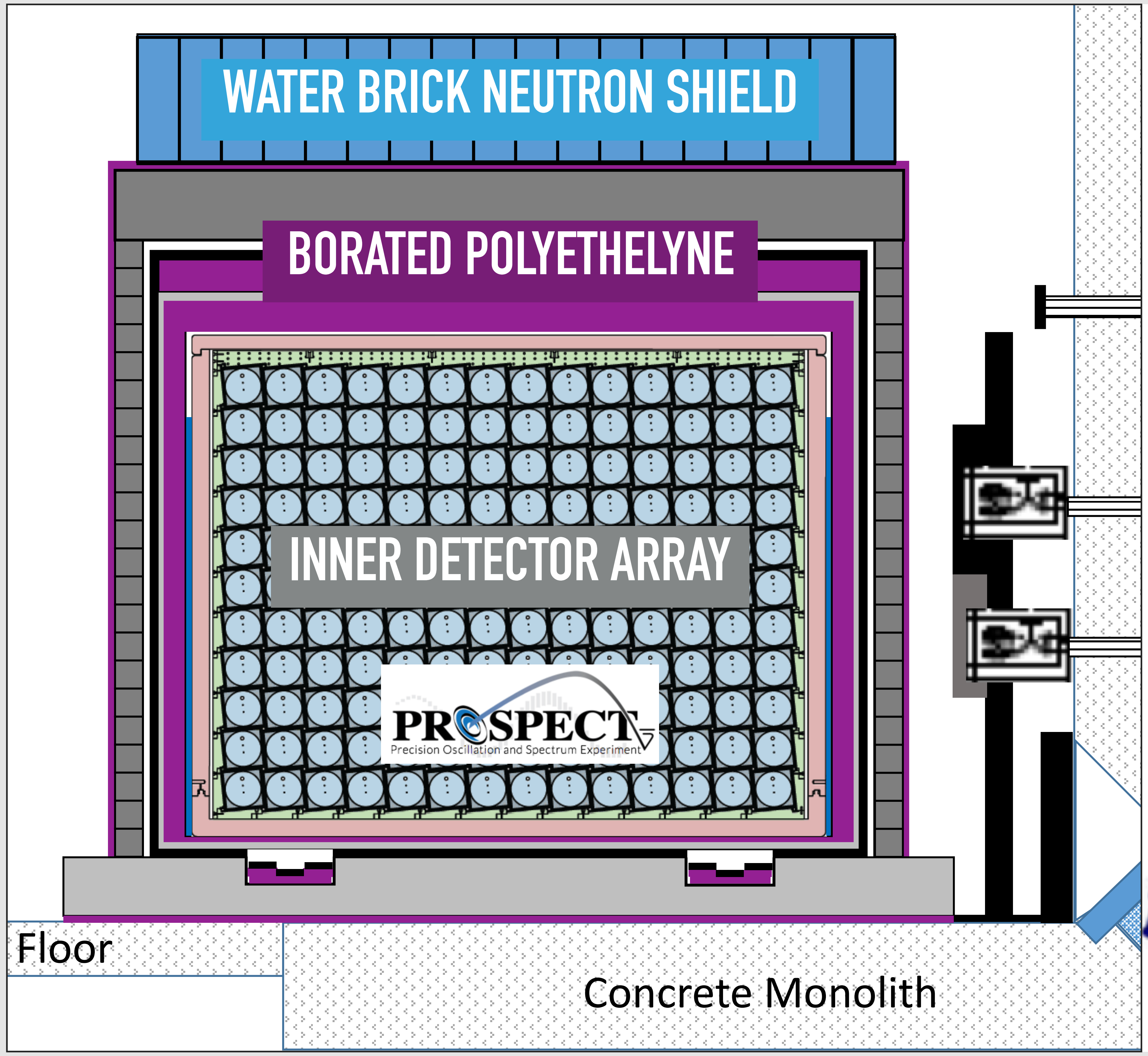
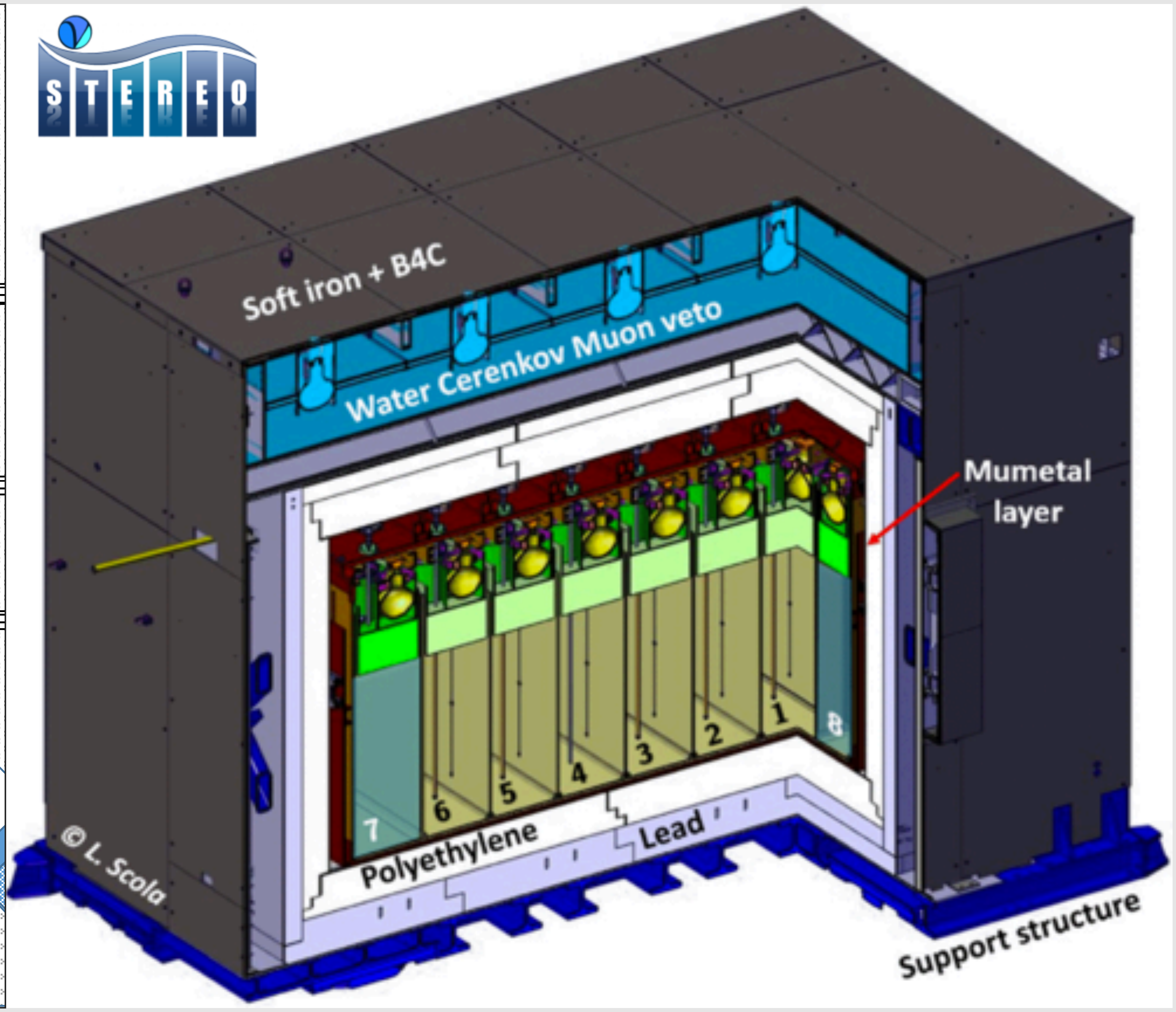
JOINT MEASUREMENT OF THE ^{235}U ANTINEUTRINO ENERGY SPECTRUM BY PROSPECT AND STEREO





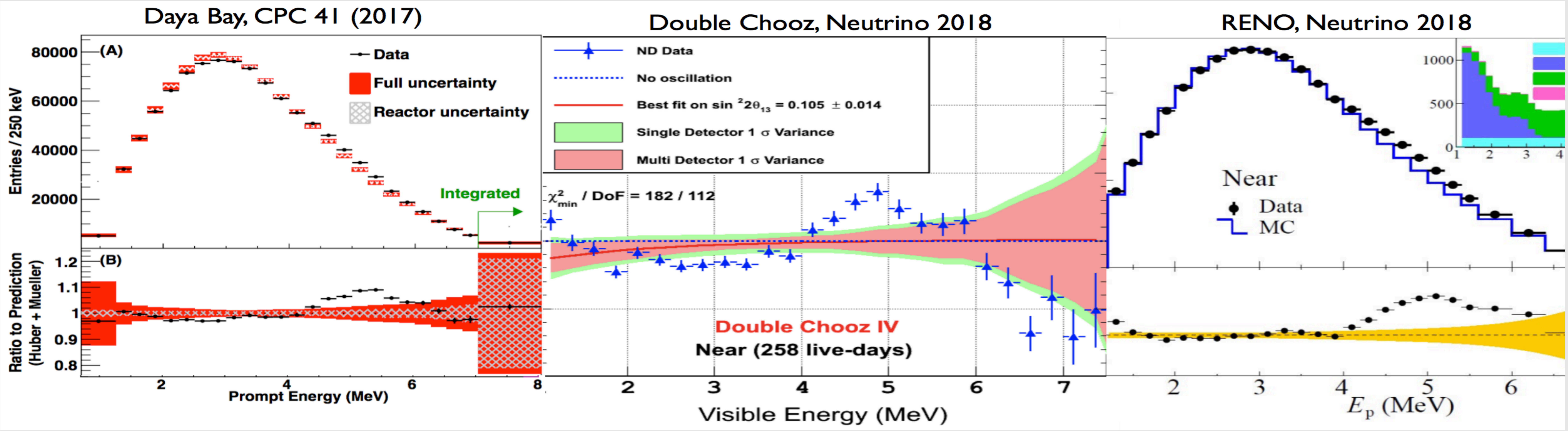
BEN FOUST
YALE UNIVERSITY
ON BEHALF OF THE PROSPECT COLLABORATION

arXiv:2107.03371

Wright Laboratory

NEUTRINO SPECTRUM MEASUREMENTS FROM POWER REACTORS

- Spectrum models don't match experimental data in low enriched uranium (LEU) power reactors
  - Poor fit overall to leading reactor models (Huber/Mueller).
  - 'Bump' in 4-6 MeV (prompt energy) range
  - Neutrino events come from a mixture of fissile isotopes: ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu
- Need new reactor data to clarify source of deviations

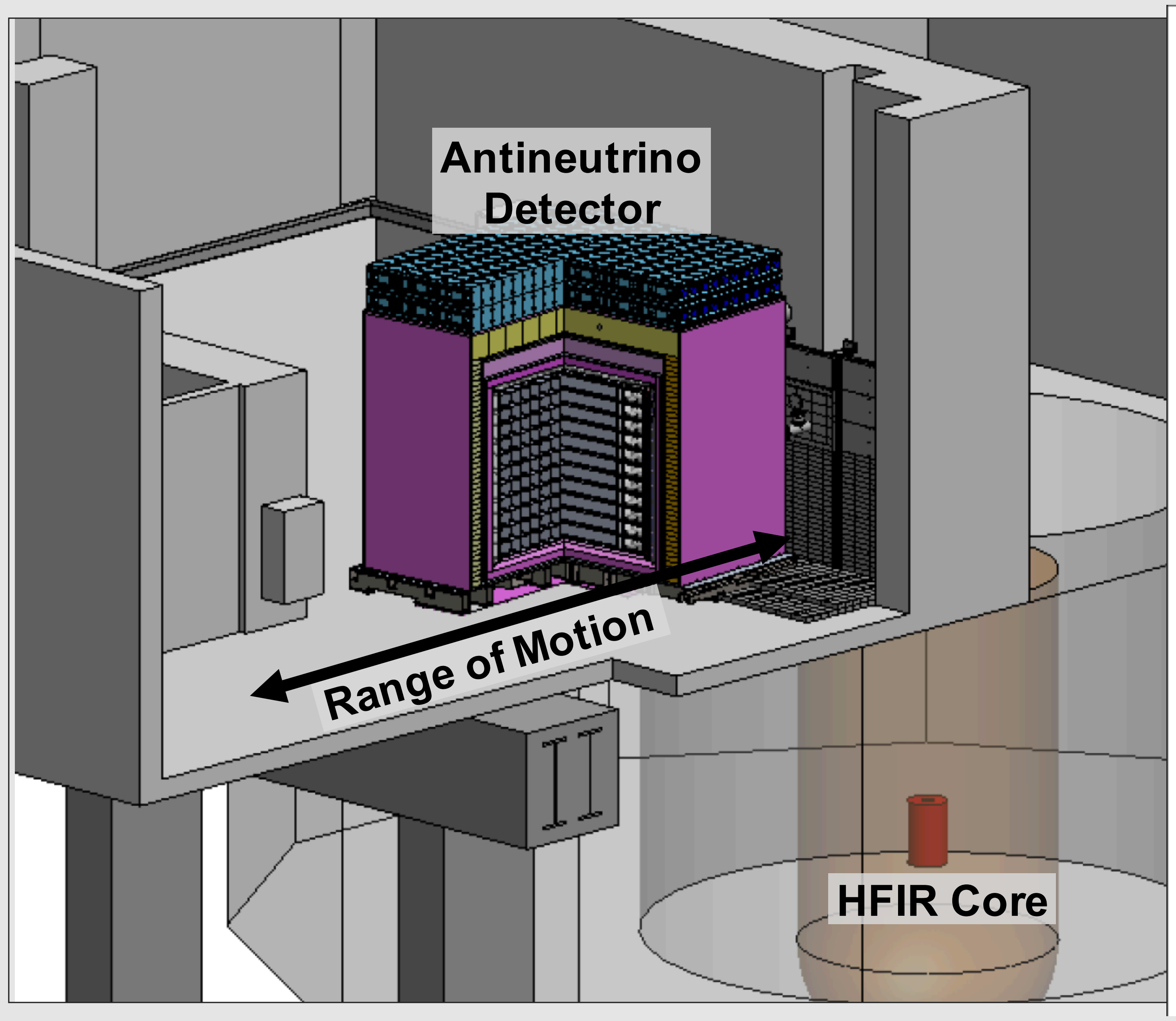


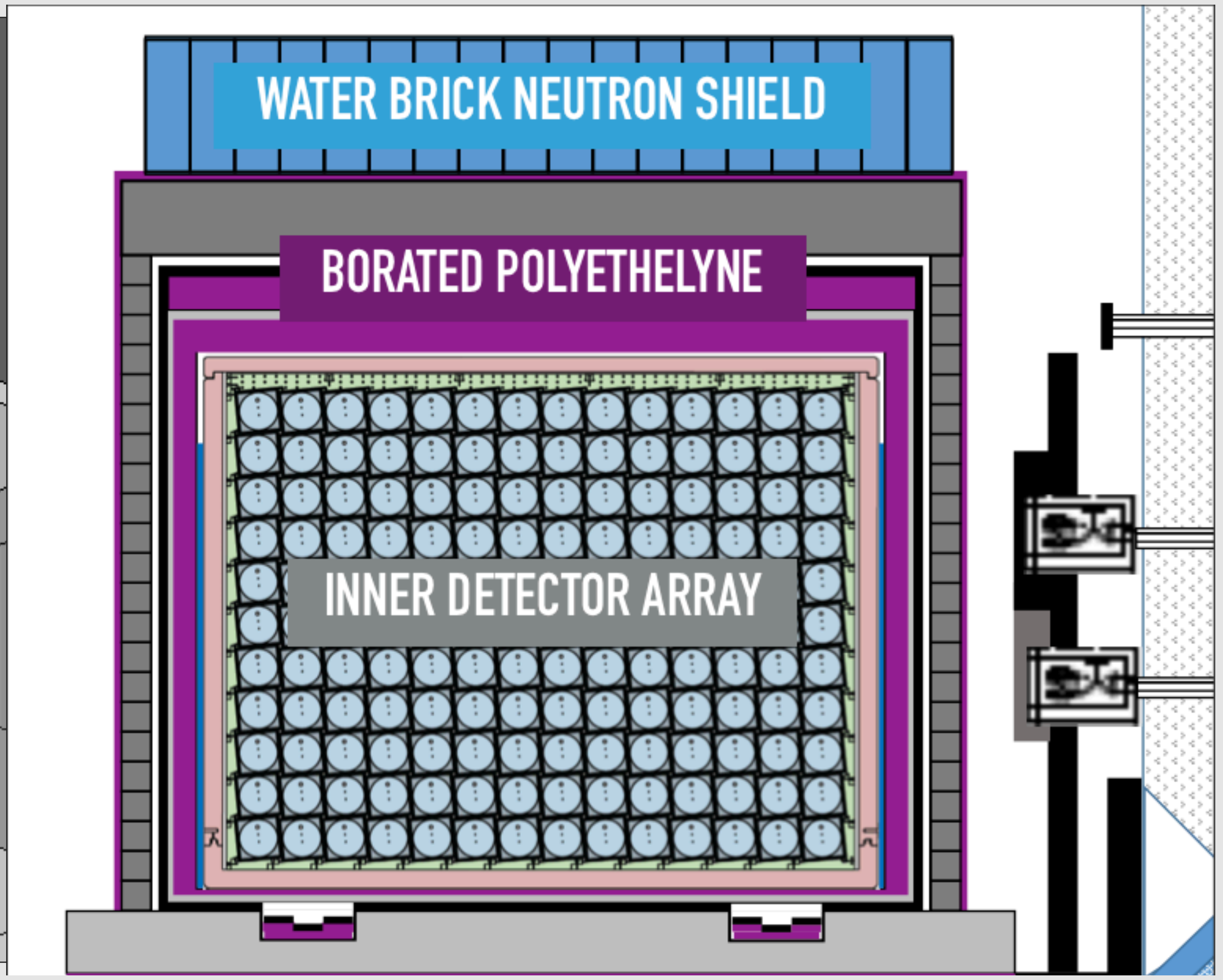
WHY A JOINT MEASUREMENT

- Reactor models do not provide a sufficient prediction of the antineutrino spectrum
- PROSPECT and STEREO are the leading measurements of the pure ^{235}U spectrum without significant contributions from other isotopes
- Both experiments' spectrum measurements are still statistics limited with relatively low systematic uncertainties
- By combining the measurements, we can increase the statistical power and produce a reference spectrum of ^{235}U for use by the community

THE PROSPECT EXPERIMENT

- Experimental Site (HFIR, ORNL):
  - 85 MW HEU reactor core with 46% duty cycle
  - >99% of $\bar{\nu}_e$ flux from ^{235}U fissions
- Detector Design
  - Segmented design for calibration access
  - Optimized for background suppression
  - Particle identification with pulse shape discrimination



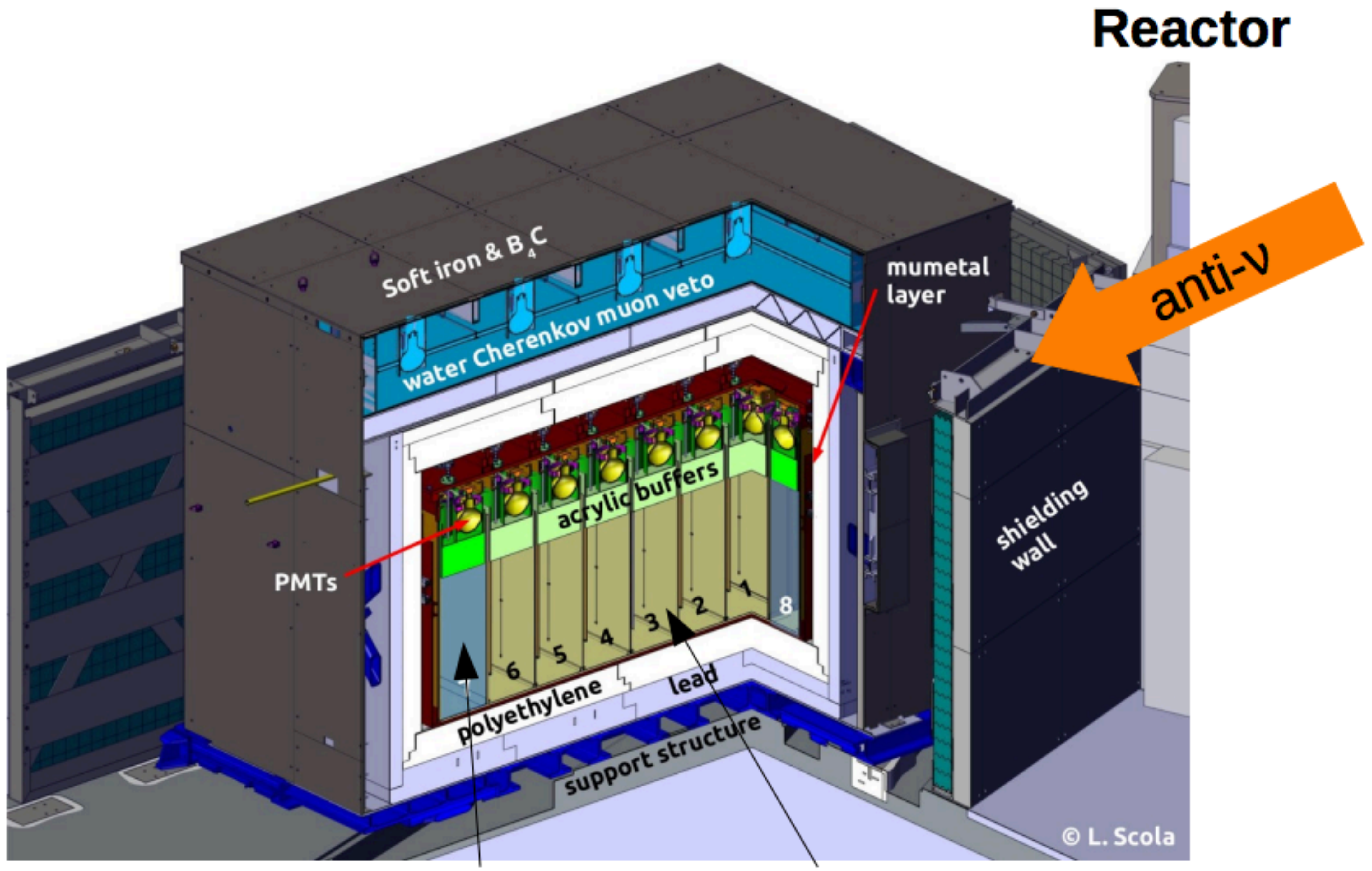


J. Ashenfelter et al., NIM A 2018.12.079

https://prospect.yale.edu/

THE STEREO EXPERIMENT

- Experimental site (RHF, ILL):
  - 58 MW HEU reactor
  - Compact core
  - >99% of flux from ^{235}U fissions
- Detector Design:
  - 6 fiducial cells
  - Liq. Scintillator + Gd
  - Pulse shape discrimination



Gamma-Catcher: unloaded liquid scintillator **Target**: Gd-loaded liquid scintillator

arxiv:2010.01876

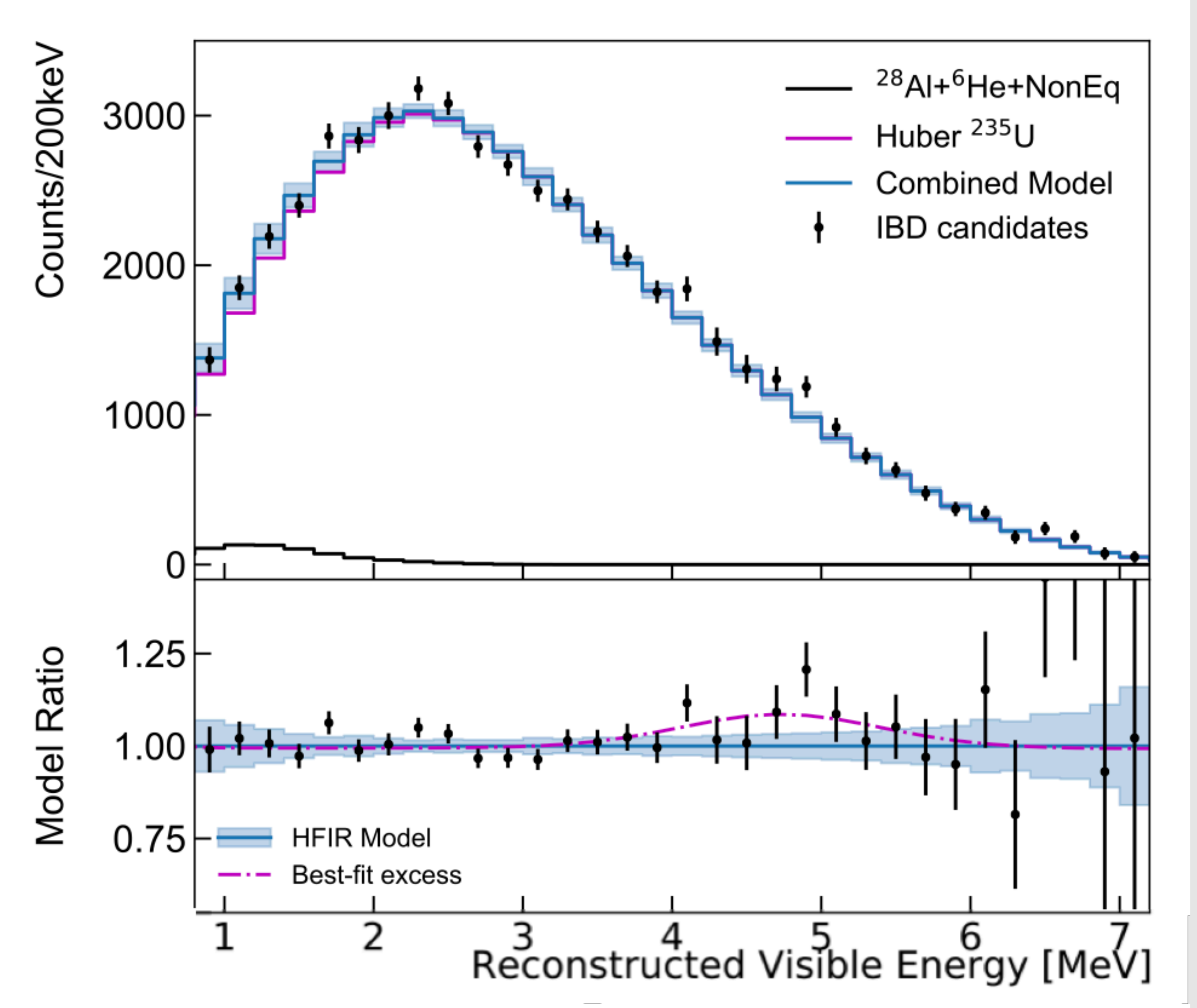
https://www.stereo-experiment.org/

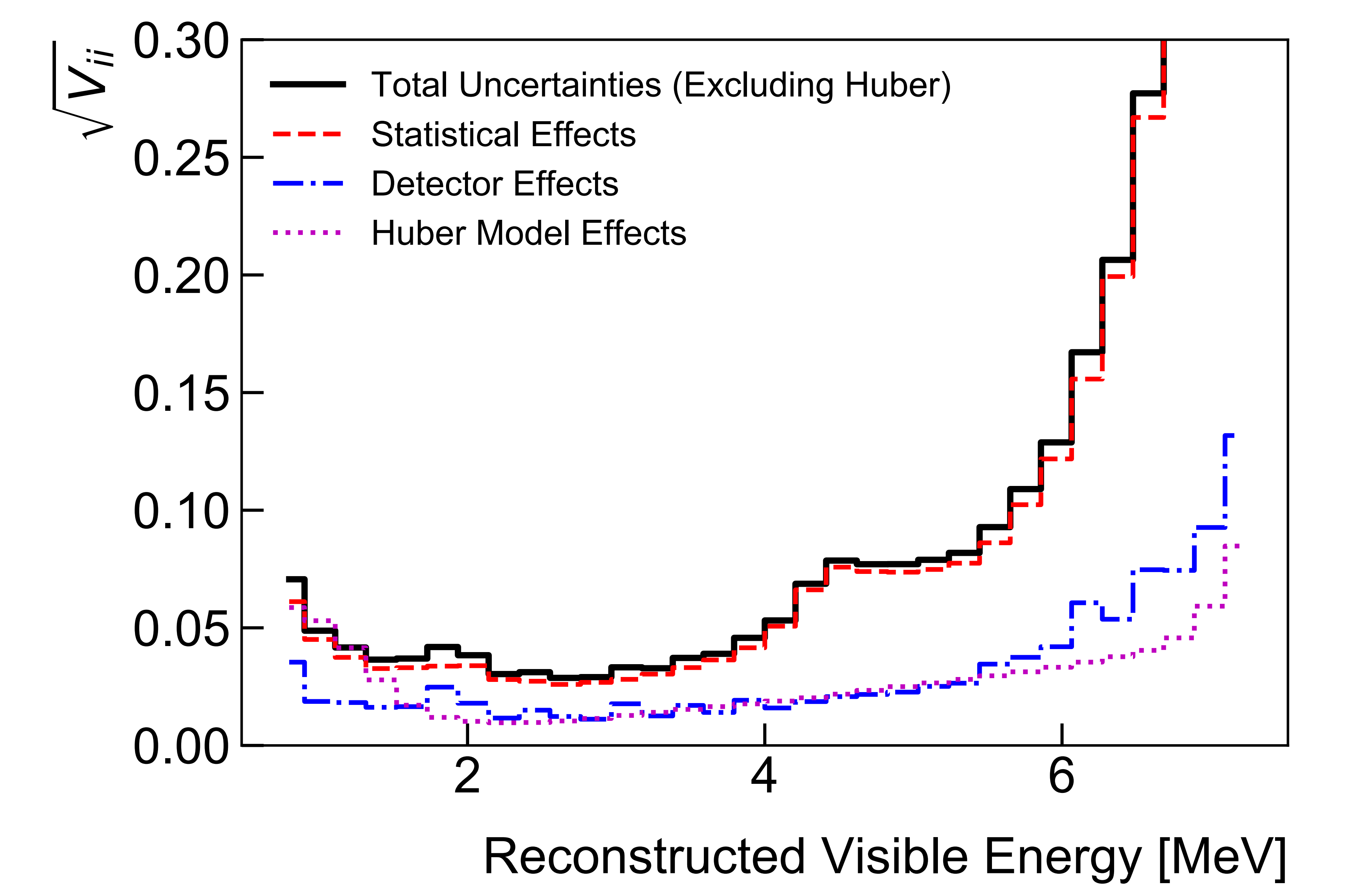
PROSPECT PROMPT SPECTRUM

- 50560 +/- 406 IBD signal events
- Best fit bump size relative to Daya Bay: 84% +/- 39%
- Disfavor both 'No ^{235}U Contribution to' and 'Only ^{235}U Contributes to' LEU bump cases at $>2\sigma$
- Still statistics limited

[M. Andriamirado et al., Phys Rev D 103, 032001](https://prospect.yale.edu/)

https://prospect.yale.edu/



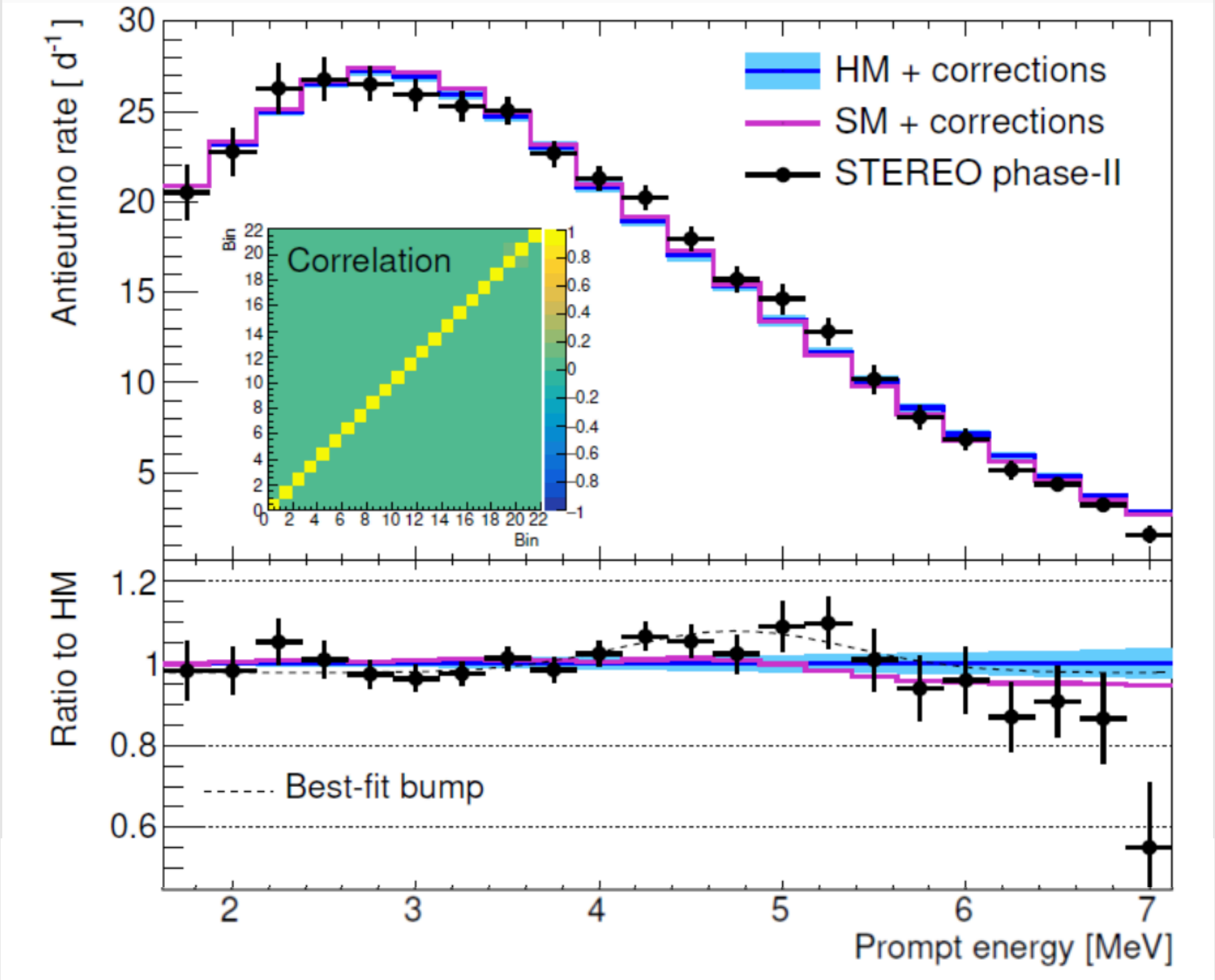


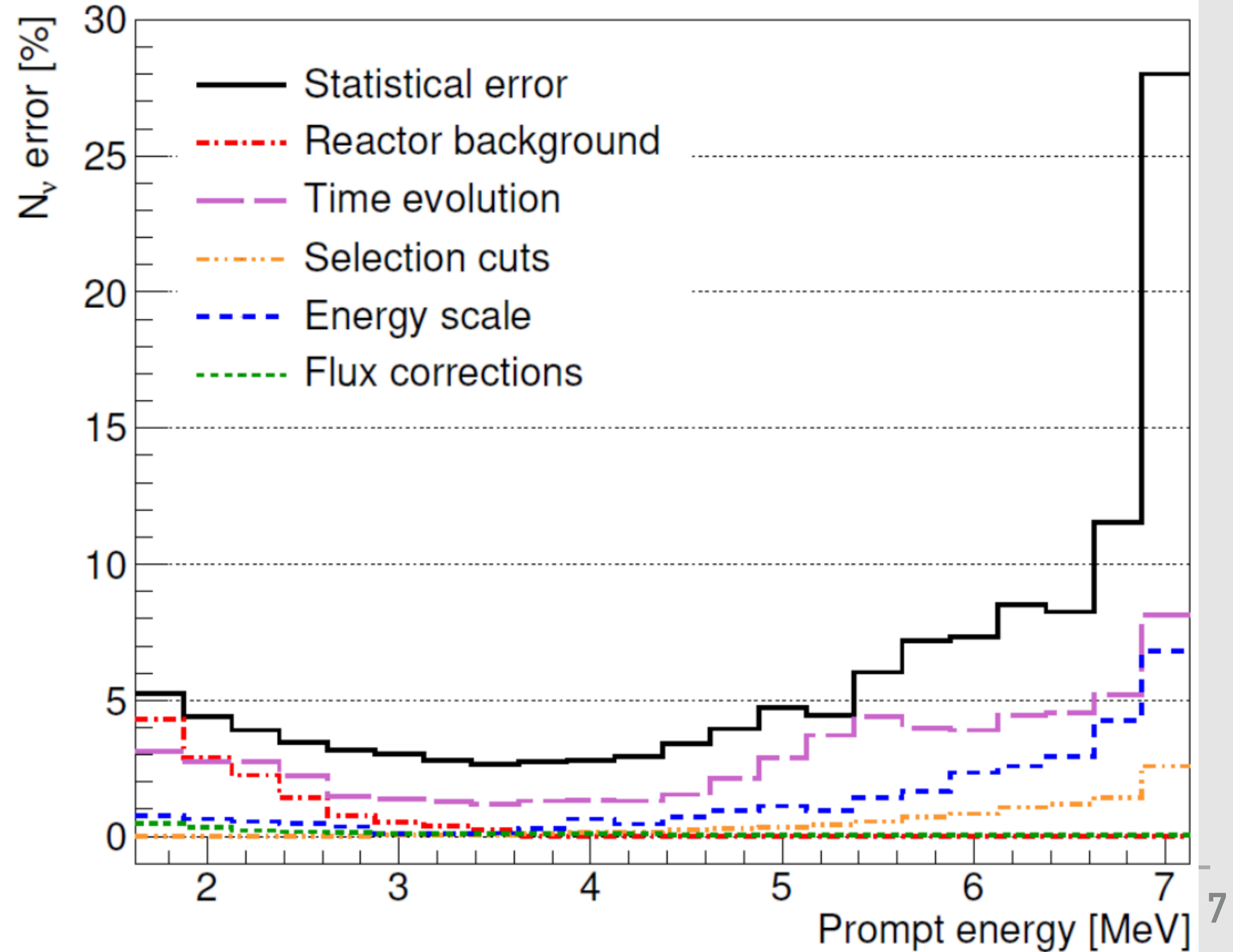
STEREO'S PROMPT SPECTRUM

- 43,000 Antineutrinos detected
- Significant bump observed in antineutrino energy: $A = 12.1 \pm 3.4\,\%$ (3.5σ) of spectrum at peak
- Findings consistent with case of ^{235}U equally contributing to LEU bump
- Still statistics limited

arxiv:2010.01876

https://www.stereo-experiment.org/





PROMPT COMPATIBILITY

- Prompt comparison avoids uncertainties of filtered unfolding!
- Move one experiment's data into the prompt space of the other with unfiltered unfolding, then refolding with the other's response

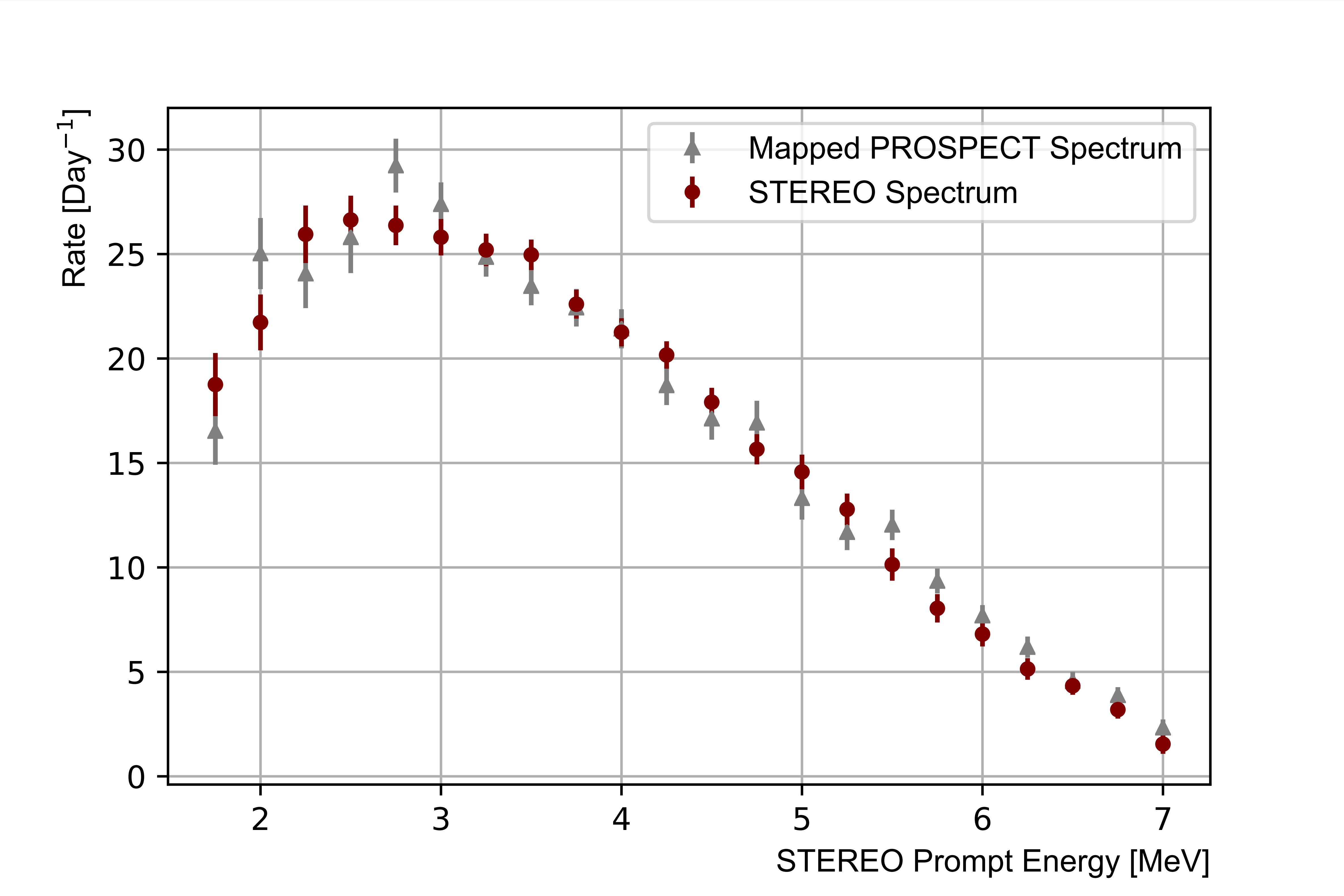
$$R_{map} = R_{STE} \cdot R_{PRO}^{-1}$$

$$M_{map} = R_{map} \cdot M_{PRO}$$

- Fit spectra with free floating normalization

$$\chi^2/ndf = 24.1/21$$

▶ Statistically Compatible Inputs



ANALYSIS METHOD: DATA UNFOLDING

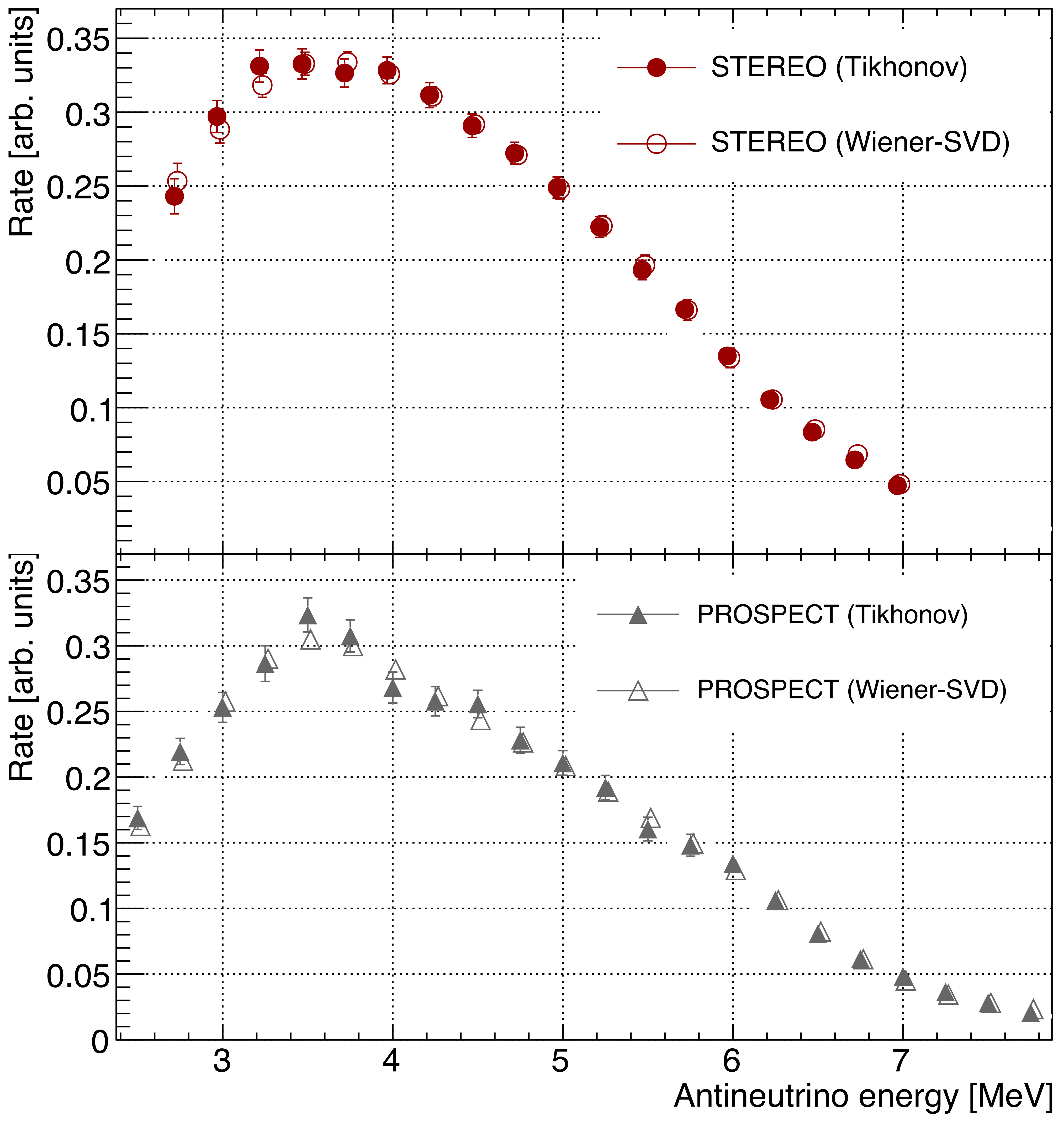
- To create a measurement independent of factors unique to each experiment, we must convert from the prompt space of each to true antineutrino energy space via ‘unfolding’
- Ideal Case: $M = R \times S \Rightarrow S = R^{-1} \times M$
  - S = true signal in neutrino energy
  - R = response matrix
  - M = measured signal in prompt energy
- Realistically:
  - R not necessarily invertible
  - M has non-signal noise elements which are blown out of proportions by R^{-1}

COMPARISON OF FRAMEWORKS

- Framework Validation:

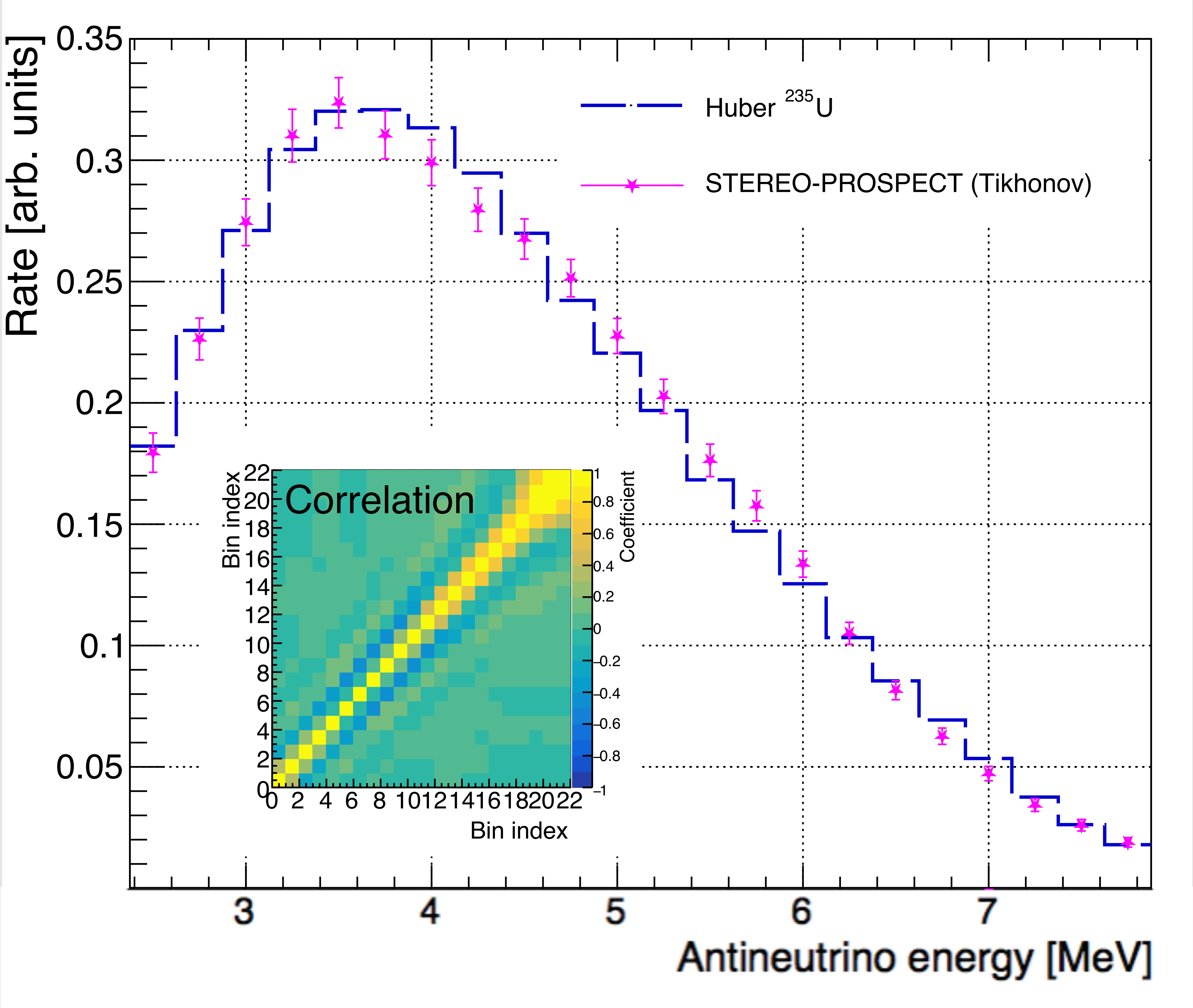
1. STEREO's Tikhonov regularization
2. PROSPECT's WienerSVD unfolding method

Cross-checked and Consistent Results



UNFOLDED SPECTRUM

- Use the Tikhonov method to present result
- Using a free floating normalization, best fit to Huber model gives $\chi^2/ndf = 30.8/21$



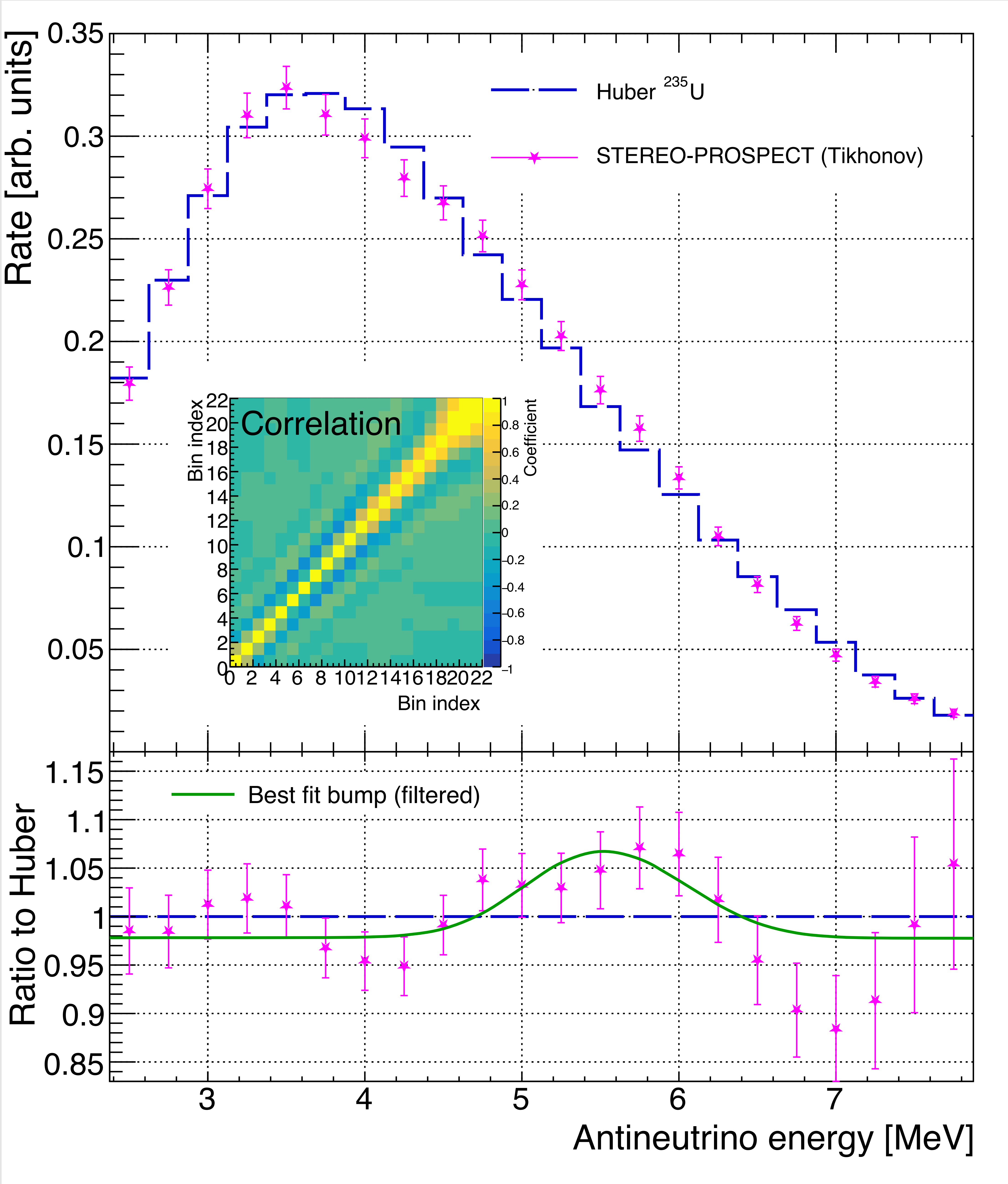
- Results available (arXiv:2107.03371)
- Thorough supplemental materials, including filter matrix
- Can be directly compared to ^{235}U model predictions

BUMP SEARCH

- Find an excess in the 5-6 MeV range
- Fit a Gaussian with free amplitude, mu, and sigma values to the excess
- The addition of the best-fit Gaussian to the Huber model gives $\Delta\chi^2/\Delta ndf = 12.0/3$ $(2.4\sigma$ significance)
- Consistent with the Daya Bay 235U spectrum in shape-only comparison ($\chi^2/ndf = 21.0/21$)

▶ Find an excess with significance 2.4σ

▶ Consistent with ^{235}U equally contributing to LEU excess



CLOSING STATEMENTS

- New results posted to arxiv just last week!

arXiv:2107.03371

- PROSPECT and STEREO datasets found to be statistically compatible
- PROSPECT and STEREO have successfully combined their separately measured high precision ^{235}U spectra
- The publication of the jointly unfolded result includes filter matrix for comparing to ^{235}U antineutrino models, can be used as a reference spectrum by community
- Find an excess with 2.4σ significance in the 5-6 MeV energy range


PROSPECT
prospect.yale.edu
Funding provided by:
HEISING-SIMONS FOUNDATION
U.S. DEPARTMENT OF ENERGY
GRFP
15 Institutions, 70 collaborators
BROOKHAVEN NATIONAL LABORATORY
NIST
Wright Laboratory
Lawrence Livermore National Laboratory
OAK RIDGE National Laboratory
Drexel
W&M
Yale

BACKUP SLIDES

COMPARISON TO DAYA BAY 235U SPECTRUM

- Use Daya Bay's published pure 235U spectrum (PRL 123, 111801 (2019))
- Interpolate Daya Bay's spectrum to match the joint binning
- Perform chi2 comparison, with a free-floating normalization parameter
- $\chi^2/ndf = 21.0/21$

SMEARING MATRIX

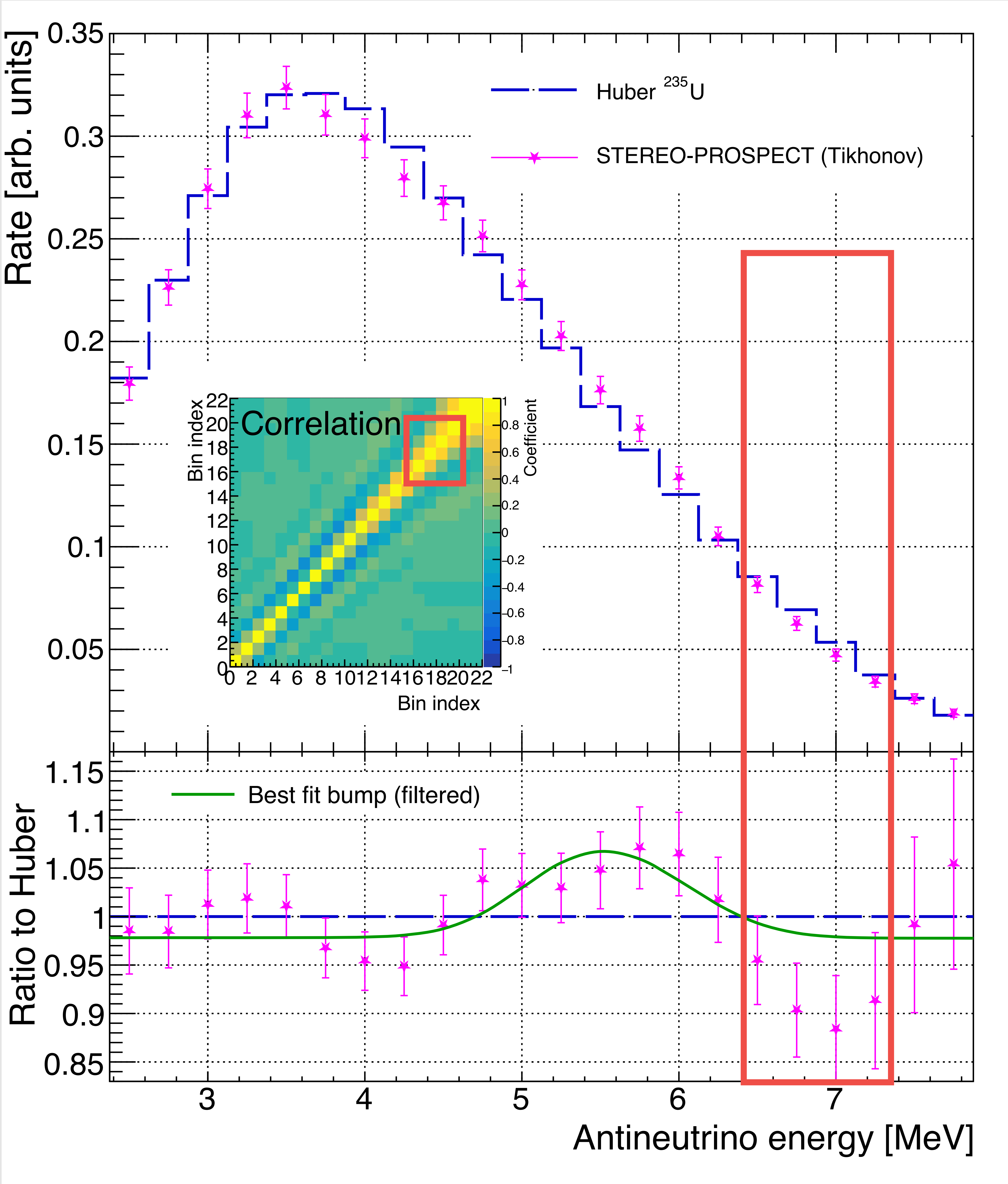
- The Ac, or smearing, matrix is used to apply the bias and smoothing effect from unfolding to a given spectrum in antineutrino energy
- This can and should be applied to models in true antineutrino energy to allow for an accurate comparison with the unfolded data
- The Ac matrix for the WienerSVD is:

$$D_{jnt} = \underbrace{C^{-1} V_C W_C V_C^T C}_{A_{C\,jnt}} (R^T (R R^T)^{-1} M_{jnt})$$

- For more information, please refer to arxiv:1705.03568

7 MEV DEFICIT SIGNIFICANCE

- Visually apparent deficit at 7 MeV (in the LEU bump region)
- Error bars imply more significant of a distortion than reality
- 7+ MeV region has much higher correlations than rest of spectrum
- Fitting a negative amplitude Gaussian shows significance of only 1.3σ



PROSPECT METHOD: WIENER-SVD UNFOLDING

- Singular Value Decomposition (SVD) on R

$$R = UDV^T$$

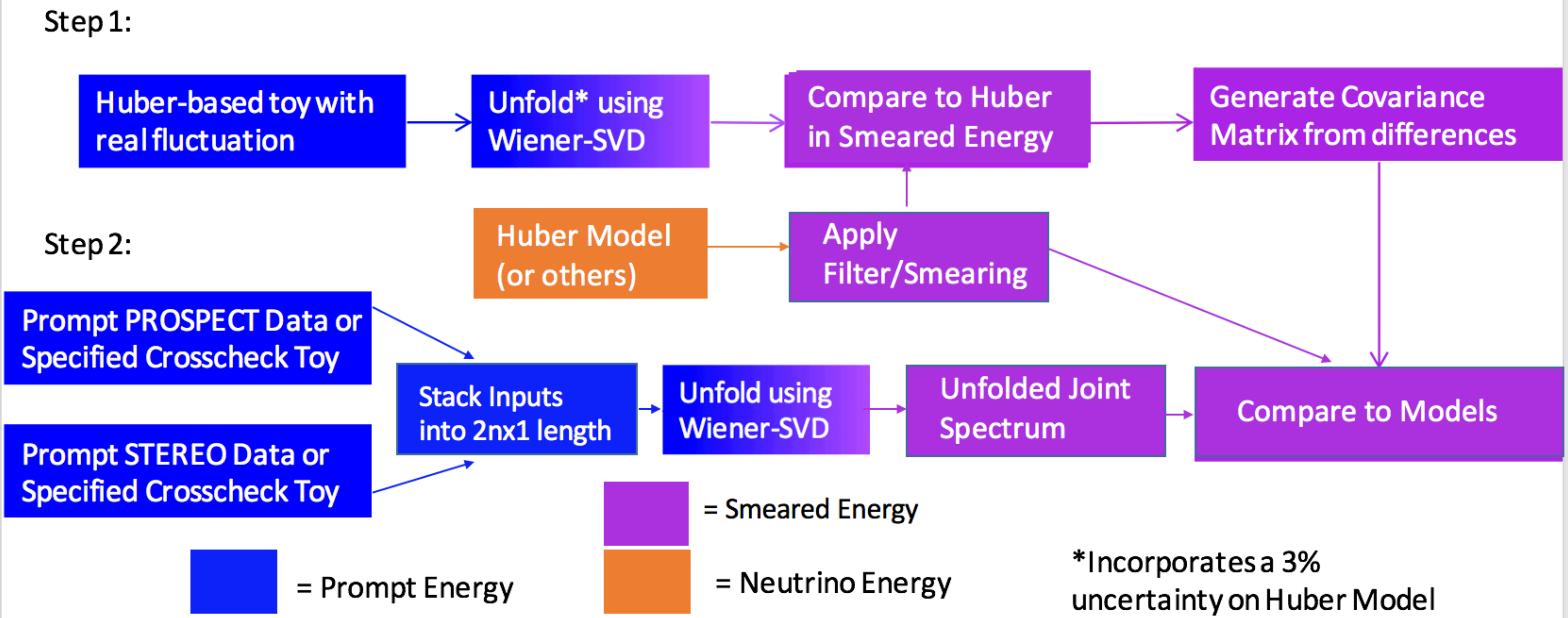
- Where D is a diagonal matrix of singular value in decreasing order (U and V are orthogonal matrices)
- If the elements d_i in D get too small, then D^{-1} will cause noise in M to blow up when calculating S.
- Use a Wiener filter W to keep d_i from getting too small

$$S = R^{-1} \times M = V(WD)^{-1}U^T \times M$$

  - See arXiv 1705.03568

JOINT WIENERSVD UNFOLDING

Uses 10,000 Huber-based toys produced by with Huber Model, folded into prompt energy, and given real, data-driven fluctuations



*Incorporates a 3% uncertainty on Huber Model for unfolding

STEREO METHOD: TIKHONOV REGULARIZATION

- Writing of the regularized χ^2 to be minimized:

$$\chi^2_{joint}(\Phi,\alpha) = (D_{ST} - R_{ST}\Phi)^T V_{ST}^{-1}(D_{ST} - R_{ST}\Phi) + (D_{PR} - \alpha * R_{PR}\Phi)^T V_{PR}^{-1}(D_{PR} - \alpha * R_{PR}\Phi) + \lambda * R(\Phi)$$

  - α is a normalization parameter to account for PROSPECT's spectrum normalization.
  - $R(\Phi)$ is a regularization term that can be written with the first or second discrete derivative of the deviation to the HM prior shape:

$$R(\Phi) = R_1(\Phi) = \sum_i \left(\frac{\Phi_{i+1}}{\Phi_{i+1}^{HM}} - \frac{\Phi_i}{\Phi_i^{HM}}\right)^2 := \Phi^T M_1 \Phi$$

$$R(\Phi) = R_2(\Phi) = \sum_i \left(\frac{\Phi_{i+1}}{\Phi_{i+1}^{HM}} - 2\frac{\Phi_i}{\Phi_i^{HM}} + \frac{\Phi_{i-1}}{\Phi_{i-1}^{HM}}\right)^2 := \Phi^T M_2 \Phi$$

  - λ is the regularization strength trading-off the agreement to the data and the smoothness of the unfolding. It is tuned following the GCV prescription[1].

- Unfolded spectrum reads:

$$\hat{\Phi} = \underbrace{\left(R_{ST}^T V_{ST}^{-1} R_{ST} + \alpha^2 R_{PR}^T V_{PR}^{-1} R_{PR}\right.}_{\text{Classical unfolding part (unregularized)}} \left. + \underbrace{\lambda M_{1,2}}_{\text{Regularization contribution}}\right)^{-1} (R_{ST}^T V_{ST}^{-1} D_{ST} + \alpha R_{PR}^T V_{PR}^{-1} D_{PR})$$

Data Spectra

14/8/21

11

[1]Grace Wahba, Gene H. Golub, Michael Heath, "Generalized Cross-Validation as a Method for Choosing a Good RidgeParameter, Technometrics", Vol. 21, NO. 2, May 1979.