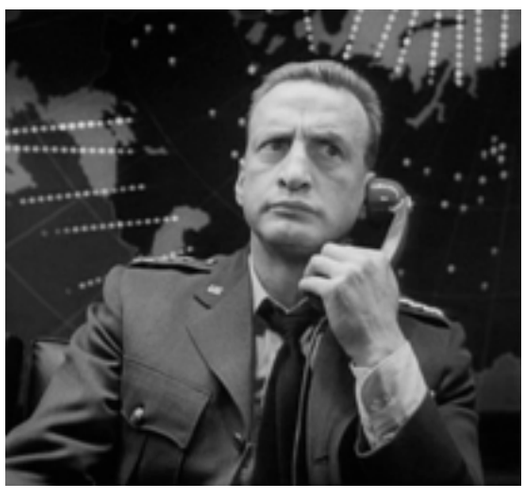
Recent Reactor $\bar{\nu}_e$ Spectrum Measurements

(or: How I Learned to Stop Worrying and Love the Anomalies)

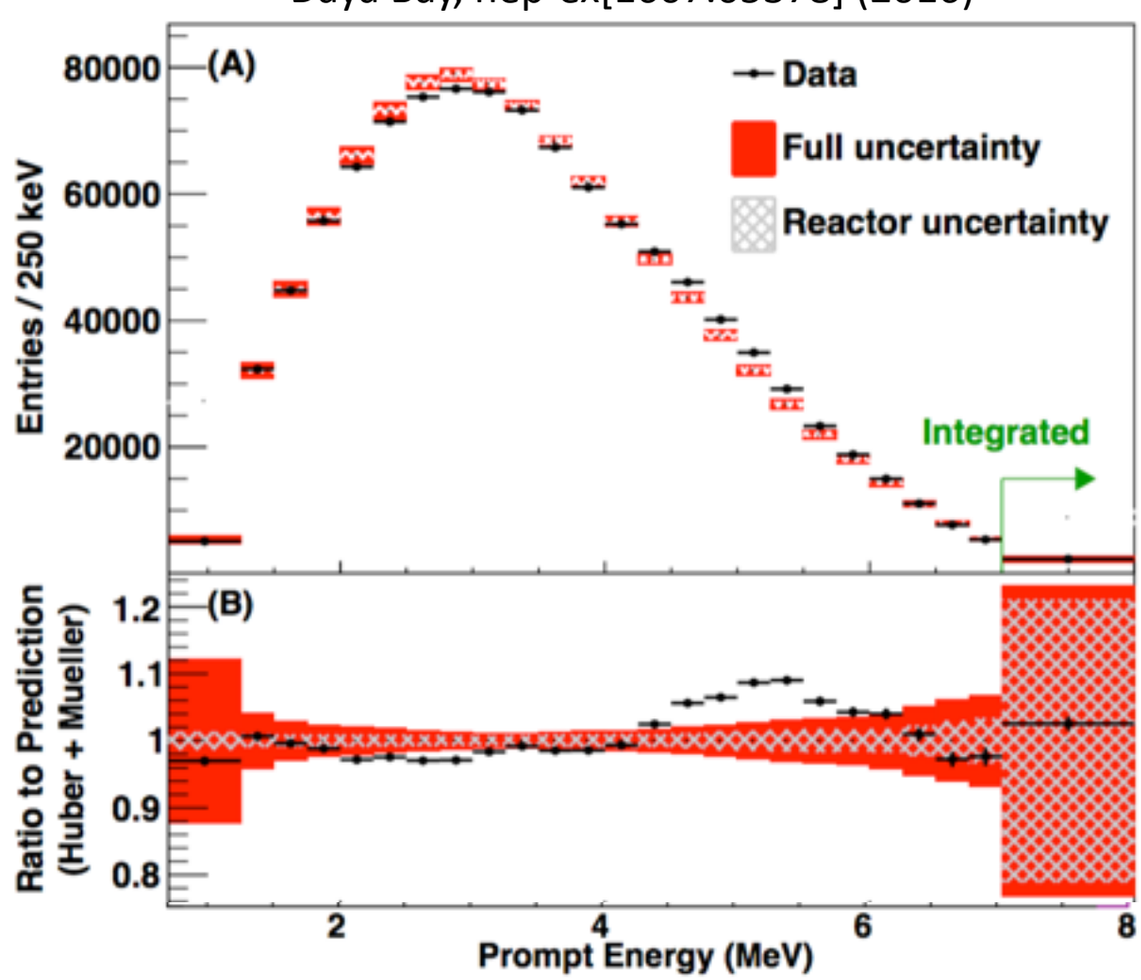
July 30, 2016

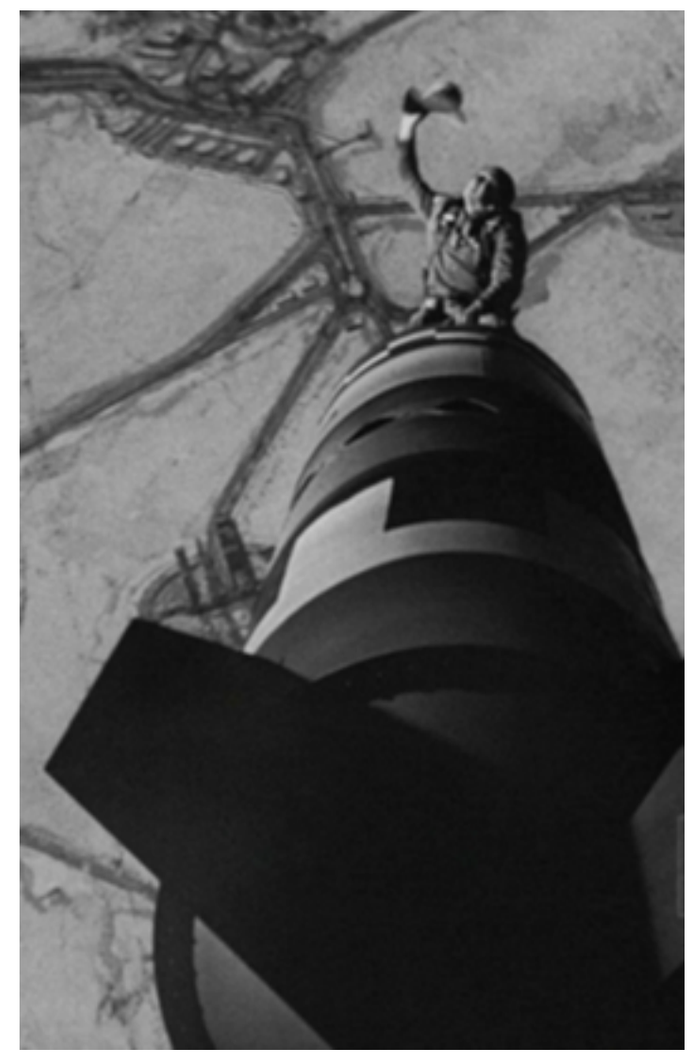
Bryce Littlejohn

Illinois Institute of Technology



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



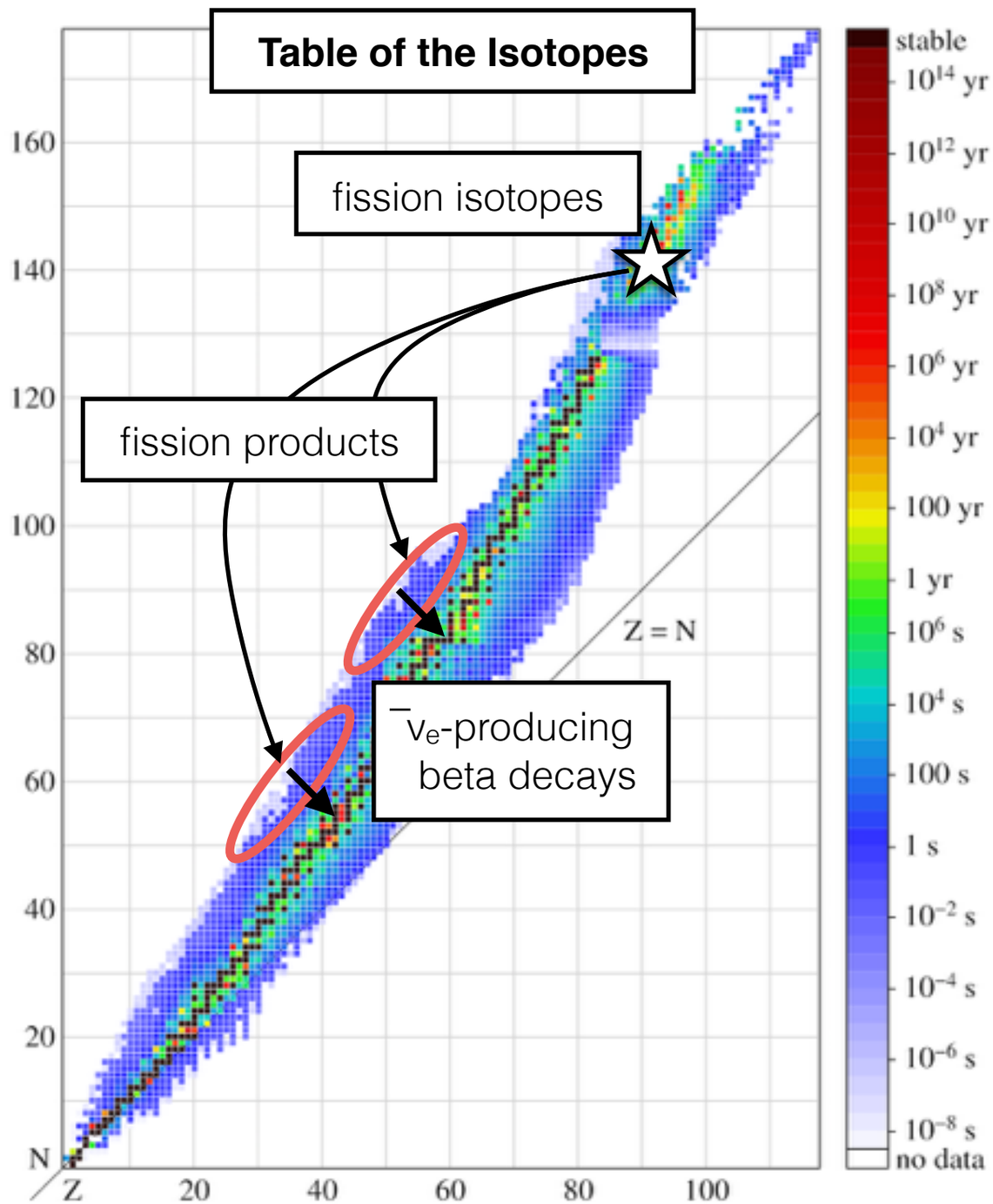


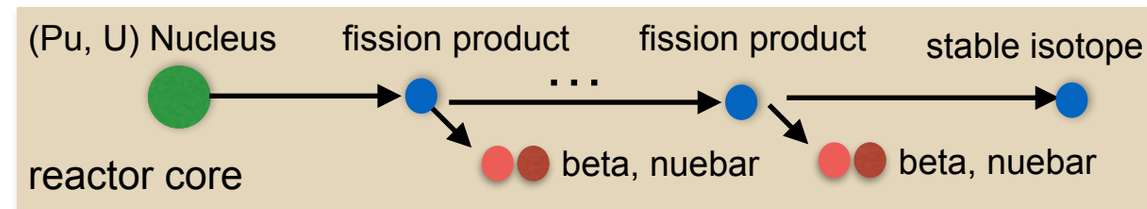
Outline

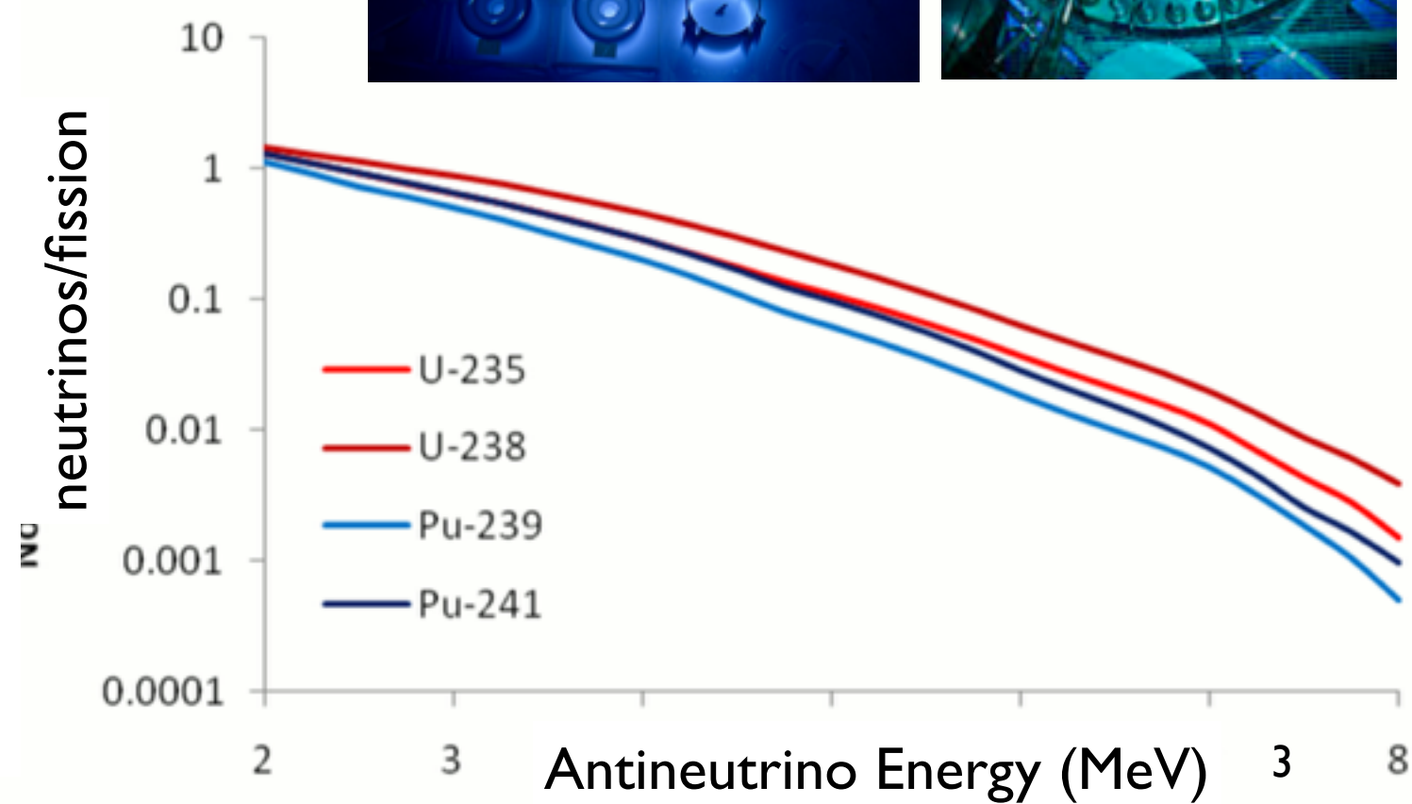
- Intro: Reactor $\bar{\nu}_e$ Flux and Spectrum Predictions
- Reactor Anomalies, Explanations
- Testing Explanations With Reactor Data
- Will show updated results as much as possible. In particular:
  - Daya Bay, Neutrino 2016
  - RENO, Neutrino 2016
  - Daya Bay, hep-ex[1607.05378] (2016)

Reactor Antineutrino Production

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

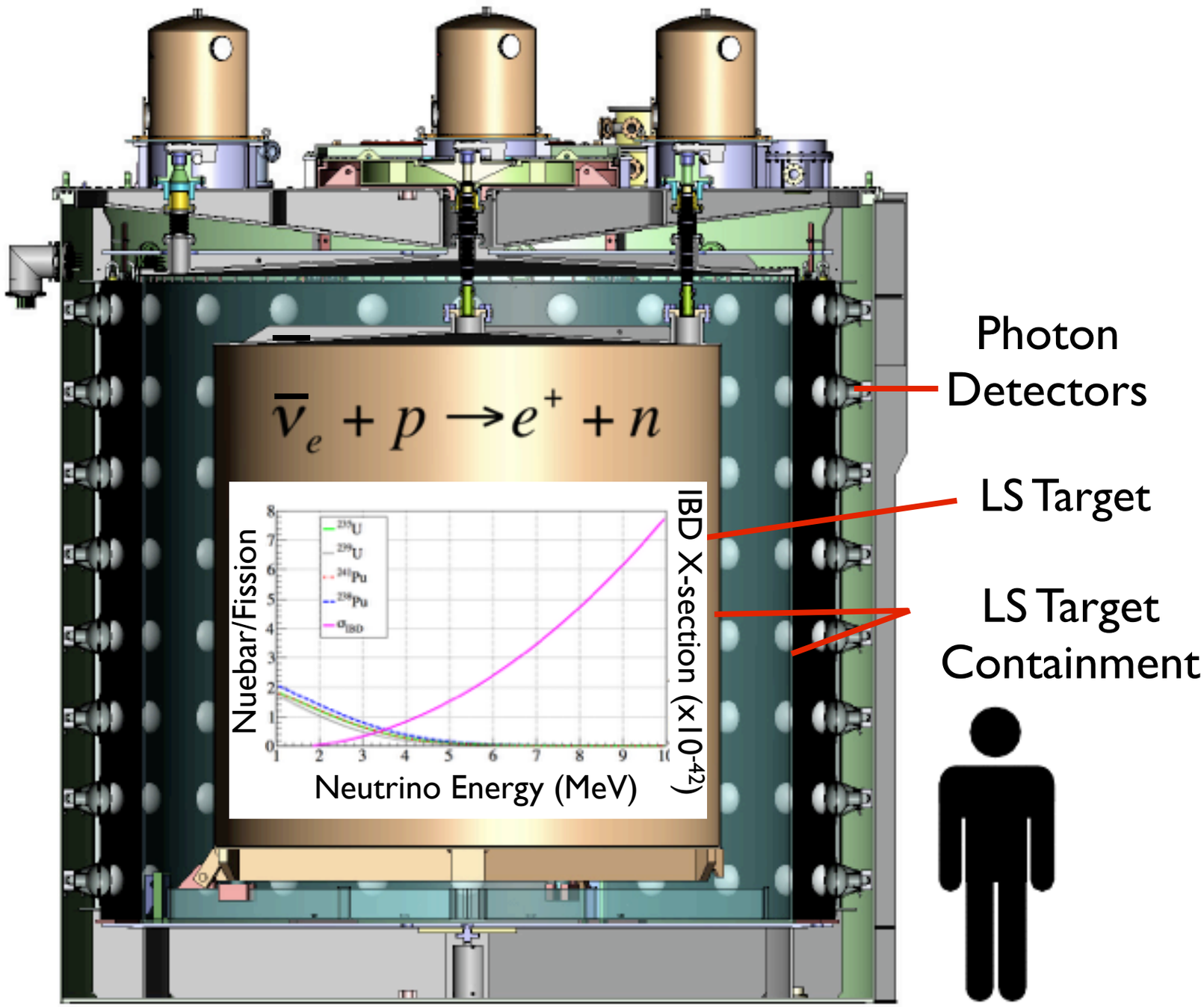




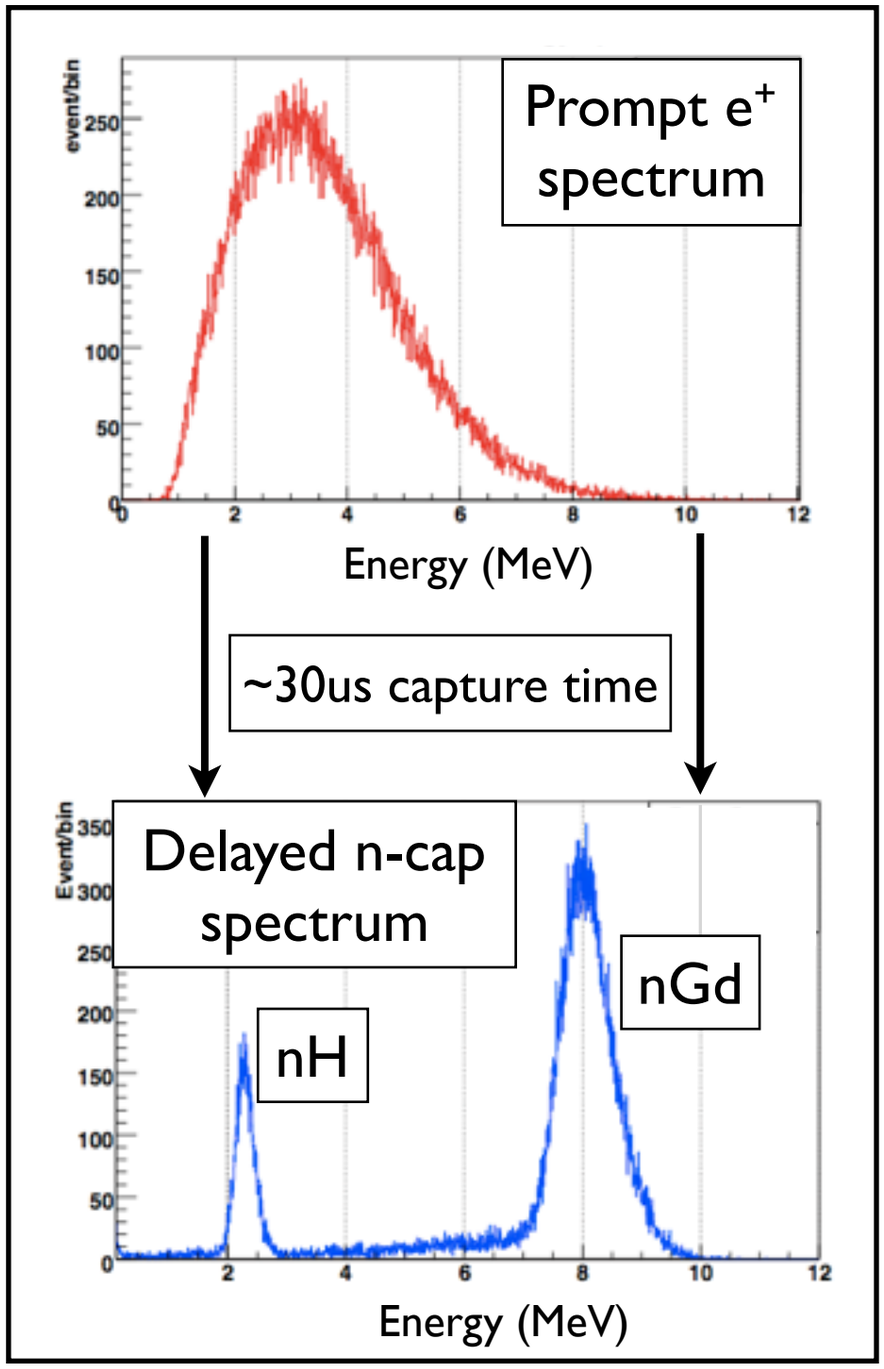


Reactor Antineutrino Detection

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



Example: Daya Bay Detector

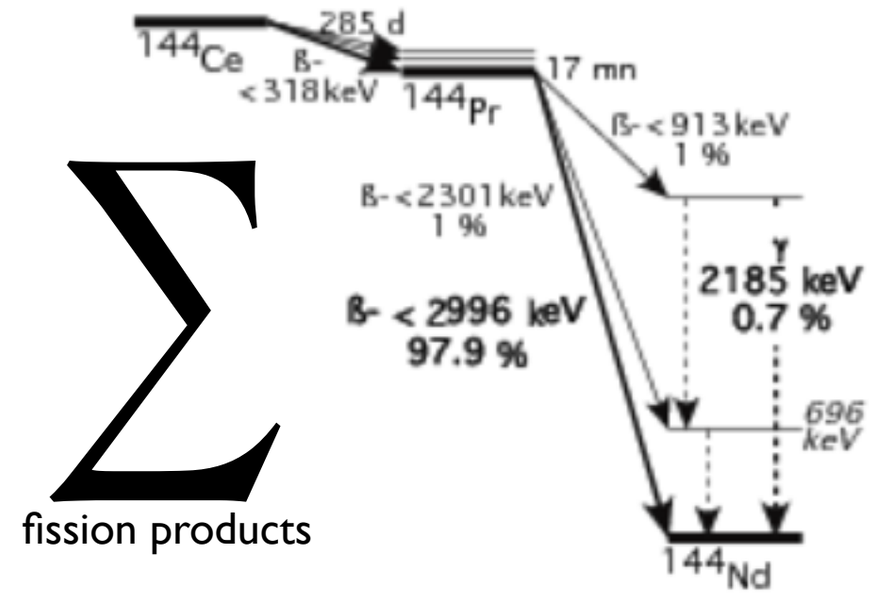


Daya Bay Monte Carlo Data

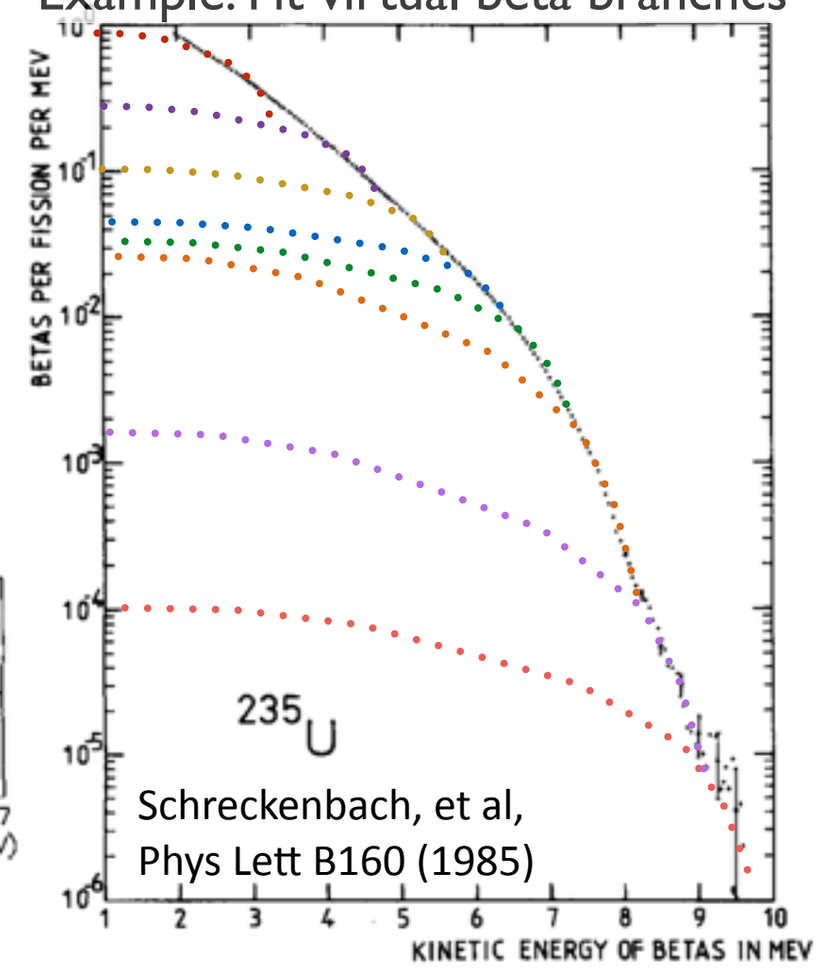
Predicting $S_i(E)$, Neutrinos Per Fission

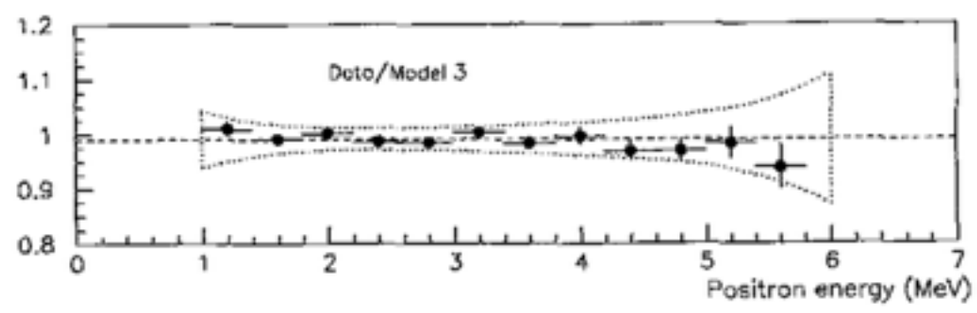
- Two main methods:
- *Ab Initio* approach:
  - Calculate spectrum branch-by-branch w/ databases: fission yields, decay schemes, …
  - **Problem:** rare isotopes / beta branches: missing, possibly incorrect info…
- Conversion approach
  - Measure beta spectra directly
  - Convert to $\overline{\nu}_e$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





Bugey 3: Phys Lett B374 (1996)

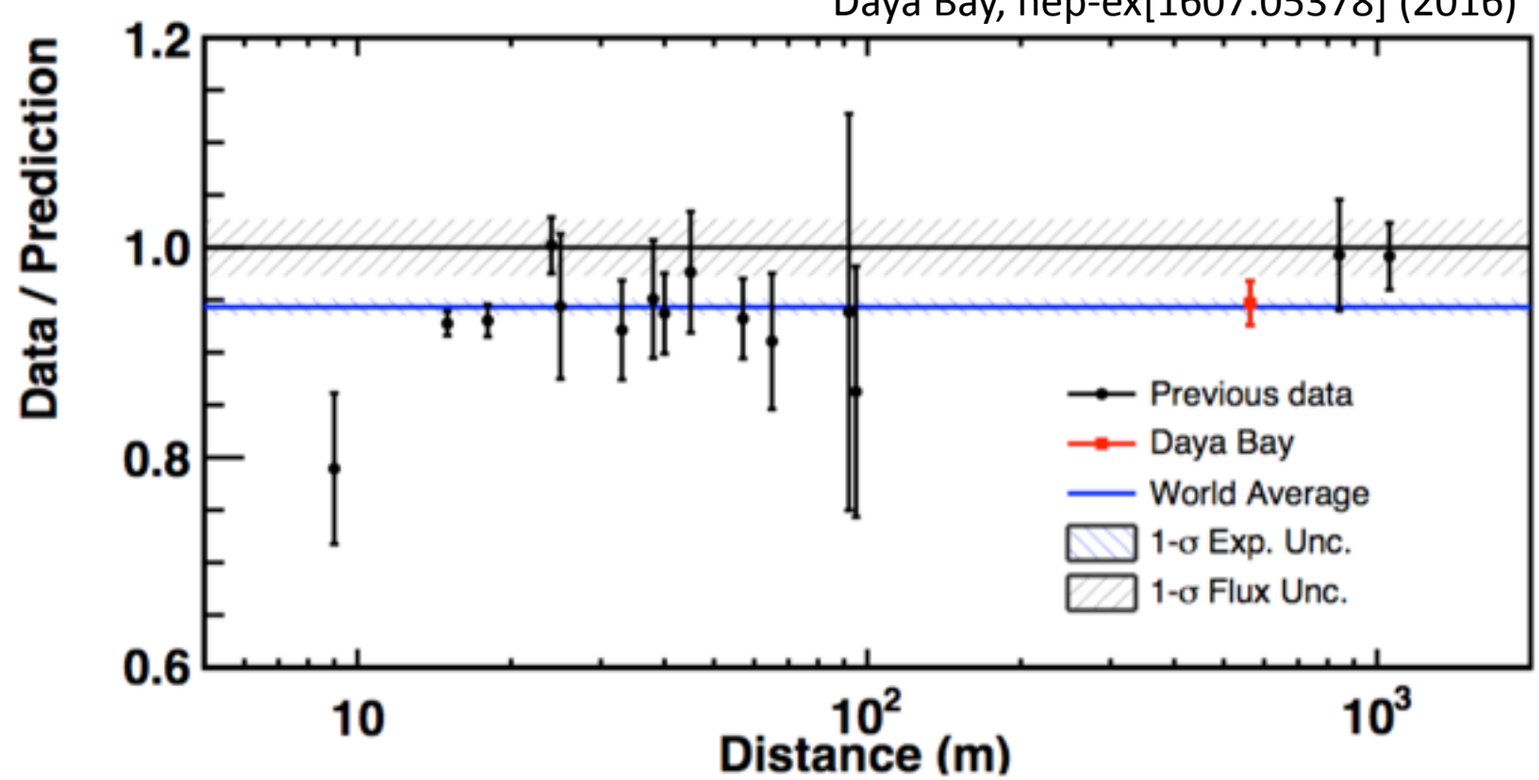
More Recent History: Problems Emerge

- 2011s: Re-calculation of conversion approach for θ_{13} measurements
  - Double Chooz collaborators: hybrid conversion/ab initio approach
  - Also Huber: pure conversion

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

- Change in flux/spectrum!
  - Flux increase from:
    - Changes to conversion corrections
    - X-section
    - Non-equilibrium isotopes

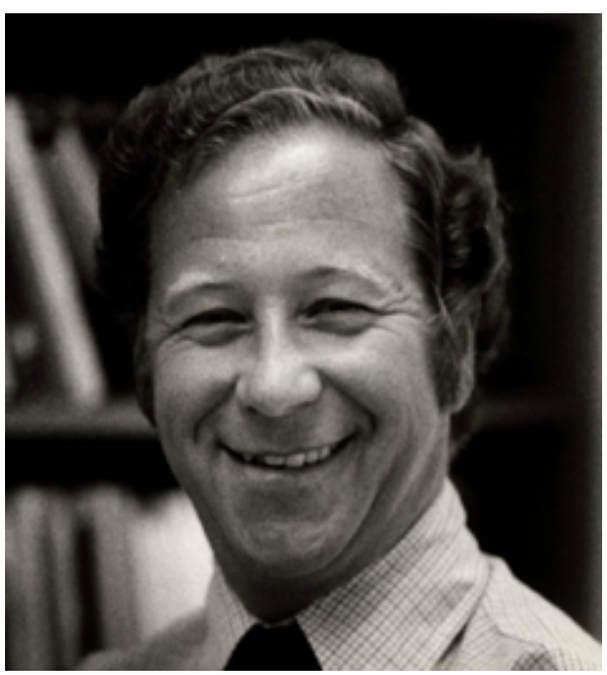
Daya Bay, hep-ex[1607.05378] (2016)



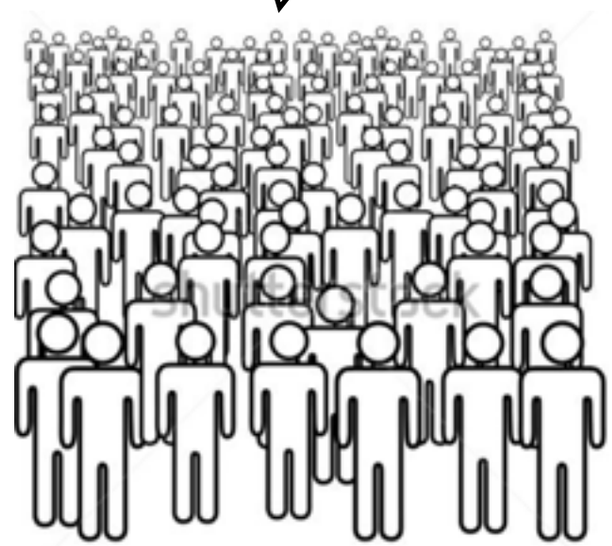
Reactor Antineutrino Anomaly?

- 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



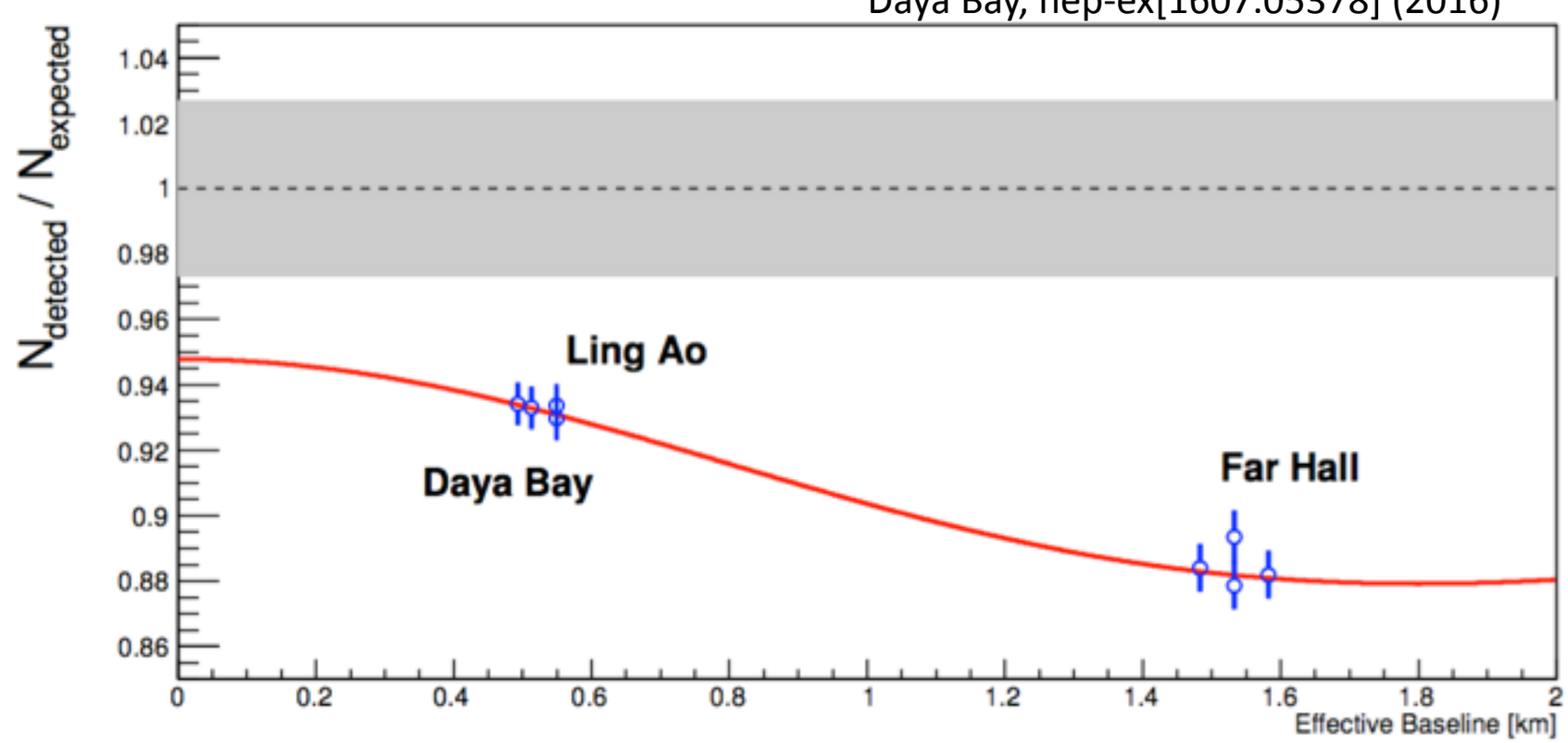
The rest of us

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.

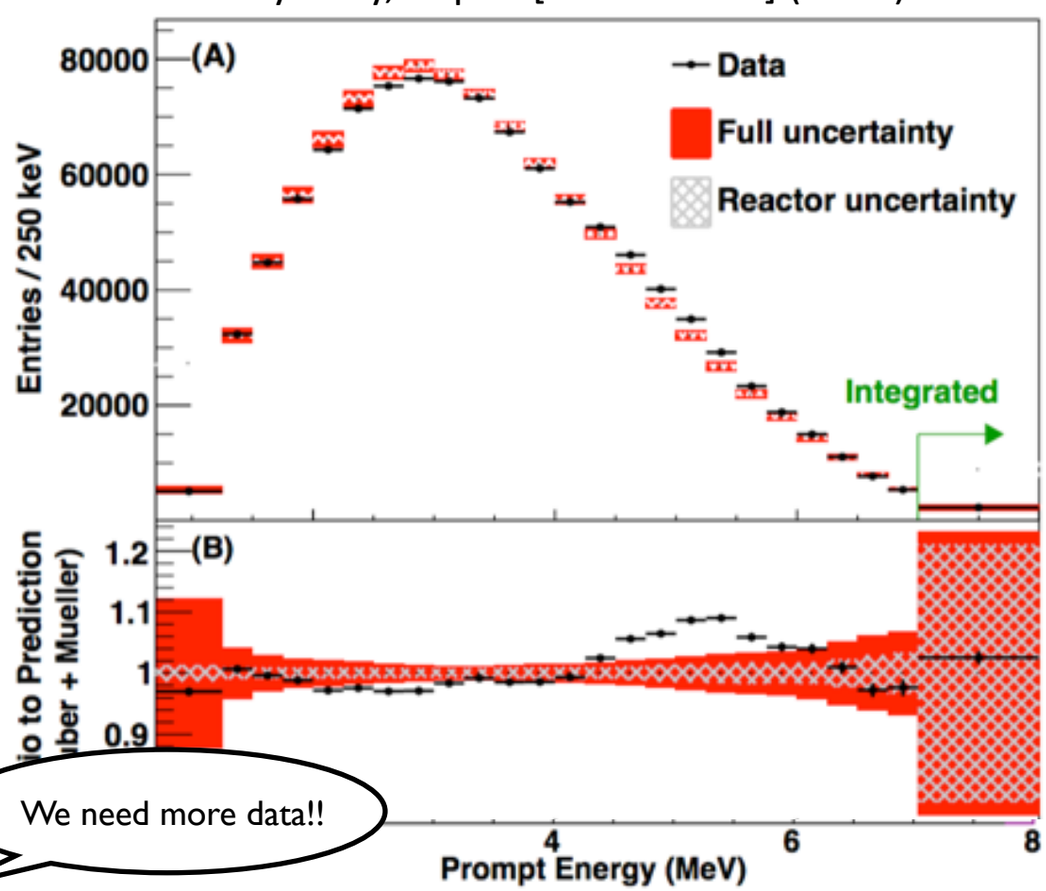
Daya Bay, hep-ex[1607.05378] (2016)



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, hep-ex[1607.05378] (2016)



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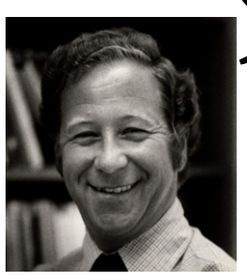
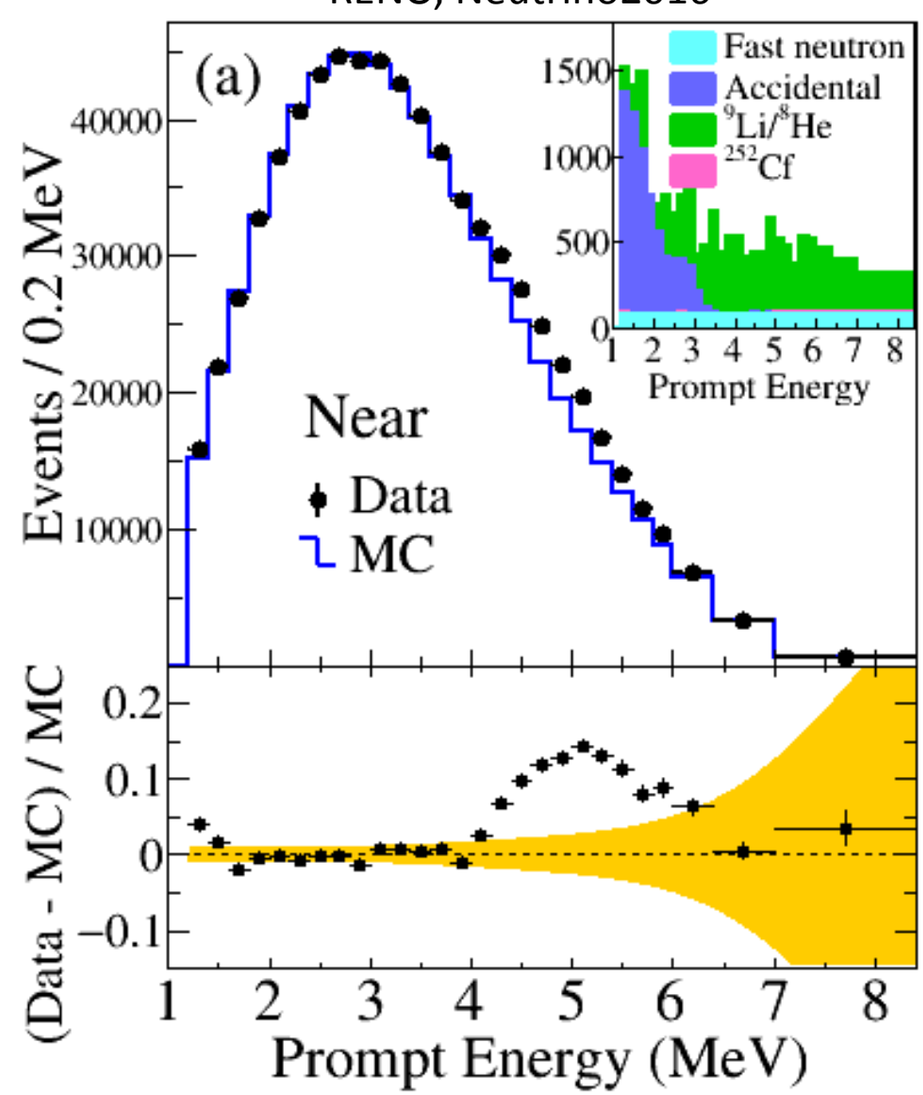
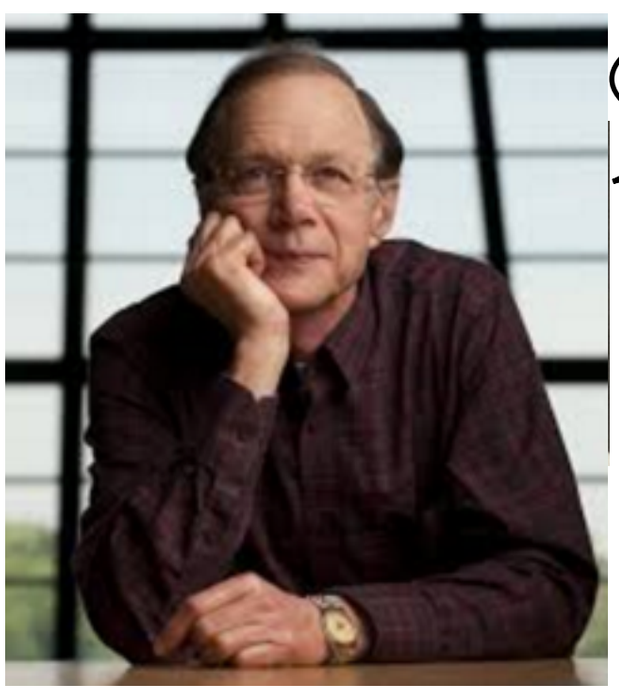


RENO, Neutrino2016



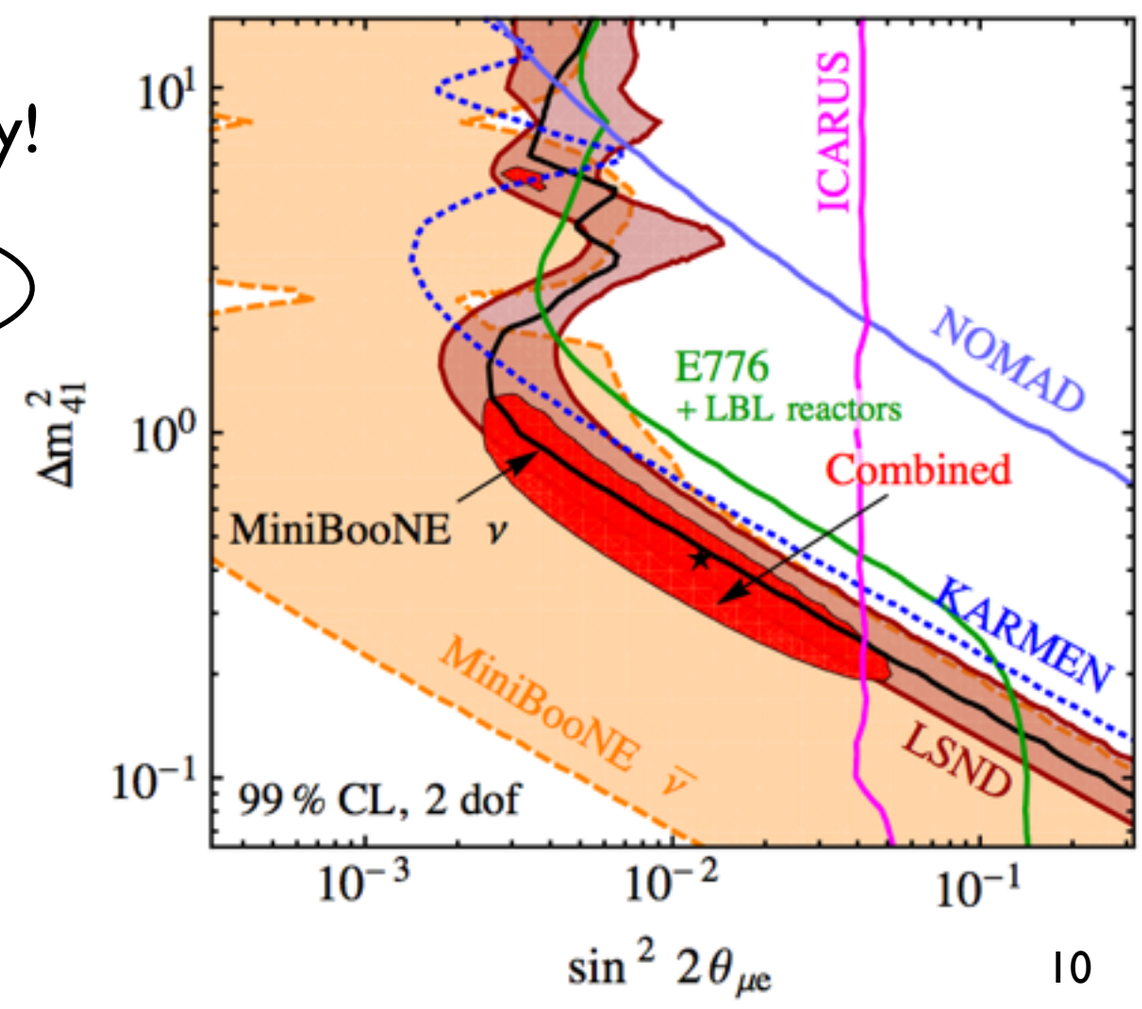
Reactor Anomaly Explanations

- 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…
- Also, to be able to interpret CP-violation results, we need to know if sterile neutrinos exist…
  - DUNE needs an answer for the anomaly!



We need more data!!

Boris Kayser, Fermilab



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.

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- What else can we do to probe this hypothesis?

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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 HOW calculations are incorrect.
  - Studying the flux AND spectrum anomalies is probably important here…
  - Will focus here only on what future neutrino experiments can do.

Skeptical Aside

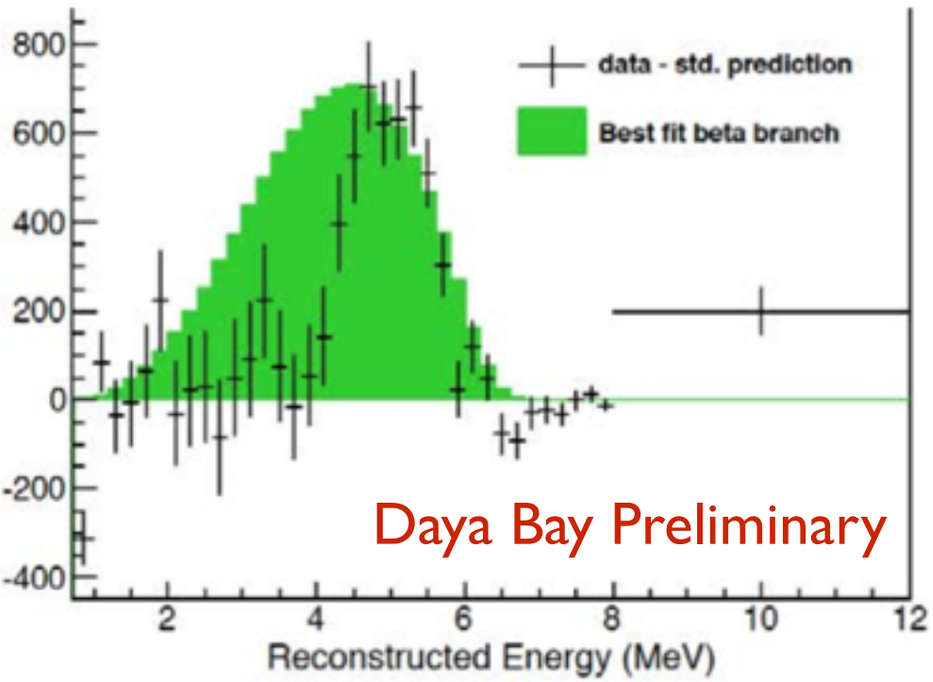
- Before we discuss what might be wrong with spectrum predictions, I forgot to mention one hypothesis:
- Neutrino experimentalists have no idea what they're doing!!!
  - 'Is the bump is just a background that hasn't been properly accounted for?'
  - 'Maybe the bump is just an absolute energy scale issue?'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

???

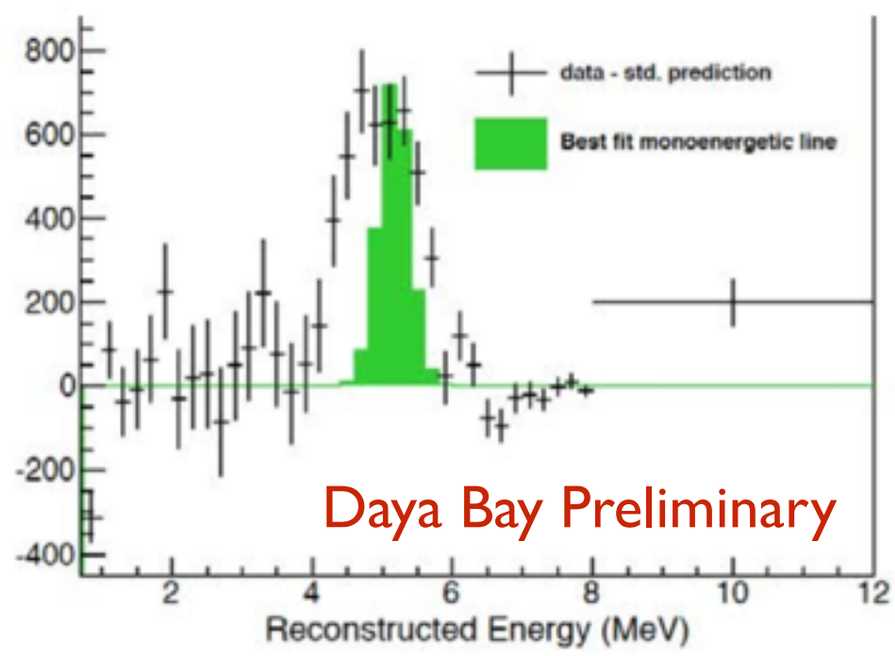
Skeptical Question 1

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

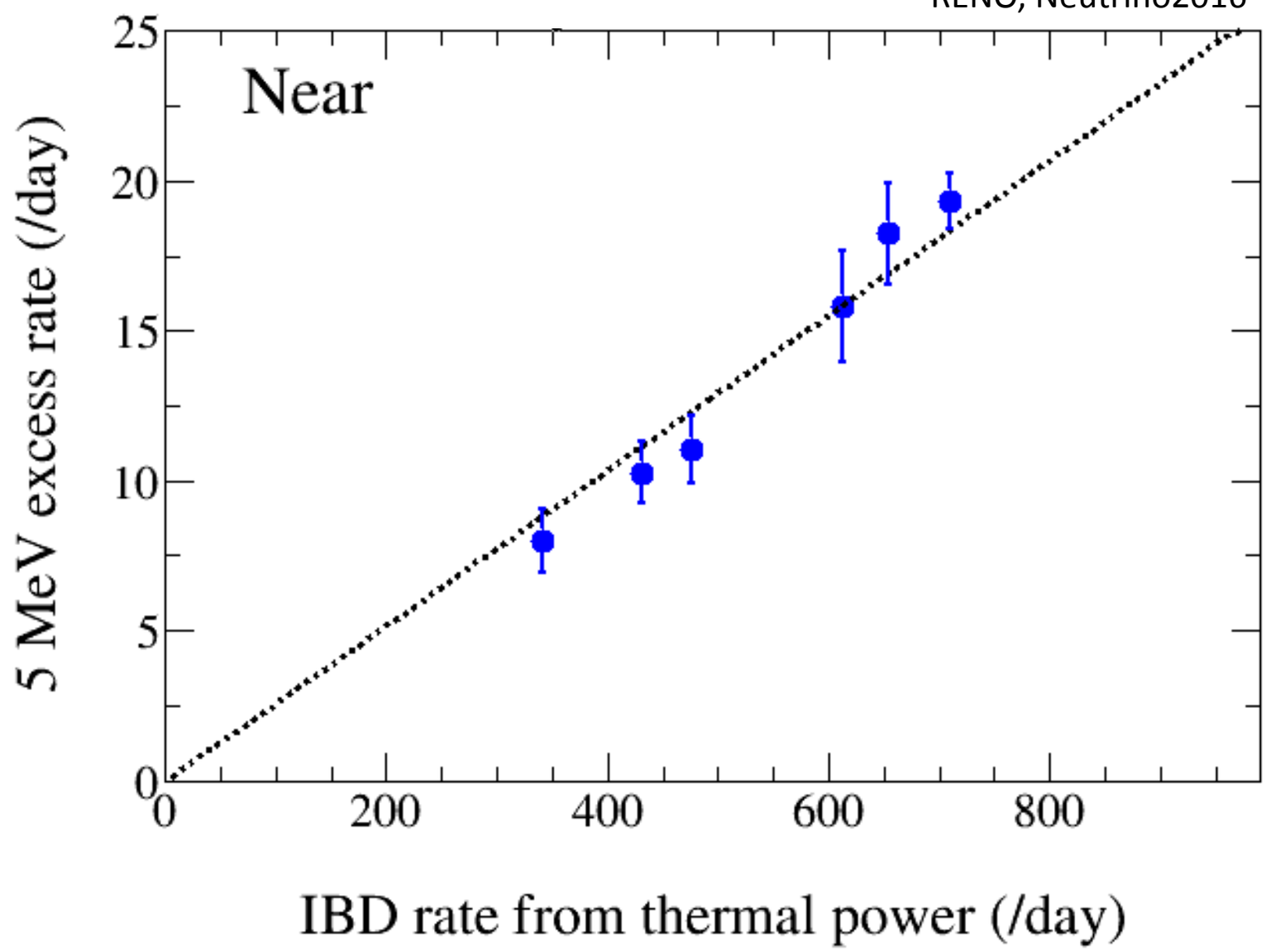
Not a beta-branch



Not a delta function



RENO, Neutrino2016

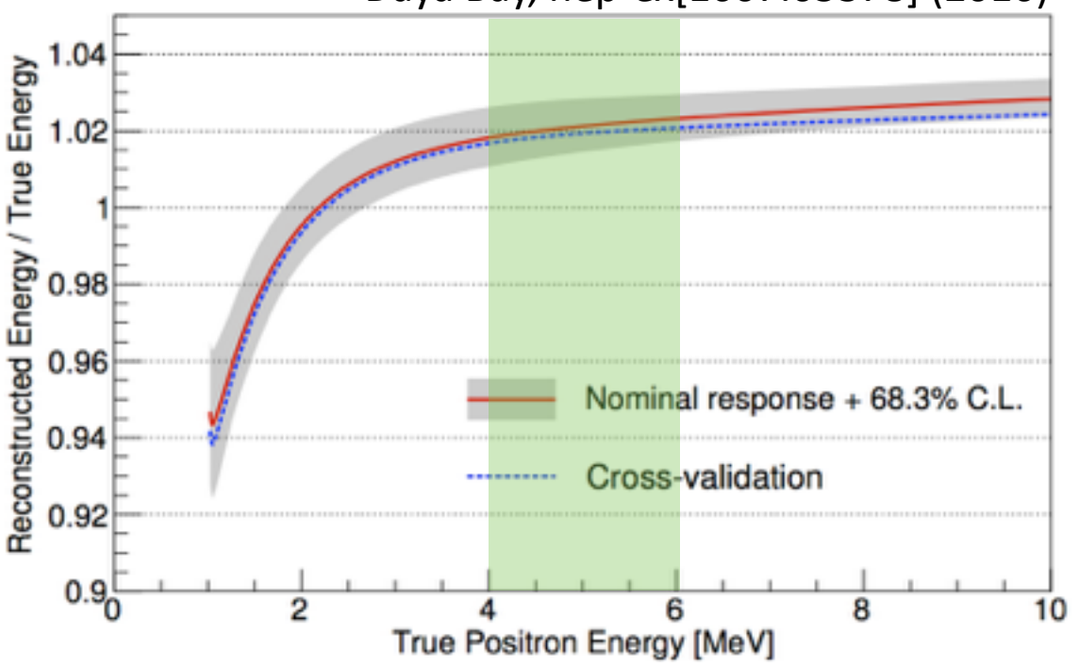


5 MeV excess scales with reactor power

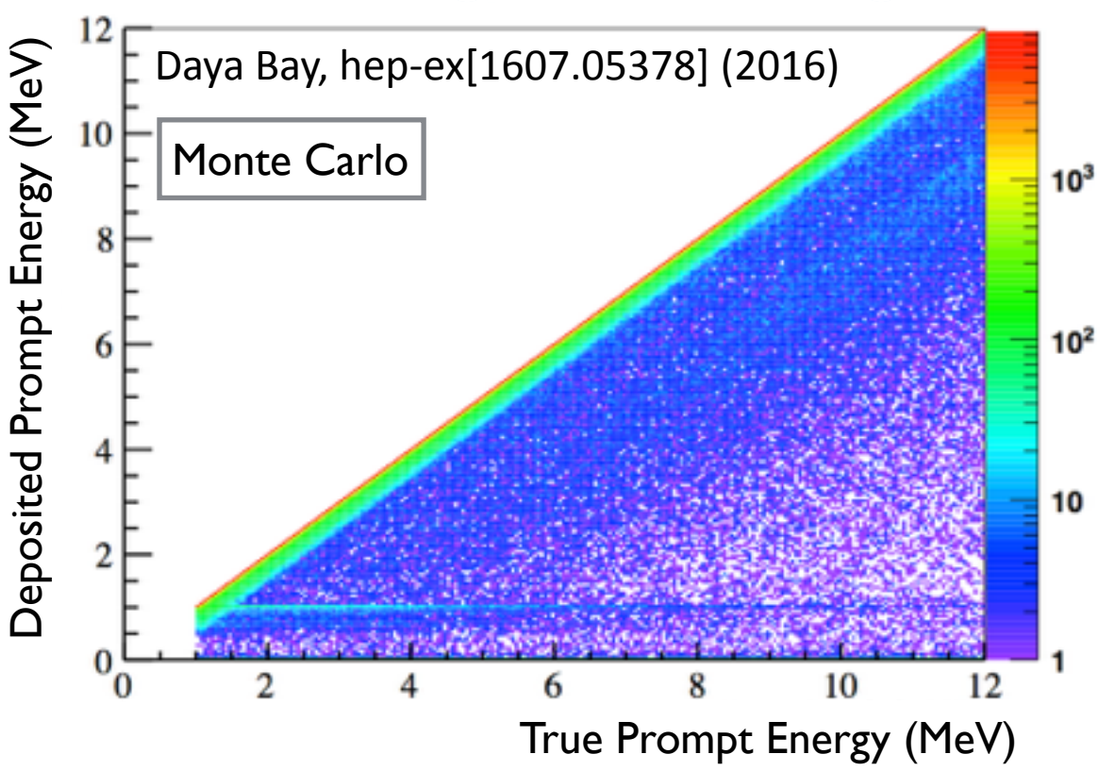
Skeptical Question 2

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

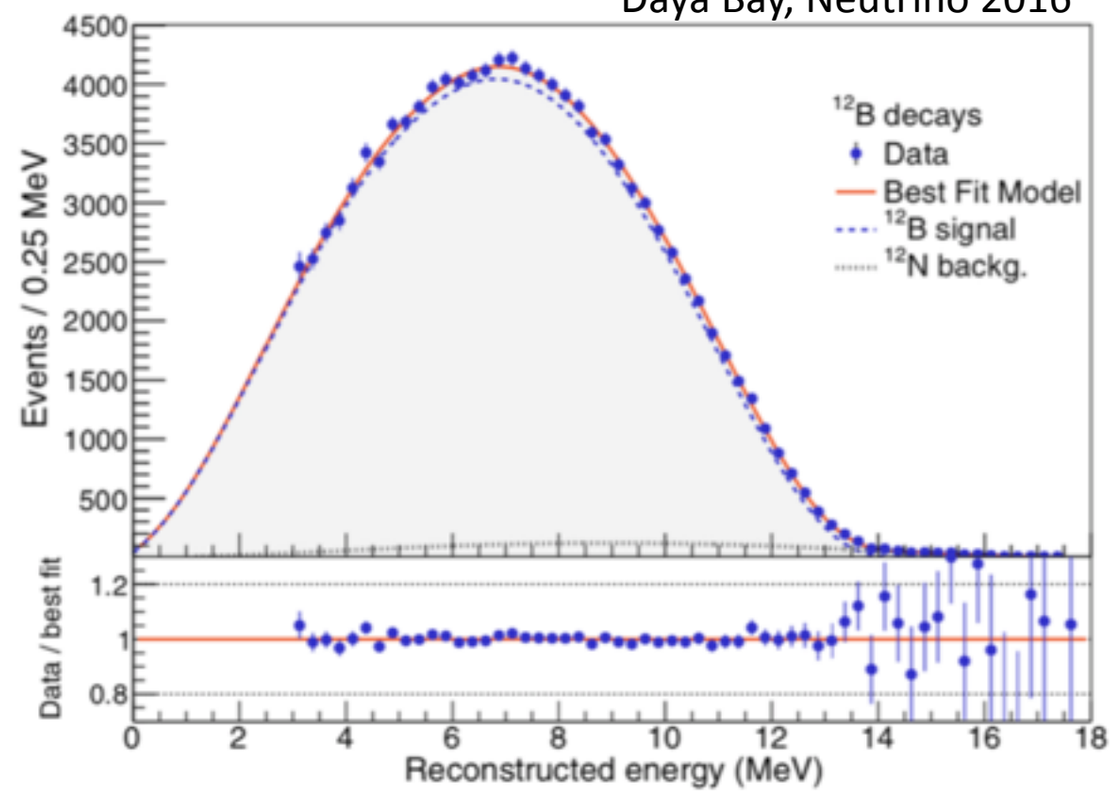
Daya Bay, hep-ex[1607.05378] (2016)



Smooth energy scale at high E…



Daya Bay, Neutrino 2016



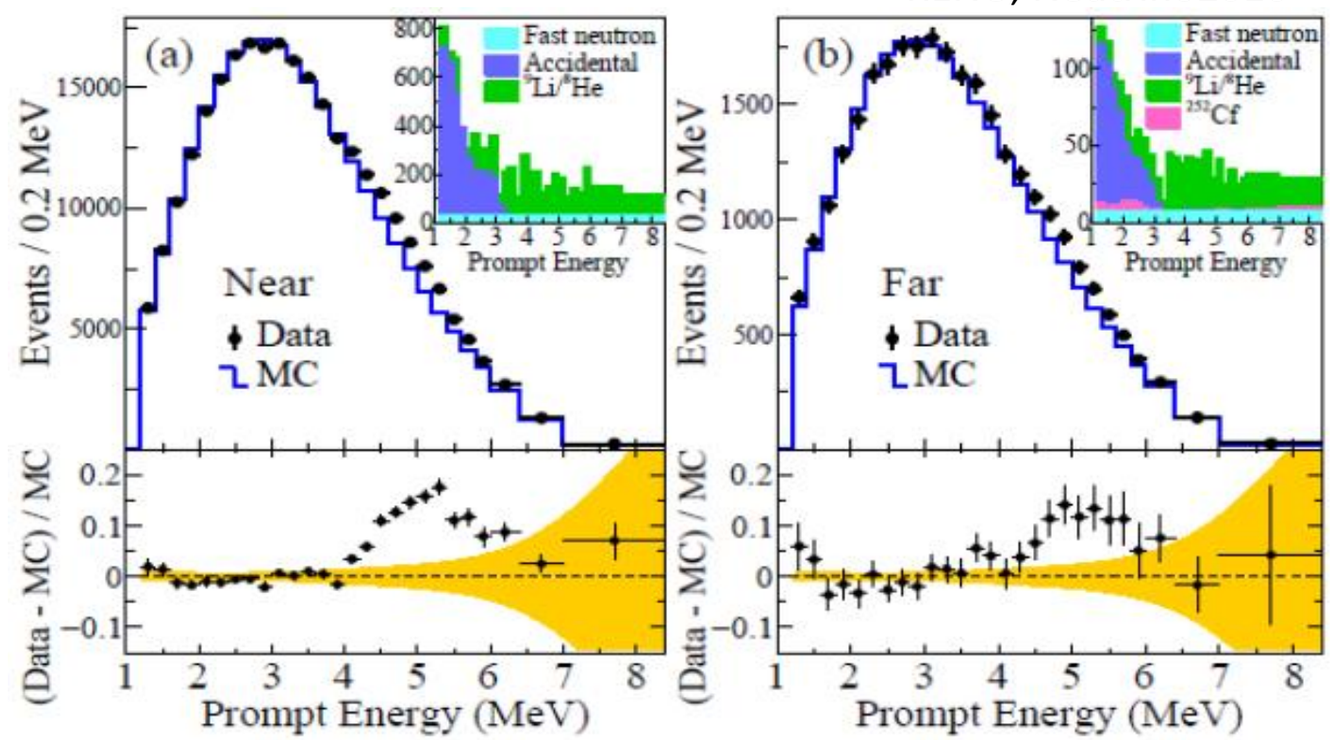
No bump or other strange behavior in B-12 spectrum WRT prediction…

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

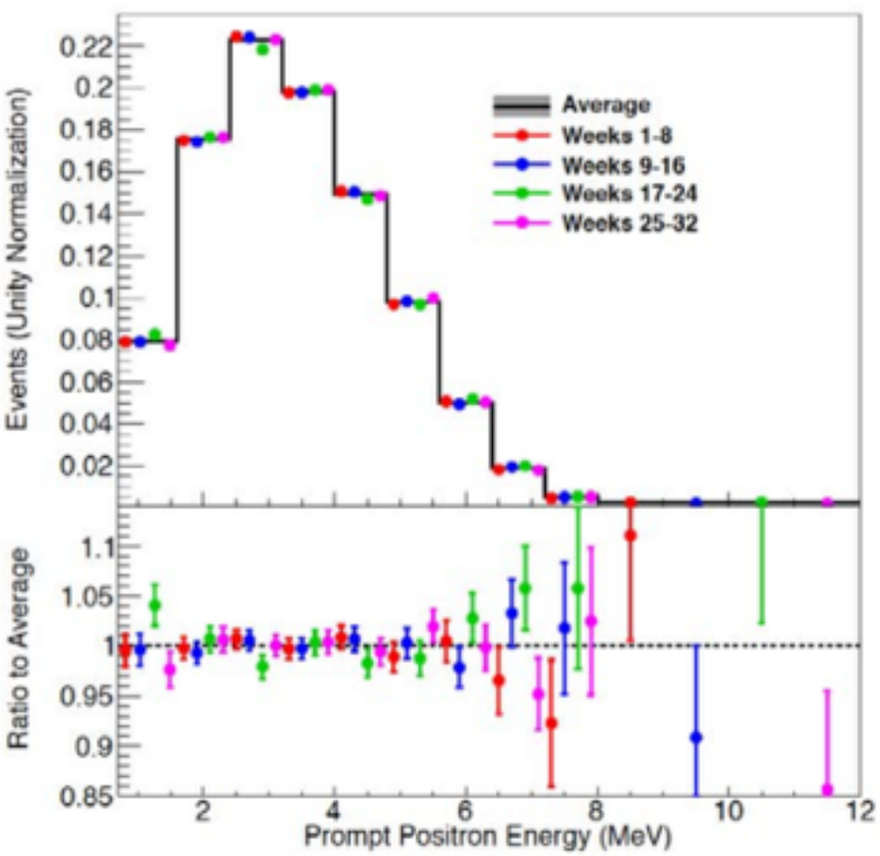
Skeptical Question 3

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

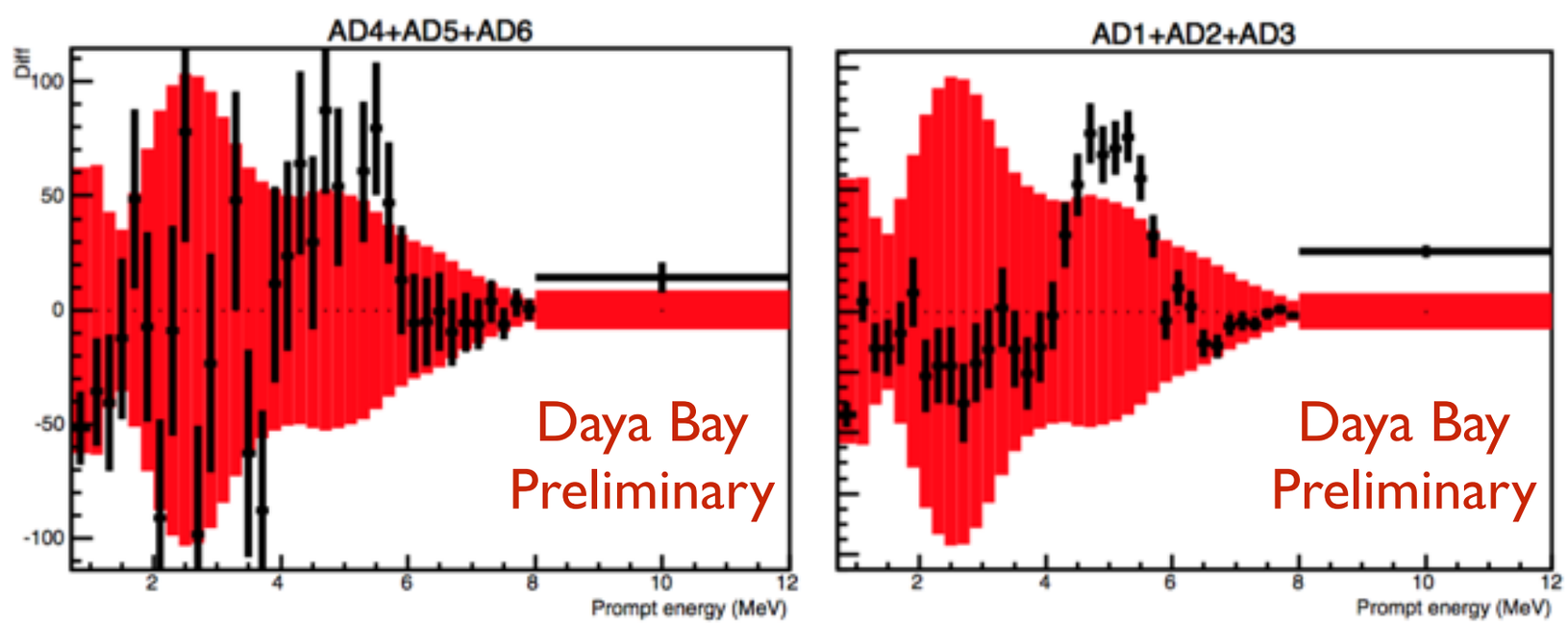
RENO, Neutrino2016



No time-dependent spectral changes observed

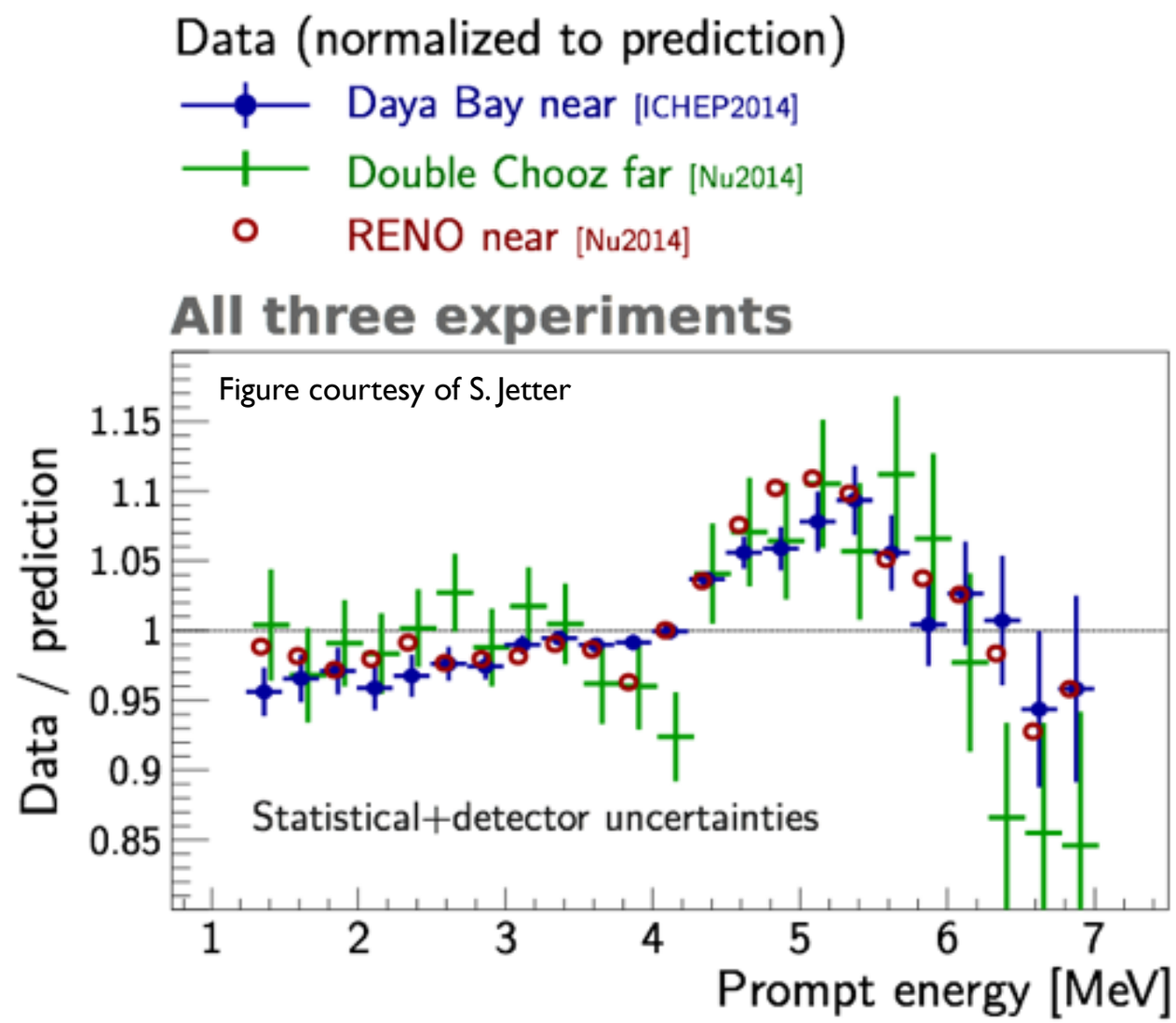


Different detectors see the same general feature



Piling On The Skeptic

- 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 <u>IS REAL</u>.
- Already discussed why we believe the flux anomaly is also very real.



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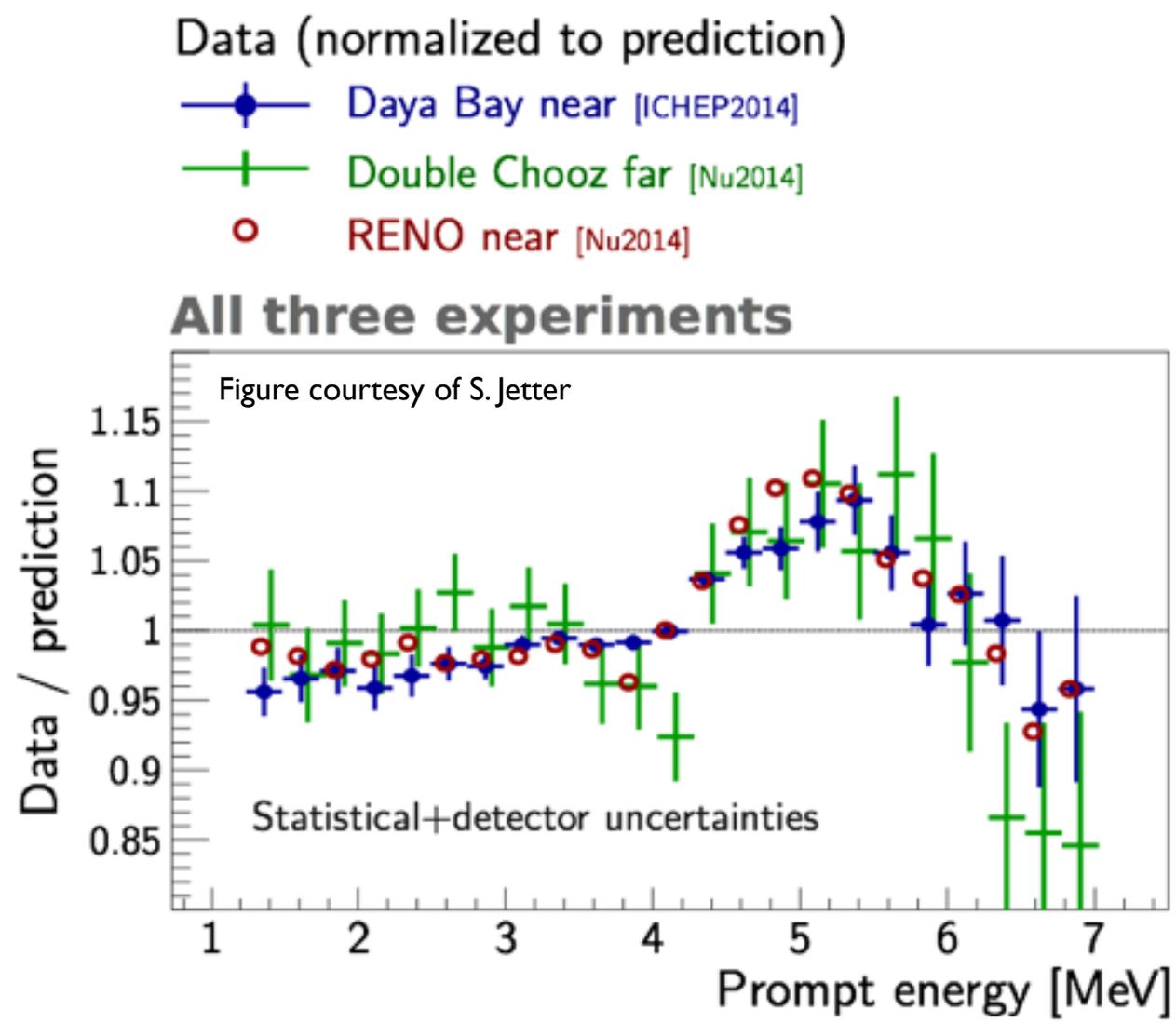
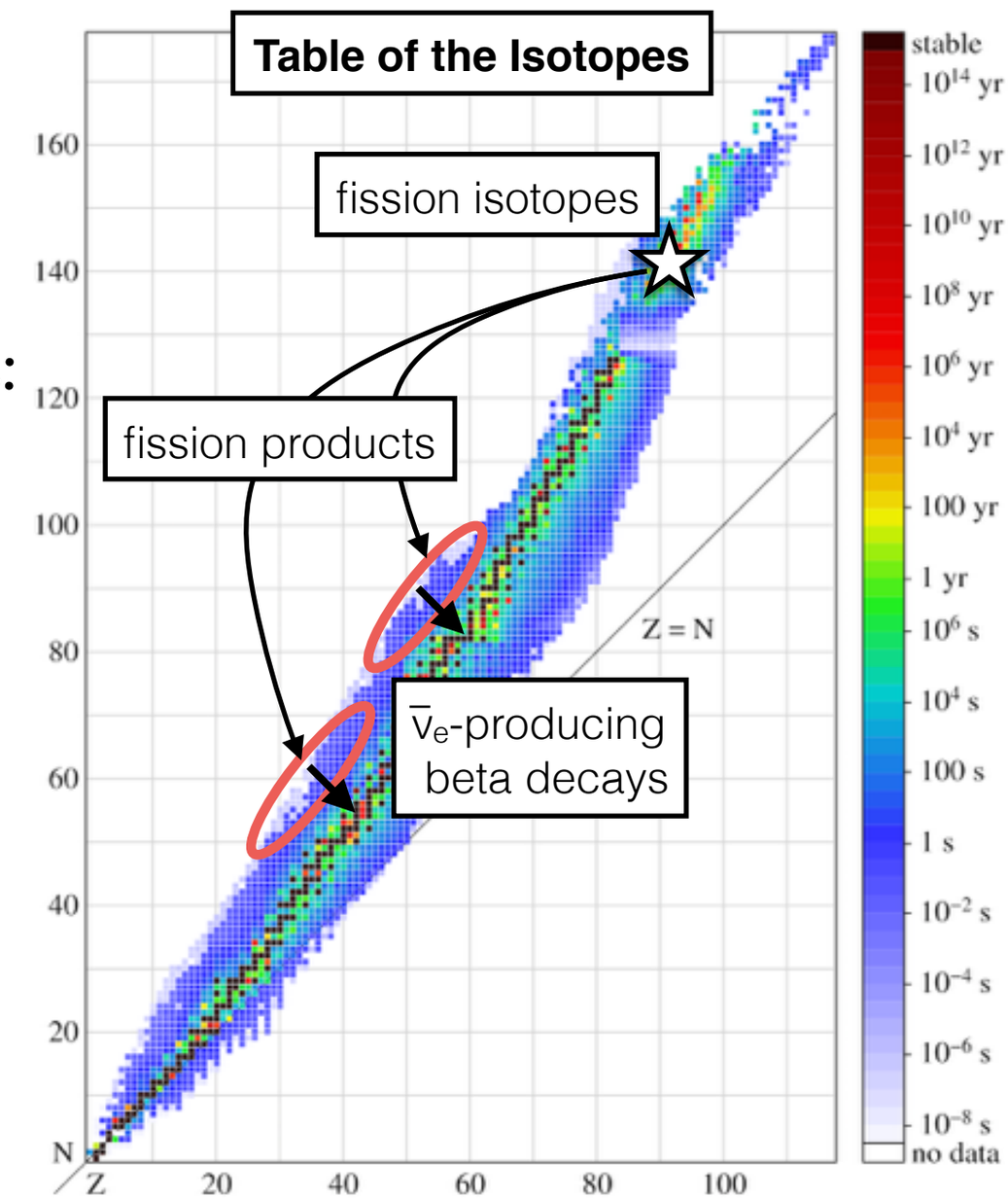
- Already discussed why we believe the flux anomaly is also very real.
- So, let's move on: what could be wrong with the predictions?



Reactor Prediction Possibilities

- A litany of hypotheses <u>HOW</u> 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, hep-ex[1512.06656] (2015)
  - Etc…



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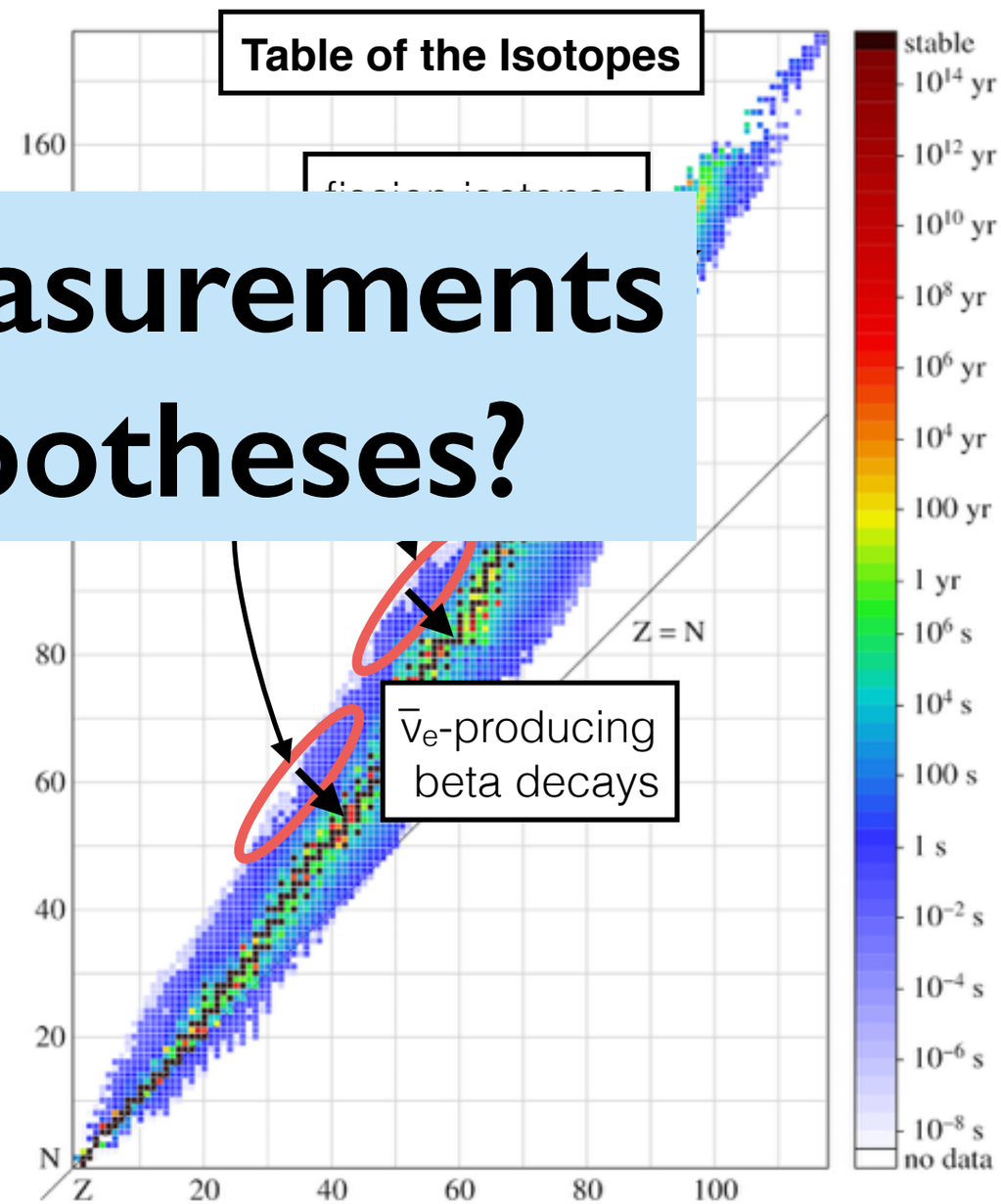
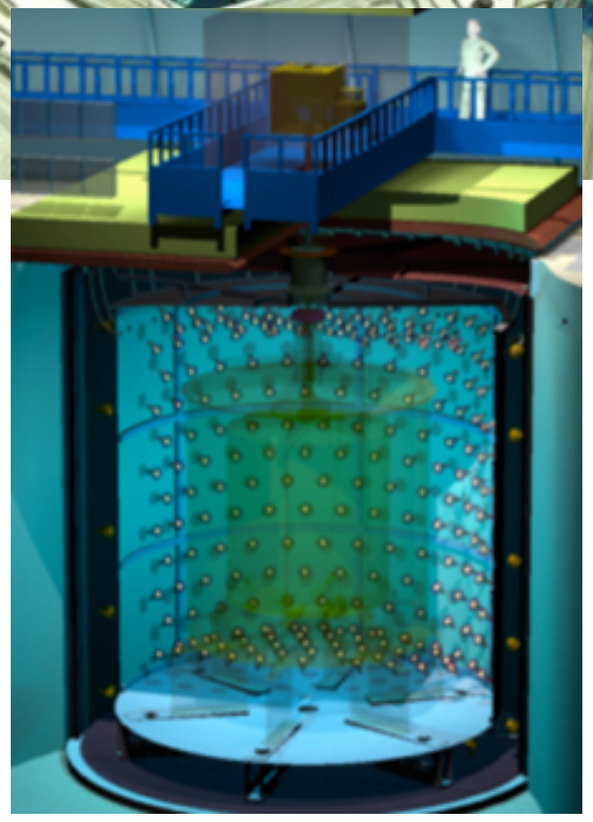
How can future measurements address these hypotheses?



Neutrino Tools At Our Disposal

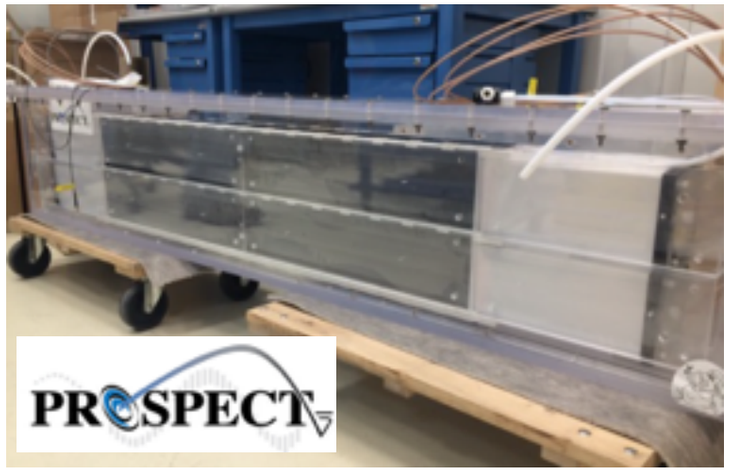
- Also have a solid group of current/future reactor experiments:

θ_{13} Experiments



Double Chooz

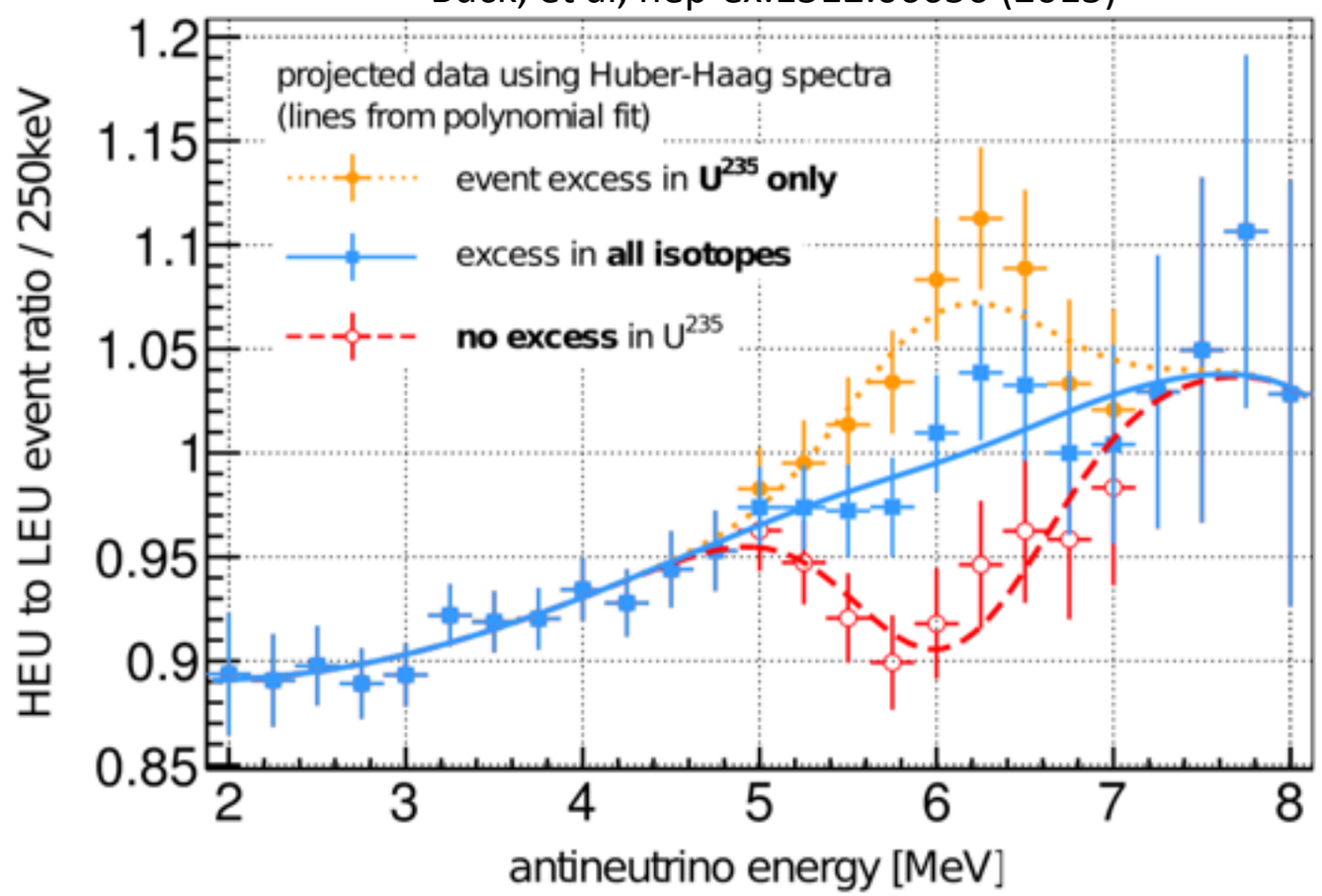
Short-Baseline Experiments



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.

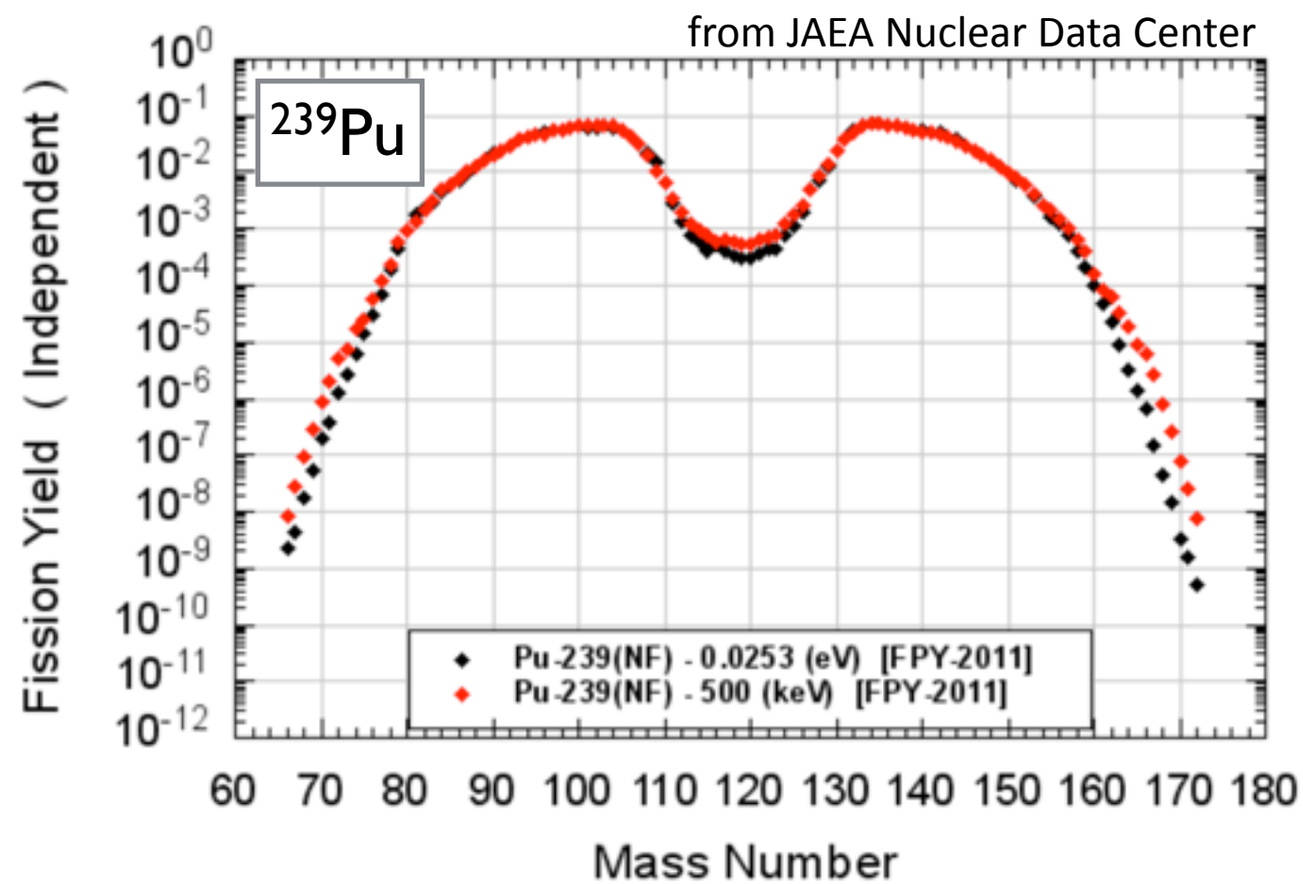
Buck, et al, hep-ex:1512.06656 (2015)



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 <u>thermal neutrons only</u>
  - 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…)



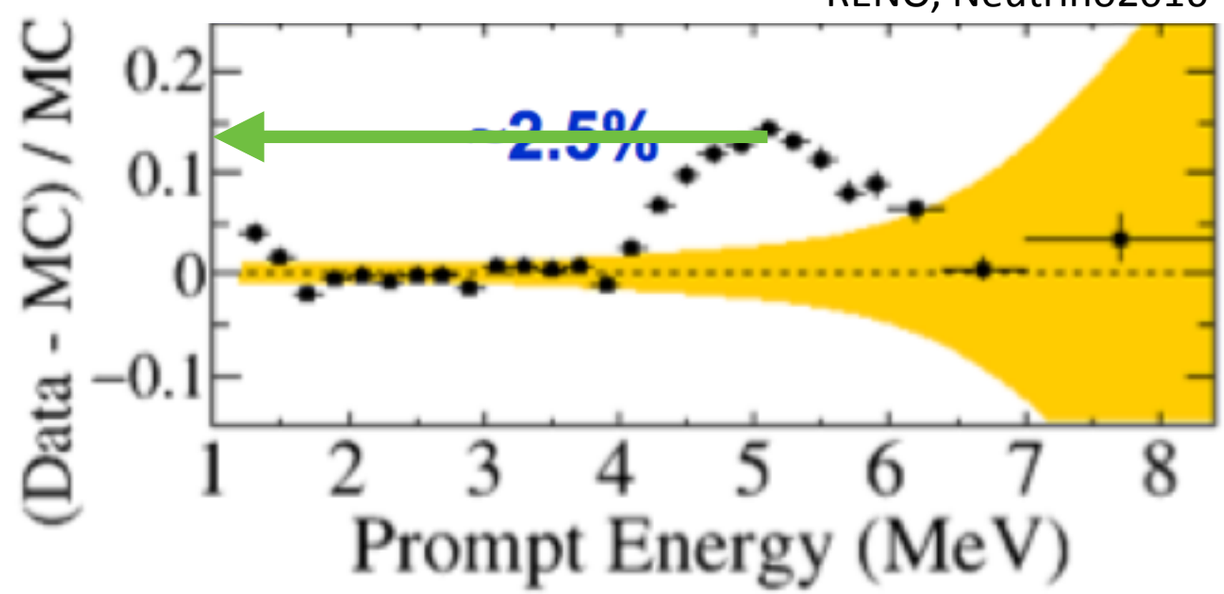
Example: Only ^{238}U?

- Size of bump is different for RENO, Daya Bay.

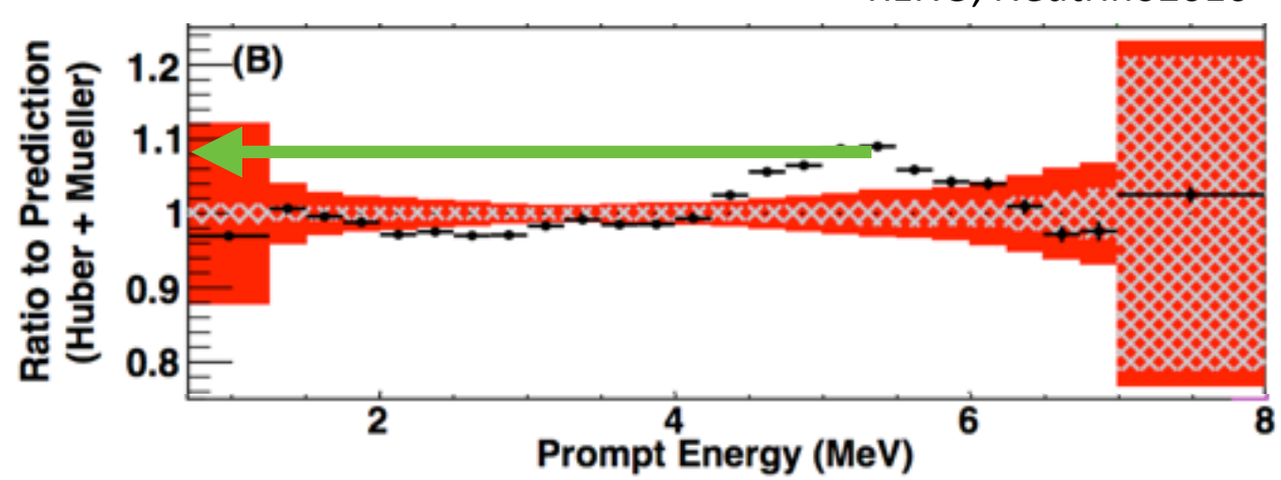
Hayes, et al, **PRD** 92 (2016)

  - ~1.5% of signal for Daya Bay, versus ~2.5% for RENO
- ^{238}U contributions are also different
  - ~7.5% for Daya Bay, versus ~12% for RENO
- If this is true, could the bump be proportional to ^{238}U contributions?
- Detailed joint analysis is essential to trust such a comparison.
  - Are energy scales equally accurate for both experiments?
  - Why do the other parts of the spectrum look different between the two?

RENO, Neutrino2016



RENO, Neutrino2016



Summary

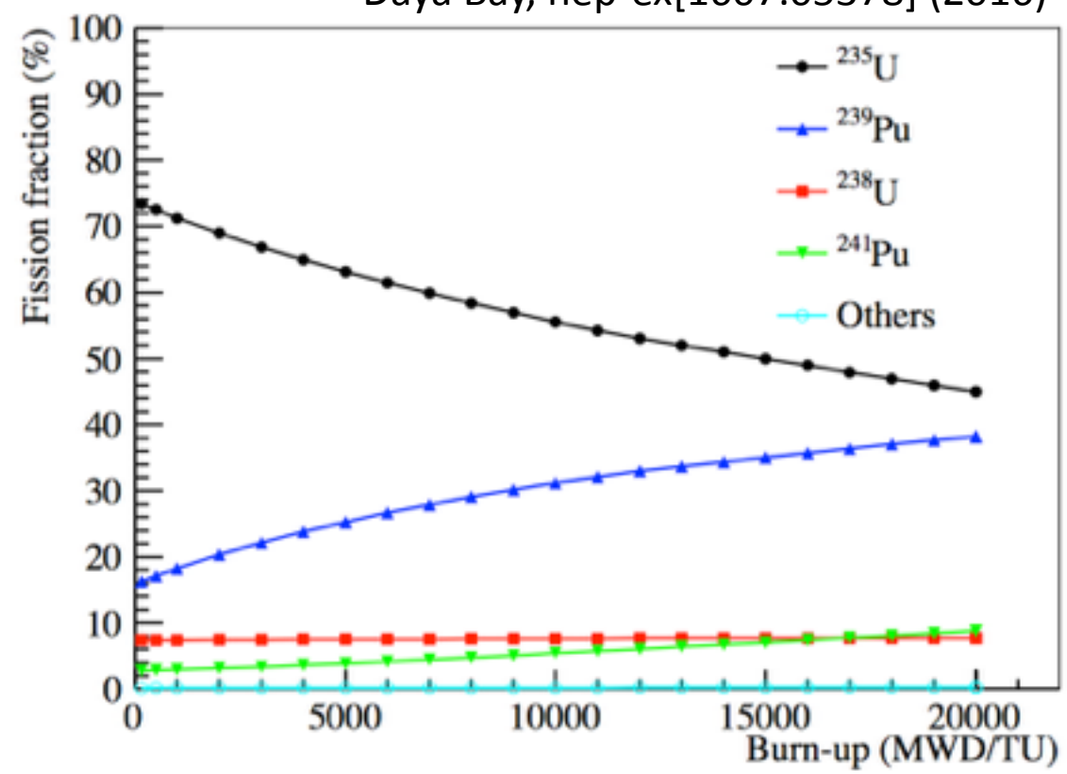
- Recent reactor spectrum and flux measurements do not agree with state-of-the-art reactor flux calculations.
- A wide variety of hypotheses exist to explain these discrepancies
- New reactor experiments and new θ_{13} experiment data are arriving just at the right time to address many hypotheses
- It's a great time to be a nuclear-physics-loving neutrino experimentalist!

END

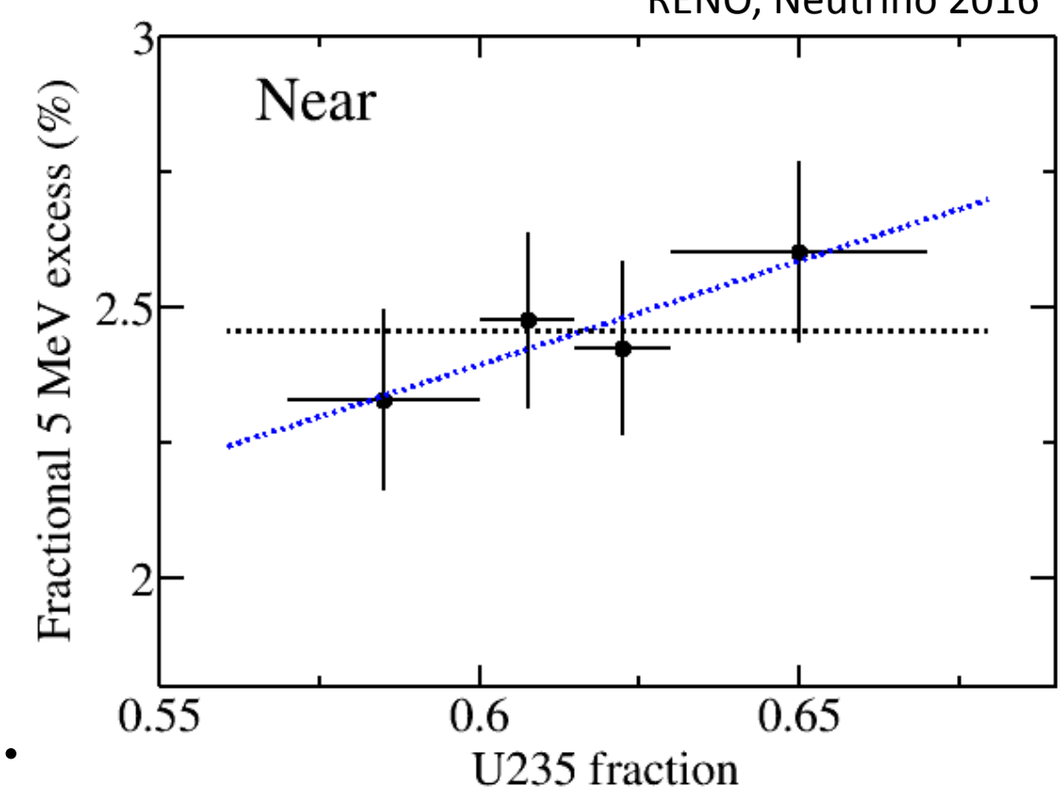
Only ^{239}Pu, or Only ^{235}U?

- 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 <u>spectrum</u>, 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 <u>should one expect?</u>
  - 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)

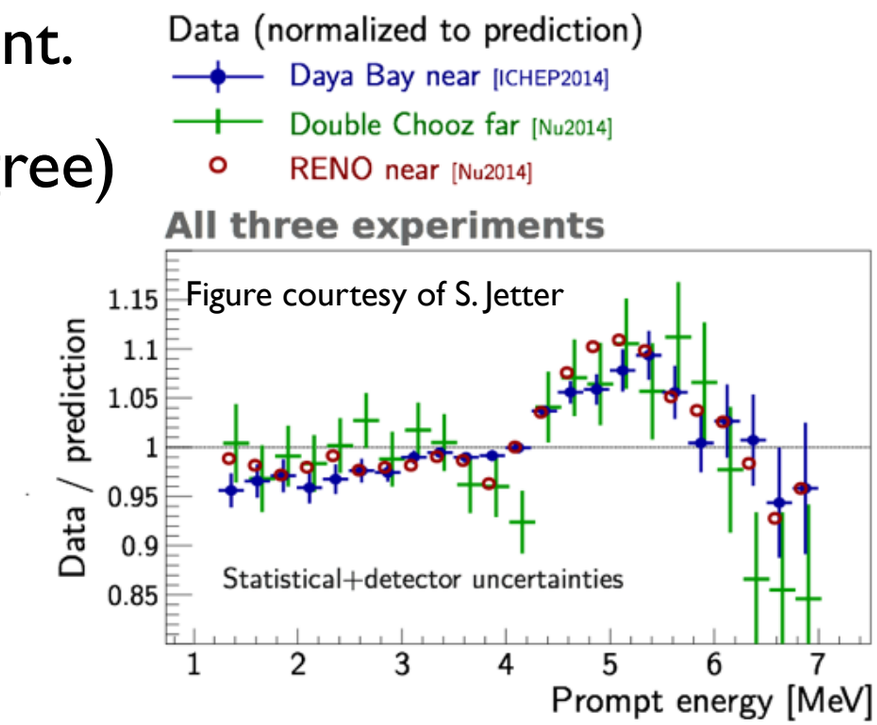


RENO, Neutrino 2016



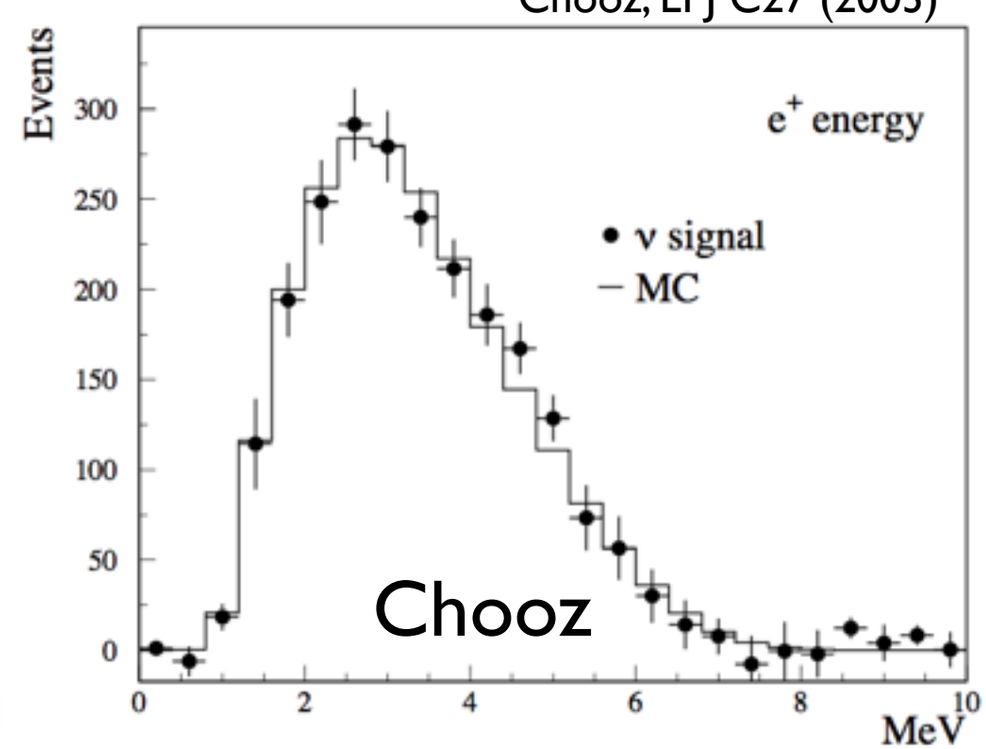
Piling On

- 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

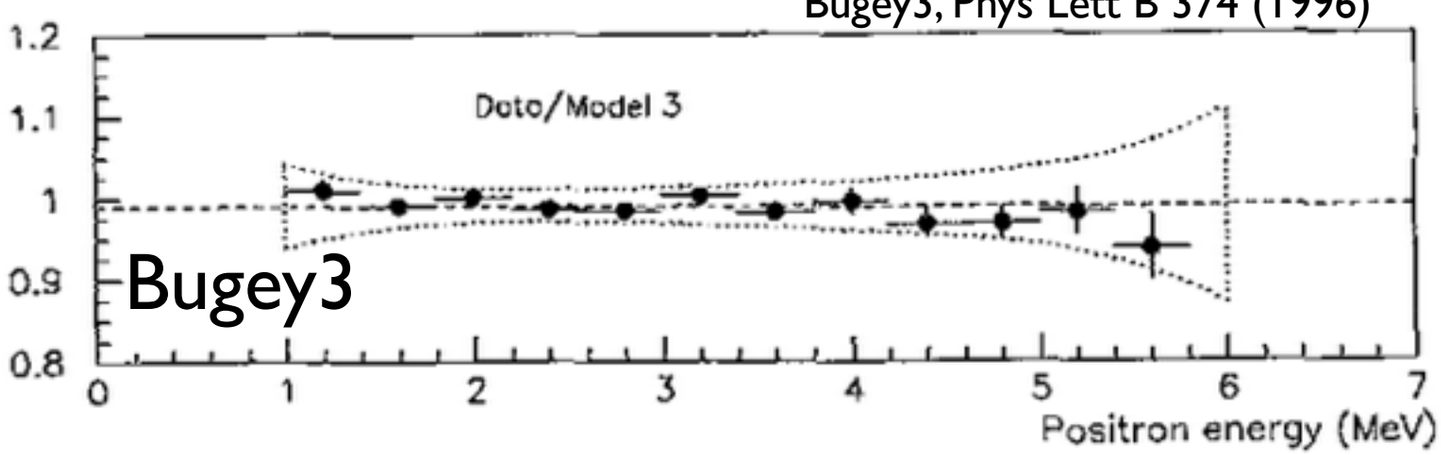


- Other notable results:
  - CHOOZ: A hint present, low CL
  - Bugey3: Seems like no feature is present?
    - Large non-scintillating volume in target? Binning?
    - Something else?

Chooz, EPJ C27 (2003)



Bugey3, Phys Lett B 374 (1996)



SBL Reactor Context

- PROSPECT: designed to provide a precision measurement for BOTH key physics goals
  - Moveable segmented detectors give best mapping of oscillation space
  - Design enables higher energy resolution other efforts
- PROSPECT has the experience, development, and infrastructure in place for the world's pre-eminent SBL reactor effort.

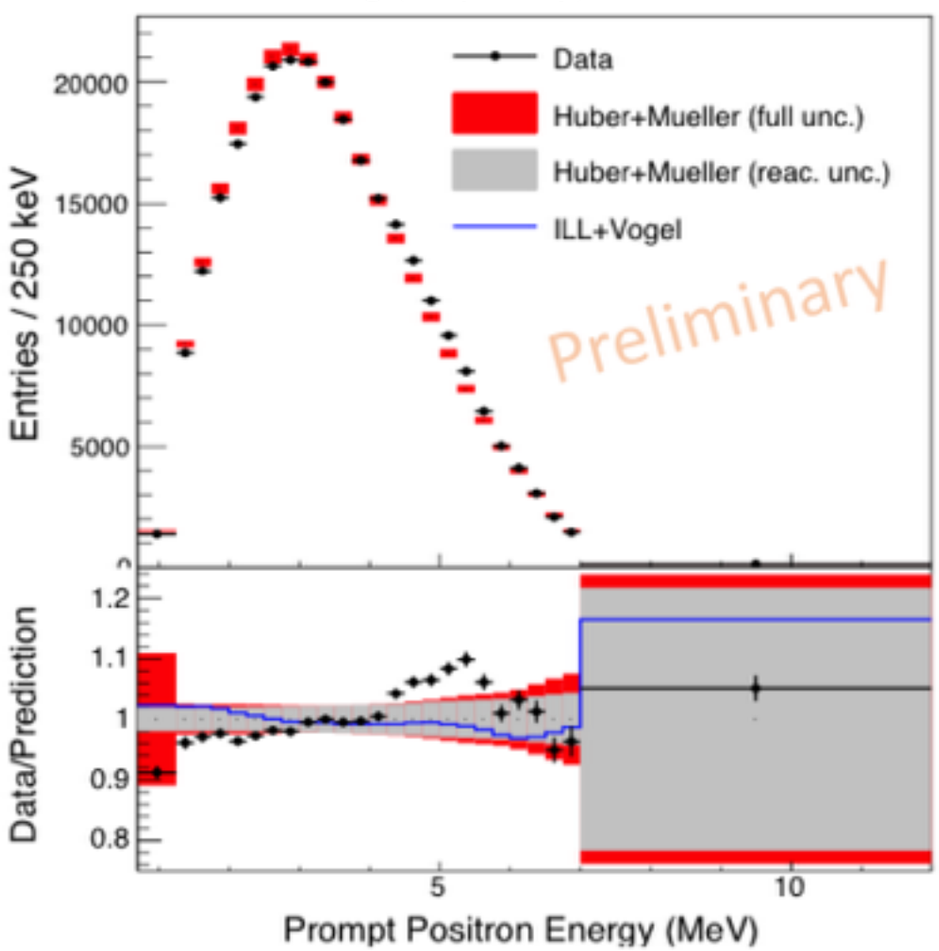
My (biased) overview of global efforts — Good : Not Good

	Effort	Dopant	Good X-Res	Good E-Res	L Range (meters)	Fuel	Exposure, MW*ton	Move-able?	Running at intended reactor?
US	**PROSPECT**	**Li**	**Yes**	**Yes**	**6.5-20**	**HEU**	**185**	**Yes**	**Yes**
	NuLat	Li/B	Yes	Yes	TBD	TBD	TBD	Yes	No
EU	Nucifer	Gd	No	Yes	7	HEU	56	No	Yes
	STEREO	Gd	Yes	Yes	9-11	HEU	100	No	Yes
	SoLid	Li	Yes	No	6-8	HEU	155	No	Yes
Russia	DANSS	Gd	Yes	No	9.7-12	LEU	2700	Yes	Yes
	Neutrino4	Gd	Yes	No	6-12	HEU	150	Yes	Yes
Asia	Hanaro	Li/Gd	No	Yes	20-ish	LEU	30	No	No

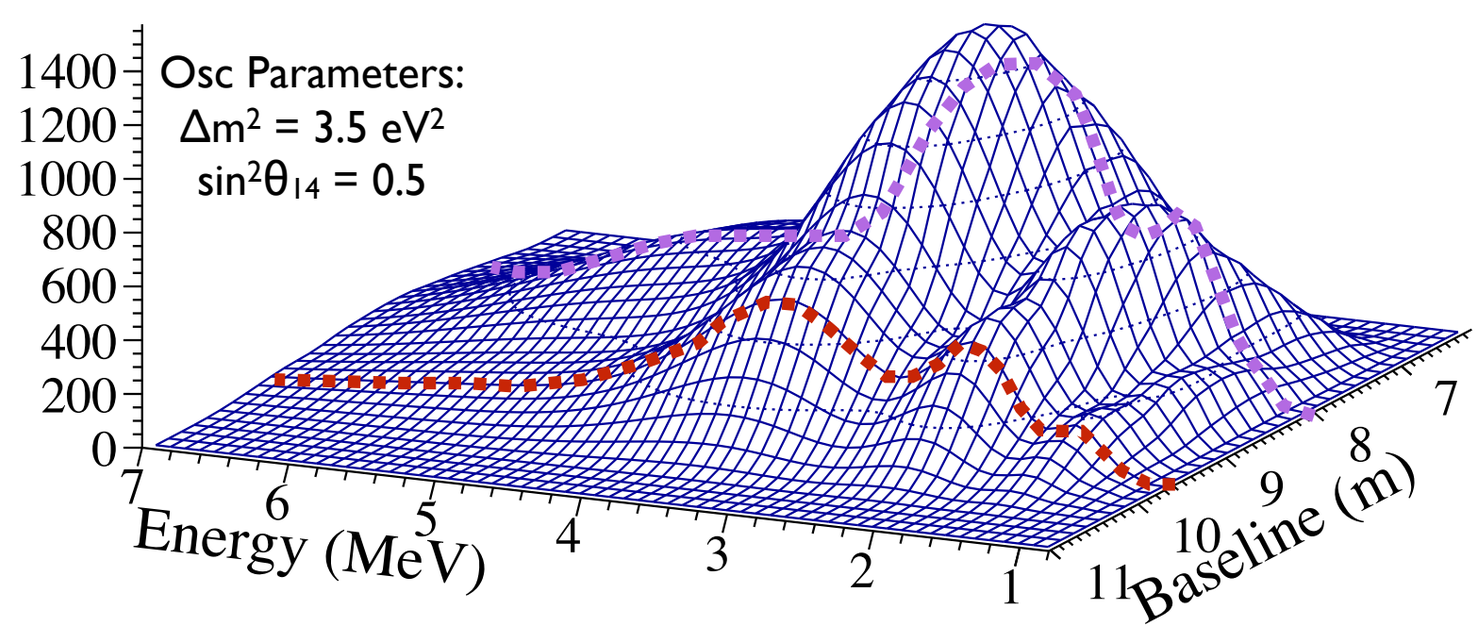
Getting New Data at Reactors

- A lot yet to be learned from/about reactor $\bar{\nu}_e$ spectra
- In particular, what is really needed is:
  - A high energy-resolution detector for precisely measuring absolute spectrum
  - A high position-resolution detector for comparing spectra between baselines
  - Must meet these requirements while also rejecting copious backgrounds

W. Zhong (Daya Bay) ICHEP 2014



Oscillated Spectrum at PROSPECT



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)

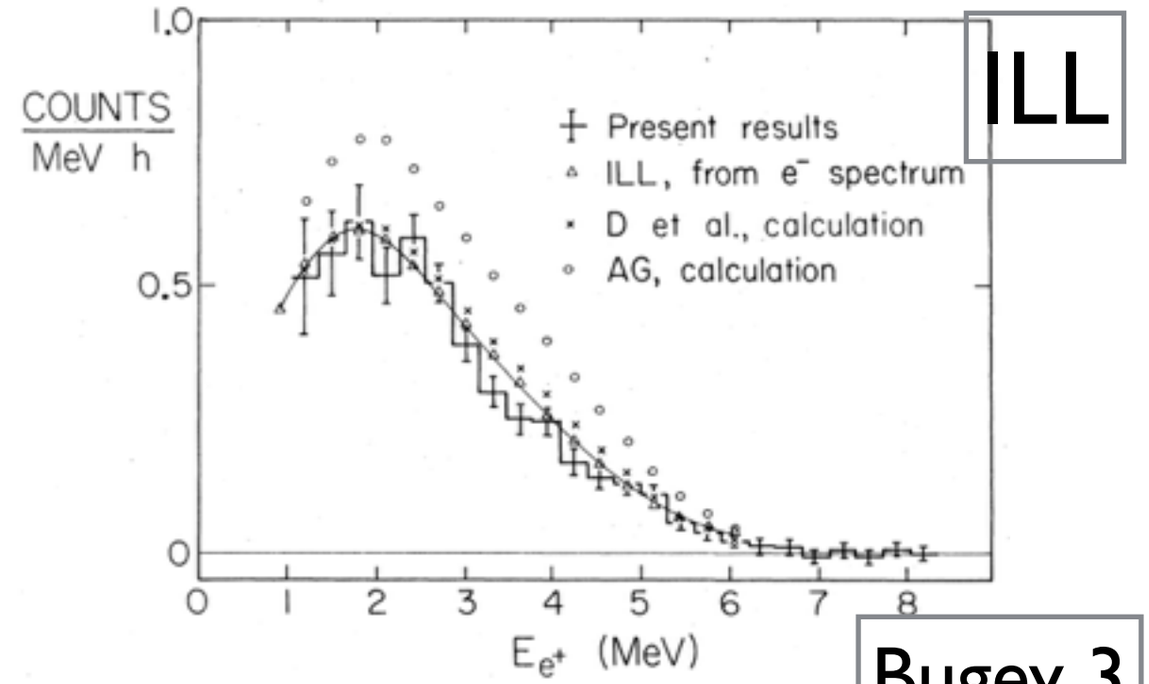
- 1980s: New reactor beta spectra: measurements — conversion now provides lower systematics

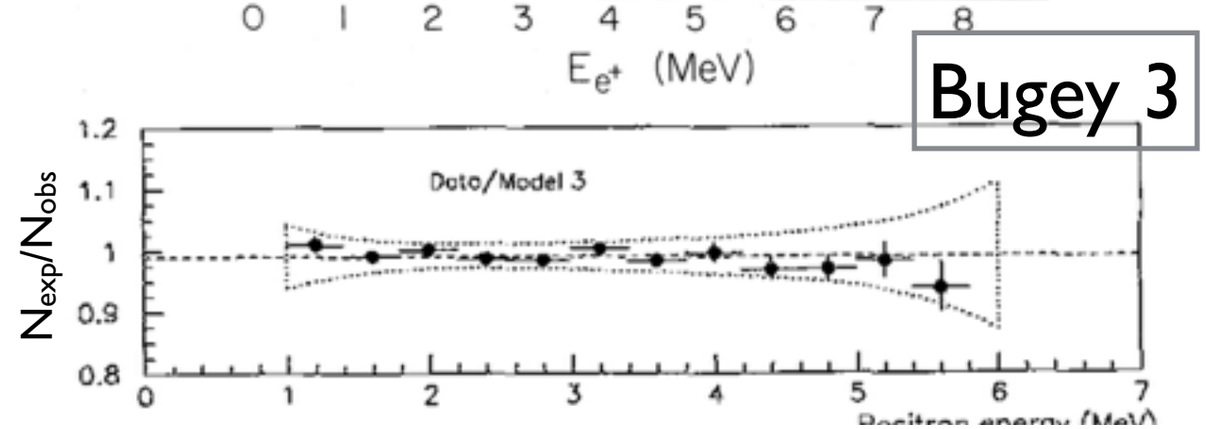
  Schreckenbach, *et al.*, Phys Lett **B**160 (1985)
  Schreckenbach, *et al.*, Phys Lett **B**218 (1989)

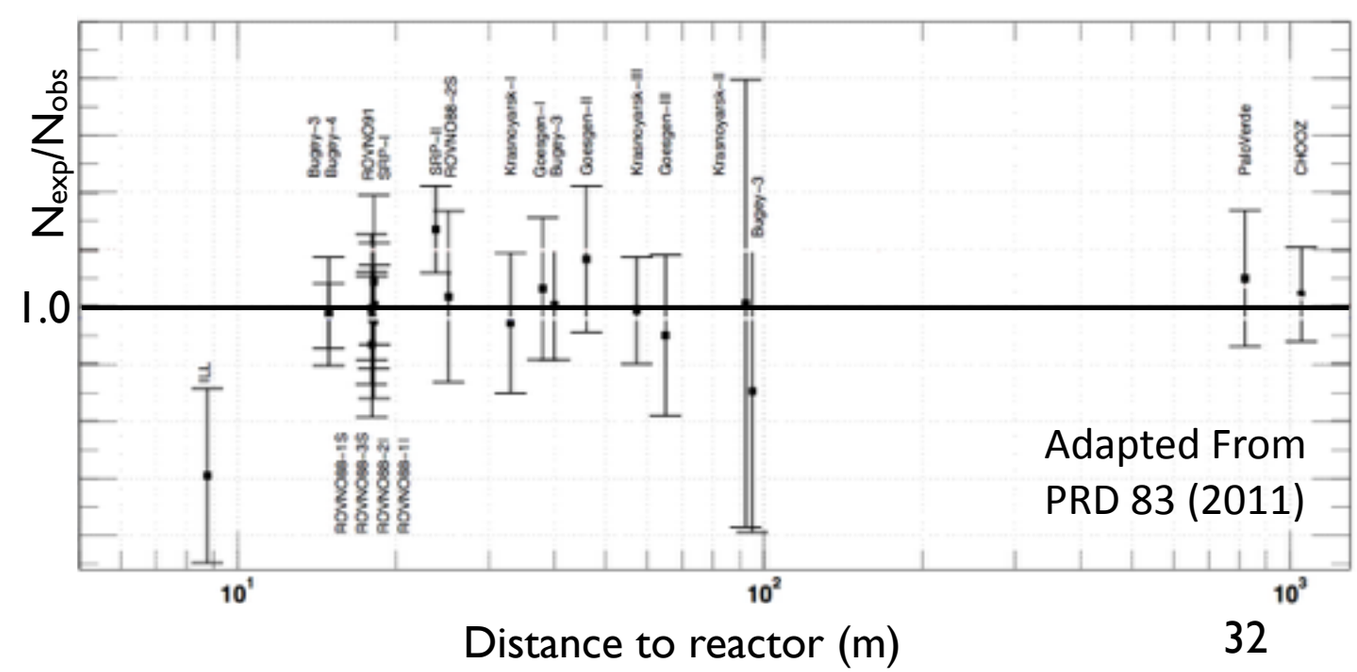
- 1990s: Bugey measurements fit converted spectrum well

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

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



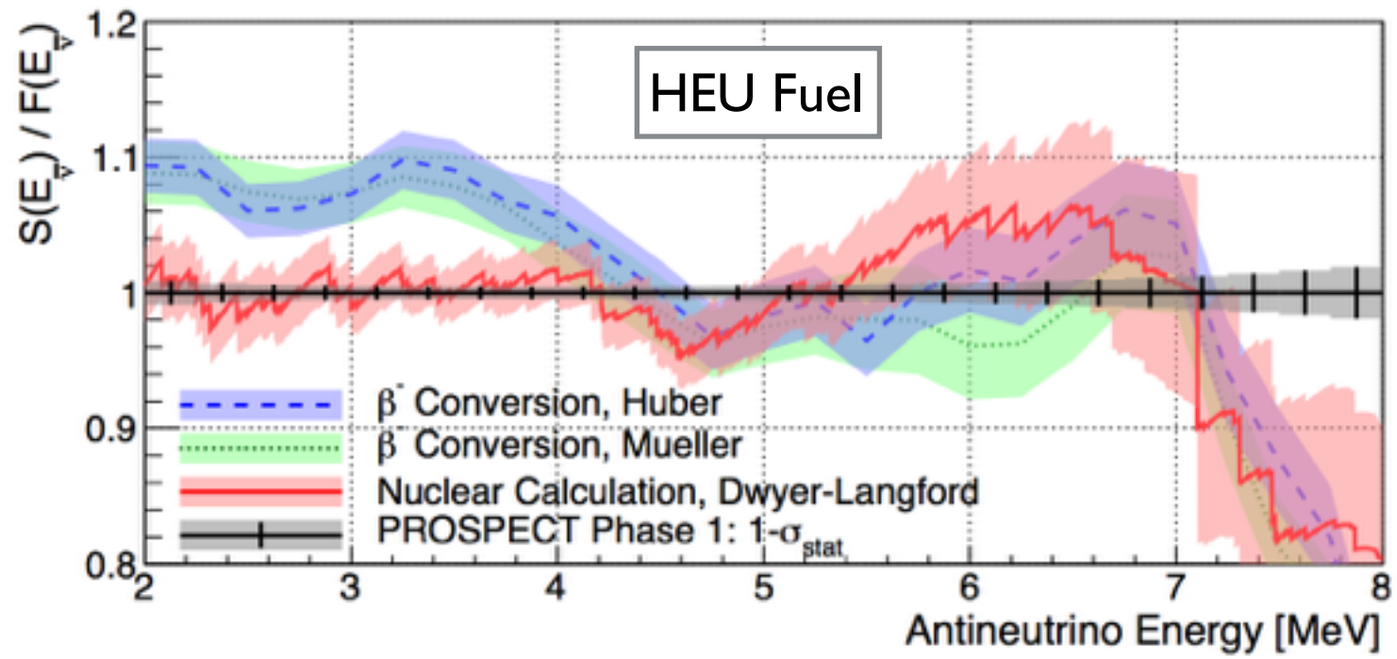


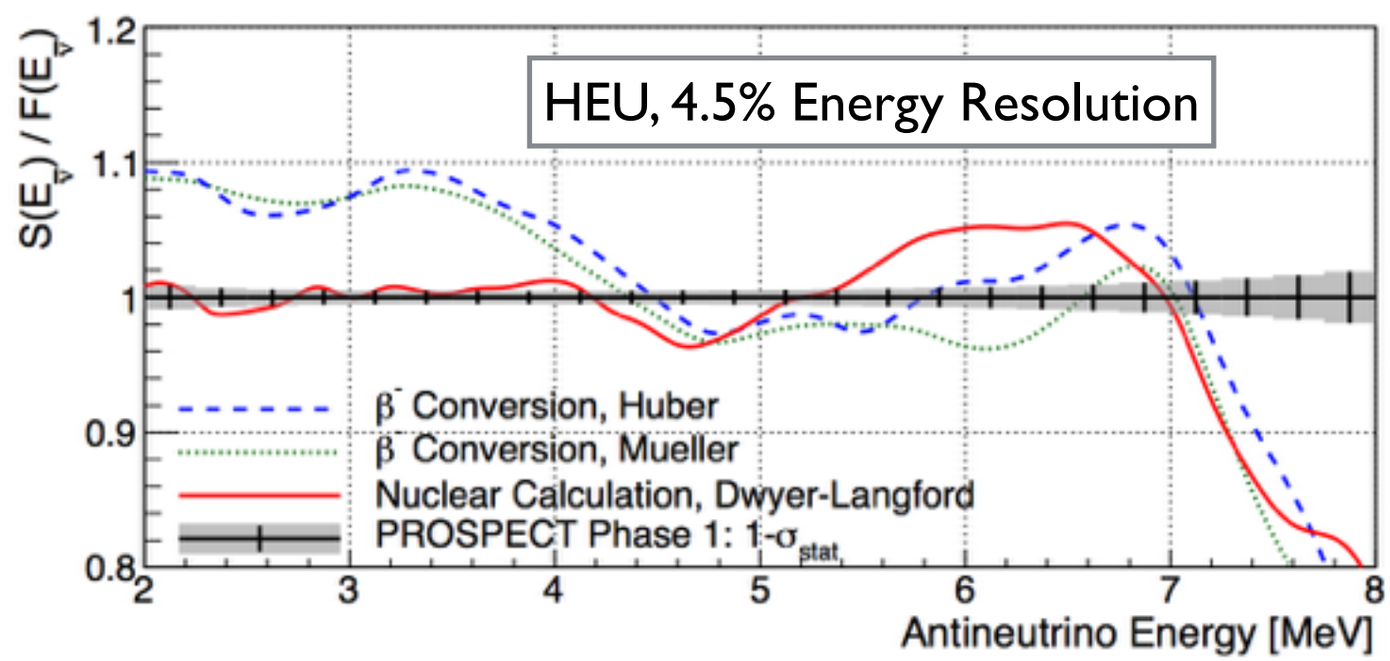


Adapted From PRD 83 (2011)

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)?





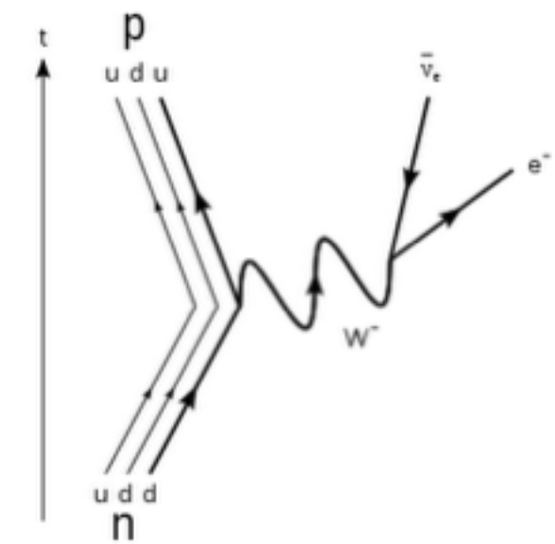
Beta Decay Recap

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

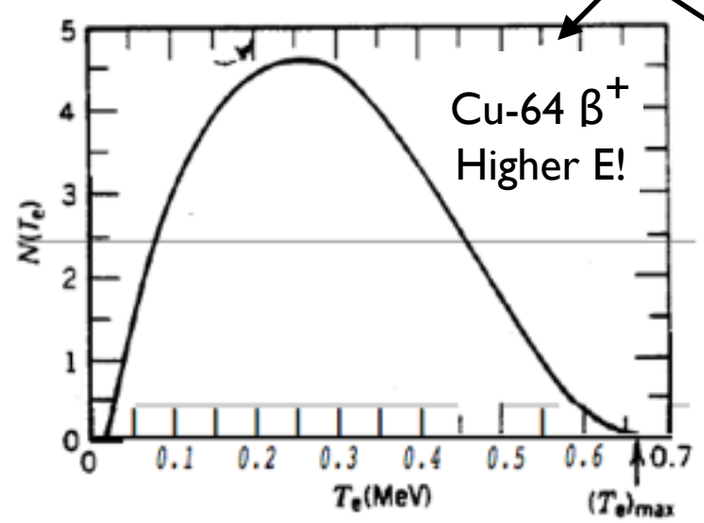
$$N_\beta(W) = K\,\underbrace{p^2(W - W_0)^2}_{\text{phase space}}\,F(Z, W)$$

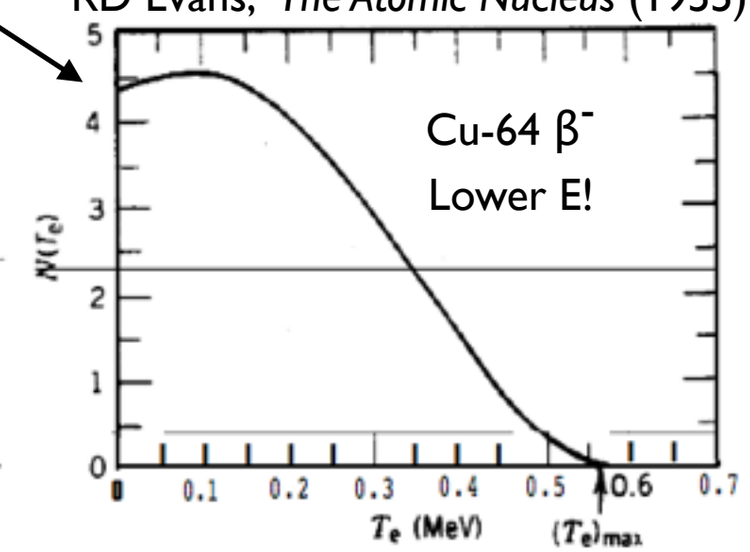
From nuclear matrix element: Extra factors of p pop in here for beta decays

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

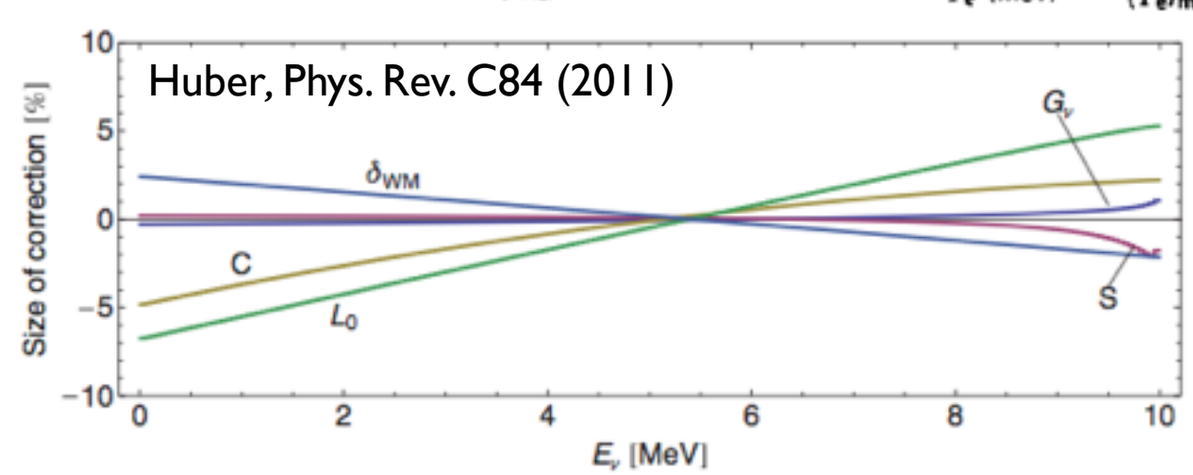


RD Evans, *The Atomic Nucleus* (1955)





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



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

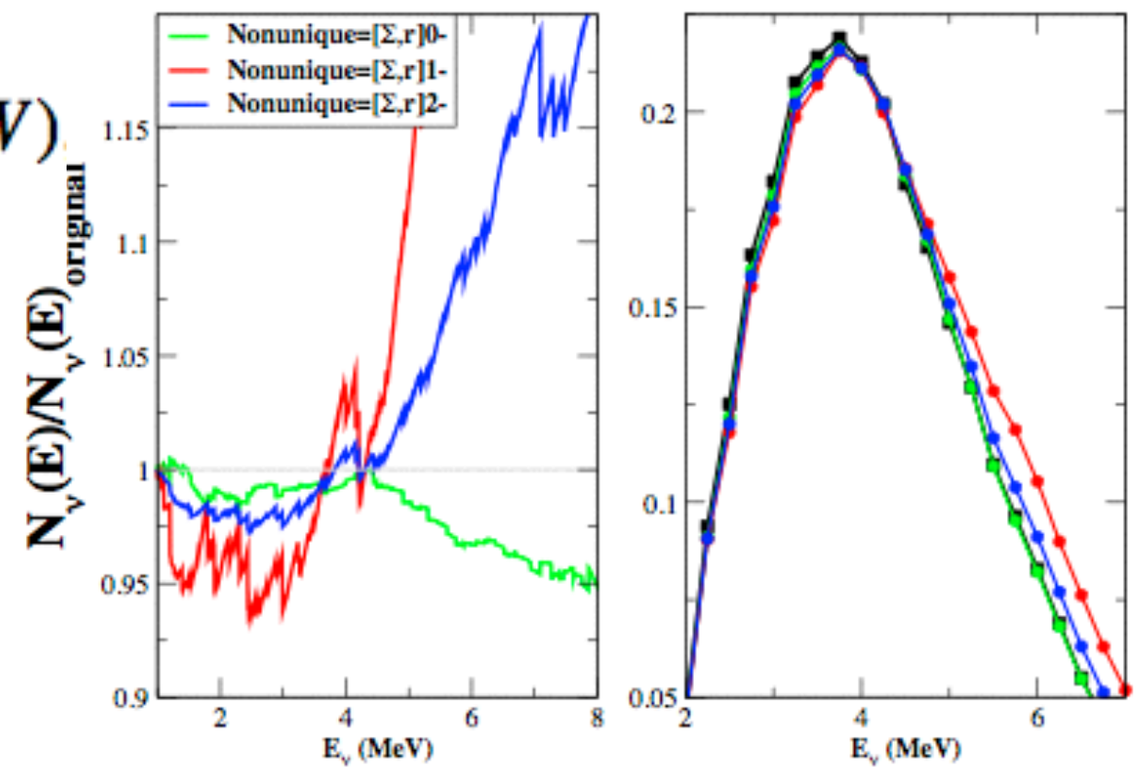
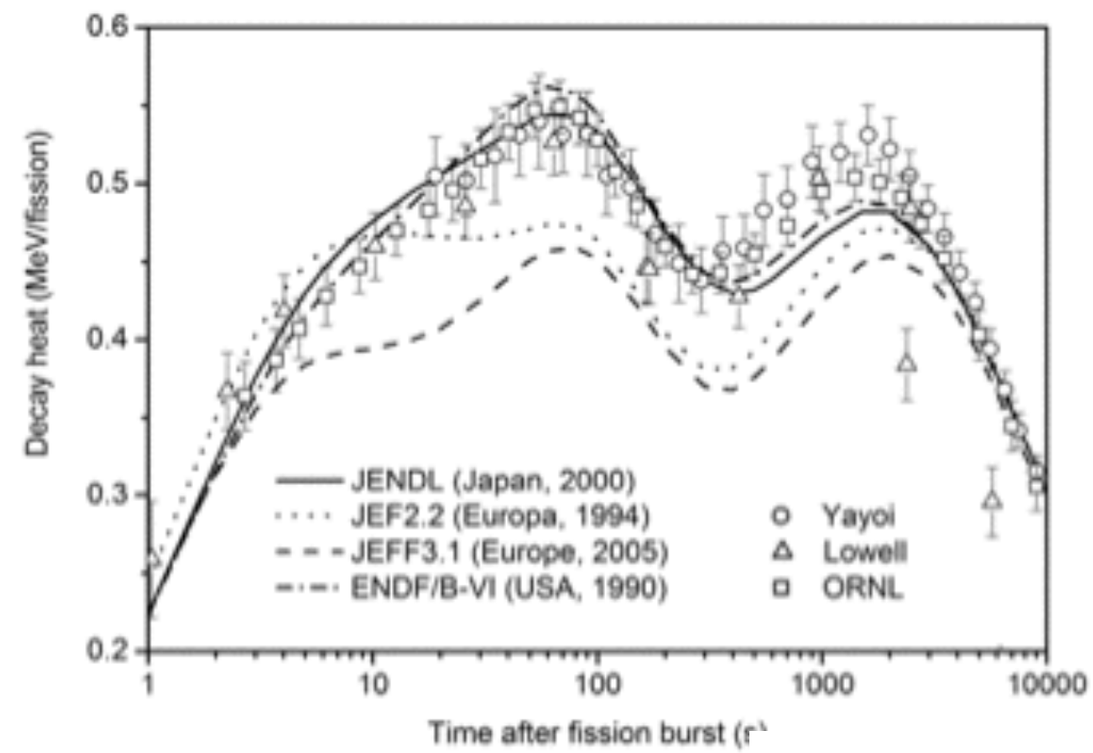


FIG. 3: Different treatments of the forbidden GT transitions contributing to the antineutrino spectrum summed over all actinides in the fission burn in mid-cycle [21] of a typical reactor. The left panel shows the ratio of these antineutrino spectra relative to that using the assumptions of Ref. [4]. 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



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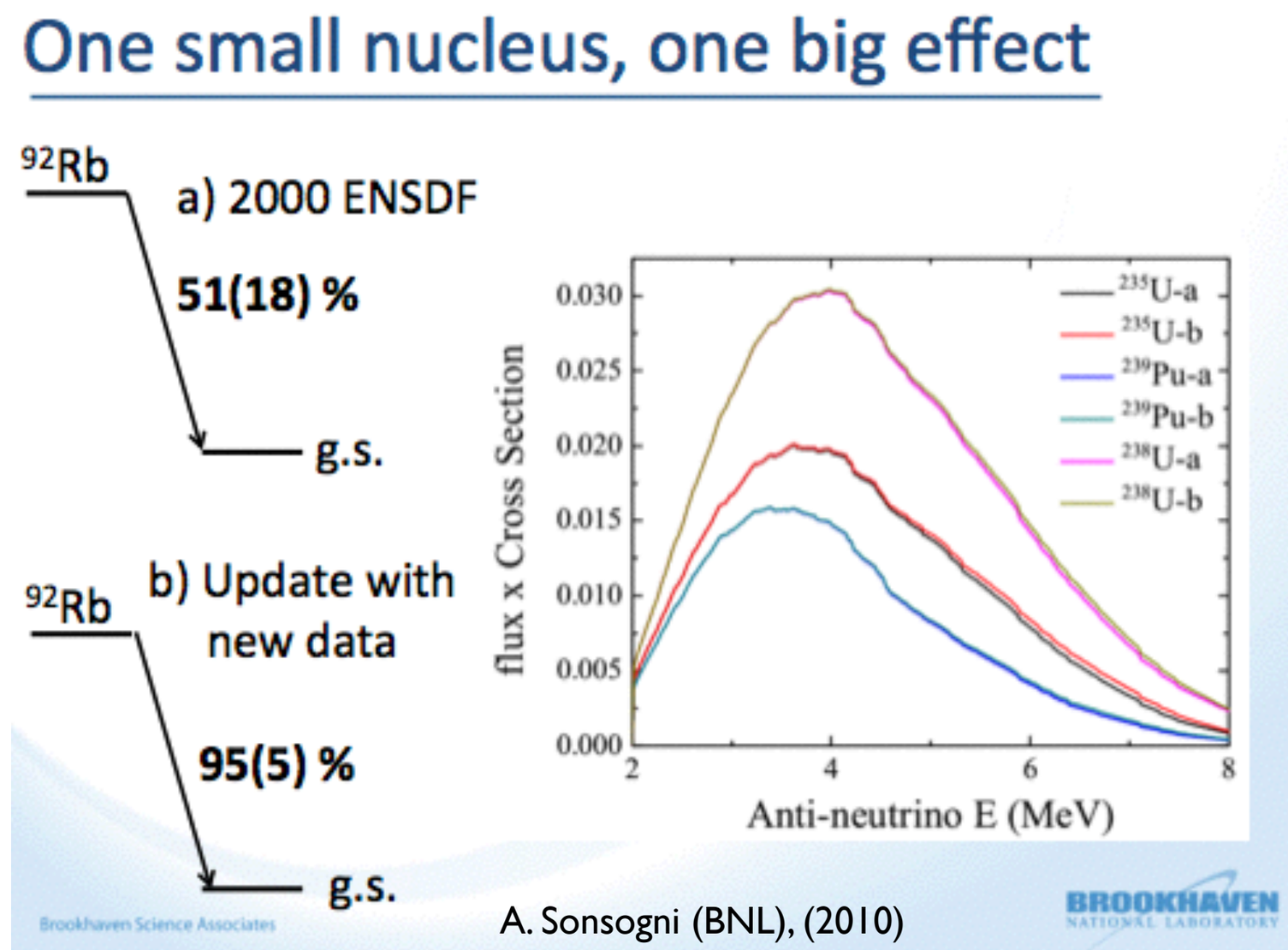
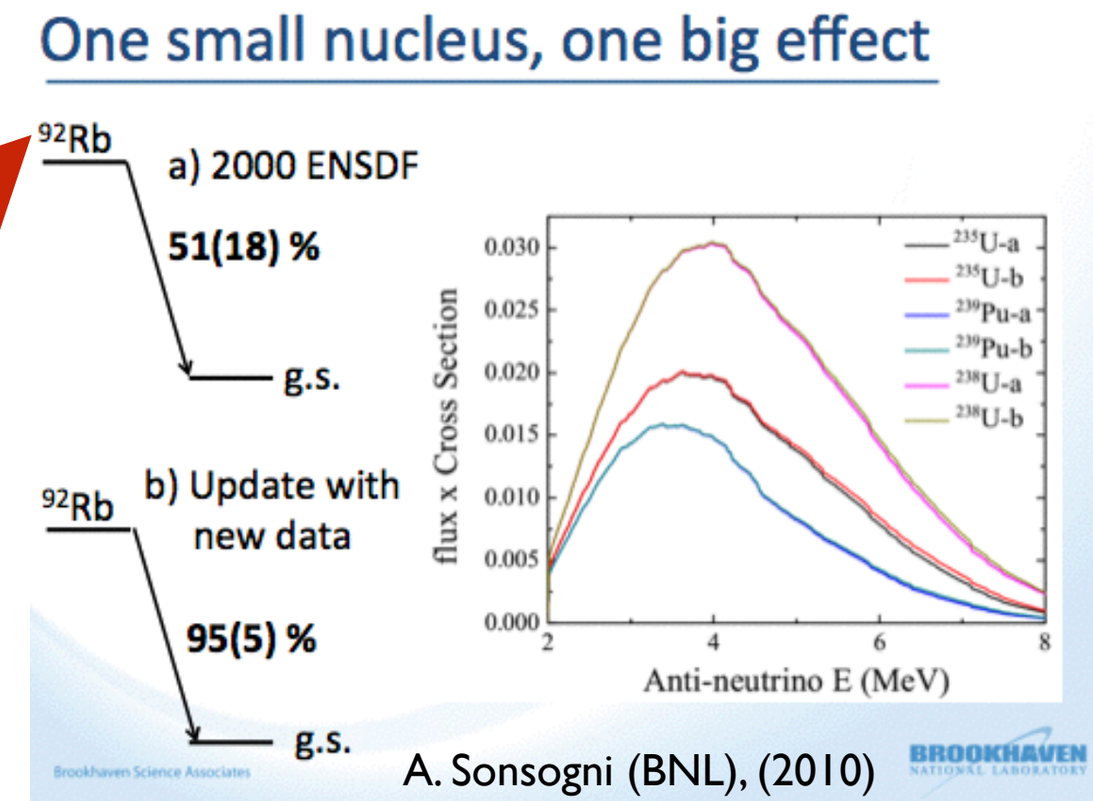
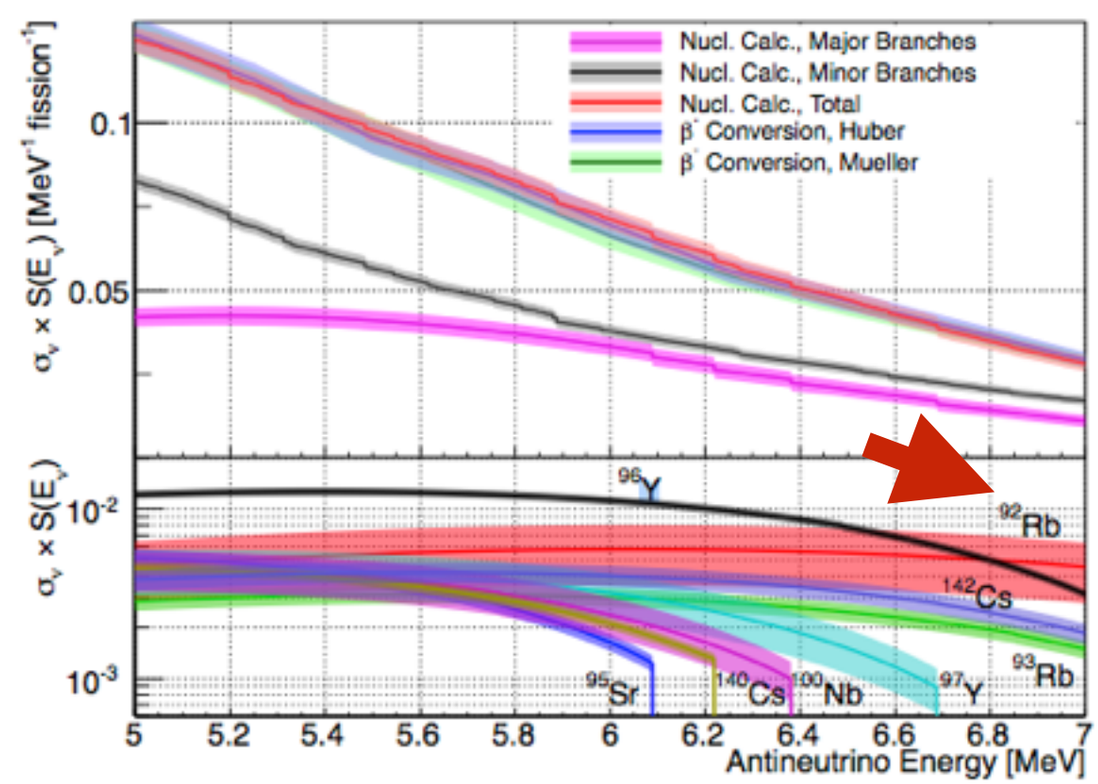
ASSESSMENT OF FISSION PRODUCT DECAY DATA FOR DECAY HEAT CALCULATIONS

Reactor Spectroscopy: Example

- TAGS:
  Total absorption gamma spectroscopy
- Measure total gamma energy, not individual gamma energies
- Allows ID of levels, BRs much easier



- If branching ratios are known better, decay released in those decays will be modelled better
- Better model = smaller safety factor = $$$ saved.

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