Evolution of the Reactor $\overline{\nu}_e$ Flux and Spectrum At Daya Bay

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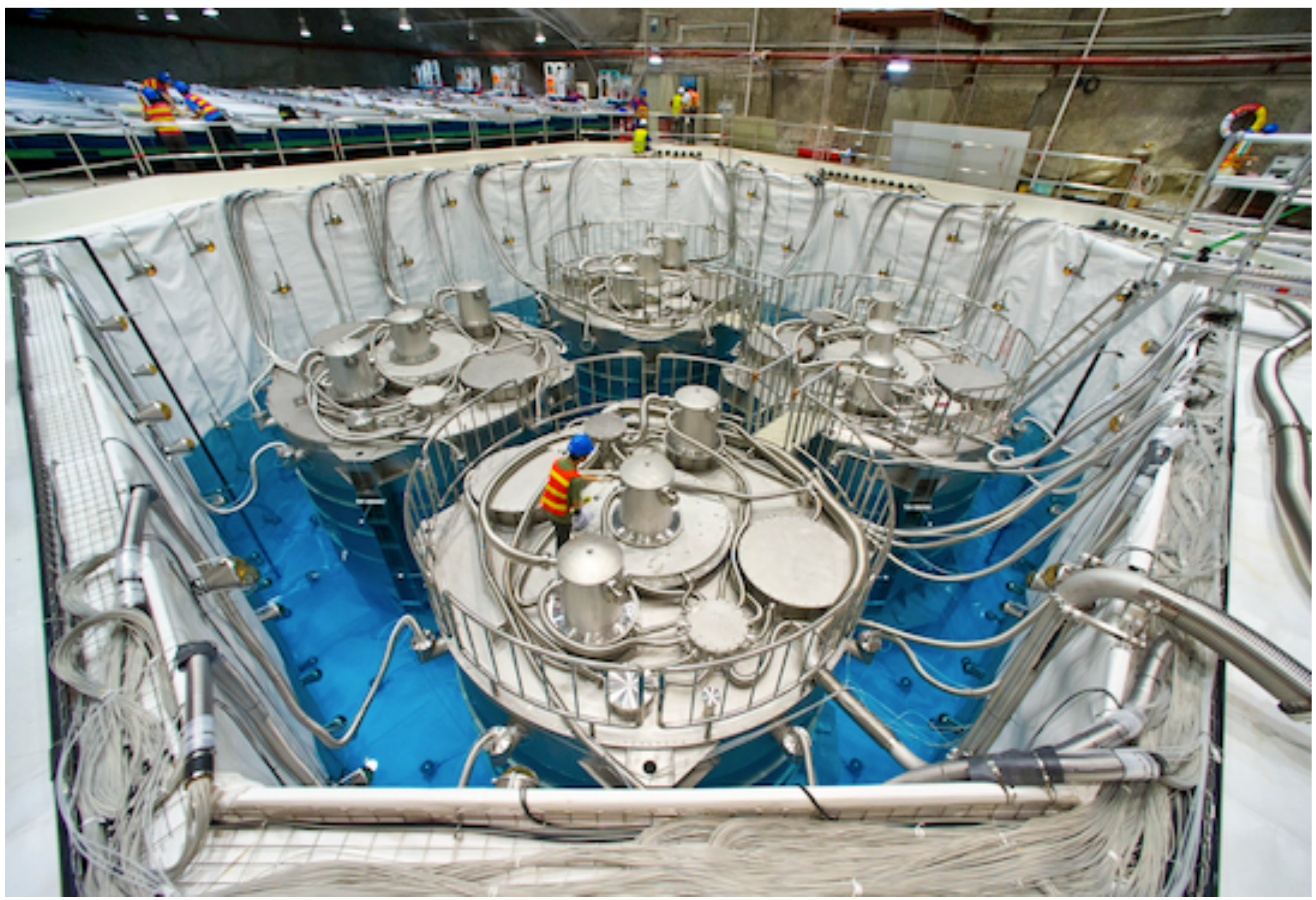
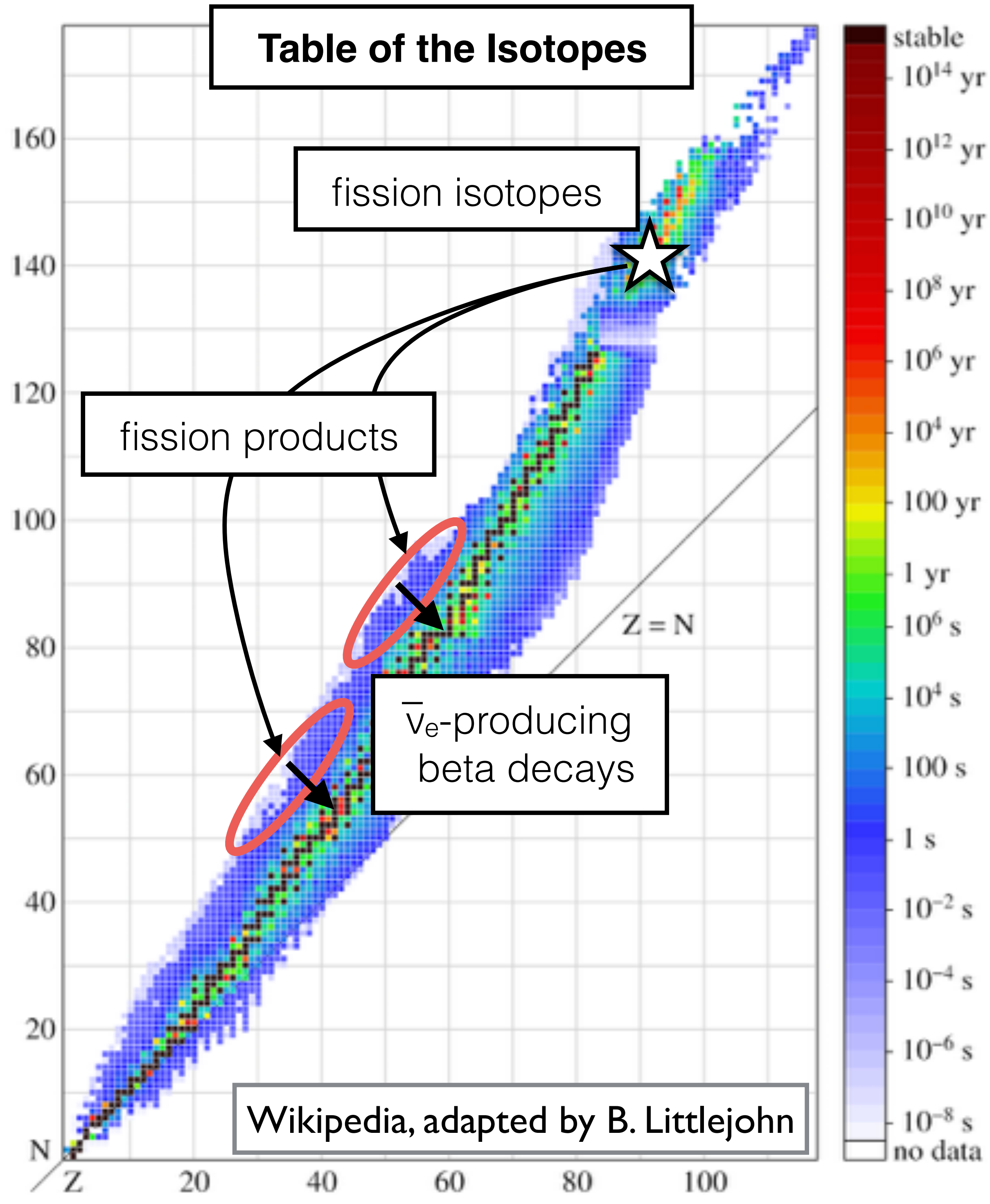
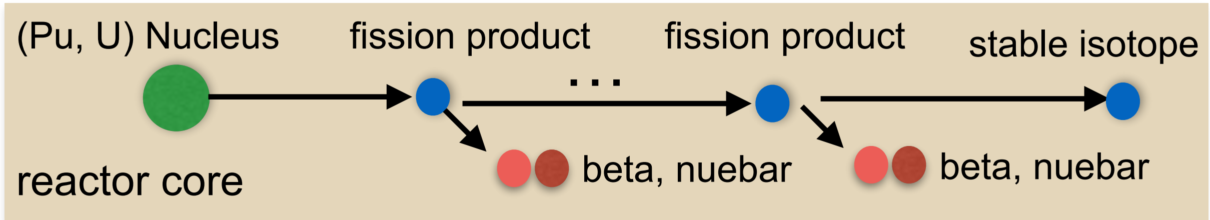


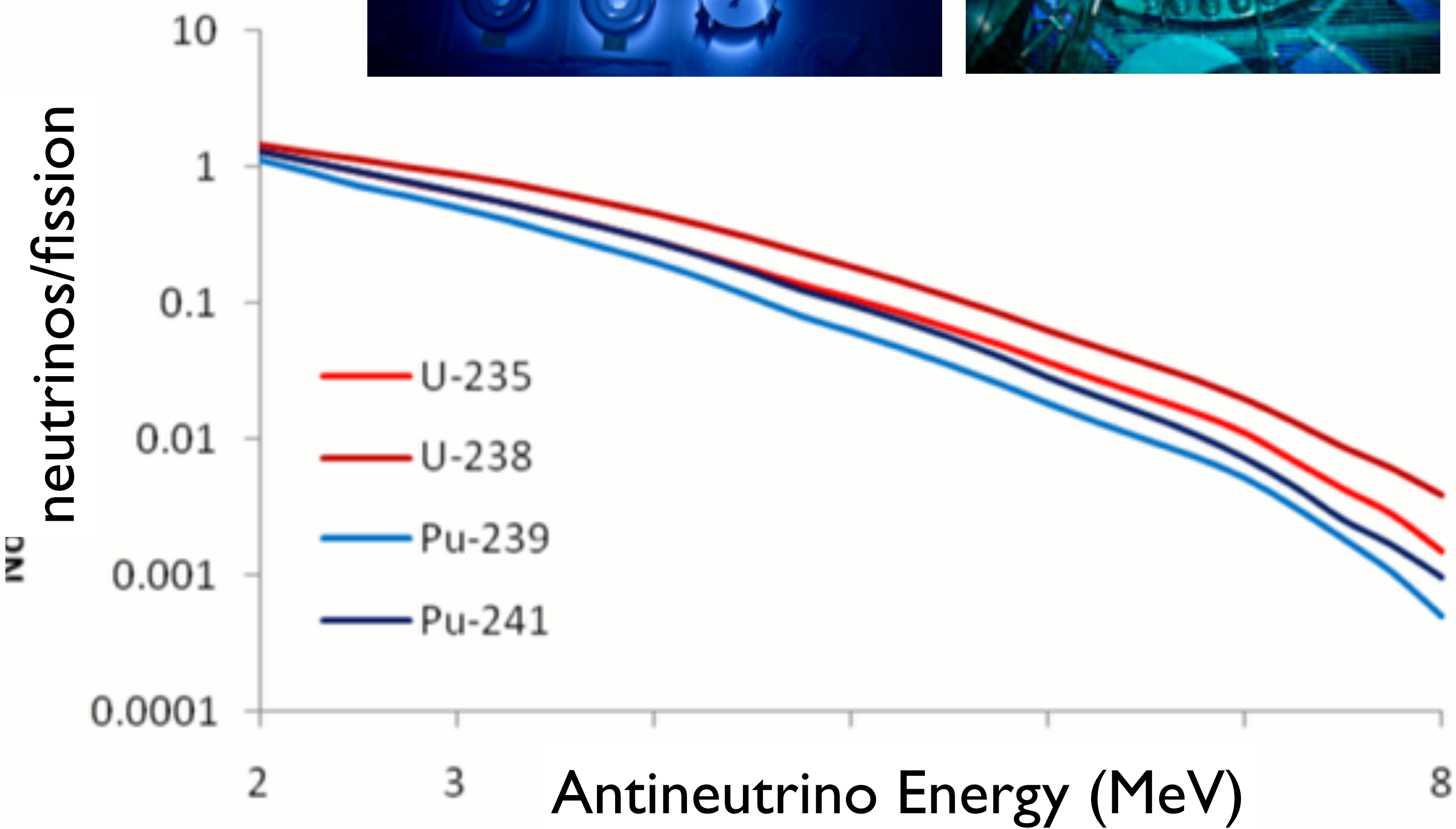
https://arxiv.org/abs/1704.01082

Reactor Antineutrino Production

- Reactor $\bar{\nu}_e$: produced in decay of product beta branches
  - Each isotope: different branches, so different neutrino energies, fluxes

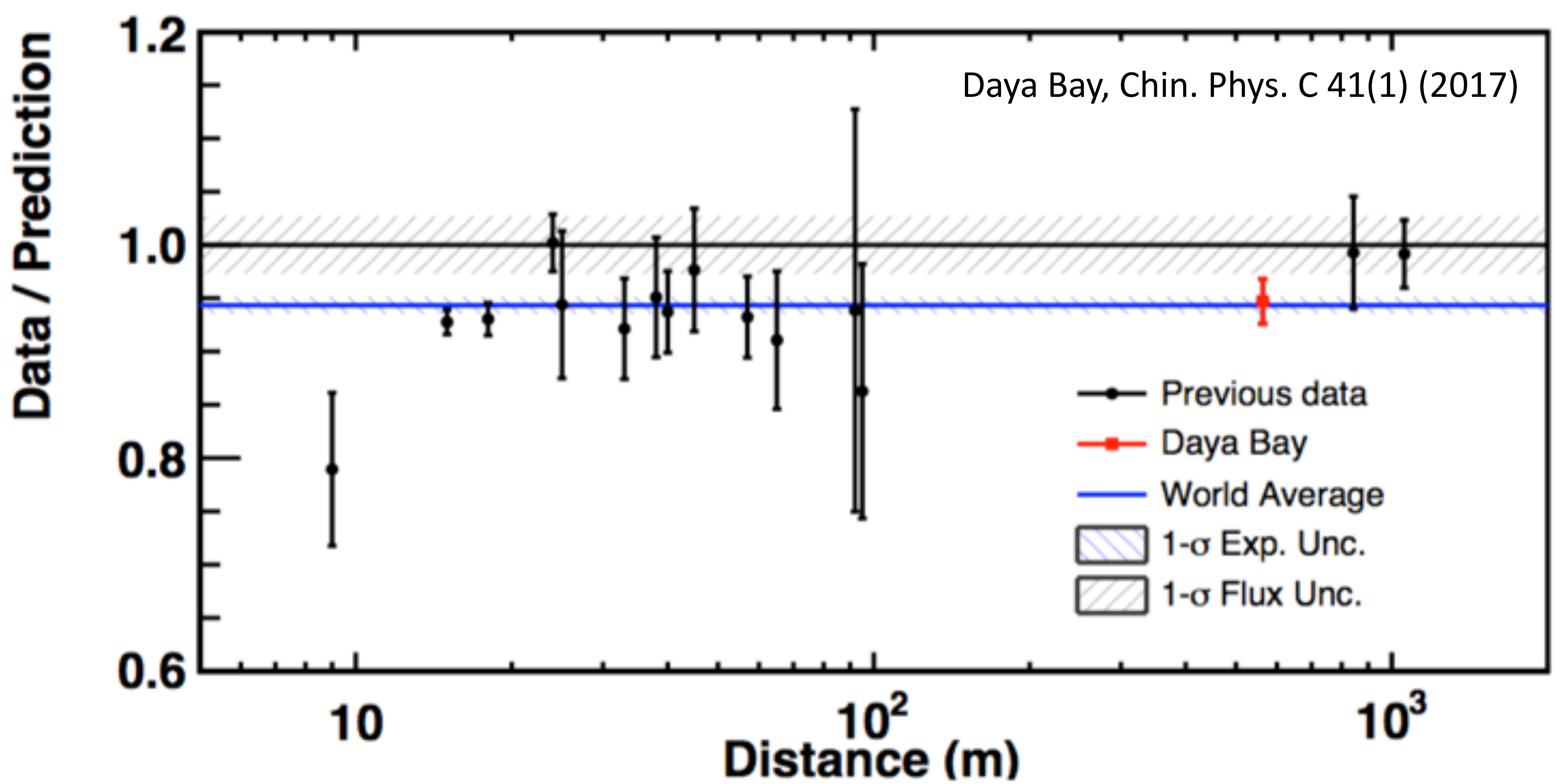






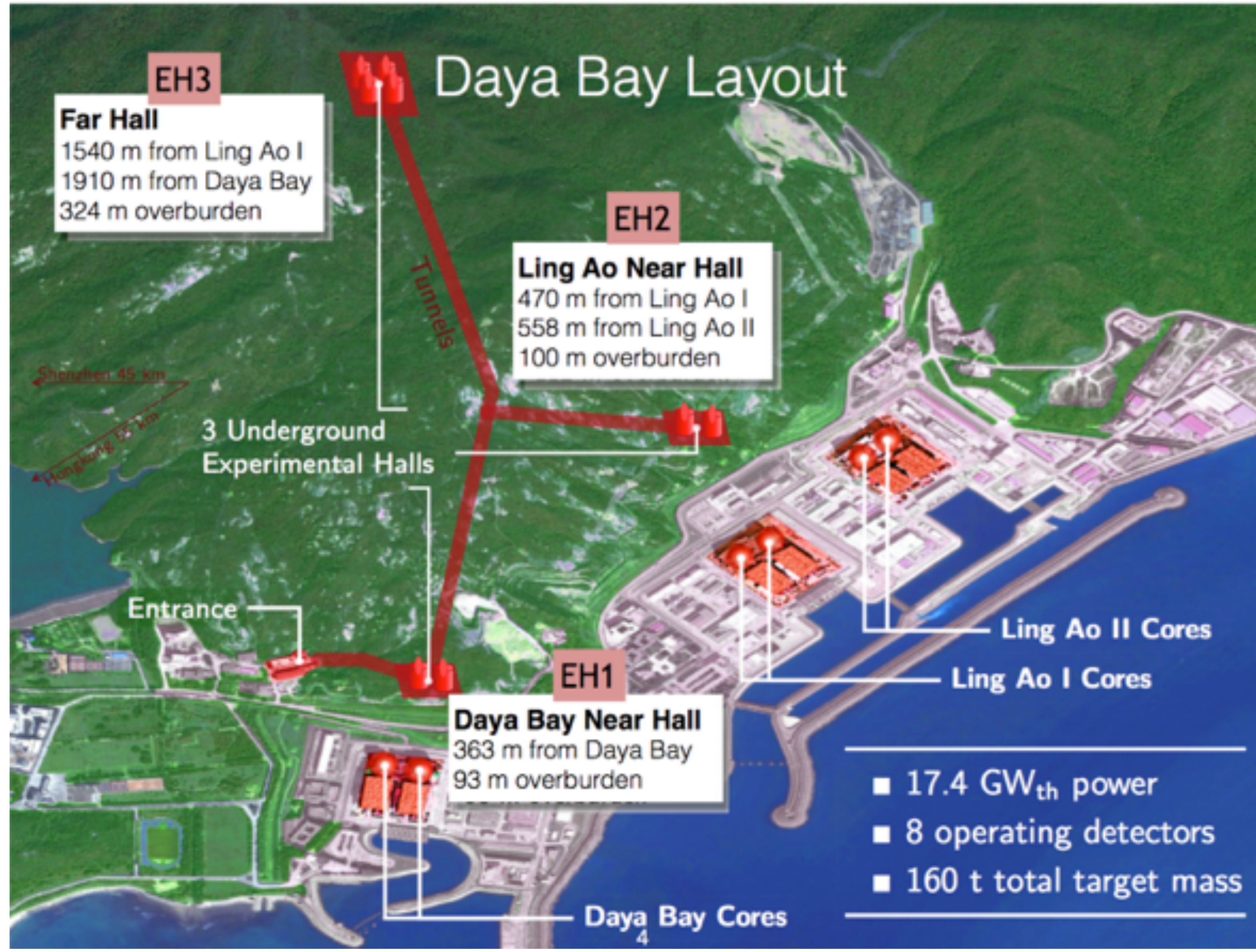
The Reactor Antineutrino Anomaly

- Existing global deficit in measured $\bar{\nu}_e$ flux at all baselines
- What's going on??? Is the anomaly real? What is the cause?
  - Many nuclear physicists: flux predictions might just be wrong!
  - Many particle physicists: no, maybe this is another hint for sterile neutrinos!
- More information needed to differentiate these two hypotheses



Daya Bay Layout

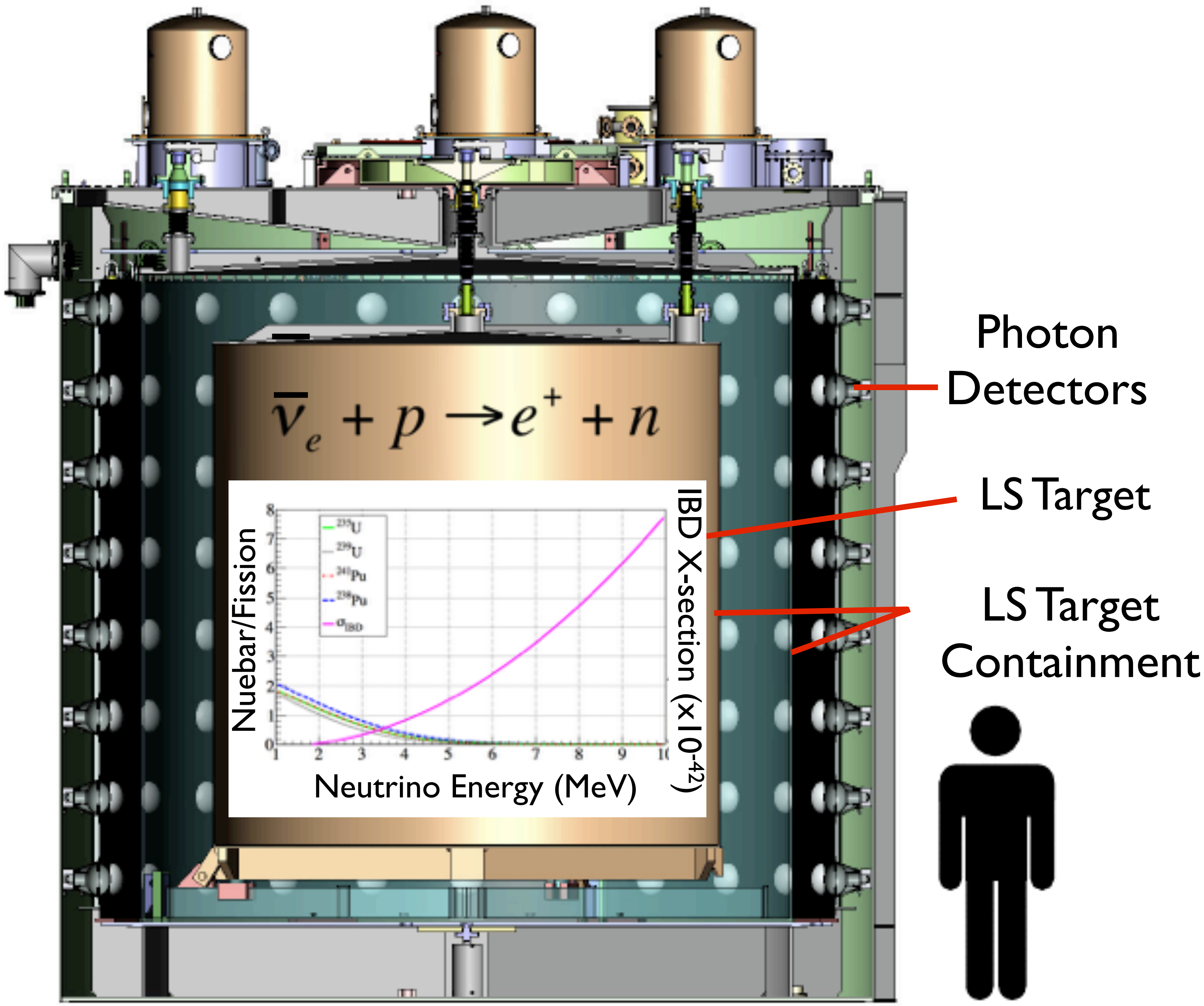
- Original concept with 8 'identical' detectors:
  - Near detectors constrain flux
  - Far detectors see if any neutrinos have disappeared.
- Daya Bay has ideal specs for doing this



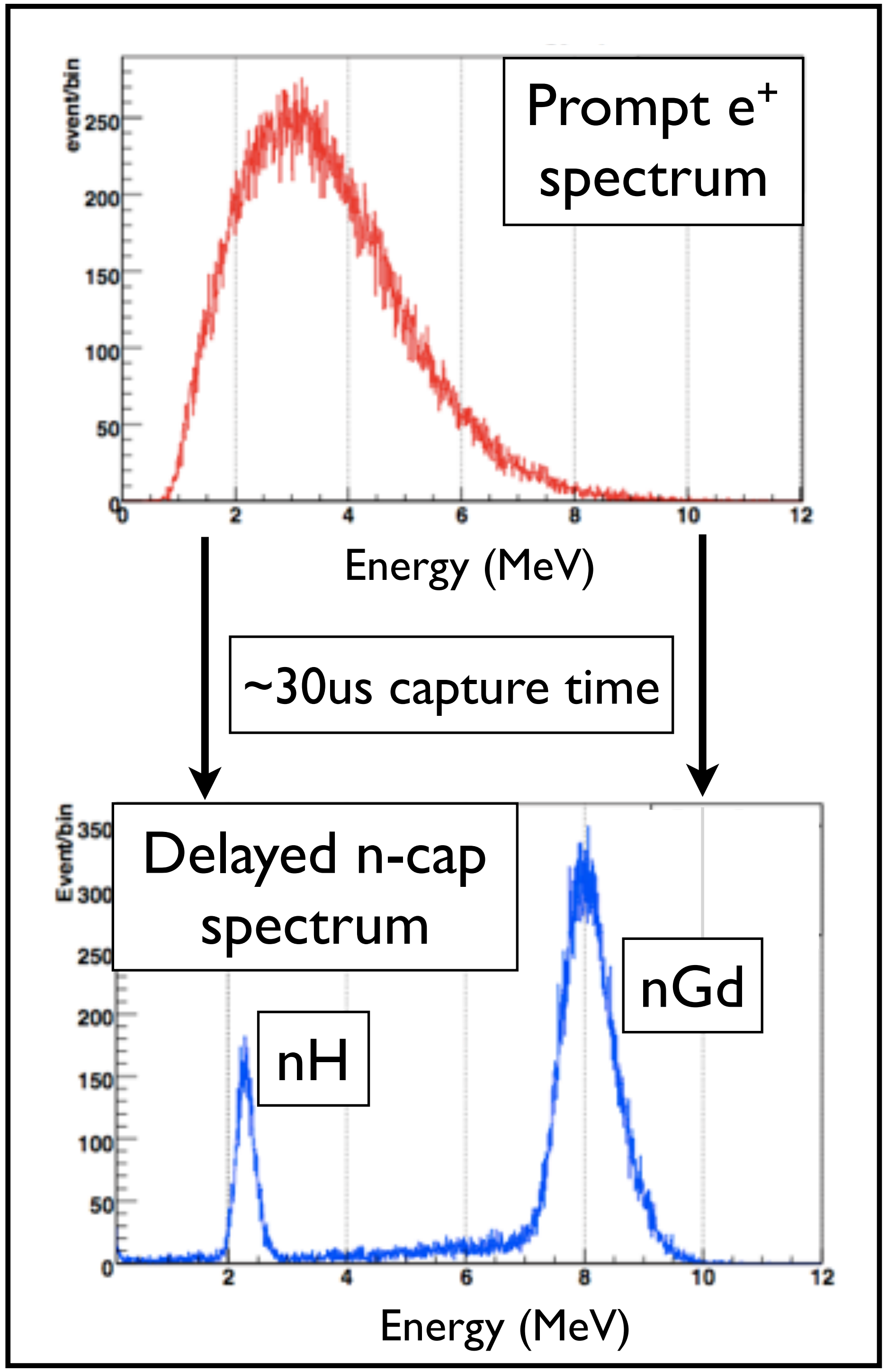
	Reactor [GW_{th}]	Target [tons]	Depth [m.w.e]
Double Chooz	8.6	16 (2 × 8)	300, 120 (far, near)
RENO	16.5	32 (2 × 16)	450, 120
Daya Bay	17.4	160 (8 × 20)	860, 250
	Large Signal		Low Background

Daya Bay Antineutrino Detectors (ADs)

- Detect inverse beta decay (IBD) with liquid scintillator, PMTs
  - IBD e+ is direct proxy for antineutrino energy



Daya Bay Detector



Daya Bay Monte Carlo

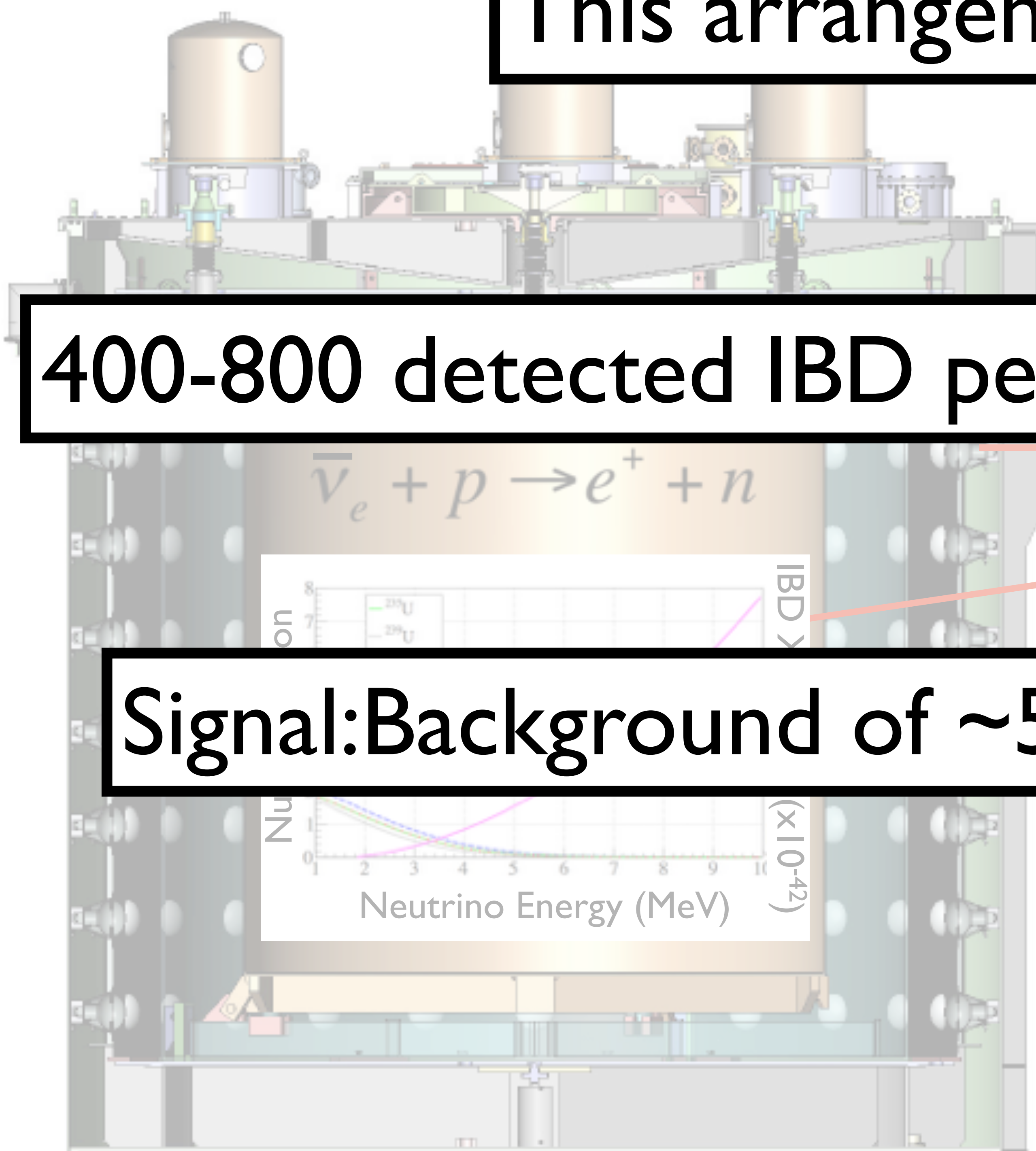
Reactor Antineutrino Detection: Daya Bay

- Detect inverse beta decay (IBD) with liquid scintillator, PMTs
  - IBD e+ is d...

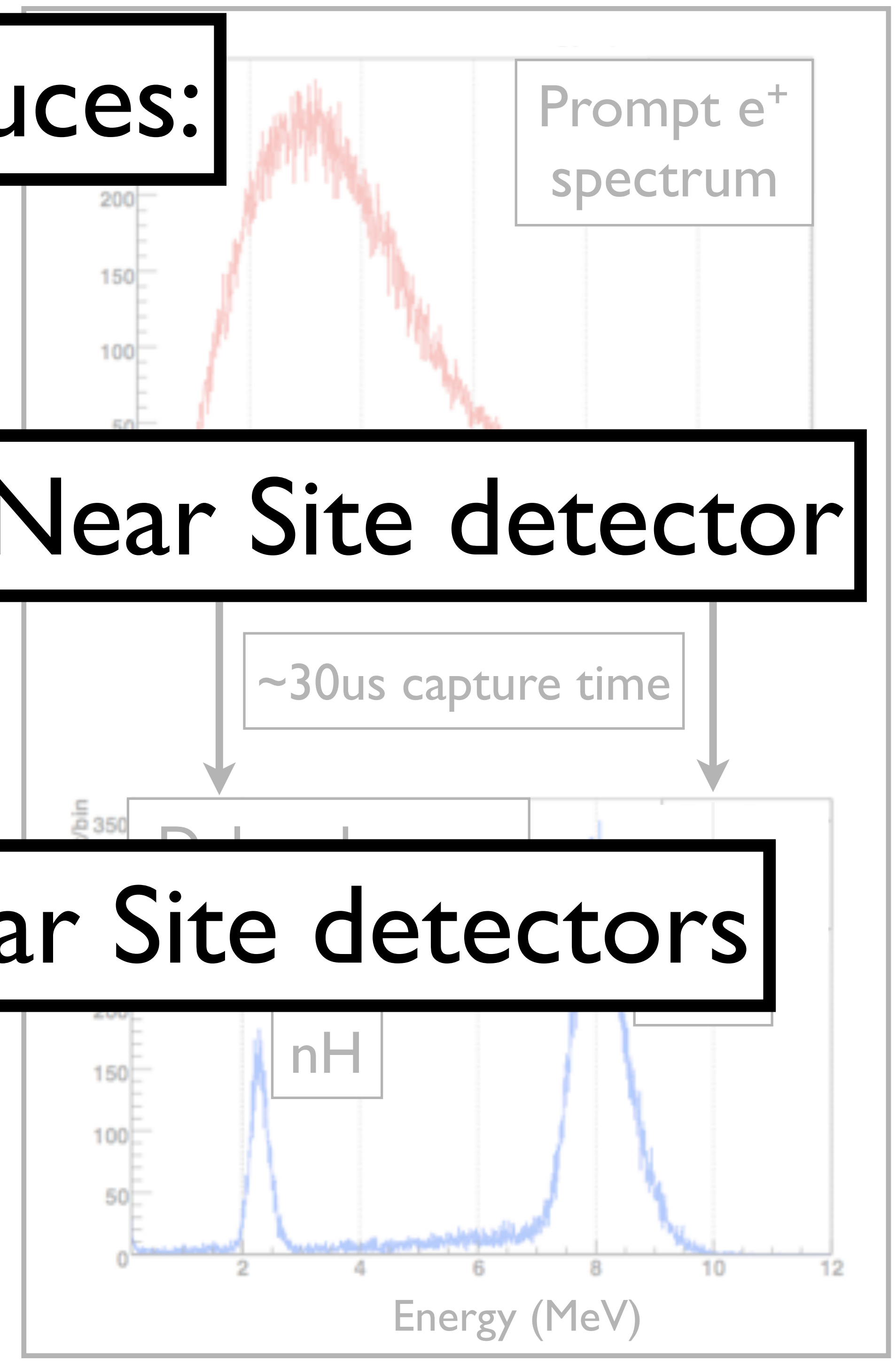
This arrangement produces:

400-800 detected IBD per day per Near Site detector

Signal:Background of ~50:1 in Near Site detectors



Daya Bay Detector



Daya Bay Monte Carlo Data

Past Daya Bay Analyses

- Previous Daya Bay analyses:
- STEP 1: Integrate all IBD over all times
- STEP 2a: Compare IBD rate/spectrum between Near, Far
- STEP 2b: Compare IBD rate/spectrum to theoretical models

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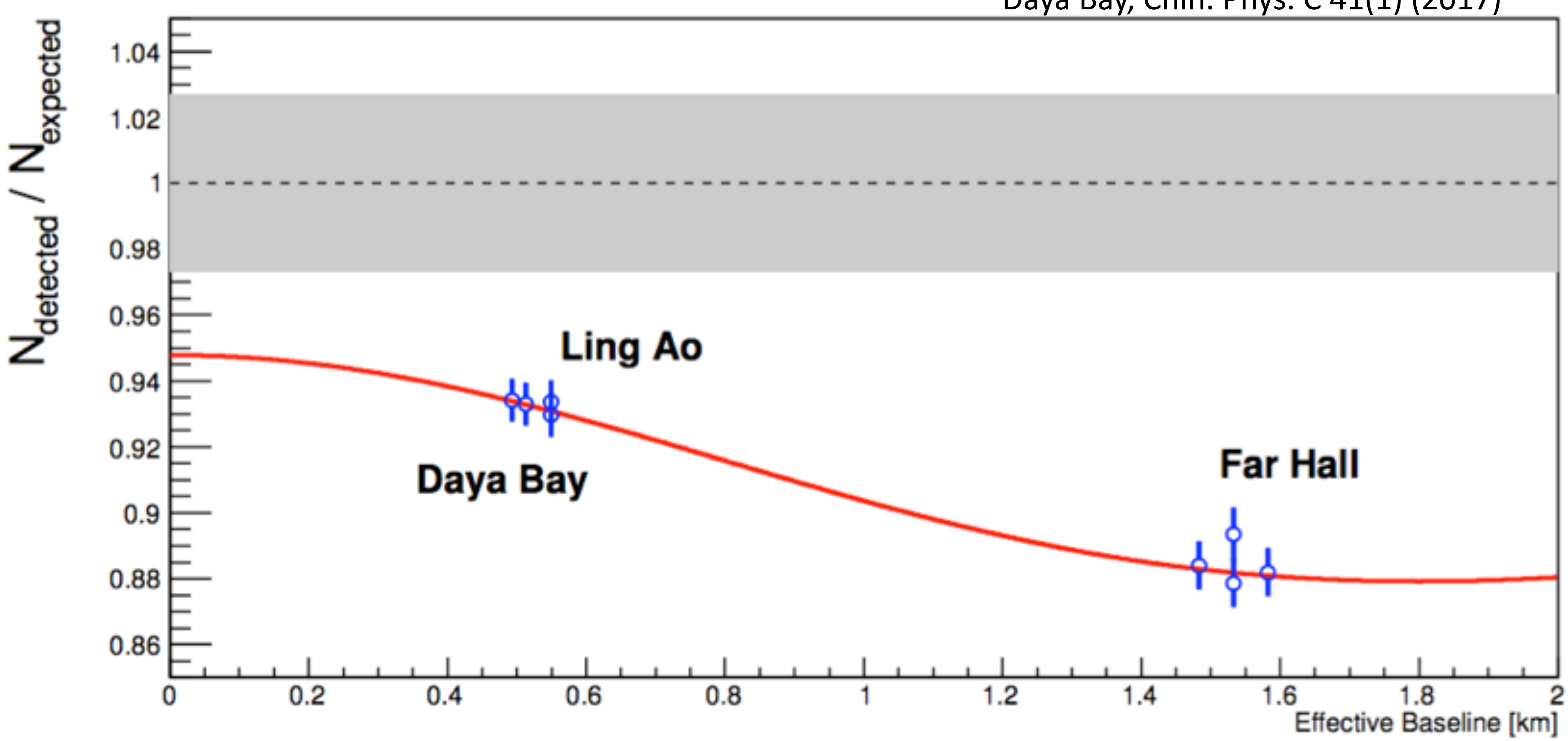

Daya Bay Evolution Analysis

- <u>DO NOT</u> 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:
  - Weight core fission fraction by power, baseline, oscillation, etc.

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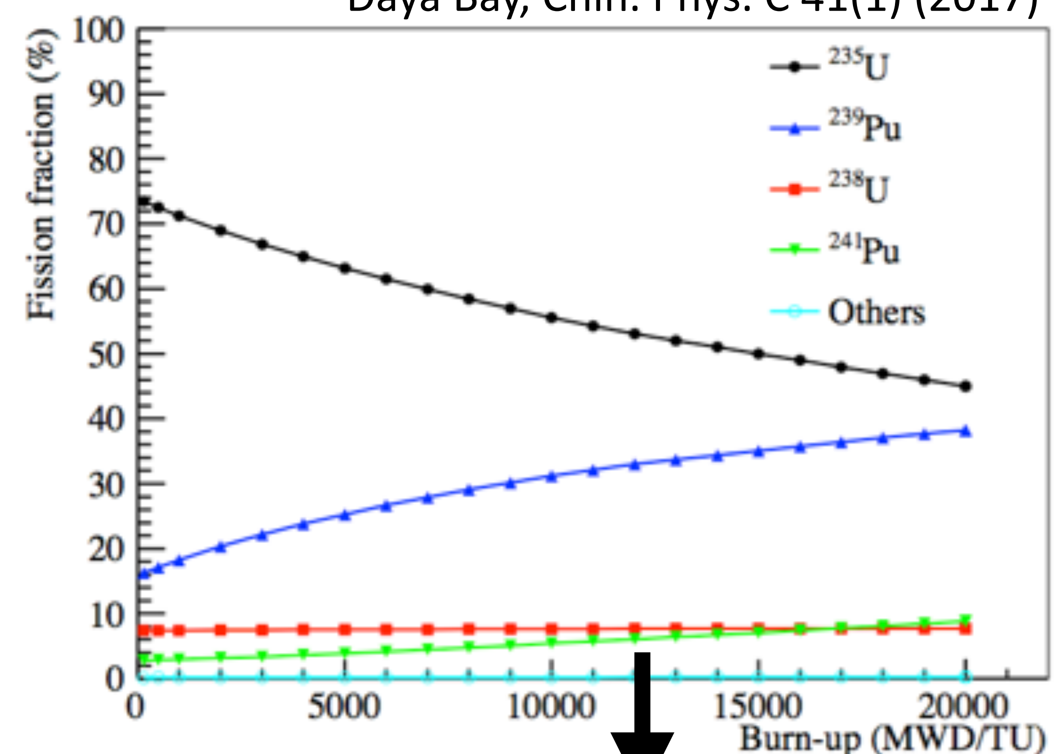
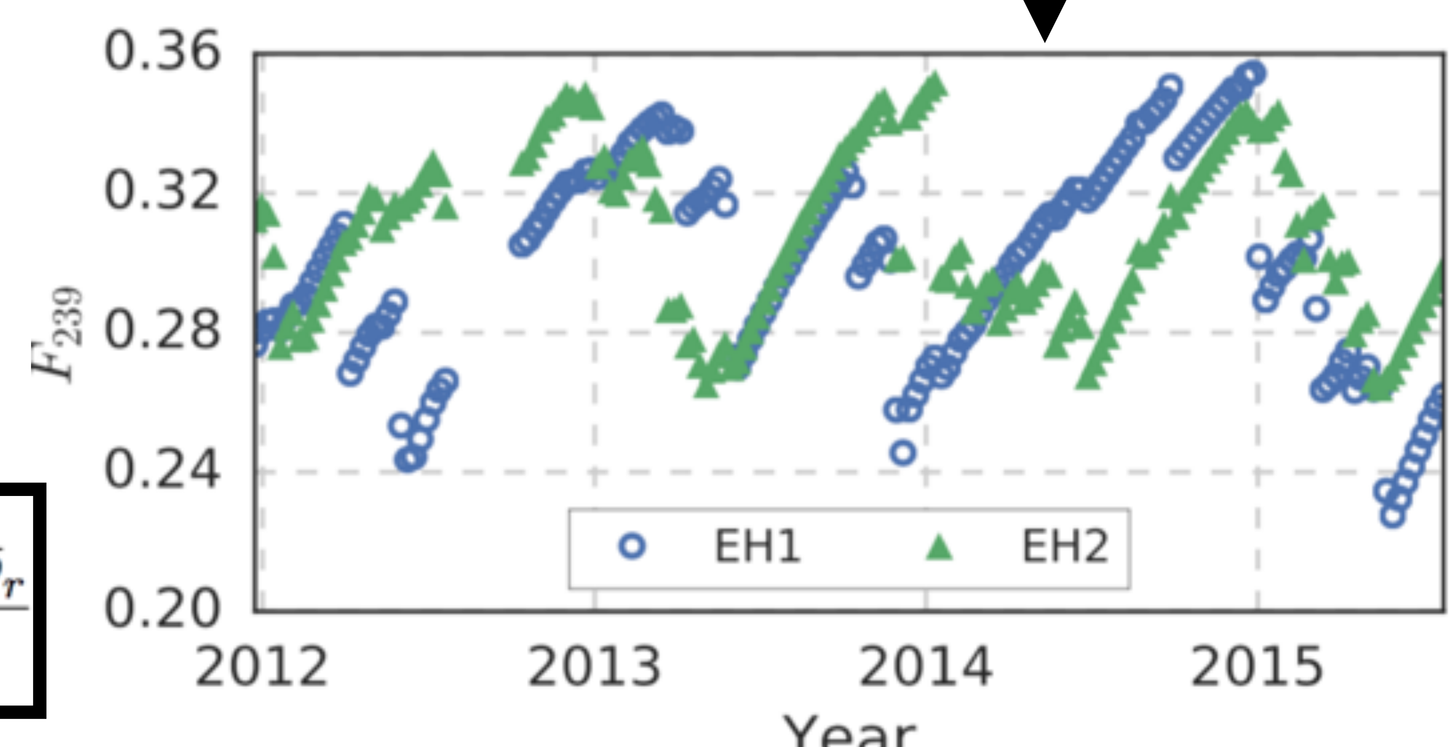


weight; then repeat x6



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

Daya Bay 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:
  - Weight core fission fraction by power, baseline, oscillation, etc.
- Calculate IBD rate (per fission) for each bin in effective fission fraction.

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

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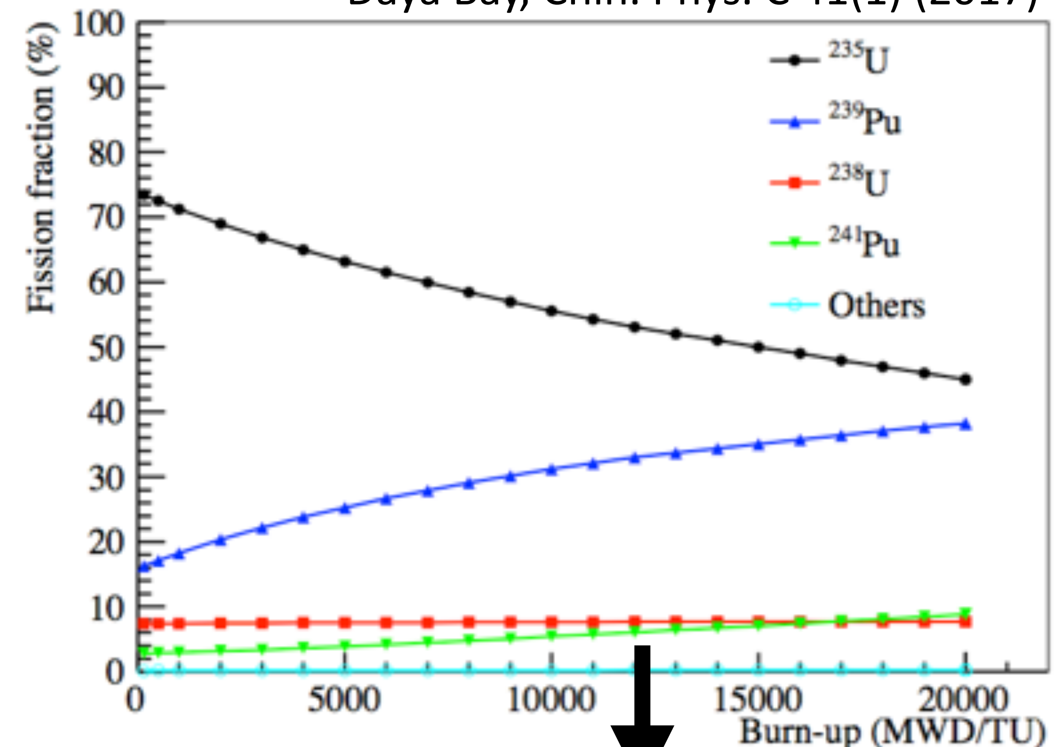
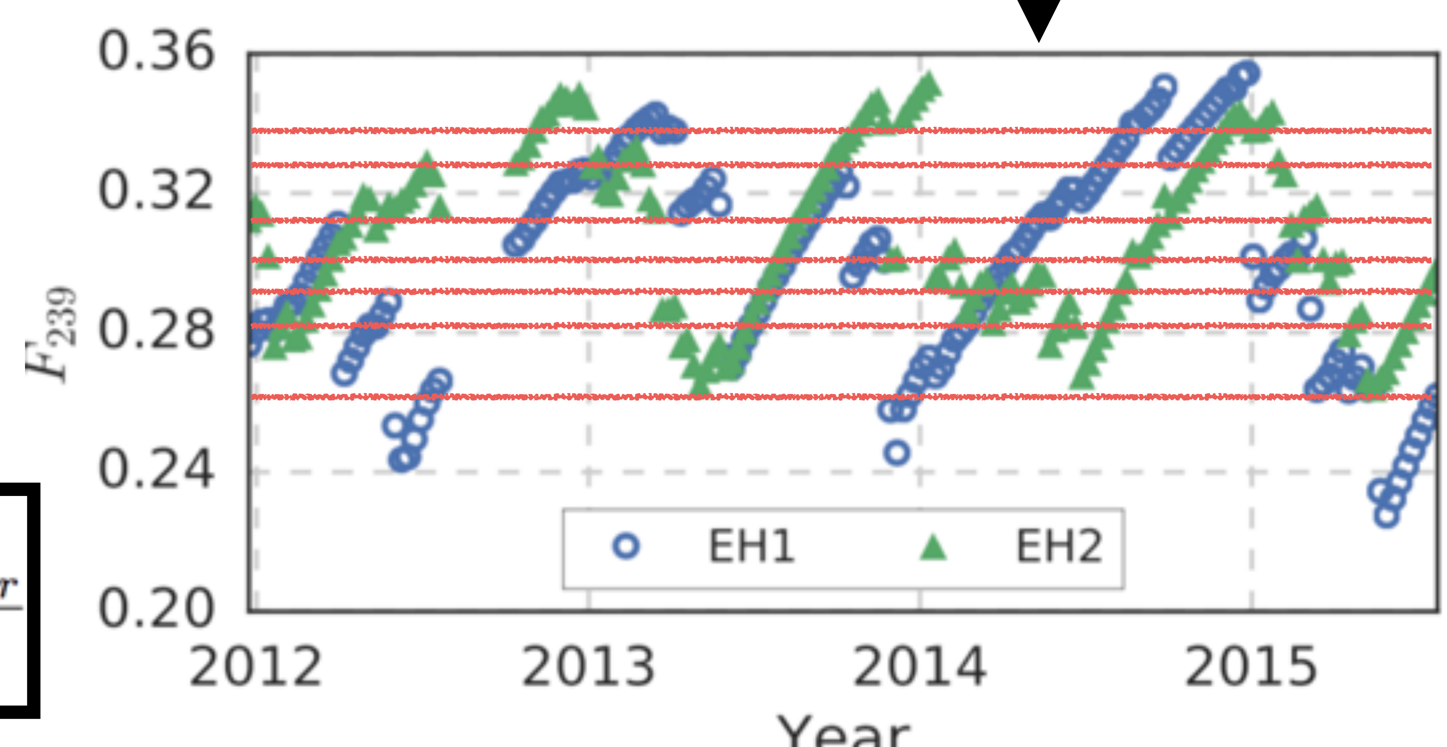
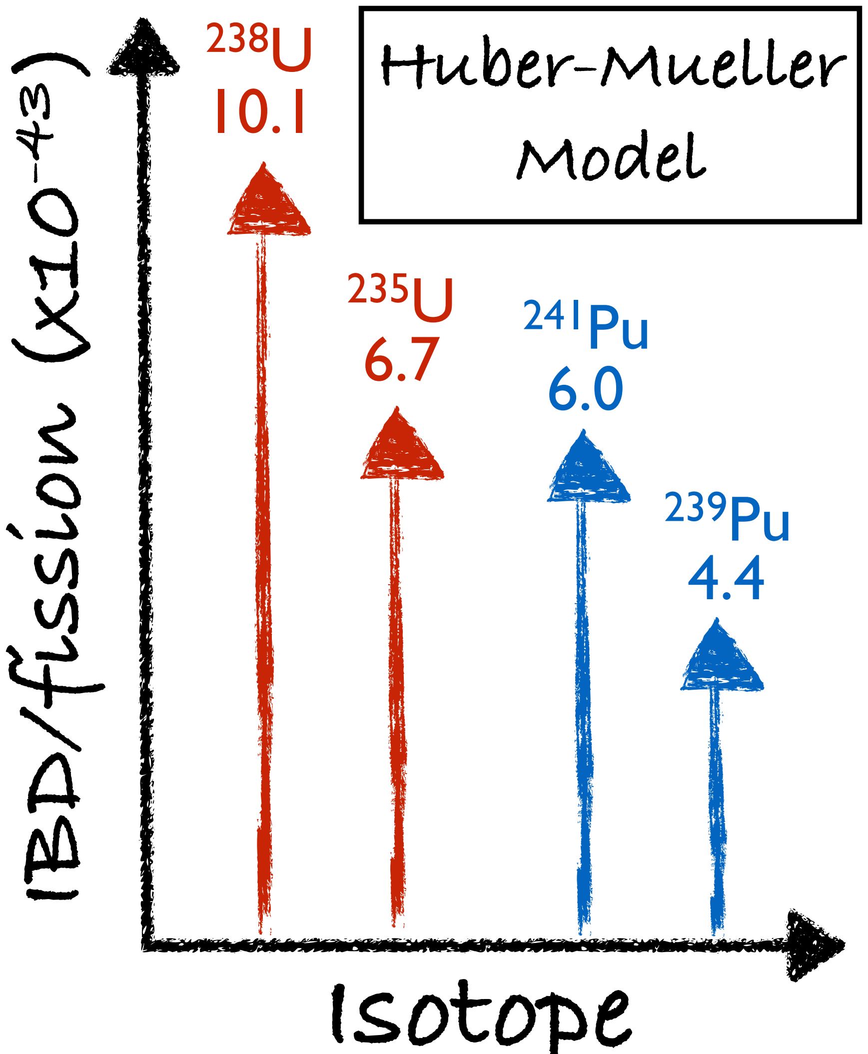


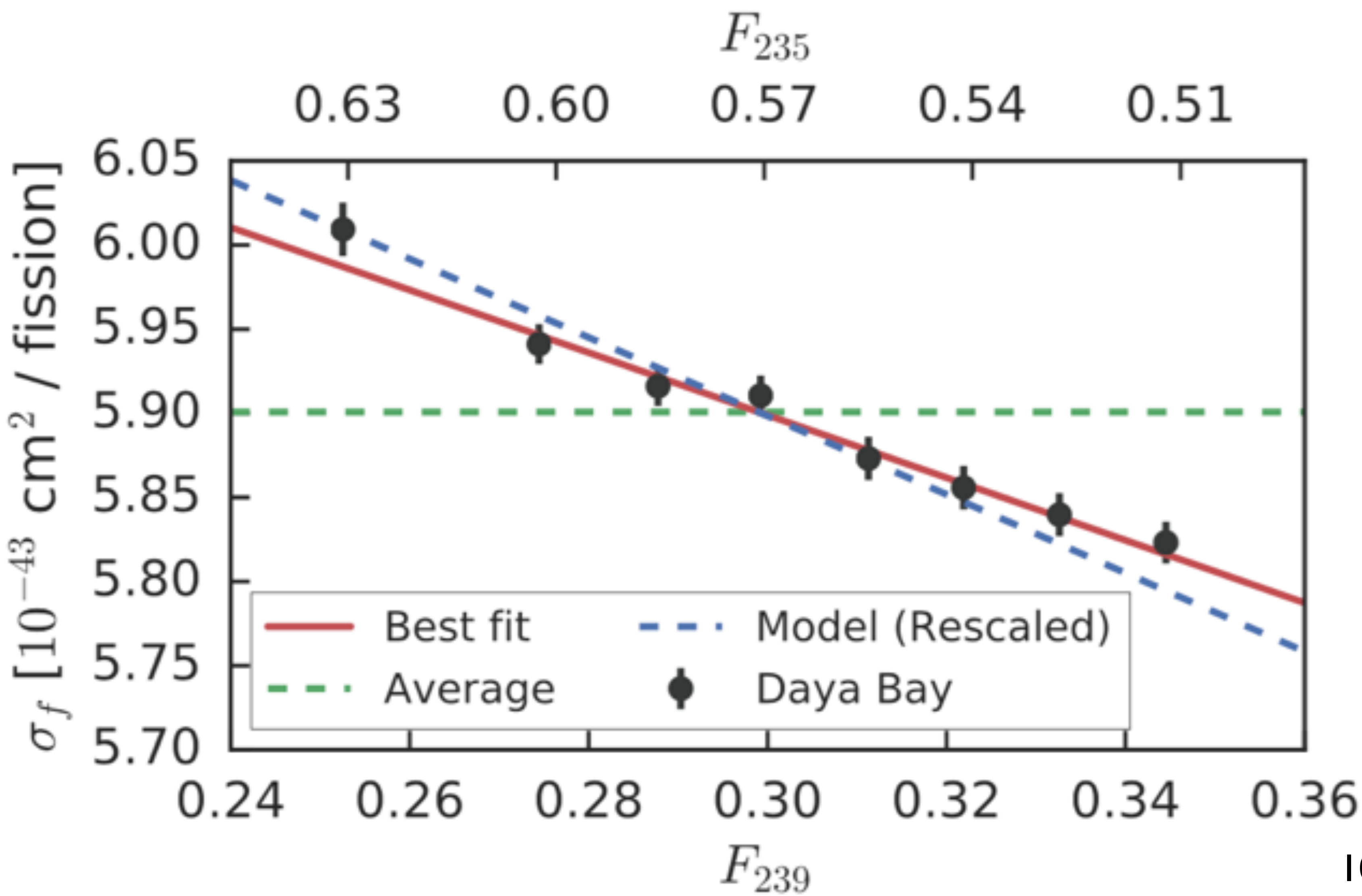
weight; then repeat x6



Result: Flux Evolution

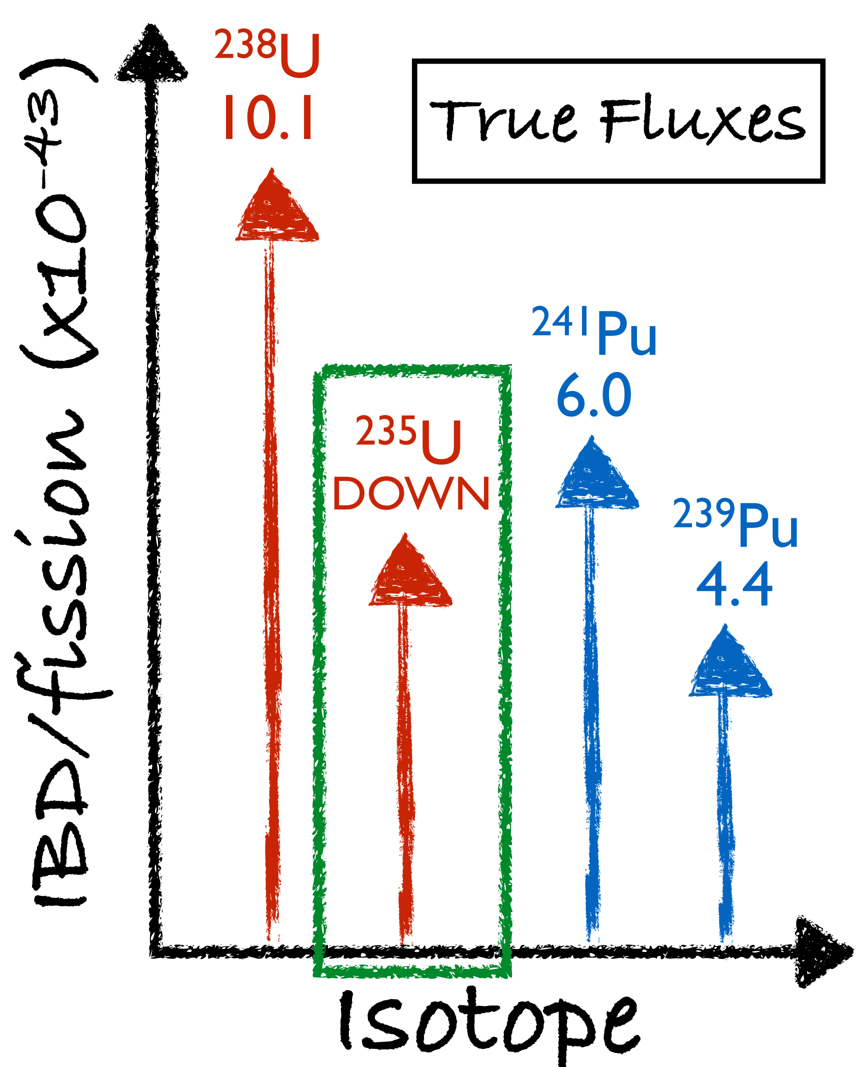
- When plotting IBD/fission versus F_{239}, we see a slope in data
- Very clear that flux is changing with changing fission fraction.
- Not too surprising; models predict ^{239}Pu makes fewer $\overline{\nu}_e$
  - Seen before in previous experiments: Rovno (90's); SONGS (00's)
- Surprising: measured, predicted slope do not agree at 2.6σ

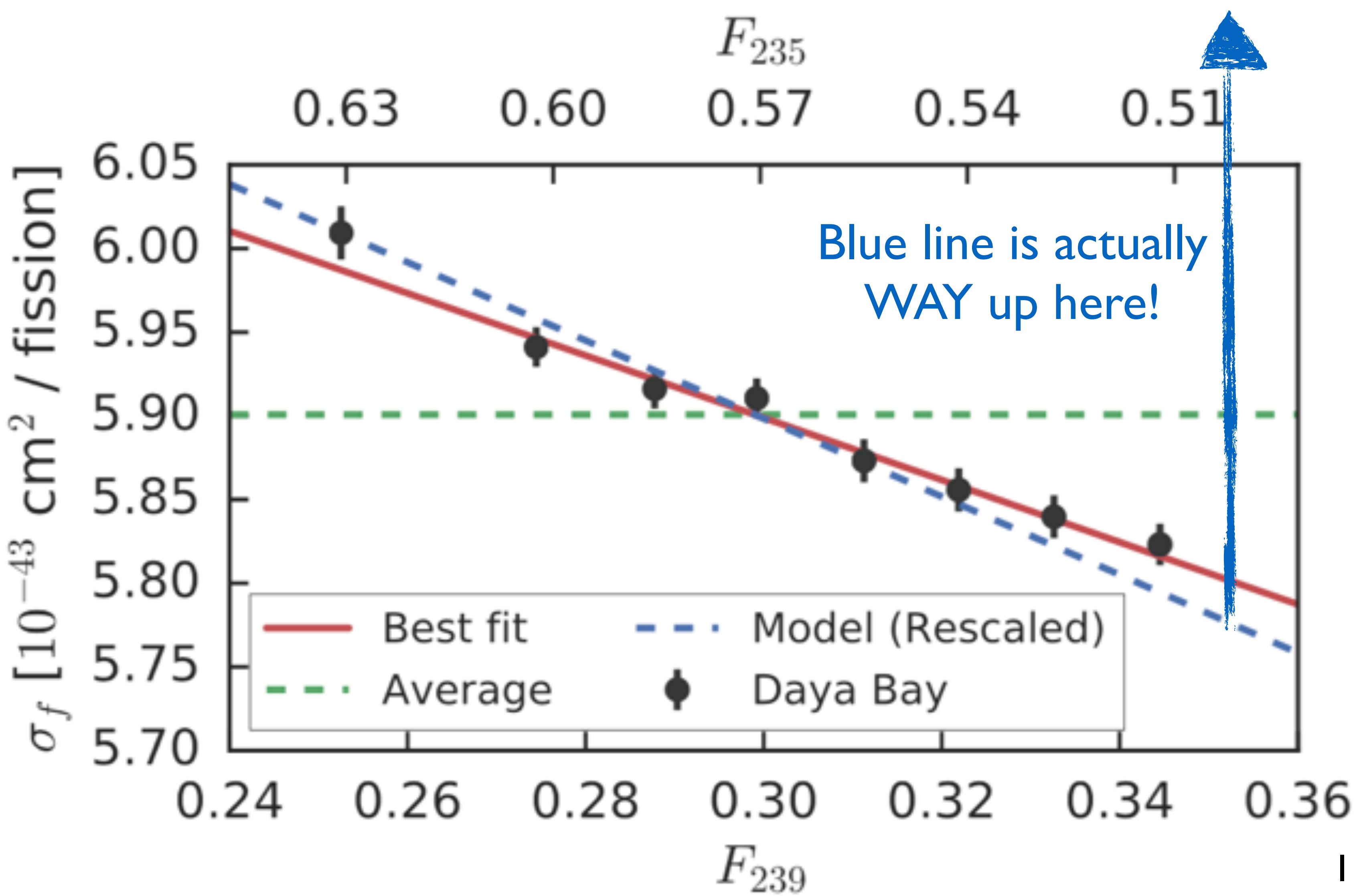




Result: Flux Evolution

- Also consider: total flux prediction is too high by 5.4%
- Suggests that ^{235}U prediction, in particular, is too high
  - Some more complicated scenarios still allowed, i.e.: ^{239}Pu UP + sterile nu
  - **Editorial opinion:** The whole reason we introduced sterile neutrinos to this picture was to avoid having to admit the models were wrong. Hmmmmm…



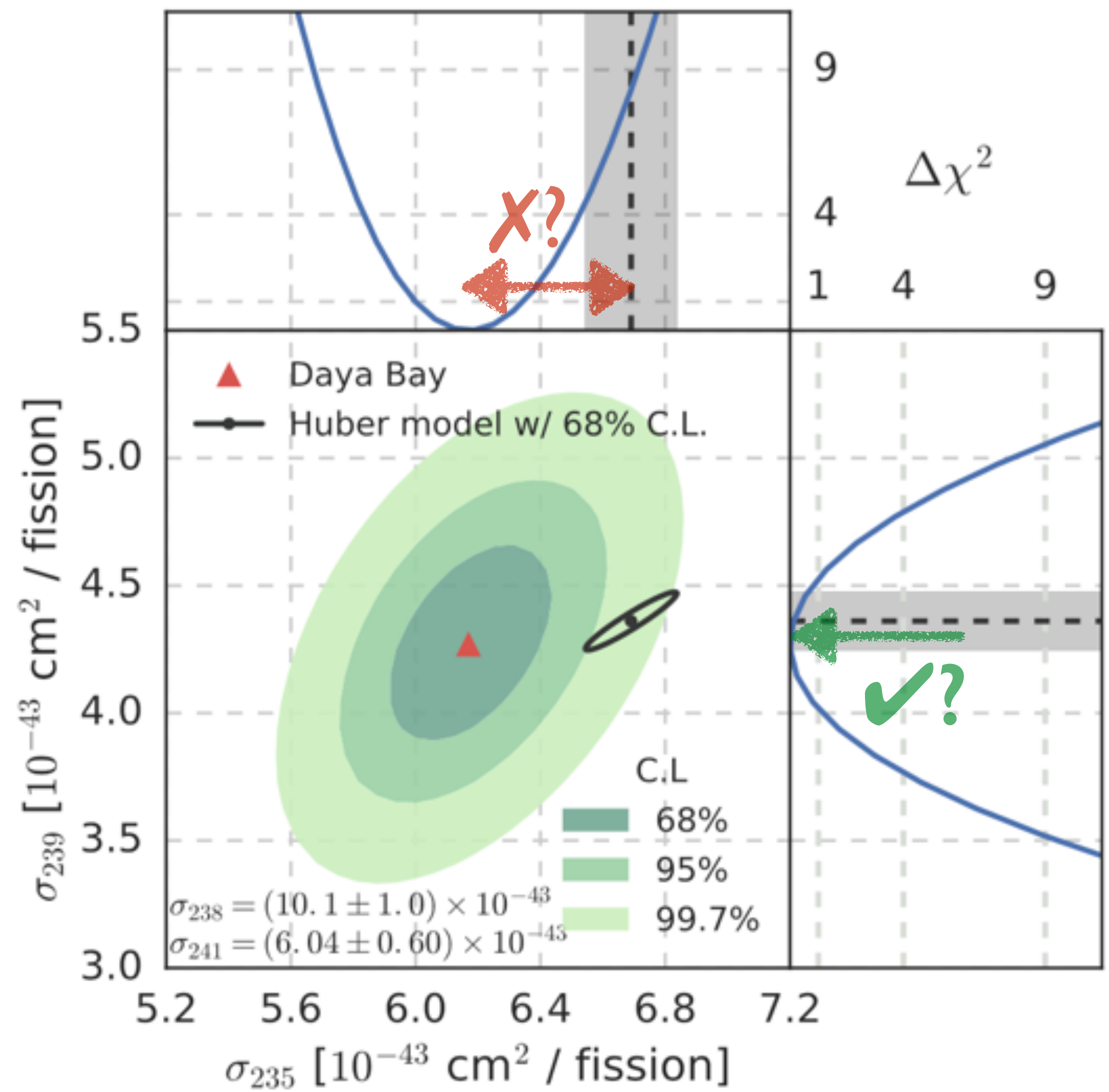


Result: Fits to Individual Isotopes

- Use this data to explicitly fit IBD/fission for ^{235}U, ^{239}Pu
  - Assume loose (10%) uncertainties on sub-dominant ^{238}U, ^{241}Pu

- As expected, fitted ^{235}U is lower than the model
  - ^{239}Pu matches model well.

- Note: CLs are significant, but not overwhelming
  - With more statistics, better systematics, there is a chance these results could shift.
  - Future DYB measurements would be valuable!



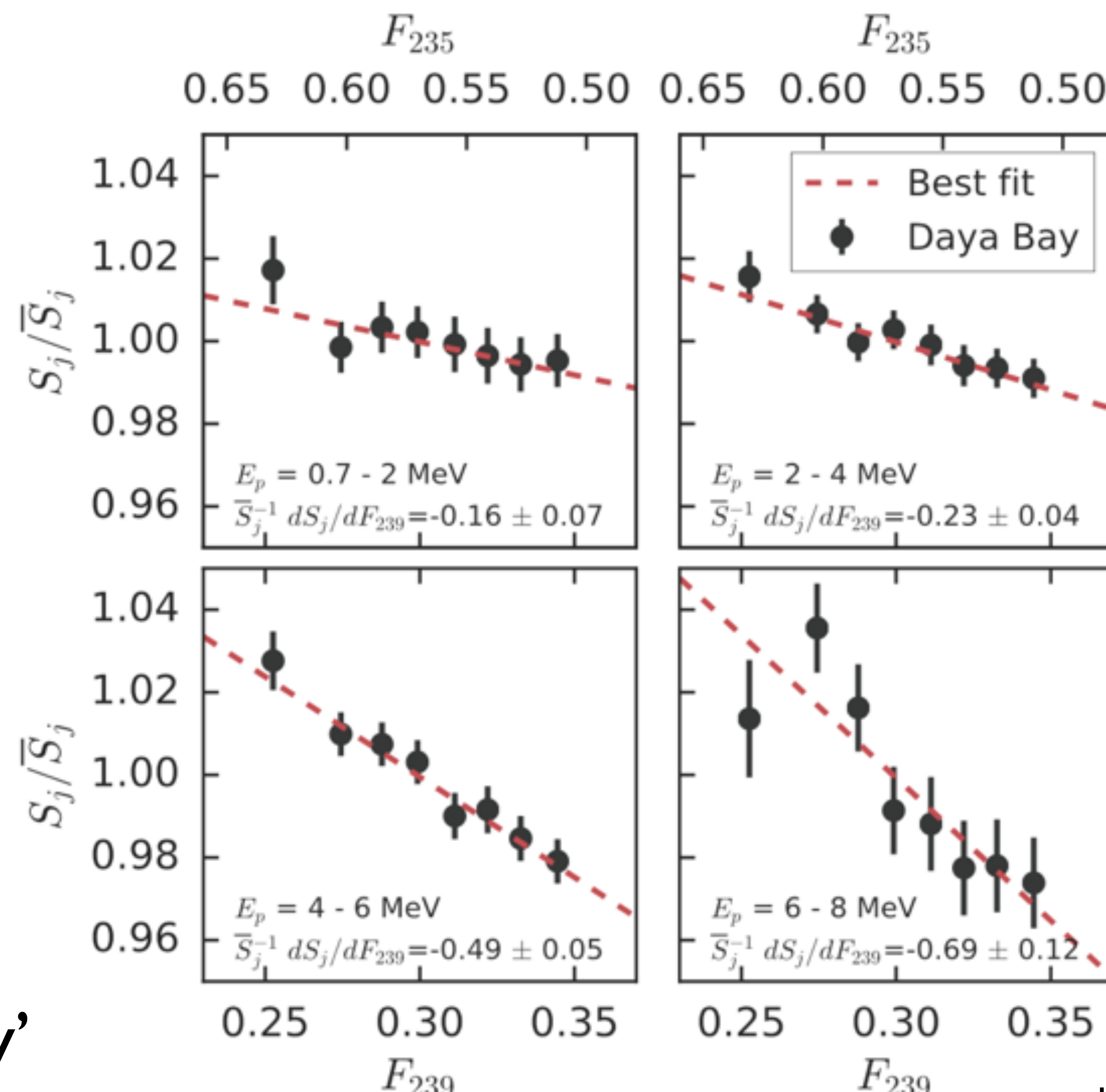
Result: Spectrum Evolution

- Shift gears: what if we add IBD energy into the mix?
  - Examine evolution in 4 separate energy ranges

- Slope is different for different energy ranges

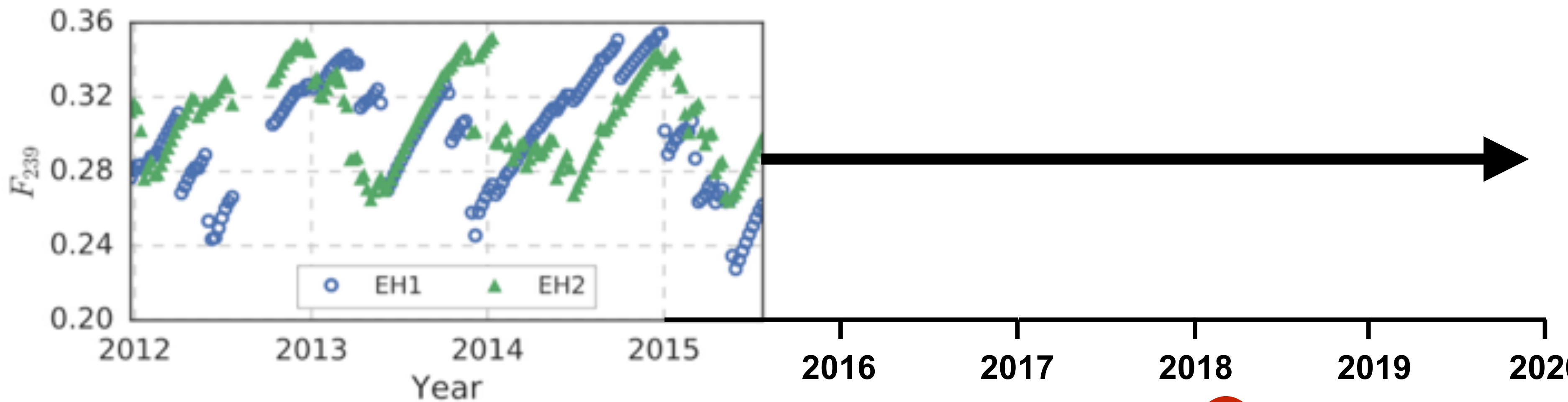
- Put another way: IBD spectrum changes w/ F_{239}
  - This is the first unambiguous measurement of this behavior

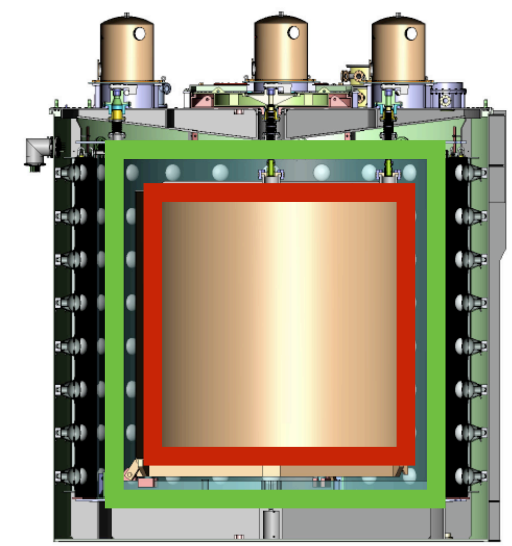
- Matches models ~well; more statistics needed to address 'spectrum anomaly'



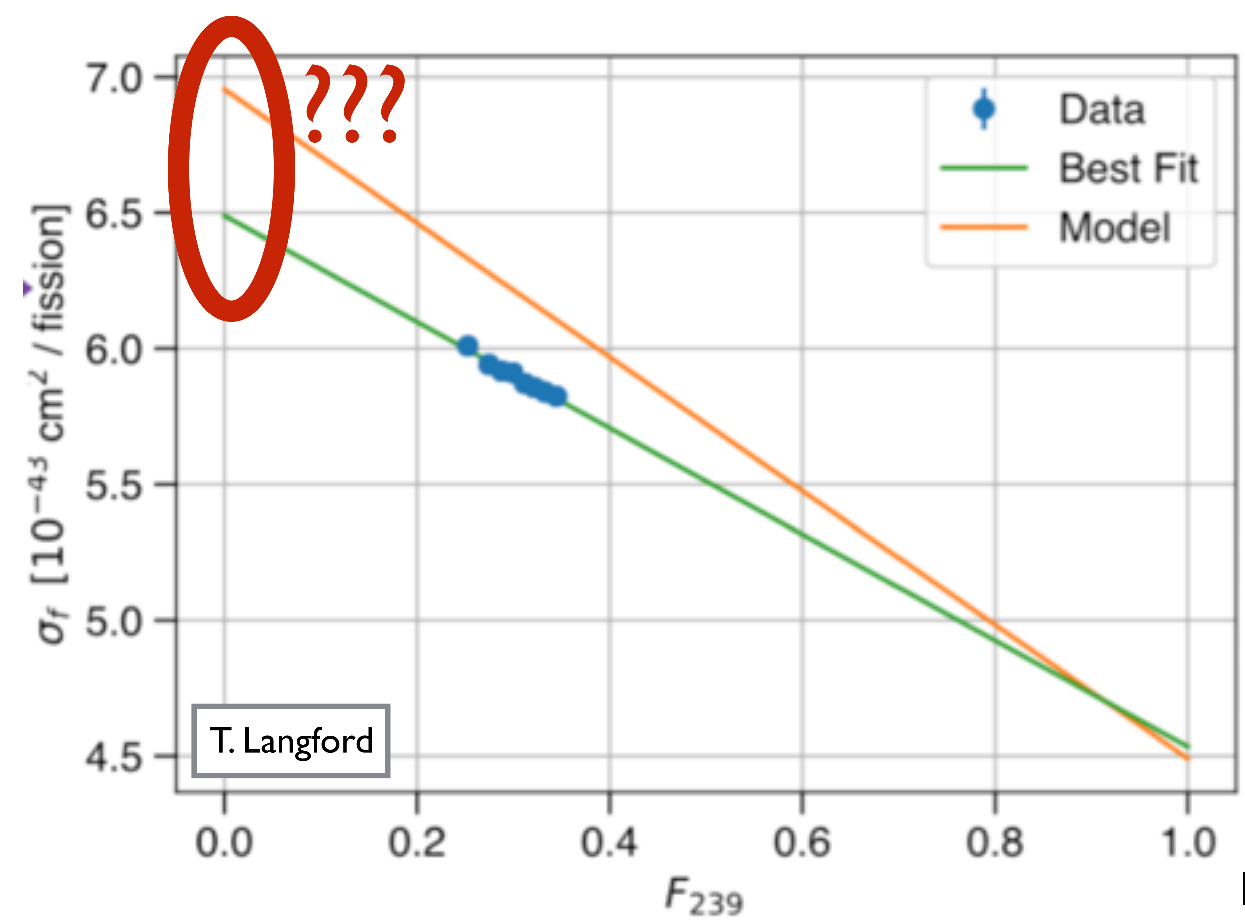
Future Prospects

- Daya Bay will improve its statistically limited measurement
  - Improved nH + nGd IBD analysis: ~1.6x more statistics
  - ~3.5 years of data down; 4.5 years of data to go!





- Highly-enriched uranium cores provide a chance to sample wider fission fraction ranges (100% ^{235}U)
  - Precise flux measurements at new short-baseline experiments (like PROSPECT) could be helpful



Thanks!

Questions?

Spectrum Evolution: Data-Model Comparison

- 4-6 MeV region: no strange behavior visible WRT models
  - No major indication that 'bump' data-model discrepancy comes from a particular isotope.
  - Data-model offset seems (maybe?) a little bit reduced, but more statistics are required to say something meaningful.

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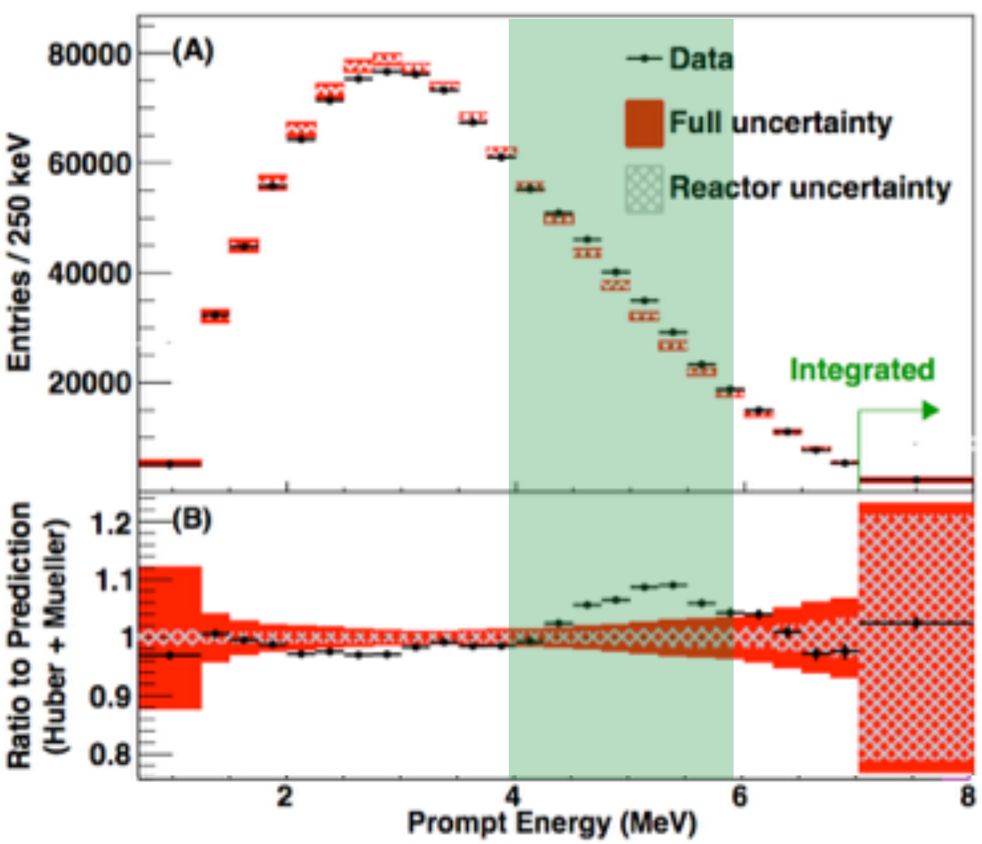

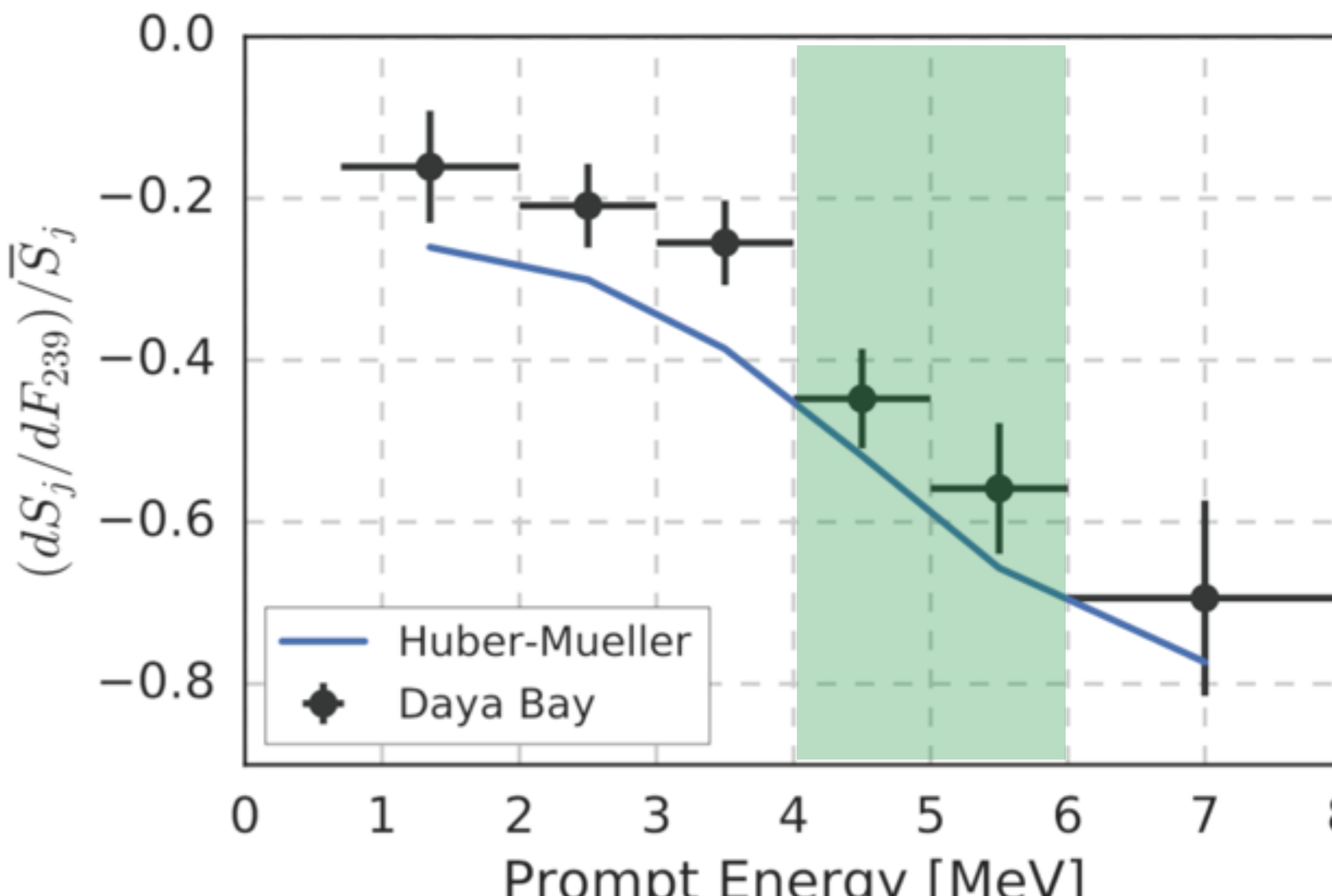

Note: From IBD/day to IBD/fission

- IBD/day depends on many time-variable quantities:
  - Reactor status and thermal power
  - Power released per fission
  - Detector livetime
  - Some other more minor, nearly-constant stuff target mass
- Show final plots in terms of IBD/fission: $\sigma_f = \sum_i F_i \sigma_i$
  - Basically take IBD/day and divide out all these variable quantities on a week-by-week basis

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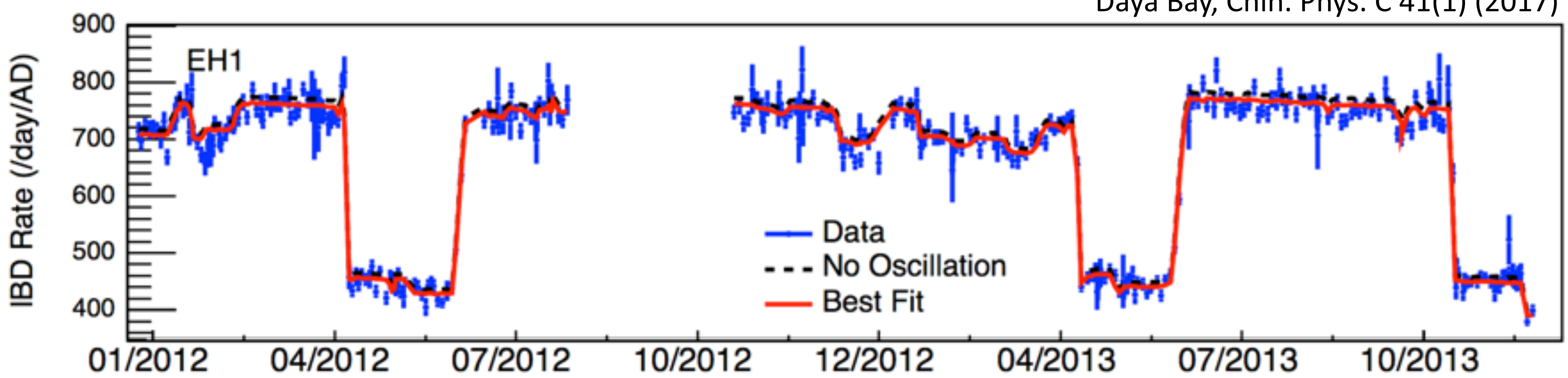
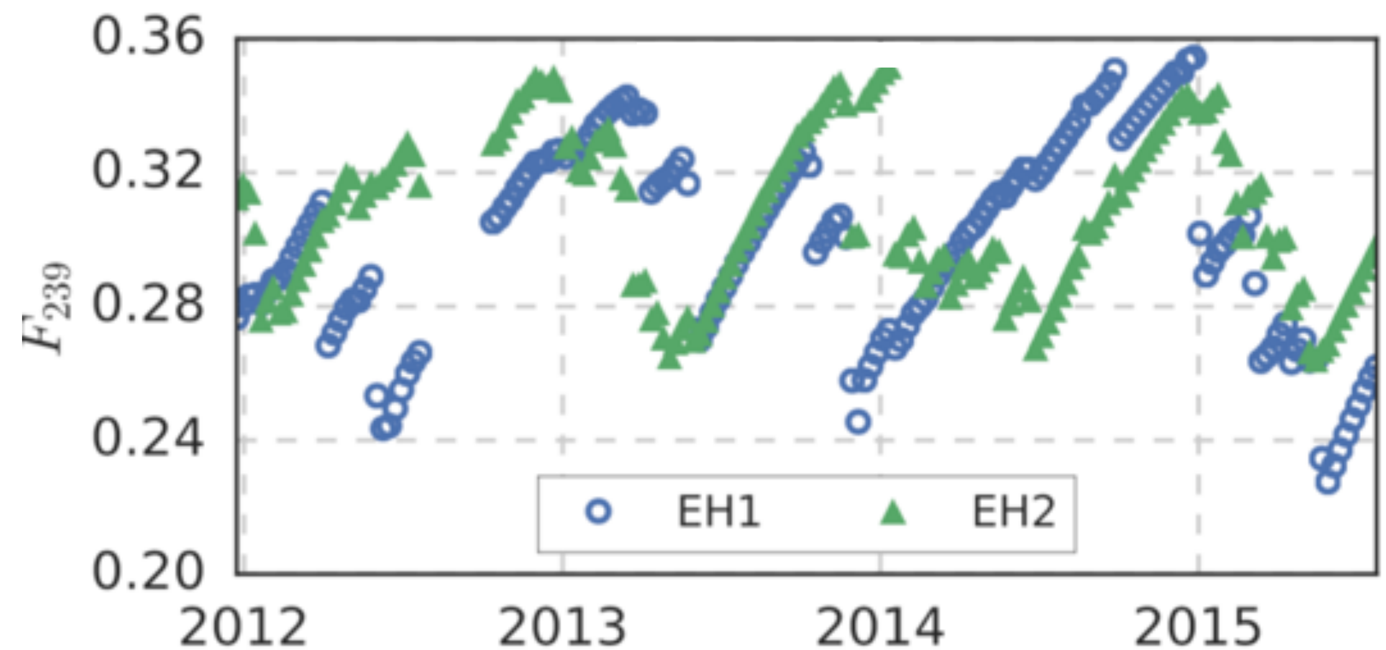


Systematics: Reactor

- **Uncertainties from various inputs to our F_i definition are not too large**
  - Reactor power
    small (0.5%), ~ constant in time, reactor-uncorrelated
  - reactor fission fraction
    sizable (5% relative); constant in time, reacor-correlated
  - energy per fission
    very small, time-constant
  - oscillations, baselines:
    very small, time-constant ;)
  - We can get into nitty gritty details in backup slides if people want…
- Statistics dominate this uncertainty

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



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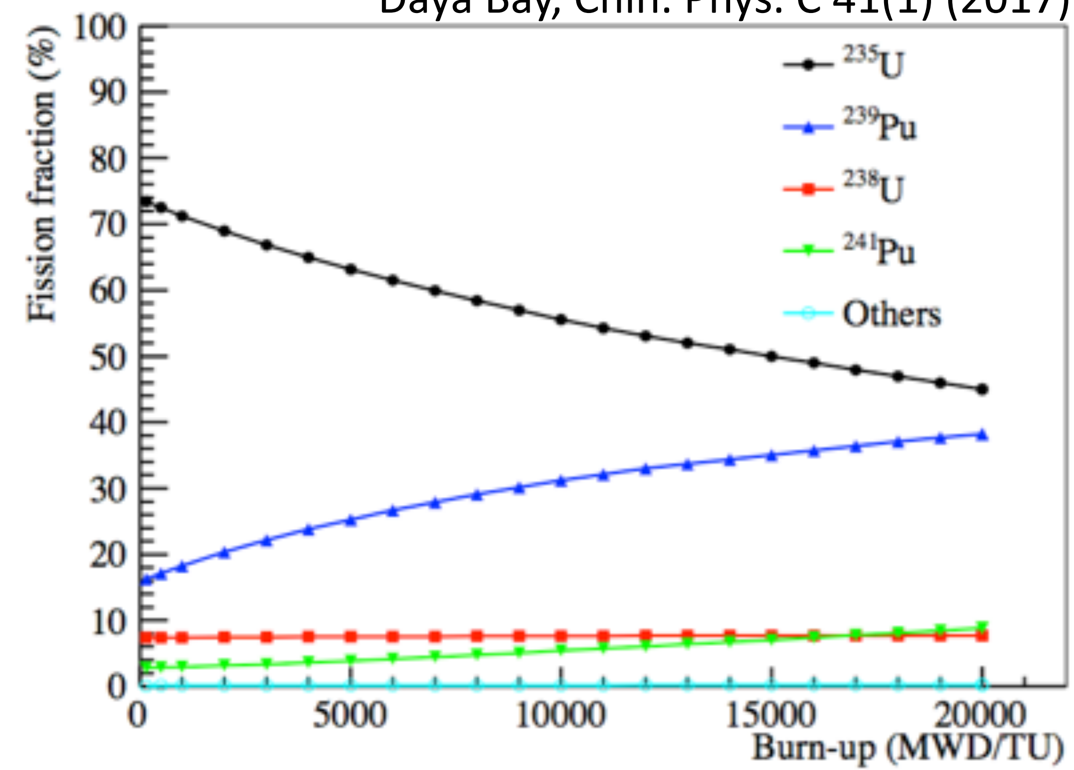
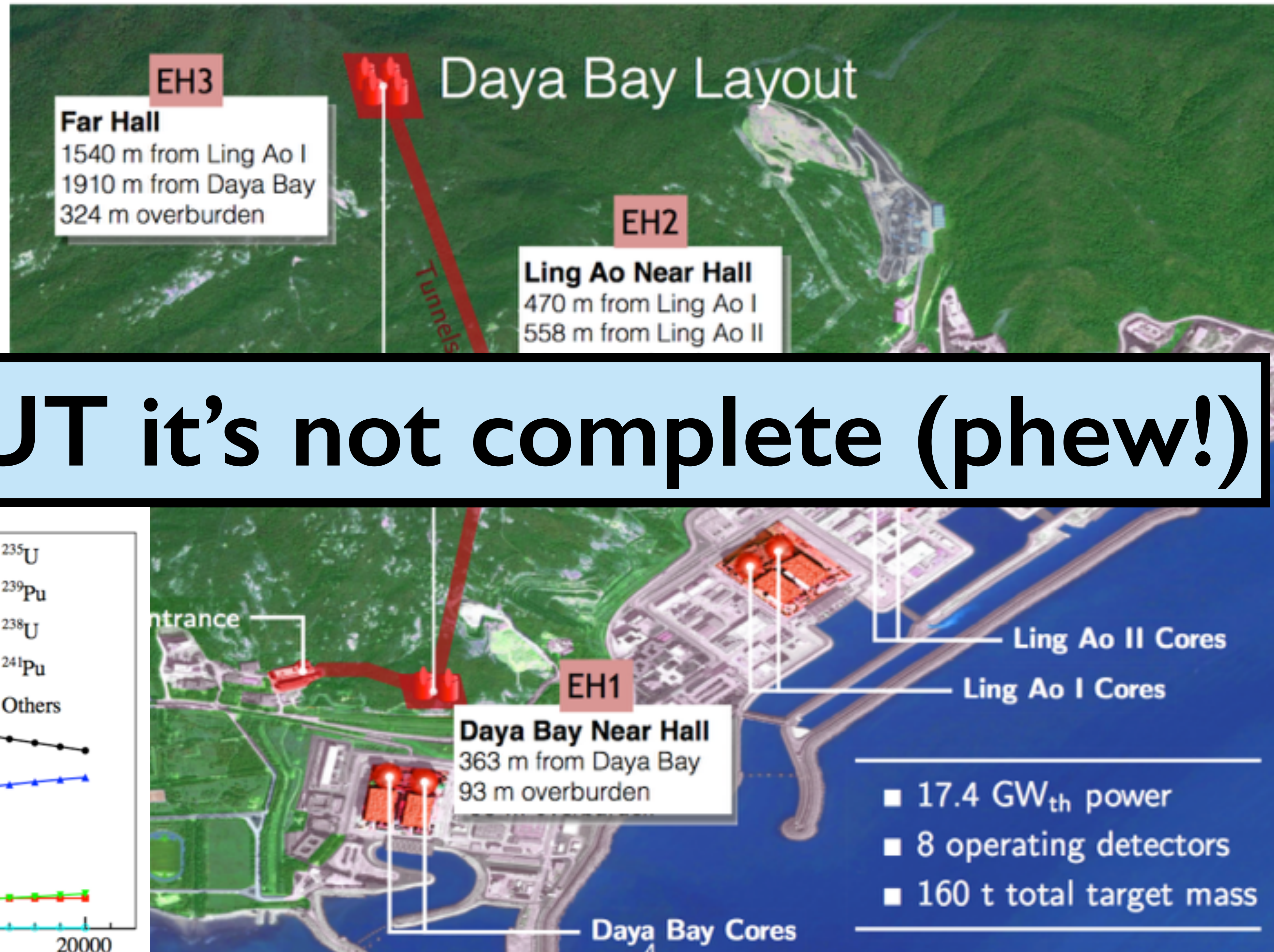
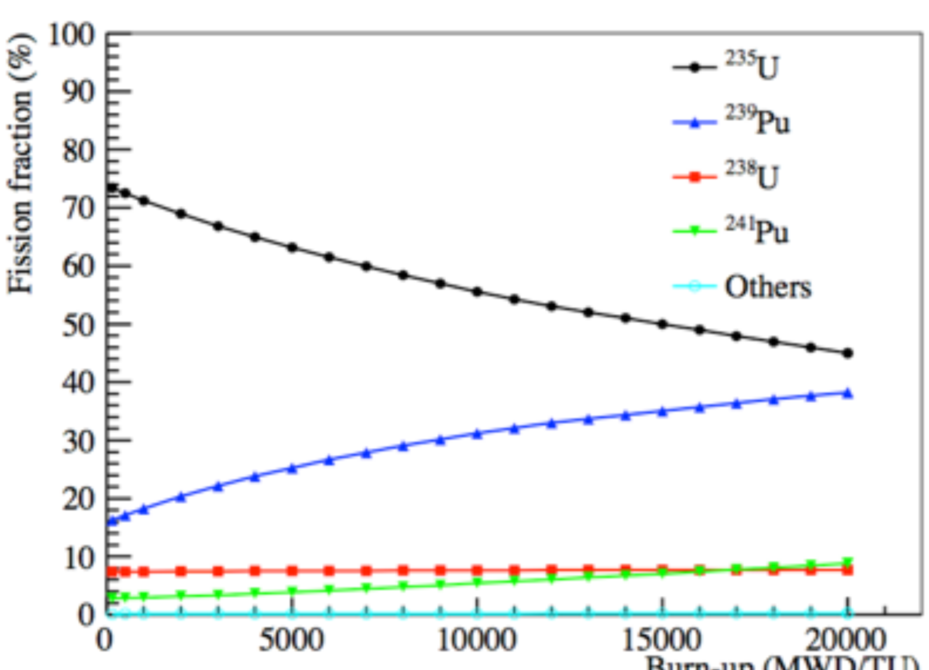


Cancellation Between Cores?

- Reactor cores' cycles are not aligned (that would be dumb!!)
- Q: Isn't there some cancellation of fission fraction variation?



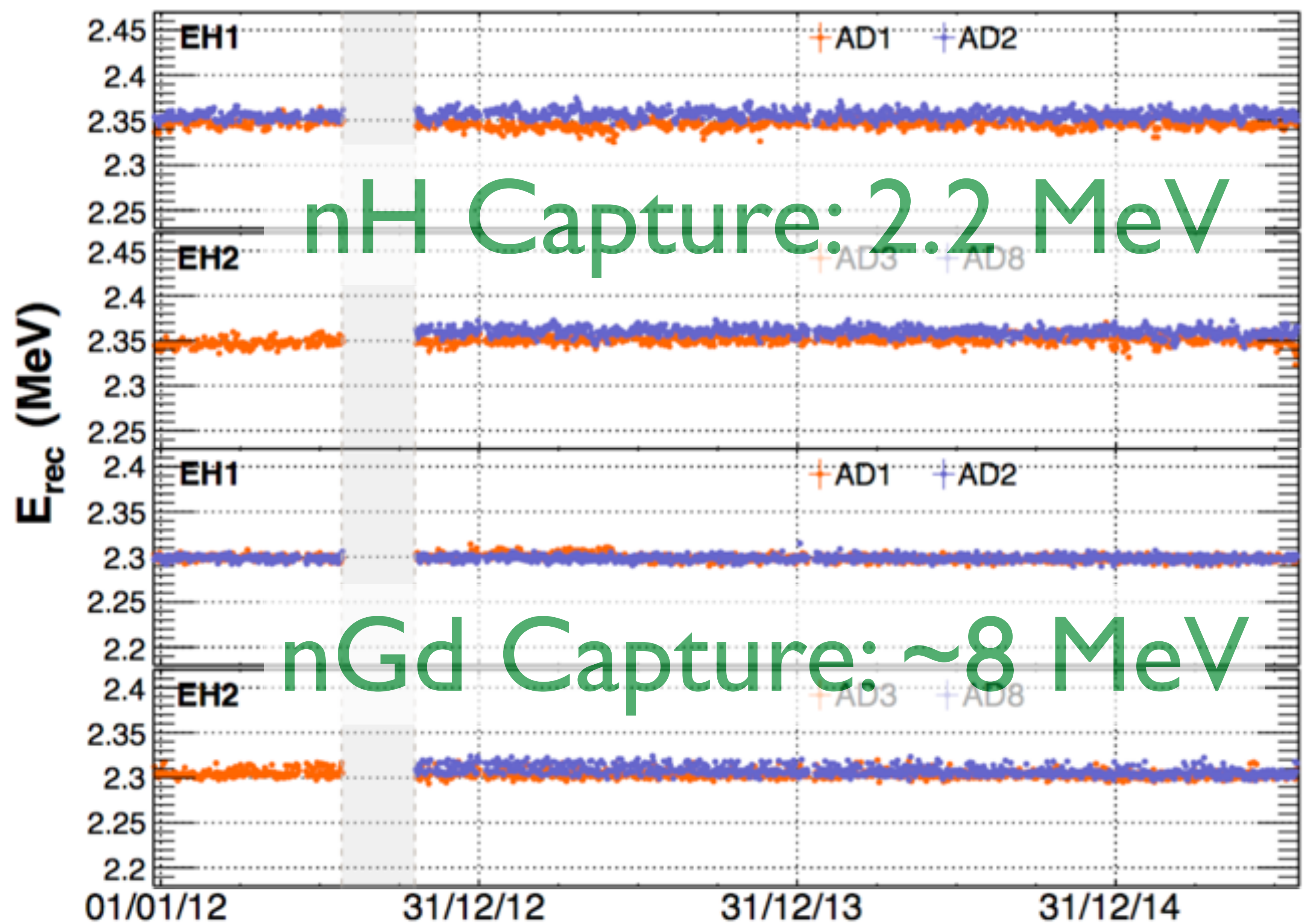
A: Yes, BUT it's not complete (phew!)



Systematics: Detector

- Major consideration: how does a detector change over time?
  - Reconstructed energy scales are **<u>extremely</u>** time-stable (<0.1% variation)
  - Most inefficient IBD cuts are energy-based: also time-stable (<0.1% variation)
- Statistics <u>REALLY</u> dominate this uncertainty
  - Absolute detection efficiency is also important, as we will see in a bit.

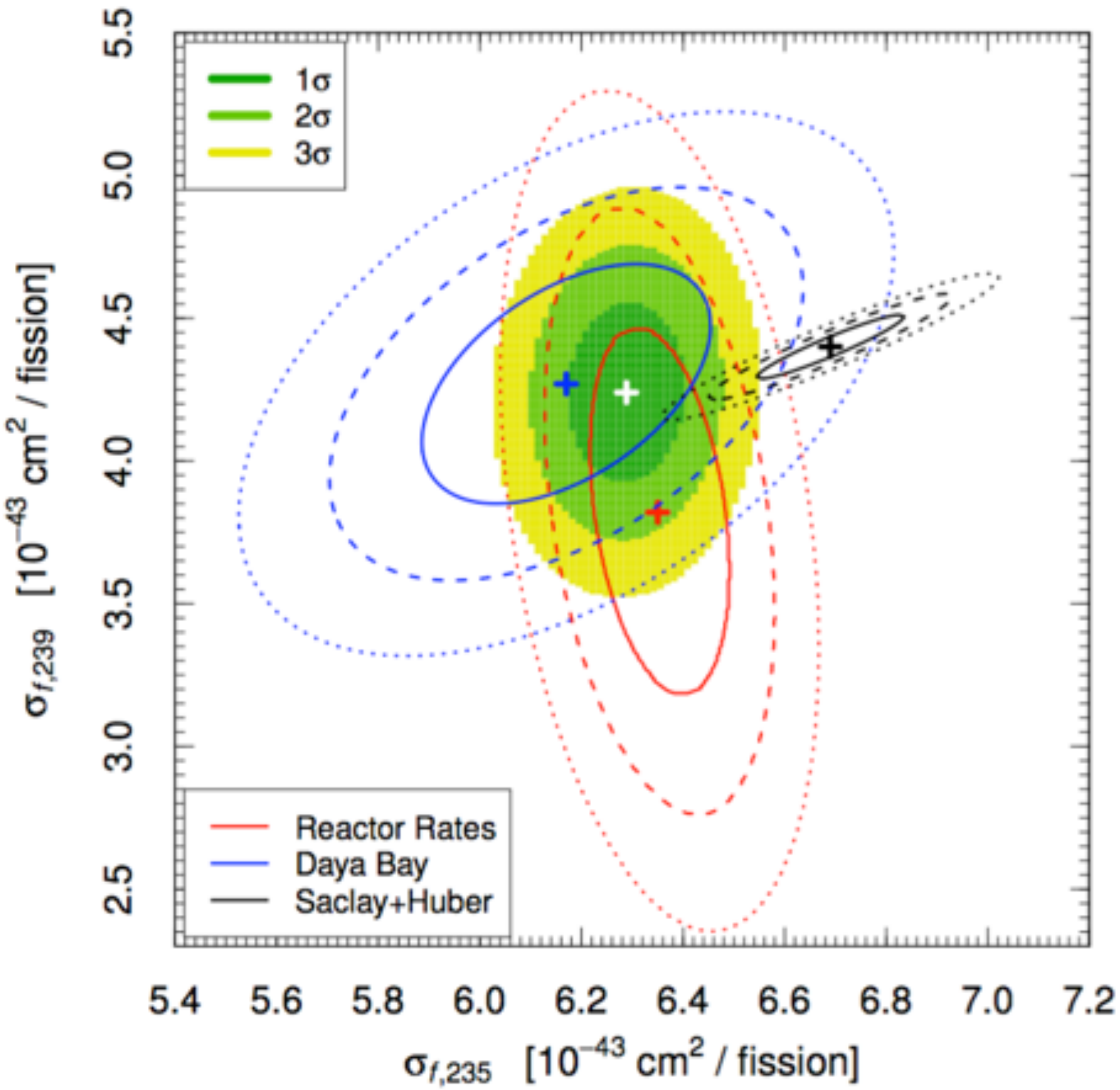
Daya Bay, PRD 95 (2017)



Global Fits: Input Data

a	Experiment	f^a_{235}	f^a_{238}	f^a_{239}	f^a_{241}	$R^{\rm exp}_{a,\rm SH}$	$\sigma^{\rm exp}_a$ [%]	$\sigma^{\rm cor}_a$ [%]	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

Global Fits: Result

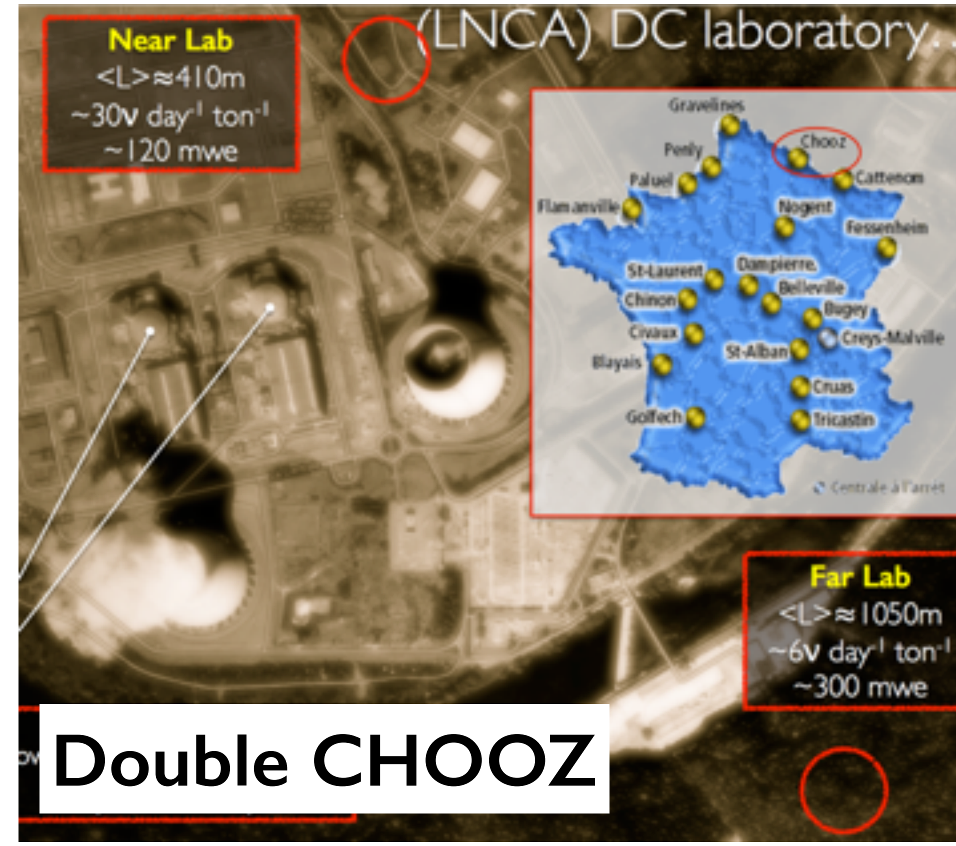


	SH	Reactor Rates	Daya Bay	Combined
$\sigma_{f,235}$	6.69 ± 0.14	6.35 ± 0.09	6.17 ± 0.17	6.29 ± 0.08
$\sigma_{f,239}$	4.40 ± 0.11	3.82 ± 0.43	4.27 ± 0.26	4.24 ± 0.21

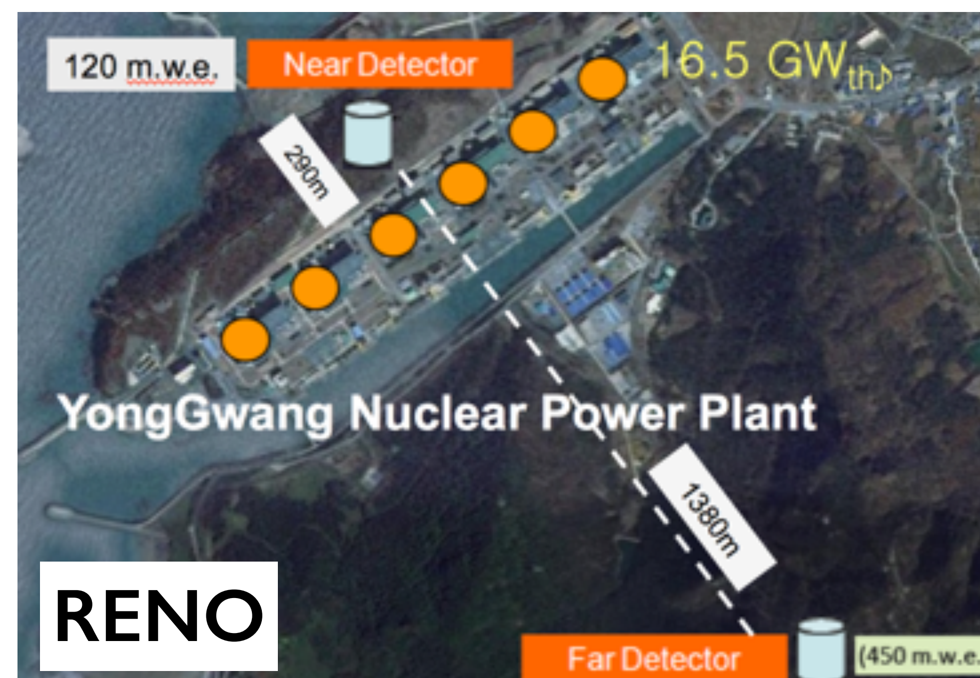
TABLE I. Comparison of the theoretical Saclay+Huber (SH) values of the cross sections per fission $\sigma_{f,235}$ and $\sigma_{f,239}$ with those obtained from the fit of the reactor rates, from the Daya Bay data [5], and from the combined fit. The units are 10^{-43} cm^2/fission.

Other Theta13 Experiments?

- Double Chooz
  - Pro: only 2 reactors, so variation in fission fraction will be a bit higher
  - Con: IBD statistics much lower: ~1000/day (DYB: ~4000/day nGd+nH); ND running since 2015: ~0.4M IBD current (DYB: >4M IBD nGd+nH)



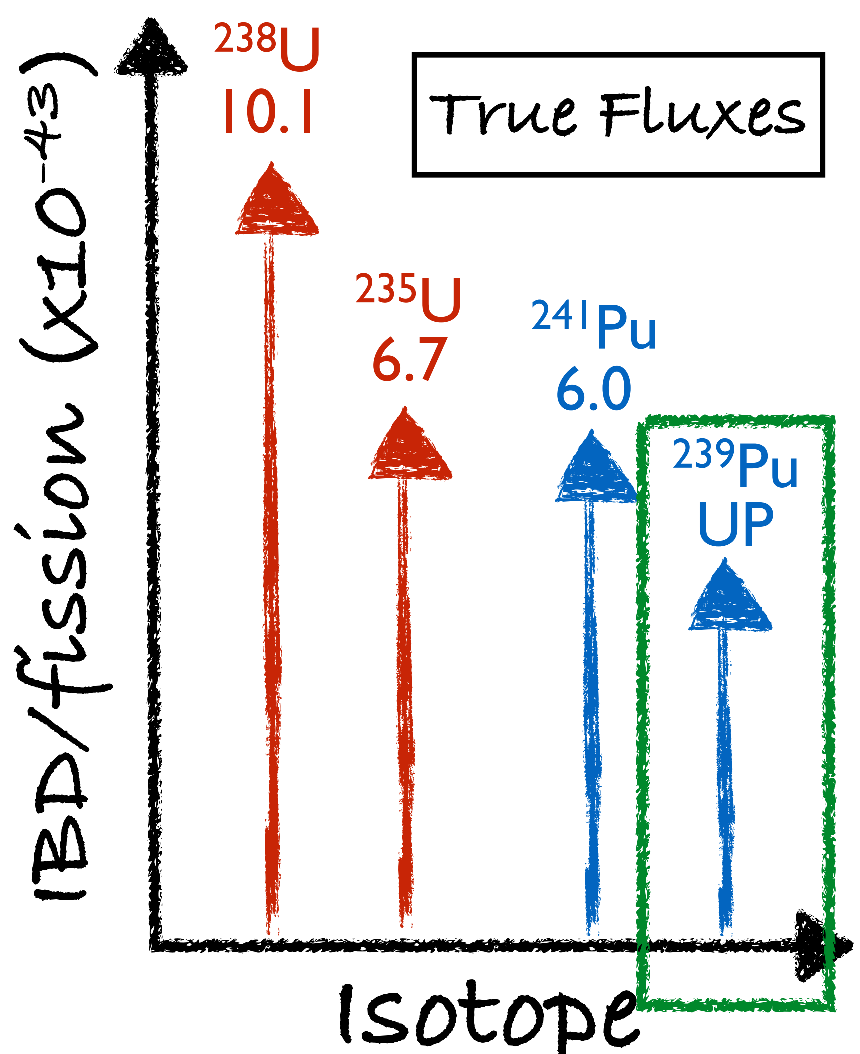
- RENO
  - Similar core-sampling for RENO, DYB
  - Con: only 1 (smaller) near detector: 16 tons; ~650 IBD/day (DYB: 80 tons)

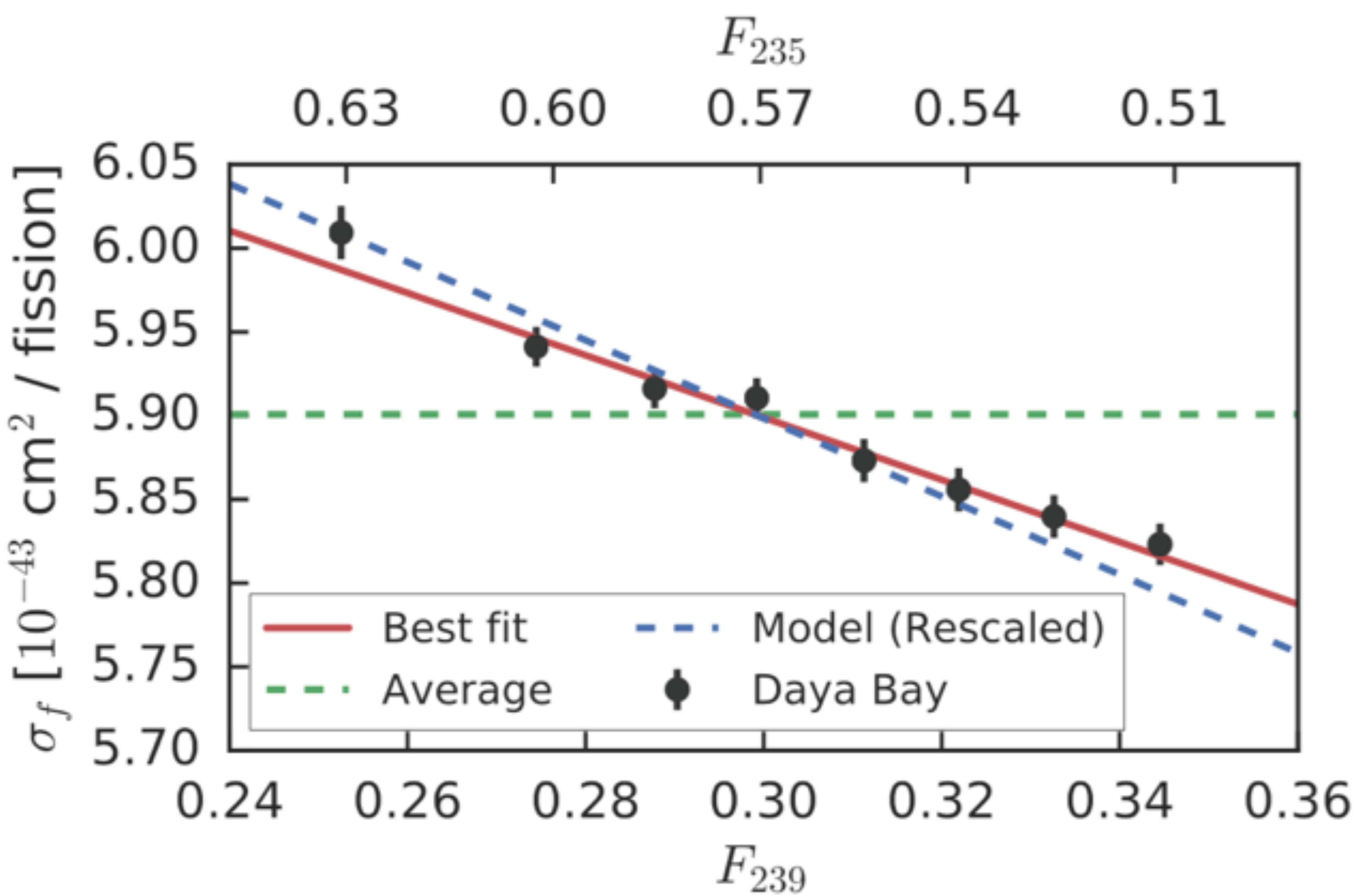


- Despite statistical limitations, it would be interesting to see new flux evolution results from these collaborations

Result: Flux Data-Model Comparison

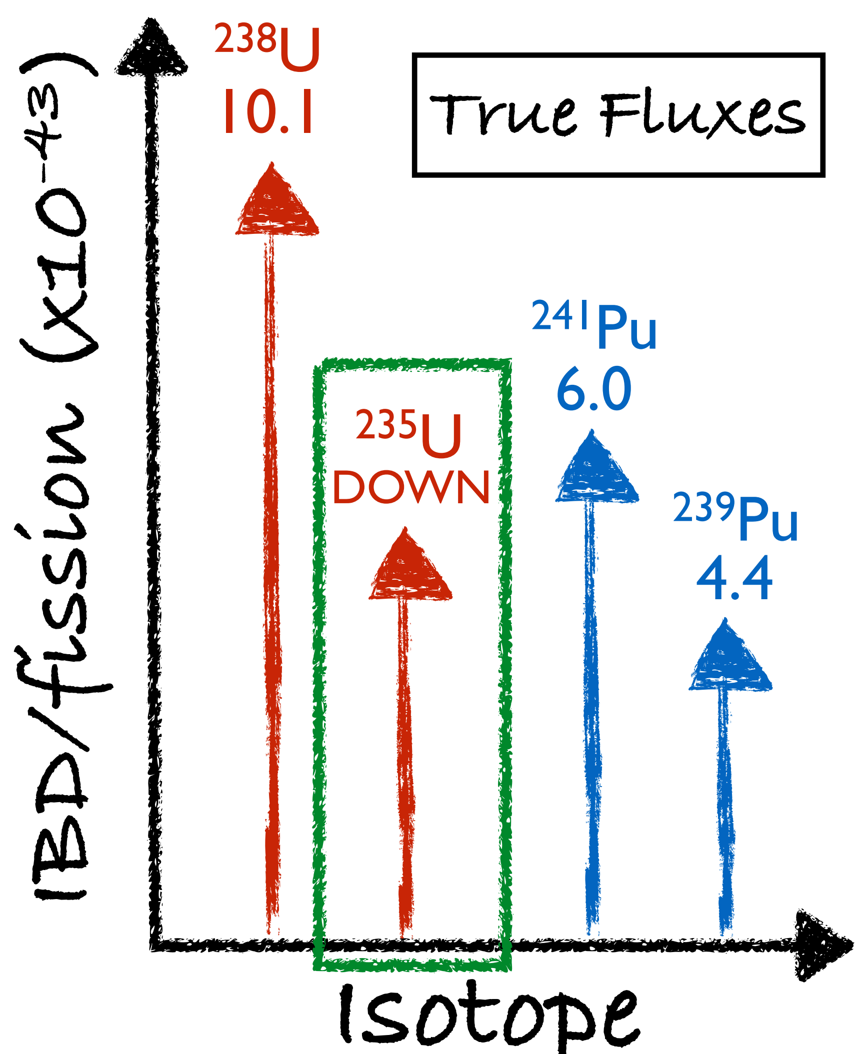
- Measured slope is different than model prediction by 3.1σ
- Could mean a couple things:
  - ^{239}Pu prediction is too low

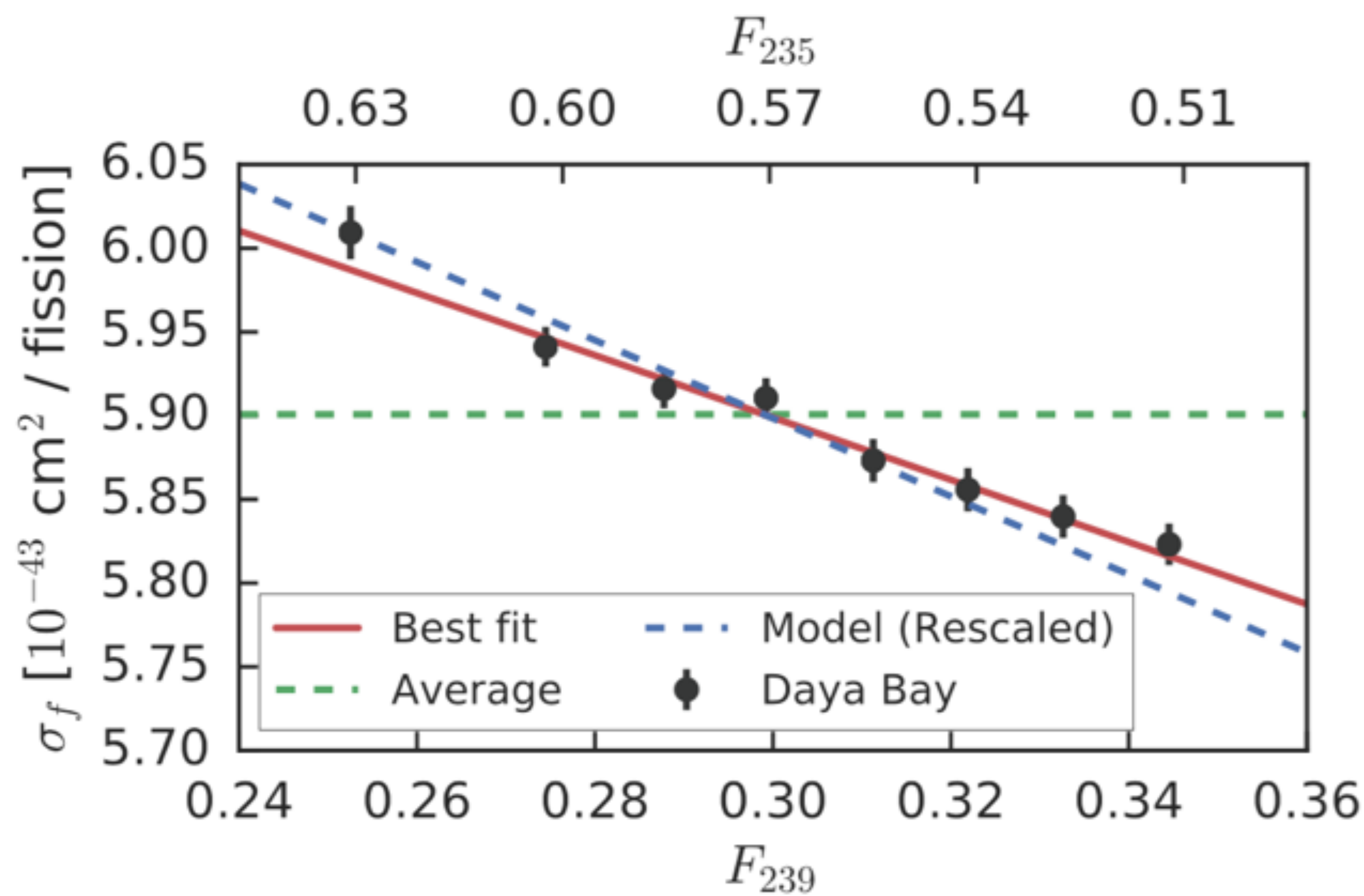




Result: Flux Data-Model Comparison

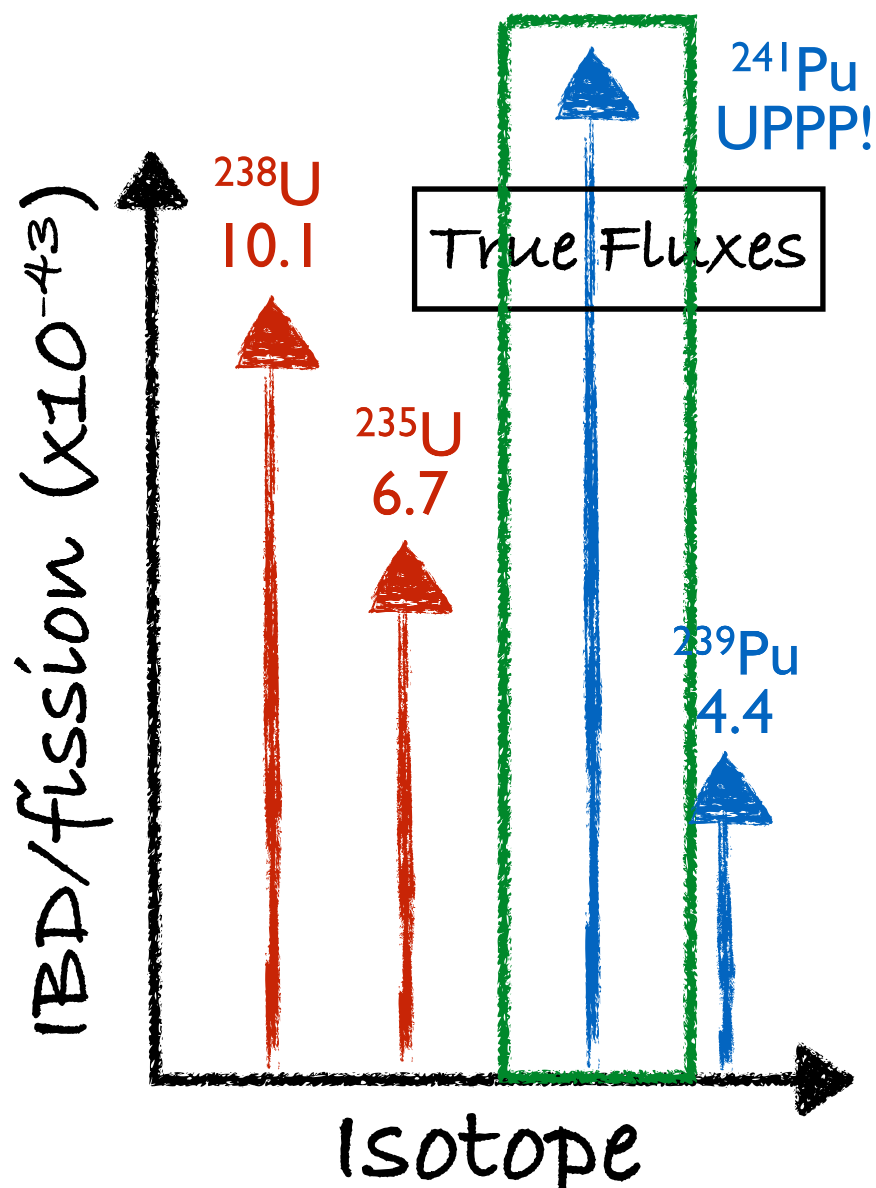
- Measured slope is different than model prediction by 3.1σ
- Could mean a couple things:
  - ^{239}Pu prediction is too low
  - ^{235}U prediction is too high

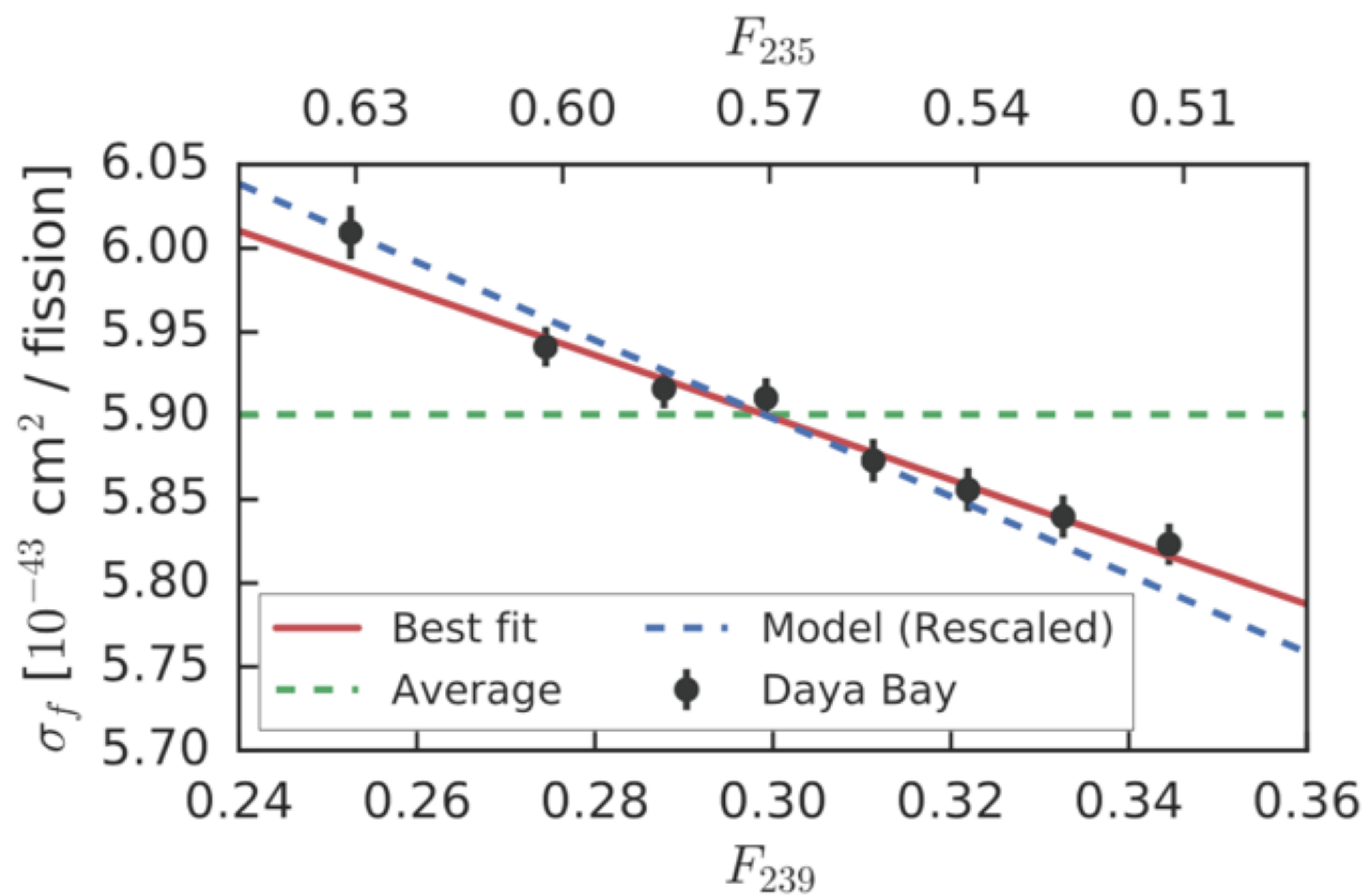




Result: Flux Data-Model Comparison

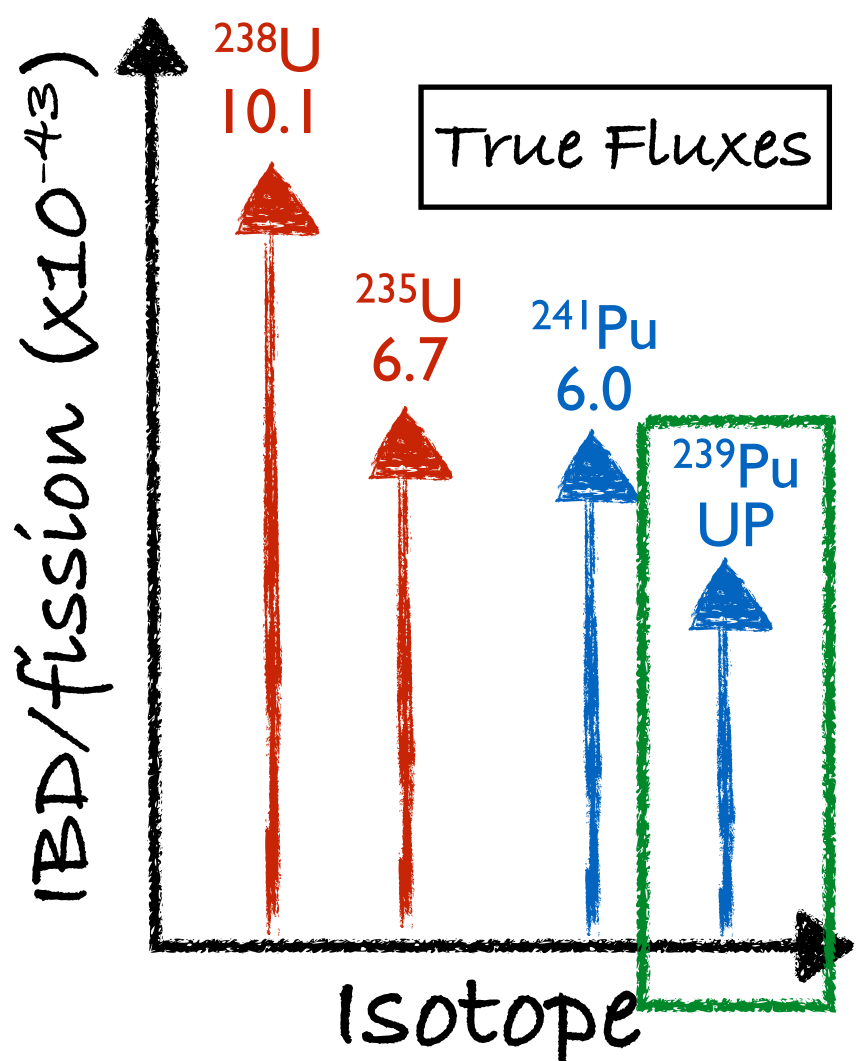
- Measured slope is different than model prediction by 3.1σ
- Could mean a couple things:
  - ^{239}Pu prediction is too low
  - ^{235}U prediction is too high
  - Something is WAY off with ^{238}U, ^{241}Pu

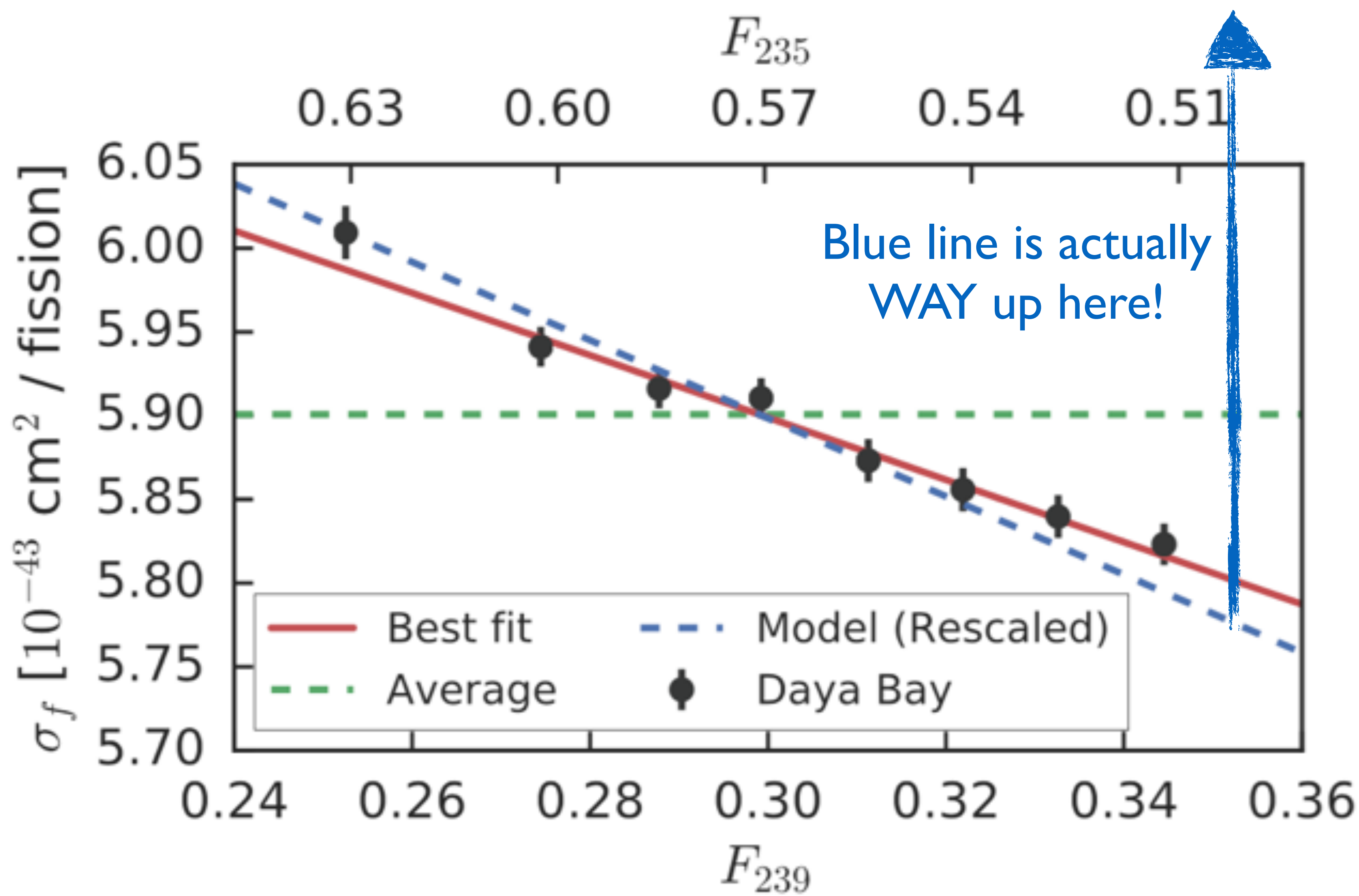




Result: More Complicated Scenarios

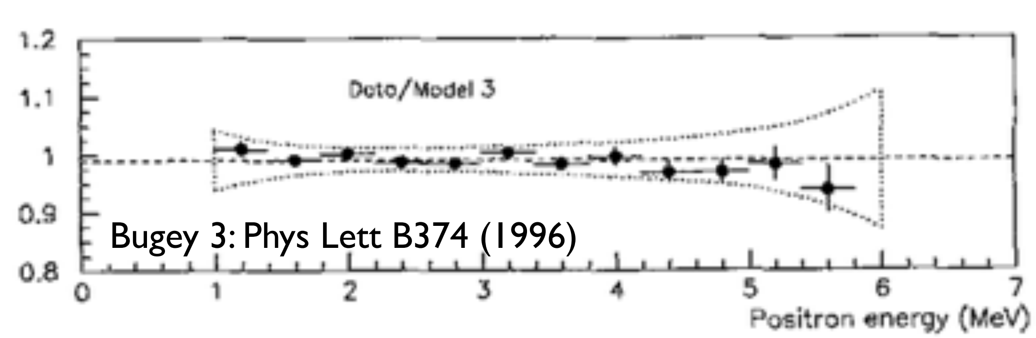
- NOTE: result doesn't explicitly rule out sterile nu altogether
  - Some more complicated scenarios still allowed, i.e.: ^{239}Pu UP + sterile nu
- An editorial opinion:
  - The whole reason we introduced sterile neutrinos to this reactor picture was to avoid having to admit the models were wrong… Hmmmmm……



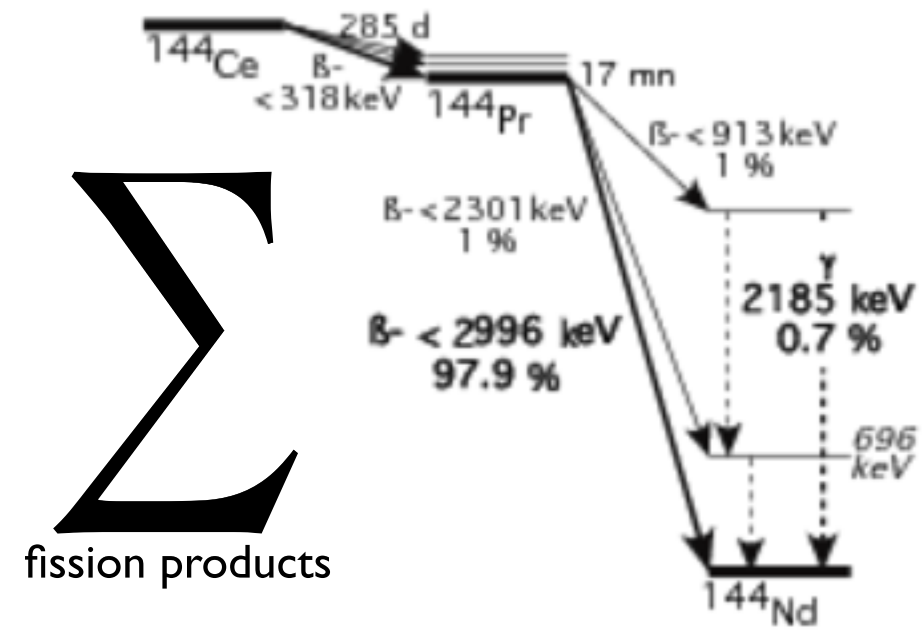


Predicting $S_i(E)$, Neutrinos Per Fission

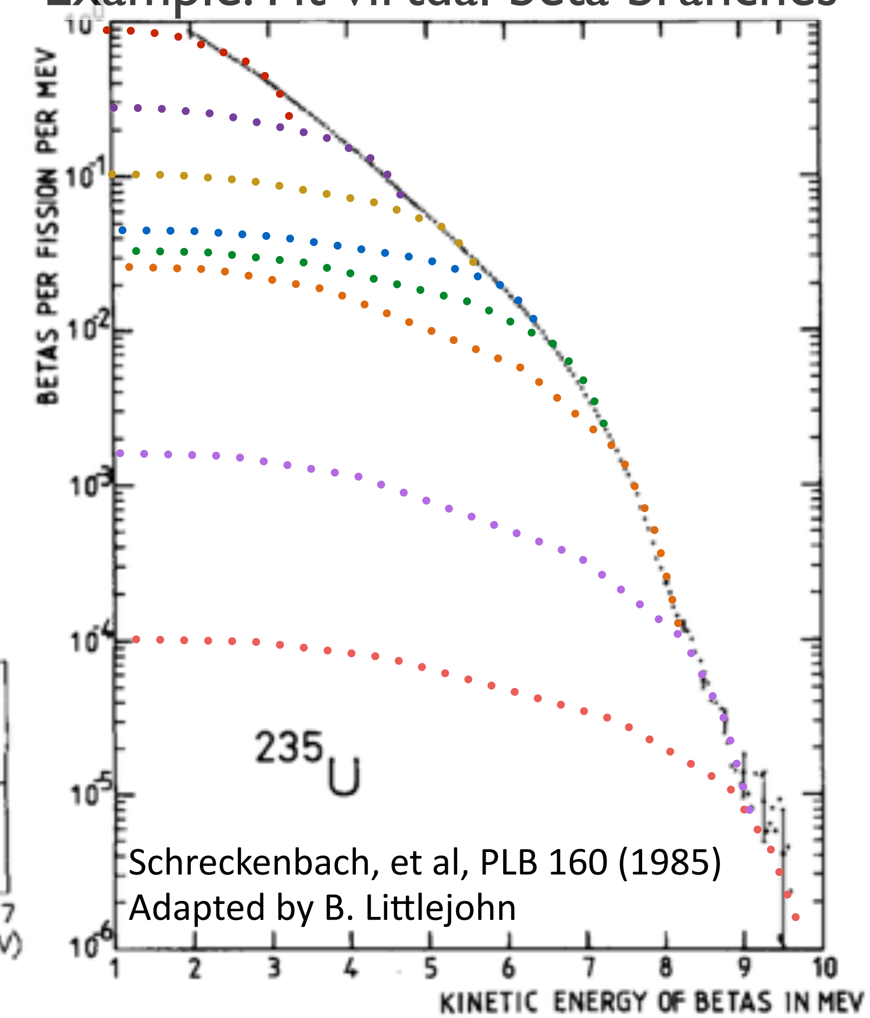
- Two main methods:
- *Ab Initio* approach:
    - Calculate spectrum branch-by-branch w/ databases: fission yields, decay schemes, …
    - **Problem:** rare isotopes / beta branches: missing, possibly incorrect info…
- Conversion approach
    - Measure beta spectra directly
    - Convert to $\overline{\nu}_e$ using 'virtual beta branches'
    - **Problem:** 'Virtual' spectra not well-defined: what forbiddenness, charge, etc. should they have?
    - The preferred method until recently - matched measured fluxes and spectra.



Example: Ce-144 Decay Scheme



Example: Fit virtual beta branches

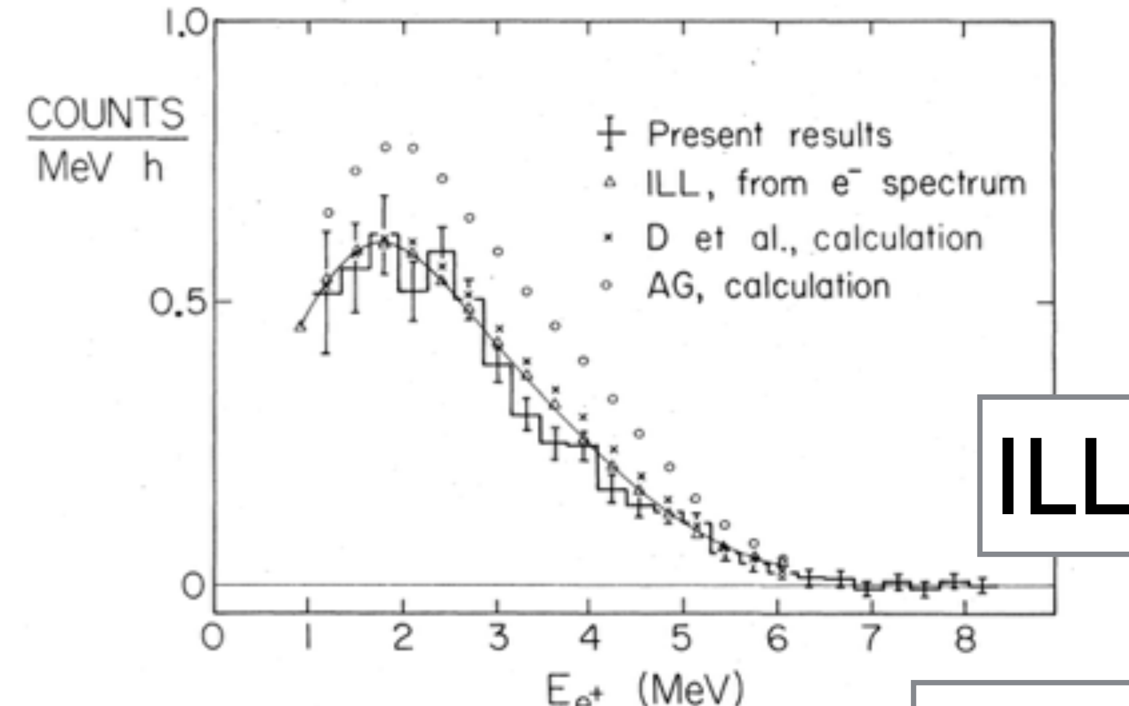


Predicting $S_i(E)$, Neutrinos Per Fission

- Early 80s: ILL $\bar{\nu}_e$ data fits newest *ab initio* spectra well

  Davis, Vogel, *et al.*, **PRC** 24 (1979)

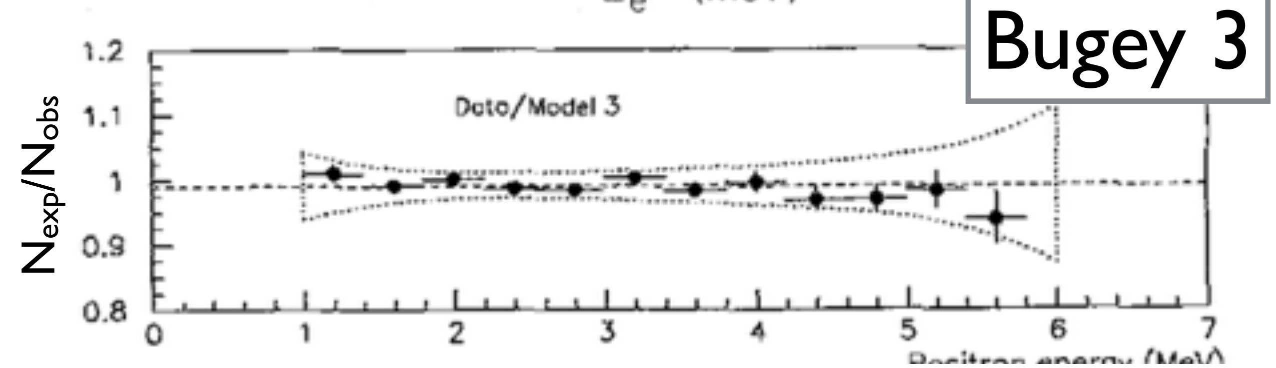
  Kown, et al., **PRD** 24 (1981)



- 1980s: New reactor beta spectra: measurements — conversion now provides lower systematics

  Schreckenbach, *et al.*, Phys Lett **B**160 (1985)

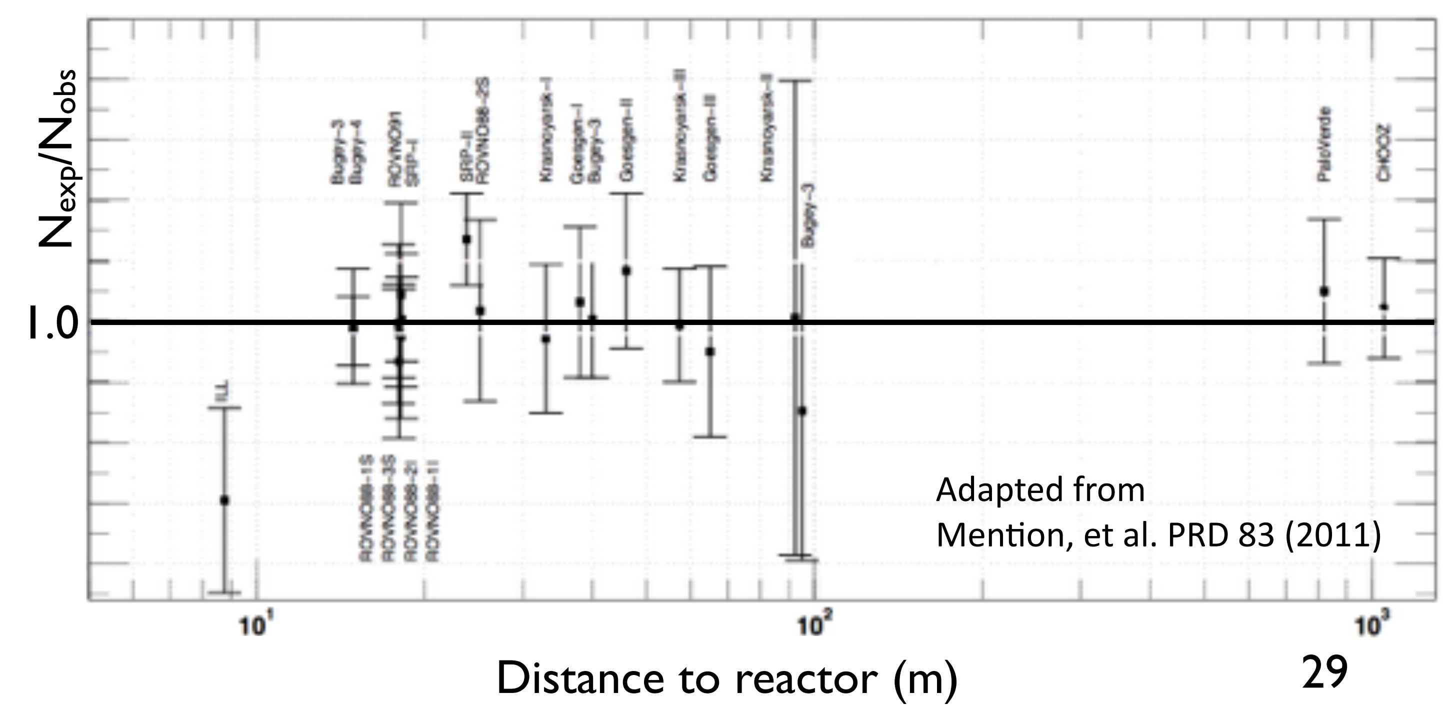
  Schreckenbach, *et al.*, Phys Lett **B**218 (1989)



- 1990s: Bugey measurements fit converted spectrum well

  B. Achkar, *et al.*, Phys Lett B374 (1996)

- 1980s-2000s: Predicted, measured fluxes agree

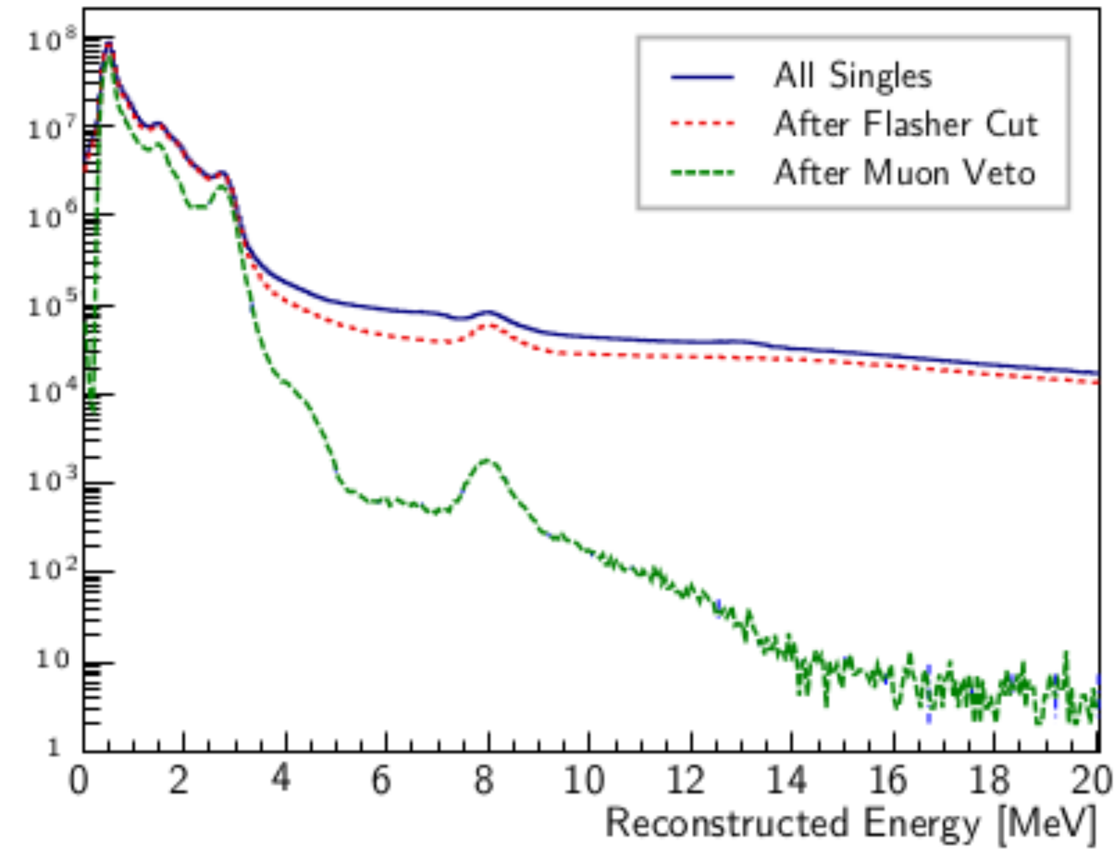


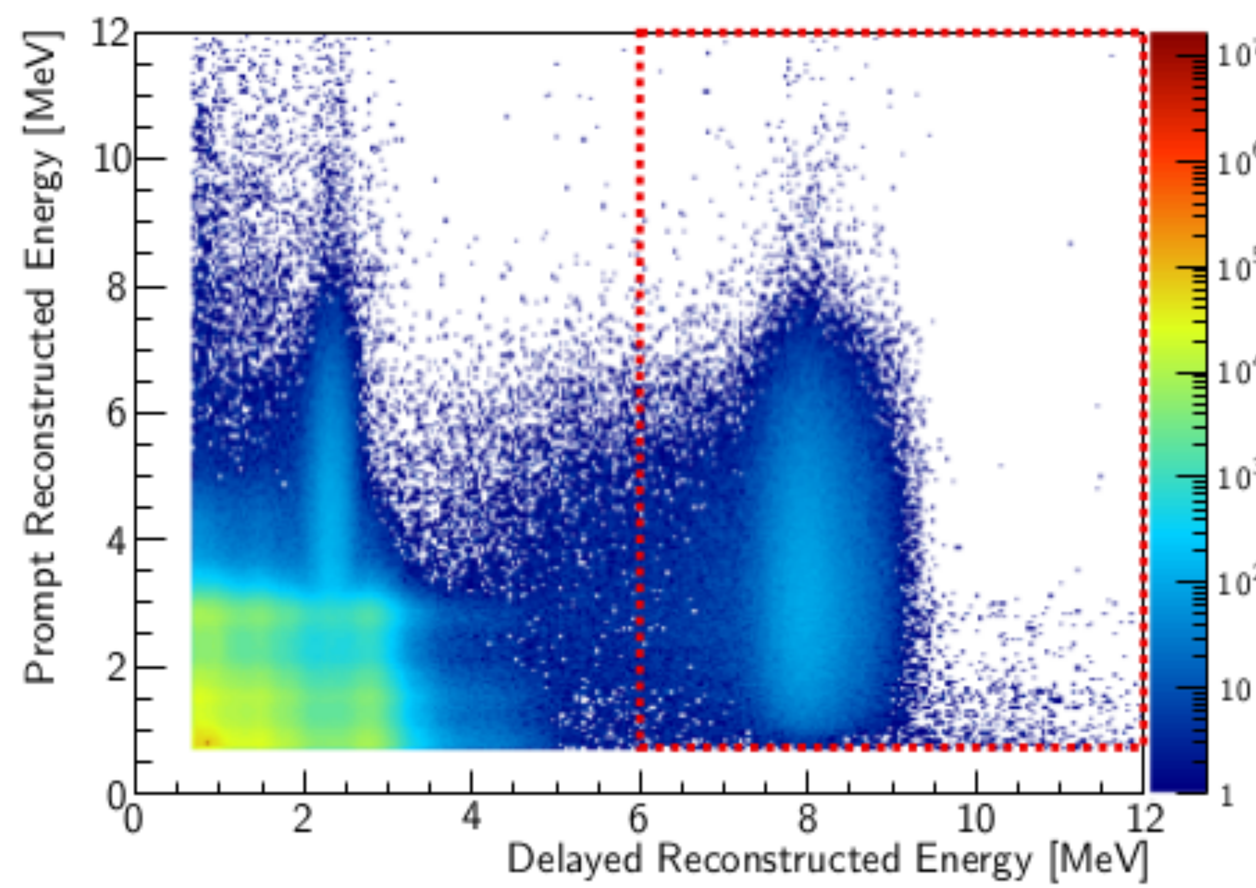
Adapted from Mention, et al. PRD 83 (2011)

IBD Signal 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

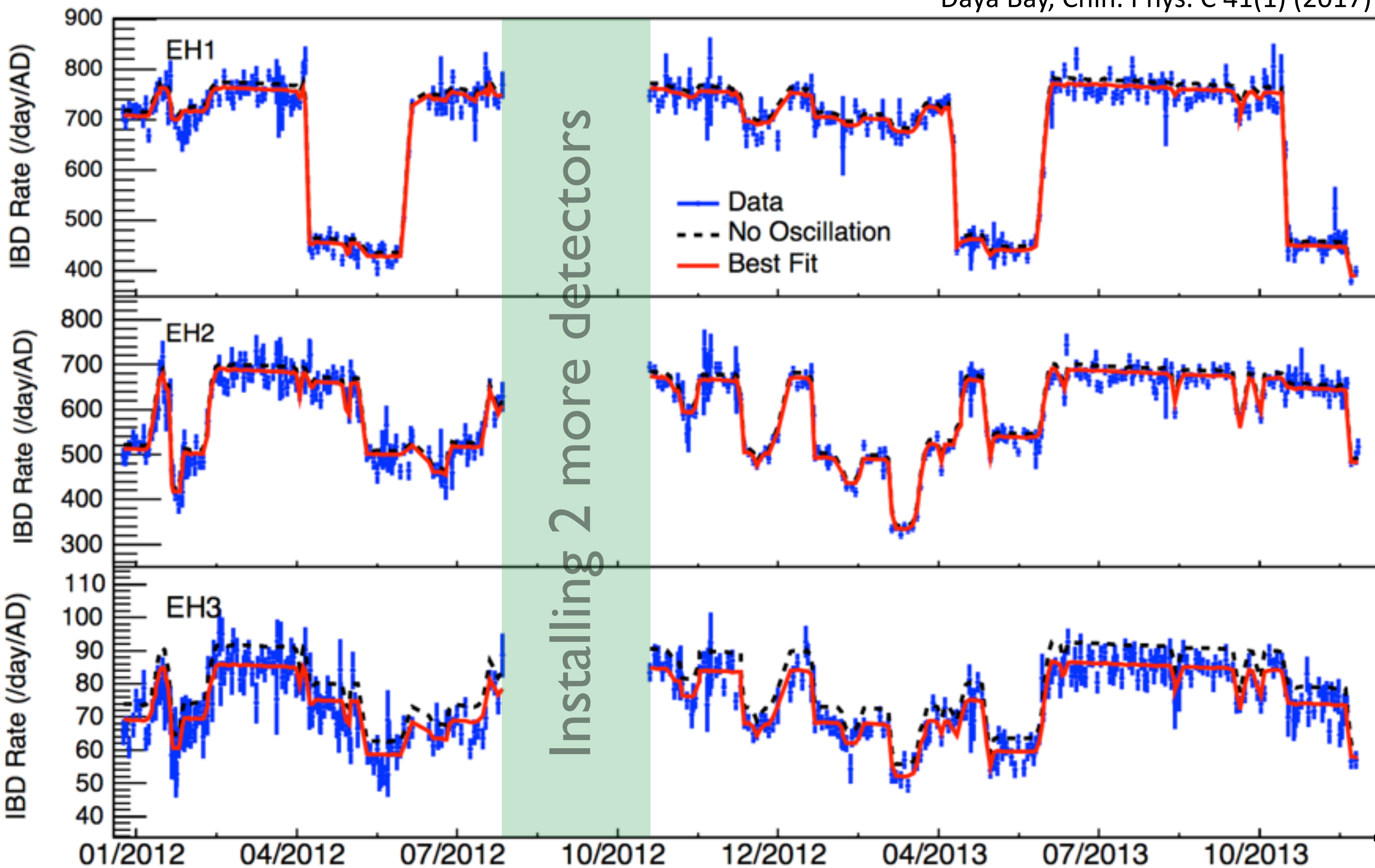




IBD Candidate Detection Rates

- ~ 400-800 IBDs in each Near Site AD per day (x4 ADs)
- Can see when reactors are turned on and off

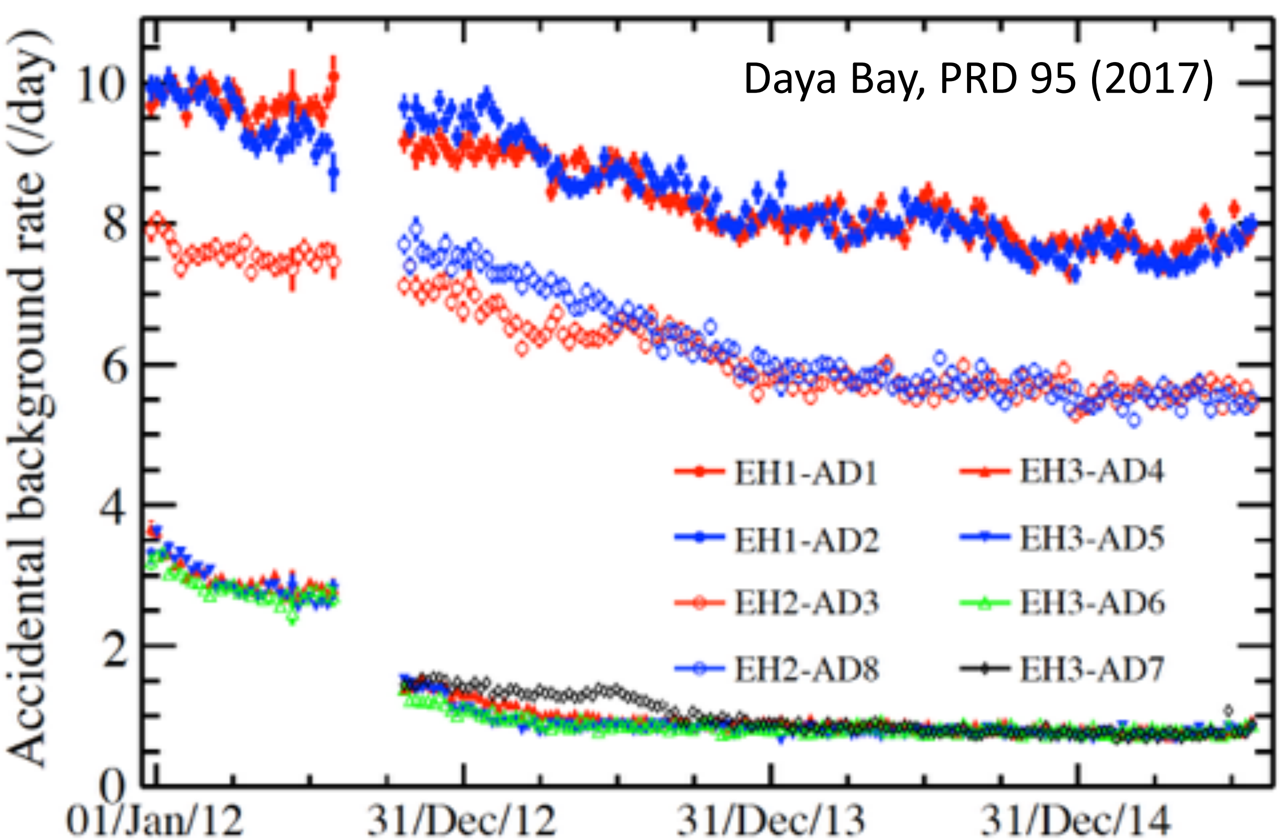
Daya Bay, Chin. Phys. C 41(1) (2017)



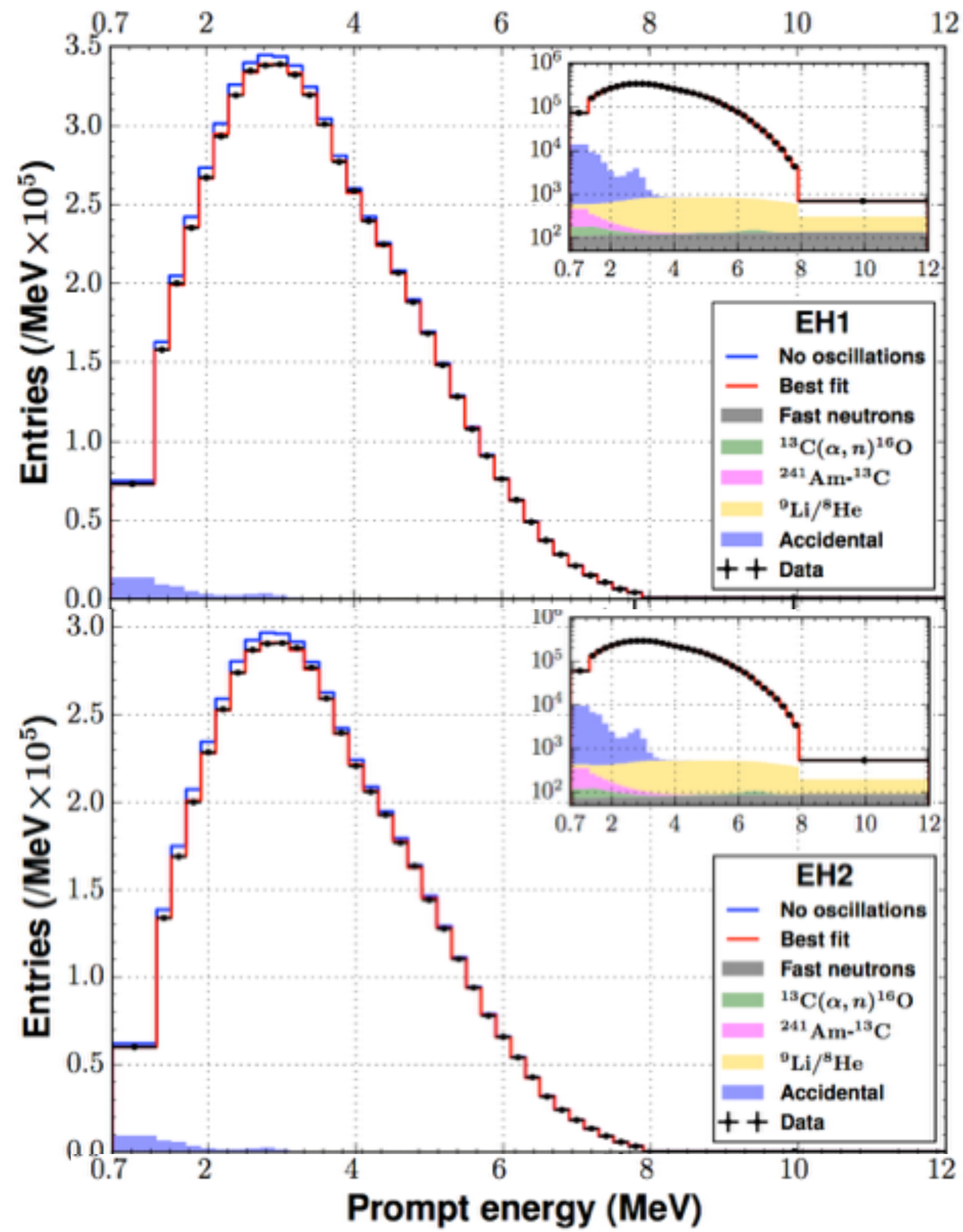
Note:
1230-day dataset goes to July 2015

Daya Bay: A Low-Background Experiment

- Backgrounds make up <2% of Near Site IBD candidates
- Primary bkg: accidentally coincident triggers
  - 1.3% of near-site signal; ~20% variation in rate with time.
- Other backgrounds are constant over time.

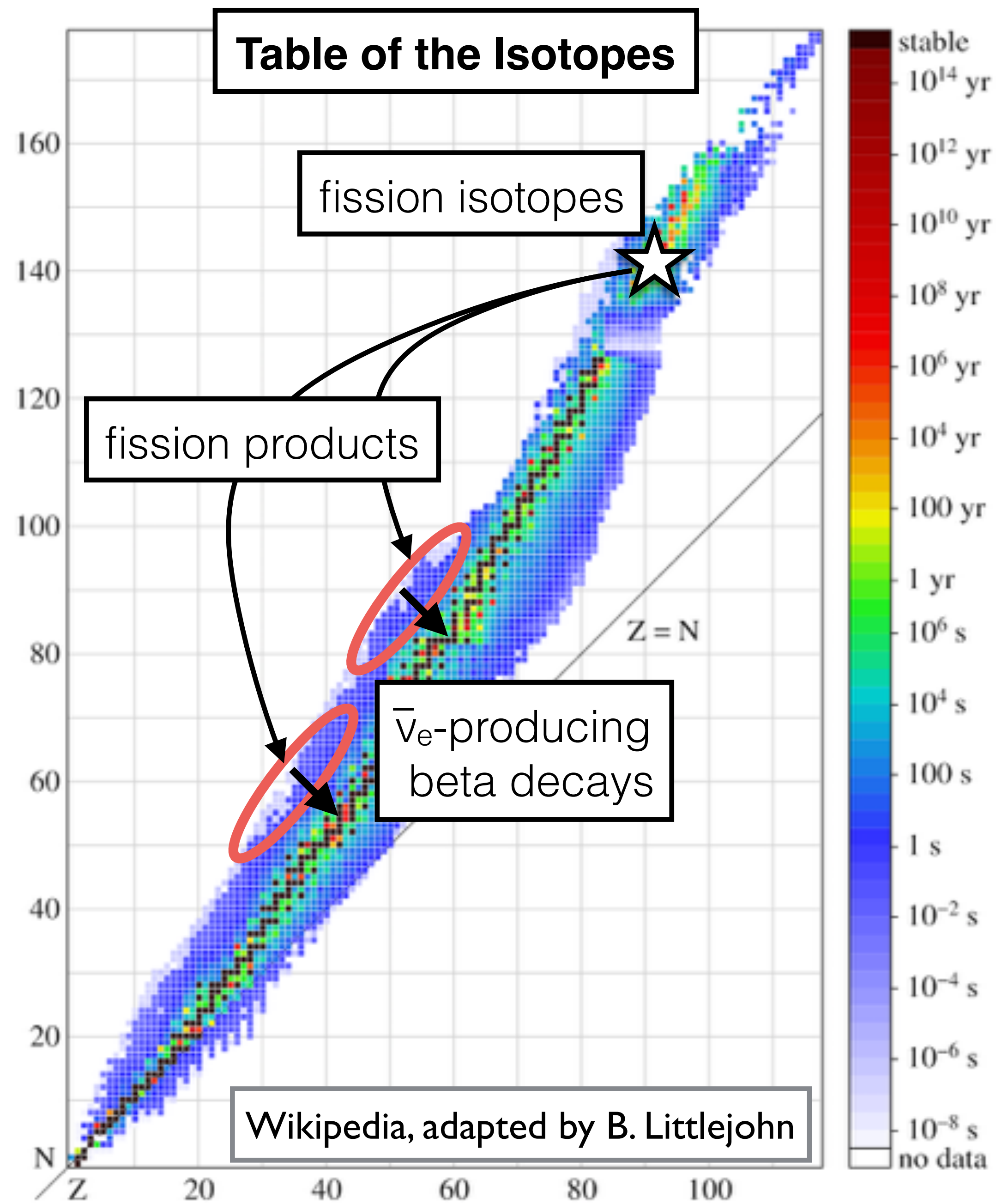


Daya Bay, PRD 95 (2017)



Reactor Prediction Possibilities

- A litany of hypotheses HOW the flux/spectrum are incorrect:
  - Maybe it's specifically related to beta-decays:
    - Maybe forbidden decays aren't treated properly. Hayes, et al, **PRL** 112 (2014), **PRD** 92 (2016)
    - Maybe prominent beta branches measurements are incorrect. See TAS measurements…
    - Maybe fission isotope beta spectrum measurements are wrong. Dwyer+Langford, **PRL** 114 (2015)
  - Maybe it's specifically related to fission yields:
    - Fission yield databases are incorrect! Sonzogni, et al **PRL** 116 (2016)
    - Fission yield dependence on neutron energy not considered correctly. Hayes, et al, **PRD** 92 (2016)
  - Maybe there's an issue with *ONLY* U238 Hayes, et al **PRD** 92 (2016)
  - Maybe there's an issue with *ONLY* Pu239 or U235 Buck, et al, Phys. Lett. B 765 (2017)
  - Etc…

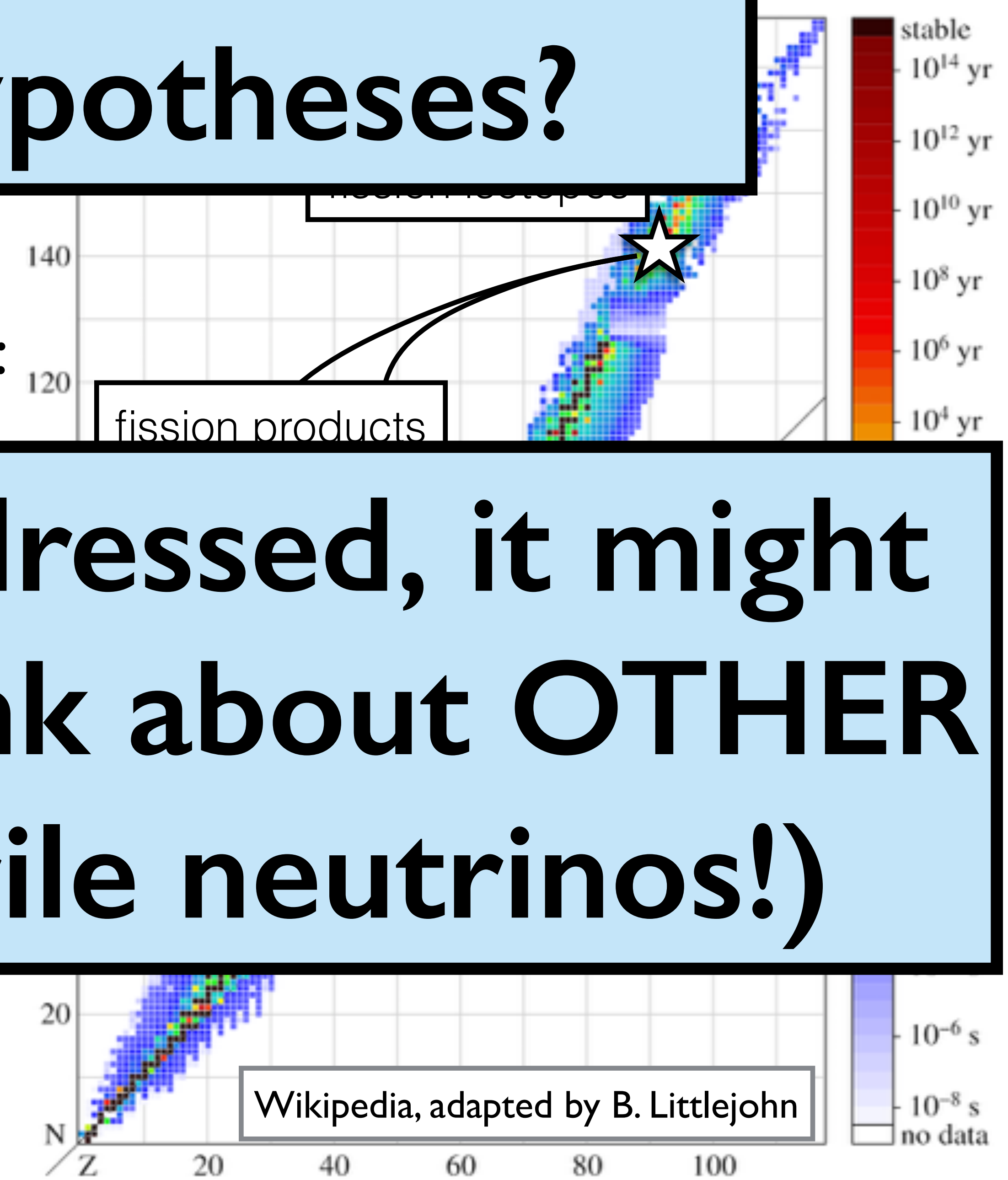


Reactor Prediction Possibilities

- A litany of hypotheses HOW the flux/spectrum are incorrect:
  - Maybe it's specifically related to beta-decays:
    - are wrong. Dwyer+Langford, PRL 114 (2015)
  - Maybe it's specifically related to fission yields:
  - Maybe there's an issue with "ONLY" Pu239 or U235 Buck, et al, Phys. Lett. B 765 (2017)
  - Etc…

How can future measurements address these hypotheses?

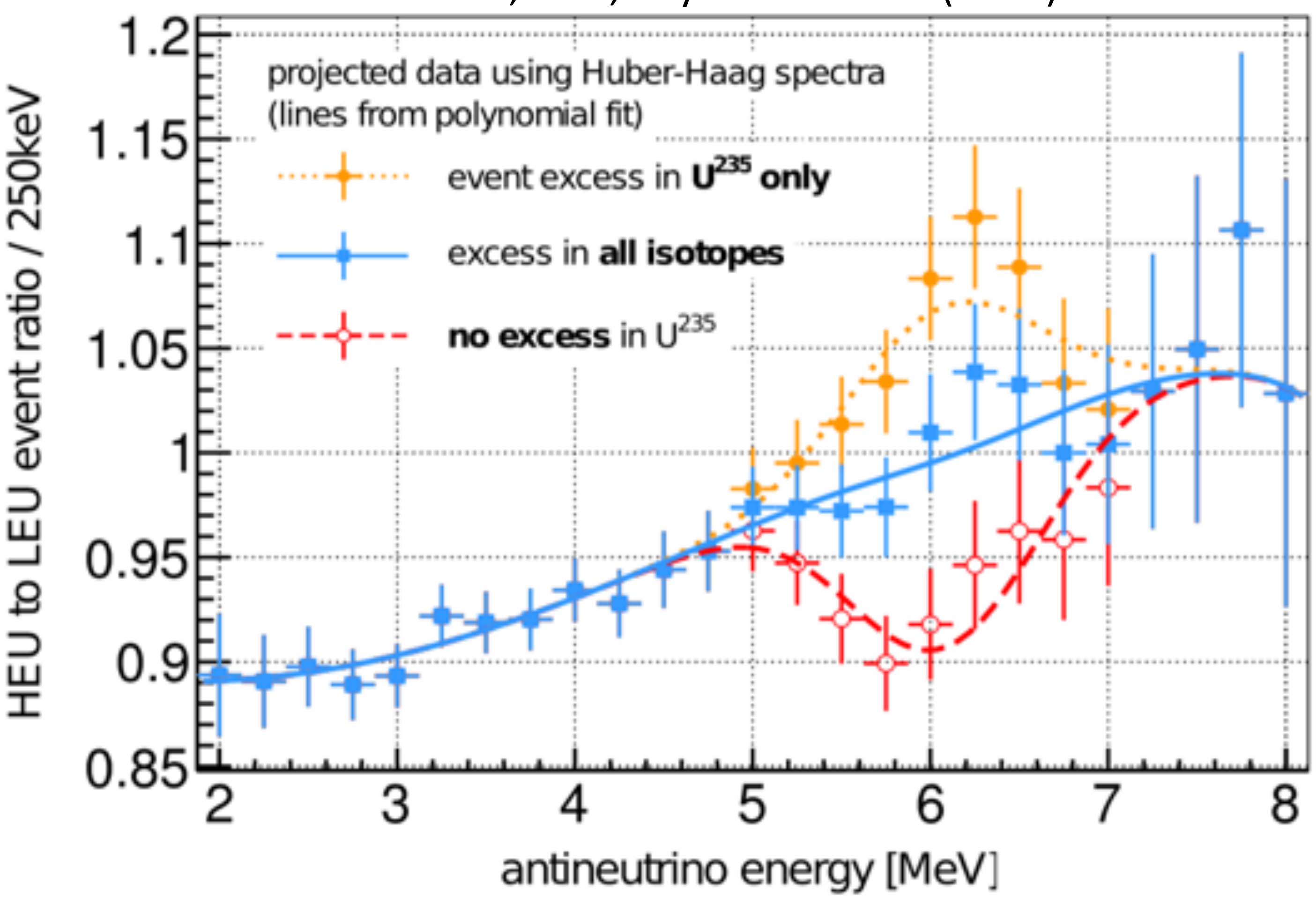
If they COULD be addressed, it might change the way we think about OTHER hypotheses (like sterile neutrinos!)



Example: Only ^{239}Pu, or Only ^{235}U?

- HEU reactors burn only ^{235}U
  - What will the data:model comparison from 4-6 MeV look like from HEU?
    - No bump = bump mainly from U235
    - Larger bump = bump mainly from Pu239
    - Same bump = something else is responsible…
  - Upcoming SBL reactor experiments are crucial
    - PROSPECT: HFIR reactor
    - STEREO: ILL reactor
    - Solid: BR2 reactor
  - Good reason to believe these experiments, combined with θ_{13} experiments, can produce meaningful new constraints.

Buck, et al, Phys. Lett. B 765 (2017)

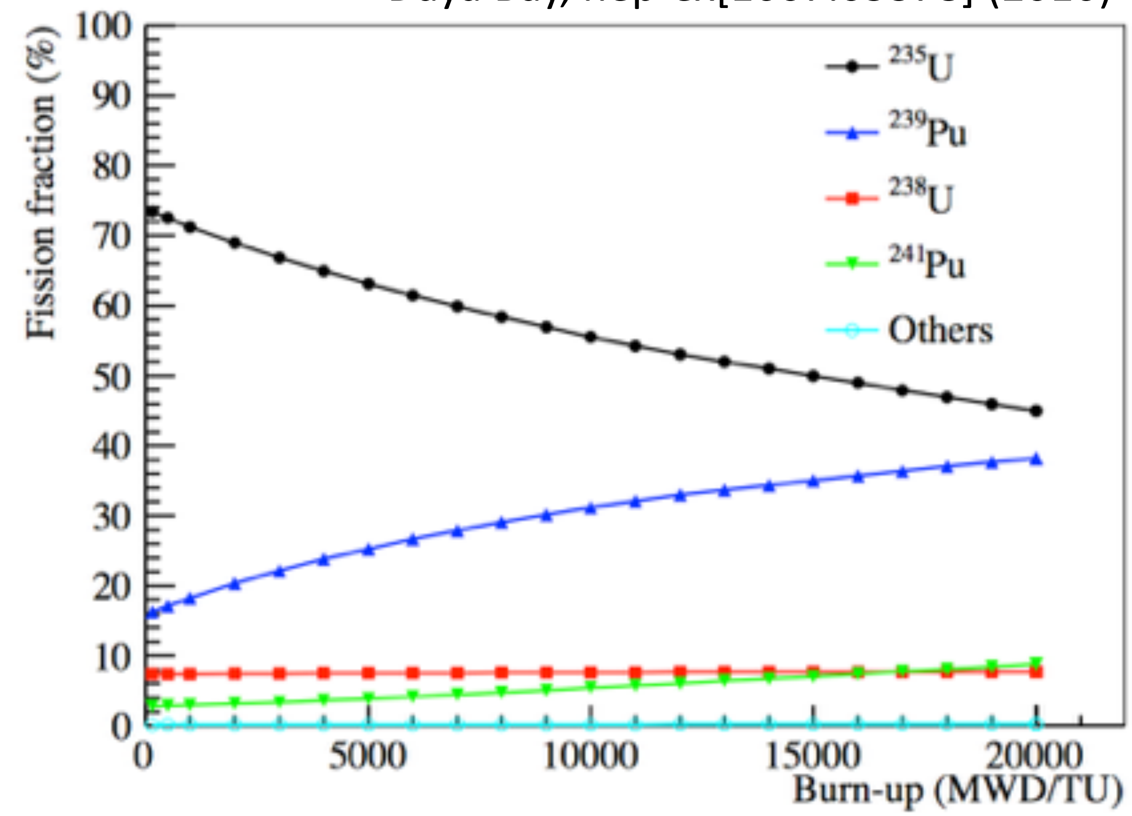


Example: hypothetical STEREO-Double Chooz spectral ratio

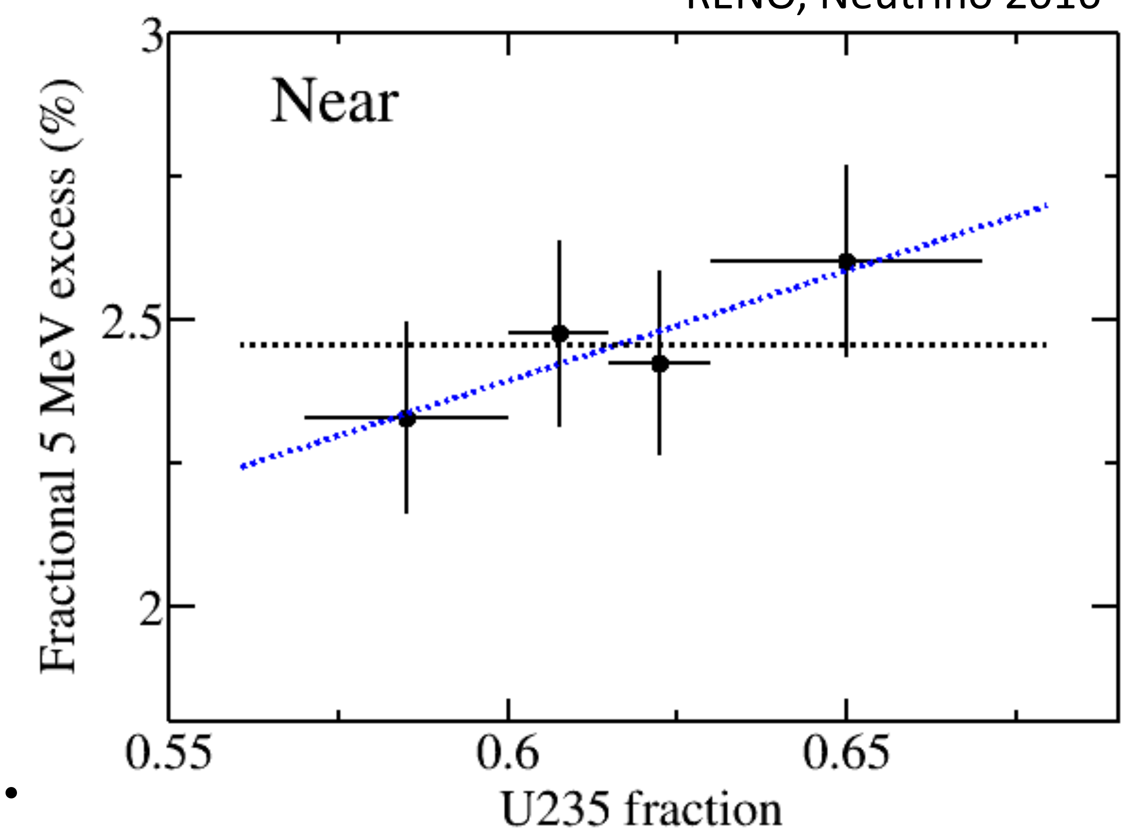
Only ^{239}Pu, or Only ^{235}U?

- Each θ_{13} experiment has reactors with varying ^{235}U and ^{239}U fractions
- Perhaps changes in bump size will accompany changes in fission fractions?
  - Note: nobody has actually measured a change in spectrum, let alone the bump, with burnup… (Rovno in 1994, maybe?)
  - Needless to say: this is VERY difficult…
- RENO's first look: inconclusive
  - No change visible within statistics
  - However, context is missing: how much change should one expect?
  - Example: If the bump is all from ^{235}U, what would that look like on this plot?
- More investigation should be done…

Daya Bay, hep-ex[1607.05378] (2016)



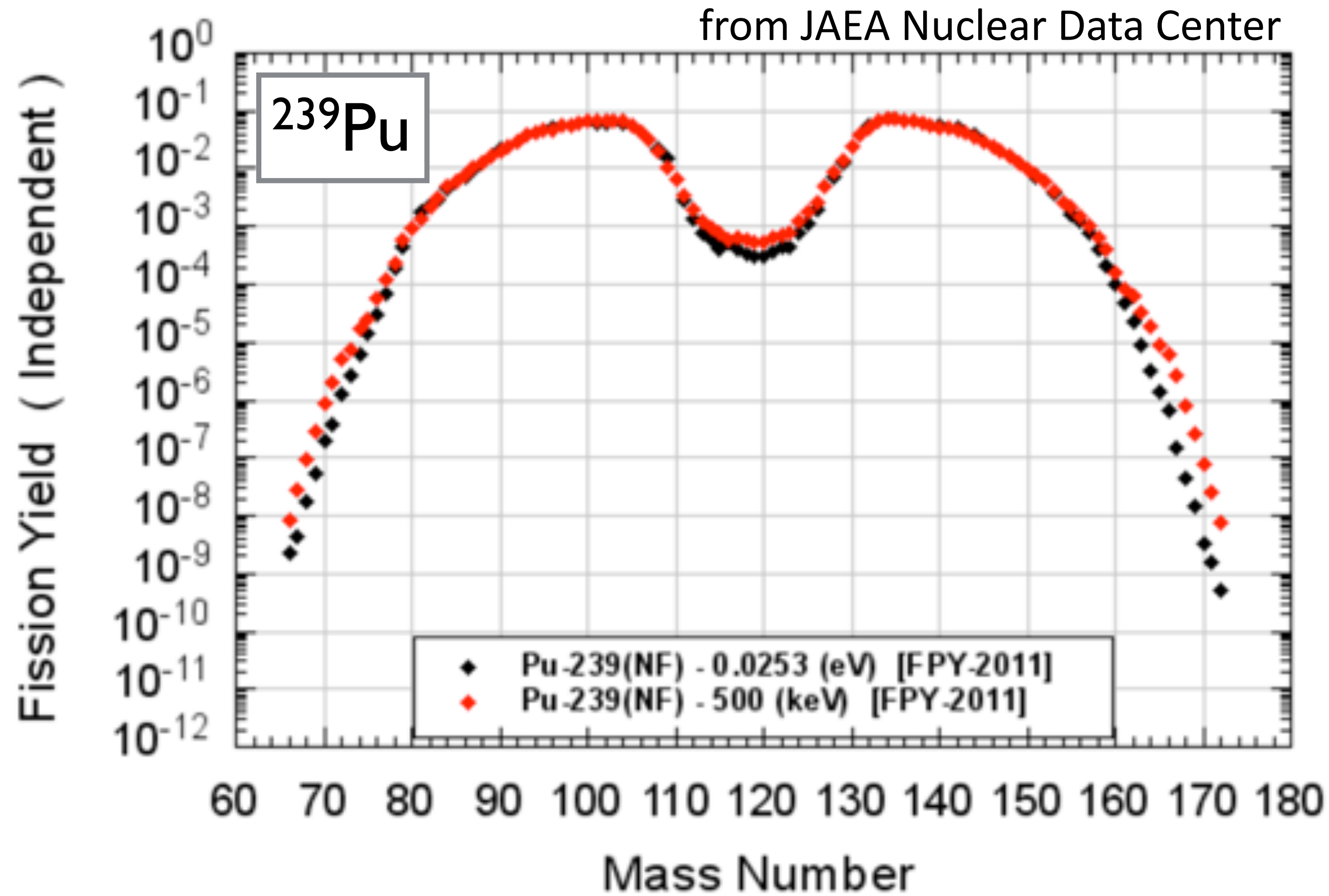
RENO, Neutrino 2016



Example: Neutron Energy Issues?

- Models based on ^{235}U, ^{239}Pu, ^{241}Pu beta spectra measurements: these come from thermal neutrons only
  - θ_{13} experiment reactors have a mix of thermal, epithermal and fast neutrons…
- It is well-known that fission yields vary with neutron energy
- Big question: how big of an effect does this have on the reactor spectrum?
- Could measure with different reactor types:
  - HFIR: More epithermal neutrons
  - NIST: Fewer epithermal neutrons
  - PROSPECT just got a new travel itinerary……? ;)
  - Note: effects may differ for ^{235}U, ^{239}Pu (must measure both…)

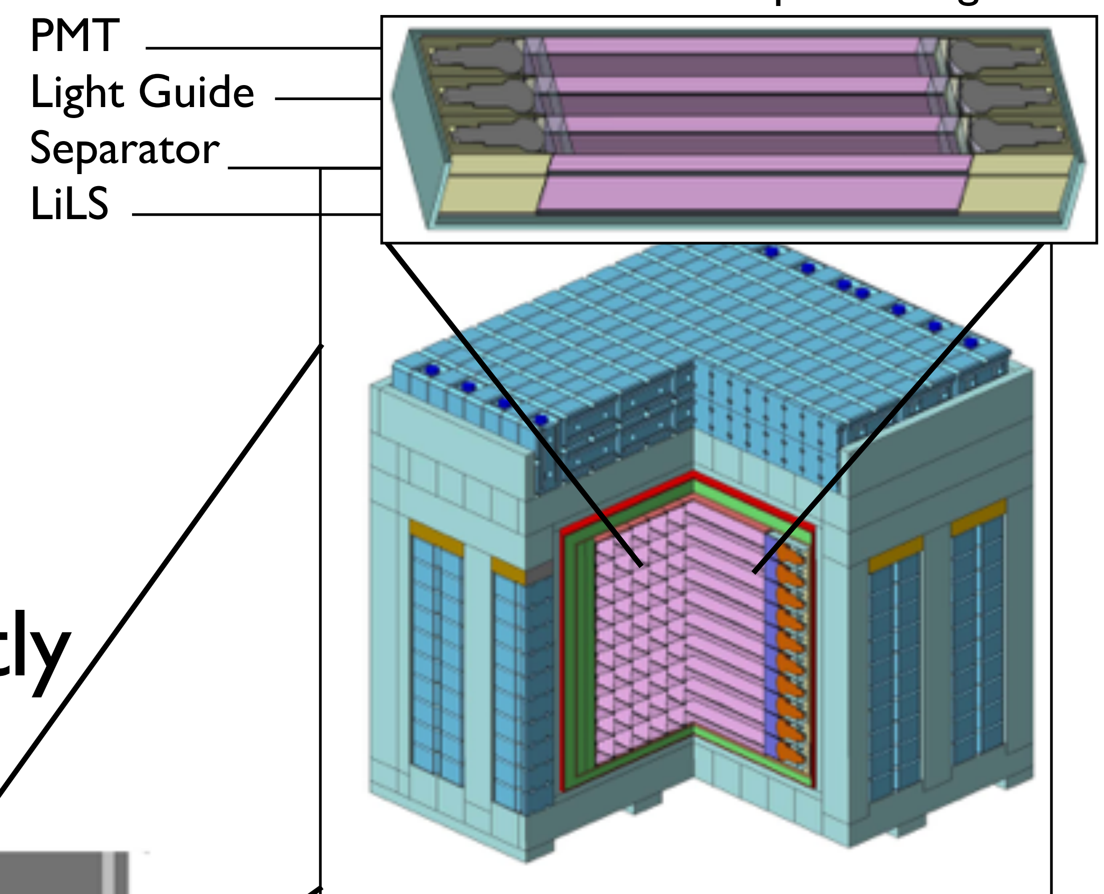
from JAEA Nuclear Data Center



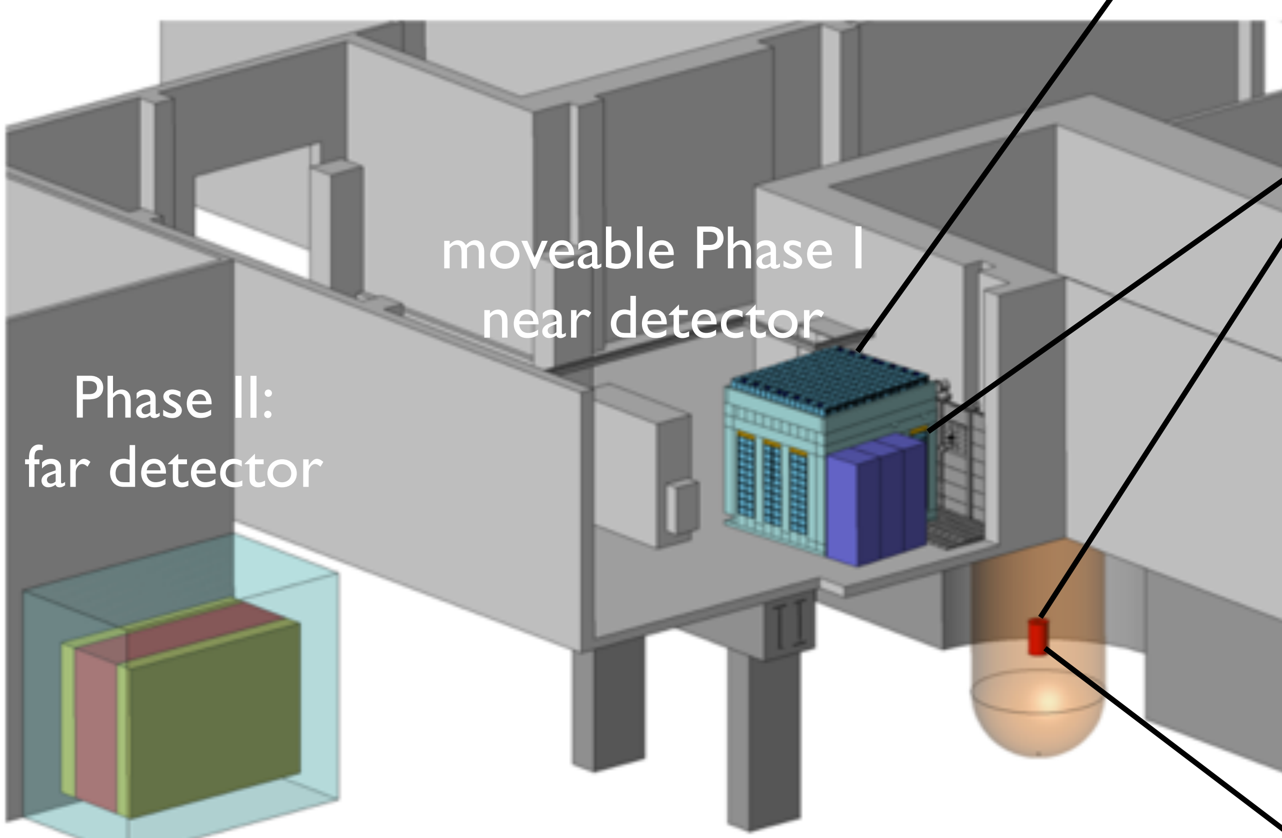
PROSPECT Experimental Layout

- HEU Reactor: HFIR
- Segmented liquid scintillator target region: ~3 tons for near detector (Phase I)
- Moveable: 7-12 m baselines
- Measure ^{235}U flux while directly probing sterile oscillations

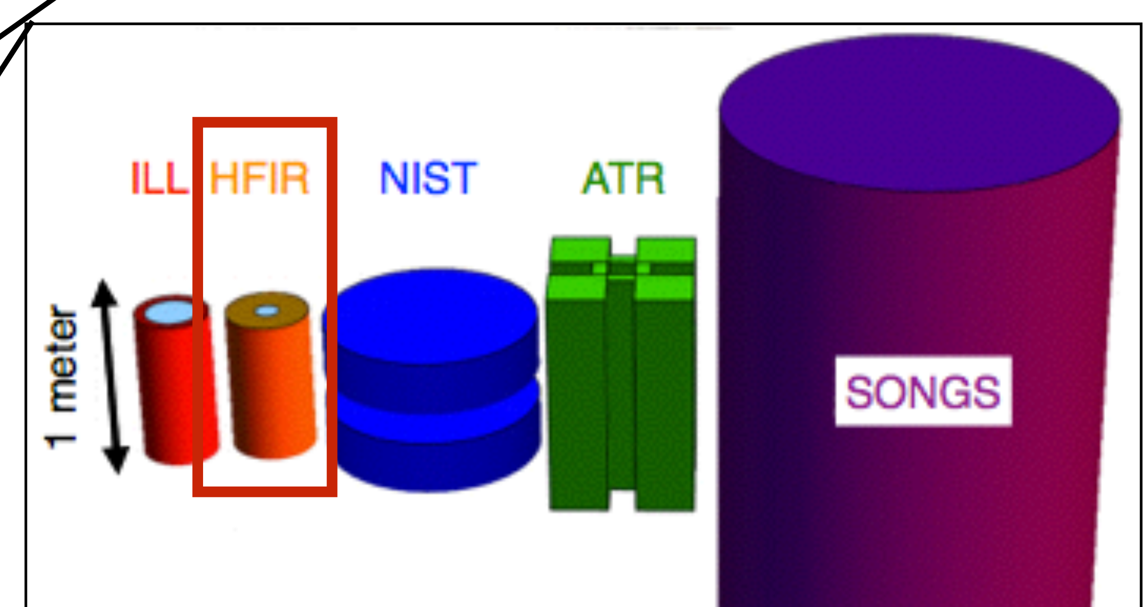
Sub-cell conceptual design



Near detector conceptual design



Two-detector PROSPECT deployment at HFIR



HFIR core shape and relative size comparison