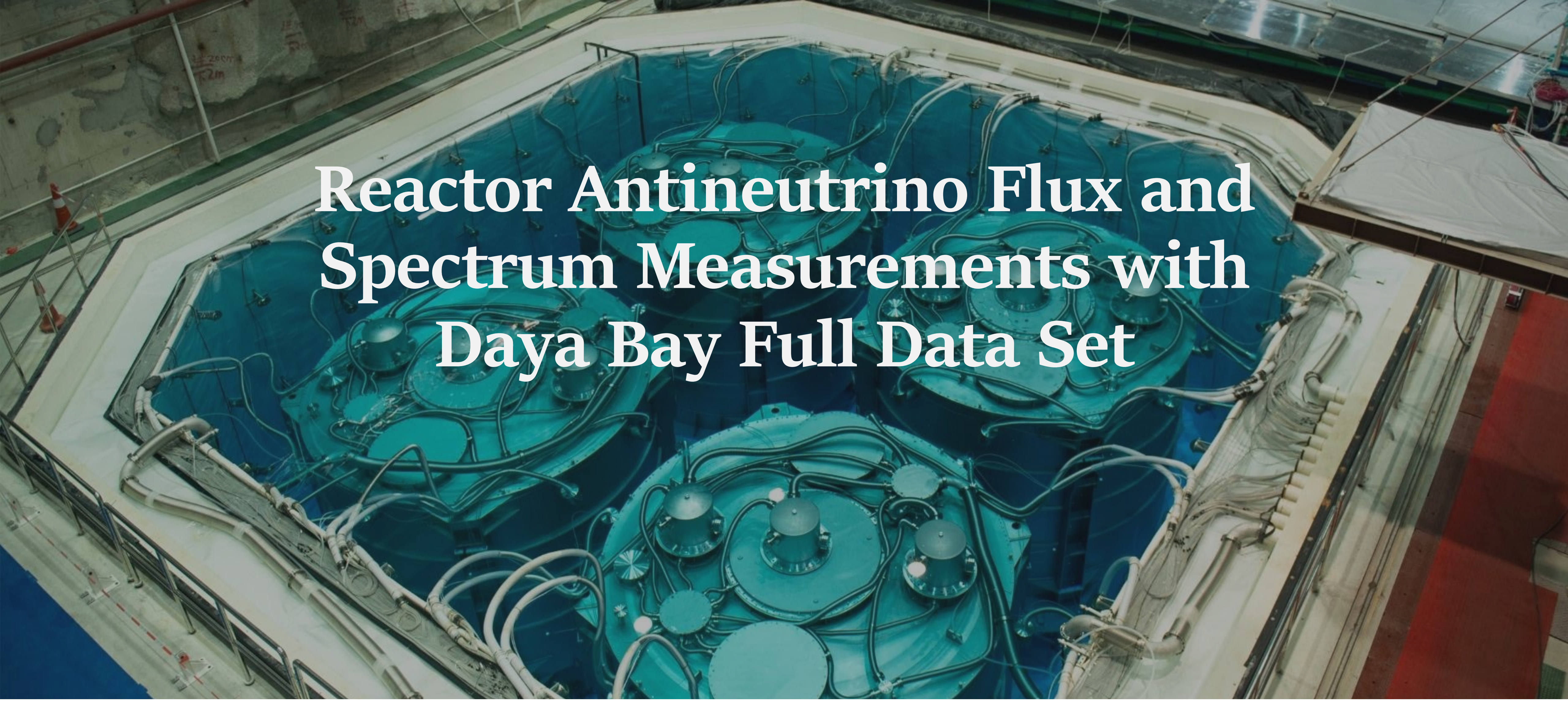

Reactor Antineutrino Flux and Spectrum Measurements with Daya Bay Full Data Set

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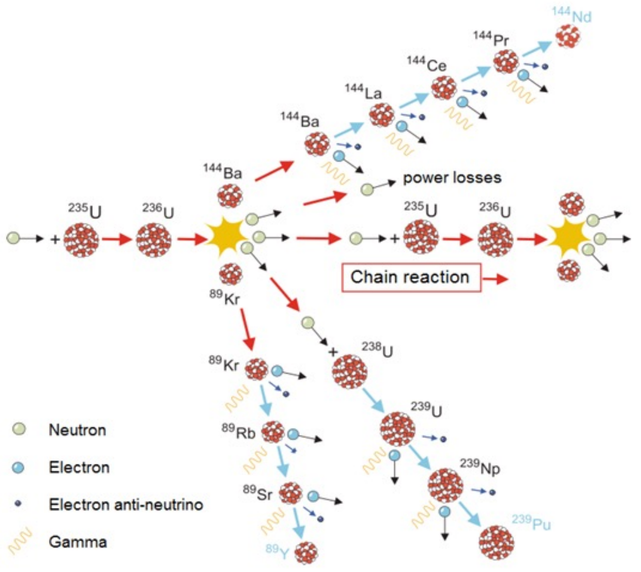
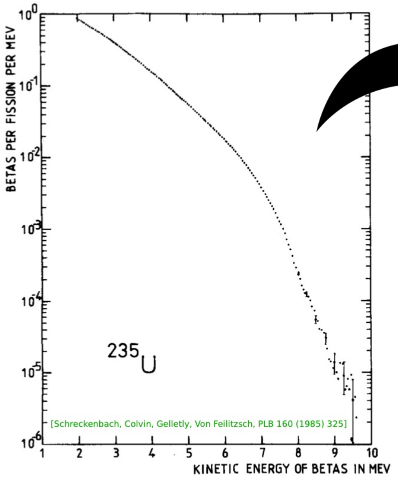
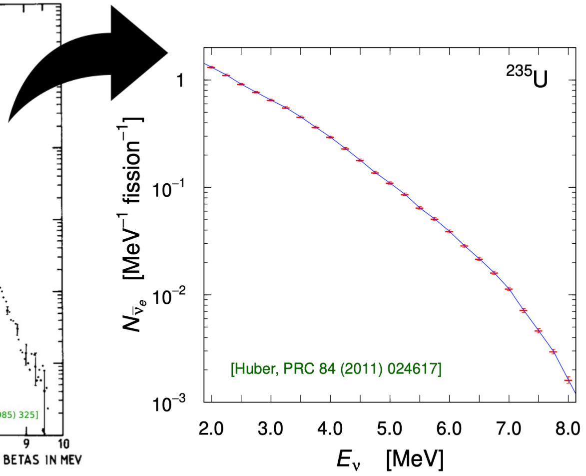
Reactor antineutrinos



Powerful $\bar{\nu}_e$ source:

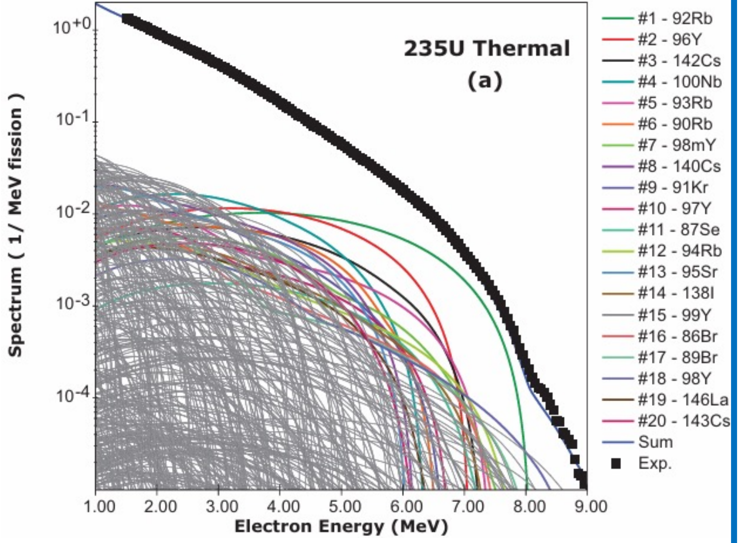
- Used to discover neutrino.
- Used to measure θ_{13}, NMO…
- β decays of fission fragments of ^{235}U, ^{238}U, ^{239}Pu, and ^{241}Pu.





Conversion model:

- convert ILL β spectra to $\bar{\nu}_e$ spectra
- ~ 30 virtual β decay branches.
- ~ 2.4% uncertainty
- **Huber-Mueller (HM) model (2012)**

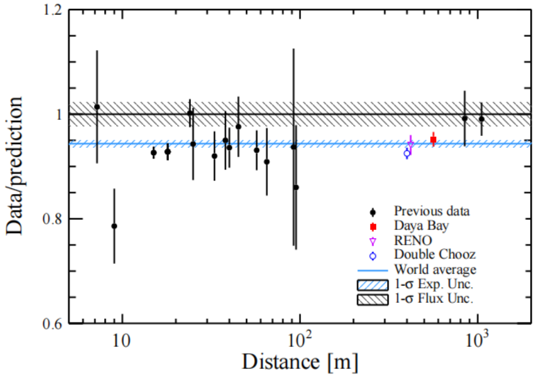


Summation model:

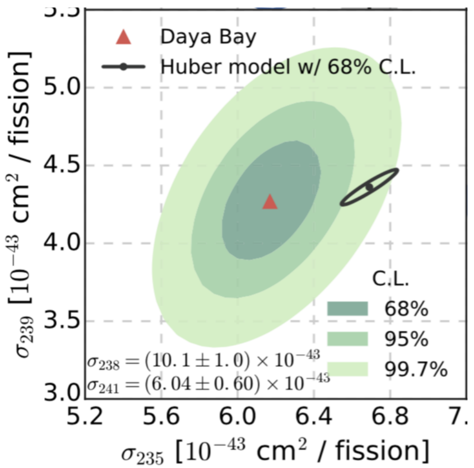
- ~1000 isotopes
- ~6000 branches
- ~10% uncertainty
- **SM2018**

Scientific problems

Flux anomaly

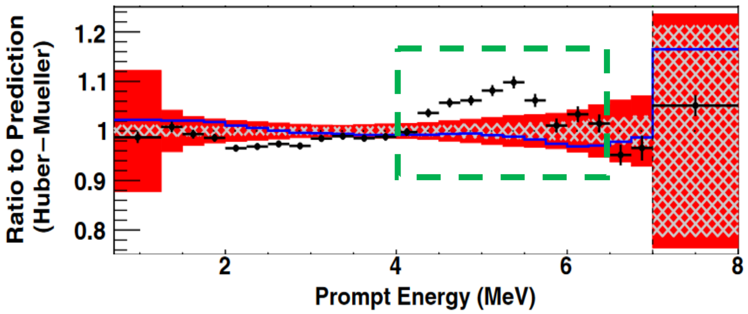


- 6% deficit compared with HM model
- Oscillations from active to eV-scale **sterile neutrinos**?
- **Model problem**?



- Flux deficit is meanly contributed by ^{235}U.
- Tend to indicate there are **problems with model**.
- Update model ^{235}U **↓ ~5%**
  - KI model (Convert)
  - SM2018 model (Summation)

5 MeV excess



- The origin of the excess has not been fully identified yet.
- **Reactor antineutrinos unpredicted by the model?**

- Precision measurements of flux/spectrum
  - Understand these anomalies better
  - Help improve the nuclear database
  - Provide inputs for model and future reactor antineutrino experiments.

Antineutrino detection

Inverse β decay (IBD)

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

Prompt

$E_{prompt} \approx E_{\nu} - 0.8$ MeV

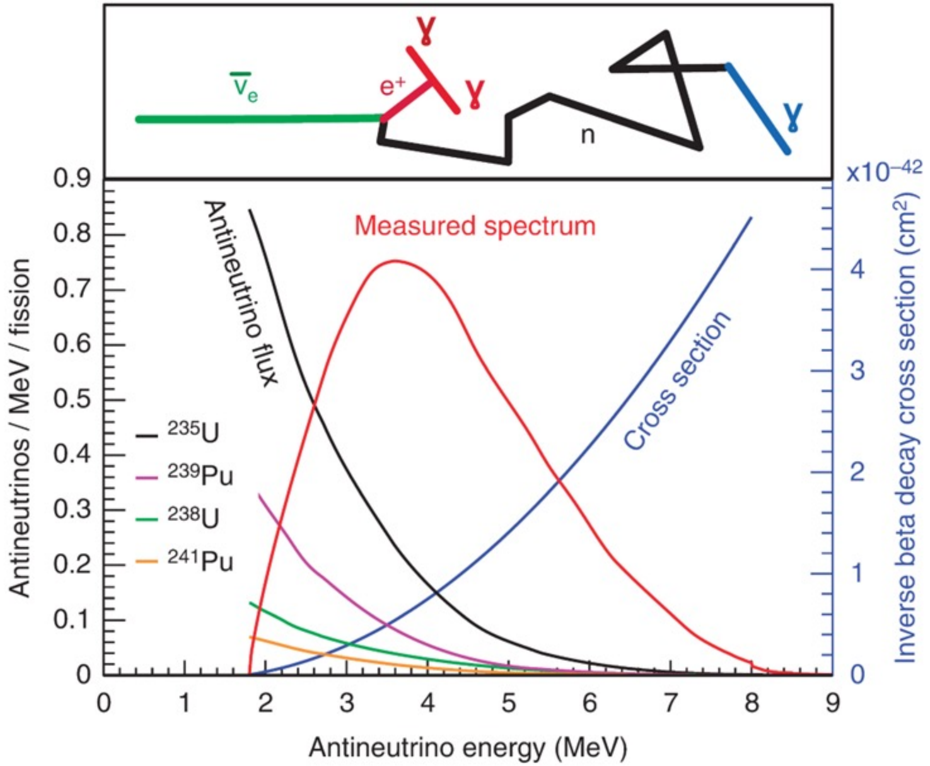
Delayed

n-Gd (~8 MeV, 30μs)

n-H (~2.2 MeV, 220μs)

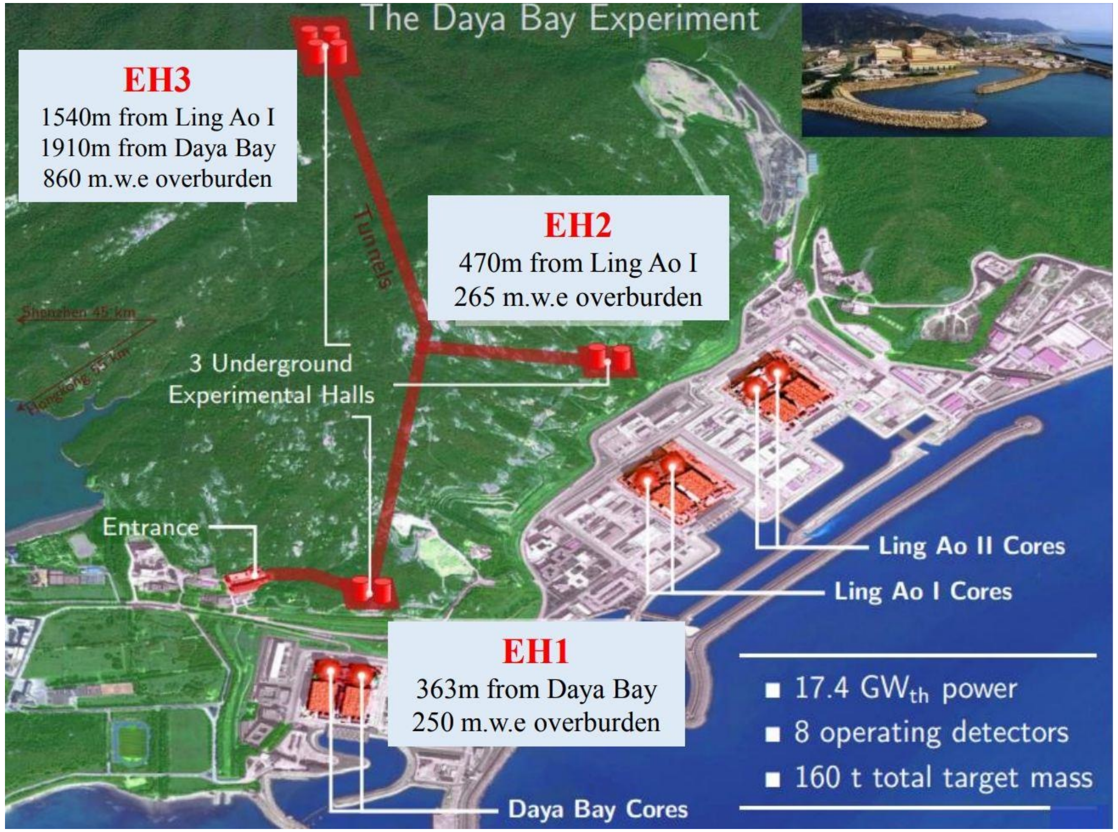
- Preserves incoming $\bar{\nu}_e$ energy information

- Positron and neutron coincidence → powerful background rejection.

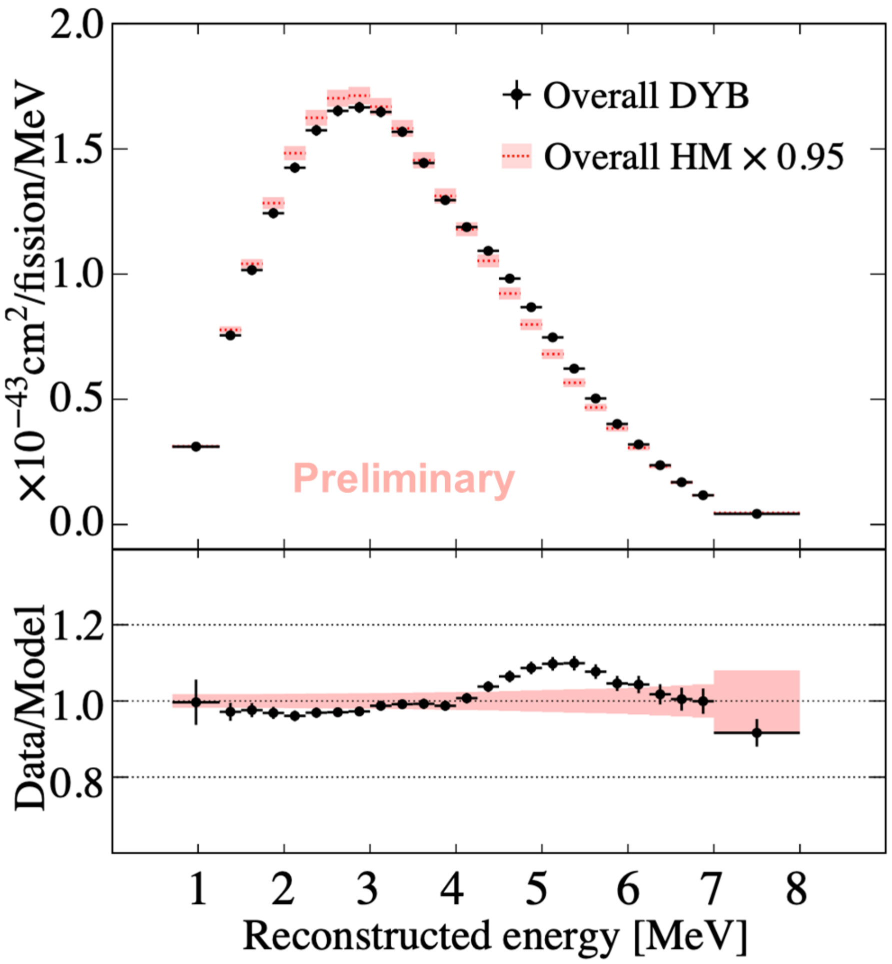


Daya Bay experiment

- 6 reactor cores, 17.4 GW_{th}
- 8 identical antineutrino detectors (ADs) at 3 sites.
- Operated for 3,158 days (Dec. 2011 ~ Dec. 2020)

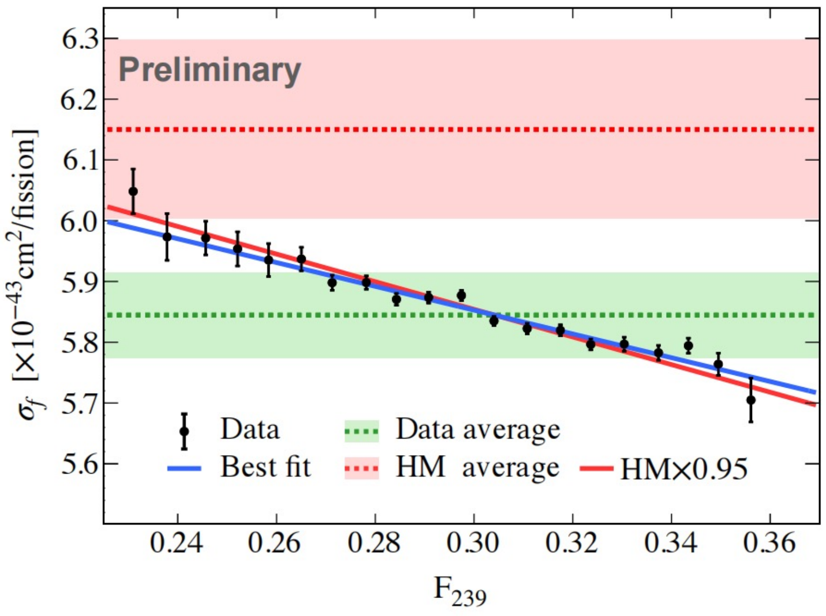


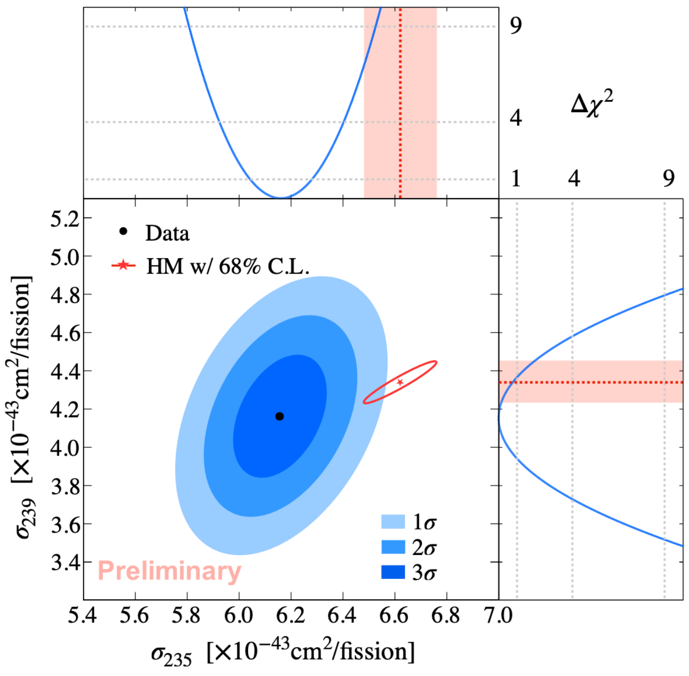
Overall spectrum

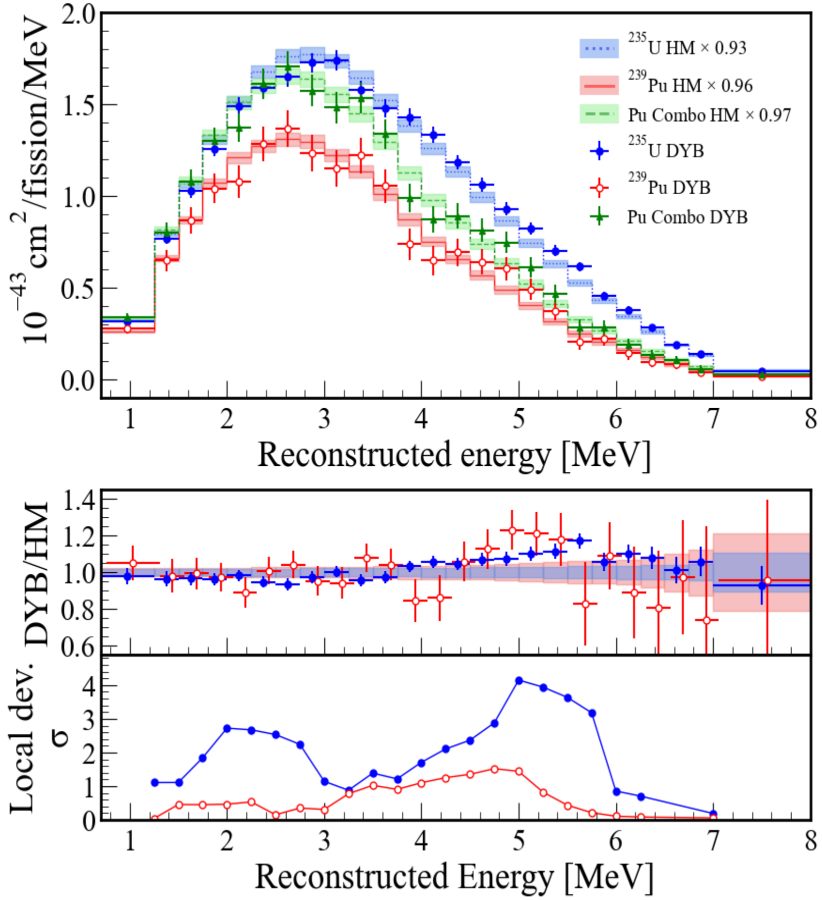


- 25 bins in 0.7~8 MeV for reconstructed energy of IBD prompt signal.
- ~1.4% precision in 2~5 MeV.
- Shape discrepancy w.r.t. HM model:
  - ~10σ significance in 4~6 MeV.

Precision measurements





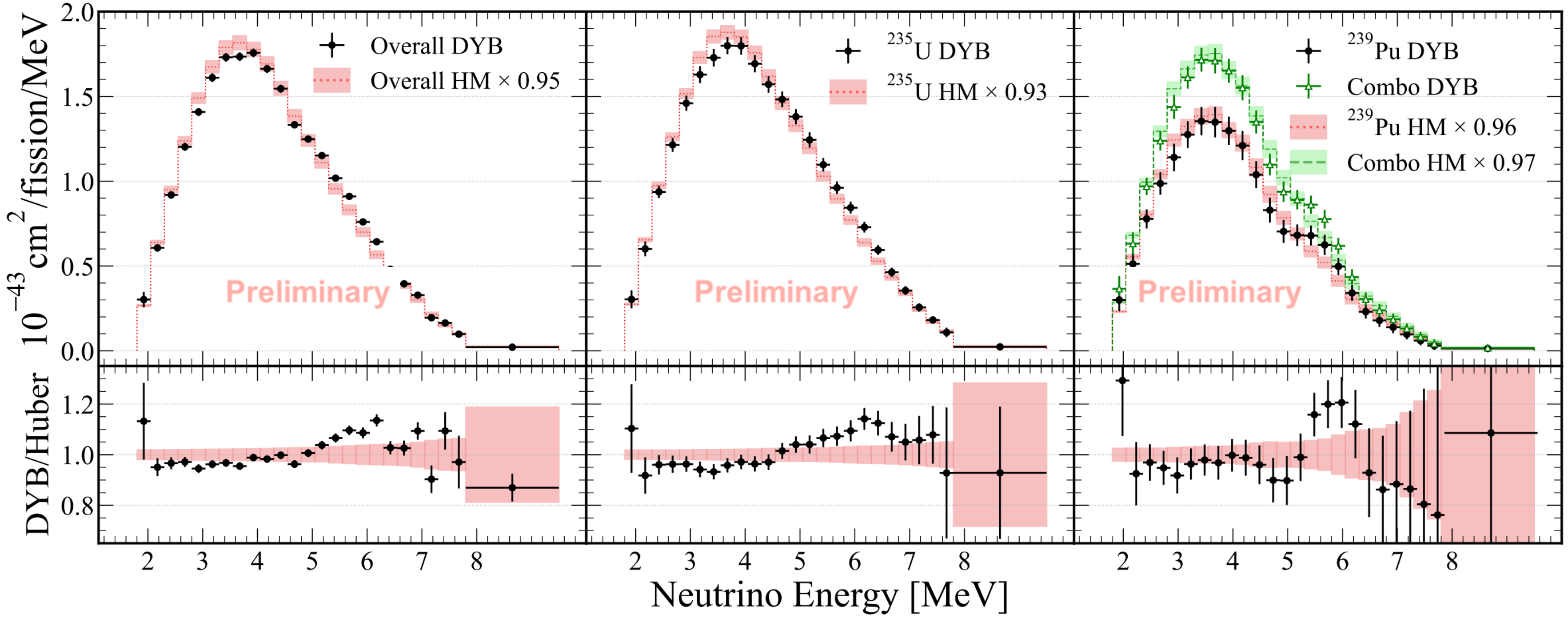


Precisions increase about 10% to 20% .

Data-based antineutrino spectrum

- **SVD unfolding method**
  - Overall, ^{235}U and ^{239}Pu spectra are unfolded together.
  - Minimizing $(S^{rec} - RS^{\nu})^{T}V^{-1}(S^{rec} - RS^{\nu}) + \tau(CS^{\nu})^{T}(CS^{\nu})$

Add bias but suppress variance



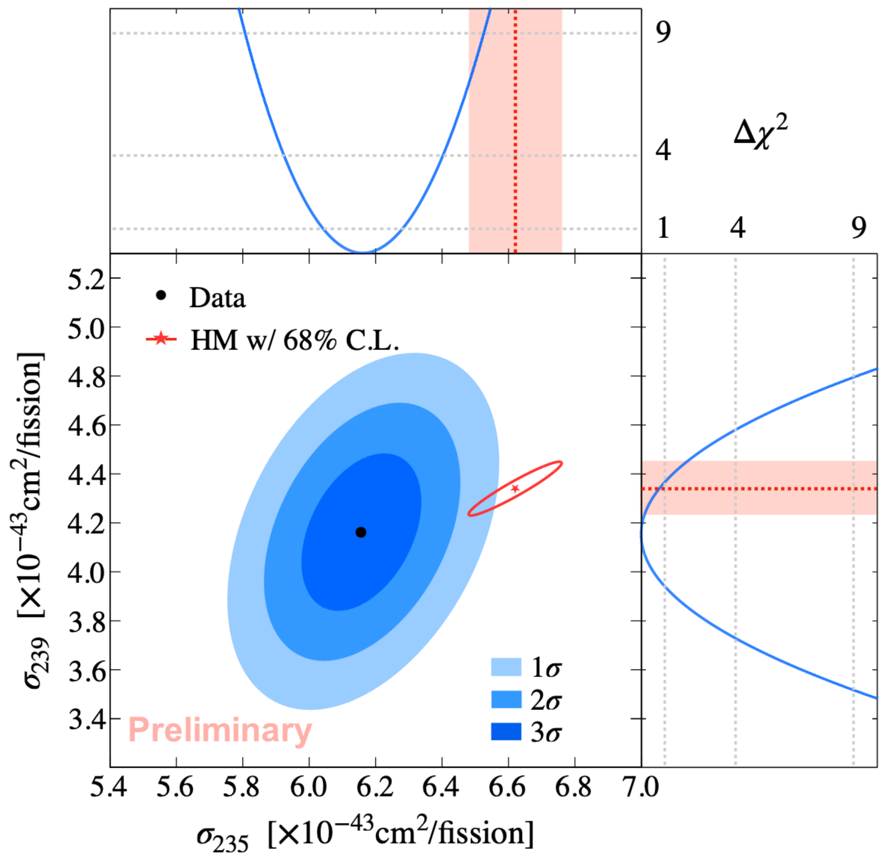
Summary

- Flux and spectra precision measurements with Daya Bay full data set.
  - The world leading ^{239}Pu flux and spectra results.
  - The world leading ^{235}U flux result.
- First time to unfold three spectra simultaneously.
  - A detailed investigation on the correlation.
- Provides a data-driven input for future reactor antineutrino studies.


香港科技大學賽馬會高等研究院
HKUST Jockey Club
Institute for Advanced Study
Many thanks!

Back up

Extract ^{235}U and ^{239}Pu yields



Overall yield evolution data

Yields to be extracted

$$\chi^2 = \chi^2(\sigma_f, F, \boldsymbol{\sigma_i}, \epsilon) + \chi^2(\sigma_{238}, \sigma_{241})$$

Eff. fiss. frac.

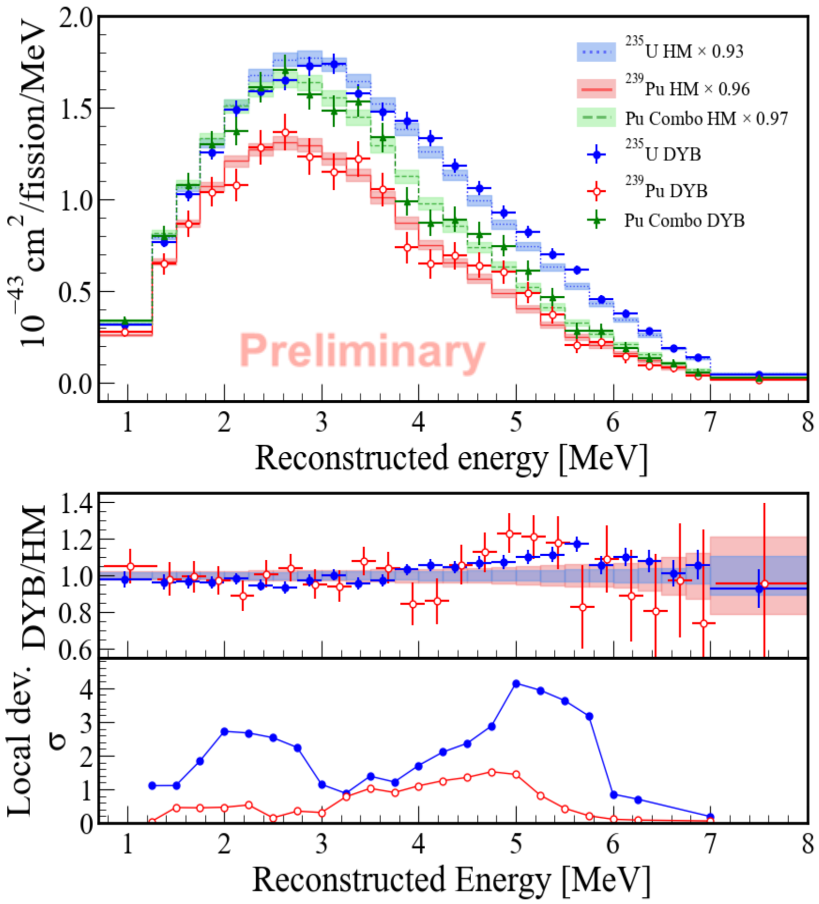
Constrained by HM

systematics

- $\sigma_{235} = (6.16 \pm 0.12)\times 10^{-43}$
- $\sigma_{239} = (4.16 \pm 0.21)\times 10^{-43}$

  (unit: $\mathrm{cm}^2/\mathrm{fission}$)
- Compare with HM:
  - **7.0% deficit (3σ significance) for ^{235}U**
  - **4.2% deficit (0.9σ significance) for ^{239}Pu**

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



Overall spectrum evolution data

Isotopic spectra to be extracted

$$\chi^2 = \chi^2(S_f, F, \boldsymbol{S_i}, \epsilon) + \chi^2(S_{238}, S_{241})$$

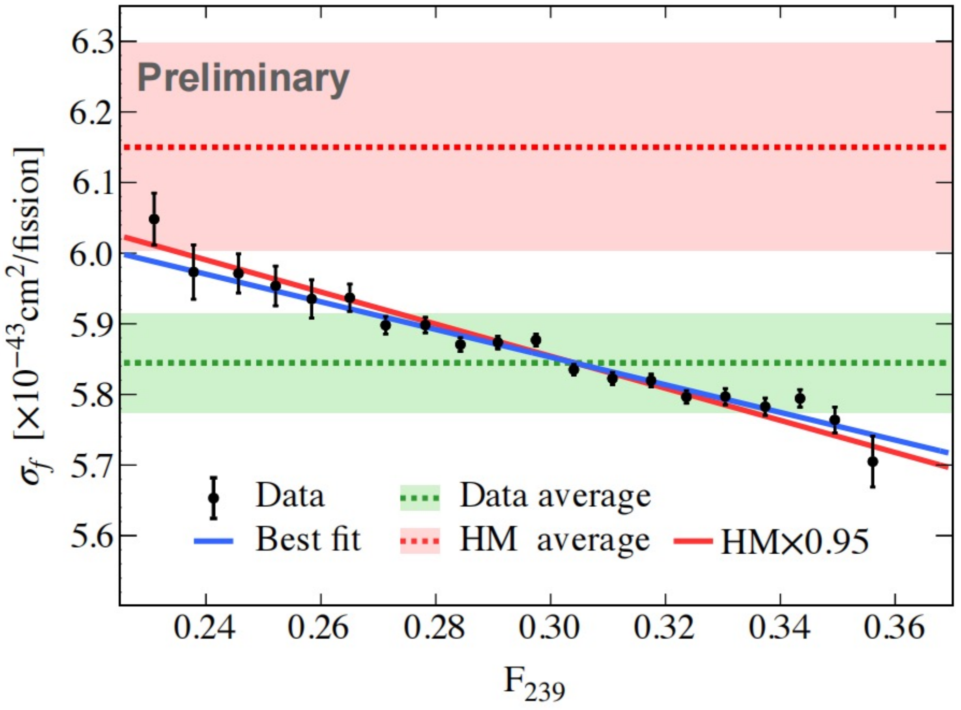
Eff. fiss. frac.

Constrained by HM (Conservative HM err. setting)

systematics

- ^{235}U:
  - ~4σ significance in 4~6 MeV
- ^{239}Pu:
  - ~1σ significance in 4~6 MeV
- Pu combo:
  - $S_{combo} = S_{239} + 0.185 \times S_{241}$
  - Reduce uncertainty by 30%

Fuel evolution



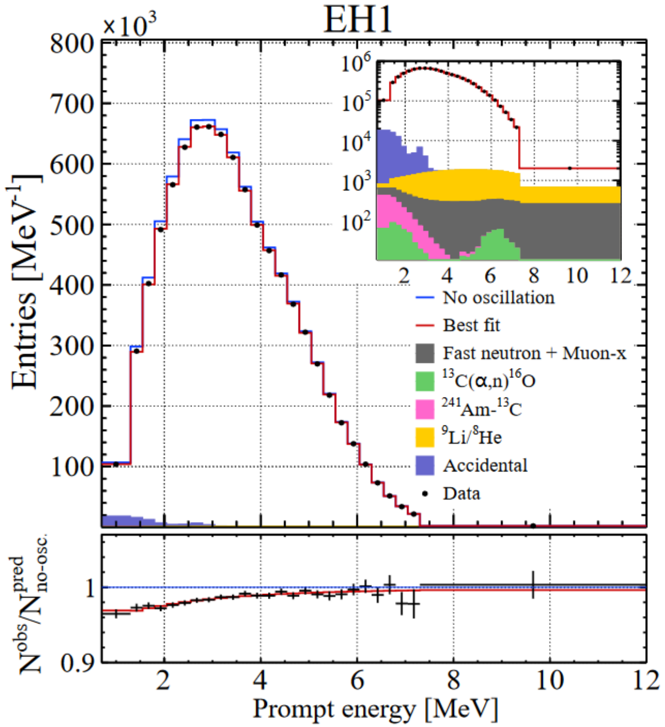
- IBD yield per nuclear fission σ:
  number of $\bar{\nu}_e$ per fission × cross section
- Overall σ_f:
  $(5.84 \pm 0.07)\times 10^{-43}\text{cm}^2/\text{fission}$
- Slope ($\frac{d\sigma}{dF_{239}}$):
  - Slope larger than HM means the ^{235}U yield is smaller than HM prediction.

IBD Datasets

	Statistics
PRL116, 061801(2016)	~0.3 million
CPC41, 013002(2017)	~1.1 million
PRL123, 111801(2019)	~3.5 million
This work	~4.7 million

- 4.7 million IBD candidates collected at 4 near ADs.
- n-Gd as delay signal.

Prompt energy and background of EH1



3158 days of data

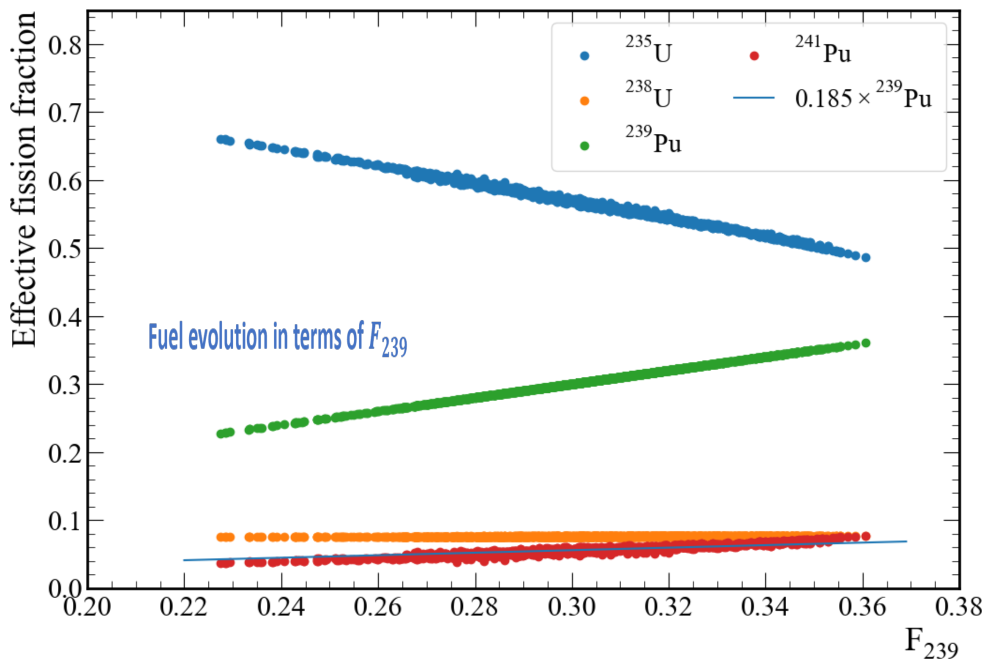
Fuel evolution

- In one burning period: ^{235}U ↓ ^{238}U — ^{239}Pu ↑ ^{241}Pu ↑
- Effective fission fraction F_i: fraction of fission isotopes viewed in detectors. (weekly basis)
- $\boldsymbol{F_{241} \approx 0.185 \times F_{239}}$

$$^{238}\mathrm{U} + n \rightarrow {}^{239}\mathrm{U} \xrightarrow[\beta-]{23.5\ \text{minutes}} {}^{239}\mathrm{Np} \xrightarrow[\beta-]{2.35\ \text{days}} {}^{239}\mathrm{Pu}$$

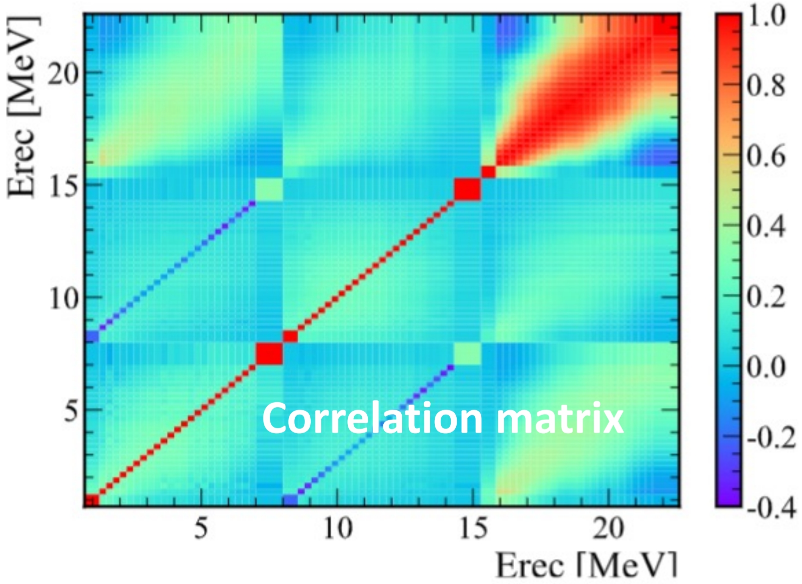
$$^{239}\mathrm{Pu} + \mathrm{n} \rightarrow {}^{240}\mathrm{Pu} + \mathrm{n} \rightarrow {}^{241}\mathrm{Pu}$$

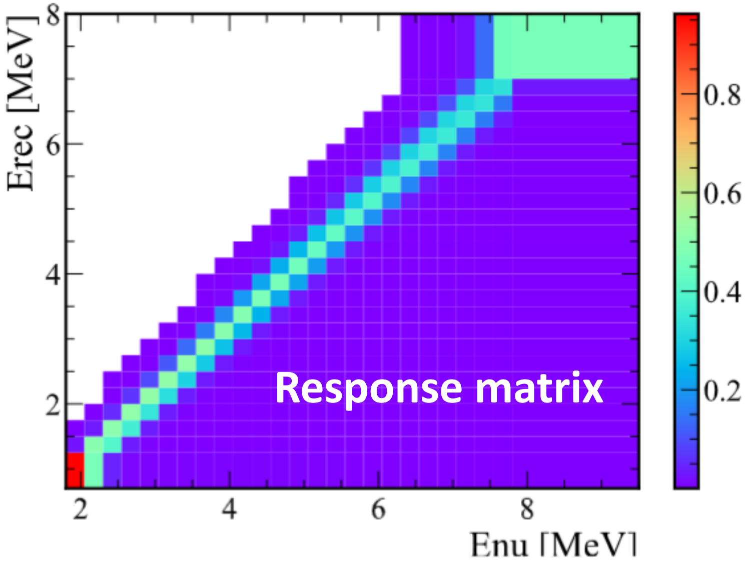
Fuel evolution in terms of F_{239}



Unfolding

- Minimizing: $(S^{rec} - RS^{\nu})^{T}V^{-1}(S^{rec} - RS^{\nu}) + \tau(CS^{\nu})^{T}(CS^{\nu})$
- $S^{rec} = [S_{overall}, S_{235}, S_{239}]$
- $C = \begin{bmatrix} C_2 & & \\ & C_2 & \\ & & C_2 \end{bmatrix}$





Reactor antineutrino model