Overview of Reactor Neutrinos

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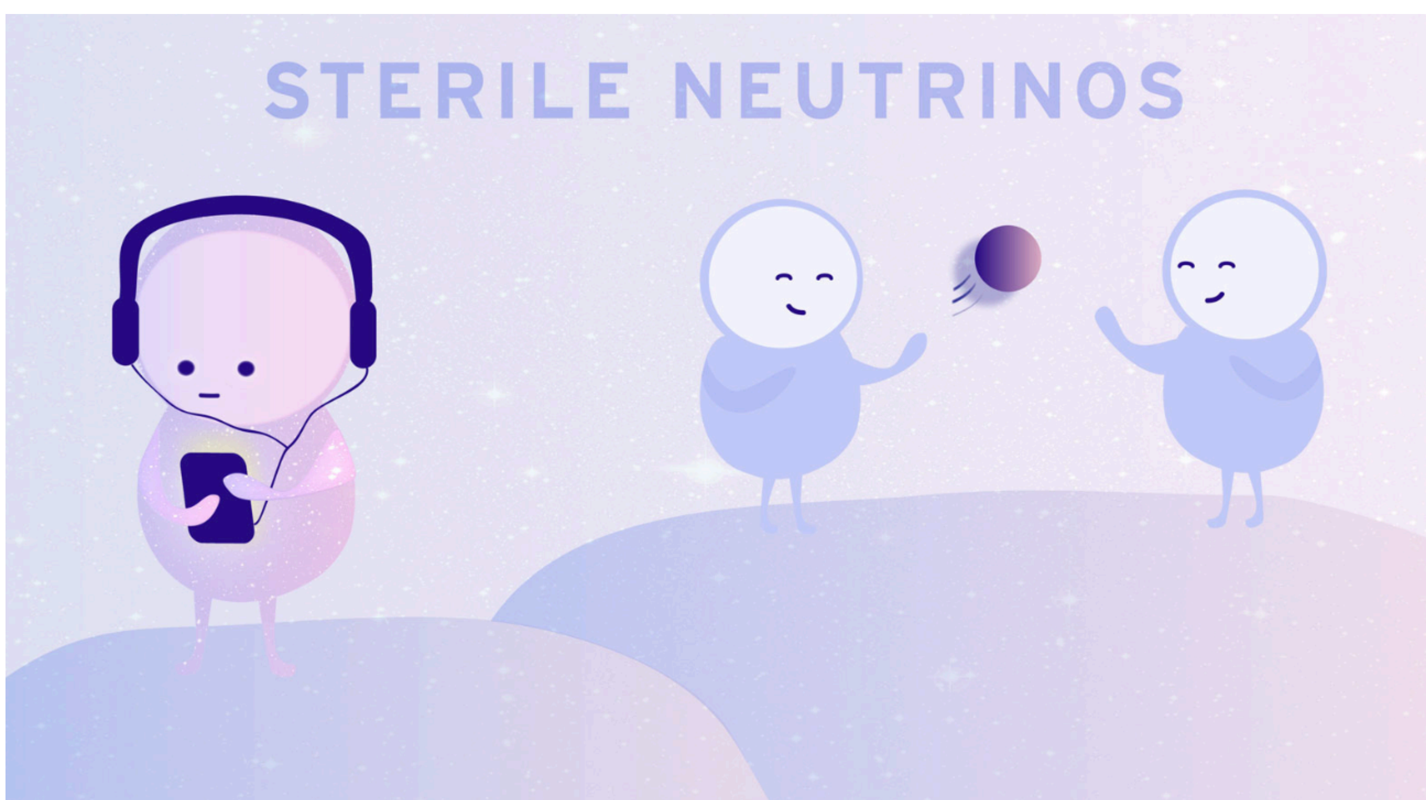
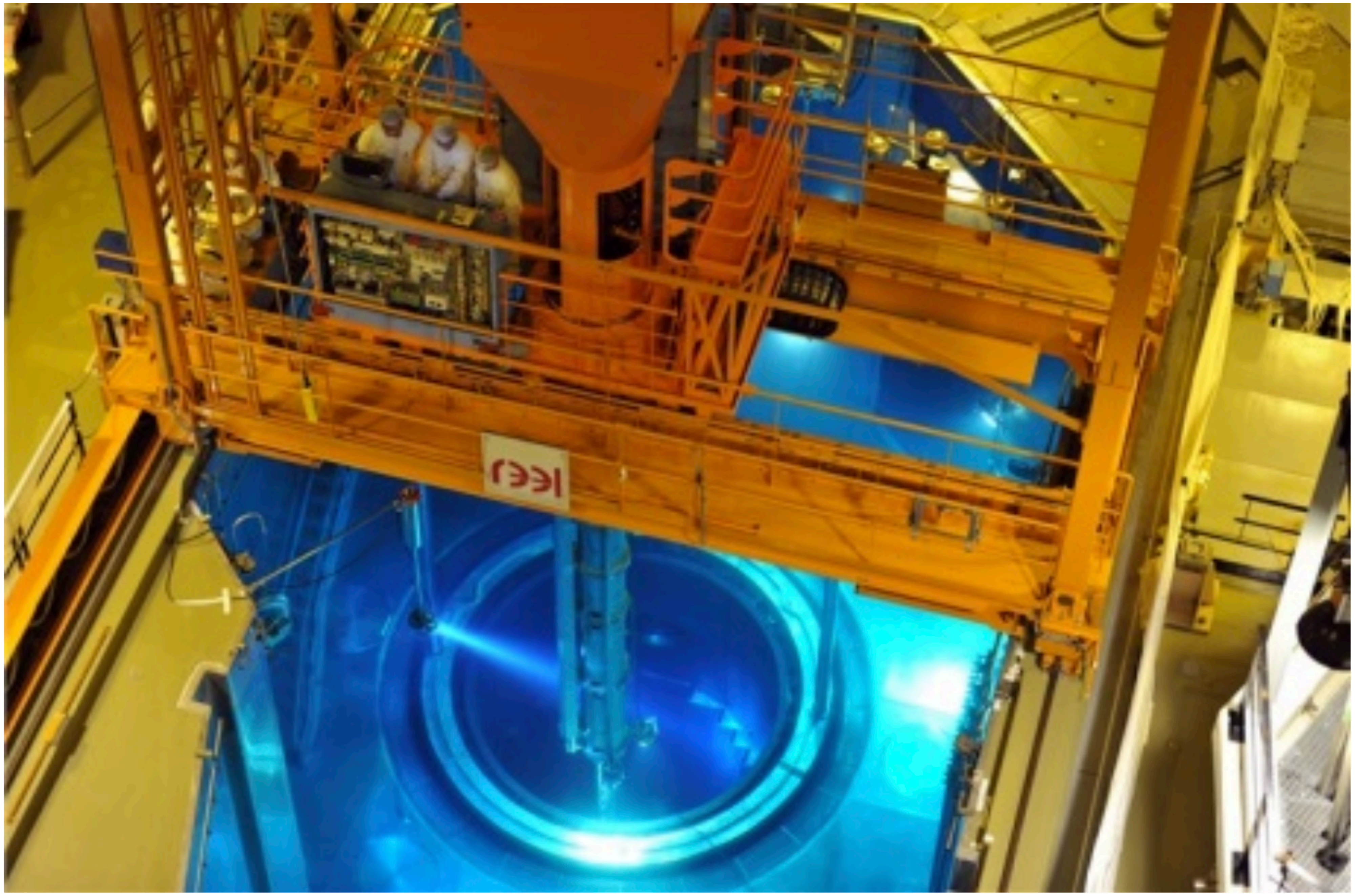
Reactor Neutrinos: An Active Field

- **Important tasks/questions with big implications:**
  - Unique+precise oscillation measurements
  - Do we understand reactor neutrino <u>fluxes</u>?
    - Sterile neutrinos?
  - Do we understand reactor neutrino <u>energies</u>?
    - Bad nuclear data; implications for nuclear applications?
    - Mass hierarchy measurements at reactors?



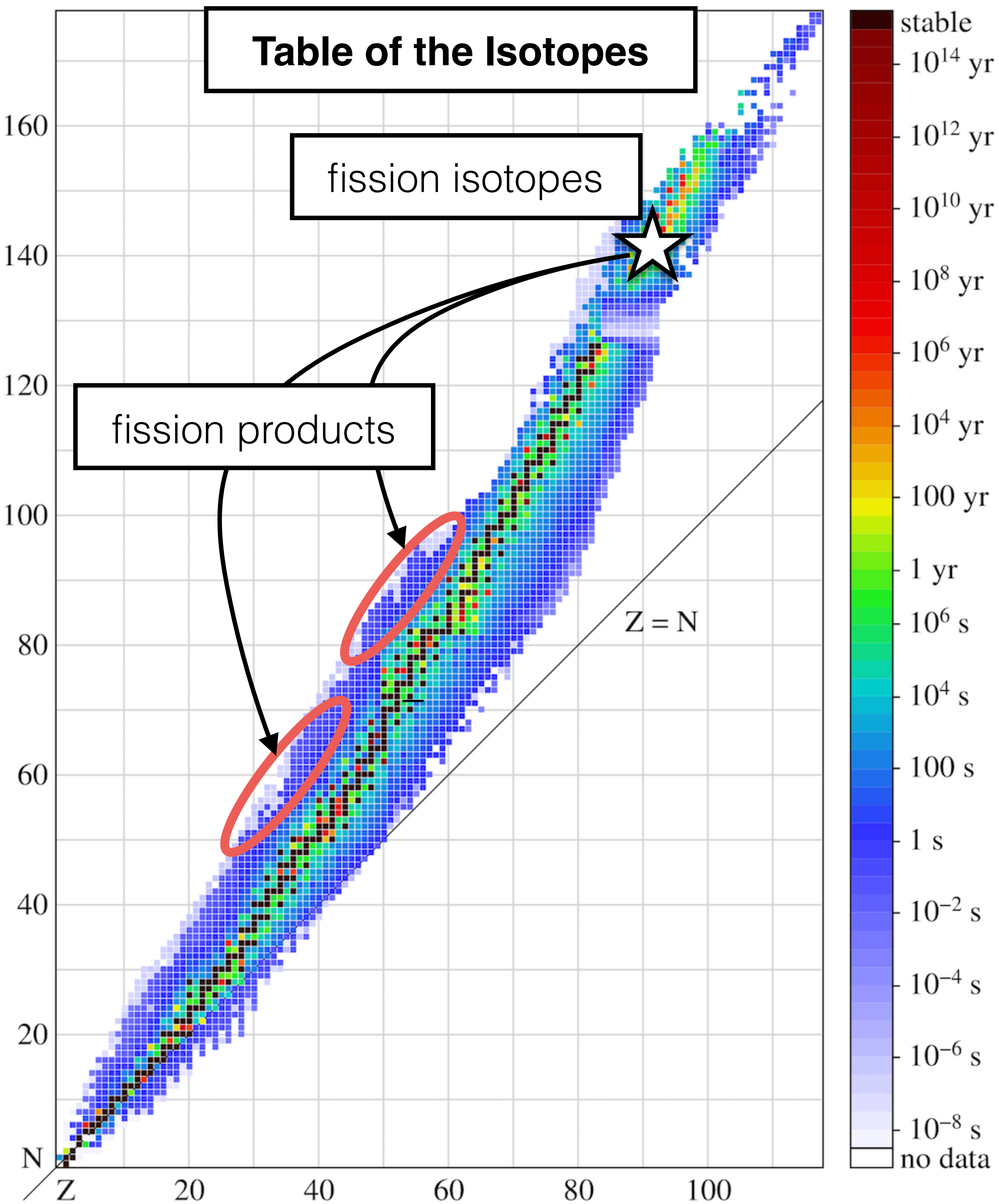
What Do Nuclear Reactors Do?

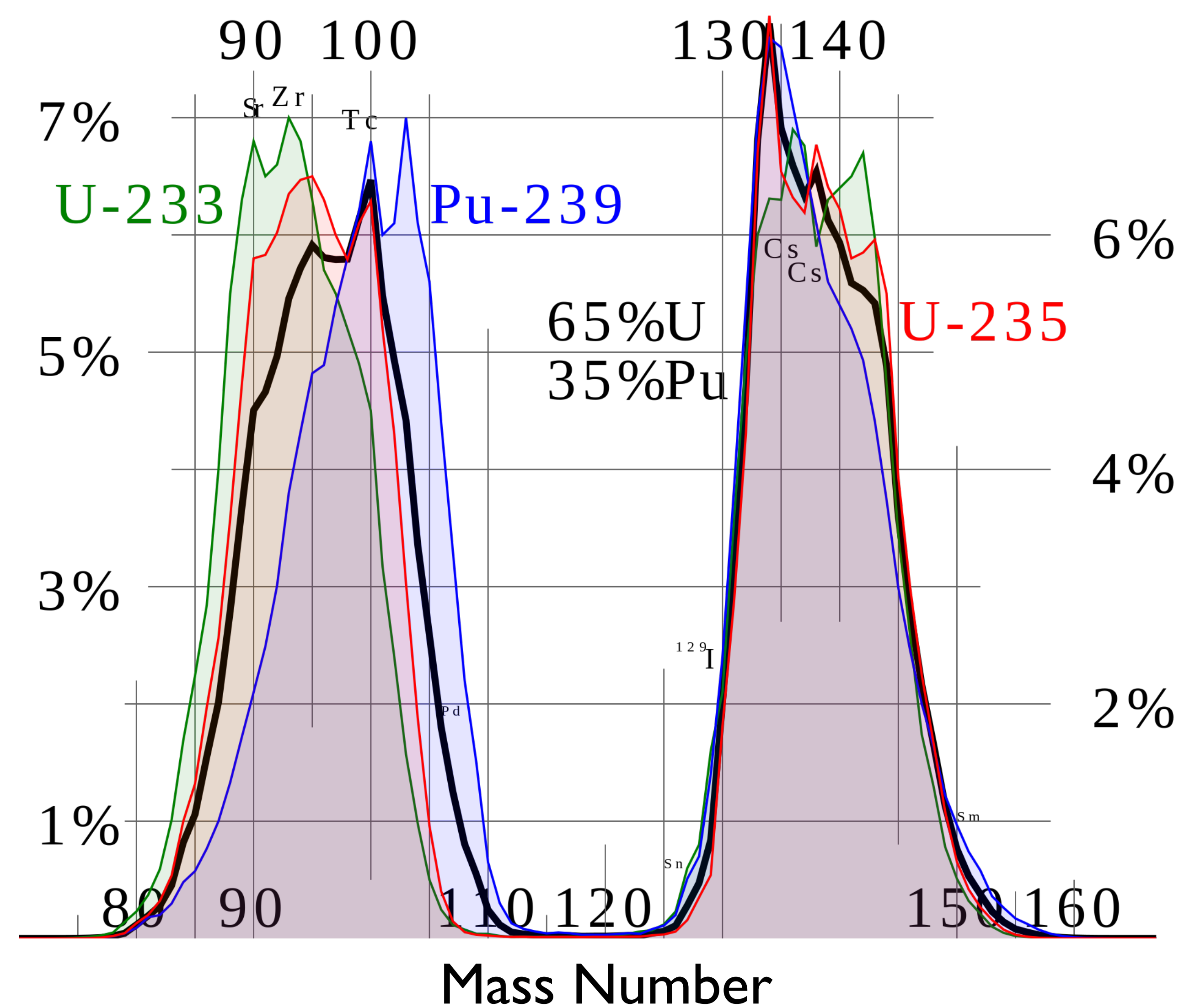


Yangjiang 2 Commercial Core: First Fuel Loading in 2015

What Do Nuclear Reactors Do?

- Heavy isotopes fission, making lighter isotopes, energy, neutrons, neutrinos, betas, and gammas.
  - Different fission isotopes yield different products





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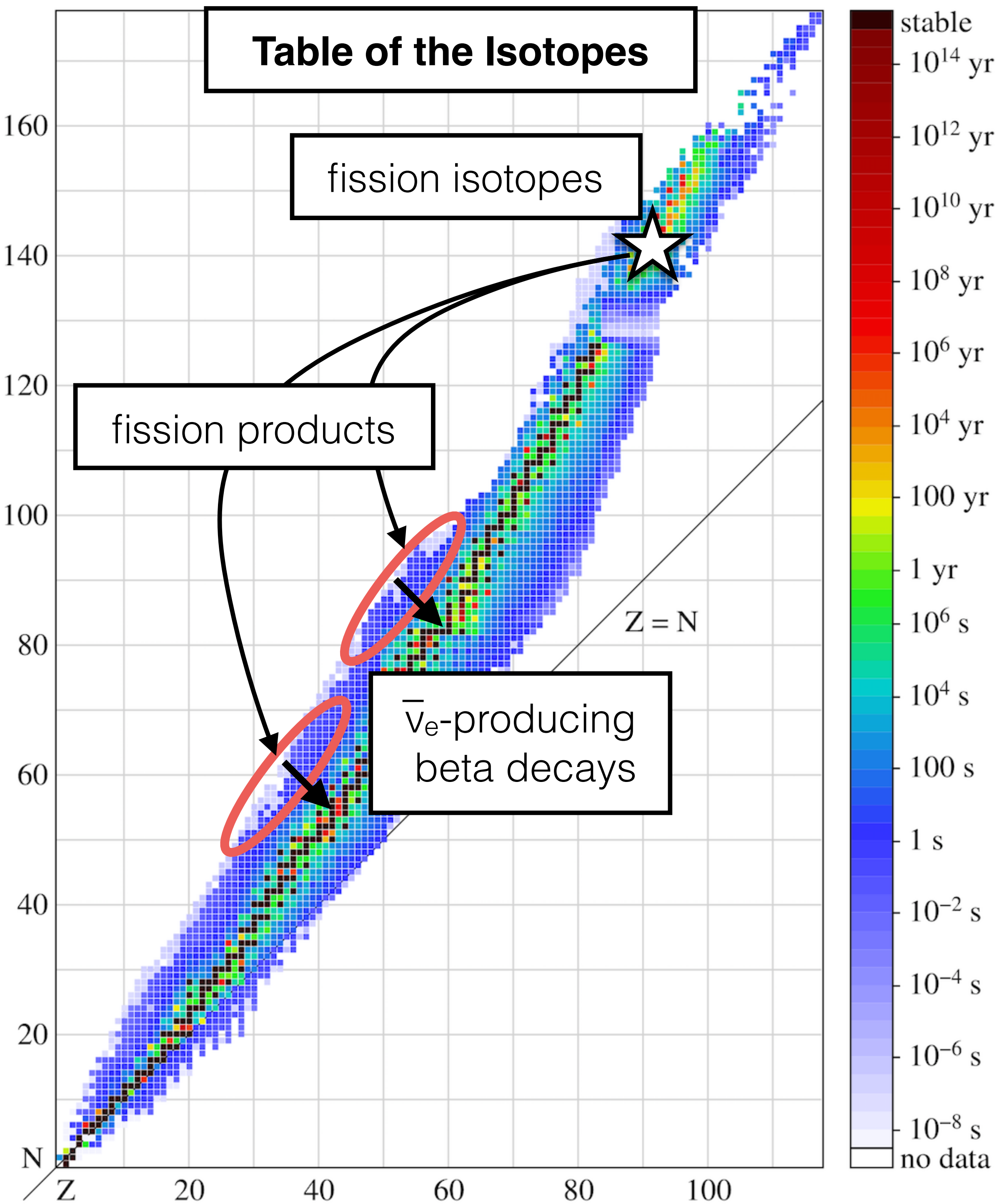

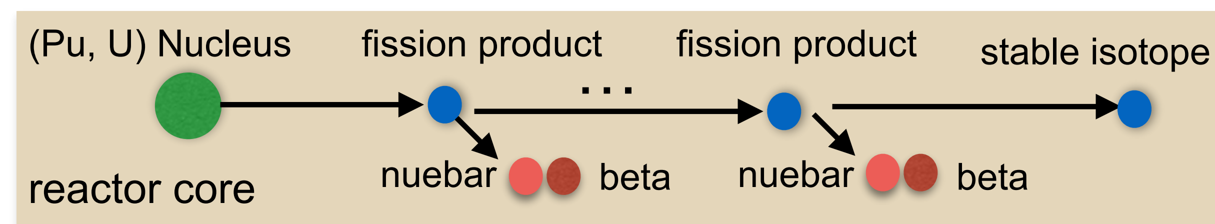

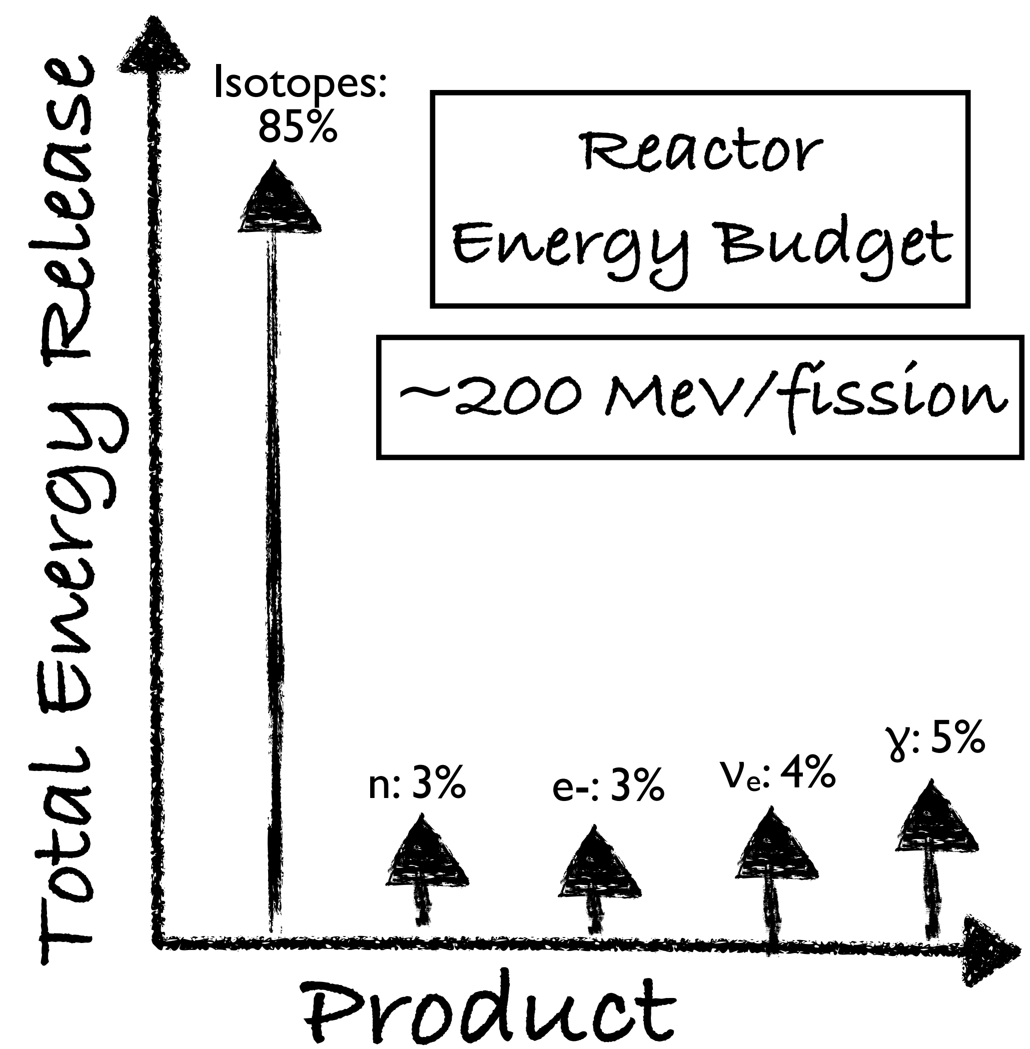

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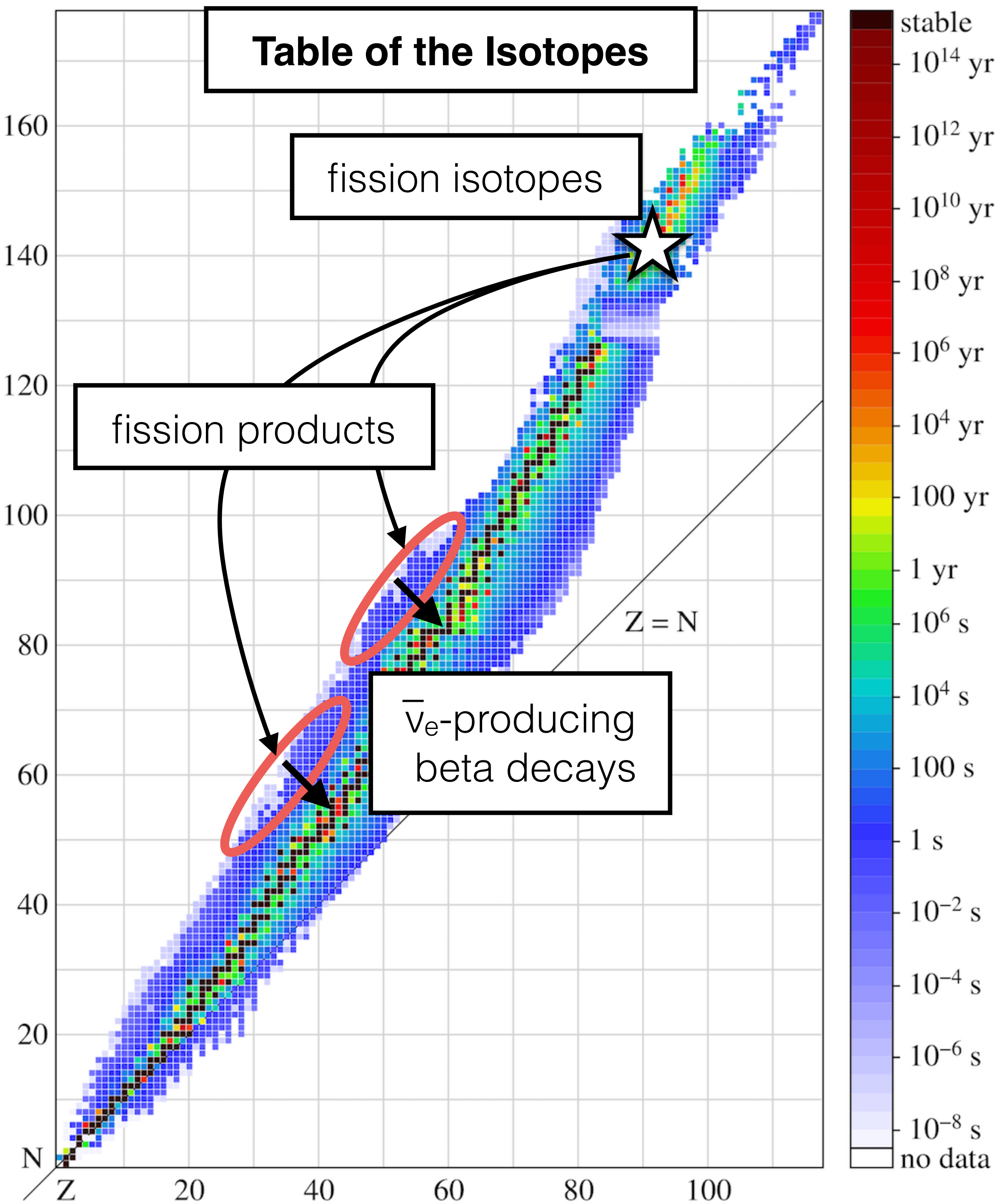
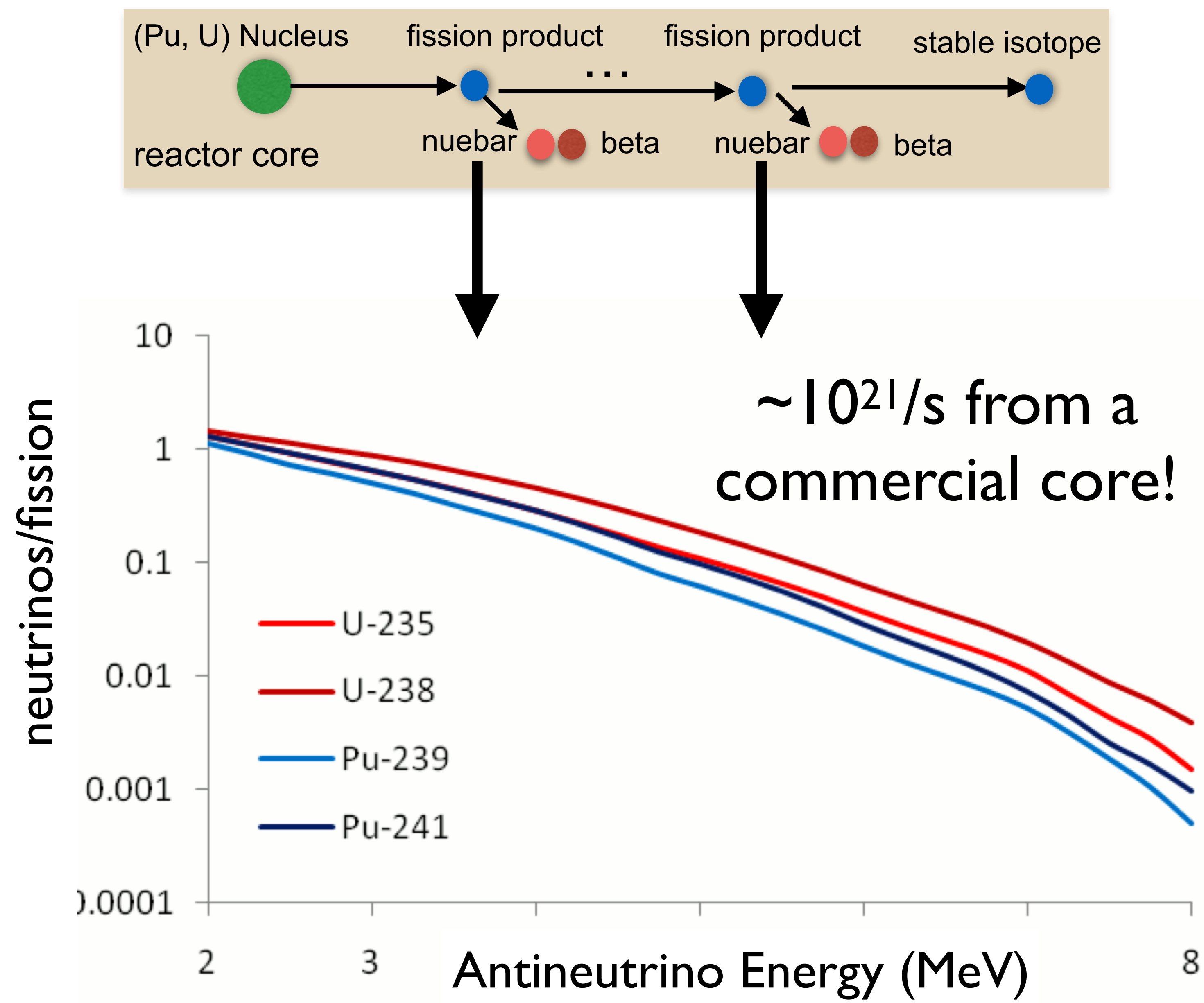
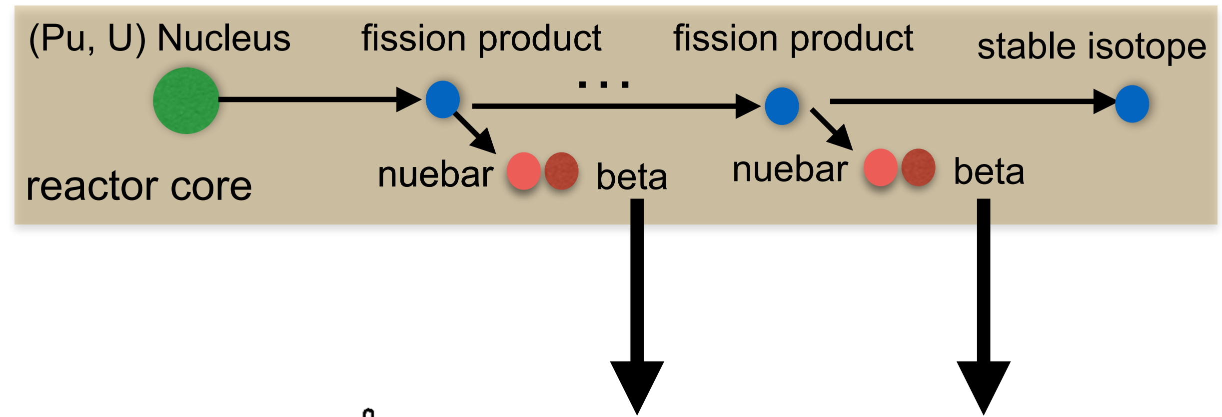


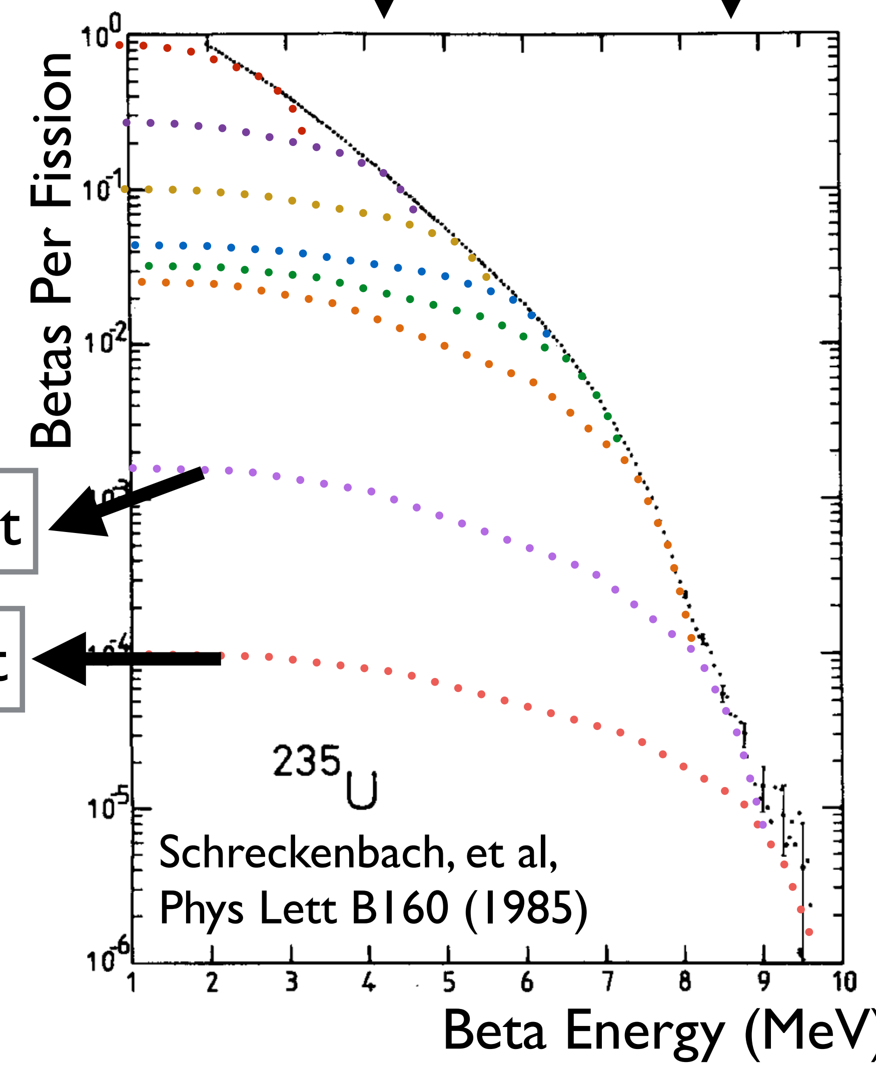


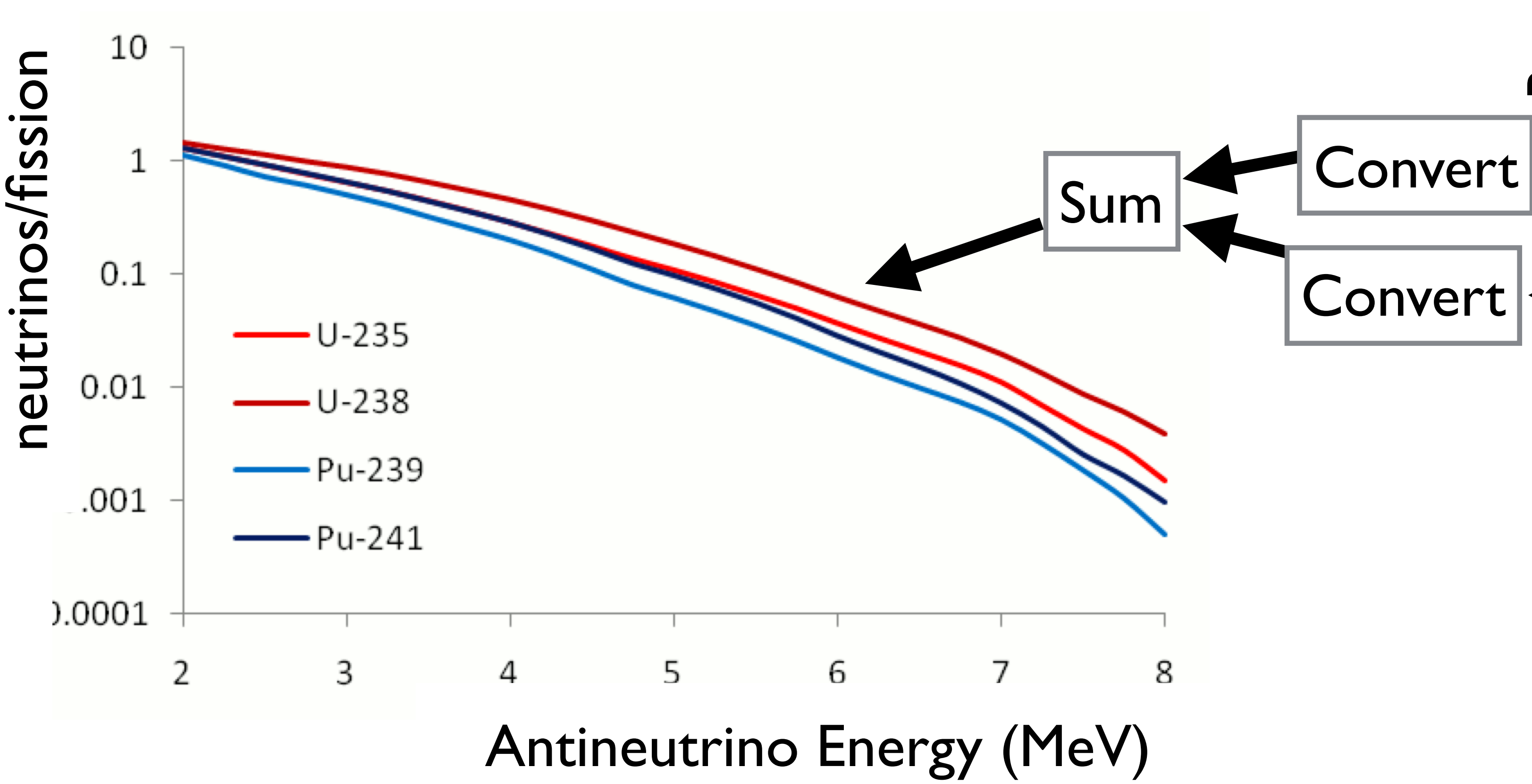
~10^{21}/s from a commercial core!

Reactor Antineutrino Production

- Reactor $\bar{\nu}_e$: produced in decay of product beta branches
- To predict flux and spectrum:
  - Measure beta energies from all fission products at once
  - Fit result with individual 'made-up' beta spectra
  - Covert to individual antineutrino spectra using E-conservation + small corrections
  - Sum to get total antineutrino energy

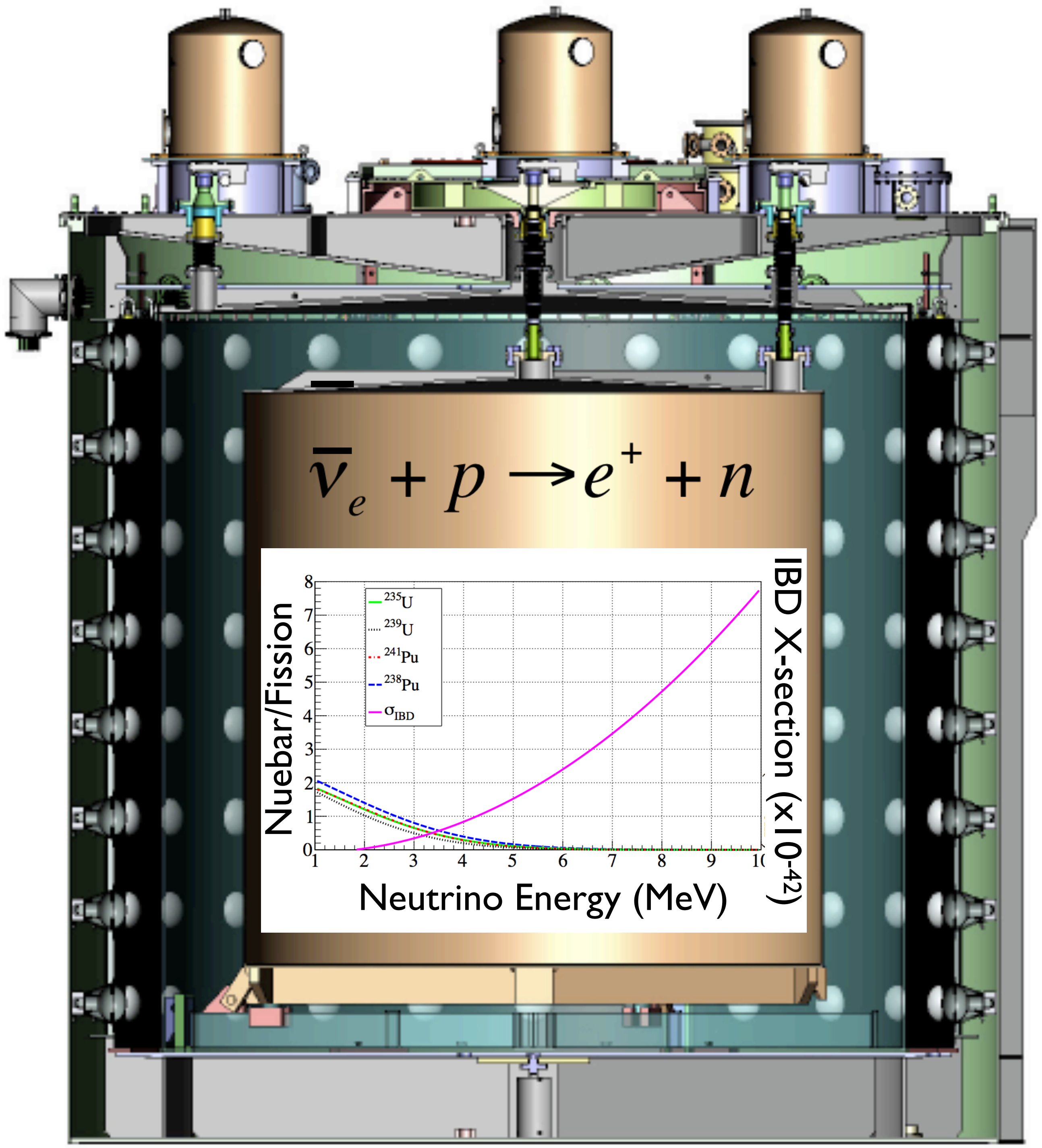




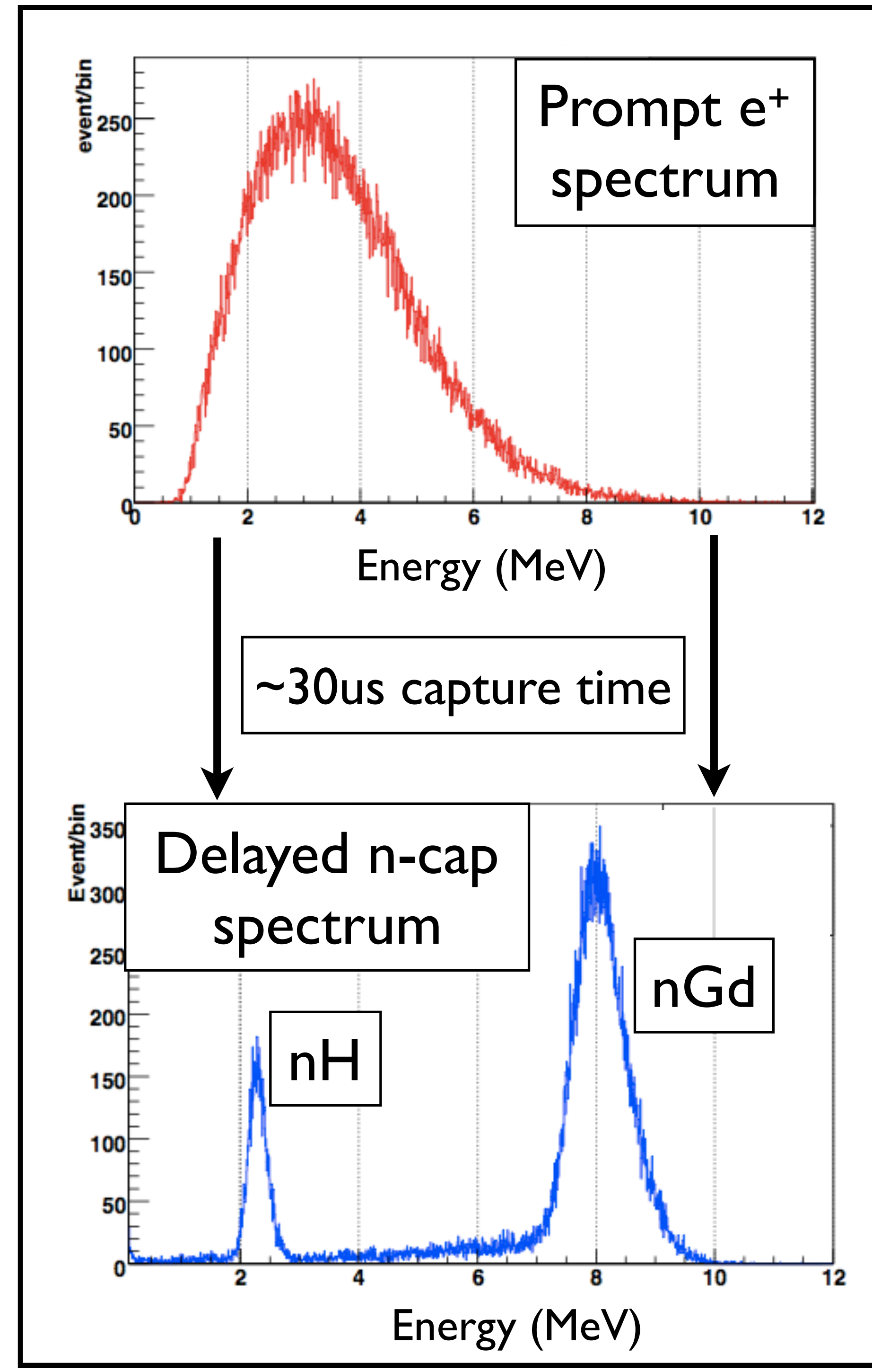


Reactor Antineutrino Detection

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



Example: Daya Bay Detector



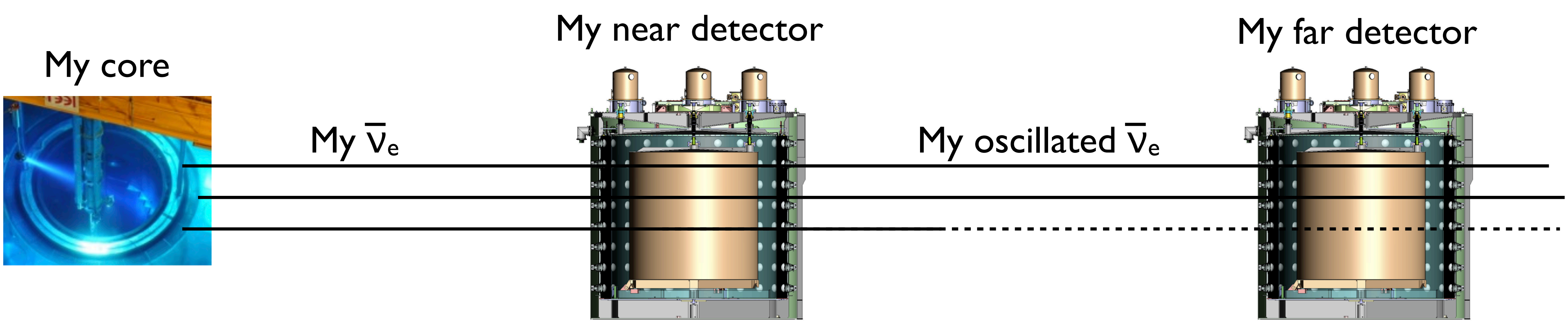
Daya Bay Monte Carlo Data

‘Flux Model Independent’ Oscillation Measurements

Reactor Neutrino Oscillation Basics

My relevant neutrino oscillation formula

$$sin^2(2\theta)sin^2(1.27\Delta m^2\frac{L}{E_\nu})$$

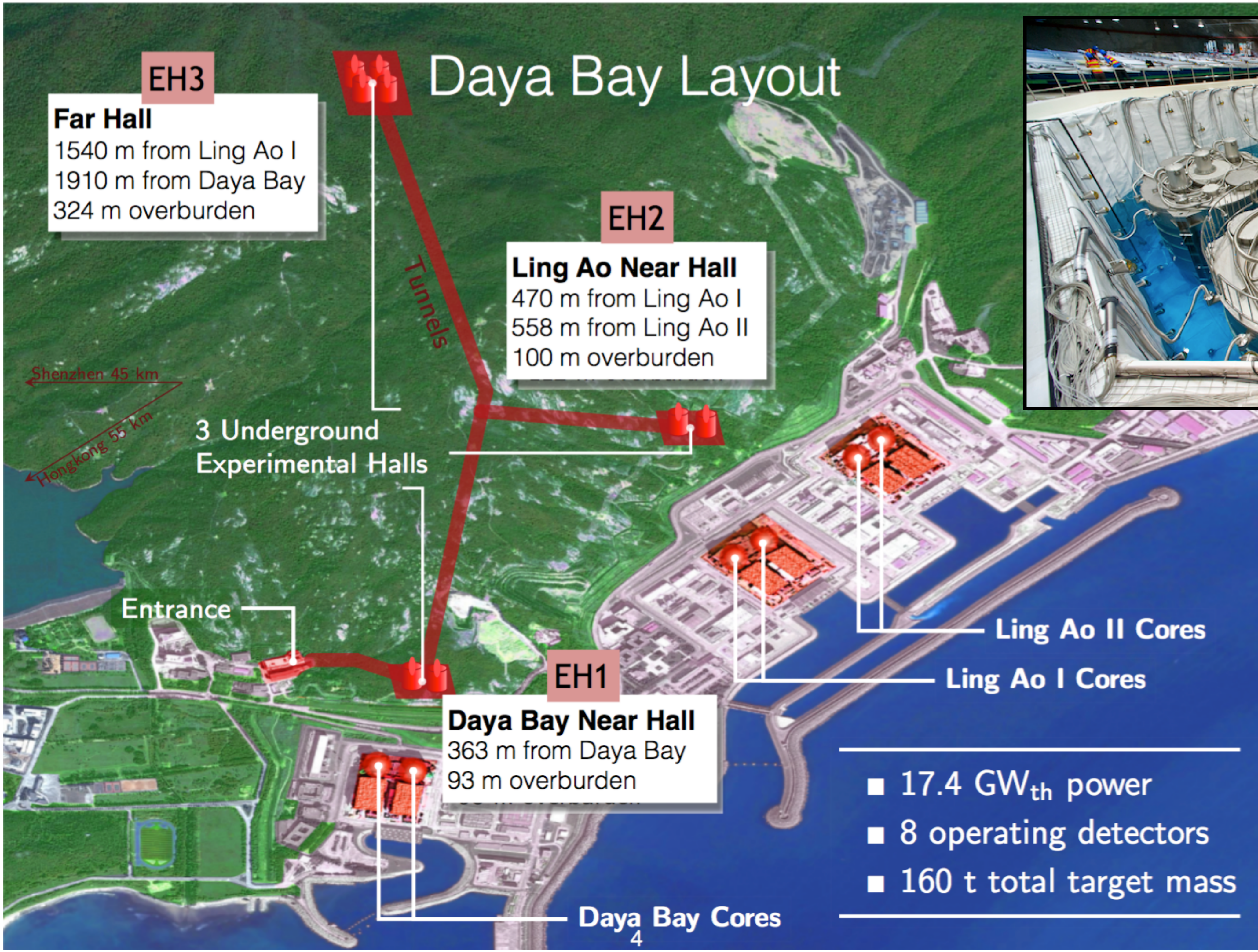


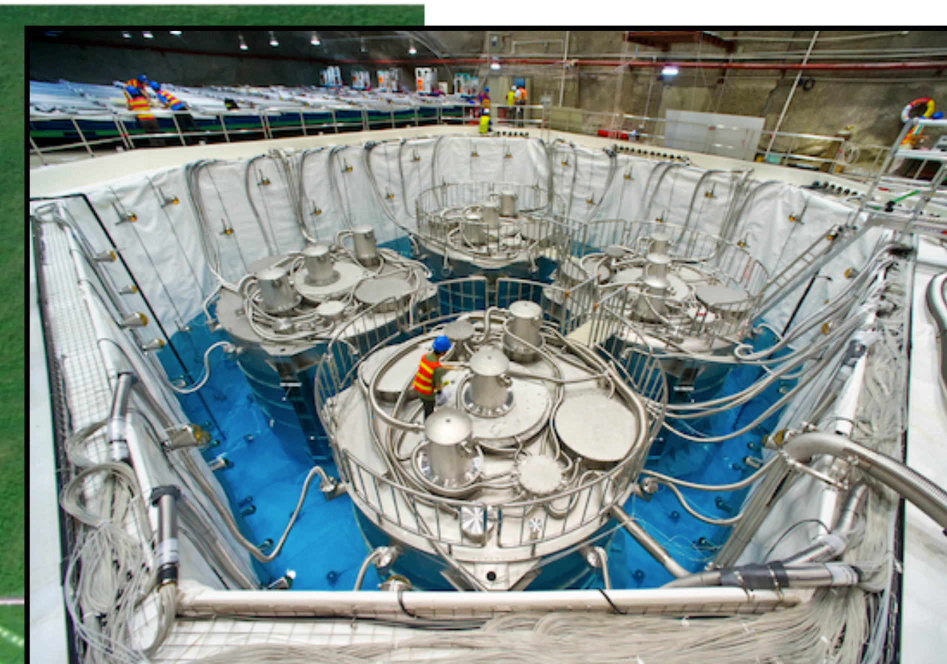
"How many neutrinos are there?"

"Scaling for $1/r^2$, are all the near detector neutrinos still there? Are they missing at specific energies?"

- Don't need to know $\bar{\nu}_e$ energy or flux precisely
- Magnitude of missing $\bar{\nu}_e$ at far detector tells me θ
- Energies where $\bar{\nu}_e$ are missing tells me mass difference Δm^2

Example: Daya Bay Experiment



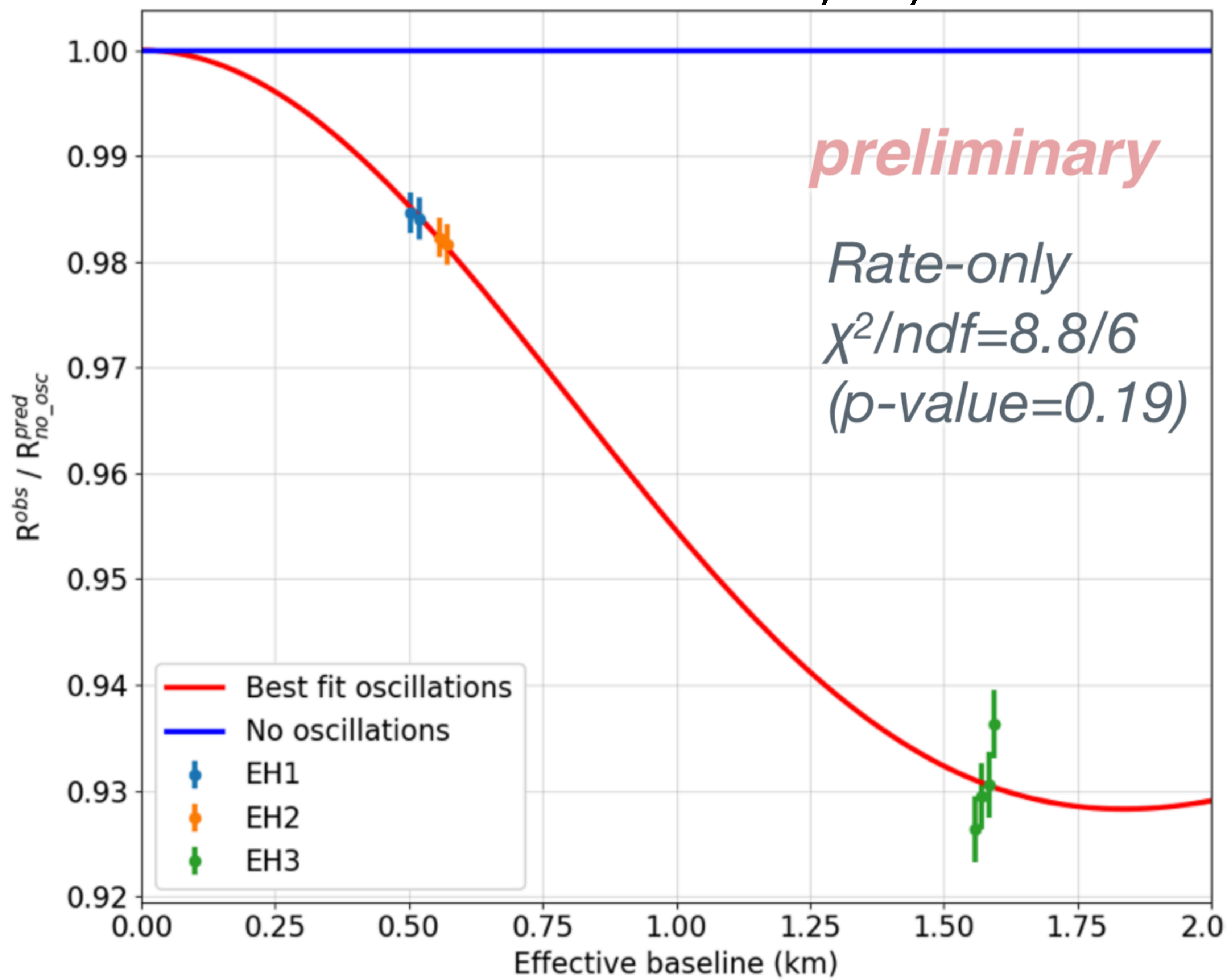


- RENO and Double Chooz use similar near/far geometry

Relative Flux Deficit: Daya Bay θ_{13}

- By measuring far detector rate deficit, Daya Bay has exquisite sensitivity to θ_{13}
  - Measure ~5% deficit with 0.2% uncertainty
  - Translates to ~3.5% uncertainty on $\sin^2\theta_{13}$
  - Uncertainty <u>still</u> statistics-dominated

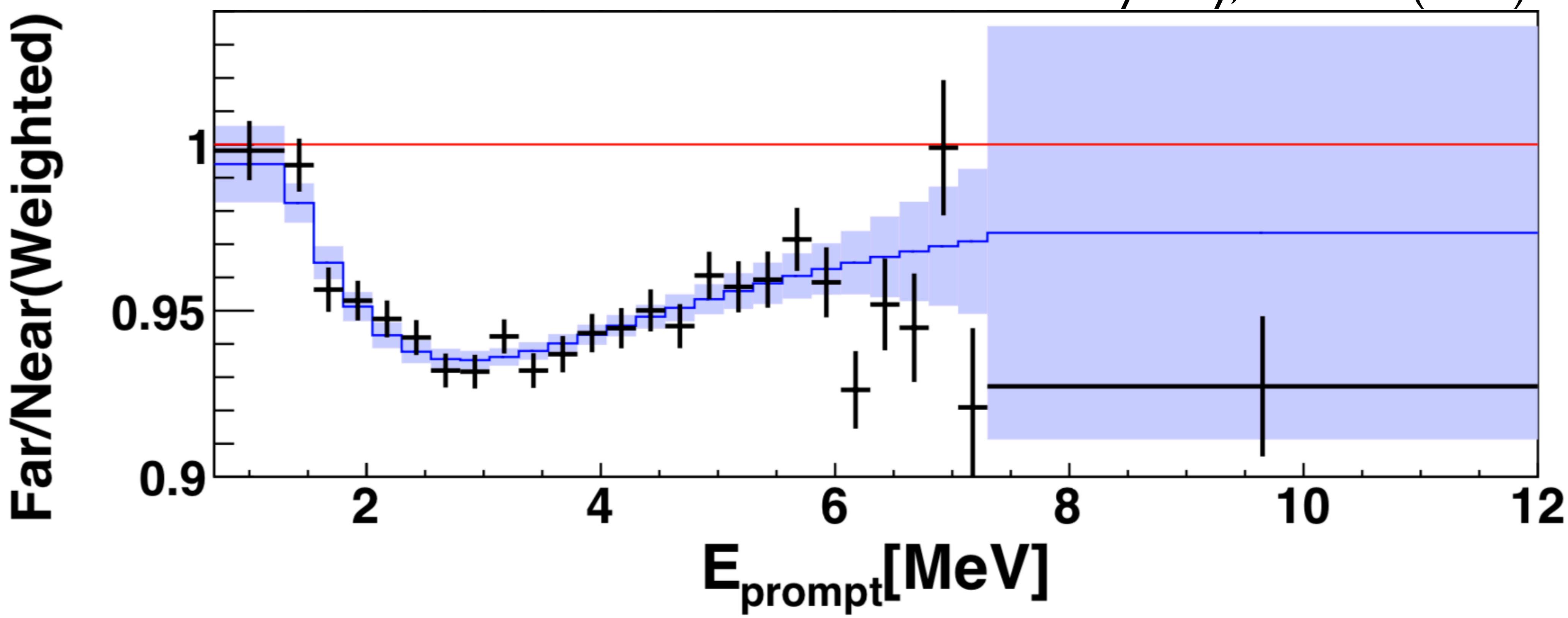
Daya Bay, Neutrino 2018



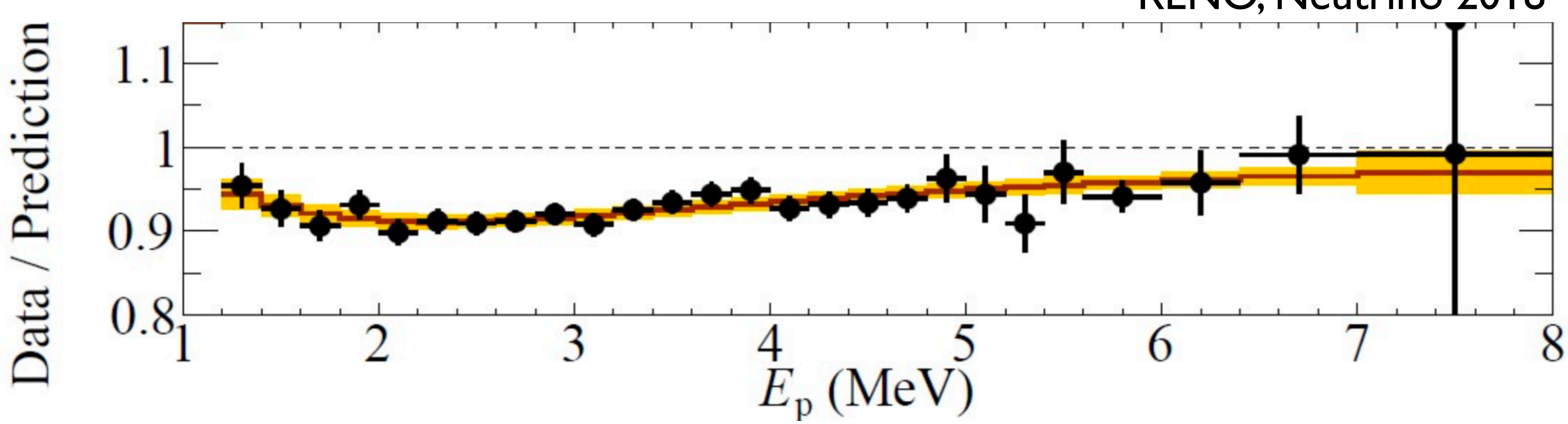
Energy-Dependent Deficit: Daya Bay Δm^2

- By measuring deficit at different energies, we can also make measurements of Δm_{ee}^2

Daya Bay, PRL 121 (2019)



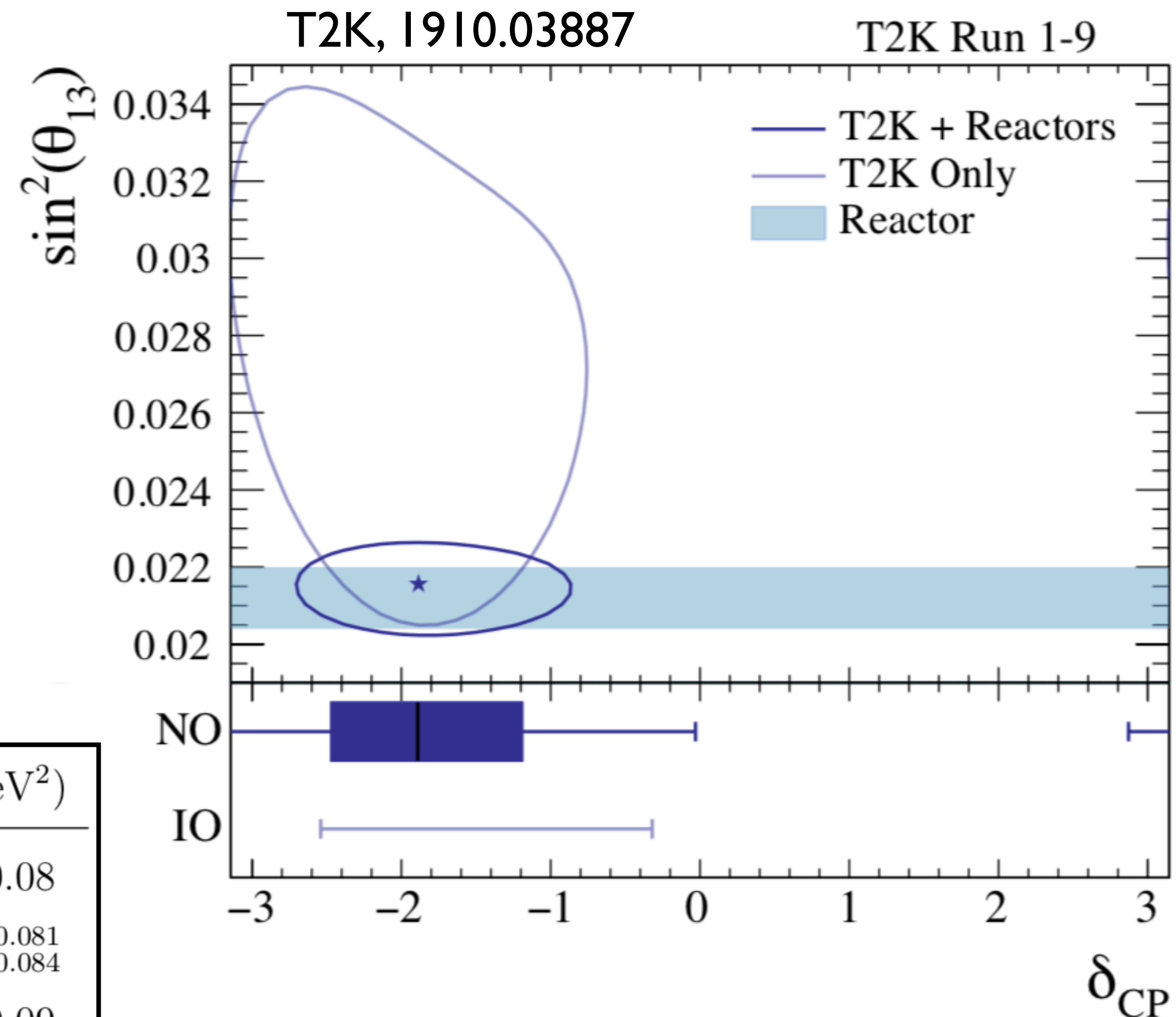
RENO, Neutrino 2018

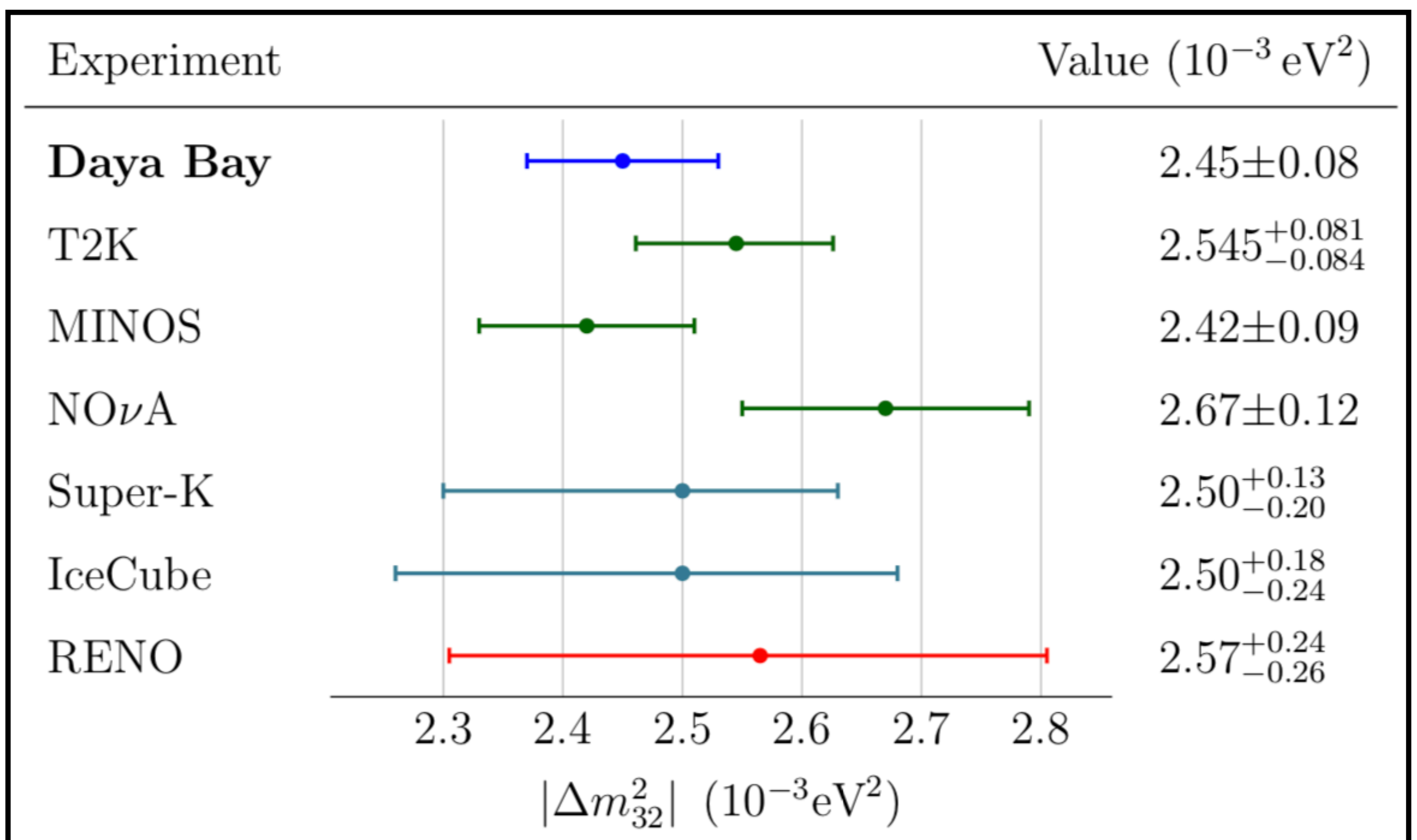


Reactor Osc in a Broader Context

- Get new power combining reactor and accelerator data
- Precision osc studies:
  - Compare osc parameters from different channels: for example: DUNE θ_{13} = DYB θ_{13}?
  - Stringently test flavor models

T2K, 1910.03887





'Realistic TBM Mixing Model'

$$\sin^2\theta_{12} = \frac{\cos^2\theta}{\cos^2\theta + 2},$$

$$\sin^2\theta_{13} = \frac{\sin^2\theta}{3},$$

$$\sin^2\theta_{23} = \frac{1}{2} + \frac{\sqrt{6}\sin 2\theta \sin\sigma}{2\cos^2\theta + 4}$$

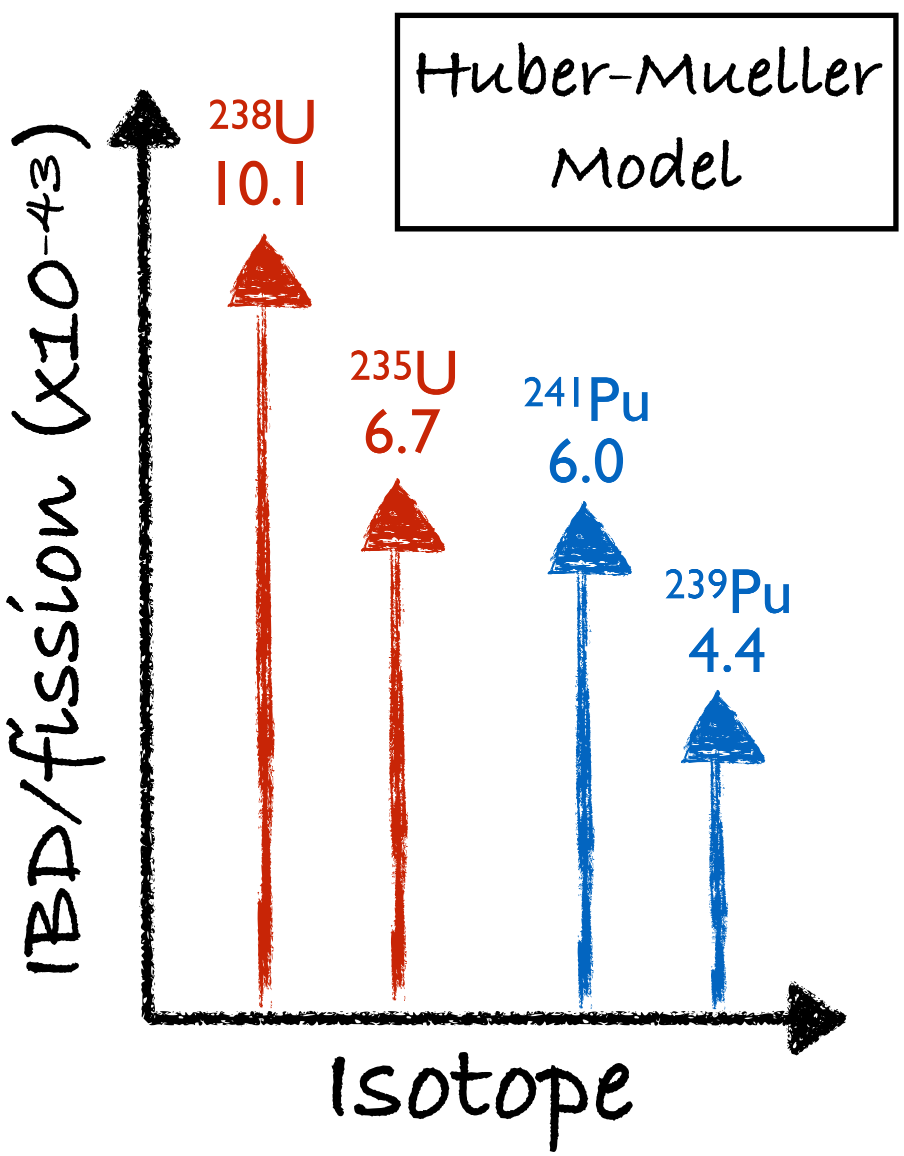
$$\tan\delta_{CP} = \frac{(\cos^2\theta + 2)\cot\sigma}{5\cos^2\theta - 2},$$

PHYSICAL REVIEW D **98,** 055019 (2018)

Comparing Prediction and Data: Reactor Antineutrino Flux

Reactor Flux Predictions

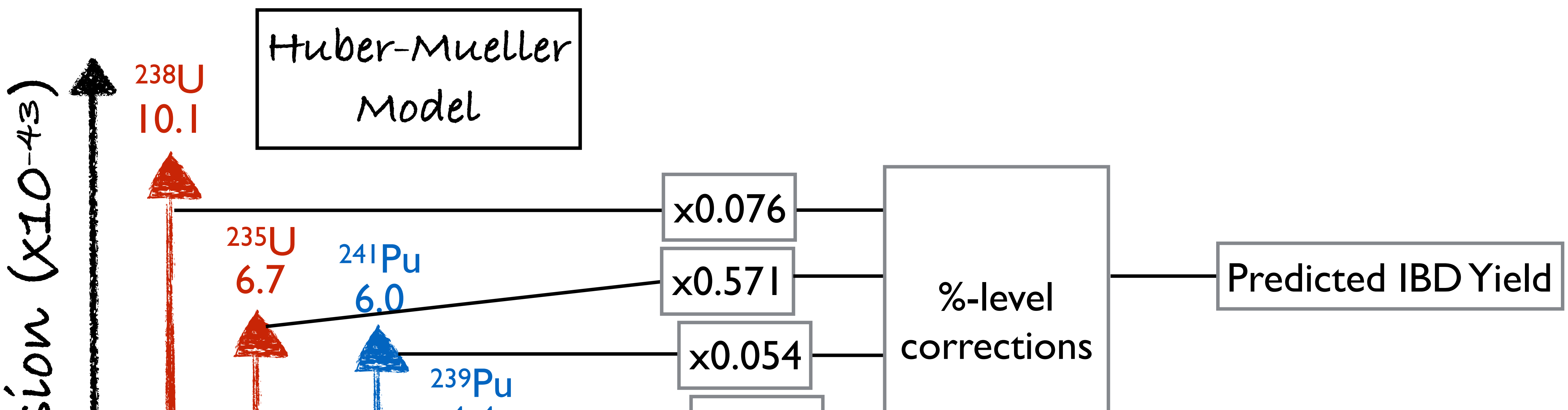
- Three isotopes' $\bar{\nu}_e$ flux predictions re-formulated in 2011
  - Note: 'flux' often cited as IBD per fission, or 'IBD yield': flux * cross-section

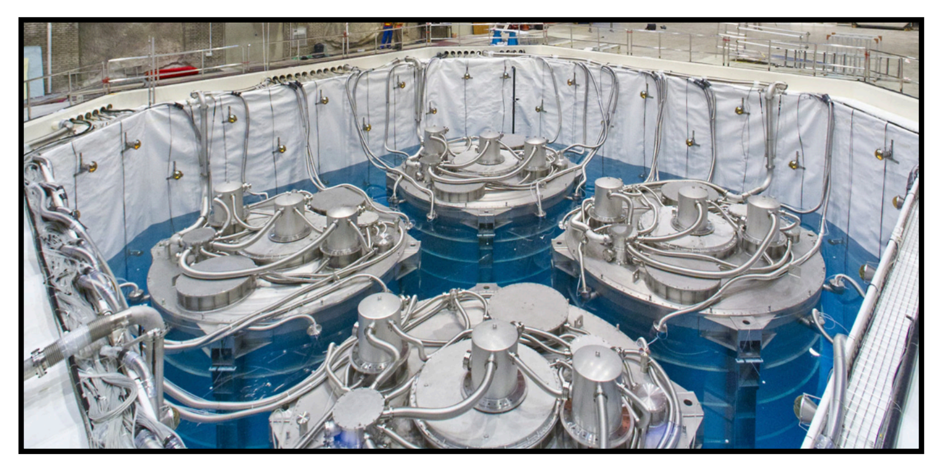


Mueller, *et al*, Phys. Rev. C83 (2011)
Mention, *et al*, Phys. Rev. D83 (2011)
Huber, Phys. Rev. C84 (2011)

Reactor IBD Yield Measurements

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

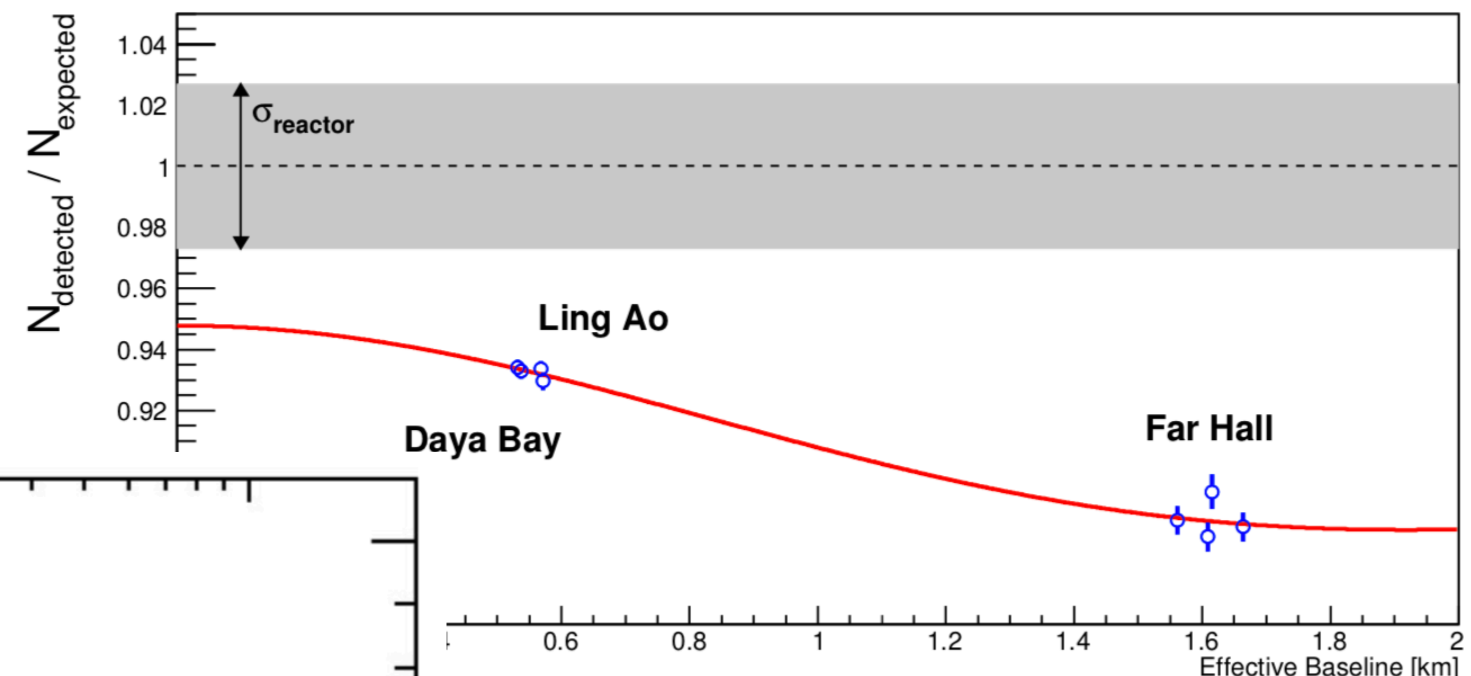




Daya Bay

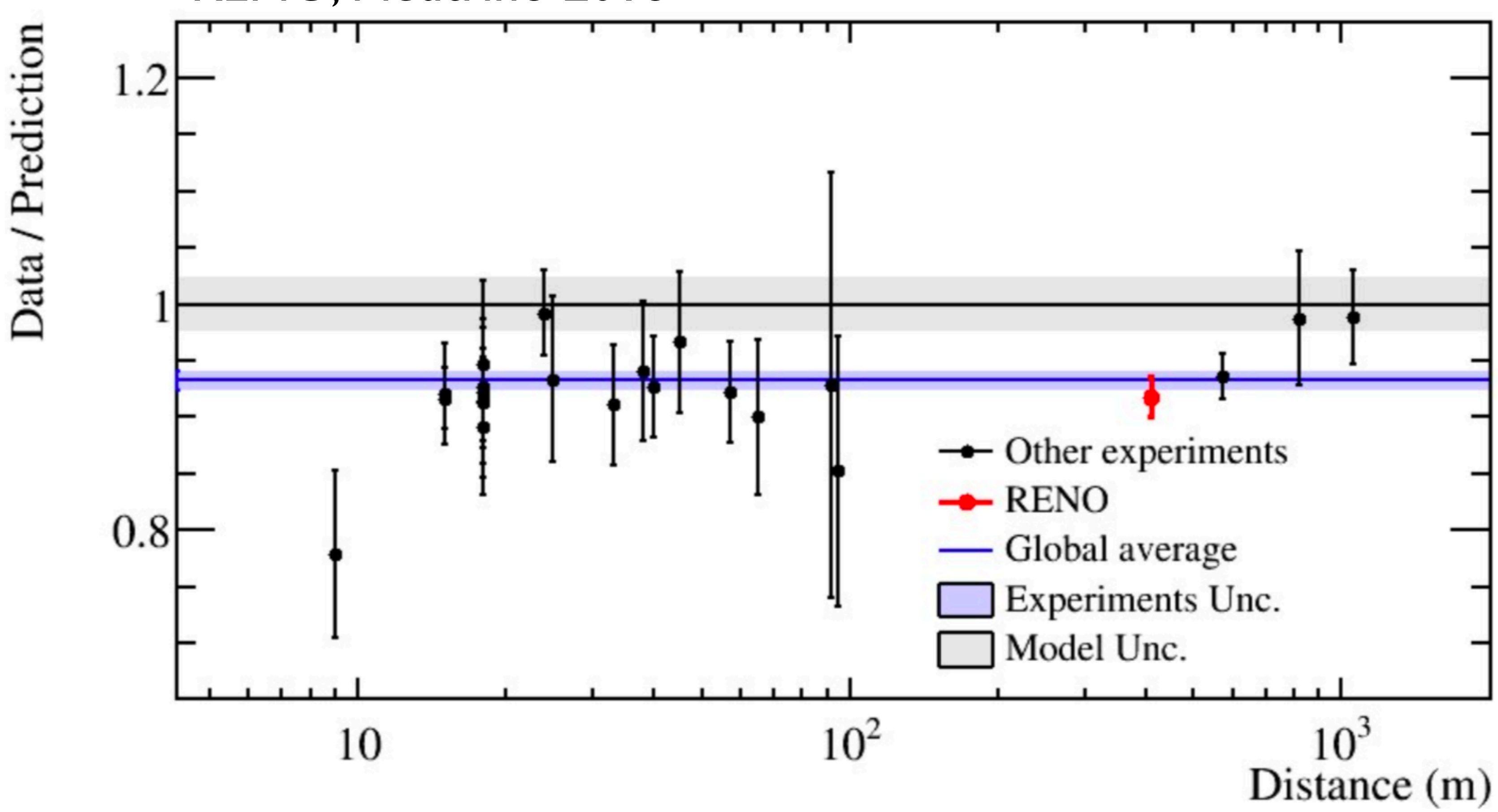
Reactor Antineutrino Flux Anomaly

- Bad news: these flux predictions don't match the data.
- New precise measurements also do not match predictions: Daya Bay (1.5%), RENO (2%), Double Chooz (~1%?)
- WHY the deficit??



Daya Bay, CPC 41 (2016)

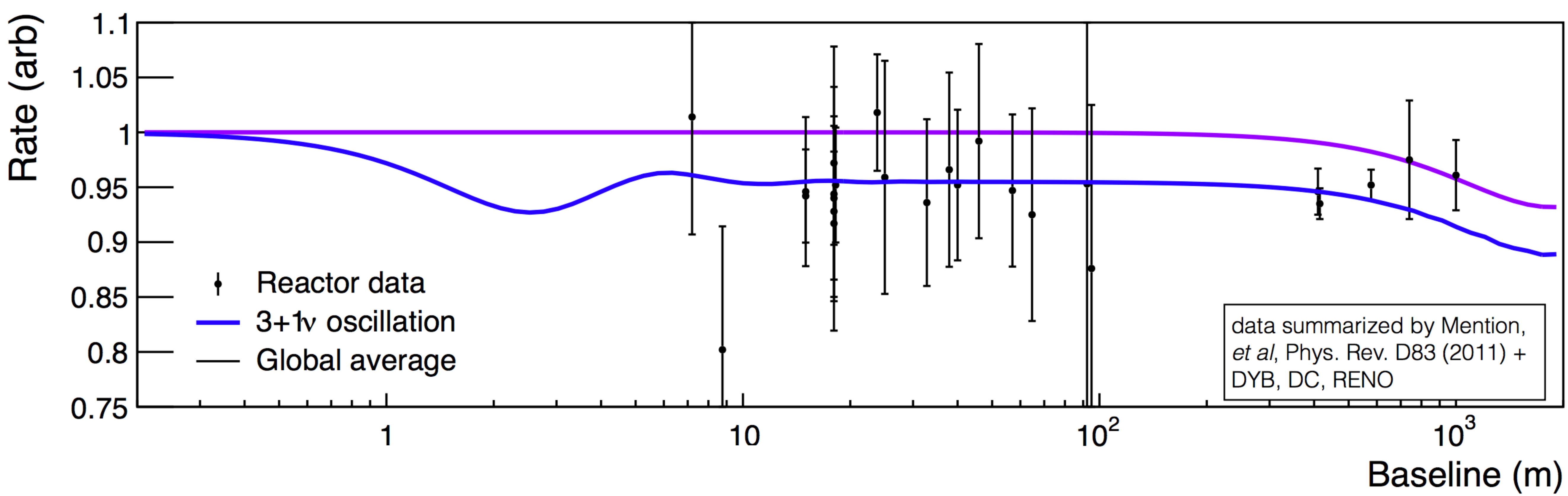
RENO, Neutrino 2018



Sterile Neutrino Oscillations

- Hypothesis 1: Some $\bar{\nu}_e$ oscillated to unobservable types
  - This hypothesis indicates a deficit that is baseline-dependent
  - To fit data, need osc maximum at small baselines: large (~eV) mass splitting
  - Only measuring average flux deficit here… not L/E behavior…

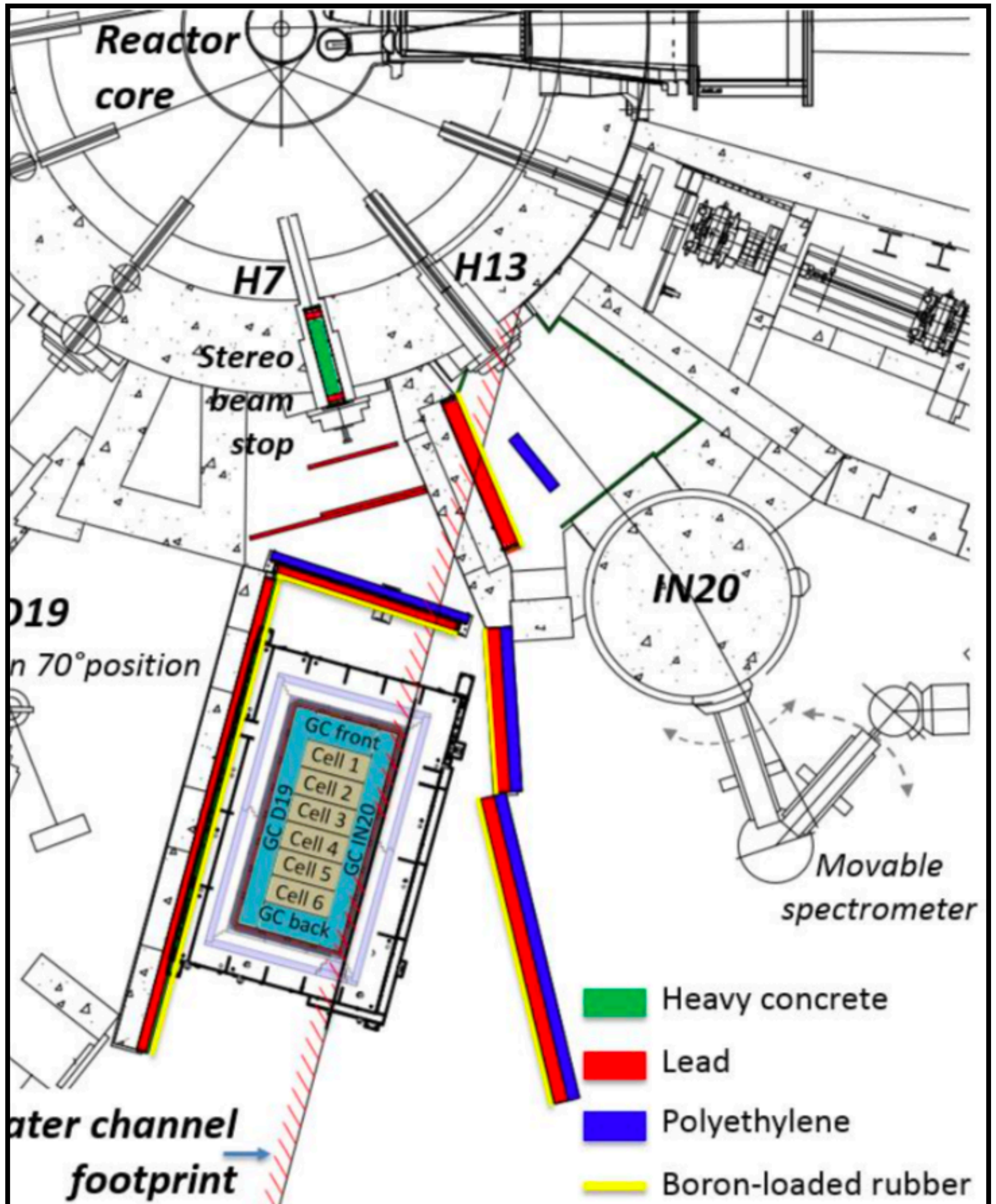
$$sin^2(2\theta)sin^2(1.27\Delta m^2\frac{L}{E_\nu})$$



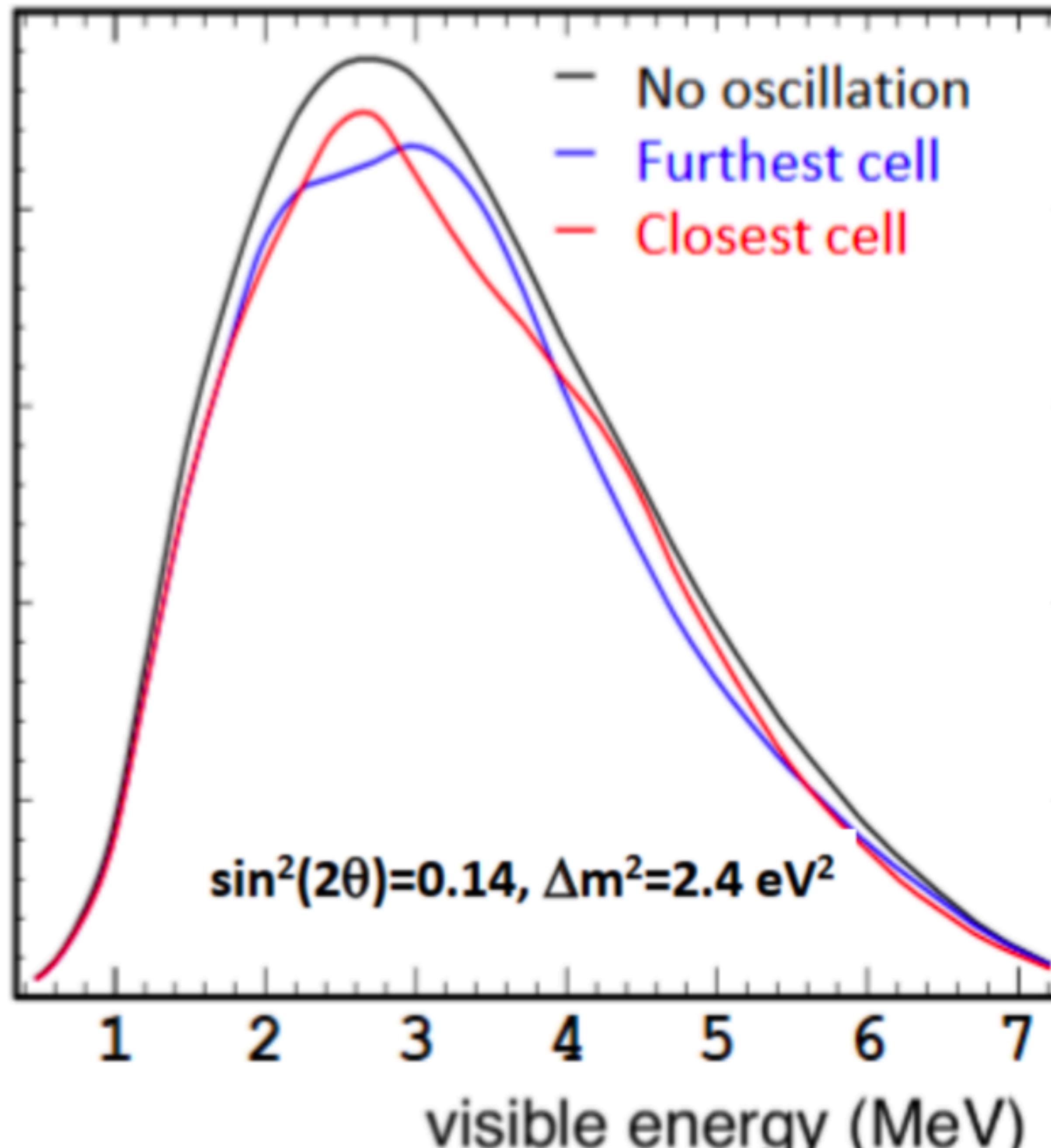
Testing Steriles: Short-Baseline Experiments

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

STEREO Experimental Layout



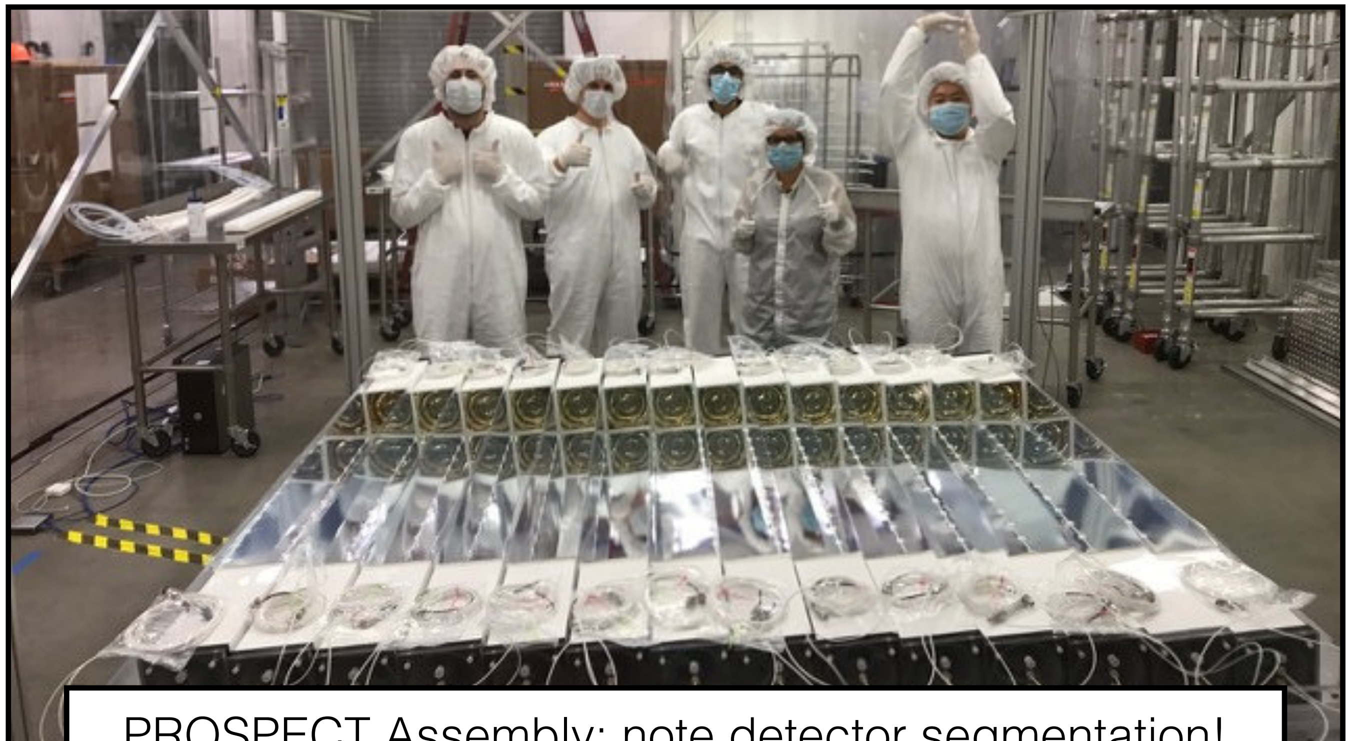
STEREO Toy Prompt Spectra From RAA Best-Fit Osc



STEREO, Neutrino 2018

Testing Steriles: PROSPECT

- PROSPECT at HFIR highly ^{235}U enriched (HEU) reactor



PROSPECT Assembly: note detector segmentation!

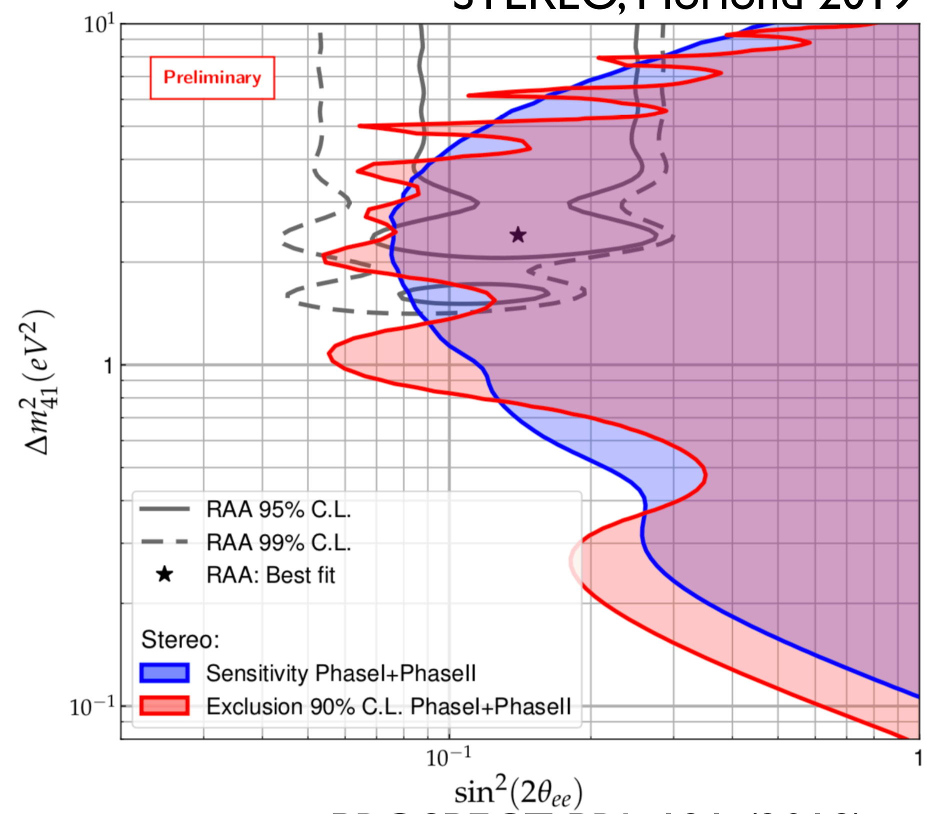
PROSPECT Installation: Rx on other side of the wall!

HFIR reactor core:
Burns <u>only</u> ^{235}U!

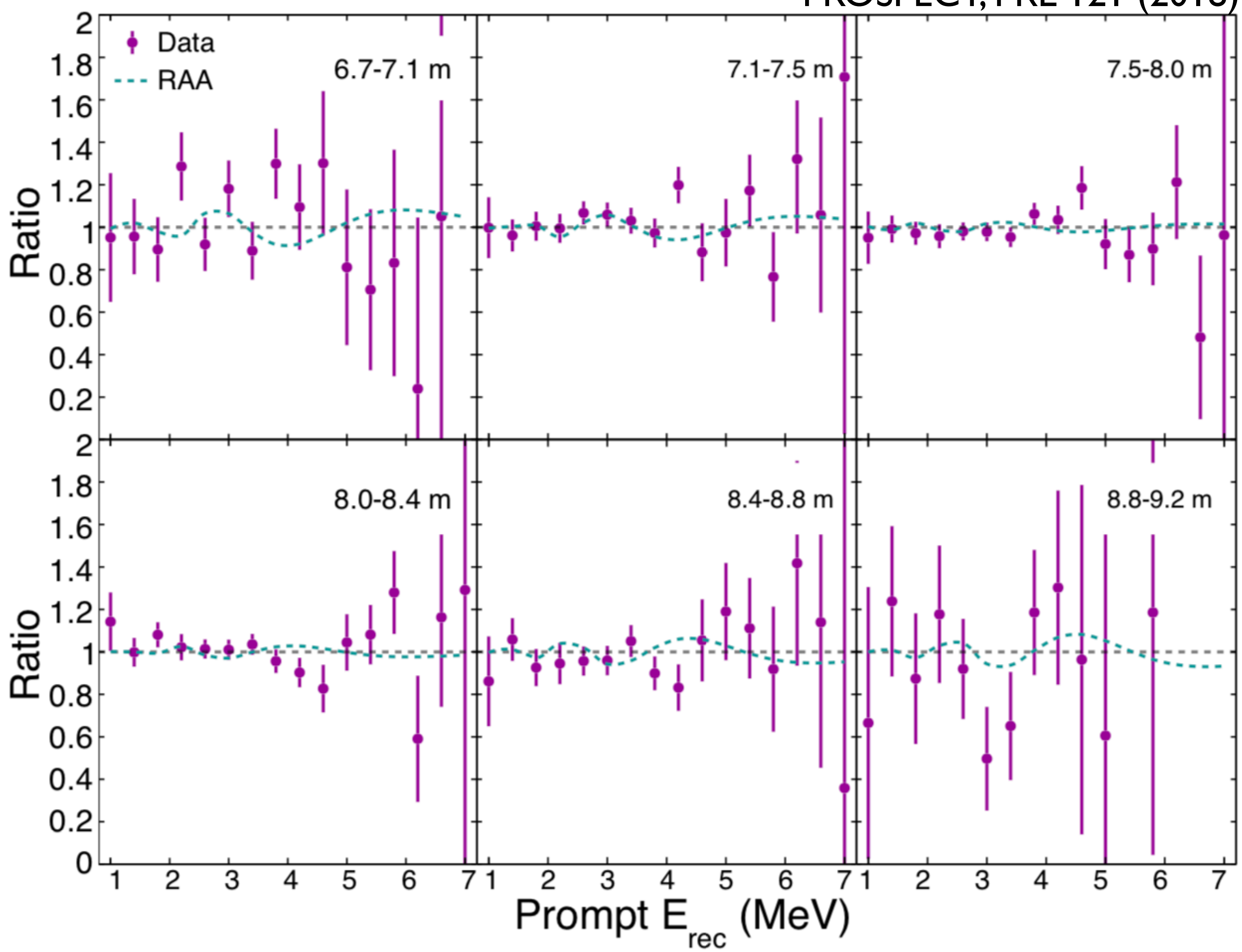
Testing Steriles: PROSPECT and STEREO

- PROSPECT and STEREO: Results are here already!
- No evidence for steriles so far
  - More statistics will bring sensitivity improvements in the coming year

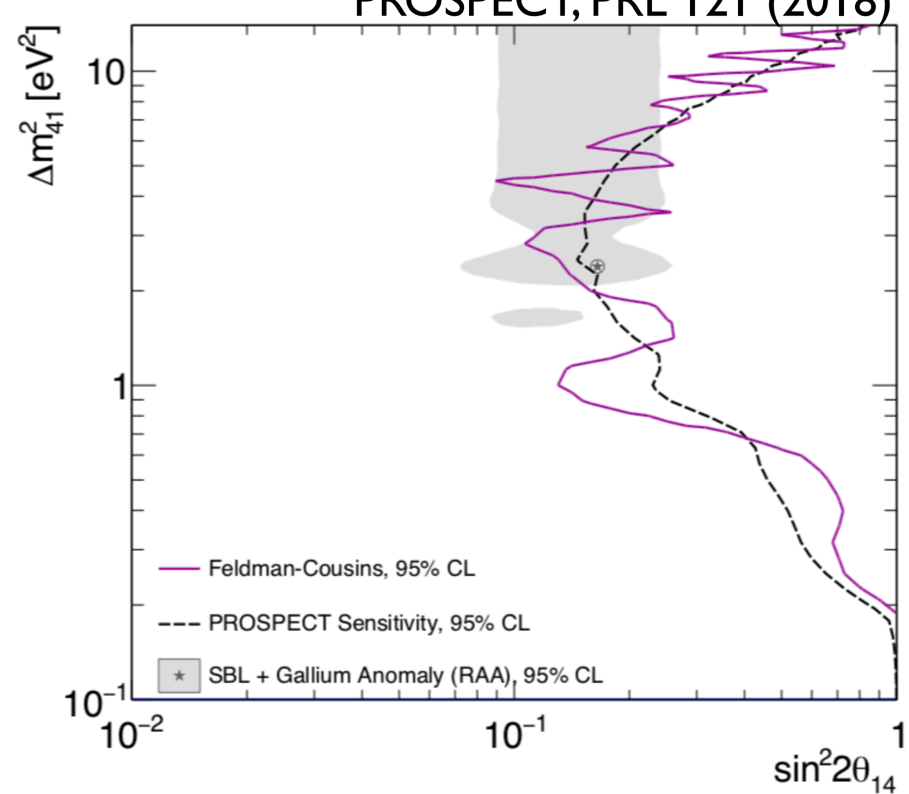
STEREO, Moriond 2019



PROSPECT, PRL 121 (2018)

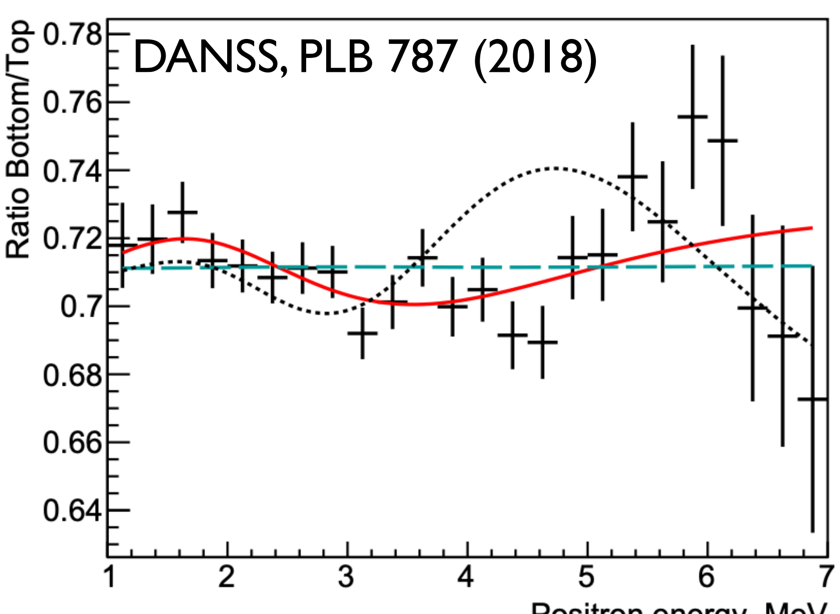


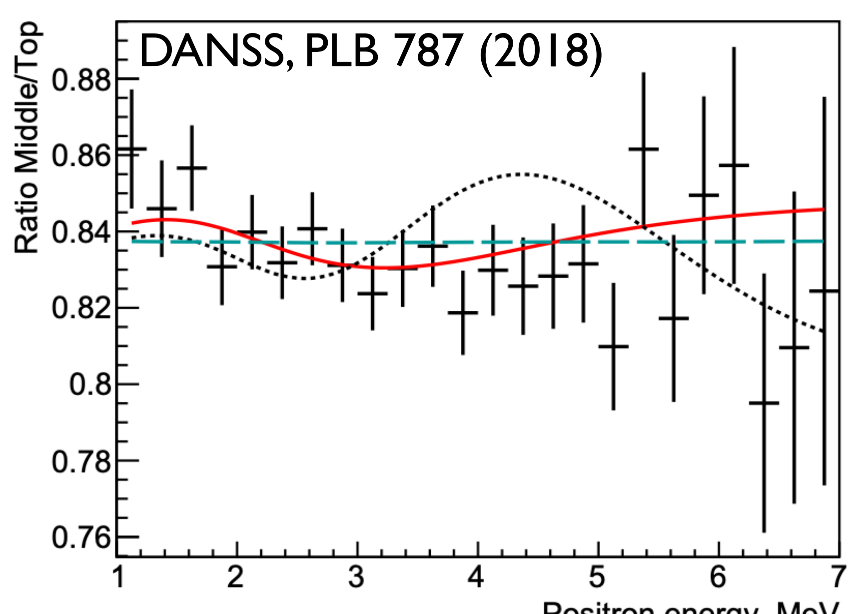
PROSPECT, PRL 121 (2018)



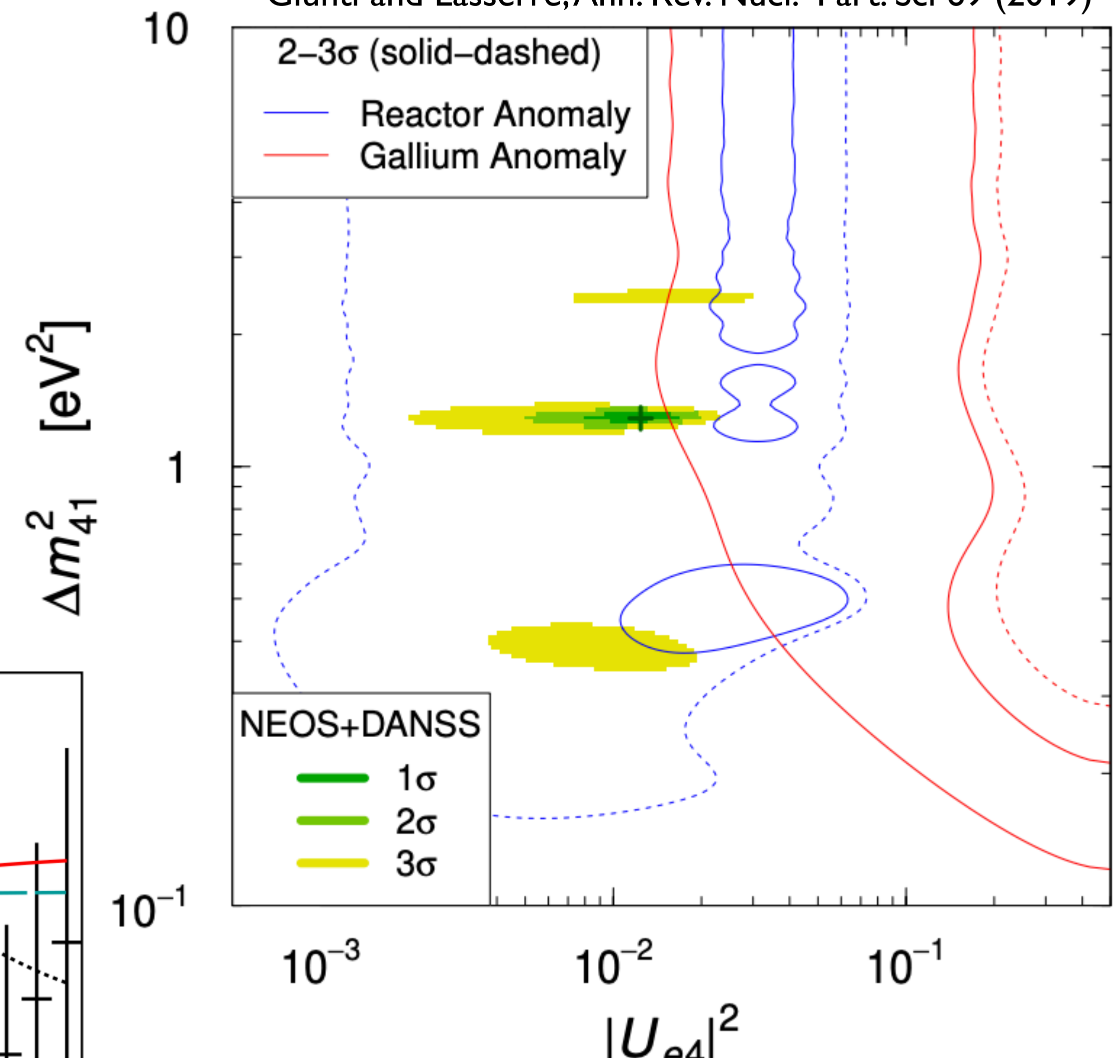
Testing Steriles: LEU Experiment Hints?

- Hints for steriles from commercial core (LEU) spectrum ratios?
  - Global fit of DANSS+NEOS ratios: ~5% osc amplitude best-fit at ~1.5 eV^2
  - <u>Note</u>: Individual experiments don't claim a statistically significant observation





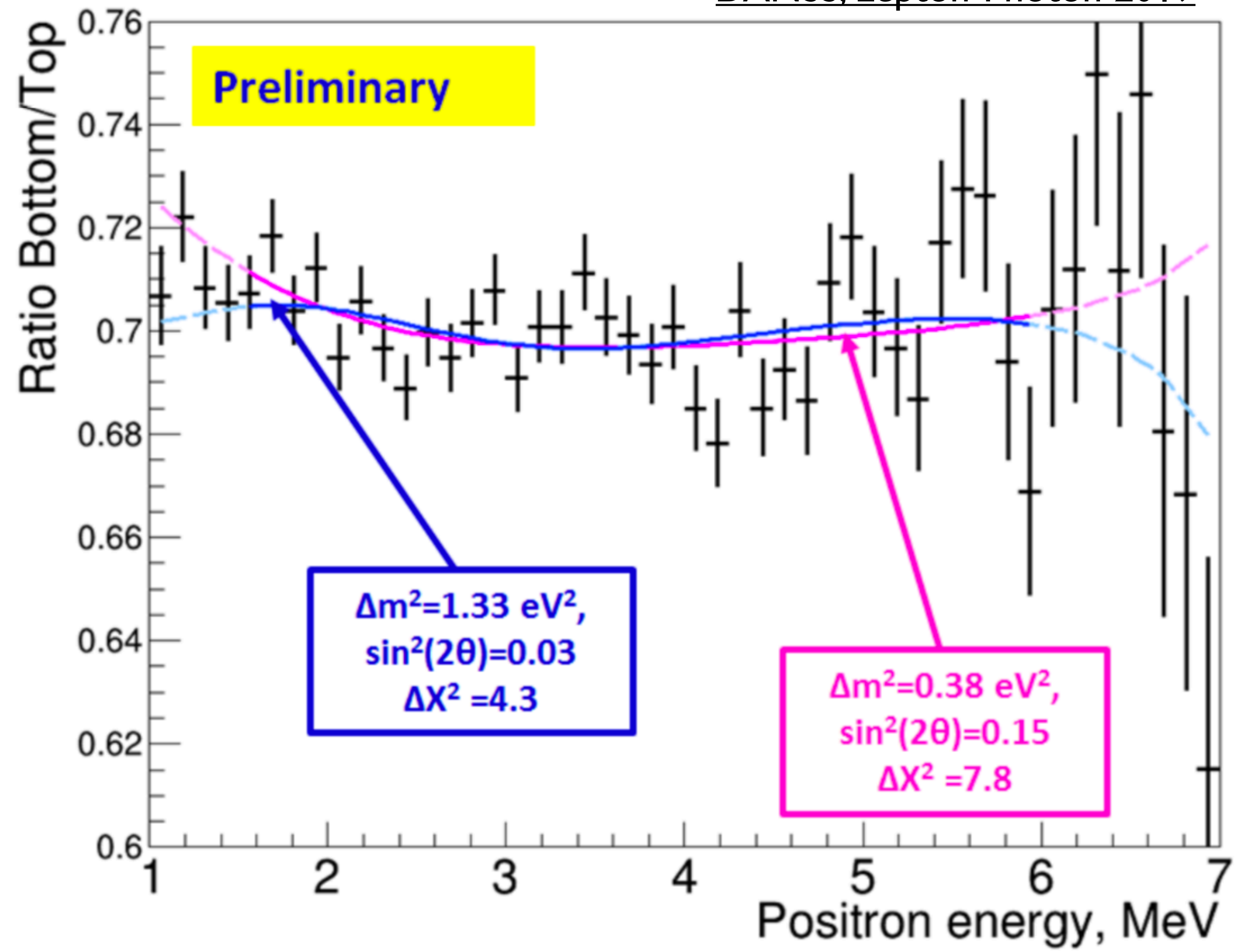
Giunti and Lasserre, Ann. Rev. Nucl. Part. Sci 69 (2019)



Testing Steriles: LEU Experiment Update

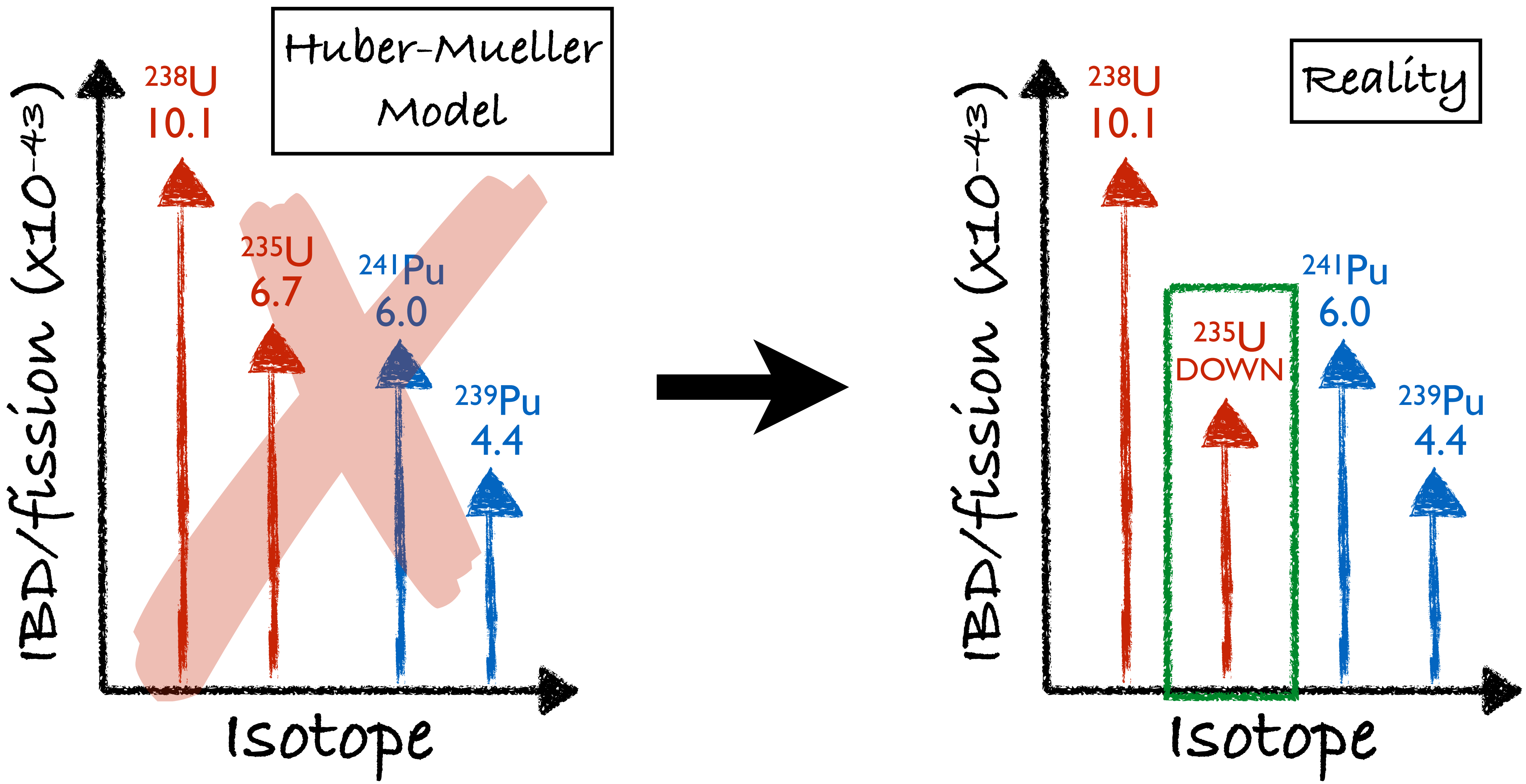
- Hints for steriles from commercial core (LEU) spectrum ratios?
- New DANSS results with improved stats, systematics handling
  - No-oscillation is only disfavored with respect to best-fit at 1.8σ
  - Even less disfavored compared to 'old best fit'
- Primary sterile hint from reactor spectra appears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

DANSS, Lepton-Photon 2019



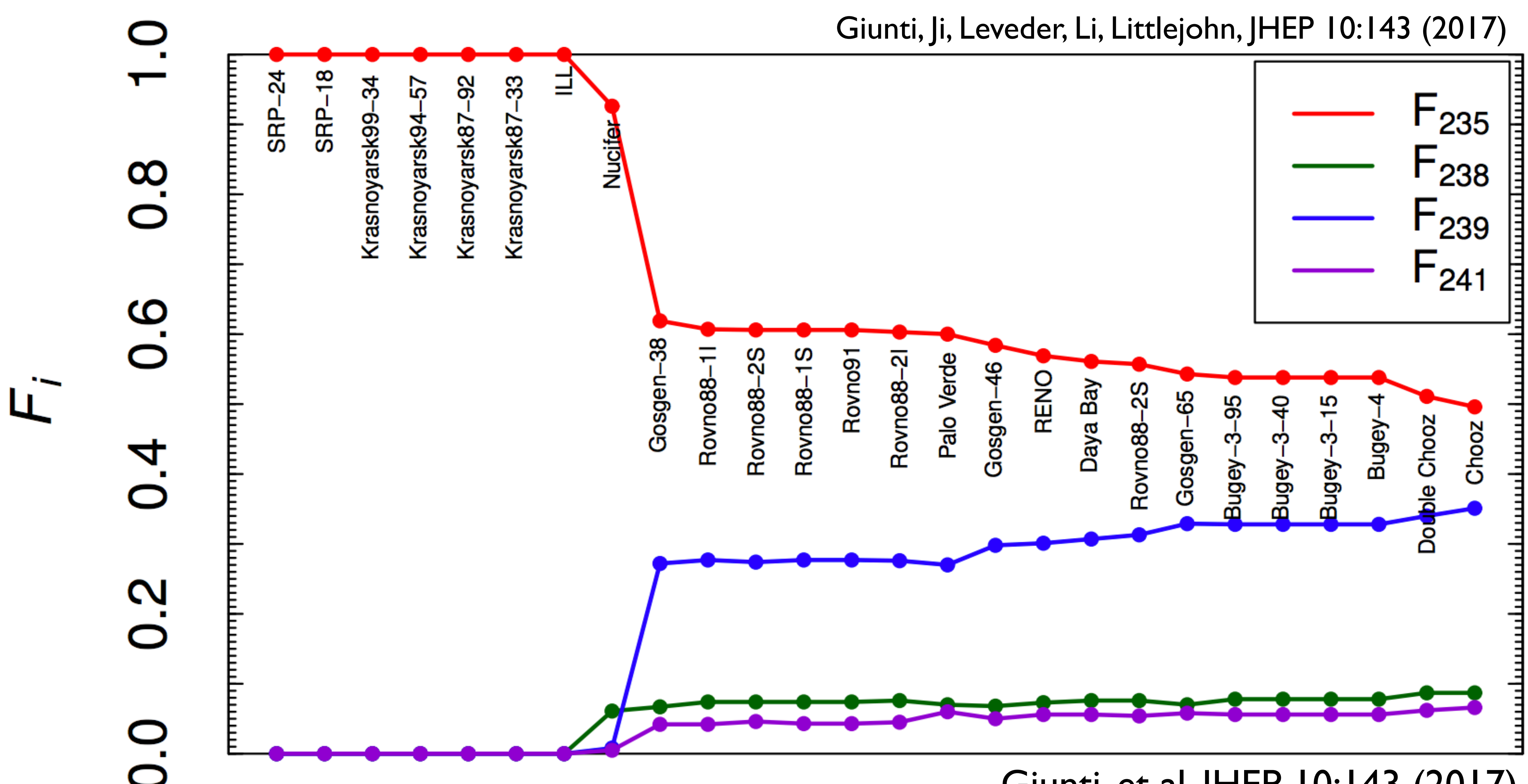
Bad Flux Predictions

- **Hypothesis 2: Something is wrong with the flux predictions**
  - Theorists have come up with lots of reasons predictions could be bad
  - Could be just one isotope; or could be all isotopes.



Bad Flux Predictions

- Hypothesis 2: Something is wrong with the flux predictions
  - This hypothesis indicates a deficit that *could be* fuel-content-dependent
  - So compare flux measurements between different reactor types?

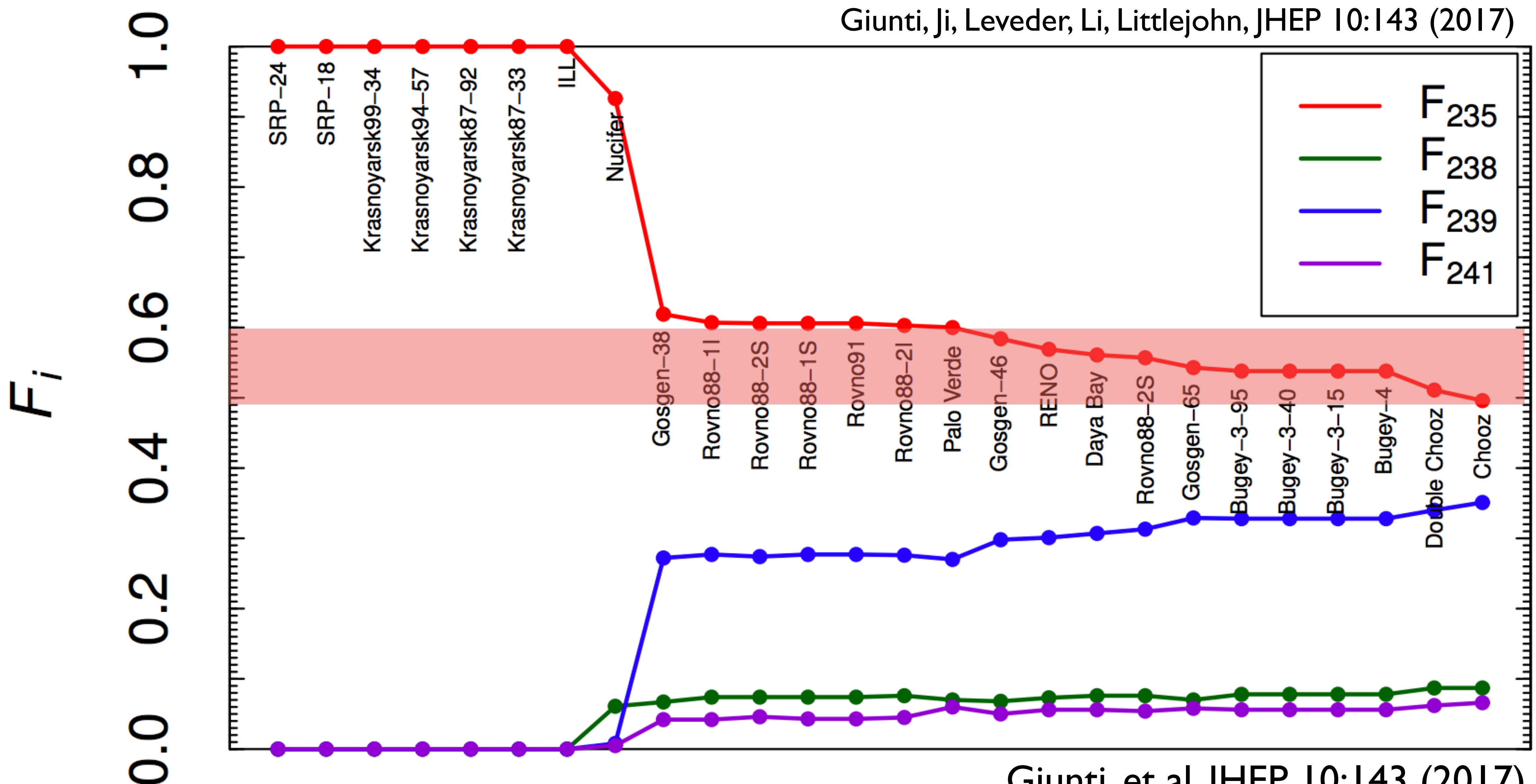


Giunti, et al, JHEP 10:143 (2017)

Bad Flux Predictions

- Hypothesis 2: Something is wrong with the flux predictions
  - This hypothesis indicates a deficit that *could be* fuel-content-dependent
  - OR: compare between different time periods in one experiment

Giunti, Ji, Leveder, Li, Littlejohn, JHEP 10:143 (2017)



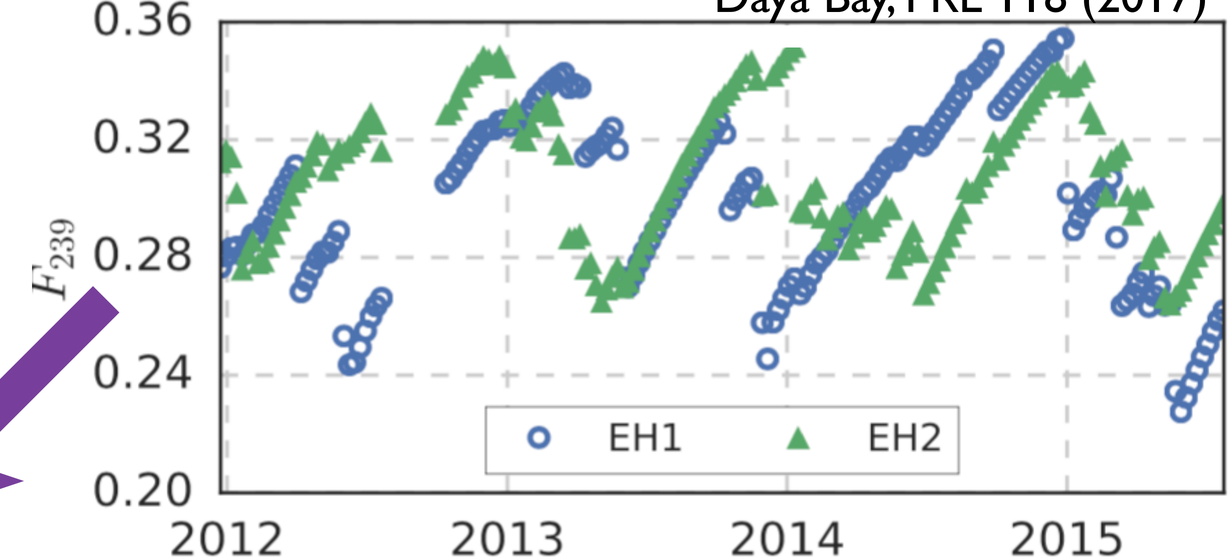
Daya Bay's observed range over time

Giunti, et al, JHEP 10:143 (2017)

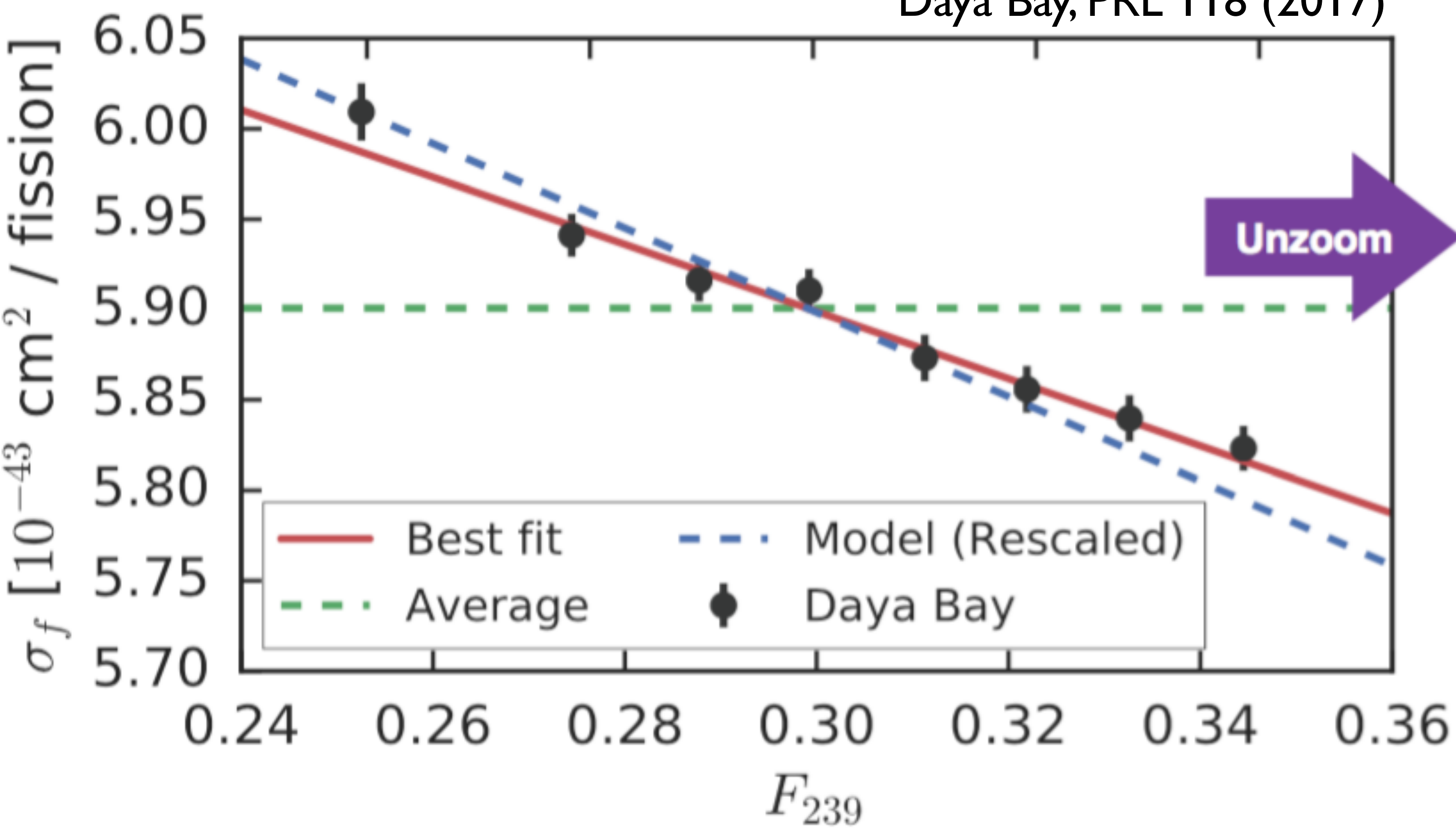
Testing Fluxes: Daya Bay Evolution

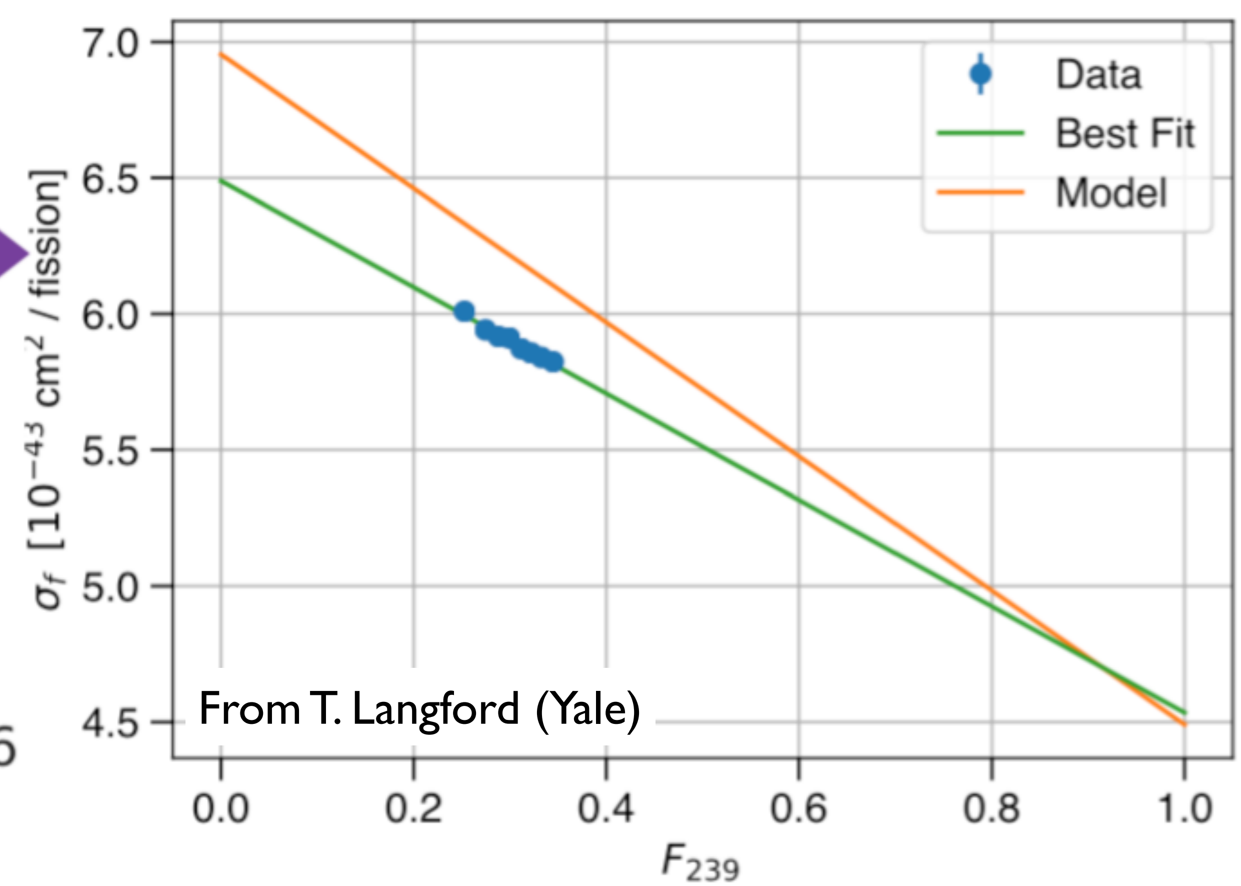
- Measure flux during periods with differing fuel content
- Flux anomaly's size depends on how much ^{235}U is burning
- Can't be explained by steriles
  - CAN be caused by bad ^{235}U flux predictions (among other things)
  - New flux measurements at ^{235}U HEU cores would also be nice

Daya Bay, PRL 118 (2017)



Daya Bay, PRL 118 (2017)





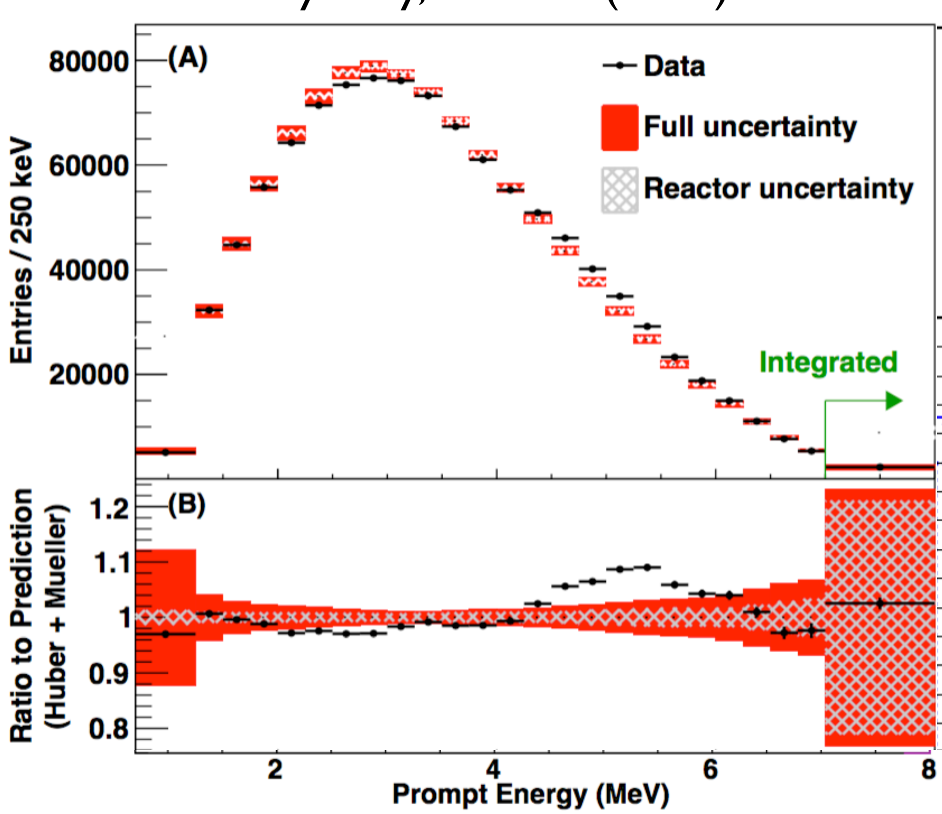
From T. Langford (Yale)

Comparing Prediction and Data: Reactor Antineutrino Spectrum

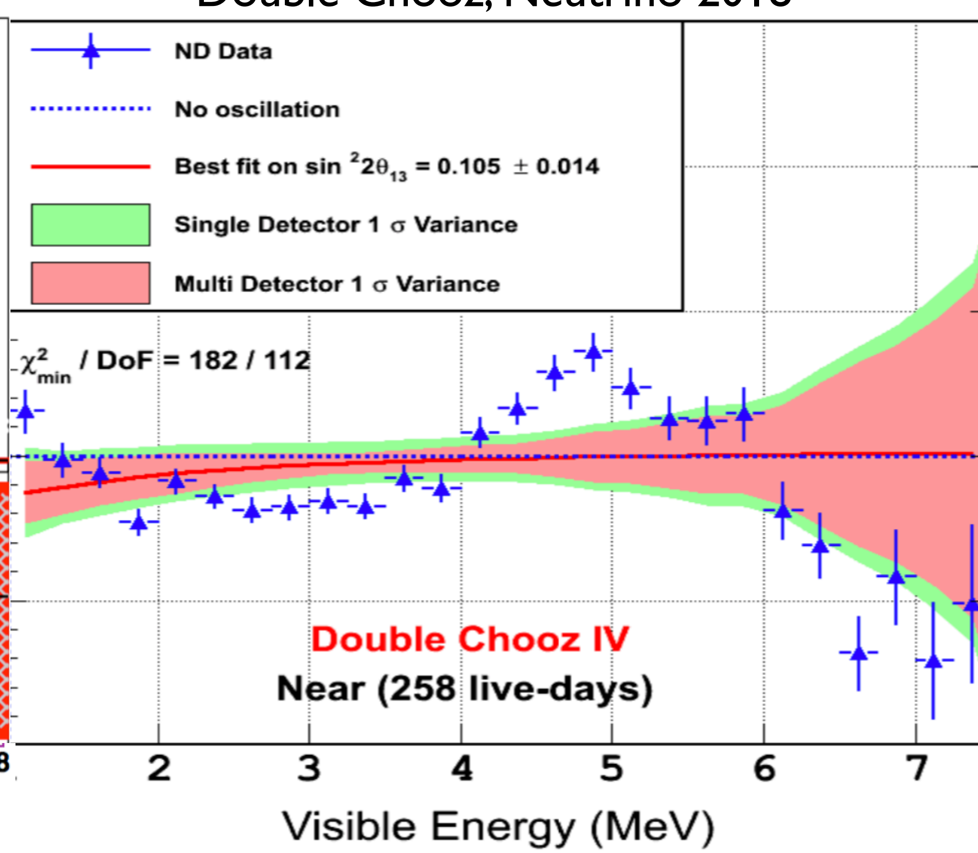
Reactor Spectrum Anomaly

- Bad news: spectrum predictions don't match the 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 <u>one</u> particular isotope to blame (like ^{235}U)? Or <u>all</u>?
    - Looks like short-baseline ^{235}U measurements can also give new info here!

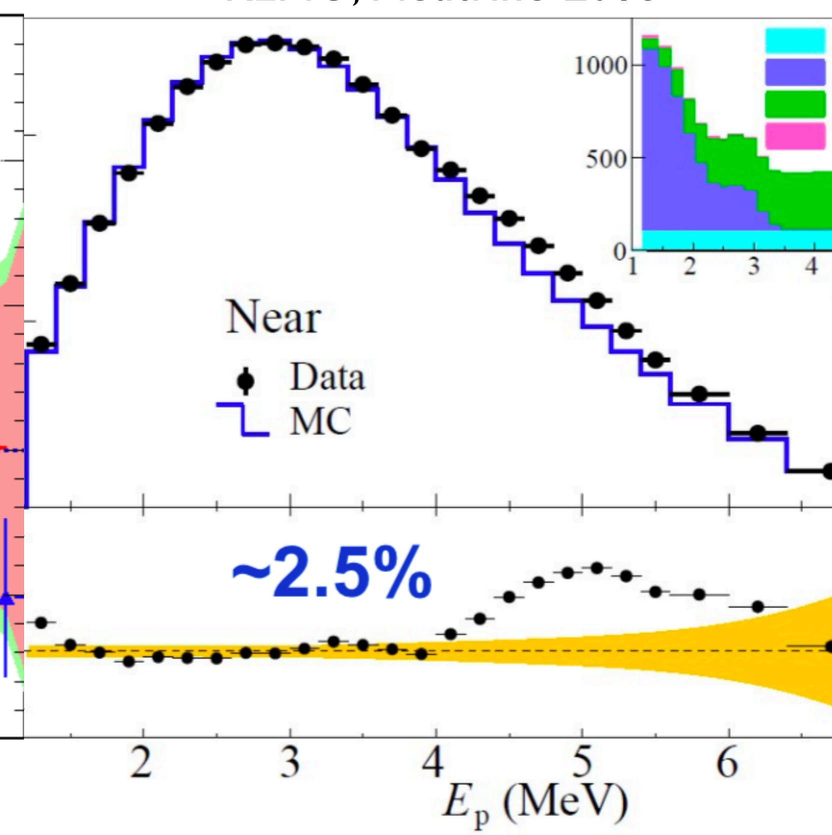
Daya Bay, CPC 41 (2017)



Double Chooz, Neutrino 2018



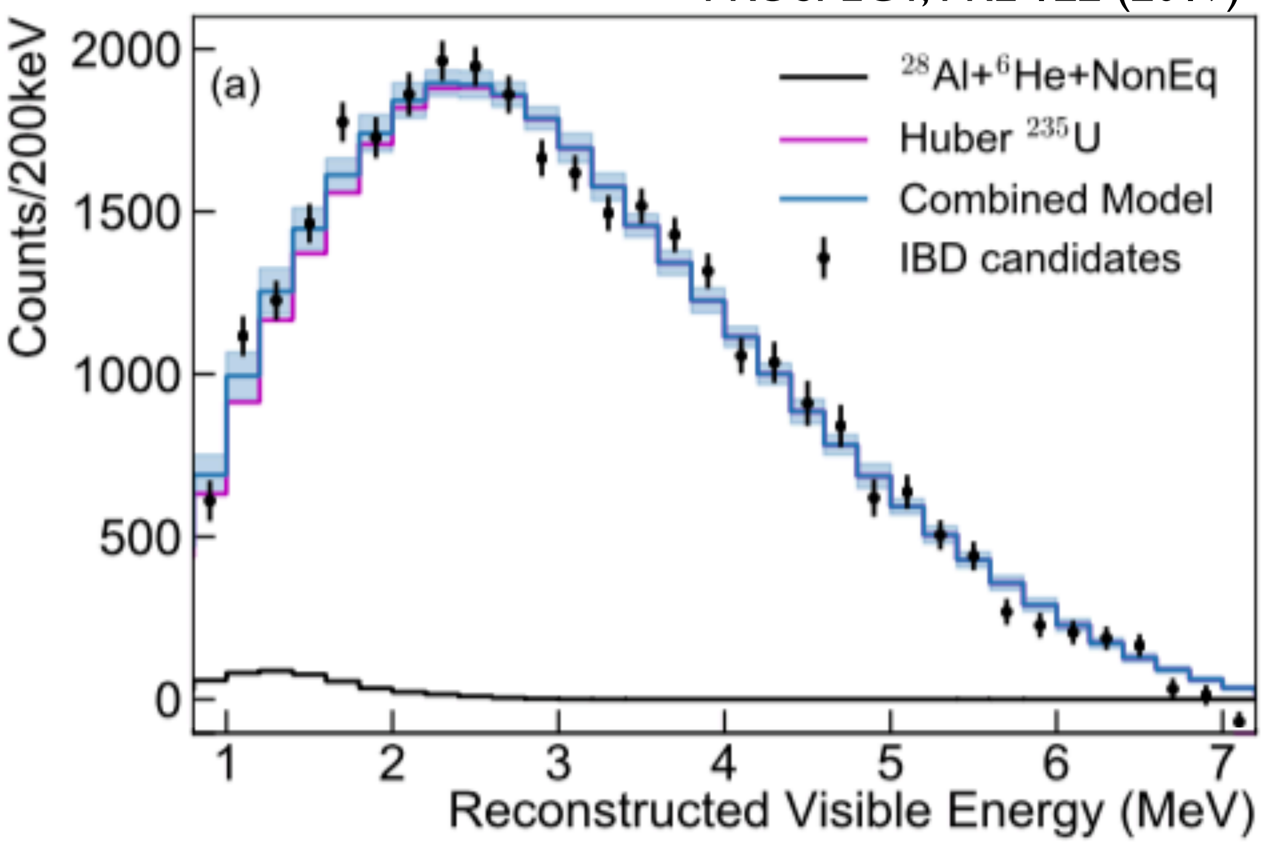
RENO, Neutrino 2018



Isotopic Origins: PROSPECT

- Measure spectrum when burning <u>only</u> ^{235}U
- PROSPECT has done this!

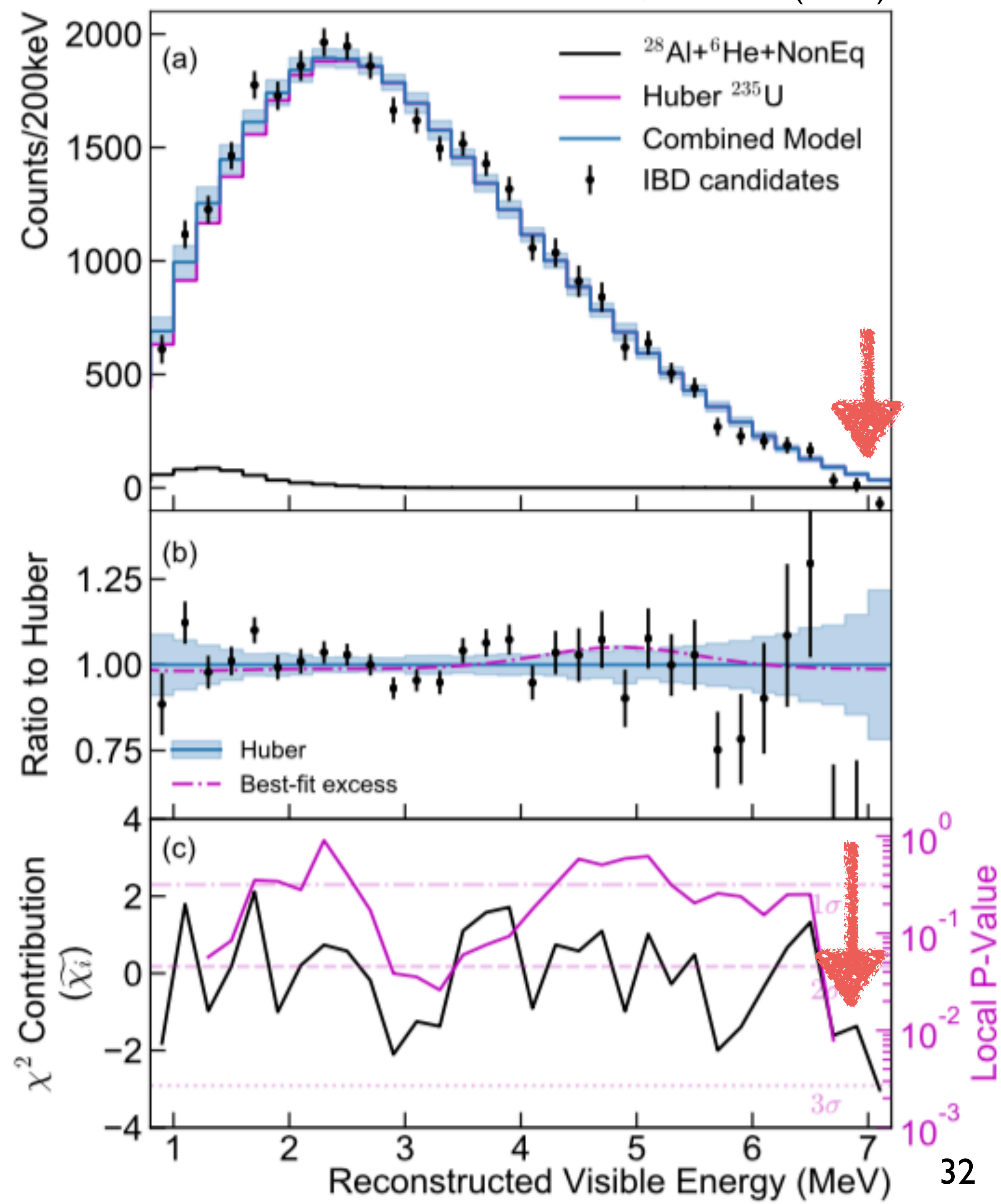
PROSPECT, PRL 122 (2019)



Isotopic Origins: PROSPECT

- Measure spectrum when burning <u>only</u> ^{235}U
- PROSPECT has done this!
- Is PROSPECT consistent with Huber's ^{235}U model?
    - $X^2/ndf = 52.1/31$; p-value = 0.01
    - Huber broadly agrees with PROSPECT, but not a great fit
    - Worst offender: high energy fit is OK otherwise.
        - Bkg issue? Unlucky statistics? Need more stats to know for sure.

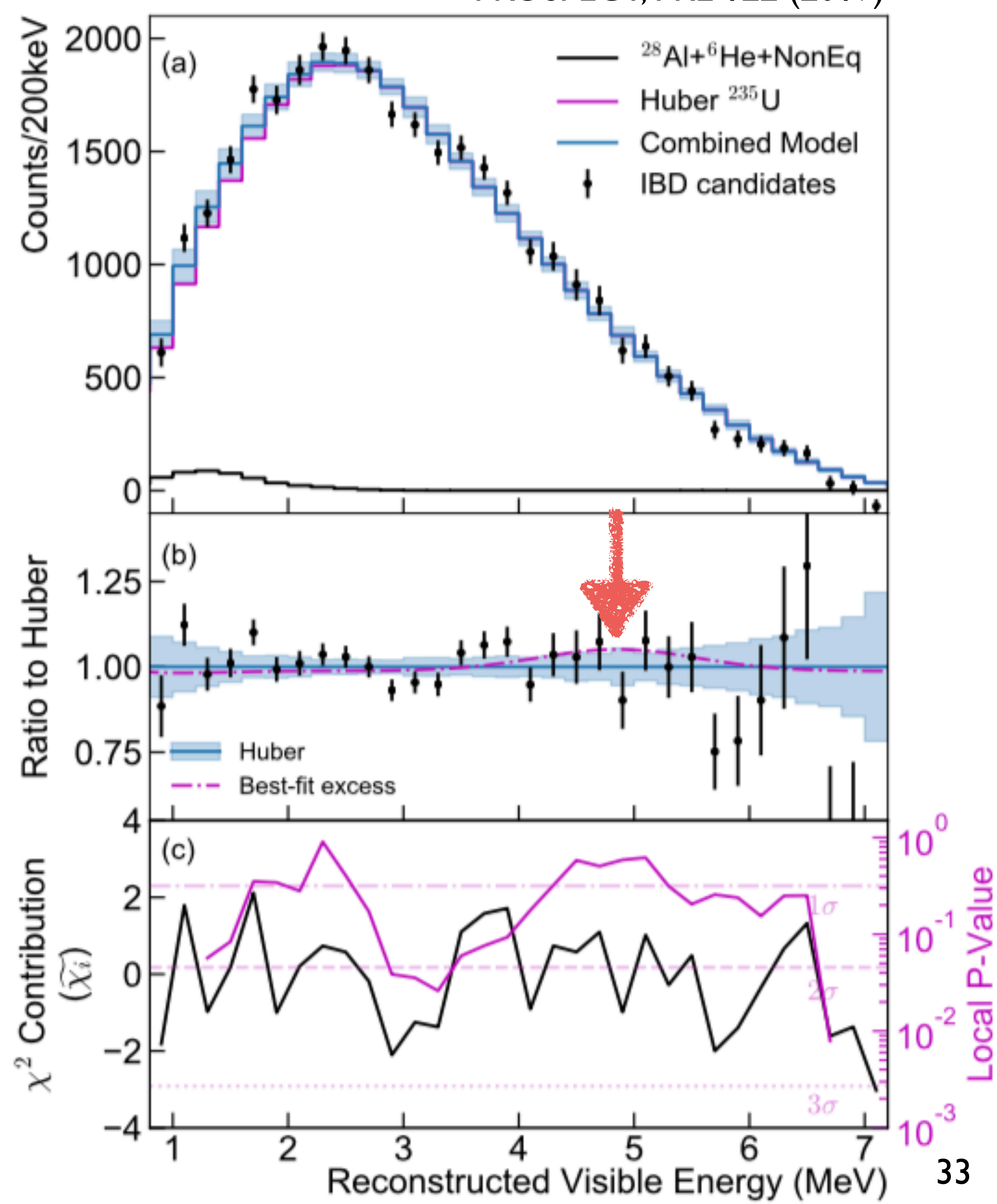
PROSPECT, PRL 122 (2019)



Isotopic Origins: PROSPECT

- Measure spectrum when burning only ^{235}U
- PROSPECT has done this!
- How does PROSPECT compare to 'bump' in θ_{13} experiments?
  - PROSPECT relative bump size WRT to Daya Bay: 69% ± 53%
  - ~consistent with 'no bump' (0%) and 'DYB-sized bump' (100%)
    - Need more stats to differentiate
  - 'Big bump' (178%) if ^{235}U is the sole bump contributor
    - Disfavored at 2.1σ

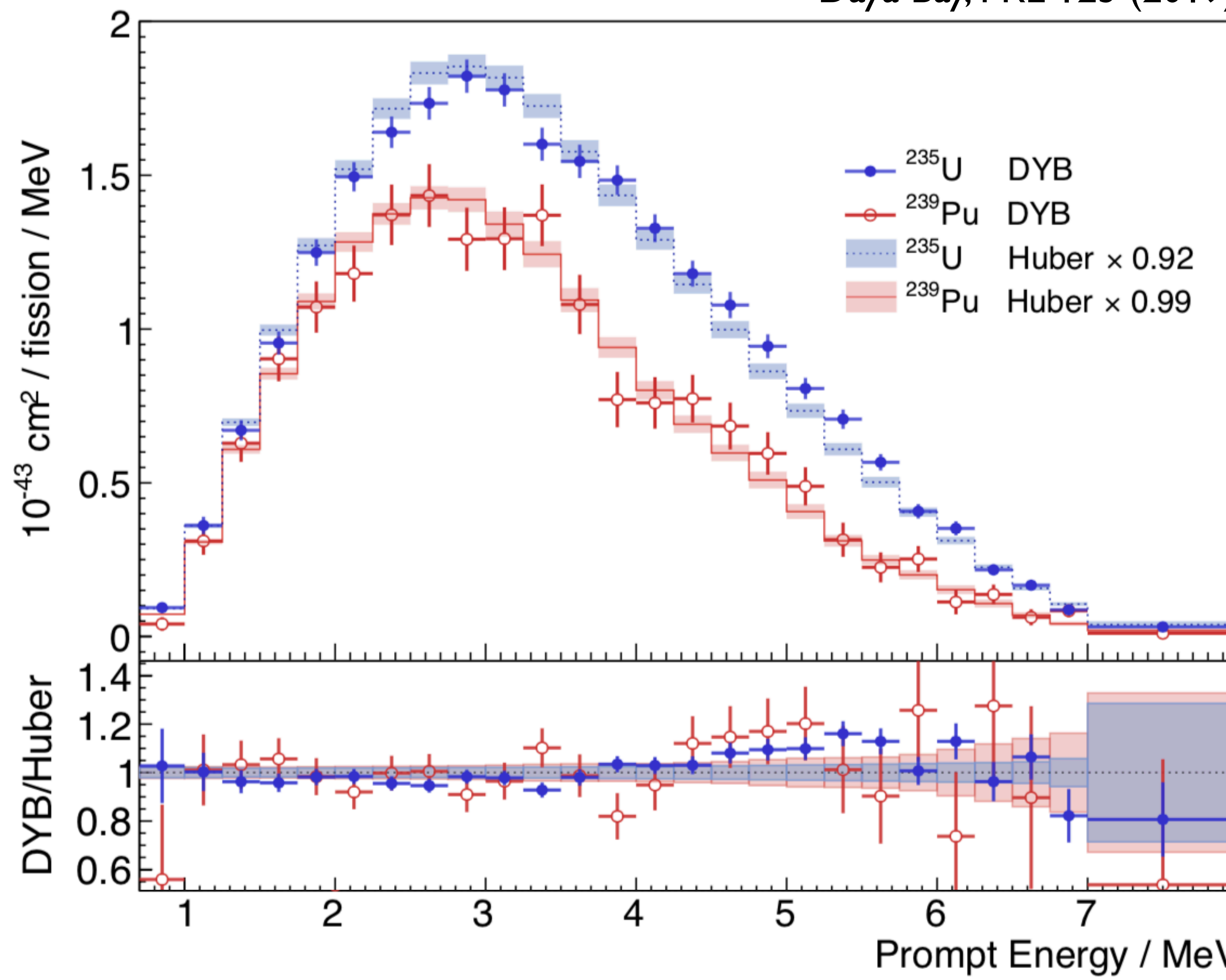
PROSPECT, PRL 122 (2019)



Daya Bay Spectrum Evolution

- Measure Daya Bay spectrum variation with fuel content.
- Should be able to 'extract' spectra of ^{239}Pu, ^{235}U $\bar{\nu}_e$
  - 'Best option': 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
- Actively pursuing joint HEU-LEU analyses.

Daya Bay, PRL 123 (2019)



Thanks!

- Things I didn't even get to mention (quiz me later!)
  - RENO Spectrum Evolution
  - Reactor IBD-CEνNS complementarity
  - New studies questioning ILL beta spectrum calibration accuracy
  - More theory studies probing inaccuracies in conversion / ab initio methods

Summary

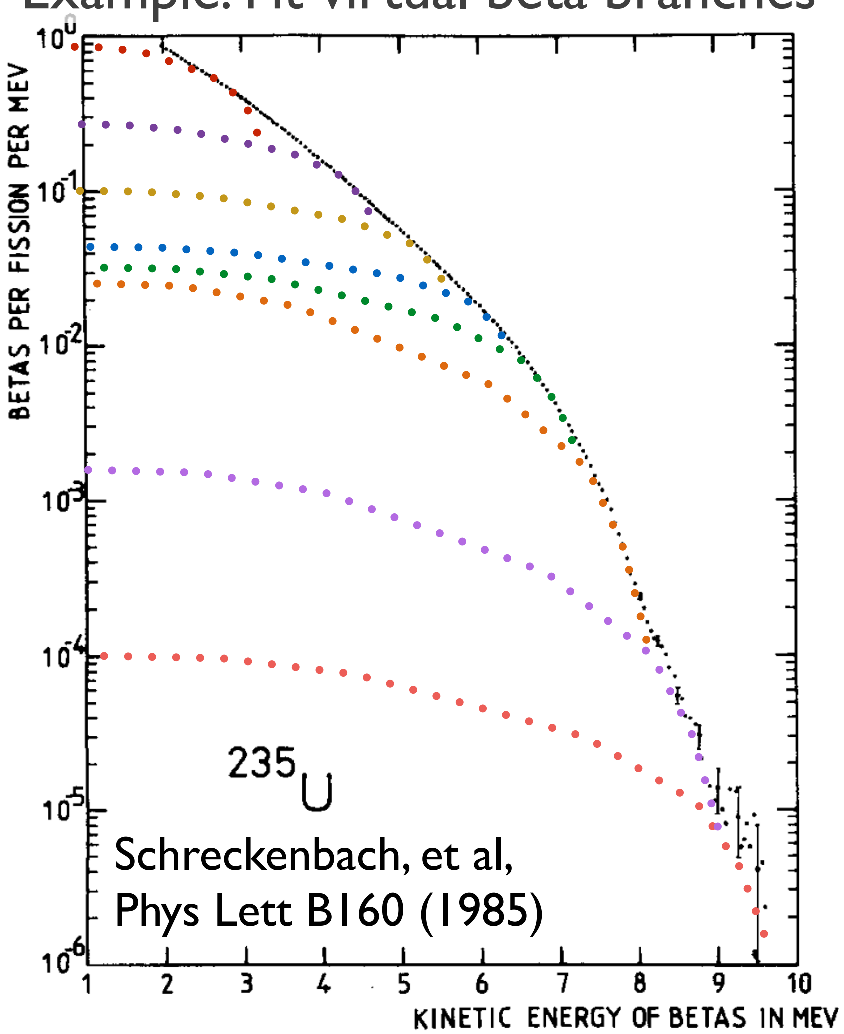
- Well-understood reactor antineutrino fluxes and spectra are vital for addressing major issues in neutrino physics today.
- New recent measurements have helped improve our understanding of the reactor flux anomaly
  - Daya Bay evolution: bad flux predictions!
  - Short-baseline measurements: no steriles so far.
- Same for reactor spectrum anomaly
  - New isotopic flux measurements at PROSPECT and Daya Bay!
- Understanding will improve in the coming year as SBL, θ_{13} experiments continue to accrue statistics
  - New data = new handles to improve nuclear physics interpretations; Theorists and experimentalists can work together here

Backups

Reactor Spectrum Predictions

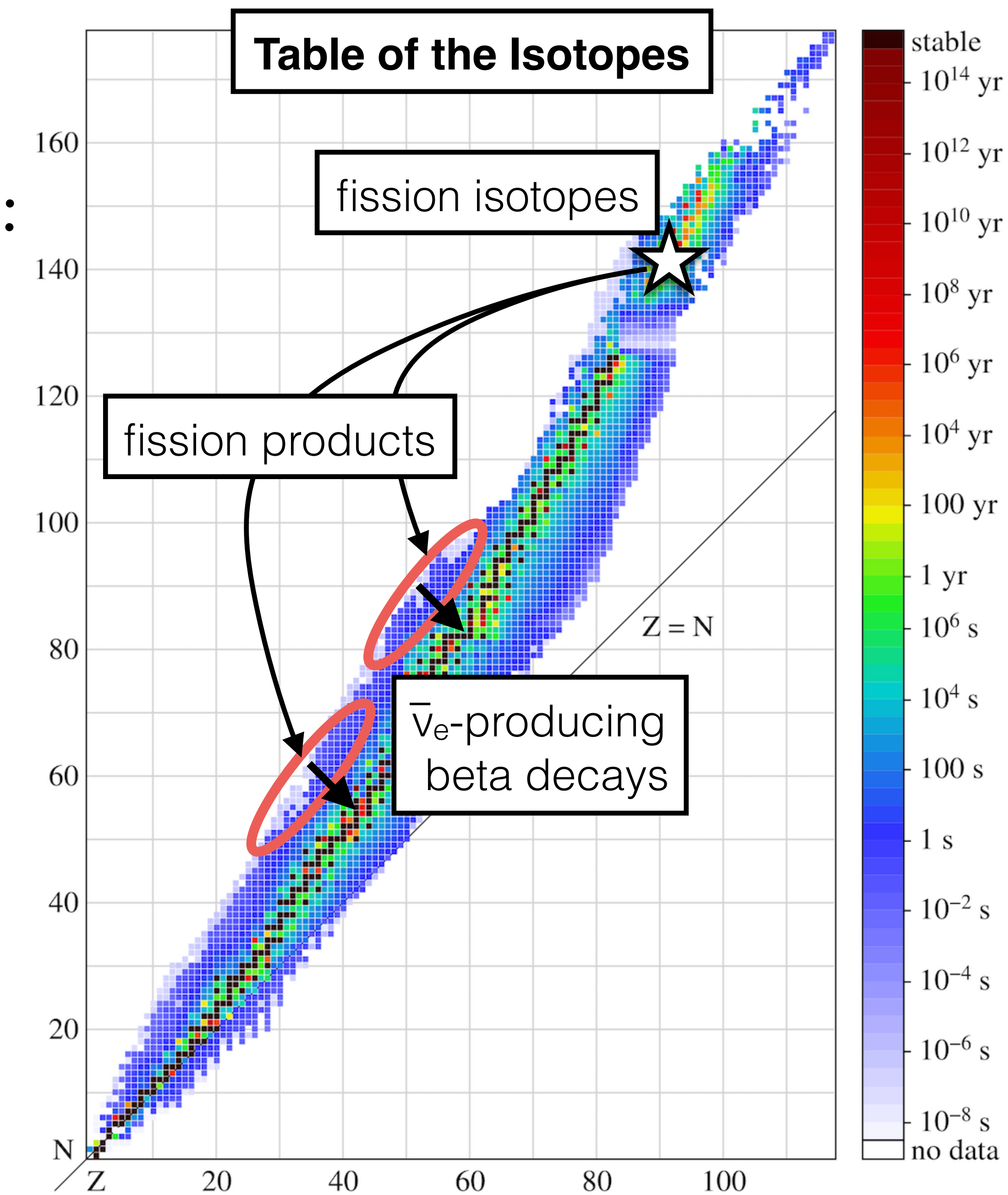
- Reminder: Convert beta spectra into antineutrino spectra
  - Except ^{238}U: there, we just use nuclear databases.
- In theory, this is simple, but in practice, spectrum depends on:
  - Fermi function, which depends on nuclear charge
  - Forbidden-ness of the beta transition
  - Smaller-order corrections (nuclear size, etc.)
- Since we're fitting 'fake' beta branches, have to parameterize all these things.
  - Usually parameterize vs. E_{beta}: 'What is the average nuclear charge for branches with this Q-value?'
  - Errors arise from parameterization, which can be hard to quantify (see A. Hayes's Neutrino2018 talk)
- One idea to get more info: is prediction bad for all isotopes? Or a specific isotope?

Example: Fit virtual beta branches



Bad Flux Prediction Possibilities

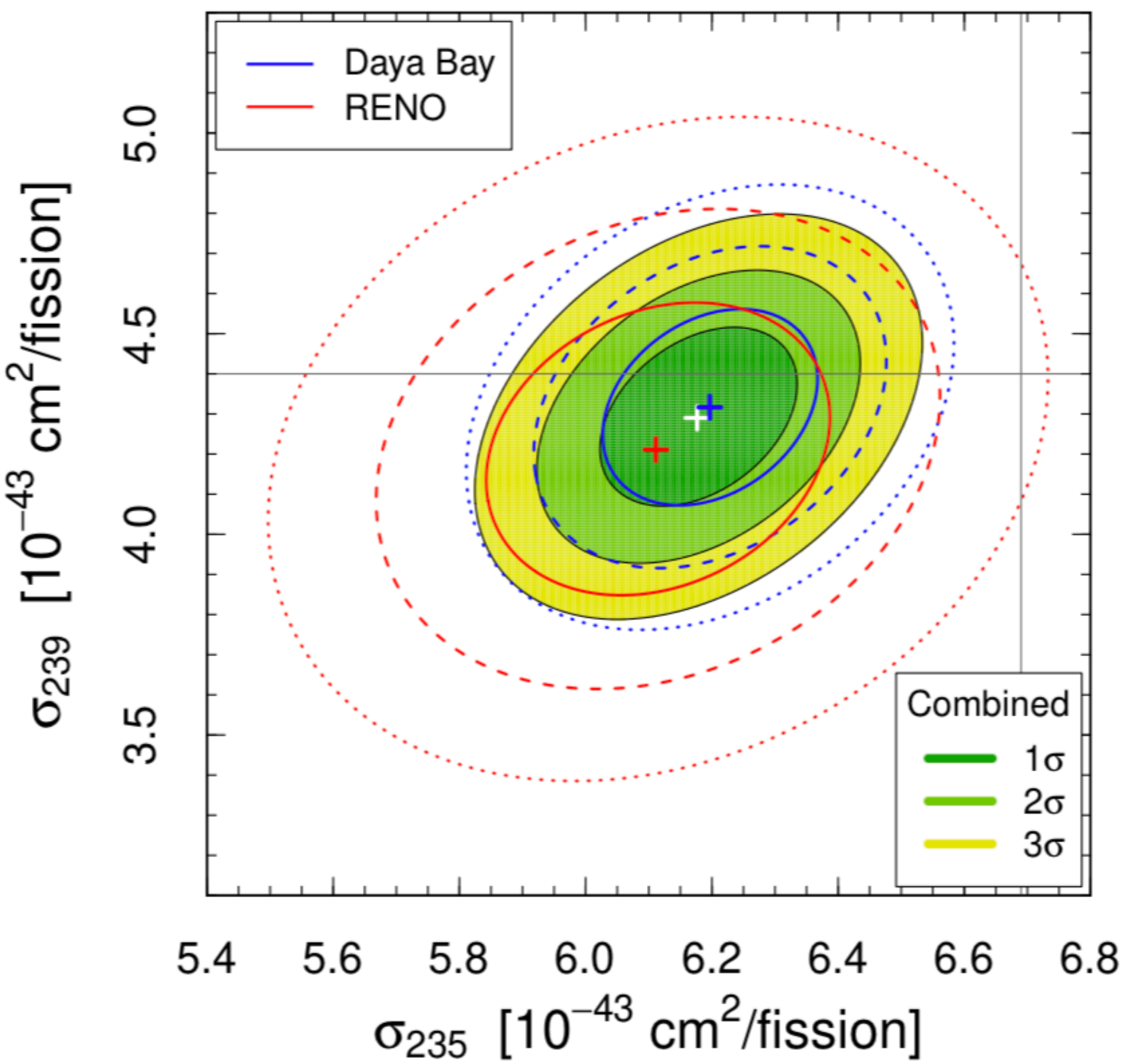
- A litany of hypotheses HOW the fluxes could be incorrect:
  - Maybe it's specifically related to beta-decays:
    - Maybe forbidden decays aren't treated properly. Hayes, et al, **PRL** 112 (2014), Hayen, et al **PRC** 99 (2019)
    - Maybe fission isotope beta spectrum measurements are wrong. Letourneau 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/

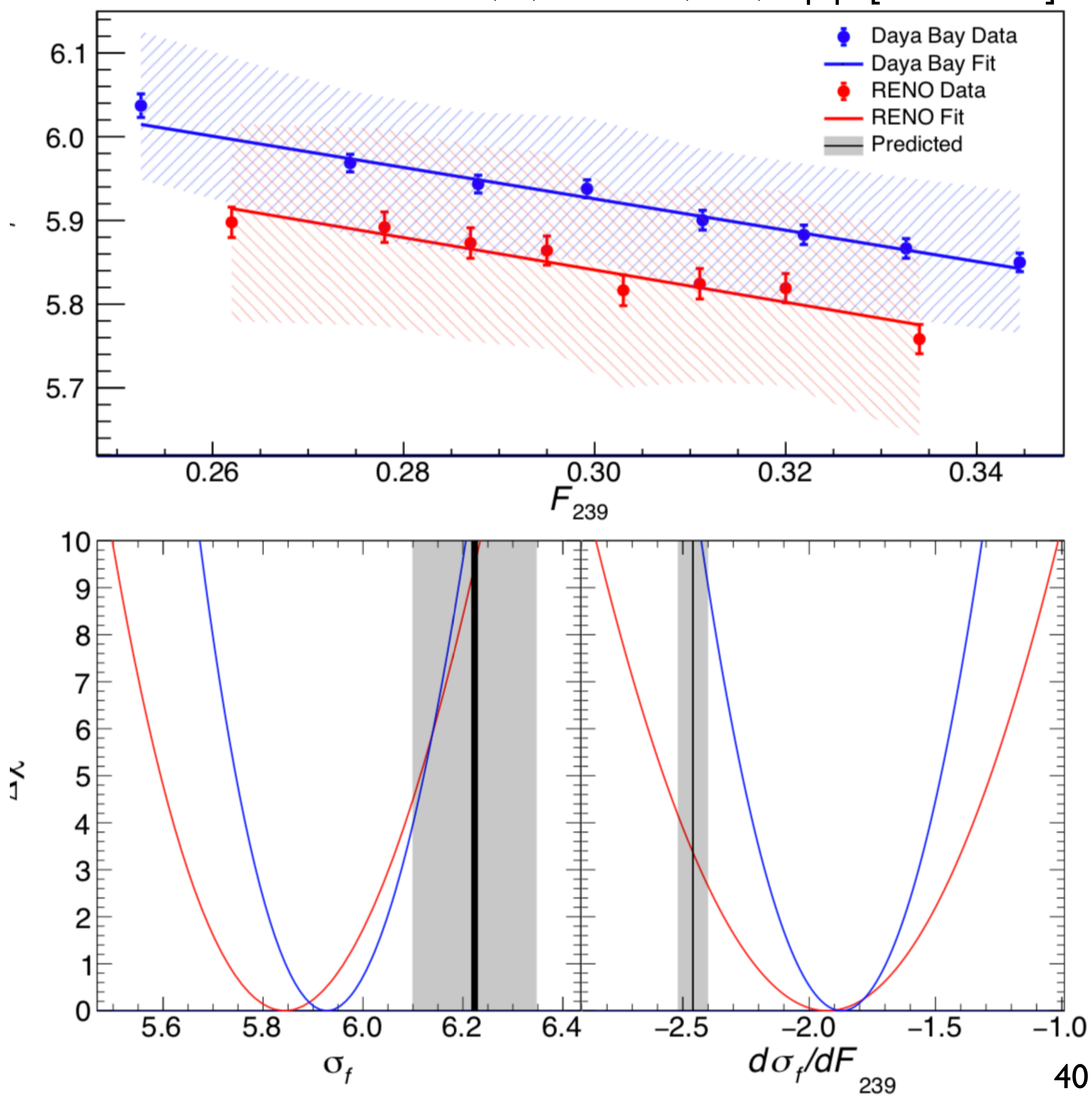


Testing Fluxes: RENO+DYB Evolution

- RENO sees similar behavior — flux evolution badly predicted
  - No-osc fits indicate ^{235}U prediction is too high.

Giunti, Li, Surukuchi, BRL, hep-ph[1901.01807]

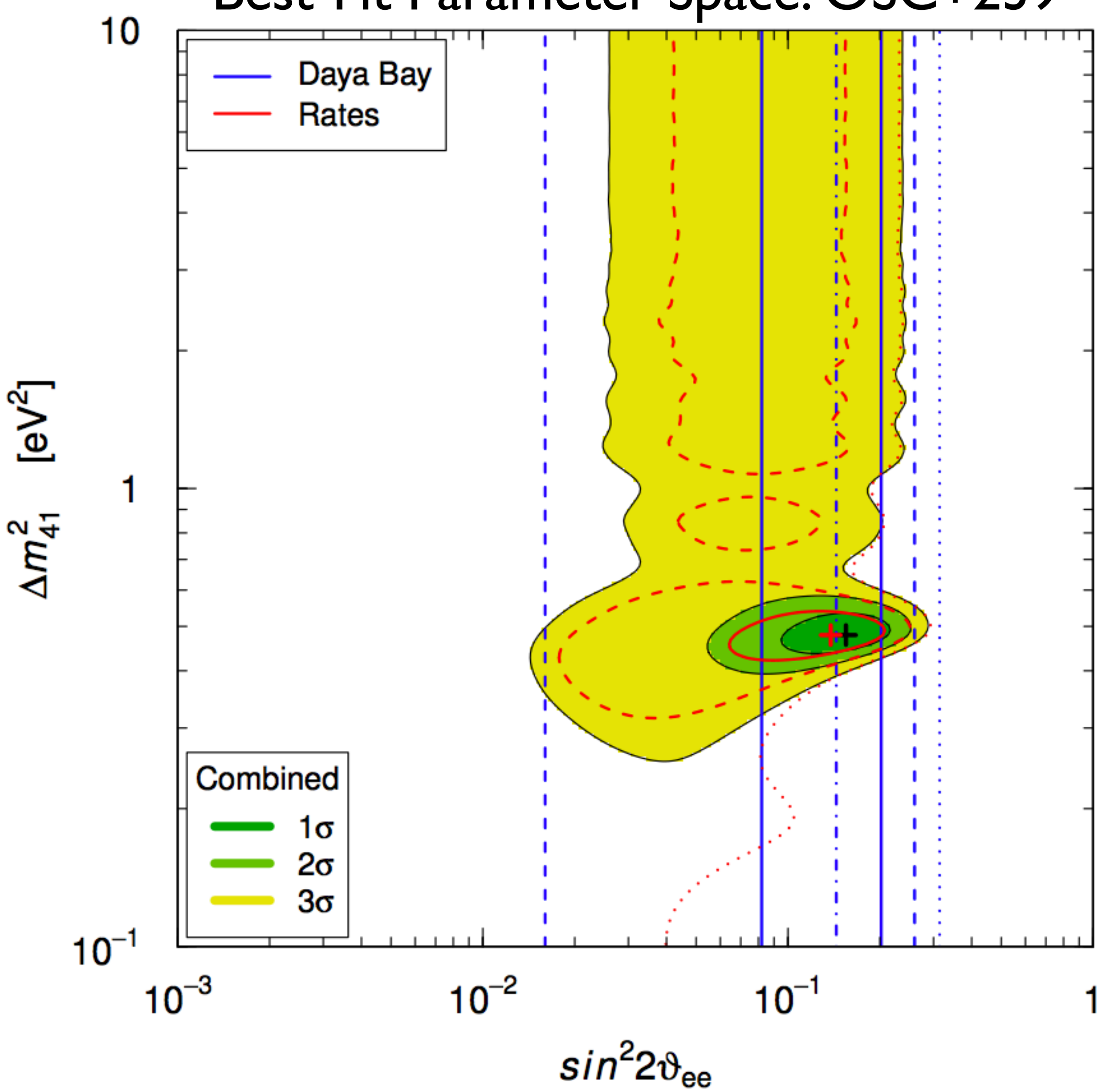




Global Flux Fits

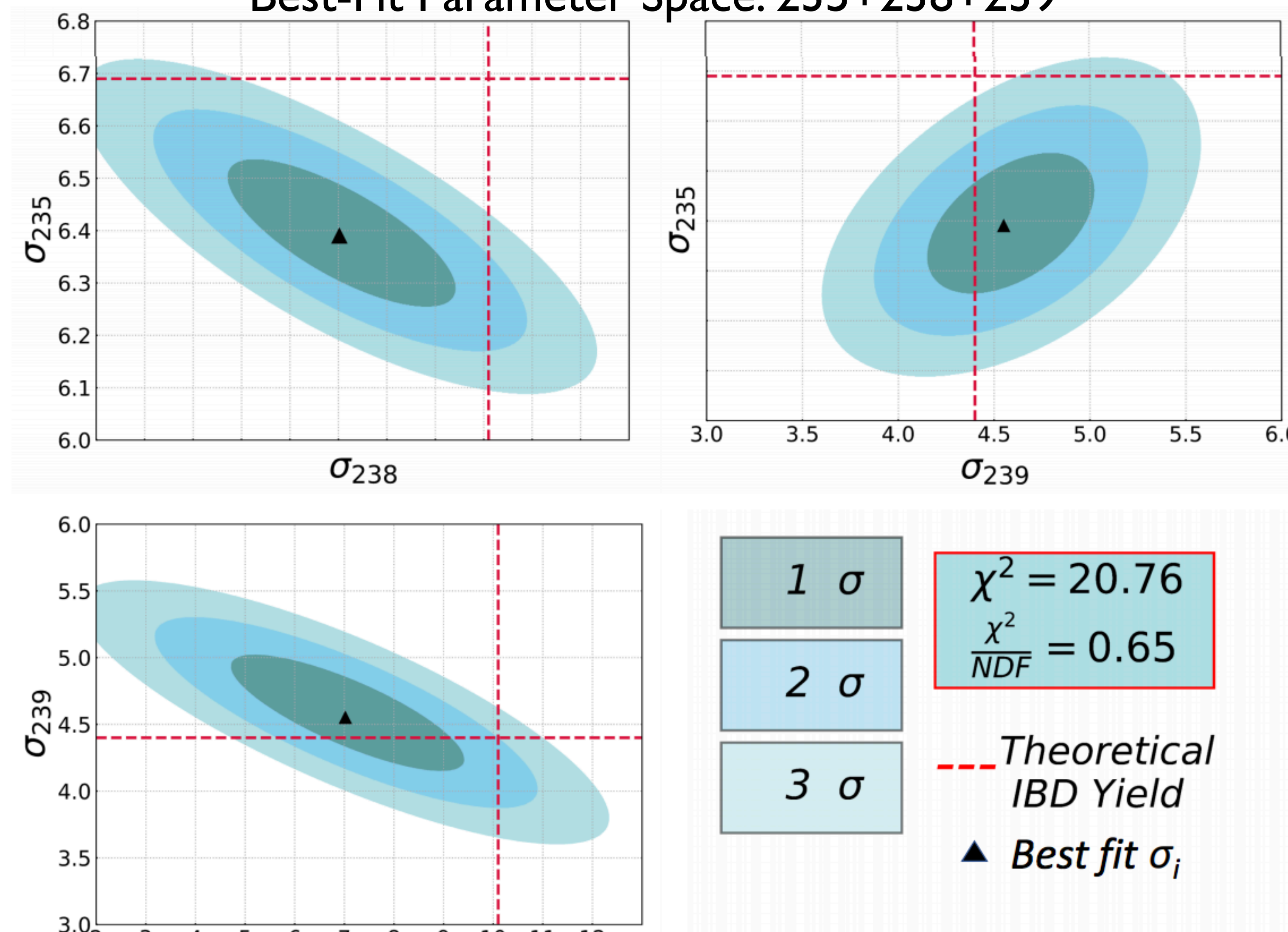
- What if we fit <u>ALL</u> global flux data: HEU, LEU, flux evolution?
  - No-Osc fits indicate ^{235}U <u>and</u> ^{238}U flux predictions are off!
  - 'Hybrid' models with both oscillations and incorrect fluxes also fit well
  - Q: Is older HEU data really reliable (<u>STEREO@Moriond</u> — A: Seems so!)
- Need more osc constraint, more fluxes to totally resolve this!

Best-Fit Parameter Space: OSC+239



Giunti, et al, JHEP 10:143 (2017)

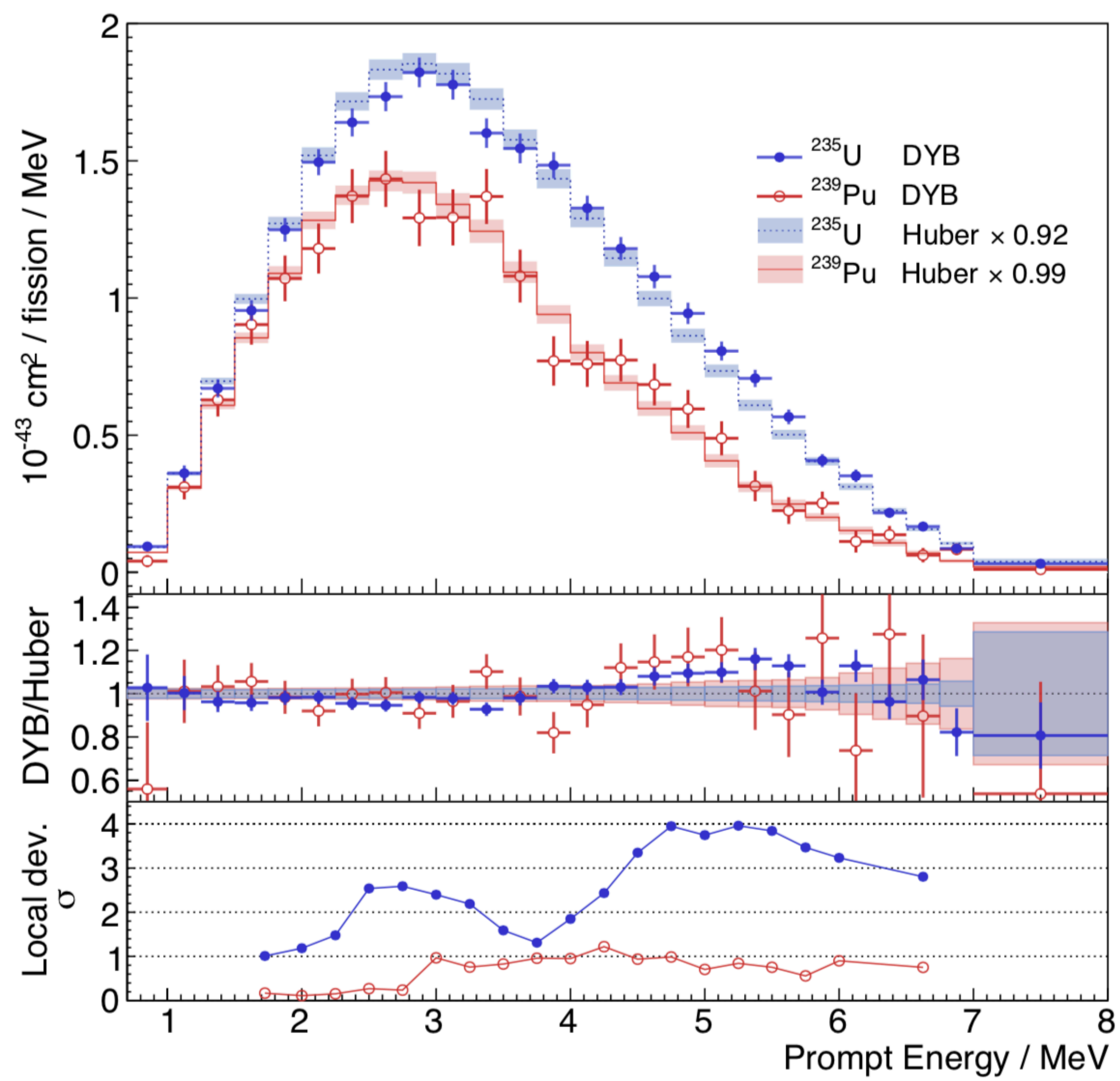
Best-Fit Parameter Space: 235+238+239



Gebre, BRL, Surukuchi, PRD 97 (2018)

Timeline 7: 2019

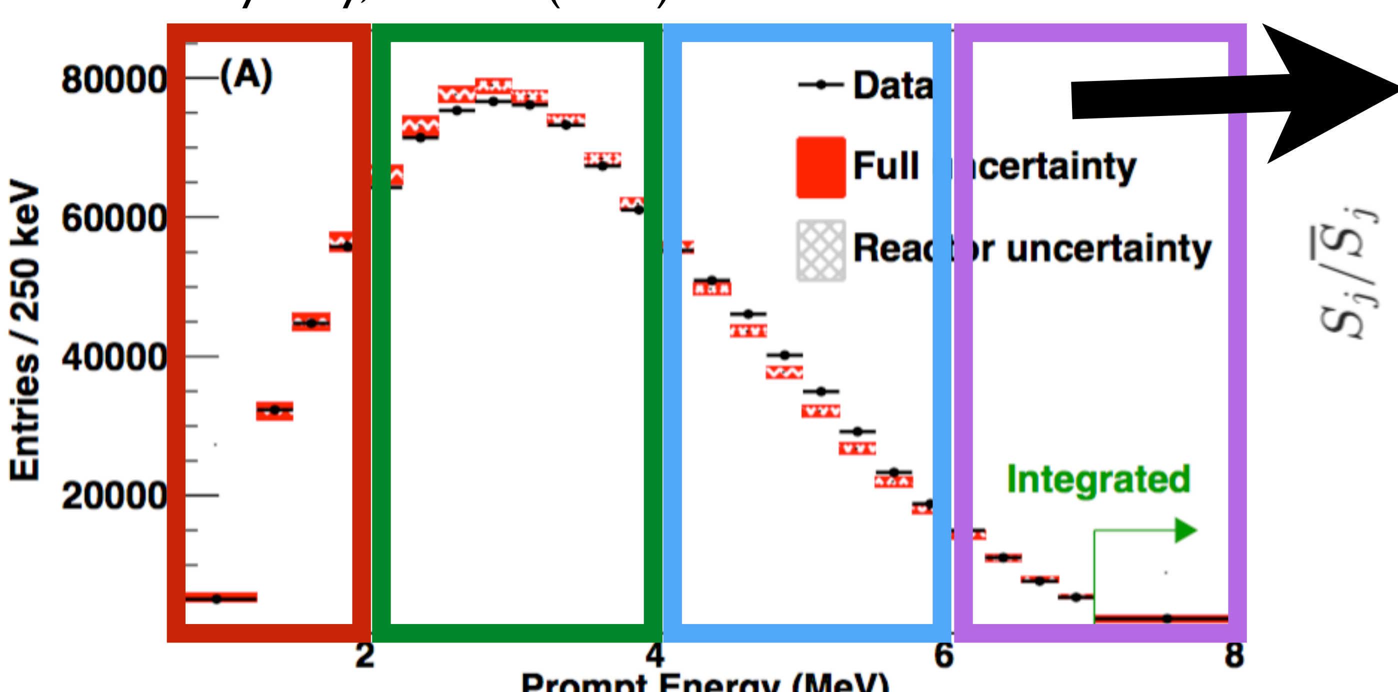
- New Daya Bay U235 and Pu239 measurement!
  - Forget 'where the bump comes from' — let's just measure the full spectra
- However, staying with the bump paradigm for a moment:
  - 'Equal contribution' 0.4sigma away from best-fit
  - 'No U235 bump' is 4.0sigma away from best-fit
  - 'No Pu239 bump' (i.e. 'mostly 235') is 1.2sigma away from best-fit

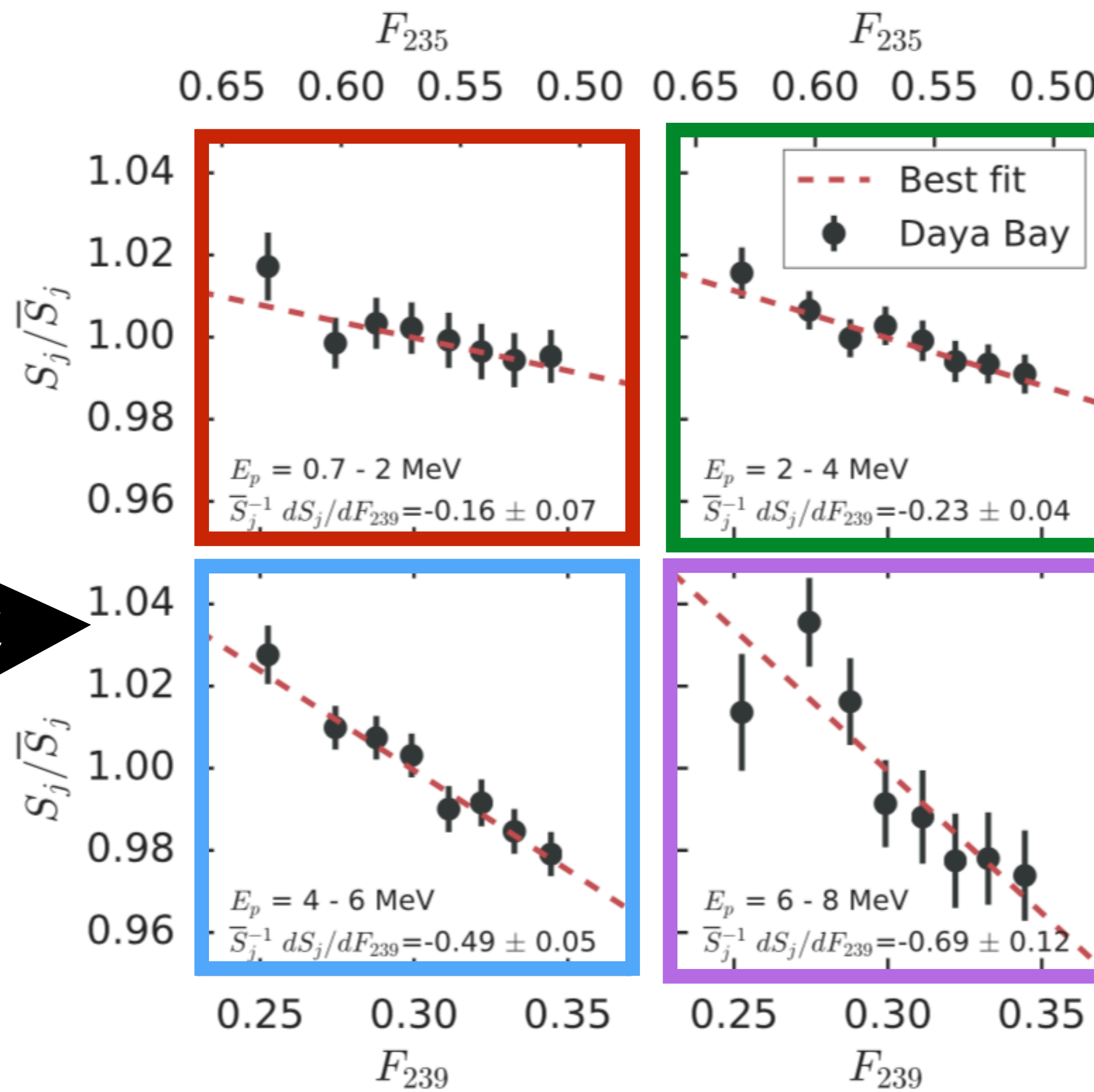


Isotopic Origins: Daya Bay

- Daya Bay approach: does bump size change with fuel content?
  - Would indicate if a single isotope is preferentially responsible for it

Daya Bay, CPC 41 (2017)



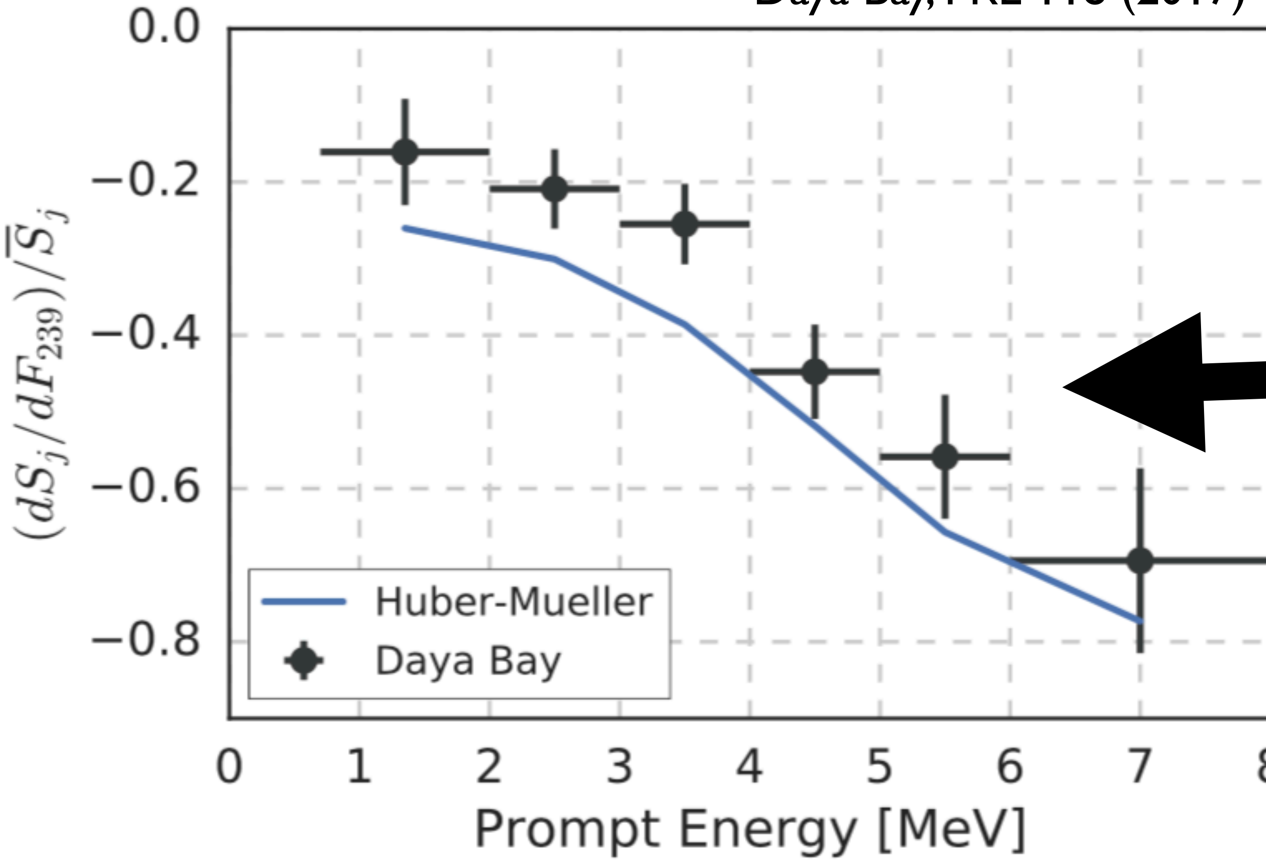


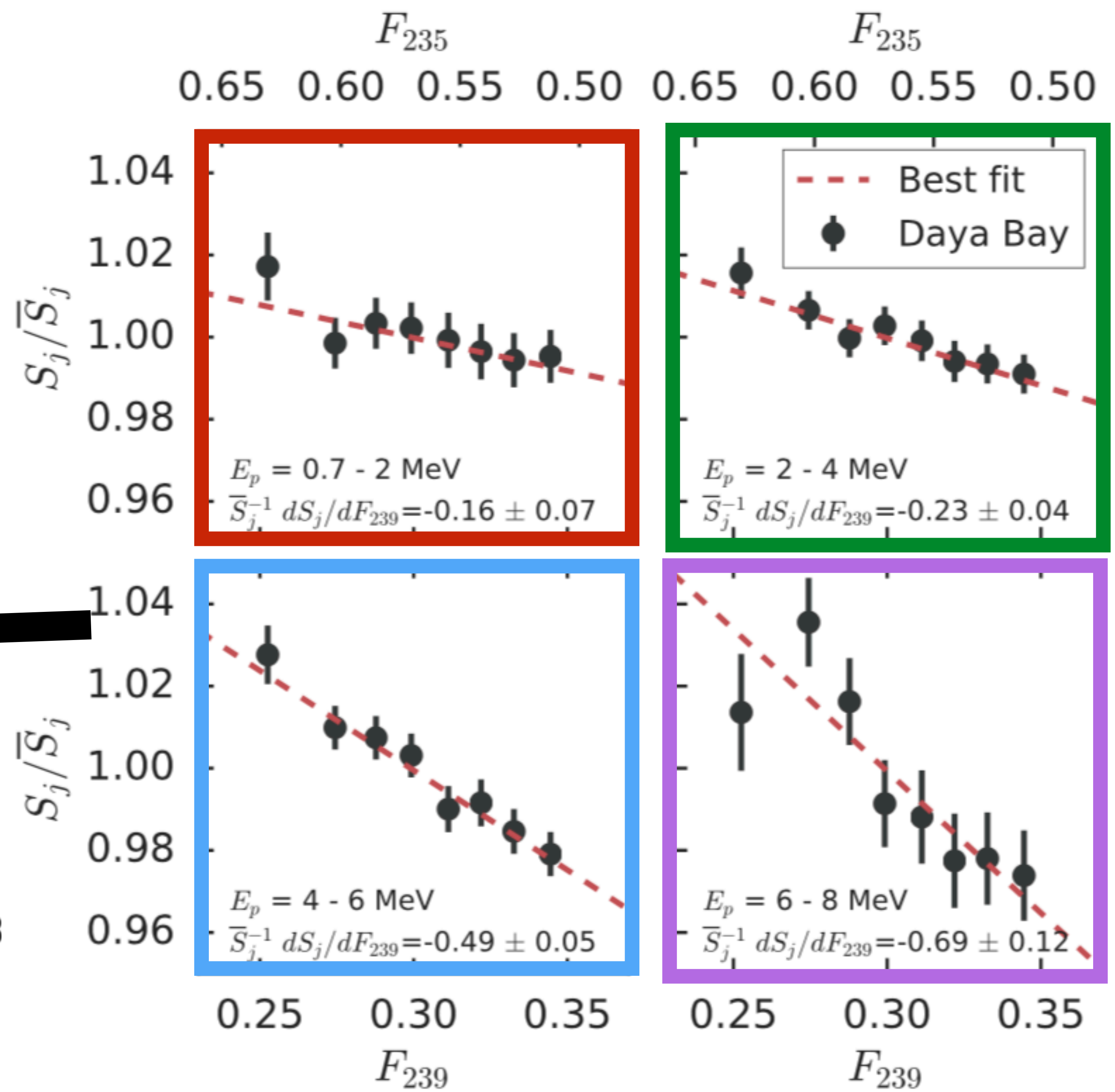
Daya Bay, PRL 118 (2017)

Isotopic Origins: Daya Bay

- Daya Bay approach: does bump size change with fuel content?
- Nothing uniquely odd happening in 4-6 MeV region…
  - Not enough statistics to draw a valuable conclusion, though

Daya Bay, PRL 118 (2017)





Daya Bay, PRL 118 (2017)

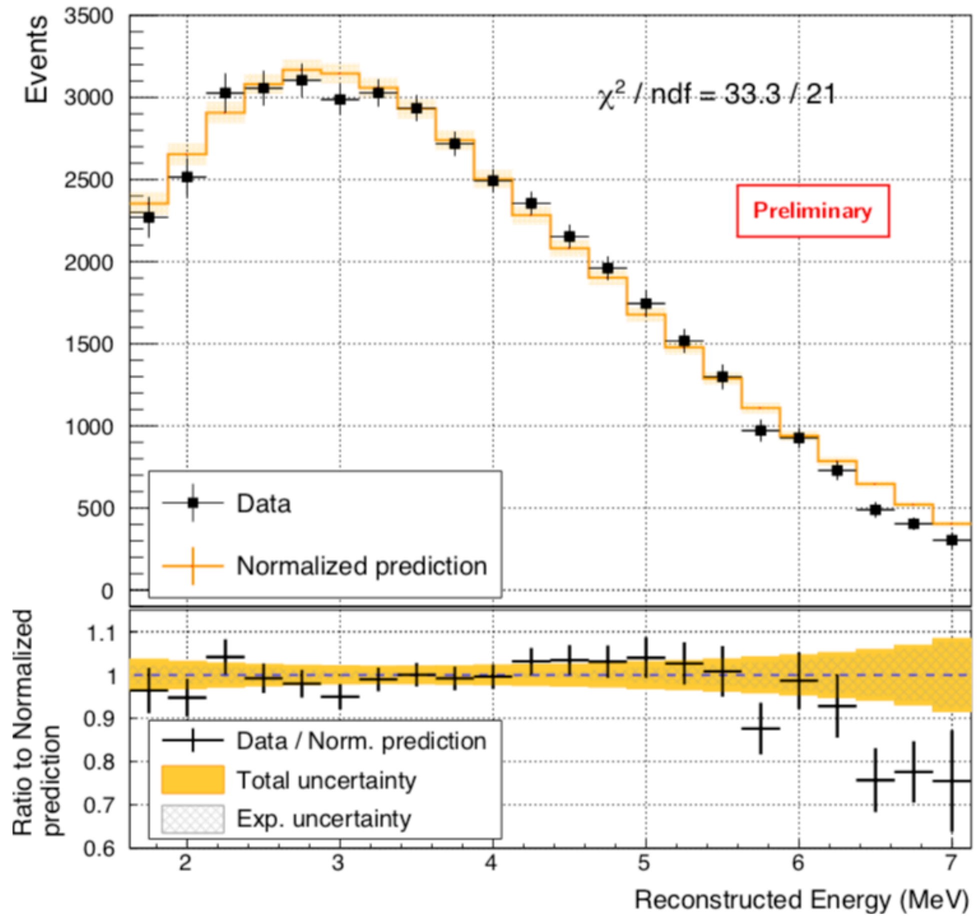
Experimental Recap

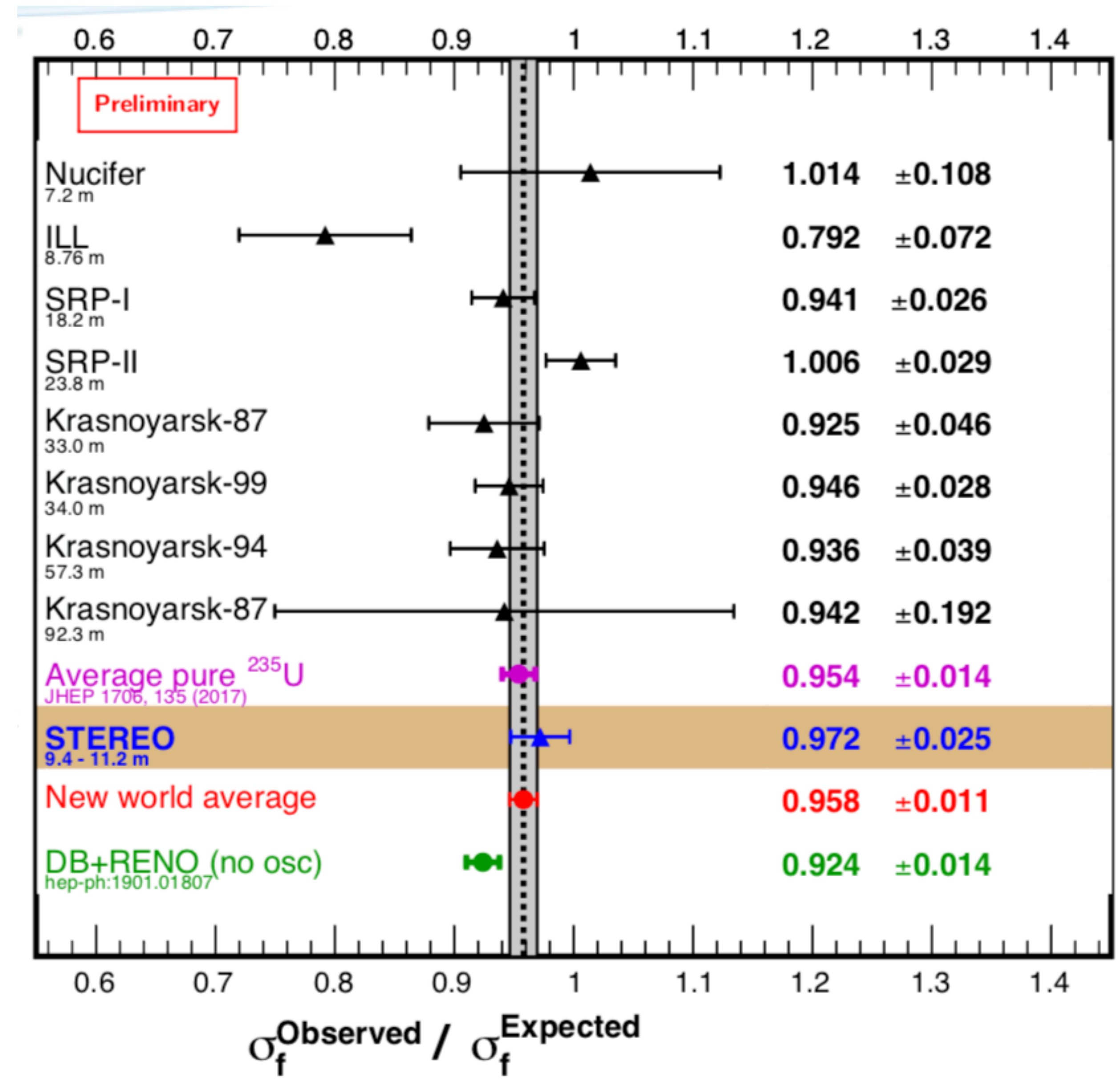
- Experimental studies trying to understand the nature of the spectrum data-prediction disagreement have formulated their research question as: 'Which isotopes produce the bump?'
- Studies weighing in so far (note - I'm oversimplifying, obs…)

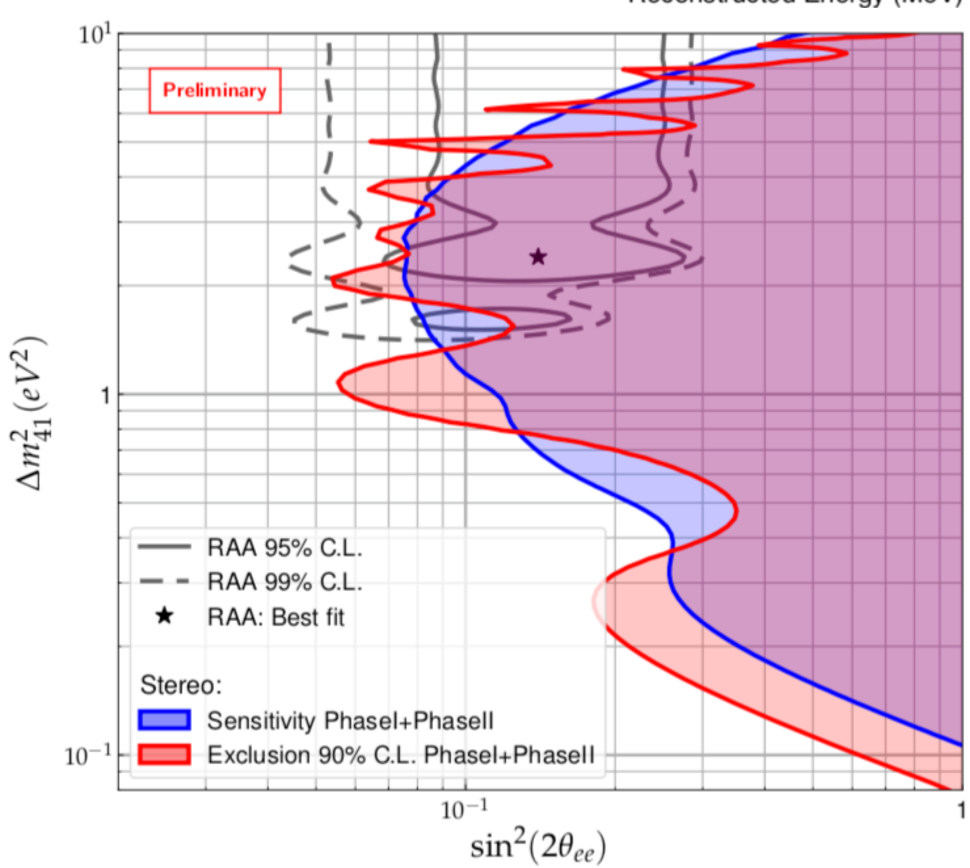
Study	~Only 235 (~No 239 bump)	Equal	No 235 bump (~Pu only)
Huber (w/ NEOS+DYB)	**OK**	**OK**	**NO**
DYB	**OK**	**OK**	**NO**
RENO	**OK**	**NO**	**NO**
PROSPECT	**NO**	**~OK**	**~OK**

- All datasets are ~compatible with a bump of some kind existing in HM
- No single hypothesis is compatible with all claims; 'Equal' would be a good hypothesis, if not for RENO's (questionable?) result

New STEREO Results at Moriond19





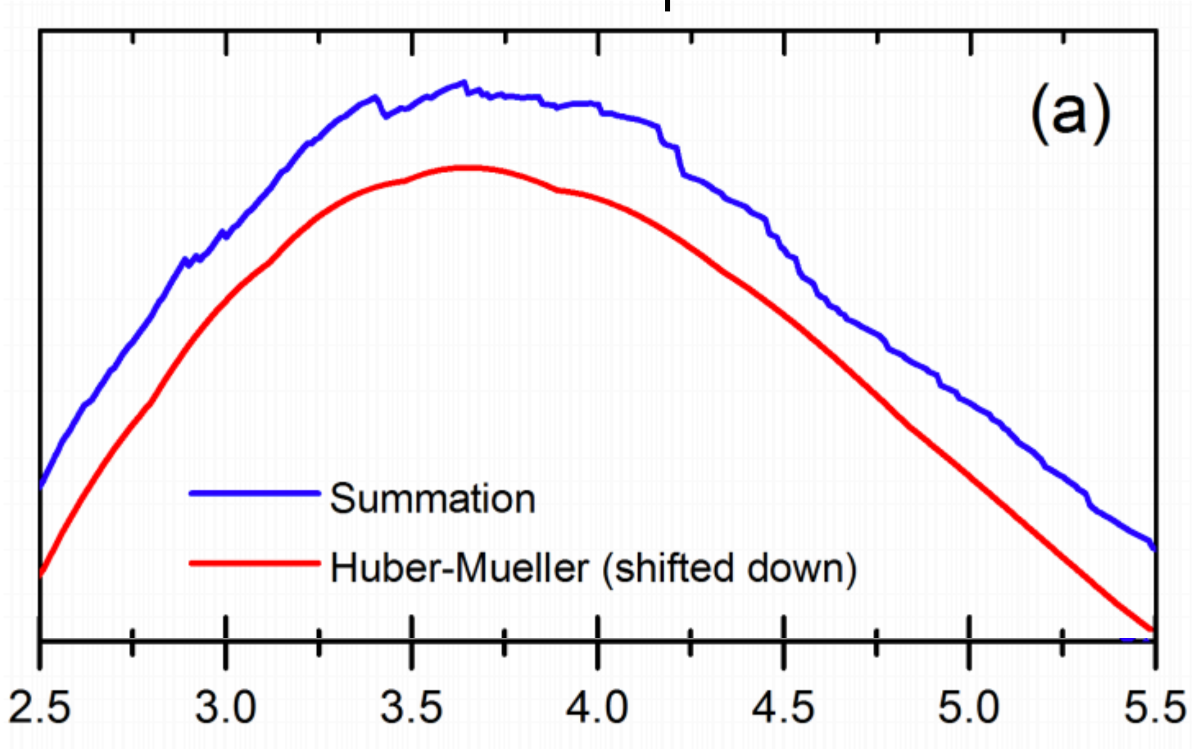


- Wow! Nice!
- Interested to see closer comparisons to PROSPECT, global fluxes, θ_{13} experiments

Fine Structure: A Problem For JUNO?

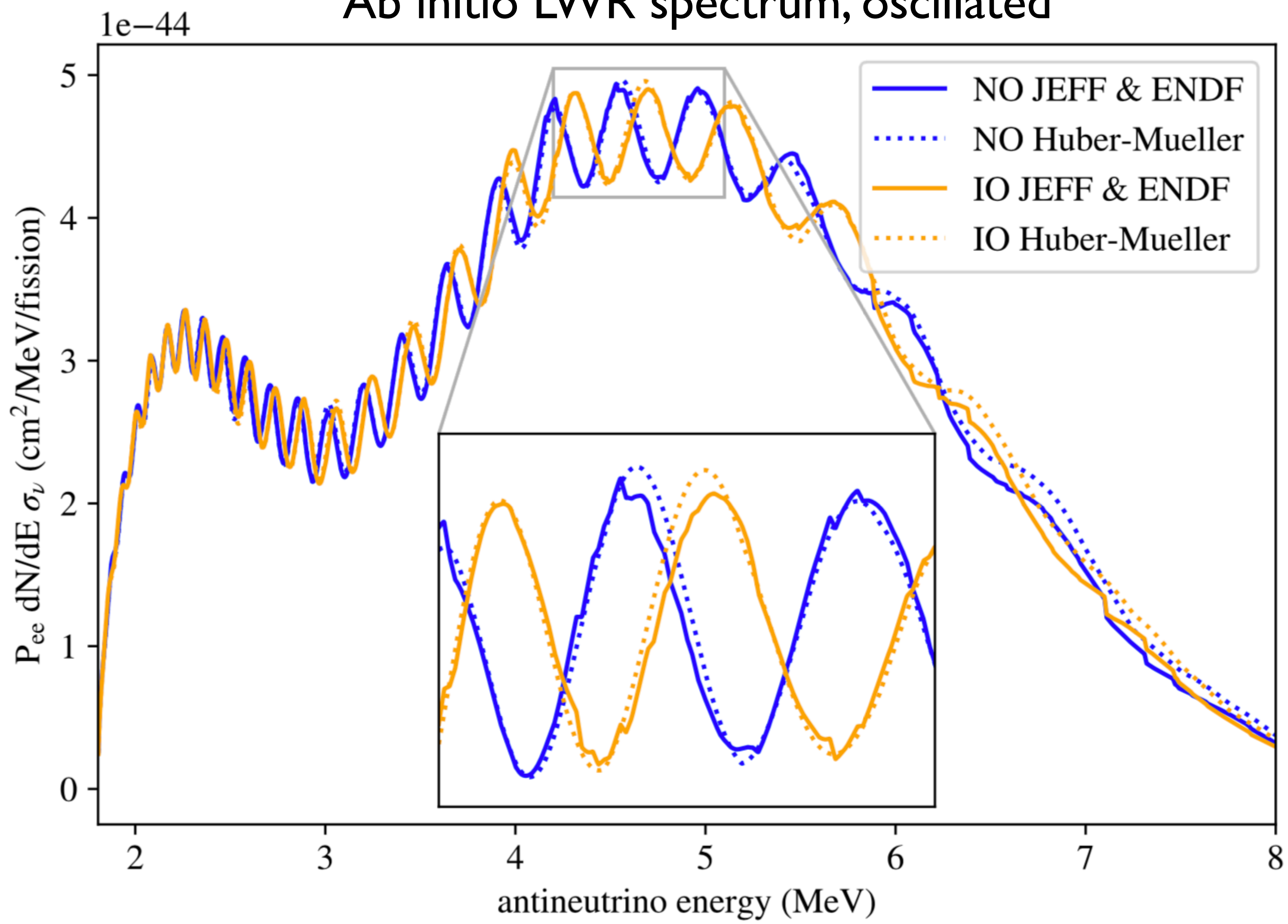
- Another ill-defined aspect of spectrum: fine structure
  - Arises from endpoints of individual beta branches in aggregate spectrum
  - Do fine structure wiggles obscure wiggle frequency from oscillations, and thus mass hierarchy measurements at reactors?

Ab initio LWR spectrum



Sonzogni et al, PRC 98 (2018)

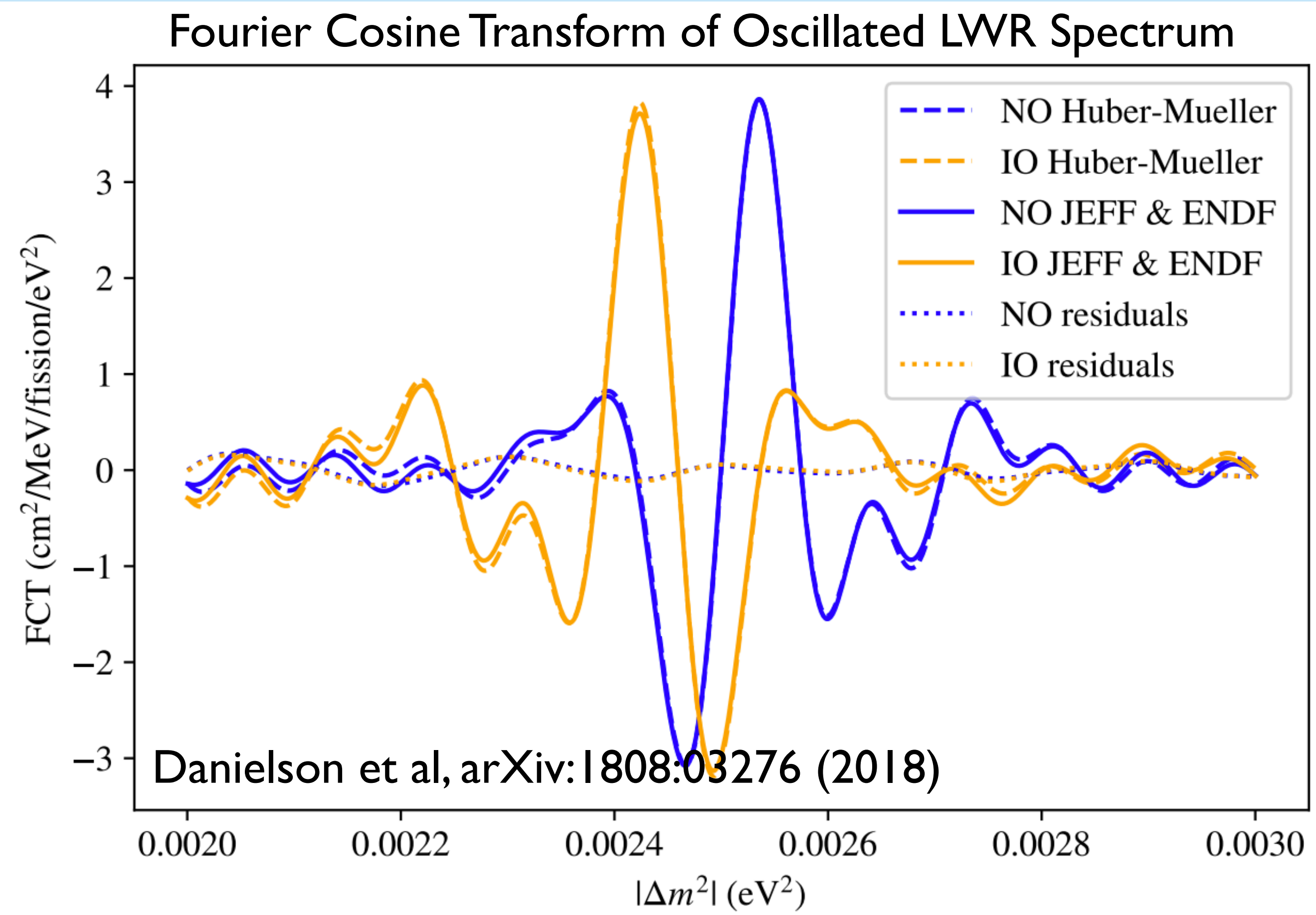
Ab initio LWR spectrum, oscillated



Danielson et al, arXiv:1808:03276 (2018)

Fine Structure: A Problem For JUNO?

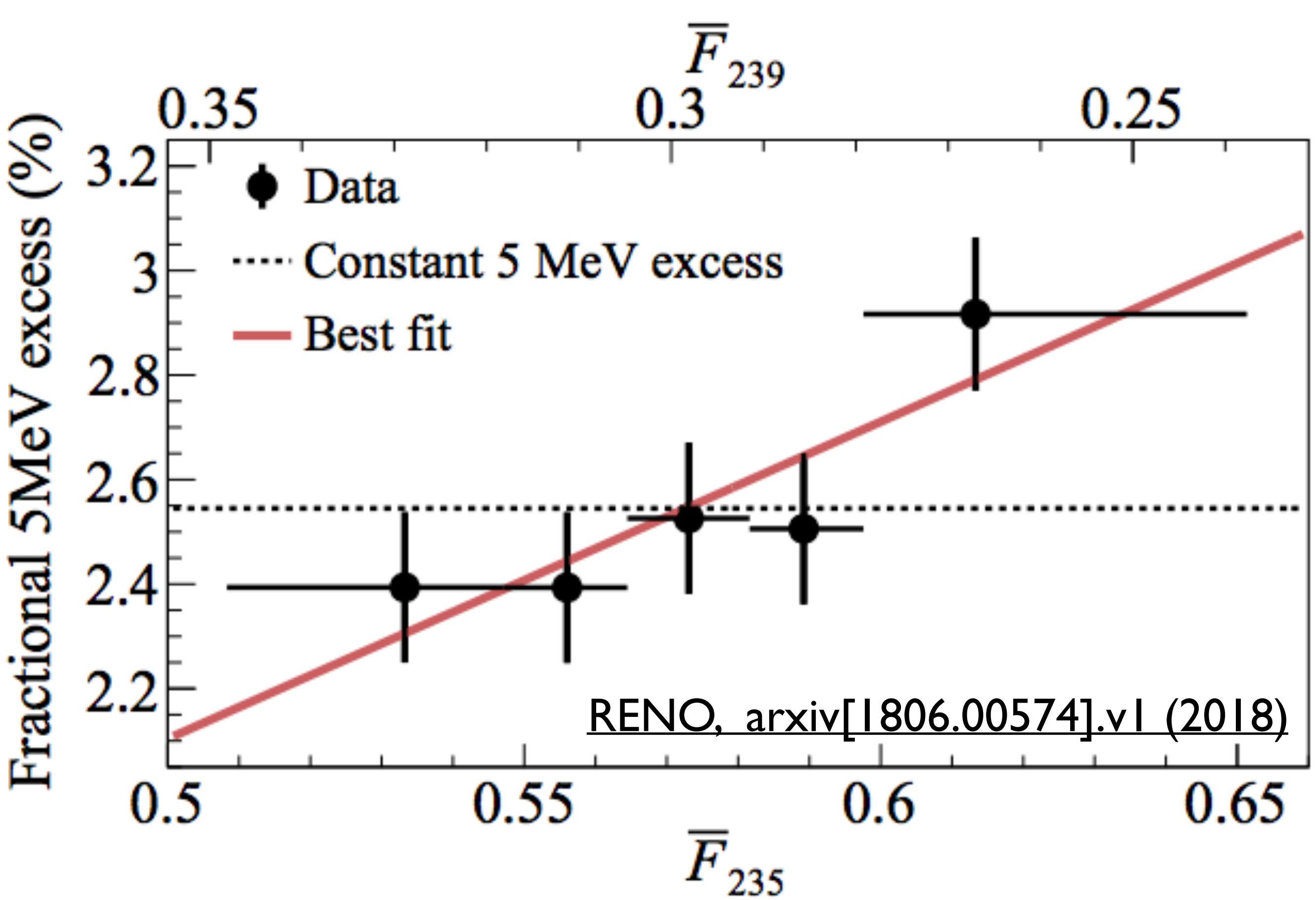
- Nuclear theorists: fine structure features are too small to affect the mass hierarchy measurement.
  - Demonstrated using a Fourier decomposition approach
- Some discussion appears to continue in community?
  - ‘Fourier decomposition not used by JUNO…’
  - ‘One specific energy range matters for hierarchy; what’s fine structure like there?’



- Some discussion of dedicated fine structure measurements
  - Need a high-resolution detector (better than JUNO)
  - Need a high-statistics measurement (ideally much more than JUNO)
  - DYB and PROSPECT could provide some info on fine structure; optimized, dedicated detector would more precisely nail down fine structure

Isotopic Origins: RENO

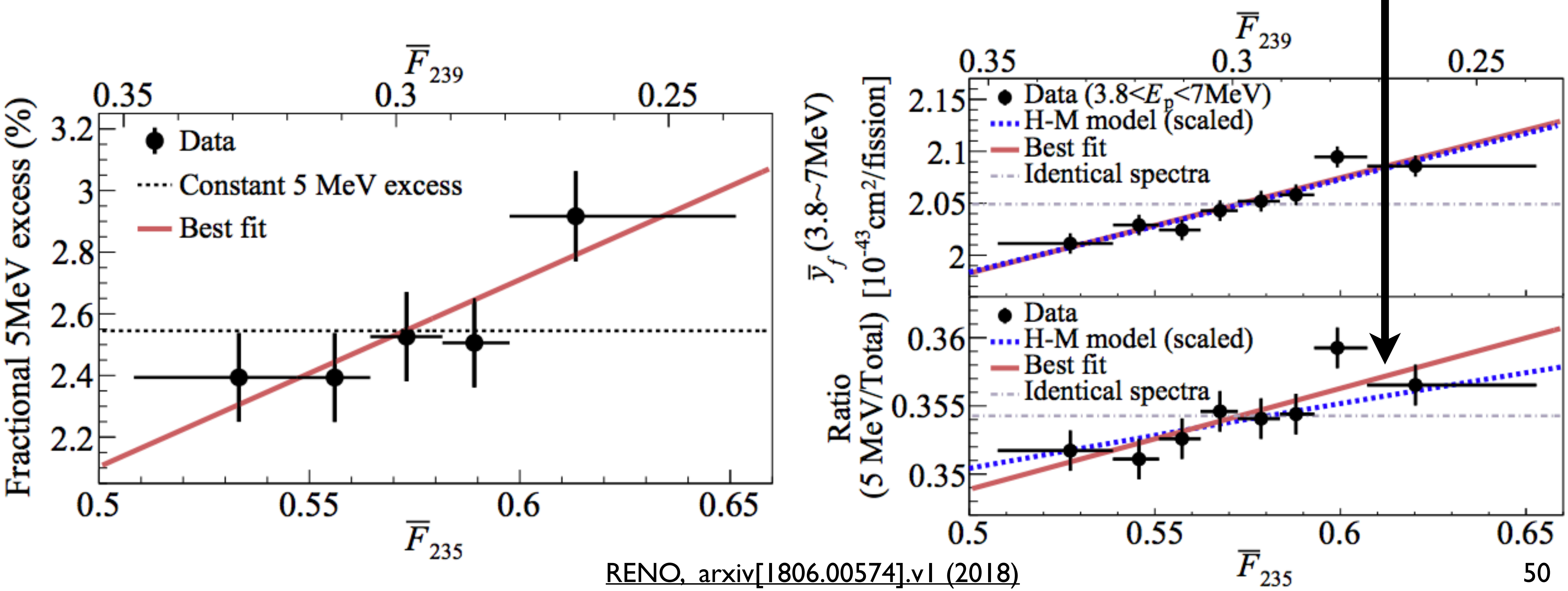
- Similar analysis at RENO: does bump change with fuel content?
  - Claim ~2.9σ indication of increasing bump size with increased ^{235}U burning



RENO, arxiv[1806.00574].v1 (2018)

Isotopic Origins: RENO

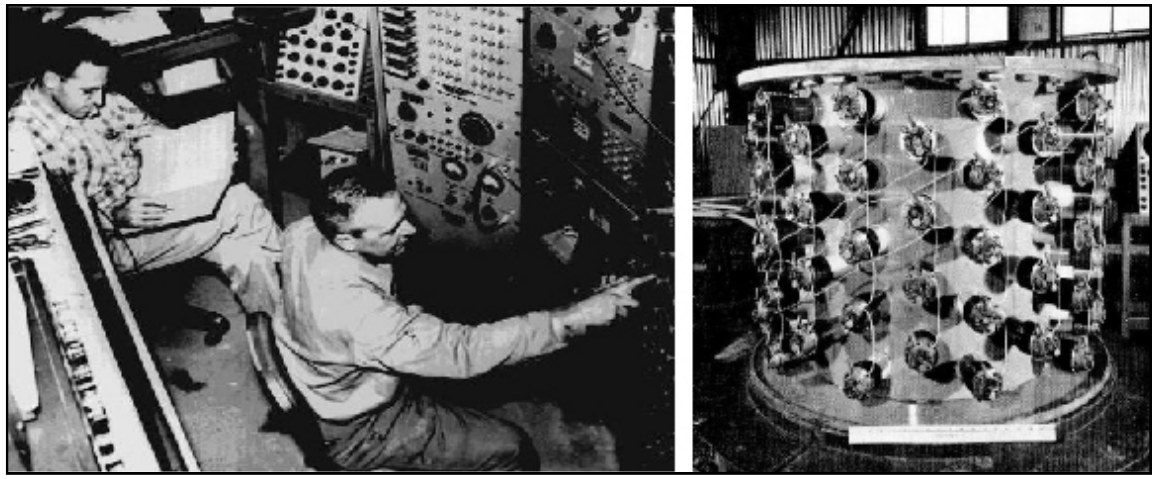
- Similar analysis at RENO: does bump change with fuel content?
  - Claim ~2.9σ indication of increasing bump size with increased ^{235}U burning
  - Ask a meddling experimentalist competitor:
    - Why does RENO have statistical capabilities to say something meaningful, while DYB doesn't?
    - Similar 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?



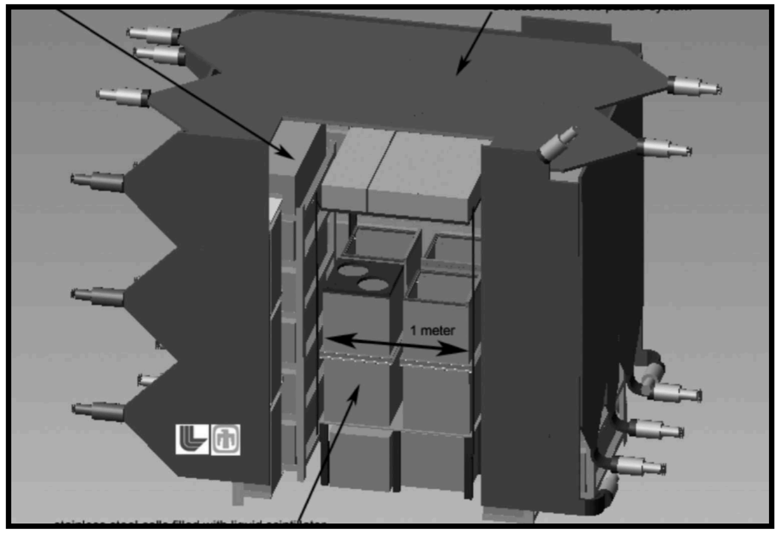
RENO, arxiv[1806.00574].v1 (2018)

Reactor Neutrino Monitoring Advances

- Last few decades have brought major advances in realized tech:

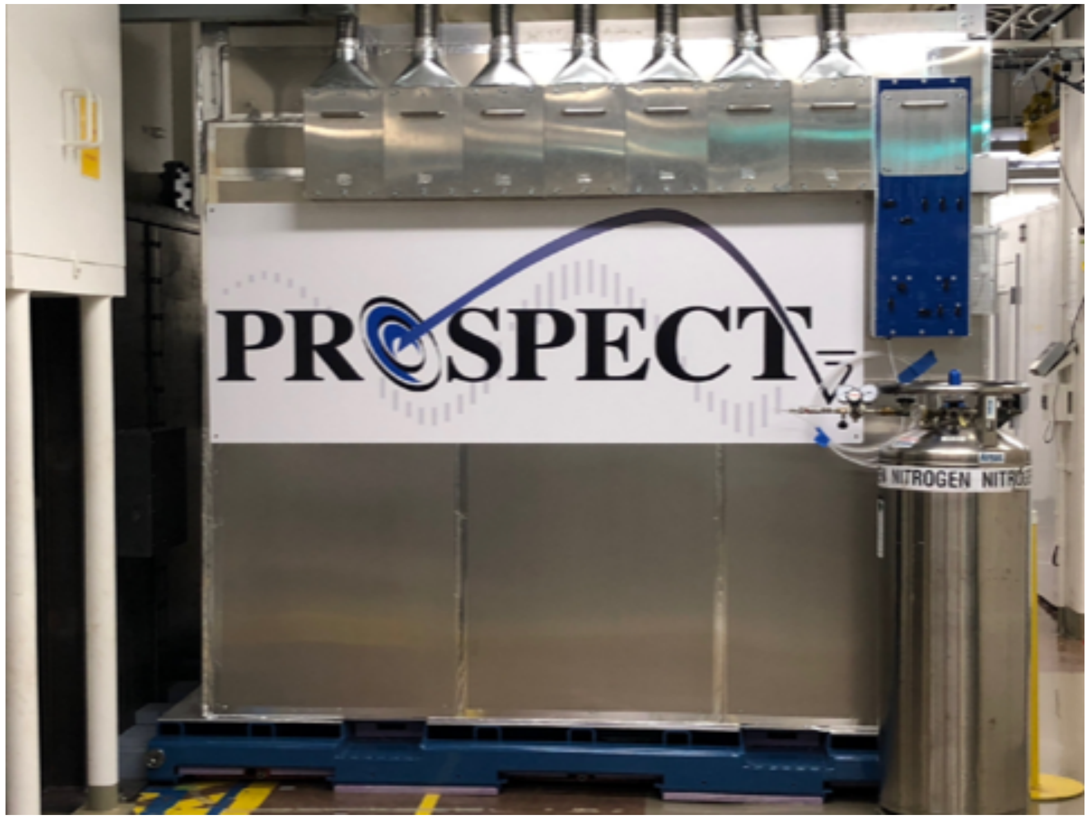


1950s: First Detection; ~1000 counts in 1 month;
5 background counts per 1 antineutrino count (S:B 1:5)



2000s: SONGS: ~230 counts per day, 25:1 S:B, but must be underground. 'semi-safe' detector liquid

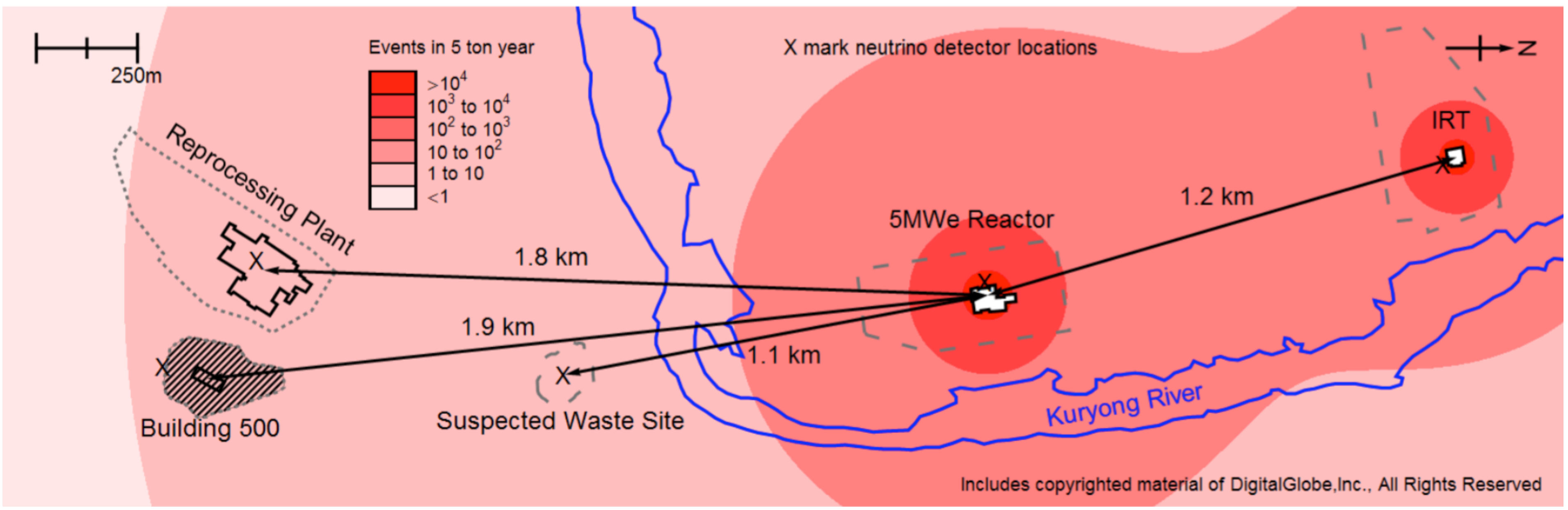
1980s: Bugey: ~1000 counts per day, S:B 10:1, but only underground. flammable/corrosive solvent detector liquids

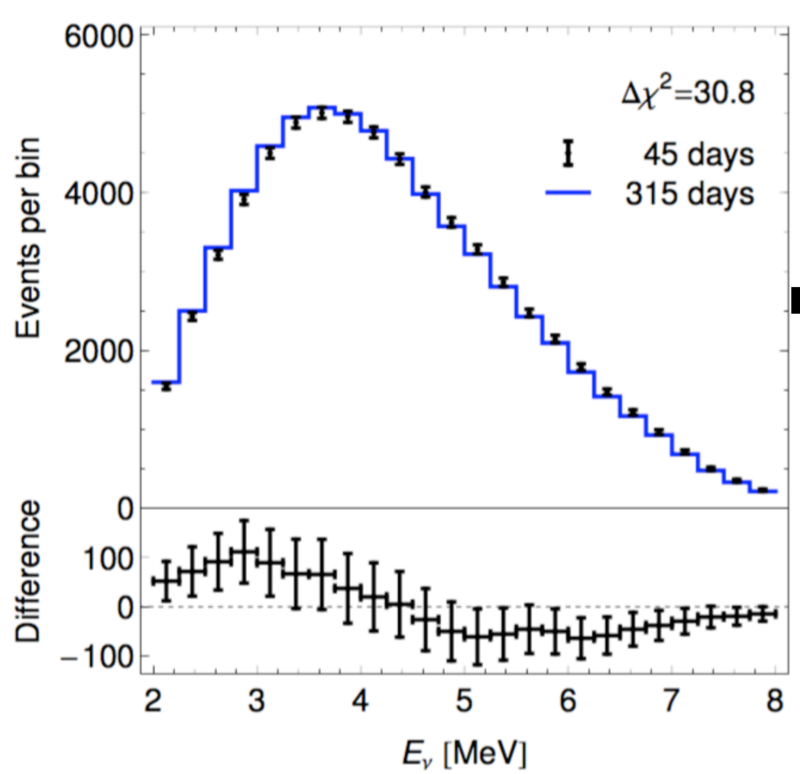


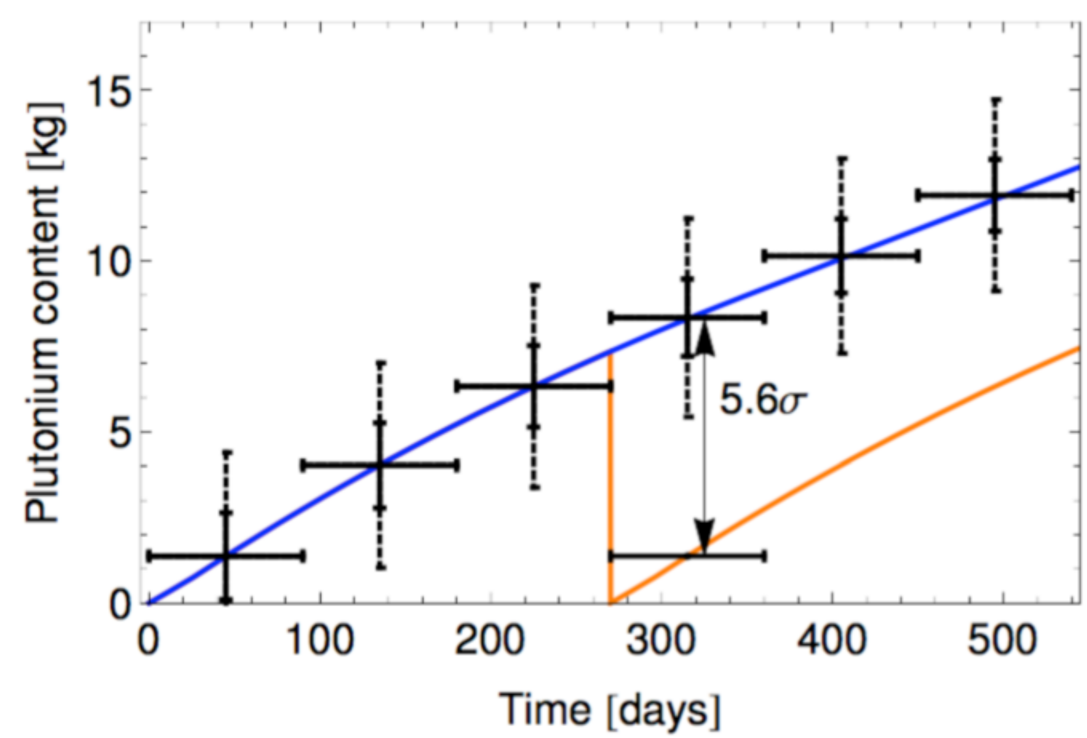
NOW: PROSPECT detector: ~750/day from only 80MW reactor, S:B 1:1 on surface, 'safe' plug-n-play detector

Spectrum Measurement Applications

- **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

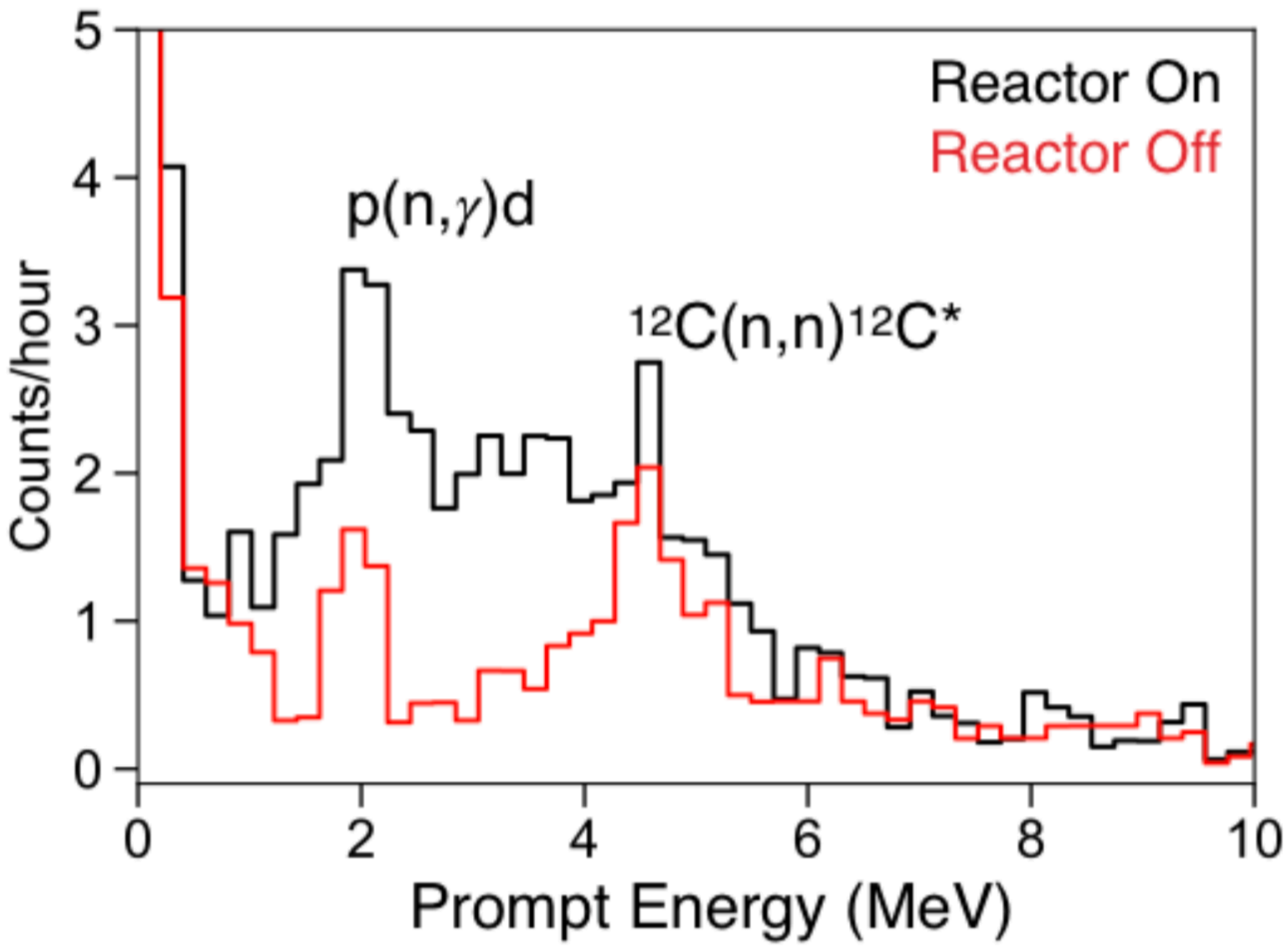


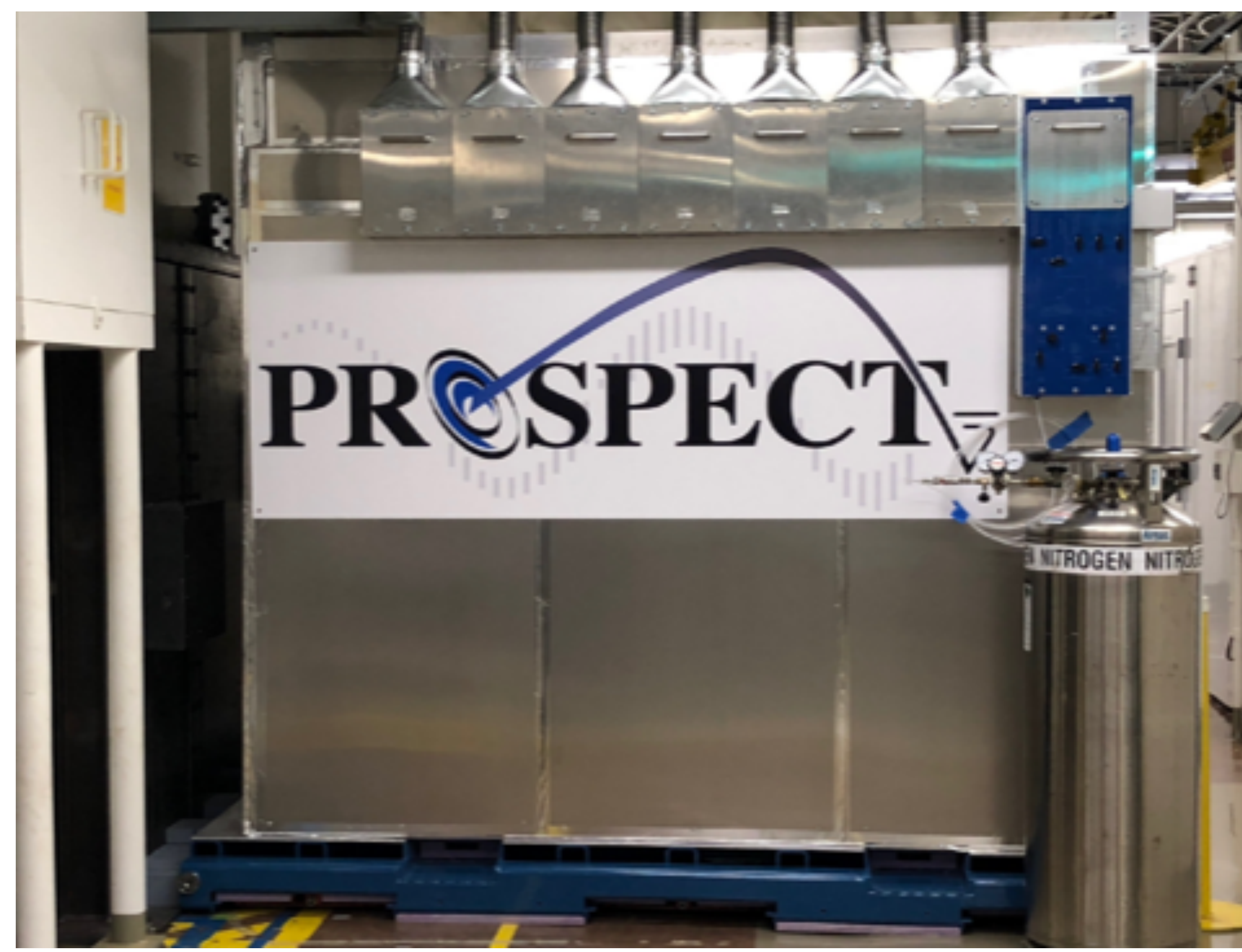




Flux Measurement Applications

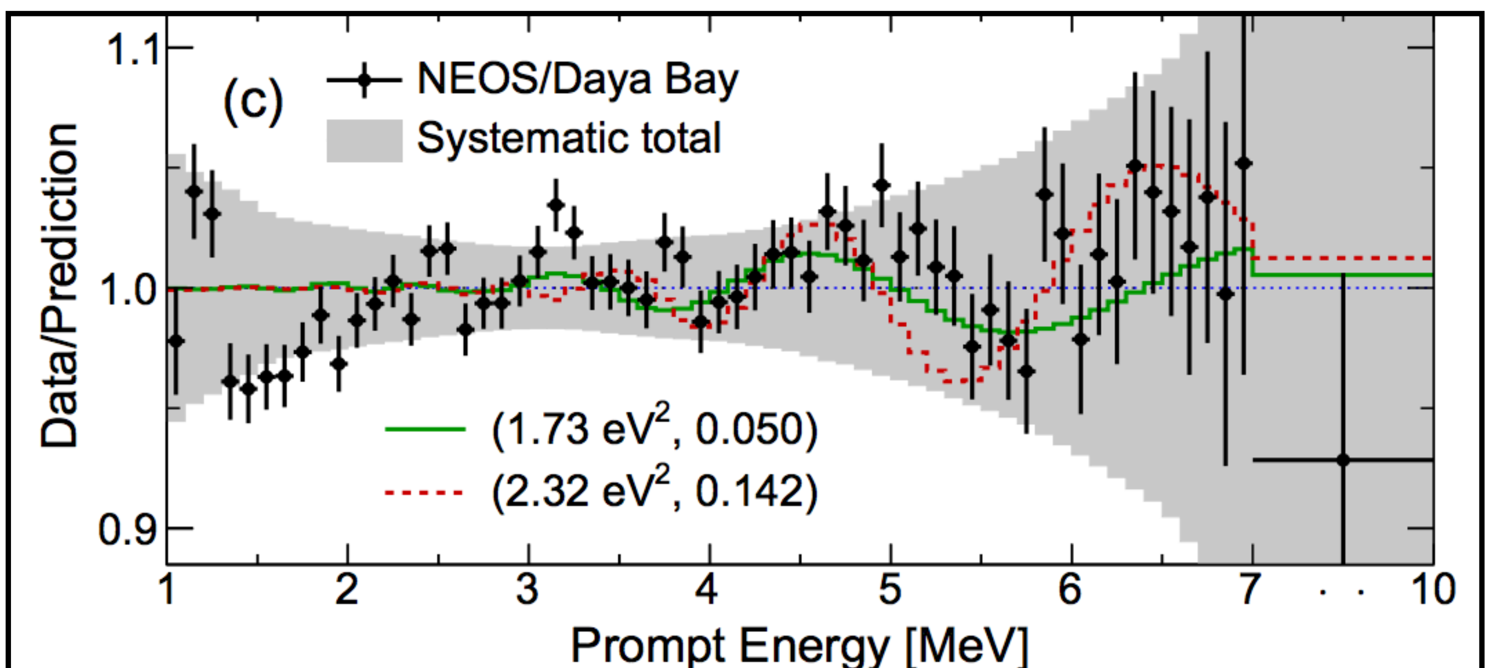
- Can perform ex-situ reactor power monitoring with compact inverse beta decay detectors
- May be helpful for specialized reactors (sodium-cooled, high-pressure gas-cooled), etc.
- We now have tech for doing this on-surface (PROSPECT)

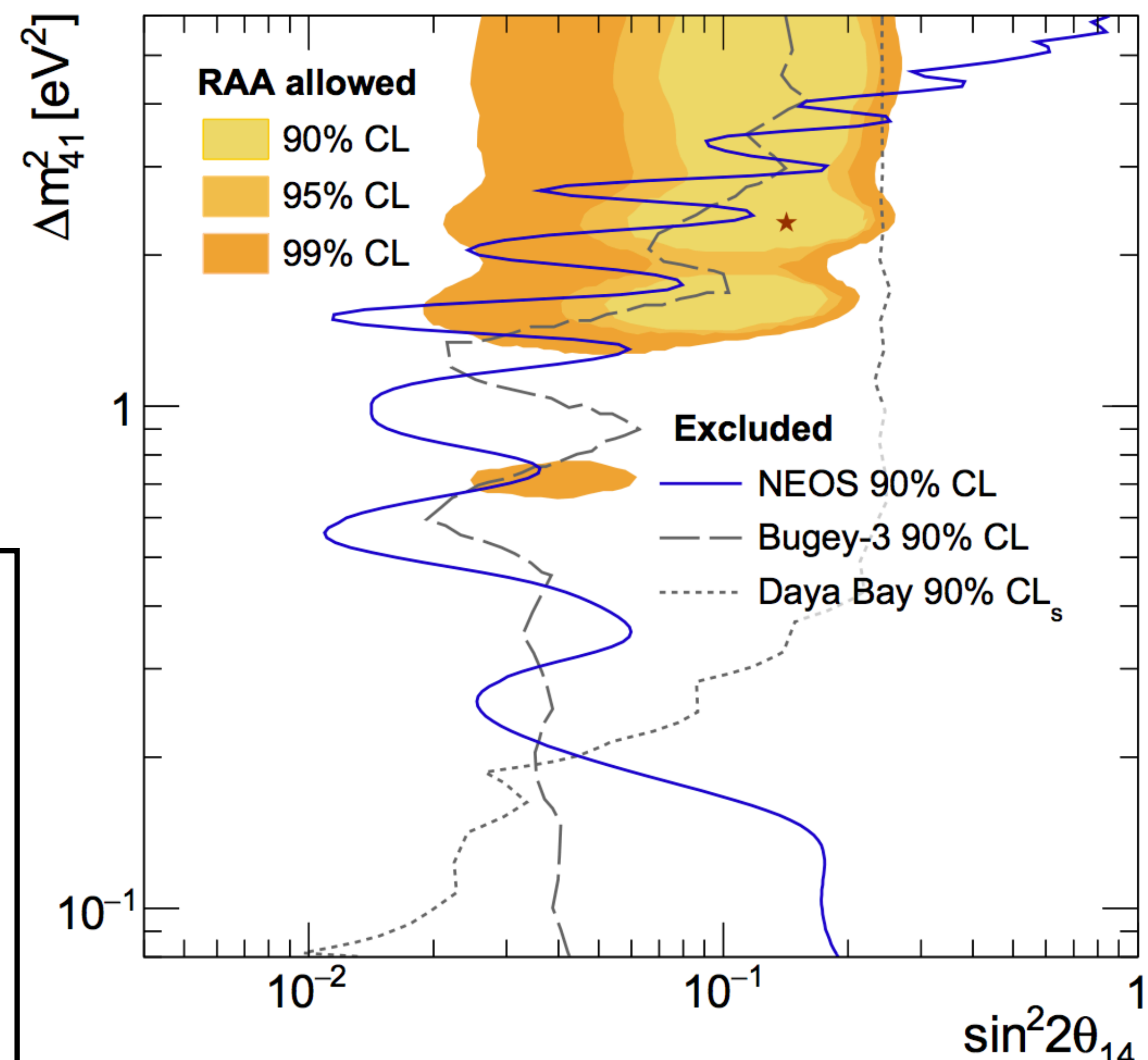




Testing Steriles: NEOS

- 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



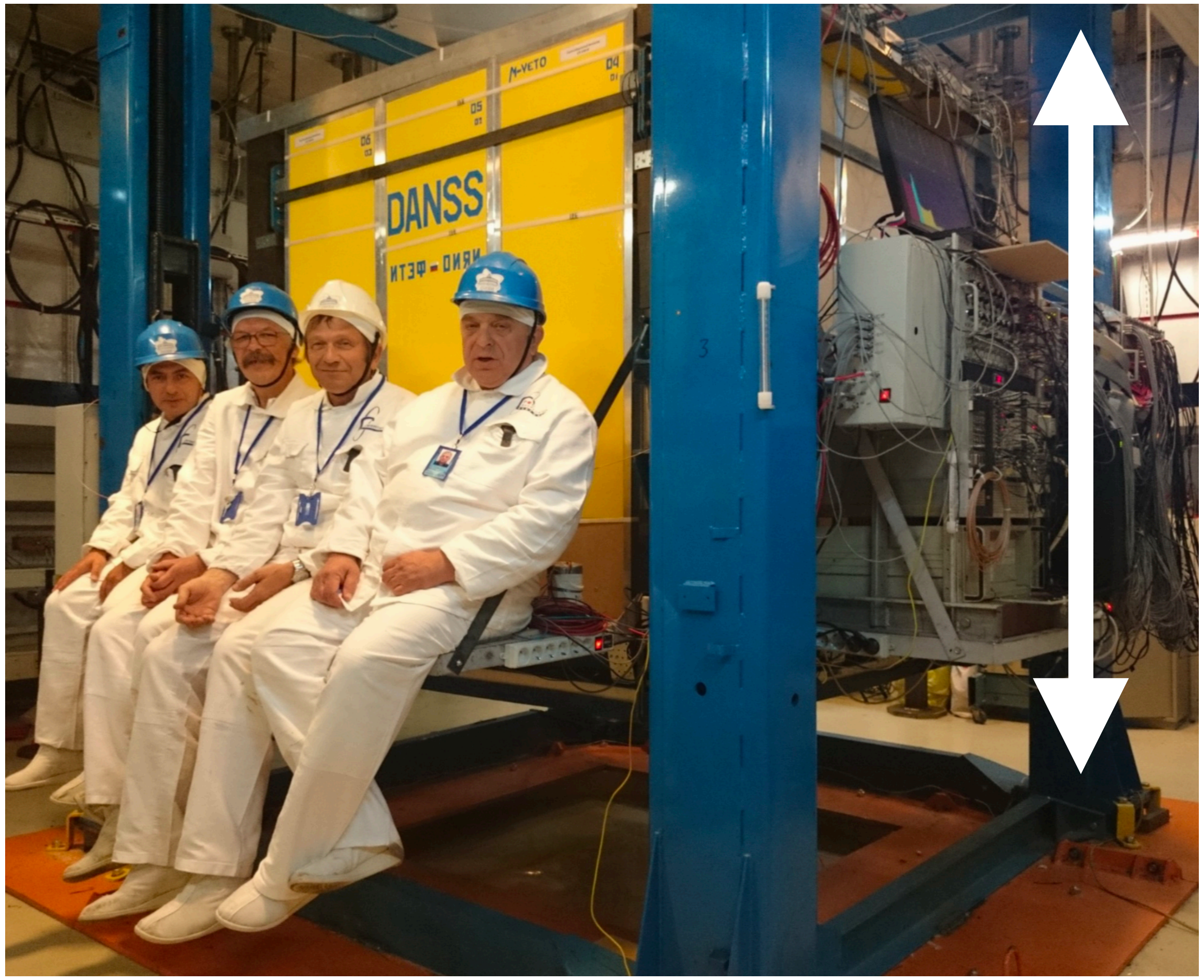


NEOS, PRL 121 (2016)

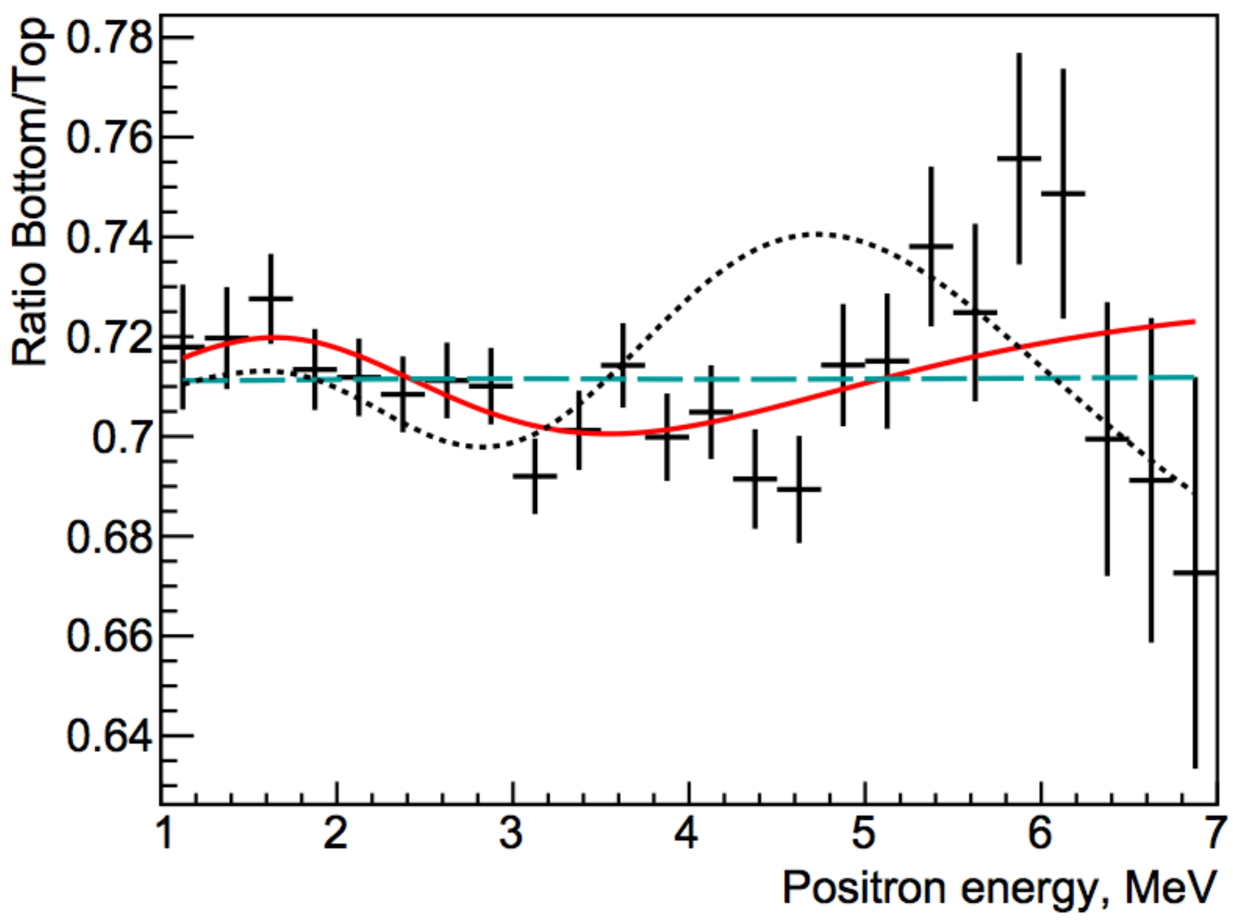
DANSS

- 2018: Compare spectra between the same detector deployed at two different baselines (10.7m and 12.7m)
  - Commercial 3m-length reactor — 5000 events per day! Awesome!
  - Have presented relative spectra between locations

Reactor up here ↑

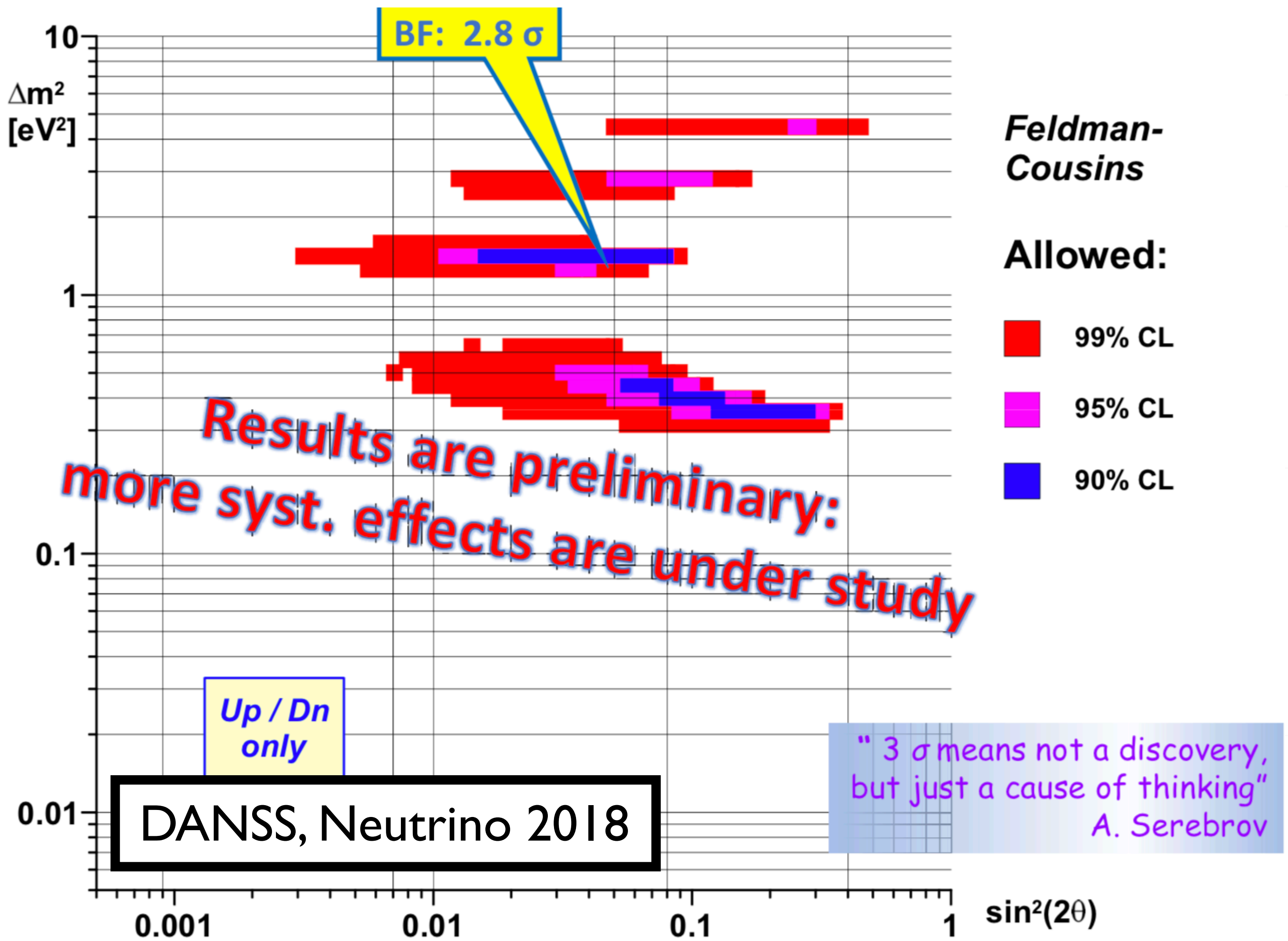


DANSS, PLB 787 (2018)

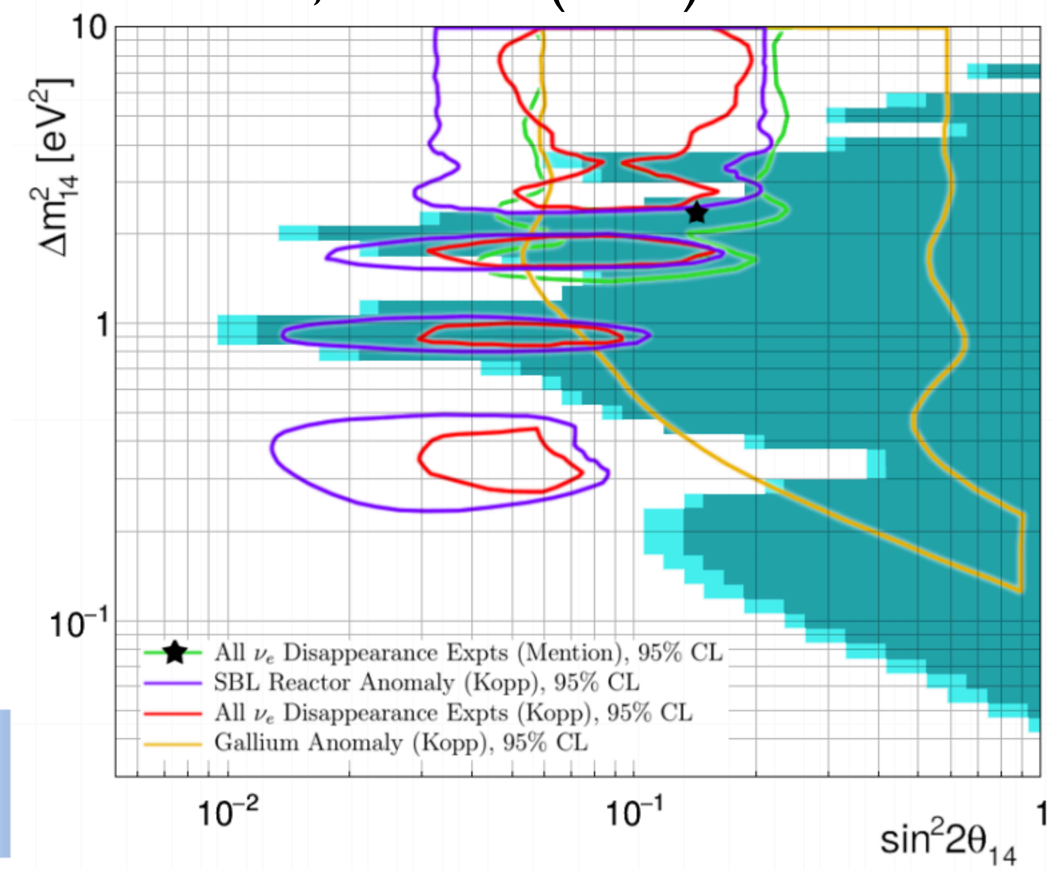


DANSS

- 2018: Compare spectra between the same detector deployed at two different baselines (10.7m and 12.7m)
  - Published results (Phys Left B): no steriles yet
  - Neutrino 2018: showed 3σ allowed region; not sure what to make of this
  - Statements about some systematics still needing to be investigated

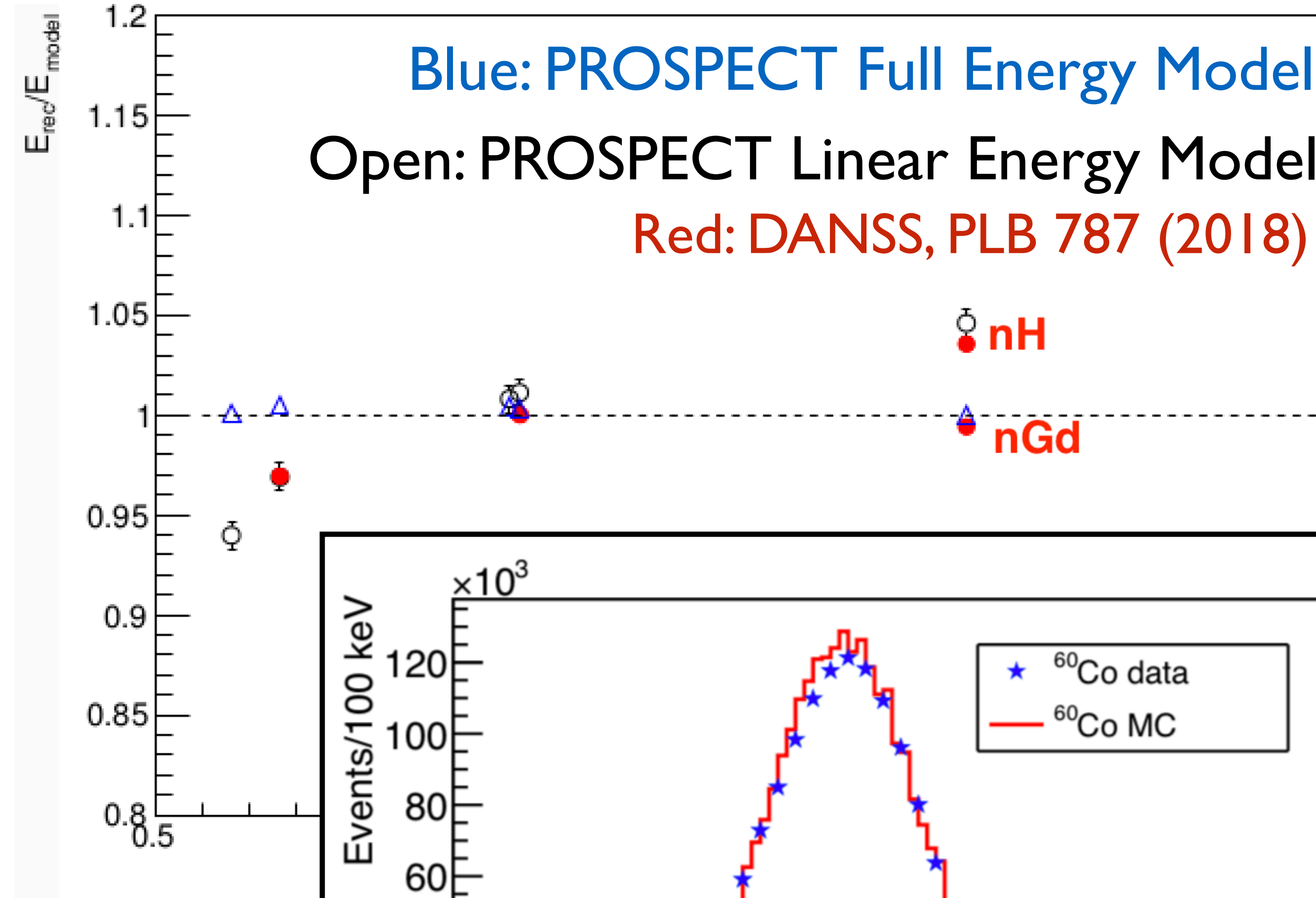


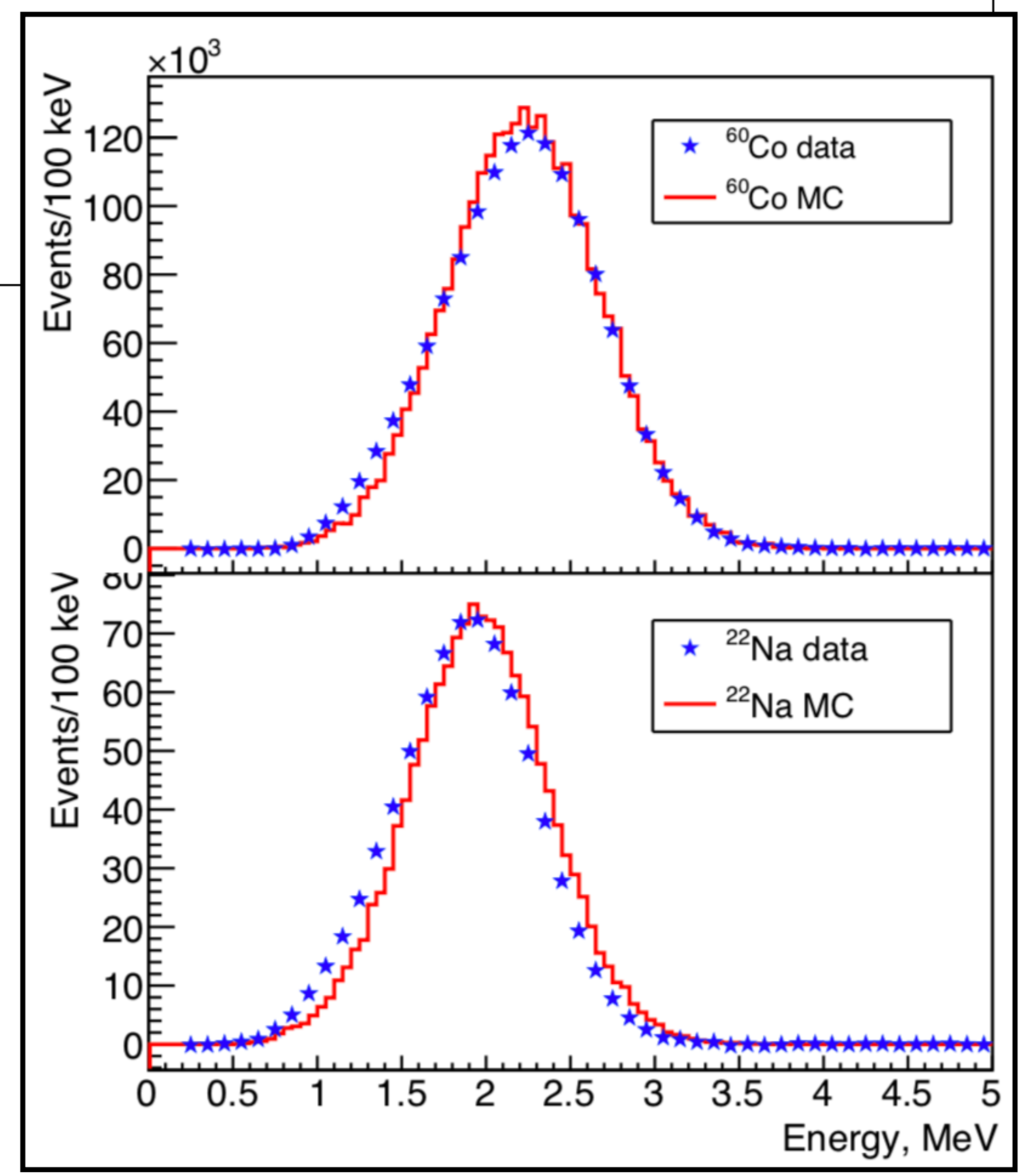
DANSS, PLB 787 (2018)

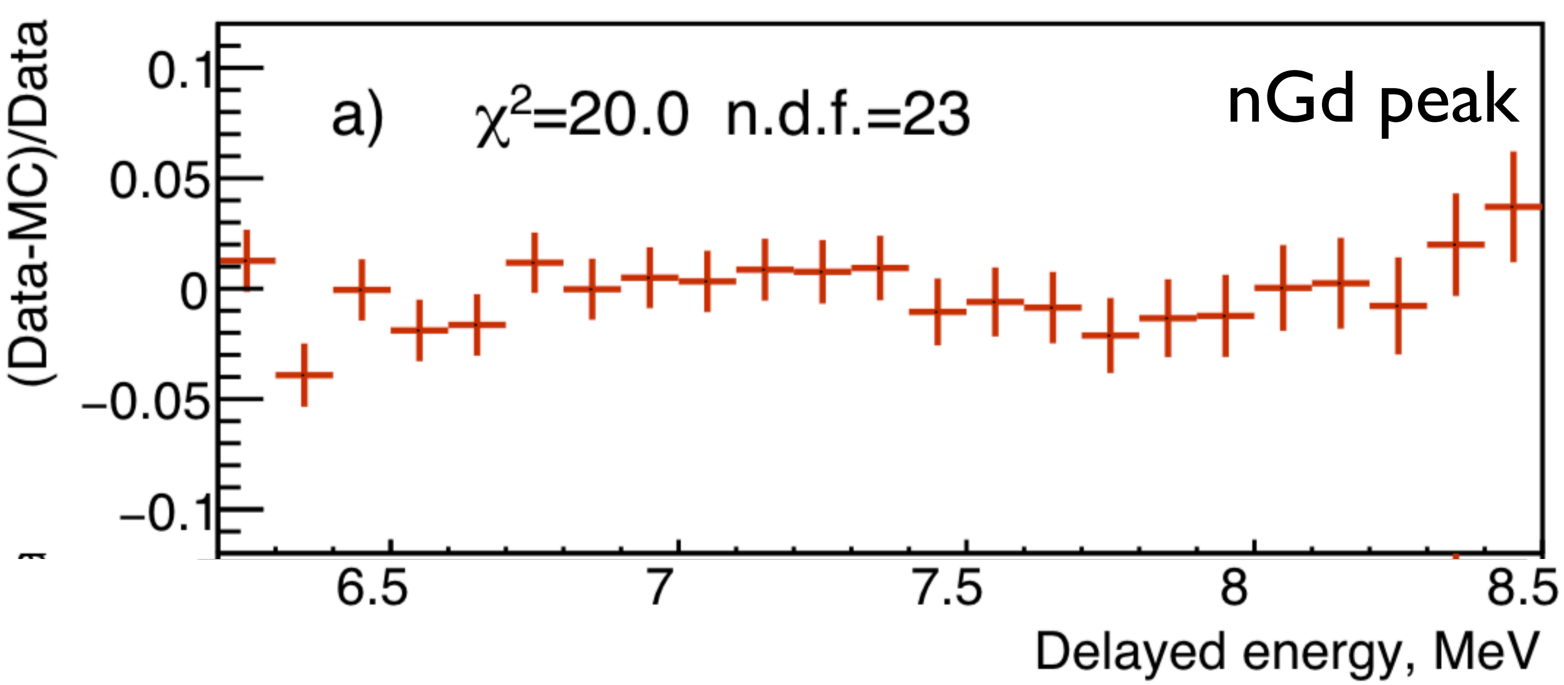


DANSS: Systematics

- DANSS systematics
  - E-scale at high energy seems well-calibrated — great!
  - What about low (<4 MeV) E?
  - What about relative low-E calibrations between positions?
  - Temperature fluctuations between different positions?







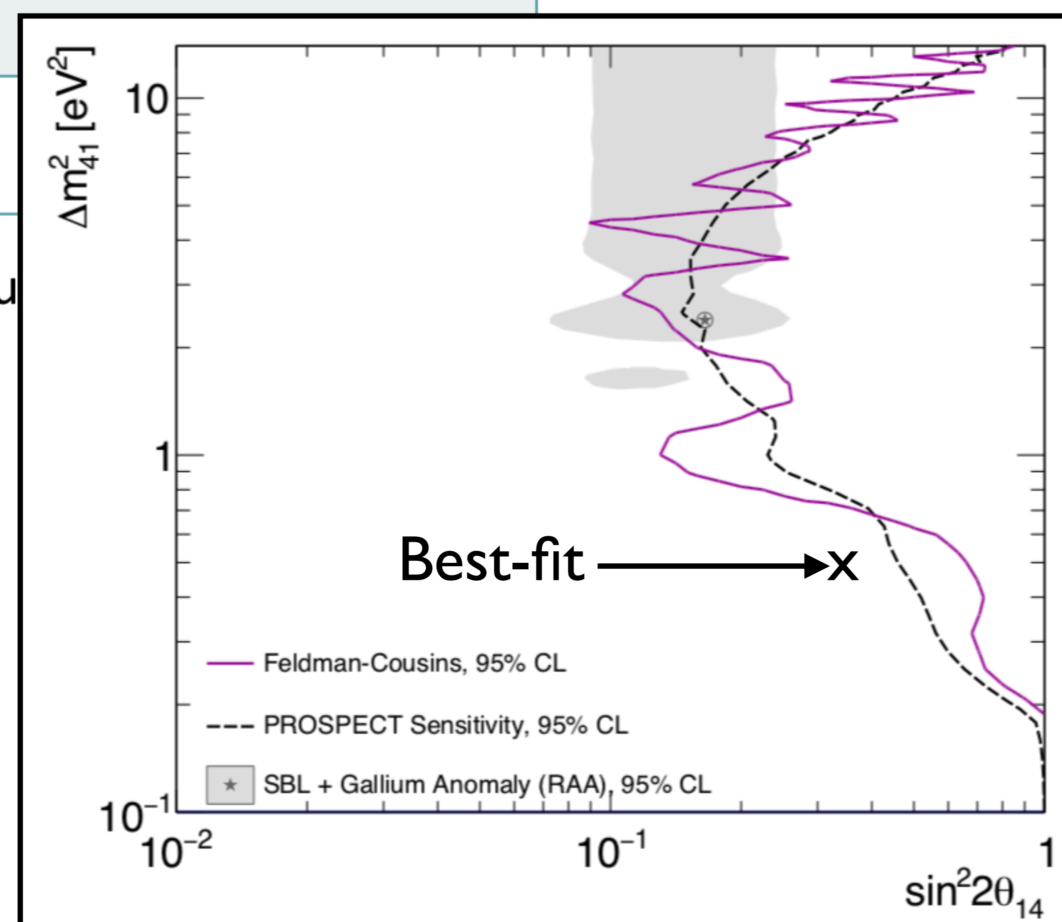
Neutrino-4

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



Neutrino-4

Feldman-Cousins Approach

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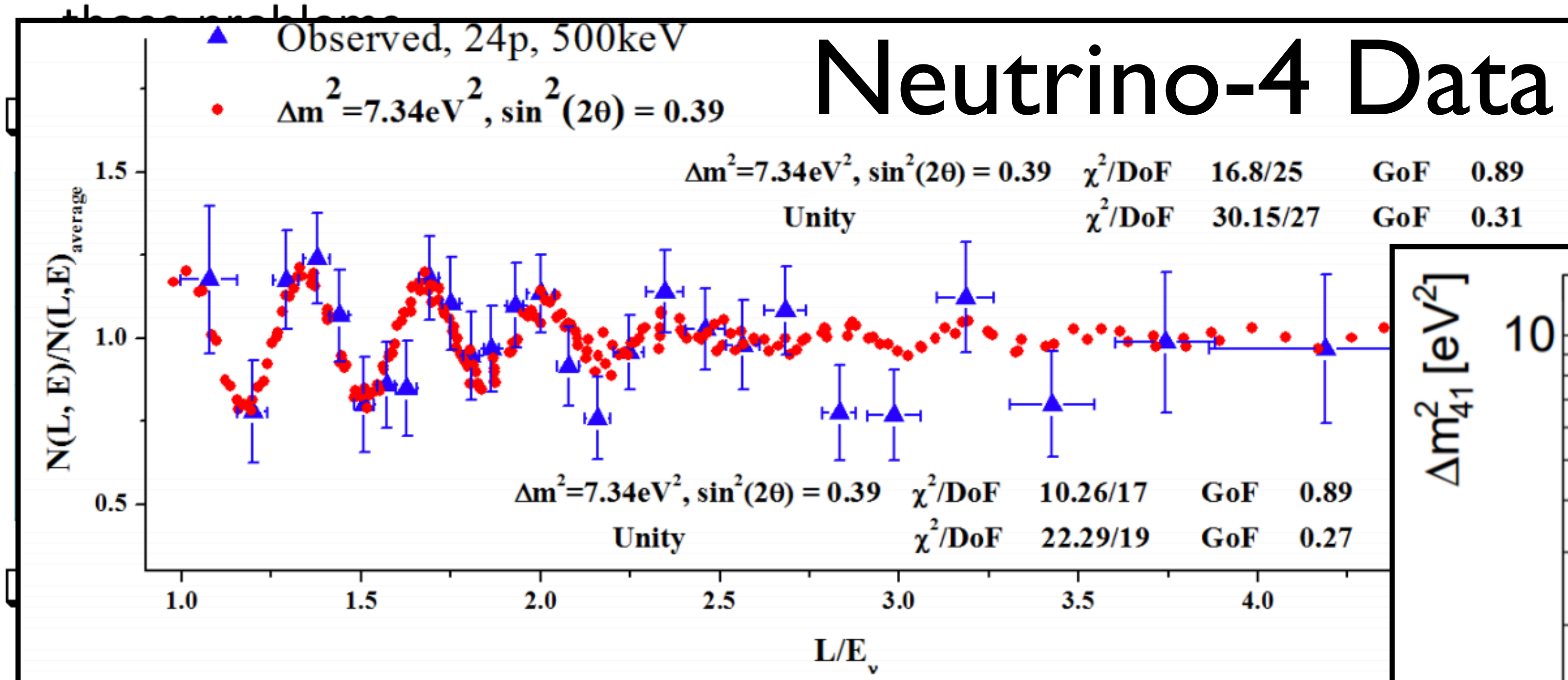
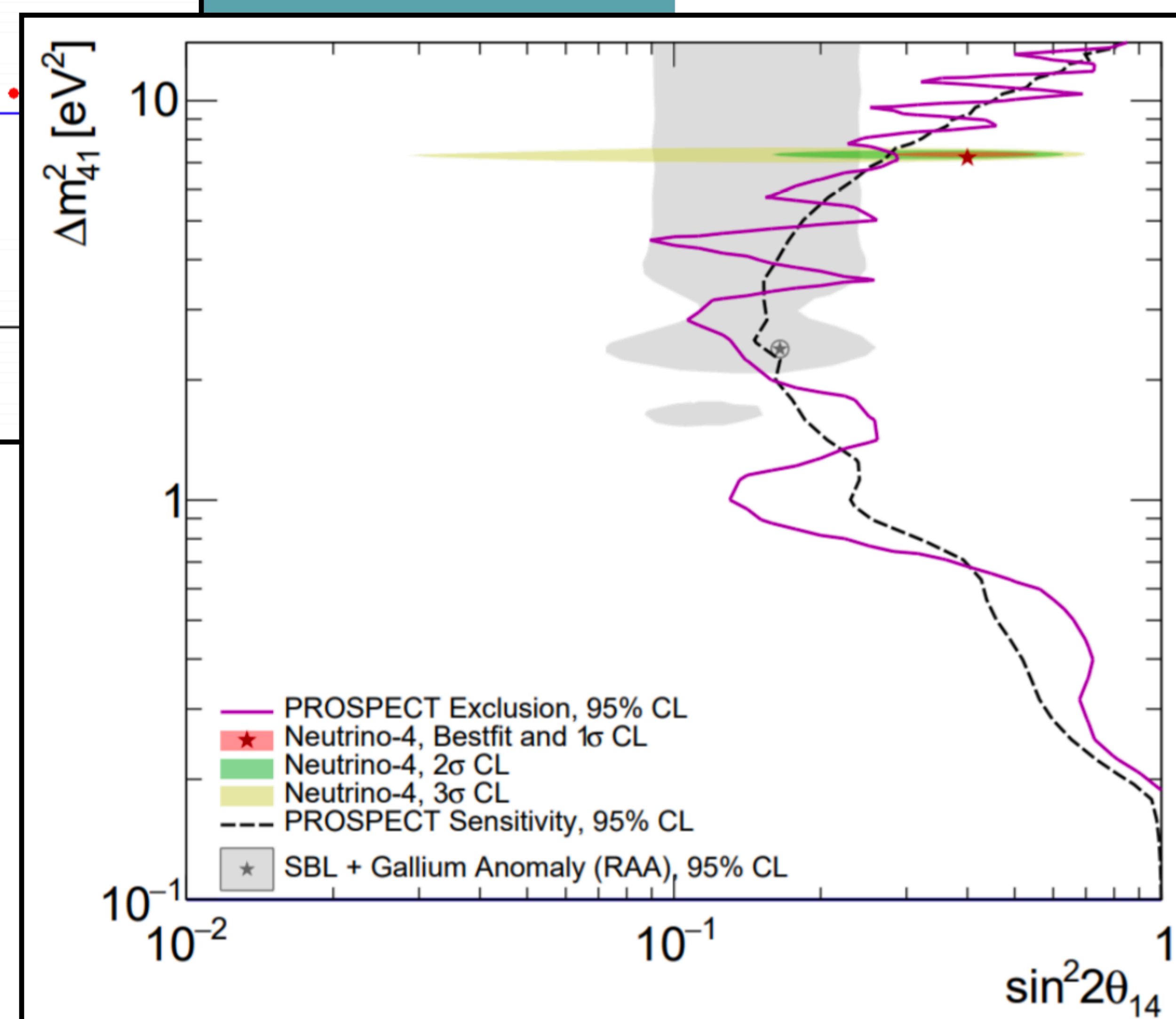


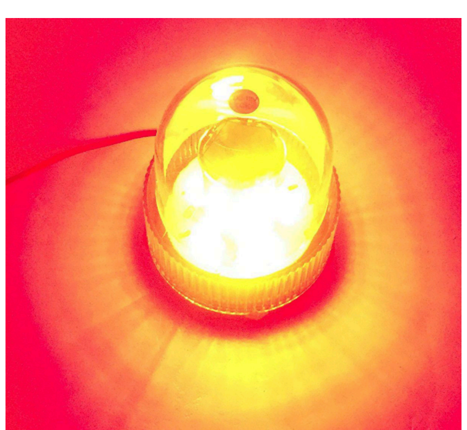
…thods:

…ile ν oscillation

We say 3ν is less compatible with data than it actually is



- Illustrates an importance of using Feldman-Cousins

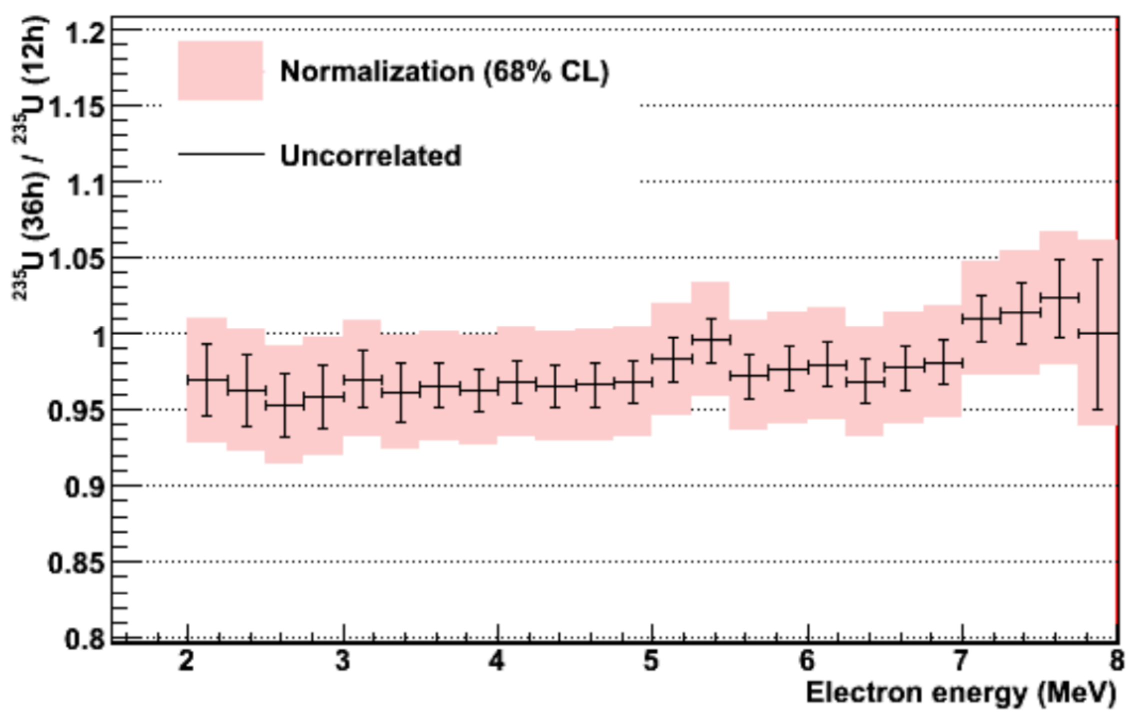


Flux Results

- 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).

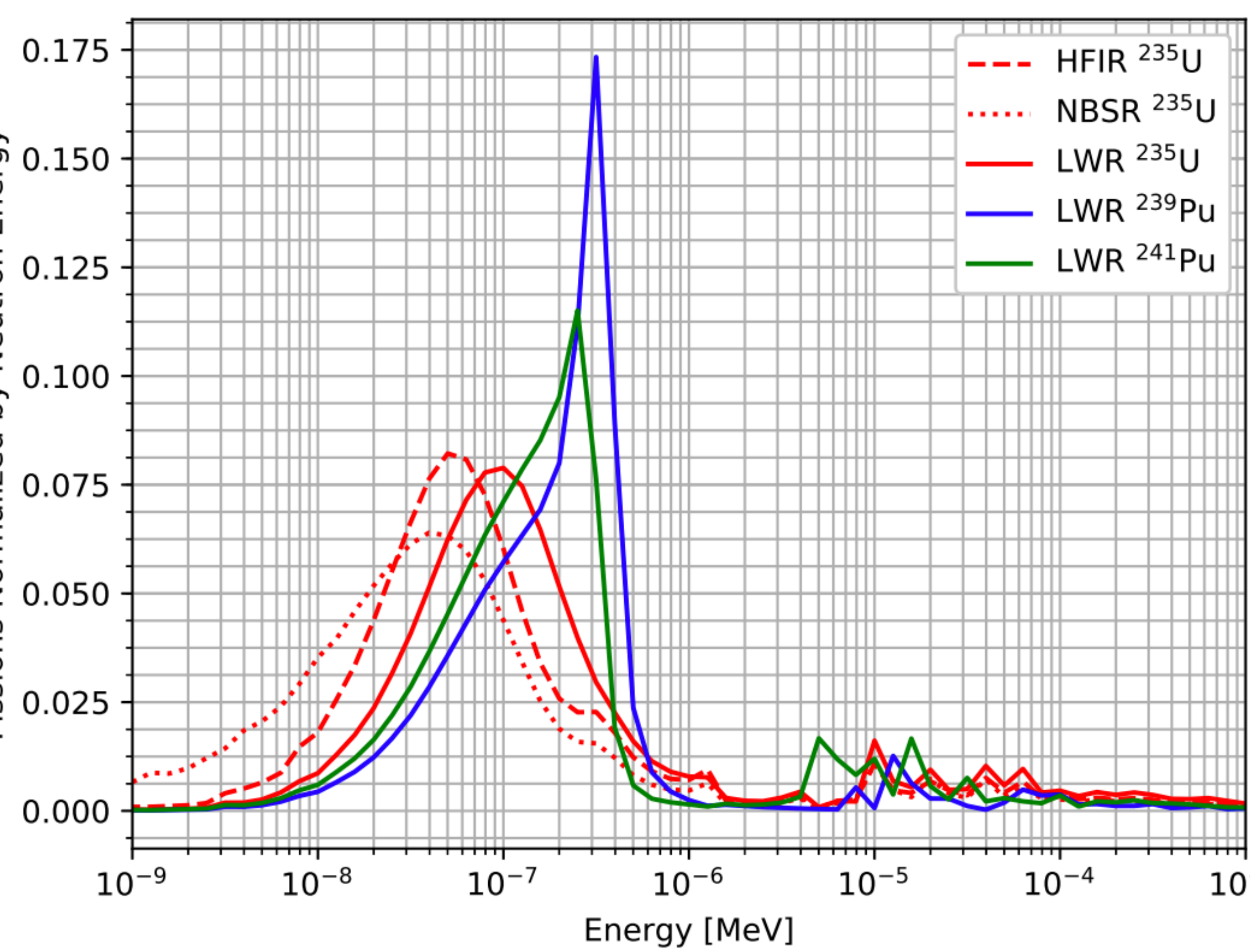
- Neutron flux calibrated out through relative measurement with respect to well-known neutron cross-sections
  - Looks like some of the 'well-known' cross-sections may have been wrong
  - This adds a 5% shift between 235 and 239 - solves DYB flux evolution?

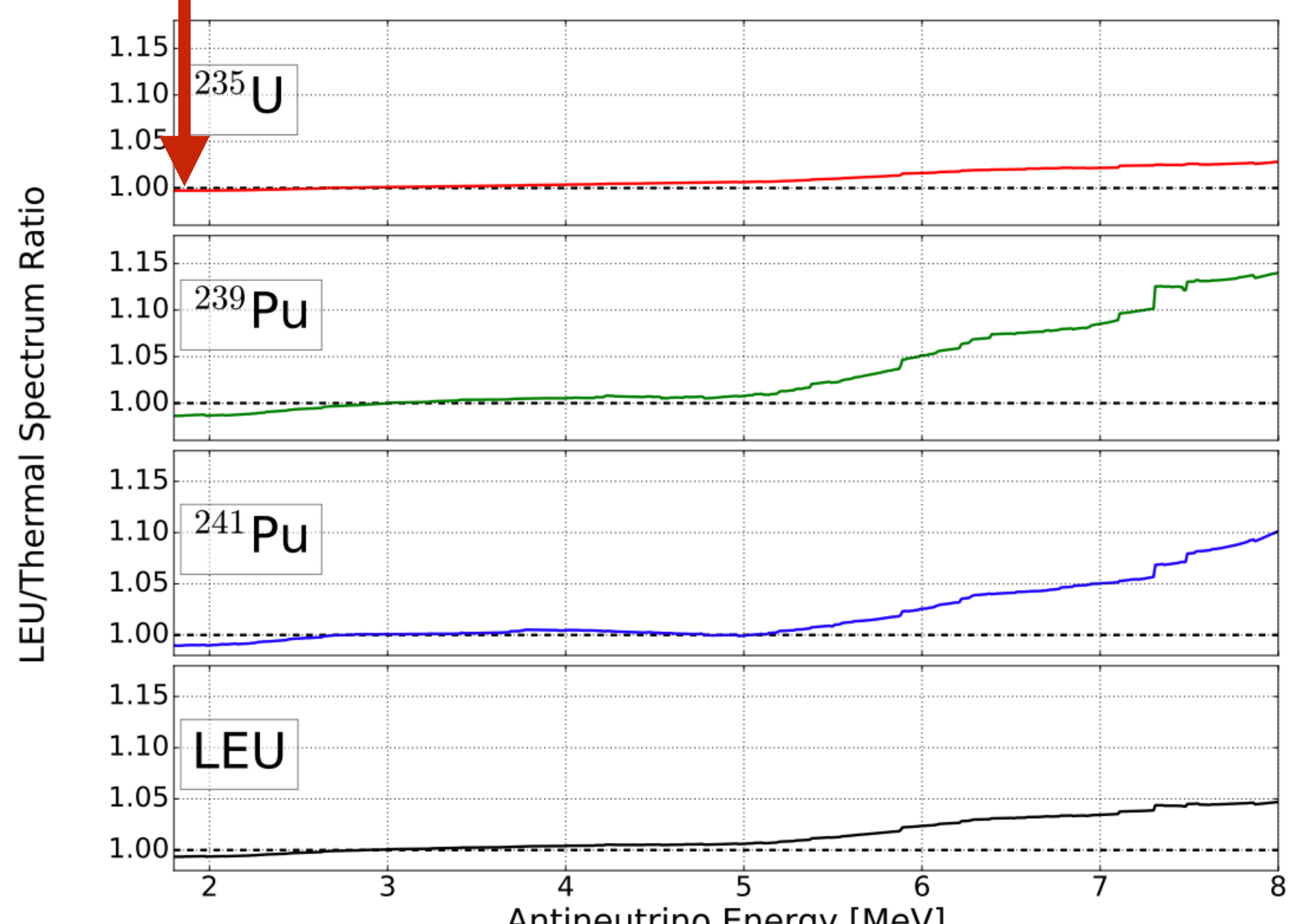
Incorrect Spectrum: Theory Studies

- Do non-thermal neutrons cause the bump?
  - ILL neutrons are thermal; LEU are NOT — different fission yields!
  - This difference has only minor impact on antineutrino fluxes and spectra.

No bumps!

No major flux offsets!



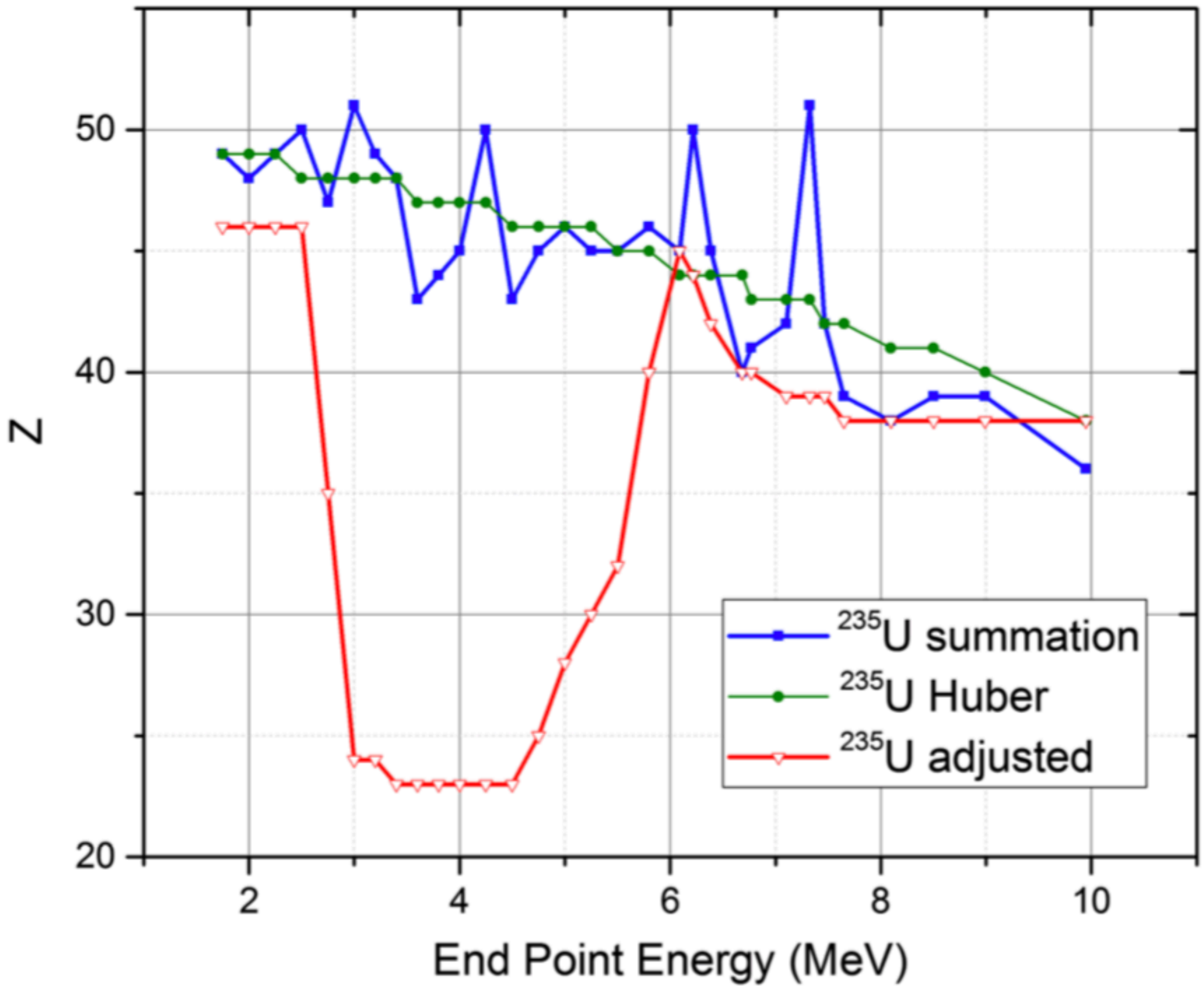


Littlejohn et al, PRD 97 (2018)

Incorrect Spectrum: Theory Studies

- Could incorrect effective nuclear charge cause the bump?
  - ‘How bad would effective charge have to be to make it cause a bump?’
  - A: <u>really bad</u>, beyond what could be reasonably expected in nuclear physics…
  - So this is not the cause.

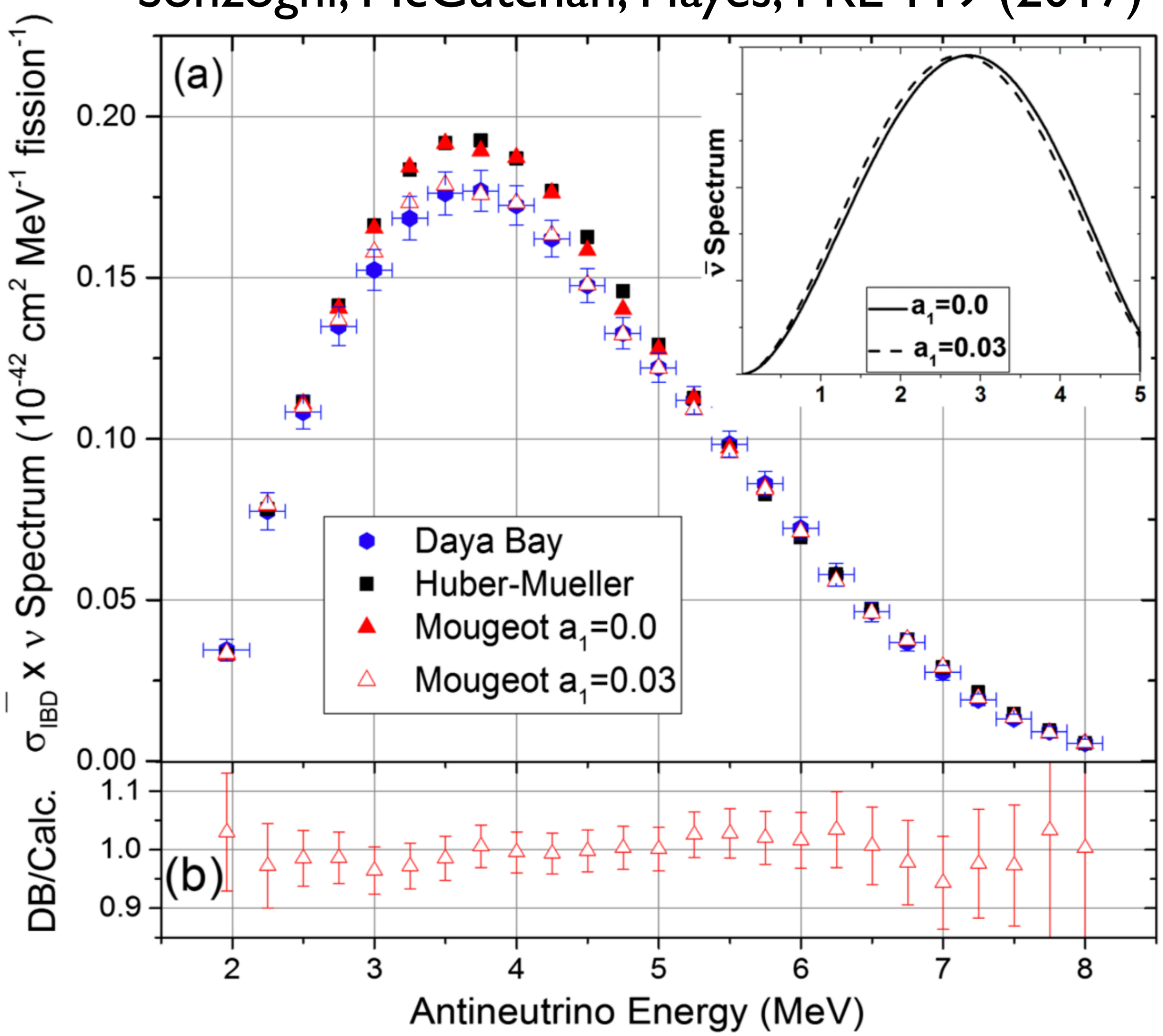
Sonzogni, McCutchan, Hayes, PRL 119 (2017)



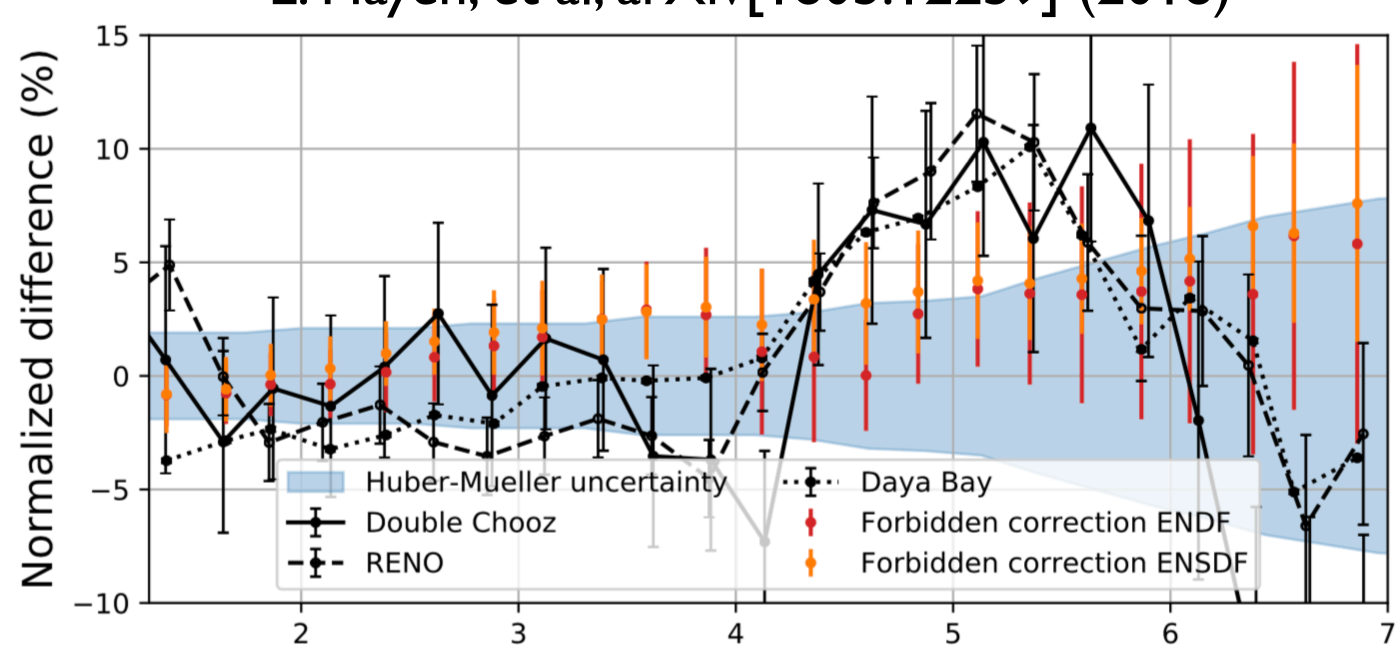
Incorrect Spectrum: Theory Studies

- Could incorrect forbidden shapes cause the bump?
  - A: It seems possible; multiple theory groups seem to agree on this.

Sonzogni, McCutchan, Hayes, PRL 119 (2017)

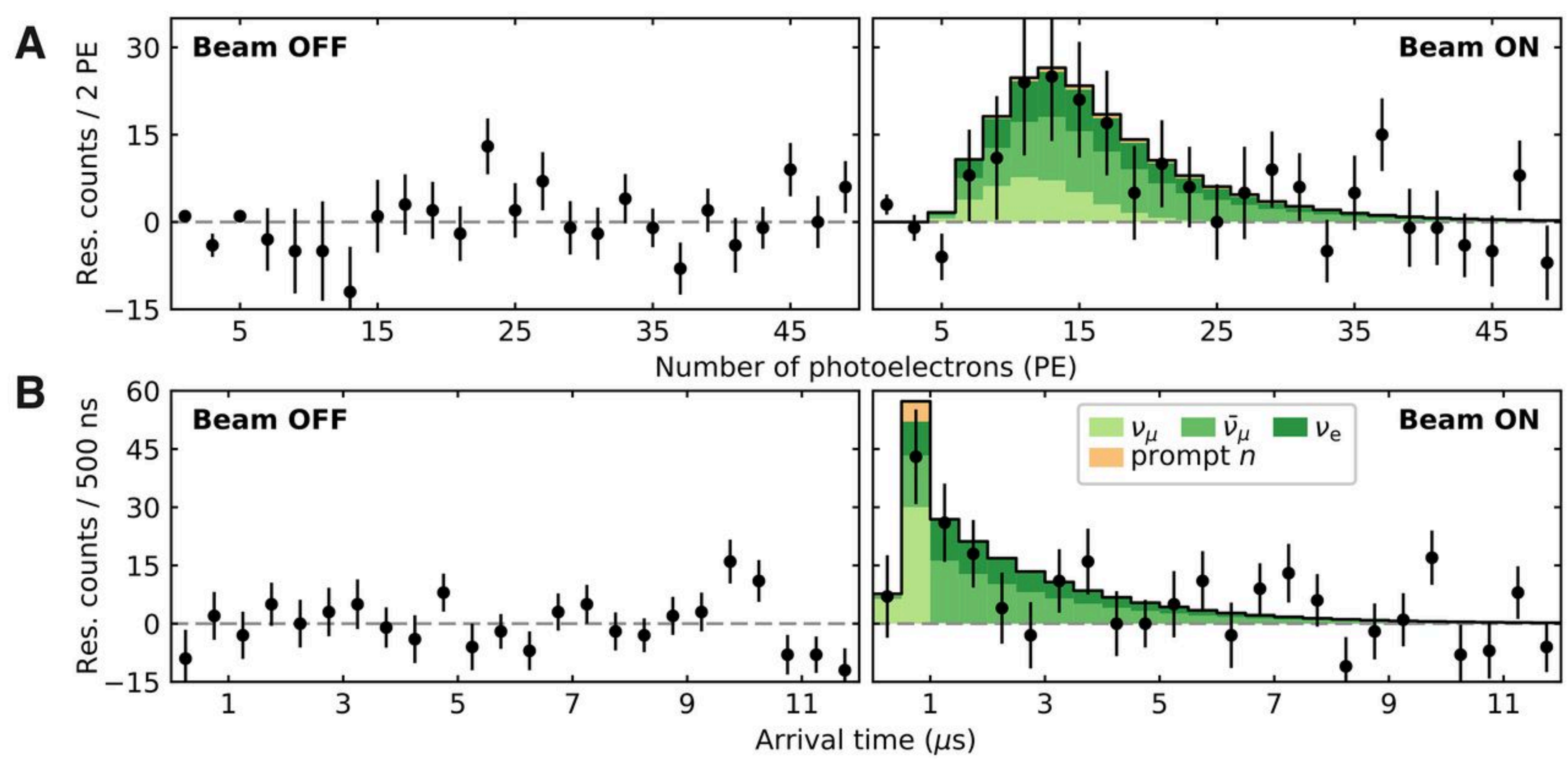


L. Hayen, et al, arXiv[1805.12259] (2018)



IBD-CEvNS Complementarity

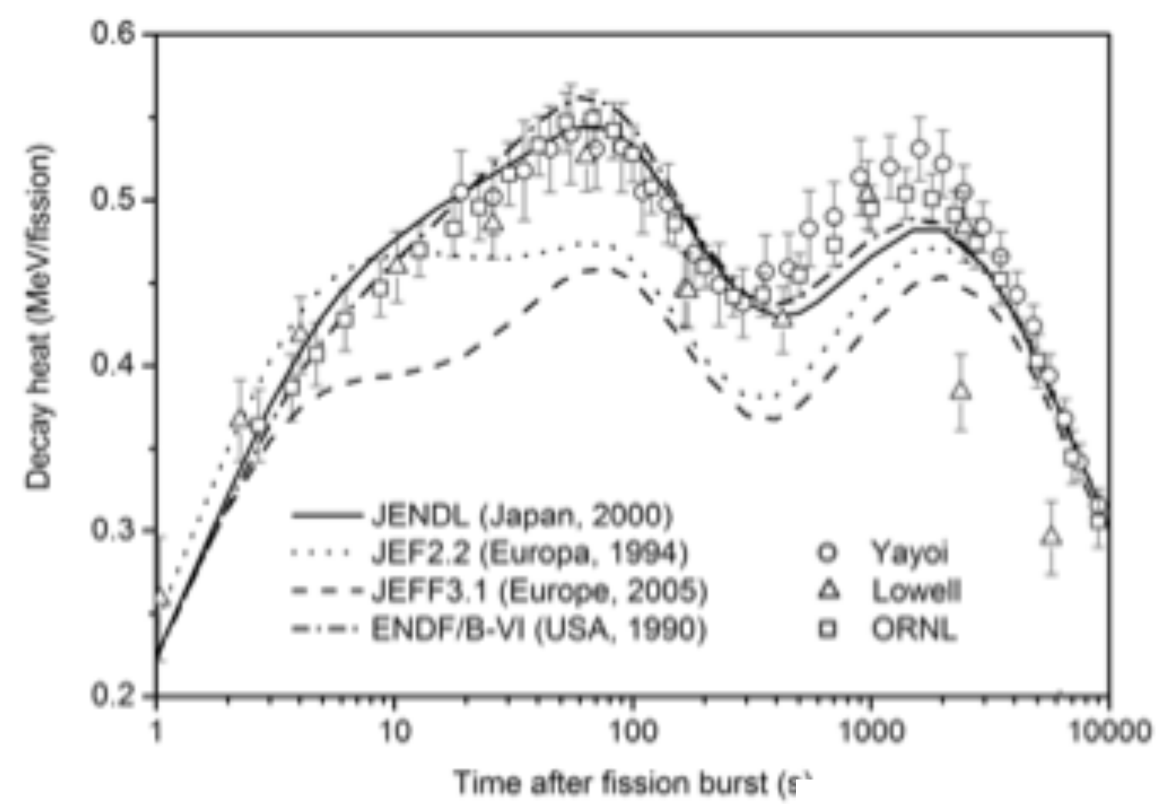
- CEvNS is predicted by standard model with high precision
  - Precision absolute measurements of CEvNS = ability to probe BSM physics!
- Ultimate limitation for CEvNS BSM-testing with reactors: the antineutrino flux
  - As we know, we cannot trust reactor flux and spectrum predictions
  - Solution: relative measurements WRT IBD measurements
  - SM likely also predicts CEvNS-IBD ratio with high precision
- So for sake of CEvNS, let's squeeze every last improvement out of absolute IBD yield and spectrum measurements!!



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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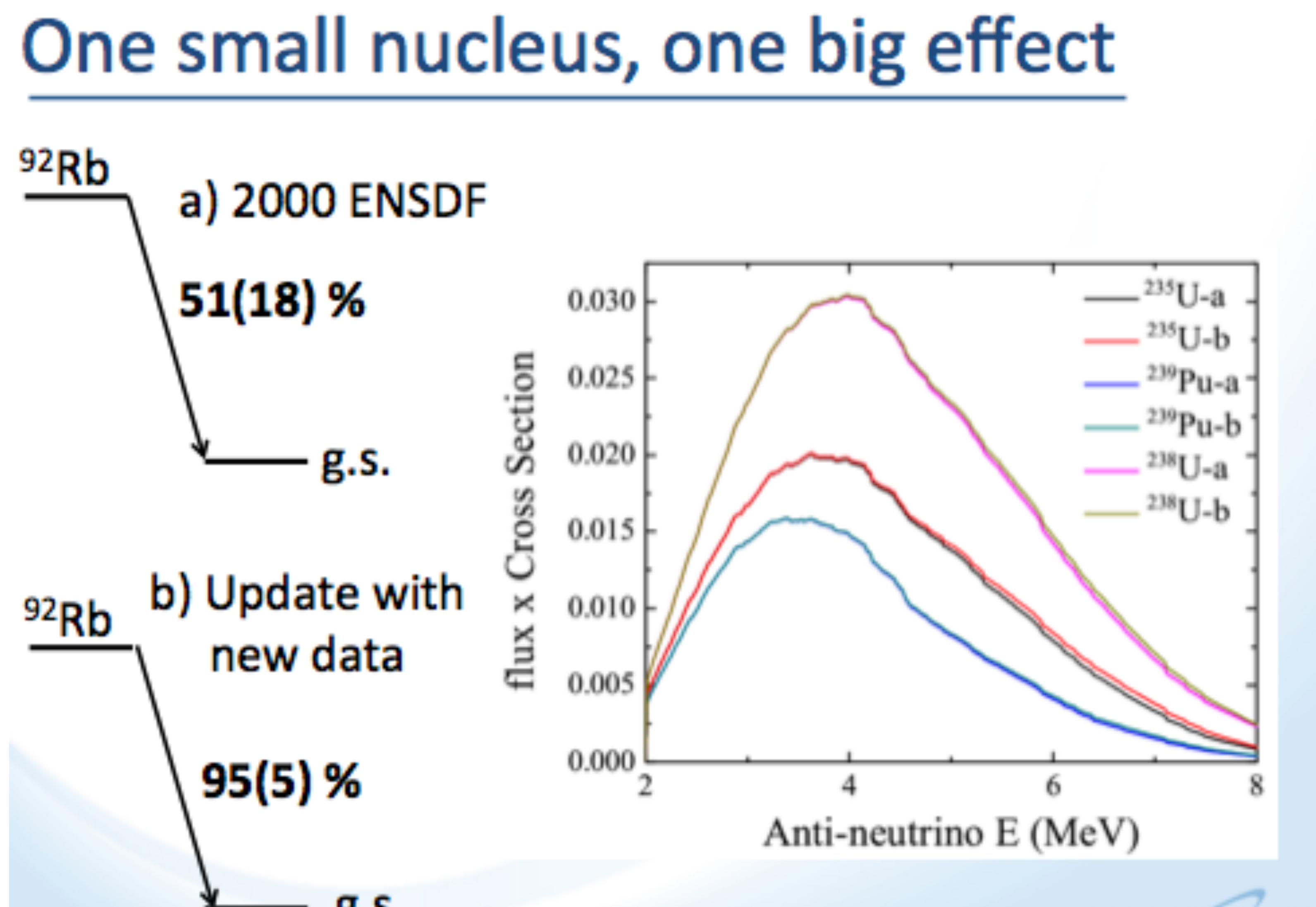
ASSESSMENT OF FISSION PRODUCT DECAY DATA FOR DECAY HEAT CALCULATIONS

Reactor Spectroscopy: Example

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

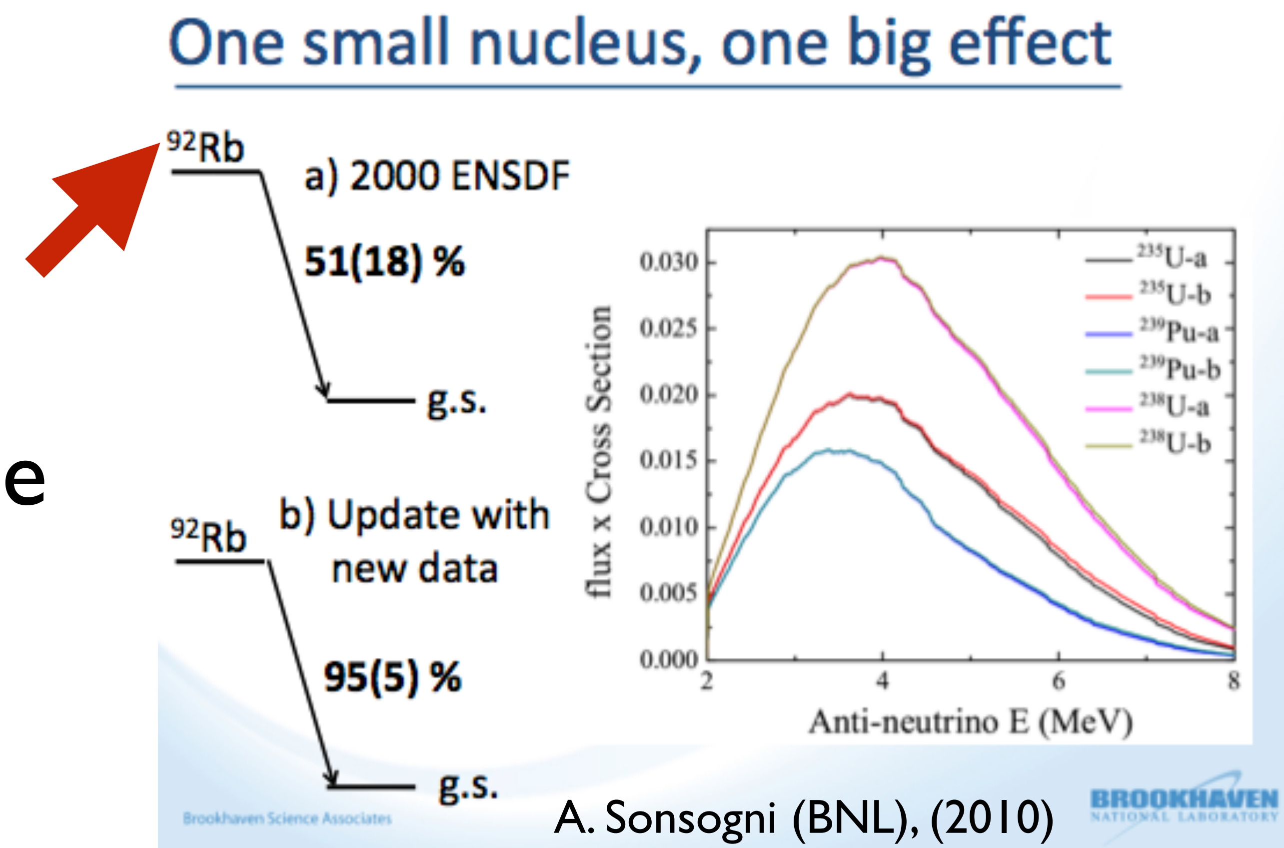


A. Sonsogni (BNL), (2010)

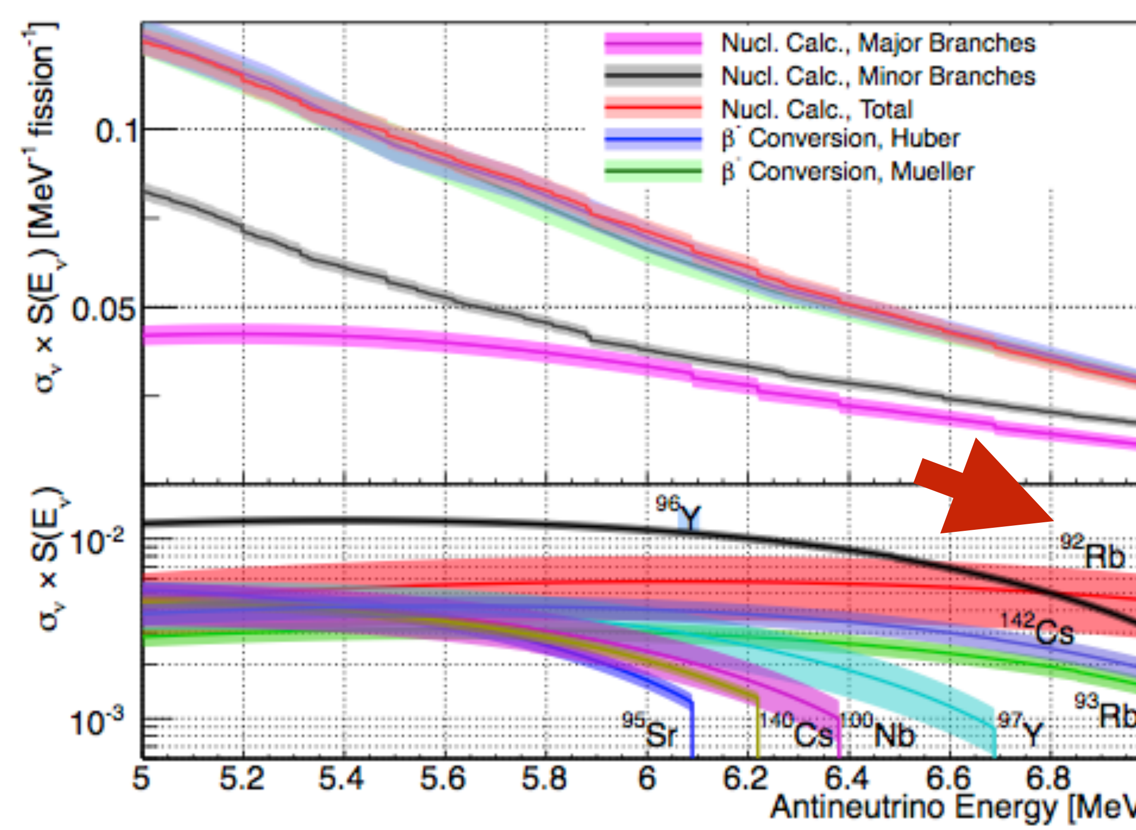
- If branching ratios are known better, decay released in those decays will be modelled better
- Better model = smaller safety factor = $$$ saved.

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



A. Sonsogni (BNL), (2010)



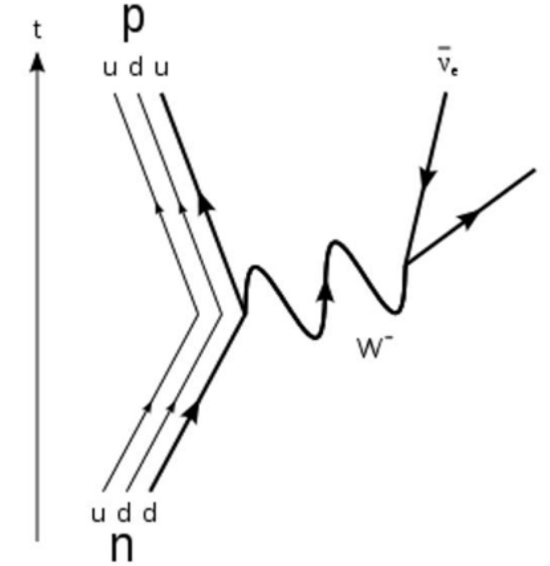
Beta Decay Recap

- 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)