Snowmass White Paper: Physics Opportunities Using Reactor Neutrinos

January 16, 2023

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O. A. Akindele, et al., hep-ex[2203.07214]

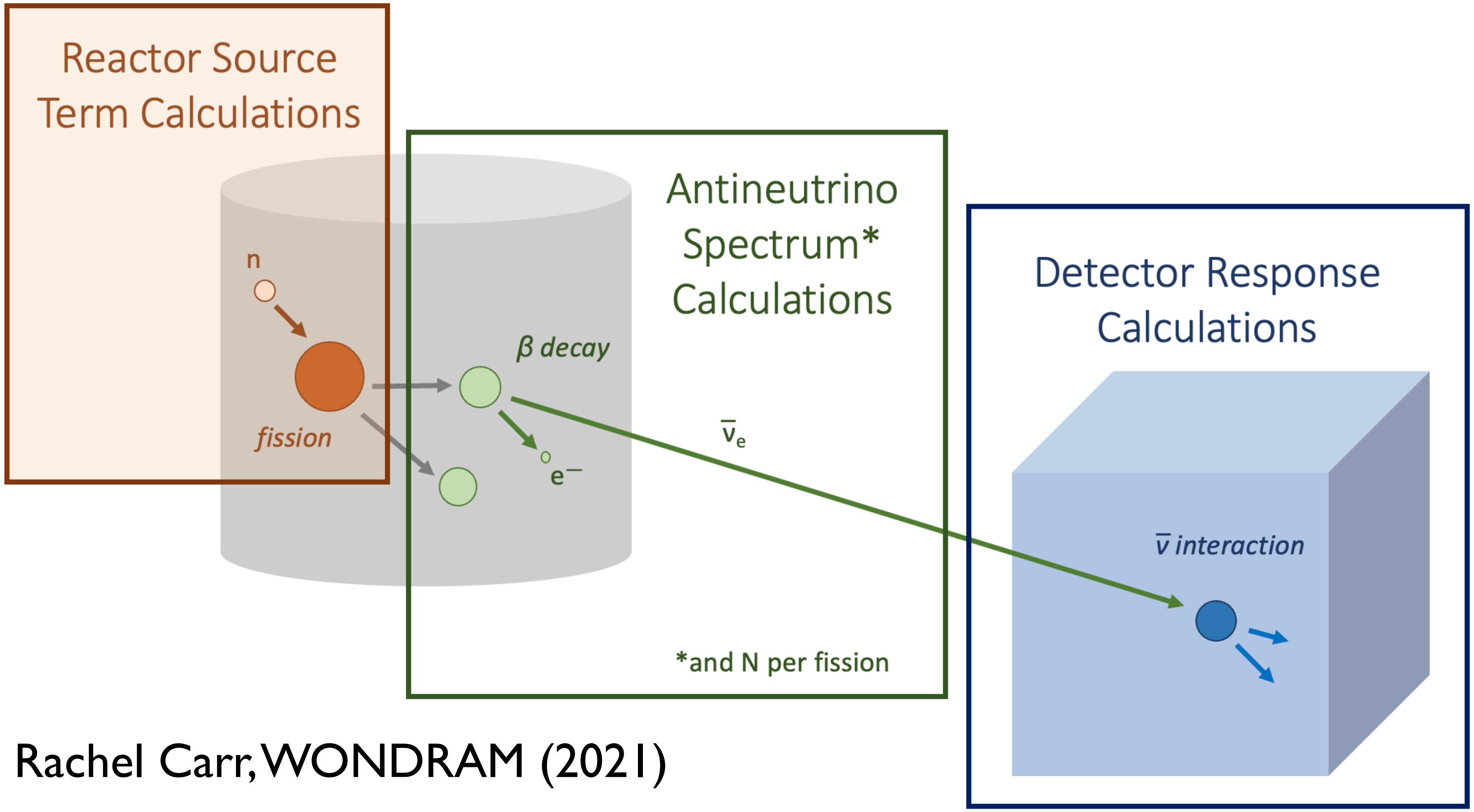
Intro: Snowmass and This Whitepaper

- A 'community planning process': what does the particle physics community care about doing in the next 10+ years?
  - Serves as the primary input for 'P5 Report,' which is the community's primary mechanism for setting priorities for US Congressional funding of DOE-HEP.
- Reactor neutrinos play a unique role in this community, so we wrote a White Paper to represent these contributions for 'the Snowmass process'
- Provides a 'state-of-the-field' review relevant to this audience
  - I will focus on parts most relevant to this audience (IAEA Nuclear Data)
  - I will re-order its discussion to make it fit this group's interests better
- Quotes/figures are from the White Paper, unless noted.
  - White paper editors aim for for this document to be published as a Topical Review in J Pays G in 2023.


P5 Panel Deputy Chair (Heeger) Member (Huber)

Intro: Making Neutrinos

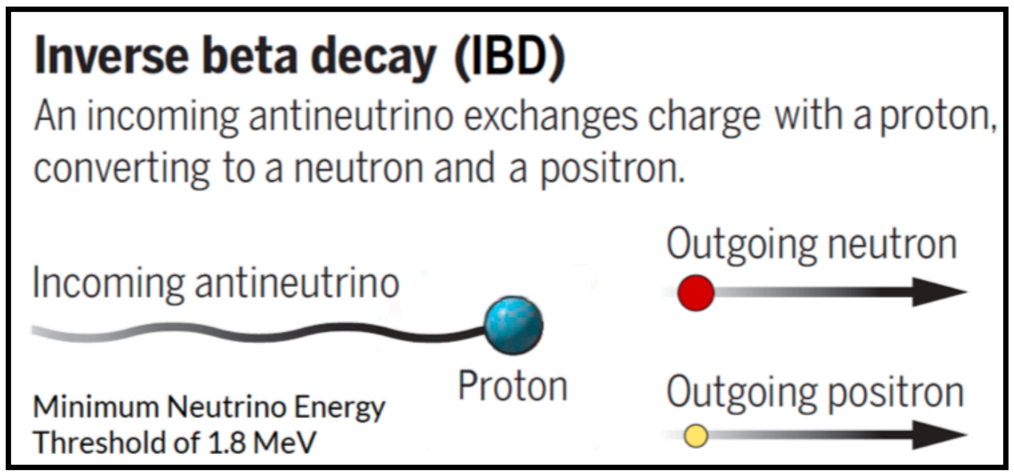
- **Run a reactor, make unstable fission products**
  - Energy release per fission: how many fission daughters are made per MW_{th}?
  - Fission yields: what unstable daughters are made? Energy dependence (fast, resonant, thermal)?
- **Produced daughters decay and make neutrinos**
  - What is the beta feeding for each isotope? To energetically high- or low-lying daughter states?
  - What shape is the beta/nuebar energy spectrum of each branch?

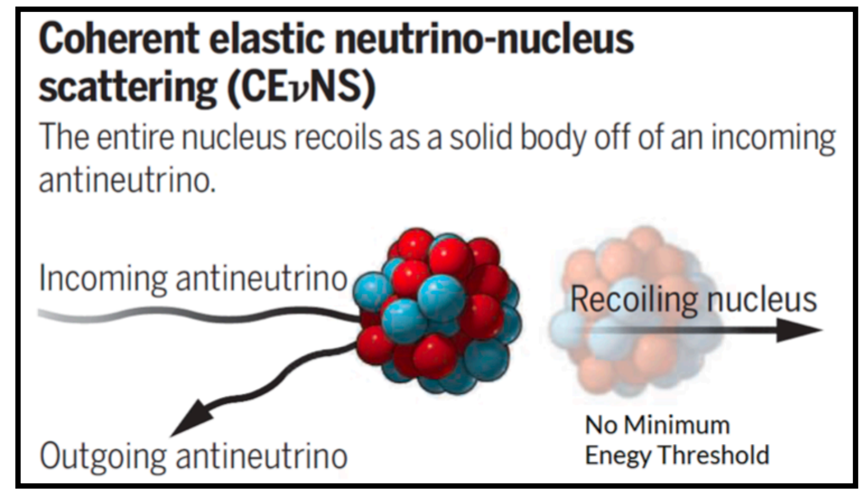


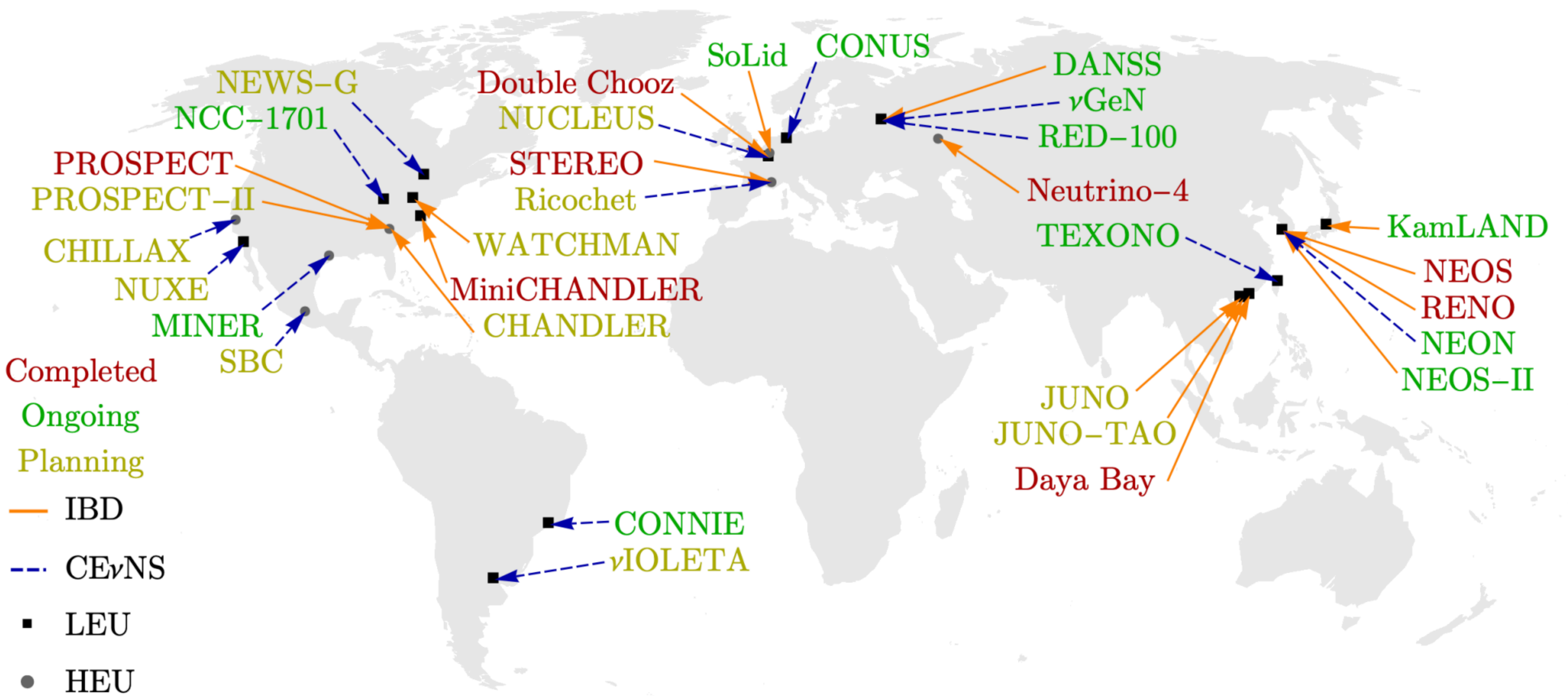
Rachel Carr, WONDRAM (2021)

Intro: Detecting Neutrinos

- Today's experiments use inverse beta decay (IBD) and coherent neutrino-nucleus scattering (CEvNS)

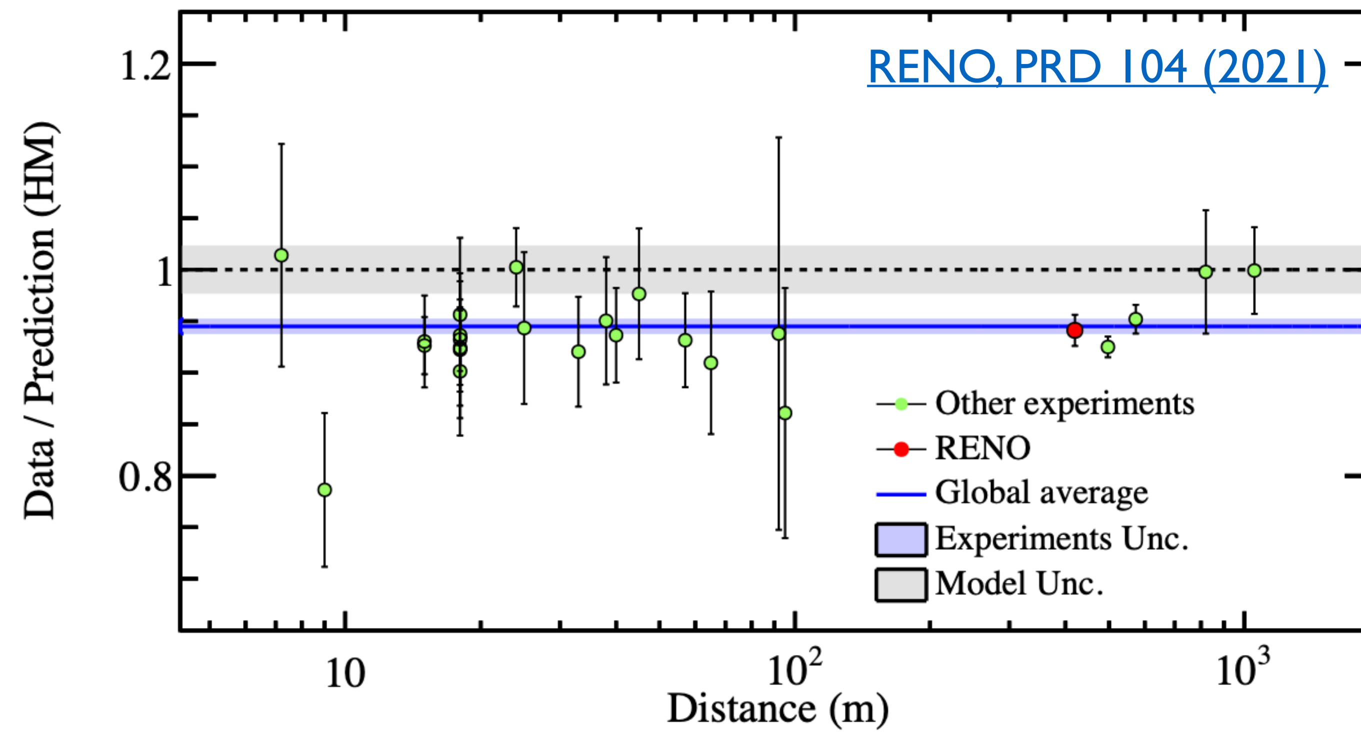




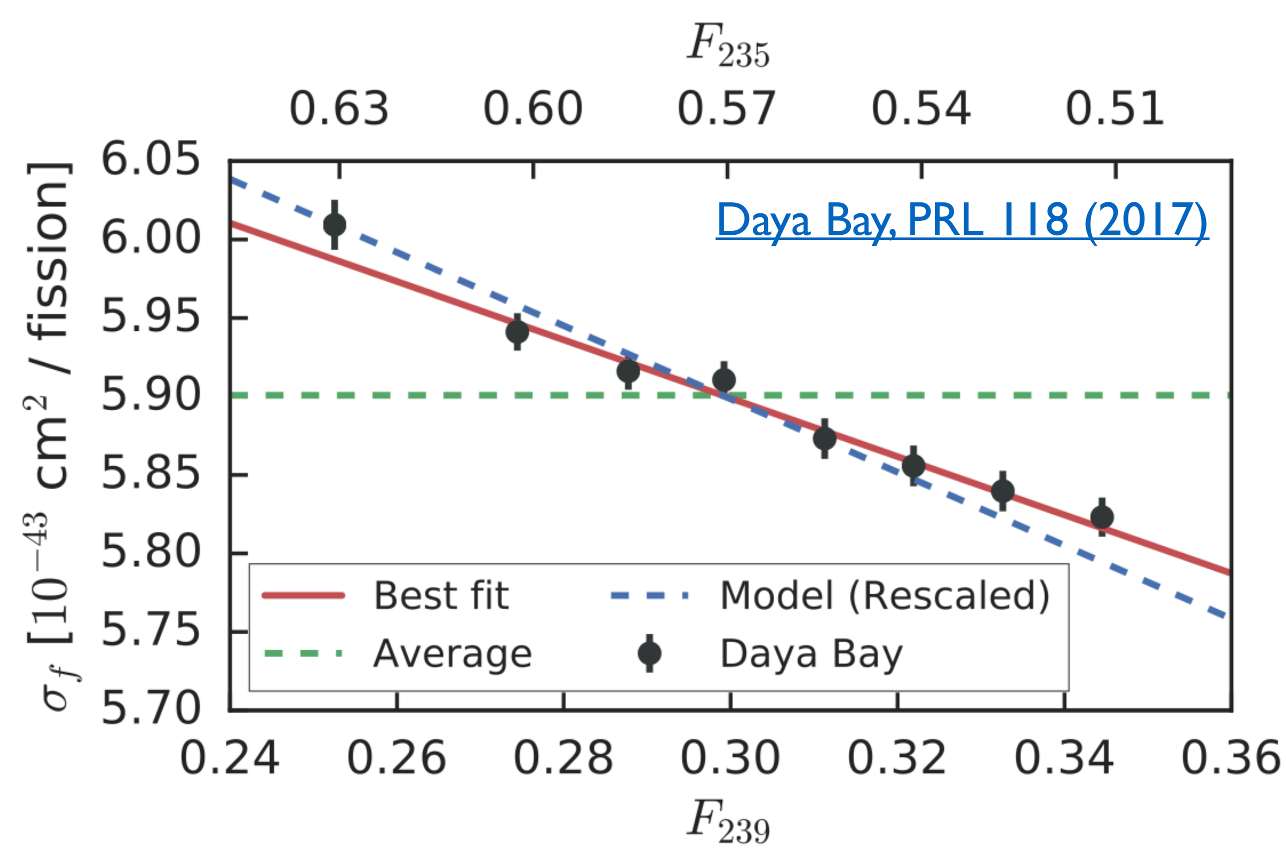


Intro: IBD Measurement Types

- ‘Absolute Flux’ (also called IBD yield per fission, or IBD yield):
    - Integrate IBD counts for all run-times
    - One measurement at one average fuel content
    - HEU and LEU reactors



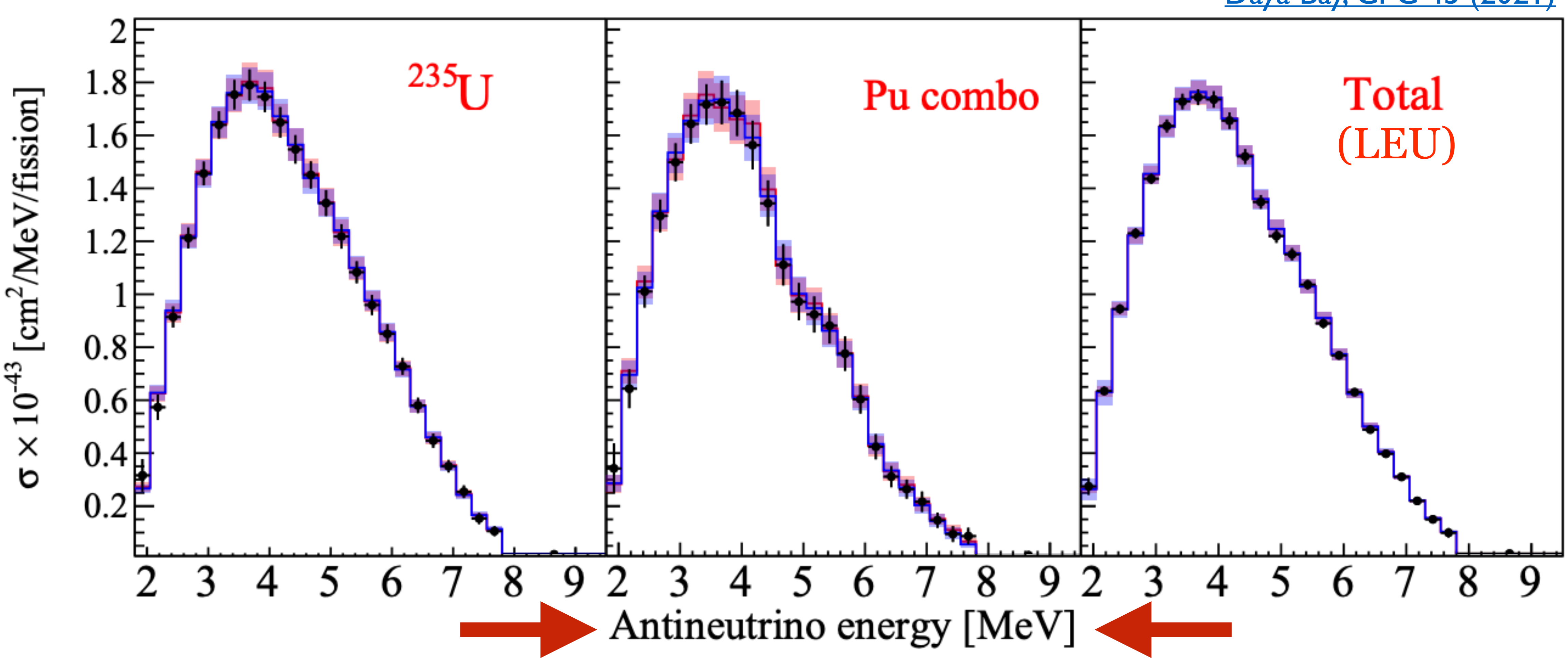
- ‘Flux Evolution’:
    - Bin IBD counts into bins of common reactor fuel content
    - Many (hopefully) highly systematics-correlated measurements
    - LEU cores, not HEU cores



Intro: IBD Measurement Types

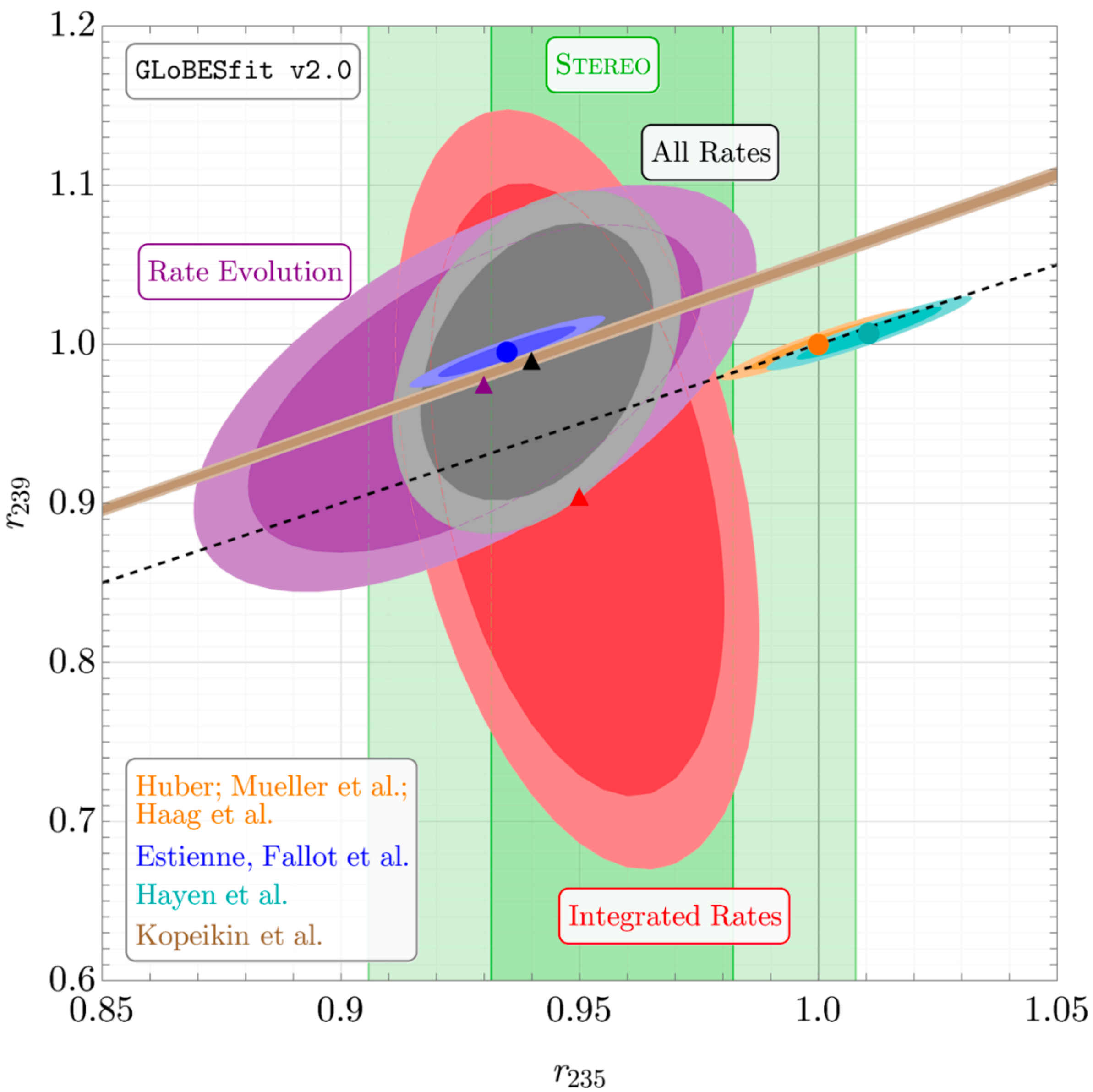
- ‘Absolute Spectrum:’
  - Bin IBD counts by reconstructed ‘prompt’ IBD positron energy
  - Can use modeled detector response to ‘unfold’ from ‘prompt energy space’ to ‘neutrino energy space.’ Can report results in either space
- ‘Spectrum Evolution:’
  - Just like flux evolution, but for spectrum. Again, LEU only, not HEU.

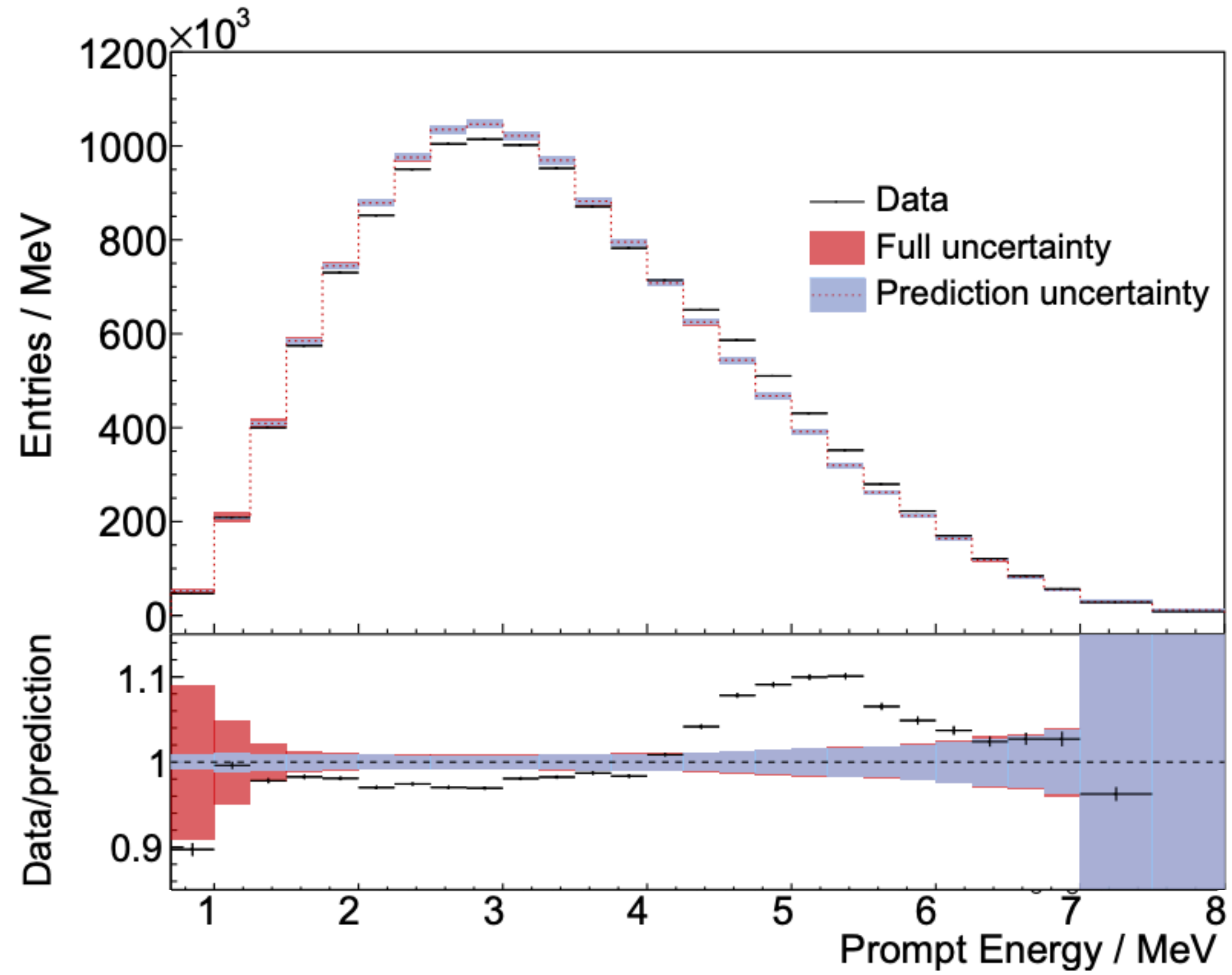
Daya Bay, CPC 45 (2021)



Why We Are Here at IAEA

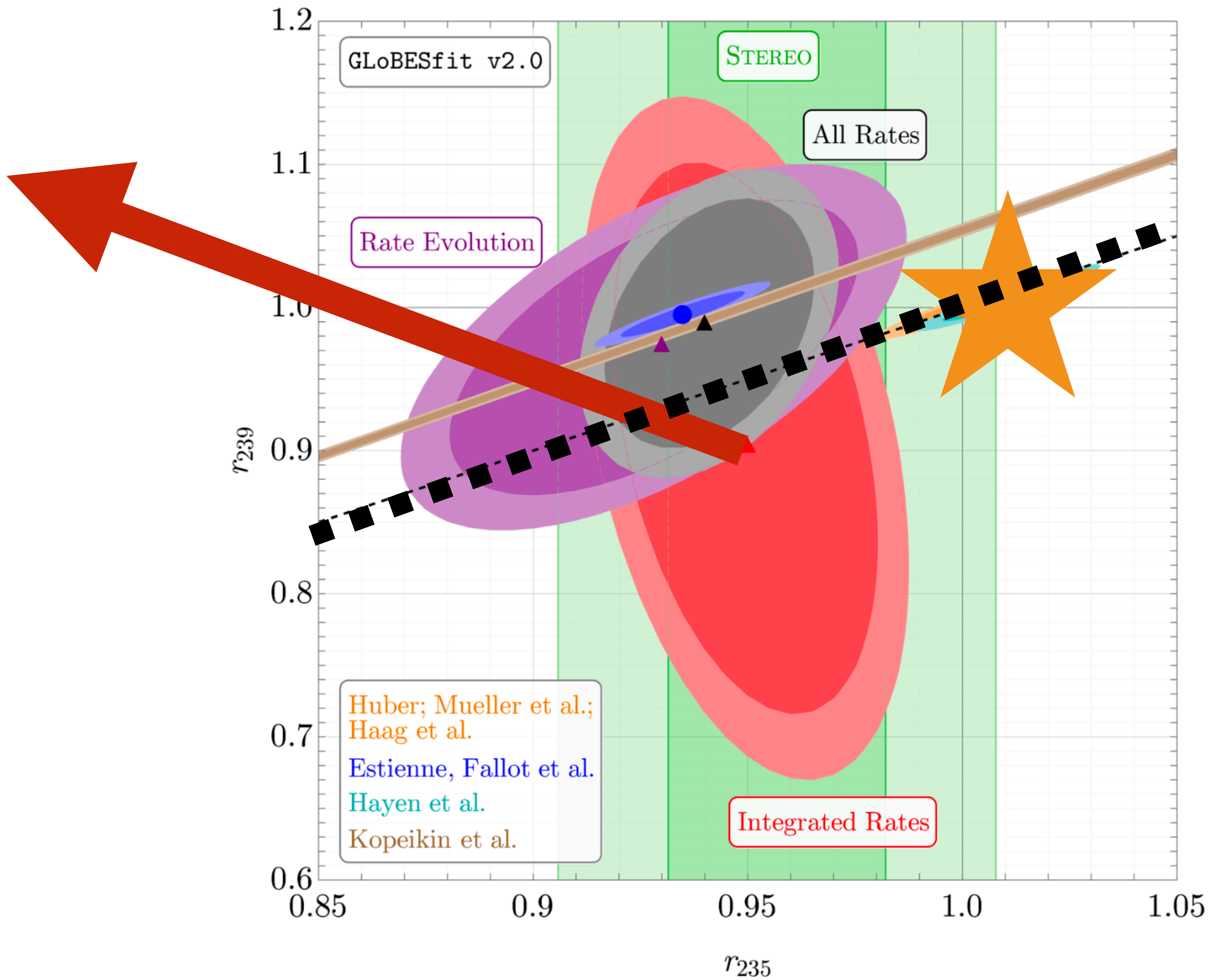
- "Recent neutrino experiments have been very successful in advancing the state of knowledge of reactor antineutrino emissions, most notably by uncovering the reactor flux and spectrum anomalies."
- "The increased precision of reactor neutrino measurements has had a broader science impact by spurring investments and improvements in non-neutrino nuclear physics measurements, nuclear data, and reactor antineutrino modeling.





Why We Are Here: Flux

- 2011: New conversion prediction shows excess with respect to historical flux (IBD yield) results, suggesting possibility of short-baseline neutrino disappearance (sterile neutrinos)



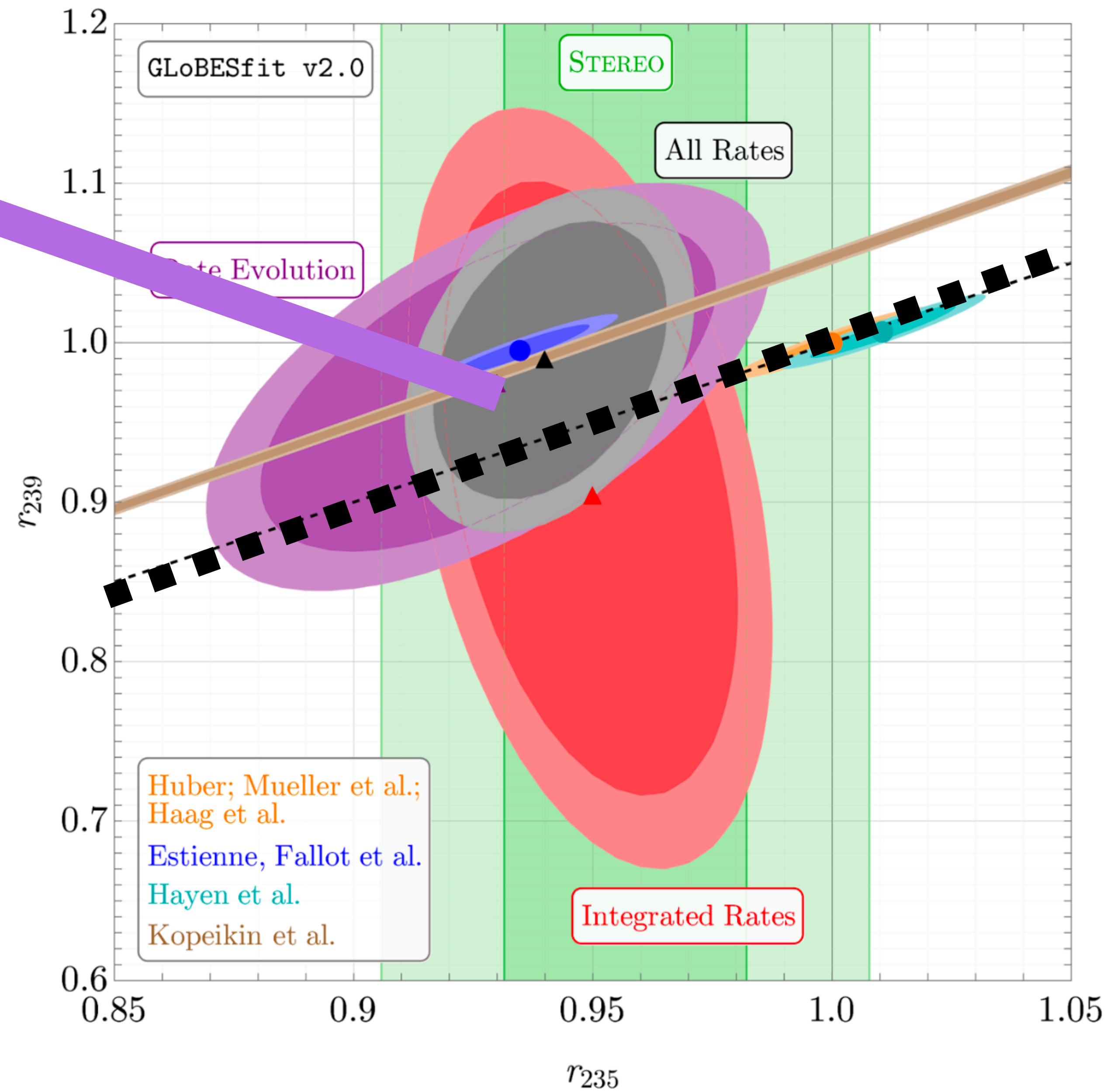
Mention et al, PRD 83 (2011)

Huber, PRC 84 (2011)

Why We Are Here: Flux

- Recent neutrino experiments have been very successful in advancing the state of knowledge of reactor antineutrino emissions, most notably by uncovering the reactor flux and spectrum anomalies.

- 2017: Daya Bay sees signs that IBD yield deficit in 235 is larger than in 239, which isn't expected from sterile oscillations

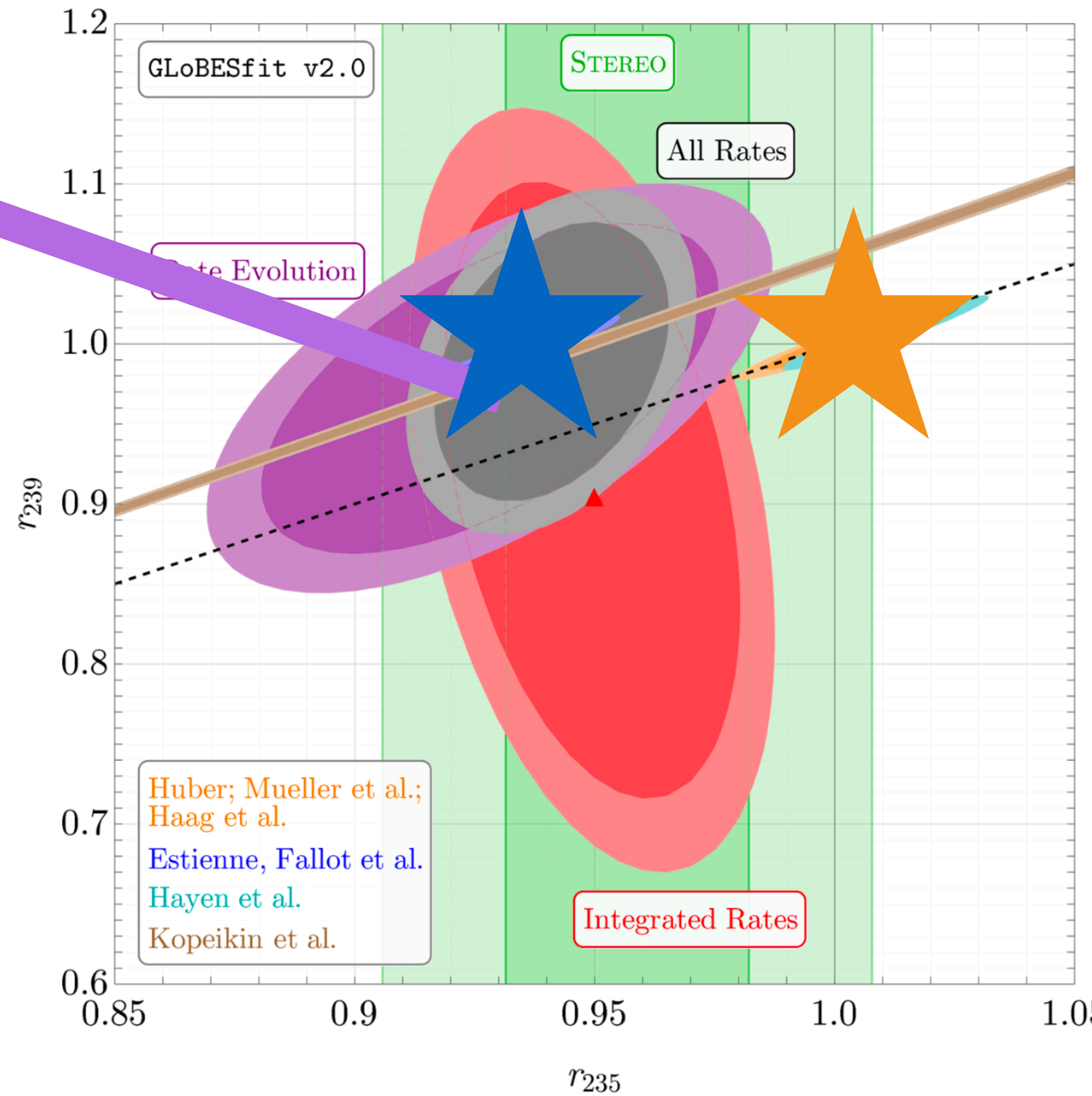


Daya Bay, PRL 118 (2017)

Why We Are Here: Flux

- Recent neutrino experiments have been very successful in advancing the state of knowledge of reactor antineutrino emissions, most notably by uncovering the reactor flux and spectrum anomalies.

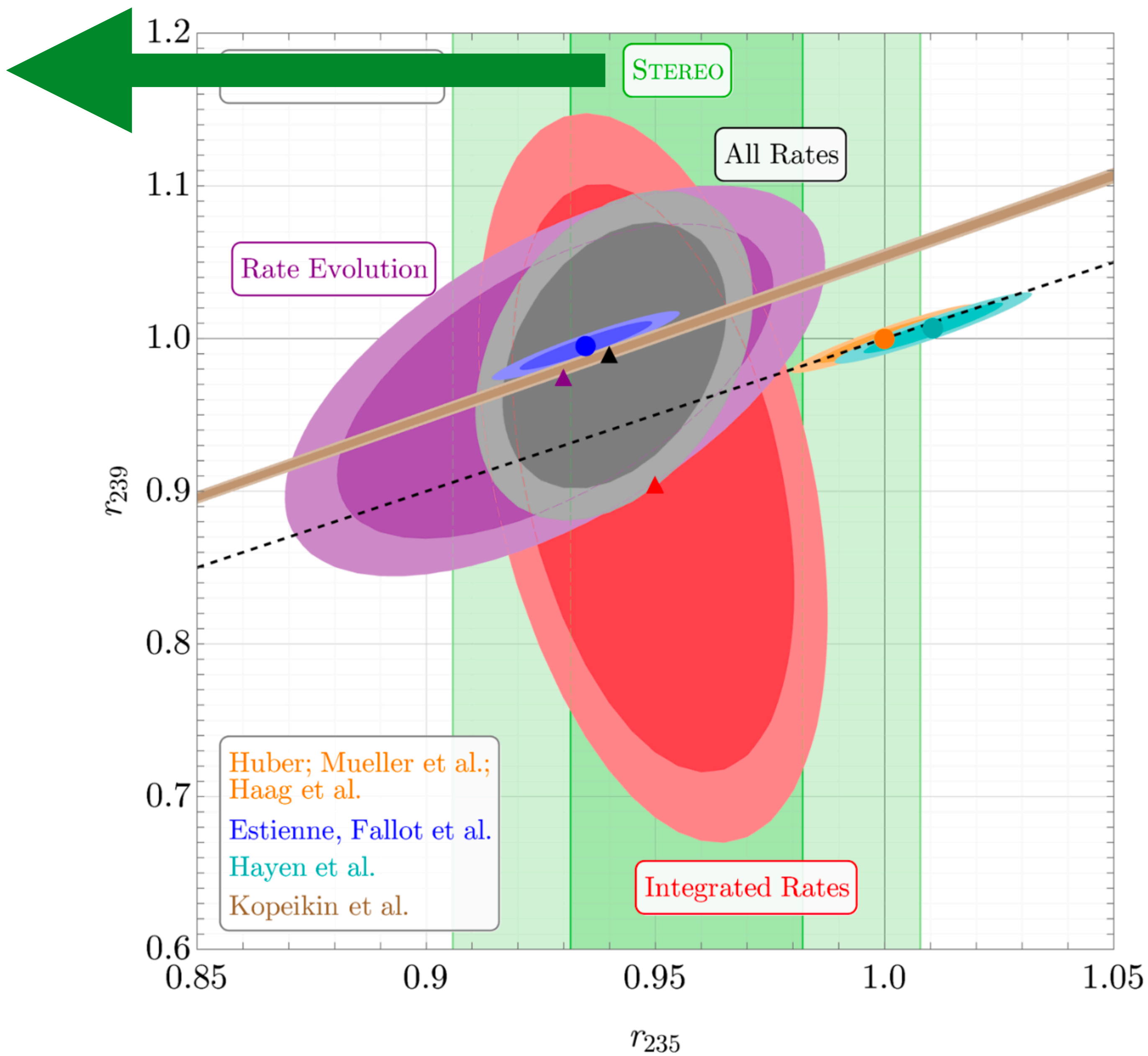
- 2017: Updated summation predictions match Daya Bay narrative, implicating conversion prediction as a flux anomaly culprit
  - 2019 TAGS-including summation has similar conclusion; also shows decreasing 'flux anomaly' with increasing TAGS data inclusion
  - 2019: Conversion with better treatment of forbidden decays reproduces old conversion flux



[Hayes et al, PRL 120 (2018)](#)
[Estienne et. al., PRL 123 (2019)](#)
[Hayen et al, PRC 100 (2019)](#)

Why We Are Here: Flux

- Recent neutrino experiments have been very successful in advancing the state of knowledge of reactor antineutrino emissions, most notably by uncovering the reactor flux and spectrum anomalies.
- 2020: STEREO confirmed 5-6% U-235 yield deficit from historical HEU experiments

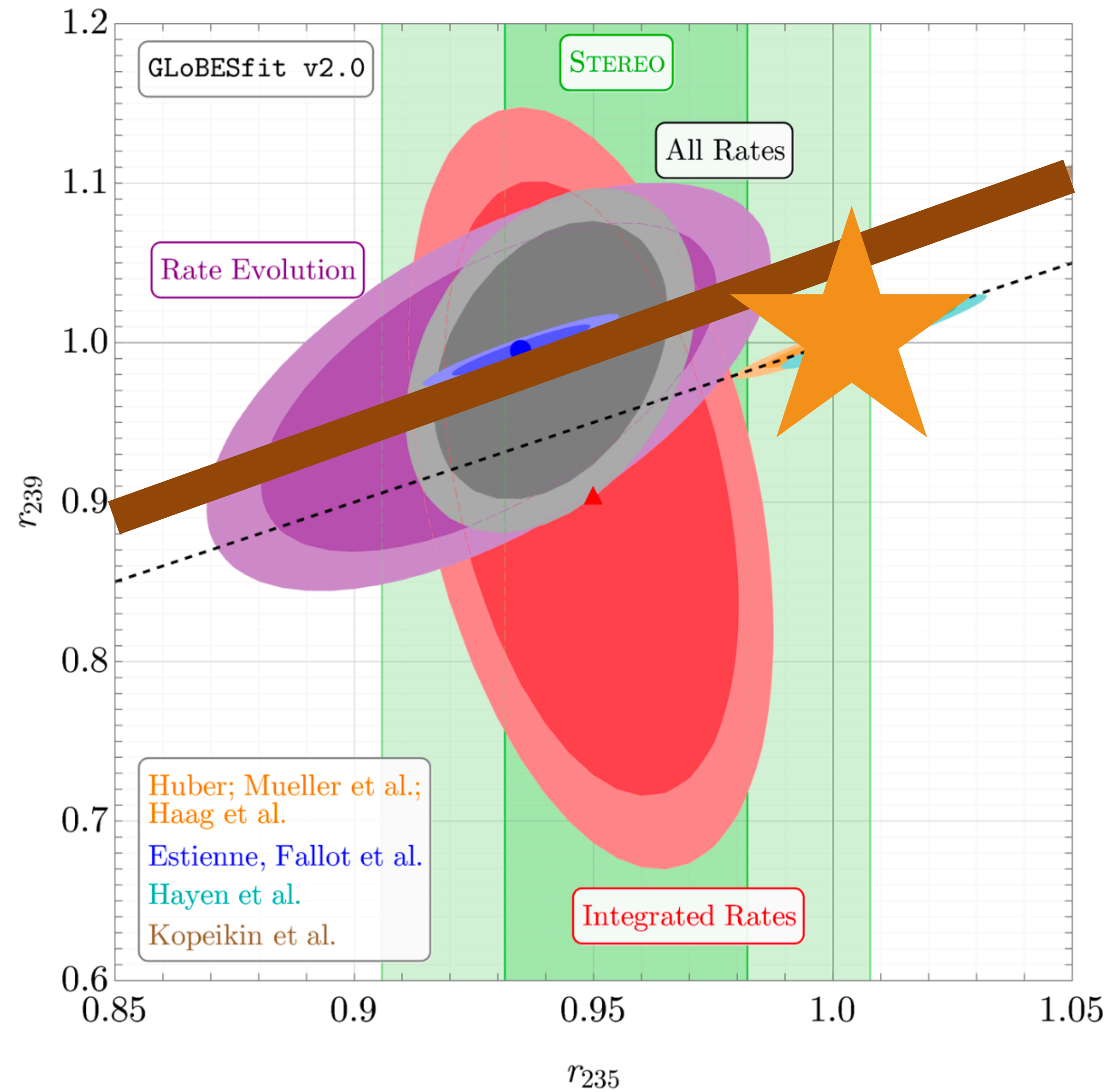


[STEREO, PRL 125 (2020)](#)

Why We Are Here: Flux

- Recent neutrino experiments have been very successful in advancing the state of knowledge of reactor antineutrino emissions, most notably by uncovering the reactor flux and spectrum anomalies.

- 2021: Kopeikin et. al. sees lower 235 fission beta yields (235/239 ratio), specifically implicating 80's ILL measurement input to conversion prediction



Kopeikin et al, PRD 104 (2021)

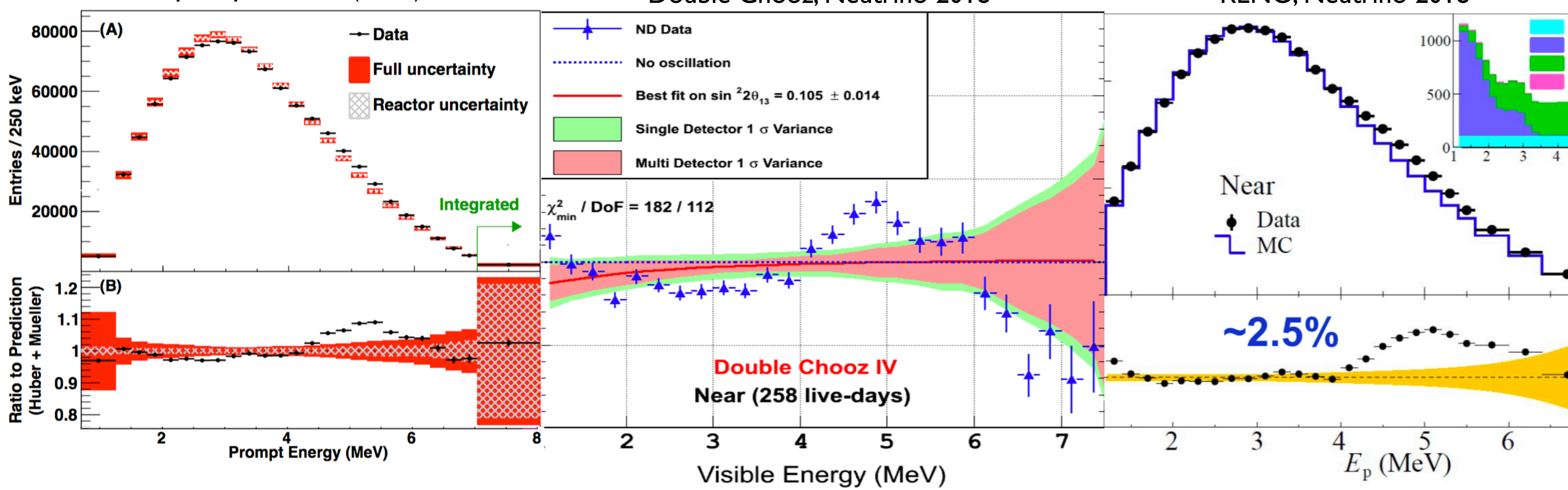
Flux: Missing Pieces

- If 1980's U-235 fission beta yield is really to blame for the flux anomaly, why isn't STEREO's HEU deficit larger than the LEU-measured deficit?
  - Could predicted U-238 IBD yield also be too high? [Gebre, Surukuchi, BRL, PRD 97 (2018)]
- How do we further reduce error bars on measured IBD yields?
  - Single-core LEU measurements (DANSS, NEOS-II, or PROSPECT-II-LEU)?
  - Correlated HEU - LEU measurements (PROSPECT-II-LEU)?
  - Can we enhance focus on sub-dominant isotopes U-238, Pu-241?
- How much do we trust Kurchatov fission beta measurements?
  - Can we repeat them with improved equipment and statistics?
- Are summation-predicted fluxes of all isotopes equally reliable?
- No flux measurements exist below the 1.8 MeV IBD threshold.
  - Very-low-threshold CEvNS detectors are the only option here

Why We Are Here: Spectrum

- 2014: θ_{13} experiments, RENO, Double Chooz, and Daya Bay, observe different spectrum than predicted by conversion predictions — 'the bump.'

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

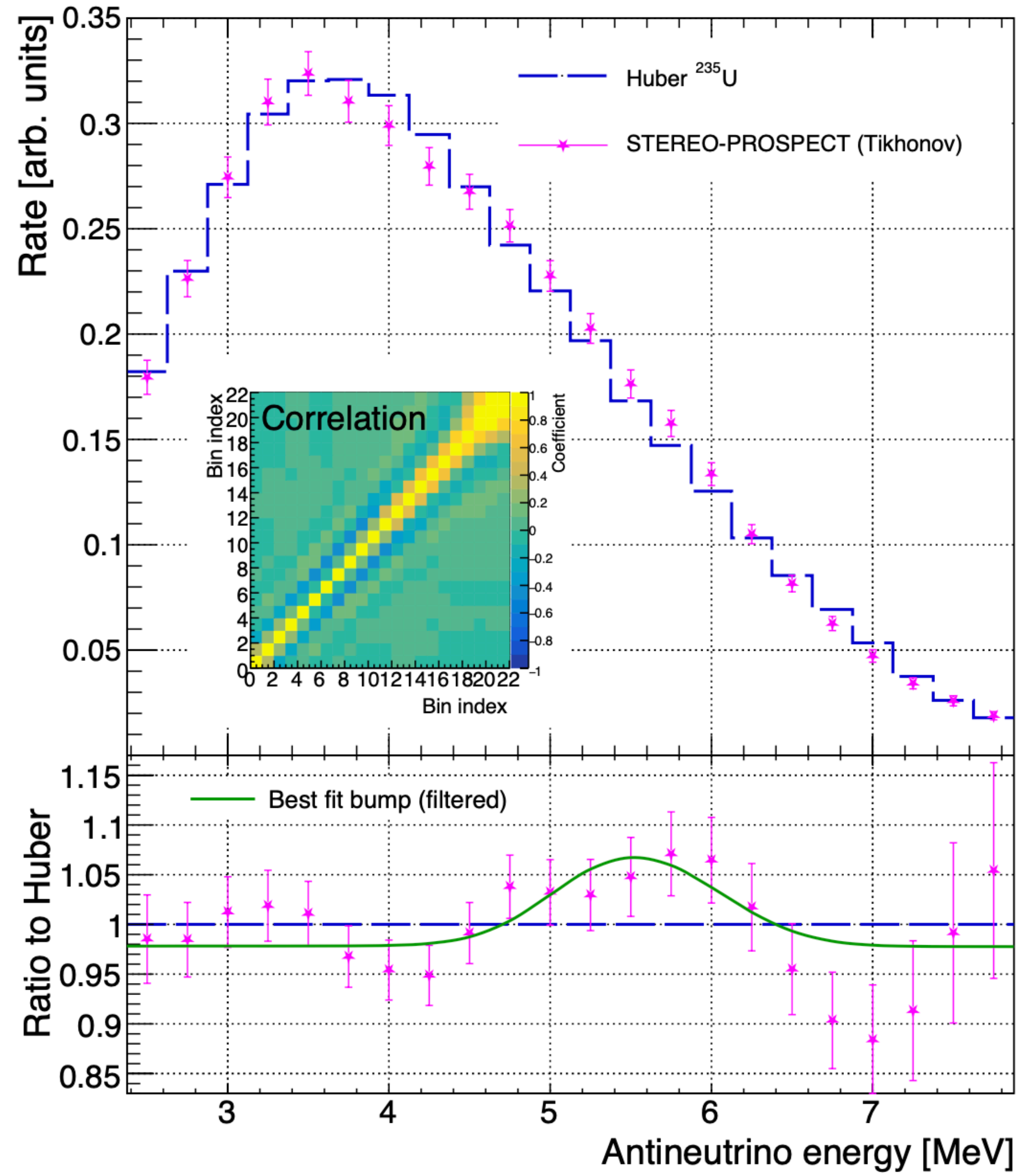


[RENO and Double Chooz: Neutrino 2014](#)

[Daya Bay: ICHEP 2014](#)

Why We Are Here: Spectrum

- 2018: PROSPECT observes a ‘bump’ when measuring only U-235 at an HEU
  - 2020: STEREO confirms this at its HEU reactor
  - 2019: first ‘spectrum evolution’ measurement from Daya Bay also shows clear bump from U-235



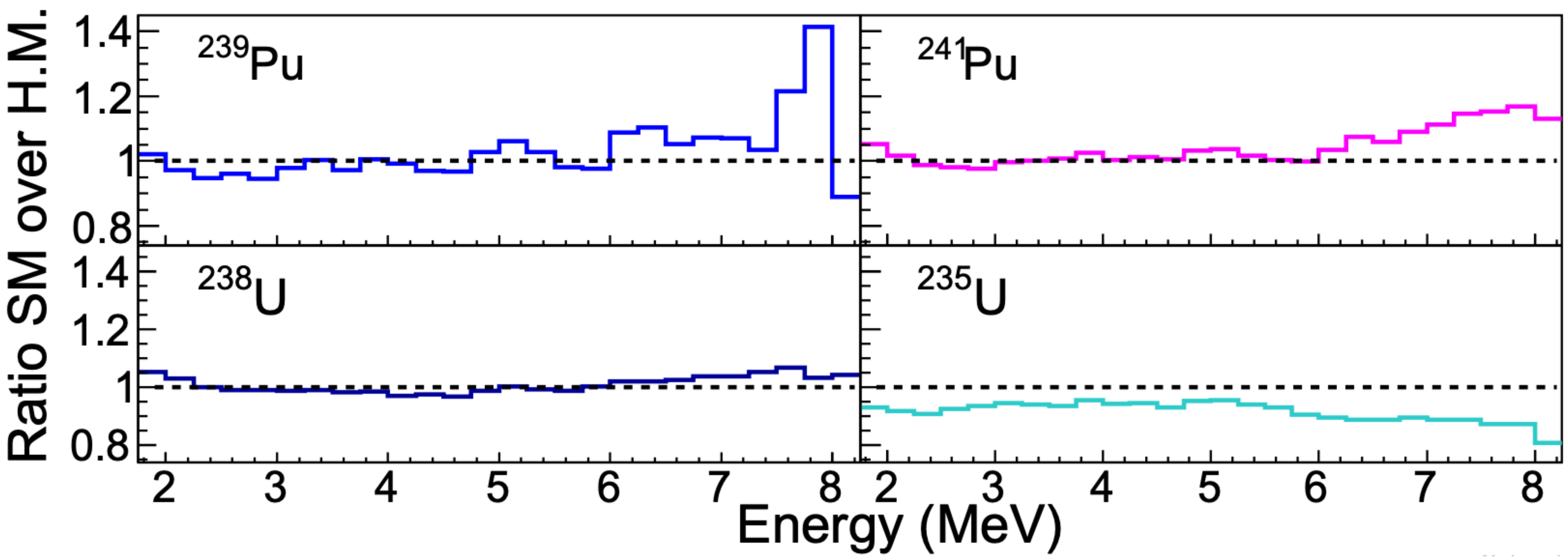
[PROSPECT, PRL 122 (2019)](#)

[STEREO, J Phys G 48 (2021)](#)

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

Why We Are Here: Spectrum

- 2019: Improved TAGS data doesn't improve summation-predicted spectrum's agreement with data.
  - Both conversion and summation predicted spectra now show similar data-model disagreement.
  - Possibly implicates theory assumption(s) common to both theory approaches? Beta spectrum shapes maybe?

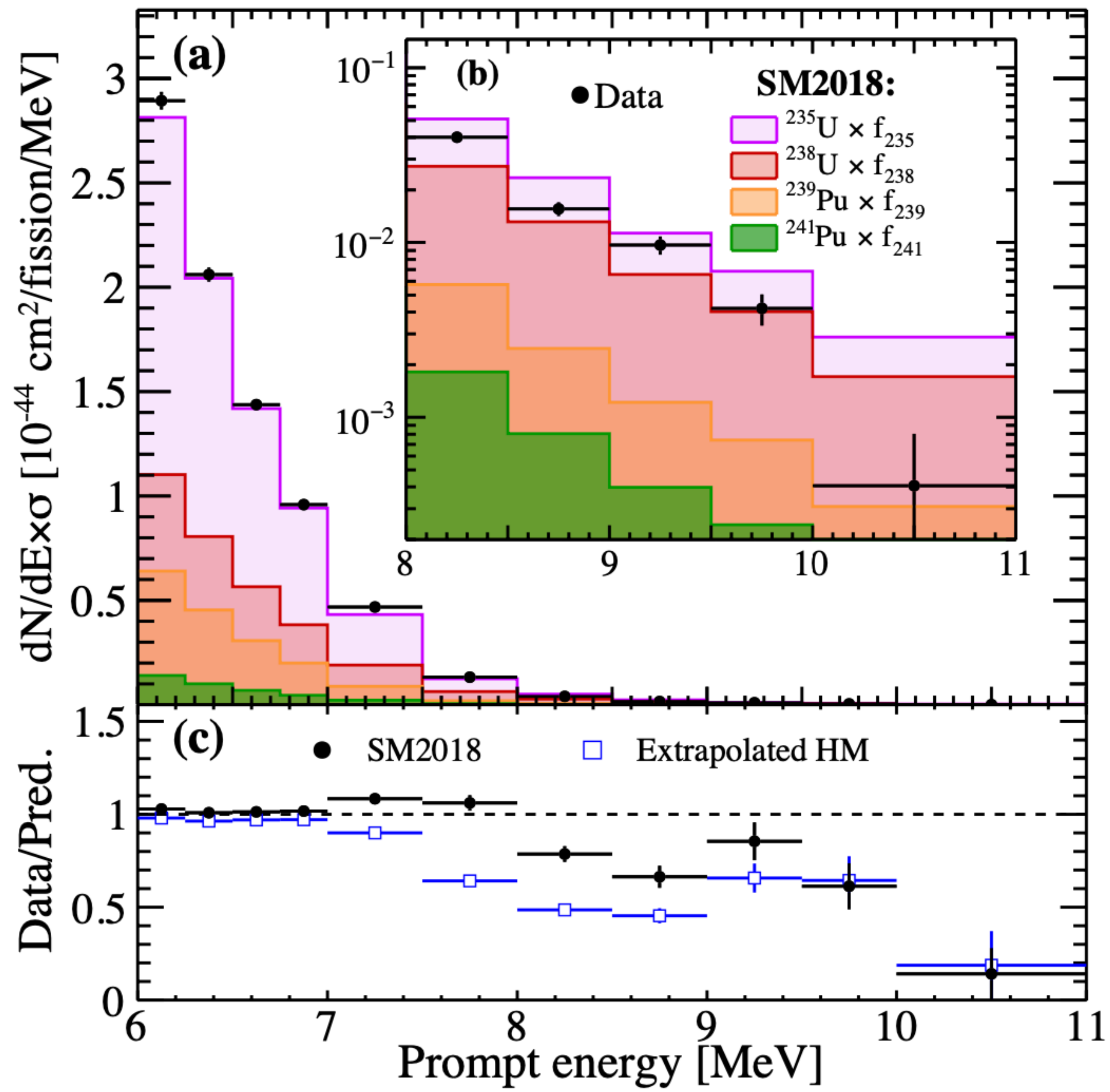


Many TAGS citations from EU and US

[Estienne et. al., PRL 123 (2019)](#)

Why We Are Here: Spectrum

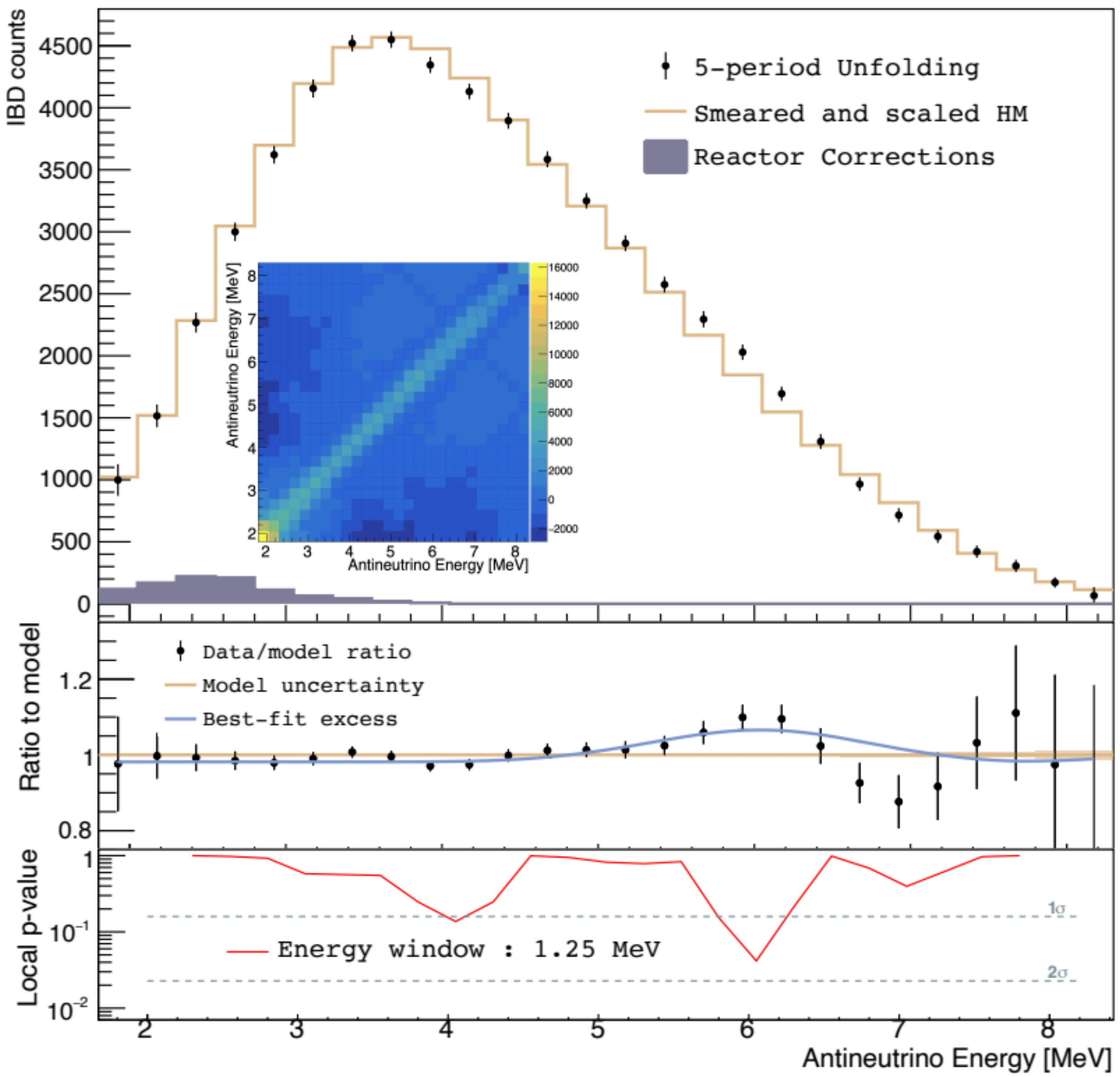
- 2022: Daya Bay high-energy spectrum shows large spectral deficit with respect to summation predictions.
  - Suggests that bad nuclear data (beta feedings?) are still out there for high-Q isotopes
  - …like perhaps some important delayed neutron emitters?

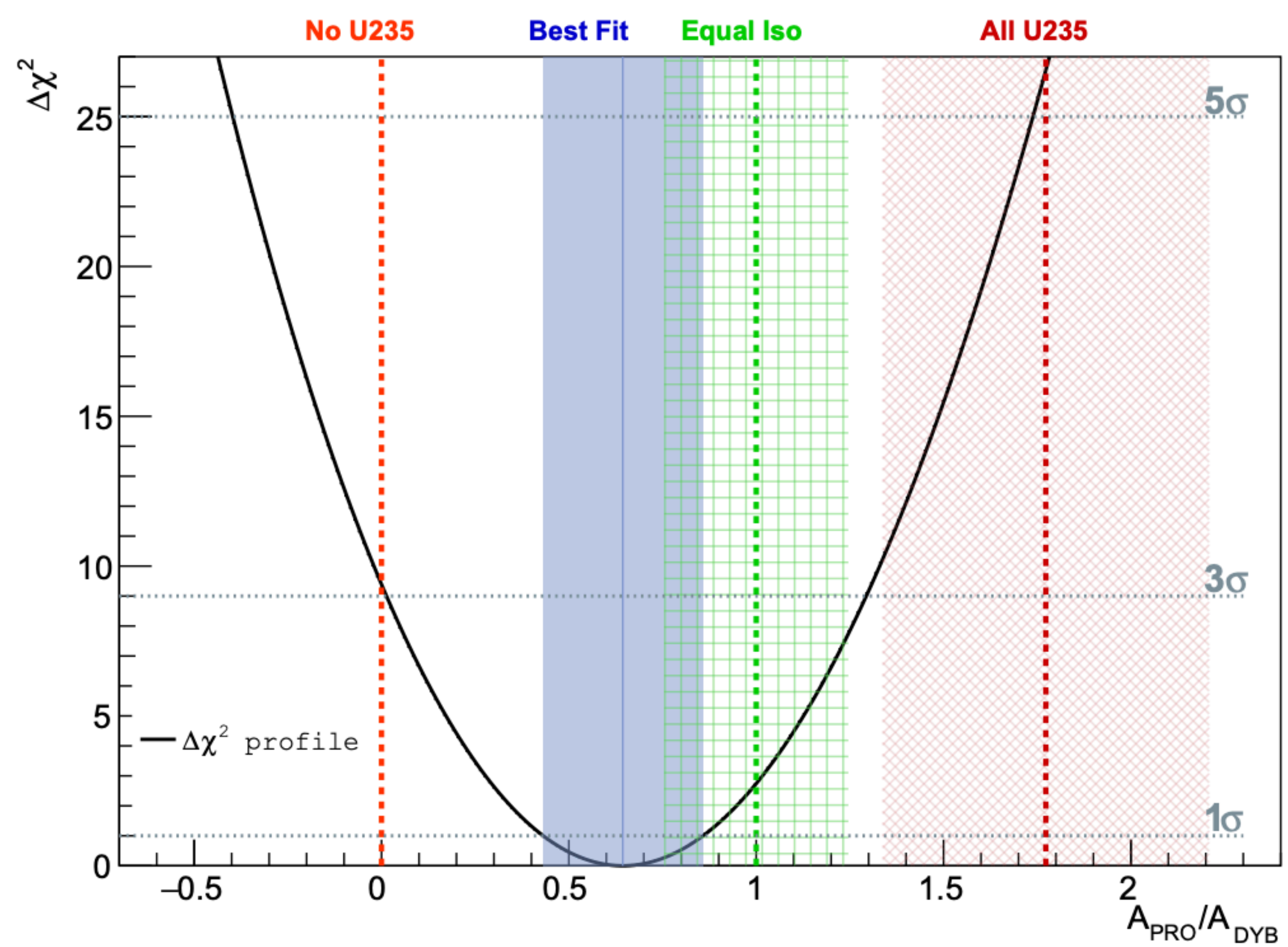


[Daya Bay, PRL 129 (2020)](#)

Why We Are Here: Spectrum

- 2023: Strong support for 'equal isotope' bump origin from final PROSPECT dataset
  - Have reached systematic limitations: uncorrelated LEU - HEU detector systematics limit ability to improve understanding further





PROSPECT, hep-ex[2212.10669]

Spectrum: Missing Pieces

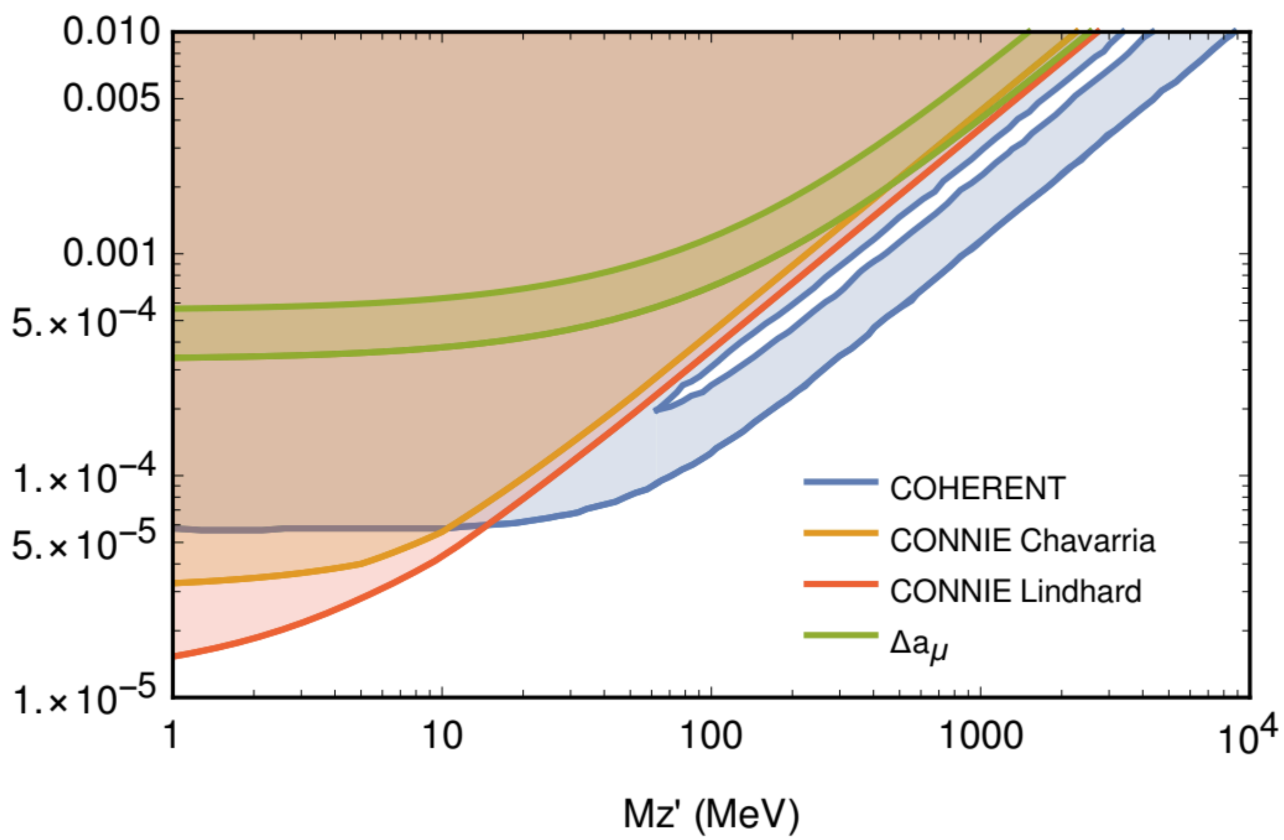
- We still don't know what's causing 'the bump.'
  - We have suspicions (beta spectrum shape mis-modeling?), but no direct results to back them up at this point.
  - Other approaches for poorly-understood isotopes?

A. Latourneau, et al, hep-ph[2205.14954]

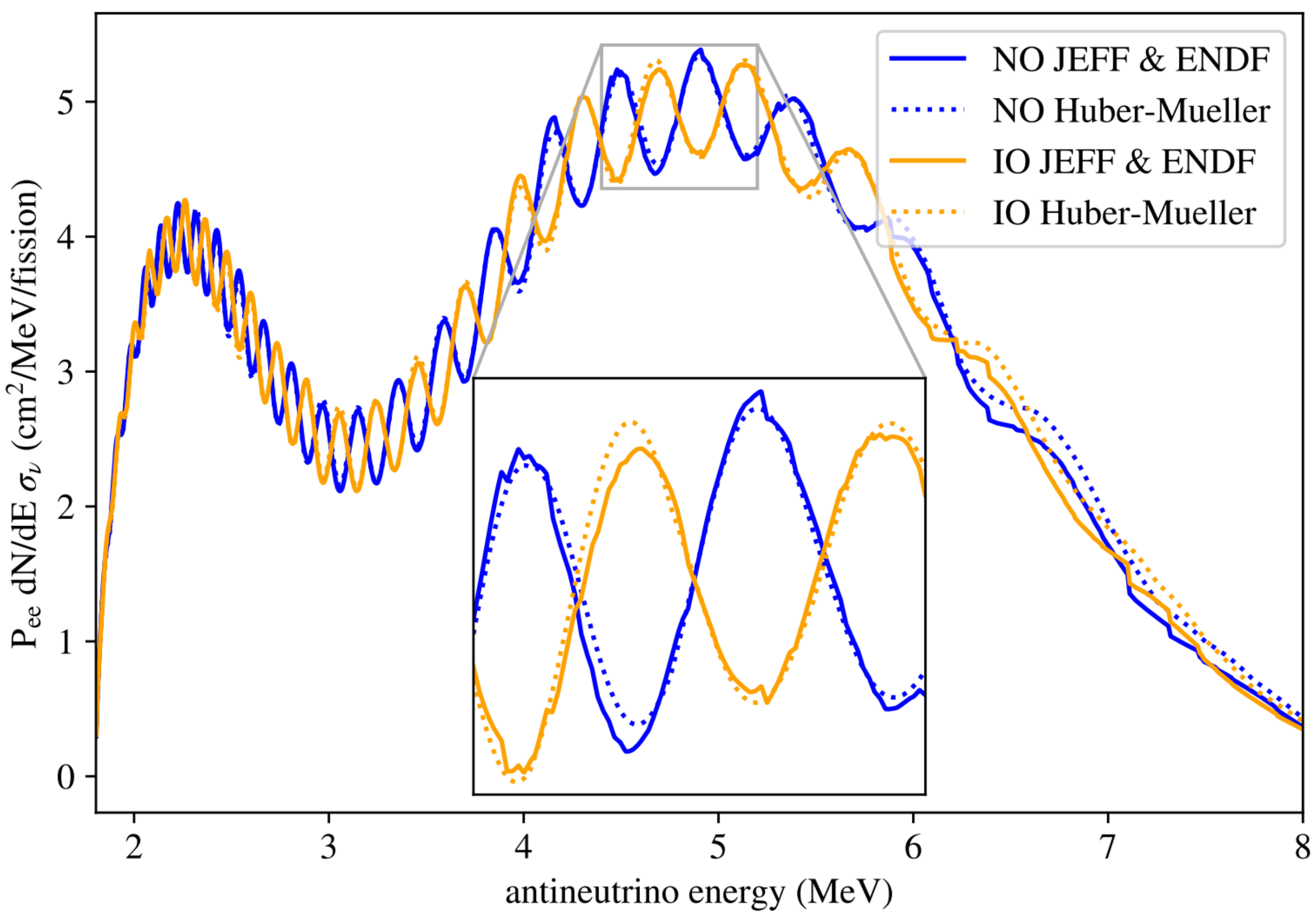
- Seems likely that pandemonium-affected data is still present in databases (certainly for high-Q isotopes?)
  - Could be remedied with further TAGS efforts
- We still any lack very-high-resolution IBD measurements
  - TAO may remedy this in the near future
  - Could uncover other 'bumps' or 'problem regions' in the process?
- Further direct interrogation of isotopic antineutrino spectra is limited by relative detector systematics
  - Can we get enhanced correlated HEU-LEU or 'spectrum evolution' datasets?

Flux/Spectrum-Dependent Particle Physics

- "Precise knowledge of the total magnitude and energy spectrum of reactor antineutrino emissions is a vital ingredient in performing some future neutrino physics measurements."
- Examples:
    - Future BSM measurements with reactor CEvNS: currently bkg- limited, ultimately flux-model-limited
    - Neutrino mass ordering (maybe?)



Hayes, Danielson, Garvey PRD 99 (2018)

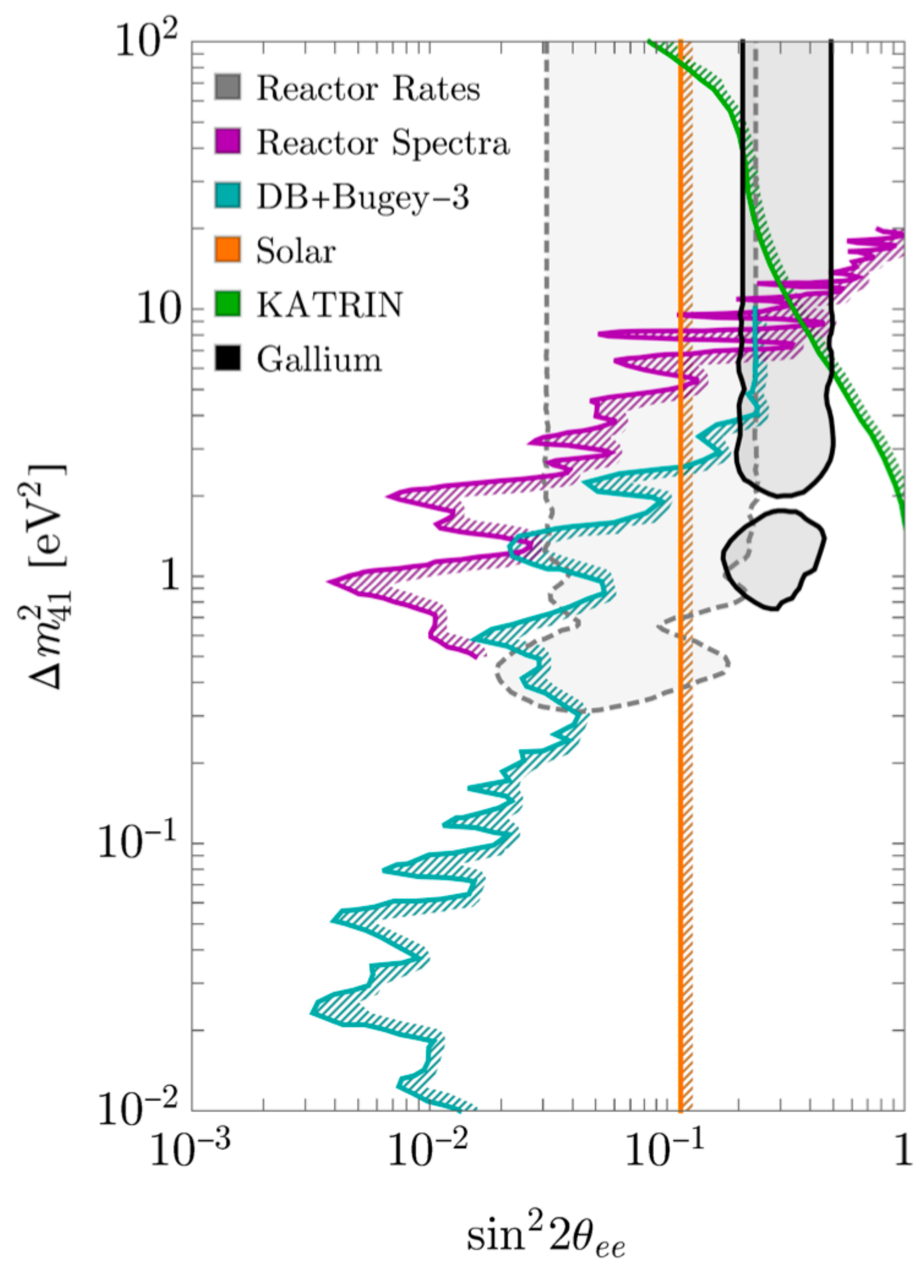


Flux/Spectrum-Agnostic Particle Physics

- OTOH, some neutrino physics is accessible at reactors with little or no knowledge of absolute flux/spectrum
  - Sterile neutrinos: "By performing correlated measurements of *IBD* spectra at multiple short baselines, reactor experiments offer a low-cost method for unambiguously probing non-standard neutrino flavor transformation"
  - Some Standard-Model mixing parameters: "In the next half-decade, reactor antineutrino experiments are expected to provide the world's best estimate for the foreseeable future of 4 out of 6 oscillation parameters"

	Δm^2_{31}	Δm^2_{21}	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$
JUNO 6 years	~0.2%	~0.3%	~0.5%	~12%
PDG2020	1.4%	2.4%	4.2%	3.2%

Daya Bay + RENO + DoubleChooz



Flux/Spectrum-Dependent Applied Physics

- "There are strong synergies between the future scientific goals, nuclear data needs, and technology pathways of [fundamental neutrino physics and neutrino-based nonproliferation applications]."
  - Examples: "Spectrum evolution" measurements provide a pathway for remotely monitoring/verifying a reactor's fissile content, while flux measurements can provide on-off verification and power load following
- Use case studies and robust monitoring regimes require reliable 'reference spectra'
  - Vice versa: applications-oriented prototypes can <u>provide</u> these reference spectra for the rest of the community
  - HEU and LEU reference spectra exist, but may not be sufficient for, i.e., advanced reactor safeguards scenarios

Enabling Technologies

- For realizing reactor CEvNS: low-threshold technology
  - Phonon detectors, solid-state ionization detectors, high-efficiency scintillators, radiation damage detectors
- For improving reactor IBD: low-background IBD counting
  - Highly segmented, PSD-capable, or doped scintillators
- For applications: plastic scintillators
  - Plastic enhances mobility, robustness, and suitability for applications

Summary

- "Next-generation IBD and non-IBD experiments are poised to improve their reactor flux and spectrum measurement precision beyond the associated modeling uncertainties, enabling data-driven improvements to reactor and nuclear physics."
- I am sure we will have a good conversation this week where we are at, and where we want to go in the future!