Analysis of the evolution of the reactor antineutrino spectrum in the framework of the JUNO-TAO experiment

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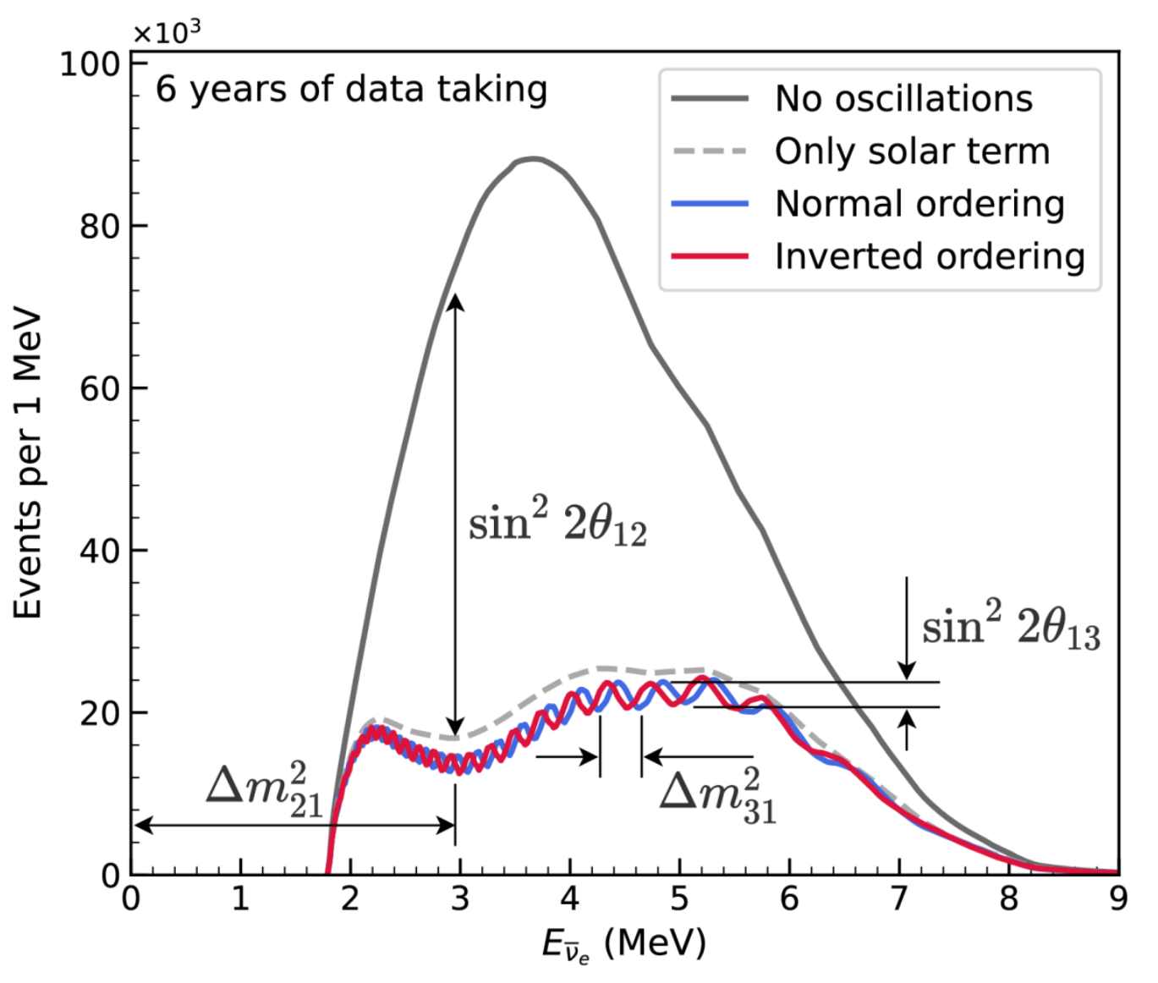
This poster presents the analysis tools that we are developing to simulate the evolution of the reactor $\bar{\nu}_e$ spectrum as a function of fuel burnup and to implement a summation $\bar{\nu}_e$ spectrum, based on most up-to-date nuclear data, to be used for future benchmark analyses of TAO data.

JUNO (JIANGMEN UNDERGROUND NEUTRINO OBSERVATORY)

- Primary physics goal: determine the neutrino mass ordering by measuring the electron antineutrino ($\bar{\nu}_e$) oscillations.
- 20 kton liquid scintillator detector surrounded by 17612 Large PMTs and 25600 Small PMTs.
- Excellent energy resolution: $3\%/\sqrt{E(\mathrm{MeV})}$.
- 700 m underground lab in southern China.
- ~ 53 km from two Nuclear Power Plants.
- Inverse Beta Decay (IBD) rate: 50 events/day.



JUNO collaboration, CPC 46, 123001 (2022)

TAO (TAISHAN NEUTRINO OBSERVATORY)

- TAO is a satellite experiment that will measure the $\bar{\nu}_e$ spectrum at 44 m from a reactor core at the Taishan NPP, to provide a reference spectrum for JUNO.
- Taishan NPP comprises 2 Pressurized Water Reactors (PWR), EPR type, each with 4.6 GW thermal power.

Taishan Nuclear Power Plant (NPP), Units 1 & 2, Guangdong, China

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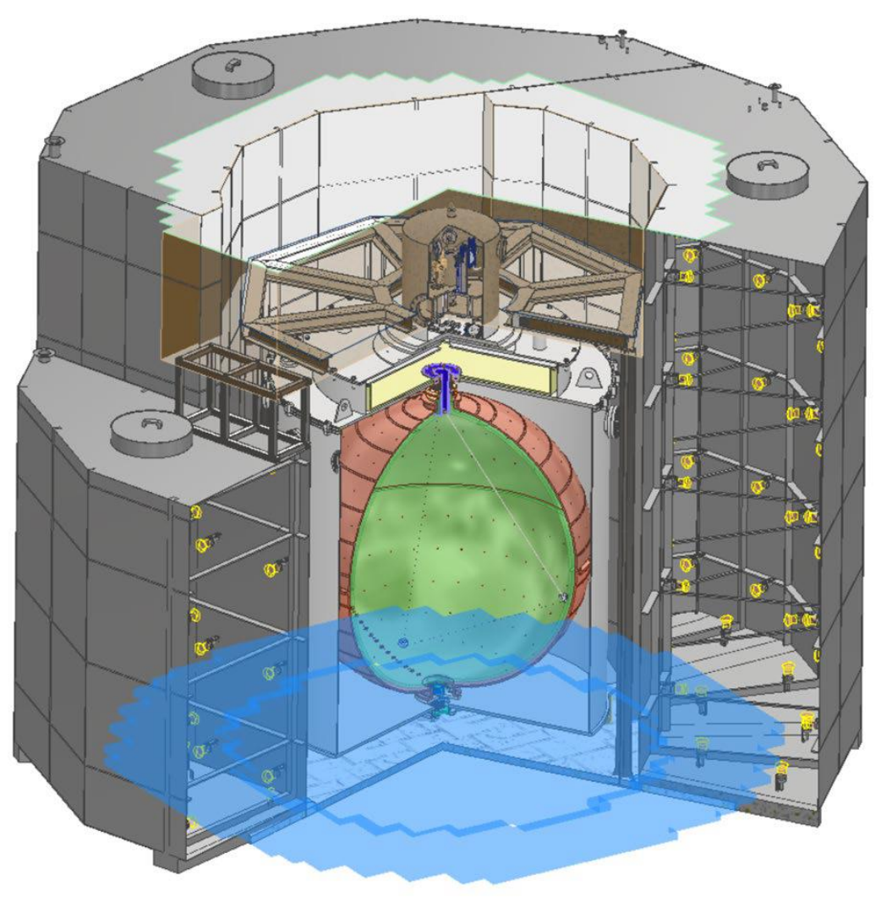


- TAO will measure the reactor $\bar{\nu}_e$ spectrum with **unprecedented energy resolution**: $< 2\%/\sqrt{E(\mathrm{MeV})}$, → experimental benchmark for nuclear databases.
- Gd-doped liquid scintillator (1-ton fiducial volume).
- SiPMs of $> 50\%$ photon detection efficiency and near complete geometrical coverage, operated at -50 °C to lower the dark noise.
- IBD rate: 2000 events/day.

SUMMATION METHOD FOR REACTOR $\bar{\nu}_e$ SPECTRUM MODELLING

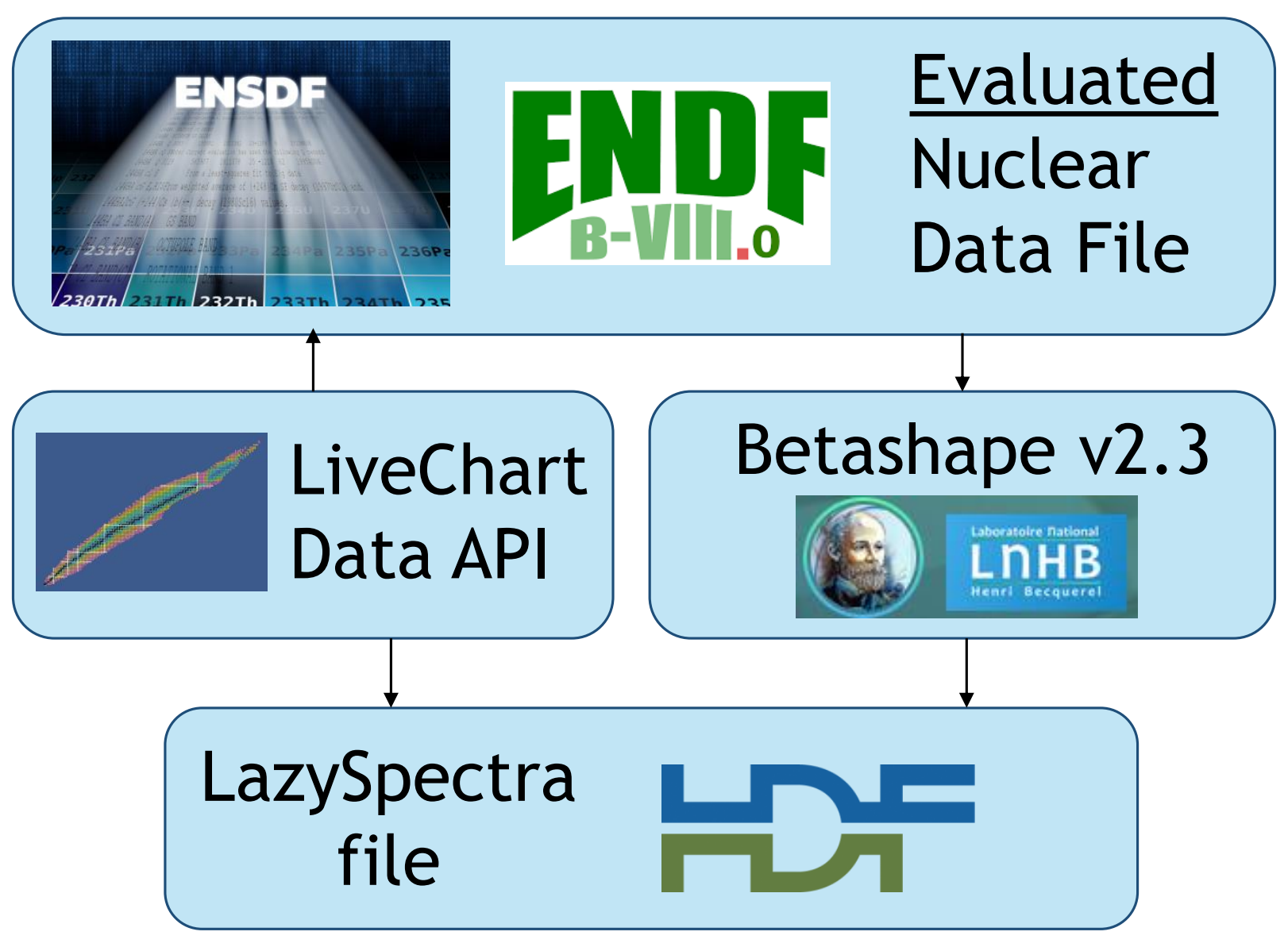
Reactor $\bar{\nu}_e$ spectrum:

$$S(E_\nu,t)=\sum_i \underbrace{f_i(t)}_{\text{Fission fraction}}\underbrace{S_i(E_\nu,t)}_{\text{Spectrum of }\bar{\nu}_e\text{ per fission of }i\text{-th nuclide}}=\sum_i f_i(t)\frac{\sum_j \overbrace{A_{i,j}(t)}^{}\ \overbrace{S_j(E_\nu)}^{\bar{\nu}_e\text{ spectrum of }j\text{-th fission product}}}{\sum_j \underbrace{A_{i,j}(t)}_{\beta^-\text{ decay activity of }j\text{-th fission product of nuclide }i}}$$

i labels the 4 main fissile nuclides in a PWR: ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu

THE LAZYSPECTRA TOOL

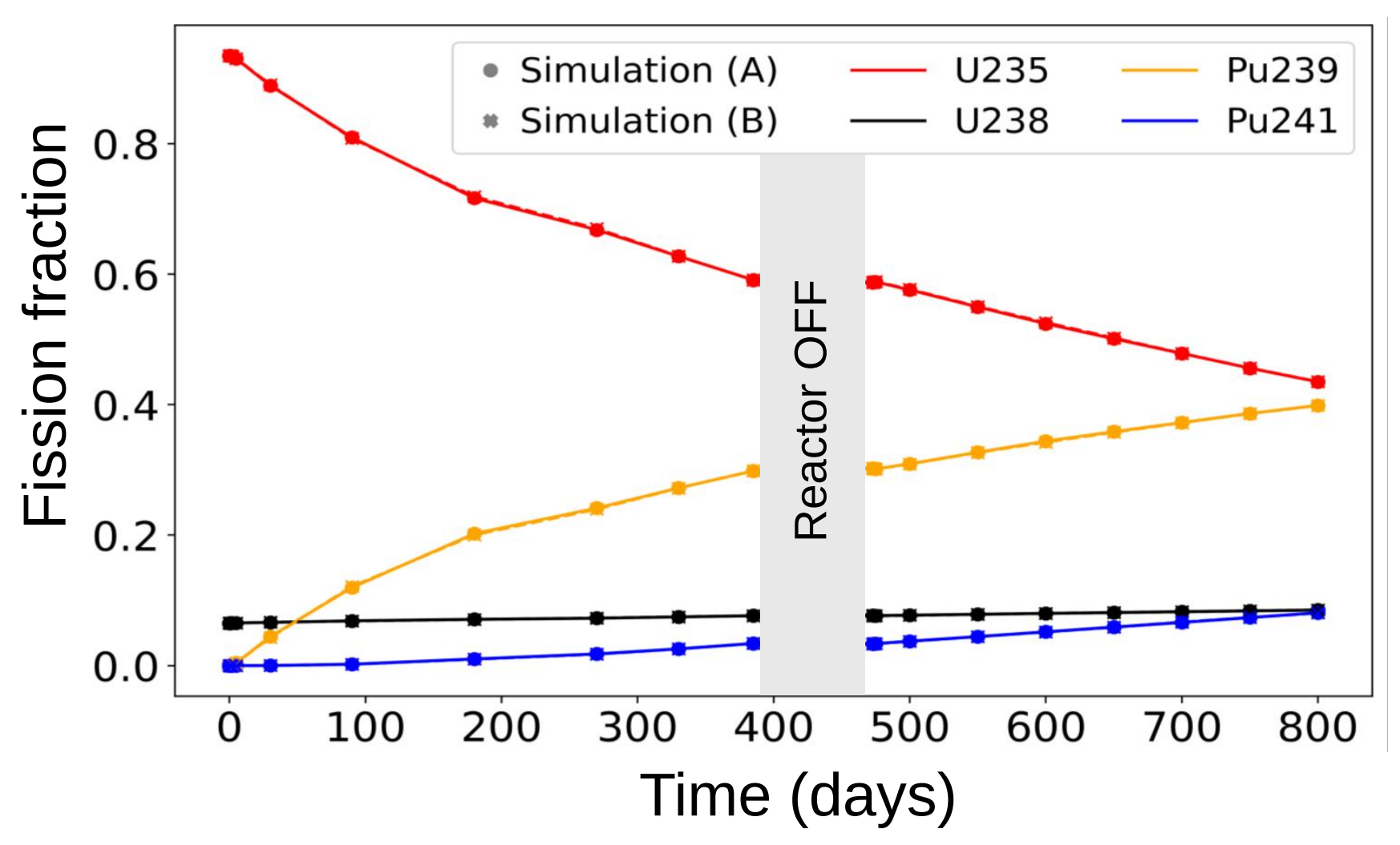
- Goal: build a summation $\bar{\nu}_e$ spectrum to be used for the analysis of TAO data (e.g. fine structures).
- Up to date with the latest nuclear data.
- State-of-the-art tool for calculating the $\bar{\nu}_e$ spectra $S_j(E_\nu)$ [1].
- Philosophy: don't reinvent the wheel.

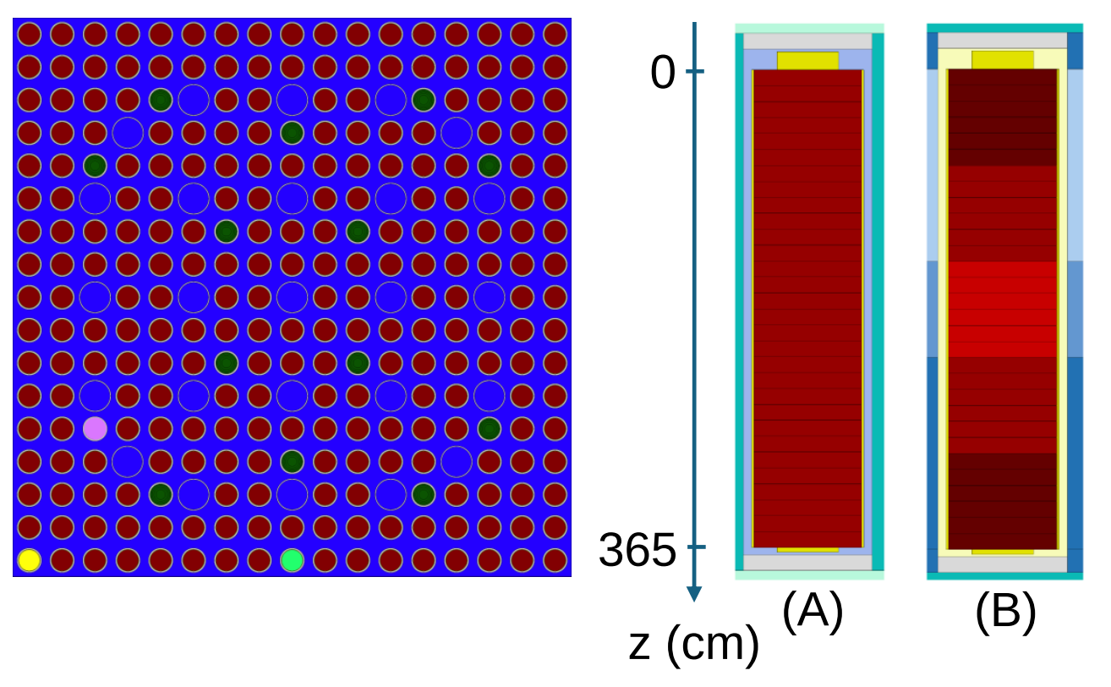


REACTOR FUEL BURNUP ANALYSIS

- Reactor simulations to predict fission fractions $f_i(t)$ and activities of fission products $A_{i,j}(t)$
- MC simulations of neutronics and calculation of fuel burnup using the Serpent (v2) code.
- Benchmark analysis with experimental data of fuel burnup available in literature for a PWR (Takahama-3) → arXiv:2311.12540

Serpent
a Continuous-energy Monte Carlo neutron and photon transport code
Leppänen, J., *et al* Ann. Nucl. Energy, 82 (2015) 142-150





Horizontal cutaway of a fuel assembly of the Takahama-3 (left); two models of the temperatures along the vertical axis of a fuel pin (right).

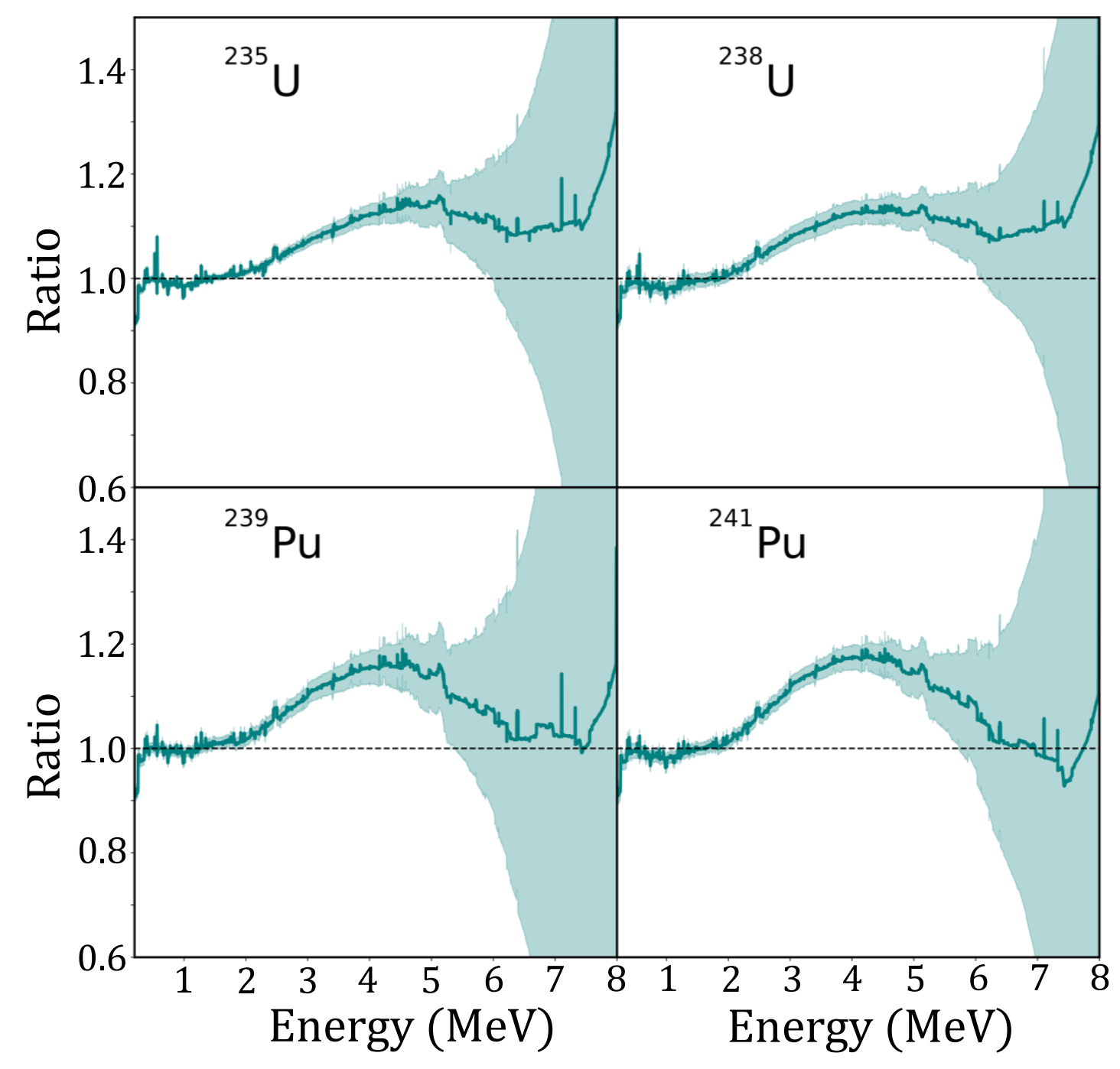
BUILDING THE REACTOR $\bar{\nu}_e$ SPECTRUM AT EQUILIBRIUM WITH LAZYSPECTRA

- Most fission products have relatively short half lives and quickly reach the equilibrium condition (production rate = decay rate).

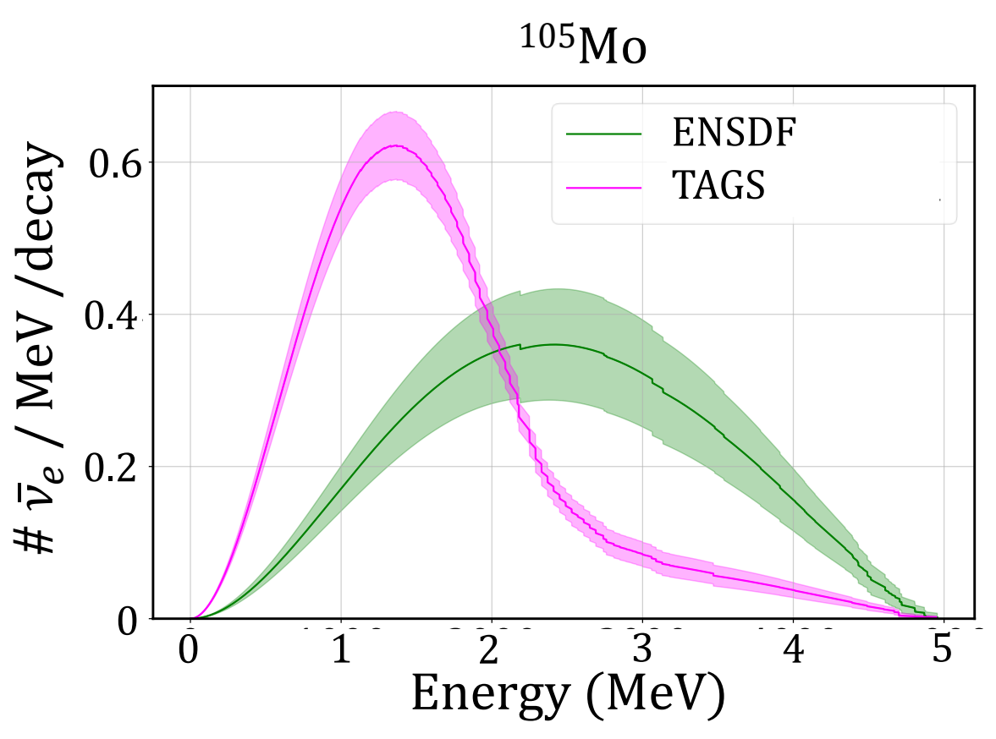
$$\underbrace{A_{i,j}\propto y_{i,j}}_{\text{Cumulative fission yields}}\quad\Longrightarrow\quad S(E_\nu,t)\propto\sum_i f_i(t)\sum_j y_{i,j}\,S_j(E_\nu)$$

- **Pandemonium effect correction** [2,3] with the Total Absorption Gamma Spectroscopy (TAGS) data (*).

$S_i(E_\nu,t)$ spectra ratio without vs with TAGS data correction

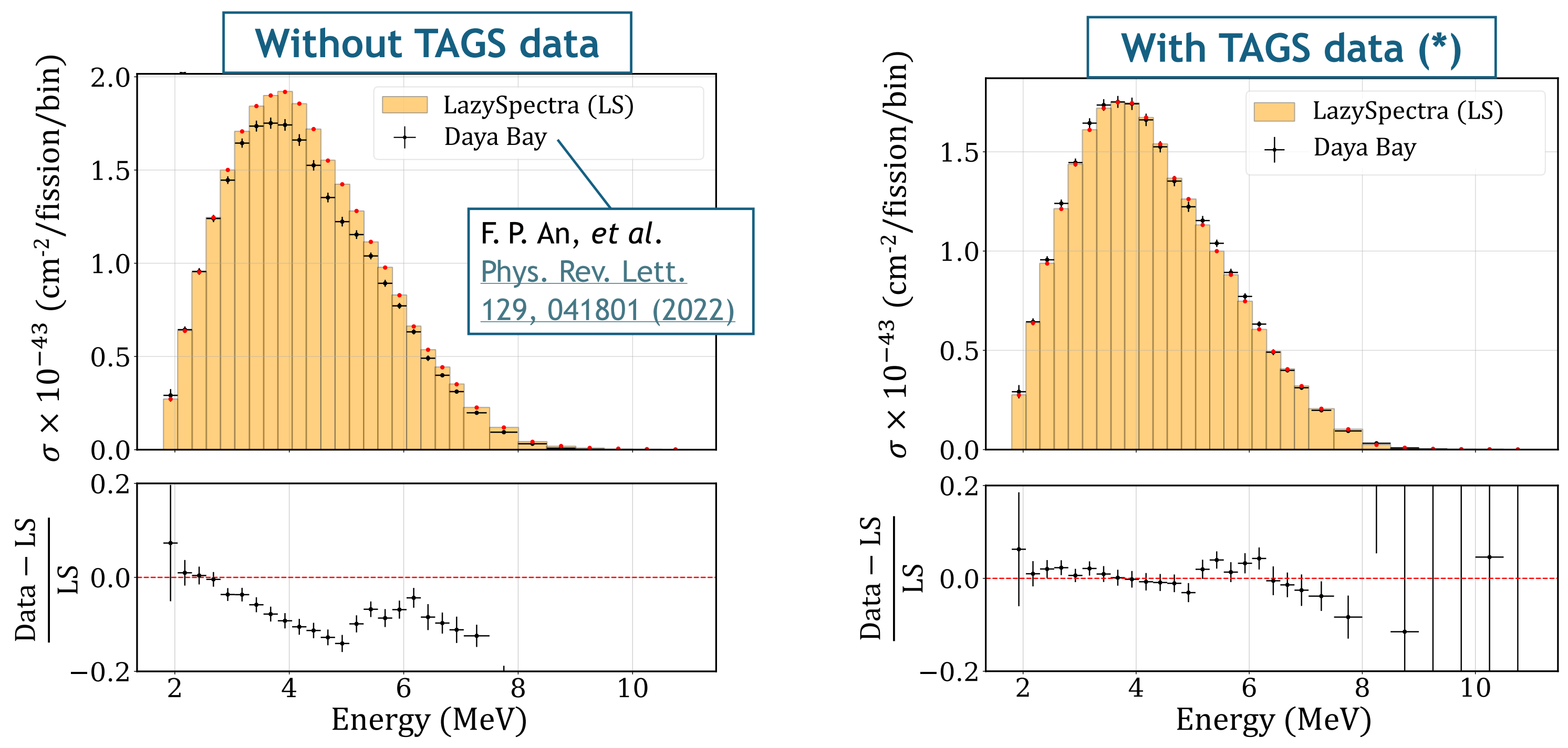


$S_j(E_\nu)$ spectrum of ^{105}Mo built with or without using TAGS corrected data



PRELIMINARY RESULTS AND NEXT STEPS

- We compare our summation $\bar{\nu}_e$ spectra (multiplied by IBD cross section) with experimental data from Daya Bay.



F. P. An, *et al.* Phys. Rev. Lett. 129, 041801 (2022)

In the next future we will focus on:

- assessment of uncertainties and impact of missing β^- decay nuclear data;
- full core analysis of EPR reactors to analyze fission fraction uncertainties.

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