Probing Supernova Neutrinos with the 20-inch PMT System in JUNO

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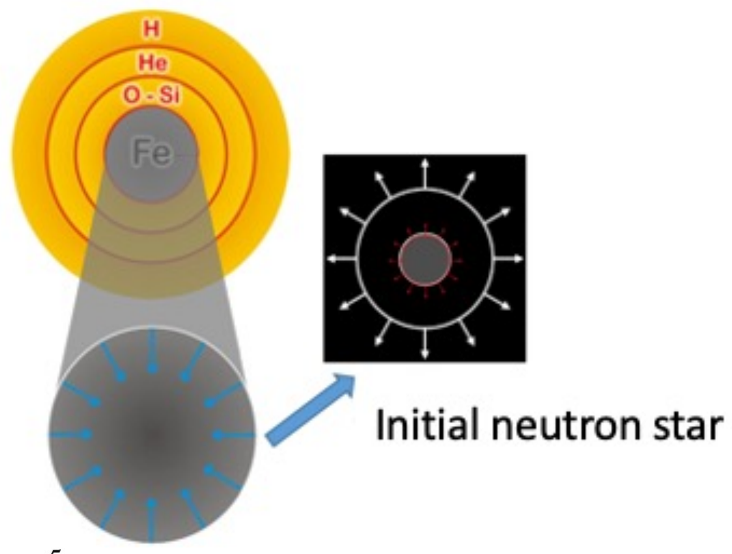
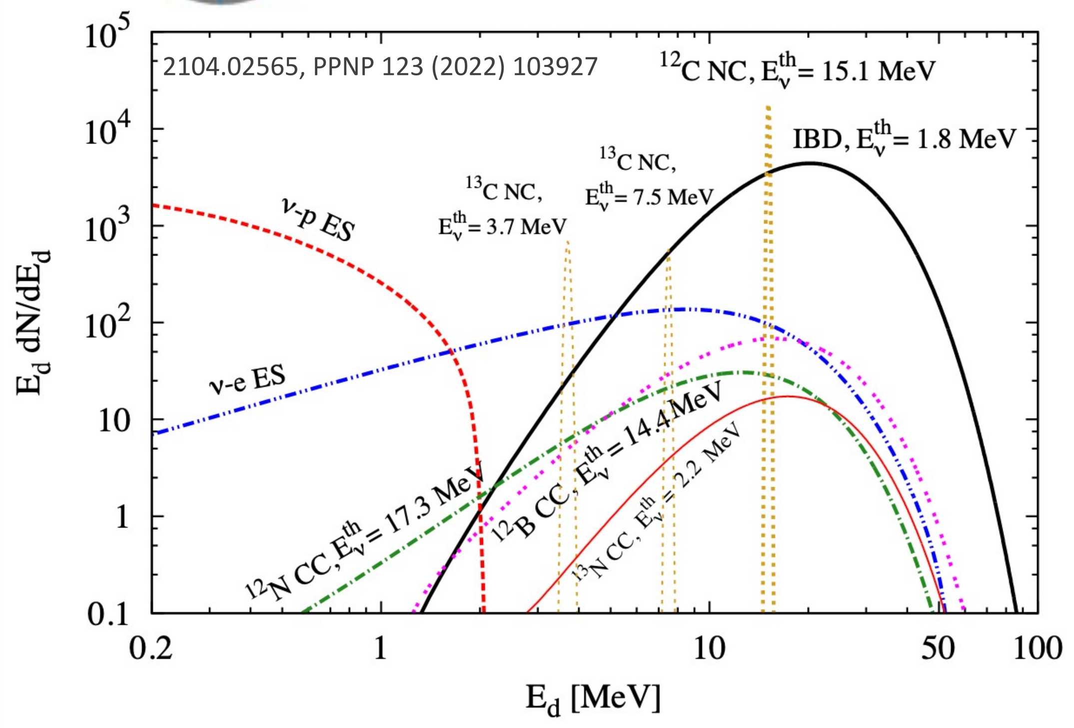
1. Core-Collapse SuperNova (CCSN) Detection in JUNO



- About 1-3 supernovae in our galaxy per century.
- 99% of the binding energy goes to neutrinos.
- Explosion time scale ~ 10 s



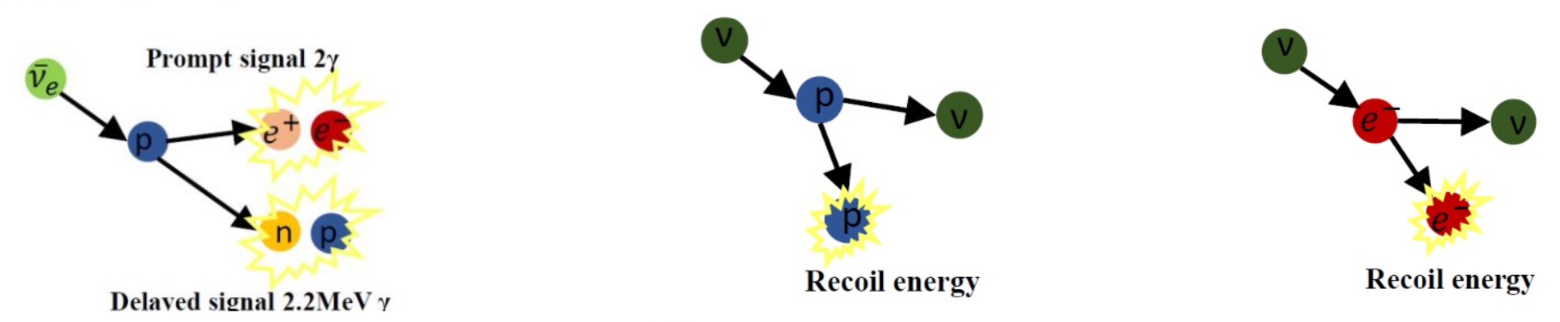
Motivation

- Details of the SN neutrino spectra are still unknown. JUNO can reconstruct the energy spectra by a high-statistics observation of supernova neutrinos of different flavours.
- This will be helpful in understanding of SN neutrino production, flavour conversion and explosion mechanism.

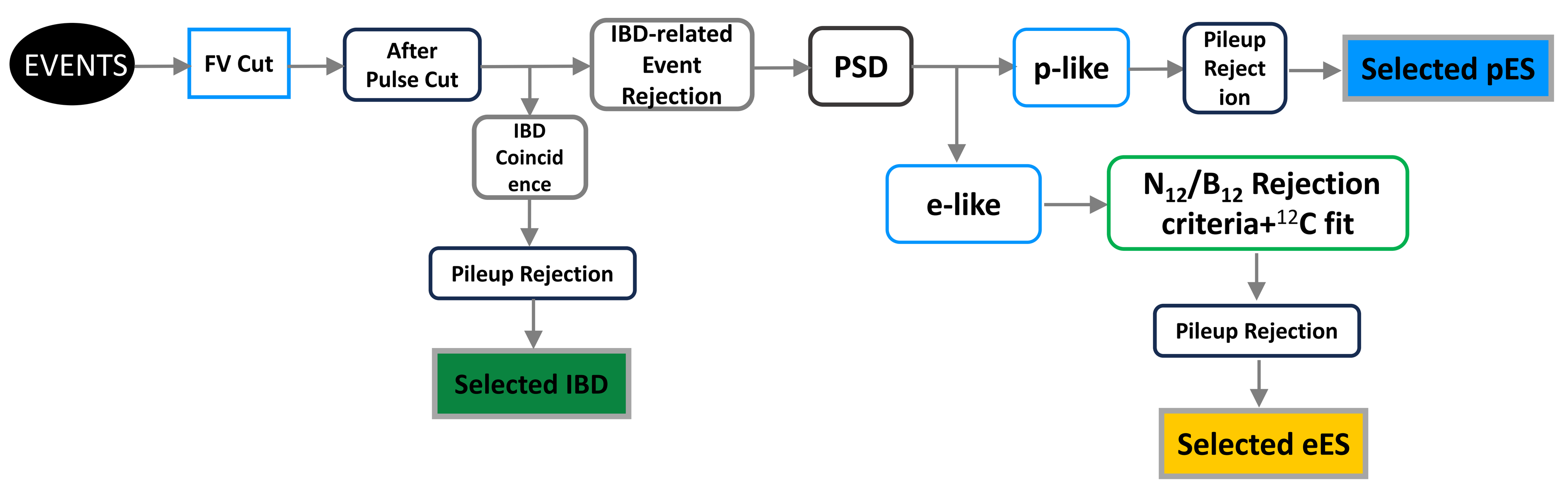
2. Detection Channels and Selection

Simulation includes Inverse Beta Decay (IBD), Electron Elastic Scattering (eES), Proton Elastic Scattering (pES), neutral current and charged current interactions on ^{12}C. After-pulse triggered events are also added.

(IBD) $\bar{\nu}_e + p \rightarrow e^+ + n$ (pES) $\nu + p \rightarrow \nu + p$ (eES) $\nu + e \rightarrow \nu + e$



In this work, only IBD, eES and pES are used to reconstruct the CCSN neutrino spectra.



- **Fiducial Volume (FV) cut:** avoid natural radioactivity from detector materials and rocks.
- **After-pulse cut**: use the correlation between the after-pulse event and the previous physical event.
- **IBD-related event rejection:** Loosen the IBD coincidence criteria. Remove those events where delayed signals can be paired with multiple prompt signals.
- **PSD**: Pulse Shape Discrimination, a machine learning model (Multilayer Perceptron) to discriminate eES from pES, based on their different hit time distribution patterns with all PMTs.
- **Pileup**: a trigger event contains photons from two or more interaction events.
- **Pileup rejection**: with a Pointnet++ machine learning model to discriminate pileup from non-pileup. Input info: PMT position (x, y, z), nPE in the PMT, first hit time in the PMT, and reconstruction qualities.

Work in Progress

	IBD	pES	eES
Purity	98.4%	96.5%	84.6%
Efficiency	95.8%	91.3%	70.0%

$$\text{Purity} = \frac{N_{sel}^{sig}\ \text{(triggered signals in selection)}}{N_{sel}\ \text{(all selected triggered events)}}$$

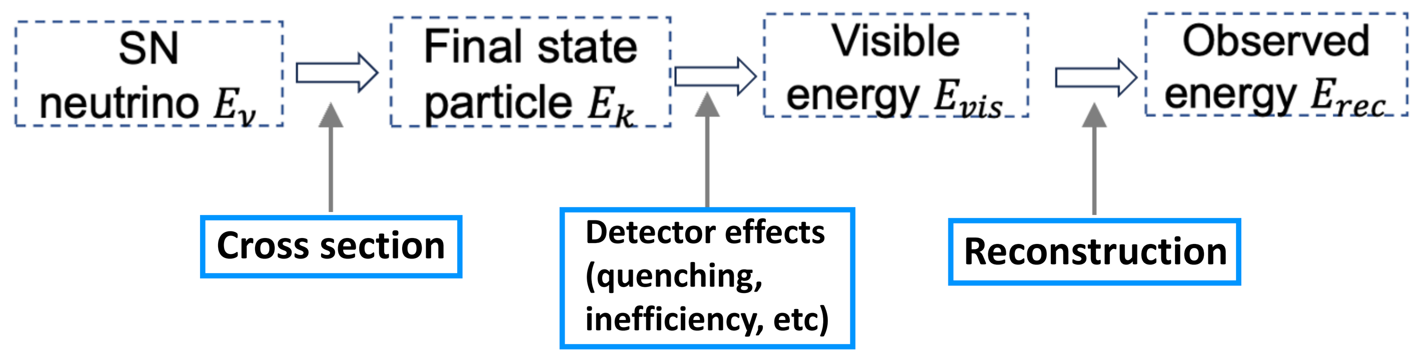
$$\text{Eff.} = \frac{N_{sel}^{sig}\ \text{(triggered signals in selection)}}{N_{truth}^{sig}\ \text{(all triggered signals)}}$$

- eES channel : low statistics. Main background: unpaired IBD events caused by pileup events

3. Unfolding Method

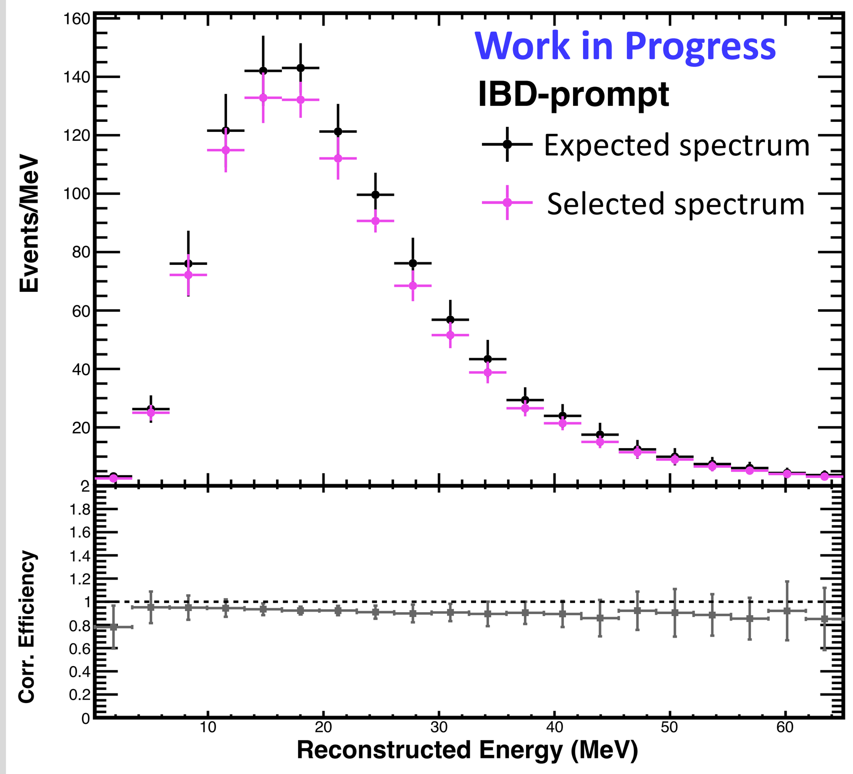
The relationship between the detector response (R), neutrino flux (F) and observed spectrum (S) can be described by a linear equation RF = S:

$$\begin{array}{c} \\ \text{IBD} \\ \text{pES} \\ \text{eES} \end{array} \begin{array}{c} \quad\nu_e \qquad\qquad \bar{\nu}_e \qquad\qquad \nu_x \\ \begin{bmatrix} N_p D_{IBD}\sigma_{\nu_e}^{IBD} & N_p D_{IBD}\sigma_{\bar{\nu}_e}^{IBD} & N_p D_{IBD}\sum\sigma_{\nu_x}^{IBD} \\ N_p D_{pES}\sigma_{\nu_e}^{pES} & N_p D_{pES}\sigma_{\bar{\nu}_e}^{pES} & N_p D_{pES}\sum\sigma_{\nu_x}^{pES} \\ N_e D_{eES}\sigma_{\nu_e}^{eES} & N_e D_{eES}\sigma_{\bar{\nu}_e}^{eES} & N_e D_{eES}\sum\sigma_{\nu_x}^{eES} \end{bmatrix} \end{array} \cdot \begin{bmatrix} F_{\nu_e} \\ F_{\bar{\nu}_e} \\ F_{\nu_x} \end{bmatrix} = \begin{bmatrix} S_{IBD} \\ S_{pES} \\ S_{eES} \end{bmatrix}$$

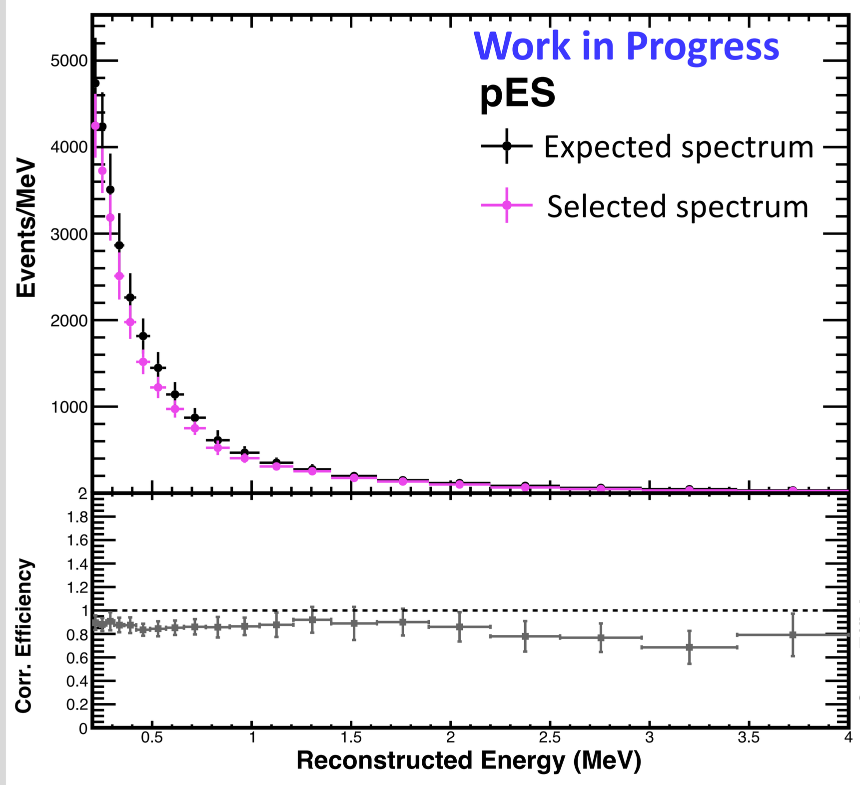


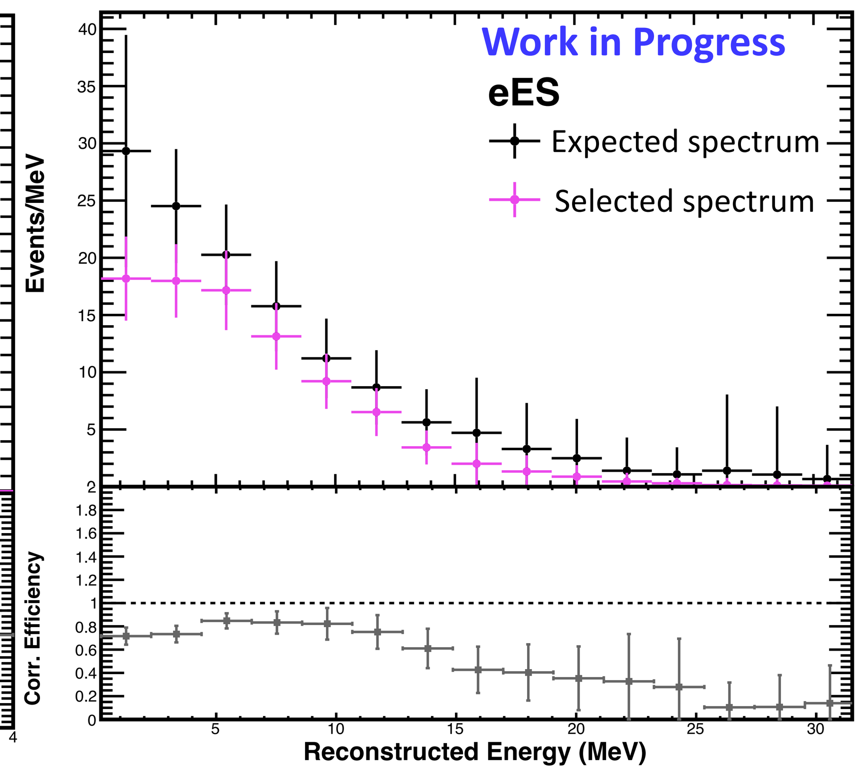
- The detector response matrix is obtained with energy threshold E_{th} = 0.2 MeV.
- These 9 interaction channels are separately simulated with a uniform spectrum.

4. Observed Spectrum

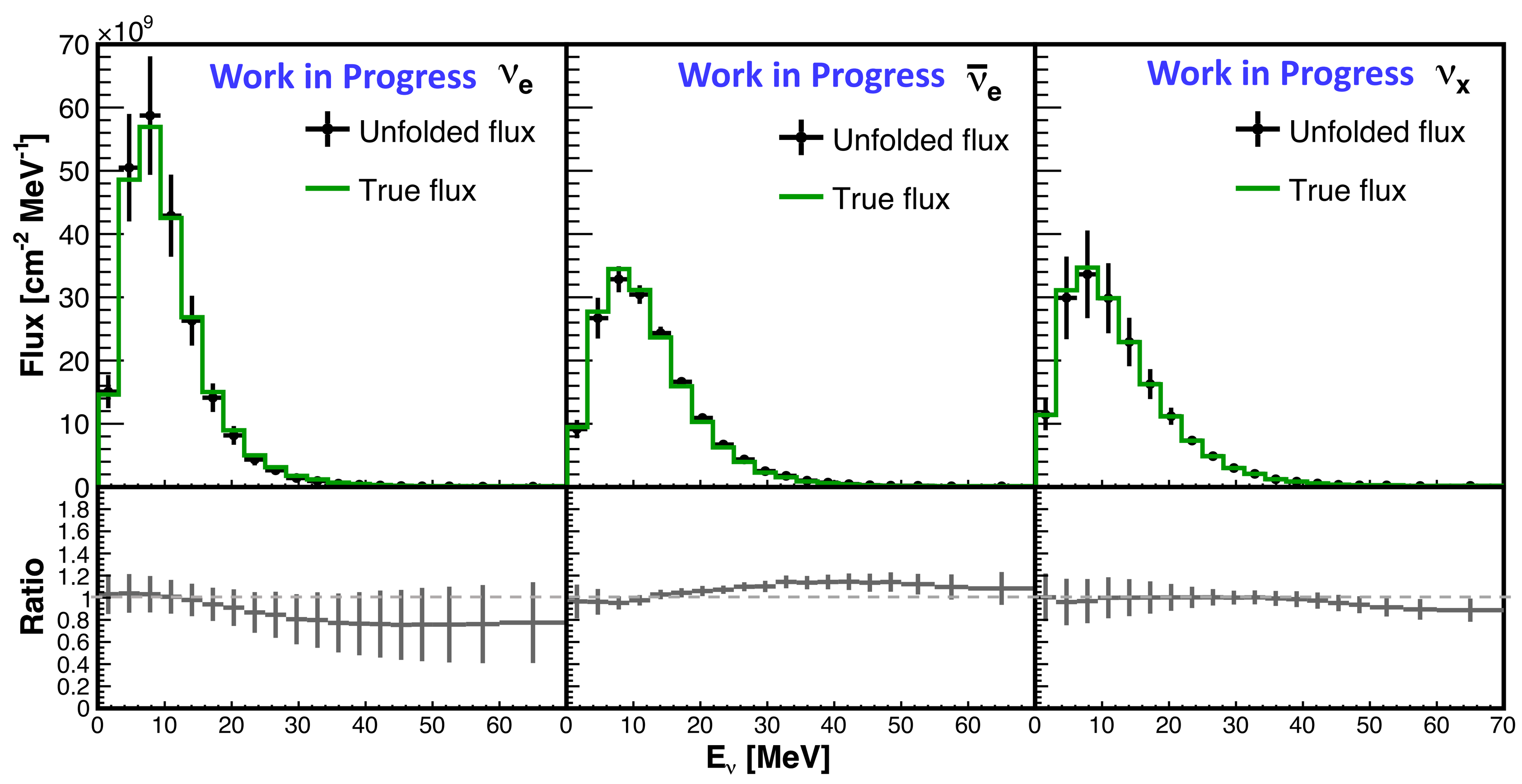


- Full chain simulation with the JUNO offline software for a 20 $M_\odot$ CCSN at 10 kpc from a Japan group mode [Astrophys. J. Suppl. 205, 2 (2013)].
- Use 50-explosion data.
- The selection efficiency includes the efficiency to remove the pileup effect.
- The expected spectrum is used as input (S) for the unfolding.





5. Unfolded Neutrino Spectra



- Only statistical errors are considered.
- Singular Value Decomposition (SVD) method to do the unfolding.
- Good agreement between the theoretical and the unfolded spectrum

References

[1] JUNO Collaboration, "JUNO Physics and Status", PPNP, 123 (20s22), 103927

[2] JUNO Collaboration,"Real-time monitoring for the next core-collapse supernova in JUNO", JCAP 01 (2024) 057

[3] Huiling Li, Xin Huang, et al. "Model-independent approach to the reconstruction of multi-flavor supernova neutrino energy spectra". Phys. Rev. D, 2019, 99(12): 123009.

6. Summary

- This analysis shows the workflow to reconstruct the CCSN neutrino spectra with the full simulation data in JUNO
- JUNO is capable of reconstructing the energy spectra of ν_e , $\bar{\nu}_e$ and ν_x through the unfolding approach.