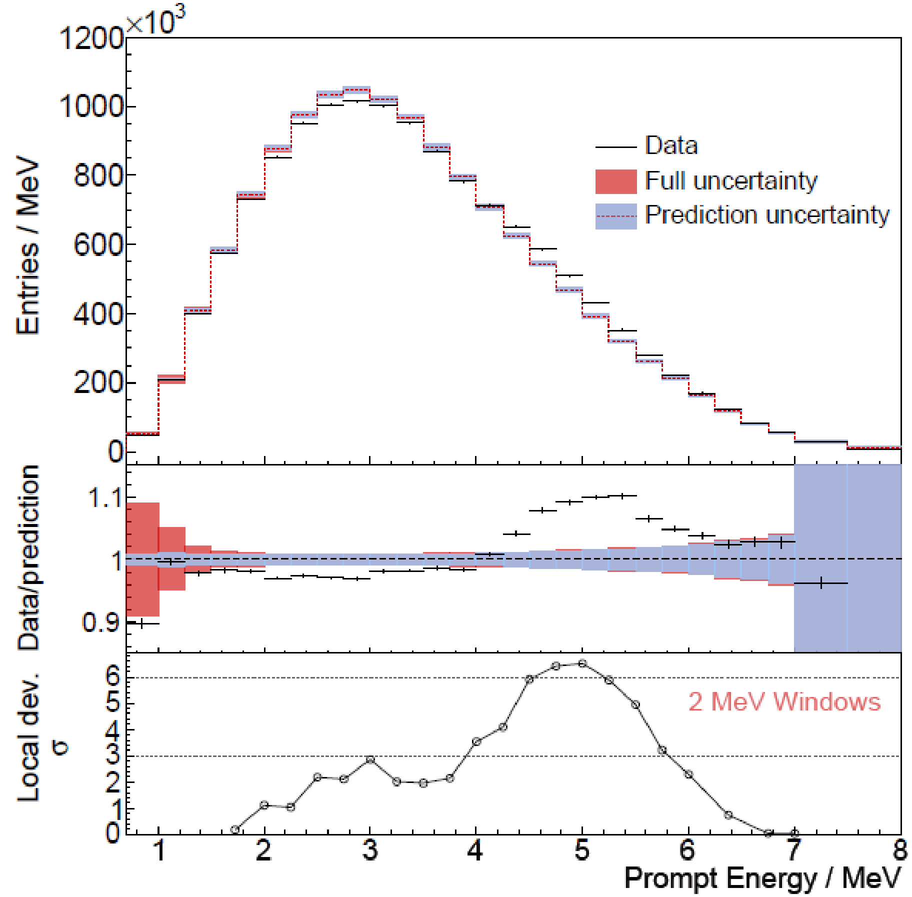
Test equal deficit from ^{235}U and ^{239}Pu, i.e. sterile neutrino, Prob=0.0049



IBD Prompt Spectrum Measurement in 1958 days

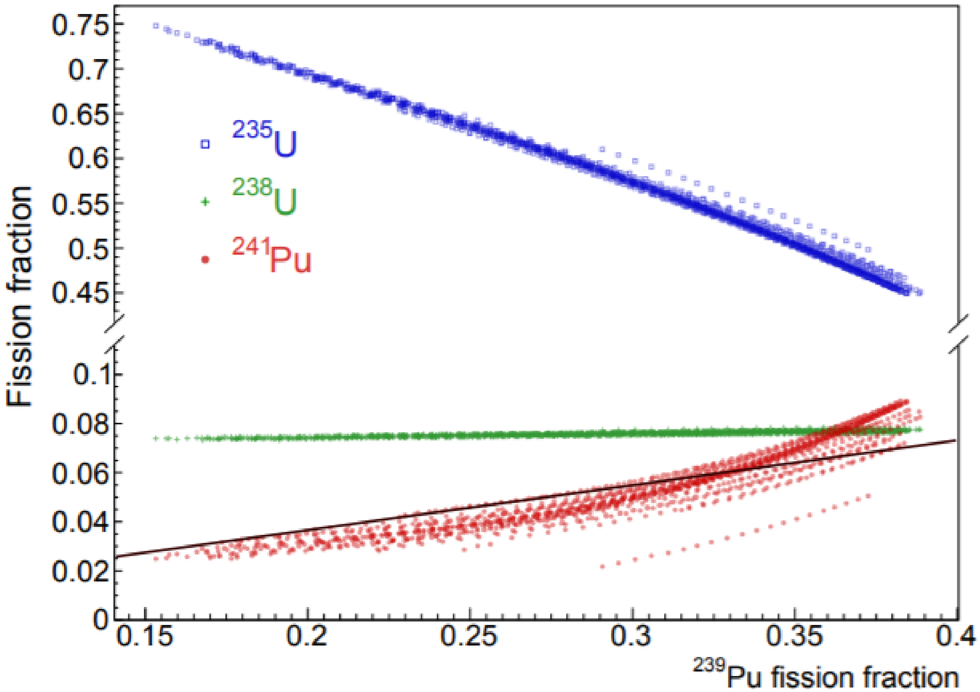
- 3.5 million IBD events
- Detector energy nonlinear response model uncertainty: 0.5%





1. The shape disagrees with the Huber-Mueller model prediction at 5.3σ
2. In the energy range of 4–6 MeV, the local discrepancy of 6.3σ

^{235}U and ^{239}Pu Spectra Decomposition



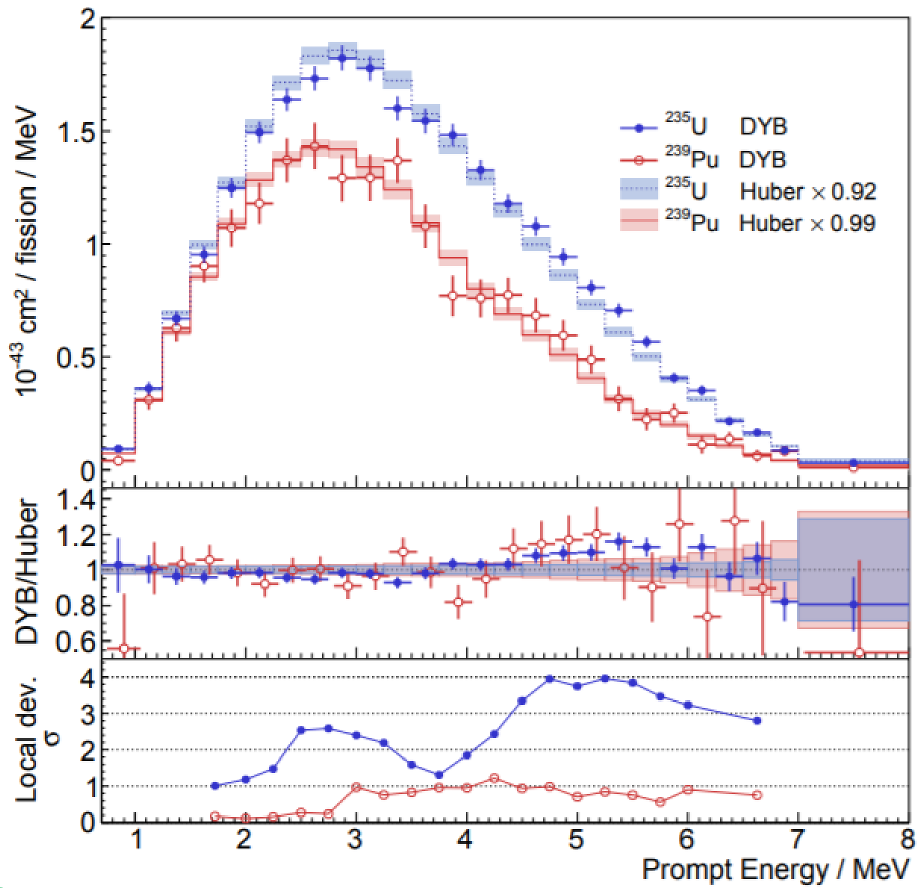
- The 3.5 M data are divided into 20 groups ordered by the ^{239}Pu effective fission fraction in each week for each AD.
- Fit the ^{235}U and ^{239}Pu spectra, as two unknown arrays (52 unknowns).
- No sensitivity to ^{238}U and ^{241}Pu and assign >10% uncertainties both on rate and shape as a prior
- Time-dependent contributions from non-equilibrium, SNF, nonlinear nuclides, and backgrounds are considered.

^{235}U and ^{239}Pu Spectra Measurement Result

- **IBD yield comparison**

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

- **Spectral comparison after normalizing the H_M model**



Similar bump excess for ^{235}U and ^{239}Pu in [4, 6] MeV
Significance of local deviations: 4σ for ^{235}U, only 1.2σ for ^{239}Pu due to larger uncertainty

Summary

- More statistics (>5 years) and better systematics (efficiency, energy response, etc.)
- Reactor antineutrino yield measurement is in tension with H-M prediction
- The yield evolution result is also in tension with H-M prediction
- First measurement of ^{235}U and ^{239}Pu antineutrino spectra

Stay tuned

Thank you for your attention. Questions and comments are welcome.