How Can Reactor IBD Help With Reactor CEvNS Physics?

November 16, 2020

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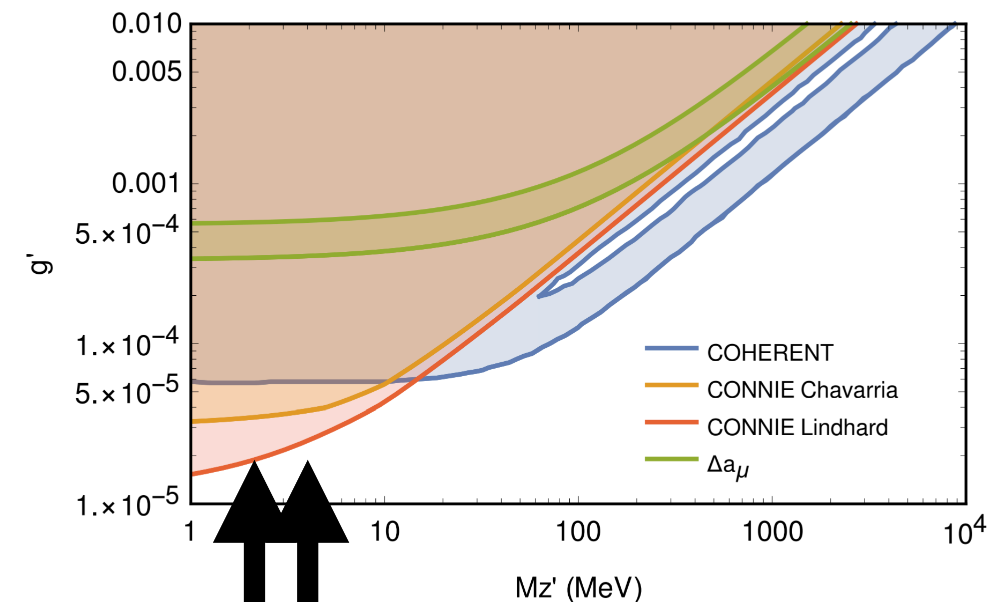
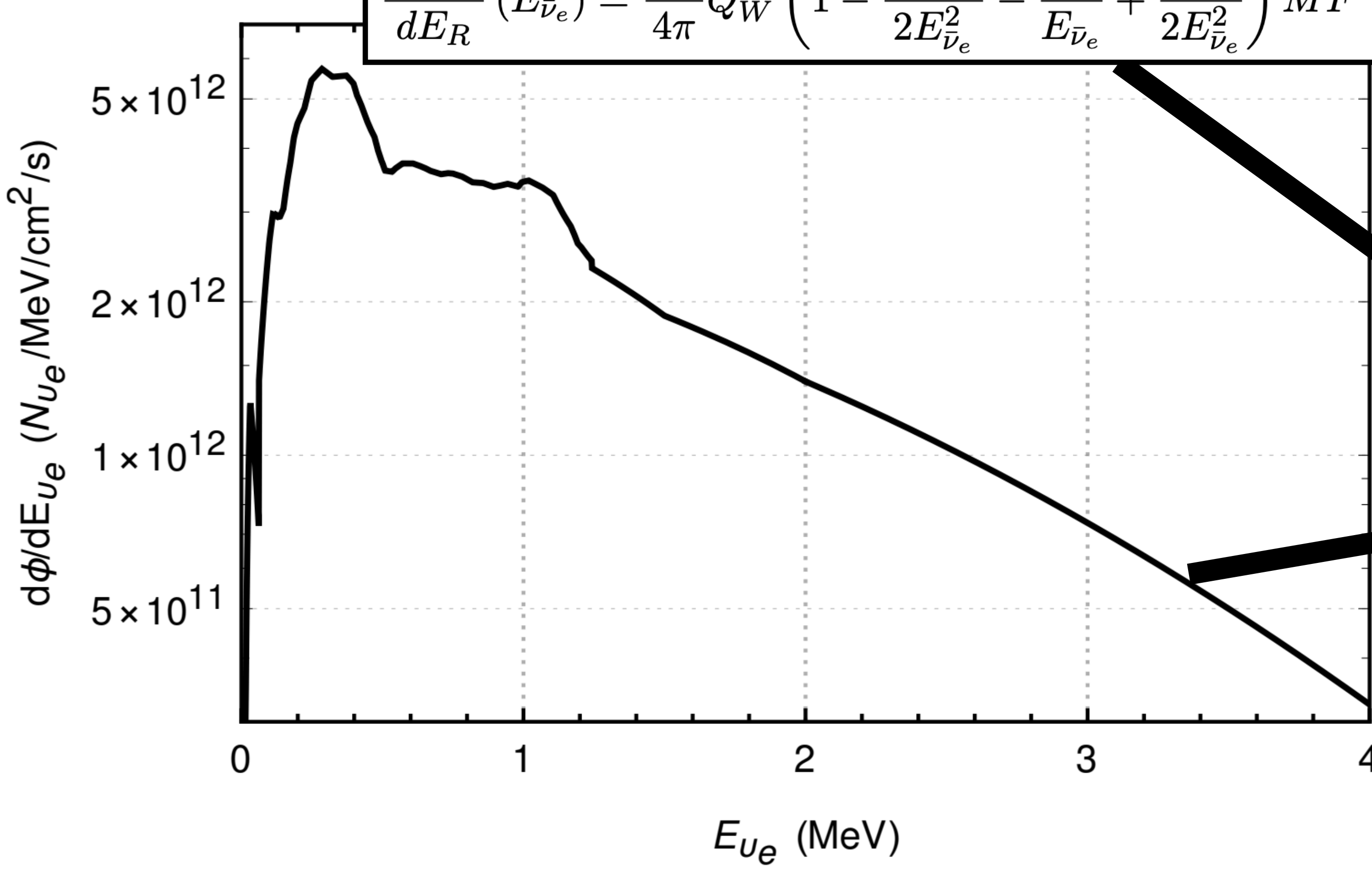
How To Do BSM with Reactor CEvNS

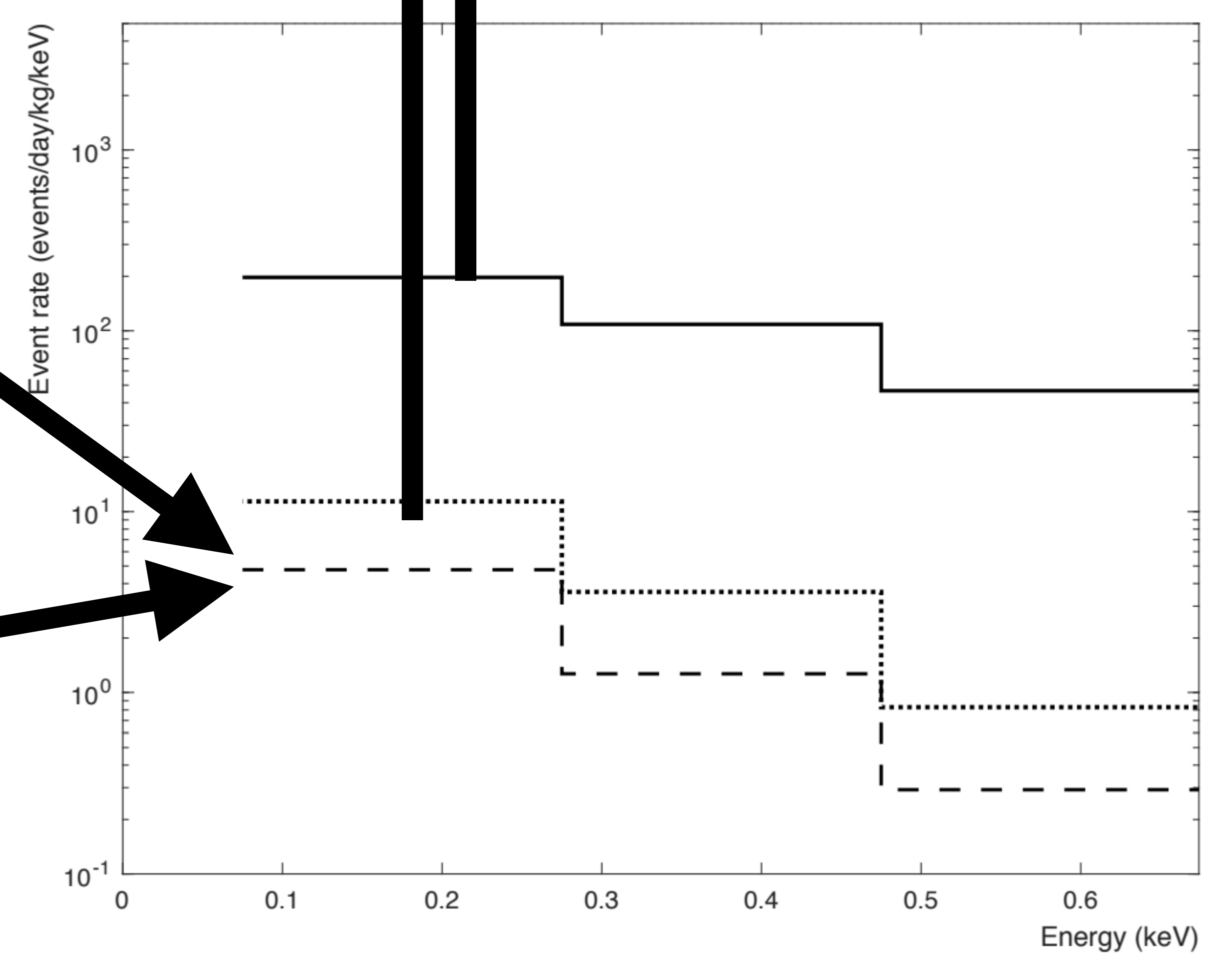
- Predict your reactor antineutrino flux times SM cross-section
- Measure it with a CEvNS detector
- Set limits on deviations from that SM prediction
- Key input: reactor antineutrino flux!

CONNIE, JHEP 54 (2020)



$$\frac{d\sigma_{SM}}{dE_R}(E_{\bar{\nu}_e}) = \frac{G_F^2}{4\pi} Q_W^2 \left(1 - \frac{M E_R}{2E_{\bar{\nu}_e}^2} - \frac{E_R}{E_{\bar{\nu}_e}} + \frac{E_R^2}{2E_{\bar{\nu}_e}^2}\right) M F^2(q)$$



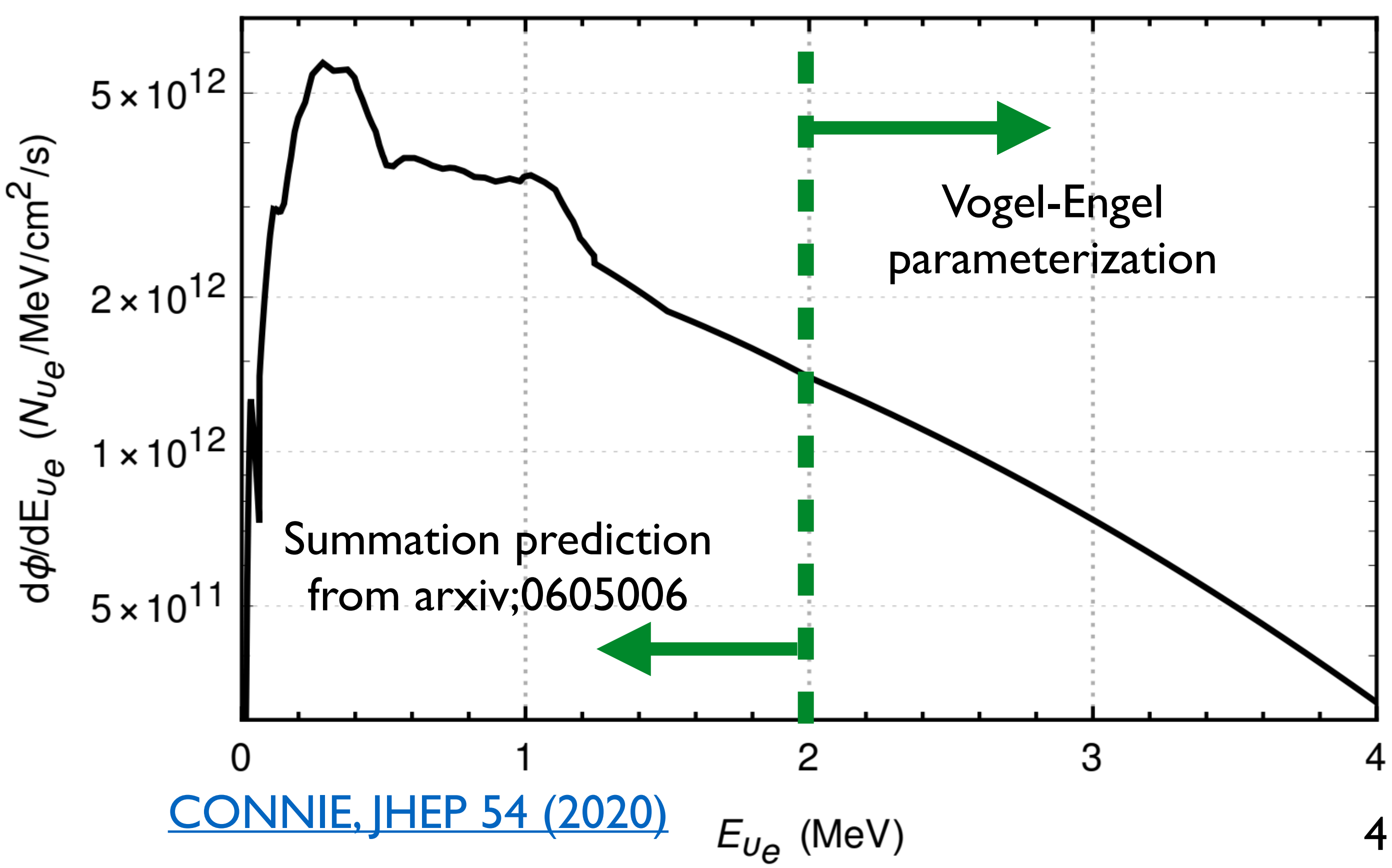


Beginning Caveat and Models

- If O(10%) uncertainties are sufficient for your physics goals, you can probably stop paying attention for the rest of this talk.
  - If you eventually want to do better than that, pay attention!

Beginning Caveat and Models

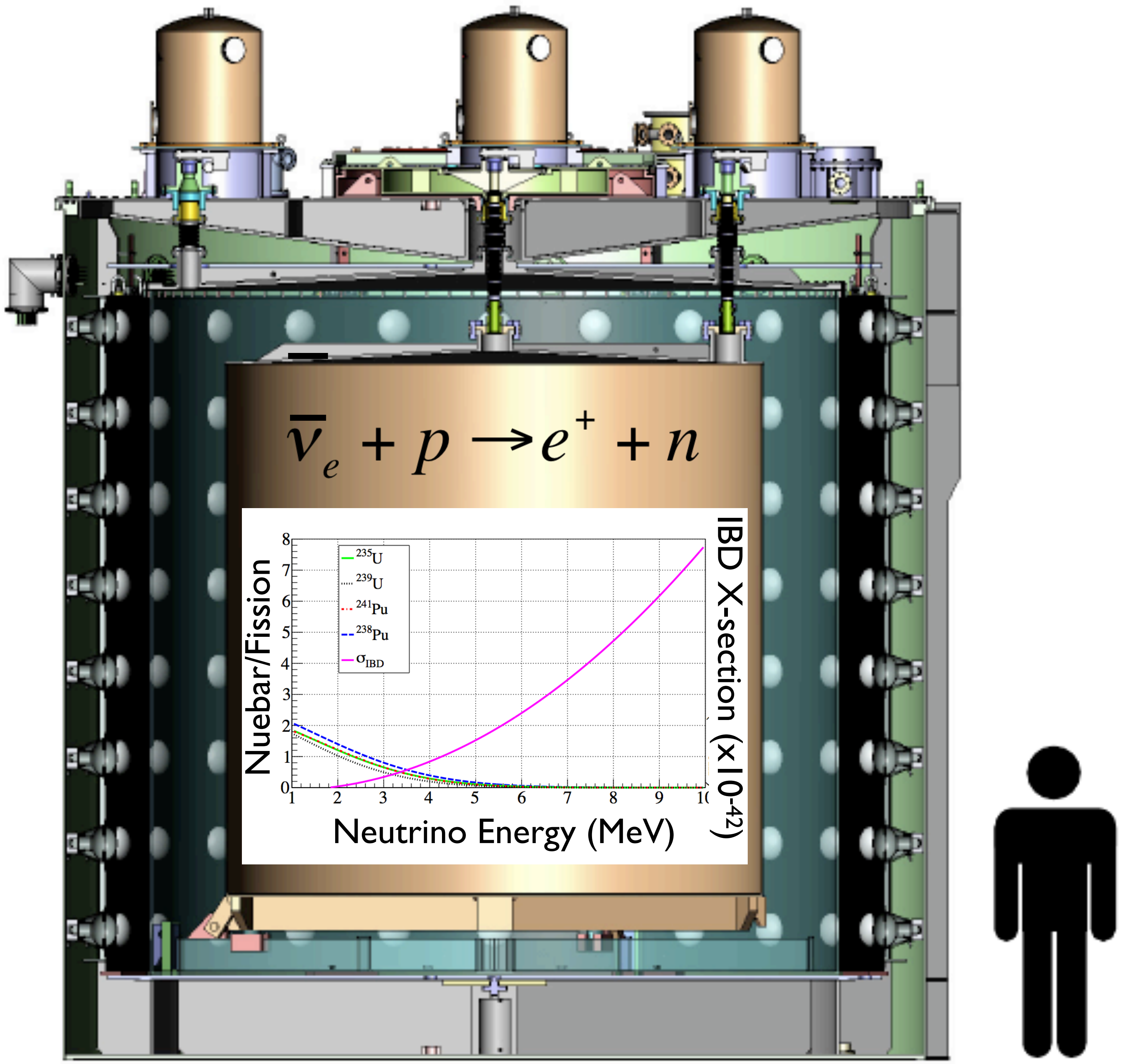
- If O(10%) uncertainties are sufficient for your physics goals, you can probably stop paying attention for the rest of this talk.
    - If you eventually want to do better than that, pay attention!
- Beyond the ~10% level, reactor flux models have some issues.
    - 'Classic' Vogel-Engel flux parameterization is outdated. Vogel and Engel, PRD 39 (1989)
    - Its improvement, Huber's conversion prediction, likely under-estimates flux and spectrum uncertainties Huber, PRC 84 (2011) Hayes et al, PRL 112 (2014)
    - Summation prediction error bands are ill-defined
    - Oh, also: they all fail to produce direct neutrino measurements!
- Real, direct measurements exist from IBD experiments
    - Use these for future precision Rx CEvNS measurements!



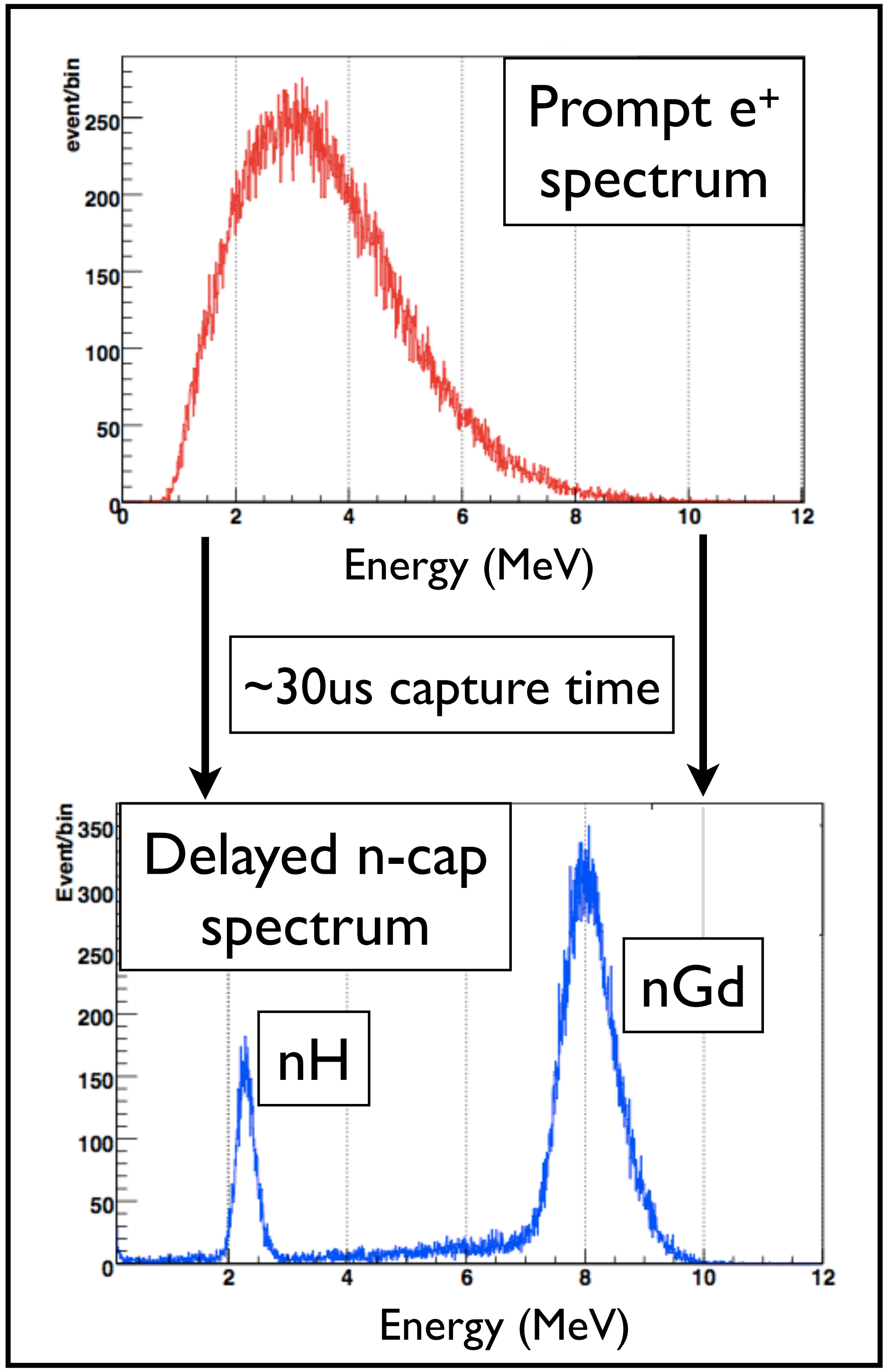
CONNIE, JHEP 54 (2020)

IBD Experiments

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



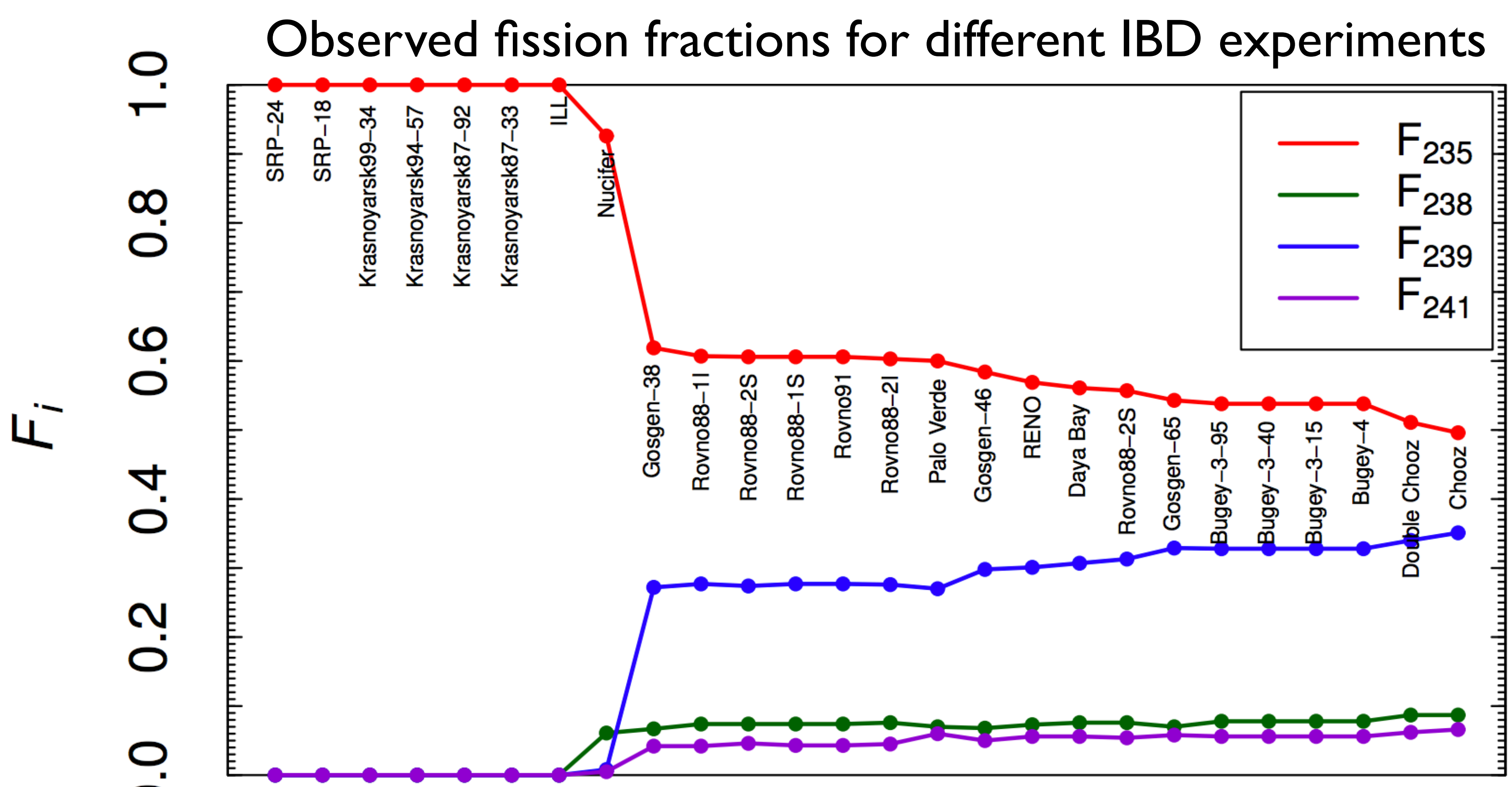
Example: Daya Bay Detector



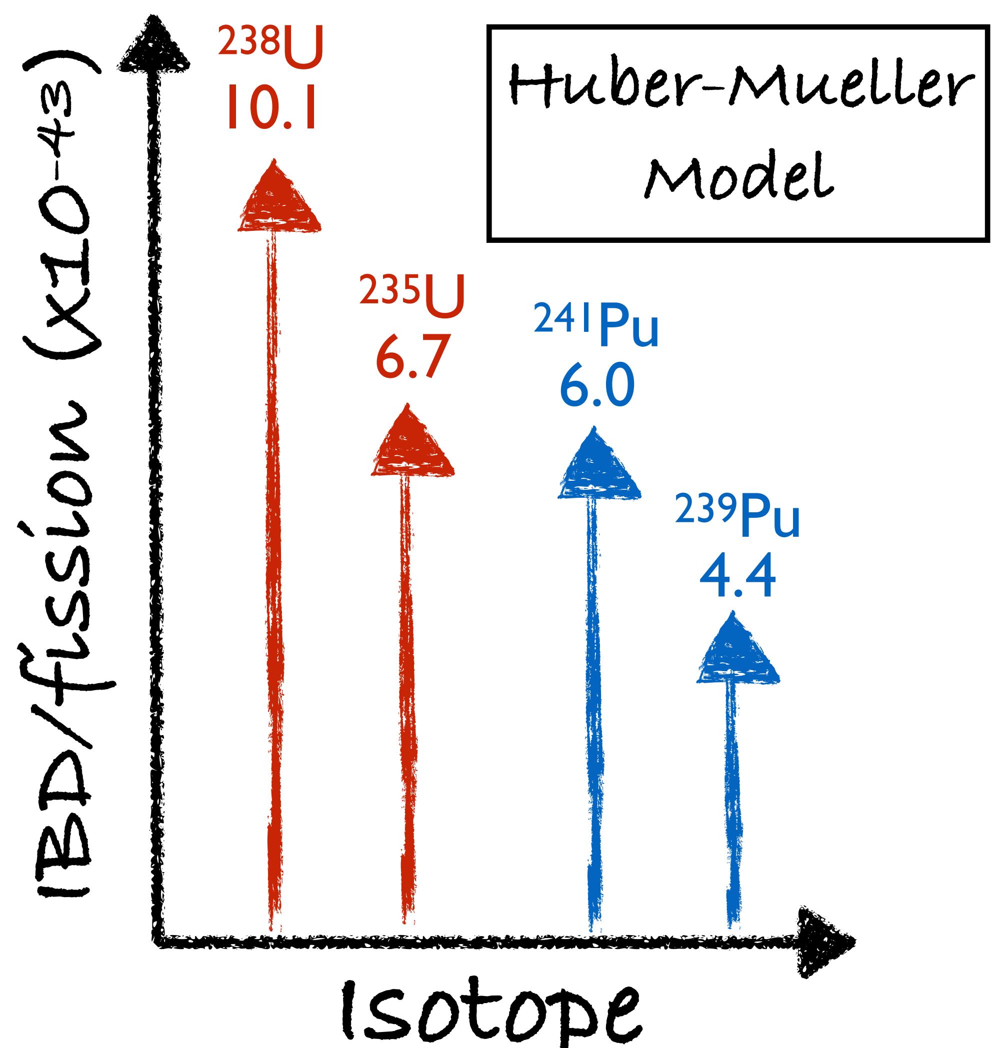
Daya Bay Monte Carlo Data

Different Reactors, Different Fluxes

- Remember: unlike DAR, it's not one-flux-fits-all for reactors!
  - Each fission isotope has its own flux and spectrum [Hayes, Vogel, Ann. Rev. Nucl. Phys. 66 (2016)]
  - So reactors with differing fuel have different antineutrino production: Highly enriched (HEU, research reactors); low-enriched (LEU, commercial reactors)
- So: robust IBD-based flux models for CEvNS require results from many reactors and experiments



Giunti, Ji, Leveder, Li, Littlejohn, JHEP 10 (2017)



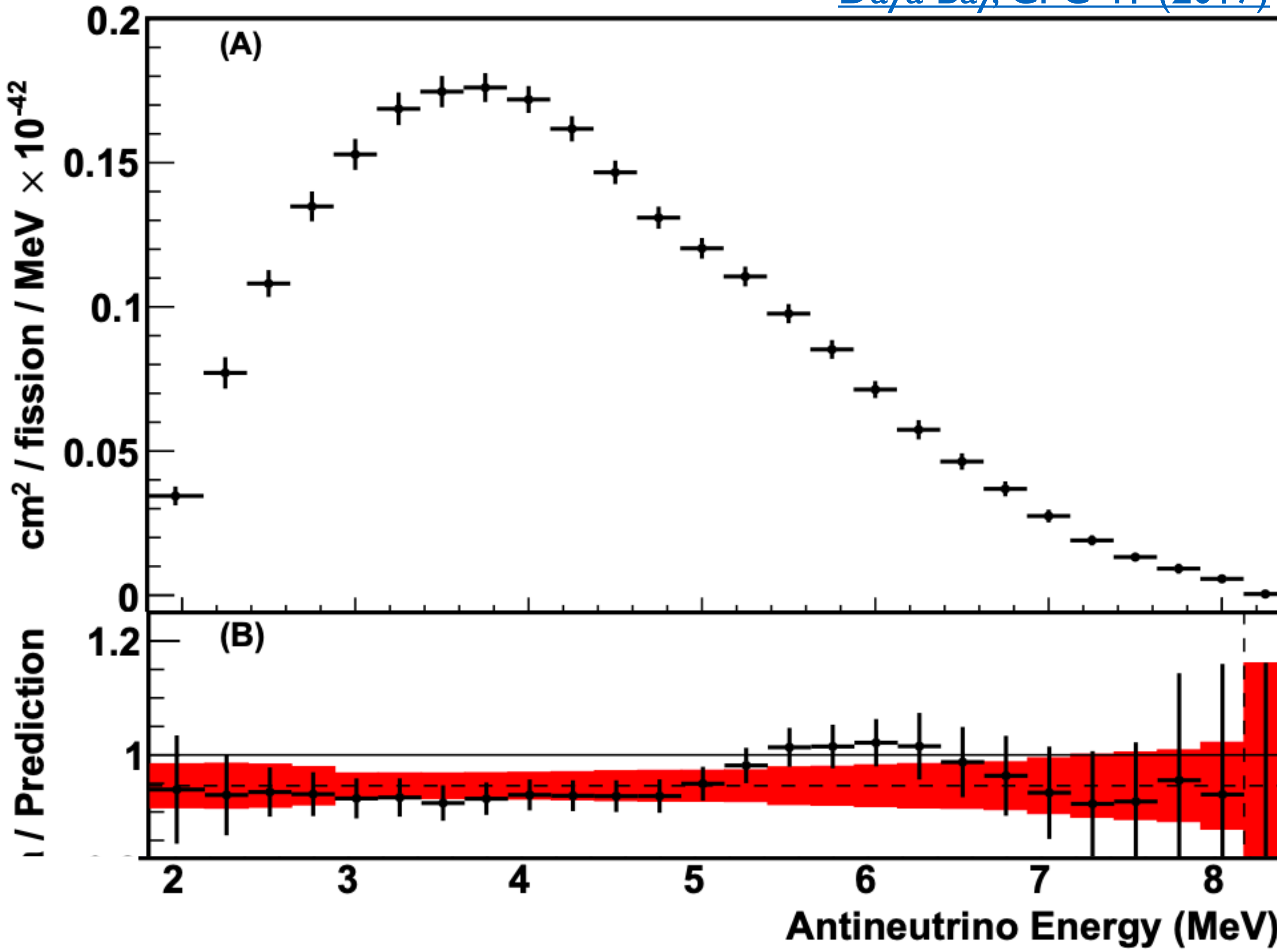
What We <u>DO</u> Know

Known: Commercial Cores

- Spectrum and flux are well-measured and reported for PWRs
  - Daya Bay and RENO have both reported unfolded time-integral flux/spectra
  - Errors comparable to (under-estimated) Huber model uncertainties
  - Expect improvements in precision in near future from Daya Bay
  - 1-2% precision energy-integrated fluxes available from DC, DYB, RENO

- Divide out IBD x-section, and you've got your >2 MeV flux model for any <u>long-term</u> Rx CEvNS measurement at a commercial core.
  - No need to worry about whether or not a 'bump' is missing from the theory prediction, or whatever

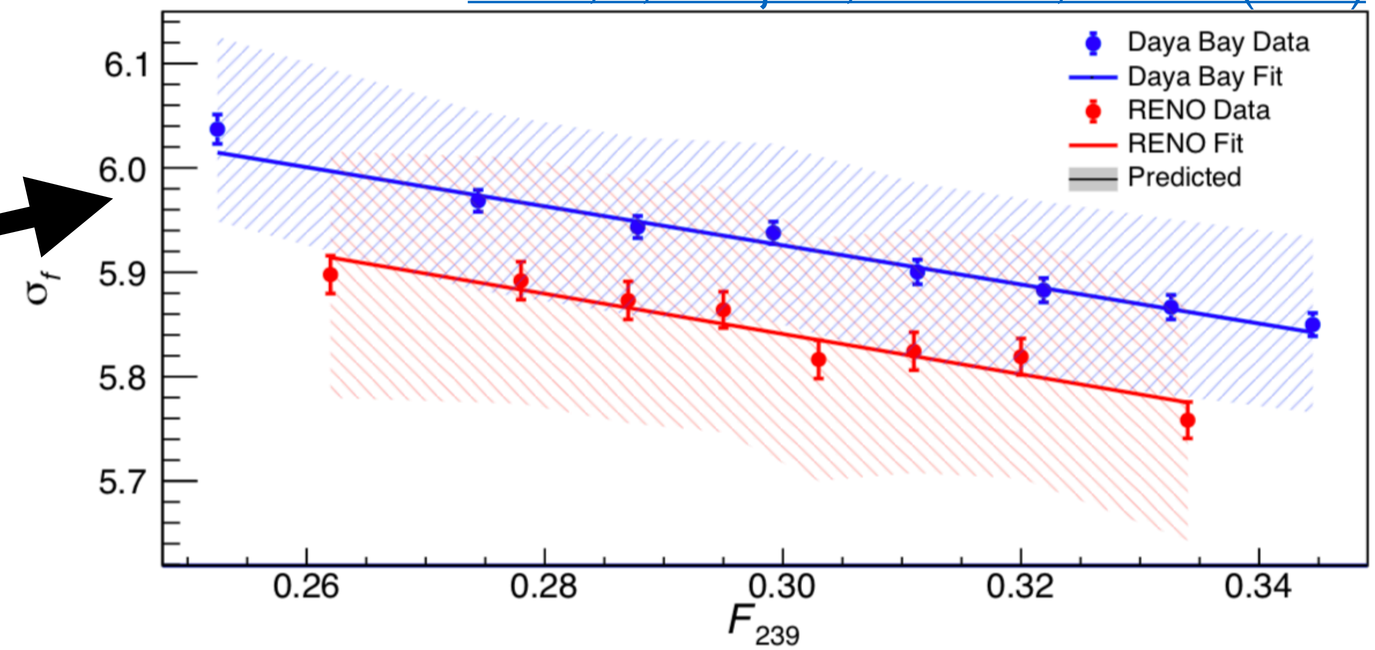
Daya Bay, CPC 41 (2017)

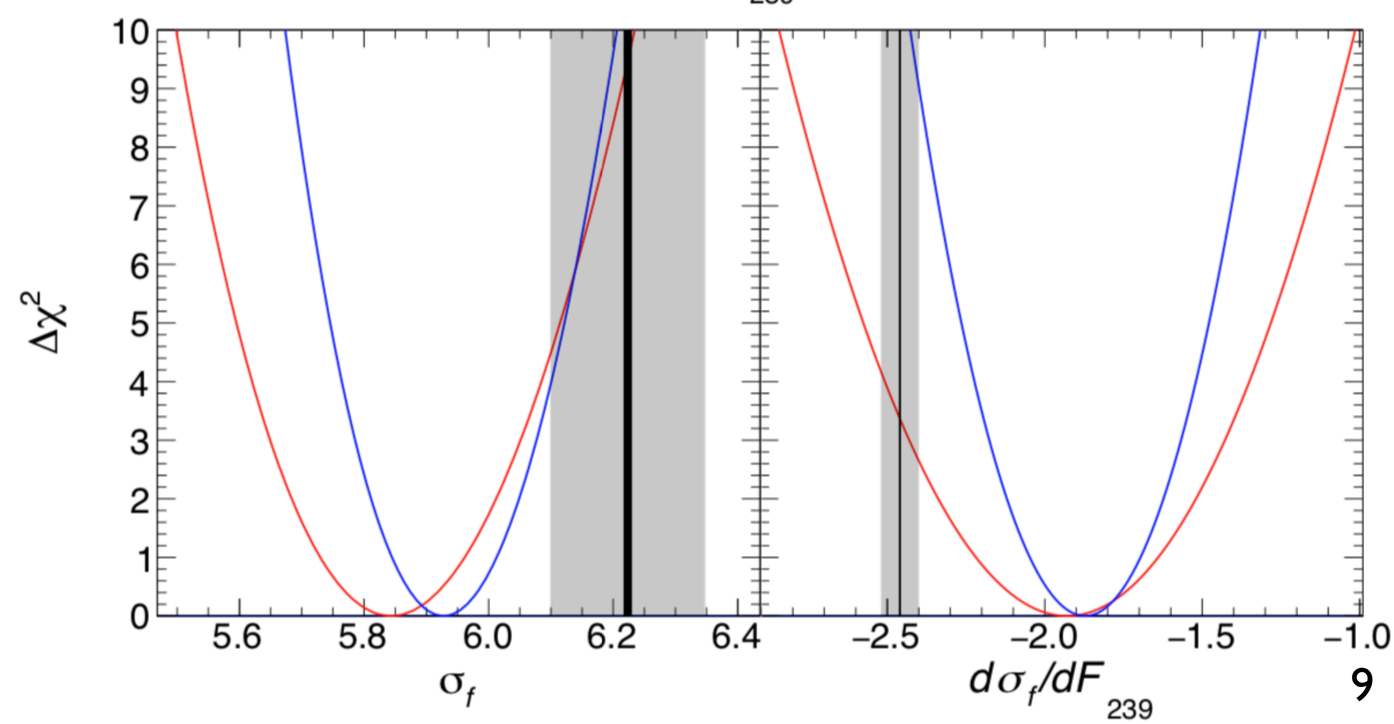


Known: Commercial Cores

- Spectrum and flux are also well-measured for PWRs at periods of differing fuel content
  - Unfolded antineutrino spectra for different time periods not yet provided: only 'measured IBD positron energy.'
  - Can expect antineutrino spectra to be available in the next year or two.
  - Absolute fluxes <u>are</u> available: again, 1-2% level precision
  - Measurements from <u>single</u> PWR core may be provided by NEOS, others in the next few years.
- Make a >2 MeV flux model for any <u>short-term</u> Rx CEvNS experiment at a commercial core by just picking out the IBD measurement matching that experiment's run period.

[Giunti, Li, Littlejohn, Surukuchi, PRD 99 (2019)](#)

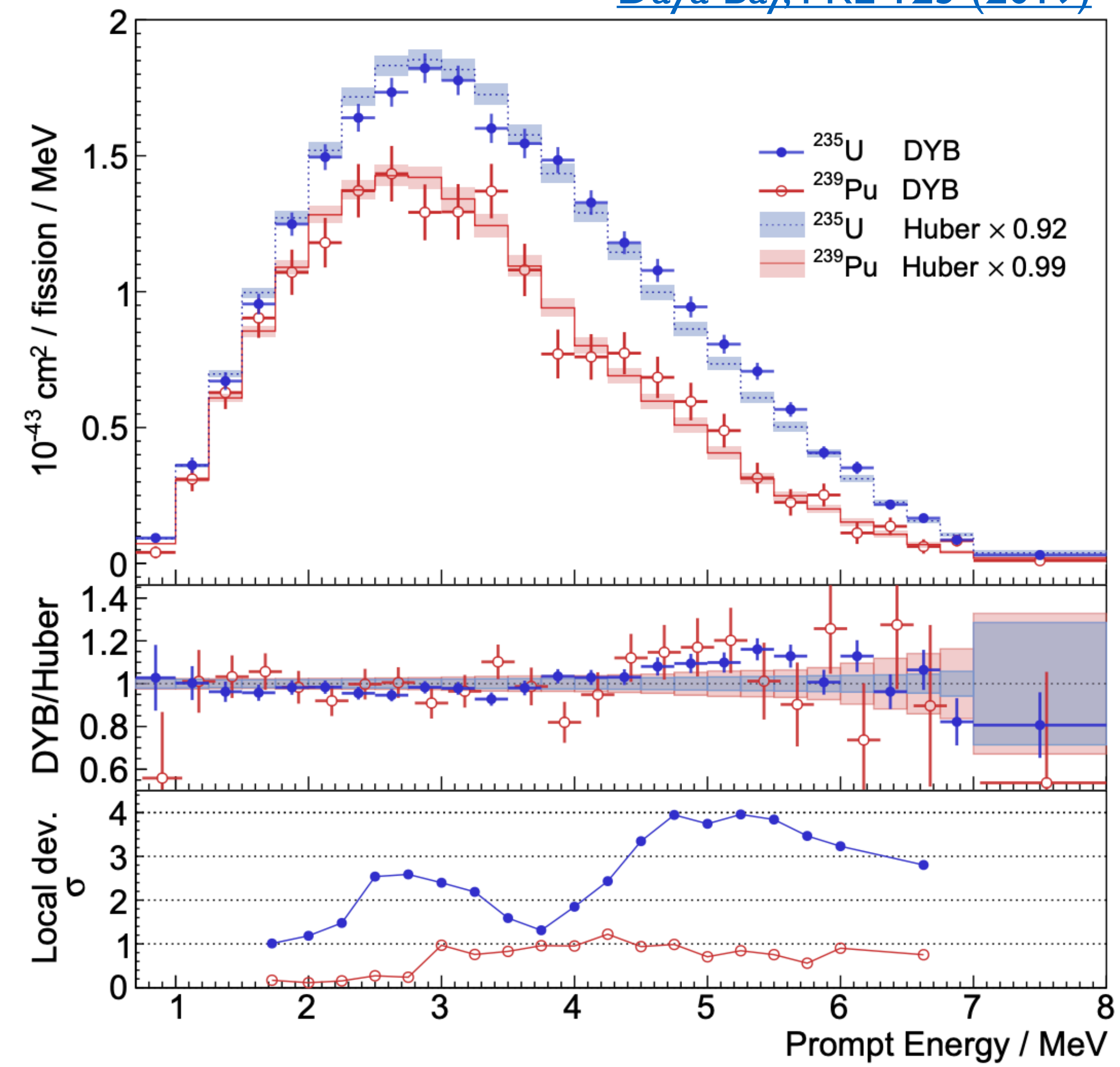




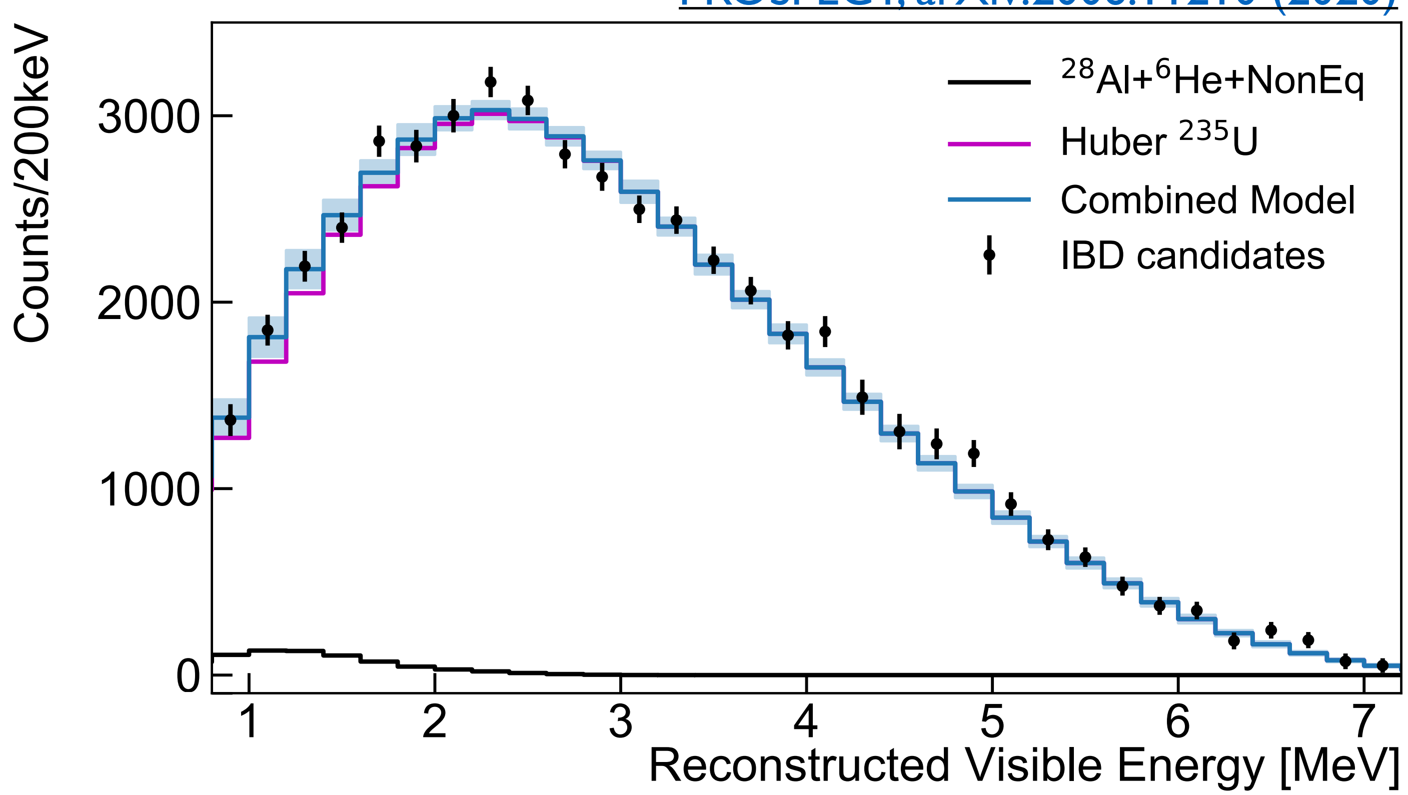
Known: HEU Core Spectrum

- Spectrum only recently well-measured for HEU cores
  - PROSPECT and STEREO reported 'measured IBD positron energy spectra'
  - Can expect antineutrino spectra to be available in the next year or two.
- Alternate approach: 'decompose' commercial measurements to get pure U-235 contribution
  - Daya Bay has done this, but again, hasn't provided unfolded antineutrinos

[Daya Bay, PRL 123 (2019)](#)



[PROSPECT, arXiv:2006.11210 (2020)](#)



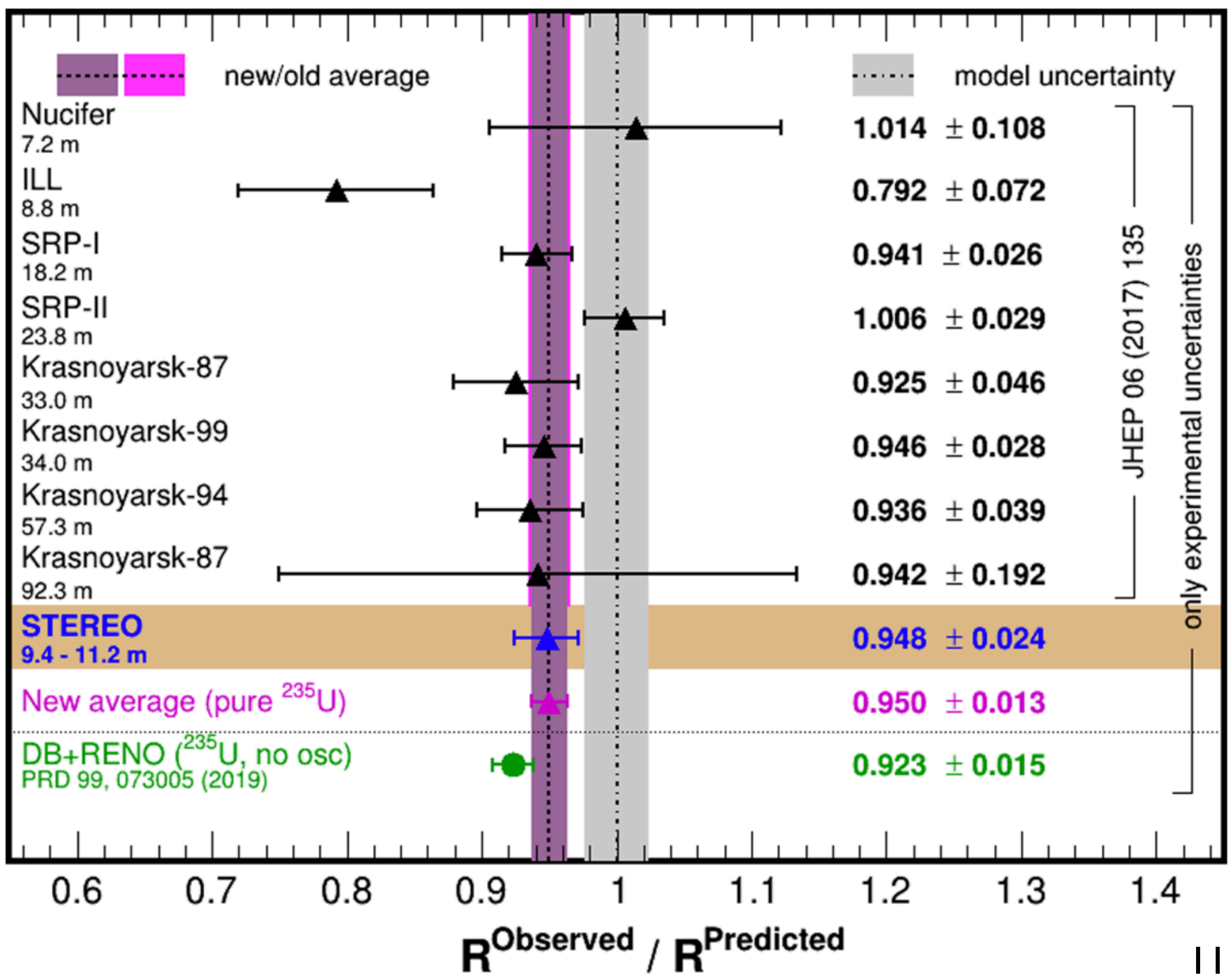
Known: HEU Core Flux

- Also have a recent HEU flux measurement from STEREO
  - Compliments historical HEU measurements, and more recent best-fit U-235 flux from Daya Bay fuel evolution result
  - Should expect a result from PROSPECT in the coming year or so

- Once you have unfolded antineutrino spectra, divide out IBD xsec, and you've got your >2 MeV flux model for any <u>HEU-based</u> Rx CEvNS measurement.

- Seems very simple, right?

[STEREO, arXiv:2004.04075 (2020)](https://arxiv.org/abs/2004.04075)

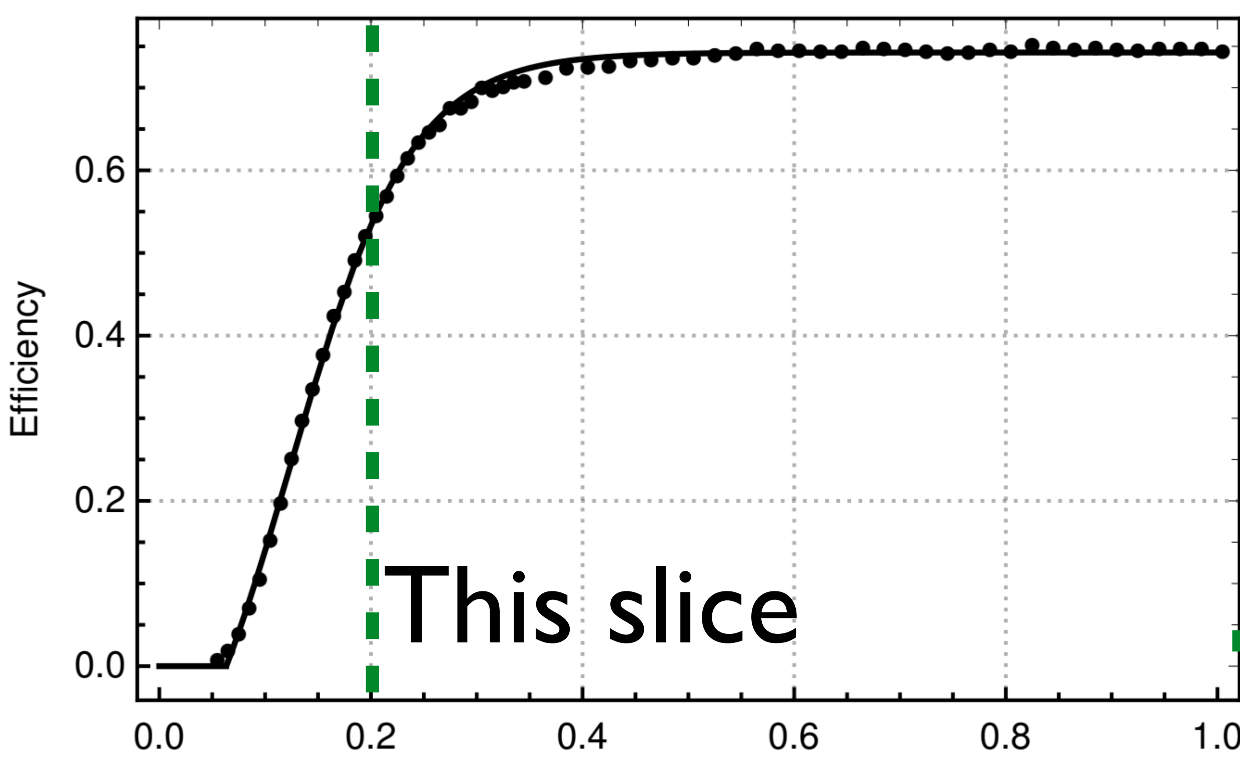


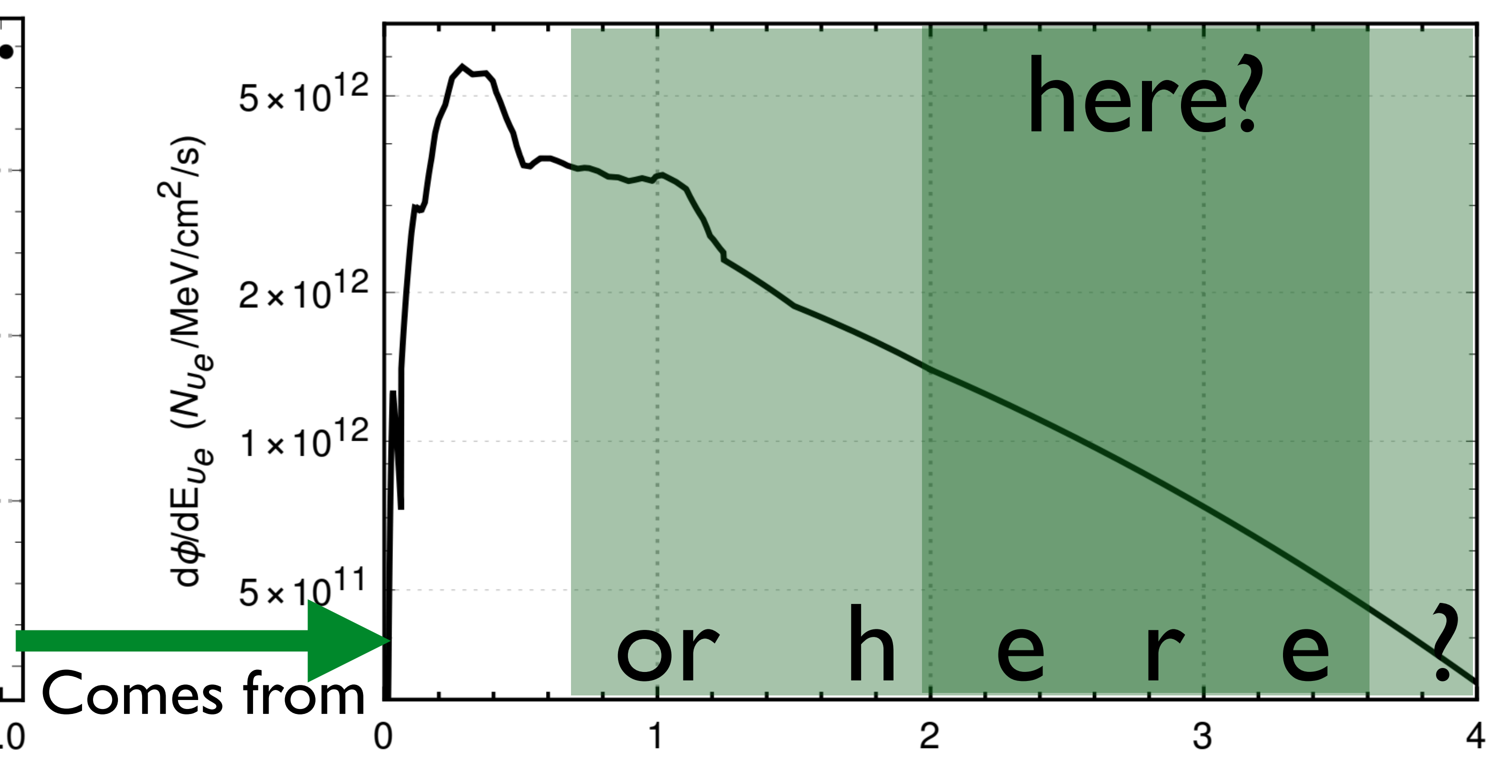
What We DO NOT Know

… or should try to understand better, at least

An Important Consideration: E_{nu} to E_{meas}

- How does neutrino energy map to measured recoil energy?
  - “How much of the E_m spectrum above 0.2 keV arises from (E_{nu}) above 2 MeV?”
  - I’m sure there’s a well-defined answer here, I’m just unlearned on the topic
- This determines a lot about what flux uncertainties matter!
  - If there’s a tight correlation, the >8MeV flux uncertainties may matter a lot to CONUS or CONNIE, and can be greatly helped by IBD measurements!
  - If there’s a very loose correlation, then the <2 MeV flux uncertainties are likely very important, in which case IBD measurements likely can’t help much.



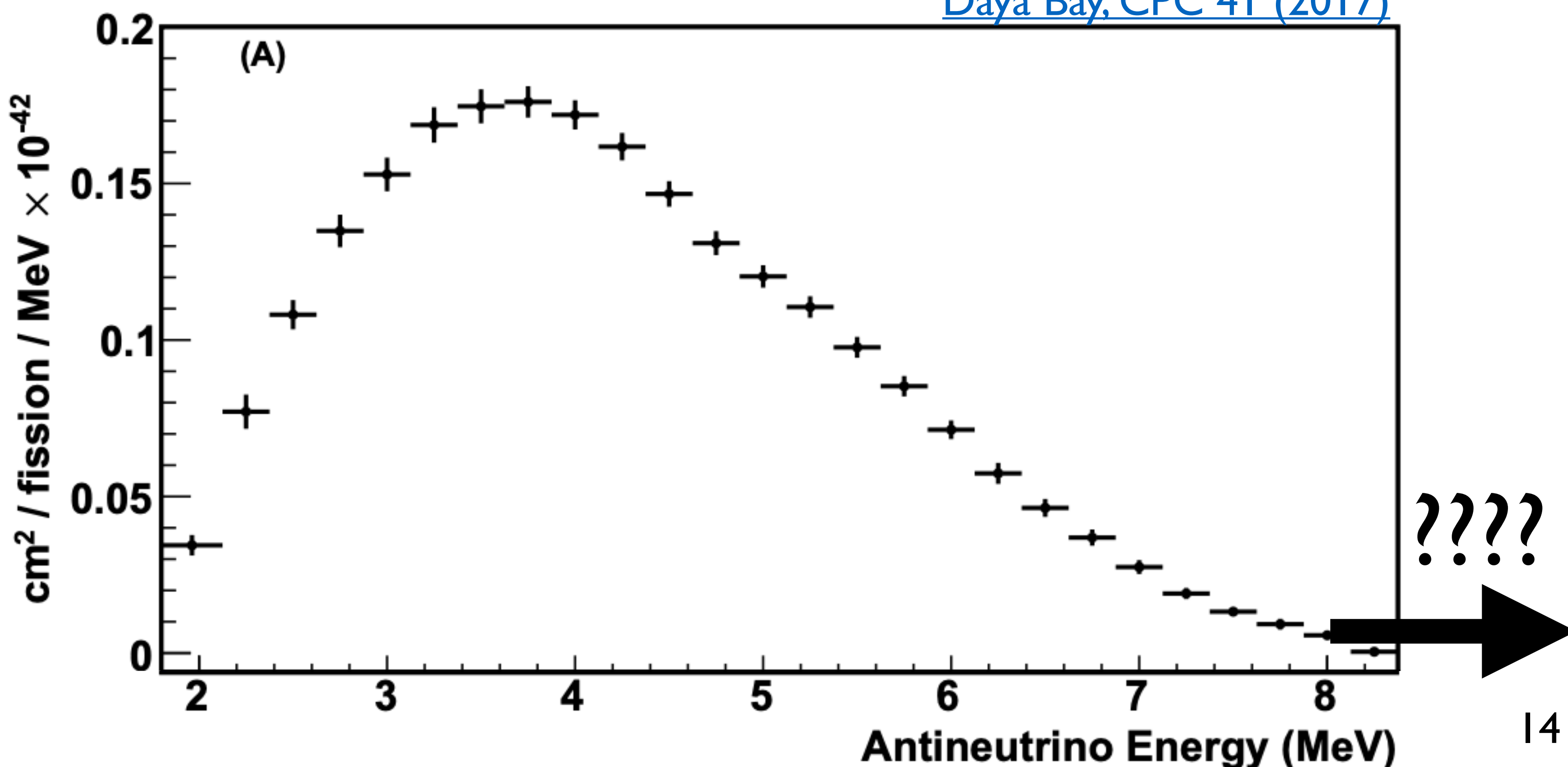


CONNIE, JHEP 54 (2020)

Not Known: High-Energy Flux

- What is it? It hasn't been reported in a precise way >8 MeV
  - Vogel-Engel, Huber, and summation predictions are ALL likely to be WAY off in this energy regime — possibly even >>10% off!
- Matters most for 'high threshold' Rx CEvNS detectors just scraping the top of the reactor neutrino spectrum.
  - Even in this case, with E_{nu}-to-E_{recoil} response smearing, perhaps this contribution isn't all that important to understand precisely
  - Perhaps CONNIE or CONUS folks will probably know the answer to this question already?
- Daya Bay will hopefully address this gap soon, with very good precision
  - Much more difficult for HEU…

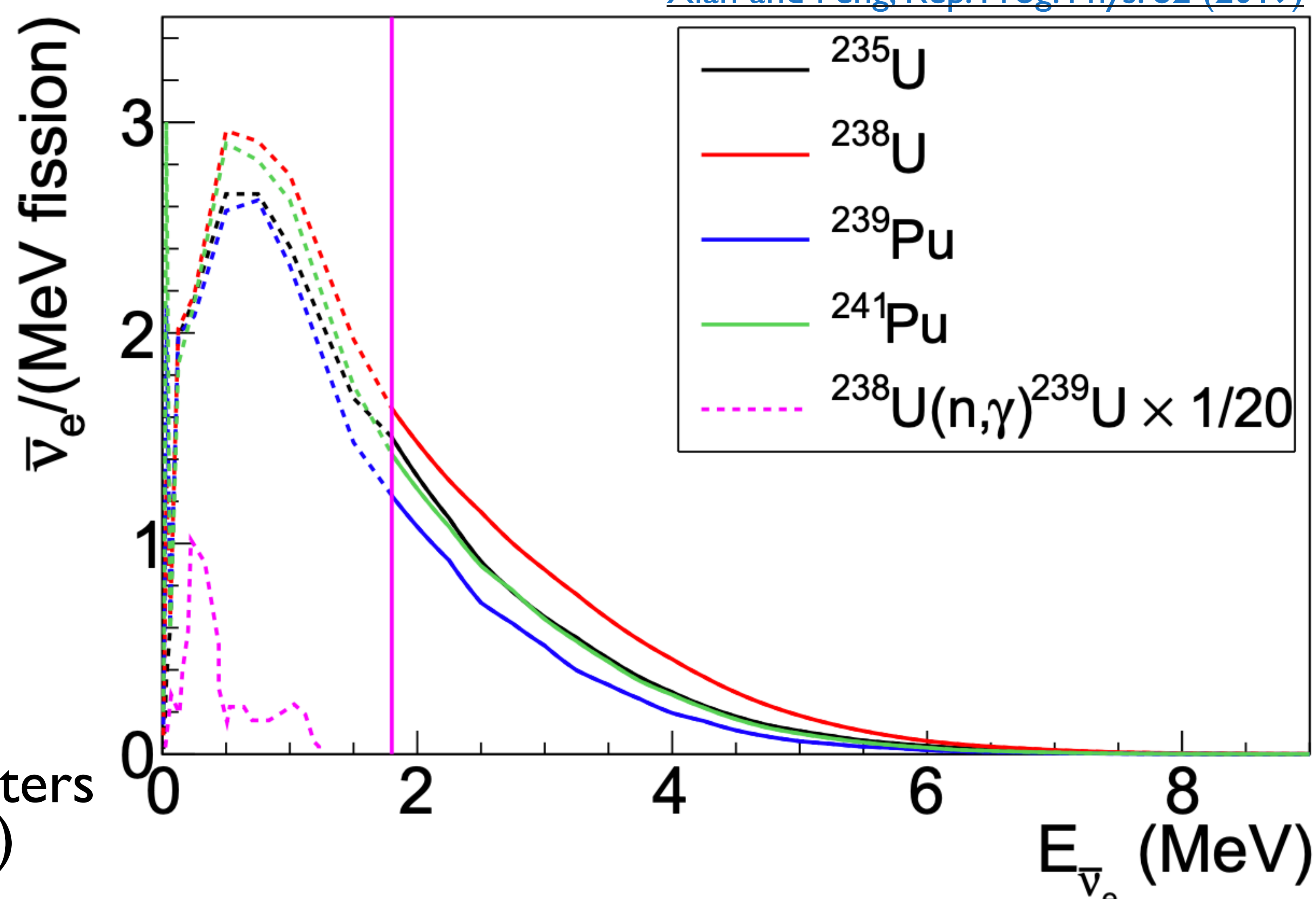
Daya Bay, CPC 41 (2017)



Not Known: <2 MeV Contributions

- What is the antineutrino content below the IBD threshold?
  - Contribution from low-energy portion of beta spectra, low-Q fission daughters, beta decays to highly excited states
  - Also non-fission sources: non-fuel as well as actinide beta decays
- I don't see much of a place for IBDs helping here
  - Non-fuel contributions: >2MeV part constrains <2MeV part!
  - For fission products, this kind of constraint is MUCH more difficult to envision.
  - Probably just stick with summation predictions, and beg theorists to define errors well
  - In short-term, this part matters the least (hardest to detect)

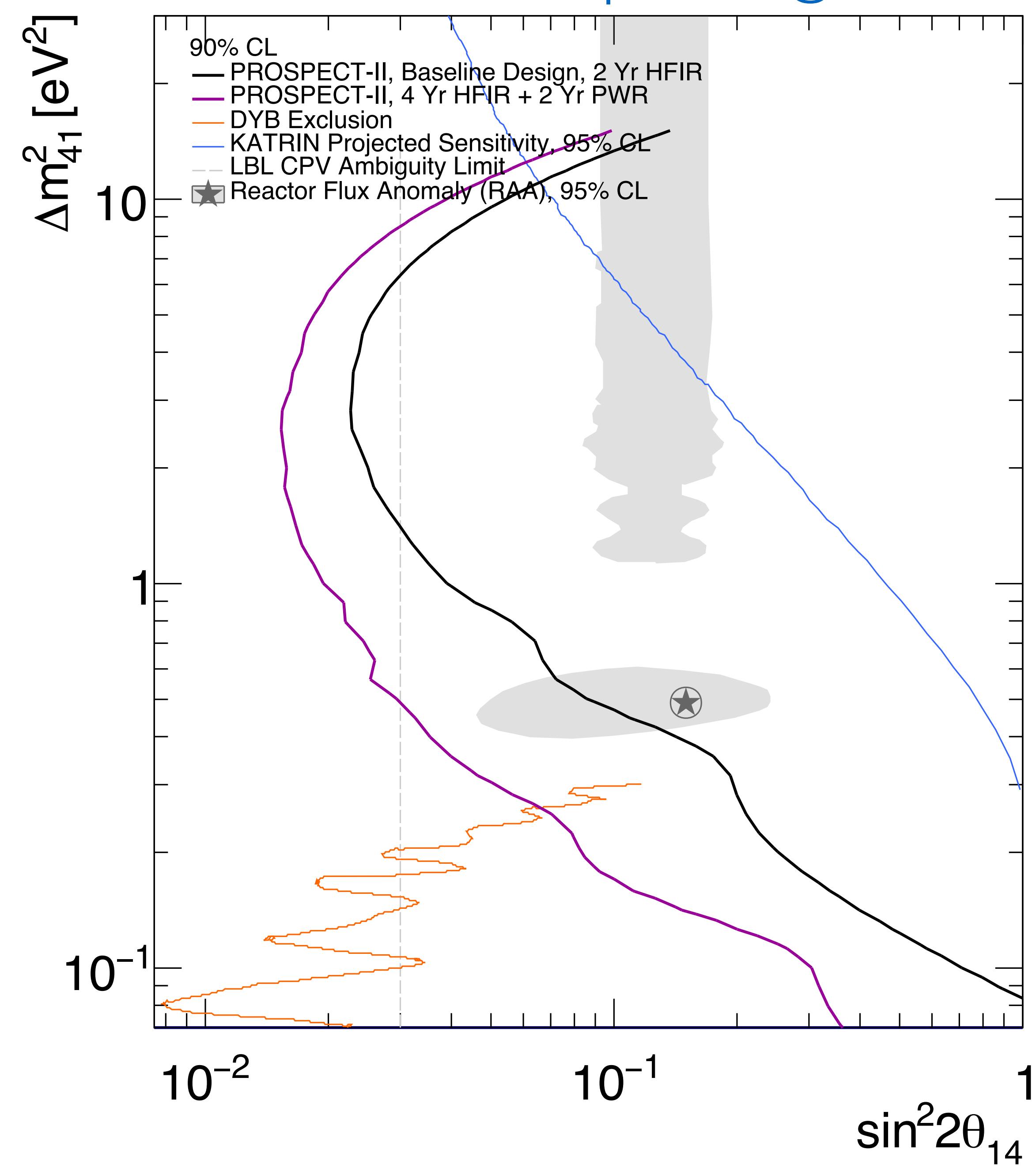
Xian and Peng, Rep. Prog. Phys. 82 (2019)



Not Known: Sterile Oscillations

- Don't know what the 'true' flux is due to possible impacts of sterile neutrino oscillations during propagation
  - On the plus side: IBD and CEvNS are oscillated in the same way (?)
- As a CEvNS experiment, you can get around this by:
  - Forming prediction from an IBD measurement at an identical baseline
  - Waiting for the sterile oscillation phase space to be nailed down to ~3% precision by other experiments in next ~5 years

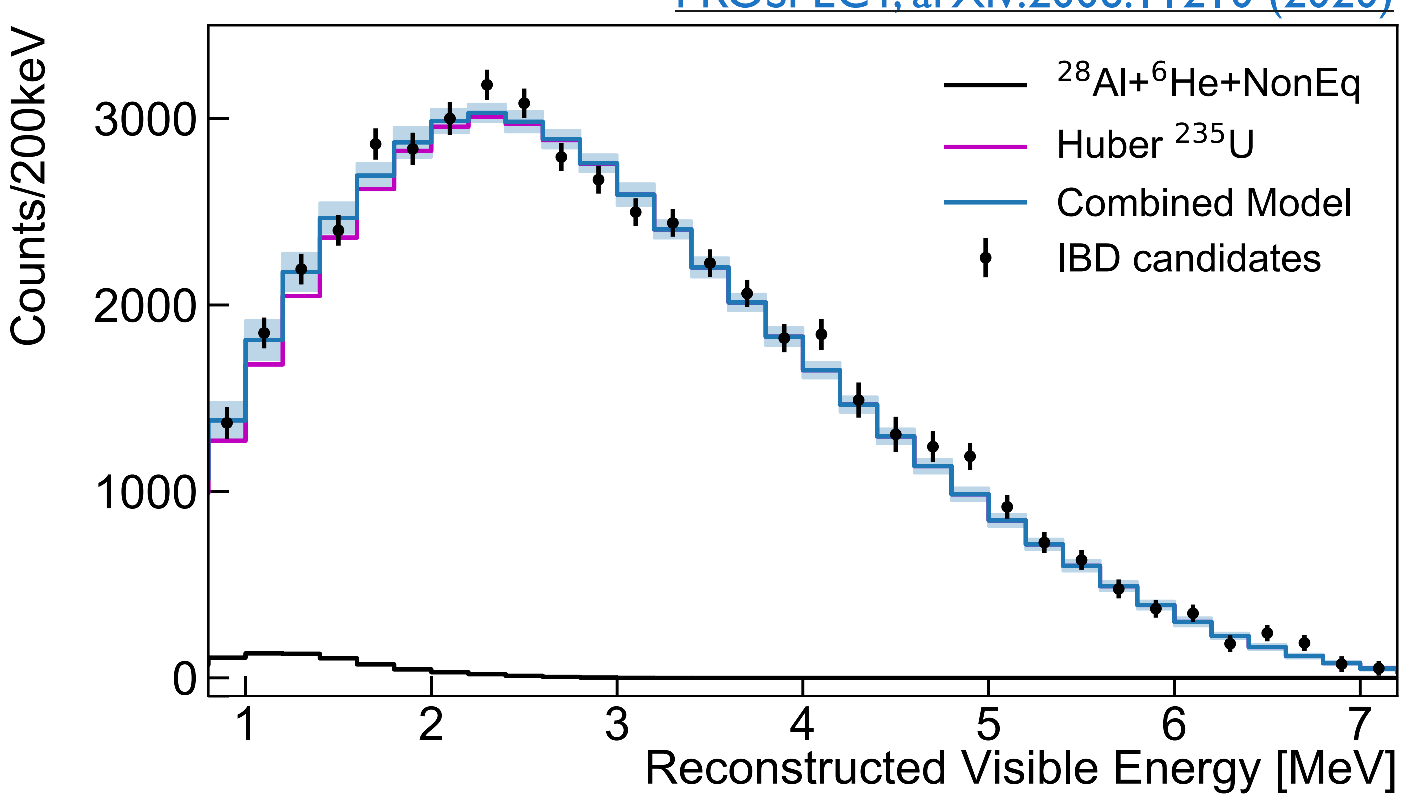
PROSPECT, presented @DNP 2020

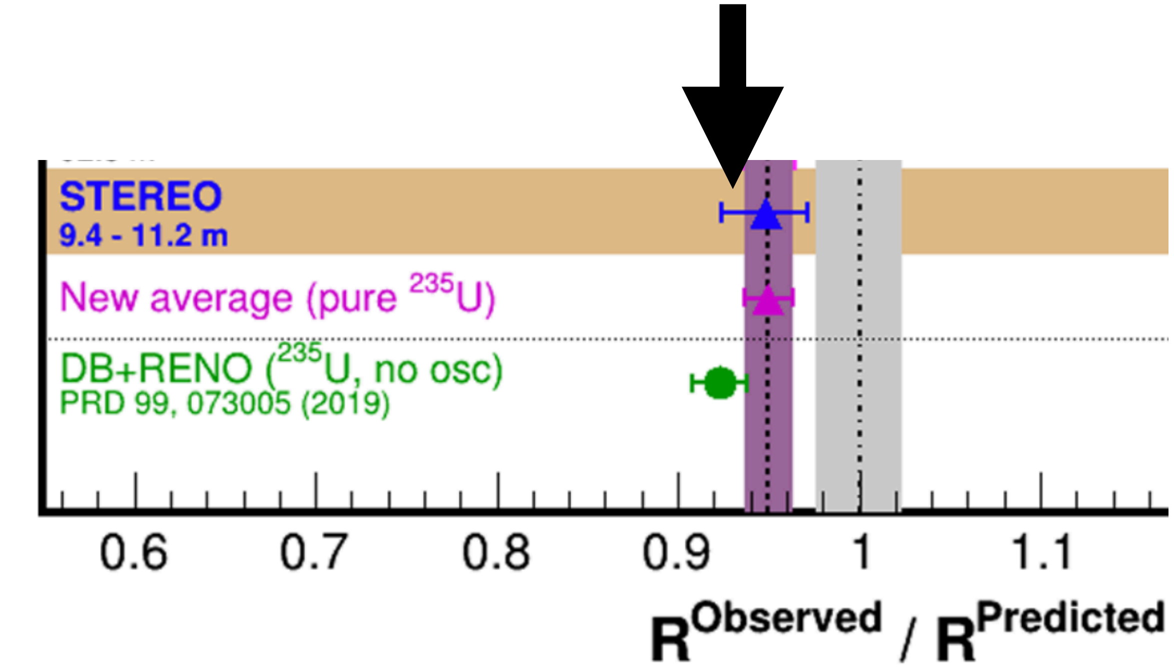


Not Known: HEU Issues

- HEU statistics are still rather low: <100k total IBDs
  - Limits precision of knowledge of the high-energy end of the spectrum
  - This will hopefully be remedied by PROSPECT-II in the next few years
- Slight conflict between DYB- and HEU-reported U-235 fluxes
  - ~3% offset: could see this as the current limitation on >2MeV flux model for an HEU-based CEvNS measurement. Perhaps there's some physics underlying this offset that can be resolved.

PROSPECT, arXiv:2006.11210 (2020)





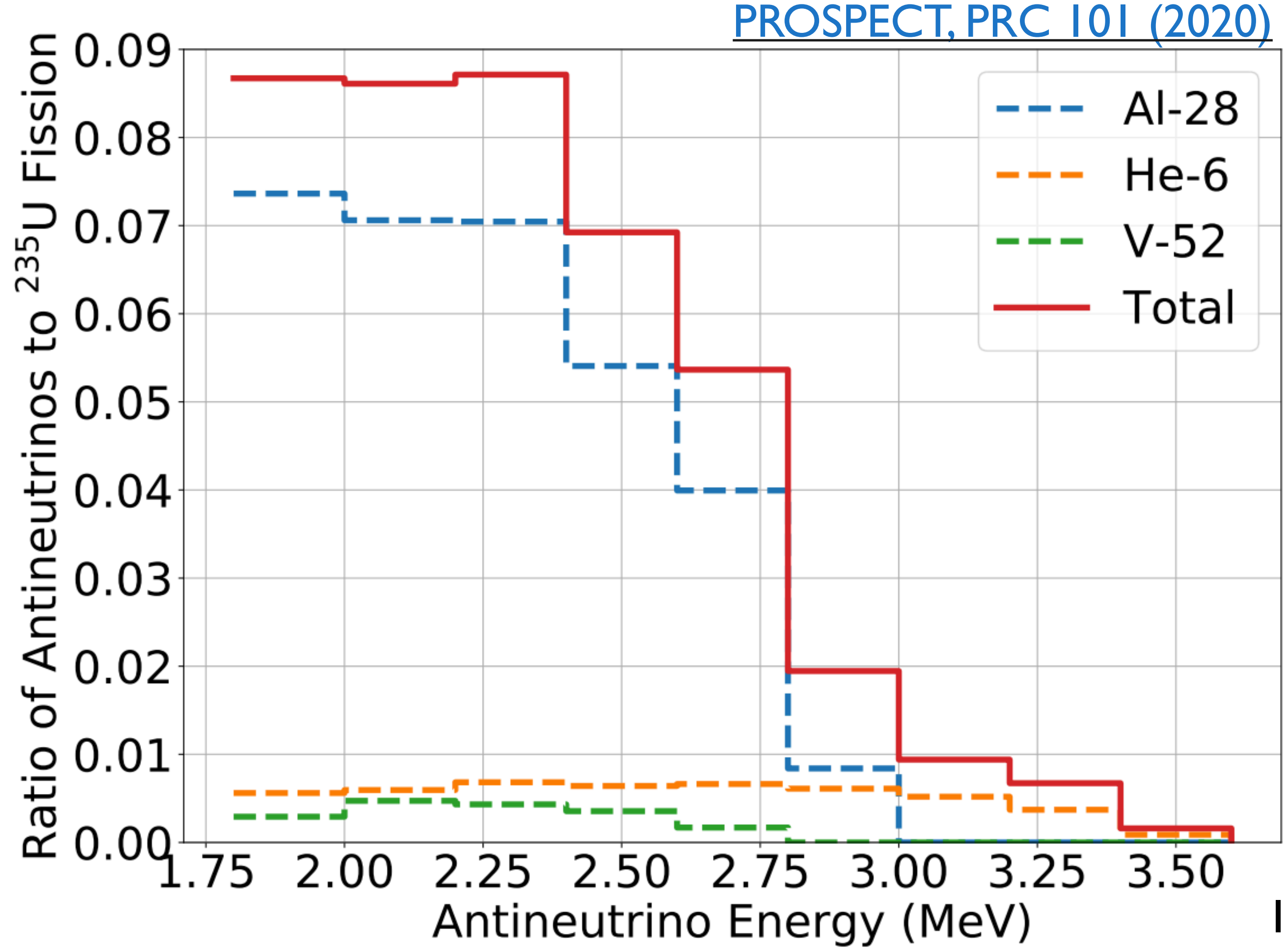
STEREO, arXiv:2004.04075 (2020)

Not Known: Non-Fuel Contributions

- How large are non-fission antineutrino contributions?
  - Substantial issue for research reactors in particular, and low energies (<3MeV)
  - For example: activation and beta decay of aluminum in HEU core structure
  - Must be predicted by non-neutrino-physicists (nuclear engineering folks) using non-neutrino Monte Carlo tools (like MCNP)
  - Note: uncertainty quantification for these contributions (due to nuclear data uncertainties) should be feasible, but have yet to be attempted, AFAIK.
- IBD exps. may help here
  - Could benchmark MC-generated predictions by comparing spectra between IBD experiments at different reactor types: i.e. between NIST and HFIR

A. Conant, PhD Thesis, Georgia Tech (2019)

PROSPECT, PRC 101 (2020)



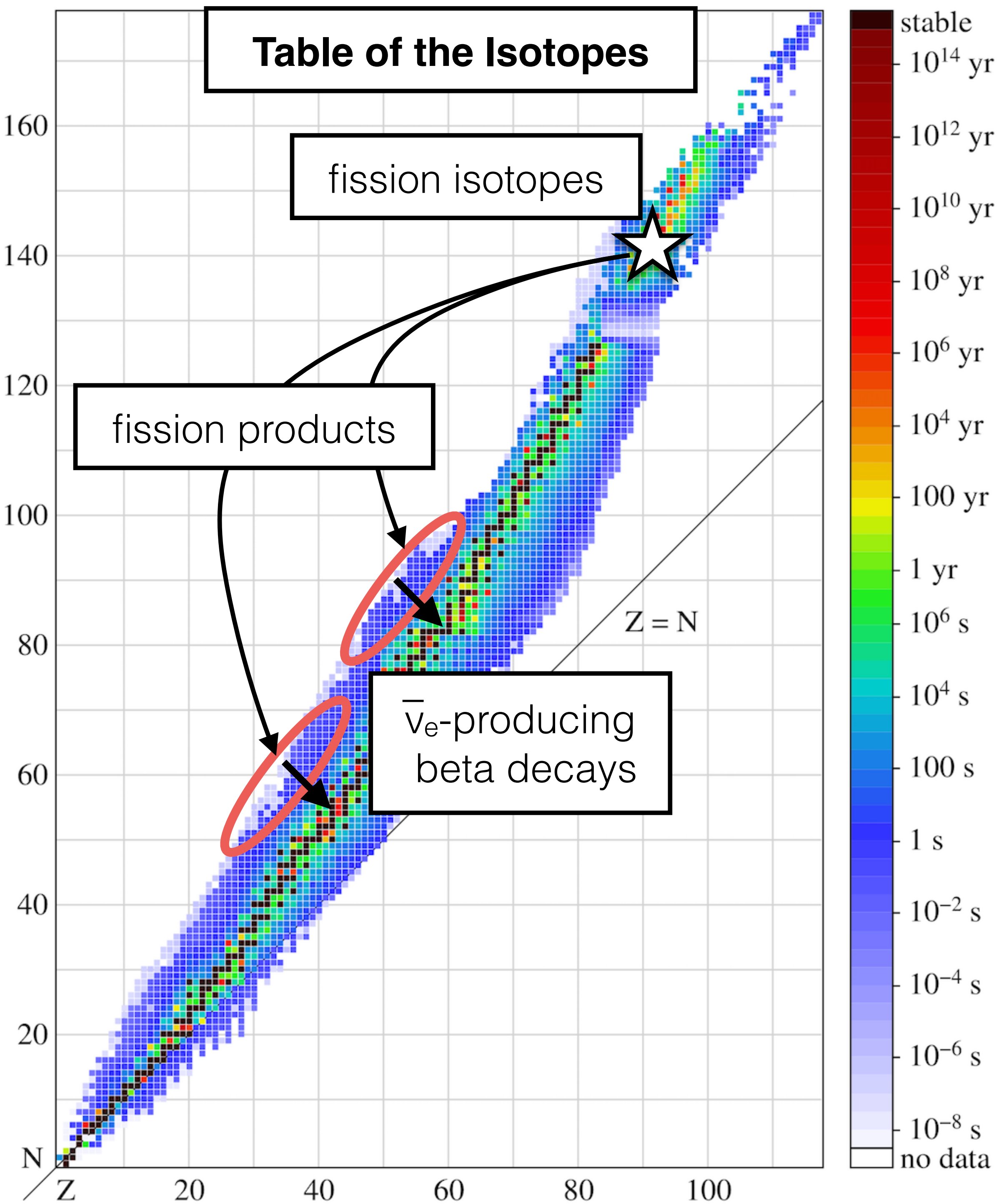
Summary

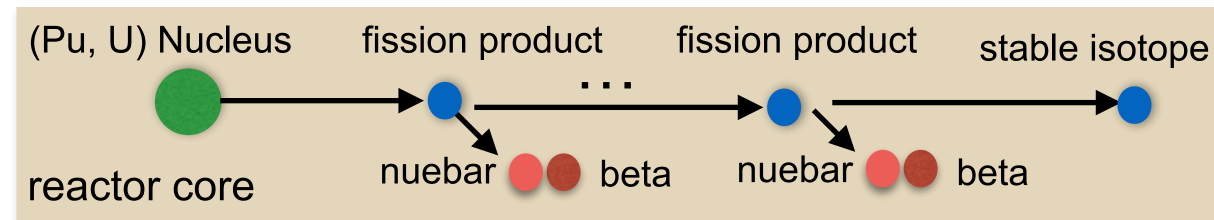
- A reactor flux prediction is one of the essential inputs to doing physics with reactor CEvNS experiments
- If a signal prediction of O(10%) precision is good enough, you probably can get away with using theoretical flux models despite their proven inaccuracy
- If you want a better prediction than this, you need to rely on IBD-based reactor flux measurements
- IBD-based models are, in some cases, already available
  - For long-running Rx CEvNS experiments at commercial cores: Daya Bay has already provided a model that will be perfect for you!
  - In the next few years, the use cases will expand as HEU measurements continue, and more experiments 'unfold' into antineutrino energy space
- IBD measurements are not a cure-all for Rx CEvNS fluxes
  - Specifically: <2 MeV fluxes are hard to constrain with IBD measurements

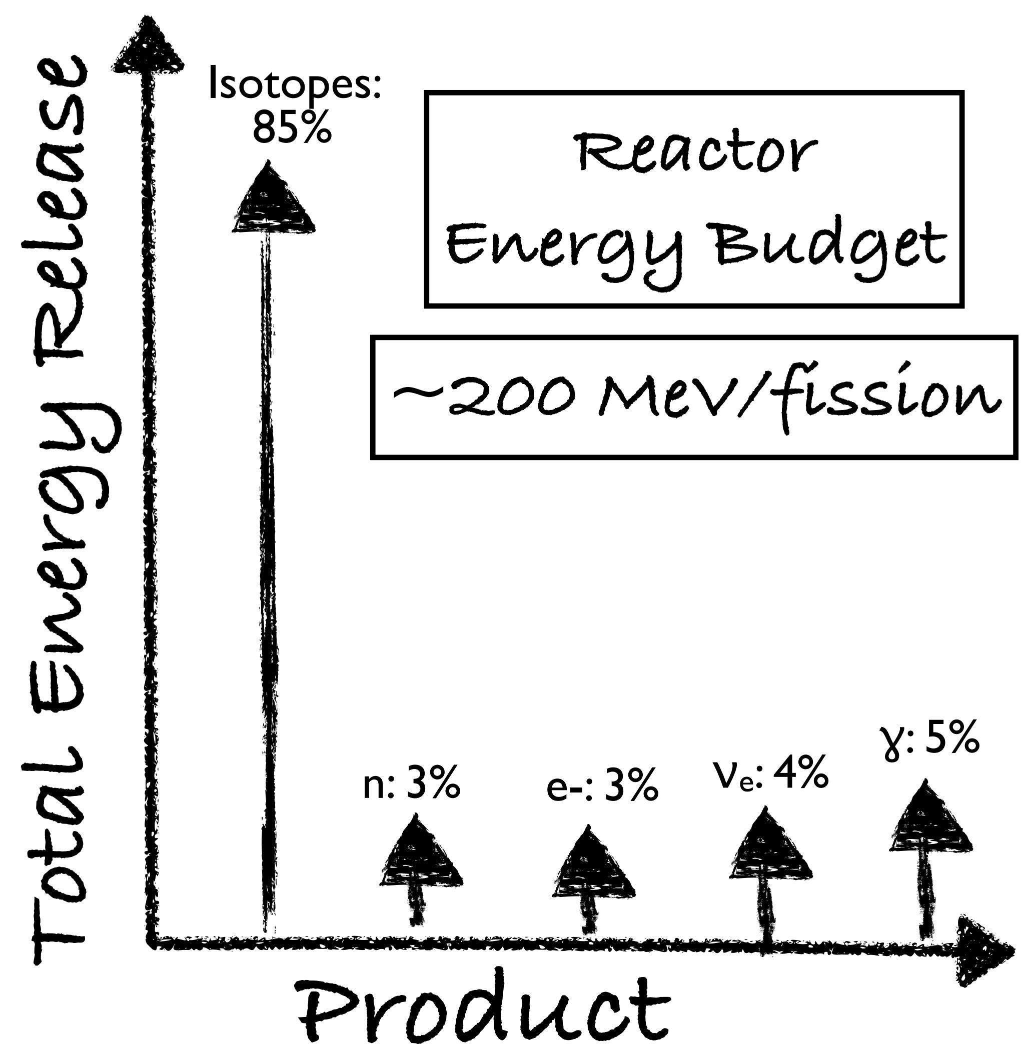
Thanks!

What Do Nuclear Reactors Do?

- Heavy isotopes fission make lighter isotopes and energy, **AND** neutrons, neutrinos, betas, and gammas!
  - Different fission isotopes yield different products



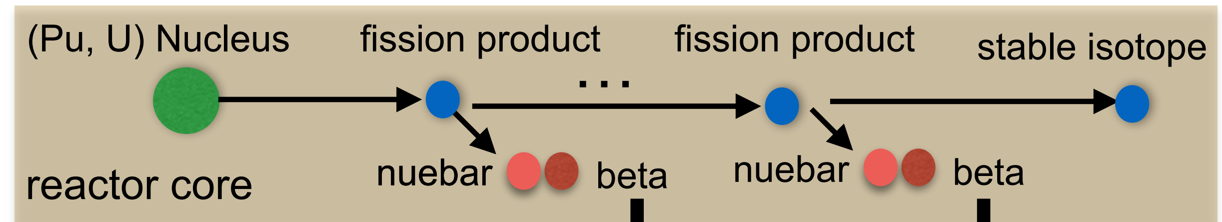


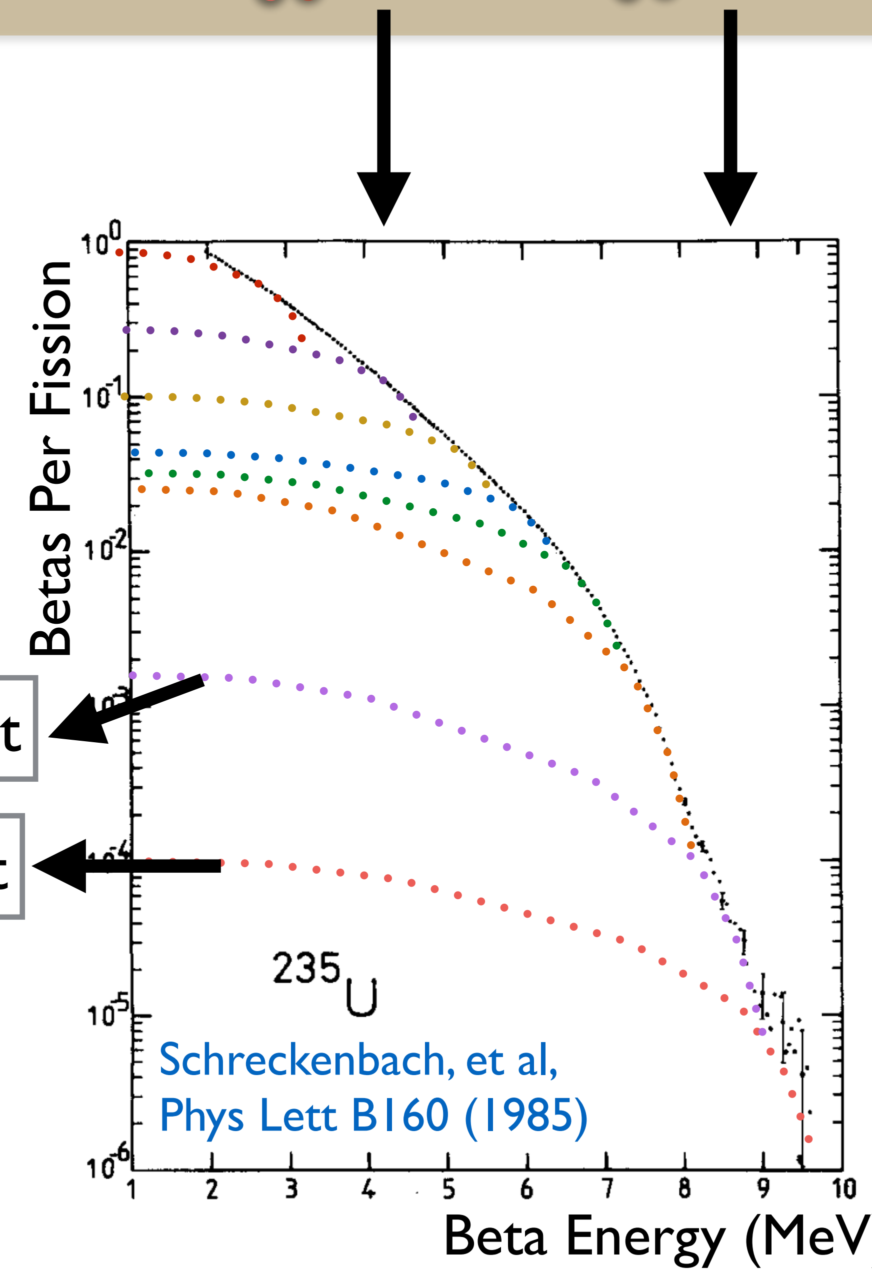


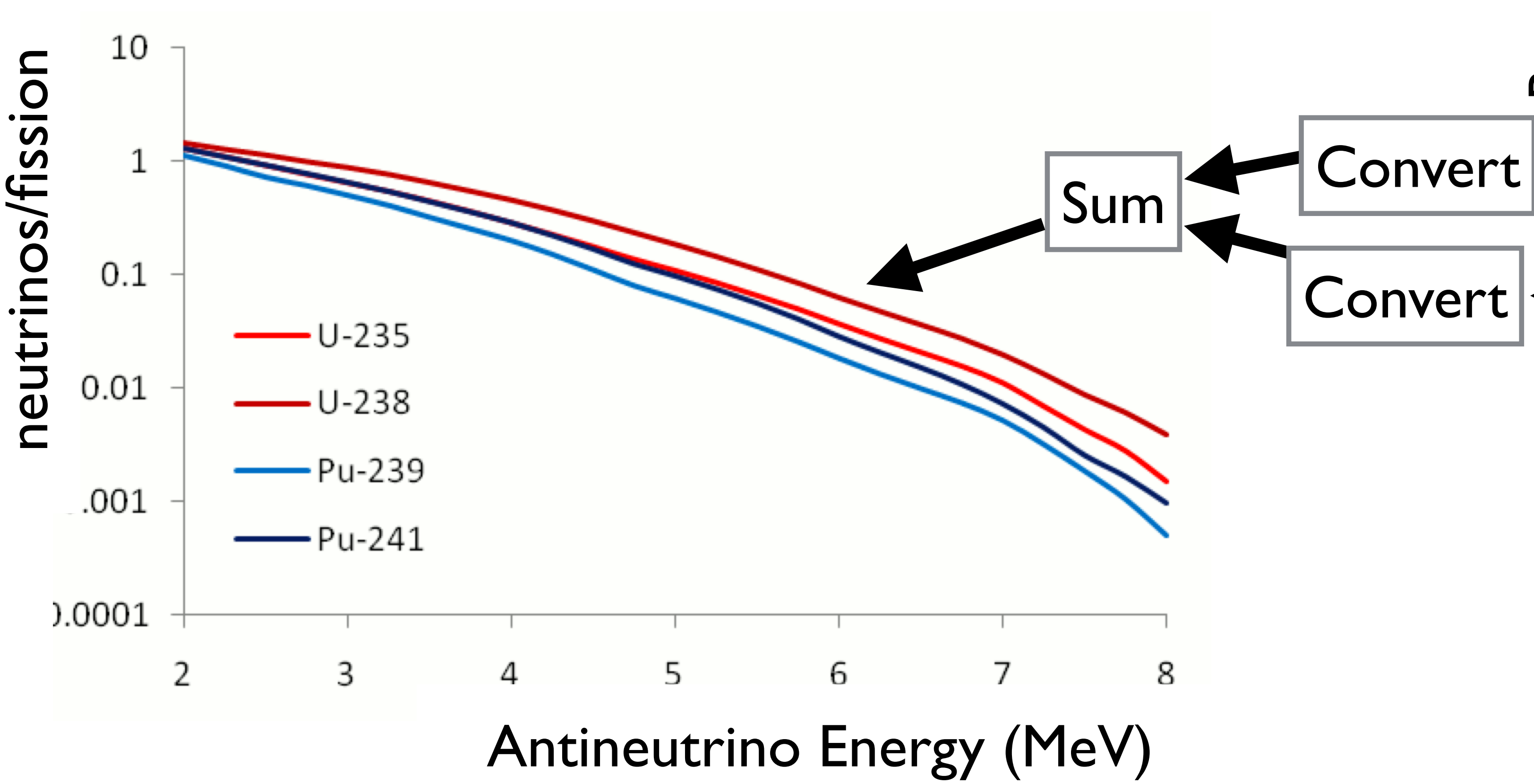
Reactor Antineutrino Production

- Reactor $\bar{\nu}_e$: produced in decay of product beta branches

- 'Conversion' prediction:
  - Measure beta energies from all fission products at once
  - Fit result with individual 'made-up' beta spectra
  - Convert to individual antineutrino spectra using E-conservation + nuclear corrections
  - Sum to get total antineutrino energy

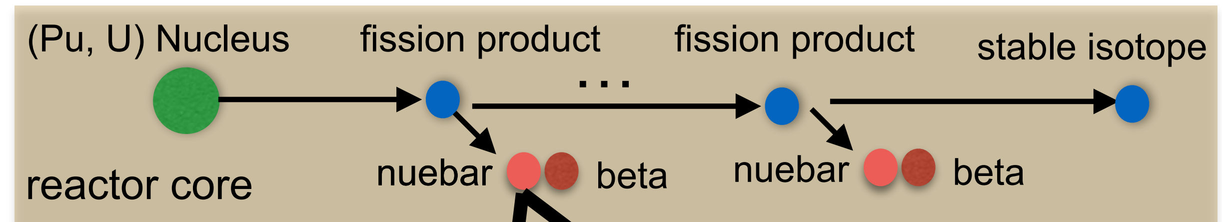


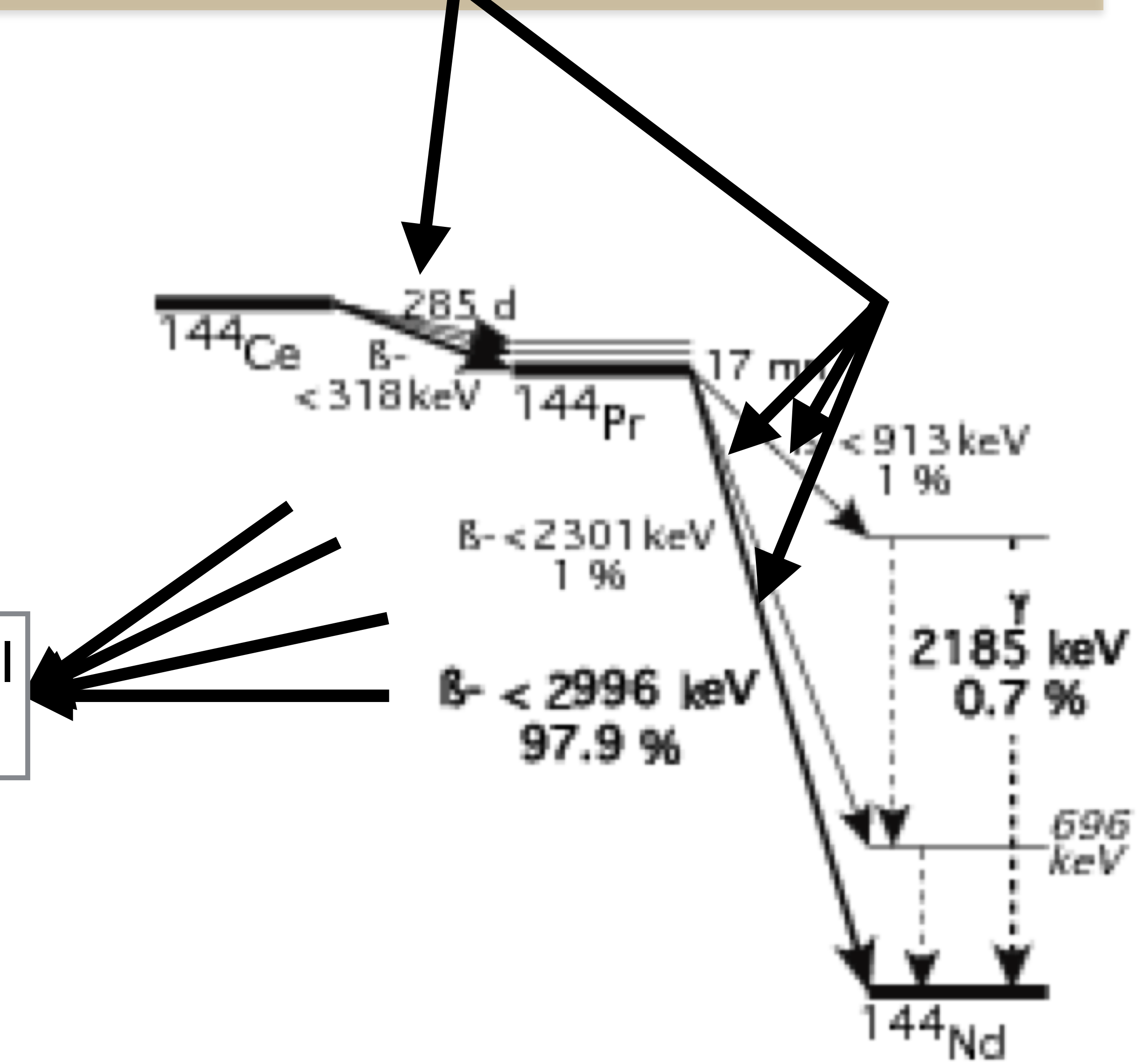




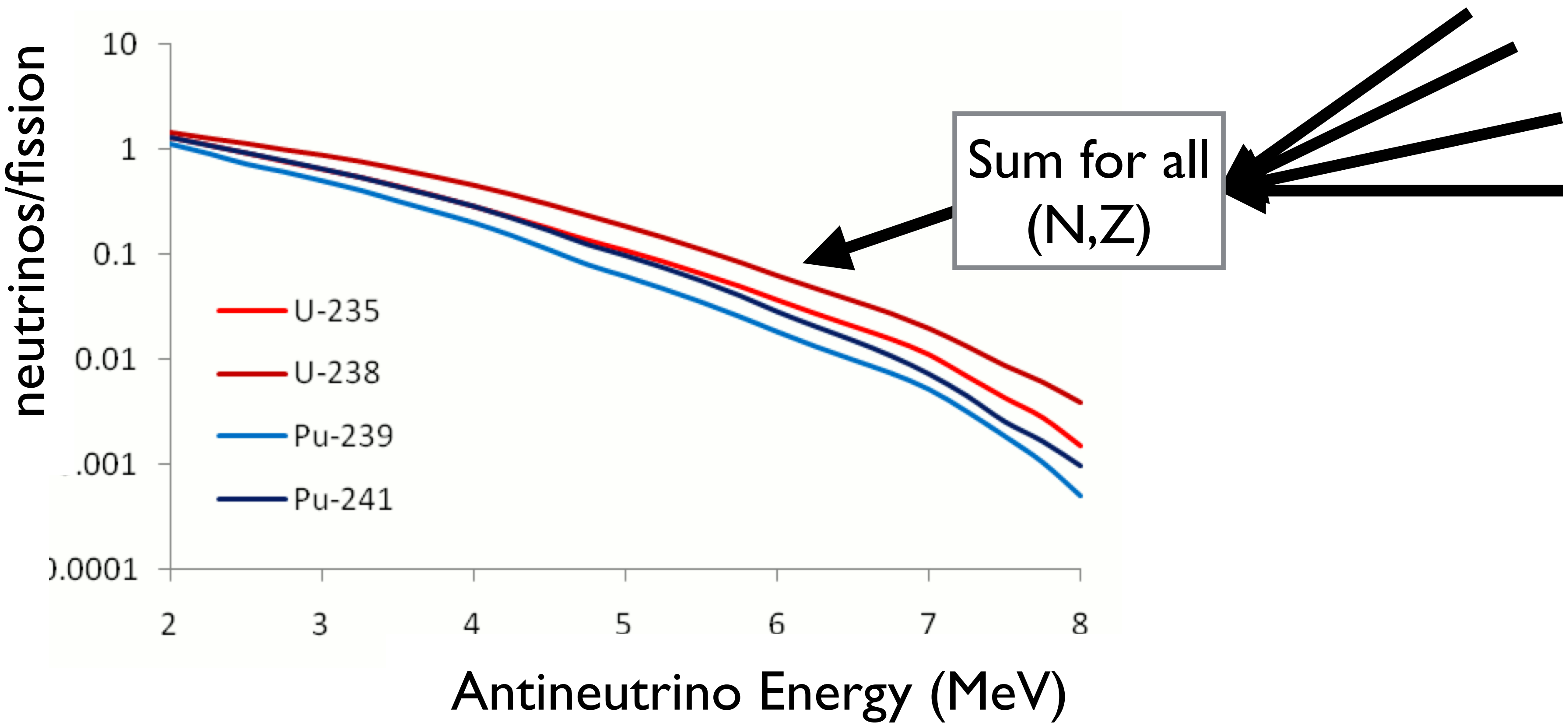
Reactor Antineutrino Production

- Reactor $\bar{\nu}_e$: produced in decay of product beta branches
- Summation prediction:
  - Measure fission yields, nuclear structure in decades of nuclear physics experiments
  - Calculate antineutrino contribution from each product + branch
  - Sum to get total antineutrino energy



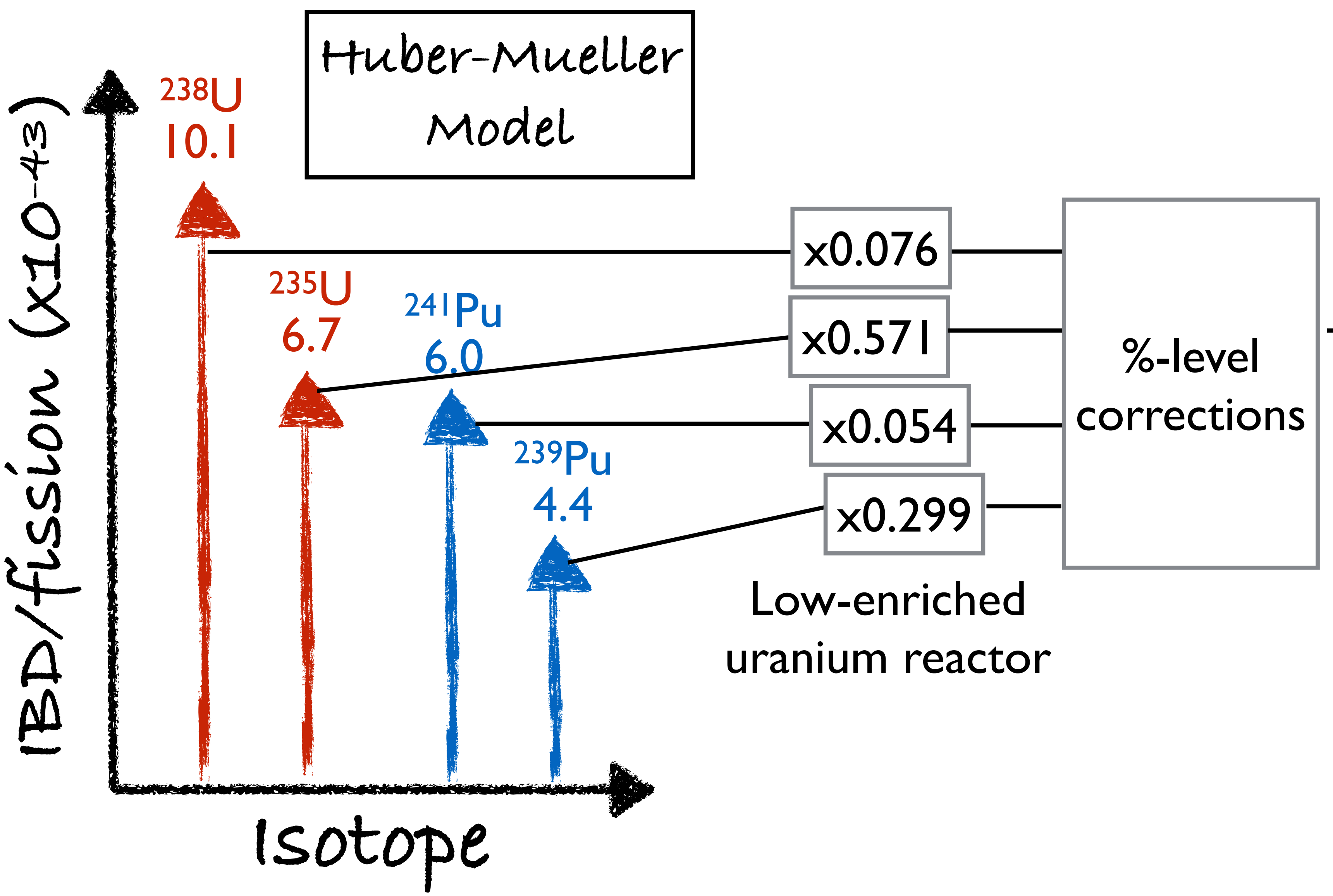


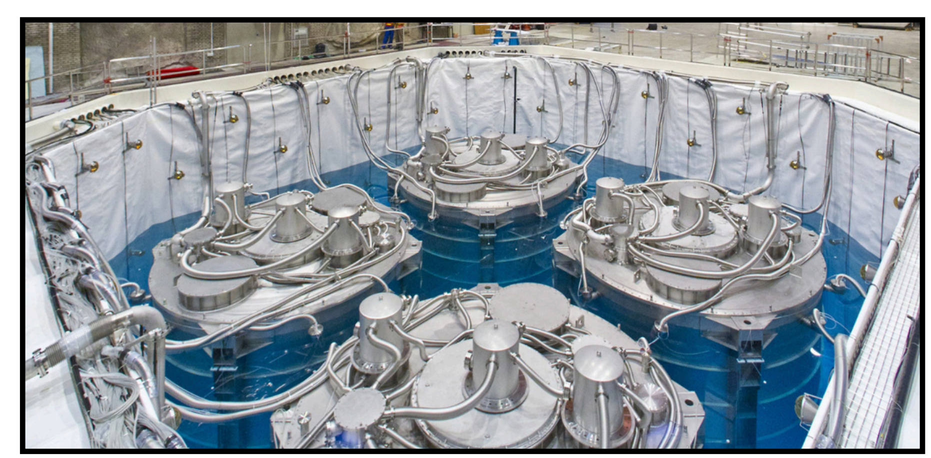
Example: Ce-144 Decay Scheme



Reactor IBD Yield Measurements

- Three isotopes' $\bar{\nu}_e$ conversion predictions redone in 2011
- To predict one experiment's yield: multiply each isotope's IBD yield by its fission fraction, correct, sum, and you're done.



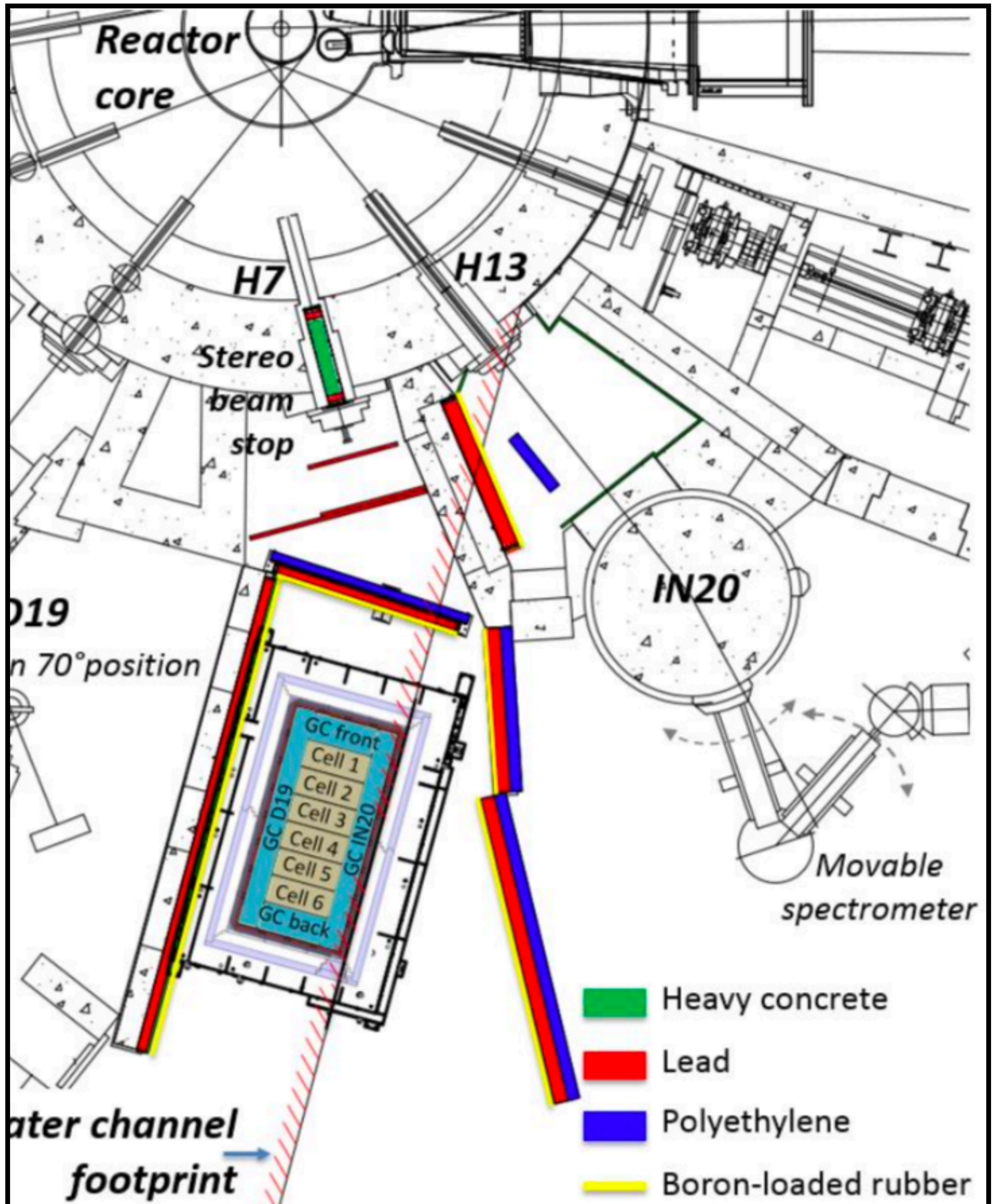


Daya Bay

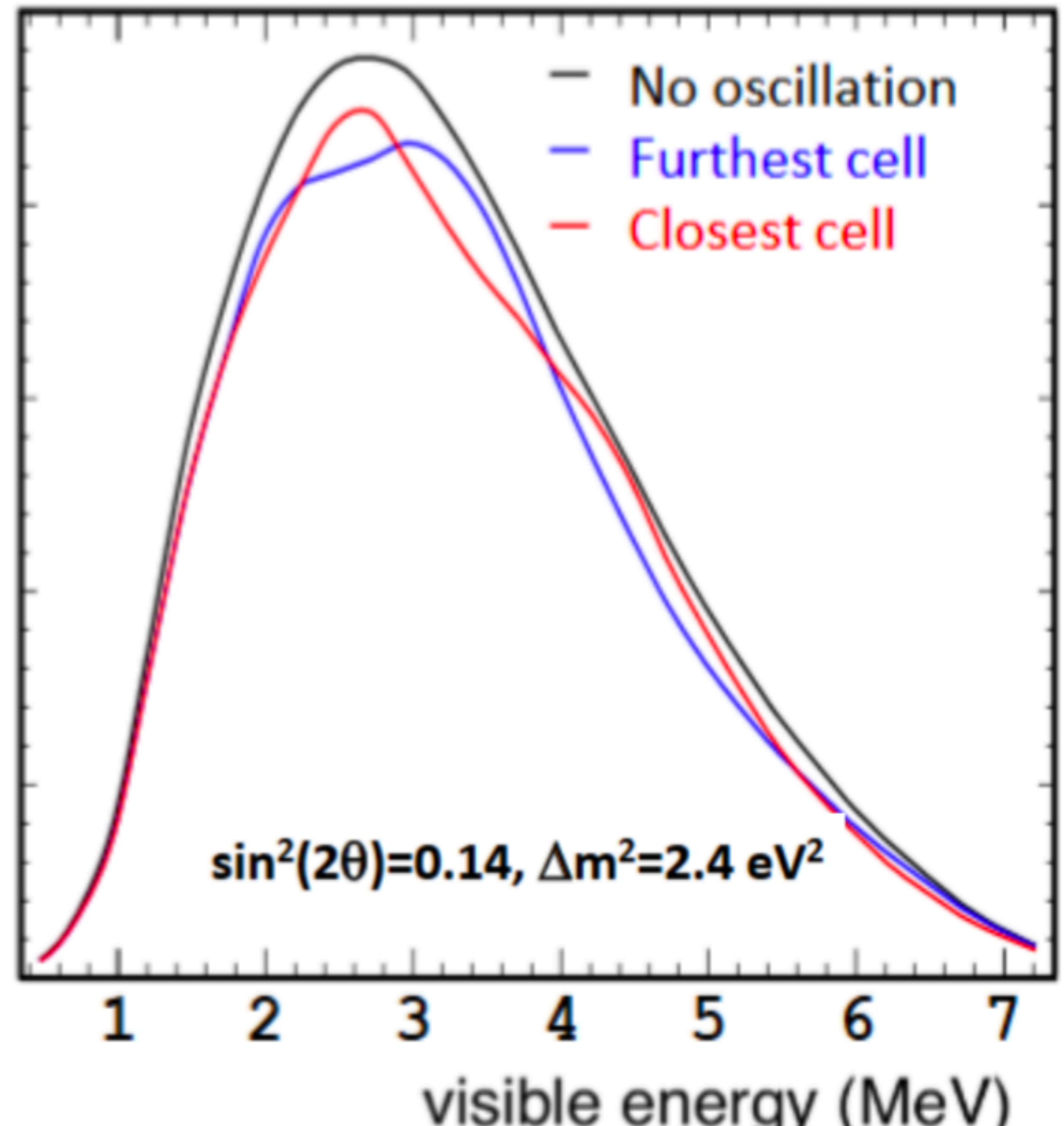
Testing Steriles: Short-Baseline Experiments

- PROSPECT, Soliδ, STEREO, etc: Compare spectra between ‘sub-detectors’ at different baselines inside a single detector

STEREO Experimental Layout



STEREO Toy Prompt Spectra From RAA Best-Fit Osc

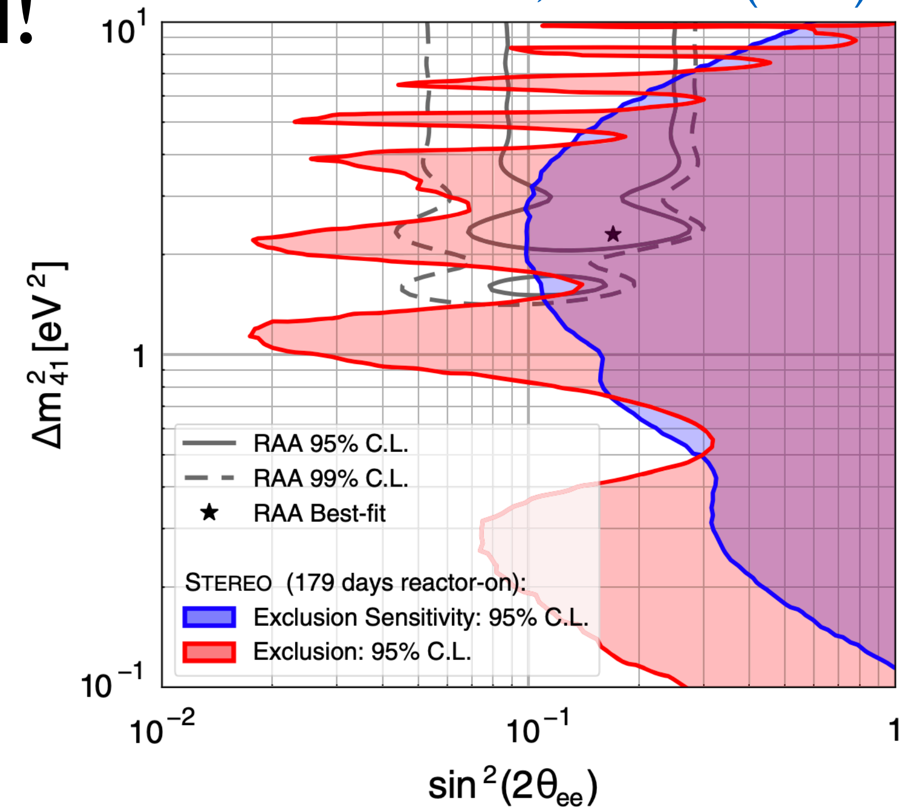


STEREO, Neutrino 2018

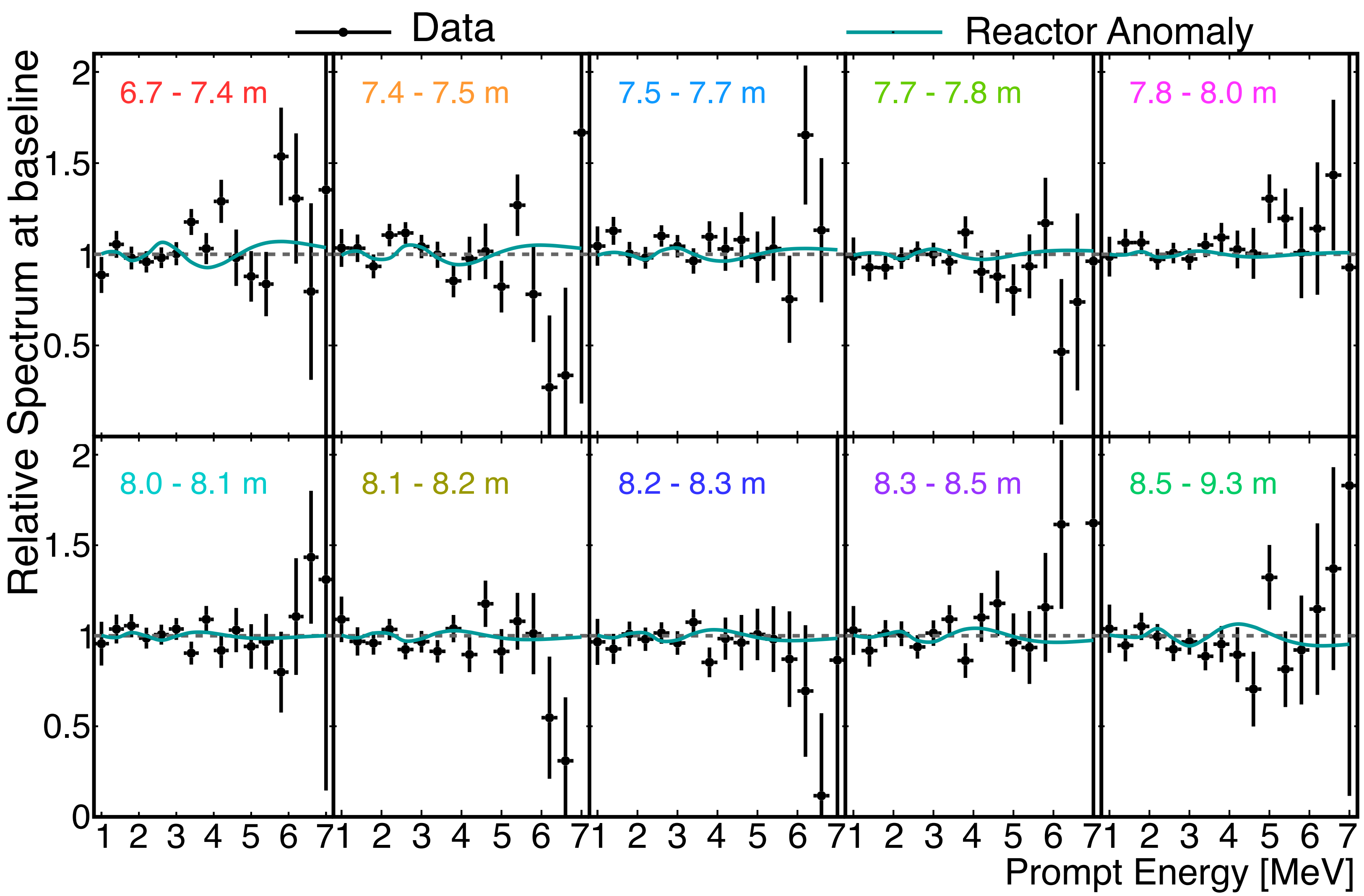
Testing Steriles: PROSPECT and STEREO

- PROSPECT and STEREO: Results in hand!
- No evidence for steriles so far
  - Also recent null results from experiments at commercial (LEU) cores: DANSS and NEOS.

STEREO, PRD 102 (2020)



PROSPECT, arXiv:2006.11210 (2020)



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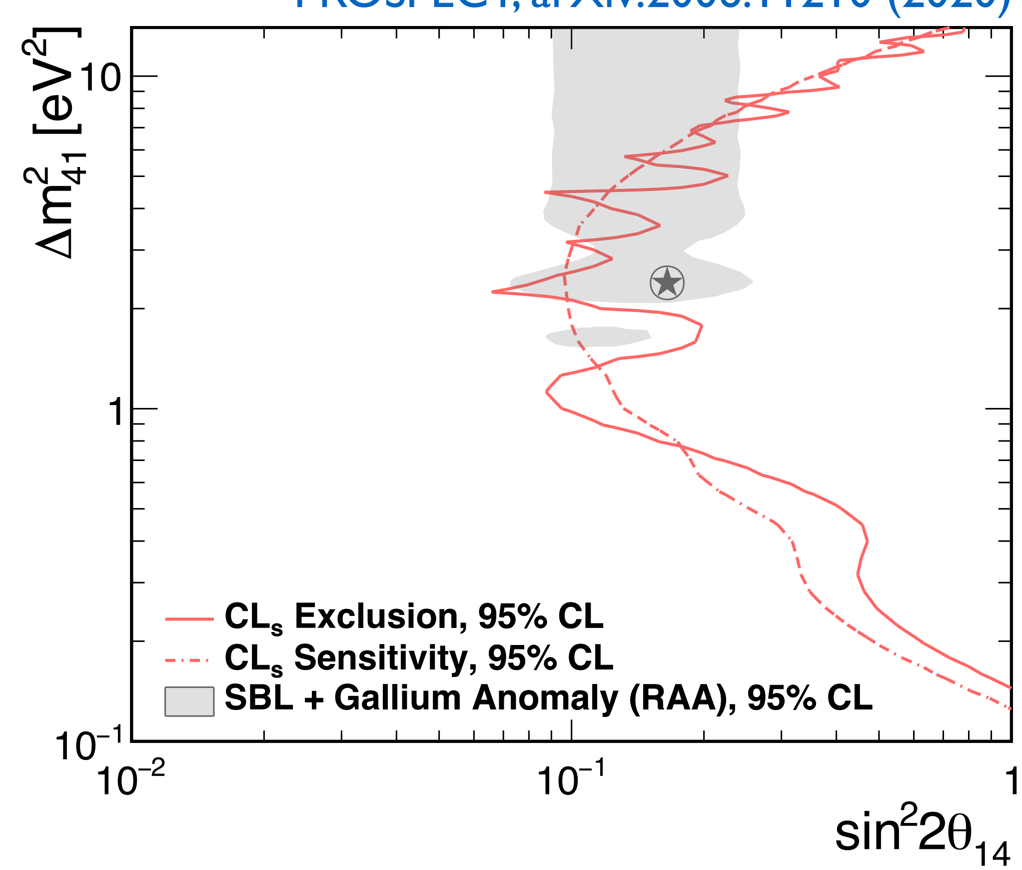
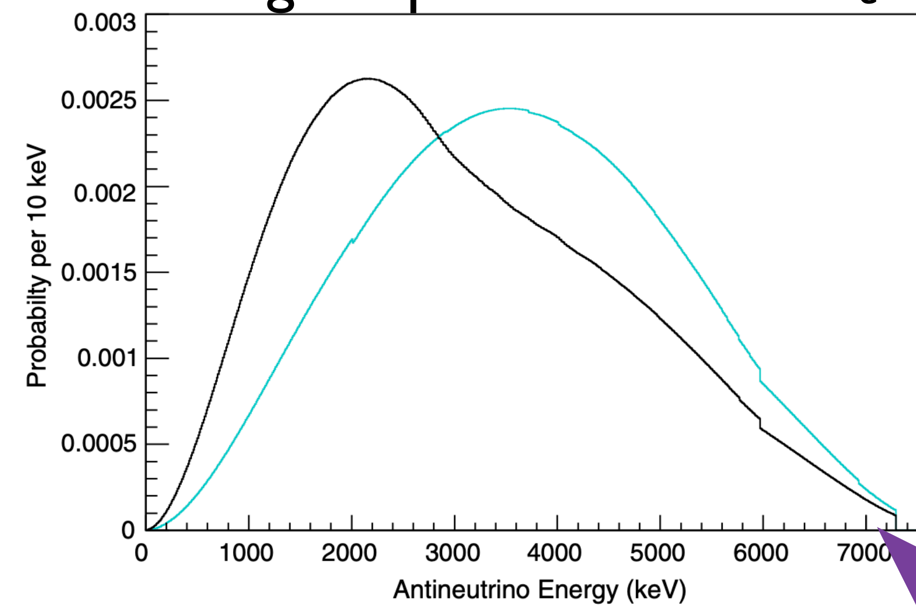


Summation Prediction: Better Agreement

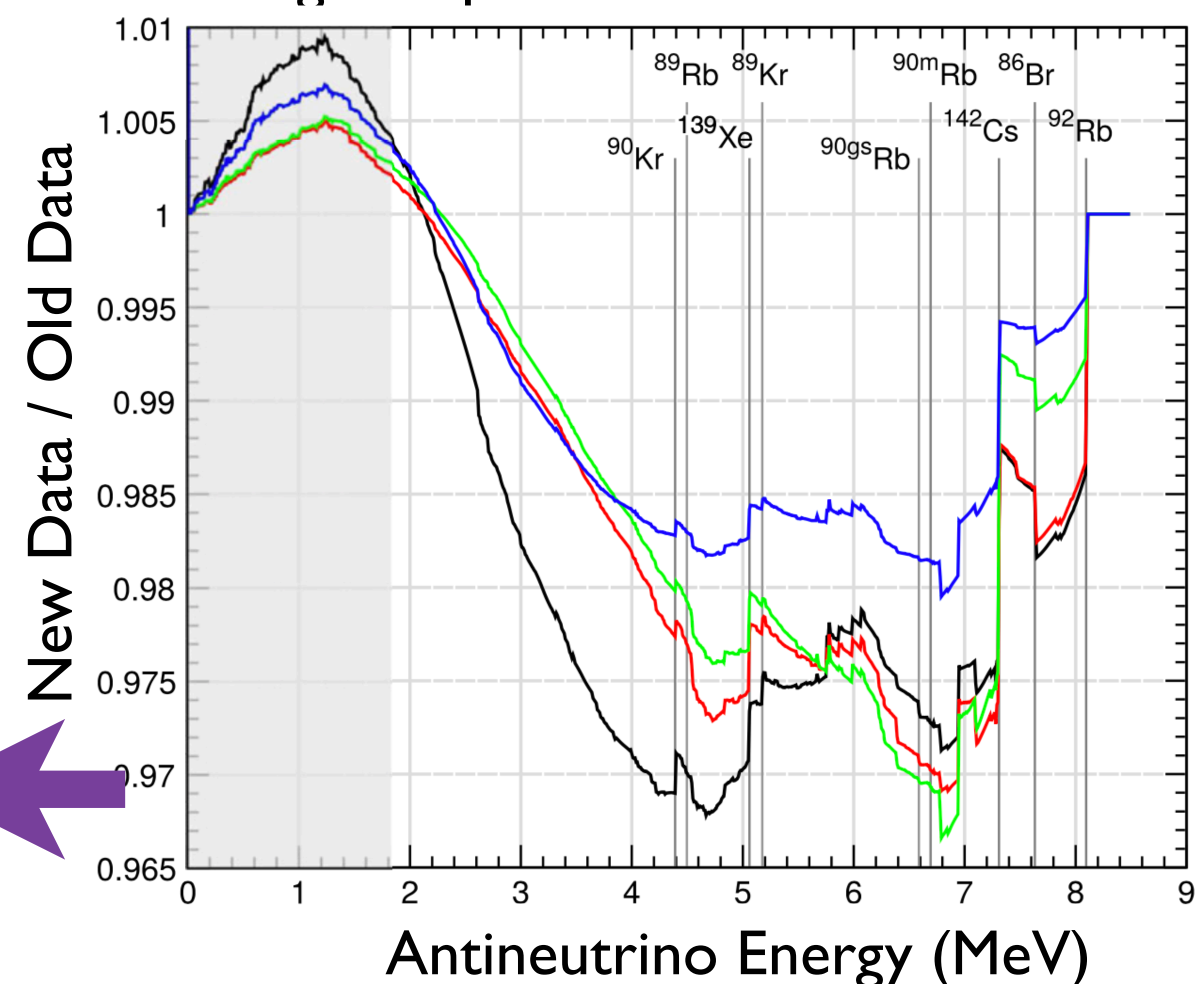
- Summation predictions re-produce flux evolution well
- Flux agreement improves with addition of new nuclear data
  - Absolute deficit still remains, though

MTAS PRL 117 092501 (2016) M. Estienne et al, PRL 123 (2020)
MTAS, PRL 119 052503 (2017) A. Zakari-Issoufou et al, PRL 115 (2015)
Many others…

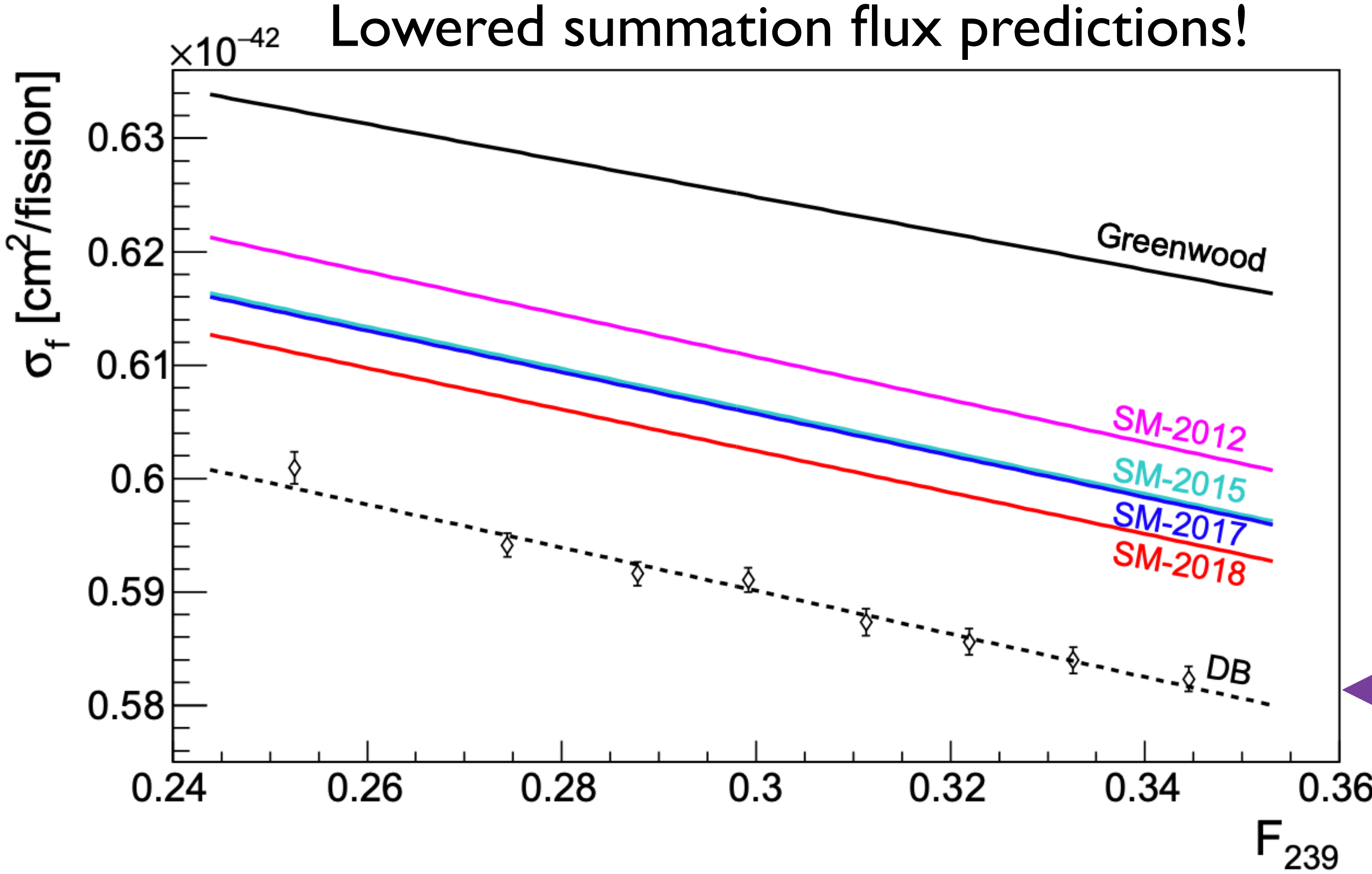
Change in predicted ^{142}Cs ν_e



Change in spectrum w/ new nuclear data



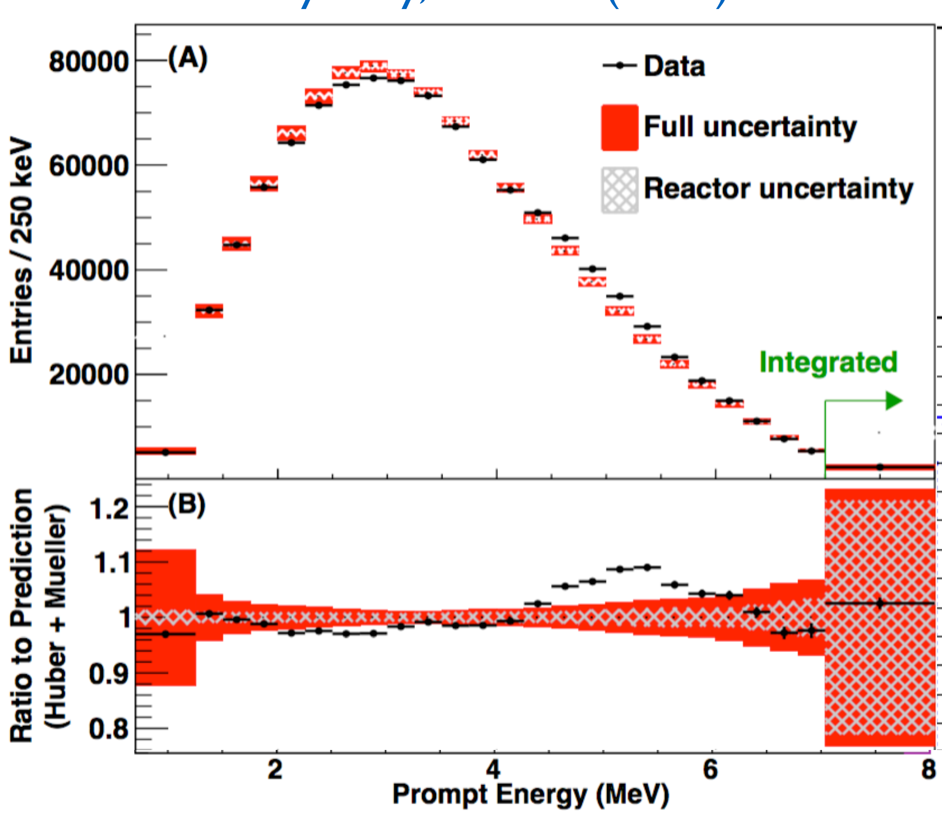
Lowered summation flux predictions!



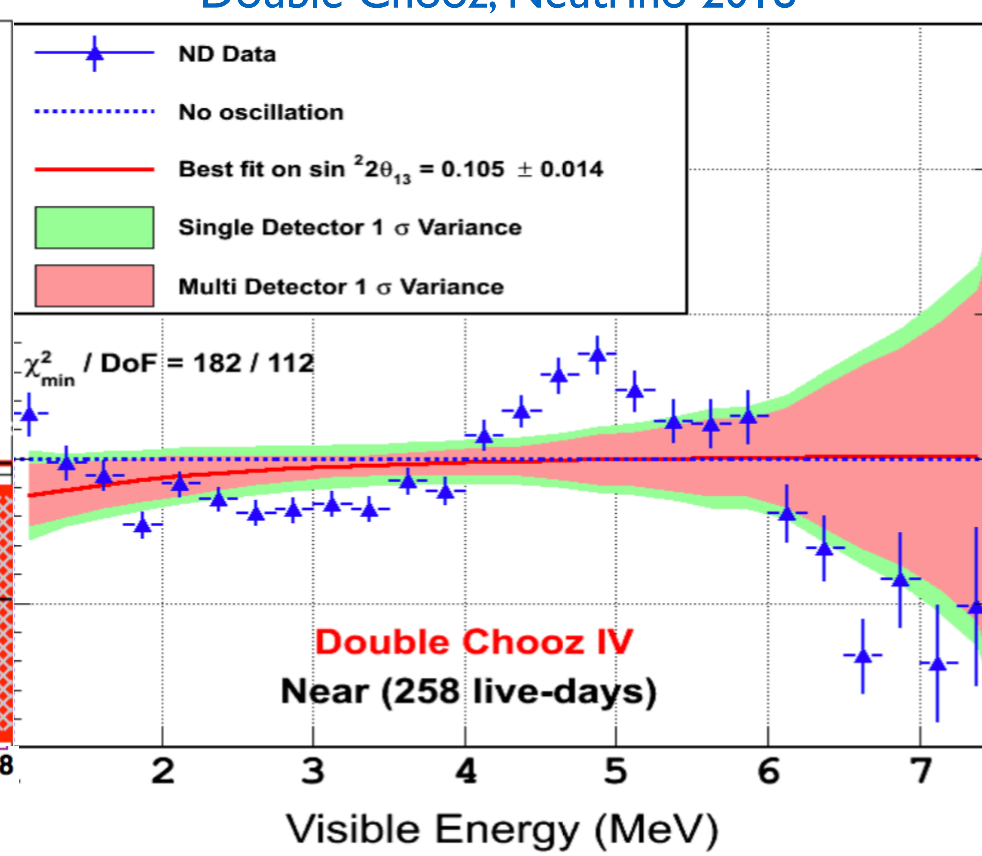
Reactor Spectrum Anomaly

- Bad news: <u>conversion</u> predictions don't match LEU data
  - Eye is first drawn to the 'bump' in the 4-6 MeV range.
  - Zooming out: kinda just looks bad generally across the entire spectrum…

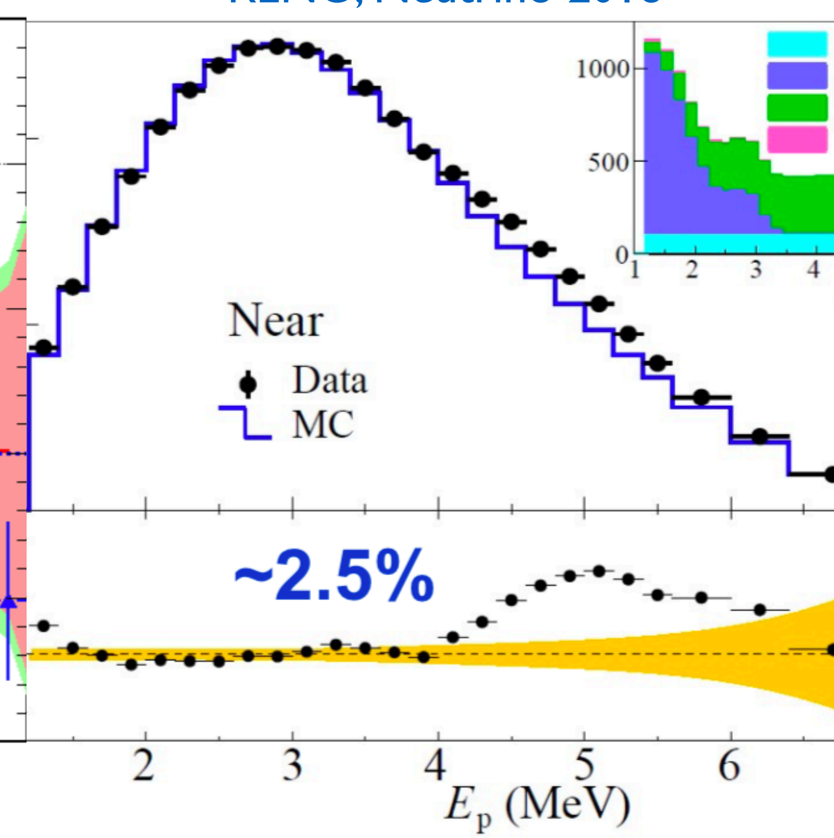
Daya Bay, CPC 41 (2017)



Double Chooz, Neutrino 2018



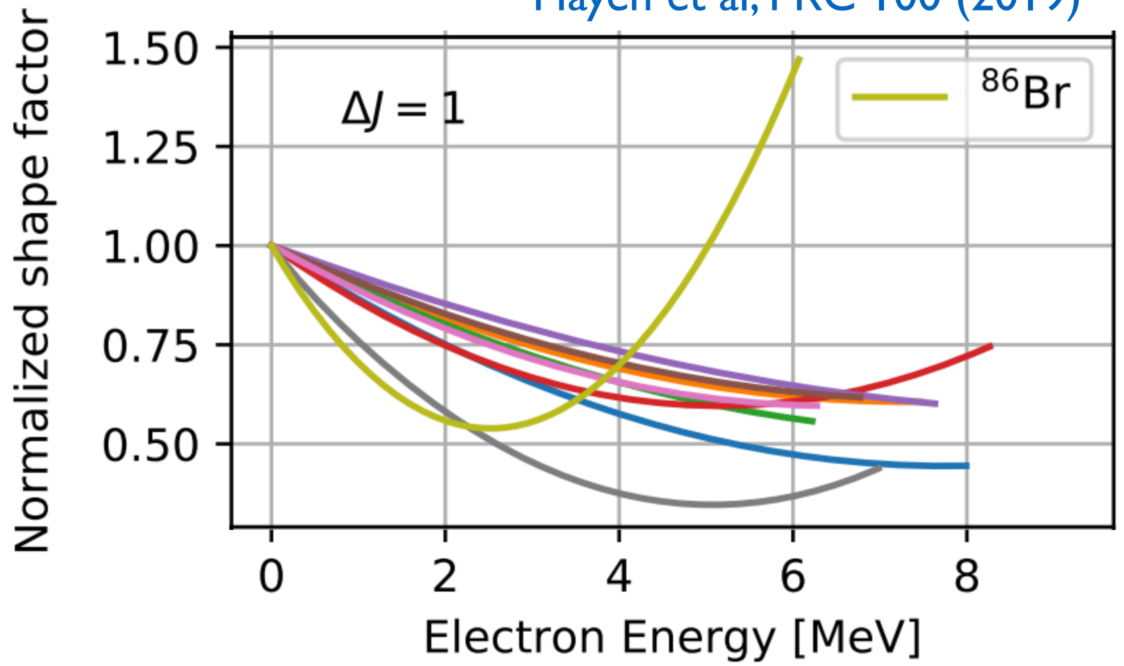
RENO, Neutrino 2018



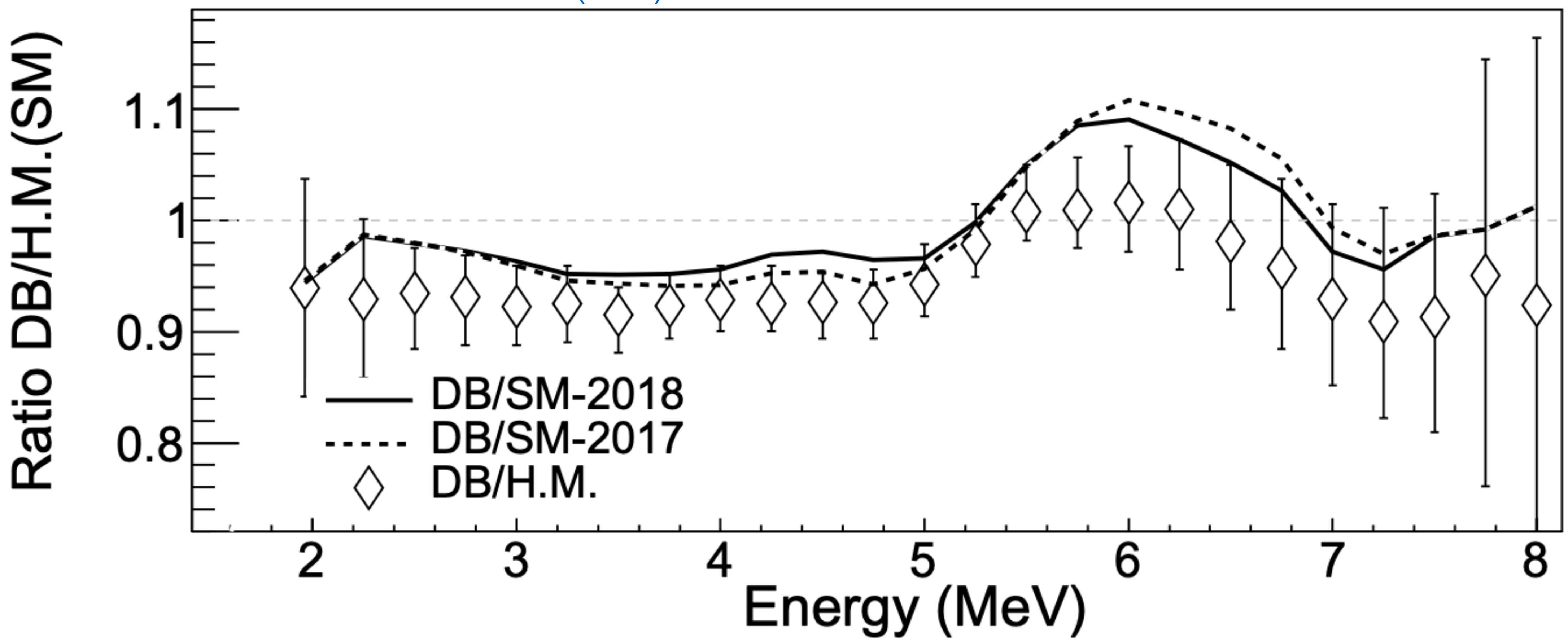
Spectrum Anomaly From Summation, Too

- This issue <u>IS NOT</u> solved by using the summation prediction
- Common flaw in both predictions?
  - Do we fully understand theory of forbidden nuclear decays?
  - Need more nuclear data to check! Forbidden beta spectrum measurements!

Hayen et al, PRC 100 (2019)



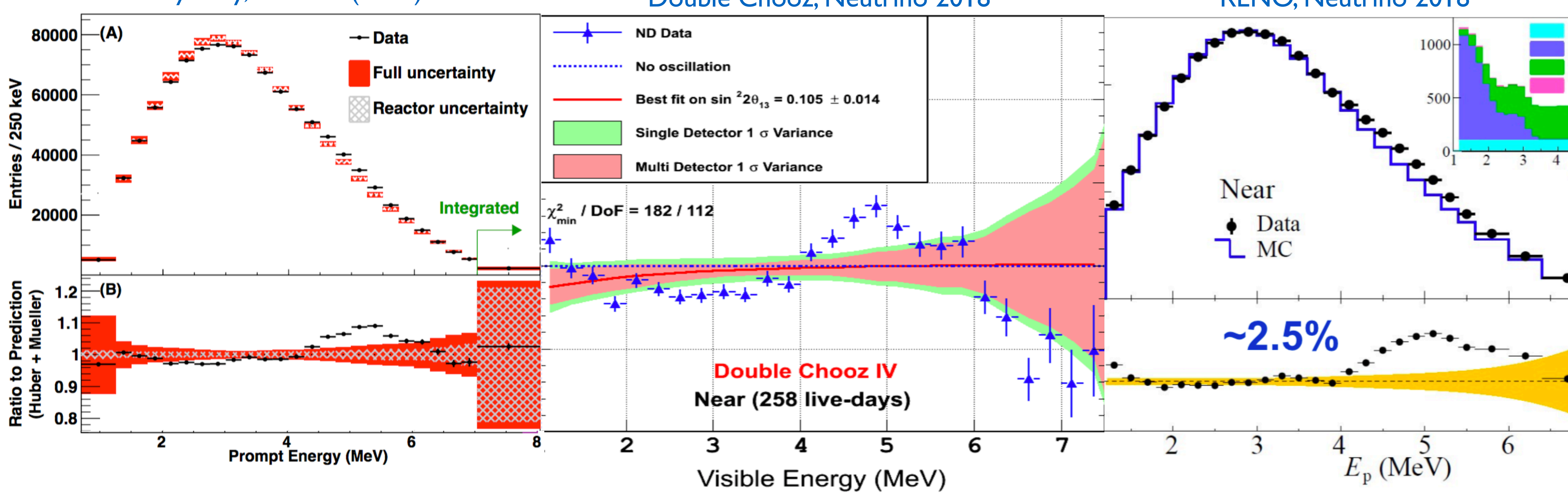
M. Estienne et al, PRL 123 (2020)



Reactor Spectrum Anomaly

- Bad news: conversion predictions don't match LEU data
  - Eye is first drawn to the 'bump' in the 4-6 MeV range.
  - Zooming out: kinda just looks bad generally across the entire spectrum…
- **HOW** is spectrum incorrectly predicted?
  - Like with flux: is one particular isotope to blame (like ^{235}U)? Or all?
  - Looks like short-baseline ^{235}U measurements can also give new info here

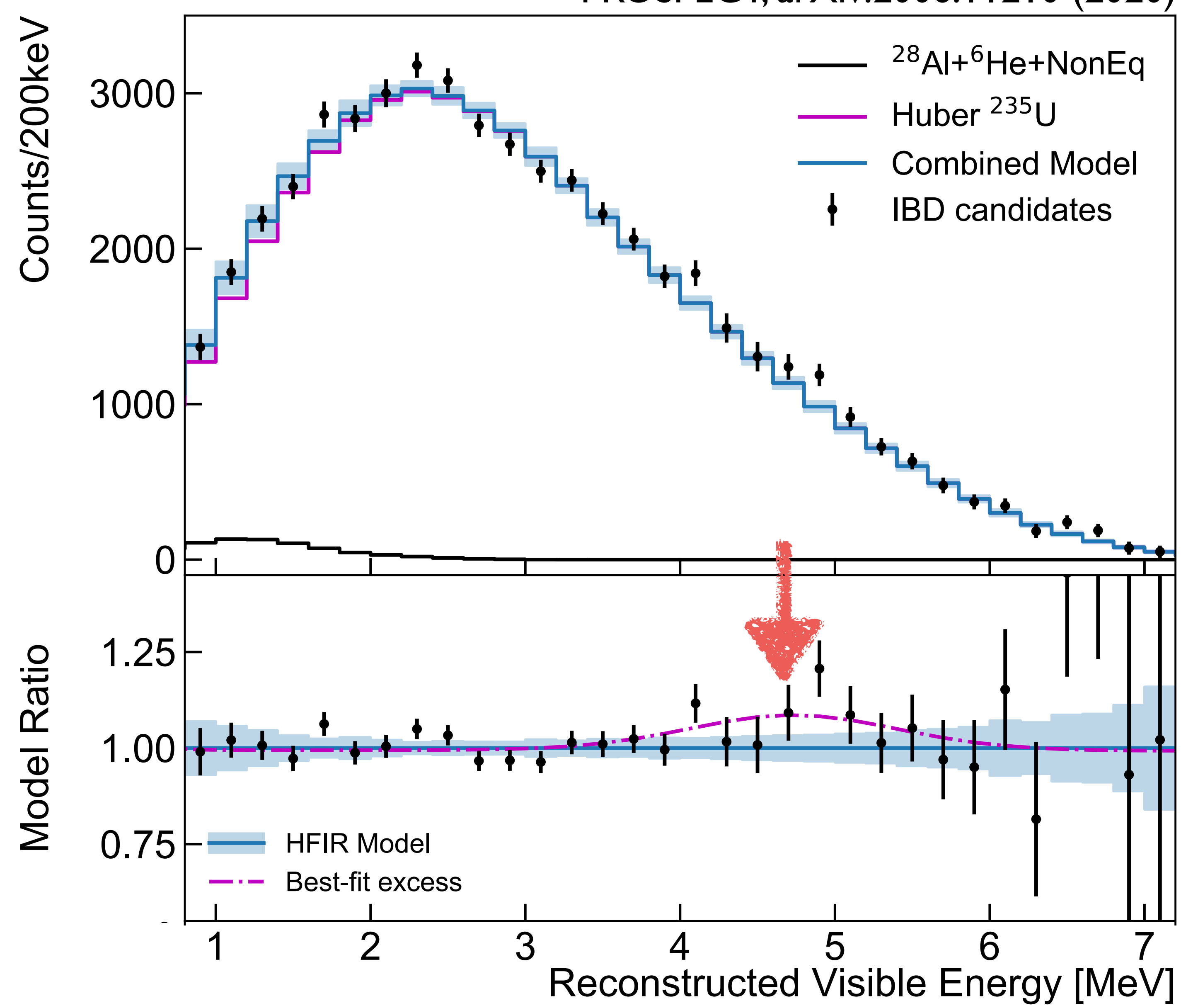
Daya Bay, CPC 41 (2017) Double Chooz, Neutrino 2018 RENO, Neutrino 2018



Isotopic Origins: PROSPECT

- Measure spectrum when burning <u>only</u> ^{235}U
- Does PROSPECT see a 'bump' like Daya Bay?
  - PROSPECT relative bump size WRT to Daya Bay: 84% ± 39%
  - Consistent with LEU bump; indicates all fission isotopes contribute to data/model issue
  - 'Big bump' (178%) if ^{235}U is major culprit; disfavored at 2.4σ
  - 'No bump' (0%) if ^{235}U is not to blame; disfavored at 2.2σ
- STEREO is ~consistent with these results, with similar precision

PROSPECT, arXiv:2006.11210 (2020)



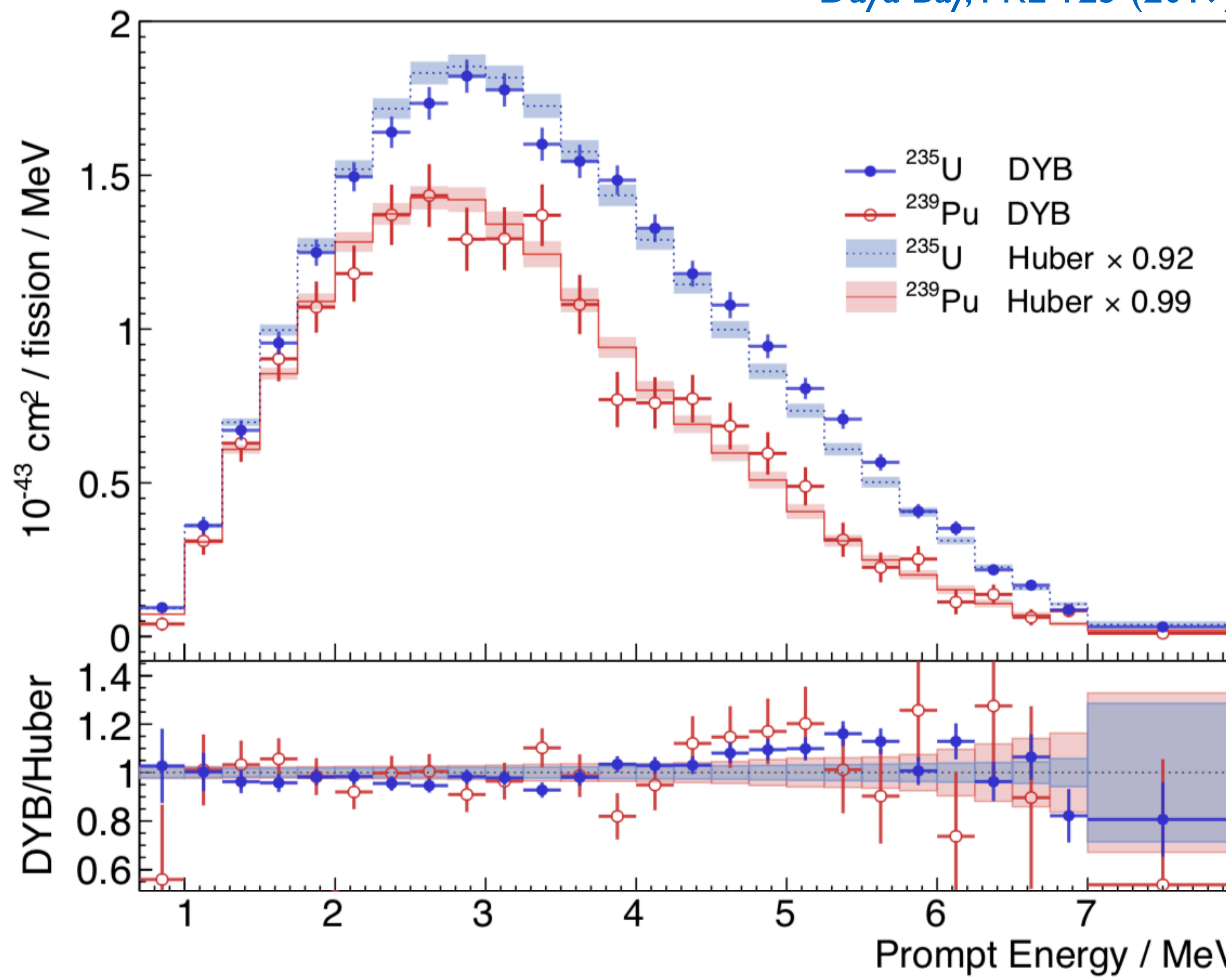
STEREO, arXiv:2010.01876 (2020)

- PROSPECT-2 can improve current statistical precision x10!

Isotopic Origins: DYB Spectrum Evolution

- Measure Daya Bay spectrum variation with fuel content.
- Enables ‘extraction’ of spectra of ^{239}Pu, ^{235}U $\bar{\nu}_e$
  - Best fit to data: both isotopes have ‘bumps’ WRT prediction
    - However, only 0.8σ better than ‘^{235}U only’ case; need more stats!
  - Result is consistent with PROSPECT’s conclusion in the previous slides
- Actively pursuing joint HEU-LEU analyses
  - Enhances ability to probe isotopic spectra

Daya Bay, PRL 123 (2019)



Isotopic Origins: A Broader View

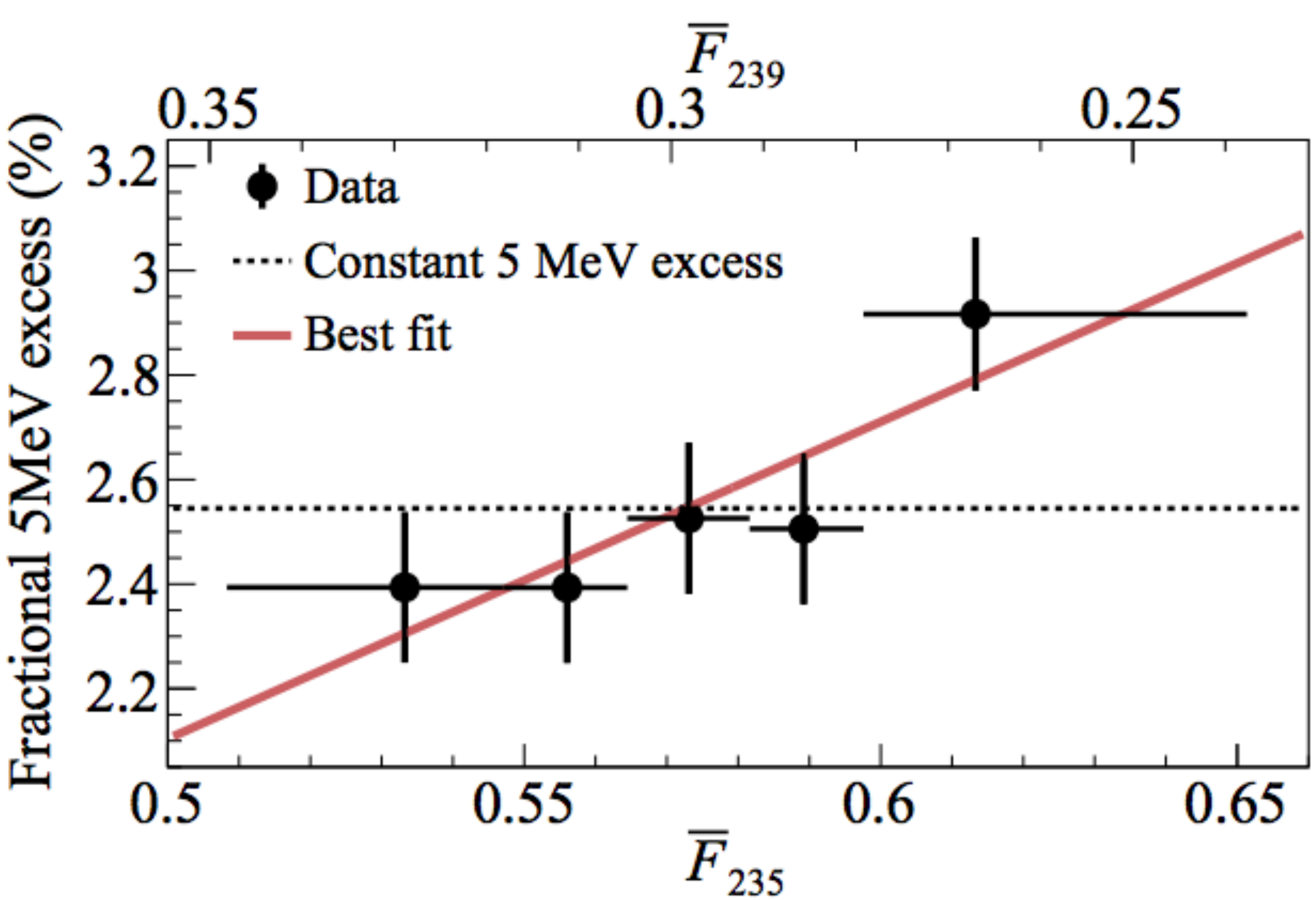
- Our simplified Q: 'Which isotopes produce the bump?'
- Experiments weighing in so far (my over-simplified summary…)

Experiment	~Only 235 (~No 239 bump)	Common origin	No 235 bump (~Pu only)	
Daya Bay	**OK**	**OK**	**NO**	Daya Bay, PRL 123 (2019)
RENO	**OK**	**NO**	**NO**	RENO, PRL 122 (2019)
PROSPECT	**NO**	**OK**	**NO**	PROSPECT, arXiv:2006.11210 (2020)
STEREO	**OK**	**OK**	**NO**	STEREO, arXiv:2010.01876 (2020)

- Most likely hypothesis: a common isotopic origin
  - Yields for different fission isotopes <u>extensively overlap!</u> X. Ma, et al, arXiv:1807.09265 (2018)
- All $\bar{\nu}_e$ data are consistent with this scenario except RENO
  - WHY? Should RENO claims be re-examined?

Isotopic Origins: RENO

- RENO: does bump size change with fuel content?
  - Claim ~2.9σ indication of increasing bump size with increased ^{235}U burning
  - Newest arXiv posting increases this to 3.1σ RENO, arXiv:2010.14989 (2020)



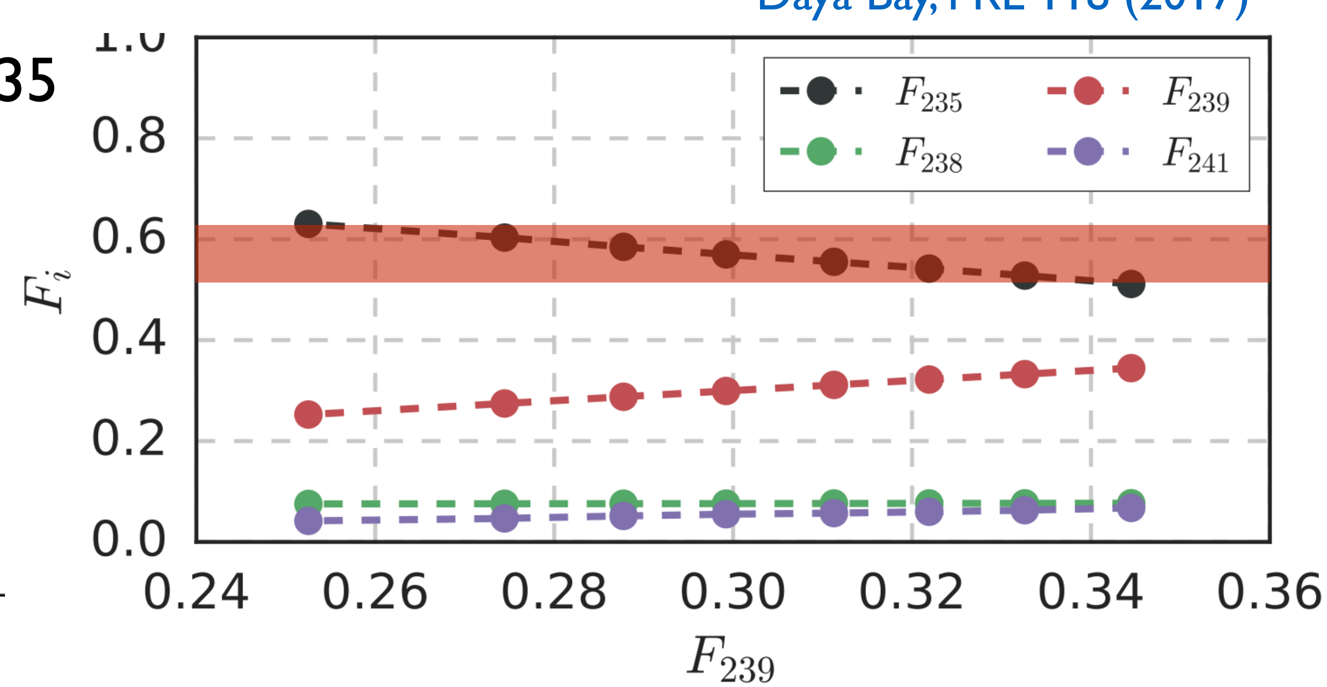
RENO, arxiv[1806.00574].v1 (2018)

Isotopic Origins: RENO

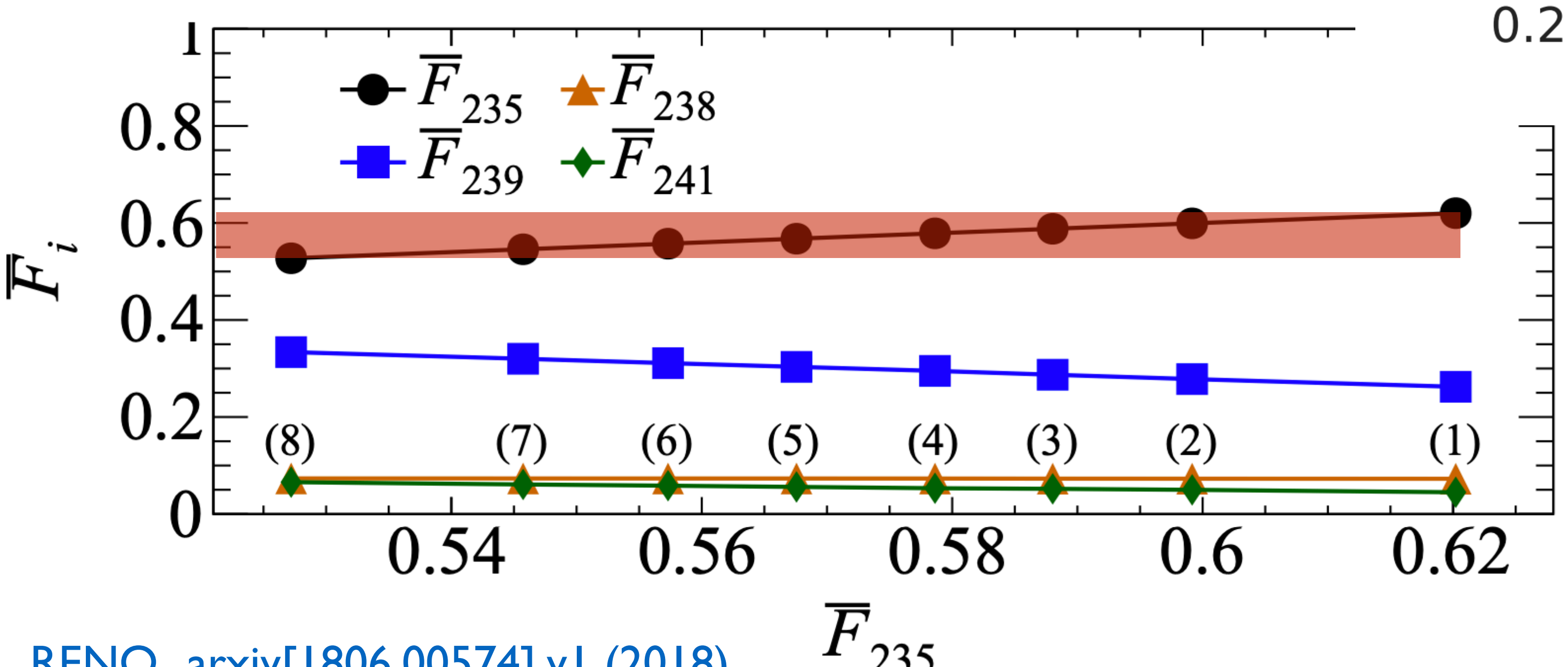
- Similar analysis at RENO: does bump change with fuel content?
  - Ask a meddling competitor:
    - Why does RENO have statistical capabilities to say something meaningful, <u>while DYB doesn't?</u> DYB statistics are **<u>>3x</u> <u>larger (!!!!)</u>**, and DYB samples slightly large range of fission fractions

Daya Bay, PRL 118 (2017)

Daya Bay: Change in binned U235 fission fraction of ~12%



RENO: Change in binned U235 fission fraction of ~10%



RENO, arxiv[1806.00574].v1 (2018)

Isotopic Origins: RENO

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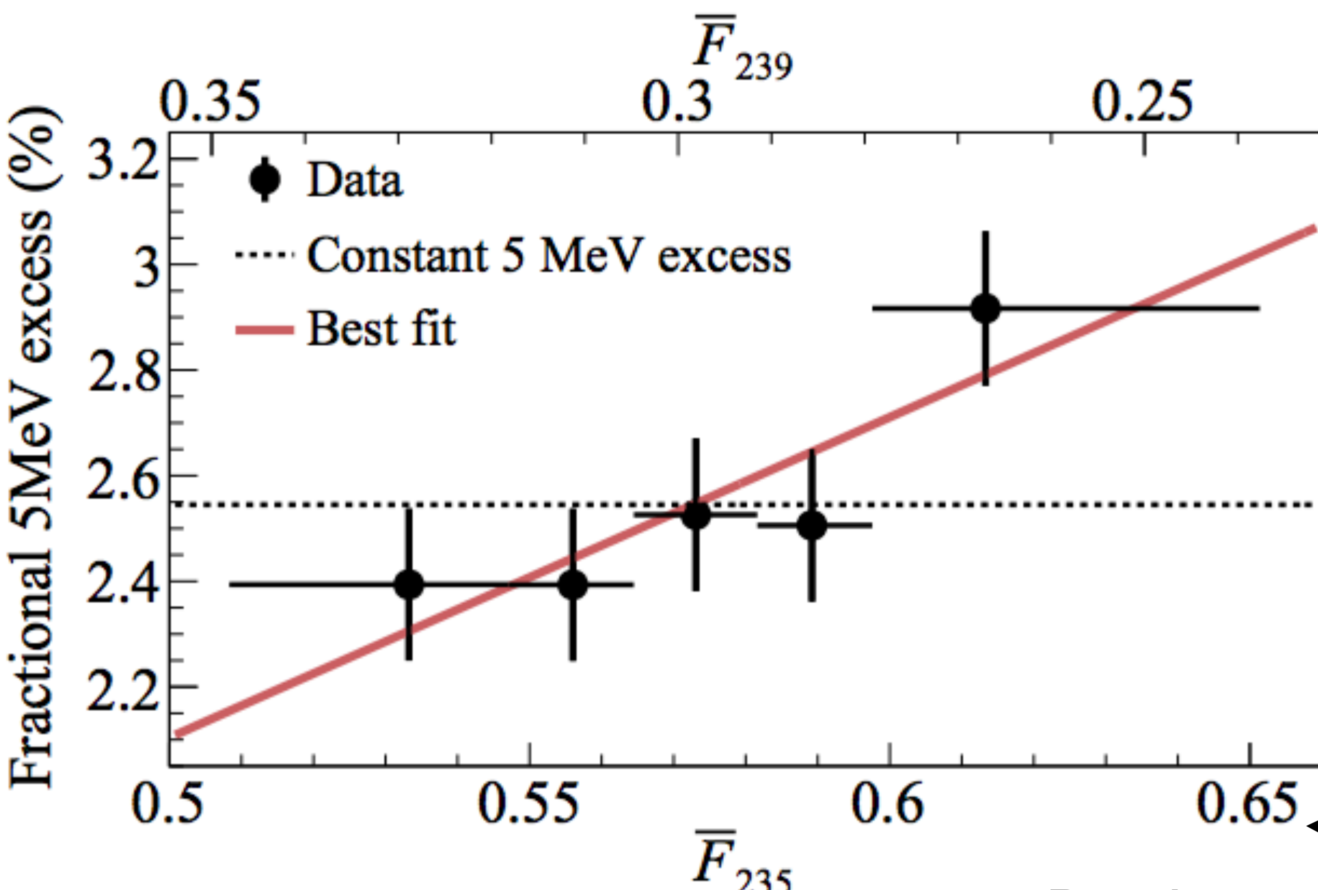
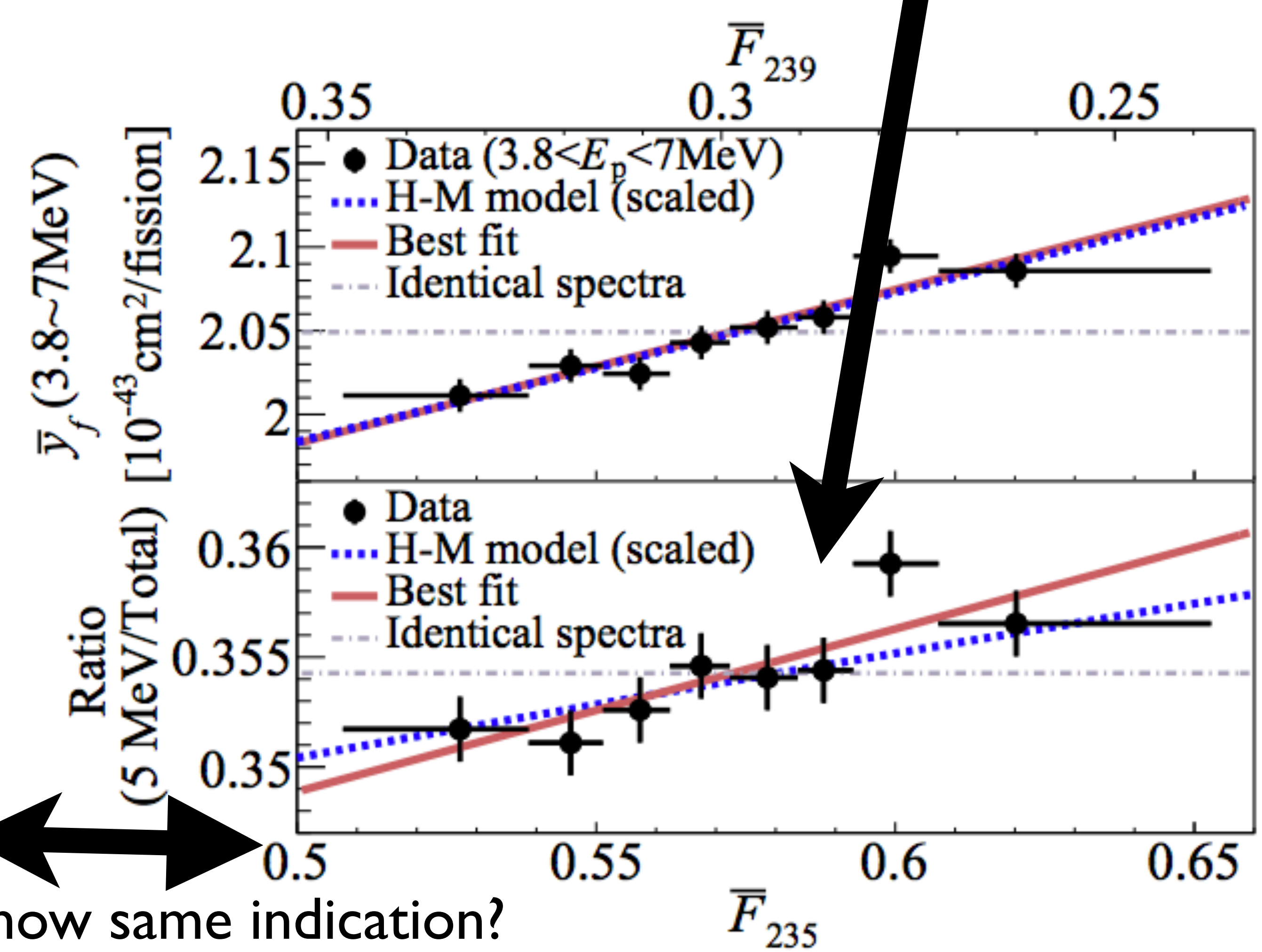
    - Similar metrics don't show similar indications (total 4-7 MeV contribution, for example)



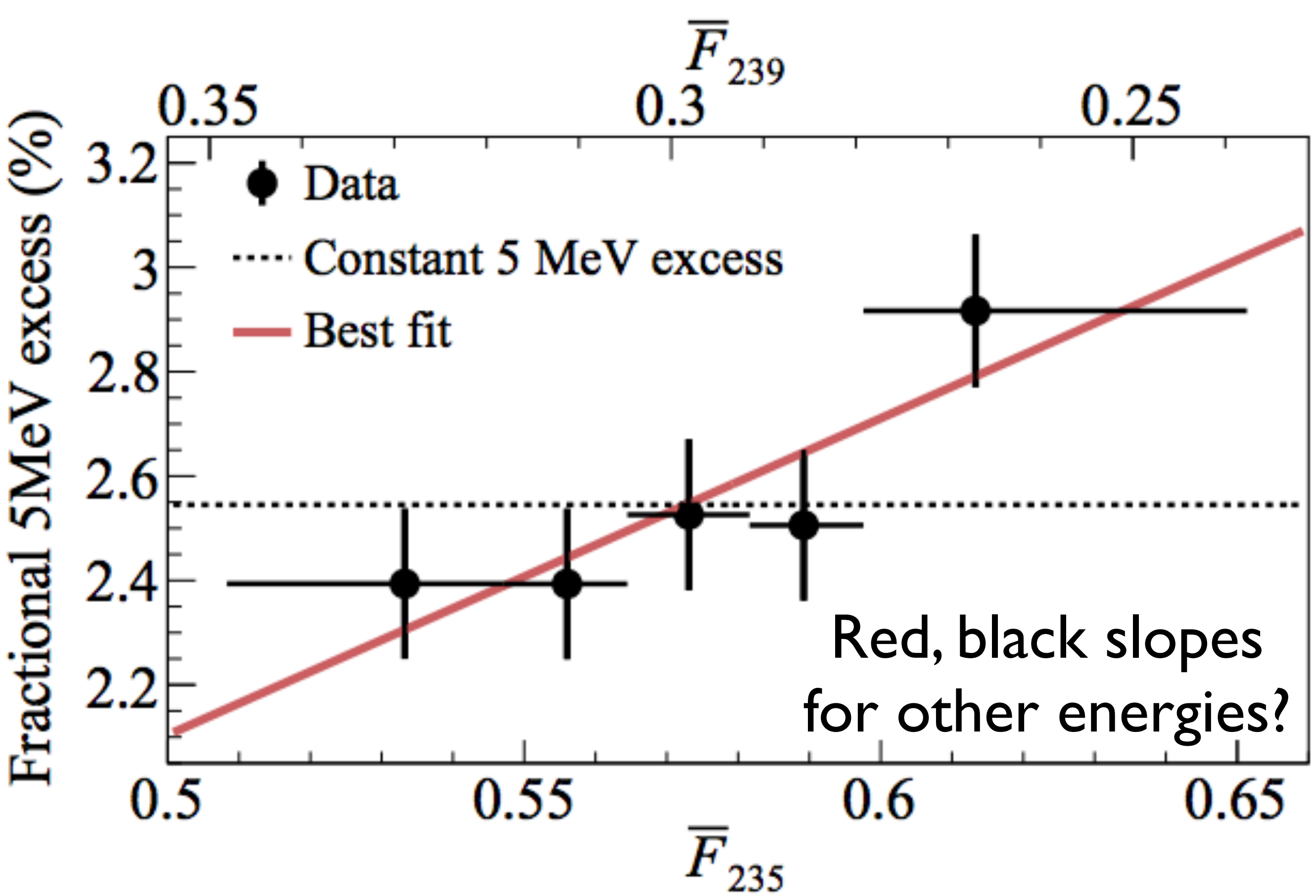


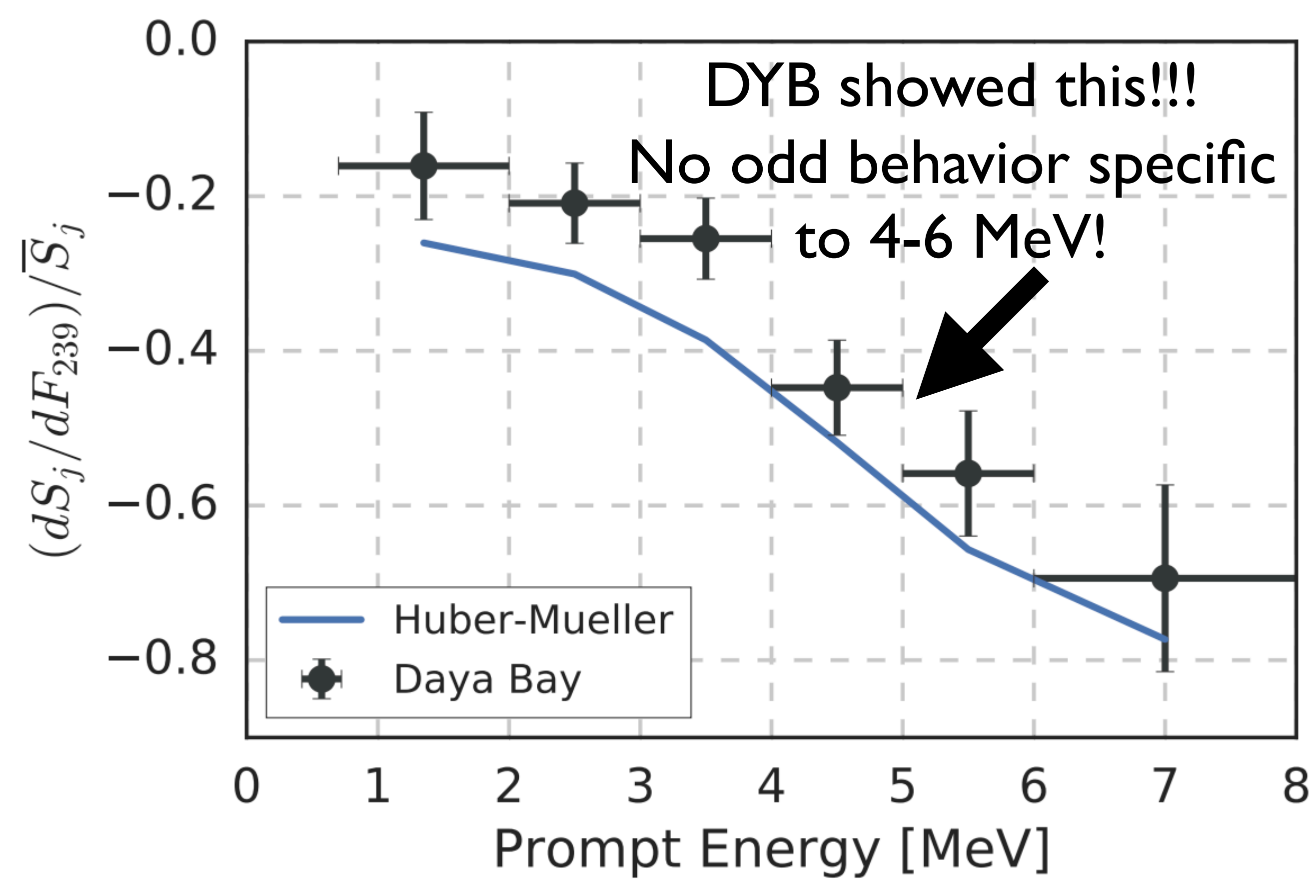
Do these show same indication?
Seems not?

RENO, arxiv[1806.00574].v1 (2018)

Isotopic Origins: RENO

- Similar analysis at RENO: does bump change with fuel content?
  - Ask a meddling competitor:
    - Why does RENO have statistical capabilities to say something meaningful, <u>while DYB doesn't?</u> DYB statistics are 50% larger, and DYB samples a larger range of fission fractions!
    - Similar metrics don't show similar indications (total 4-7 MeV contribution, for example)
    - What about behavior in other energy regions? Is 4-7 MeV region an outlier?

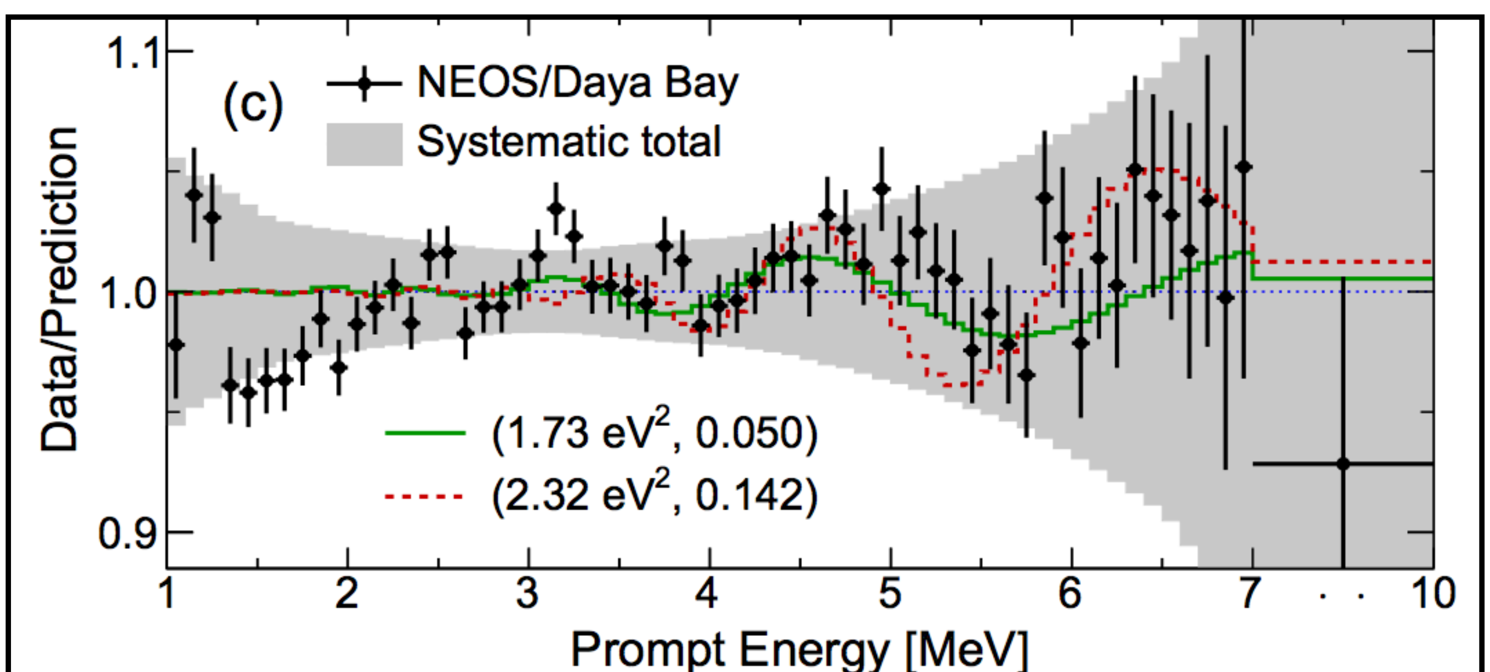


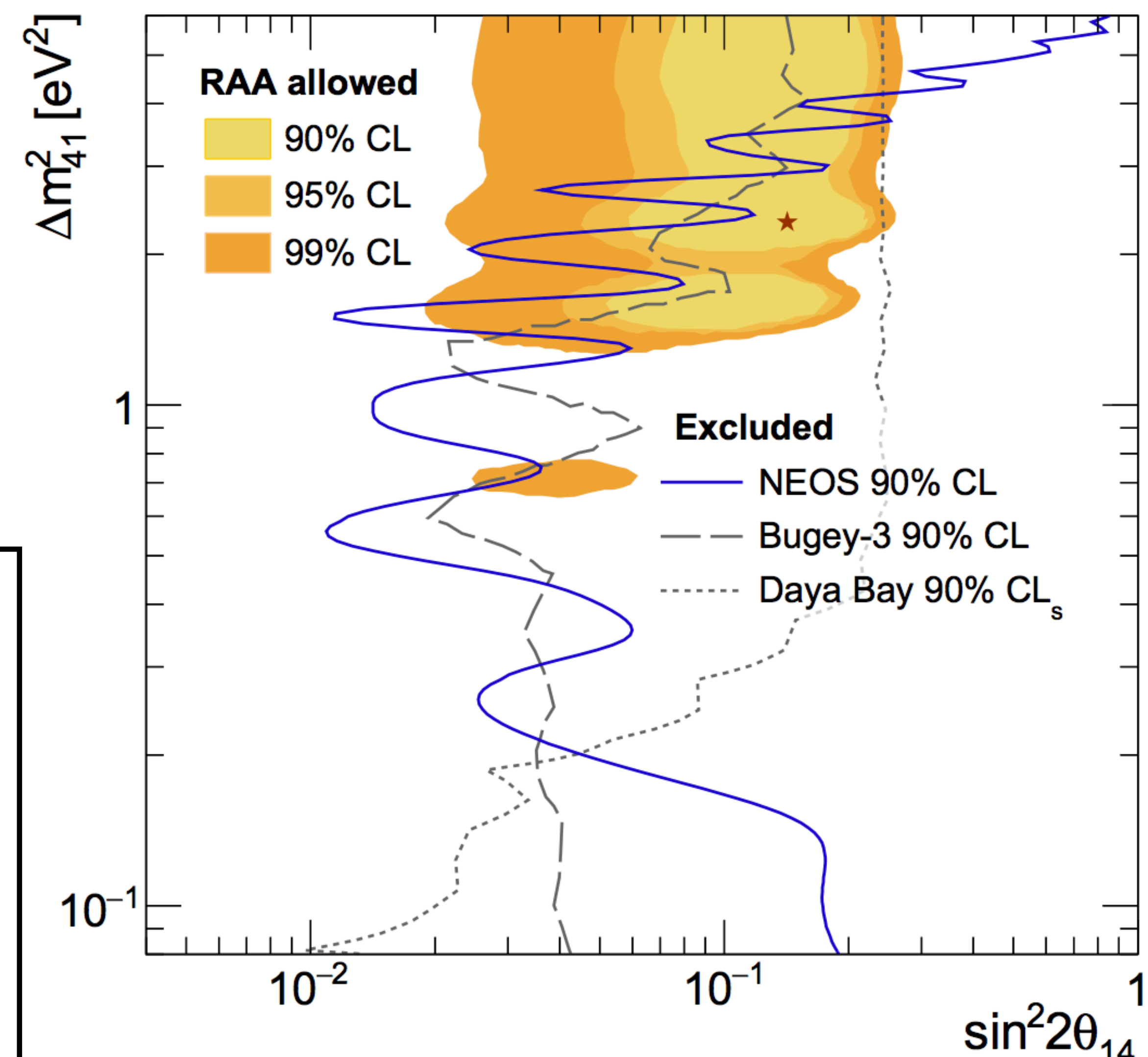


RENO, arxiv[1806.00574].v1 (2018)

Testing Steriles: NEOS

- 2016: Compare spectra between two experiments at different baselines: NEOS (25m) and Daya Bay (~500m)
  - NEOS: compact detector underground in commercial reactor's tendon gallery
  - Everyone knows DYB…
- No strong evidence for steriles
  - Limited by uncorrelated DYB-RENO systematics
  - Limited by larger core size and distance



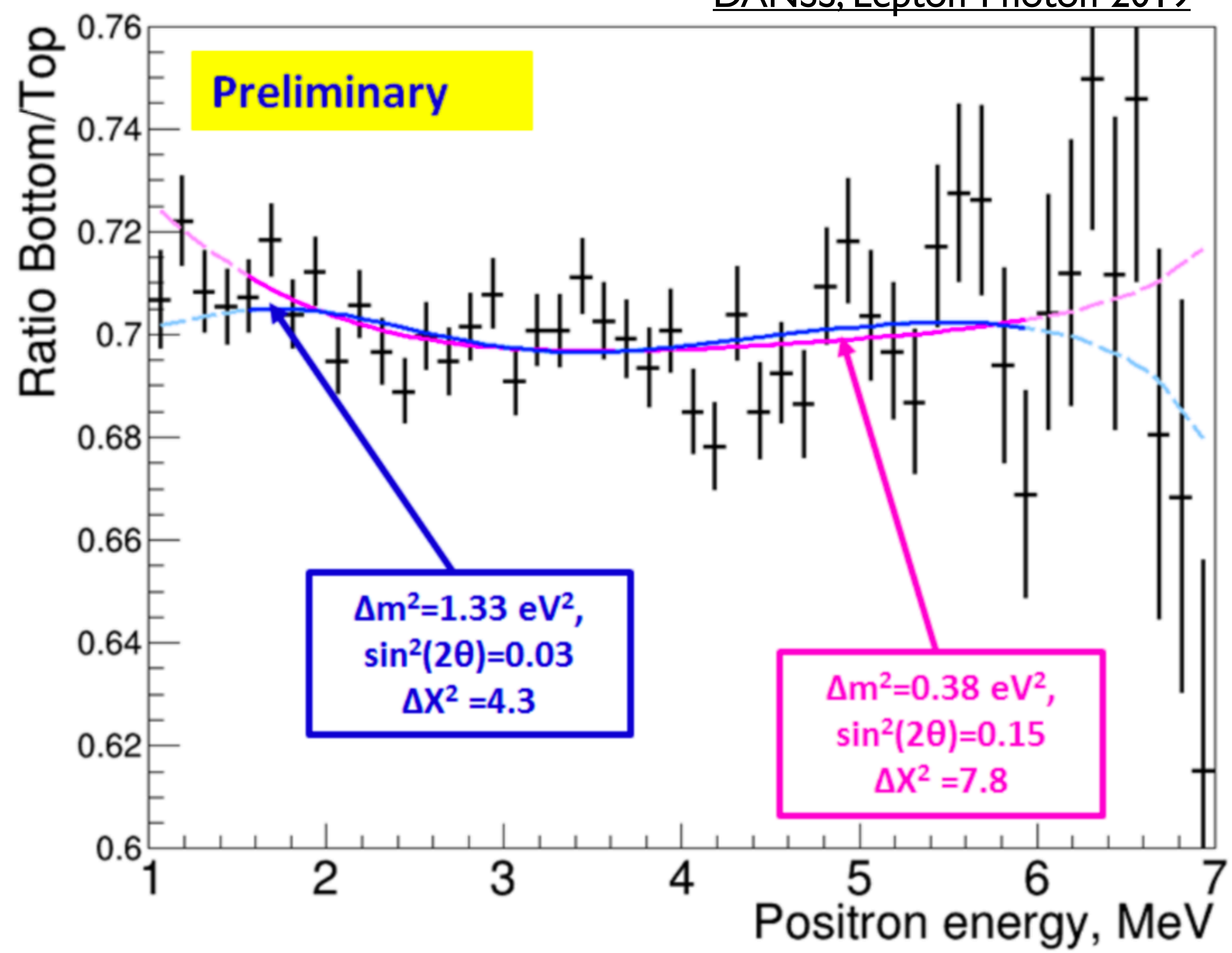


NEOS, PRL 121 (2016)

Testing Steriles: LEU Experiment Update

- Hints for steriles from commercial core (LEU) spectrum ratios?
- New DANSS results with improved stats, systematics handling
  - No-oscillation is only disfavored with respect to best-fit at 1.8σ
  - Even less disfavored compared to 'old best fit'
- Primary sterile hint from reactor spectra appears to have faded.
  - Looking forward to a full publication and systematics details
  - New data from NEOS soon?

DANSS, Lepton-Photon 2019



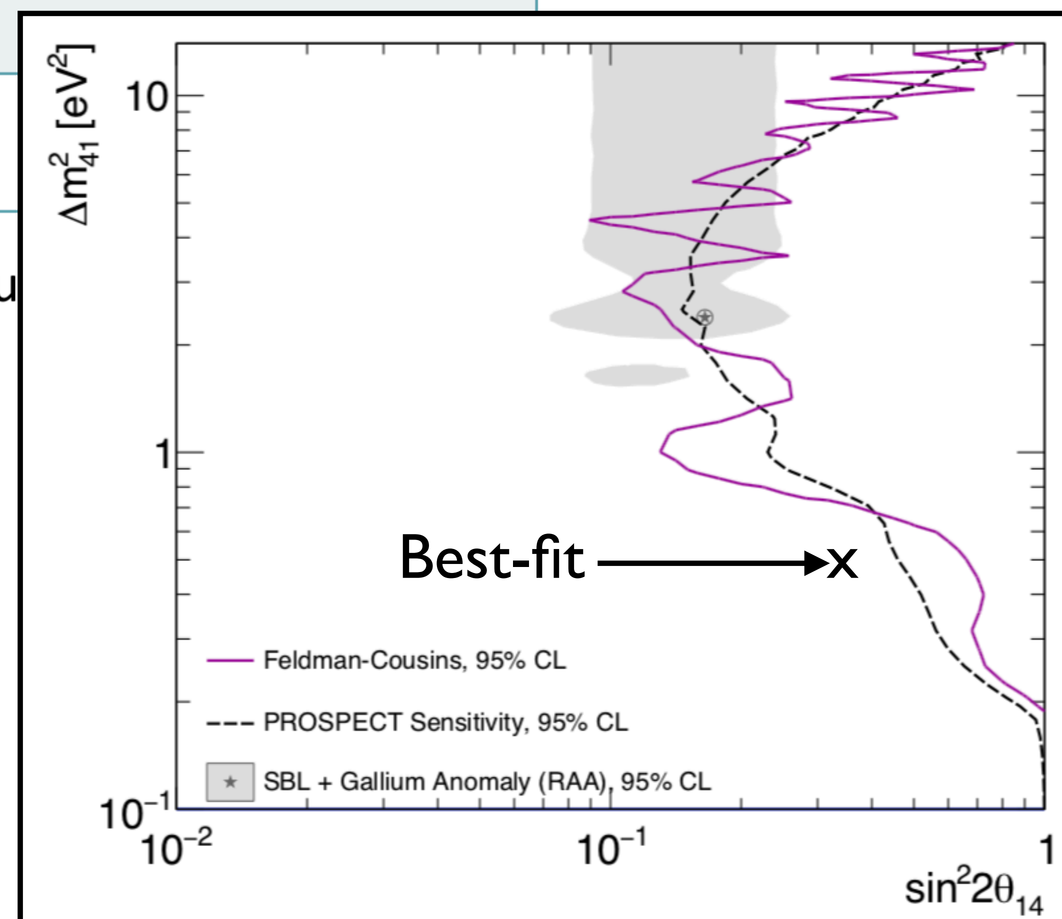
Testing Steriles: Neutrino-4

Feldman-Cousins Approach

- ❑ Standard (incorrect) method does not handle boundary features such as bounded nature of $sin^2 2\theta$ (0,1) or cases when oscillation frequency approaches energy bin size. Feldman-Cousins method solves those problems
- ❑ Comparing p-values for Feldman-Cousins and standard (incorrect) methods:

P-values	3ν-oscillation hypothesis	RAA sterile ν oscillation hypothesis
Feldman-Cousins	0.58	0.013
Standard (incorrect) confidence intervals assignment	0.14	0.005

- ❑ If standard (incorrect) confidence levels used instead of Feldman-Cou
  - We say 3ν is less compatible with data than it actually is
- ❑ Illustrates an importance of using Feldman-Cousins



Testing Steriles: Neutrino-4

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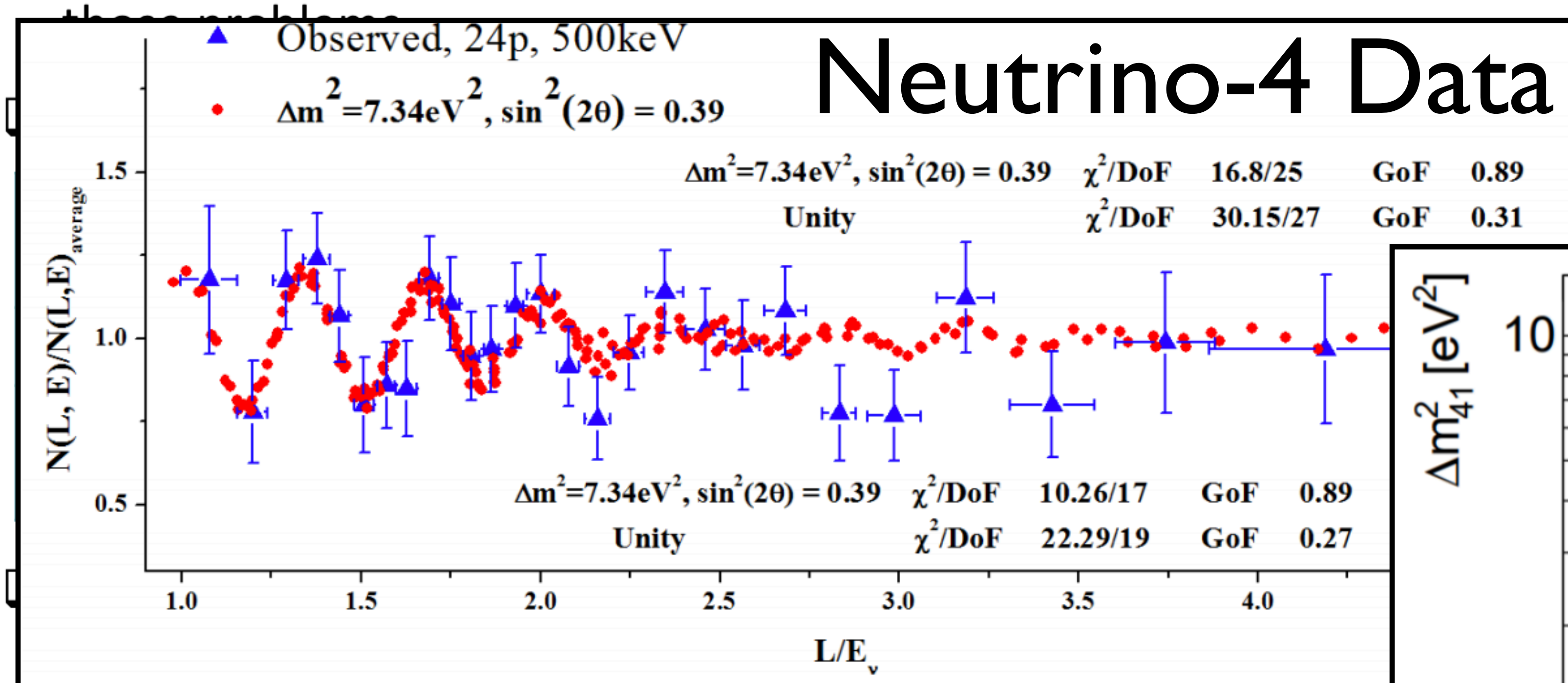
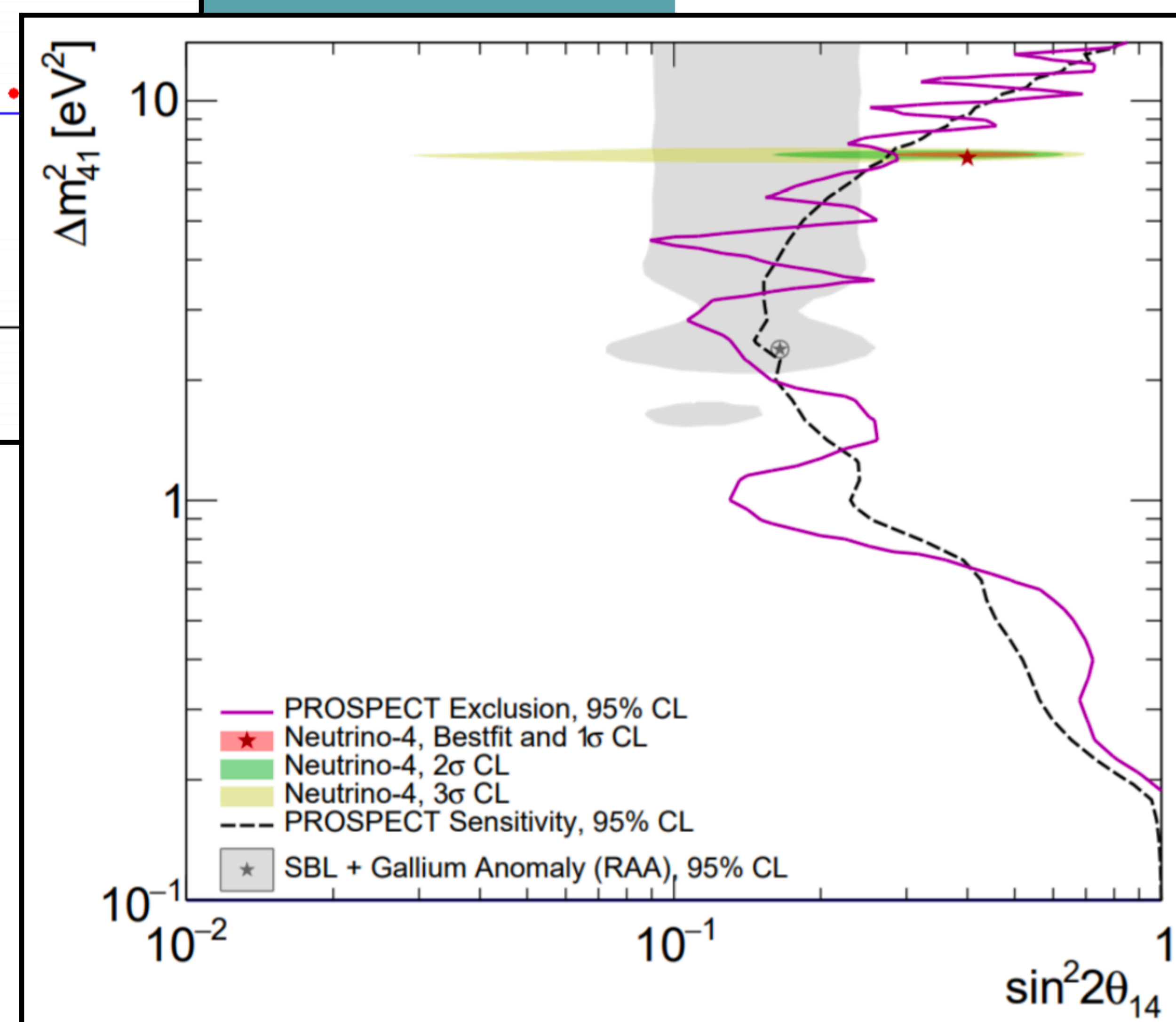
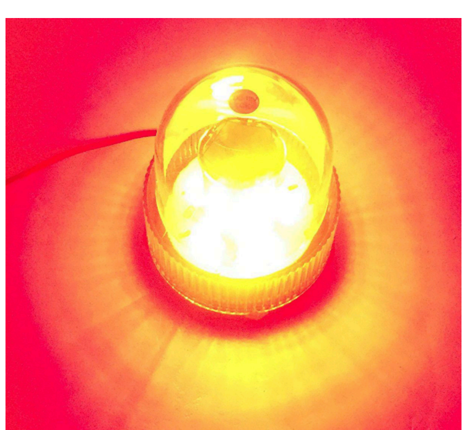


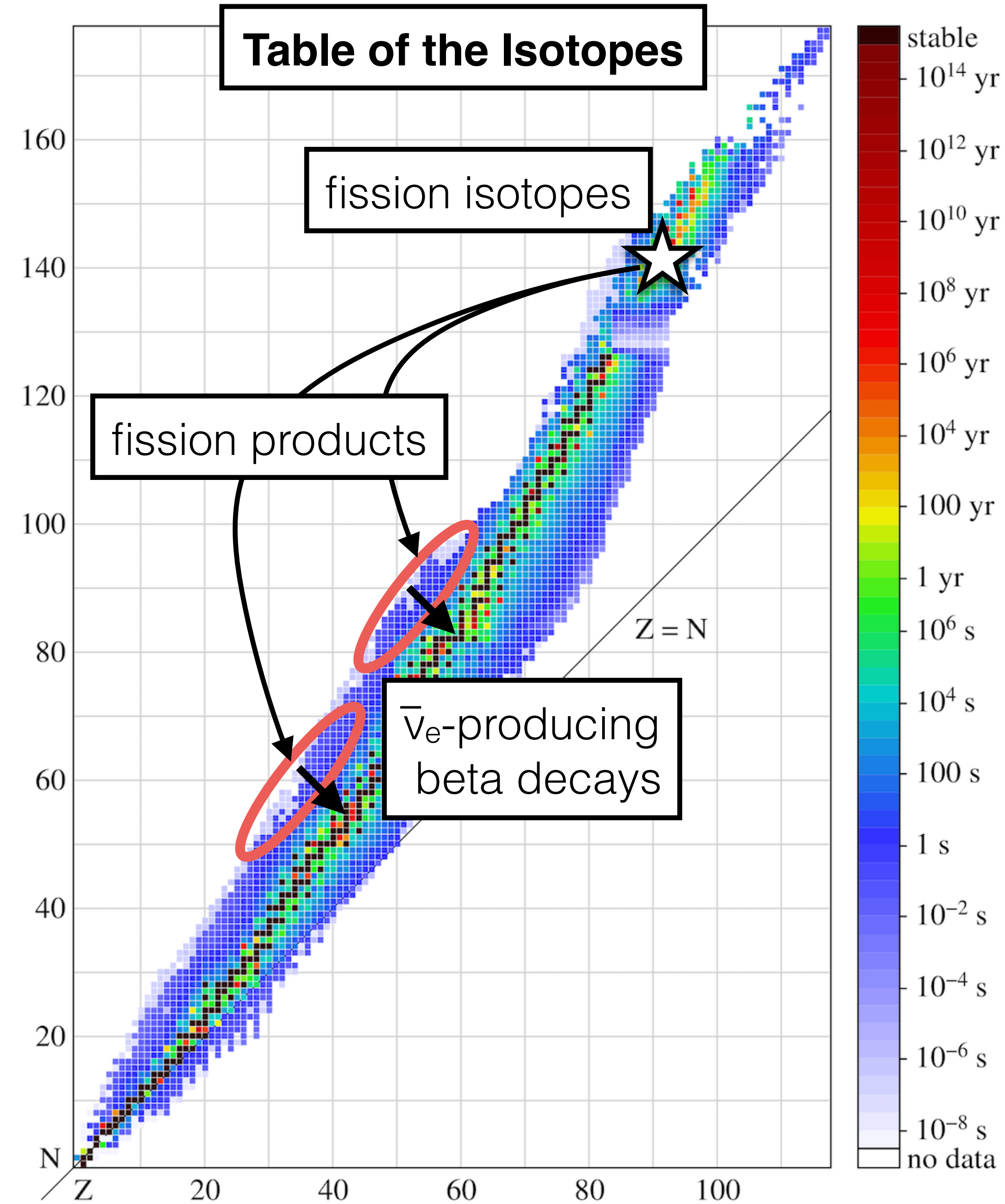


- Illustrates an importance of using Feldman-Cousins



Bad Flux Prediction Possibilities

- A litany of hypotheses HOW the fluxes could be incorrect:
  - Maybe it's specifically related to beta-decays:
    - Maybe forbidden decays aren't treated properly. Hayes, et al, **PRL** 112 (2014), Hayen, et al **PRC** 99 (2019)
    - Maybe fission isotope beta spectrum measurements are wrong. Letourneau and Onillon @ AAP 2018
  - 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? Littlejohn, et al **PRD** 97 (2018)
  - Maybe there's an issue with *ONLY* U238? Hayes, et al **PRD** 92 (2016); Gebre, et al **PRD** 97 (2018)
  - Etc…
  - **GOOD Recent Convo @ IAEA:** https://www-nds.iaea.org/index-meeting-crp/Antineutrinos/

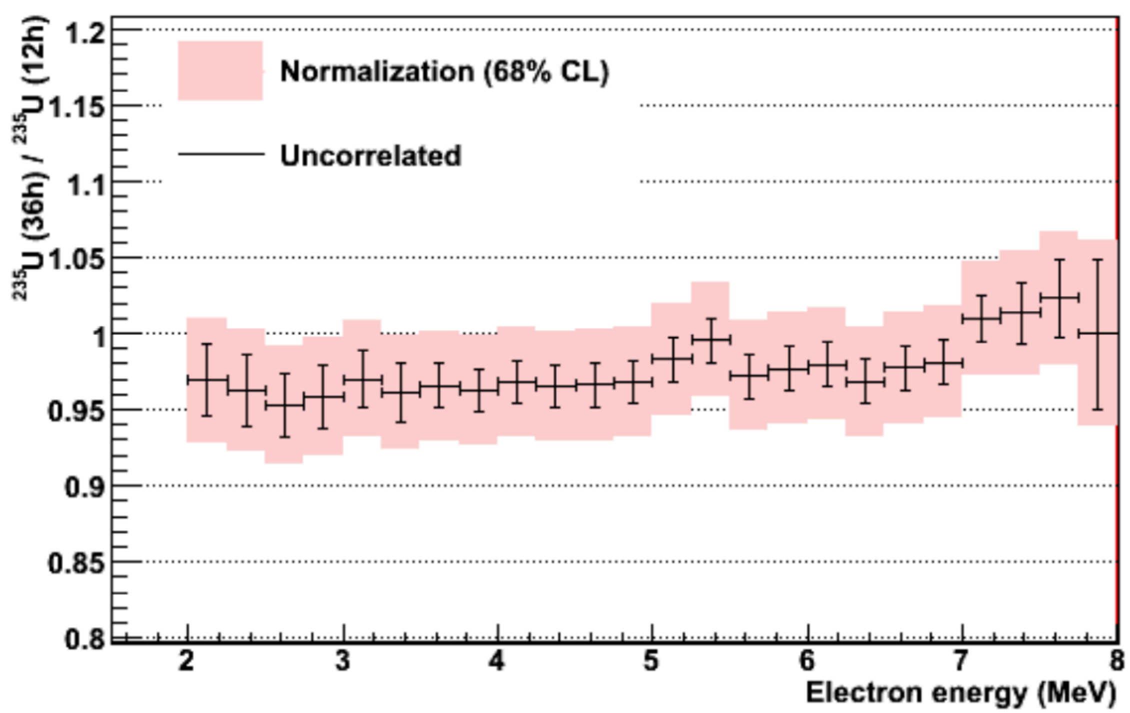


Flux Results

- Letourneau and Onillon: "Investigation of the ILL spectra normalization," presented at AAP 2018 in Livermore, CA

Four measurement performed at the ILL in the 80's

- **^{235}U(1):** [1] *K. Schreckenbach et al., PLB99 (1981) 251*
  - Normalized on: **^{197}Au(n,e$^-$)^{198}Au**
- **^{235}U(2):** [2] *K. Schreckenbach et al.", PLB160 (1985) 325*
  - Normalized on: **^{207}Pb(n,e$^-$)^{208}Pb and**
    β-decay following ^{115}In(n, γ)^{116m}In
- **^{239}Pu:** [3] *F. Feilitzch et al.", PLB118 (1982) 162*
  - Normalized on: **^{197}Au(n,e$^-$)^{198}Au and ^{115}In(n,γ)^{116}In**
- **^{241}Pu:** [4] *A.A Hahn et al., PLB218 (1989) 365*
  - Normalized on: **^{207}Pb(n,e$^-$)^{208}Pb and ^{115}In(n,e$^-$)^{116m}I**



Ratio of the two measured electron-energy spectra for ^{235}U from [1] (36 h) and [2] (12 h).

- Neutron flux calibrated out through relative measurement with respect to well-known neutron cross-sections
  - Looks like some of the 'well-known' cross-sections may have been wrong
  - This adds a 5% shift between 235 and 239 - solves DYB flux evolution?