Evolution of Reactor Antineutrino Flux and Spectrum at Daya Bay

Phys. Rev. Lett. 118, 251801

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on behalf of Daya Bay Collaboration

DPF 2017 - APS Division of Particle and Fields

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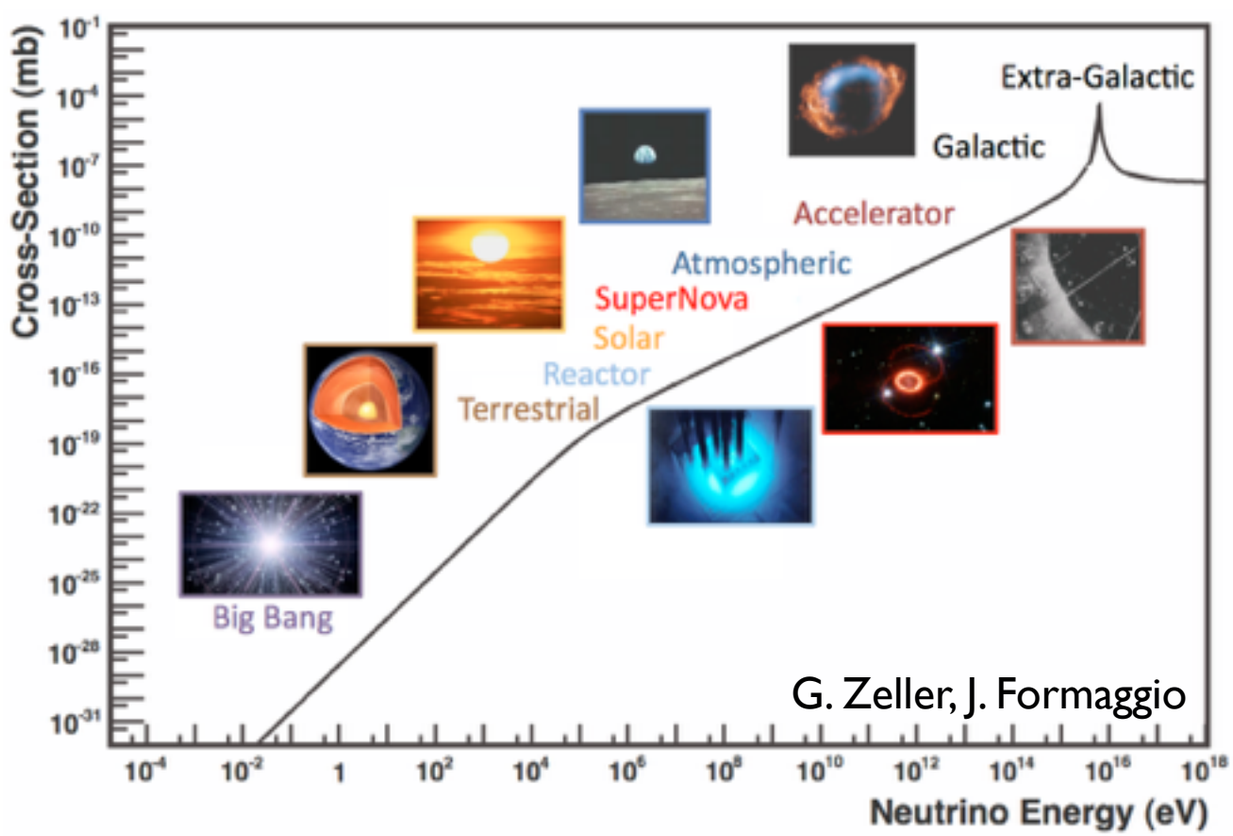
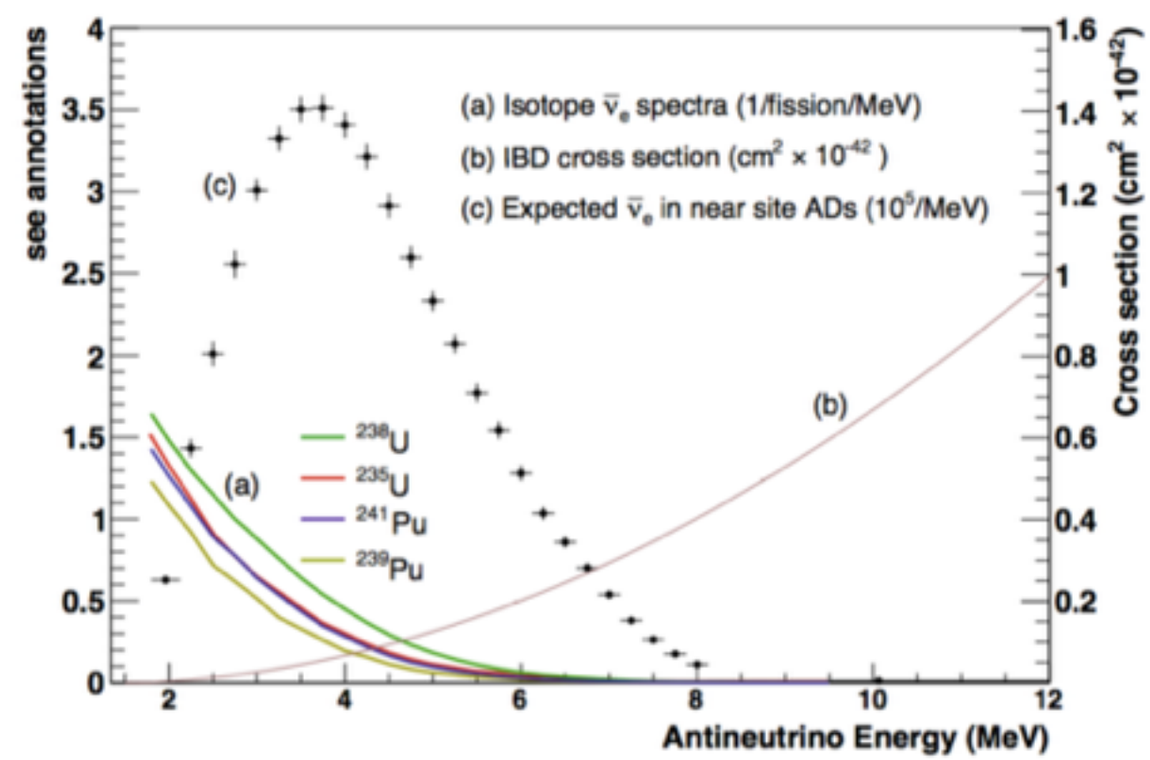
Reactors: Great Antineutrino Source

- Nuclear reactors are a powerful $\overline{\nu}_e$ source.
- More than 99 % of $\overline{\nu}_e$ are the fission products of ^{235}U, ^{239}Pu, ^{241}Pu, ^{238}U.
- 2×10^{20} fission/second per GW_{th} (~6 $\overline{\nu}_e$ per fission)





Reactor antineutrino anomaly

Big question: Do we have a reactor antineutrino anomaly?

- Previous experiments could have been biased to report flux measurements that agreed with existing predictions of the time

- Probably attributable to uncertainties in beta to ν_e conversion

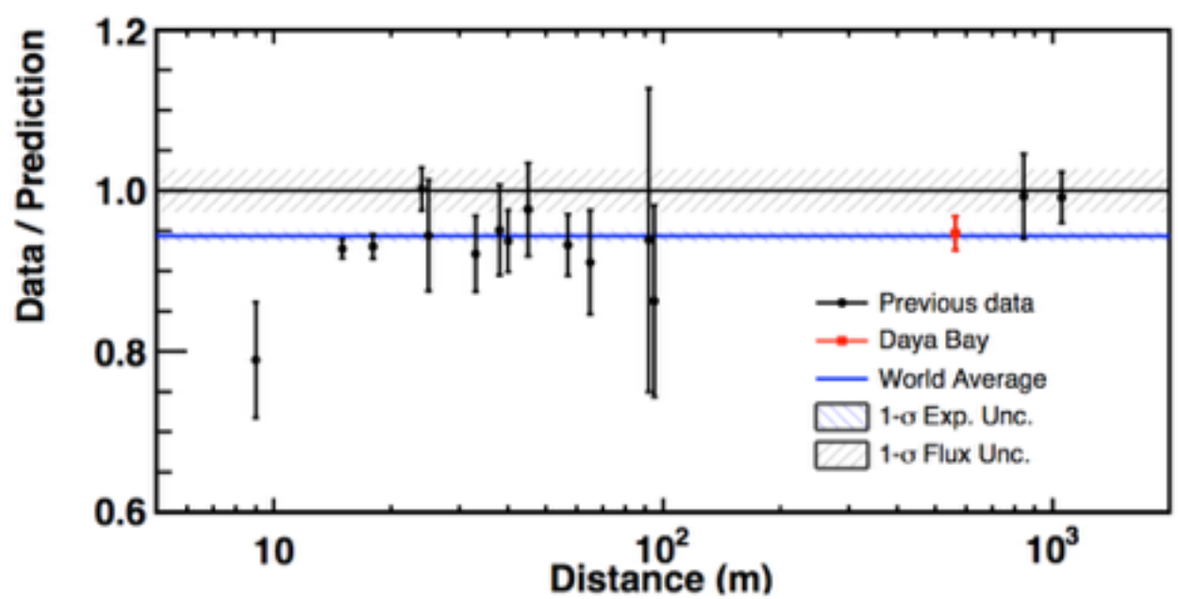
- The deficit could result from short base line sterile neutrino oscillations

Reactor antineutrino anomaly

- The previous experiments could have been biased to report flux measurements that agreed with existing predictions of the time: **NO**

- Daya Bay also see the reactor flux deficit: ~5.4% deficit relative to 2011 Huber/Mueller flux prediction.

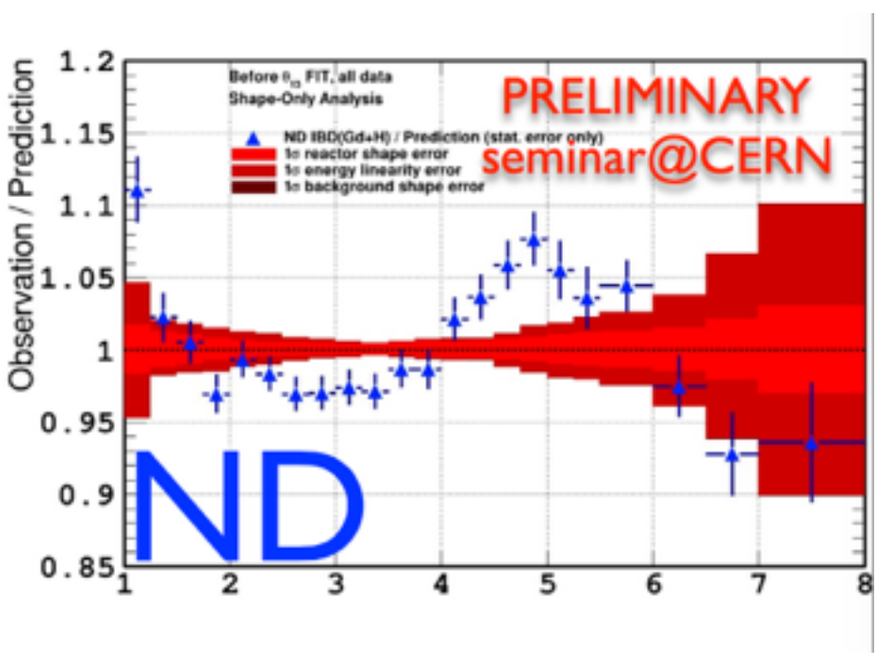
- Blind analysis: no reactor power data available until the analysis is totally fixed



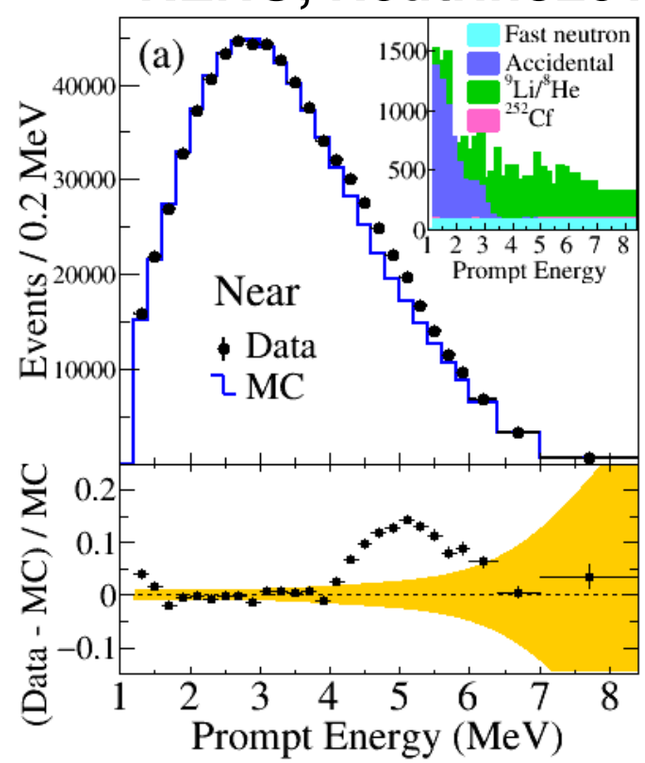
Reactor antineutrino anomaly

- Probably attributable to uncertainties in beta to ν_e conversion: **YES**
- Prompt energy spectrum disagree with predictions.
- If measured spectrum does not match, why should measured flux?

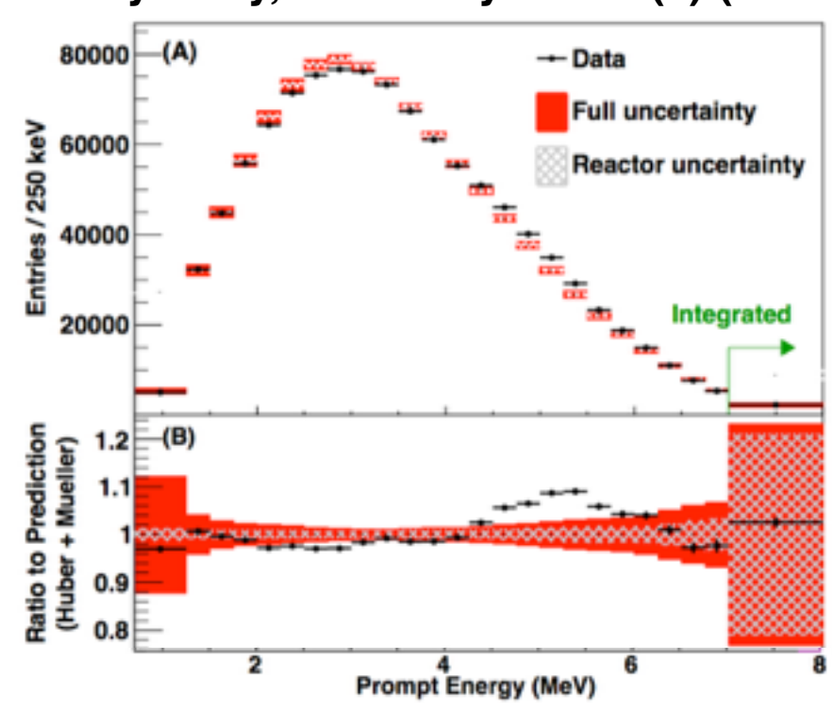
Double Chooz



RENO, Neutrino2016



Daya Bay, Chin. Phys. C 41(1) (2017)



Reactor antineutrino anomaly

- The deficit could result from short base line sterile neutrino oscillations: **YES**

- Consistent with hints of 1 eV sterile neutrinos (LSND, MiniBooNE, Gallex)

- In order to interpret CP violation results we need to know if sterile neutrinos exist.

- !DUNE needs the anomaly explanation!

The impact of sterile neutrinos on CP measurements at long baselines

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[b] *Theoretical Physics Department, Fermilab, P.O. Box 500, Batavia, IL 60510 USA*
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Abstract: With the Deep Underground Neutrino Experiment (DUNE) as an example, we show that the presence of even one sterile neutrino of mass ~1 eV can significantly impact the measurements of CP violation in long baseline experiments. Using a probability level analysis and neutrino-antineutrino asymmetry calculations, we discuss the large magnitude of these effects, and show how they translate into significant event rate deviations at DUNE.

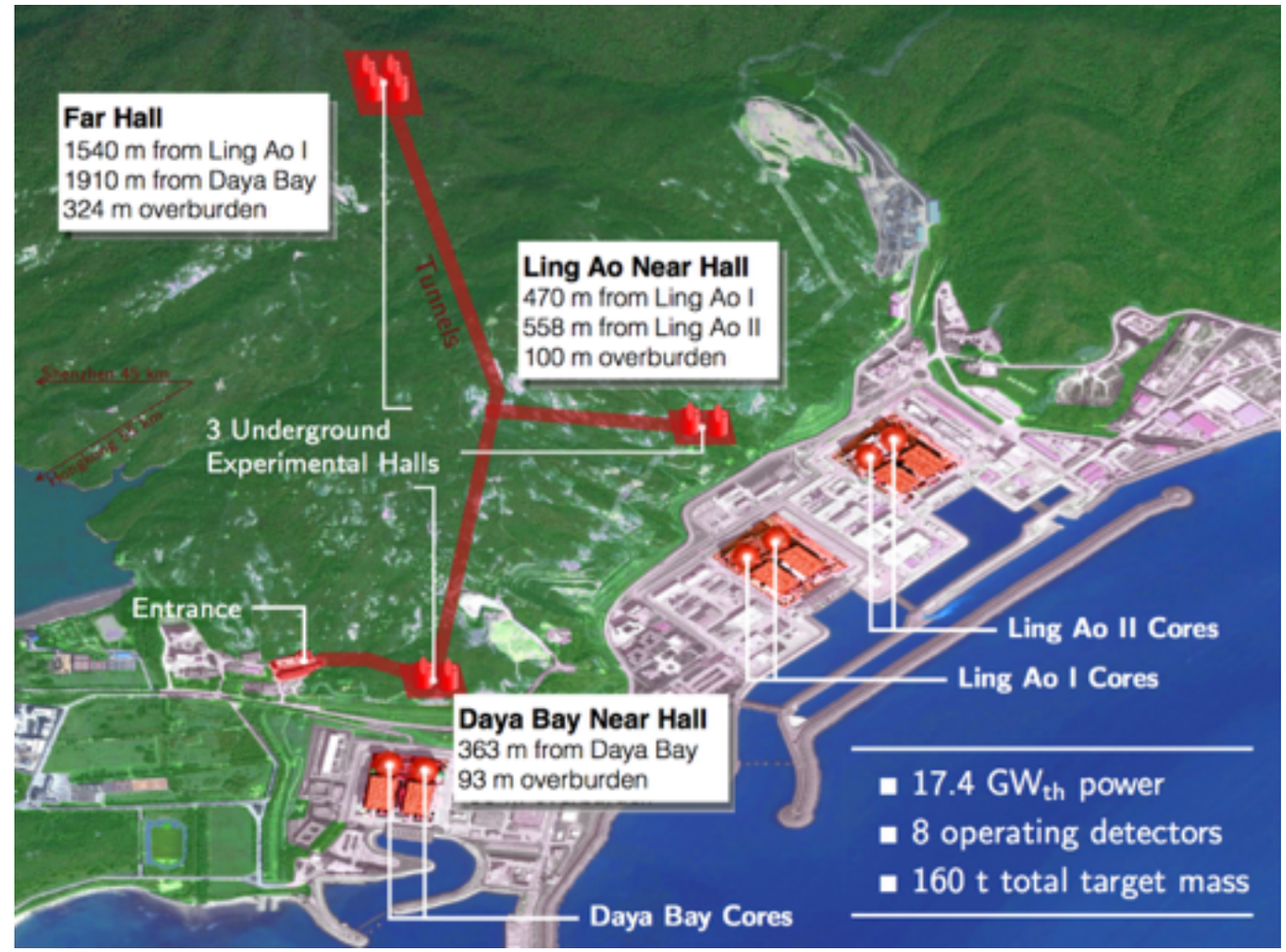
10.1007/JHEP11(2015)039

Reactor antineutrino anomaly: Recap

- **Reactor flux model predictions are not totally correct**
- **eV scale sterile neutrinos exist**
  - Need more information to determine which of these hypothesis (or both) are correct!

Daya Bay Layout

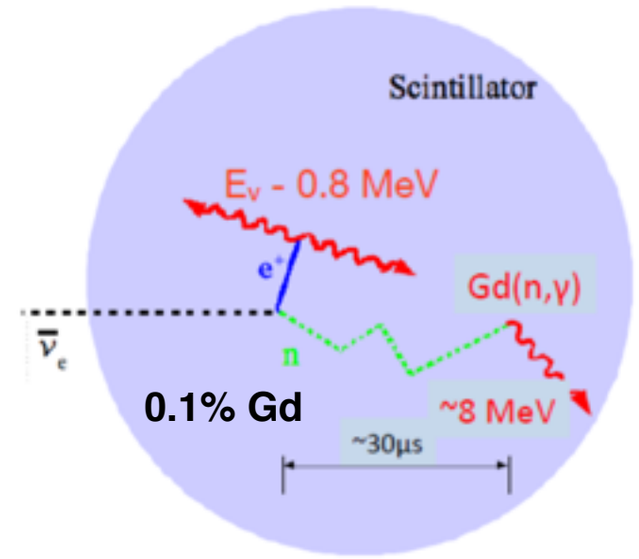
- Original concept with 8 'identical' detectors:
  - Near detectors constrain flux.
  - Far detectors see if any neutrinos have disappeared.
- Daya Bay has ideal features for doing this!

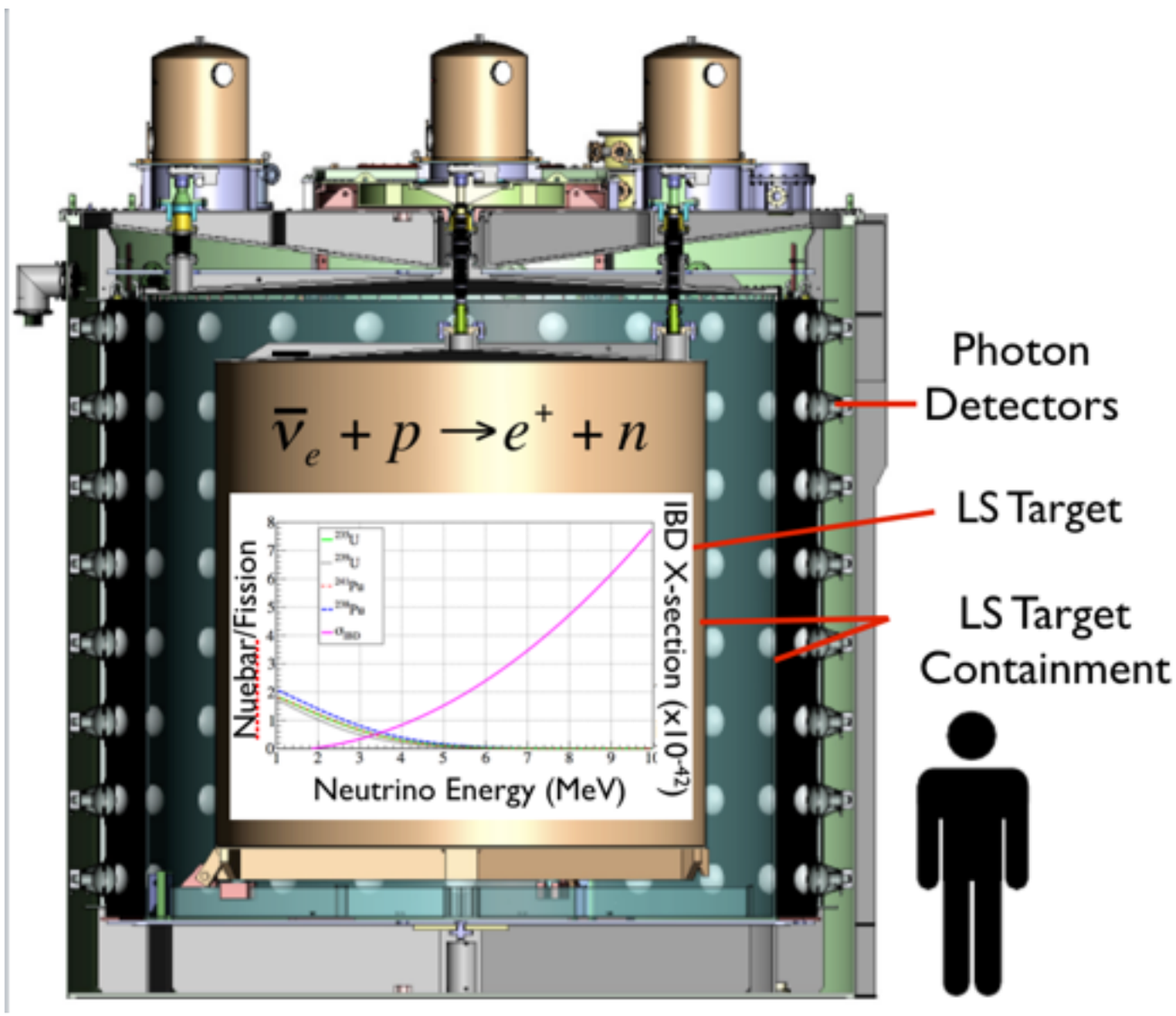


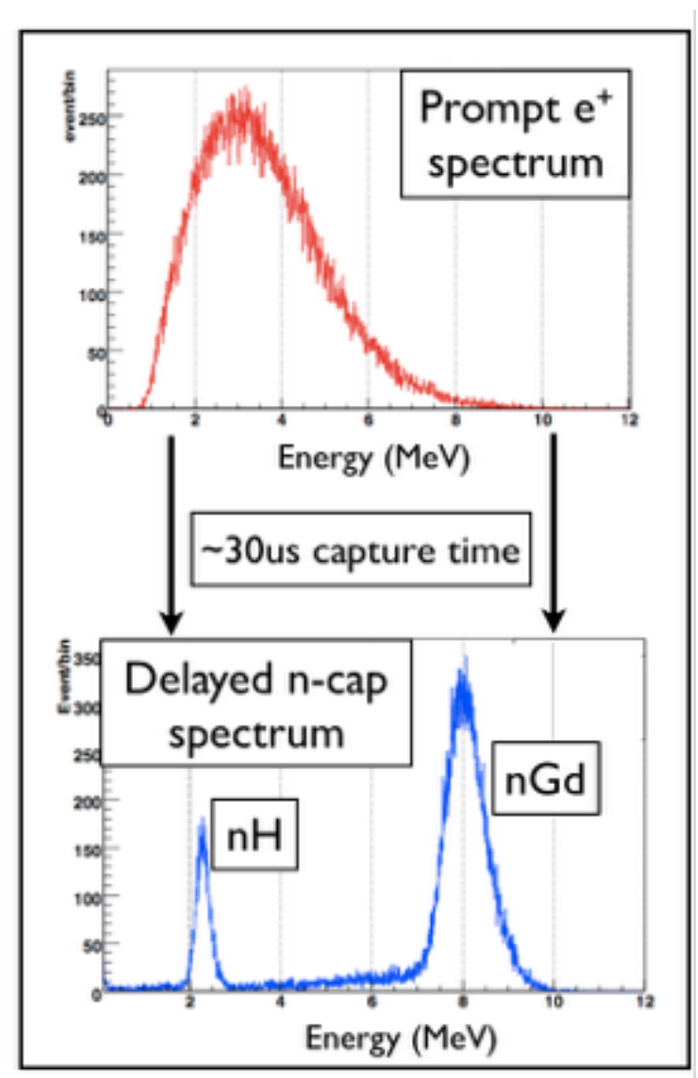
	Reactor [GW_{th}]	Target [tons]	Depth [m.w.e]
Double Chooz	8.6	16 (2 × 8)	300, 120 (far, near)
RENO	16.5	32 (2 × 16)	450, 120
Daya Bay	17.4	160 (8 × 20)	860, 250
	Large Signal		Low Background

The Daya Bay antineutrino detector

- Detect inverse beta decay with liquid scintillator.
- IBD positron is direct proxy for antineutrino energy







IBD Selection

① Reject spontaneous PMT light emission ("flashers")

② Prompt positron:
0.7 MeV < Ep < 12 MeV

③ Delayed neutron:
6.0 MeV < Ed < 12 MeV

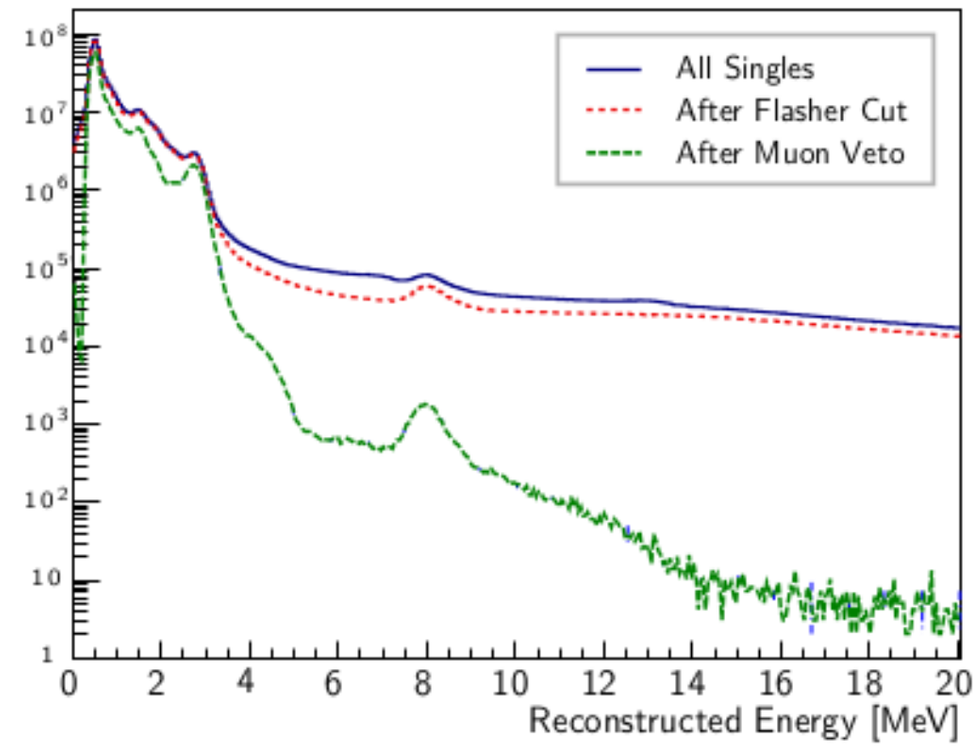
④ Neutron capture time:
1 μs < t < 200 μs

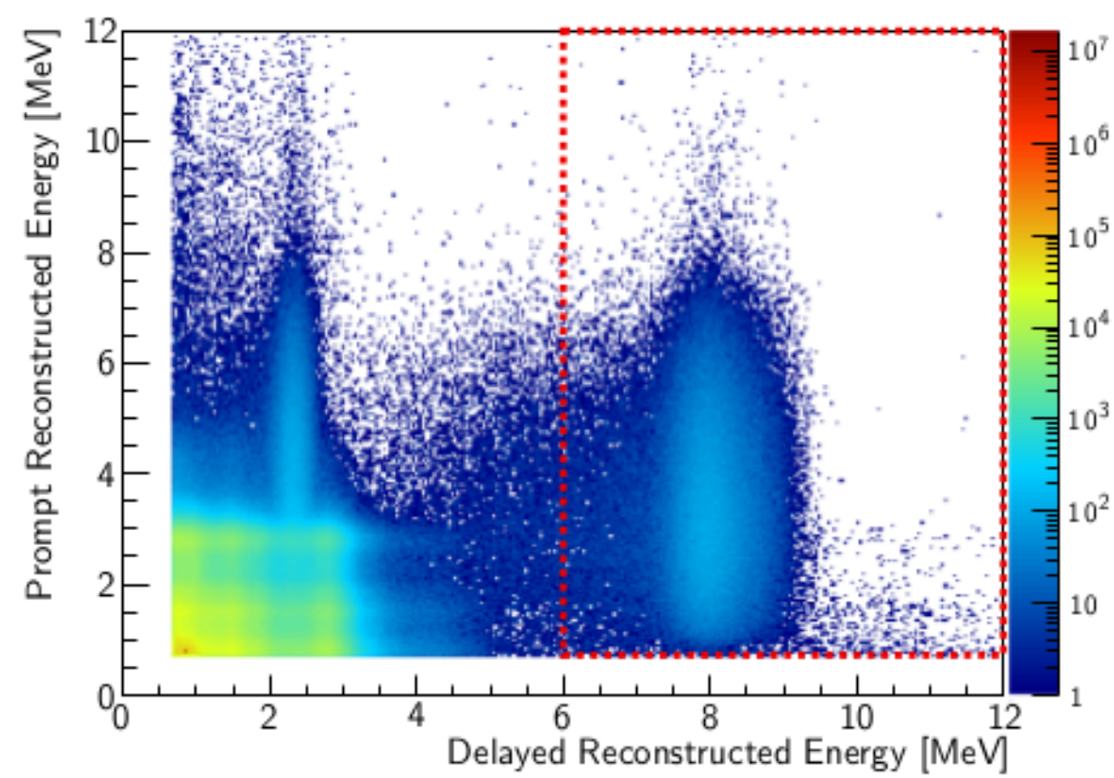
⑤ Muon veto:

- Water pool muon (>12 hit PMTs): Reject [-2μs; 600μs]
- AD muon (>3000 photoelectrons): Reject [-2 μs; 1400μs]
- AD shower muon (>3×10^5 p.e.): Reject [-2 μs; 0.4s]

⑥ Multiplicity:

- No additional prompt-like signal
  400μs before delayed neutron
- No additional delayed-like signal
  200μs after delayed neutron





IBD Selection

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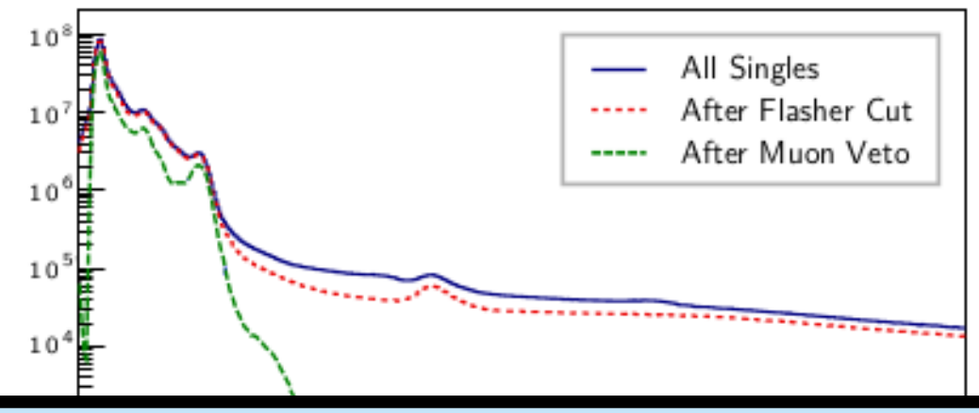

After this selection on 1230 days of data, we get <u>2.5 million</u> candidates; <u>2.2 million</u> from 4 Near Site detectors.

Reject [-2 μs; 1400μs]

- AD shower muon (>3×10^5 p.e.):
  Reject [-2 μs; 0.4s]

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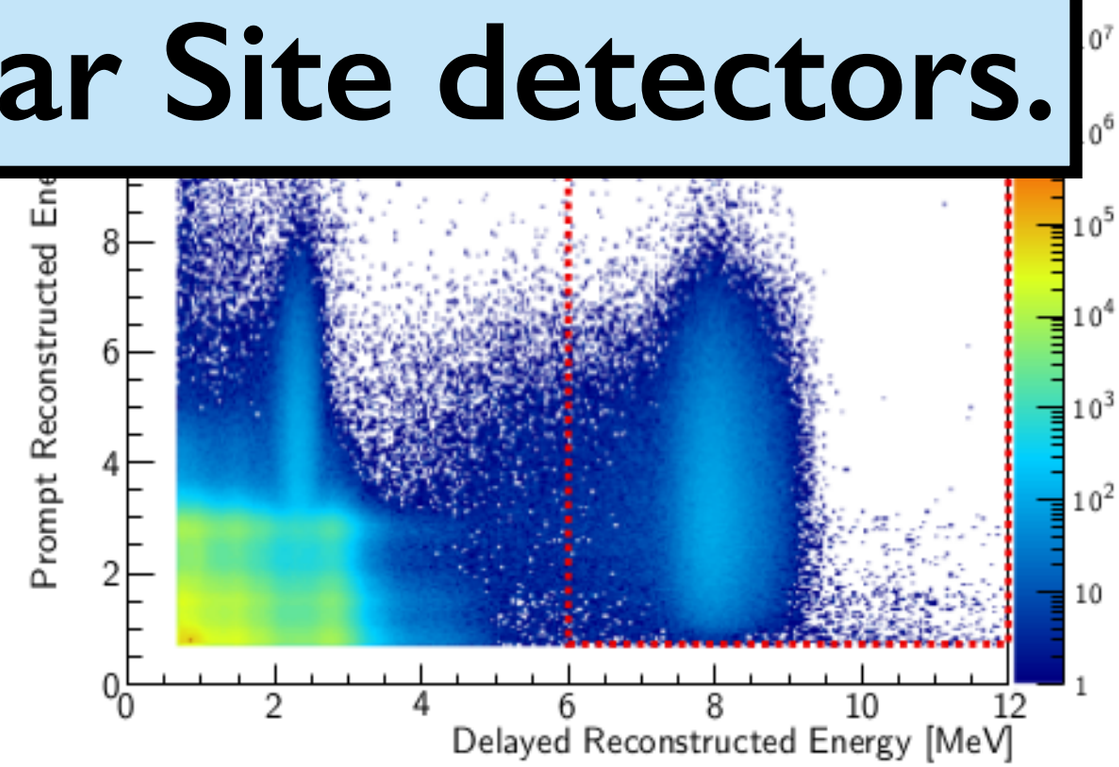

Daya Bay New results: Fuel evolution analysis

- DO NOT time integrate: instead, look at reactors' fission fractions
  - % of fissions from ^{235}U ^{239}Pu, ^{238}U, ^{241}Pu
- Calculate 'effective fission fraction' observed by each detector:

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

- Basically weight's each reactor's fission fraction by distance, power, and oscillation

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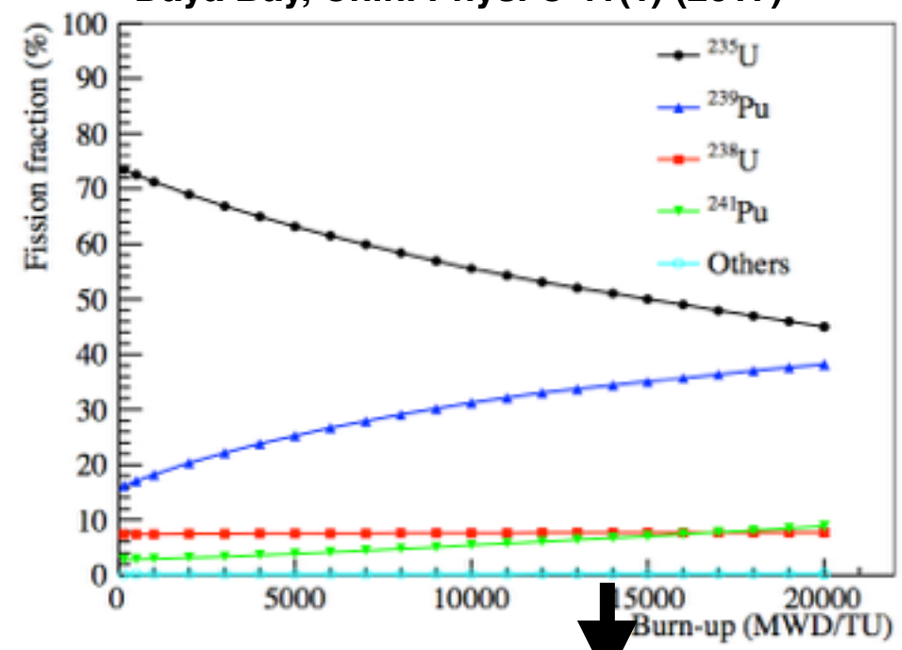
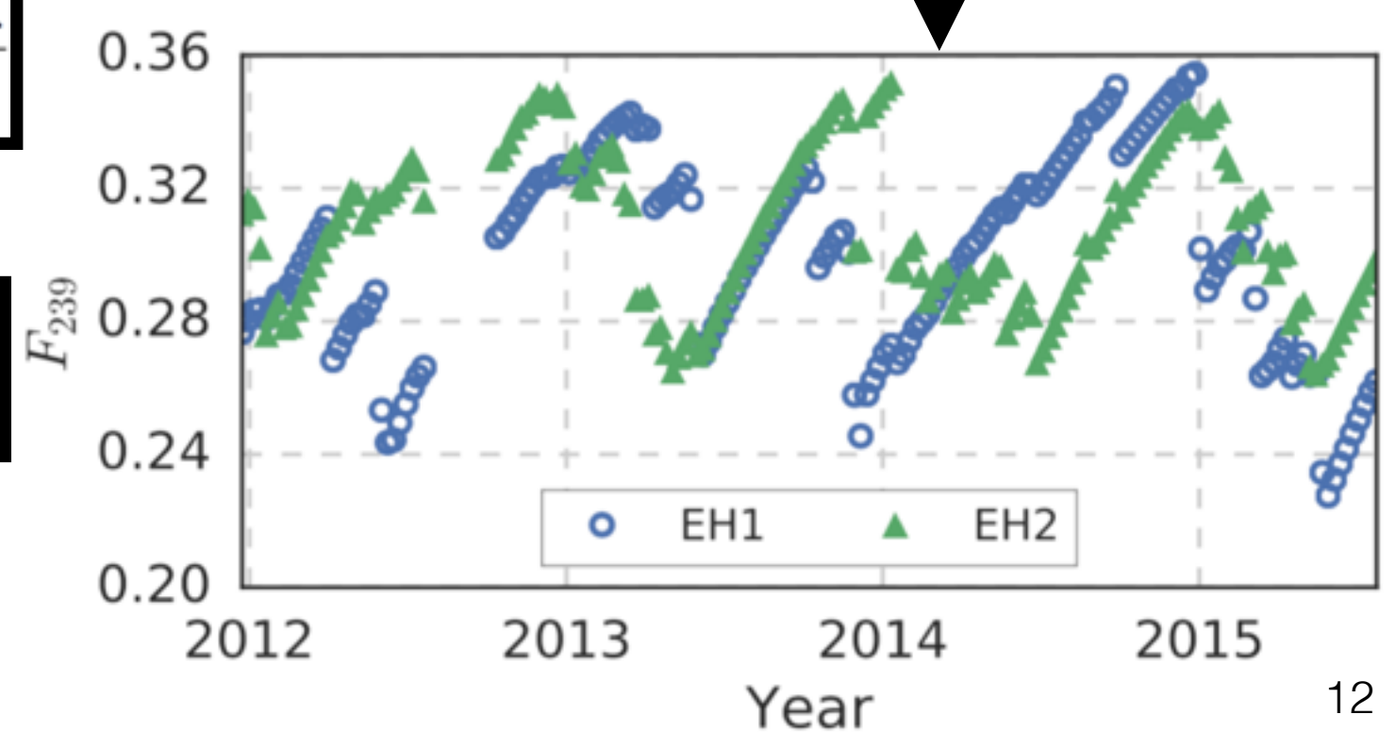


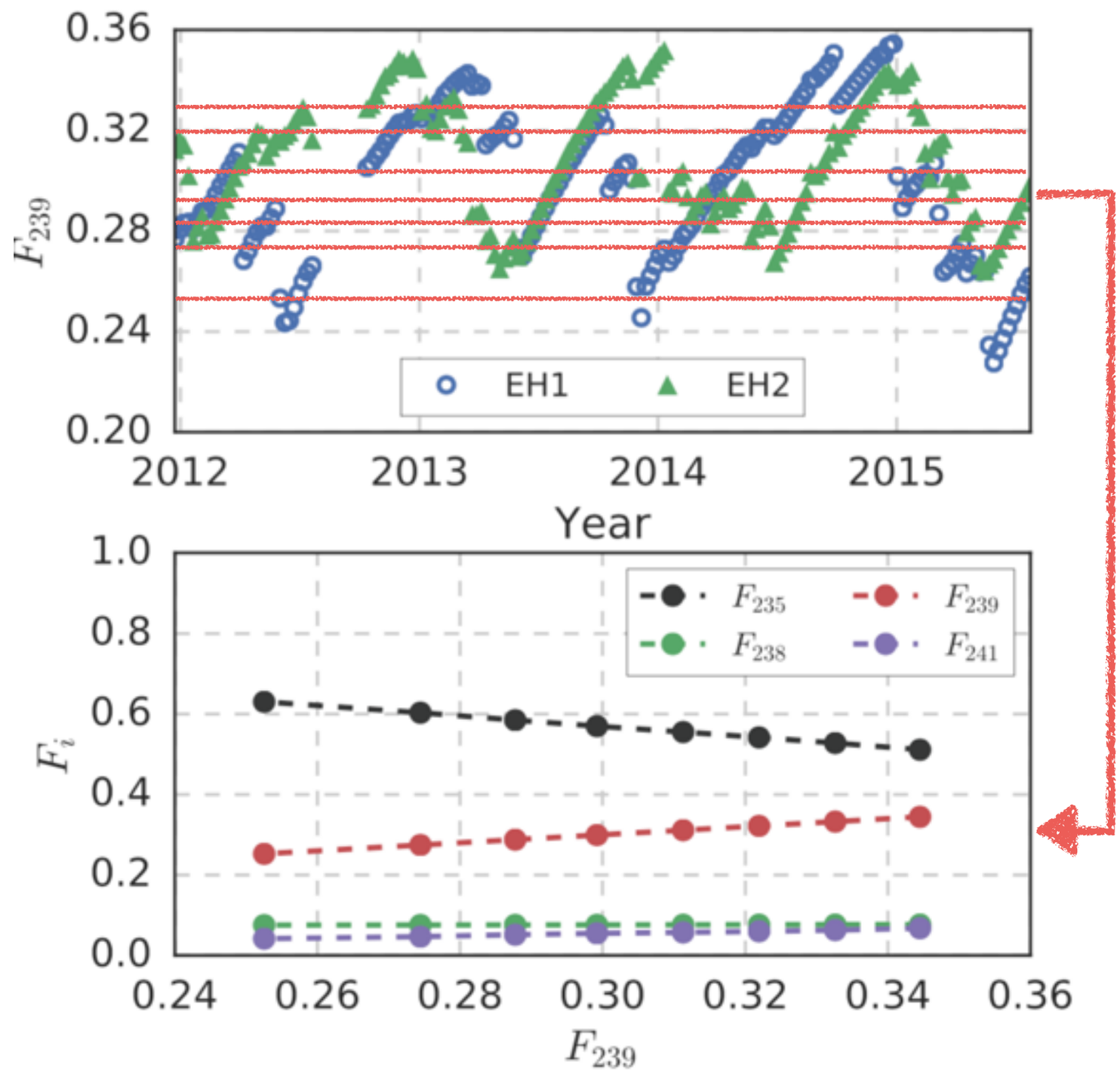
Weight for each of the 6 reactor cores



David

Daya Bay New results: Fuel evolution analysis

- We have fission fractions and IBDs versus time
- Let's compare IBDs from periods of differing effective fission fractions!
- Doing this by combining periods of common fission fraction.
  - We choose 8 bins in ^{239}Pu effective fission fraction, F_{239}



From IBD/day to IBD/fission σ_f

- IBD/day depends on many time-dependent quantities:
  - Reactor status and thermal power
  - Power released per fission
  - Detector livetime
    - Some other more minor, nearly-constant stuff i.e target mass.
- Show final plots in terms of IBD/fission
  - Basically take IBD/day and correct for time-dependent quantities on a week-by-week basis

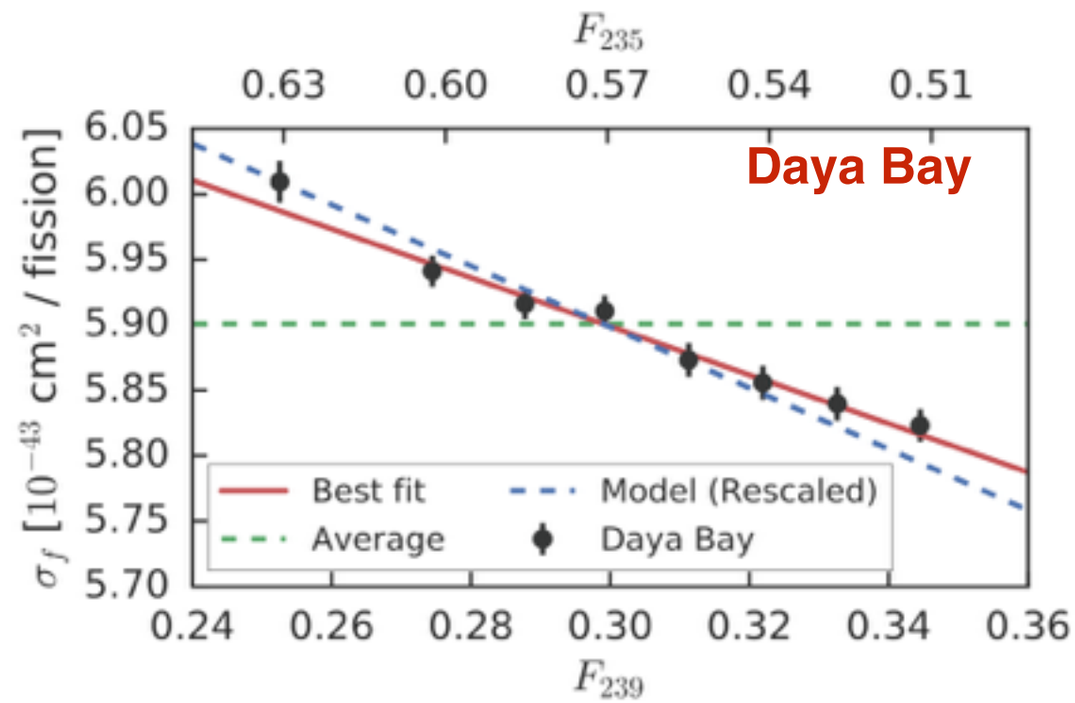
Results: Flux Evolution

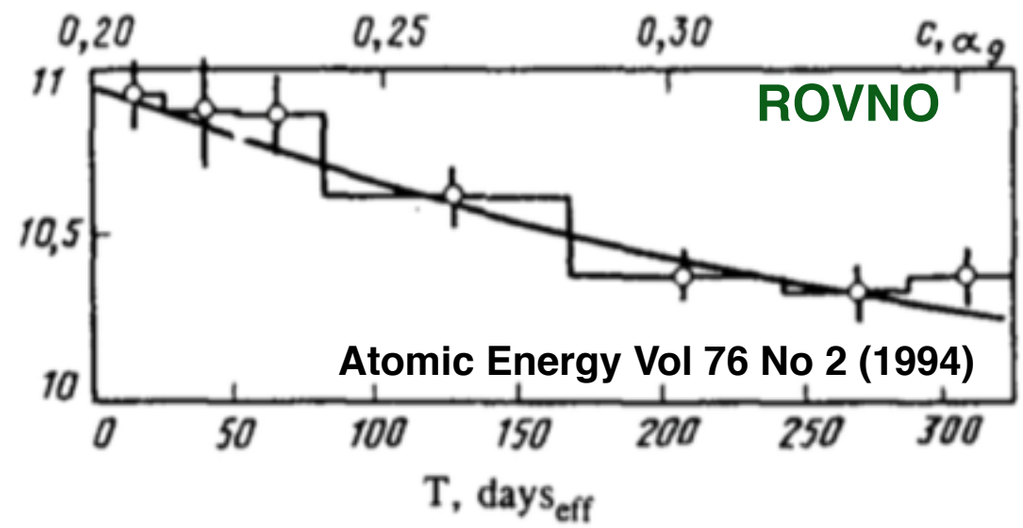
- **When plotting IBD/fission versus F_{239}, we see a slope in data**

- Very clear that flux is changing with changing fission fraction.

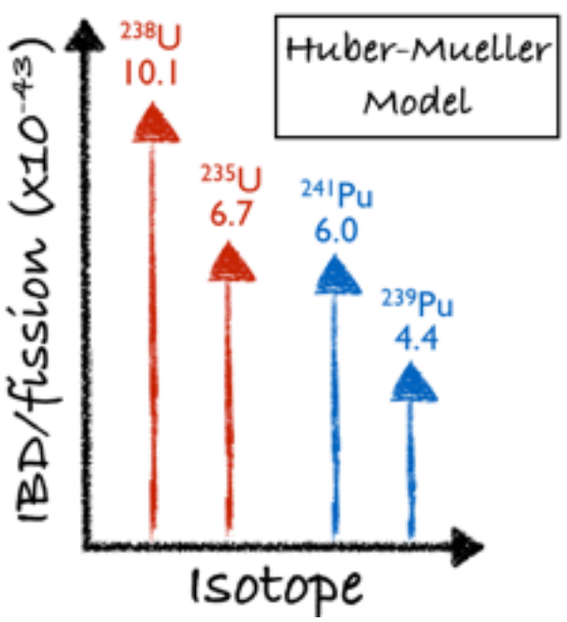
- Not too surprising; models predict ^{239}Pu makes fewer $\overline{\nu}_e$

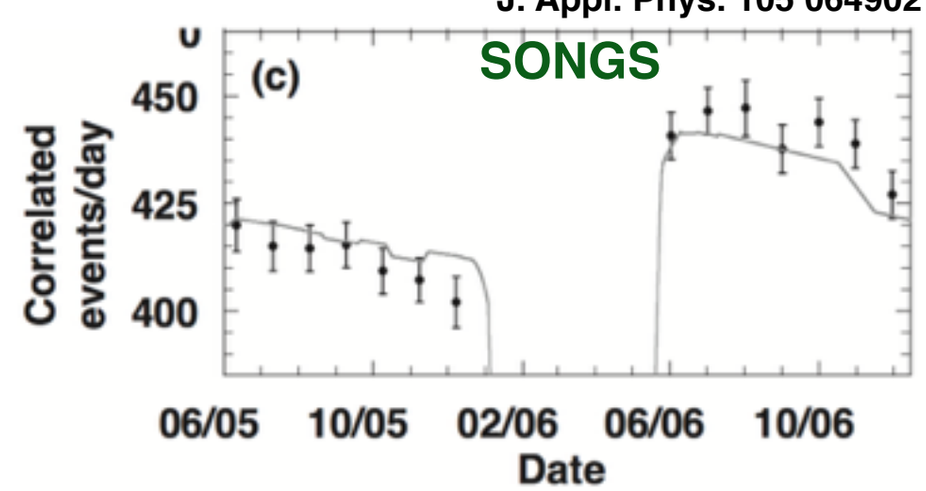
- Seen before in previous experiments: **Rovno (90's); SONGS (00's)**





J. Appl. Phys. 105 064902

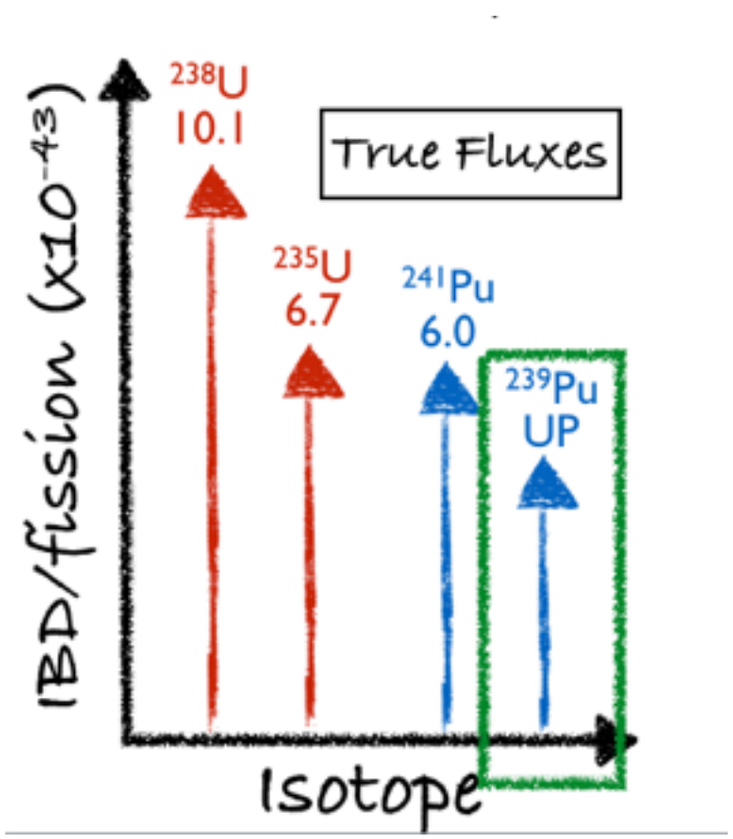


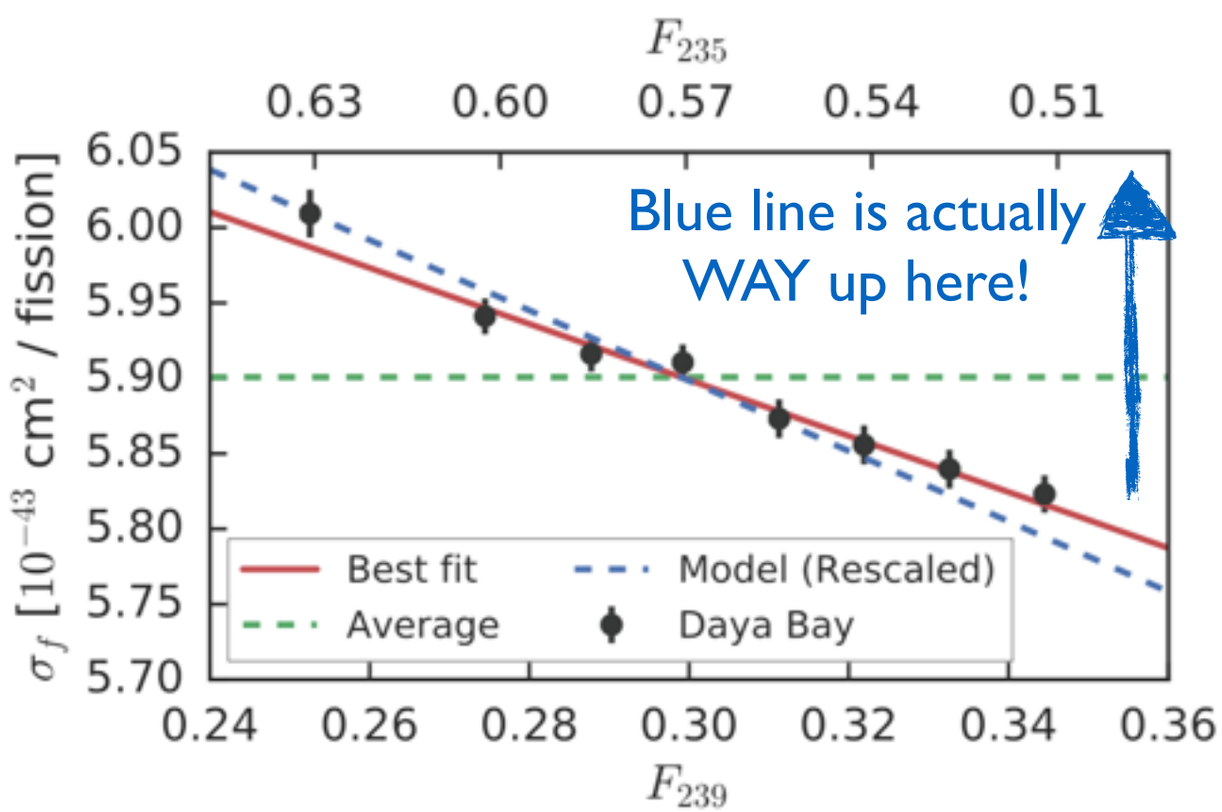


David Martinez

Results: Flux Evolution

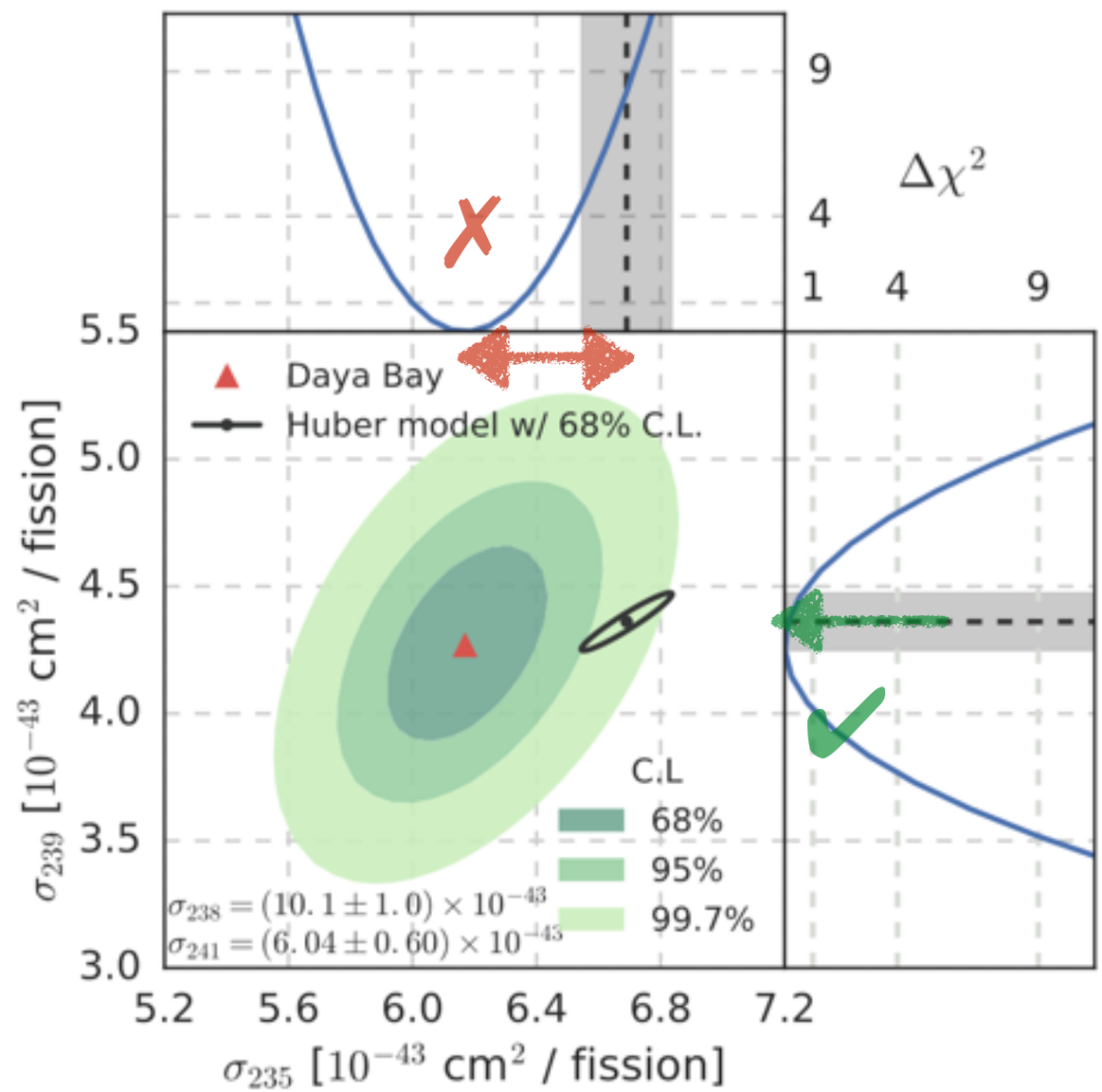
- Also consider: total flux prediction is too high by 5.4%
- **Suggest that ^{235}U prediction is too high**
  - More complicated scenarios still allowed: ^{239}Pu UP + sterile neutrino.
  - Whatever the case reactor flux models must be wrong in some way.
  - To truly rule out sterile neutrinos, direct tests of L/E with SBL reactor experiments are required.





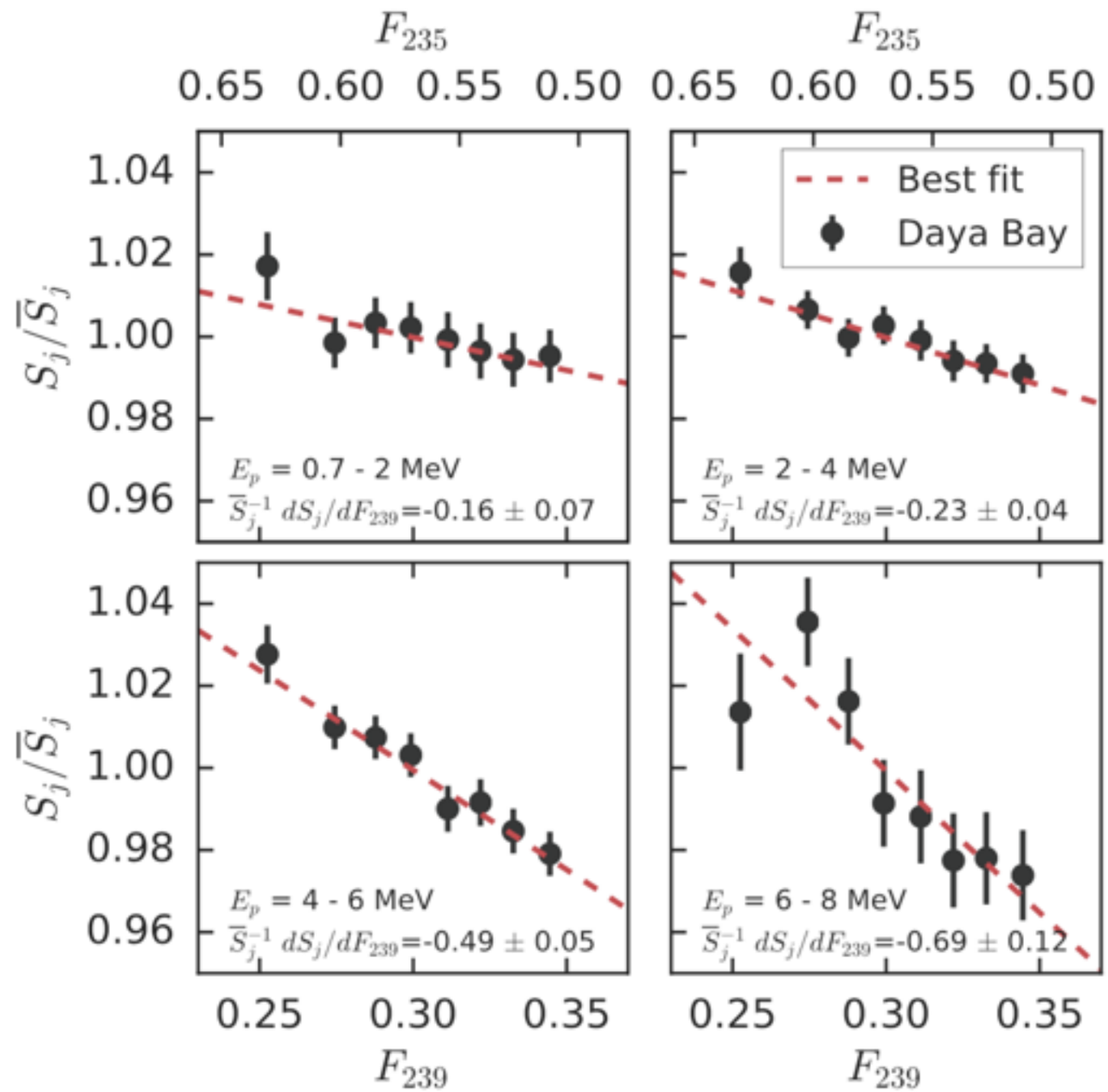
Result: Fitting For Individual Isotopes

- Use this data to explicitly fit IBD/fission for ^{235}U, ^{239}Pu
  - Assume loose (10%) uncertainties on sub-dominant ^{238}U, ^{241}Pu
- Dominant uncertainties:
  - Statistics
  - Absolute detection efficiency
- The explanation of ^{235}U only being wrong fits the data well.
  - ^{239}Pu also matches model well.
- Note: CLs are significant, but not overwhelming
  - Future Highly Enriched Uranium (HEU) and Daya Bay measurements will be necessary for improvements.



Results: Spectrum Evolution

- What if we add IBD energy into the mix?
  - Examine evolution in 4 separate energy ranges
- Slope is different for different energy ranges.
- Put another way: IBD spectrum is changing with F_{239}
  - **This is the first unambiguous measurement of this behavior**
  - **Highly relevant to ν_e based nuclear non-proliferation**



Spectrum Evolution: Data-Model Comparison

- 4-6 MeV region: no strange behavior visible with respect to the models
  - No major indication that 'bump' data-model discrepancy comes from a particular isotope. Statistics are too low for a meaningful test.

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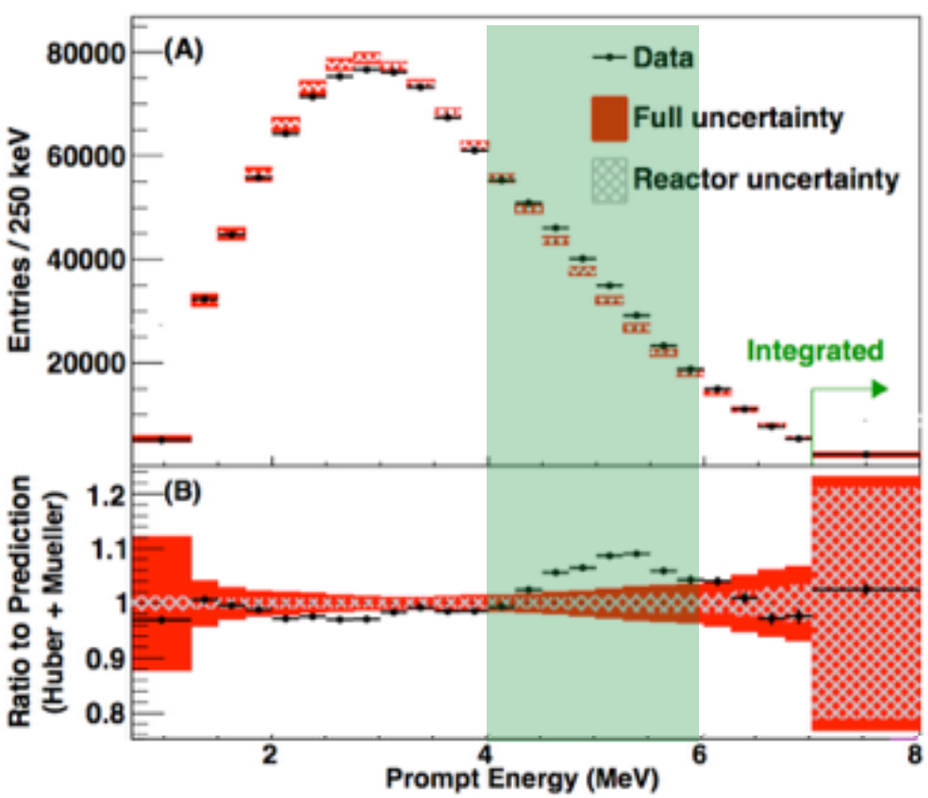
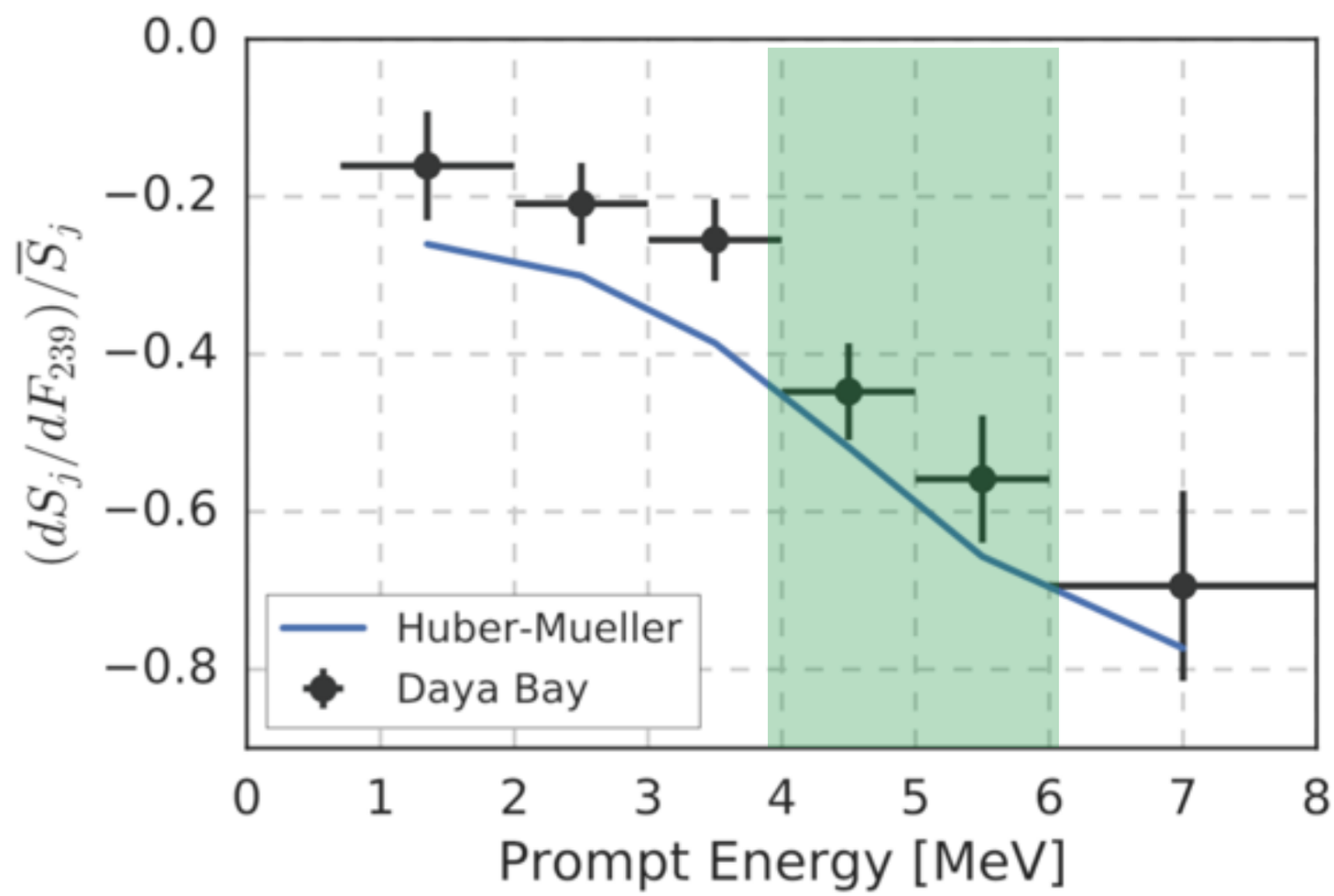
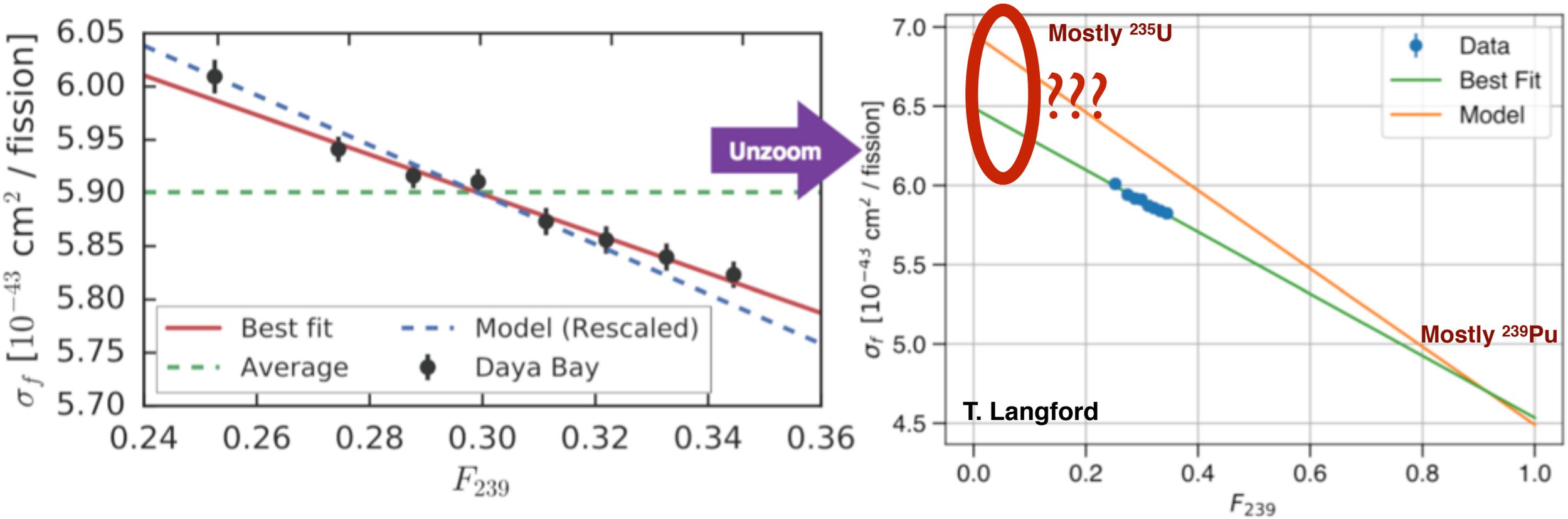




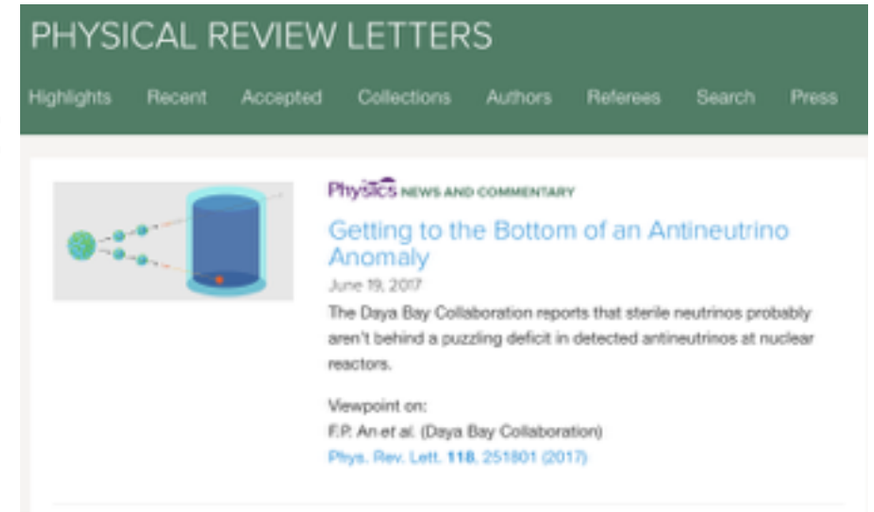
Future: New HEU Measurements

- Would be great to probe a wider range of fission fractions



- Highly Enriched Uranium cores provide a chance to sample wider fission fraction ranges.
  - **If ^{235}U is to blame, antineutrino flux deficit should be even larger here**
- Enter PROSPECT at highly-enriched ^{235}U HFIR reactor in Oak Ridge, Tennessee

Summary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Physics NEWS AND COMMENTARY

Getting to the Bottom of an Antineutrino Anomaly

June 19, 2017

The Daya Bay Collaboration reports that sterile neutrinos probably aren't behind a puzzling deficit in detected antineutrinos at nuclear reactors.

Viewpoint on:
F.P. An *et al.* (Daya Bay Collaboration)
Phys. Rev. Lett. **118**, 251801 (2017)

- Various reasons to question reactor $\bar{\nu}_e$ models:
  - "The Reactor Antineutrino Anomaly"
  - "Spectrum anomalies"
- New Daya Bay flux and spectrum evolution results uncover <u>another</u> flaw: **flux evolution is incorrectly predicted.**
  - Indicates that incorrect flux predictions are partially responsible for reactor flux anomaly
- Upcoming measurements can further clarify this picture:
  - SBL reactor measurements at HEU cores are essential for probing the nature of the spectral anomaly, and for making conclusive, model-independent tests for sterile neutrinos.

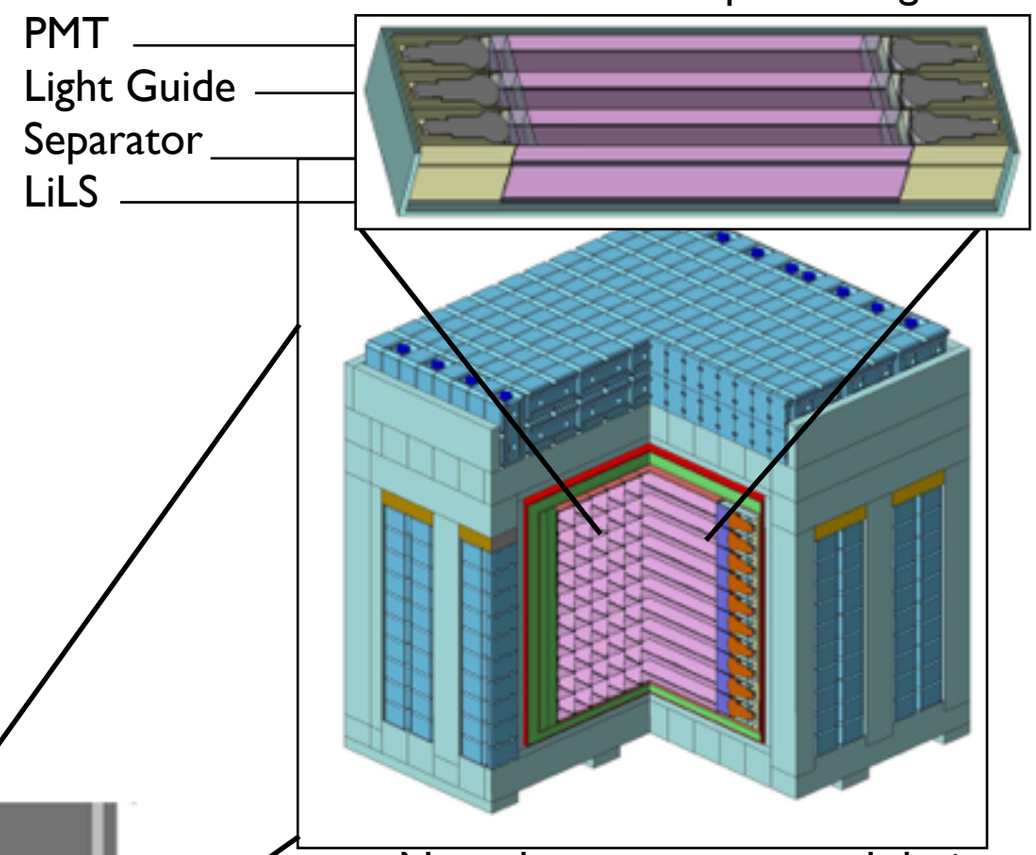
Thanks!
Gracias!

image A. Obando (http://arturobando.blogspot.com)

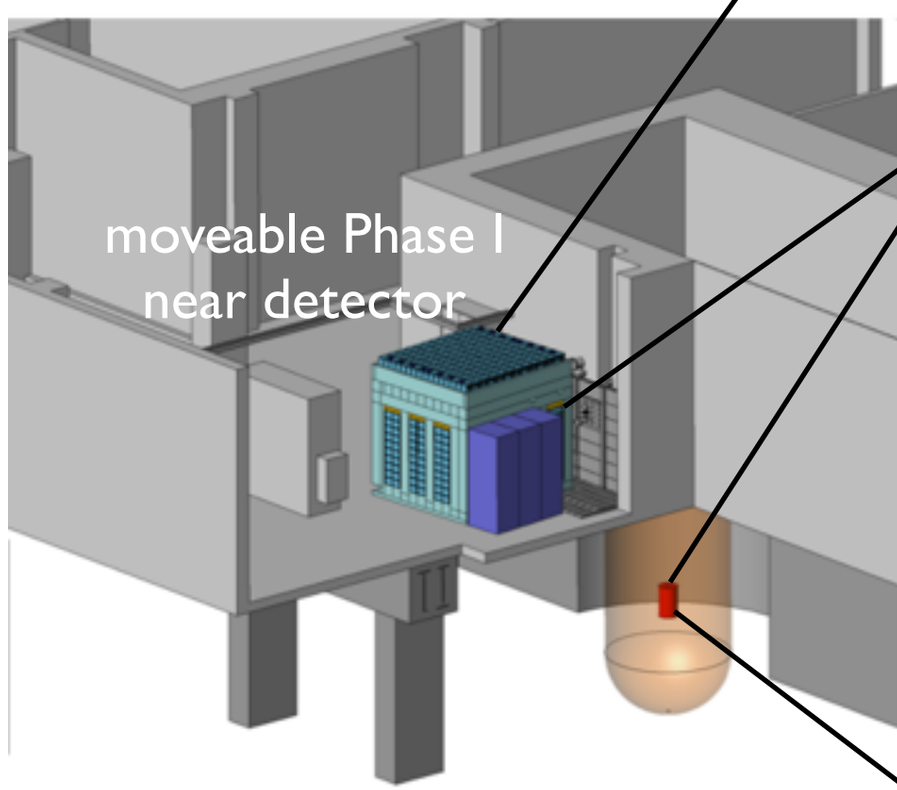
BACKUP

PROSPECT Experimental Layout

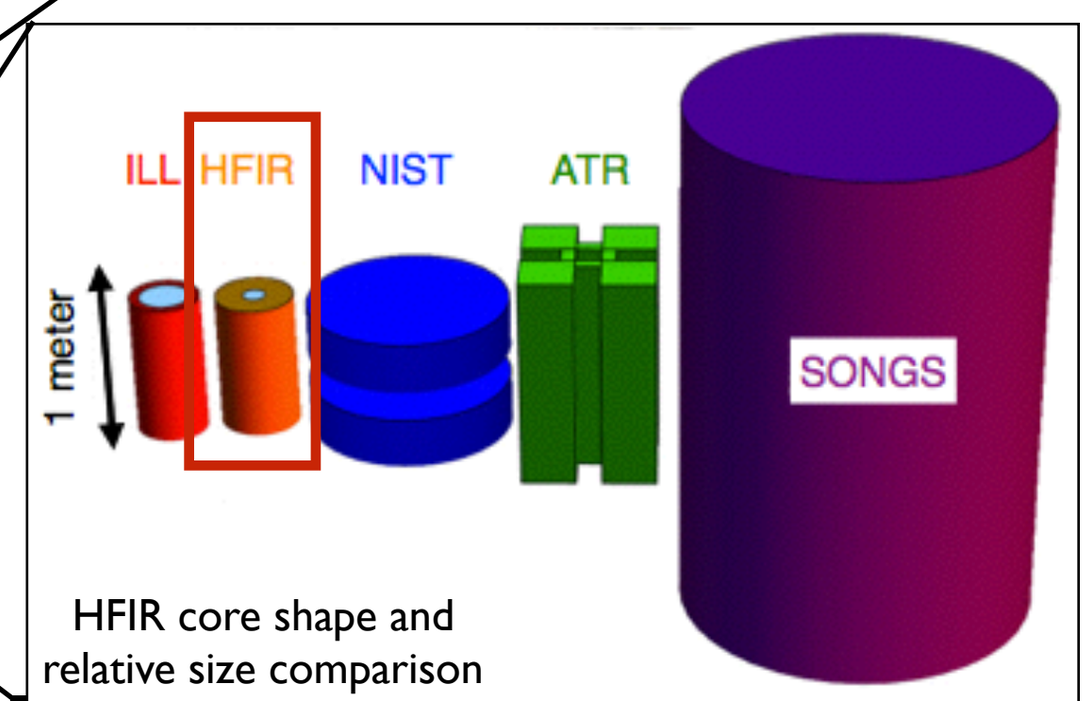
- HEU Reactor: HFIR
- Segmented liquid scintillator target region: ~4 tons for near detector (Phase I)
- Moveable: 7-12 m baselines
- Measure ^{235}U spectrum while directly probing sterile oscillations independent of reactor models



Near detector conceptual design



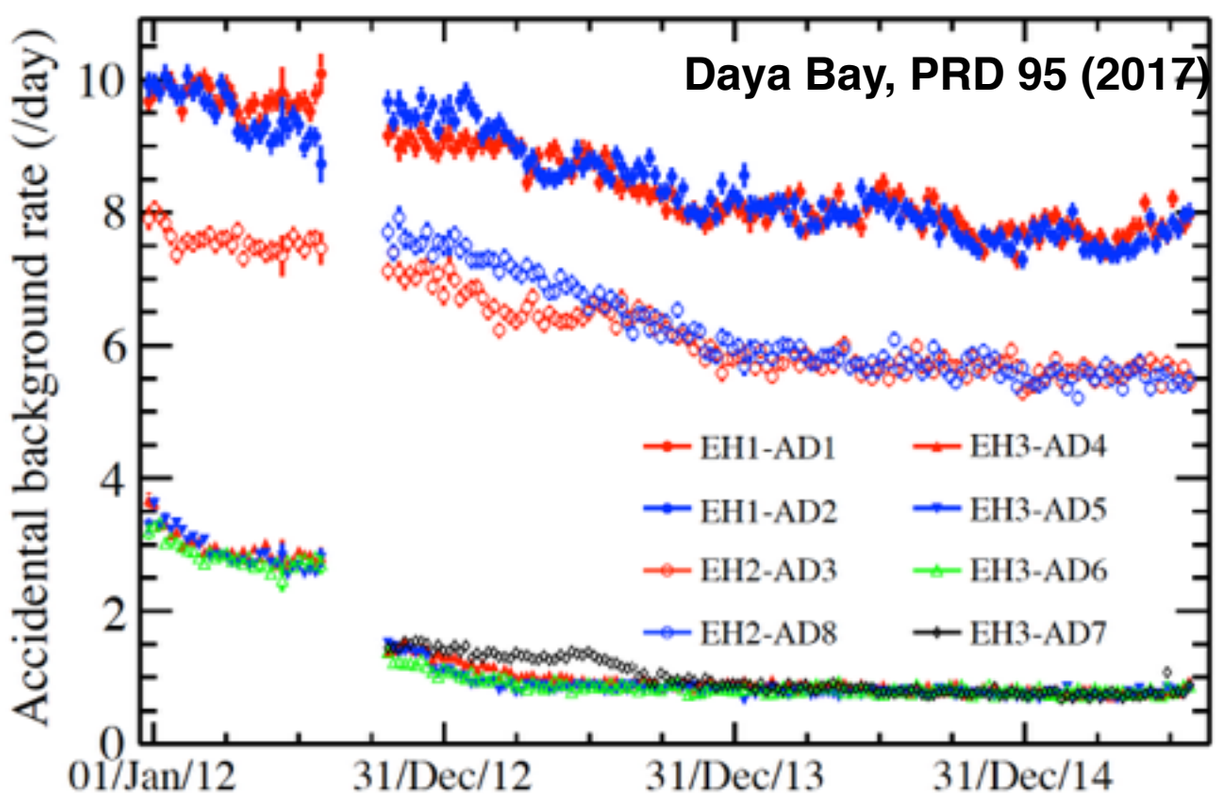
PROSPECT deployment at HFIR

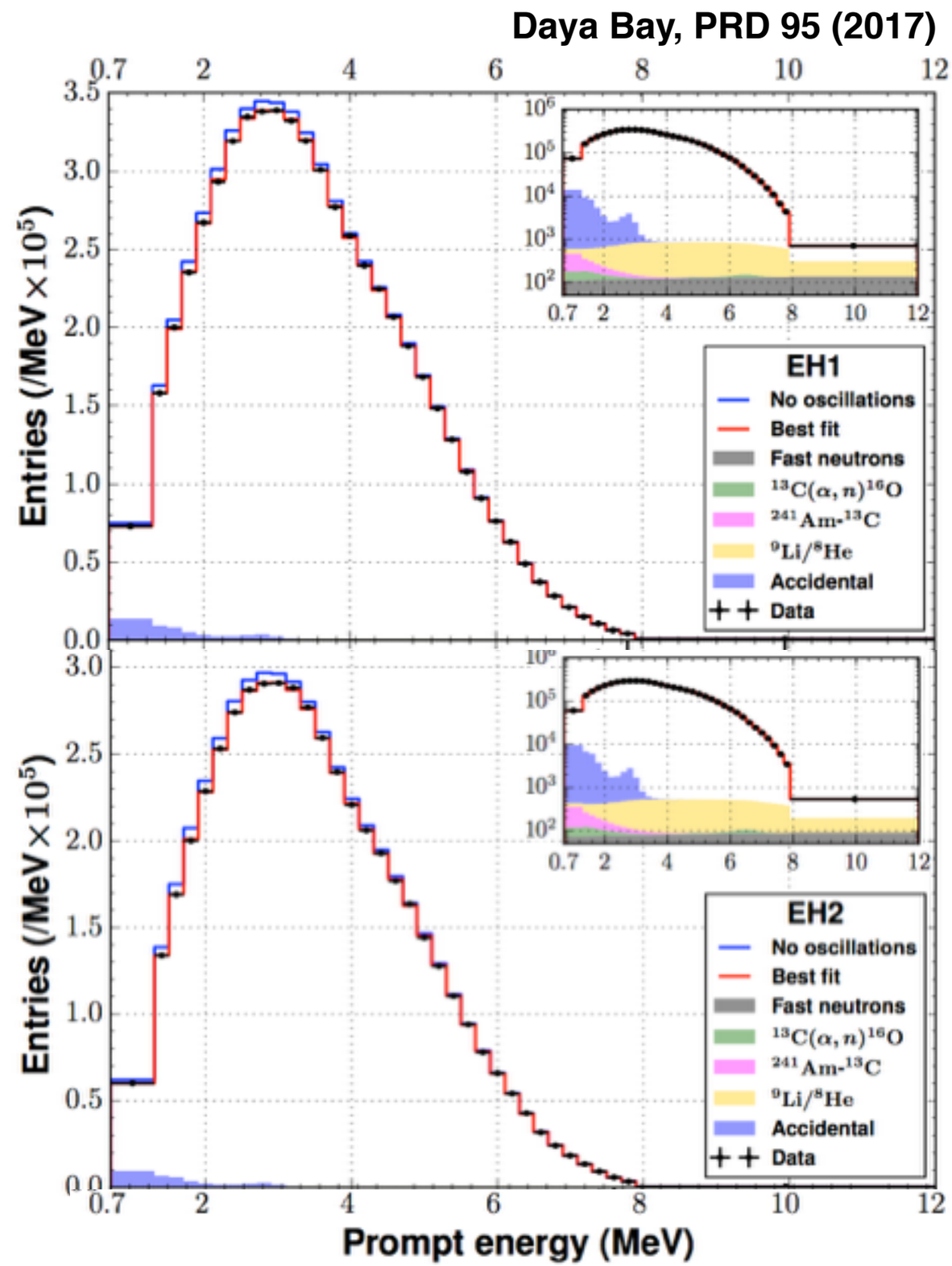


HFIR core shape and relative size comparison

Backgrounds

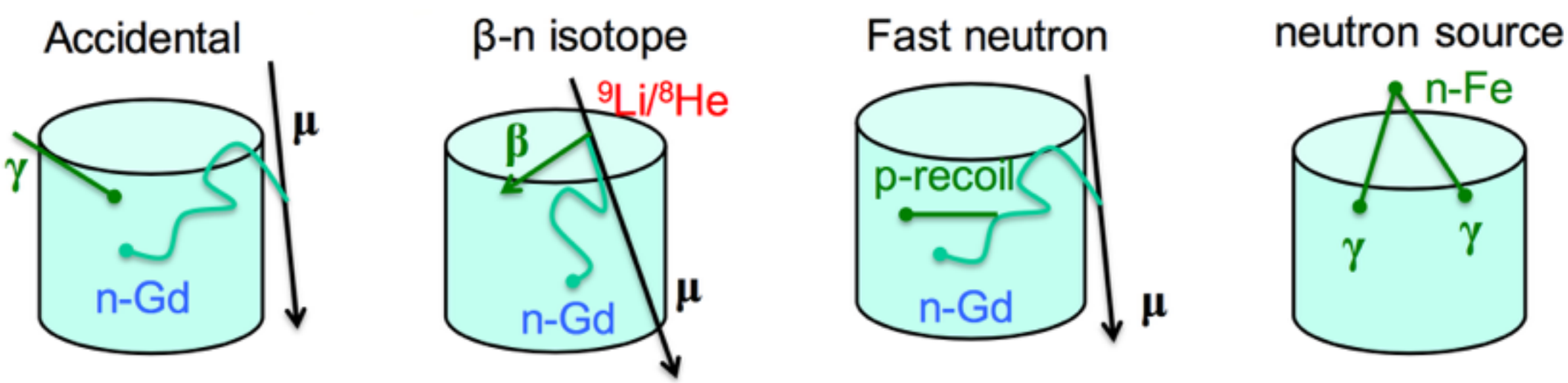
- Backgrounds make up <2% of Near Site IBD candidates
- Primary background: accidentally coincident triggers
  - 1.3% of near-site signal;
  - Other backgrounds are constant over time.





BACKGROUNDS

- Accidental coincidence between prompt and delayed signals ~1%
- During detector operation it was found that neutrons from the 241 Am-13 C calibration sources within the ACUs occasionally introduced several γ rays, correlated in time, to the detector. Contamination from this background was estimated to be ≲0.1%
- Fast neutrons: Muon interactions in the environment near the detector generated energetic, or fast neutrons <0.1%
- 9Li/8He b-n followers produced by cosmic muon spallation. 0.3-0.4%



The Daya Bay antineutrino detector

3 calibration units per detector.
3 sources per unit:
Ge68 (1.02 MeV)
Co60 (2.5 MeV)
Am241-C13(8 MeV)

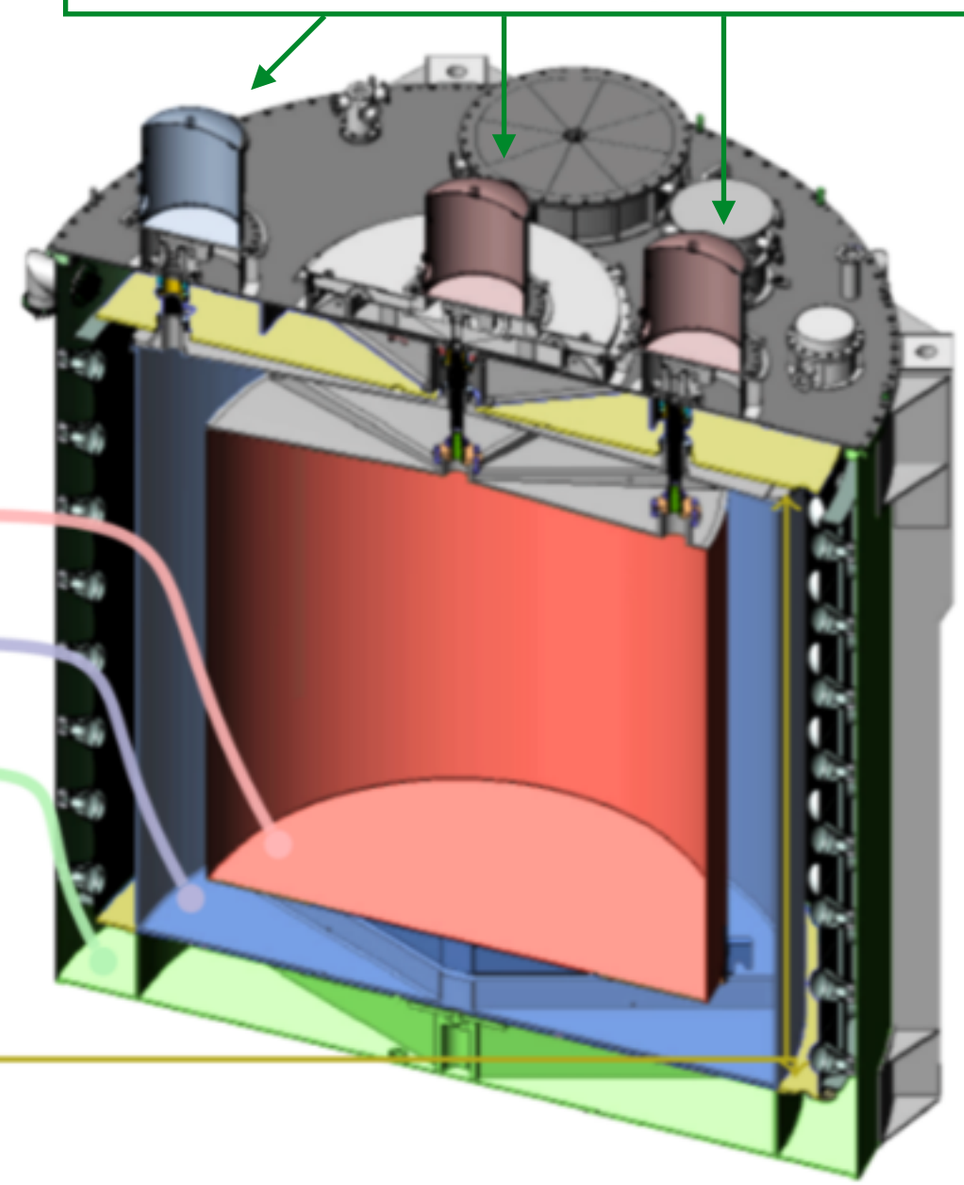
8 functionally identical detectors
reduce systematic uncertainties

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



Antineutrino flux measurement: IBD Yield per nuclear fission(sigma_f) and per GWth (Y)

- Calculate sigma_f^d for each detector

  - Md: number of measured IBD events in the d-th detector with backgrounds subtracted.
  - N_r^f is the predicted number of fissions from the r-th reactor core
  - E^iso (mean energy release per fission for each isotope)
  - f^iso_r (average fission fraction of rth core for each isotope)
  - W_r: average thermal power of r-th core
  - e_d^D : Total detection efficiency
  - Ldr: distance between d-th detector and r-th reactor core
  - P_sur^dr: Survival probability given and AD-core pair
  - N_d^T : Total number of target protons in the GdLS of each AD.

$$M_d = \sum_{r=1}^{6} \frac{N_r^f}{4\pi L_{dr}^2} \sigma_f^d N_d^{\mathrm{T}} P_{sur}^{dr} \epsilon_d^D ,$$

$$N_r^f = \int \frac{W_r}{\sum_{iso=1}^{4} f_r^{iso} E^{iso}} \mathrm{d}t.$$

$$Y_d \equiv \sigma_f^d N_r^f / W_r$$

DATA

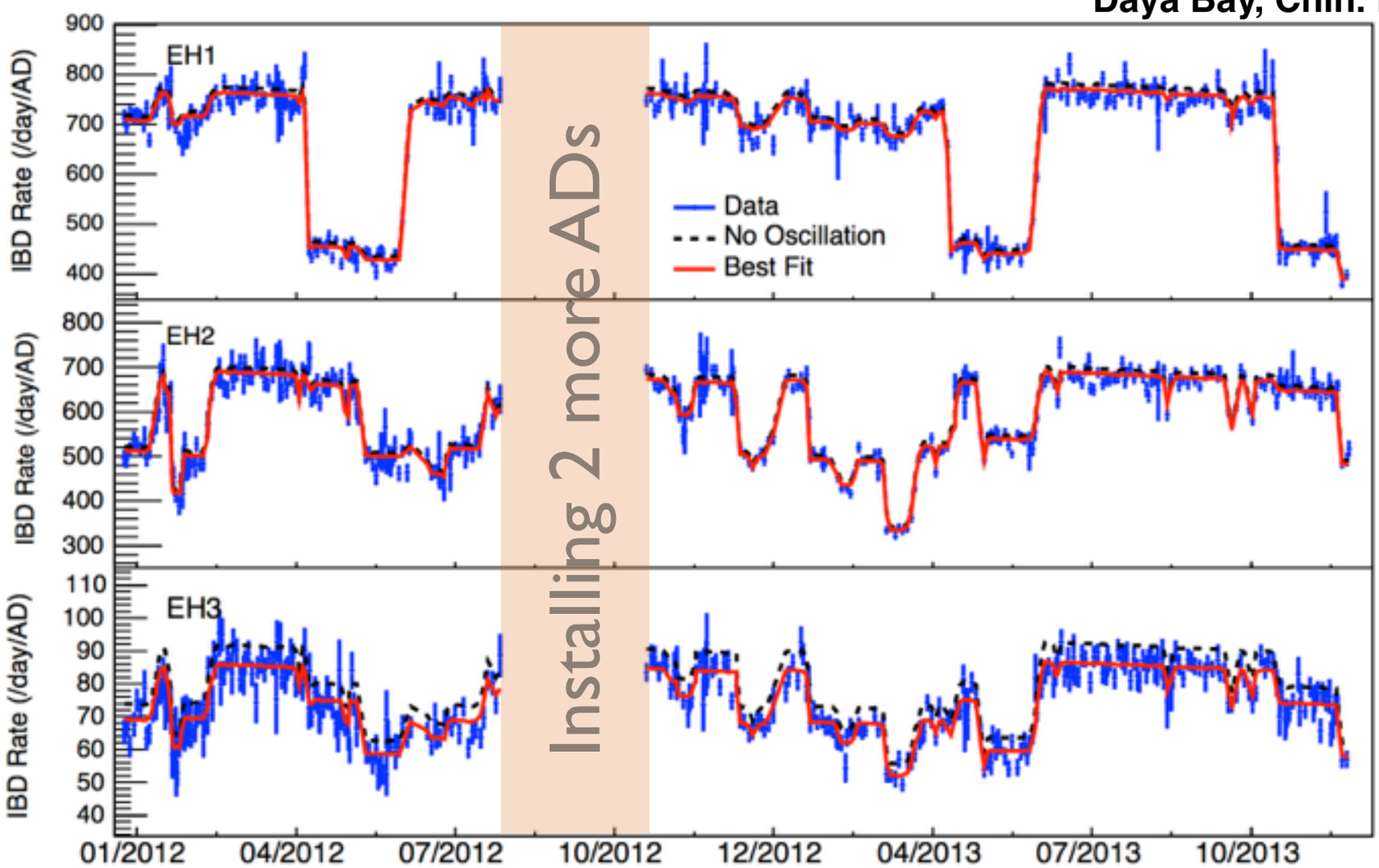
$$\sigma_f = \sum_{iso=1}^{4} f_{iso} \int S_{iso}(E_\nu)\sigma(E_\nu) dE_\nu$$

Predicted (Huber-Mueller or ILL-Vogel)

IBD candidate rates

- ~ 400-800 IBDs in each near site antineutrino detector per day (x4 ADs)
- Can see when reactors are turned on and off

Daya Bay, Chin. Phys. C 41(1) (2017)



Info:
1230-day dataset
goes to July 2015

Systematics: Detector

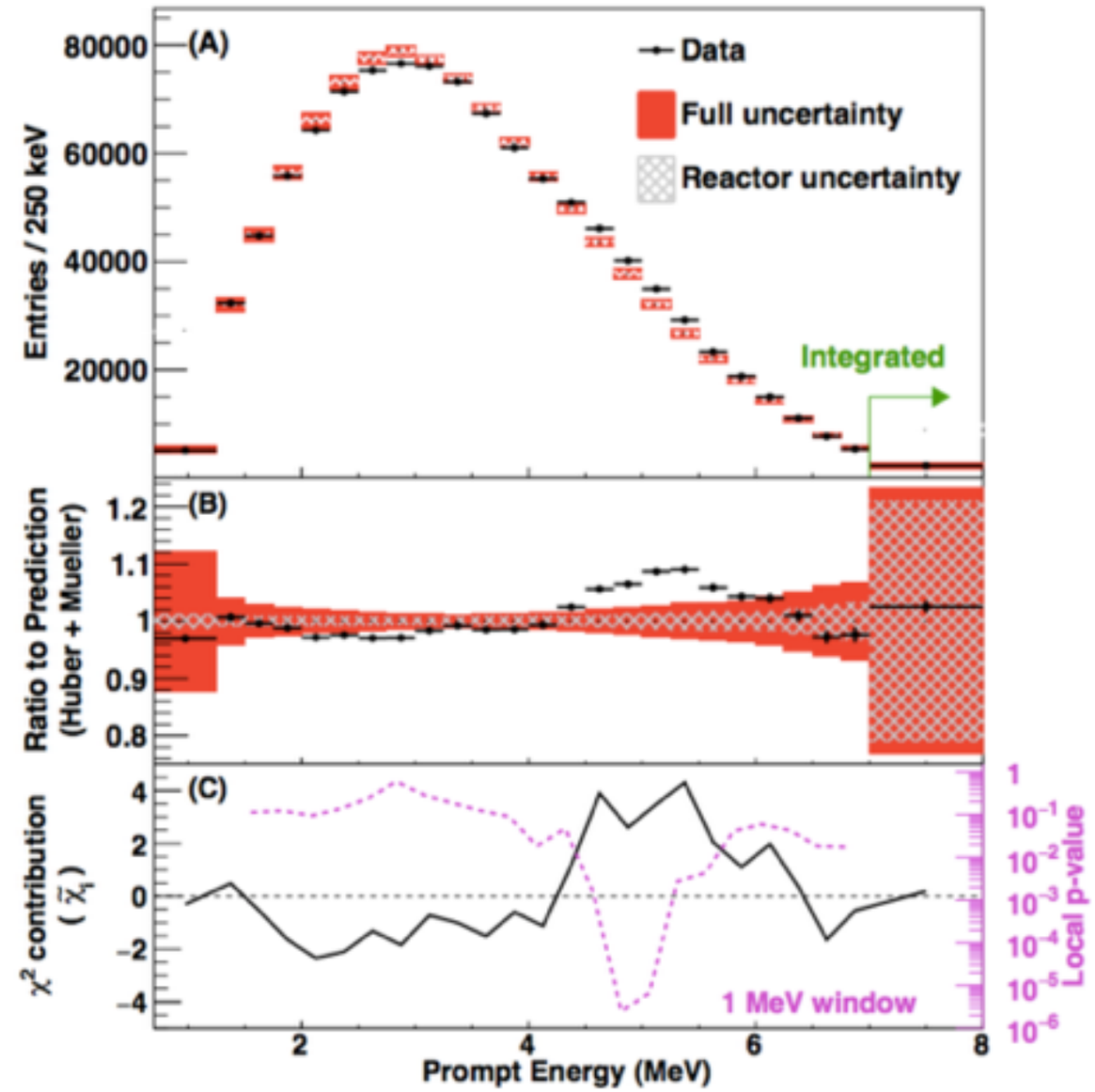
- How does a detector change over time?
  - Reconstructed energy scales are **<u>extremely</u>** time-stable (<0.1% variation)

Daya Bay prompt energy spectrum measurement and the "excess" in the 4-6 MeV region

- Measurements of neutrino capture time, vertex distributions,delayed energy spectrum of events around 5 MeV region are consitent with the rest of IBD events

- Theoretical predictions do not account for the excess of the 4-6 MeV excess in the prompt energy spectrum with a local significance of 4.4 sigma

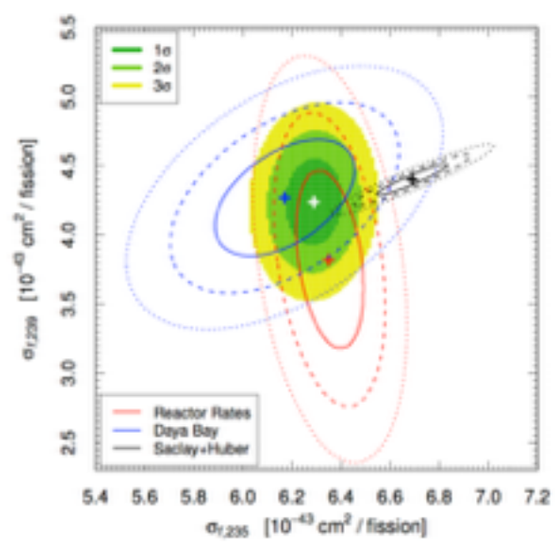
- Huber/Mueller prediction can not described the entire prompt energy spectrum at 2.9 sigma



The hatched and red filled bands represent the square-root of diagonal elements of the covariance matrix (sqrt(Vii)) for the reactor related and the full systematic uncertainties, respectively

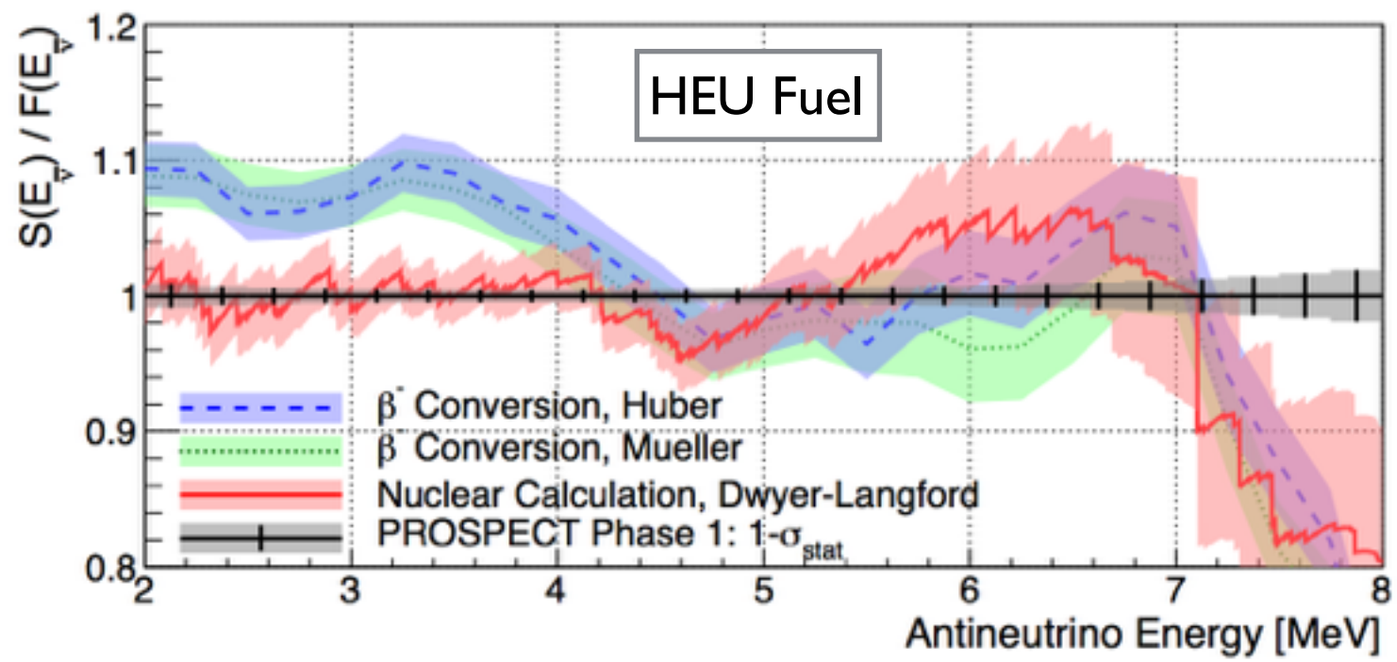
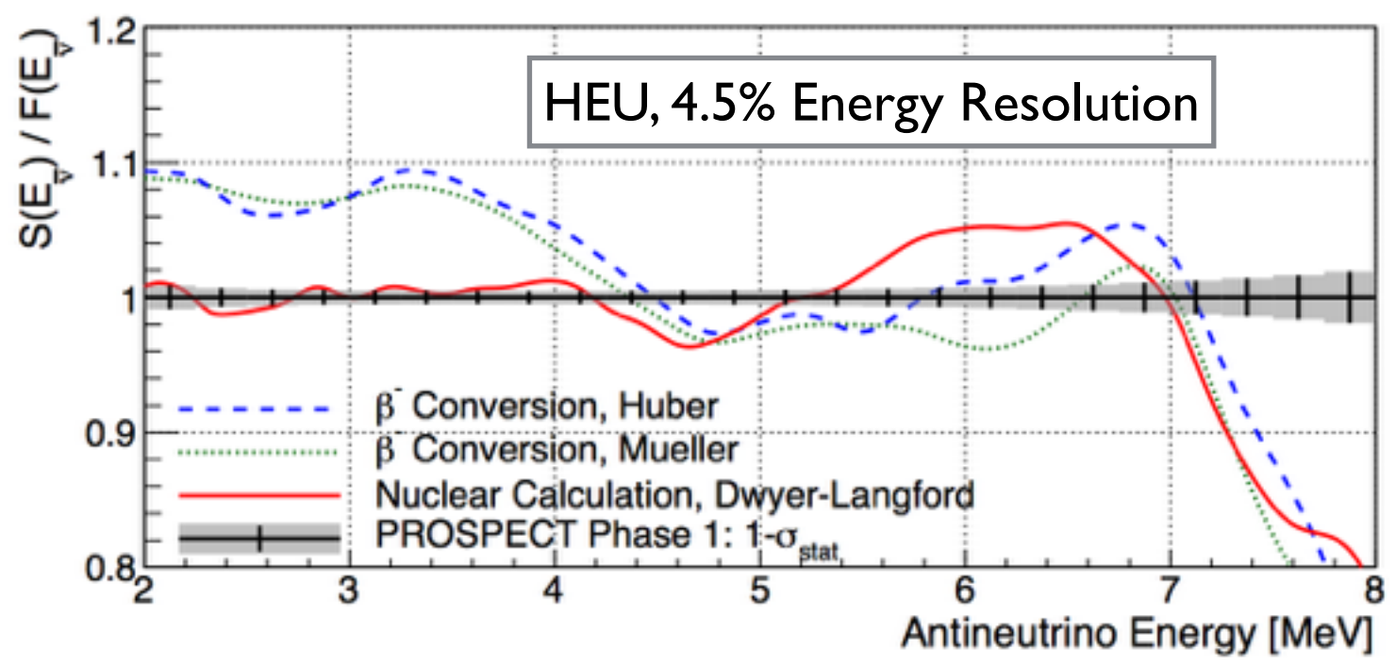
Global fit data and results

a	Experiment	f^a_{235}	f^a_{238}	f^a_{239}	f^a_{241}	$R^{exp}_{a,SH}$	σ^{exp}_a [%]	σ^{cor}_a [%]		L_a [m]
1	Bugey-4	0.538	0.078	0.328	0.056	0.932	1.4	1.4		15
2	Rovno91	0.606	0.074	0.277	0.043	0.930	2.8			18
3	Rovno88-1I	0.607	0.074	0.277	0.042	0.907	6.4	3.8	2.2	18
4	Rovno88-2I	0.603	0.076	0.276	0.045	0.938	6.4			18
5	Rovno88-1S	0.606	0.074	0.277	0.043	0.962	7.3	3.8		18
6	Rovno88-2S	0.557	0.076	0.313	0.054	0.949	7.3			25
7	Rovno88-2S	0.606	0.074	0.274	0.046	0.928	6.8			18
8	Bugey-3-15	0.538	0.078	0.328	0.056	0.936	4.2	4.0		15
9	Bugey-3-40	0.538	0.078	0.328	0.056	0.942	4.3			40
10	Bugey-3-95	0.538	0.078	0.328	0.056	0.867	15.2			95
11	Gosgen-38	0.619	0.067	0.272	0.042	0.955	5.4	2.0	3.8	37.9
12	Gosgen-46	0.584	0.068	0.298	0.050	0.981	5.4			45.9
13	Gosgen-65	0.543	0.070	0.329	0.058	0.915	6.7			64.7
14	ILL	1	0	0	0	0.792	9.1			8.76
15	Krasnoyarsk87-33	1	0	0	0	0.925	5.0	4.1		32.8
16	Krasnoyarsk87-92	1	0	0	0	0.942	20.4			92.3
17	Krasnoyarsk94-57	1	0	0	0	0.936	4.2	0		57
18	Krasnoyarsk99-34	1	0	0	0	0.946	3.0	0		34
19	SRP-18	1	0	0	0	0.941	2.8	0		18.2
20	SRP-24	1	0	0	0	1.006	2.9	0		23.8
21	Nucifer	0.926	0.061	0.008	0.005	1.014	10.7	0		7.2
22	Chooz	0.496	0.087	0.351	0.066	0.996	3.2	0		≈ 1000
23	Palo Verde	0.600	0.070	0.270	0.060	0.997	5.4	0		≈ 800
24	Daya Bay	0.561	0.076	0.307	0.056	0.946	2.0	0		≈ 550
25	RENO	0.569	0.073	0.301	0.056	0.946	2.1	0		≈ 410
26	Double Chooz	0.511	0.087	0.340	0.062	0.935	1.4	0		≈ 415



	SH	Reactor Rates	Daya Bay	Combined
$\sigma_{f,235}$	6.69 ± 0.14	6.35 ± 0.09	6.17 ± 0.17	6.29 ± 0.08
$\sigma_{f,239}$	4.40 ± 0.11	3.82 ± 0.43	4.27 ± 0.26	4.24 ± 0.21

TABLE I. Comparison of the theoretical Saclay+Huber (SH) values of the cross sections per fission $\sigma_{f,235}$ and $\sigma_{f,239}$ with those obtained from the fit of the reactor rates, from the Daya Bay data [5], and from the combined fit. The units are 10^{-43} cm^2/fission.

PROSPECT Physics: Absolute Spectrum

- How much fine structure exists in reactor spectrum?
  - Ab initio calculations suggest significant fine structure from endpoints of prominent beta branches
- PROSPECT can provide highest-ever energy resolution on the spectrum
  - Thus, will give best fine structure measurement
  - Goal resolution: 4-5%
  - Provide constraints on individual beta branches (reactor spectroscopy)?
  - Input for next reactor experiments (JUNO)?