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

May 31, 2017

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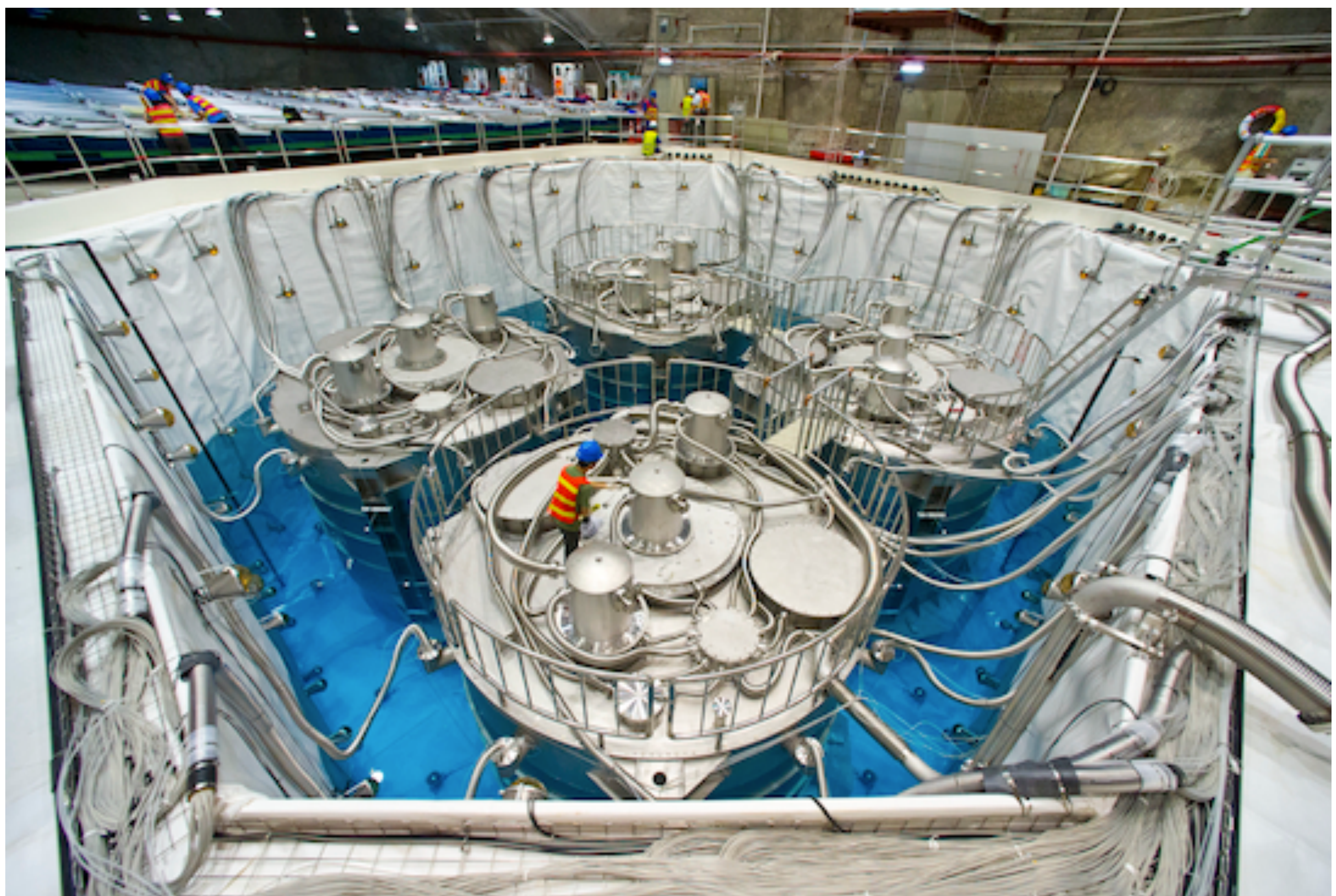
Illinois Institute of Technology



https://arxiv.org/abs/1704.01082

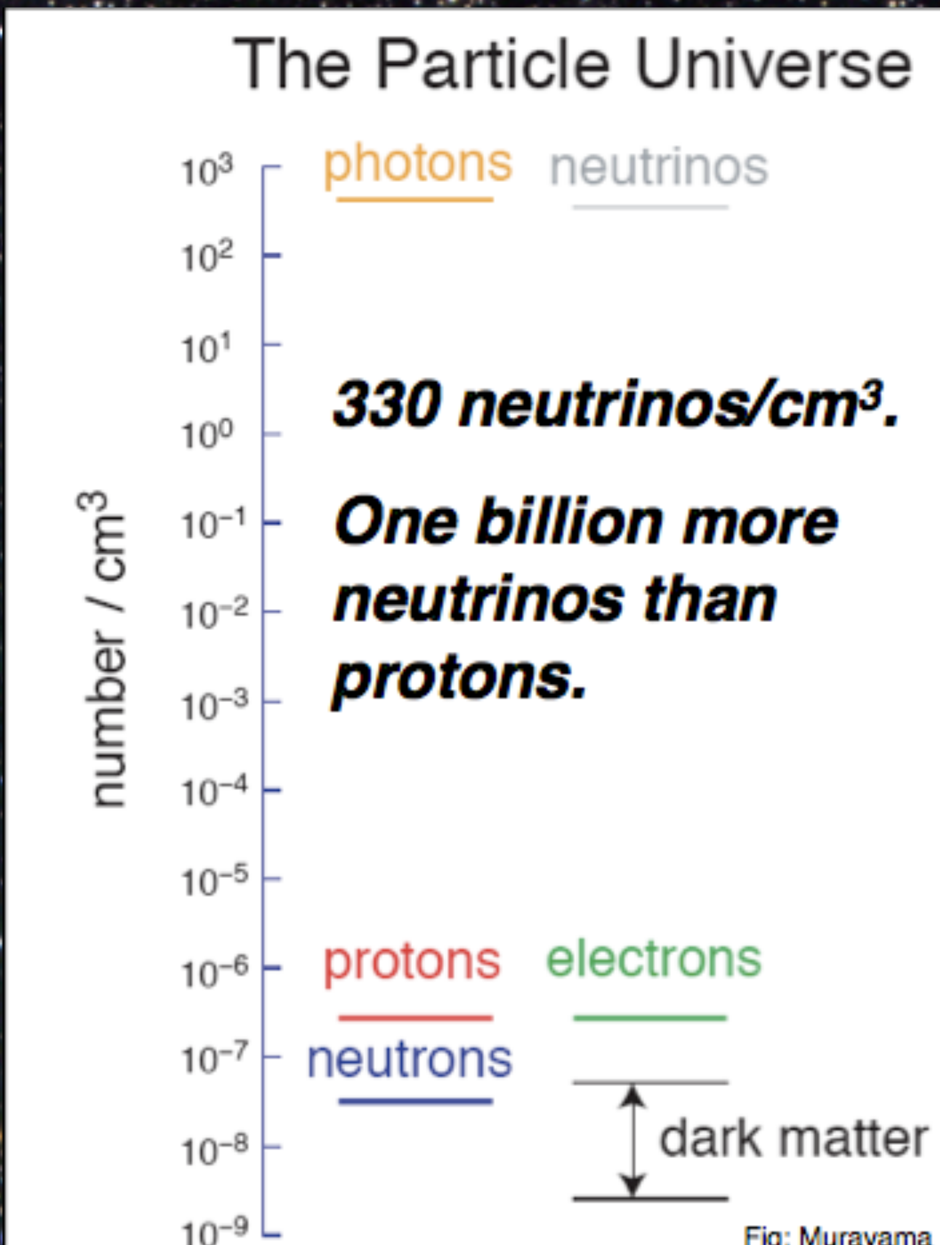
Outline

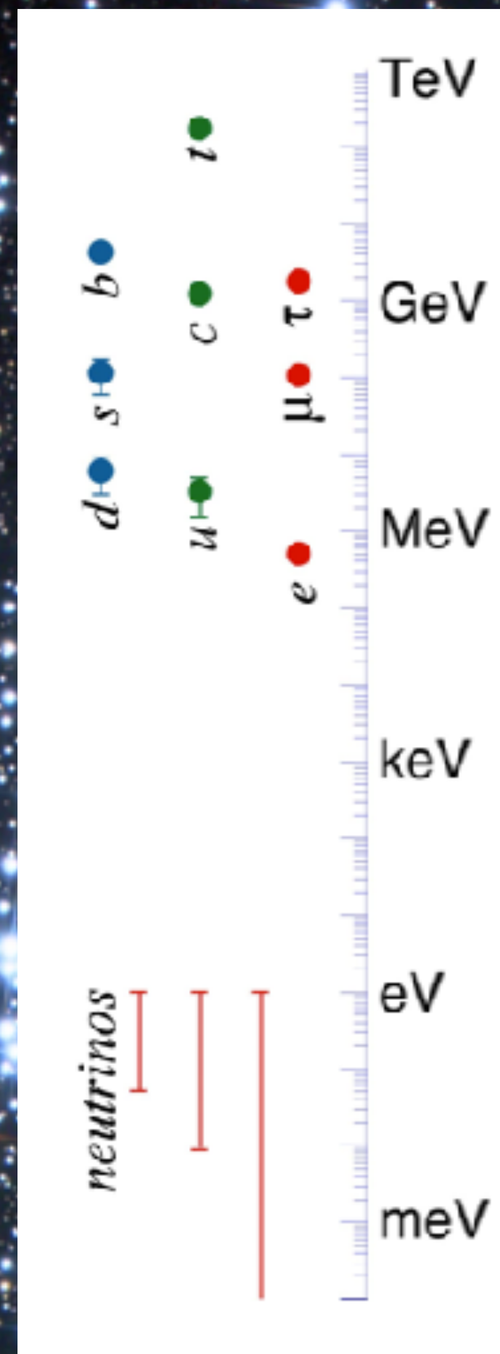
- Intro: Neutrinos and Reactor $\overline{\nu}_e$ Flux/Spectrum Predictions
- Reactor Anomalies, Explanations
- Testing Explanations With Reactor Data
- Will show updated results as much as possible. In particular:
  - BRAND NEW Daya Bay analysis: arXiv:hep-ex[1704.01082] (PRL-Accepted)
  - Also, some plots from other semi-recent results:
    - Daya Bay, Chin. Phys. C 41(1) (2017)
    - Daya Bay, PRD 95 (2017)

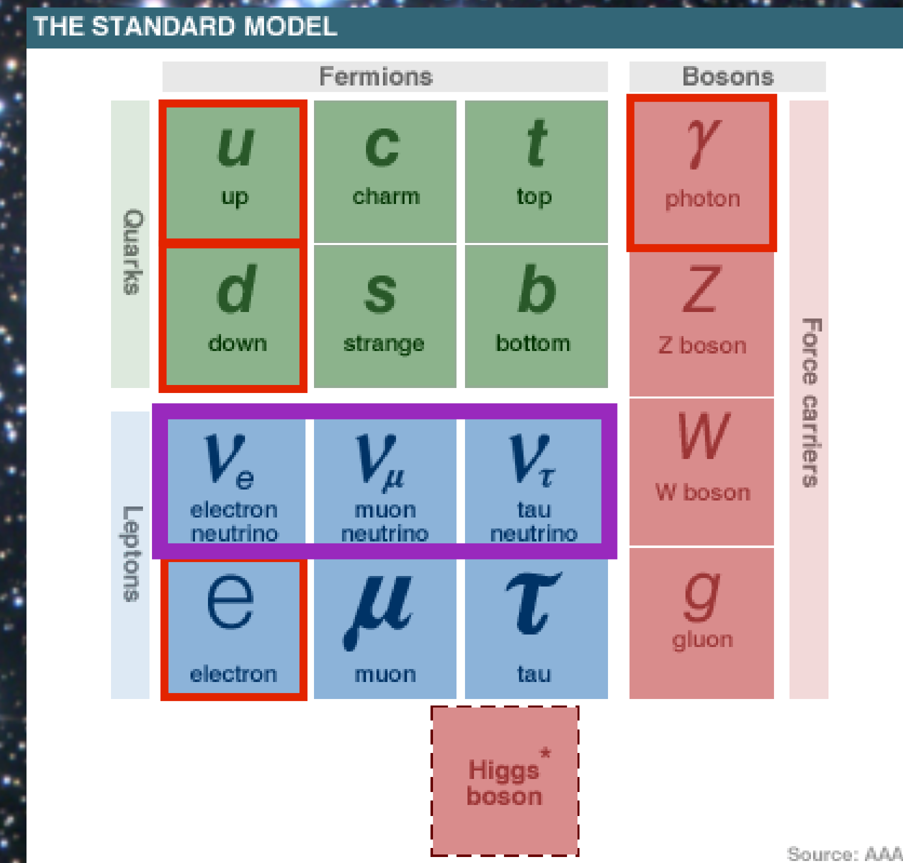
      …~45 pages of all the reactor oscillations detail you could ever want…
    - RENO, Neutrino 2016

Neutrinos

The Universe's most common particle, after photons







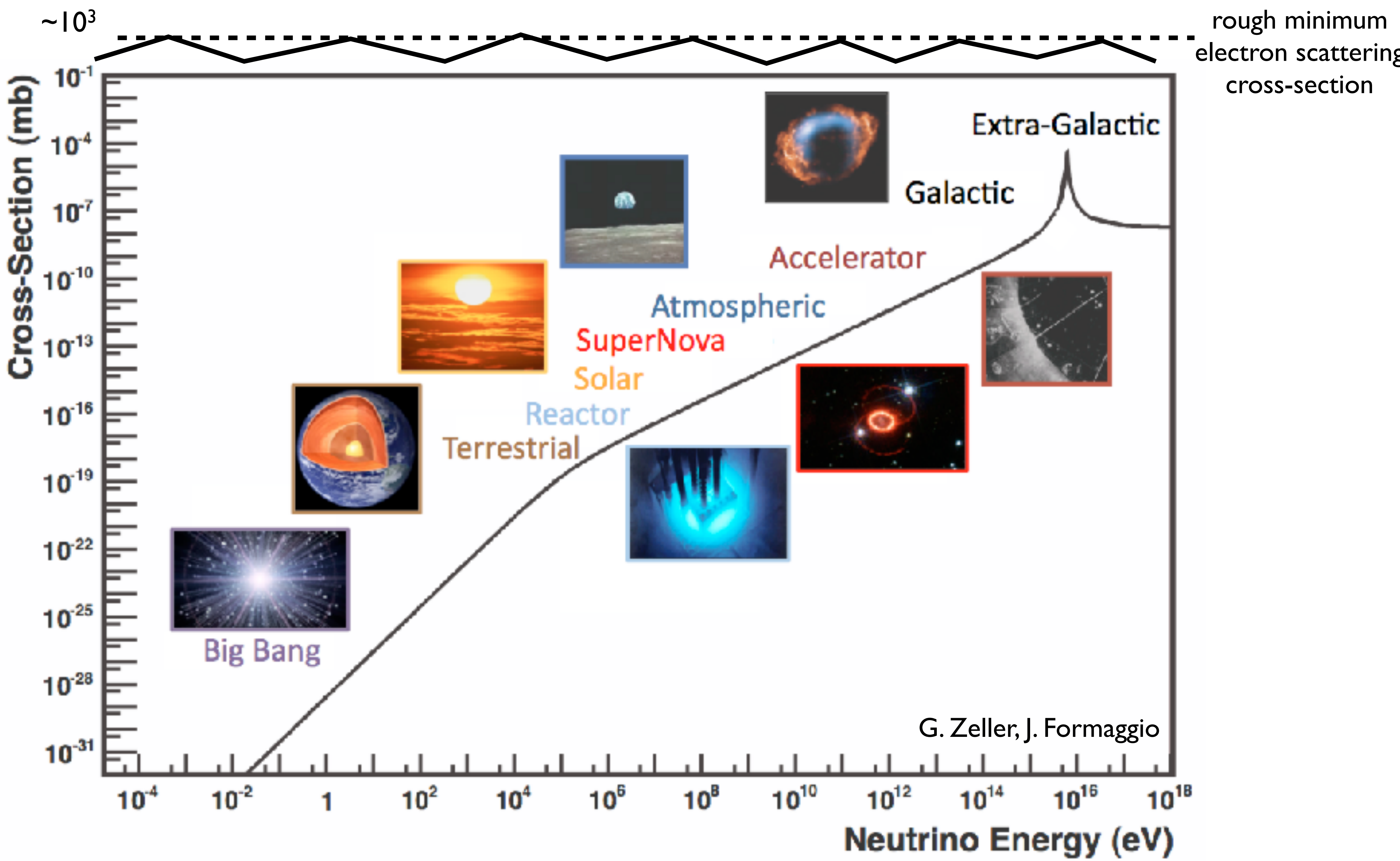
Far less massive than all other fermions

Also, no electric charge

Don't forget antiparticles!

Neutrino Varietals

- Created wherever there is radioactivity!
- Many neutrino sources and energies, interacting via weak force



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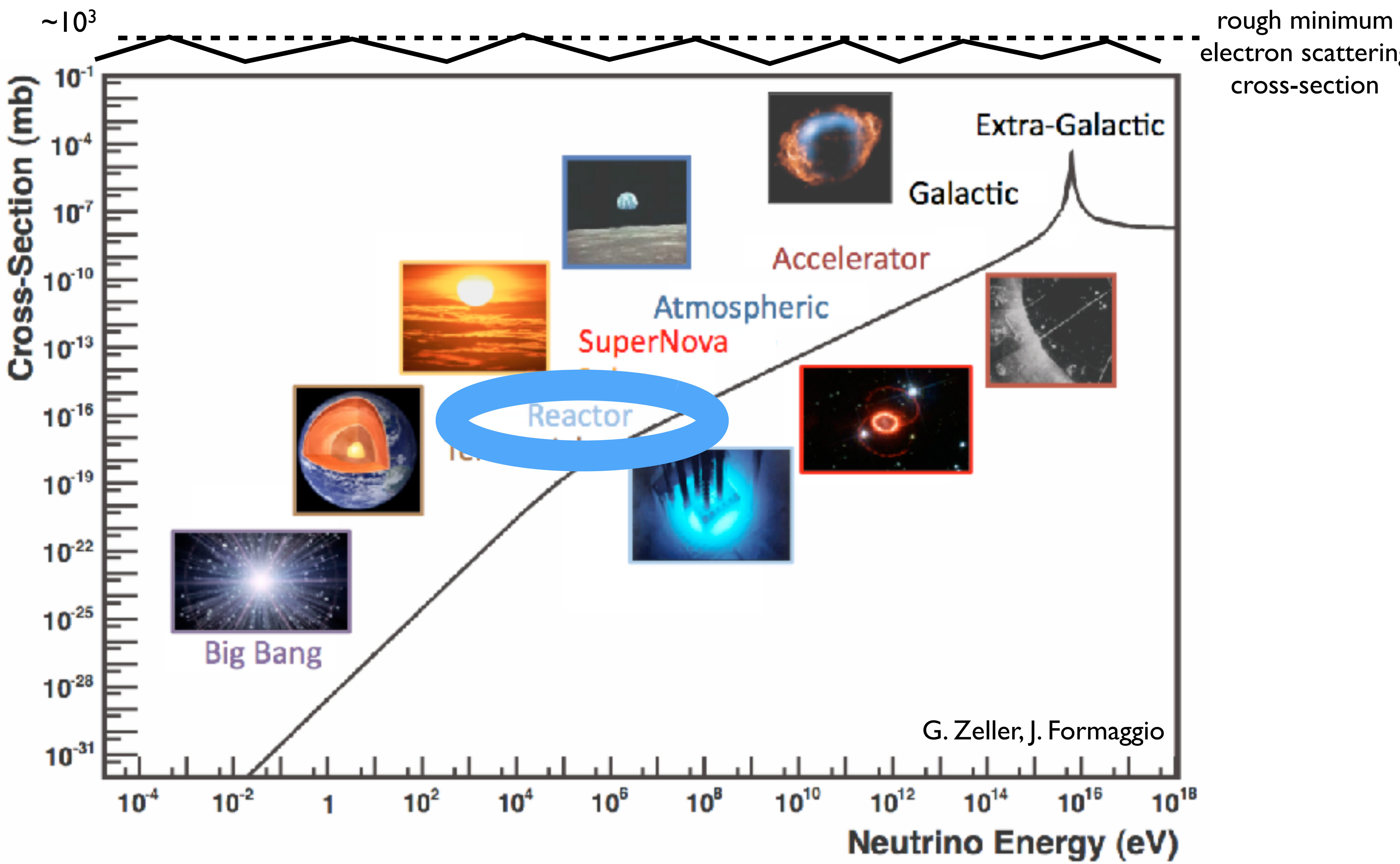
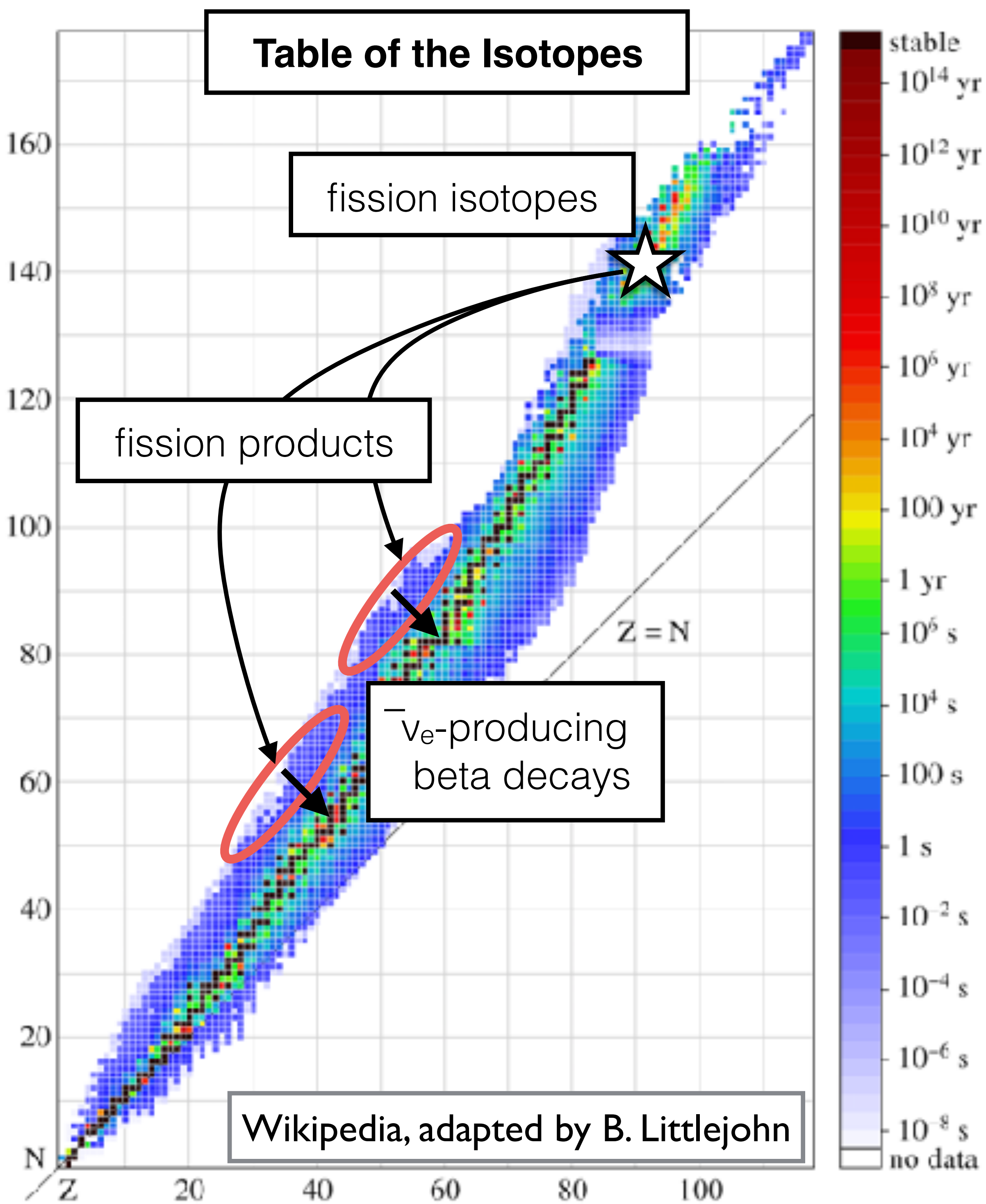
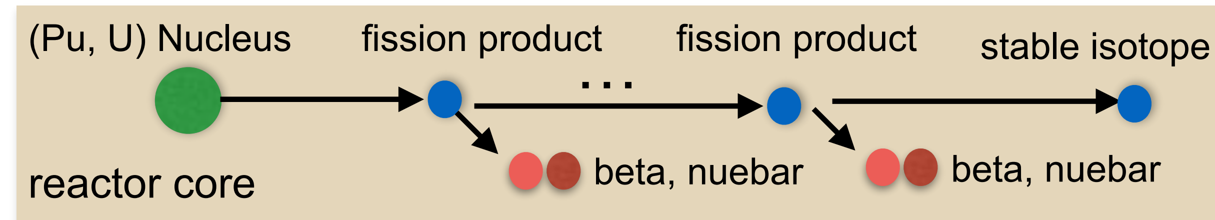


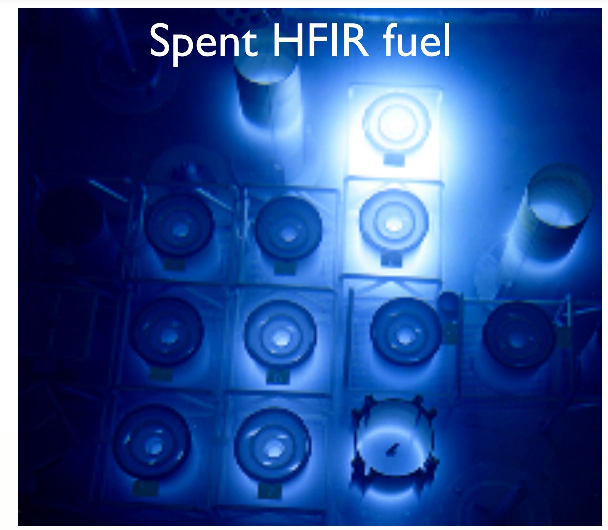
Reactor = Great Antineutrino Source

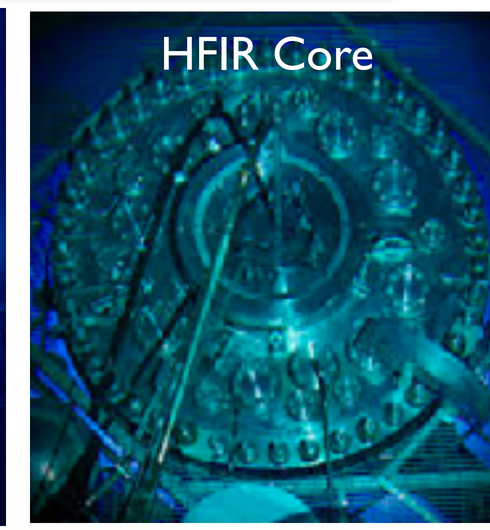
Reactor Antineutrino Production

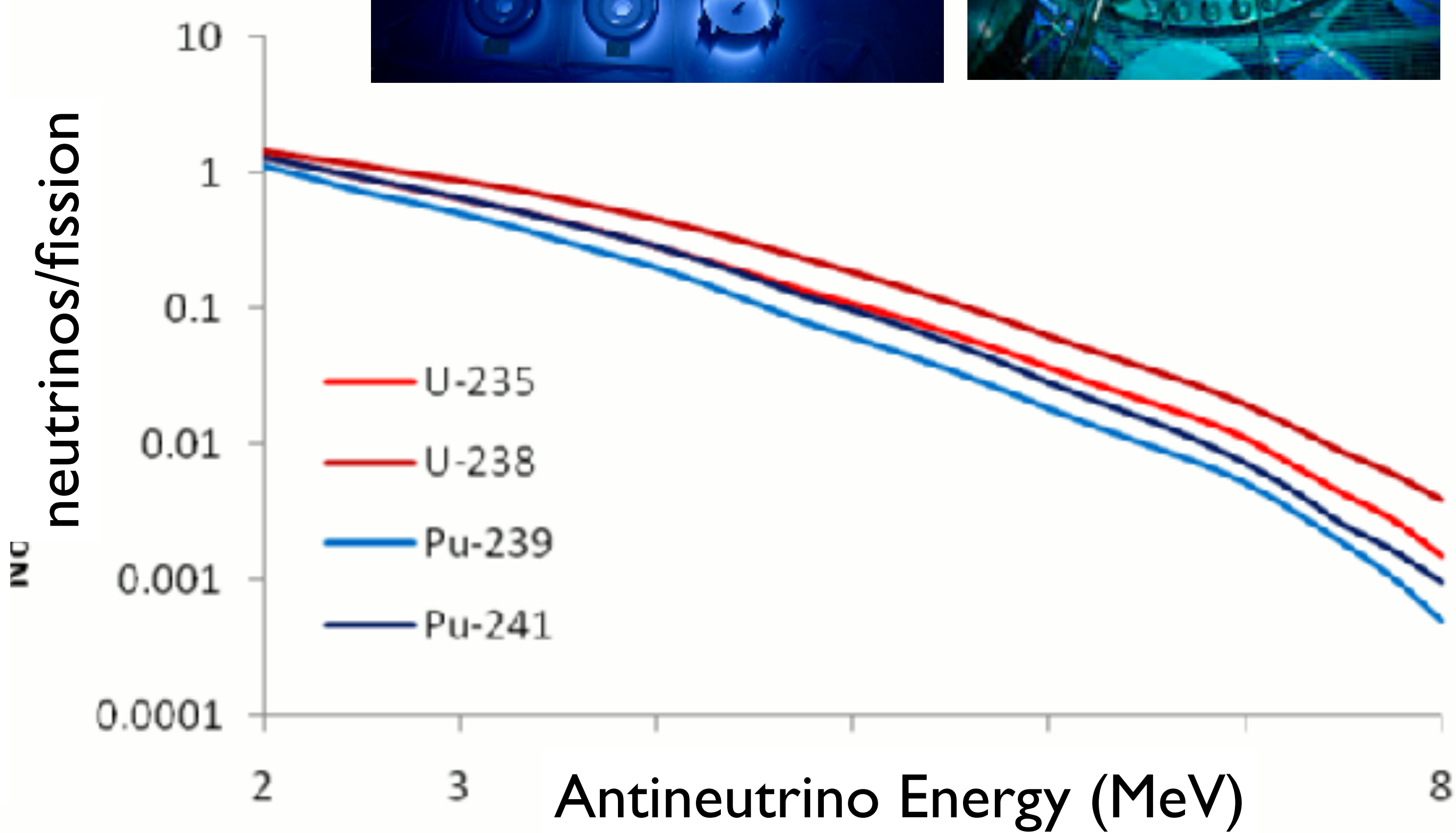
- Reactor $\bar{\nu}_e$: produced in decay of product beta branches
  - Each isotope: different branches, so different neutrino energies (slightly)





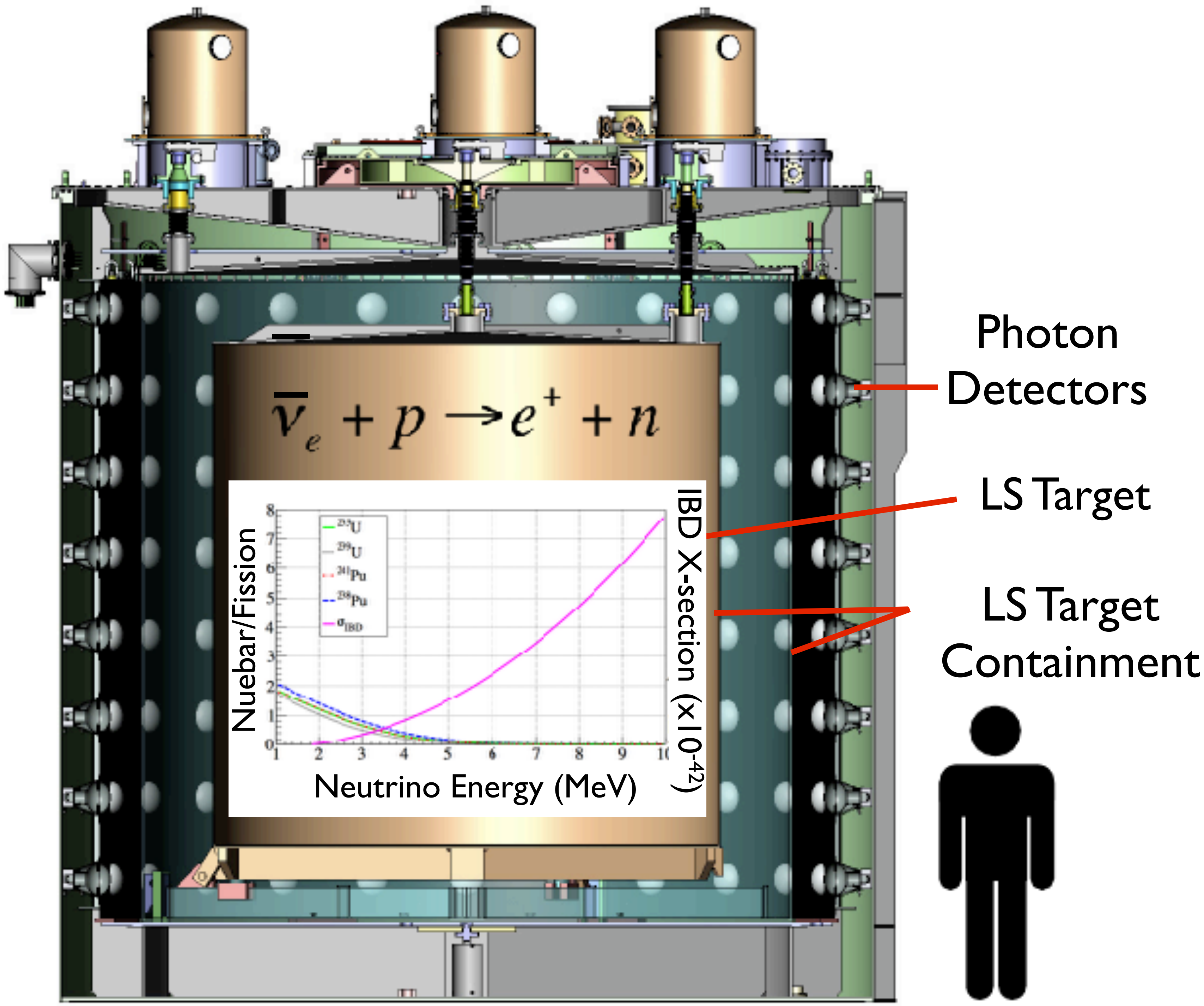




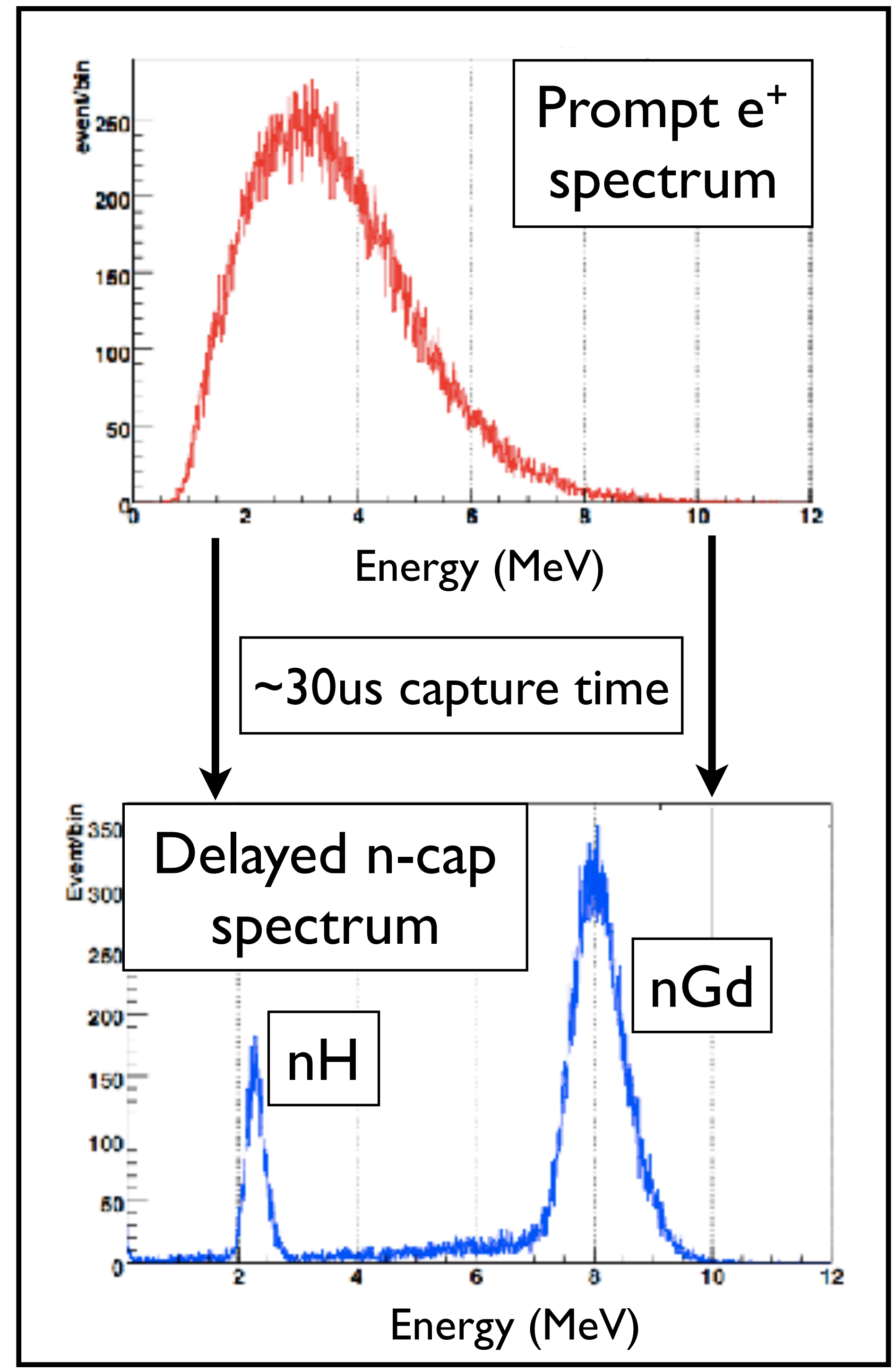


Reactor Antineutrino Detection

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



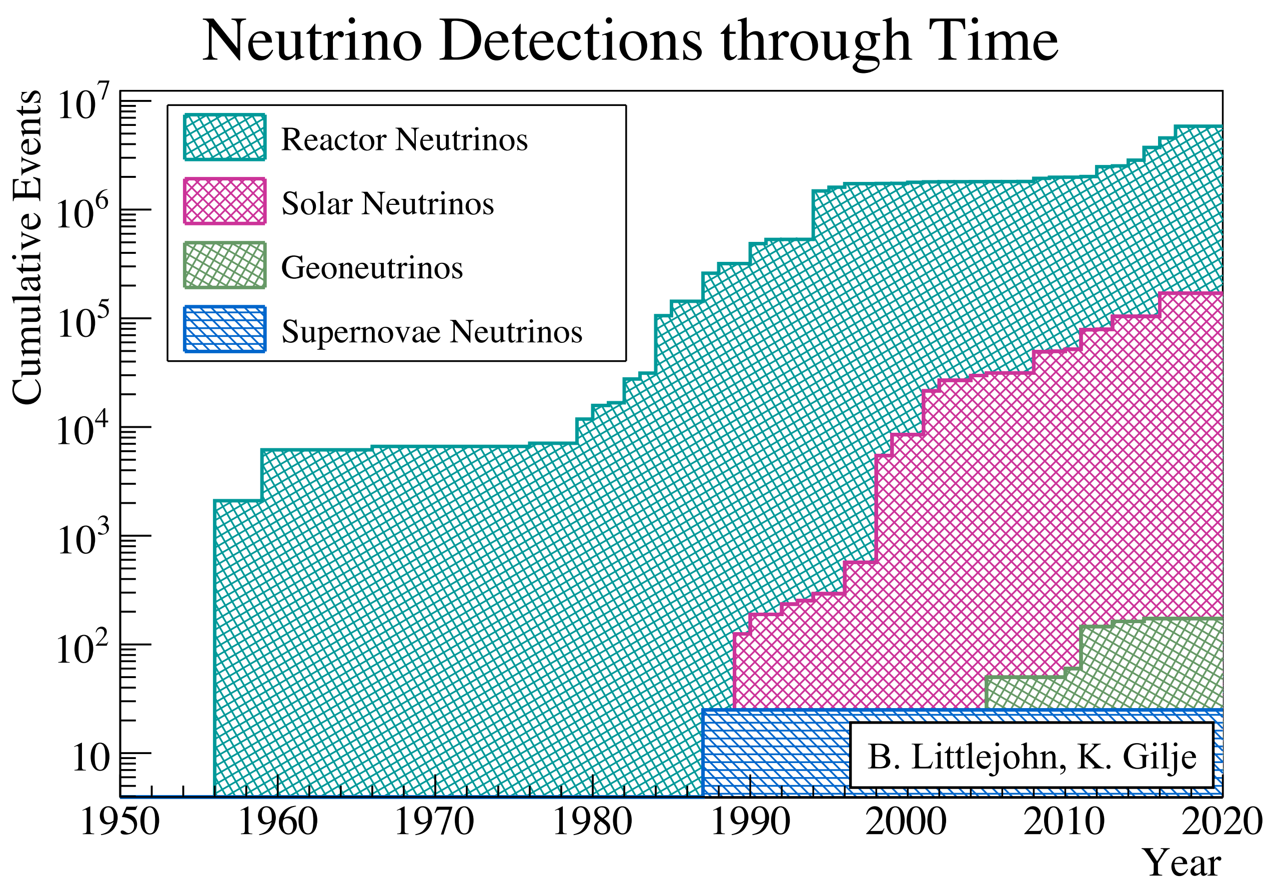
Example: Daya Bay Detector



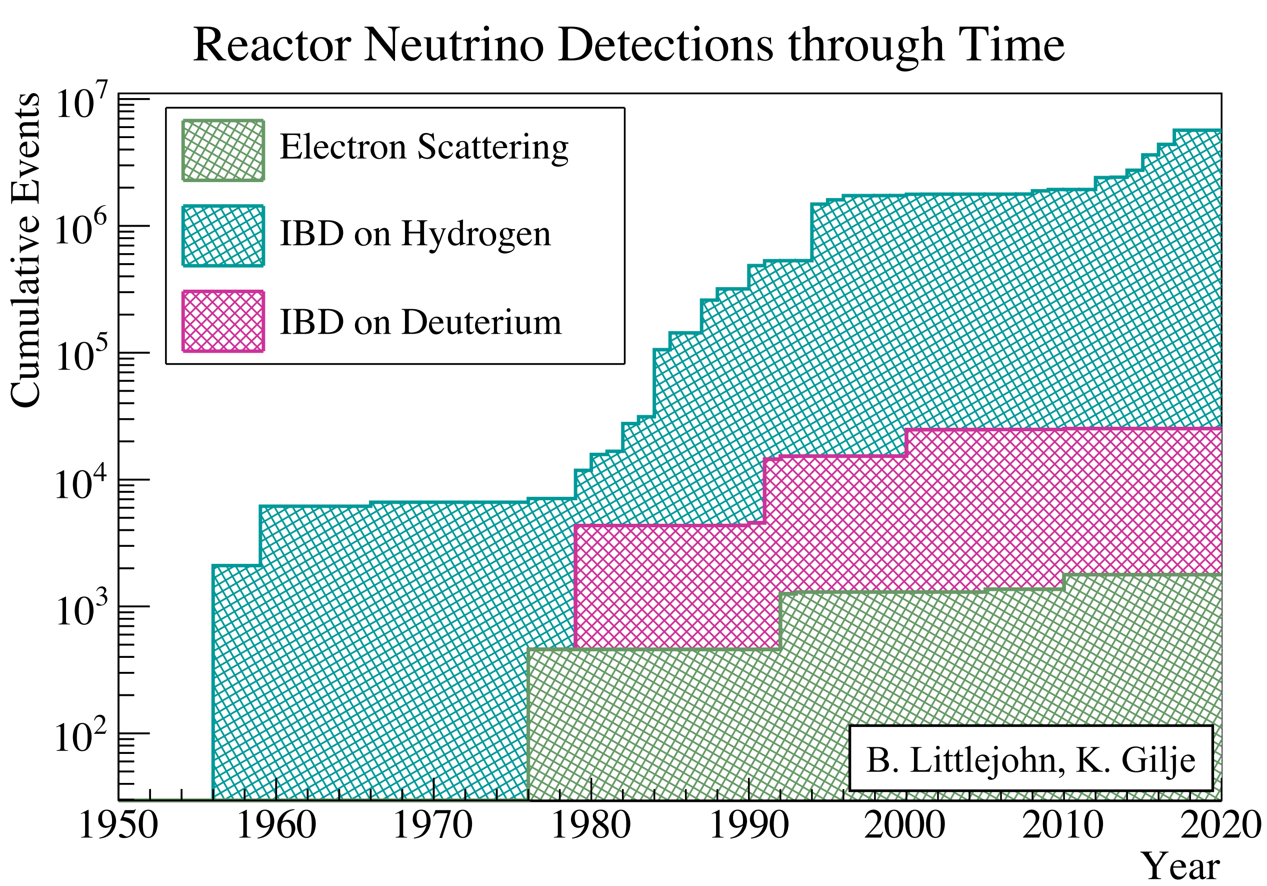
Daya Bay Monte Carlo Data

Reactor Neutrinos: Some Perspective

- Reactors make A LOT of neutrinos
- That means a lot of detections, which can be used for good physics!



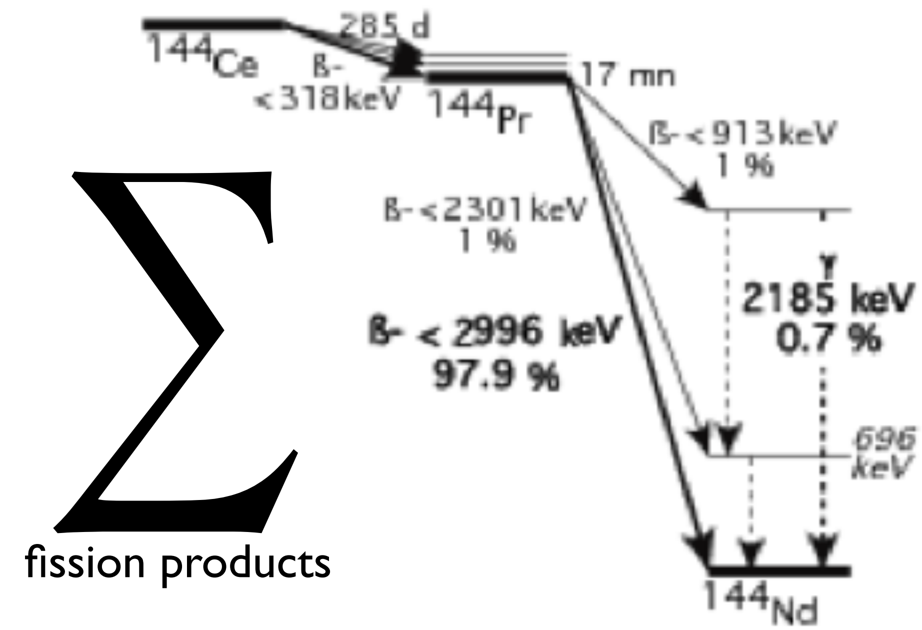
- Inverse beta decay is our most-common method for reactor antineutrino detectors

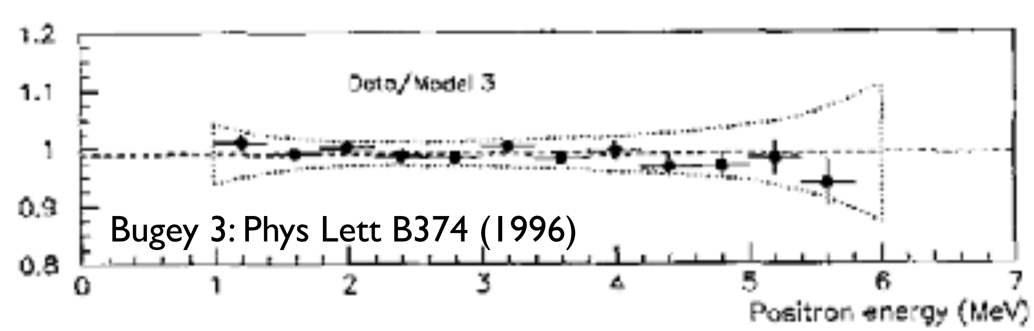


Predicting $S_i(E)$, Neutrinos Per Fission

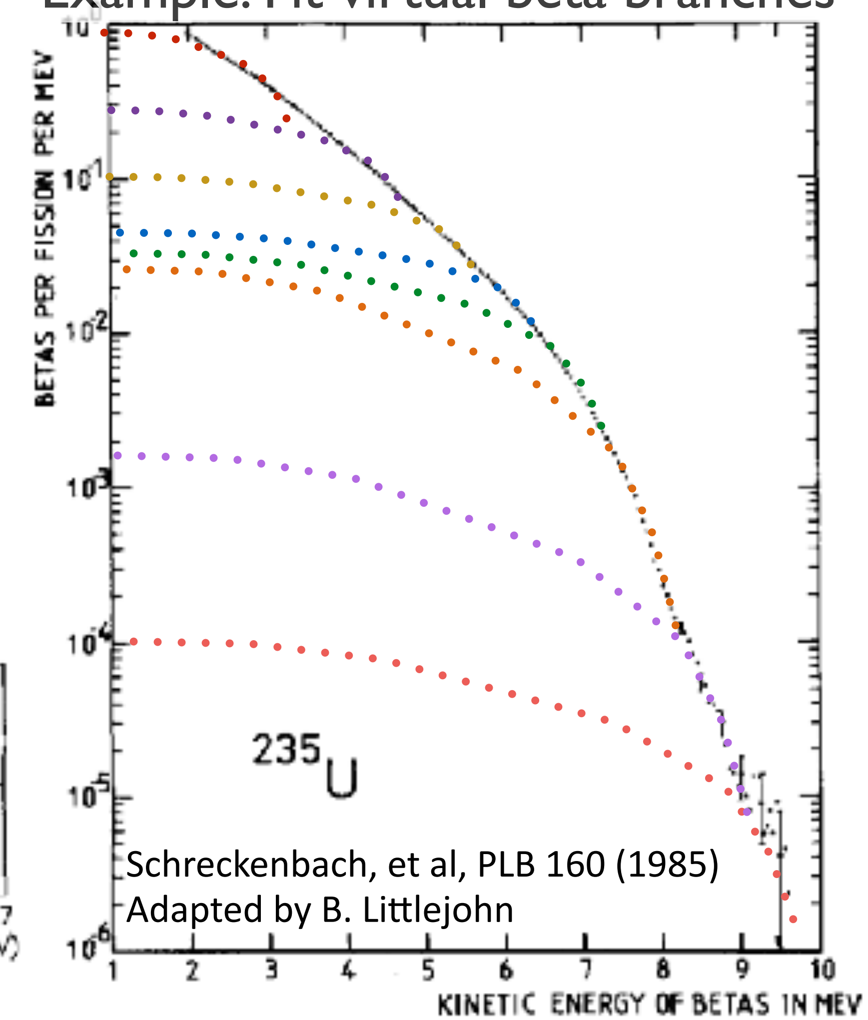
- Two main methods:
- *Ab Initio* approach:
  - Calculate spectrum branch-by-branch w/ databases: fission yields, decay schemes, …
  - **Problem:** rare isotopes / beta branches: missing, possibly incorrect info…
- Conversion approach
  - Measure beta spectra directly
  - Convert to $\overline{\nu}_e$ 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)

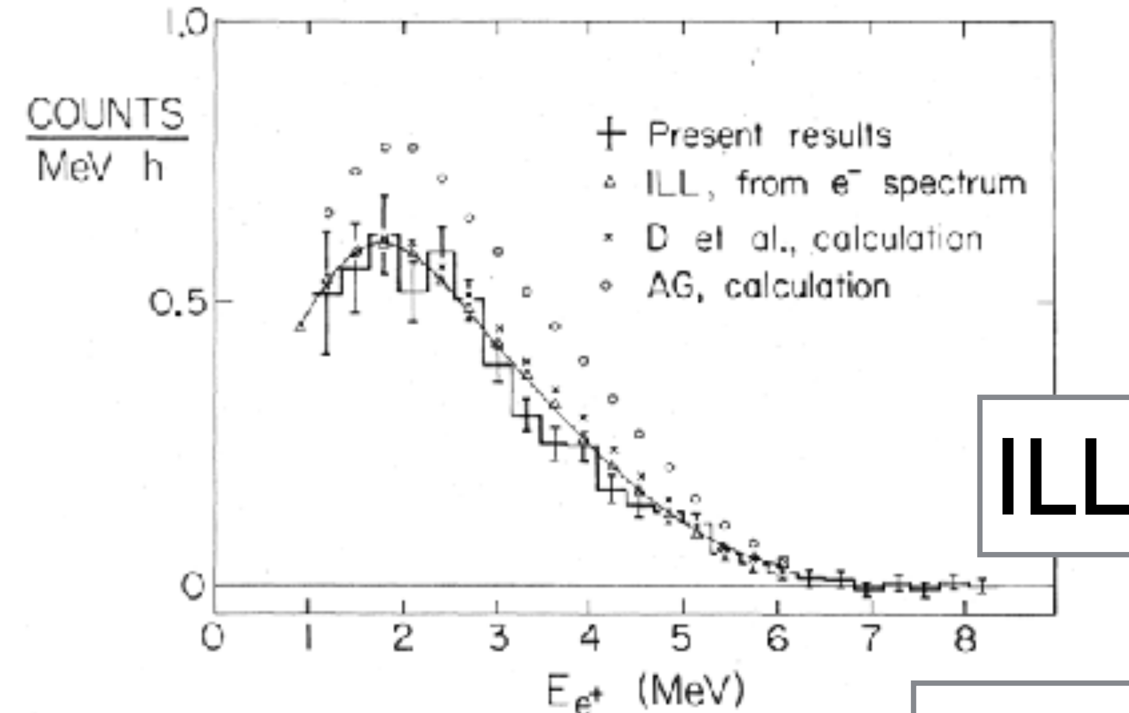
- 1980s: New reactor beta spectra: measurements — conversion now provides lower systematics

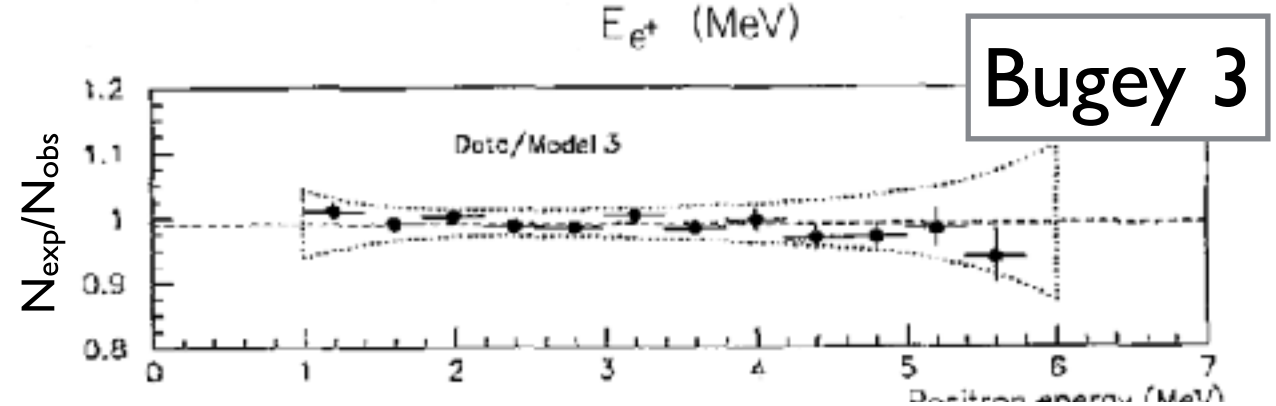
  Schreckenbach, *et al.*, Phys Lett **B**160 (1985)
  Schreckenbach, *et al.*, Phys Lett **B**218 (1989)

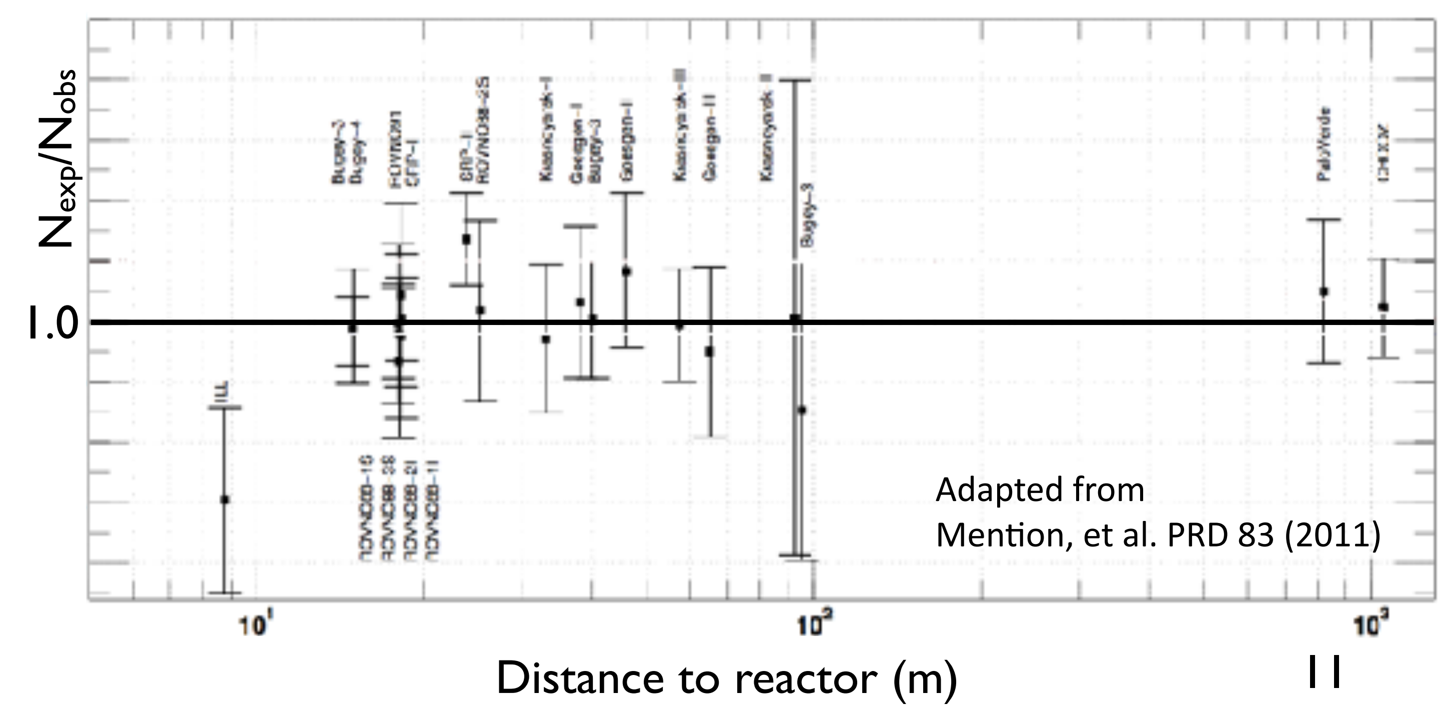
- 1990s: Bugey measurements fit converted spectrum well

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

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

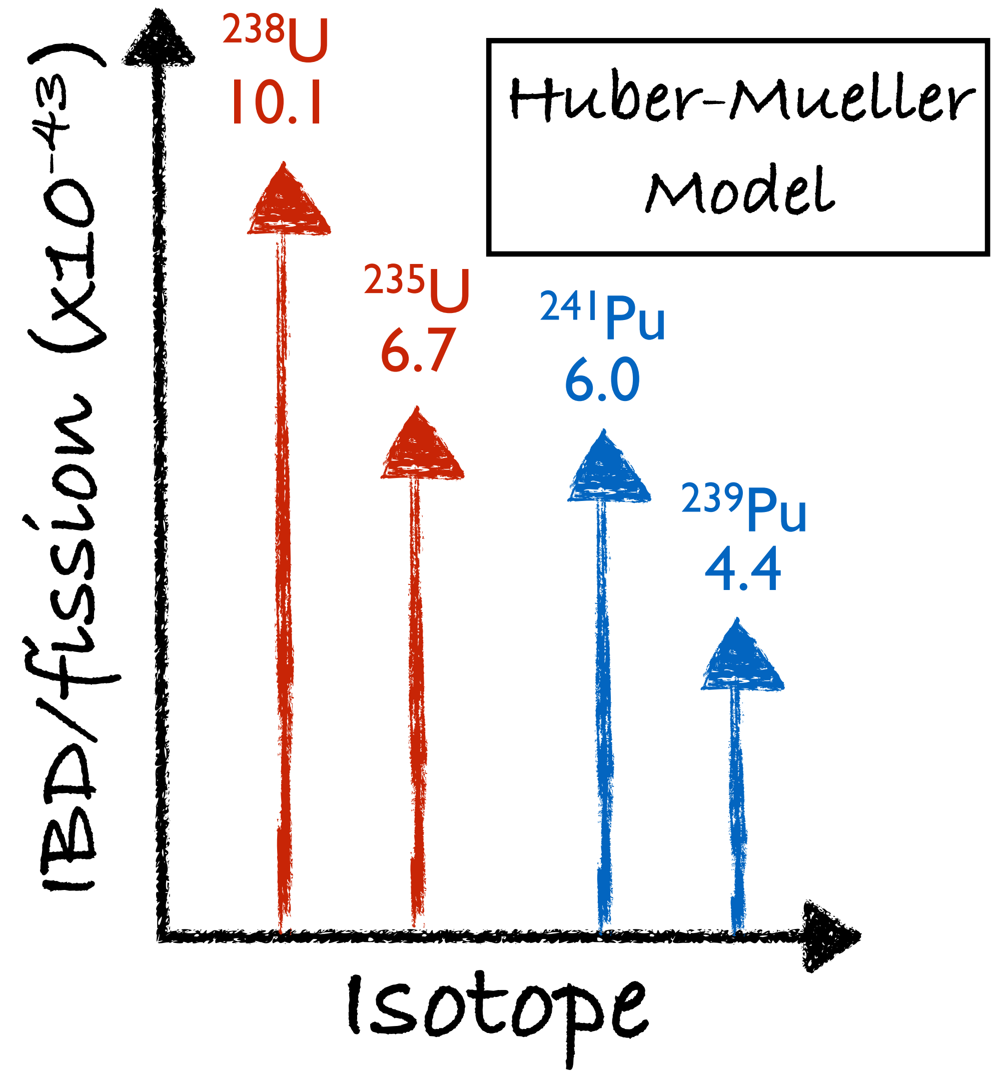


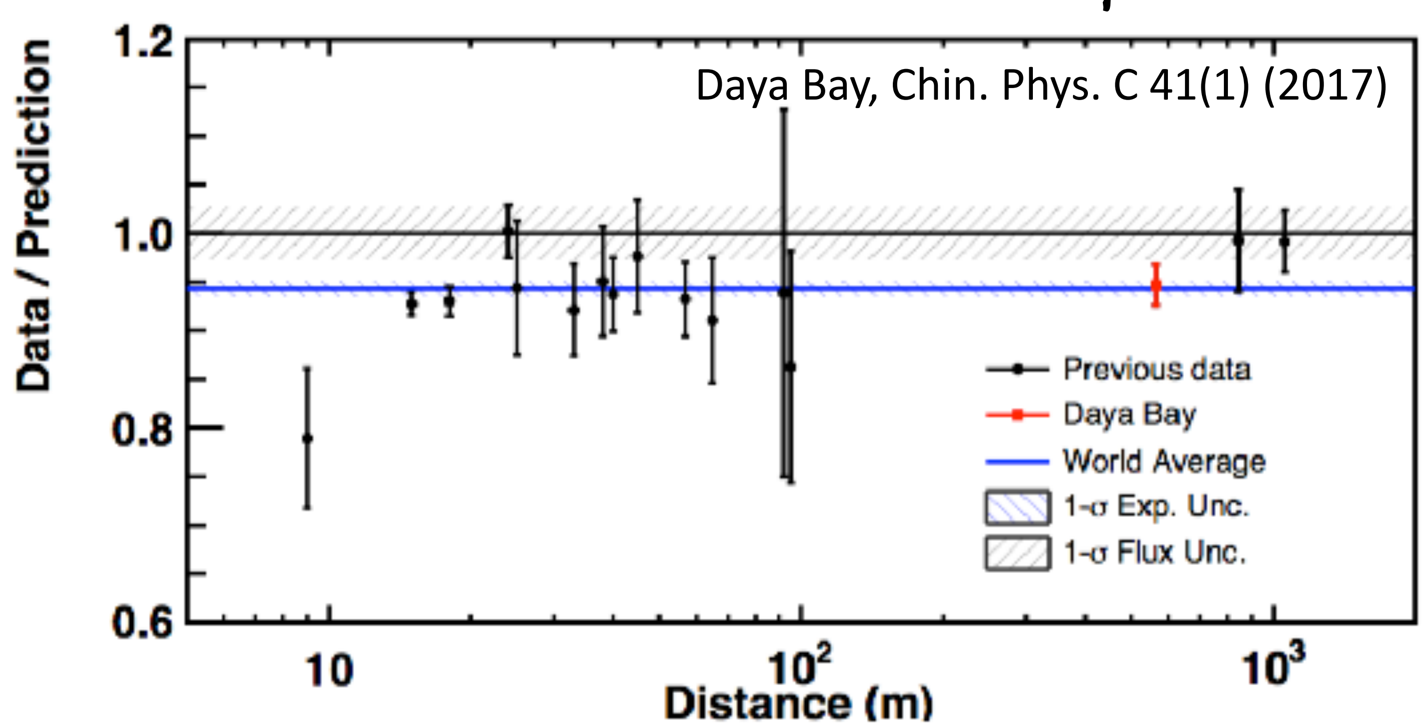




More Recent History: Problems Emerge

- 2011s: Re-calculation of conversion approach for θ_{13} measurements
  - Double Chooz collaborators: hybrid conversion/ab initio approach
  - Also Huber: pure conversion
- Change in flux/spectrum!
  - Flux increase from:
    - Changes to conversion corrections
    - X-section
    - Non-equilibrium isotopes



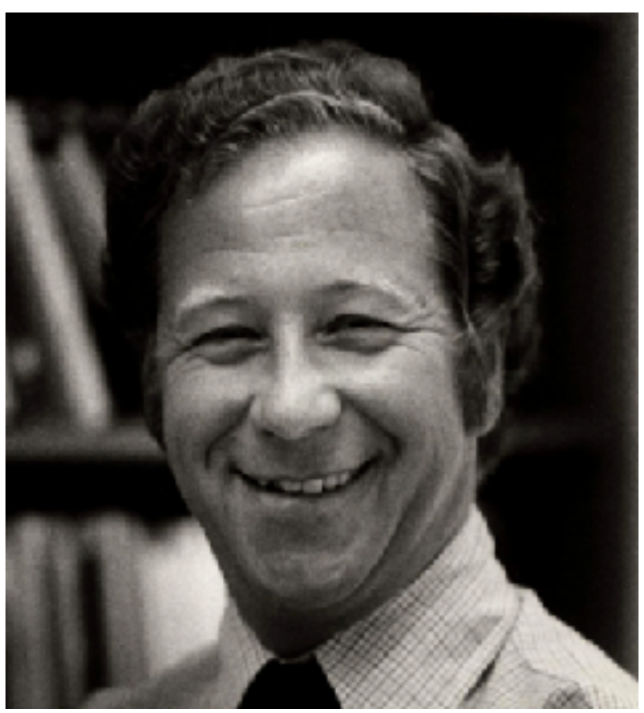


Mueller, *et al*, Phys. Rev. C83 (2011)
Mention, *et al*, Phys. Rev. D83 (2011)
Huber, Phys. Rev. C84 (2011)

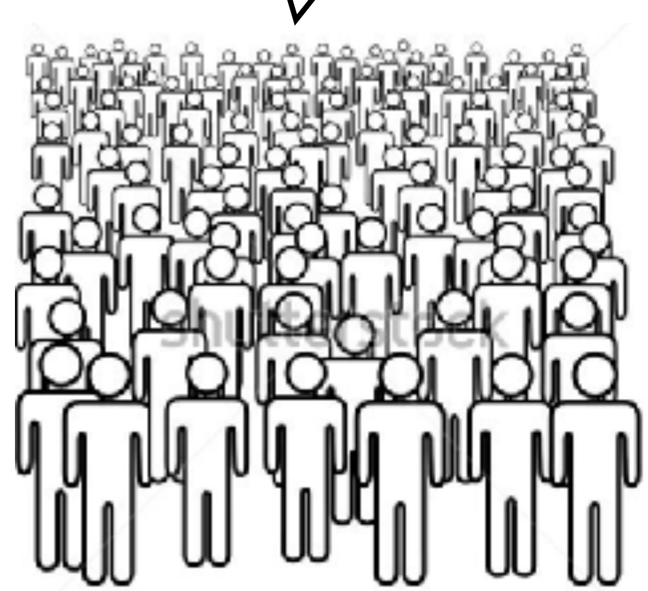
Reactor Antineutrino Anomaly?

- Do we have a 'reactor antineutrino anomaly?'
  - "No: the previous experiments could have been biased to report flux measurements that agreed with existing predictions of the time."
  - "Yes: but probably attributable to uncertainties in the beta-to-ν_e conversion."
  - "Yes: the deficit could result from short-baseline sterile neutrino oscillations."

We need more data!!



P. Vogel, Caltech



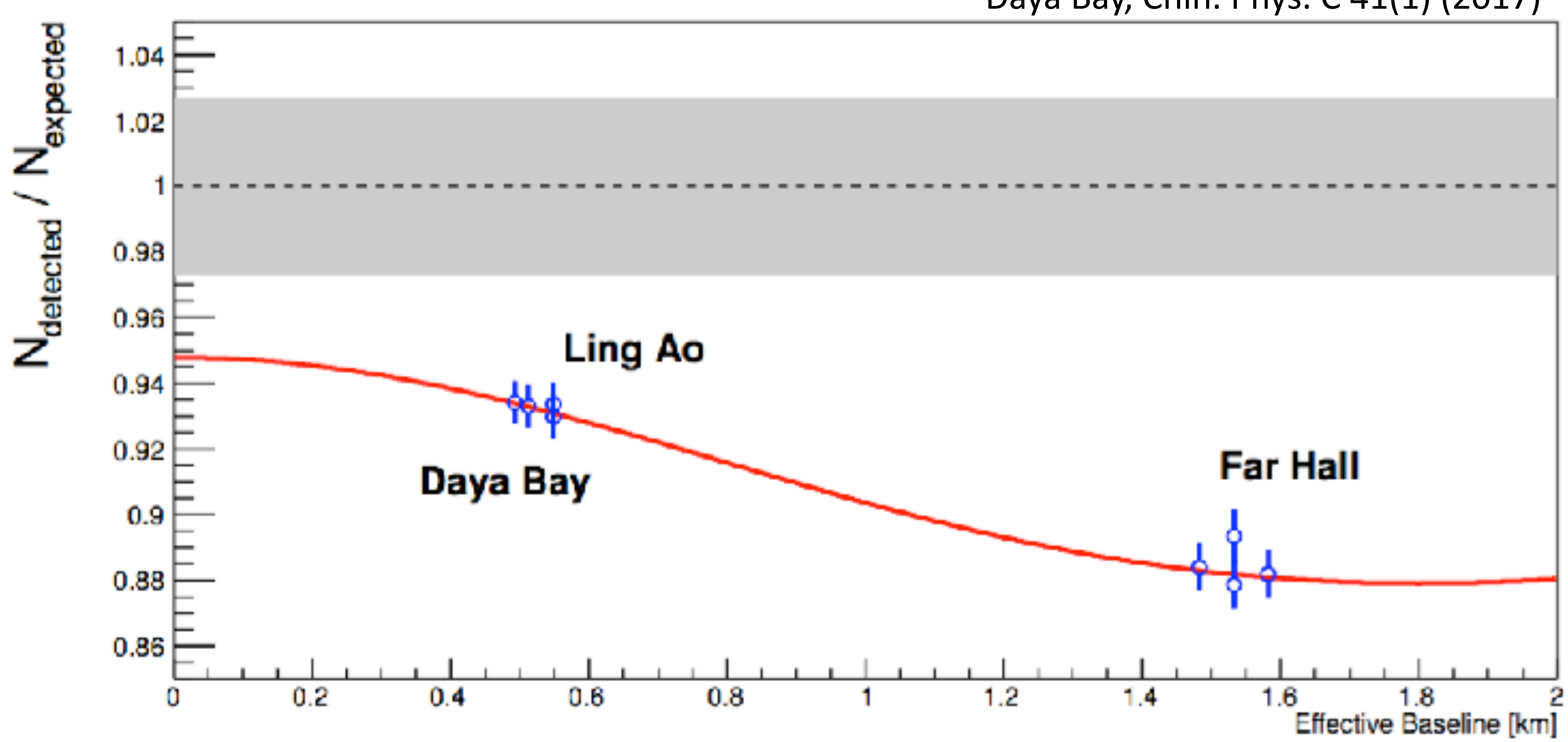
The rest of us

P. Huber, VTech

Reactor Anomaly Explanations

- Do we have a 'reactor antineutrino anomaly?'
  - ~~"No: the previous experiments could have been biased to report flux measurements that agreed with existing predictions of the time"~~
- Daya Bay also sees the reactor flux deficit
  - ~5% deficit relative to 2011 Huber/Mueller flux prediction
  - Blind analysis: No reactor power data available until analysis is totally fixed
  - Neutrino2016: RENO also sees deficit.

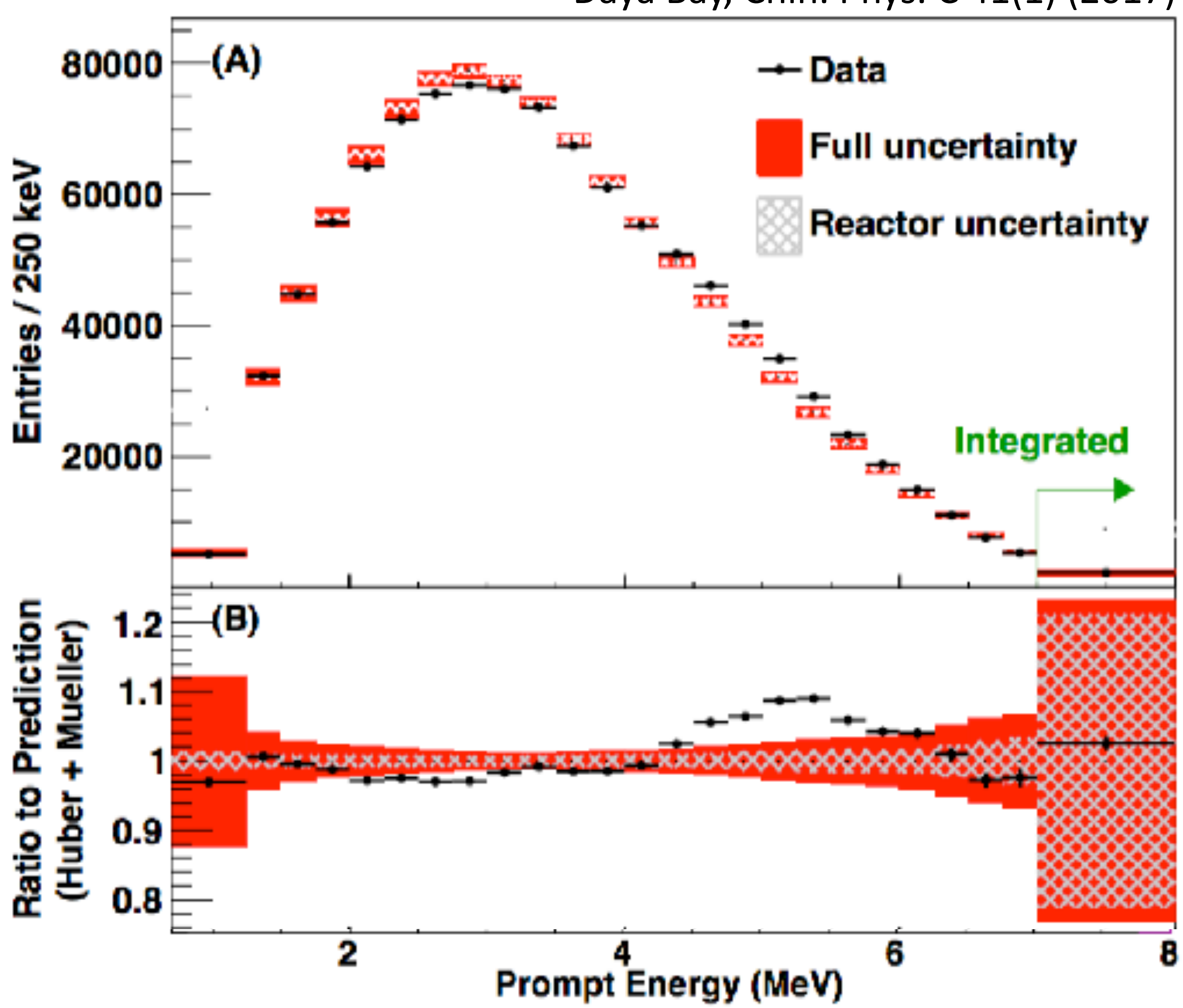
Daya Bay, Chin. Phys. C 41(1) (2017)



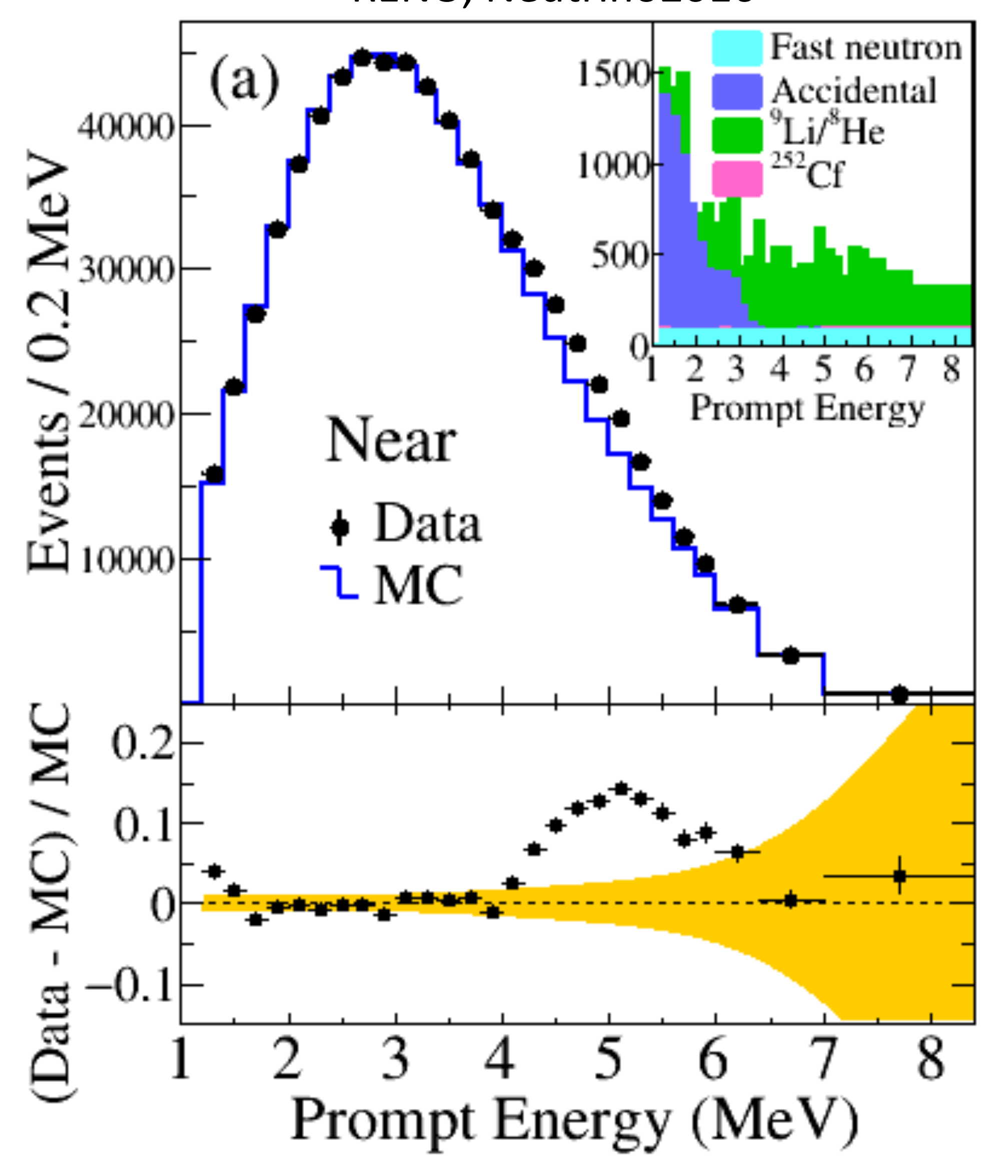
Reactor Anomaly Explanations

- Do we have a 'reactor antineutrino anomaly?'
  - "Yes: it's probably attributable to problems in the beta-to-ν_e conversion"
- Spectra from θ_{13} experiments disagree with predictions
  - "If measured spectrum doesn't match, why should measured flux?"

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

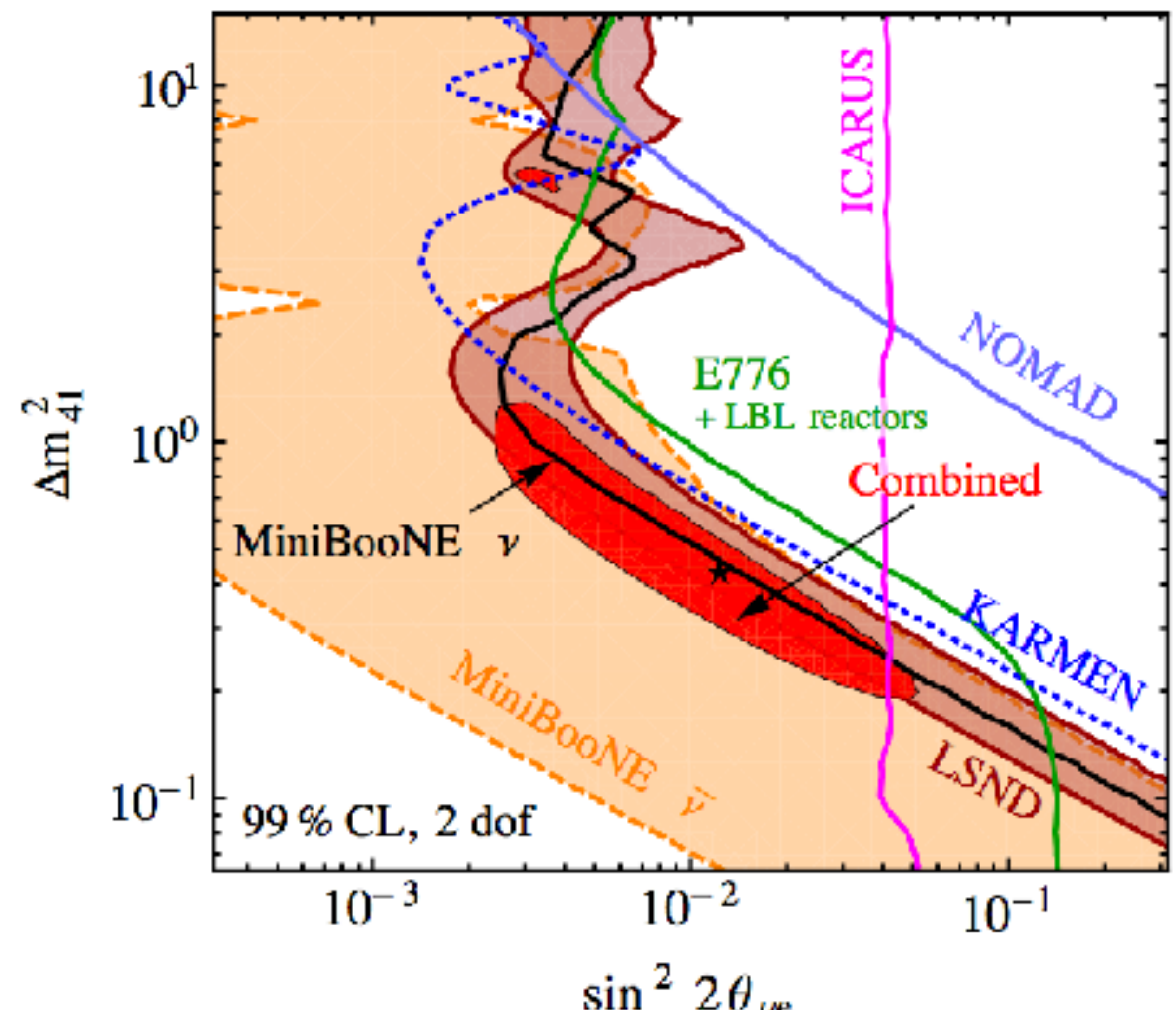


RENO, Neutrino2016



Reactor Anomaly Explanations

- Do we have a 'reactor antineutrino anomaly?'
  - "Yes: the deficit could result from short-baseline sterile neutrino oscillations"
- Consistent with existing hints for 1 eV sterile neutrinos
  - However, tension with null ν_μ disappearance measurements (Hello, IceCube…)
- Also, to be able to interpret CP-violation results, we need to know if sterile neutrinos exist…
  - DUNE needs an answer for the anomaly!
  - Similar situation for neutrinoless double beta decay



A Recap

- We don't know what's causing the reactor flux anomaly.
- The two hypotheses we cannot yet rule out:
  - eV-scale sterile neutrinos exist
  - Reactor antineutrino flux calculations are not totally correct.

???

A Recap

- We don't know what's causing the reactor flux anomaly.
- The two hypotheses we cannot yet rule out:
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  - Reactor antineutrino flux calculations are not totally correct.
- What else can we do to probe this hypothesis?

???

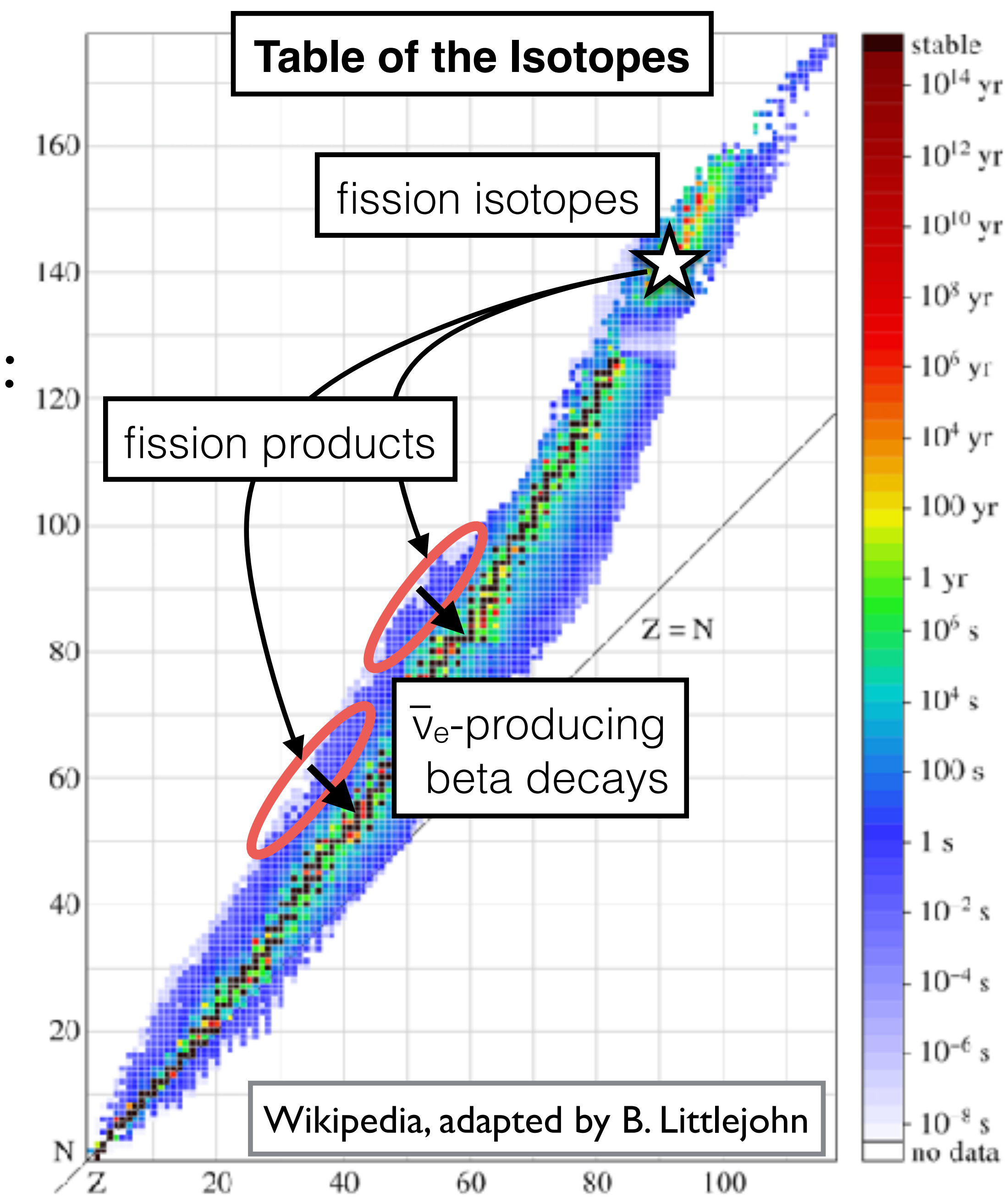
A Recap

- We don't know what's causing the reactor flux anomaly.
- The two hypotheses we cannot yet rule out:
  - eV-scale sterile neutrinos exist
  - Reactor antineutrino flux calculations are not totally correct.

- What else can we do to probe this hypothesis?
  - In particular, would want to understand <u>HOW</u> calculations are incorrect.
  - Studying the flux <u>AND</u> spectrum anomalies is probably important here…
  - Will focus here only on what future <u>neutrino</u> experiments can do.

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…



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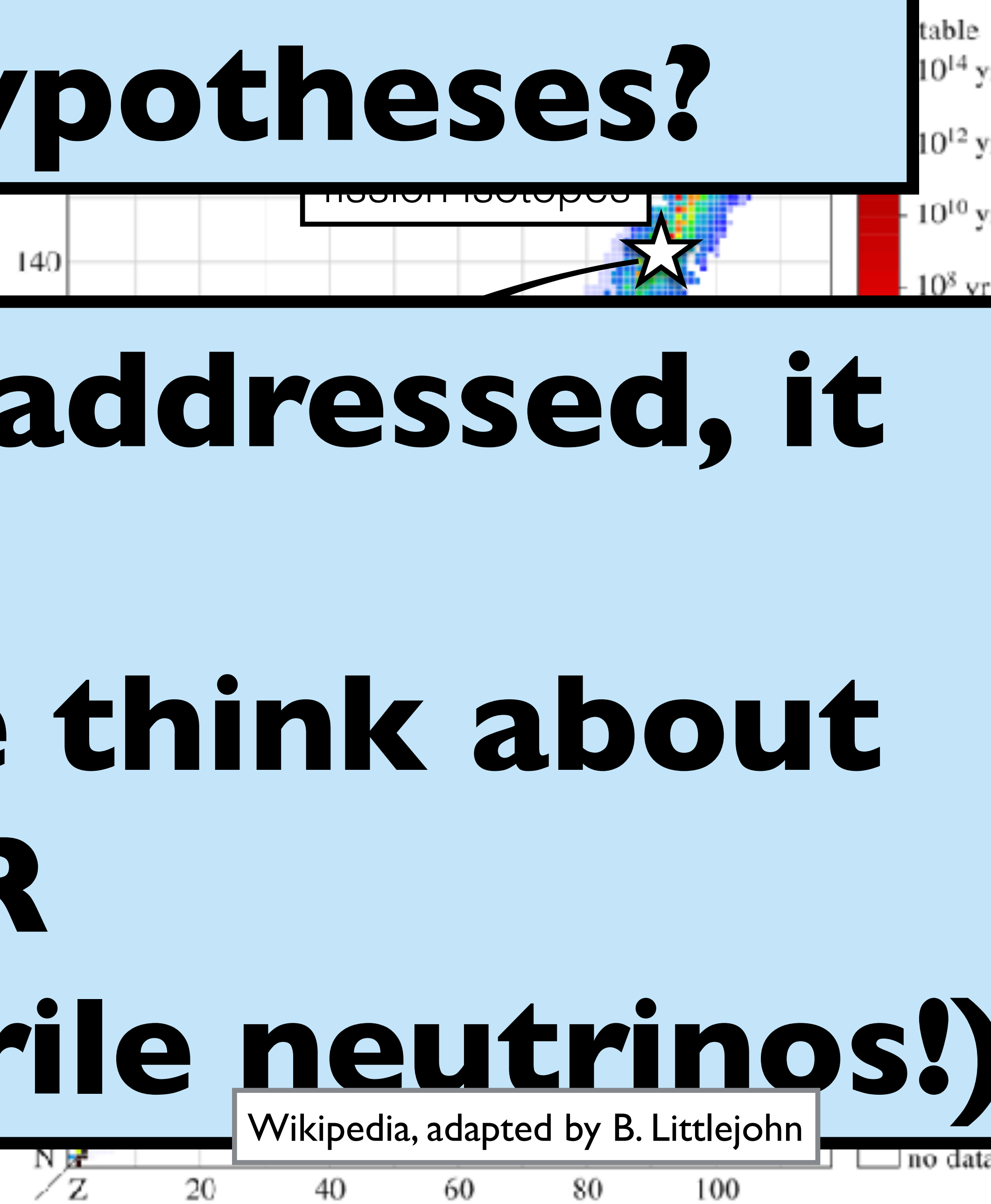
  - Maybe it's specifically related to beta-decays:
    - Maybe fission isotope beta spectrum measurements are wrong. Dwyer+Langford, **PRL** 114 (2015)
  - Etc…

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!)

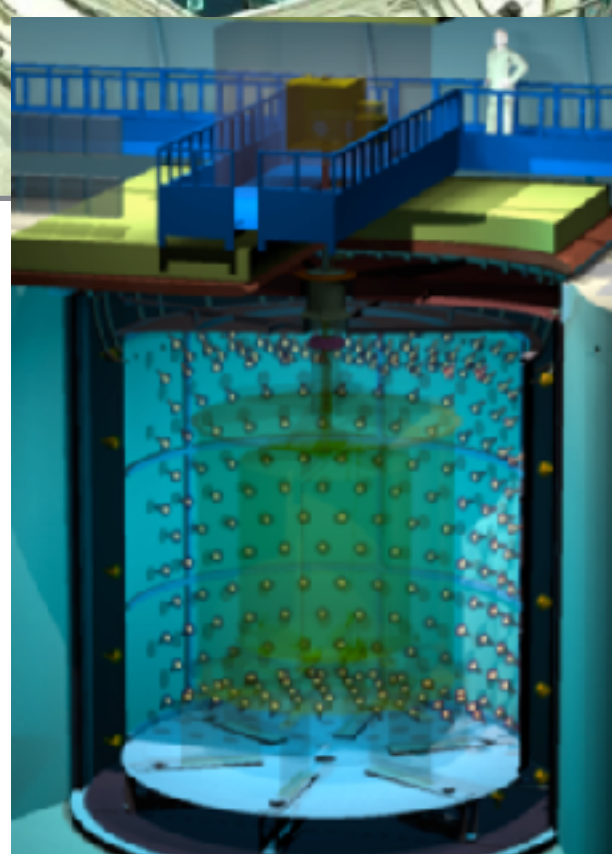


Wikipedia, adapted by B. Littlejohn

Neutrino Tools At Our Disposal

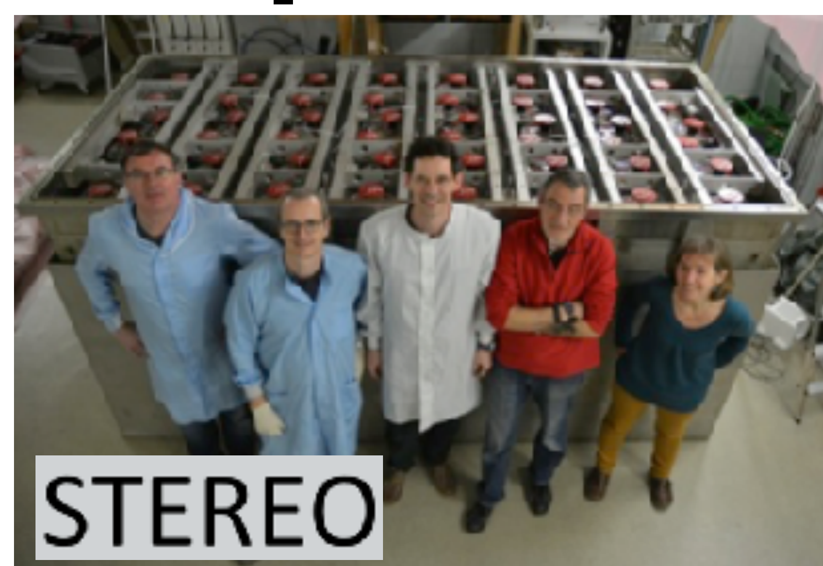
- Also have a solid group of current/future reactor experiments:

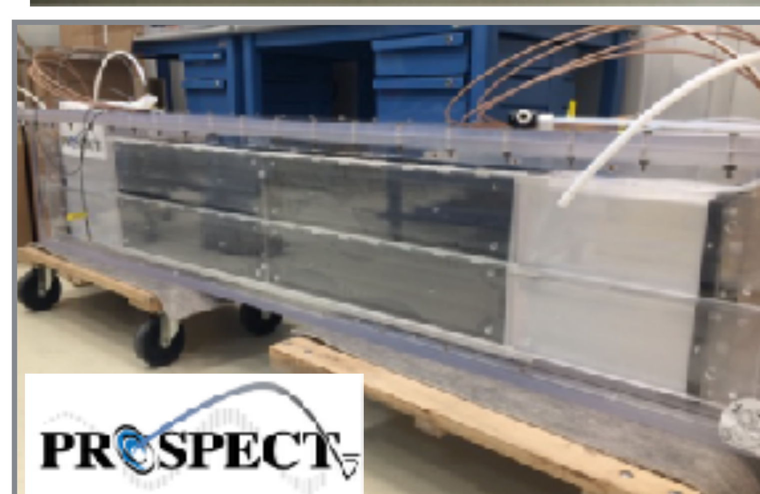
θ_{13} Experiments



Double Chooz

Short-Baseline Experiments





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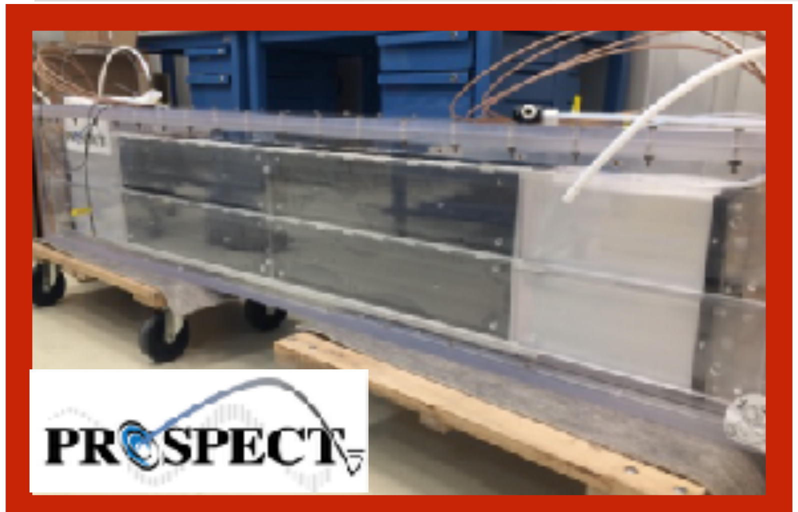
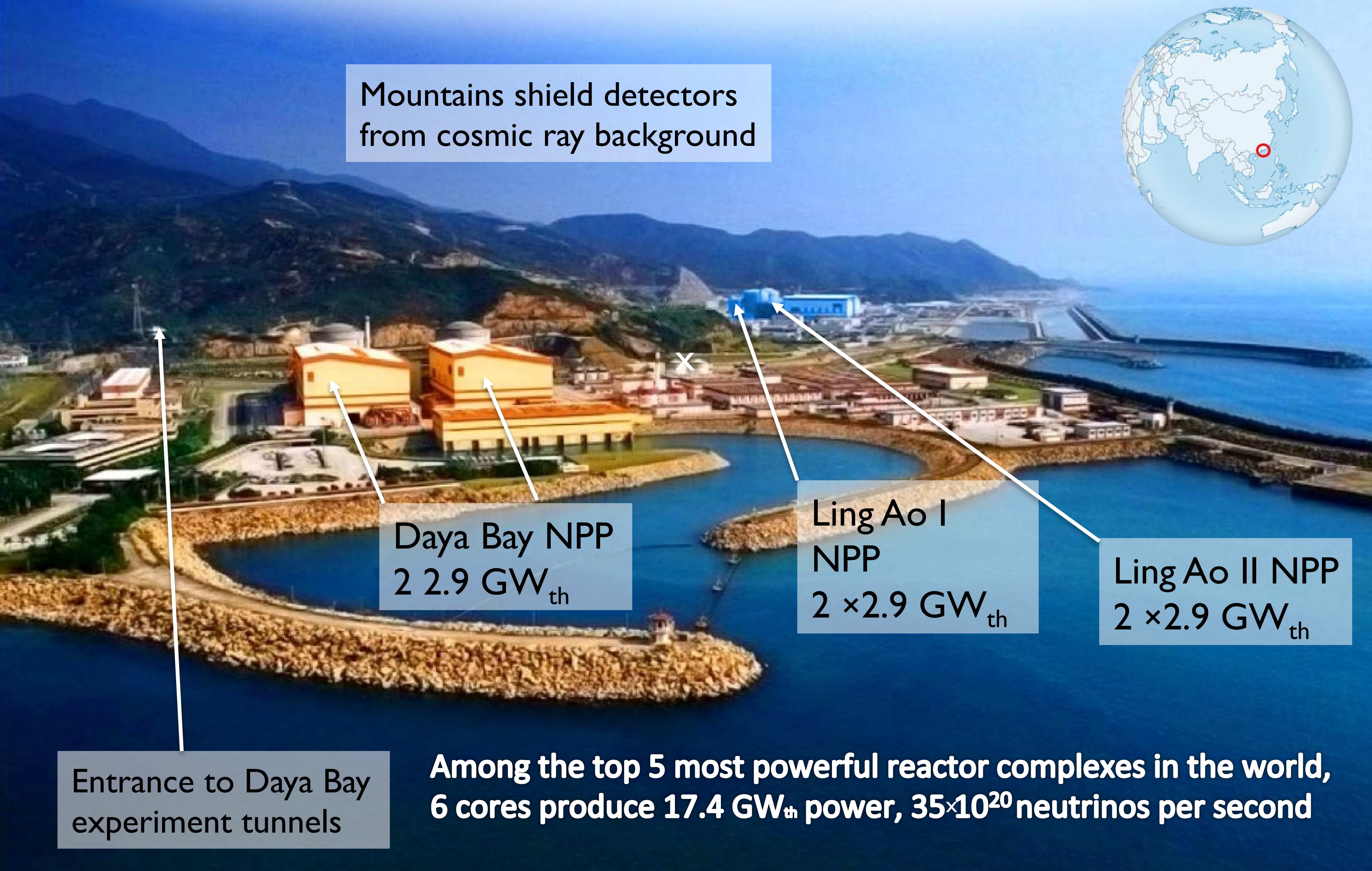


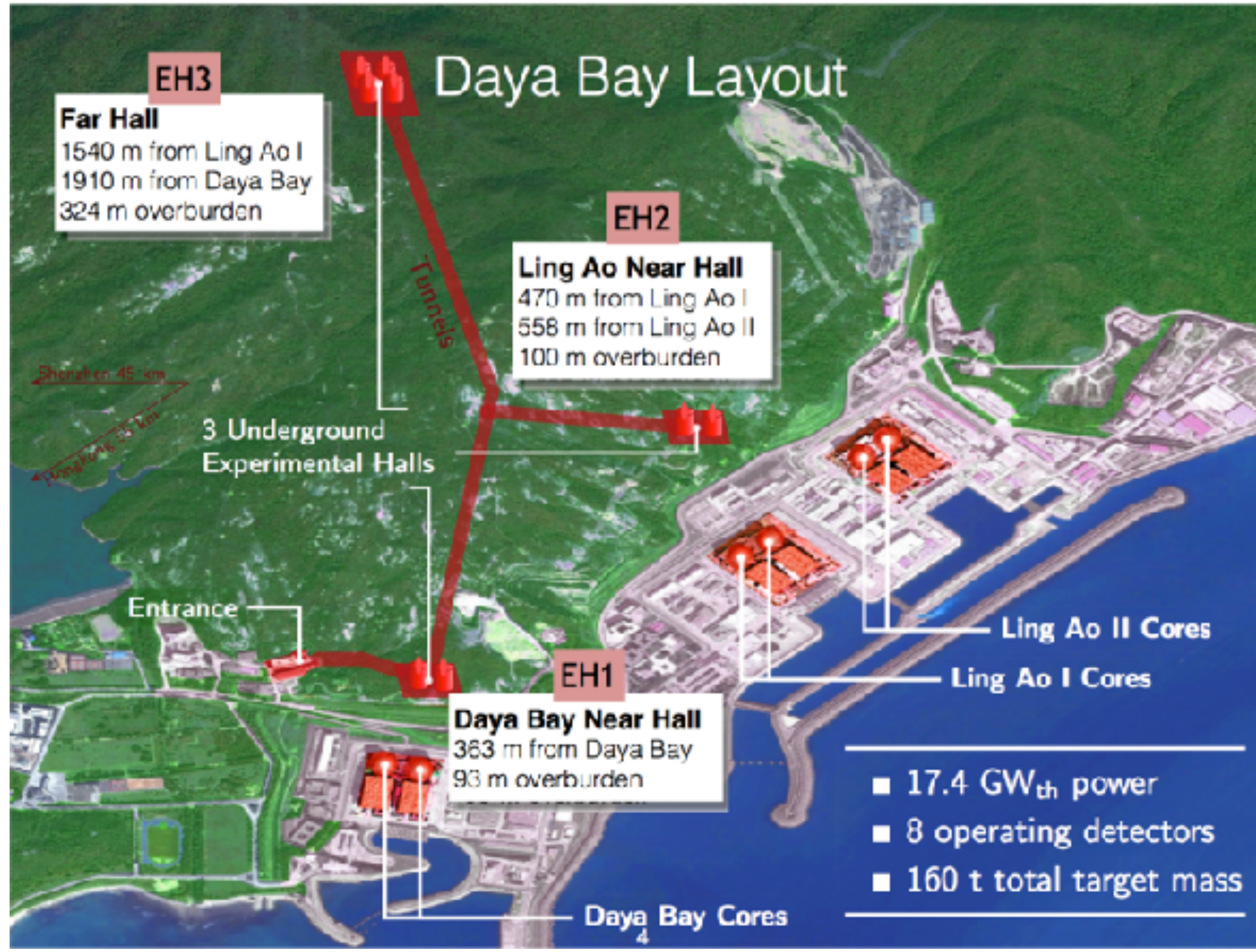
A Powerful Neutrino Source at an Ideal Location



Among the top 5 most powerful reactor complexes in the world, 6 cores produce 17.4 GW_{th} power, $35{\times}10^{20}$ neutrinos per second

Daya Bay: Site, Halls

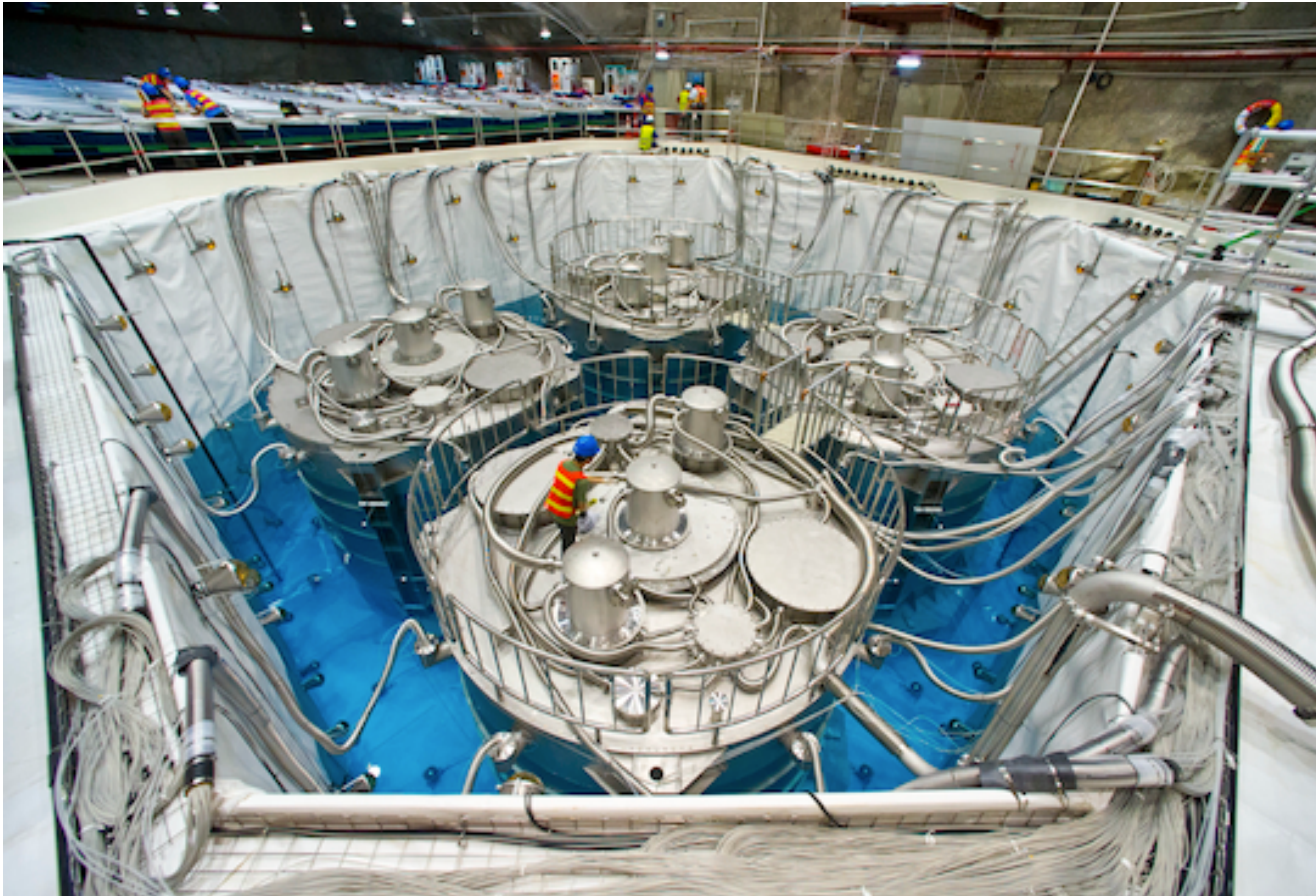
- Original concept with 8 ‘identical’ detectors:
  - Near detectors constrain flux
  - Far detectors see if any neutrinos have disappeared.
- Daya Bay has ideal specs for doing this!



	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

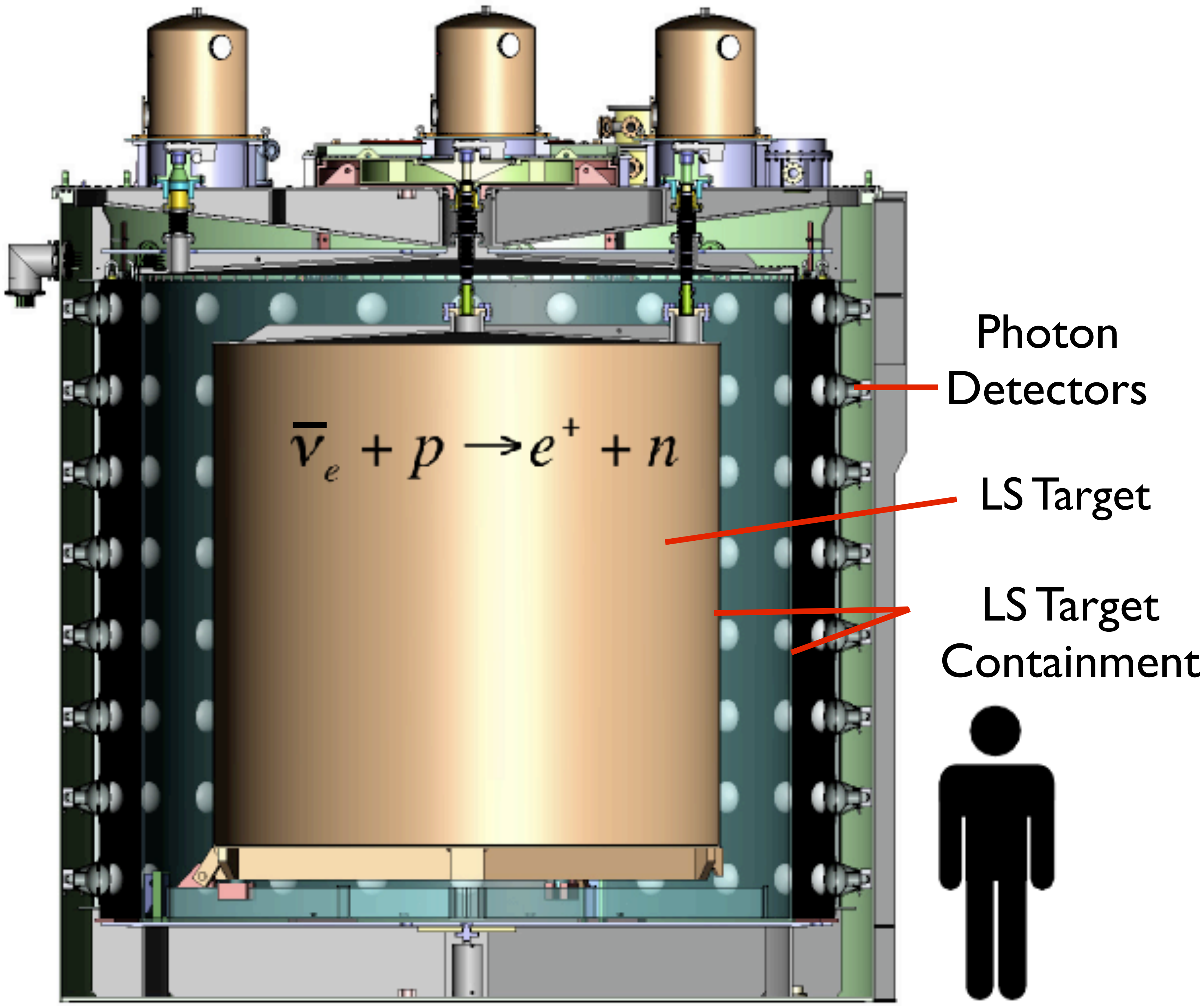
Daya Bay: Experimental Hall, Before

Daya Bay: Experimental Hall, After

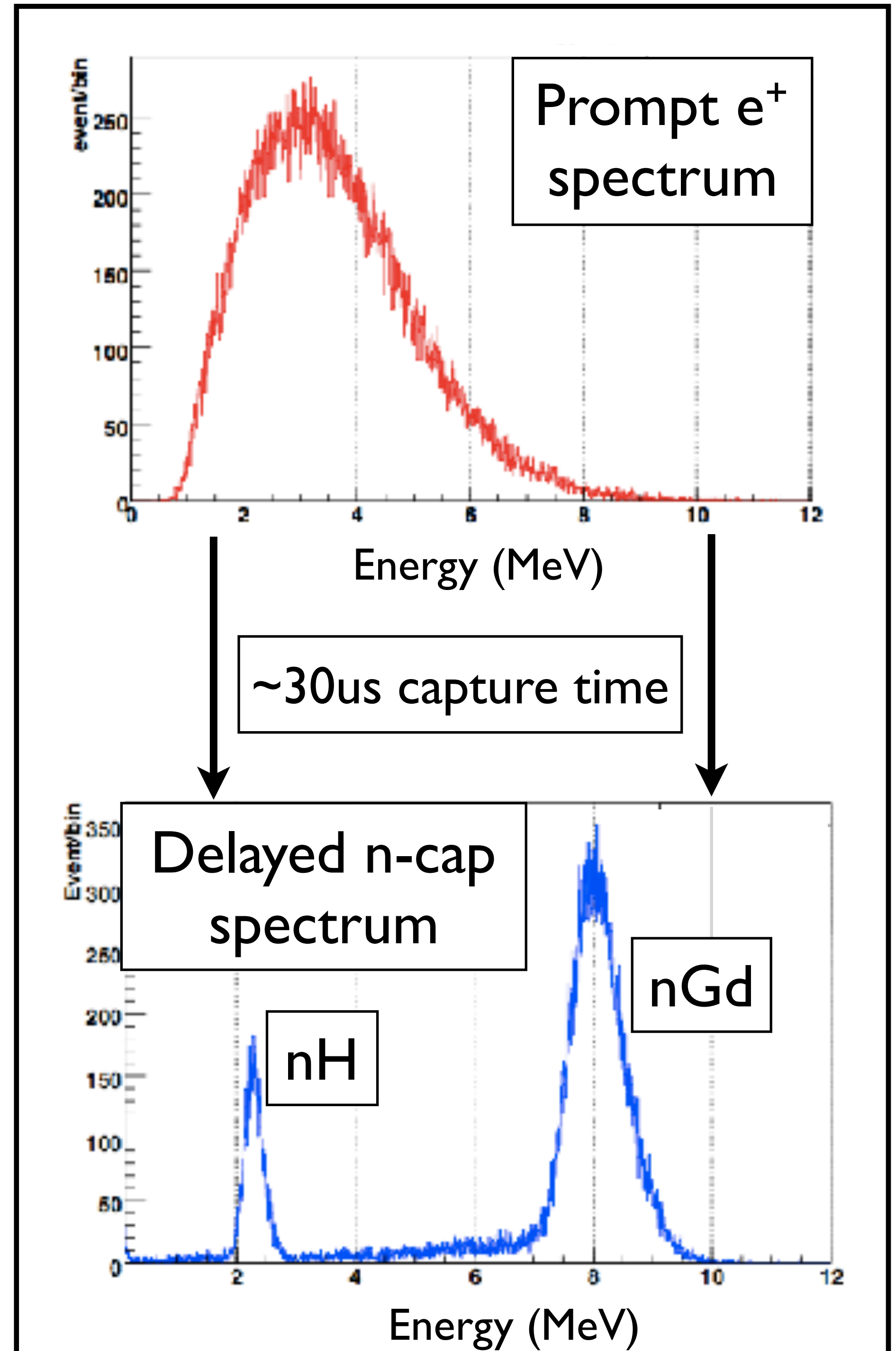


Daya Bay: Detection Method

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

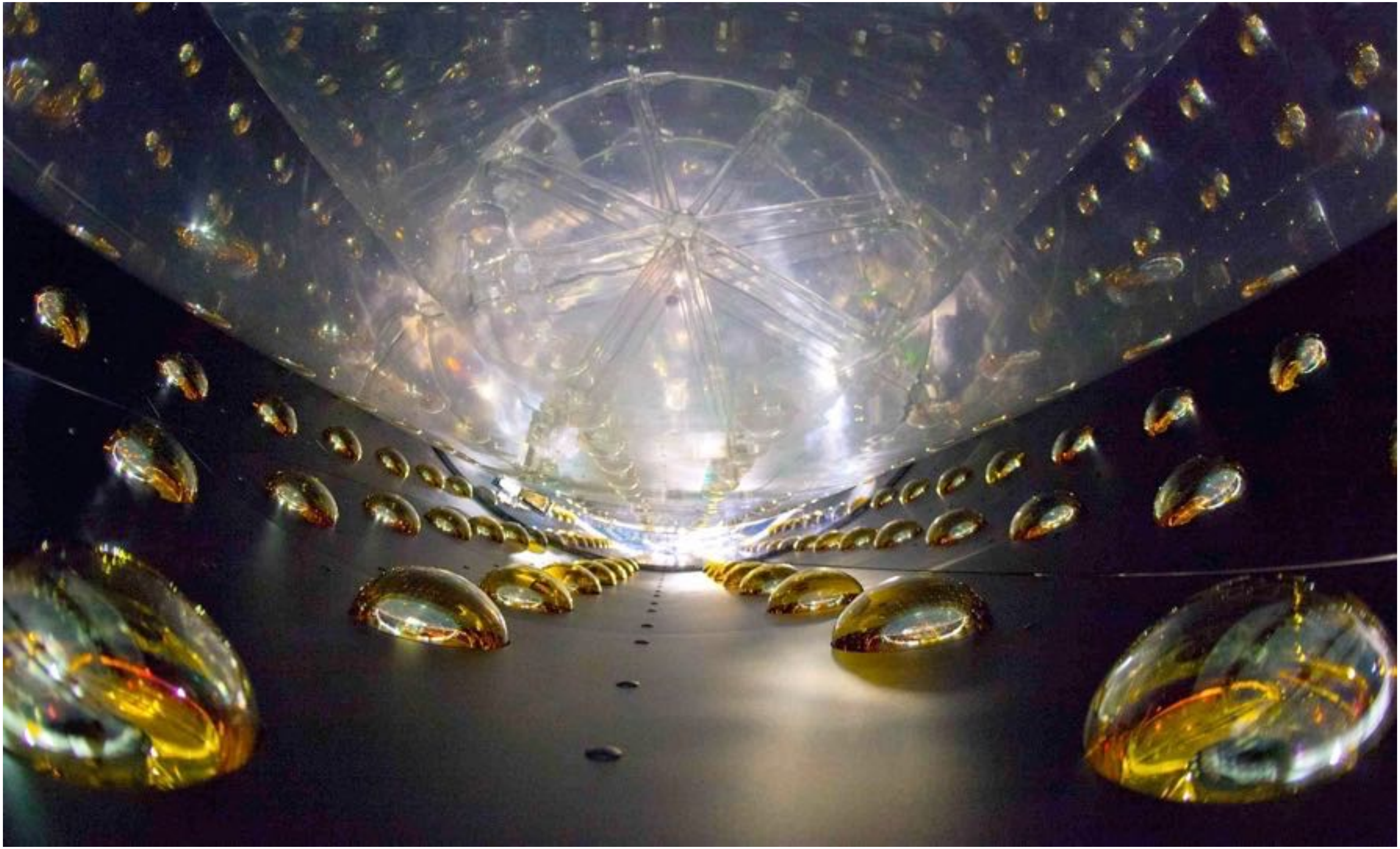


Example: Daya Bay Detector



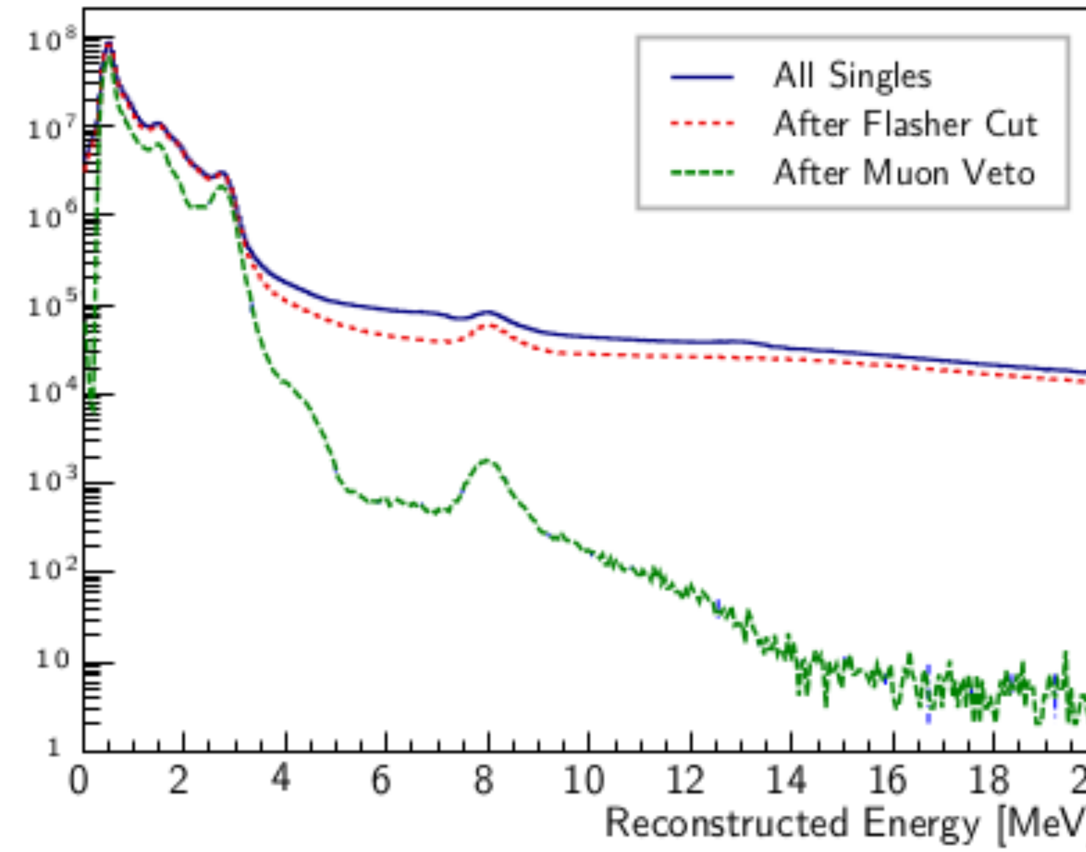
Daya Bay Monte Carlo Data

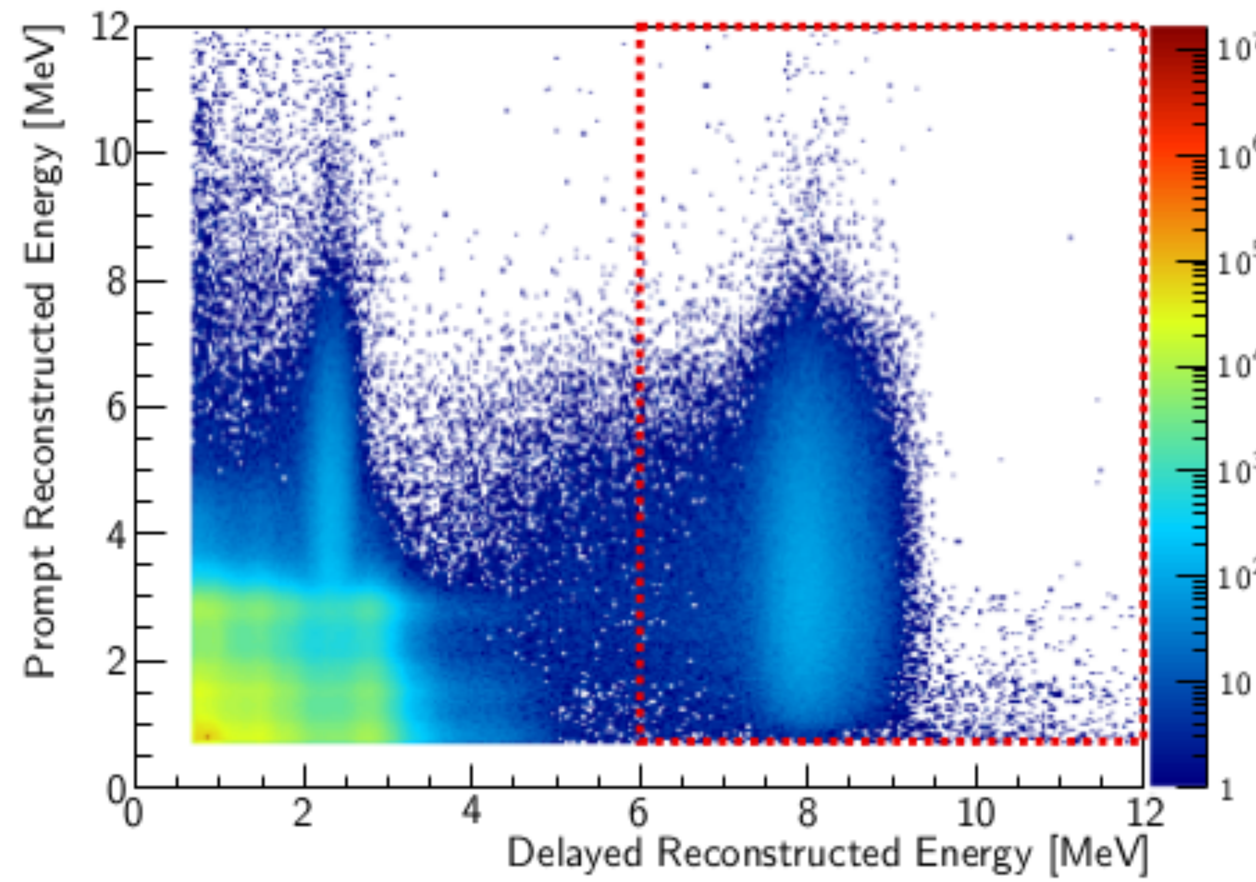
Daya Bay: AD Interior



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 Signal Selection

① Reject spontaneous PMT light emission ("flashers")

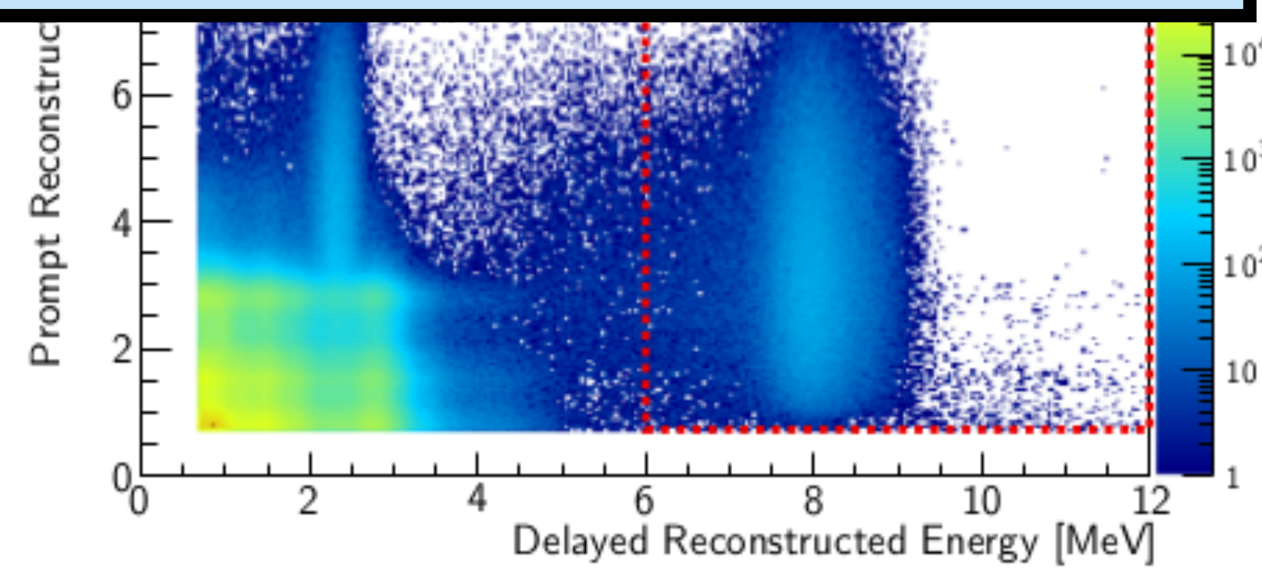
② Prompt positron:

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

Reject [-2 µs; 0.4s]

⑥ Multiplicity:

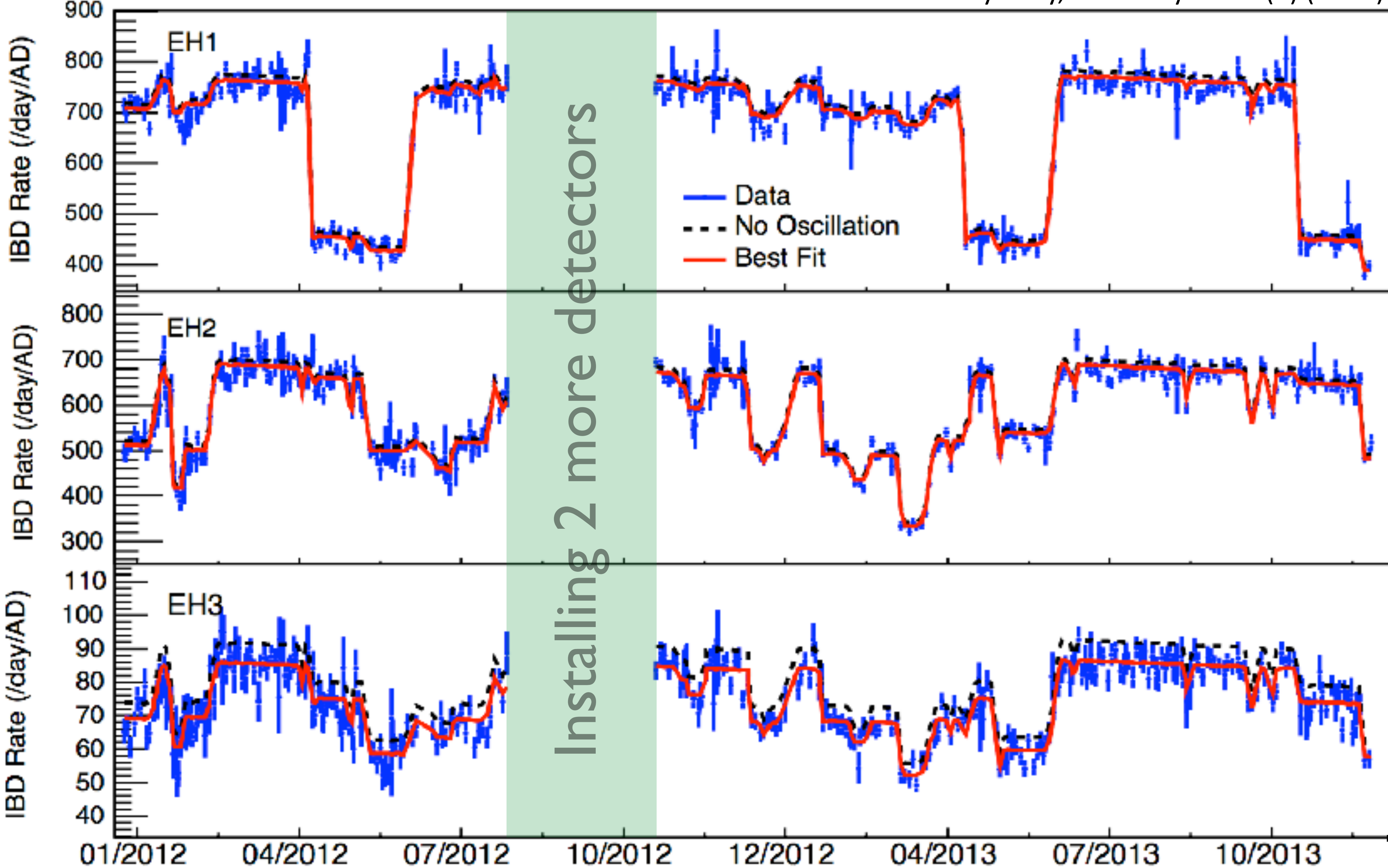
- No additional prompt-like signal
  400µs before delayed neutron
- No additional delayed-like signal
  200µs after delayed neutron



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

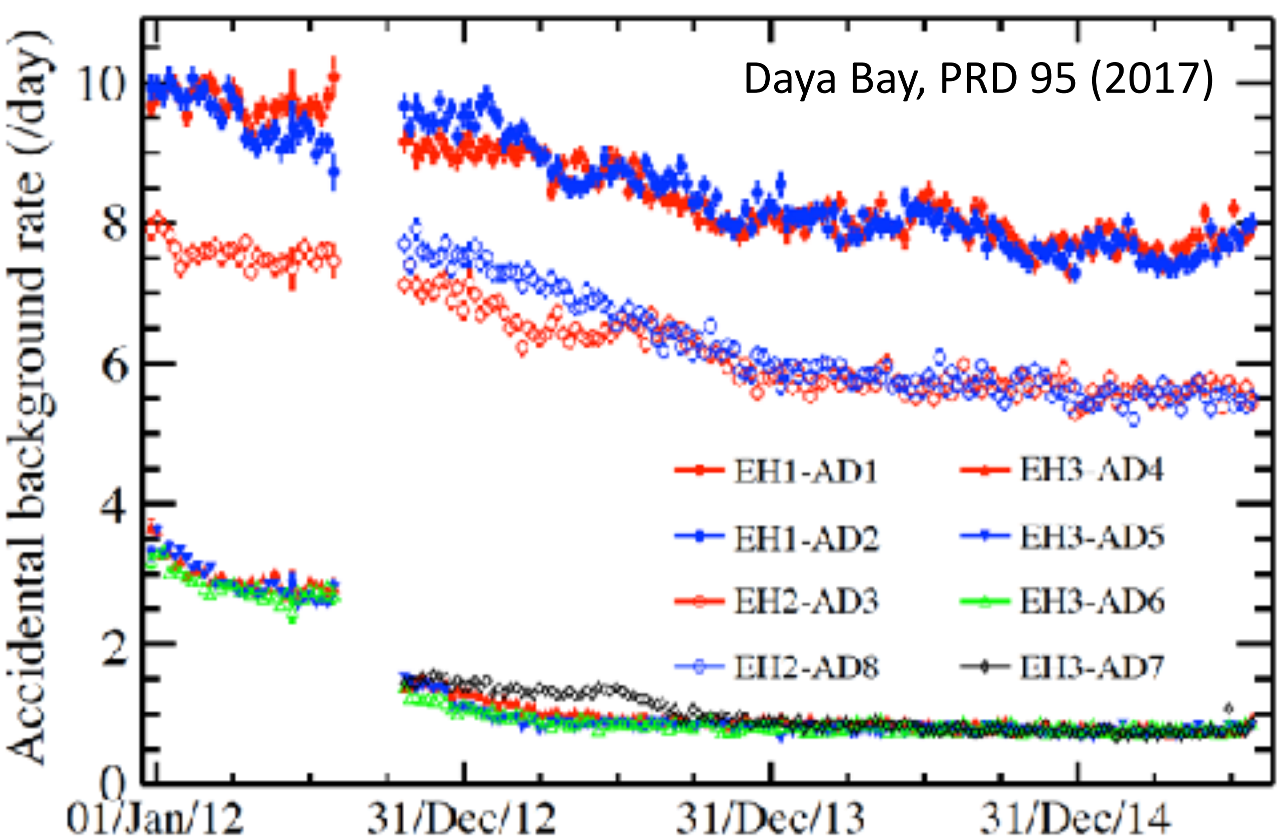
Daya Bay, Chin. Phys. C 41(1) (2017)



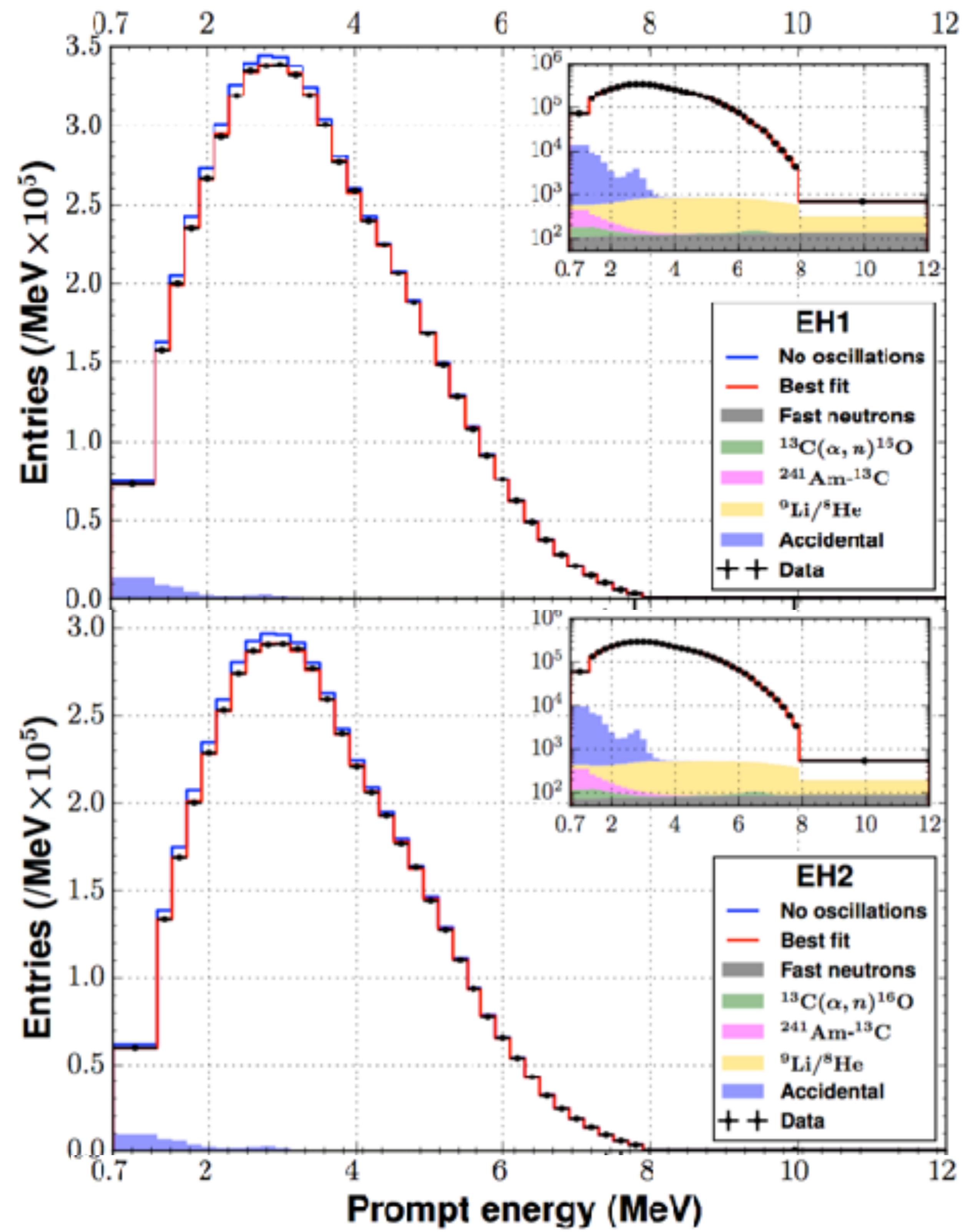
Note:
1230-day dataset goes to July 2015

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.



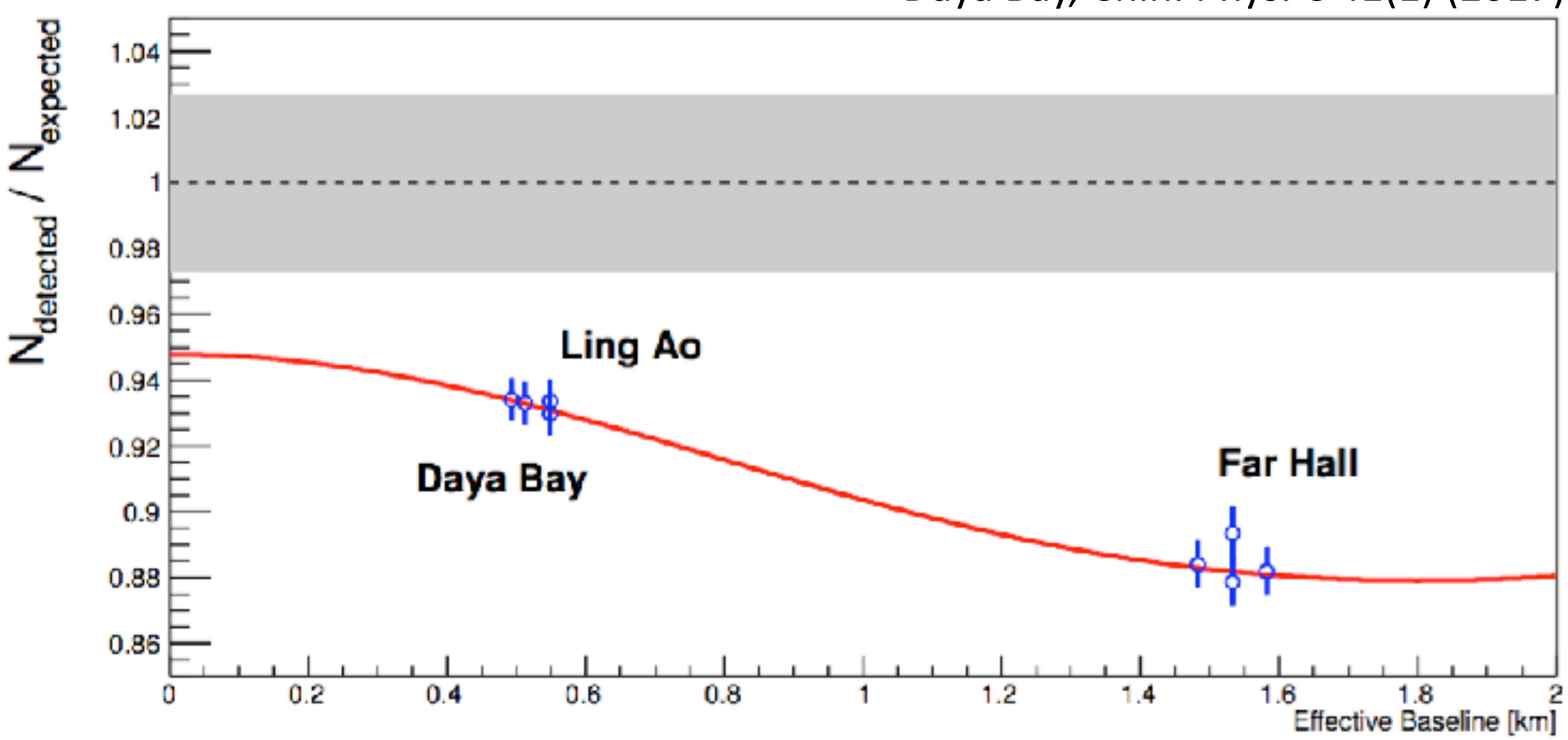
Daya Bay, PRD 95 (2017)



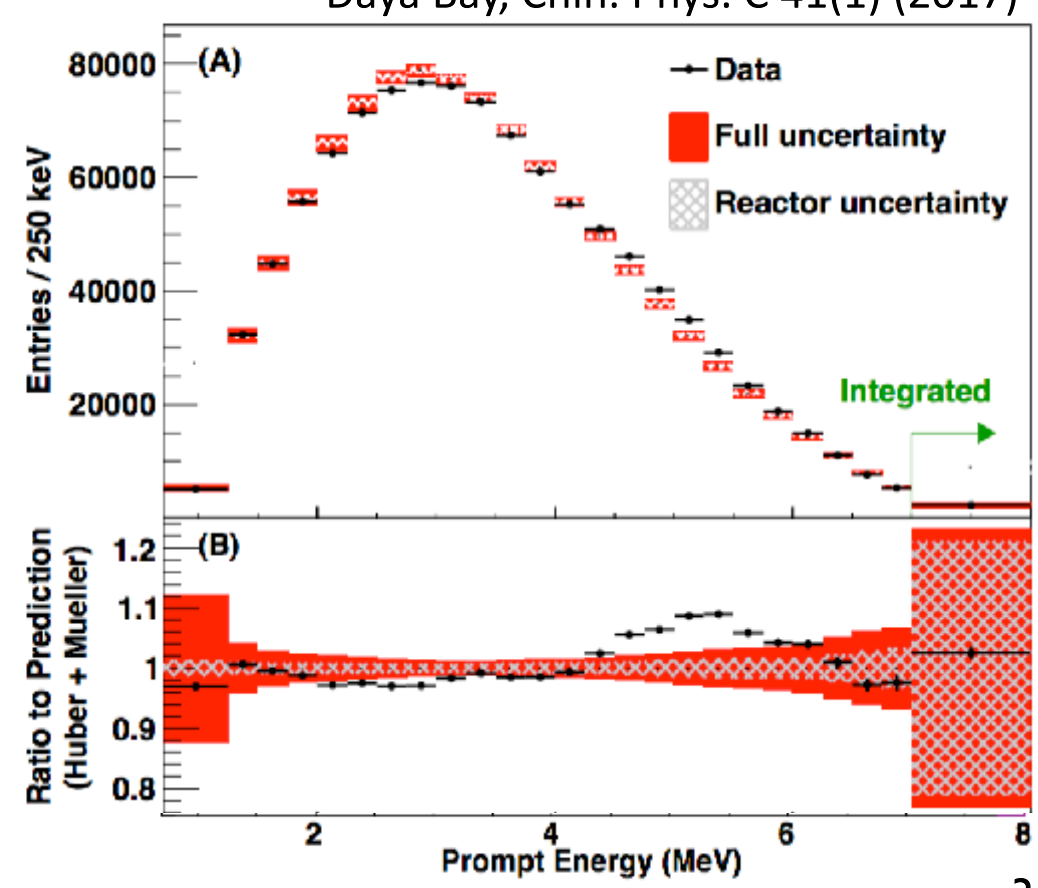
Past Daya Bay Analyses

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

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



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



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:

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

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

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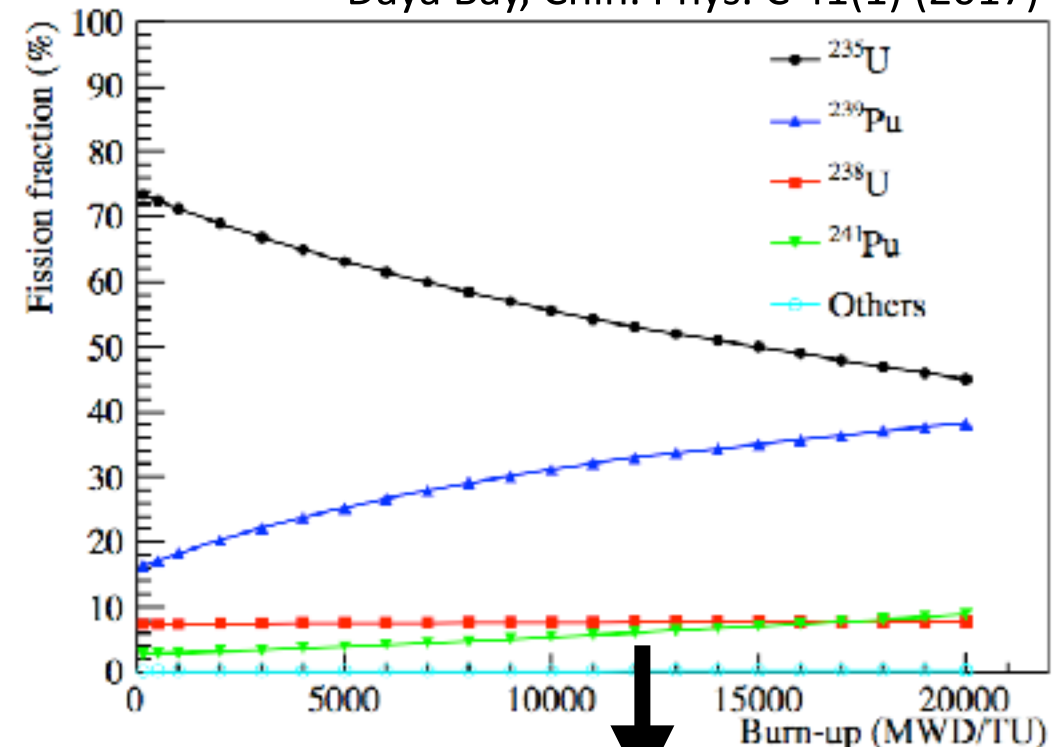
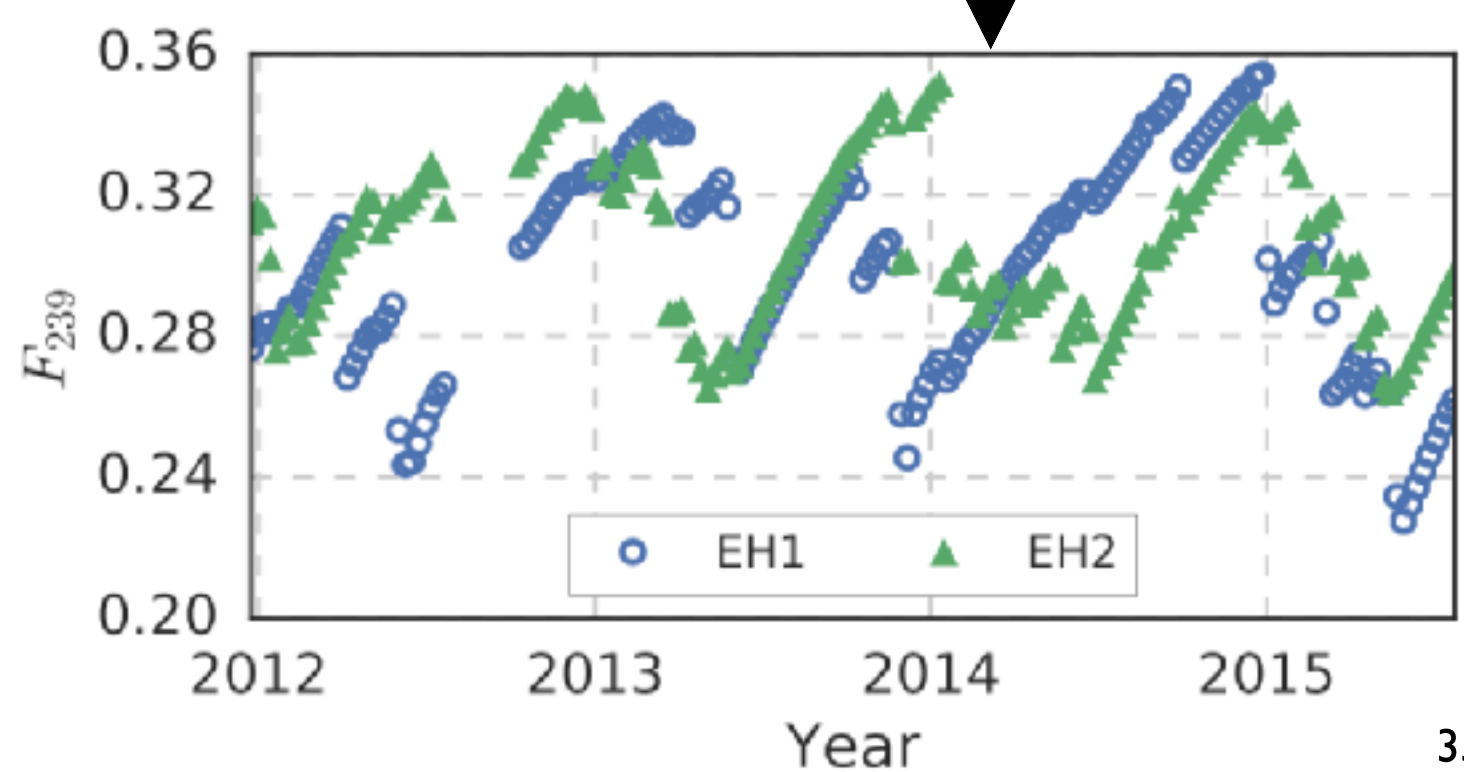


weight; then repeat x6



Cancellation Between Cores?

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

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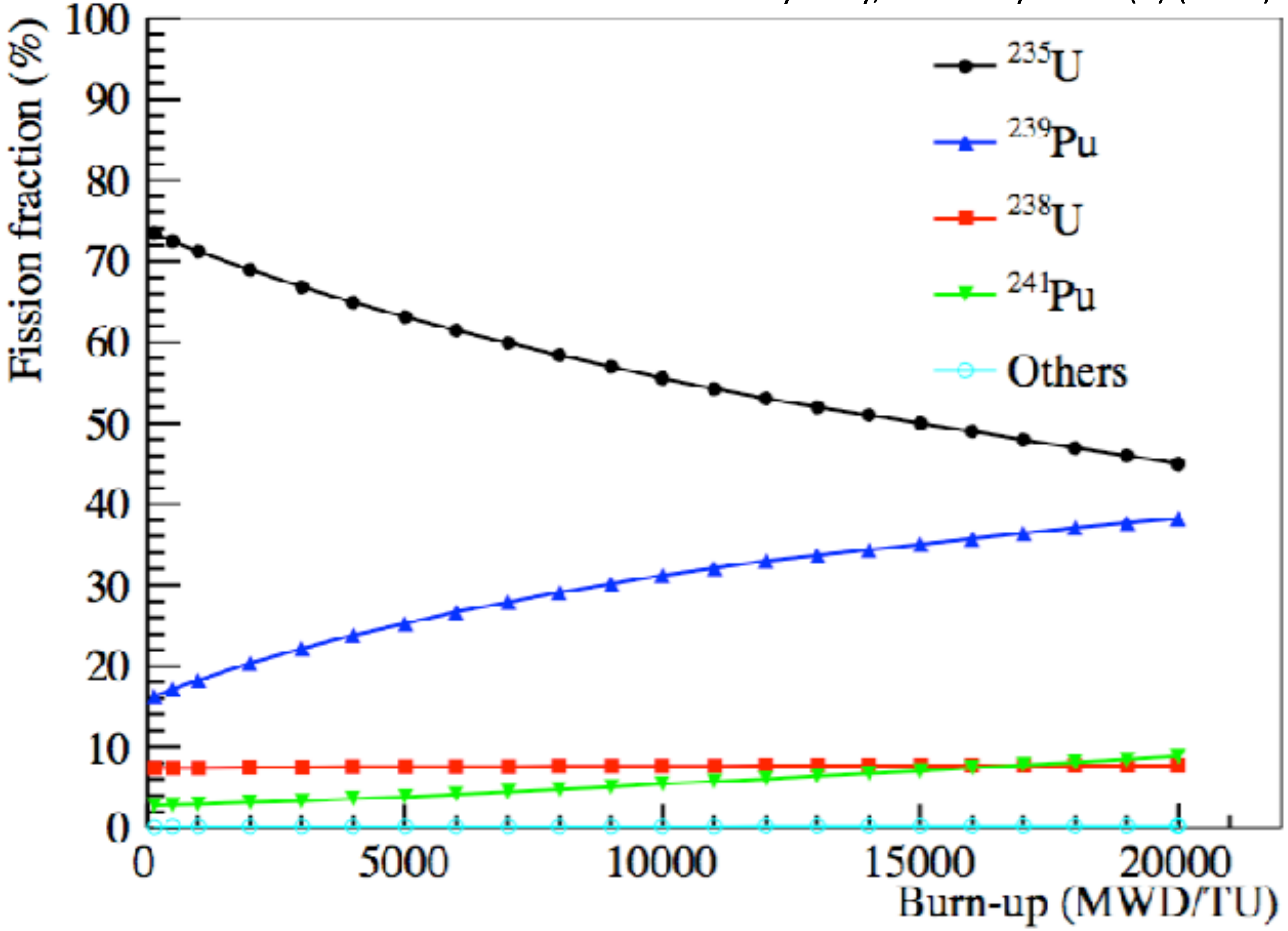

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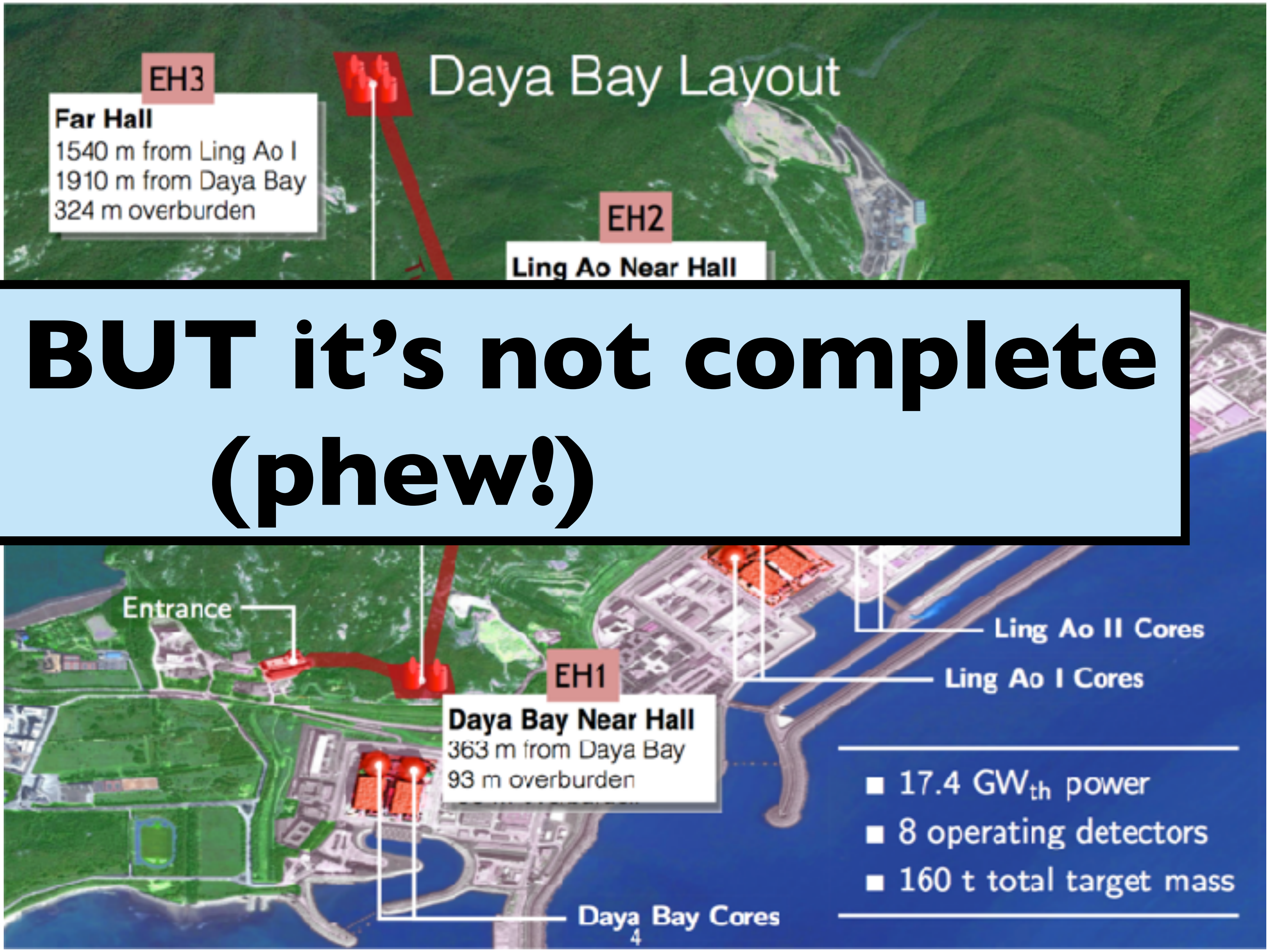
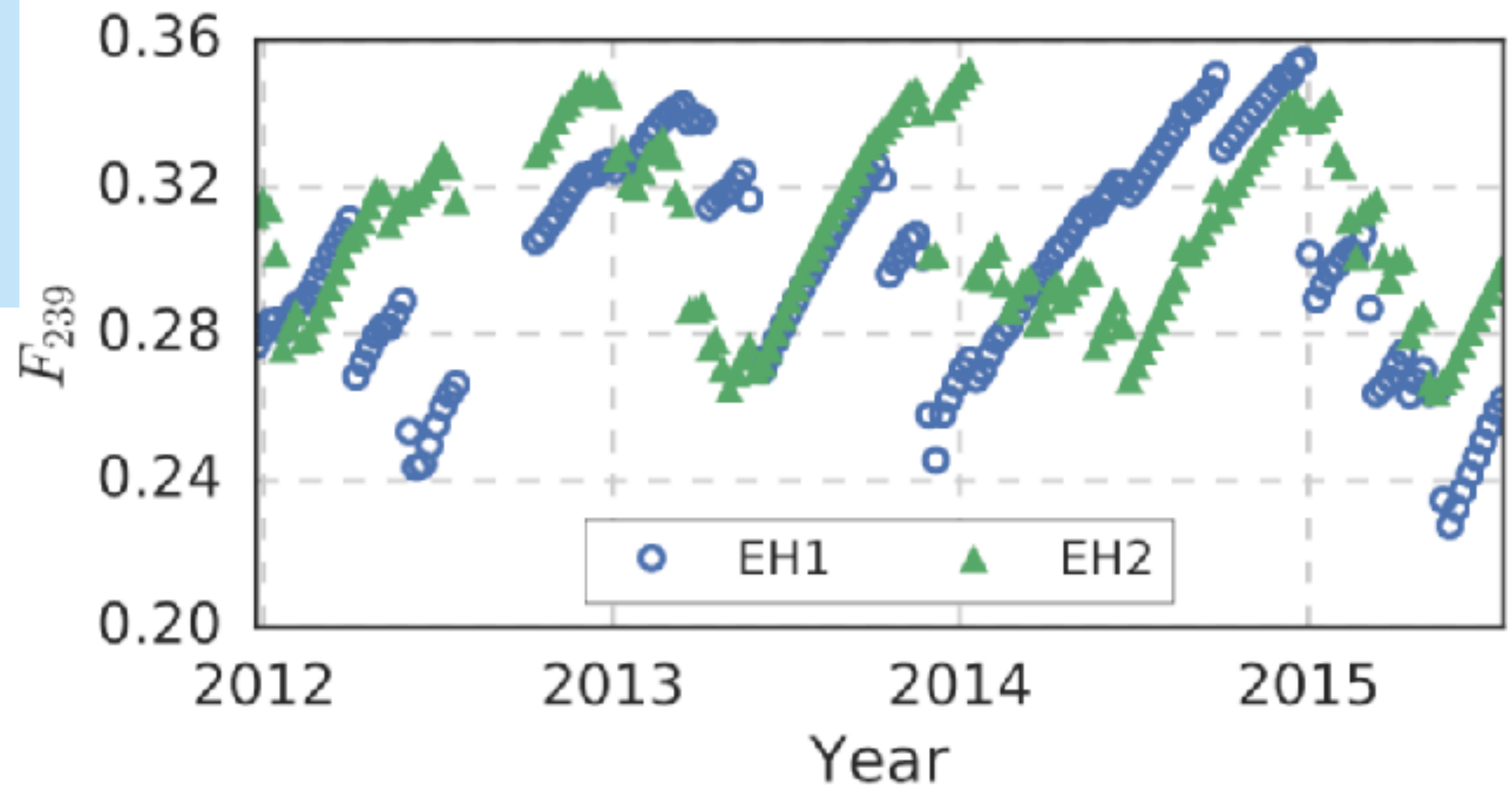
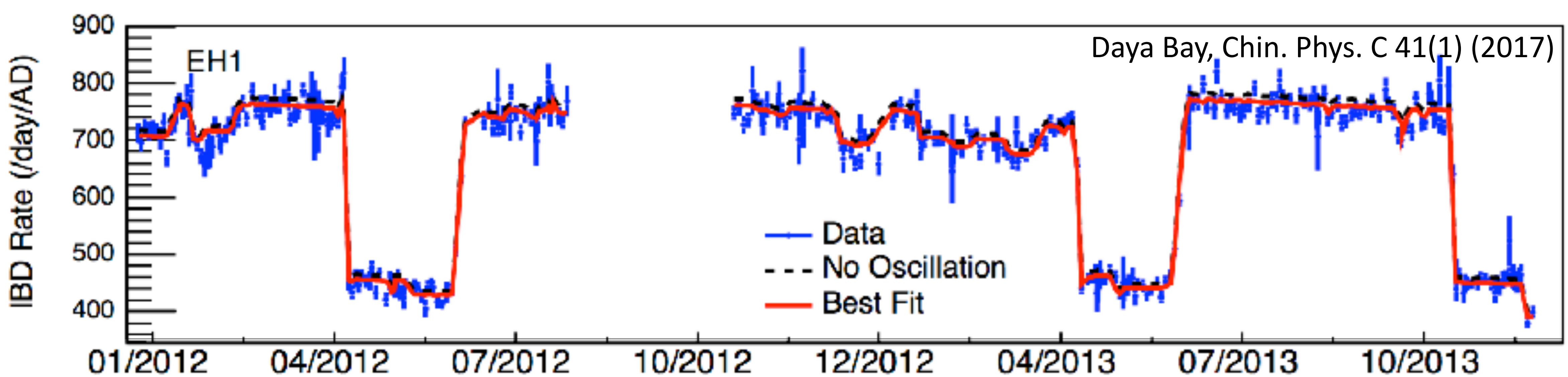


A: Yes, BUT it's not complete (phew!)

Daya Bay Evolution Analysis

- So: now we have fission fractions and IBDs versus time
- Let's compare IBD from periods of differing effective fission fractions!





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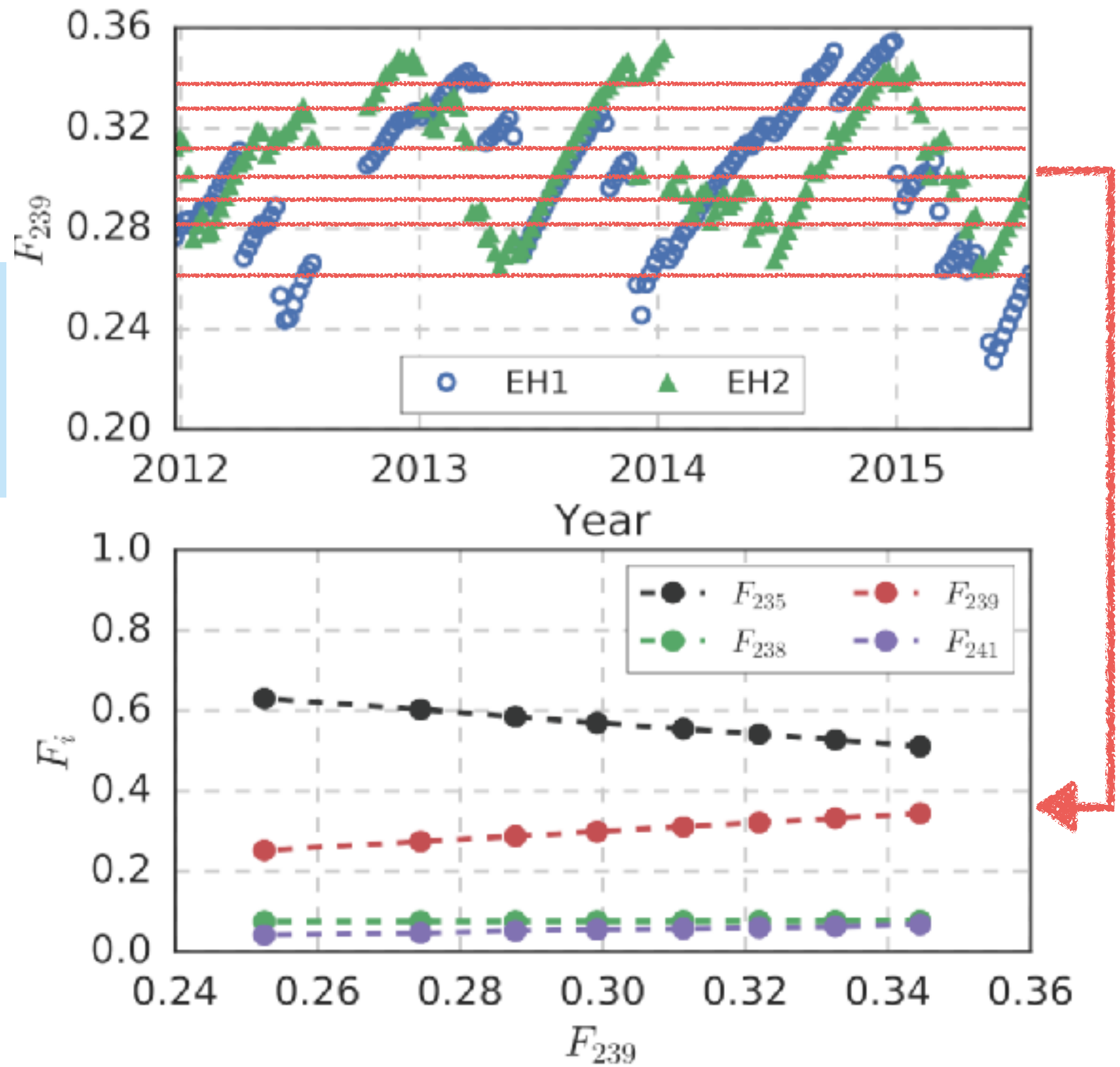
Daya Bay Evolution Analysis

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

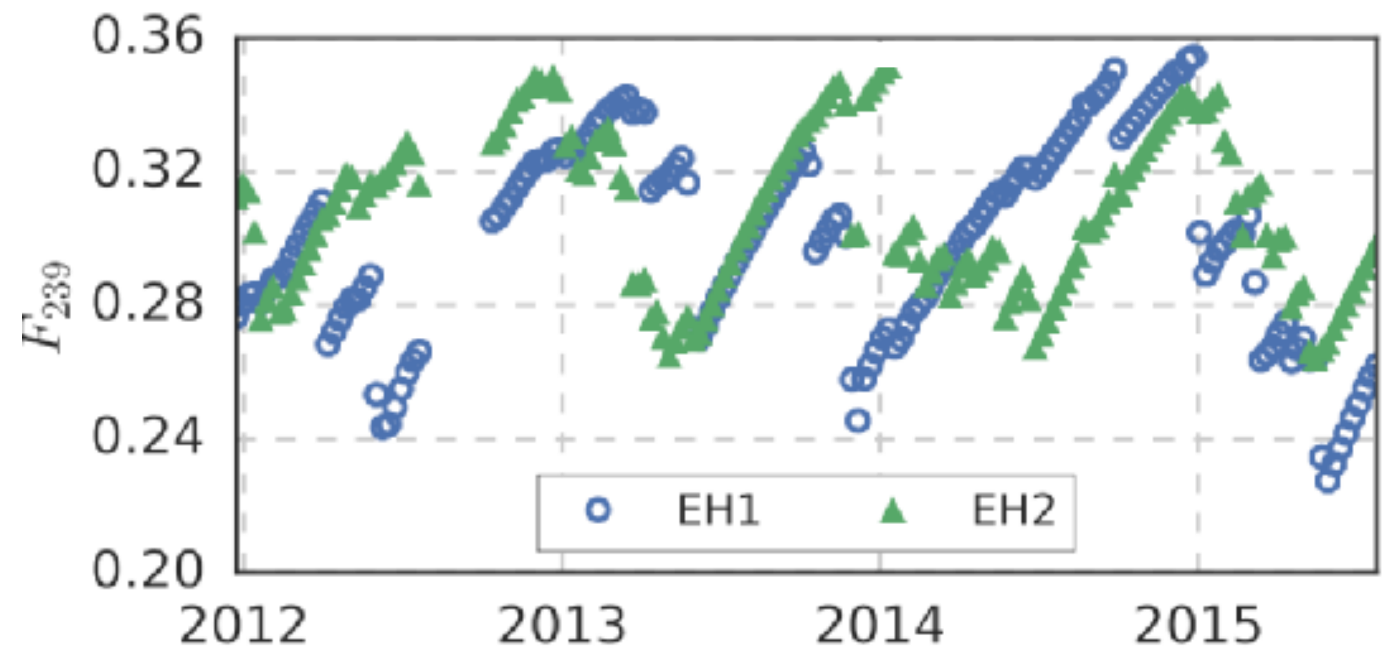


Systematics: Reactor

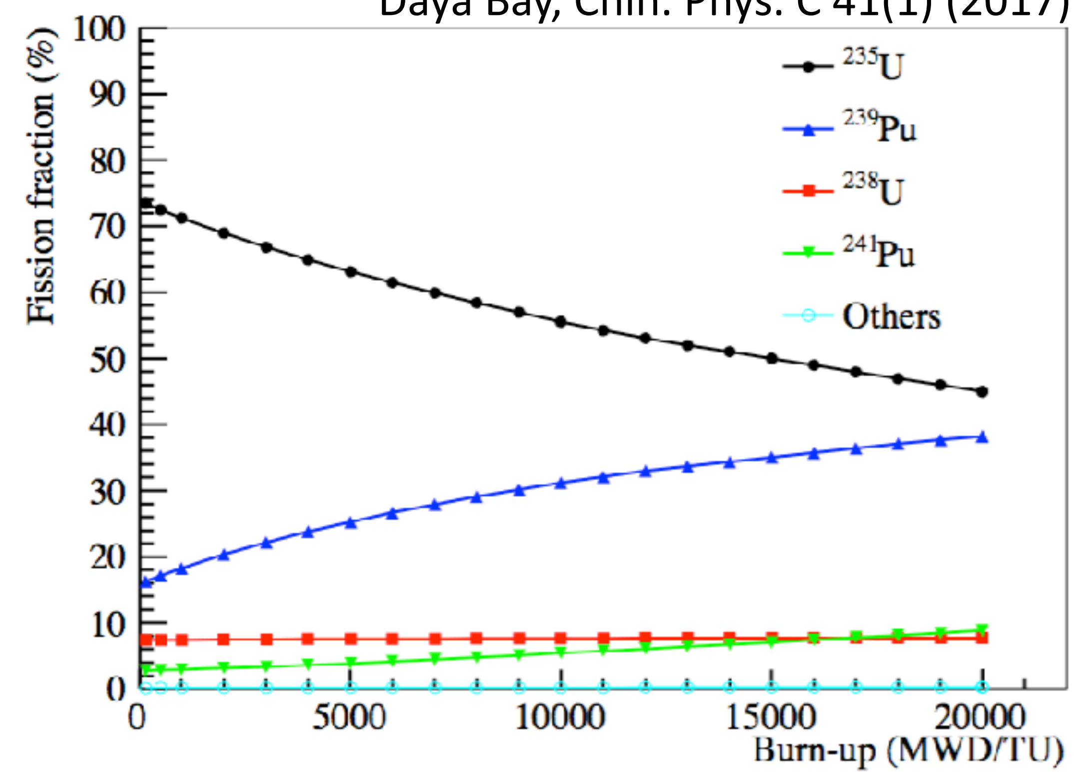
- Uncertainties from various inputs to our F_i definition are not too large

  - 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…

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



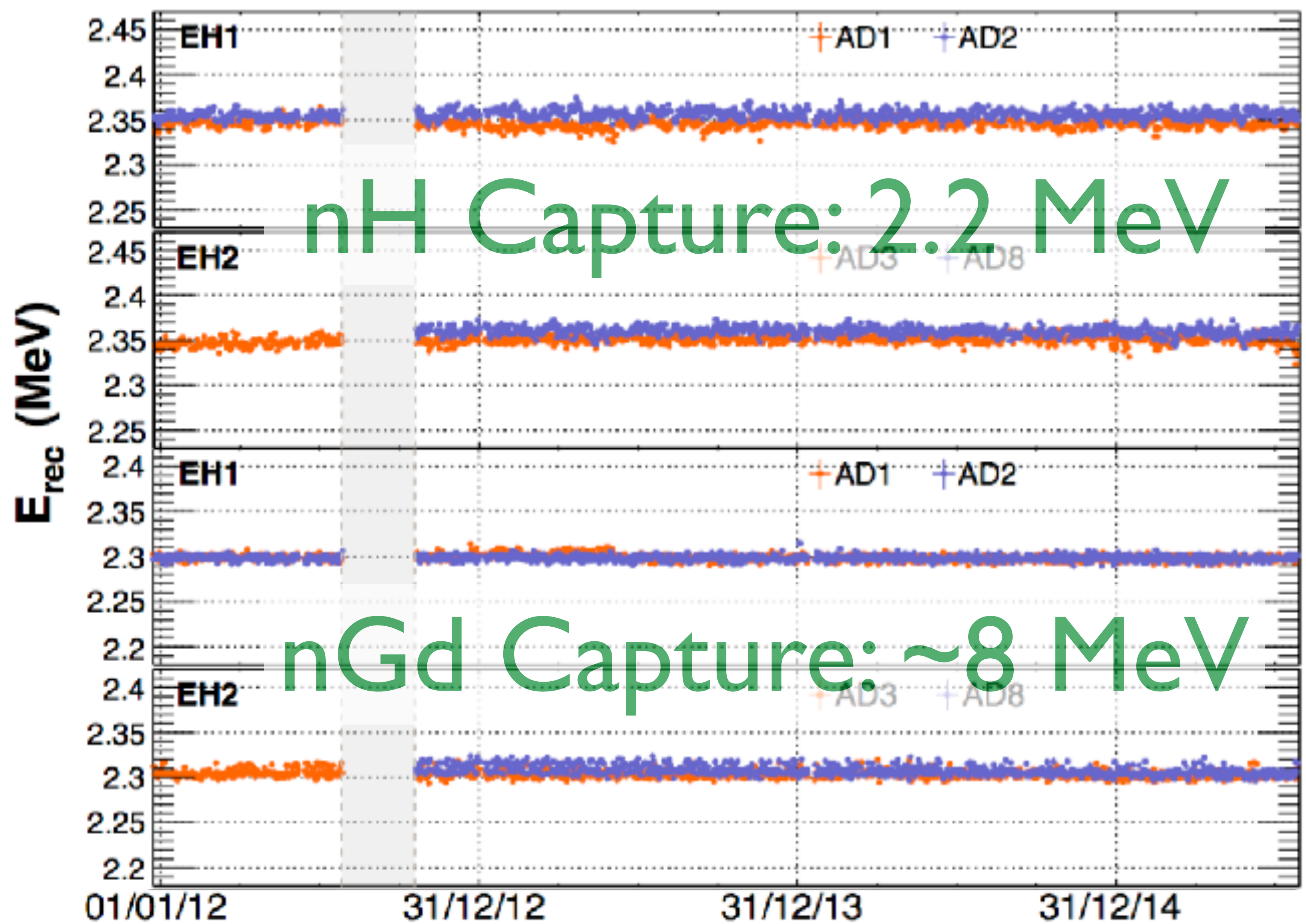
Daya Bay, Chin. Phys. C 41(1) (2017)



Systematics: Detector

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

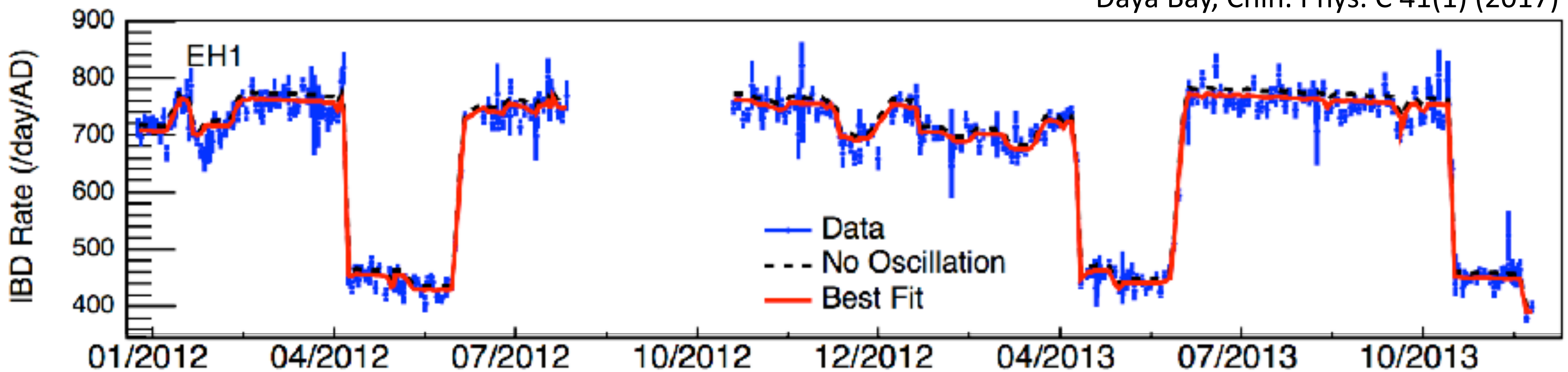
Daya Bay, PRD 95 (2017)



Note: From IBD/day to IBD/fission

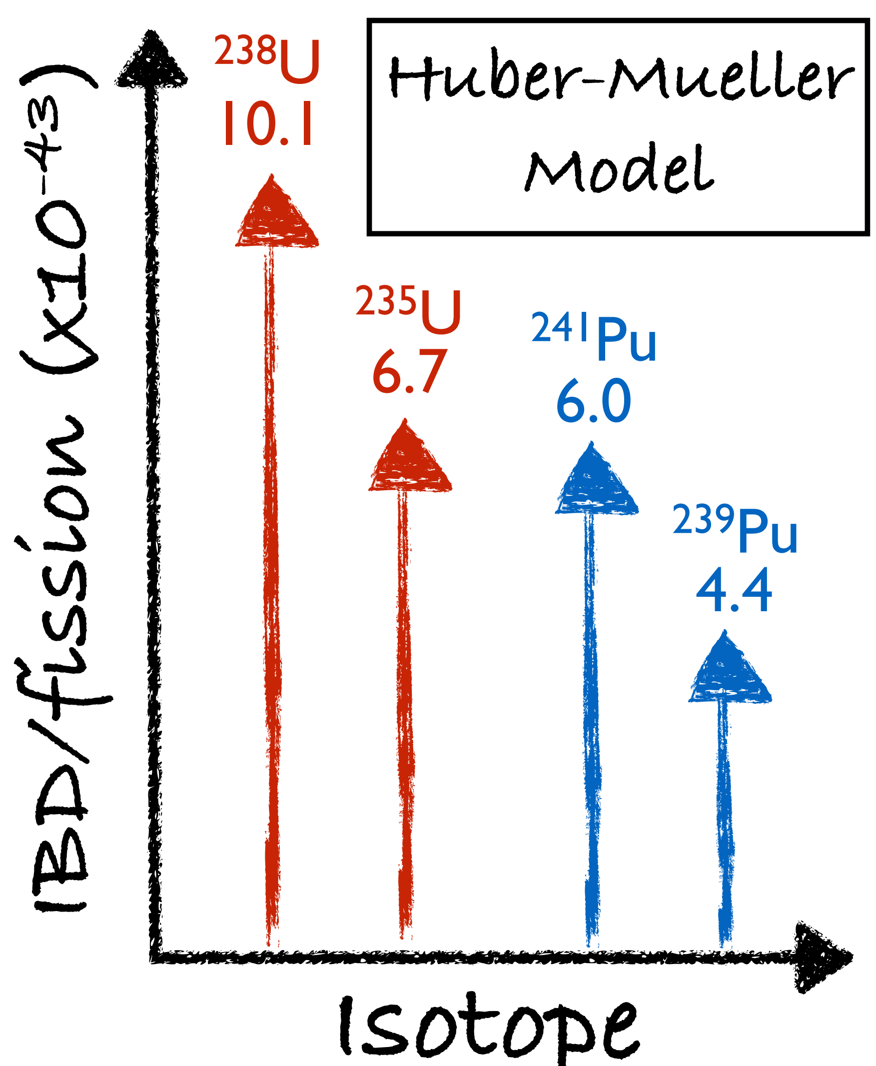
- IBD/day depends on many time-variable quantities:
  - Reactor status and thermal power
  - Power released per fission
  - Detector livetime
  - Some other more minor, nearly-constant stuff target mass
- Show final plots in terms of IBD/fission: $\sigma_f = \sum_i F_i \sigma_i$
  - Basically take IBD/day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

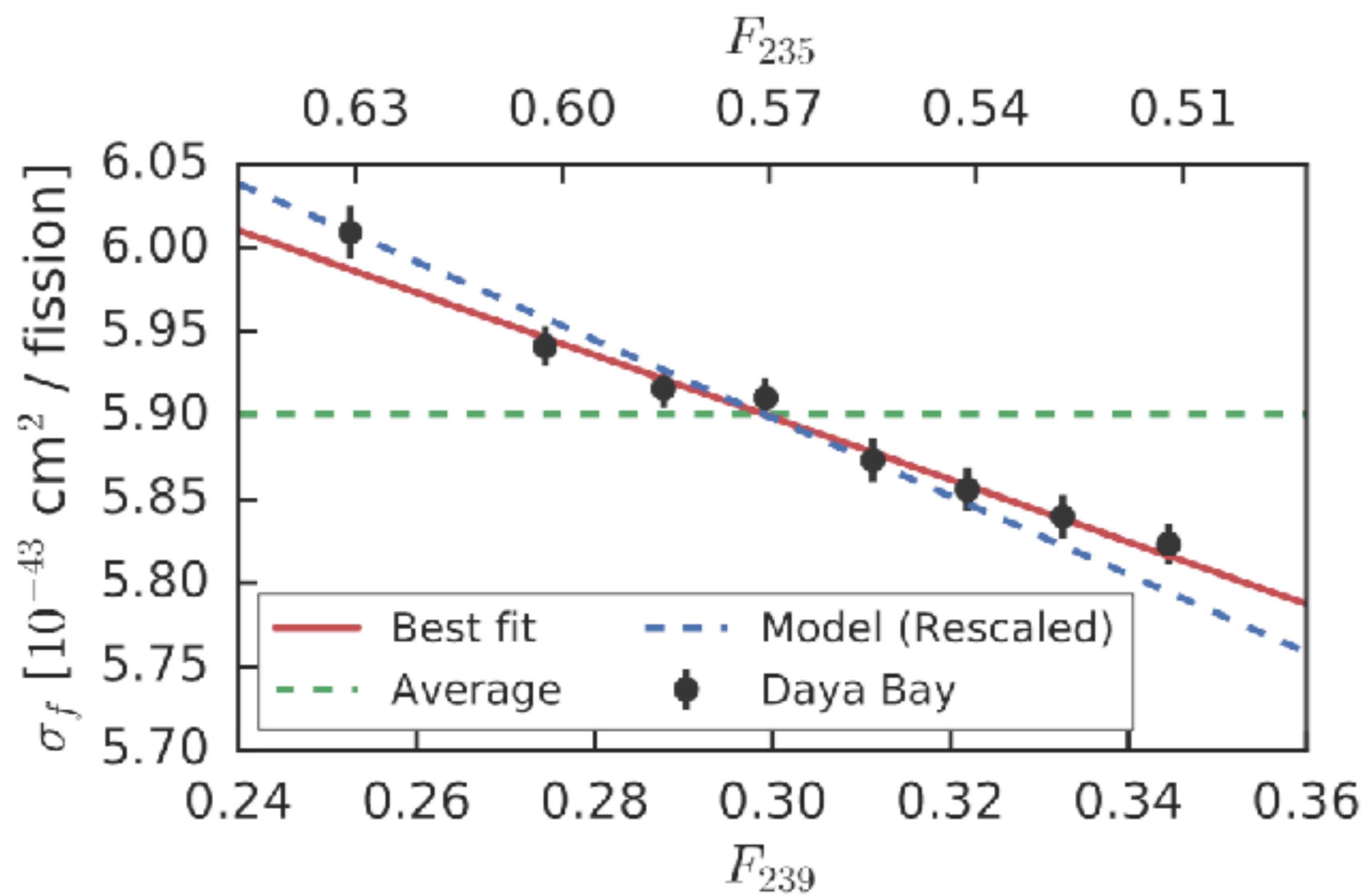
Daya Bay, Chin. Phys. C 41(1) (2017)



Result: Flux Evolution

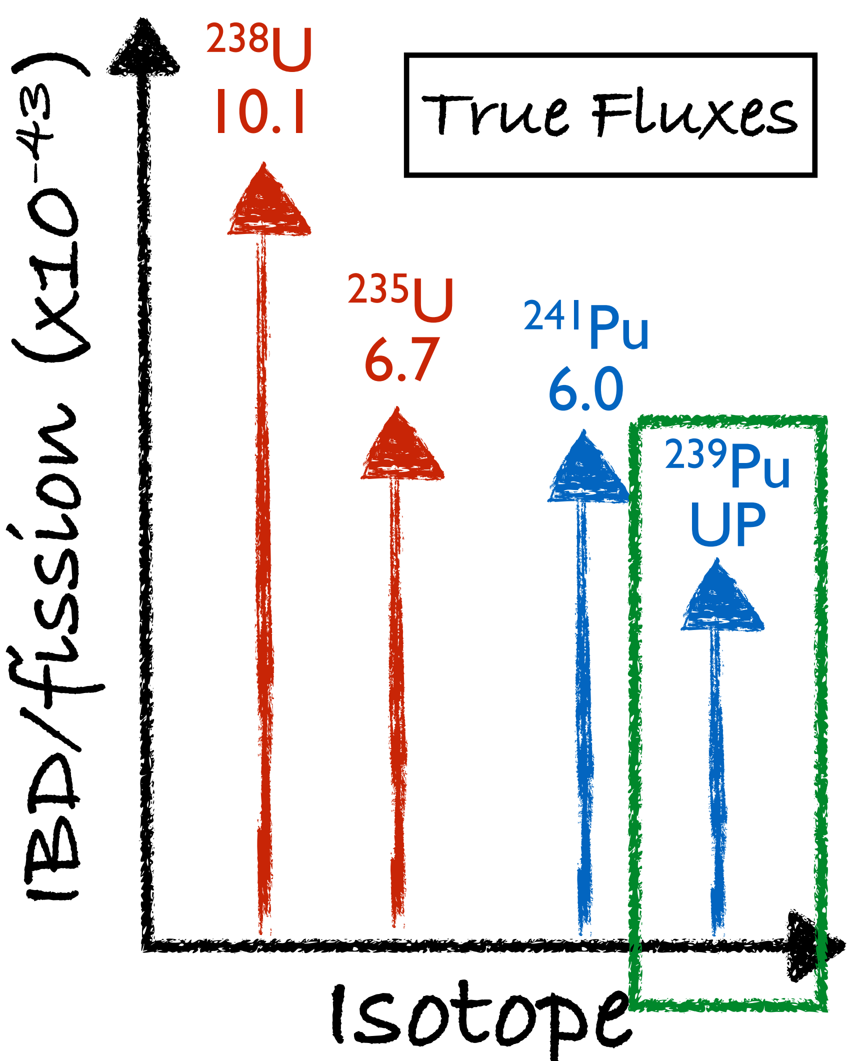
- When plotting IBD/fission versus F_{239}, we see a slope in data
- Very clear that flux is changing with changing fission fraction.
  - Not too surprising; models predict ^{239}Pu makes fewer $\overline{\nu}_e$
  - Also, seen before in previous experiments: Rovno (90's); SONGS (00's)
- Statistical uncertainty limits the measurement of this slope.

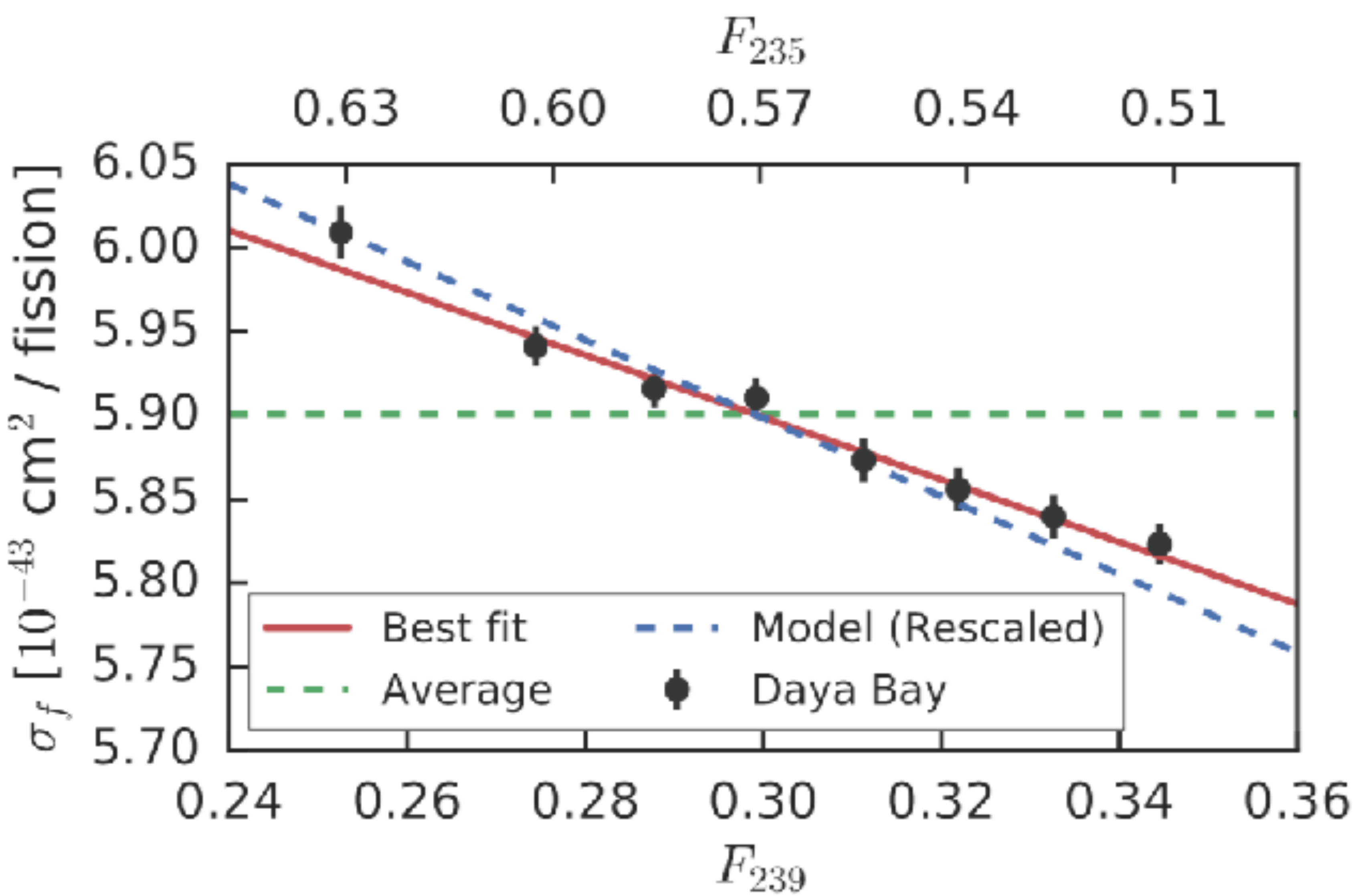




Result: Flux Data-Model Comparison

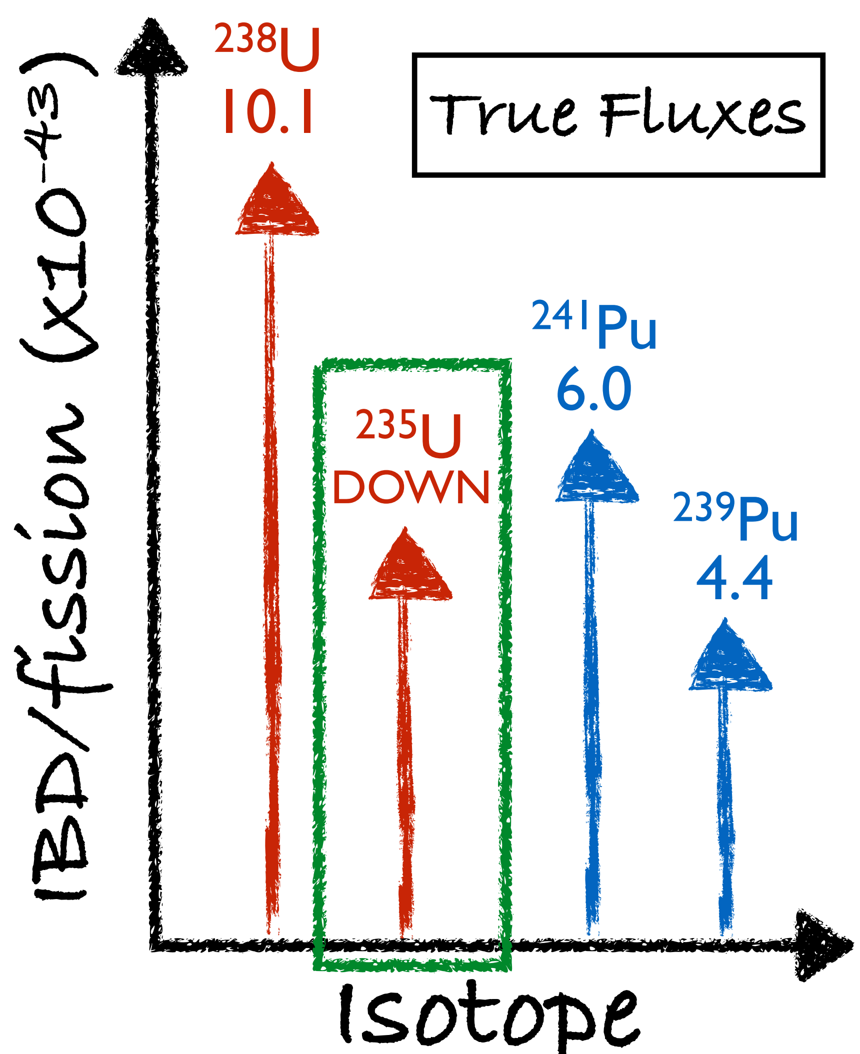
- Measured slope is different than model prediction by 2.6σ
- Could mean a couple things:
  - ^{239}Pu prediction is too low

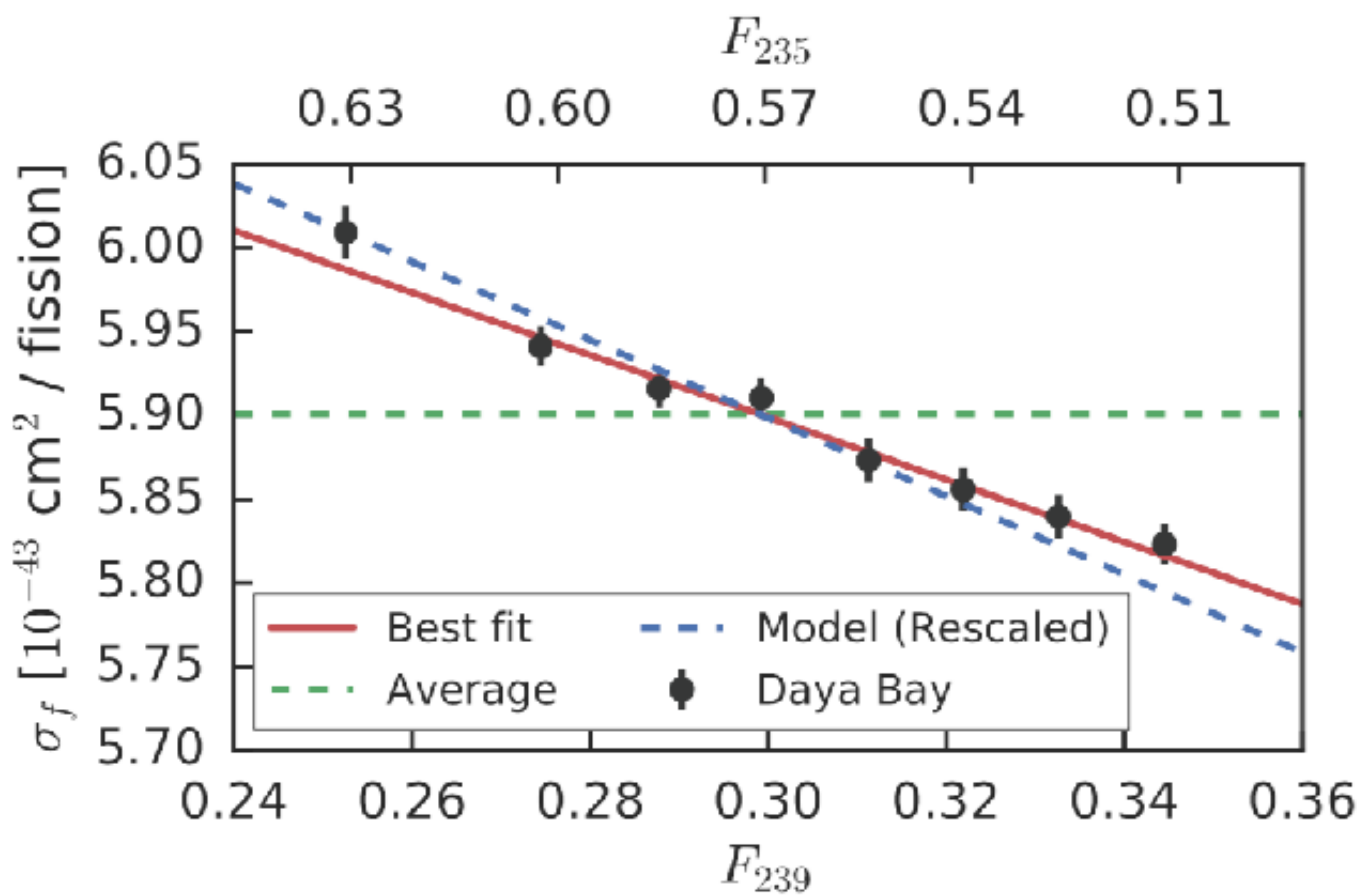




Result: Flux Data-Model Comparison

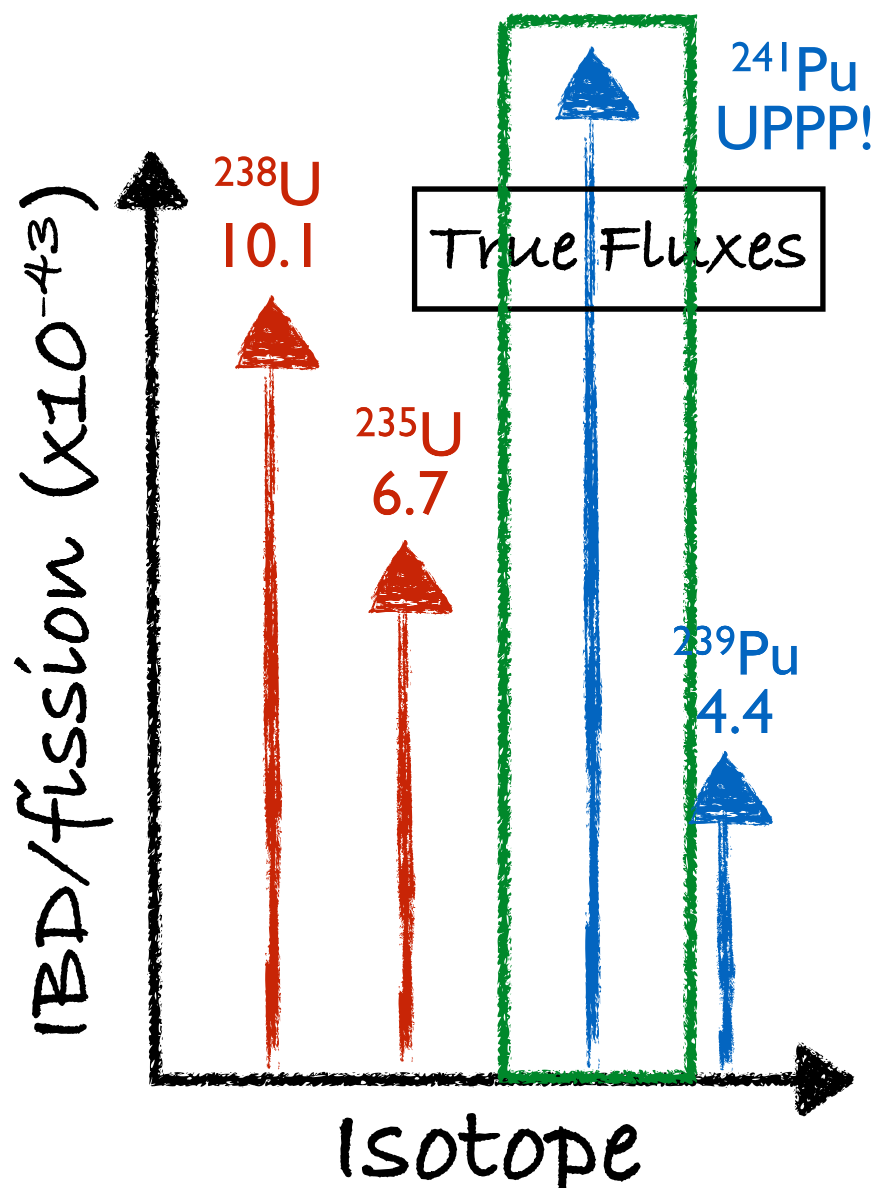
- Measured slope is different than model prediction by 2.6σ
- Could mean a couple things:
  - ^{239}Pu prediction is too low
  - ^{235}U prediction is too high

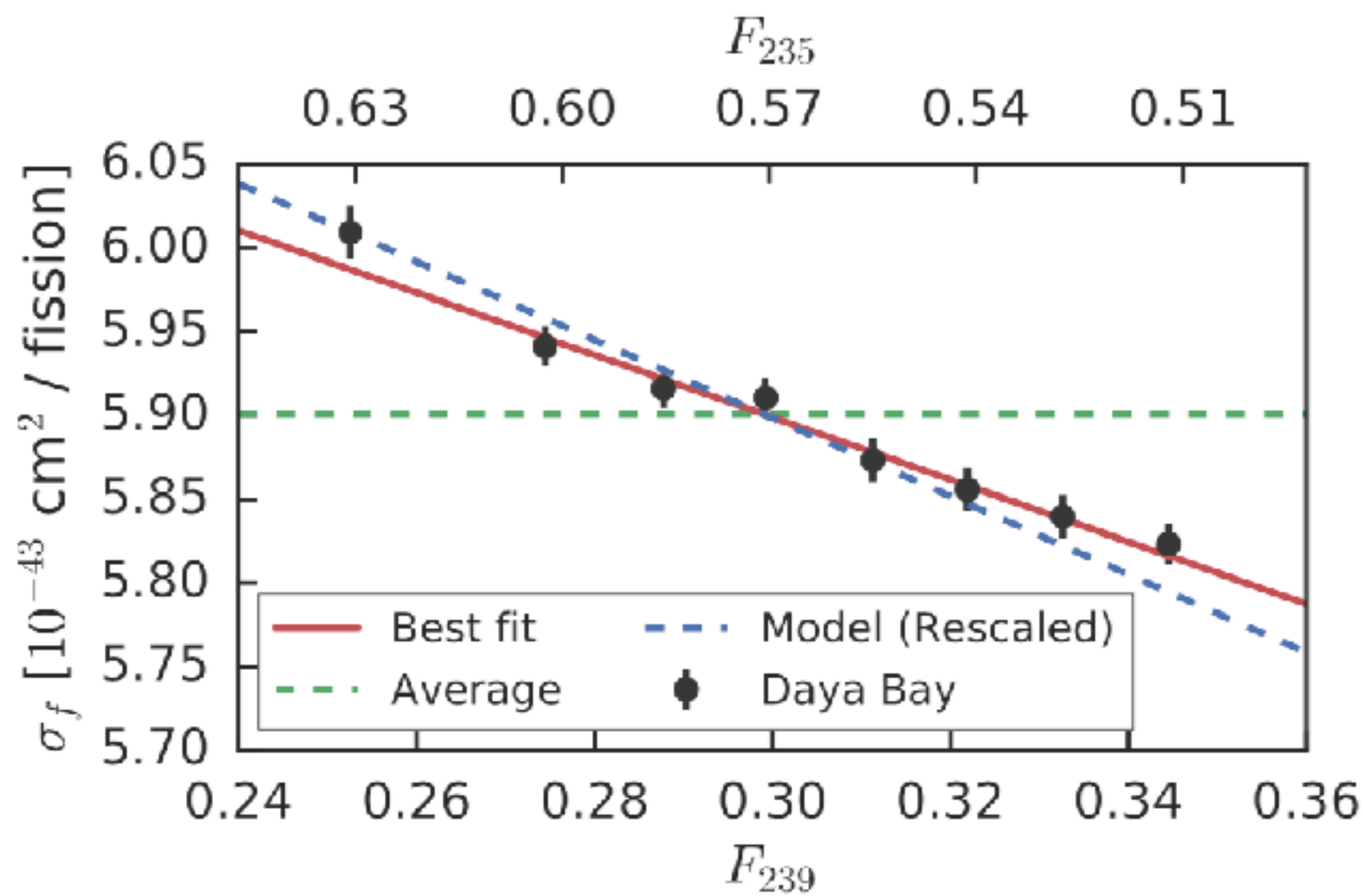




Result: Flux Data-Model Comparison

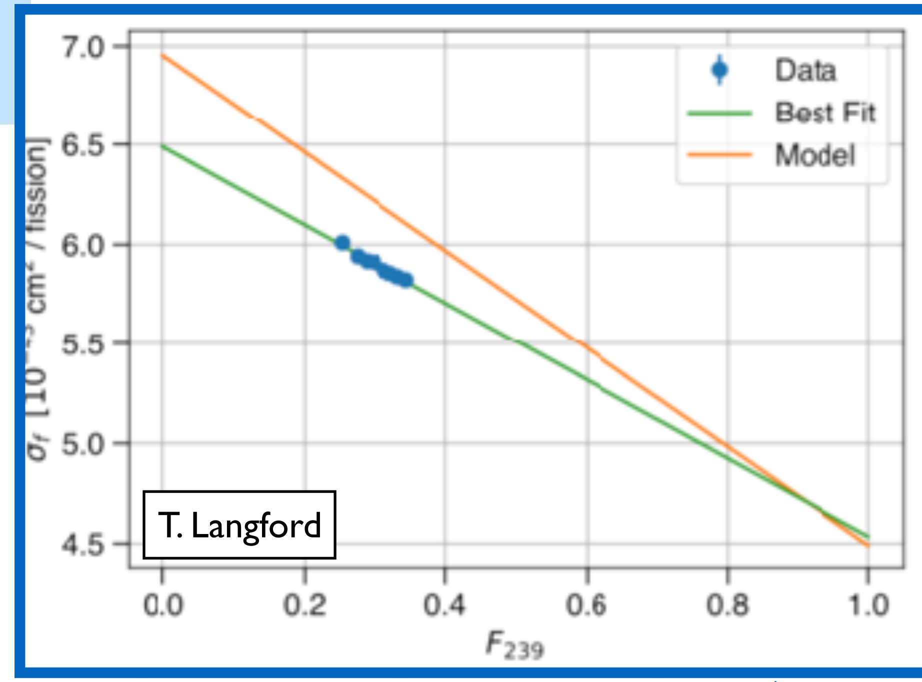
- Measured slope is different than model prediction by 2.6σ
- Could mean a couple things:
  - ^{239}Pu prediction is too low
  - ^{235}U prediction is too high
  - Something is WAY off with ^{238}U, ^{241}Pu

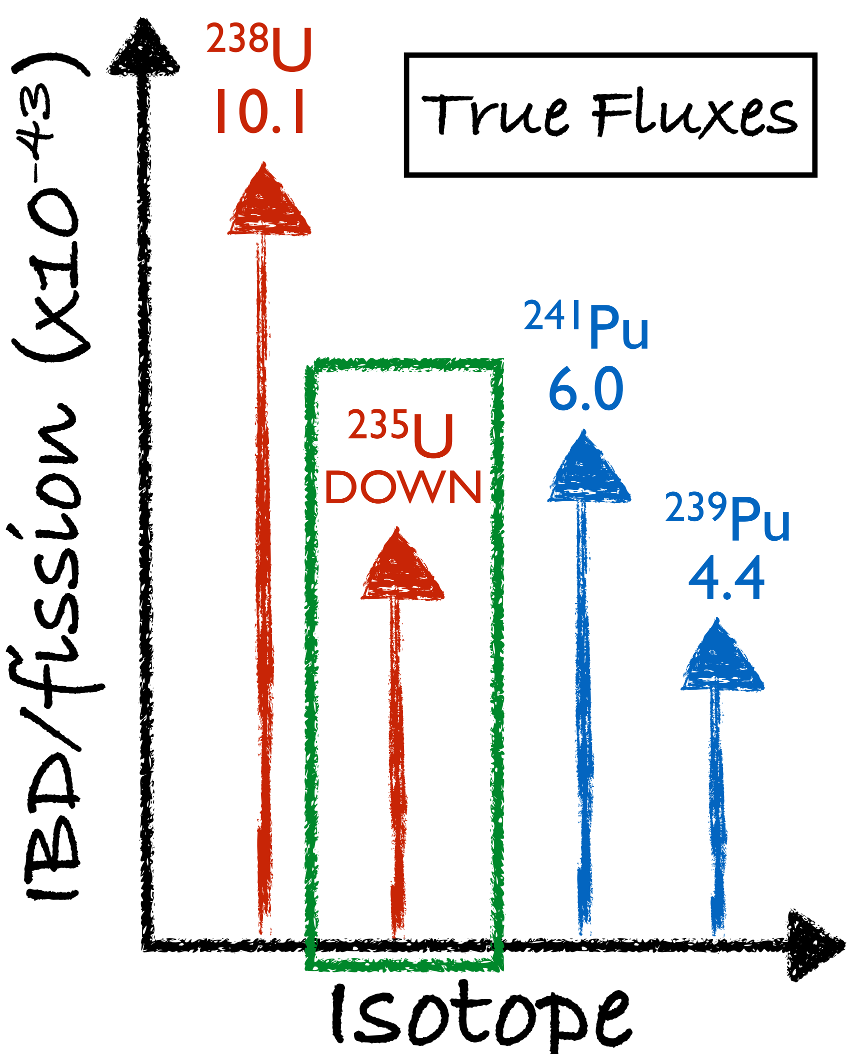


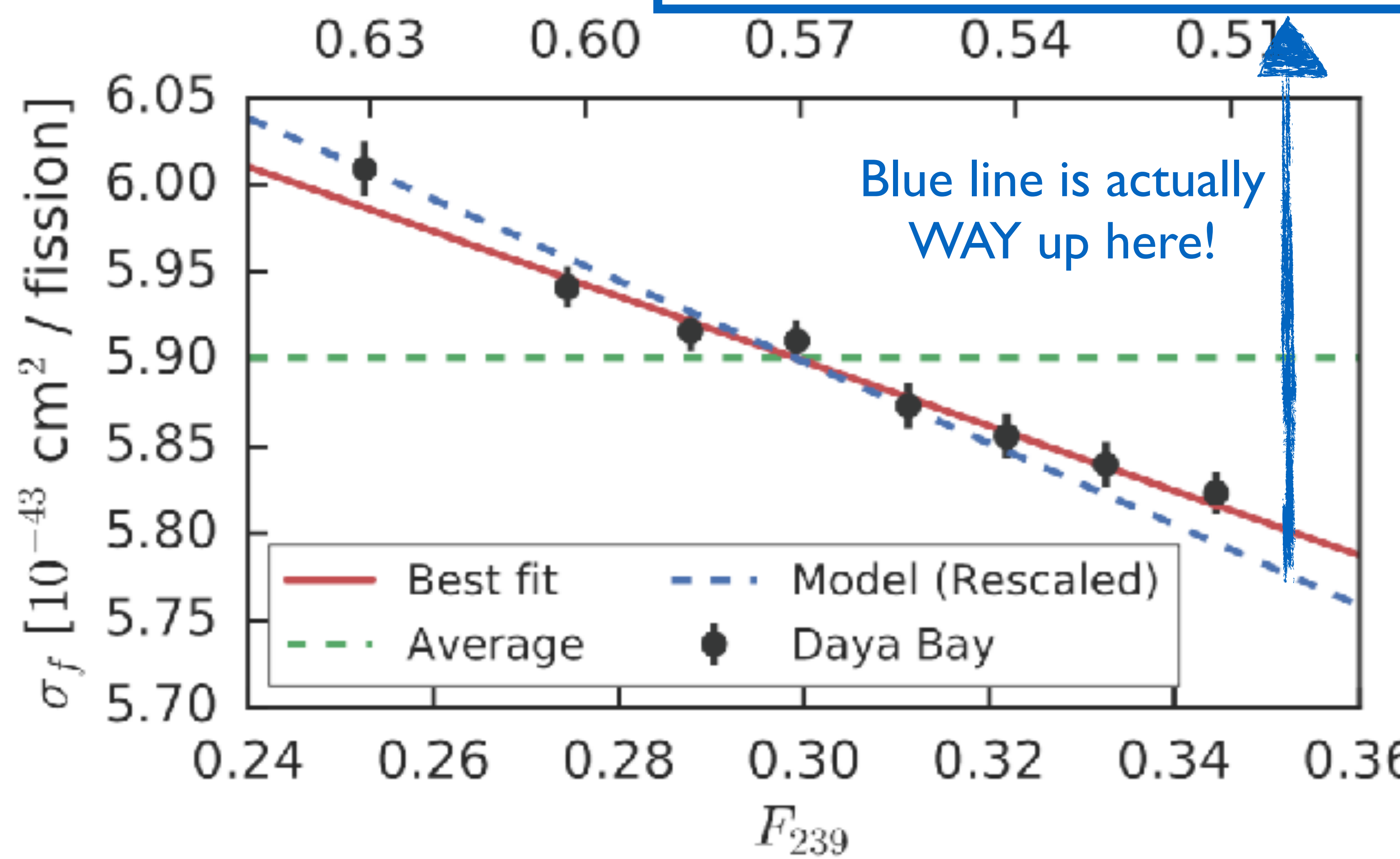


Result: What About Absolute Flux?

- Also: total flux prediction high by 5.4%
- 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

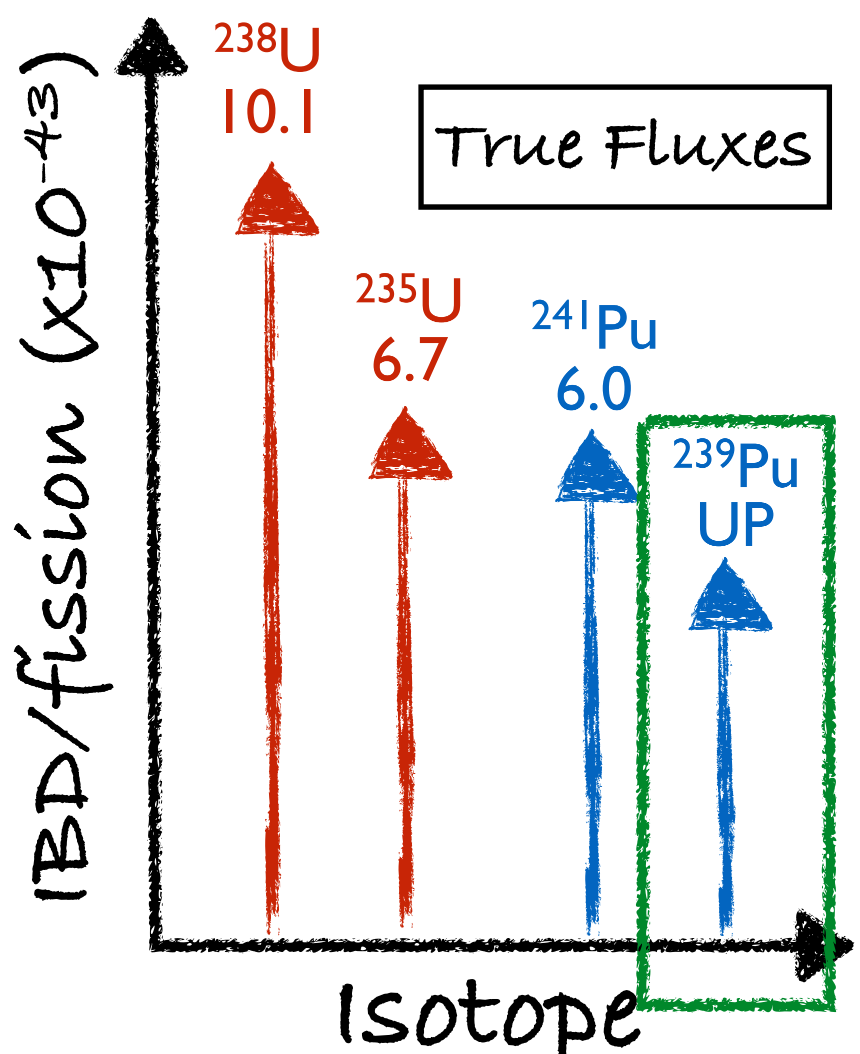


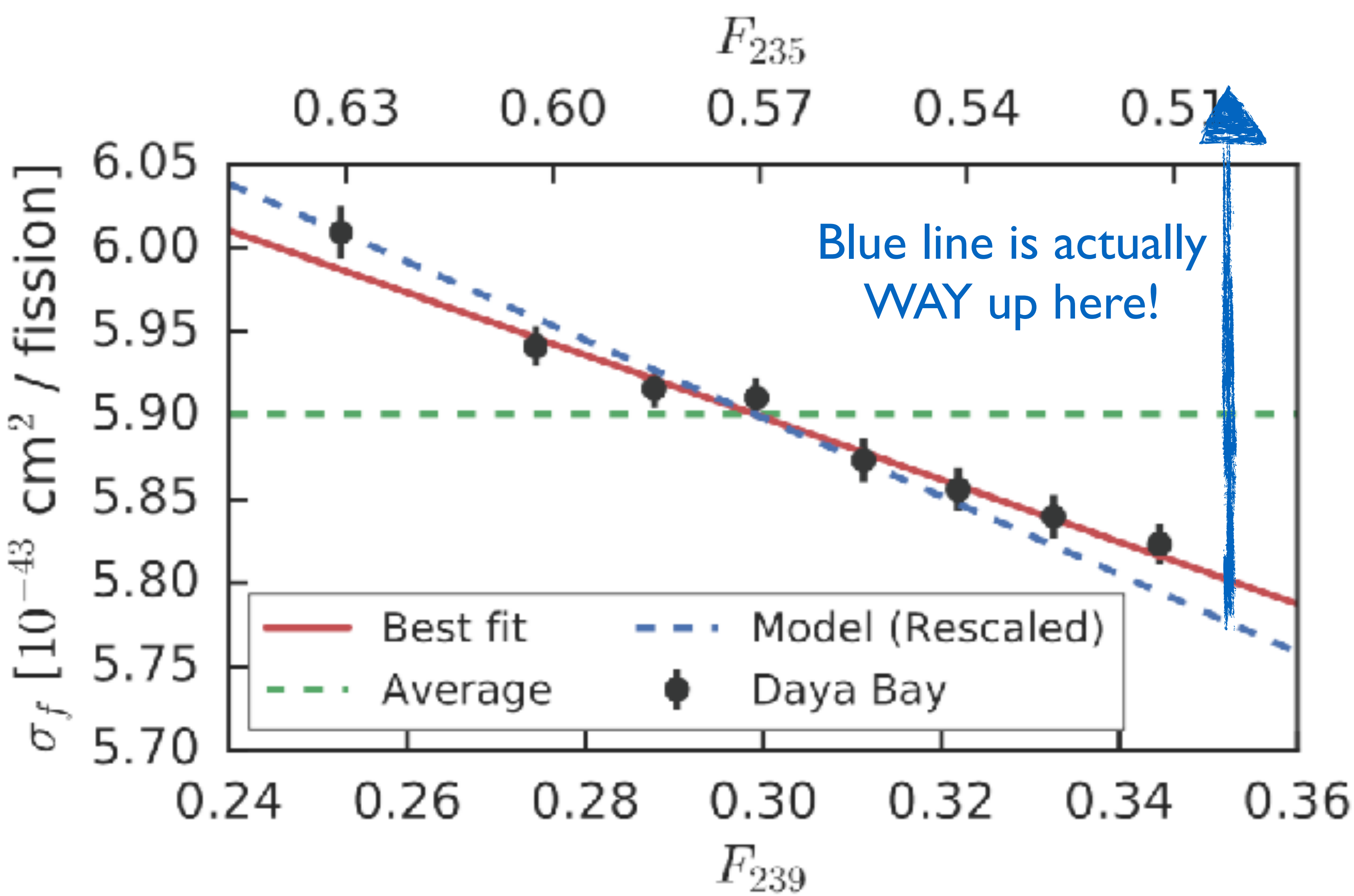




Result: More Complicated Scenarios

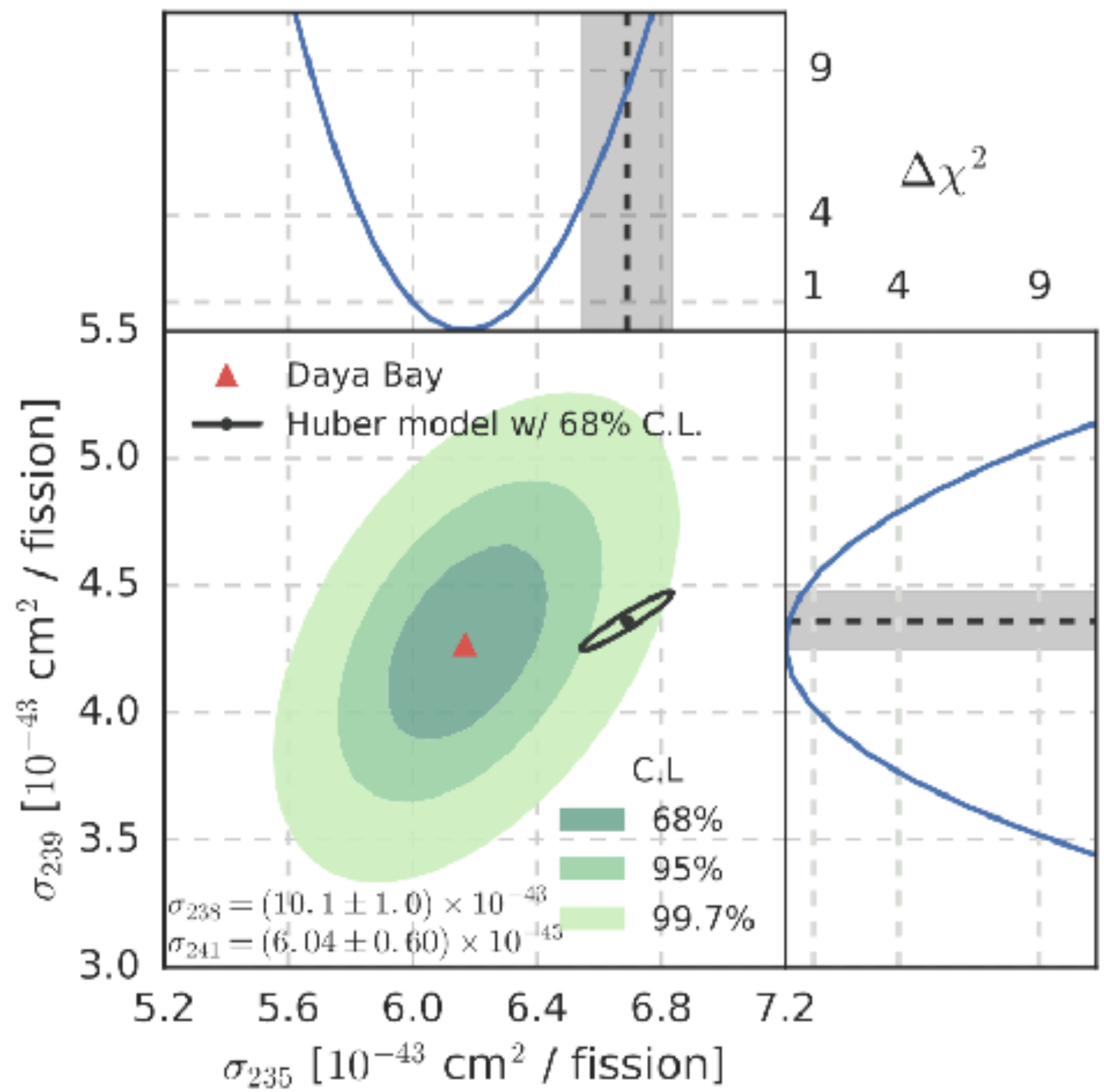
- NOTE: result doesn't explicitly rule out sterile nu altogether
  - Some more complicated scenarios still allowed, i.e.: ^{239}Pu UP + sterile nu
- Whatever the case, flux models must be wrong in some way
  - Need a direct L/E probe to fully address steriles (like SBL reactor experiments)





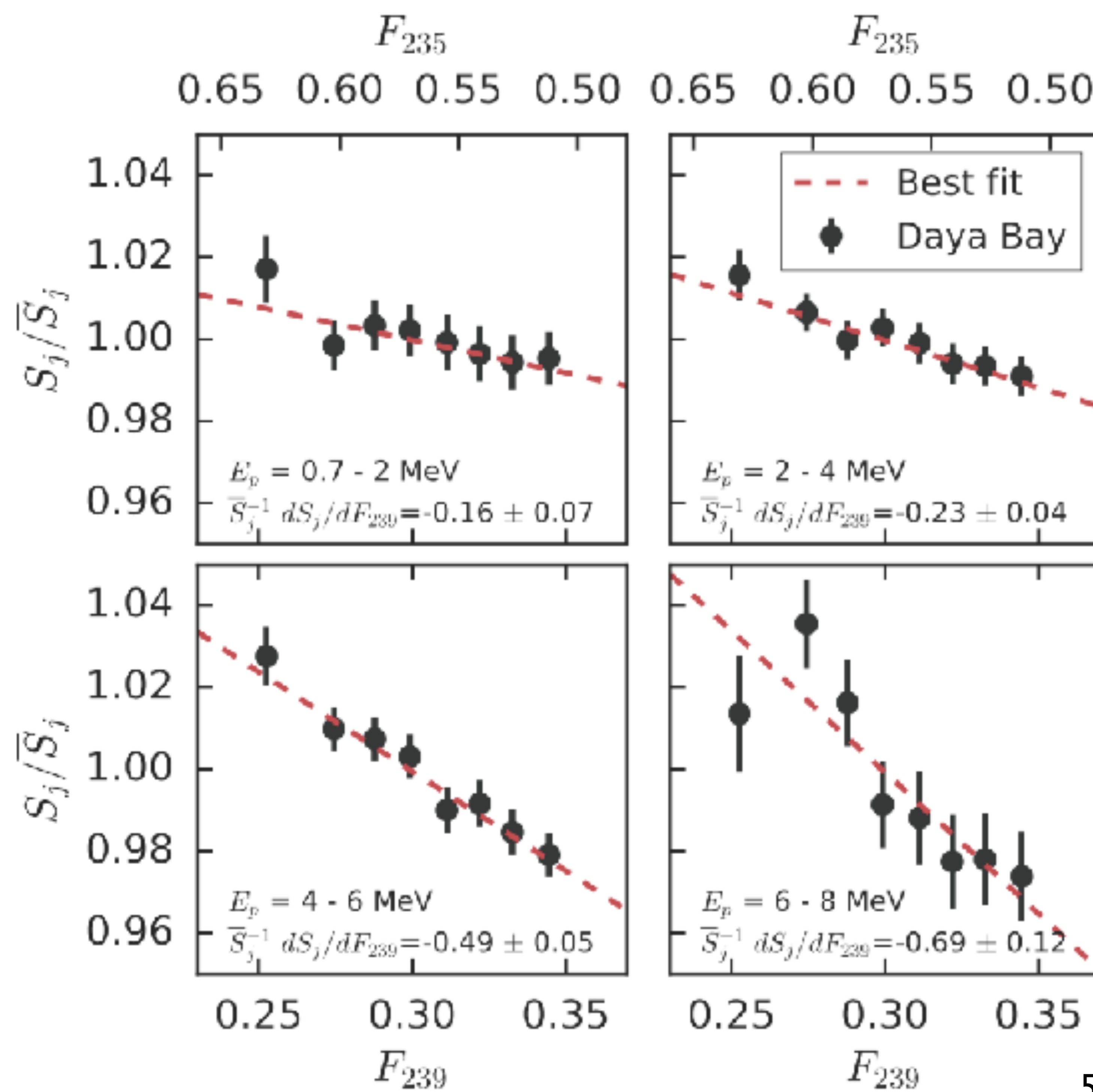
Result: Fitting For Individual Isotopes

- 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:
  - Absolute detection efficiency
  - Assumptions mentioned above
  - To a much lesser extent, stats
- As expected, fitted ^{235}U is lower than the model
  - ^{239}Pu also matches model well.



Result: Spectrum Evolution

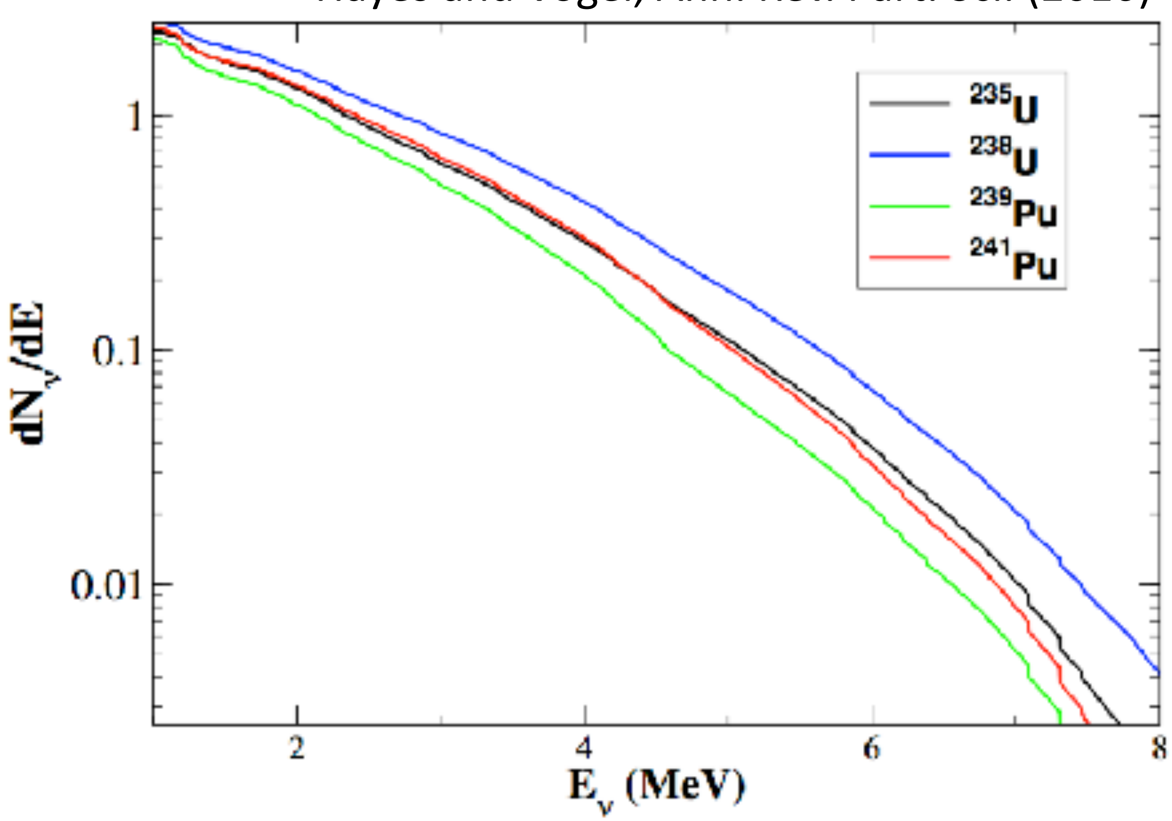
- Shift gears: what if we add IBD energy into the mix?
  - Examine evolution in 4 separate energy ranges
- Slope is different for different energy ranges
- Put another way: IBD spectrum is changing with F_{239}

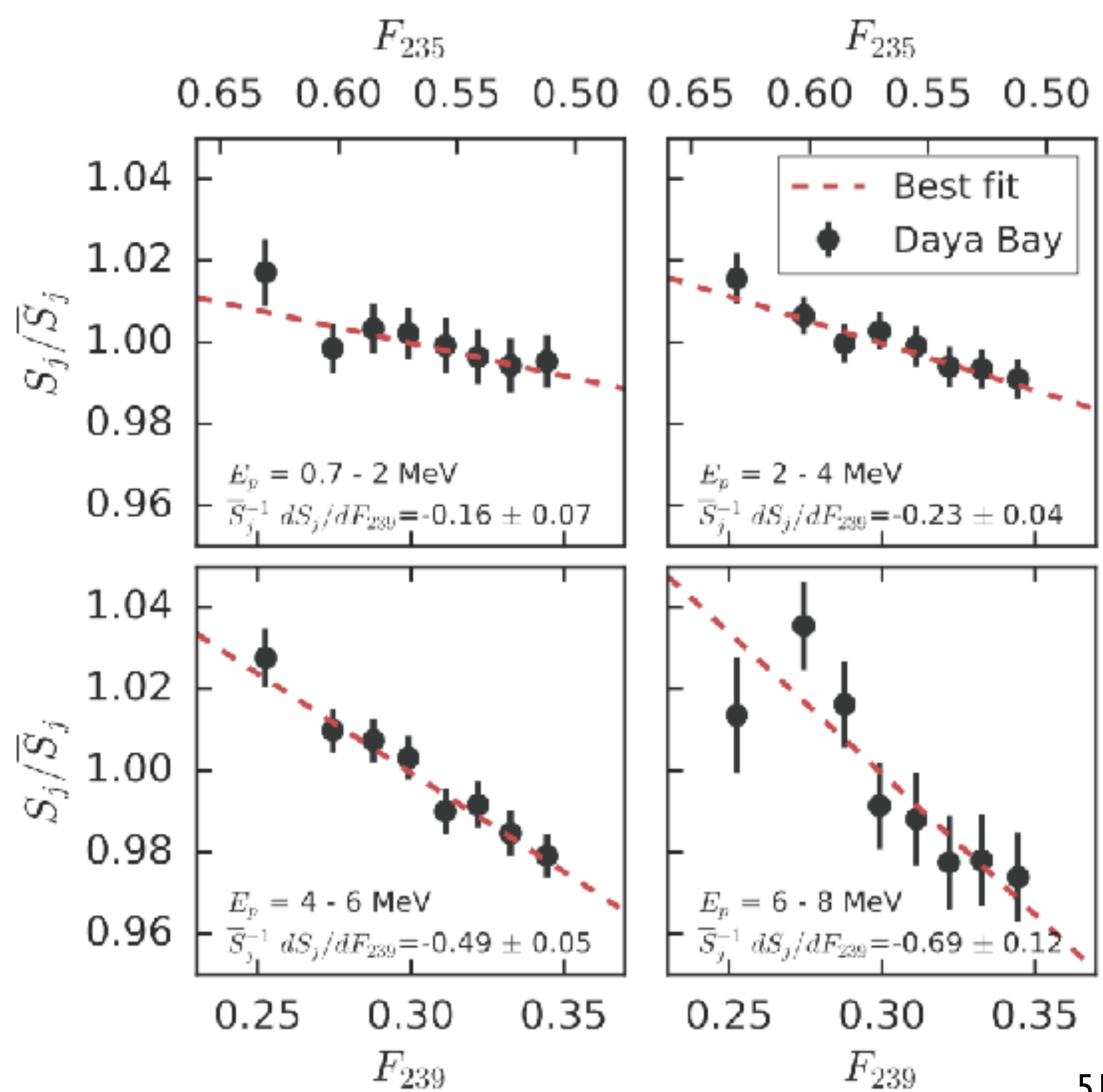


Result: Spectrum Evolution

- Put <u>another</u> way: have observed that fission isotopes differ in the antineutrino energy spectra they produce
  - This is the first time this has been unambiguously measured.
  - Most models do predict this, however.

Hayes and Vogel, Ann. Rev. Part. Sci. (2016)

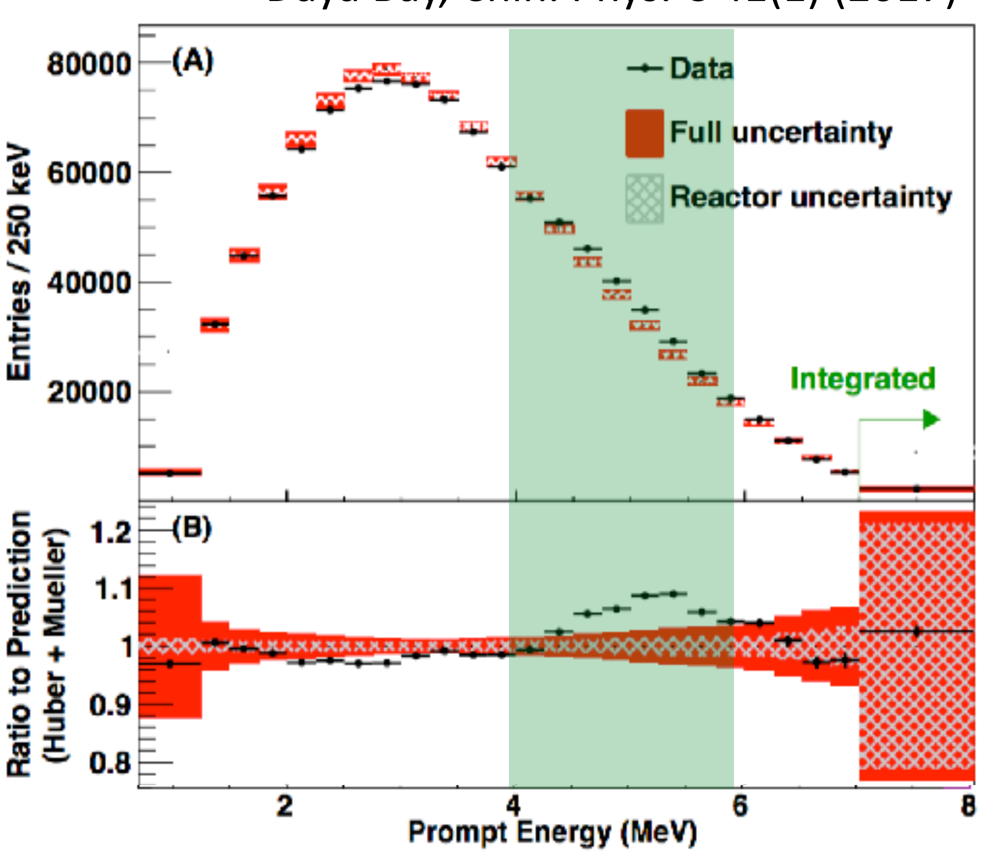


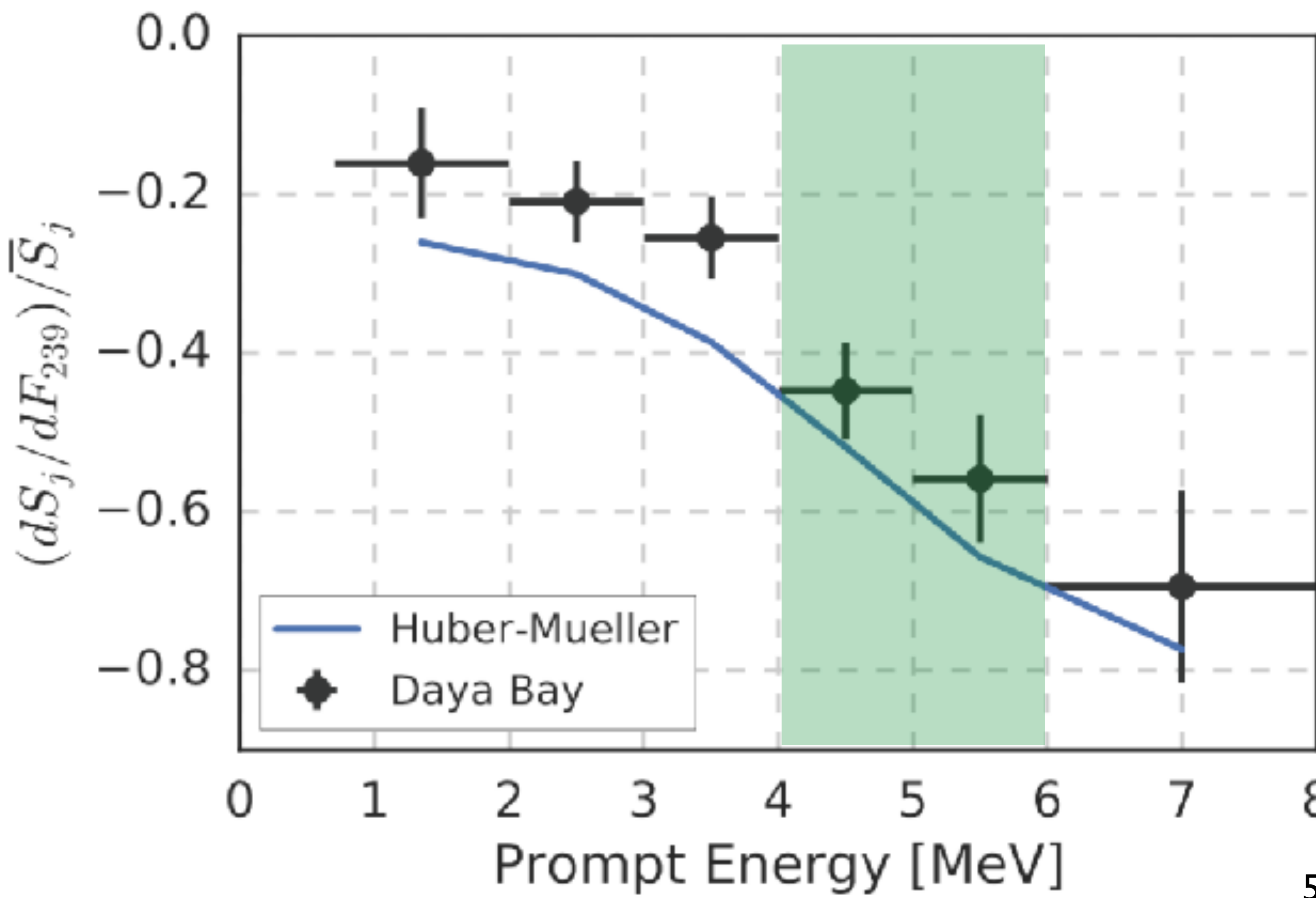


Spectrum Evolution: Data-Model Comparison

- 4-6 MeV region: no strange behavior visible WRT models
  - No major indication that 'bump' data-model discrepancy comes from a particular isotope.
  - HEU experiments will be crucial to test the isotopic origin of this feature.

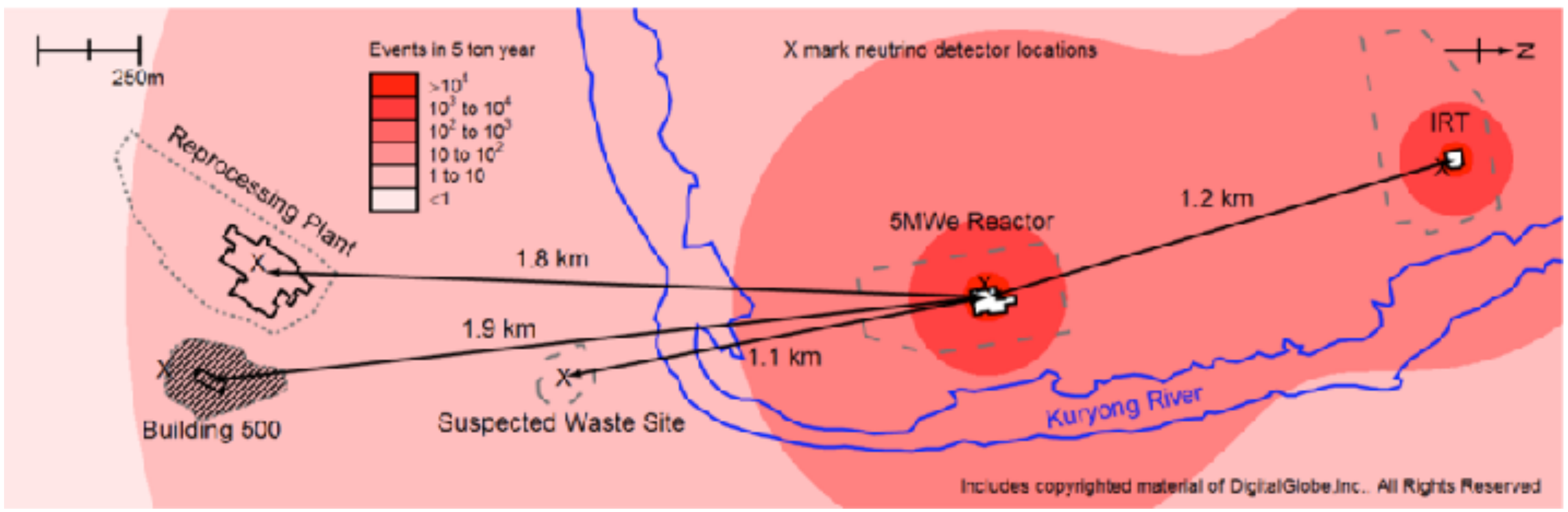
Daya Bay, Chin. Phys. C 41(1) (2017)

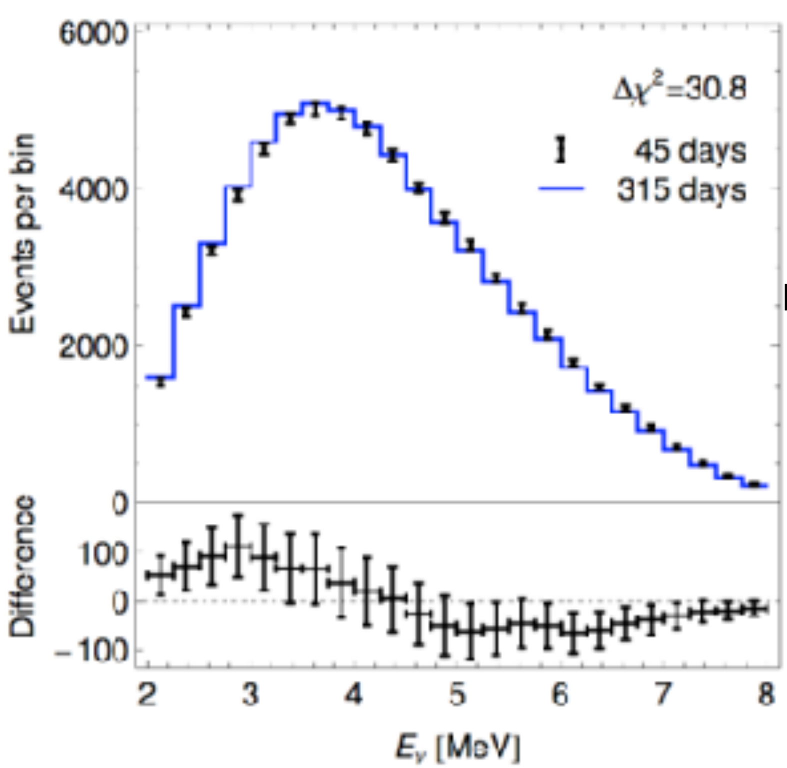


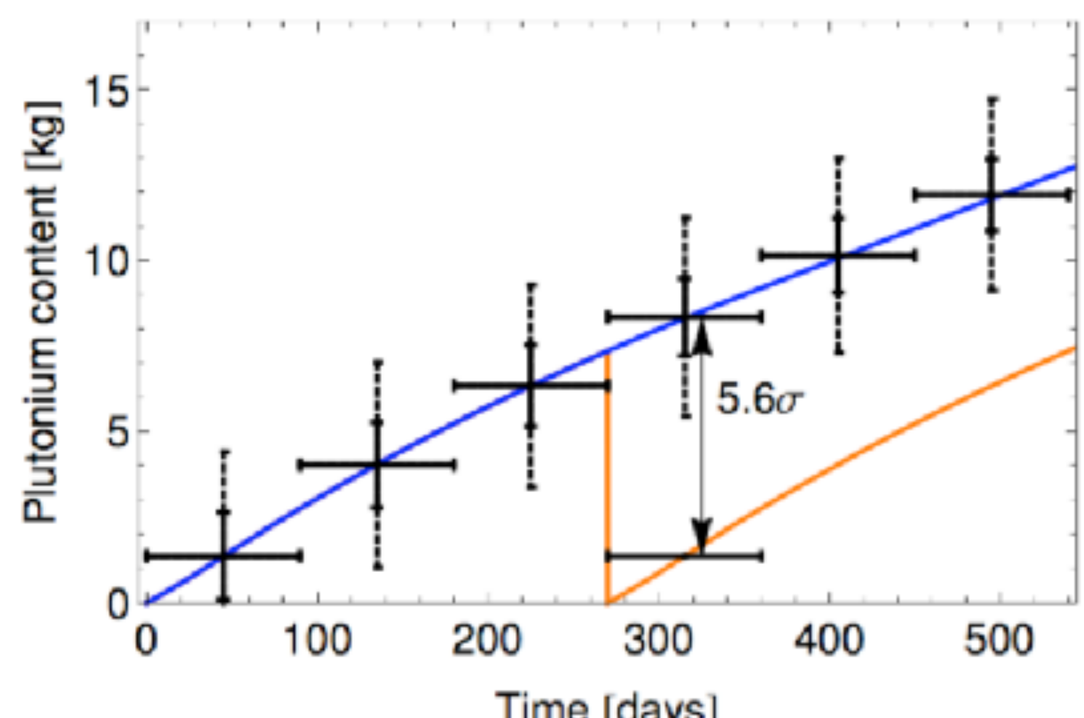


Result: Spectrum Evolution

- Note: An experimental demonstration of reactor monitoring
  - Theory-based case-studies of Iranian, North Korean nuclear reactors: arXiv[1403.7065], arXiv[1312.1959]
  - Unambiguous monitoring of reactor's ^{239}Pu content utilizing a reactor's antineutrino spectrum

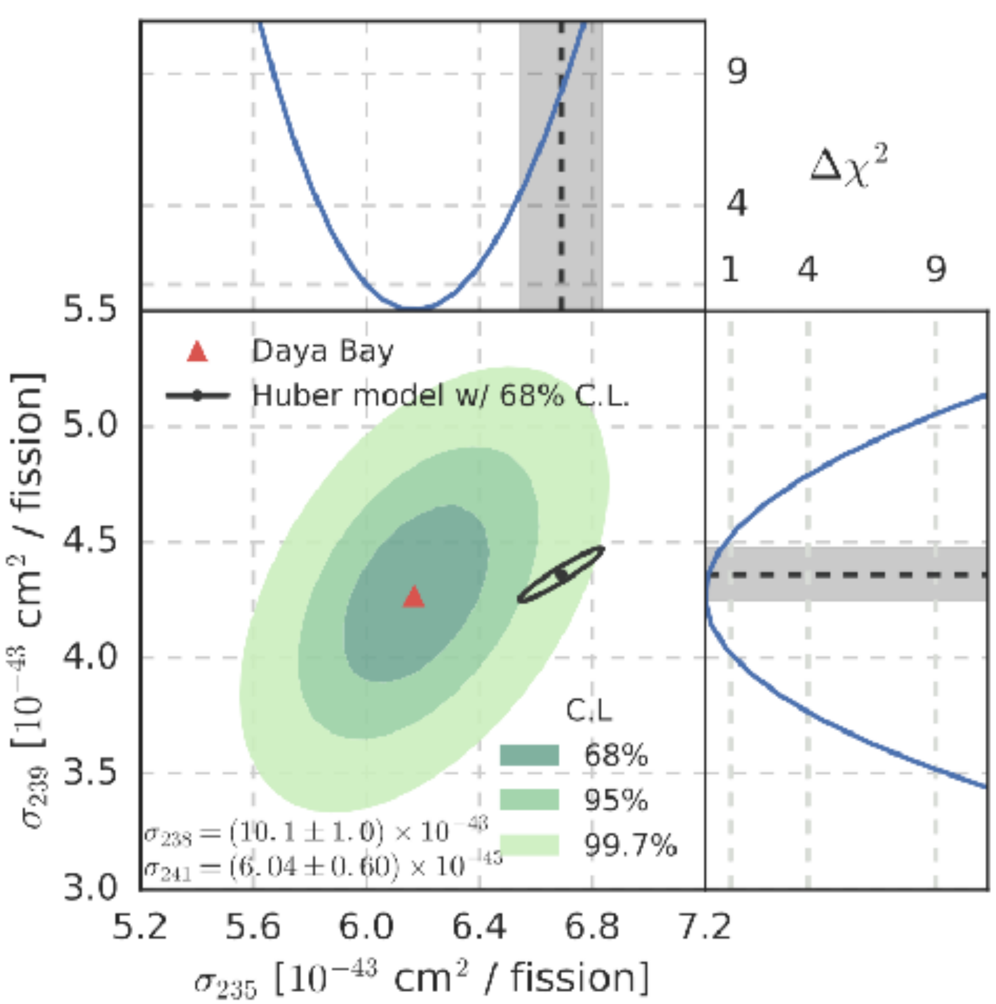


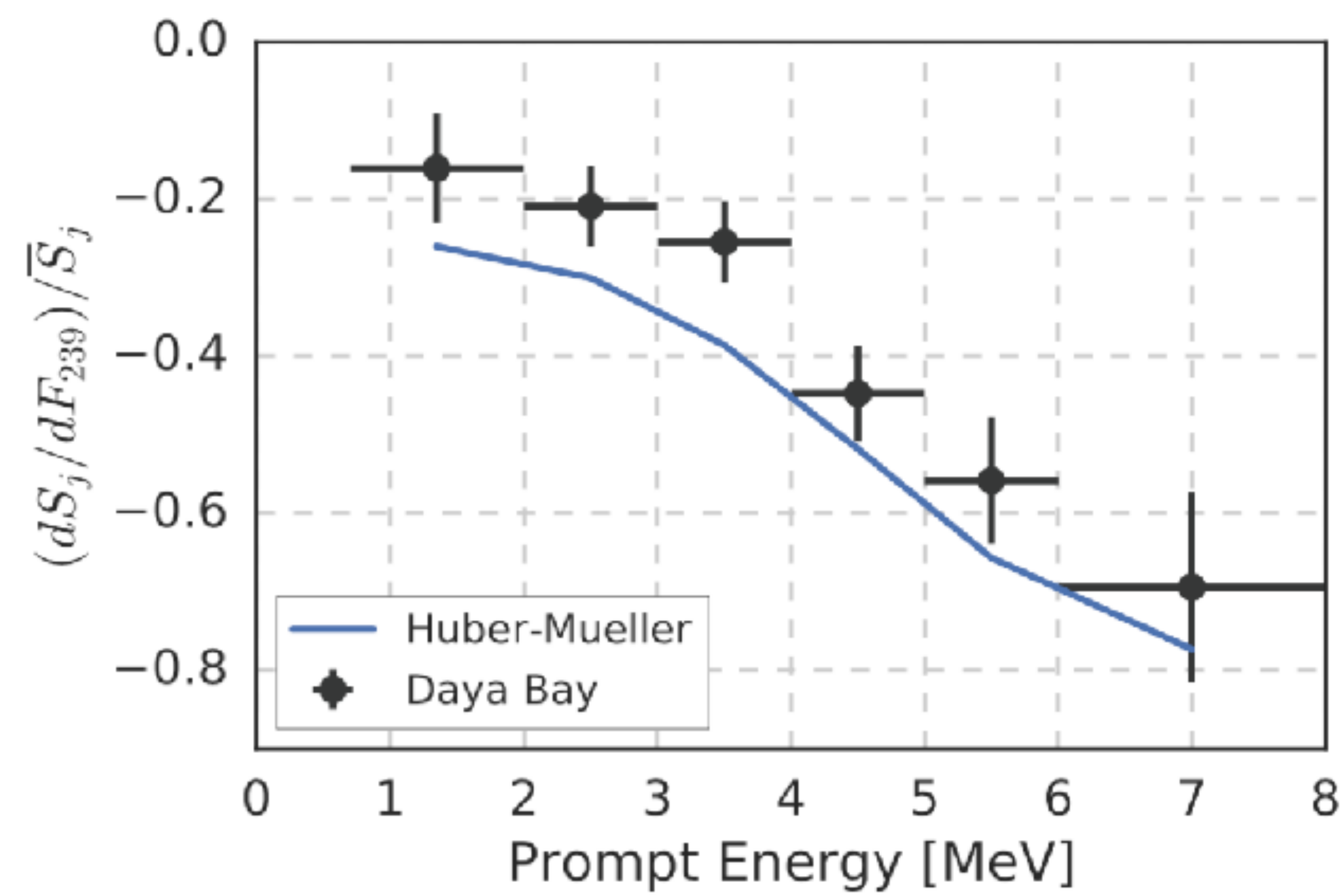




Recap; Future Improvements

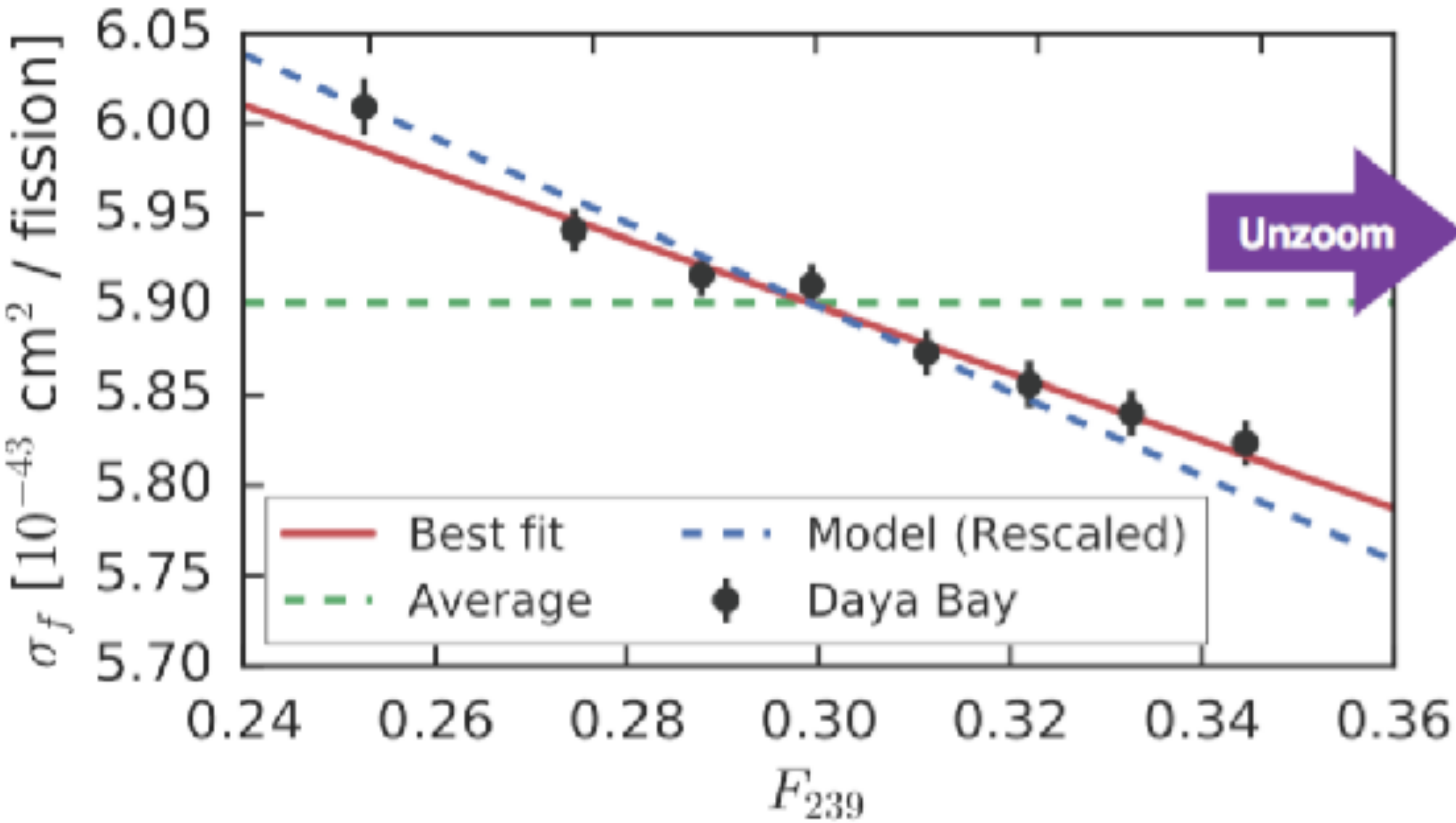
- Daya Bay observes evolution of both the IBD flux and spectrum
- Spectrum evolution matches prediction fairly well.
- Flux evolution does not match predictions
  - Combined w/ integrated flux deficit, result suggests ^{235}U prediction is too high
- How do we improve our certainty in these statements?

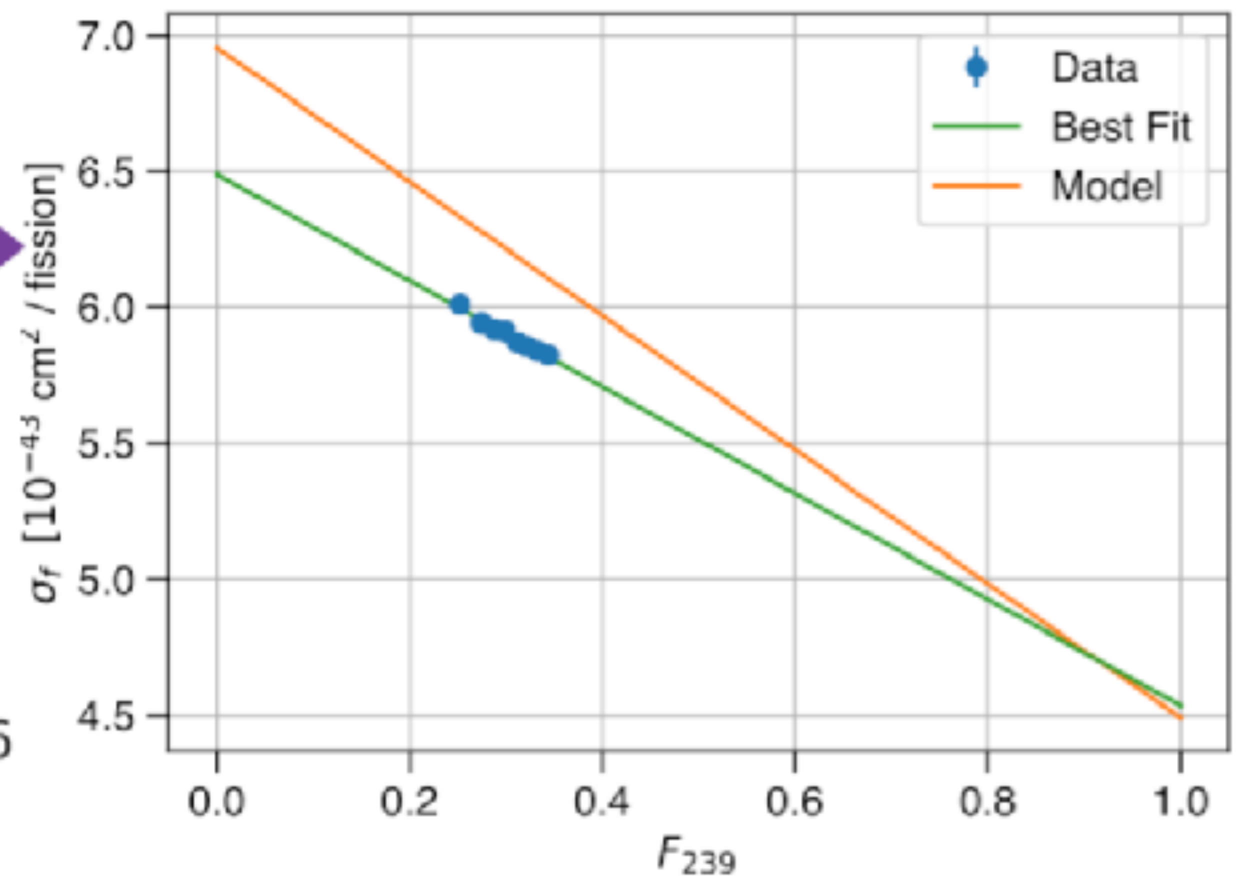




Future: New HEU Measurements

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





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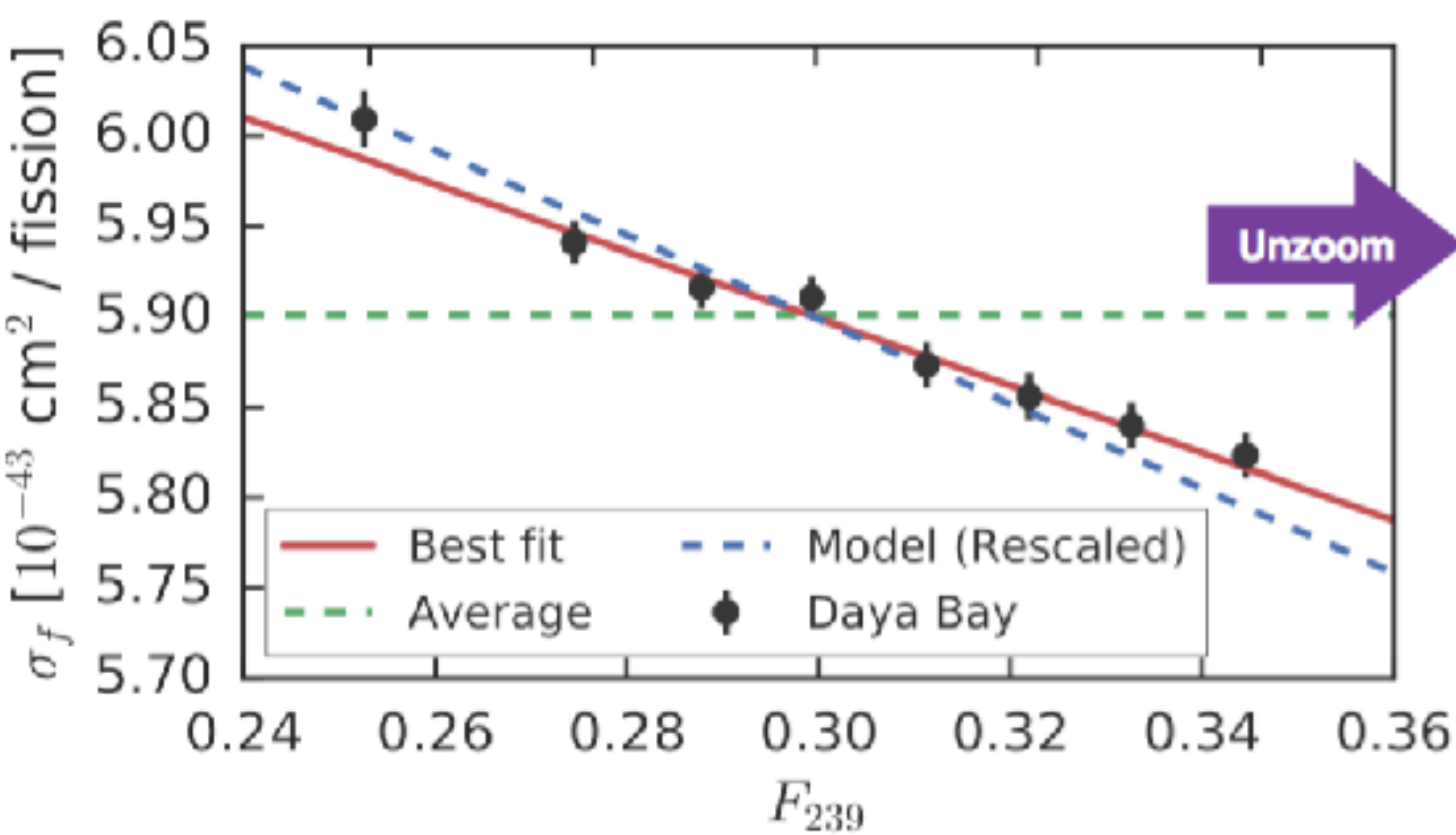
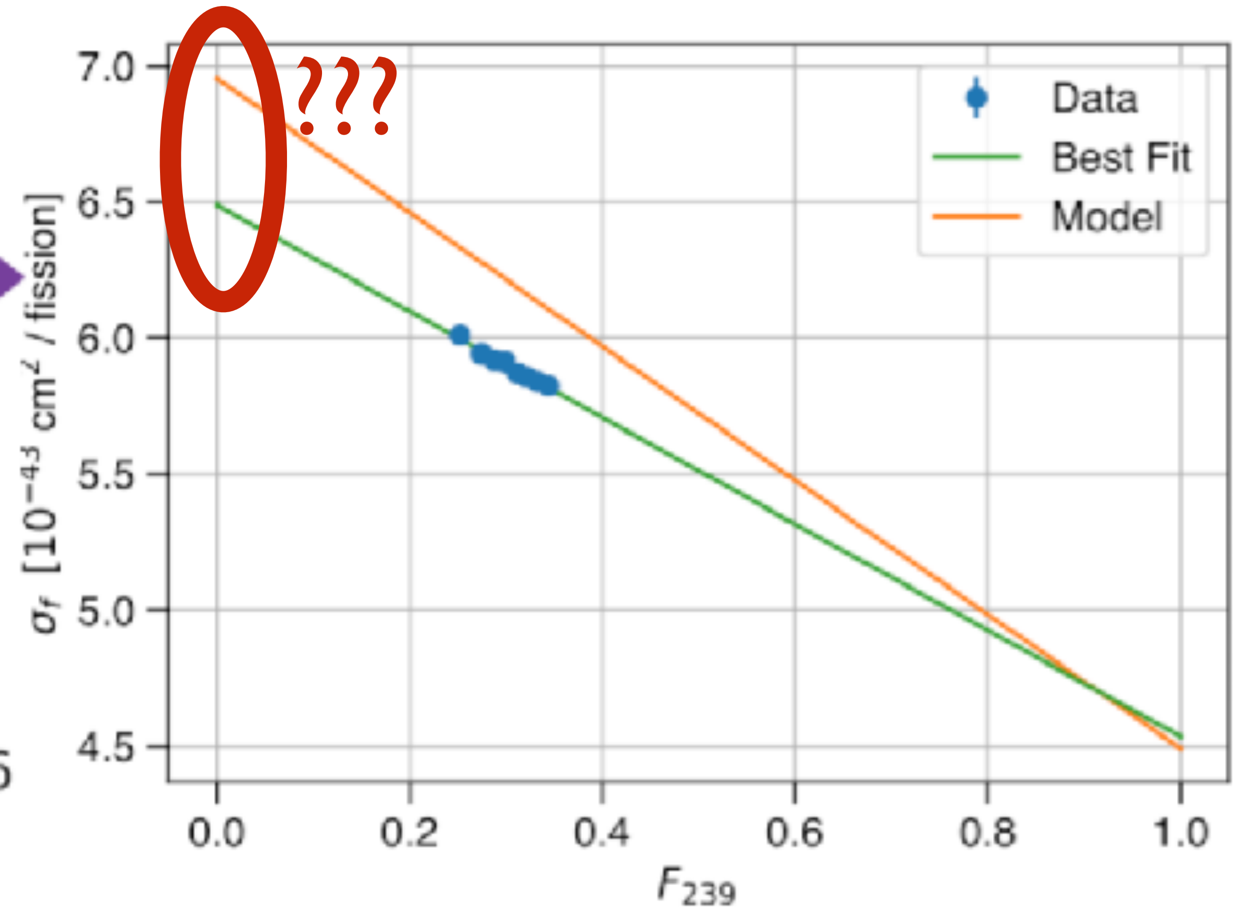


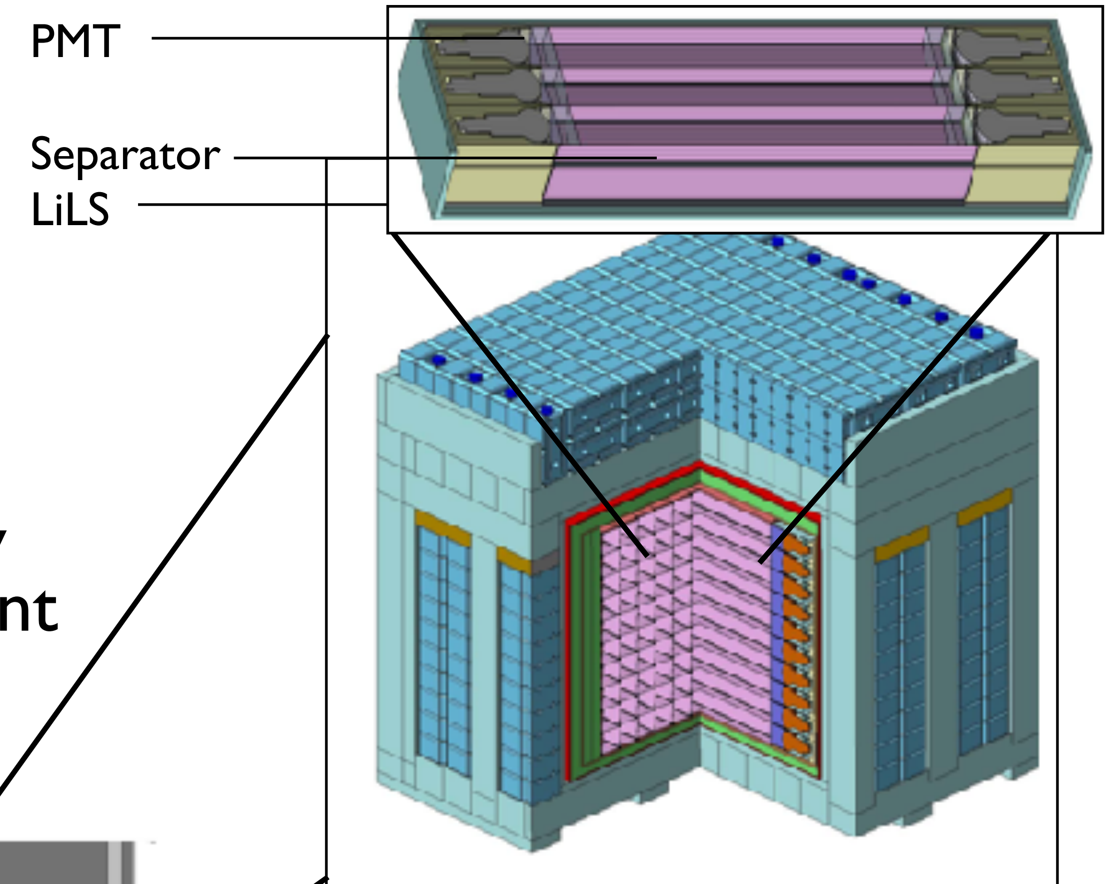


- How about 100% U235, instead of ~50-60%?
  - If ^{235}U is to blame, antineutrino flux deficit should be even larger here
- Enter PROSPECT: at highly-enriched ^{235}U HFIR reactor in Oak Ridge, Tennessee

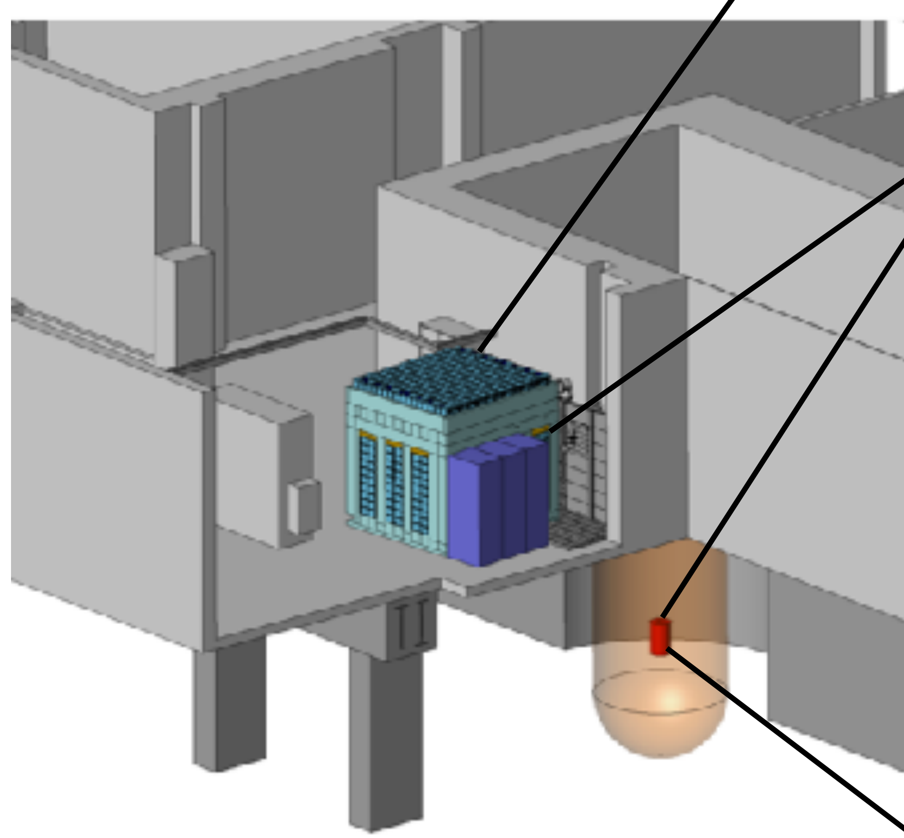
PROSPECT Experimental Layout

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

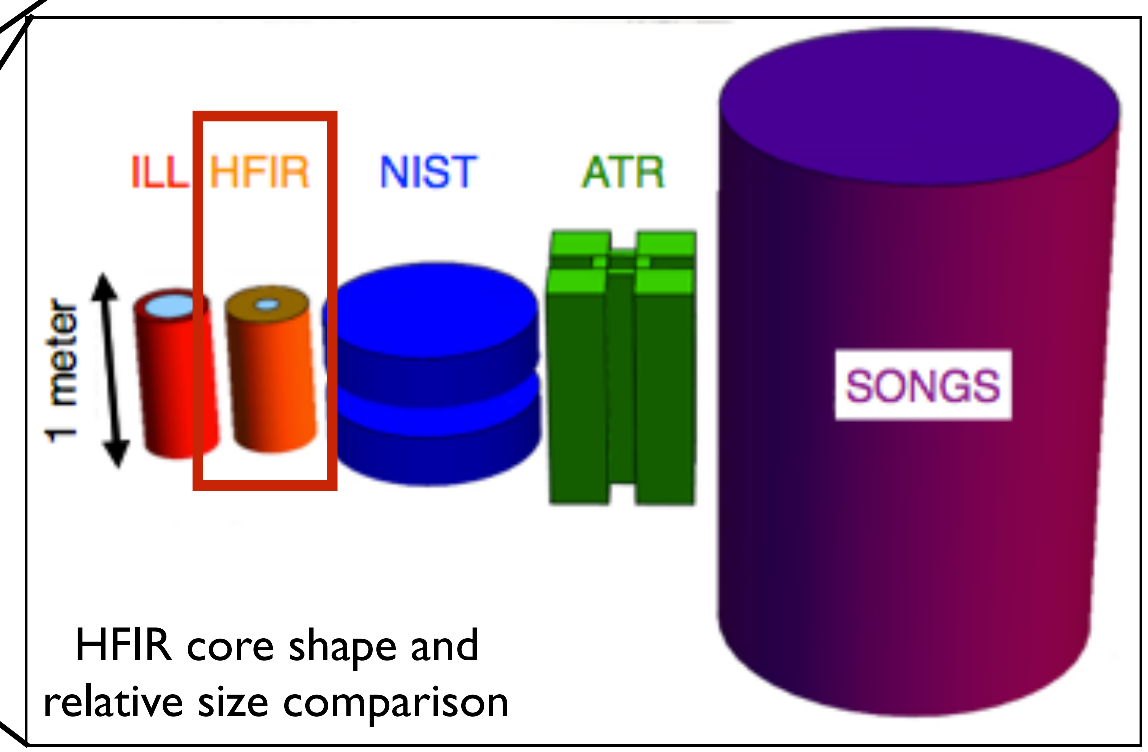
Sub-cell conceptual design



Near detector conceptual design



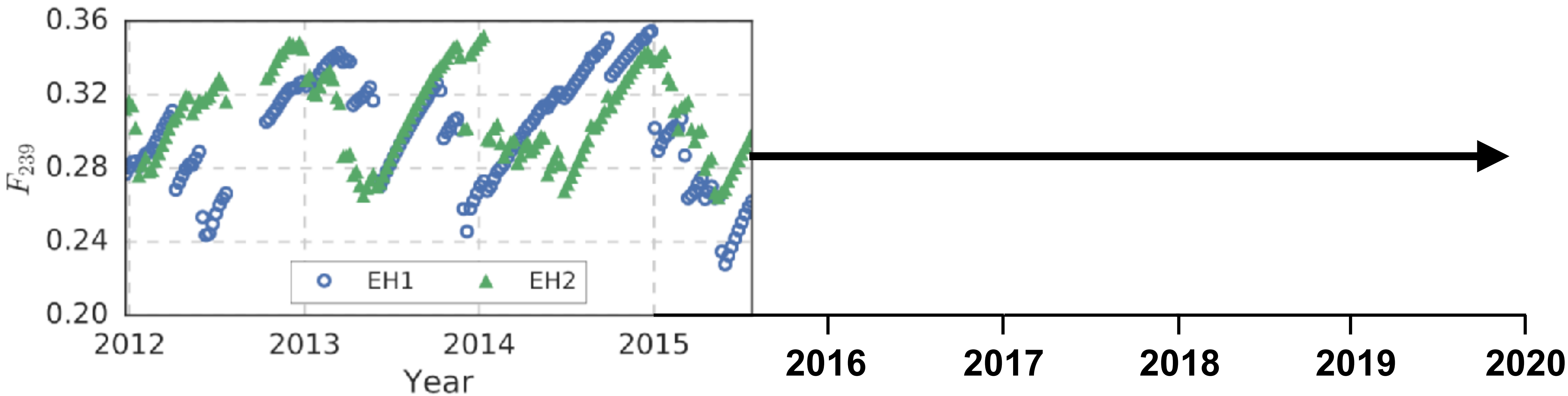
PROSPECT deployment at HFIR



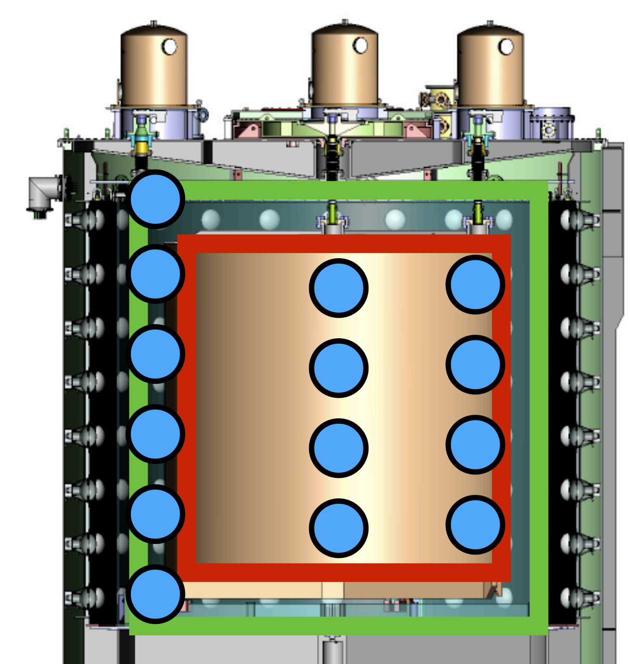
HFIR core shape and relative size comparison

Future: New Daya Bay Data

- One issue with current measurement: statistics limitation
  - Good news: ~3.5 years of data down; 4.5 years of data to go



- Current result uses ~half of available target
  - IBD selection looking for **nH** + **nGd** will increase statistics a factor of ~1.6
- Special neutron calibration campaign can improve detection efficiency estimates, measurement of σ_{235} and σ_{239}



Summary

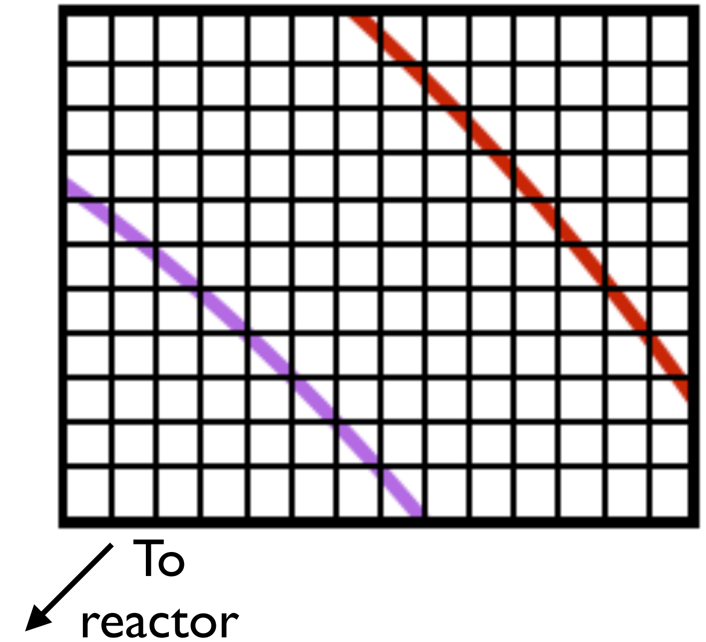
- We have a variety of reasons to distrust reactor $\overline{\nu}_e$ models:
  - "The Reactor Antineutrino Anomaly"
  - "The Bump"
- New Daya Bay results uncover <u>another</u> flaw: flux's evolution is incorrectly predicted
  - Indicates that flux predictions are at least partially responsible for the reactor antineutrino anomaly
- Upcoming measurements will further clarify this picture
  - SBL reactor measurements at HEU cores are essential for probing the nature of the spectral anomaly and making model-independent tests of sterile neutrinos
  - Future Daya Bay statistical and systematics improvements can enhance the analysis shown today.

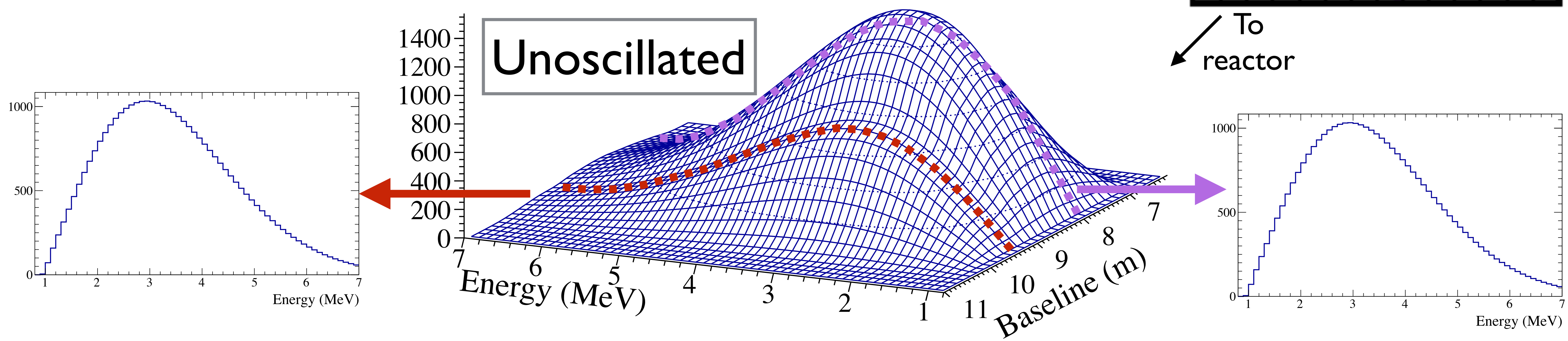
Thanks!

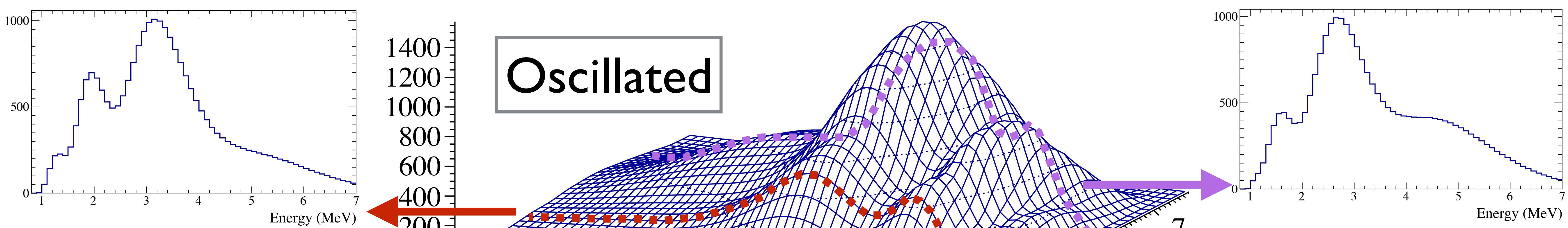
One Detector, Many Baselines For Oscillation

- Purely relative oscillation search between baselines within a single detector
- Position resolution provided by segmentation primarily enables this capability
  - Think: measurement with 100+ nearly identical detectors

PROSPECT cross-section



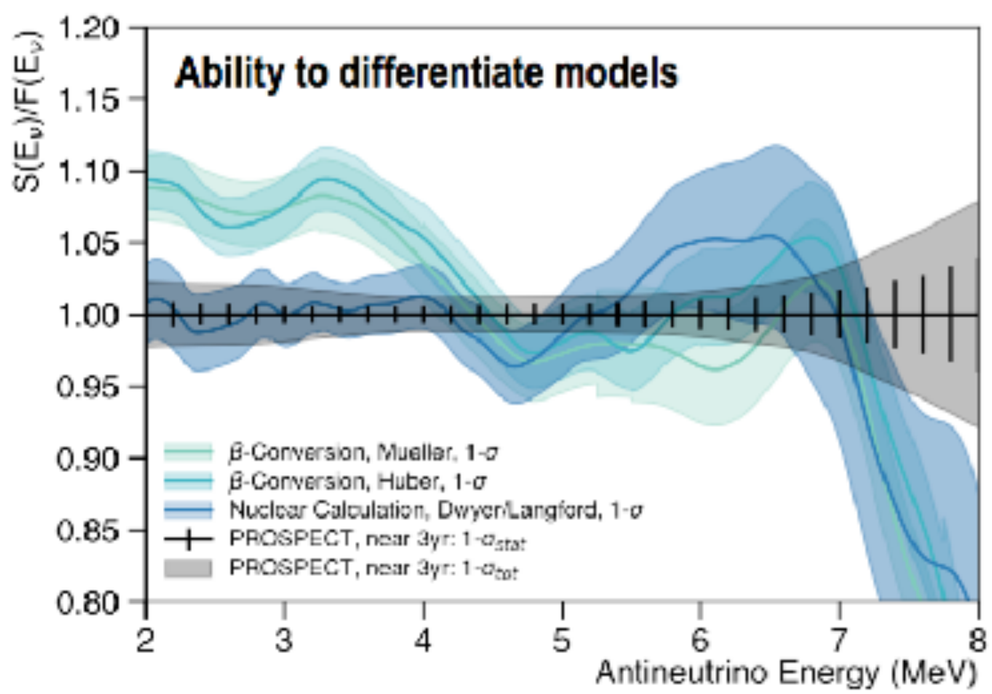


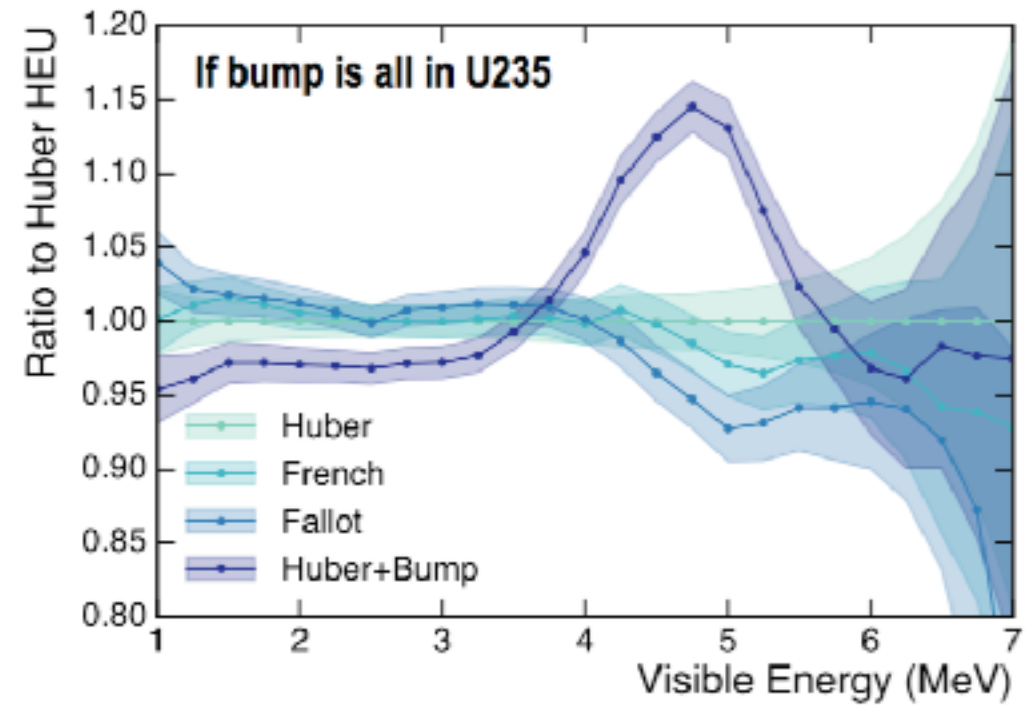


Exp. Parameters:
HFIR 1year, 3ton target
30% Eff, 5% E-res

Osc Parameters:
$\Delta m^2 = 3.5$ eV^2
$\sin^2\theta_{14} = 0.5$

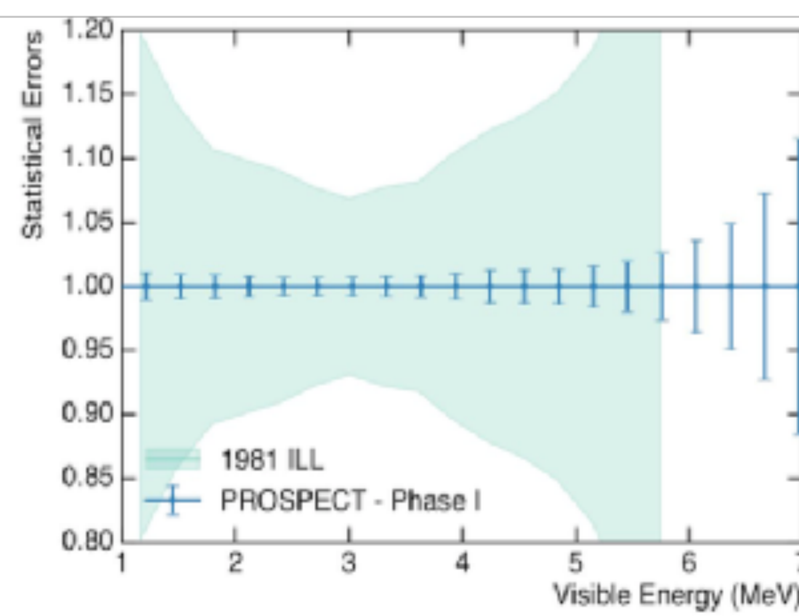
Absolute ^{235}U Spectrum Measurement





With ~160k IBD events per year, PROSPECT precision will surpass model uncertainties

- will be able to directly test various calculations
- HEU/LEU complementarily may provide information on the source of the 'bump'
- provide benchmark spectrum for future HEU reactor experiments

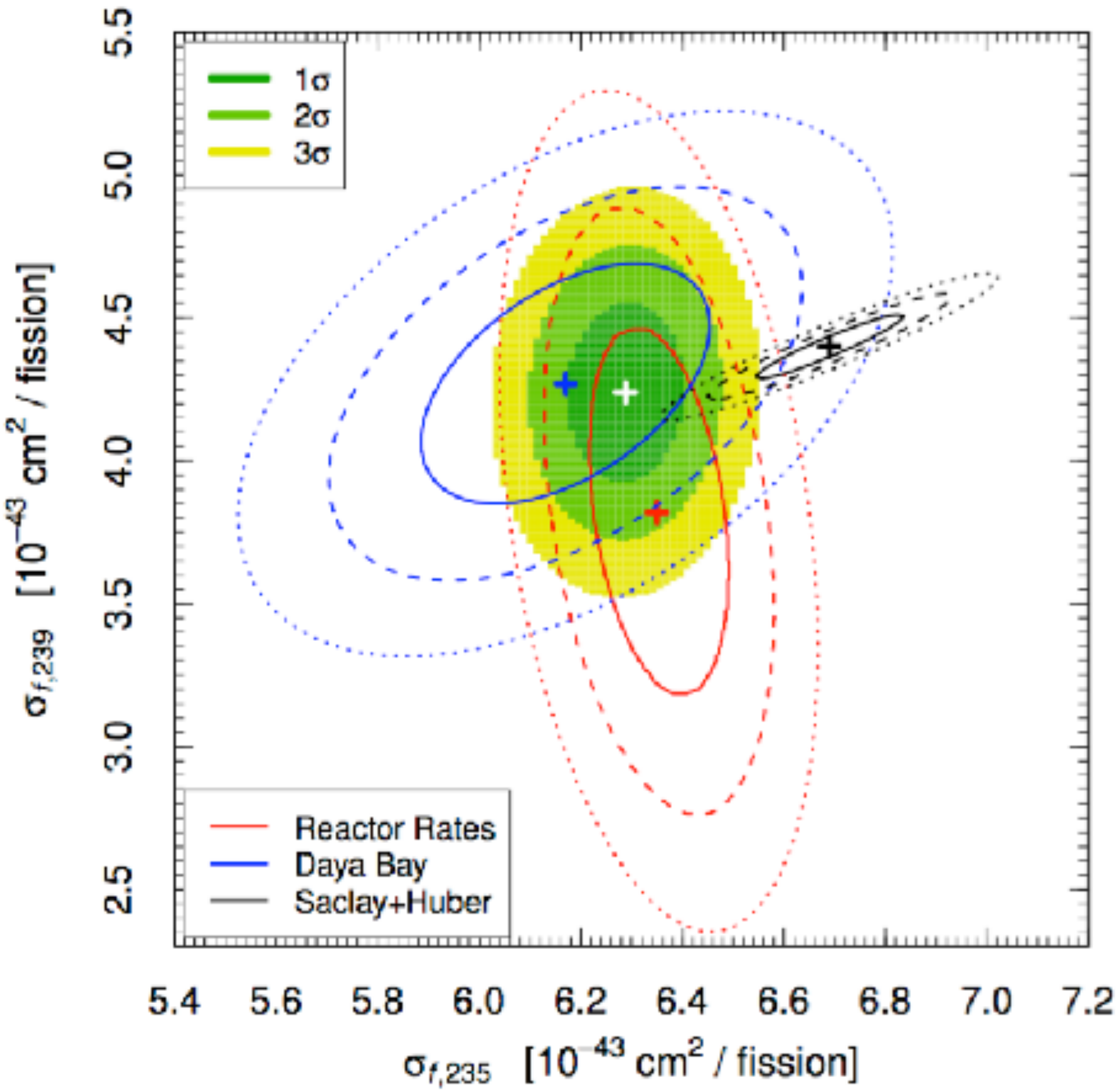


Statistical uncertainty of PROSPECT compared with the former spectrum by ILL , ***Arxiv: 1512.02202***

Global Fits: Input Data

a	Experiment	f^a_{235}	f^a_{238}	f^a_{239}	f^a_{241}	$R^{\text{exp}}_{a,\text{SH}}$	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	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	2.2	18
6	Rovno88-2S	0.557	0.076	0.313	0.054	0.949	7.3	3.8	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		15
9	Bugey-3-40	0.538	0.078	0.328	0.056	0.942	4.3	4.0	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		37.9
12	Gosgen-46	0.584	0.068	0.298	0.050	0.981	5.4	2.0	45.9
13	Gosgen-65	0.543	0.070	0.329	0.058	0.915	6.7	3.8	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

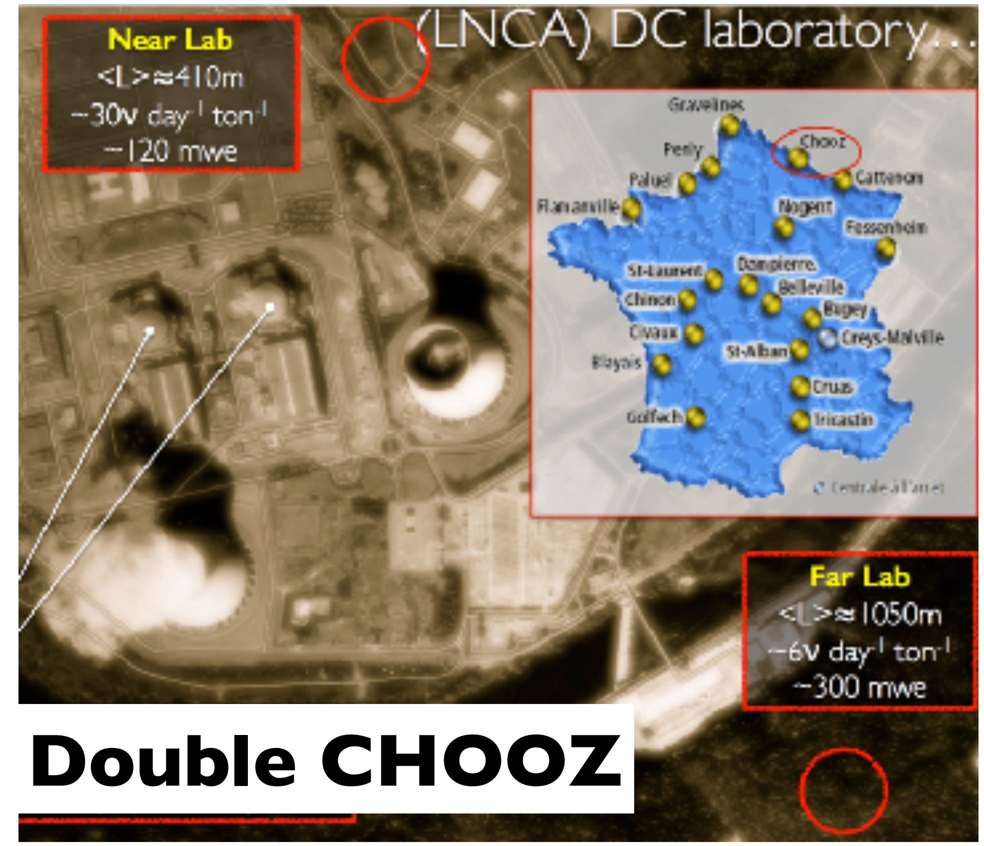


	SH	Reactor Rates	Daya Bay	Combined
$\sigma_{f,235}$	6.69 ± 0.14	6.35 ± 0.09	6.17 ± 0.17	6.29 ± 0.08
$\sigma_{f,239}$	4.40 ± 0.11	3.82 ± 0.43	4.27 ± 0.26	4.24 ± 0.21

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)



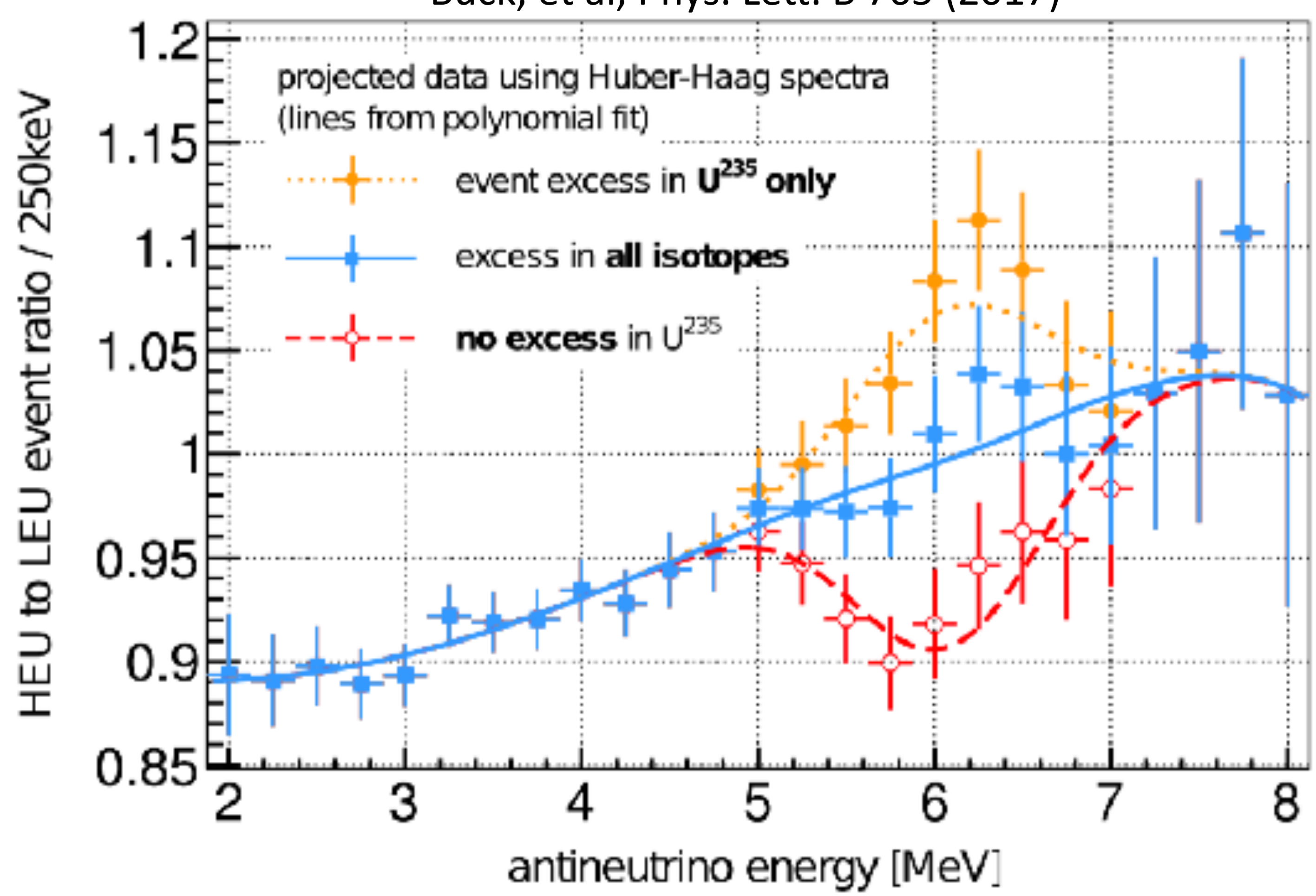
- RENO
  - Similar core-sampling for RENO, DYB
  - Con: only 1 (smaller) near detector: 16 tons; ~650 IBD/day (DYB: 80 tons)

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

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

- HEU reactors burn <u>only</u> ^{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)

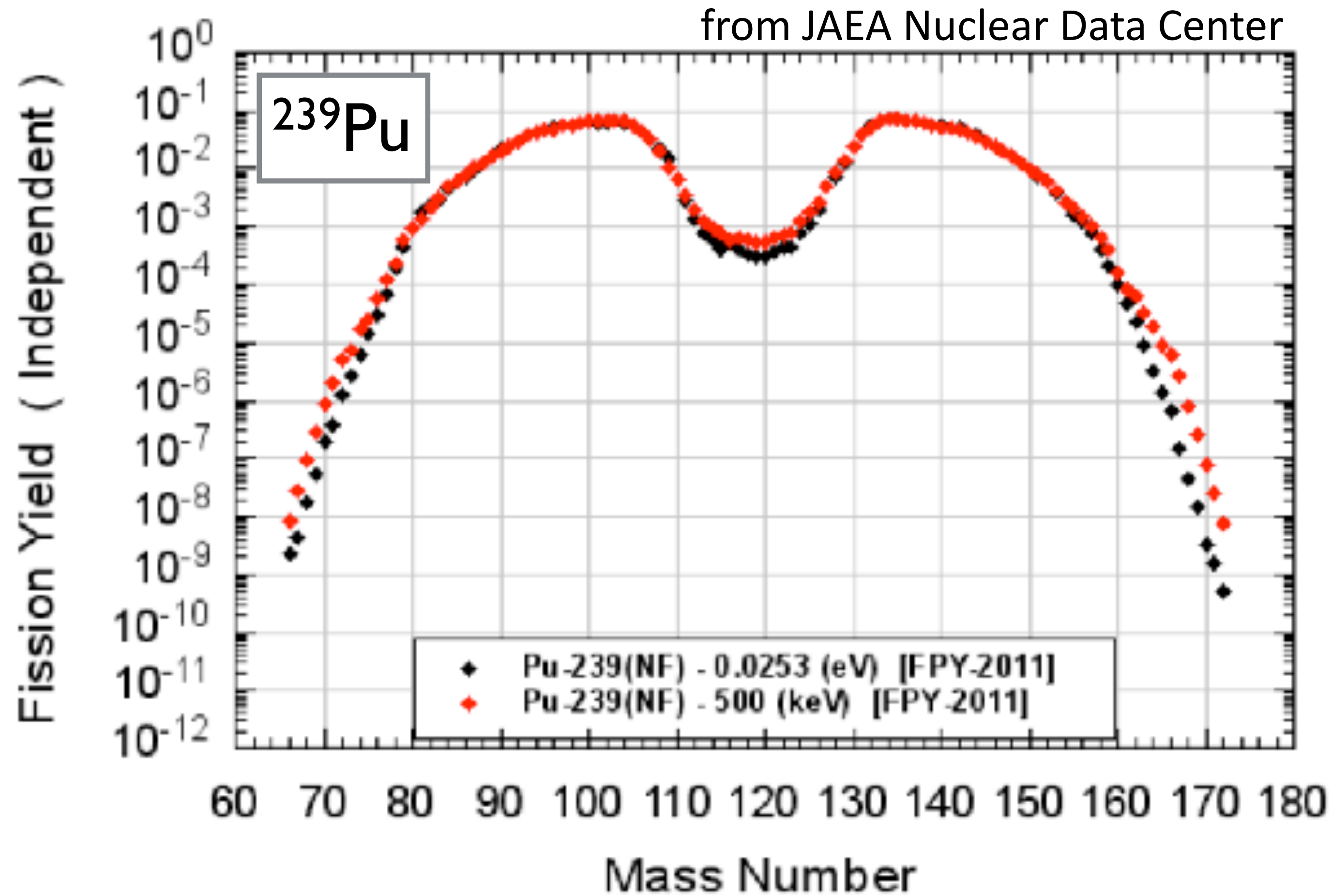


Example: hypothetical STEREO-Double Chooz spectral ratio

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…)

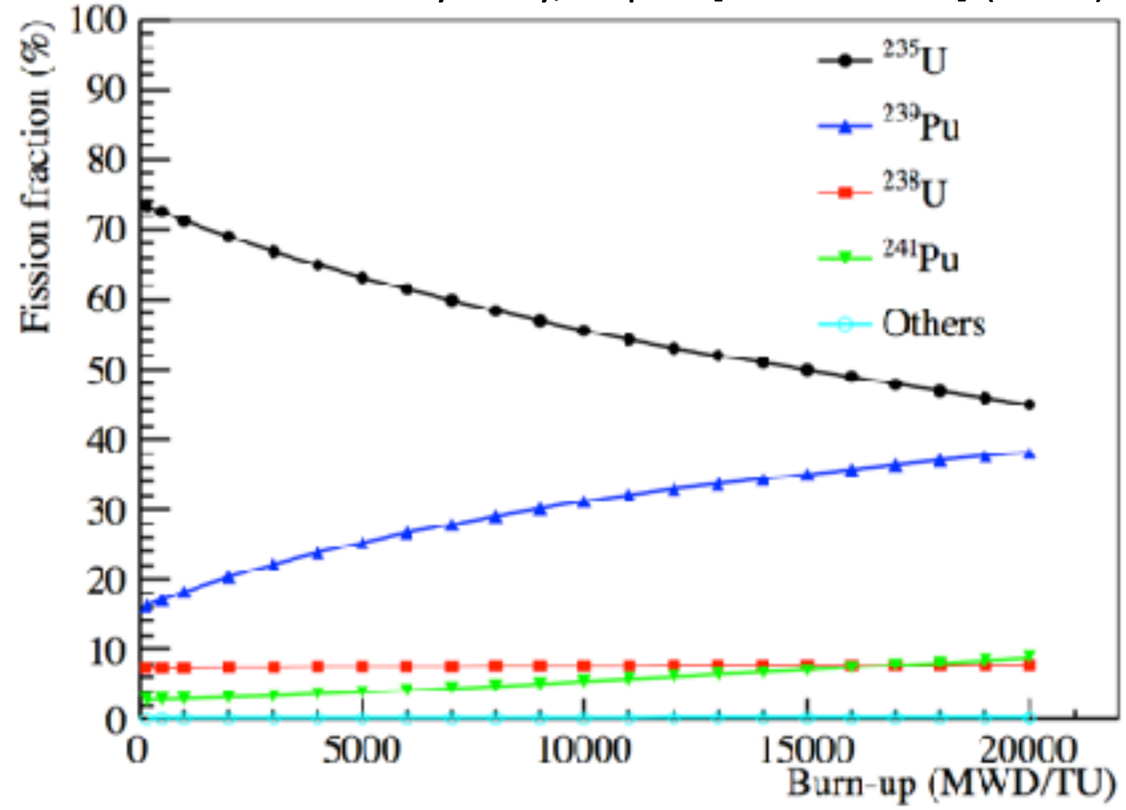
from JAEA Nuclear Data Center



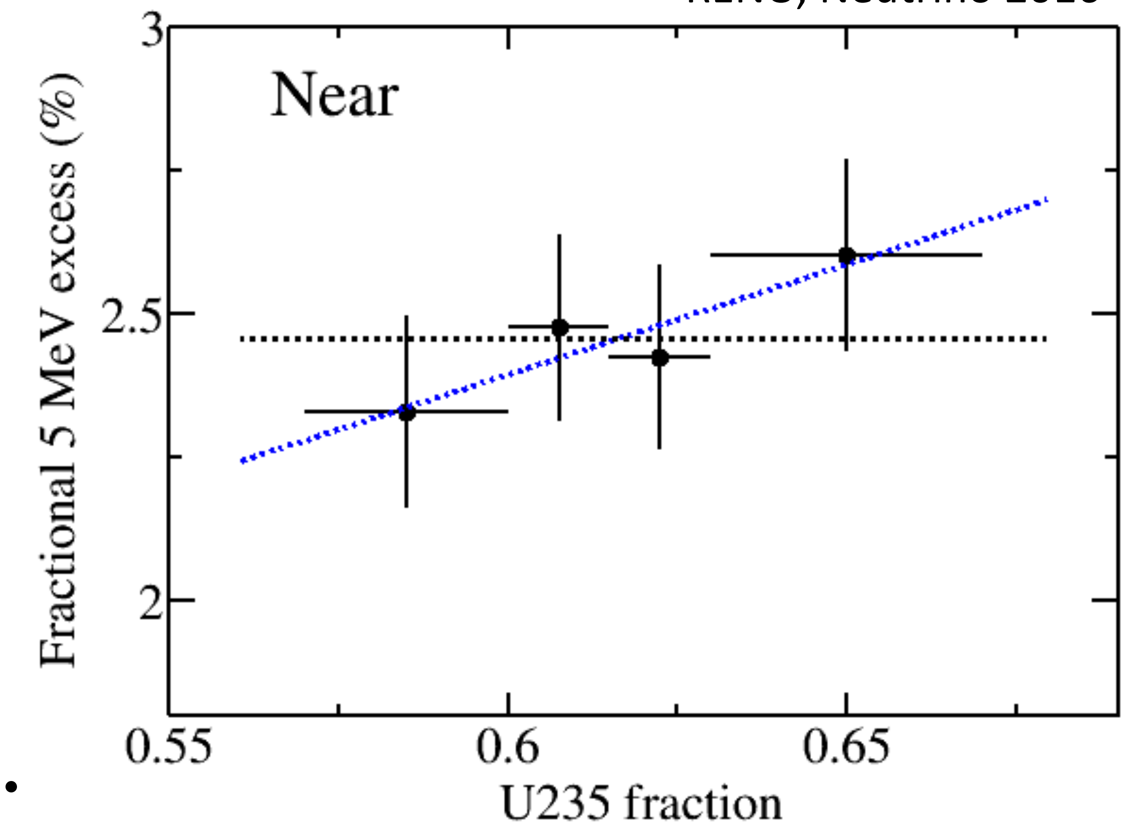
Only ^{239}Pu, or Only ^{235}U?

- 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)

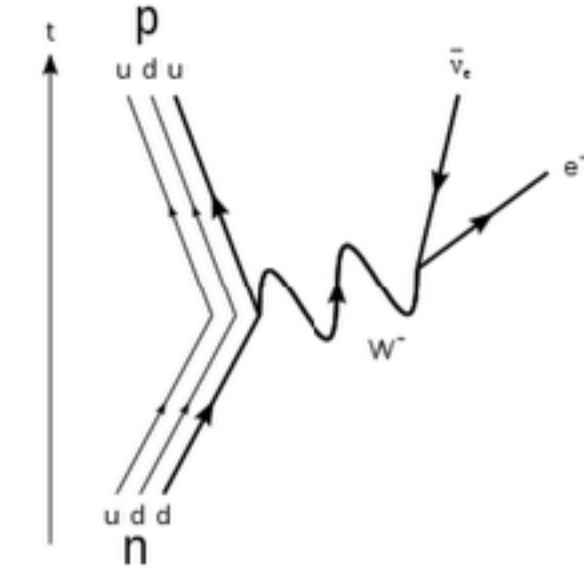


RENO, Neutrino 2016



Beta Decay Recap

- W-mediated weak interaction
- Use Fermi's Golden rule to calculate:



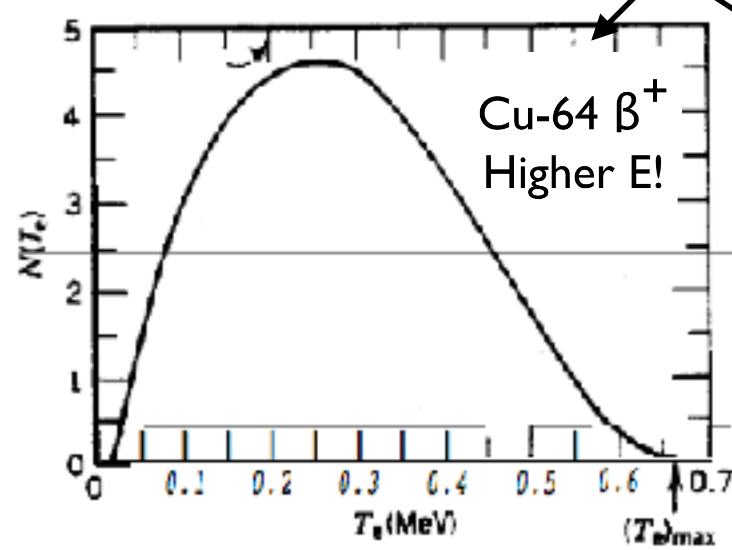
$$N_\beta(W) = K\,\underbrace{p^2(W - W_0)^2}_{\text{phase space}}\,F(Z, W)$$

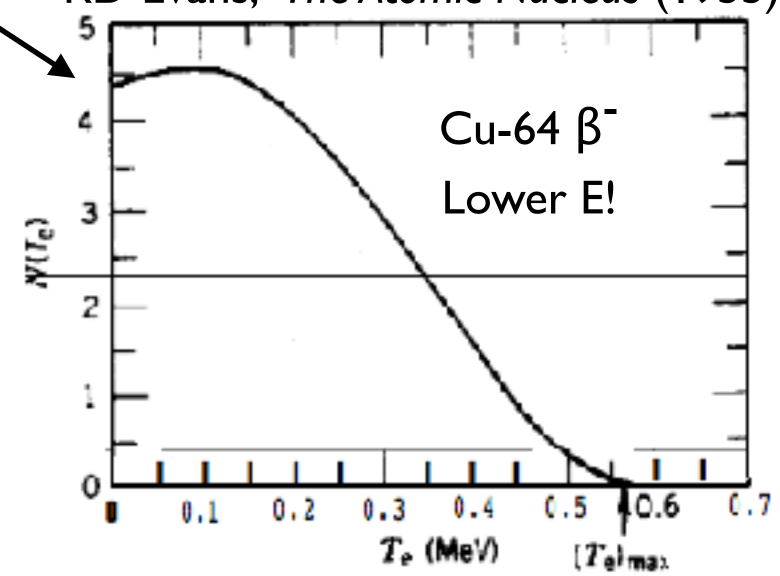
From nuclear matrix element:
Extra factors of p pop
in here for beta decays

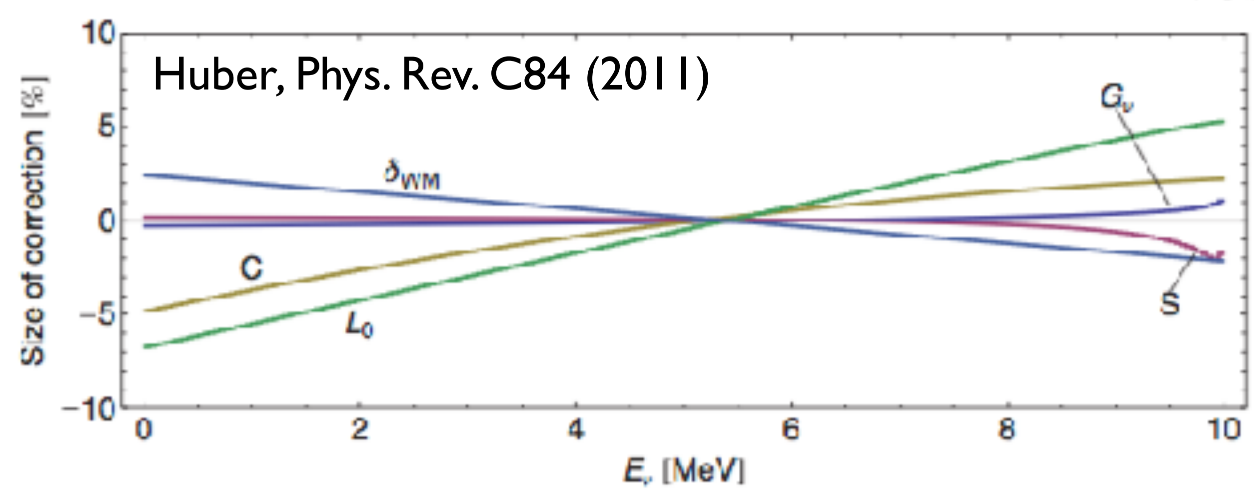
QED correction: semi-classicaly,
positive nucleus attracts
product beta; lowers its energy

- Other corrections:
  - Finite size: C, L_0
  - Electron screening: S
  - Radiative corrections: C
  - Weak magnetism: d_{wm}

RD Evans, *The Atomic Nucleus* (1955)







Forbidden Decay Handling

- W-mediated weak interaction
- Use Fermi's Golden rule to calculate

$$N_\beta(W) = K\,\underbrace{p^2(W - W_0)^2}_{\text{phase space}}\ F(Z, W)$$

From nuclear matrix element:
Extra factors of p pop
in here for beta decays

- Hayes, et. al, PRL 112 (2014): conversion result highly dependent on forbidden-ness of virtual branches
  - Capable of shifting predicted flux downward by 5%
  - Has not been shown what forbidden decay treatment would reproduce both reactor beta and nuebar spectra — but it might be possible to do so

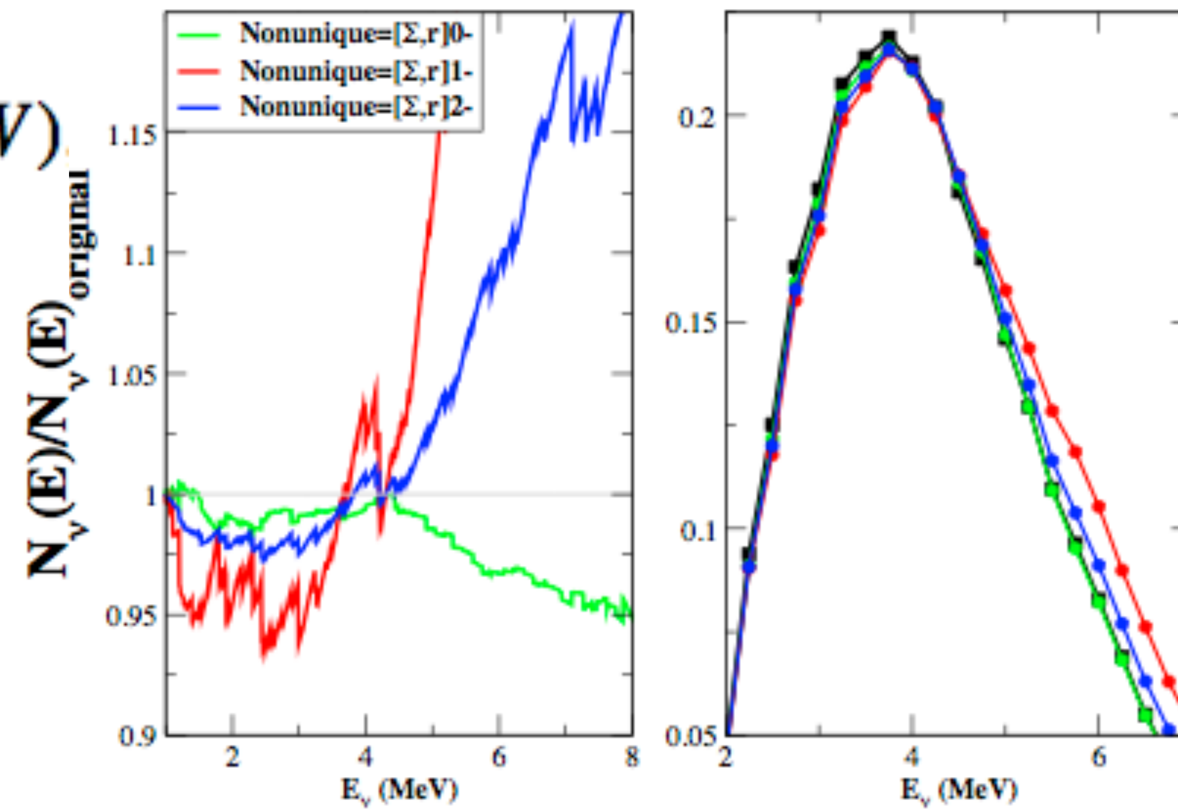
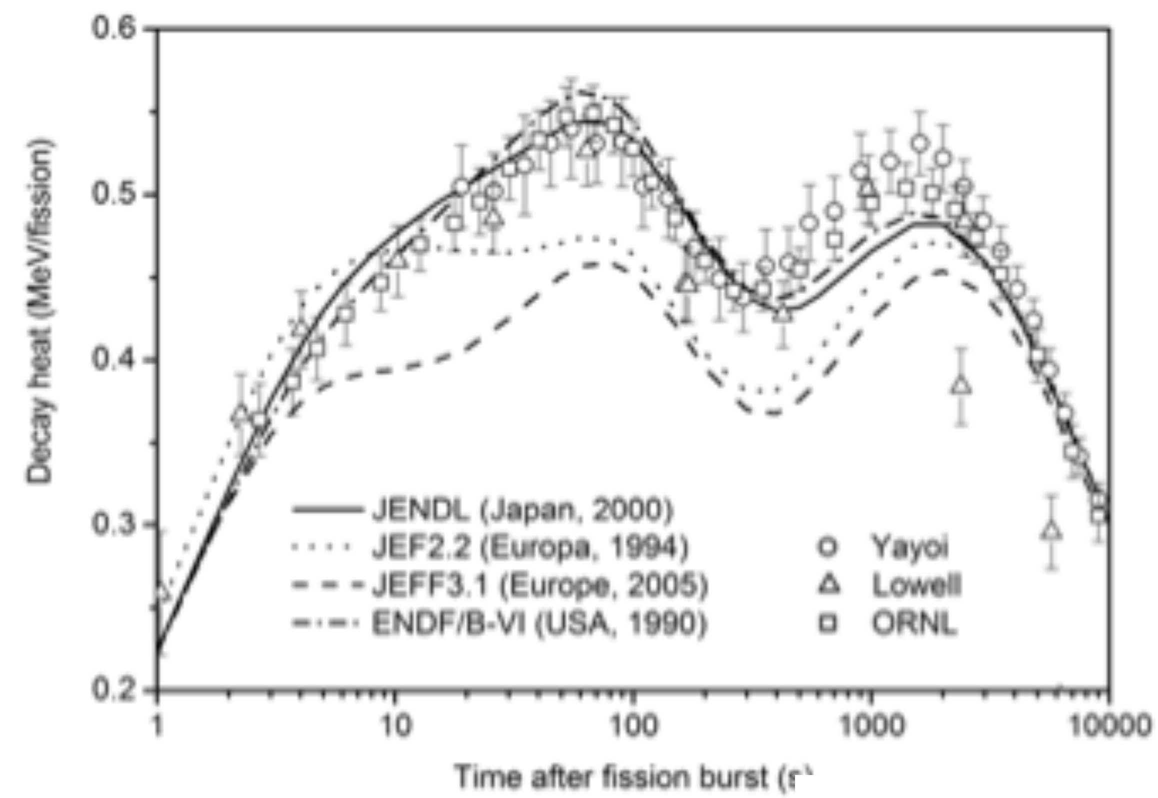


FIG. 3: Different treatments of the forbidden GT transitions contributing to the antineutrino spectrum summed over all actinides in the fission burn in mid-cycle [21] of a typical reactor. The left panel shows the ratio of these antineutrino spectra relative to that using the assumptions of Ref. [4]. The right panel shows the spectra weighted by the detection cross section, where the additional curve in black uses the assumptions of Ref. [4]. The spectra are strongly distorted by the forbidden operators, being lower below the peak and in some cases more than 20% larger above the peak than Ref. [4]. The corresponding change in the number of detectable antineutrinos relative to [4] is -0.75%, 5.8% and 1.85% for the 0^-, 1^-, and 2^- forbidden operators, respectively.

Reactor Spectroscopy: Application

- Why is there more decay heat than predicted 3-3000s after a reactor is turned off???
- Means we need higher cooling safety factors during reactor-off periods: This costs $$$!!!
- Hypothesis: maybe we measured branching fractions of some rare isotopes incorrectly…

Figure 3. Electromagnetic decay heat following thermal fission burst of ^{239}Pu – data from JENDL, JEF-2.2, JEFF-3.1 and ENDF/B-VI are shown together with experimental data from Yayoi, Lowell and Oak Ridge National Laboratory

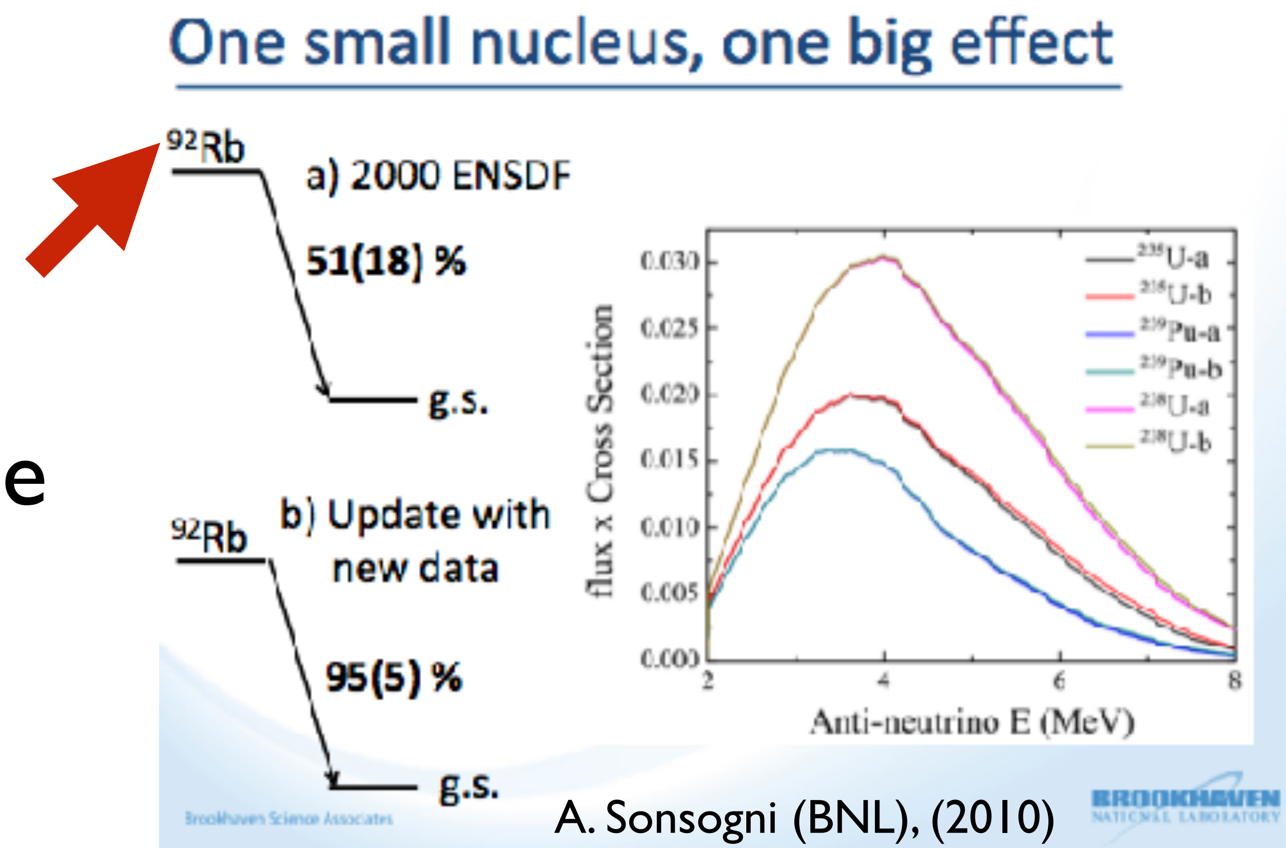


VOLUME 25 Nuclear Science NEA/WPEC-25

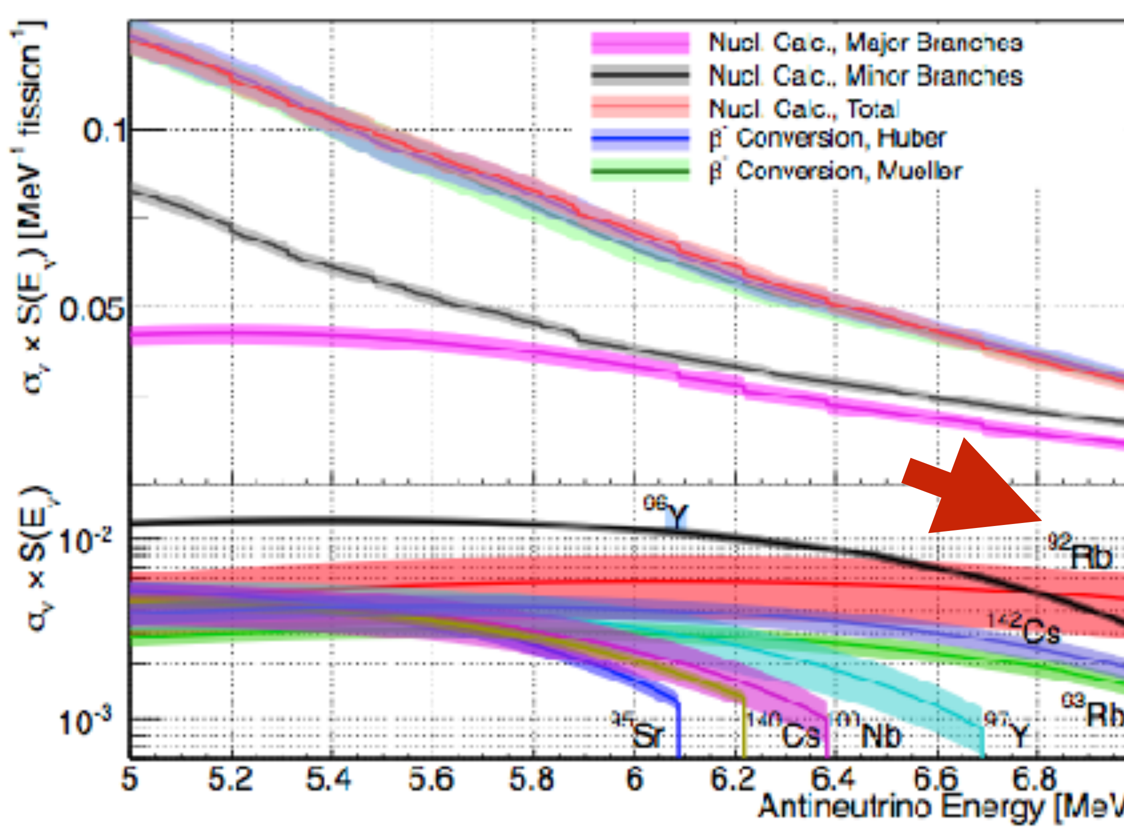
ASSESSMENT OF FISSION PRODUCT DECAY DATA FOR DECAY HEAT CALCULATIONS

Reactor Spectroscopy: Implications

- 5 MeV 'bump' region produced by many isotopes of great concern to this decay heat measurement!
- Two anomalies from the same source?
- Reactor spectroscopy measurements can provide:
  - Direct check on existing TAGS measurements
    - TOTALLY different systematics!
  - NEW data if TAGS has not been done!
  - Isotopes: Rb-92, Sr-97, Cs-142



A. Sonsogni (BNL), (2010)



Skeptical Aside

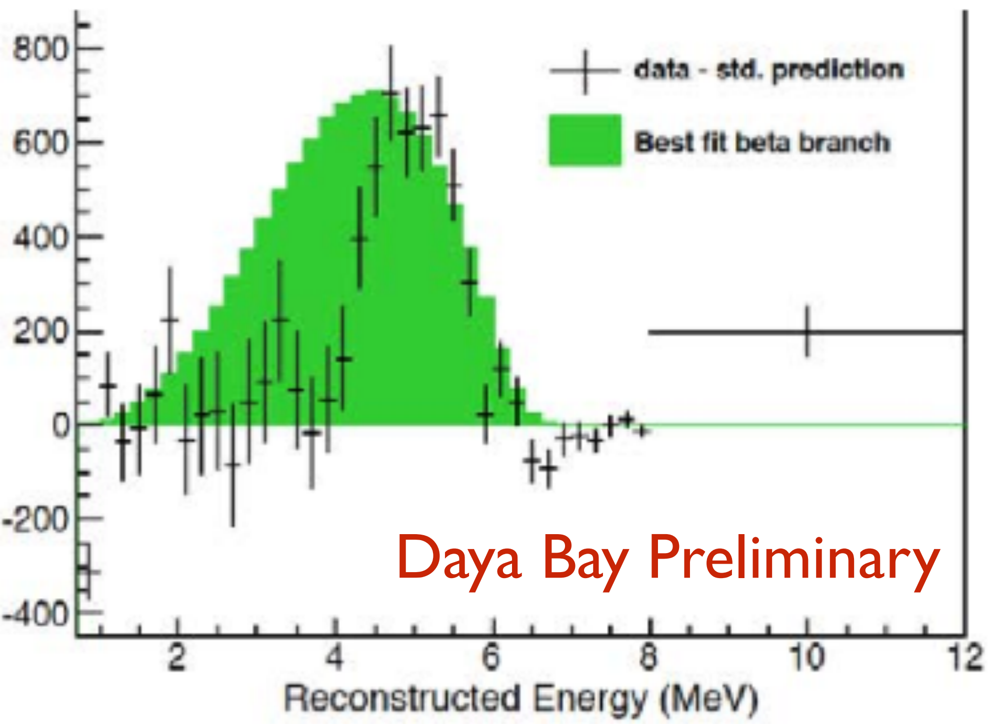
- Before we discuss what might be wrong with spectrum predictions, I forgot to mention one hypothesis:
- Neutrino experimentalists have no idea what they're doing!!!
- For example, what about that spectrum anomaly:
  - 'Is the bump is just a background that hasn't been properly accounted for?'
  - 'Maybe the bump is just an absolute energy scale issue?'
  - 'Is there any other strange behavior in the way this excess pops up in the data?'

???

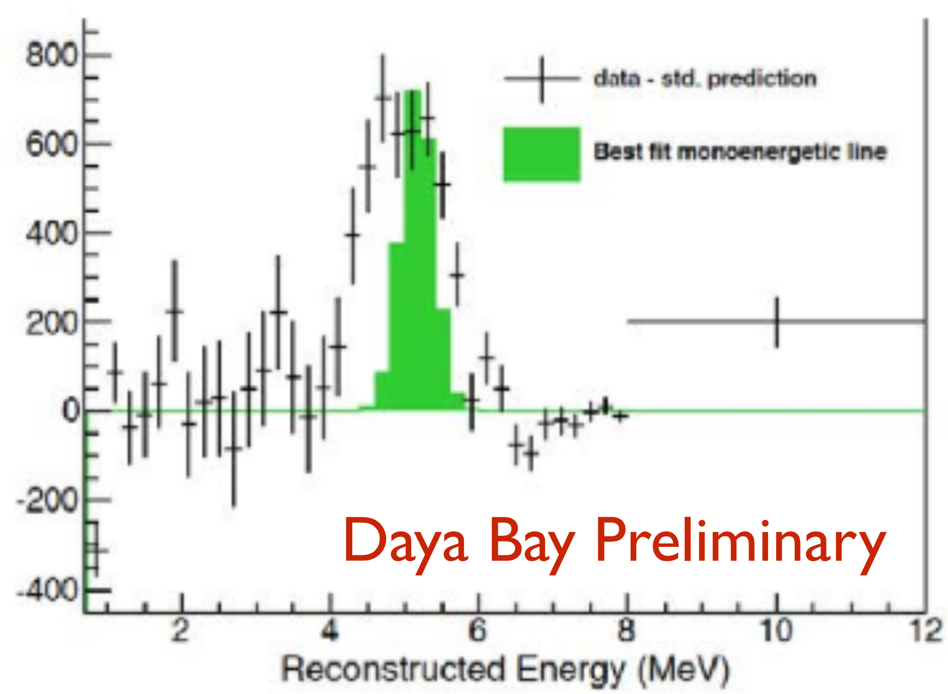
Skeptical Question 1

- 'Maybe it's just a background that hasn't been accounted for.'

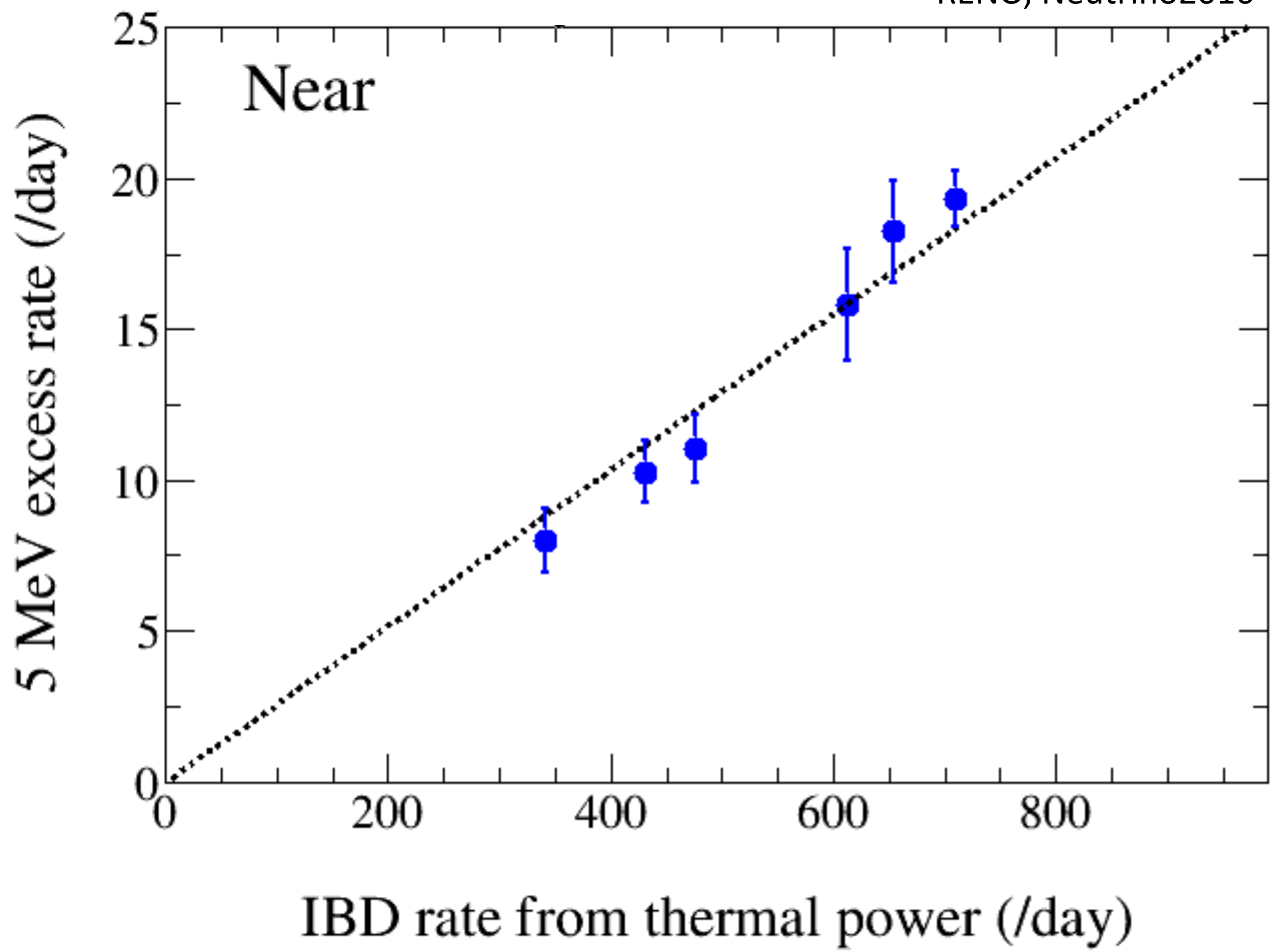
Not a beta-branch



Not a delta function



RENO, Neutrino2016

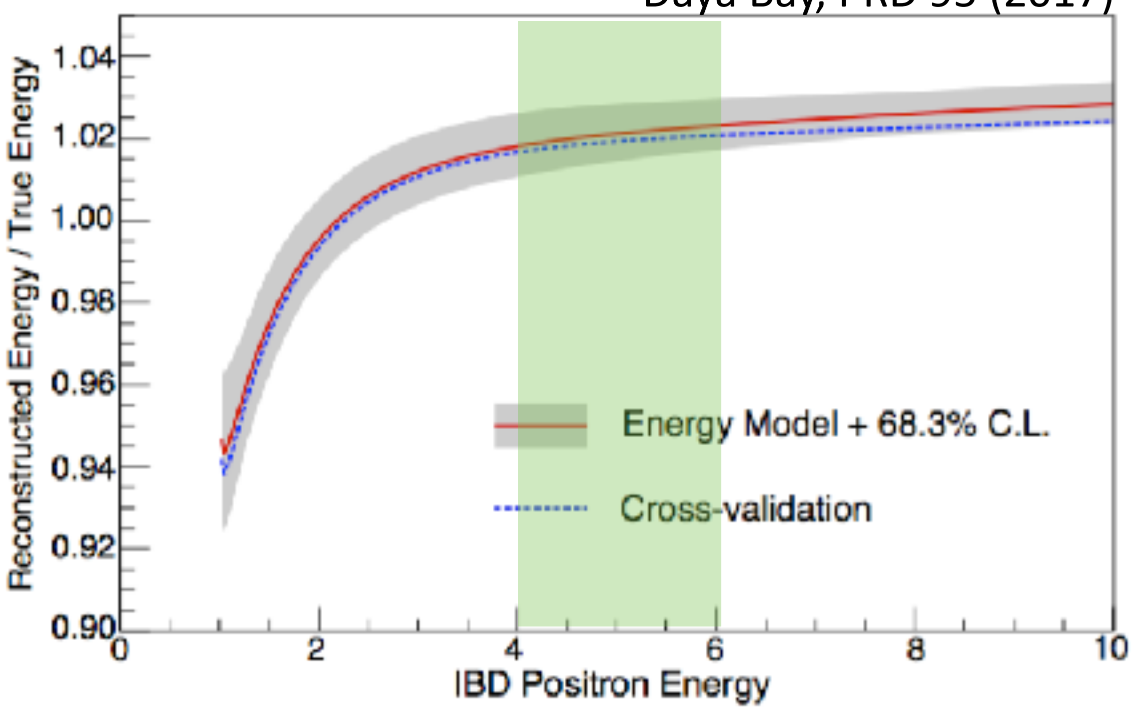


5 MeV excess scales with reactor power

Skeptical Question 2

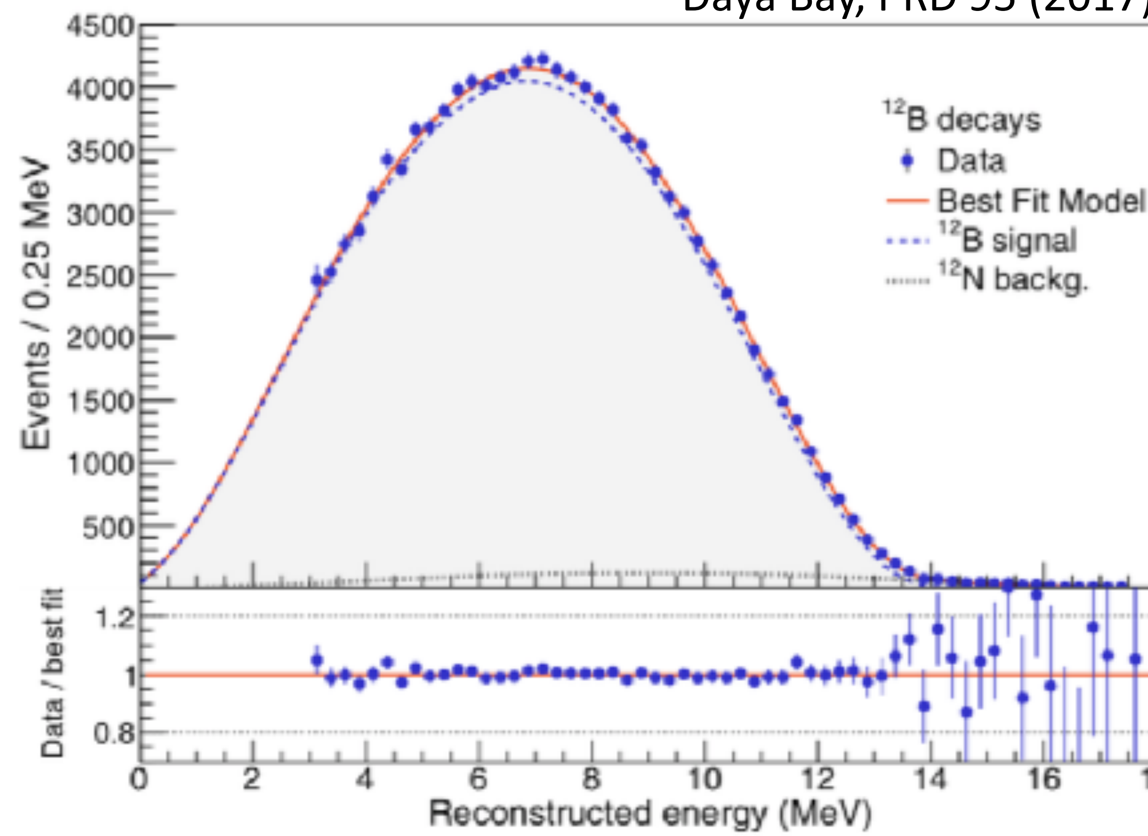
- ‘Maybe this is just an absolute response scale issue’

Daya Bay, PRD 95 (2017)

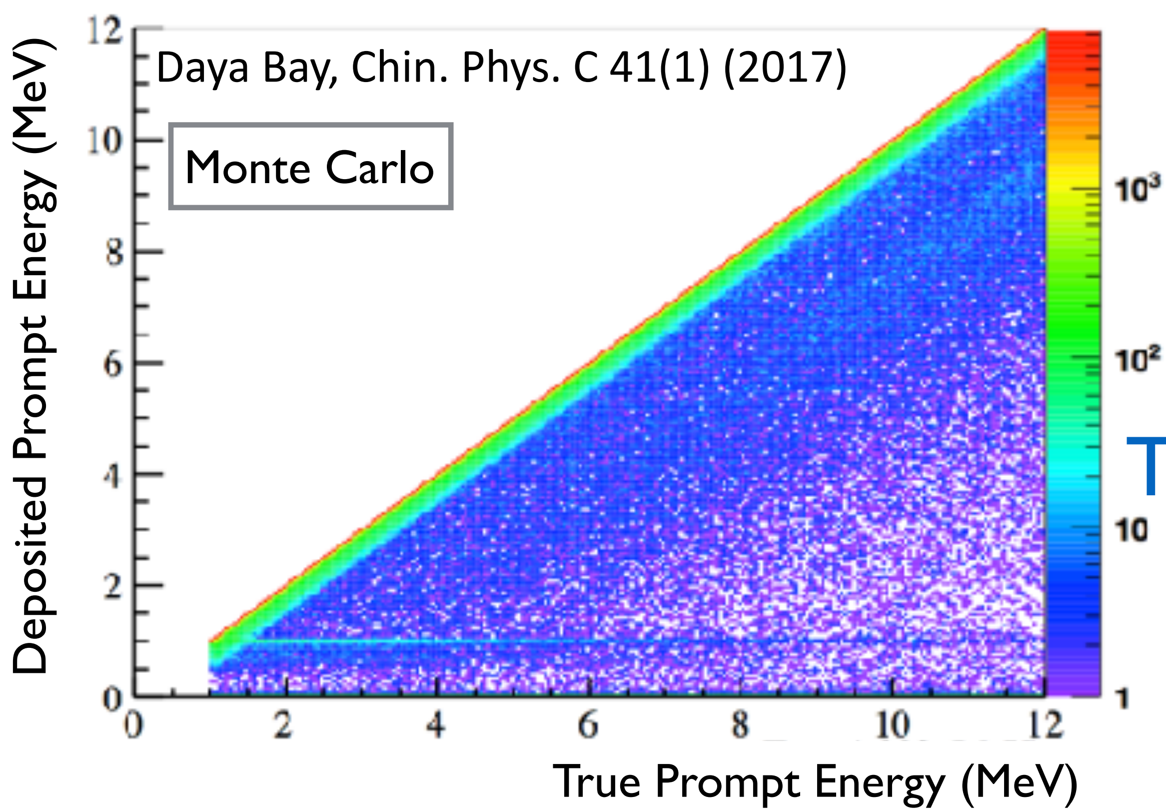


Smooth energy scale at high E…

Daya Bay, PRD 95 (2017)



No bump or other strange behavior in B-12 spectrum WRT prediction…

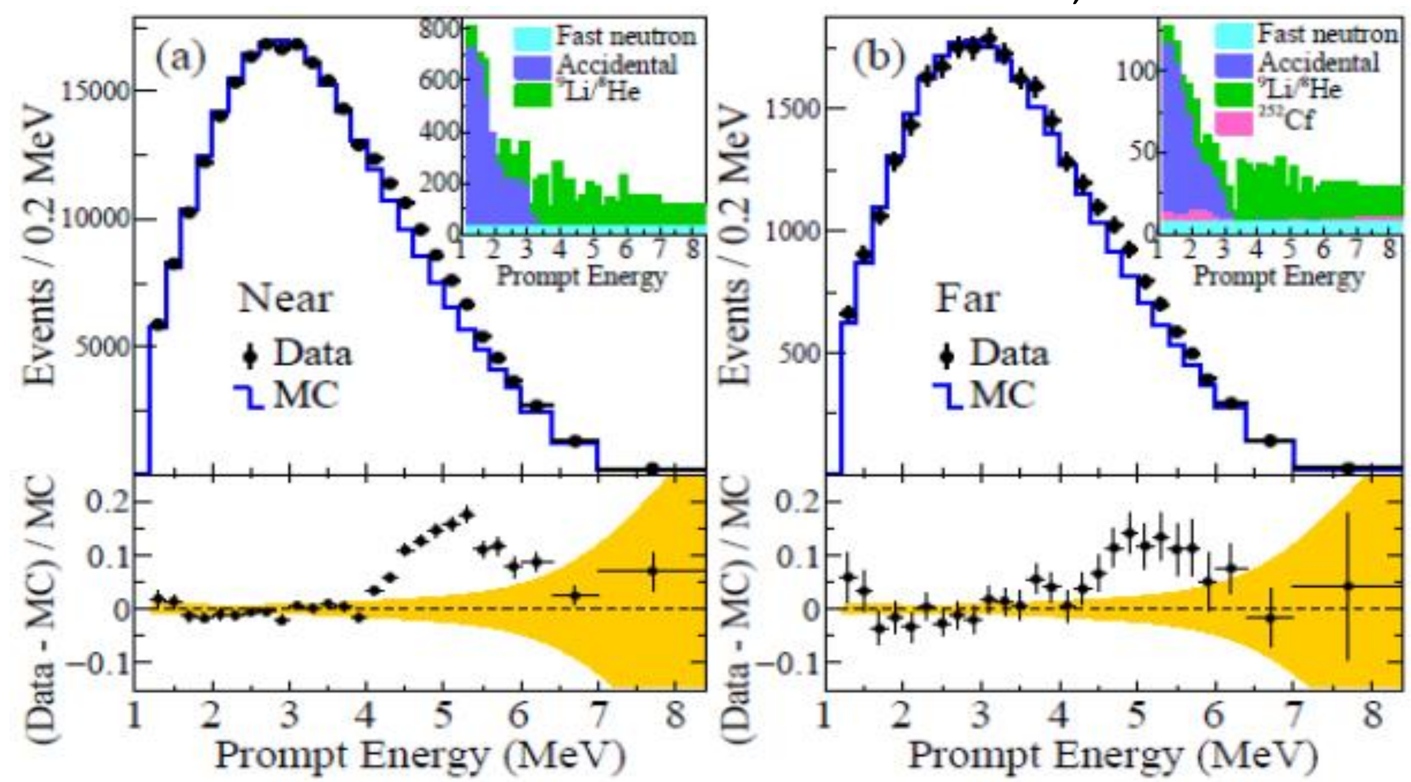


True → Measured energy conversion is quite simple - not much to mess up here…

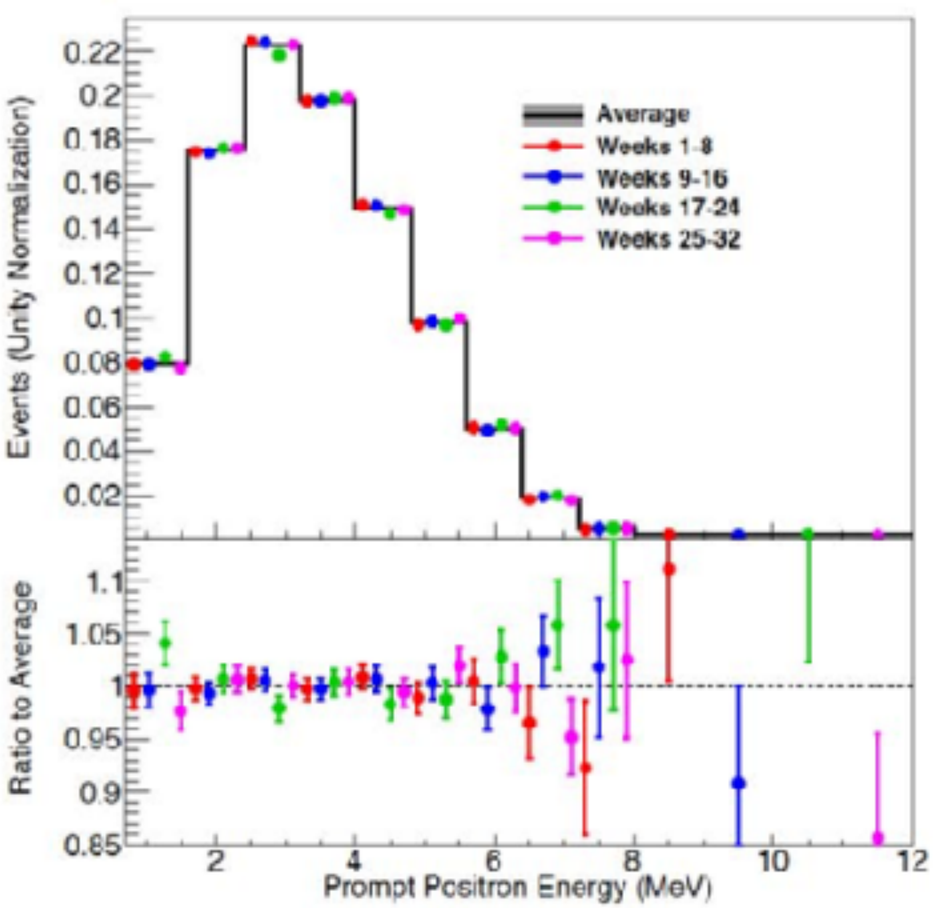
Skeptical Question 3

- ‘Is there any other strange behavior in the way this excess pops up in the data?’

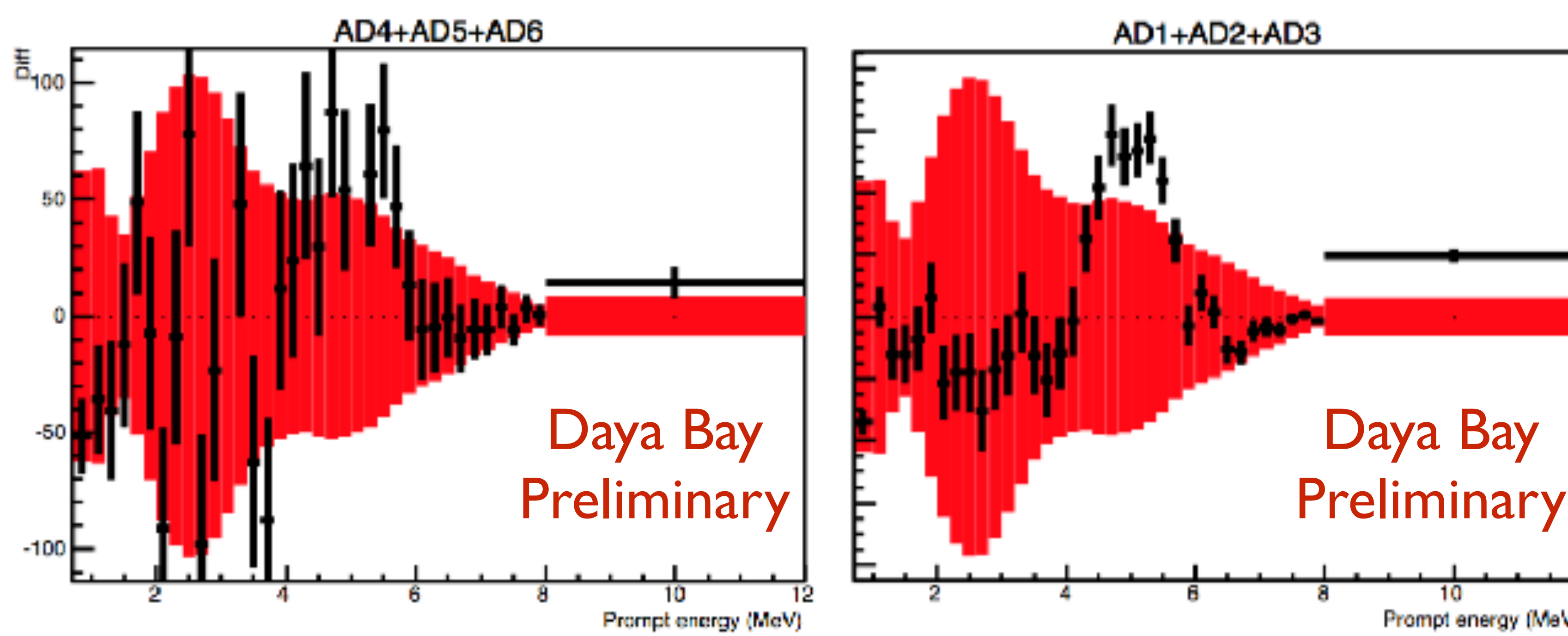
RENO, Neutrino2016



No time-dependent spectral changes observed

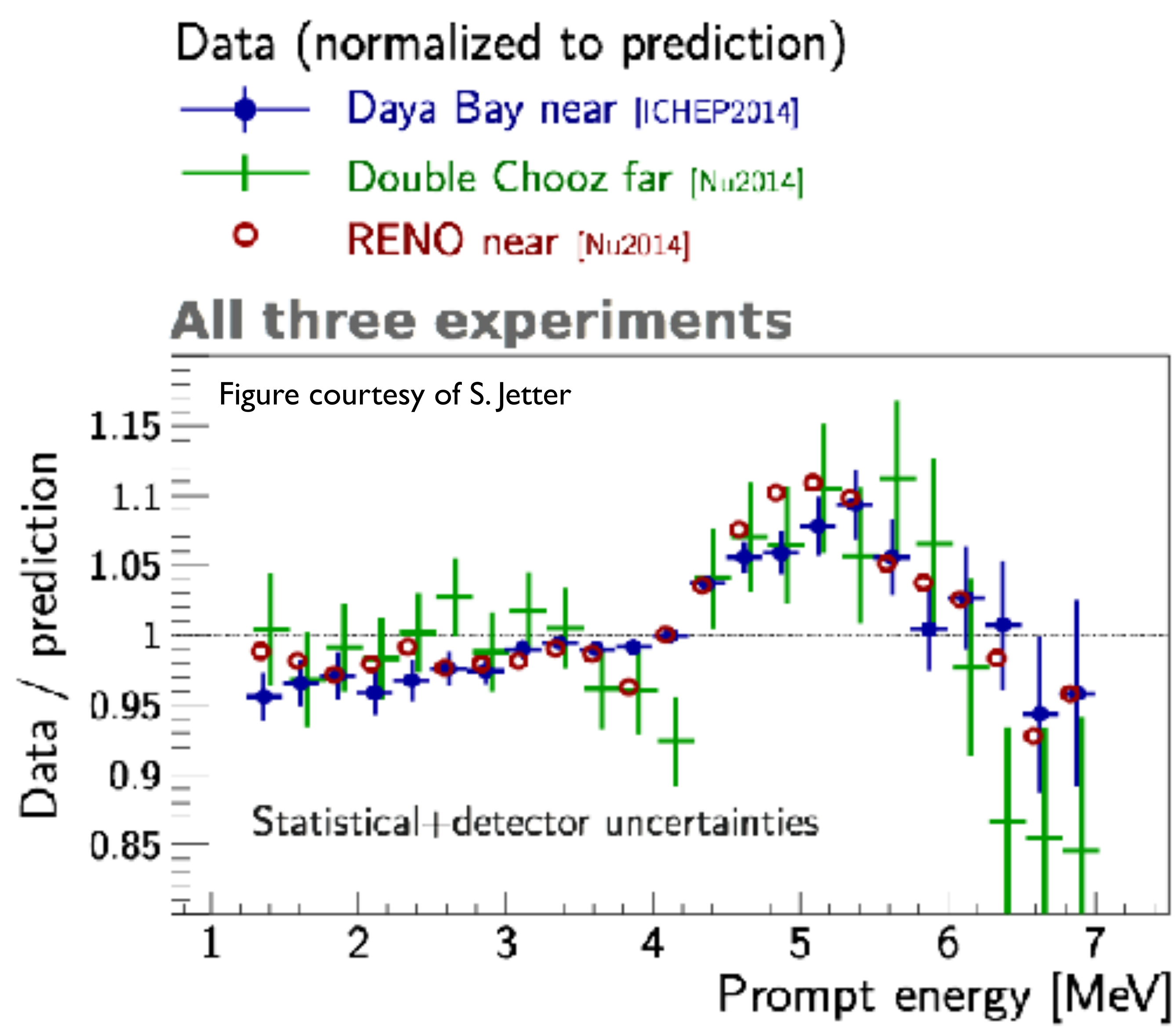


Different detectors see the same general feature



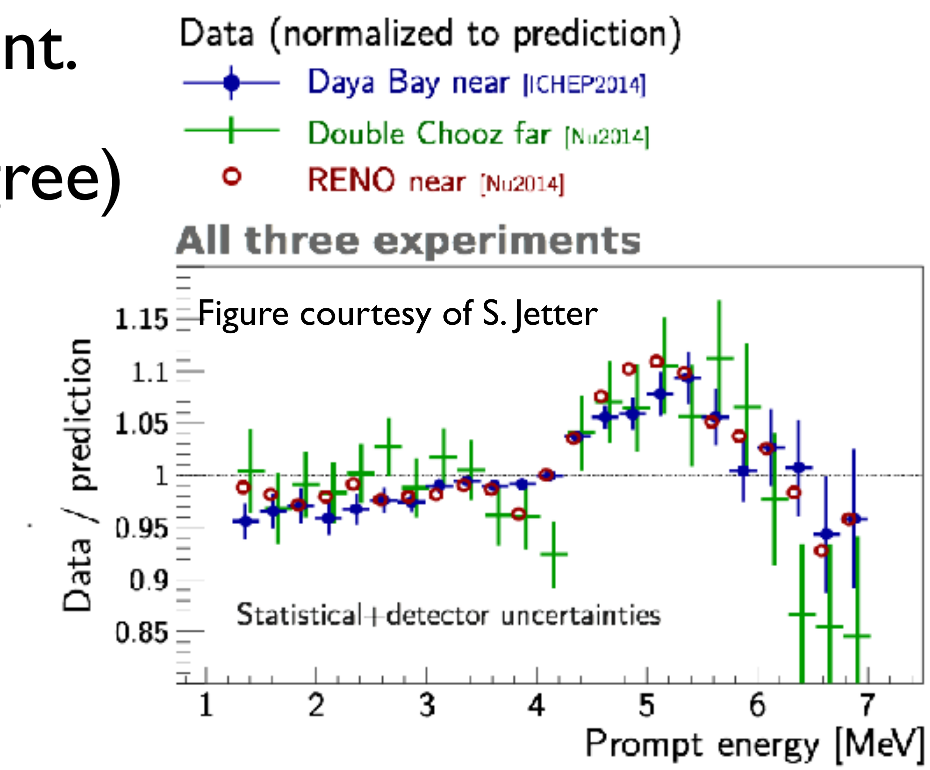
Piling On

- All three θ_{13} experiments a similar feature!!!
  - Not just one faulty experiment — broad agreement.
  - Different electronics and scintillator
  - Overburdens, backgrounds vary widely between experiments
- There is no getting around it — the bump IS REAL.
- Already discussed why we believe the flux anomaly is also very real.
  - Also, for more detail on flux result, see CPC paper: 35 pages of detail!
- So, let's move on: what could be wrong with the predictions?



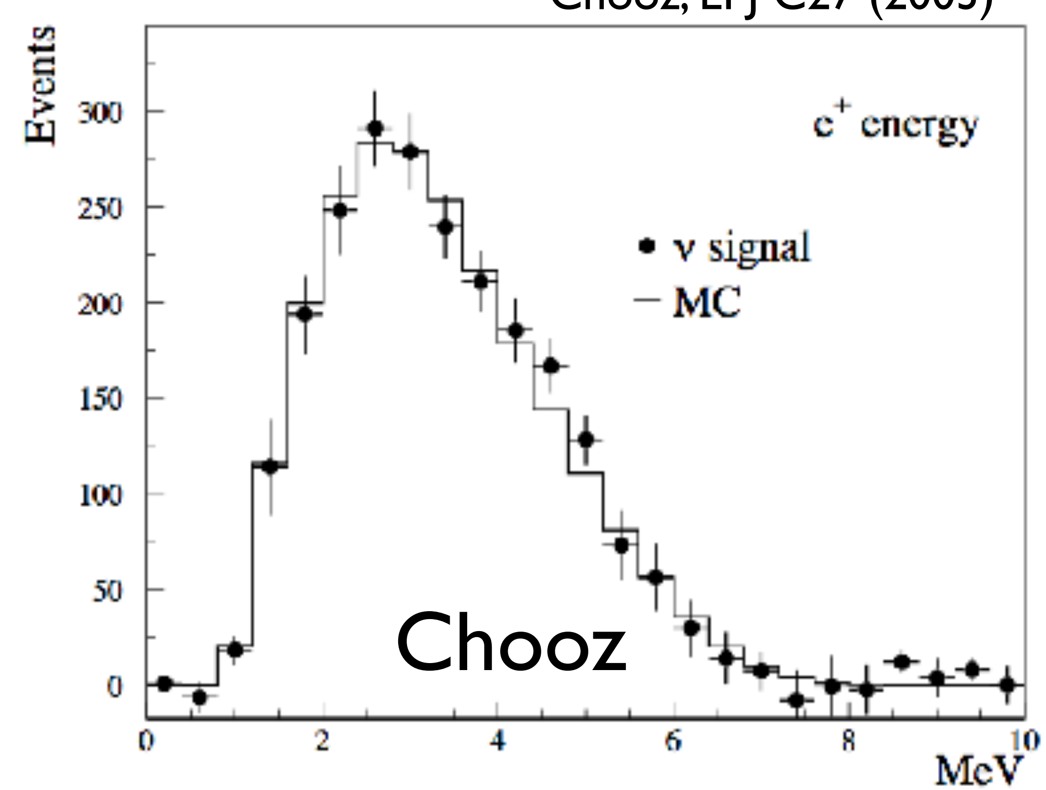
Piling On

- Re-emphasize — All three experiments see the same thing!!!
  - Not just one faulty experiment — broad agreement.
  - Different electronics and scintillator (to some degree)
  - Overburdens, backgrounds vary widely between experiments

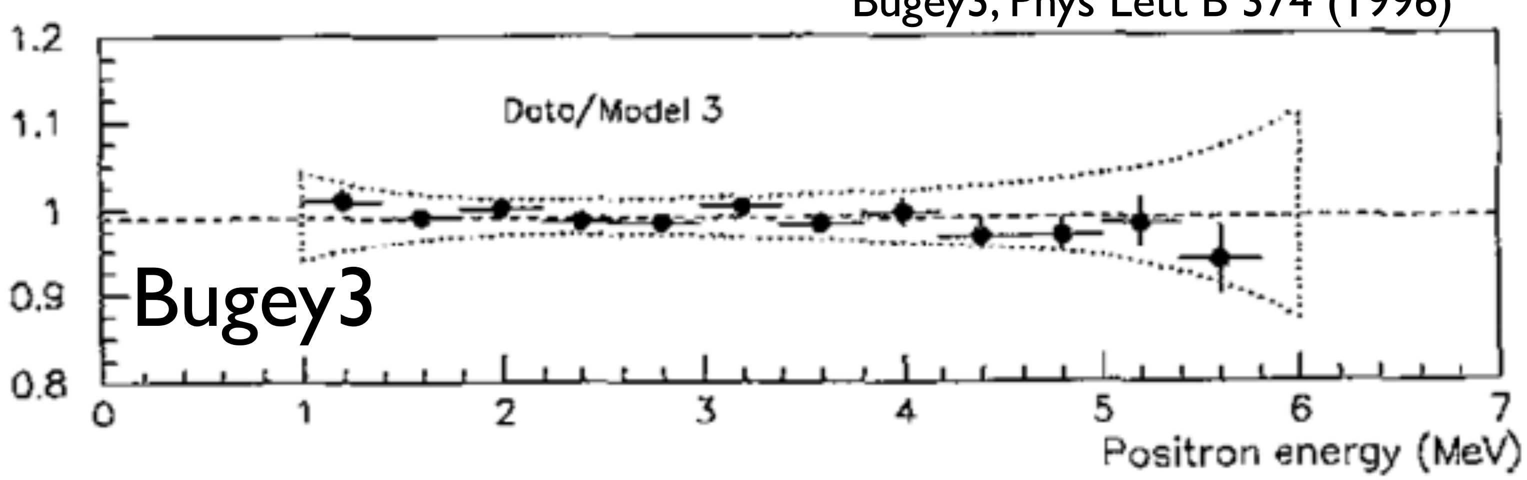


- Other notable results:
  - CHOOZ: A hint present, low CL
  - Bugey3: Seems like no feature is present?
    - Large non-scintillating volume in target? Binning?
    - Something else?

Chooz, EPJ C27 (2003)



Bugey3, Phys Lett B 374 (1996)



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)?